Search for top squarks in the four-body decay mode with single lepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

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The CMS Collaboration*

Abstract

A search for the pair production of the lightest supersymmetric partner of the top quark, the top squark ($\tilde{t}_1$), is presented. The search targets the four-body decay of the $\tilde{t}_1$, which is preferred when the mass difference between the top squark and the lightest supersymmetric particle is smaller than the mass of the W boson. This decay mode consists of a bottom quark, two other fermions, and the lightest neutralino ($\tilde{\chi}^0_1$), which is assumed to be the lightest supersymmetric particle. The data correspond to an integrated luminosity of 138 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV collected by the CMS experiment at the CERN LHC. Events are selected using the presence of a high-momentum jet, an electron or muon with low transverse momentum, and a significant missing transverse momentum. The signal is selected based on a multivariate approach that is optimized for the difference between $m(\tilde{t}_1)$ and $m(\tilde{\chi}^0_1)$. The contribution from leading background processes is estimated from data. No significant excess is observed above the expectation from standard model processes. The results of this search exclude top squarks at 95% confidence level for masses up to 480 and 700 GeV for $m(\tilde{t}_1) - m(\tilde{\chi}^0_1) = 10$ and 80 GeV, respectively.

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*See Appendix A for the list of collaboration members

The CMS collaboration., Tumasyan, A., Adam, W. et al., J. High Energ. Phys. 2023, 60 (2023). https://doi.org/10.1007/JHEP06(2023)060

Structure

Chapter 1. The framework

SUSY – Introduction & motivations

Chapter 2. The process

The top squark four-body decay mode

Chapter 3. The details

Object & event basics, preselection, multivariate analysis, background estimation

Chapter 4. The results

Results, discussion & summary

The framework / SuSy – Introduction & Motivations

Motivating SuSy through the eletroweak hierarchy problem

Eletroweak scale ~ 10^2 GeV → SM works as an effective theory at this scale

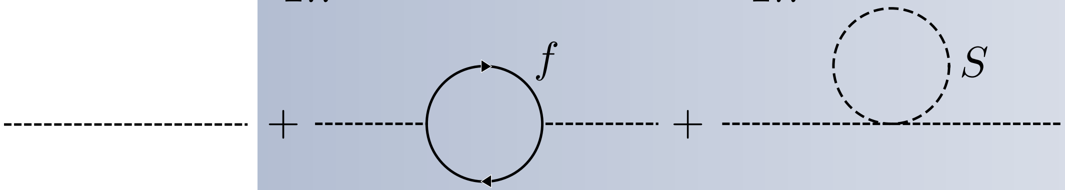
Planck scale ~ 10^{18} GeV → SM is not applicable as is...

Quadratic divergencies of the Higgs mass

Higgs mass :: Detected in 2012 to be 125 GeV

But to keep it so at the Planck scale would require *a lot* of fine-tunning

$$M_H^2 \sim M_{H0}^2 + \frac{g_f^2}{4\pi^2}\left(\Delta^2 + m_f^2\right) - \frac{g_S^2}{4\pi^2}\left(\Delta^2 + m_S^2\right)$$



Quadratic corrections

Δ goes with the energy scale

But that minus sign...

Introducing SuSy :: SuperSymmetry

$g_f = g_S$ → Quadratic terms cancel → Higgs mass remains stable under energy scale

Spacetime symmetry with generators Q :: $Q|\text{Fermion}\rangle = \text{Boson}$, $Q|\text{Boson}\rangle = \text{Fermion}$

Superpartners	Changes spin	Supermultiplet
up quark → up squark (sup)	spin-0 → spin-1/2	Equal mass & quantum numbers

R-parity

Necessary to tackle the baryon and lepton number violating terms. Consequences:

→ SuSy particles are always pair produced from SM particles

→ A SuSy particle must decay to at least one other SuSy particle

→ There exists an LSP (Lightest SuSy Particle) :: Neutral, massive & weakly interact.

The framework / SuSy – Introduction & Motivations

SuperSymmetry breaking

If superpartners of SM particles have equal masses, why haven't we detected them?

$\rightarrow$ Symmetry must be spontaneously broken in Nature

Minimal SuSy SM (MSSM) :: Introduces a soft SuSy breaking term

124 free parameters, able to be further simplified to a smaller phase space

SuSy searches :: What is interesting to start searching now?

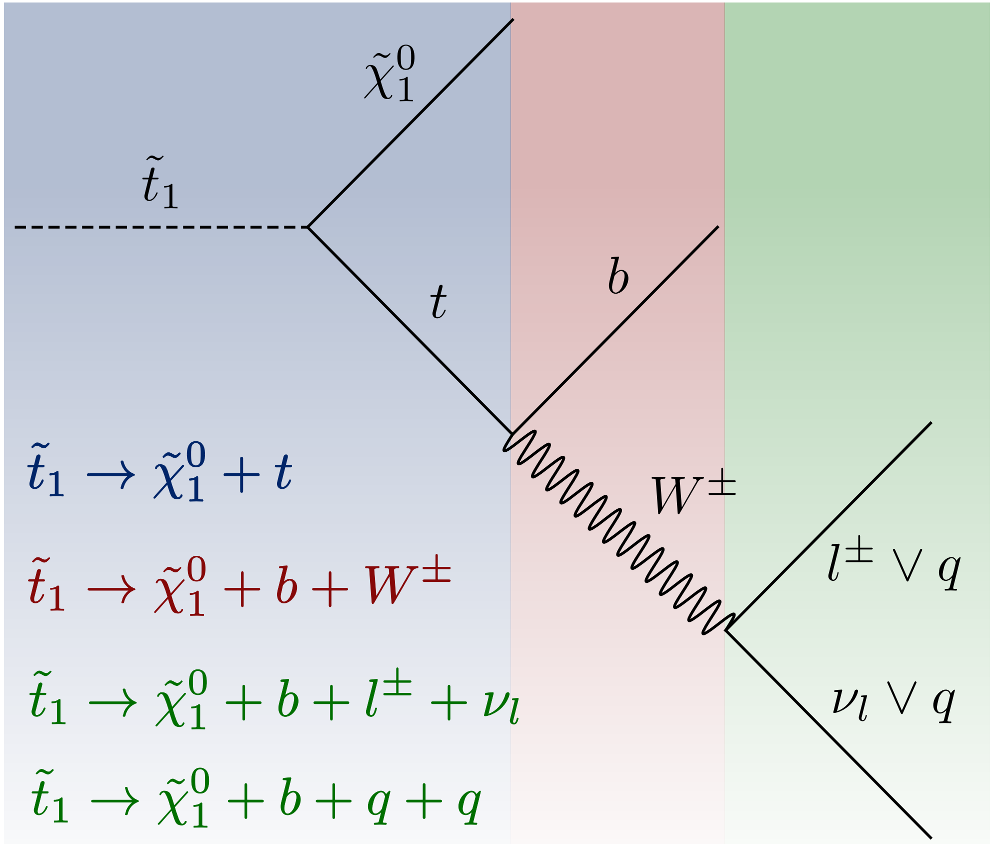
Processes that allow access to LSP :: Assumed to be the lightest neutralino

High t mass $\rightarrow$ Largest mass splitting to its superpartners $\rightarrow$ Lightest *stop* (NLSP)

Cosmological data suggests compressed mass regime $\rightarrow$ Small Δm(NLSP - LSP)

The process / Top squark four-body decay

Decay modes of the stop



$\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 + t$

$\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 + b + W^{\pm}$

$\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 + b + l^{\pm} + \nu_l$

$\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 + b + q + q$

Two-body decay

Larger than top quark :: Δm $>$ 170 GeV

Three-body decay

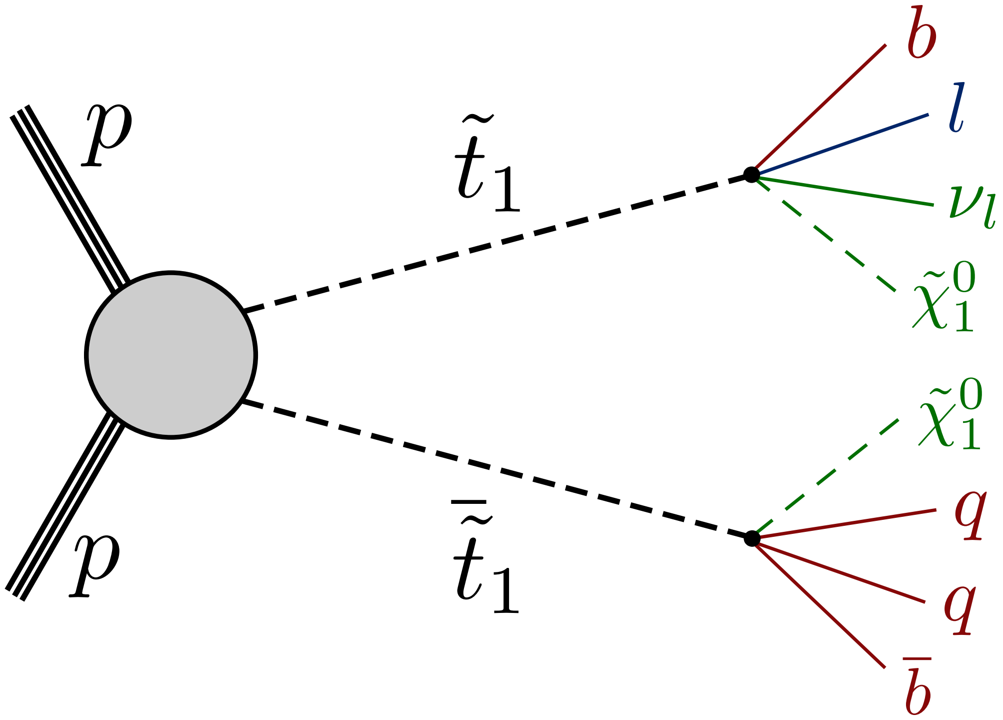
Larger than W-boson :: Δm $>$ 80 GeV

Four-body decay

Compressed mass regime :: Δm $<$ 80 GeV

The process / Top squark four-body decay

***pp* collison at $\sqrt{s}$ = 13 TeV**



Dataset

2016 analysis + 2017 & 2018 data

Total L_{int} = 138 fb^{-1}

Experimental signature

→ Single lepton

→ Large MET (p_T^{miss})

→ 4 jets (2 of them b-jets)

The details / Object & event basics

Background processes

W + jets Z + ννbar + jets multi-jet ttbar single-t diboson ttbar + X

Sampled phase space

$m(\tilde{t}_1) = \{250, 275, ..., 775, 800\}$ GeV $\Delta m = \{10, 20, ..., 70, 80\}$ GeV

CMS PF algorithm

5 candidates

→ e, μ, γ

→ Charged hadrons

→ Neutral hadrons

Jets: $|\eta| < 2.4$, $p_T > 30$ GeV, **b-tagging:** Loose-to-tight (90-99.9%)

Prompt leptons (PV origin: $|d_{xy}| < 0.02$ **cm,** $|d_z| < 0.1$ **cm*)***

$I_{abs} < 5$ GeV ($p_T < 25$ GeV), $I_{rel} < 0.2$ ($p_T > 25$ GeV)

Electrons: $|\eta| < 2.5$, $p_T > 5$ GeV, Loose (90%)

Muons: $|\eta| < 2.4$, $p_T > 3.5$ GeV, Loose (98%)

The details / Preselection

Online selection

Data events → $p_T^{miss} > 120$ GeV, $H_T^{miss} > 120$ GeV (Jet-only MET)

Due to increasing L_{int} year-on-year → $H_T > 60$ GeV (All jets scalar p_T sum)

SuSy processes vs. SM processes

Neutralinos existence → More MET than a typical SM process → $p_T^{miss} > 280$ GeV

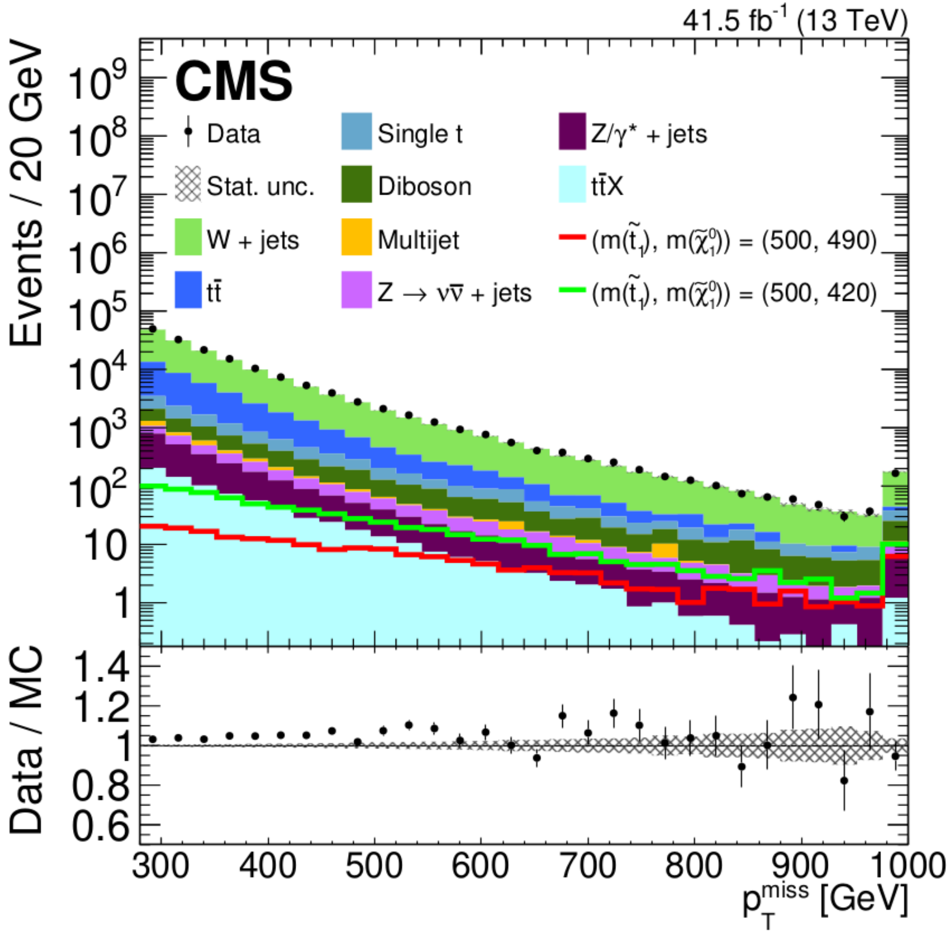
Suppression of SM processes

Background contribution: W + jets (70%), ttbar (20%), remaining (10%)

Suppressing :: W + jets → $H_T > 200$ GeV, ttbar → One e or μ + One jet

Require hard ISR :: Boosts neutralinos → Leading jet $p_T > 110$ GeV

The details / MET distribution of 2017 data after preselection



From this distribution

Agreement between data & simulation

→ Motivates use of simulated distributions

Two different Δm regions showcased

→ Slightly different behaviors

Alongisde $p_T(l)$ & N_{jet} distributions

No discrepancy between 2017 & 2018 data

Distributions are quite different

→ Motivates multivariate analysis

The details / Multivariate analysis → Boosted Decision Trees (BDTs)

Discriminating variables

Preselected events are fed to train BDTs → One per Δm region

Set of 12 variables serve as inputs to BDTs → Return BDT output

→ MET related :: p_T^{miss}, m_T

→ Lepton related :: $p_T(l)$, $\eta(l)$, $Q(l)$

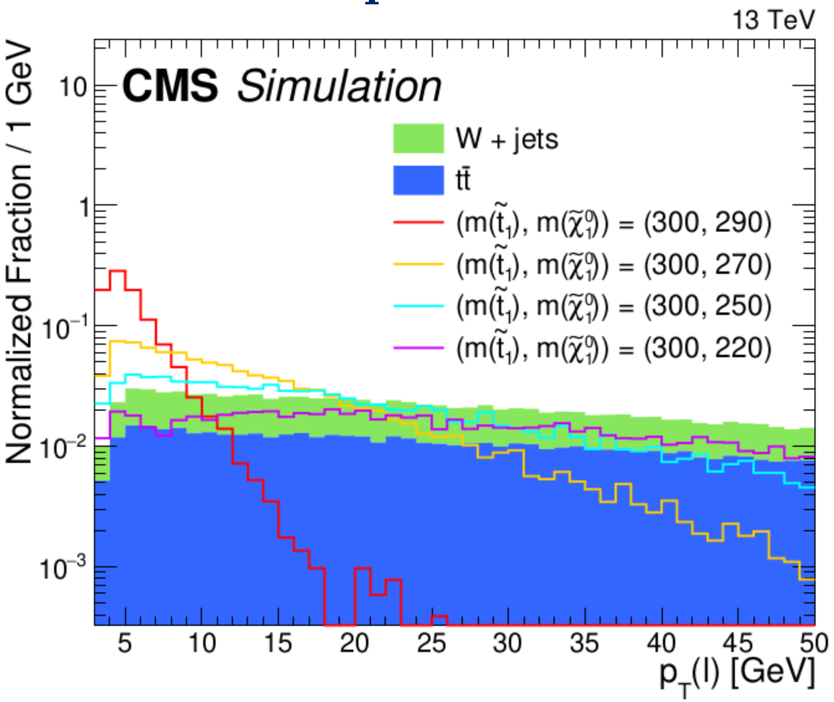
→ Jet related :: p_T^{ISR}, $p_T(b)$, N_{jet}, H_T

→ b-jet related :: $N_{loose}(b)$, $\Delta R(l, b)$, $D(b)$

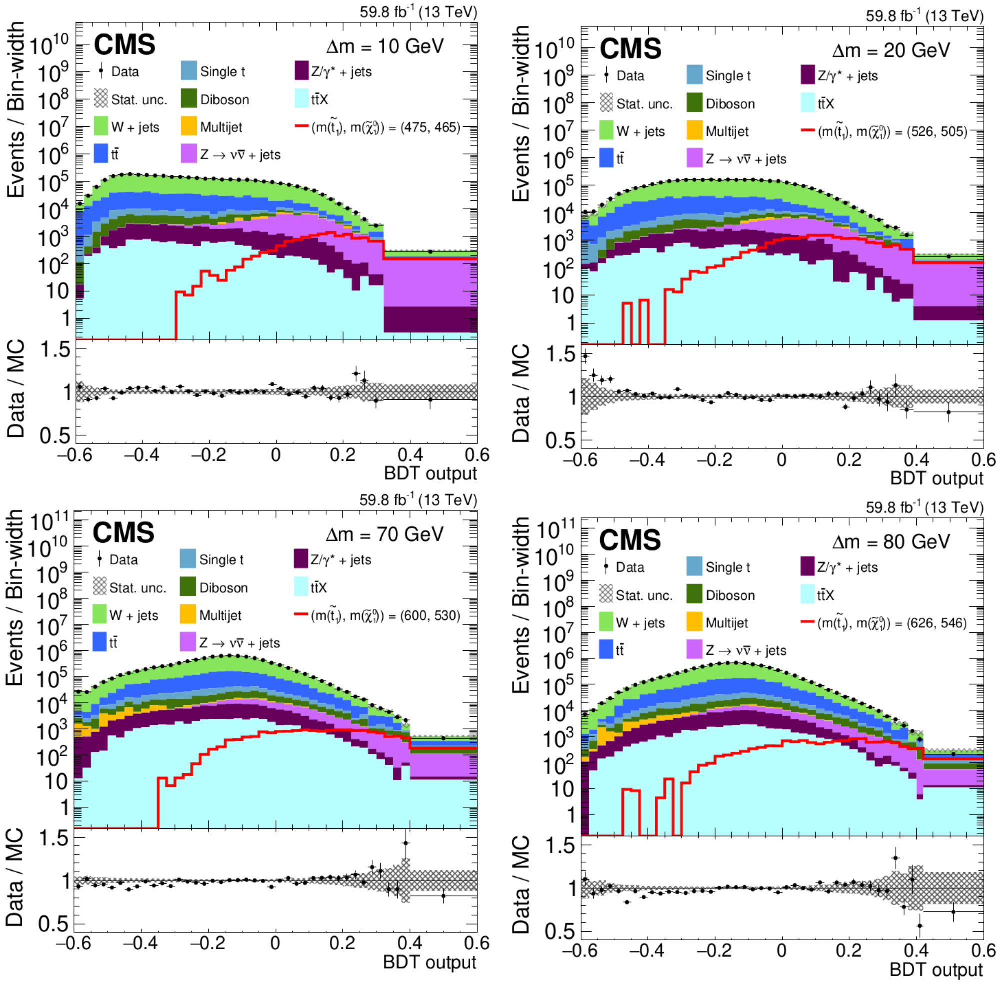
Discriminate signal vs. background

Large sensativity to Δm ⟼

Little sensativity to *stop* mass



The details / BDT output distributions of 2018 data for four Δm regions



BDT output interpretation

Closer to -1 :: Background-like

Closer to +1 :: Signal-like

BDT output signal thresholds ~ [0.3, 0.4]

Minimize expected upper limit of σ

Background suppression ~ 10^3

Important regions

Last bins → SRs

Near SRs to validate simulation → VRs

Data driven background rich → CRs

The details / Background estimation

Prompt background

W + jets, ttbar

Nonprompt background

Z + νν̄bar + jets, multi-jet

Background yield estimates

$$Y_{\mathrm{np}}^{\mathrm{SR}} = \frac{\epsilon_{\mathrm{TL}}}{1-\epsilon_{\mathrm{TL}}}\left[N^{\mathrm{L!T}}(\mathrm{Data}) - N_{\mathrm{p}}^{\mathrm{L!T}}(\mathrm{MC})\right]$$

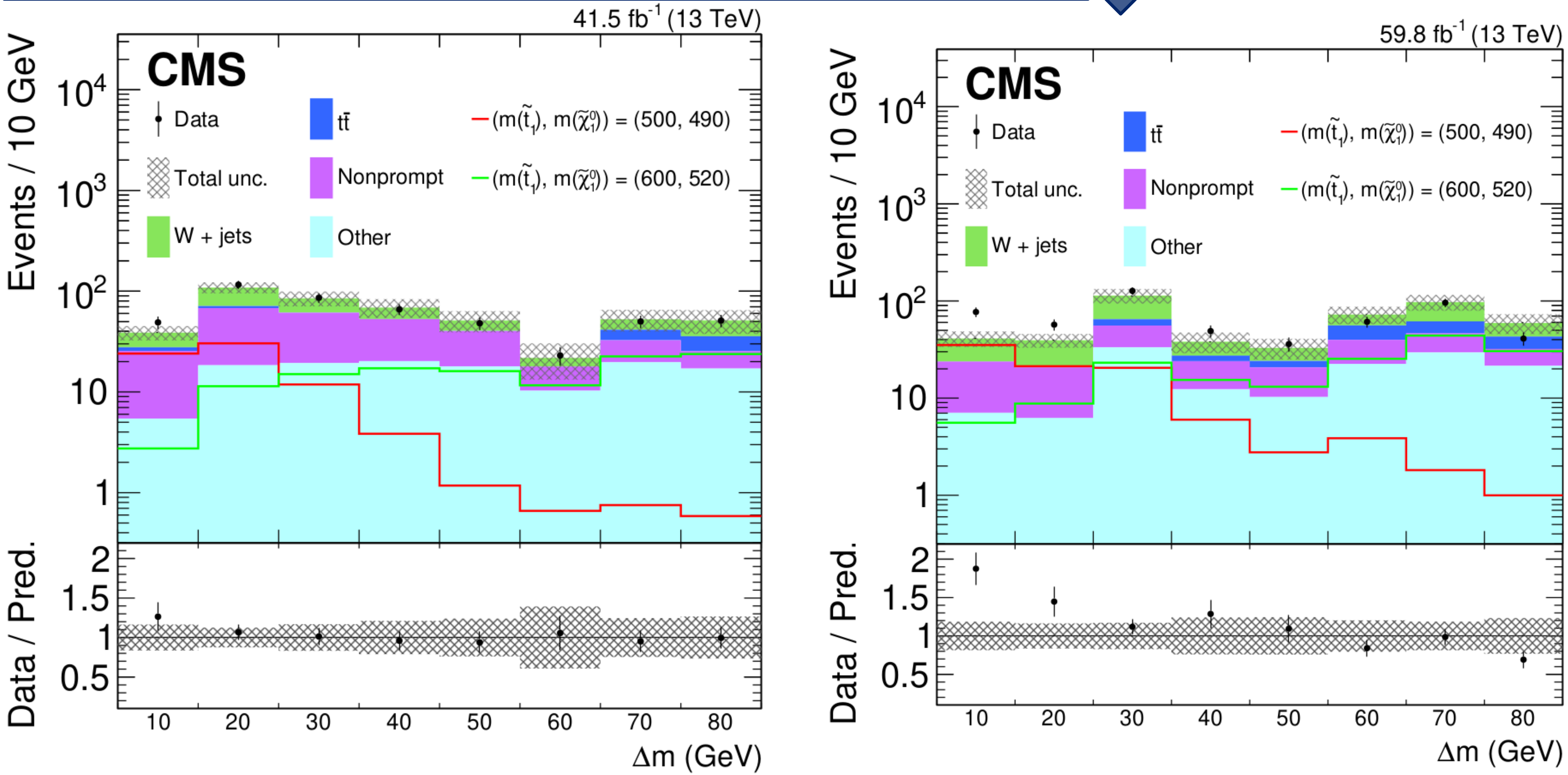
$$Y_{\mathrm{p}}^{\mathrm{SR}}(X) = \frac{N_{\mathrm{p}}^{\mathrm{SR}}(X)}{N_{\mathrm{p}}^{\mathrm{CR}}(X)}\left[N^{\mathrm{CR}}(\mathrm{Data}) - N_{\mathrm{p}}^{\mathrm{CR}}(\mathrm{non}\text{-}X) - Y_{\mathrm{np}}^{\mathrm{CR}}\right]$$

Year	Δm (GeV)	BDT >	$Y_{\mathrm{p}}^{\mathrm{SR}}$(W+jets)	$Y_{\mathrm{p}}^{\mathrm{SR}}(\mathrm{t\bar{t}})$	$Y_{\mathrm{np}}^{\mathrm{SR}}$
2017	10	0.31	11.0 ± 2.4	2.2 ± 2.9	20.1 ± 3.5
	20	0.32	37.4 ± 4.6	3.3 ± 5.2	49.6 ± 7.0
	30	0.38	23.8 ± 3.8	0.0 ± 7.2	41.7 ± 6.1
	40	0.40	15.9 ± 2.6	0.0 ± 8.1	32.6 ± 5.5
	50	0.43	10.9 ± 2.0	0.0 ± 6.7	22.3 ± 4.0
	60	0.47	3.9 ± 0.8	0.0 ± 6.2	7.6 ± 2.2
	70	0.39	11.1 ± 2.0	8.9 ± 7.6	12.9 ± 2.9
	80	0.41	15.6 ± 4.3	10.3 ± 9.7	8.3 ± 2.2
2018	10	0.32	17.3 ± 4.3	0.0 ± 2.4	16.7 ± 3.6
	20	0.39	18.4 ± 2.8	0.3 ± 3.1	14.5 ± 3.4
	30	0.35	48.5 ± 8.1	9.1 ± 9.4	22.5 ± 4.8
	40	0.43	10.7 ± 3.1	3.4 ± 4.5	11.7 ± 2.9
	50	0.46	8.7 ± 3.0	3.4 ± 4.5	10.5 ± 2.8
	60	0.41	16.5 ± 4.7	16.2 ± 8.8	17.3 ± 3.8
	70	0.40	35.6 ± 8.7	15.2 ± 8.6	16.9 ± 5.2
	80	0.42	16.3 ± 3.7	10.9 ± 7.8	10.7 ± 4.3

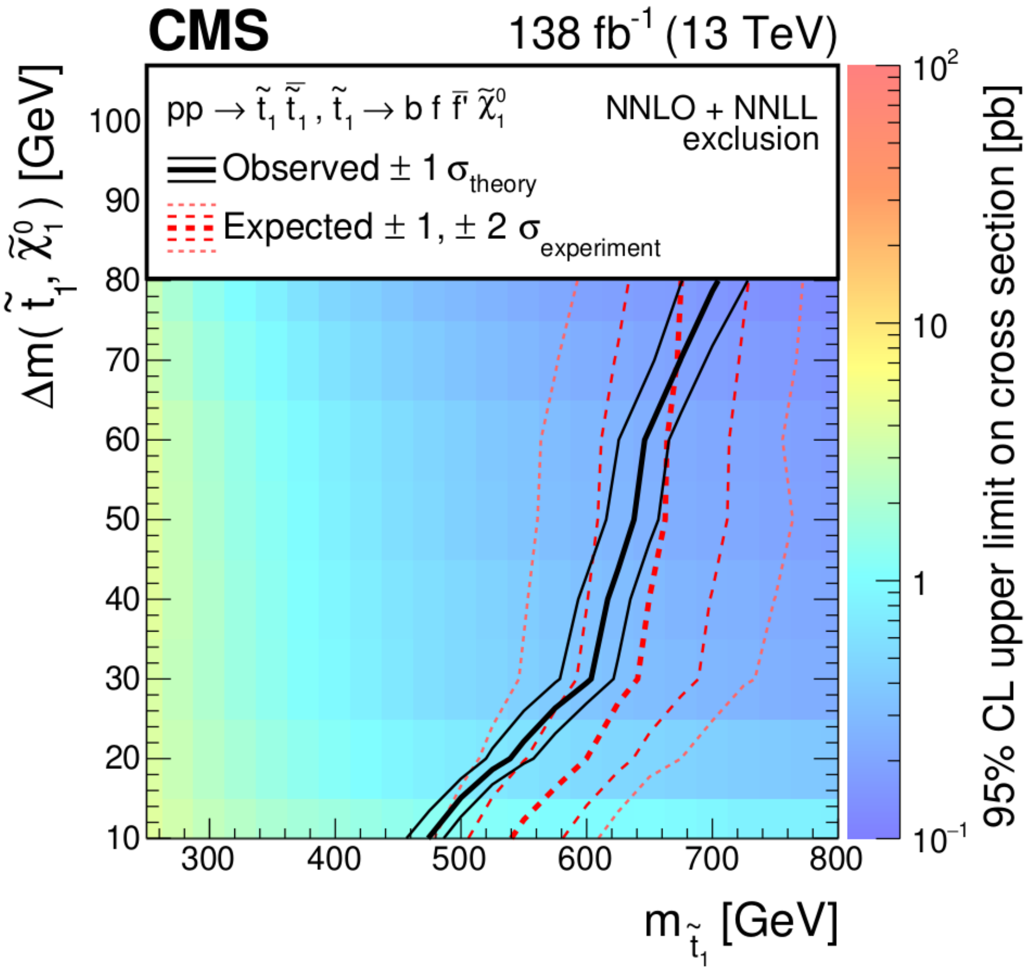
The details / Relative systematic uncertainties

	2017		2018	
Source	Background	Signal	Background	Signal
Integrated luminosity	—	2.3	—	2.5
JES	0–2	3–9	0–2	5–10
JER	0–1	0–1	0–1	0–1
b tagging	0–1	0–6	0–1	0–1
Trigger	0–1	1	0–1	1
Lepton efficiency	0–1	0–1	0–1	0–1
Pileup	1–5	0–3	1–4	0–1
ISR ($t\bar{t}$ and signal)	0–1	0–5	0–1	0–5
ISR (W+jets)	0–4	—	0–4	—
Renorm./Fact. scales	0–7	0–1	0–10	0–1
$p_{\mathrm{T}}^{\mathrm{miss}}$ modeling (FASTSIM)	—	0–2	—	0–2
W+jets total	2–6	—	4–9	—
$t\bar{t}$ total	1–5	—	2–7	—
Nonprompt lepton total	2–5	—	2–4	—

The results / Observed yields in the 8 Δm regions



The results / 95% CI upper limits in phase space on the σ



Expected vs. observed events

For each signal point, the color grid:

→ 95% CI upper limit on the σ

For each Δm region:

→ Observed (black) and expected (red) exclusion limits for the *stop* mass

→ Only divergence is seen for Δm = 10 GeV

Conclusions

Δm = 10 GeV → *stop* mass > 480 GeV

Δm = 80 GeV → *stop* mass > 700 GeV

Thank you!

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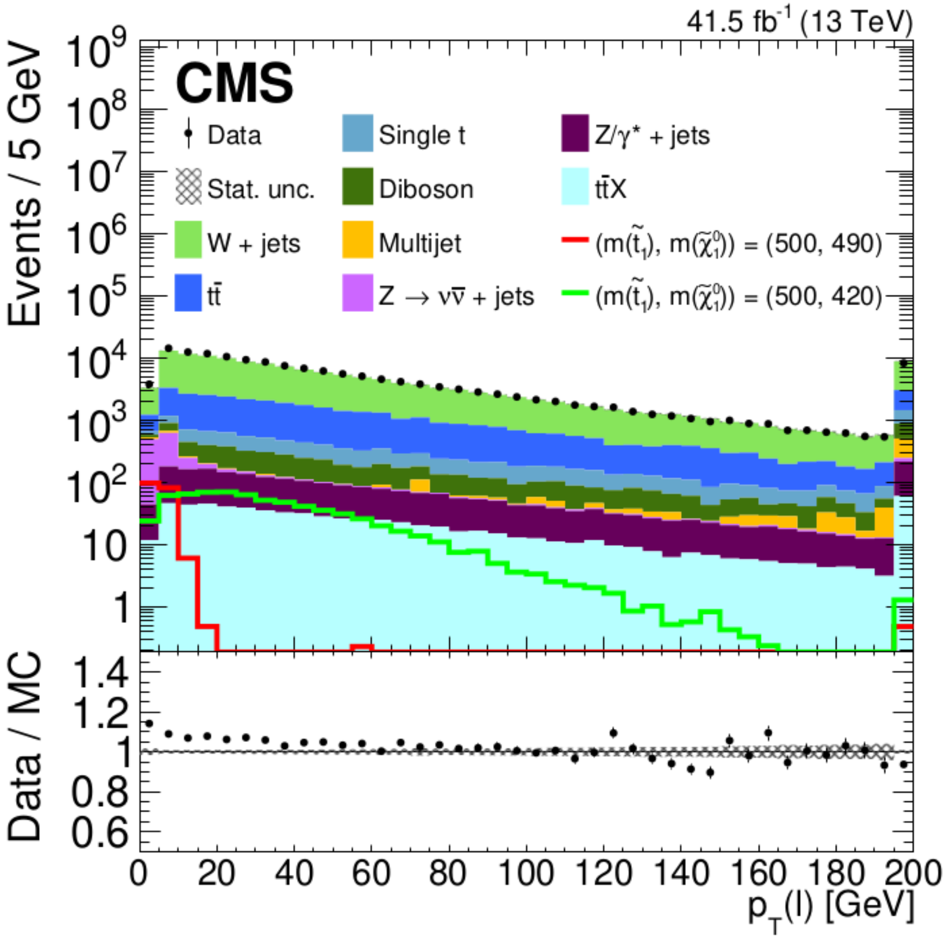

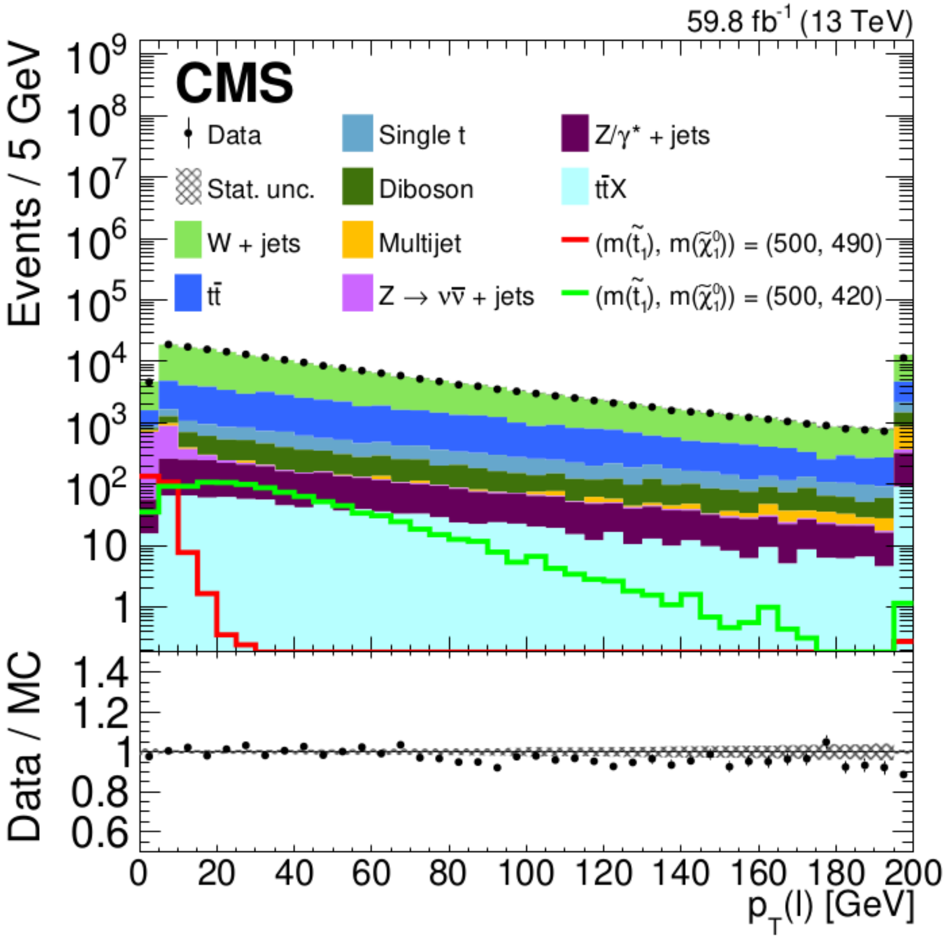

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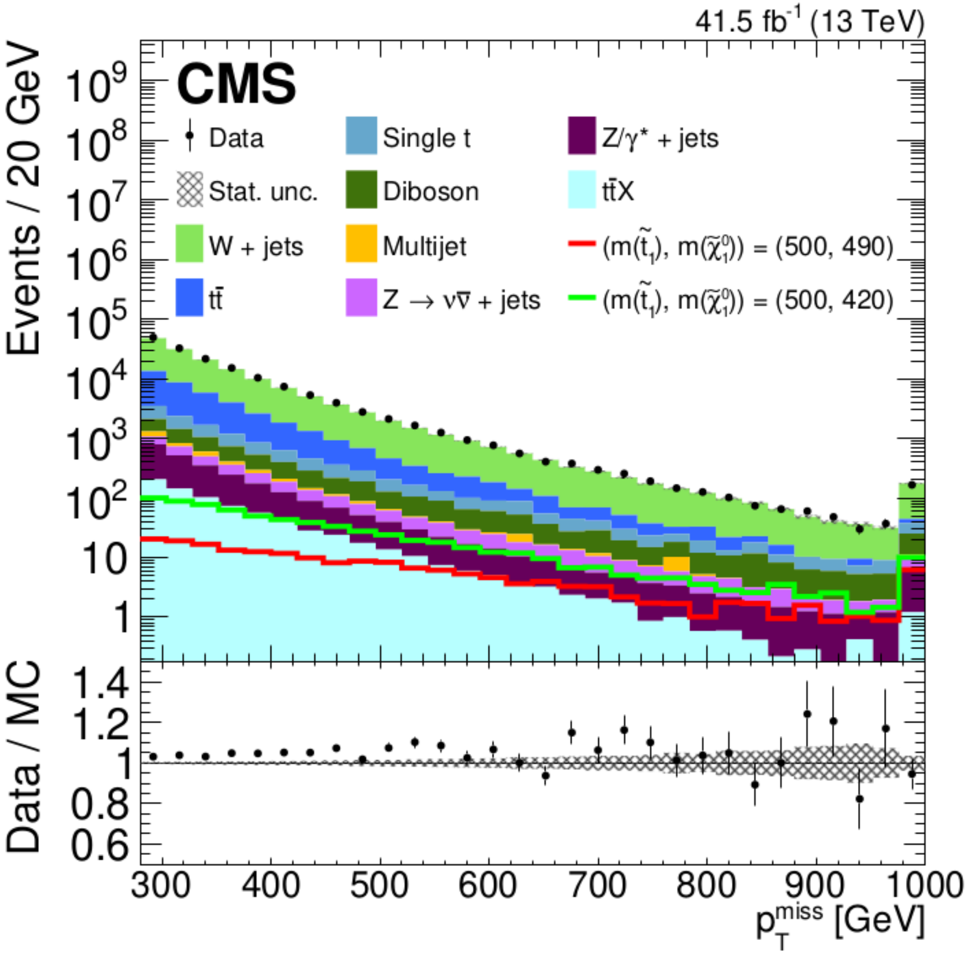

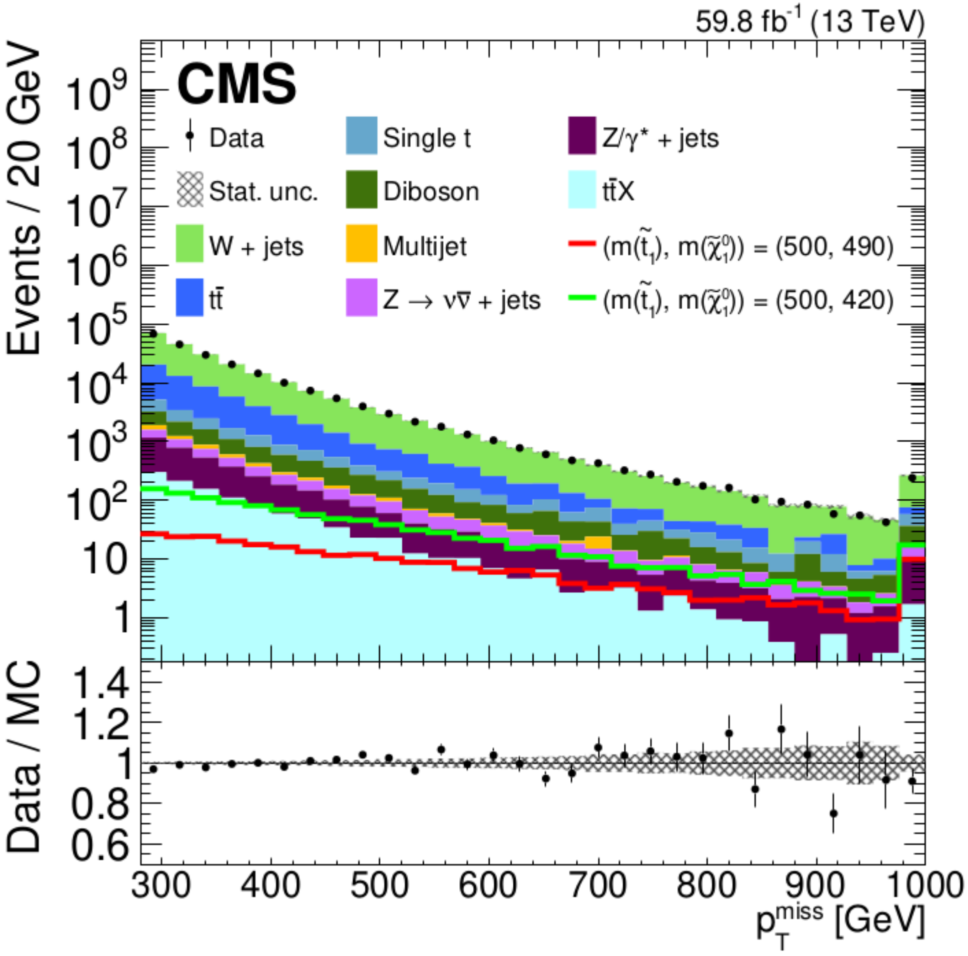

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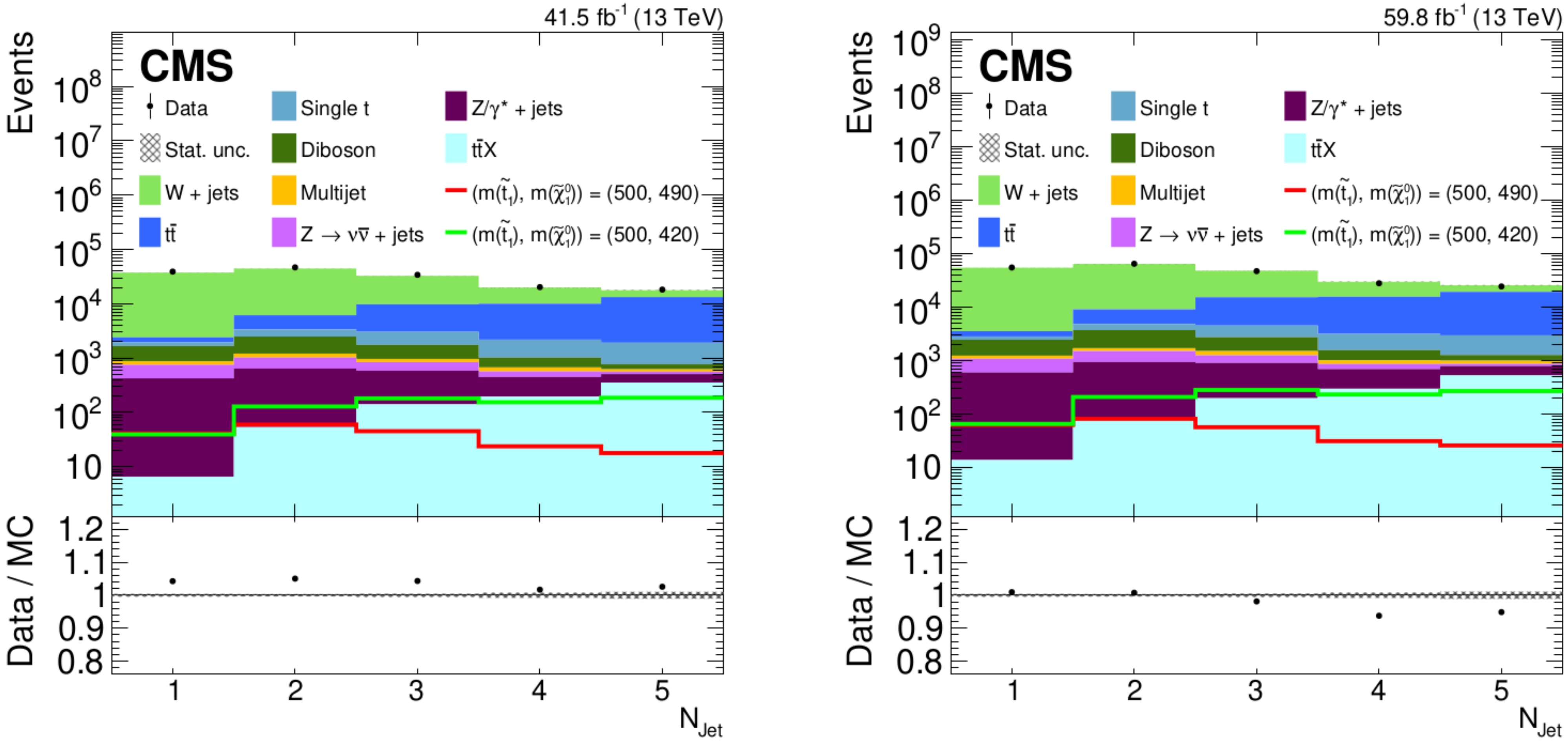

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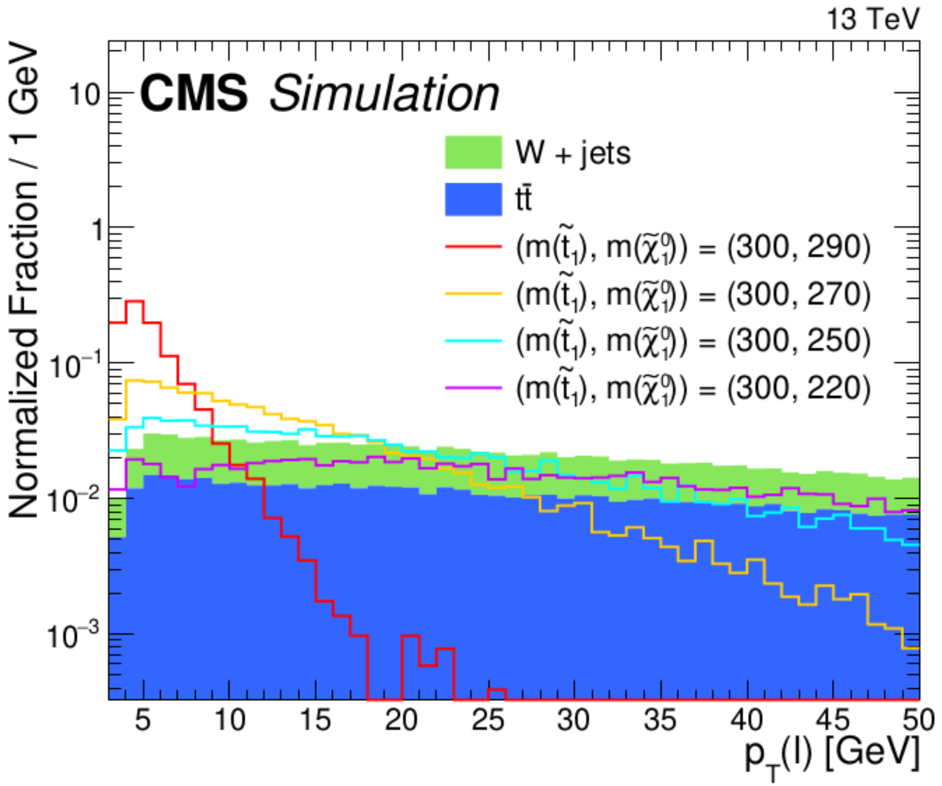

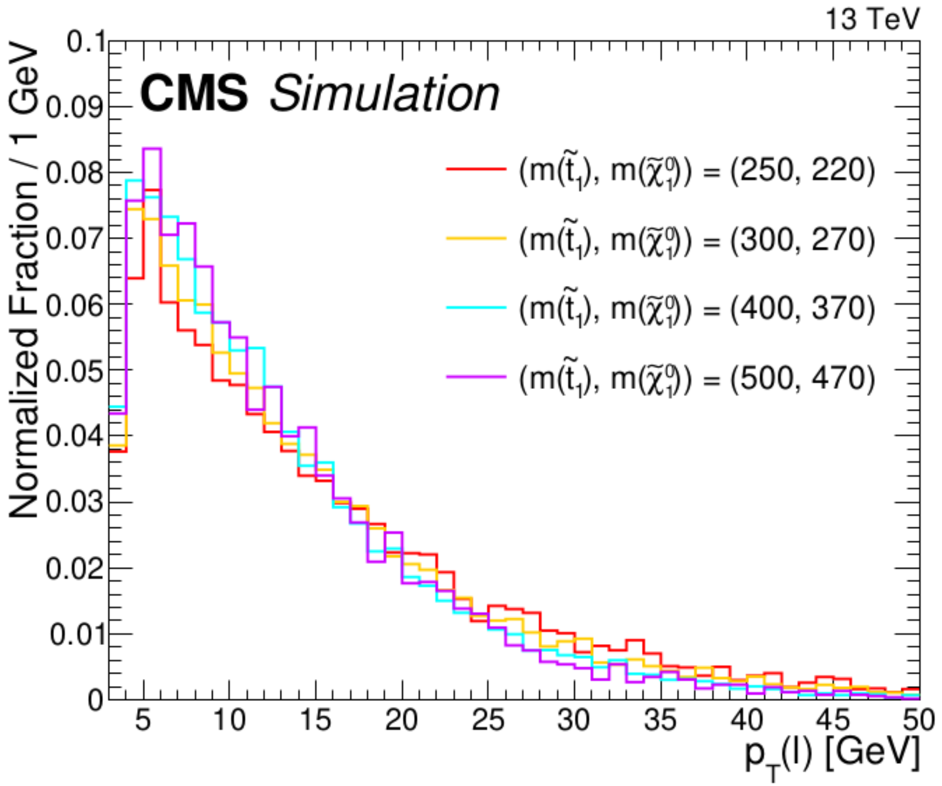

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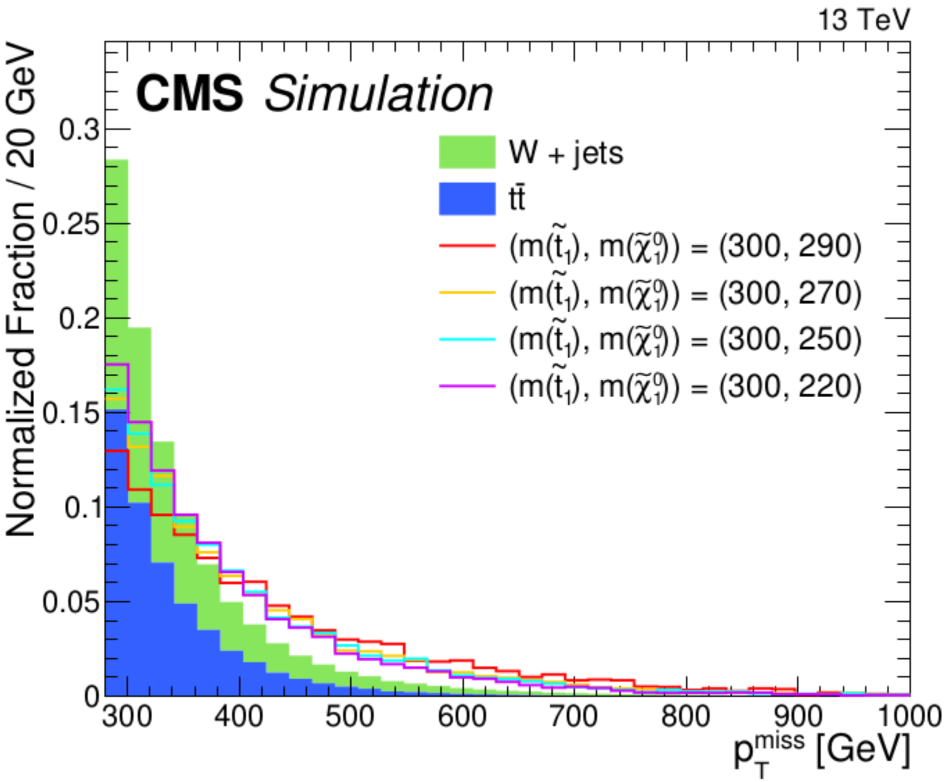

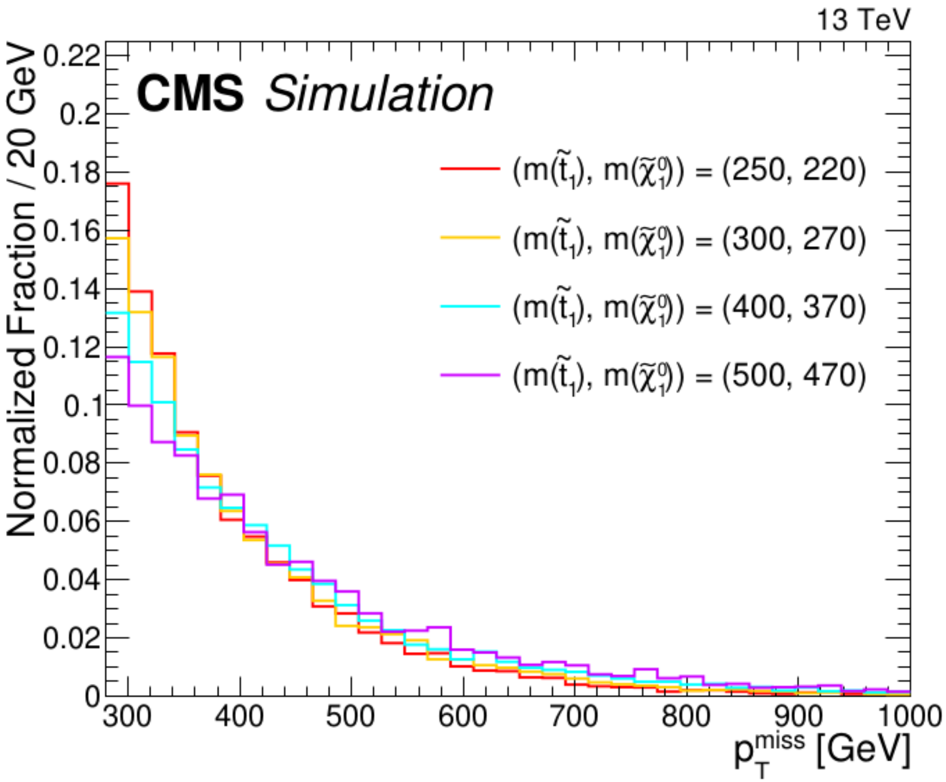

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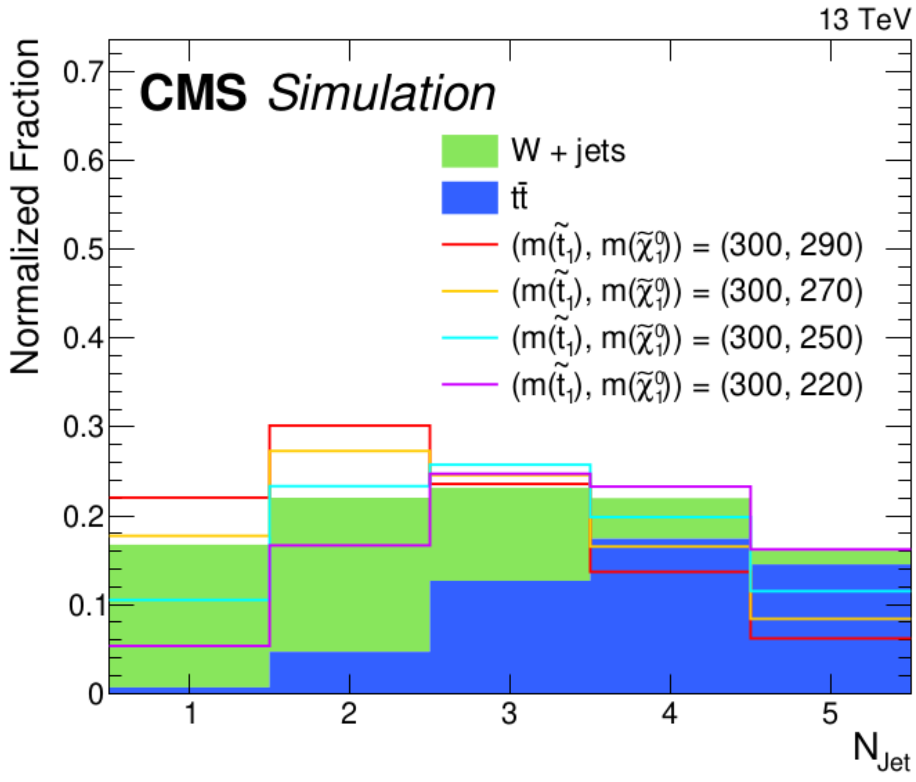

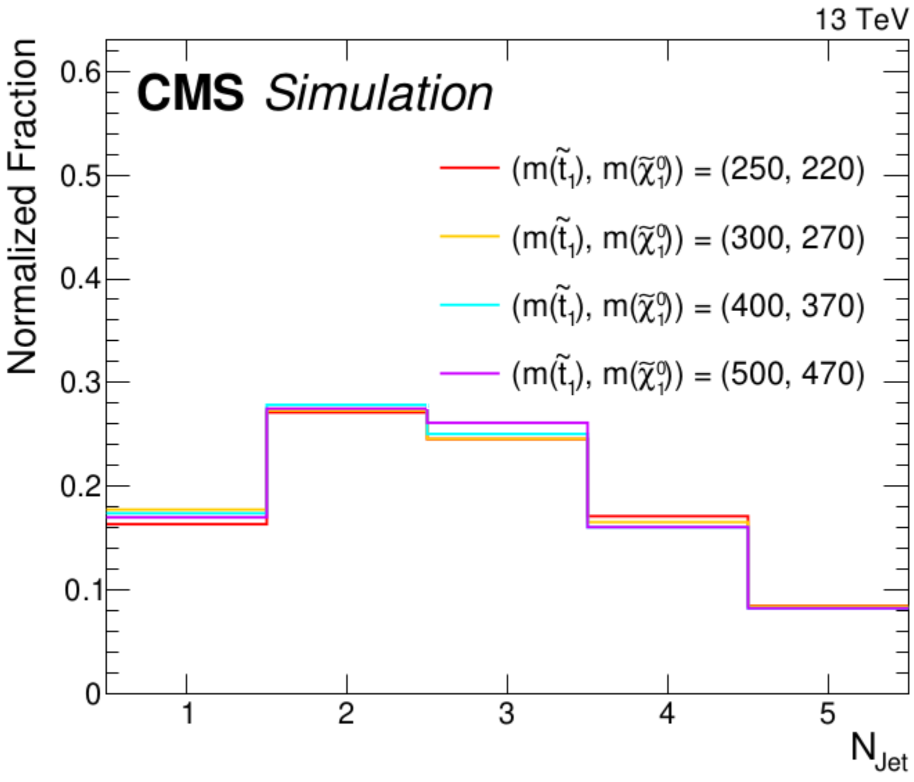

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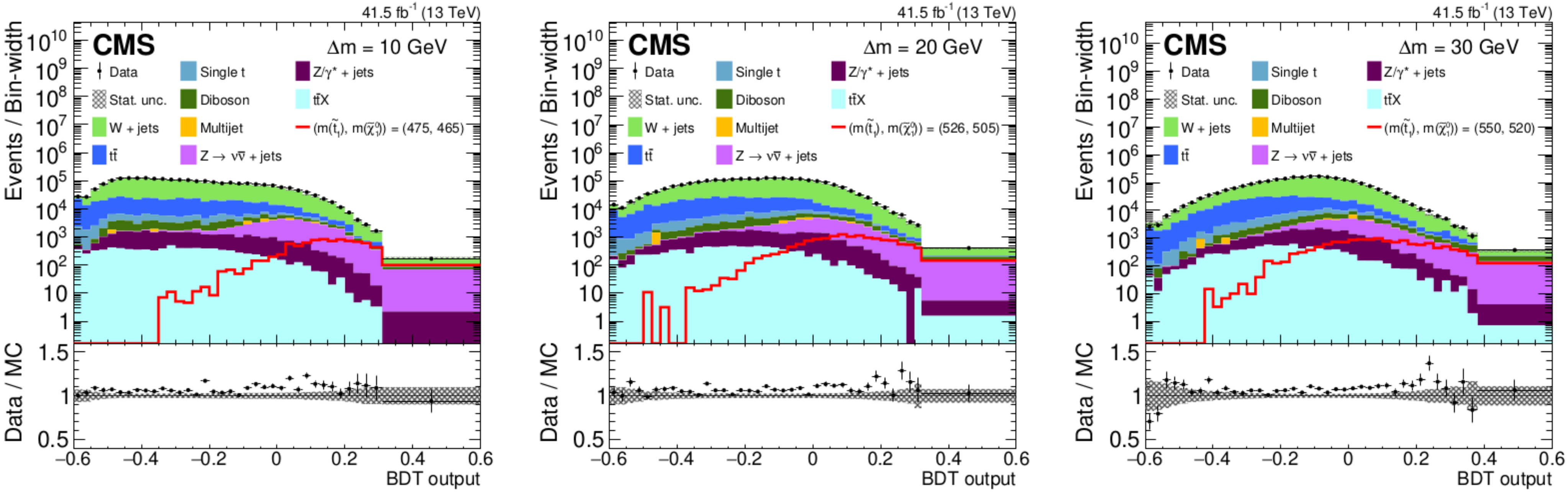

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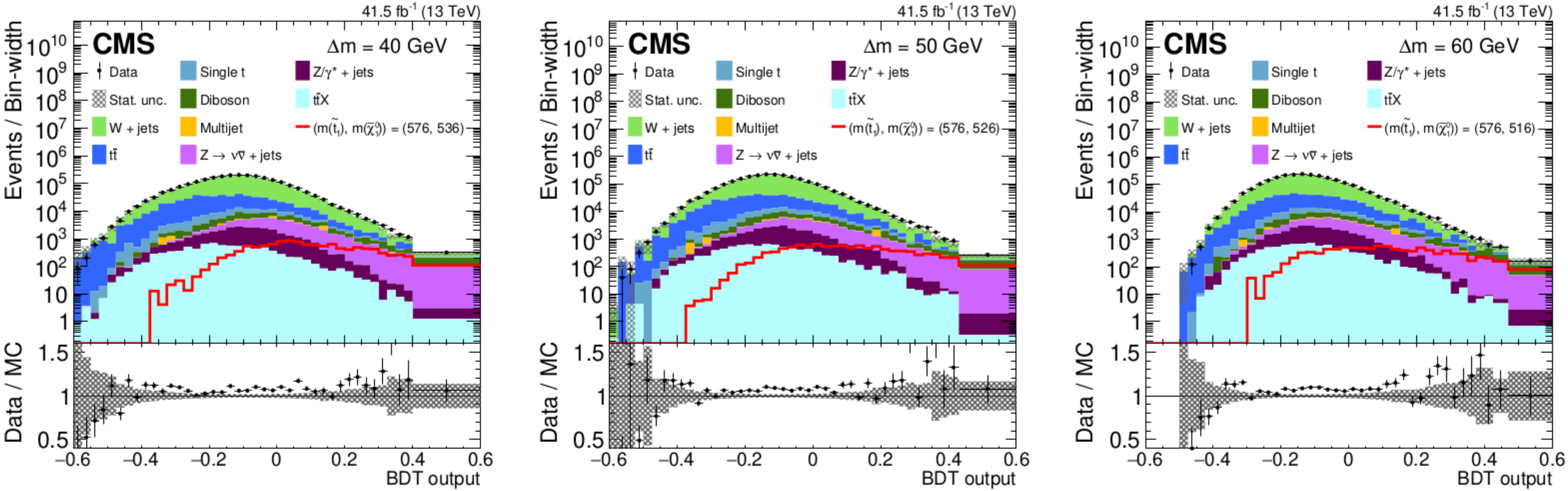

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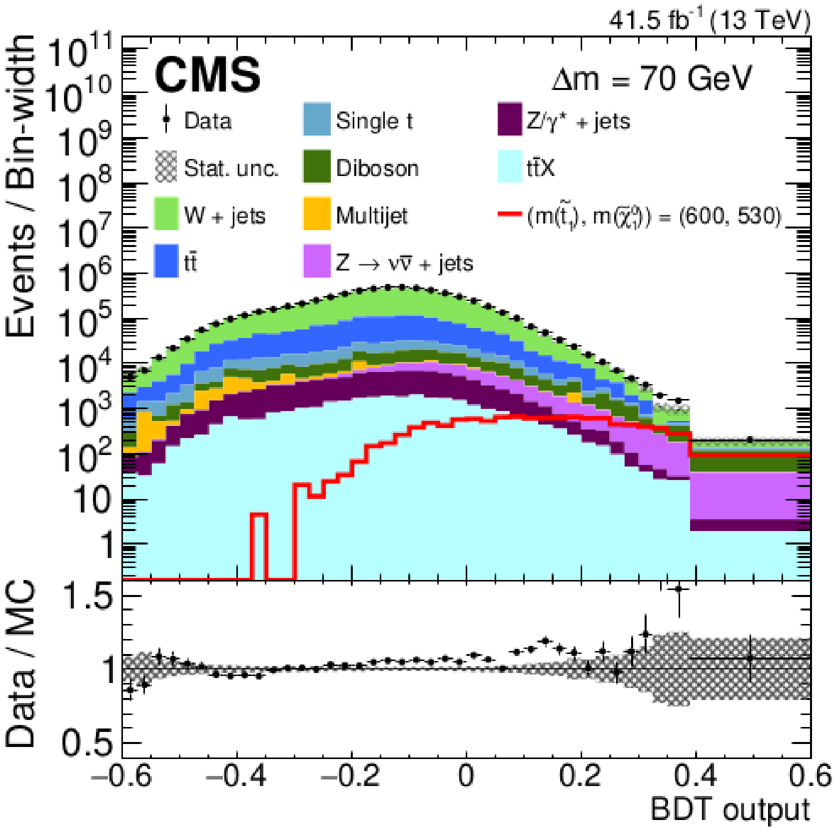

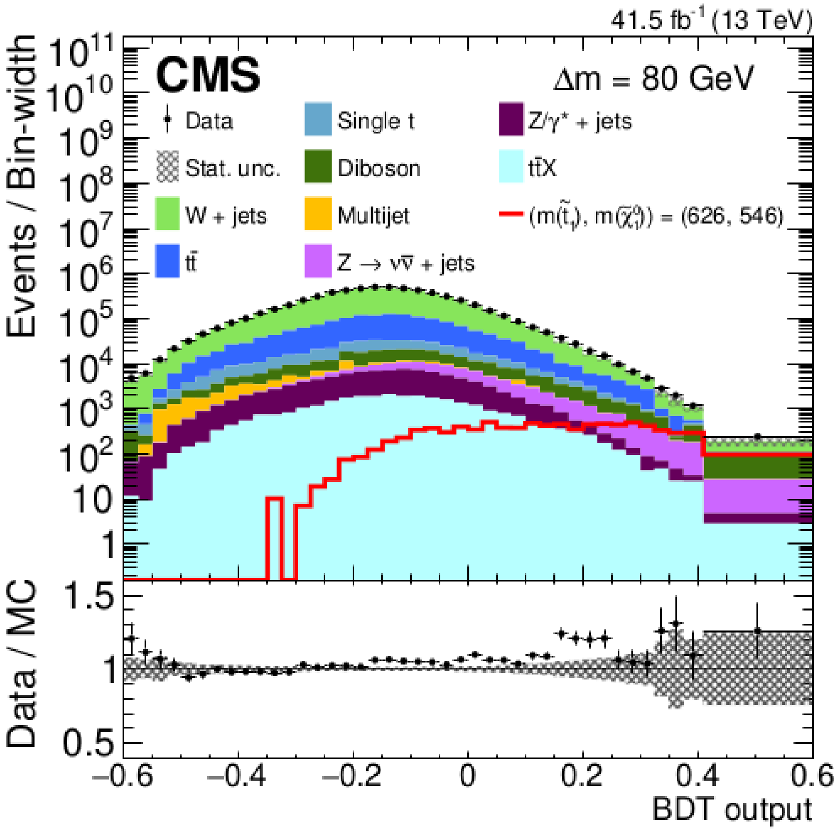

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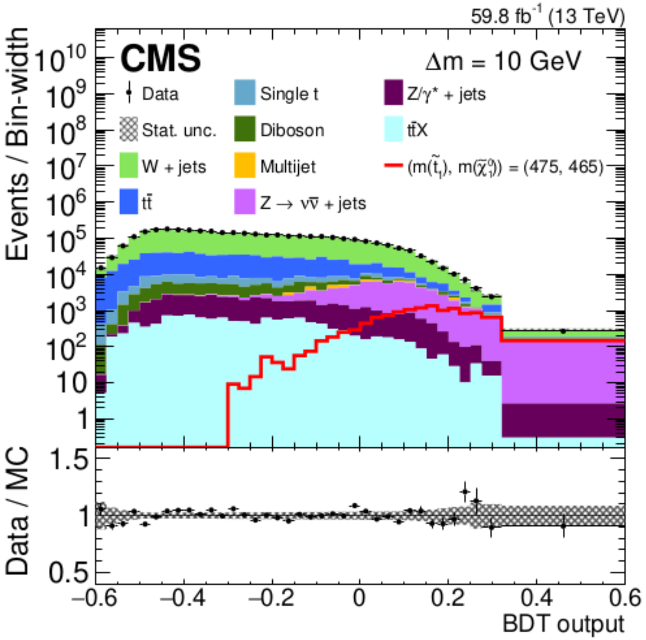

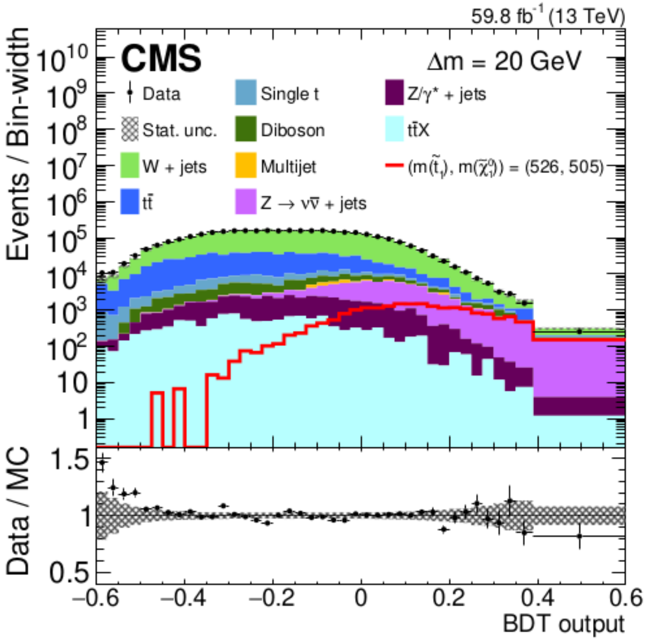

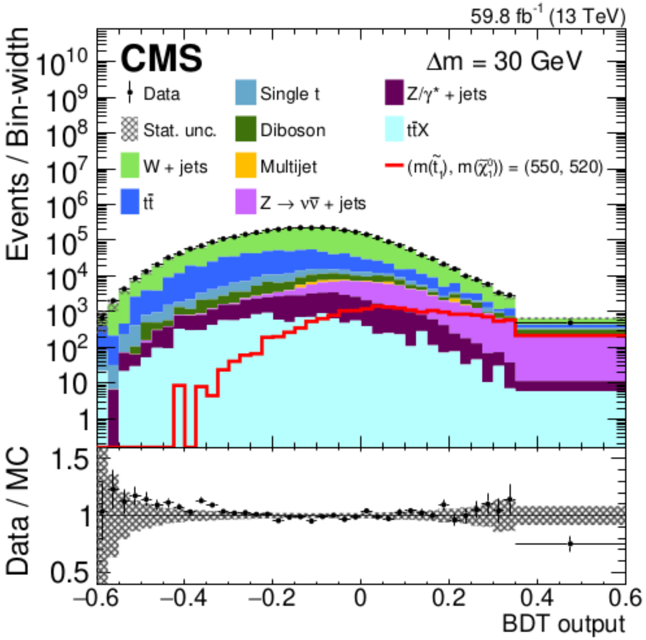

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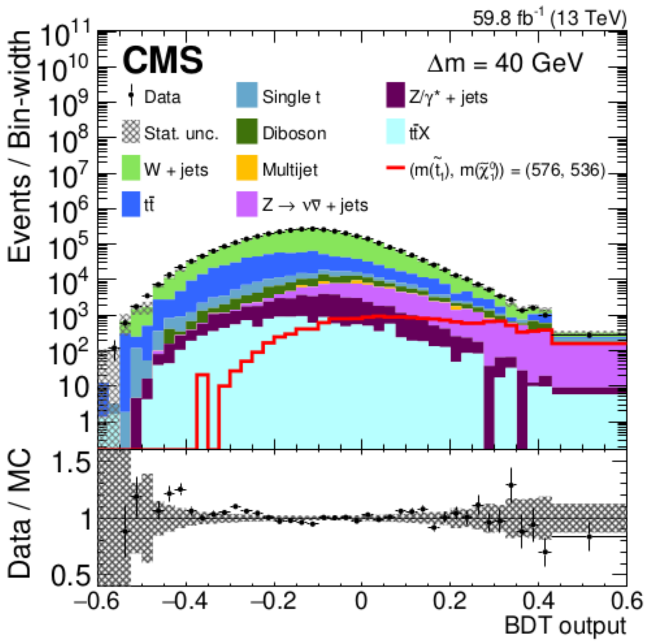

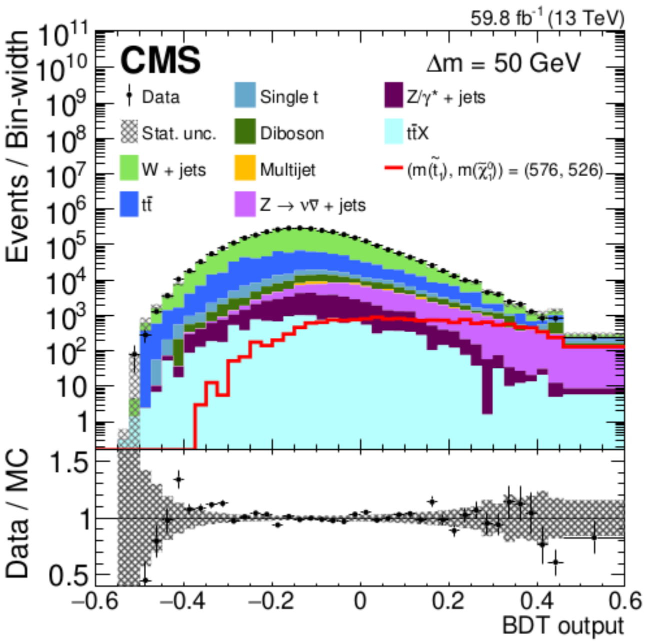

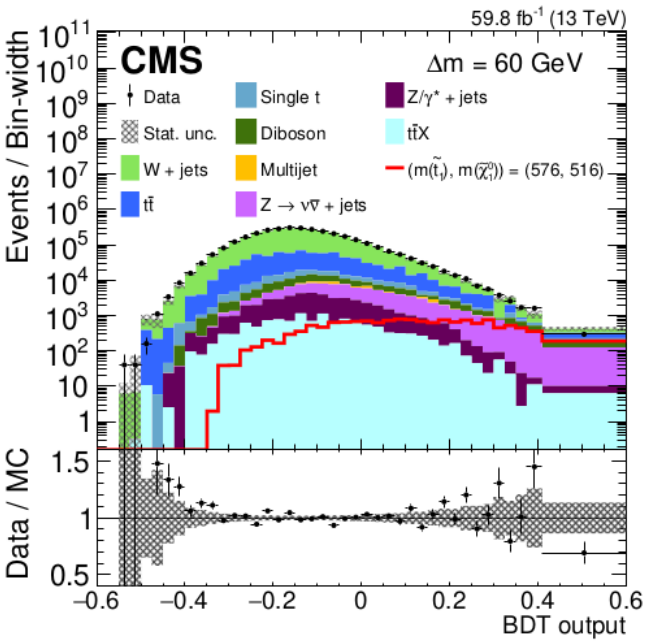

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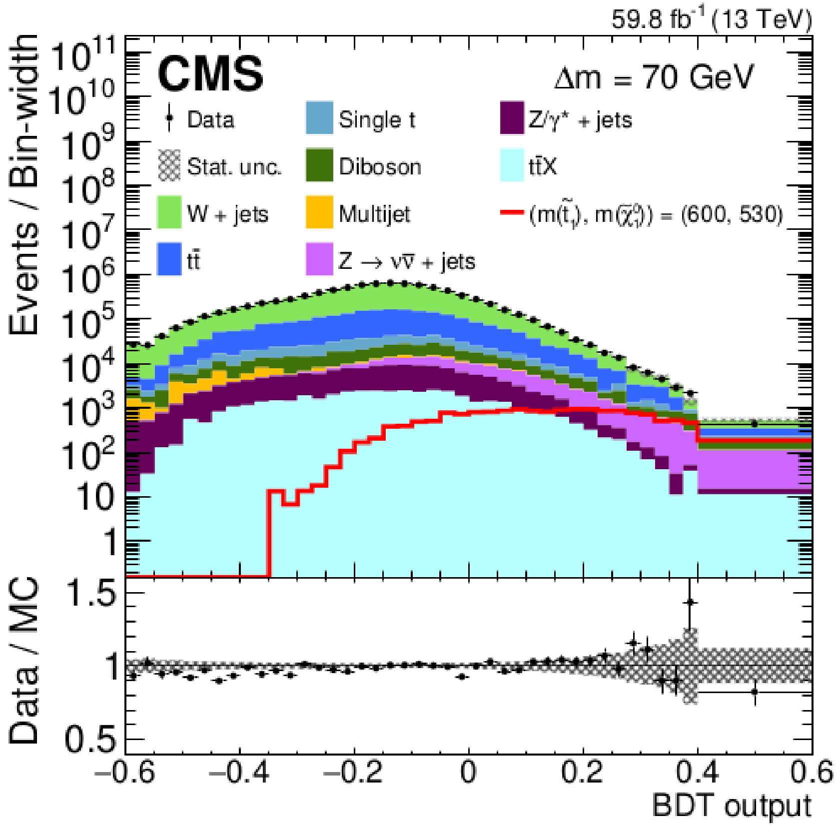

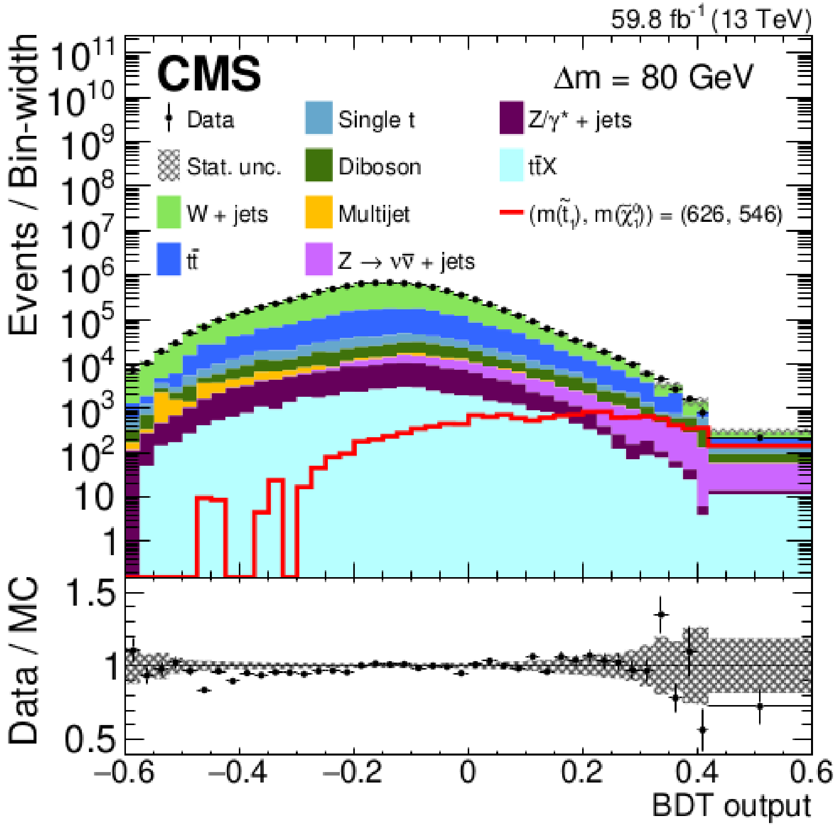

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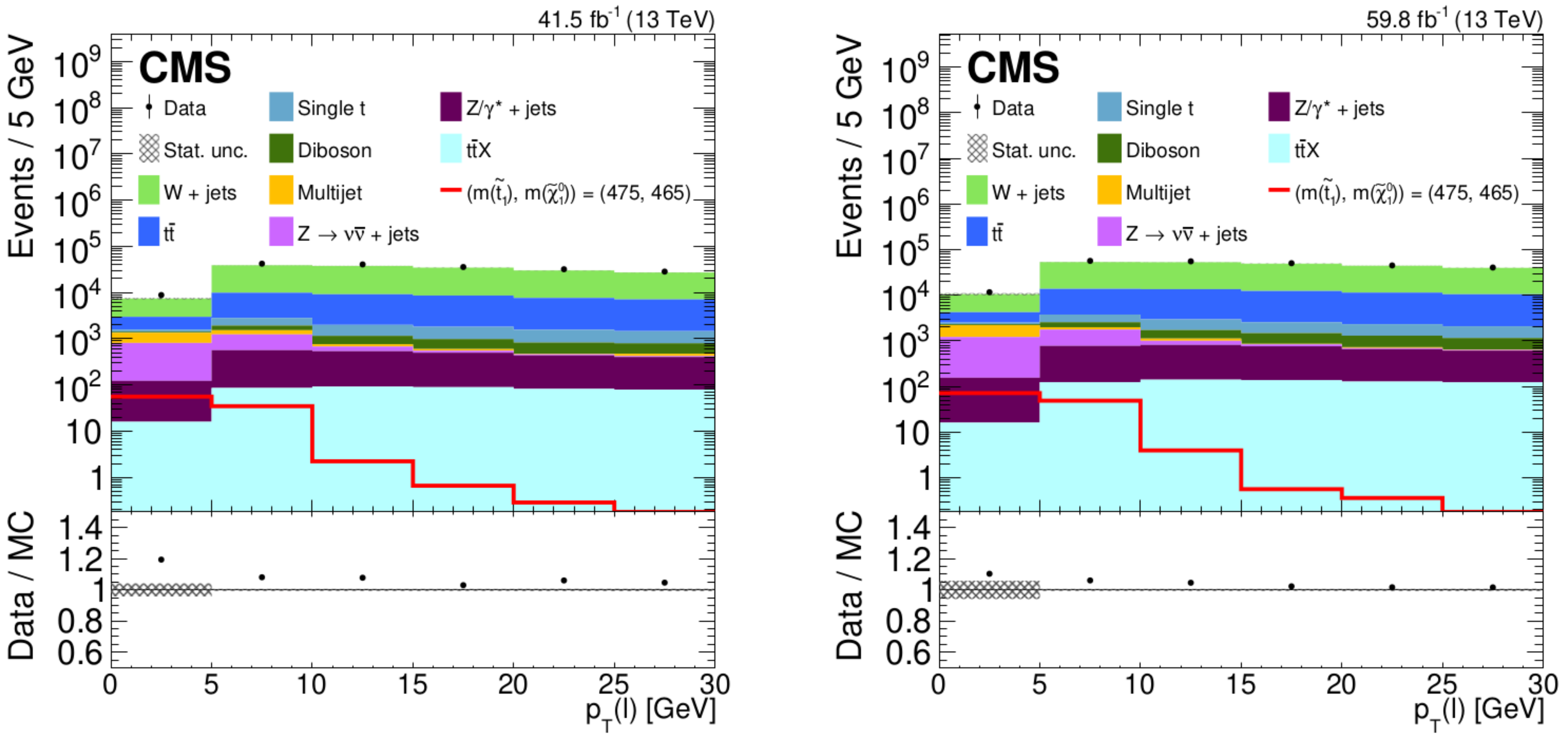

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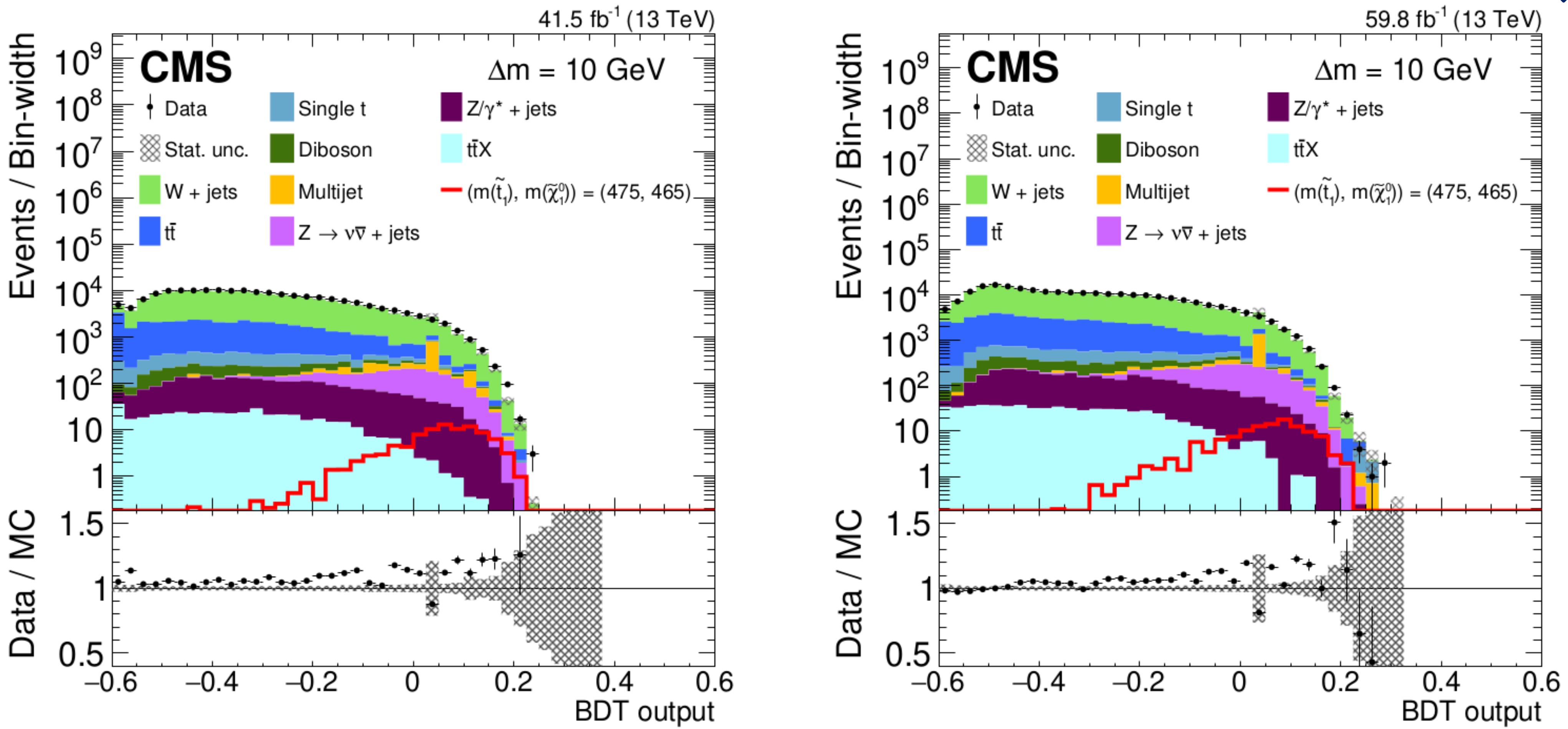

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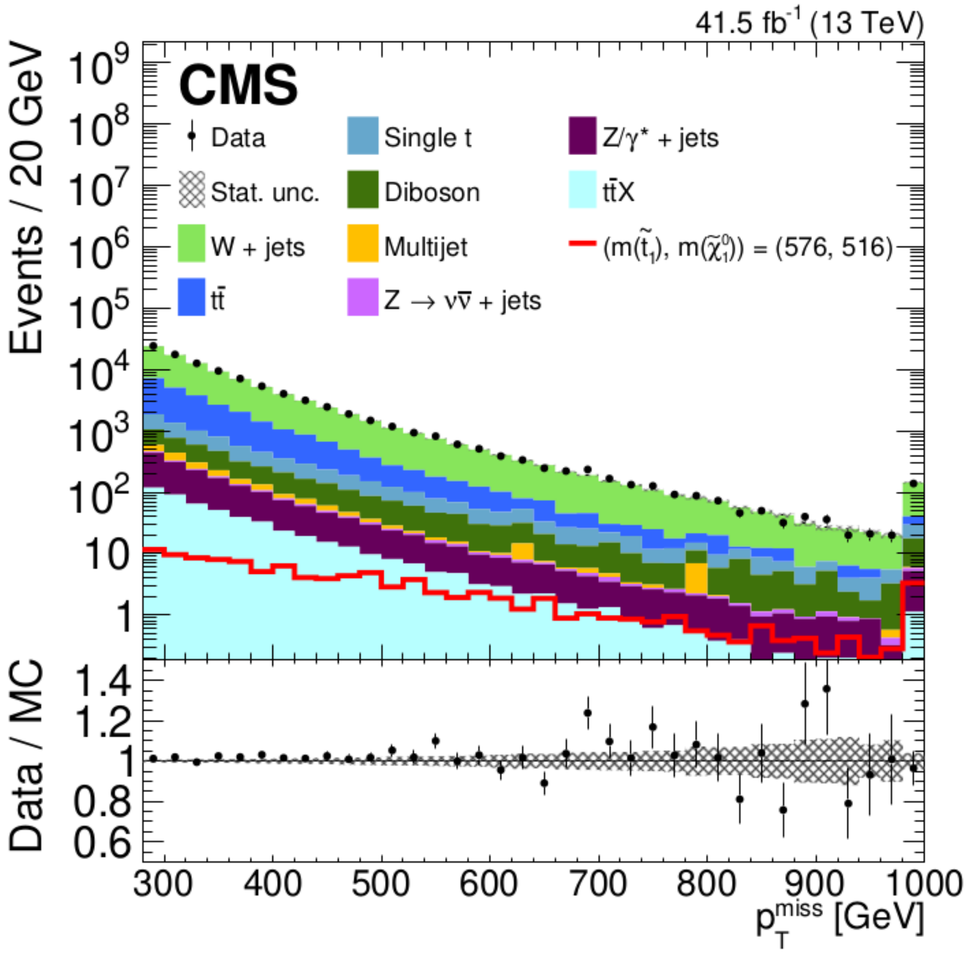

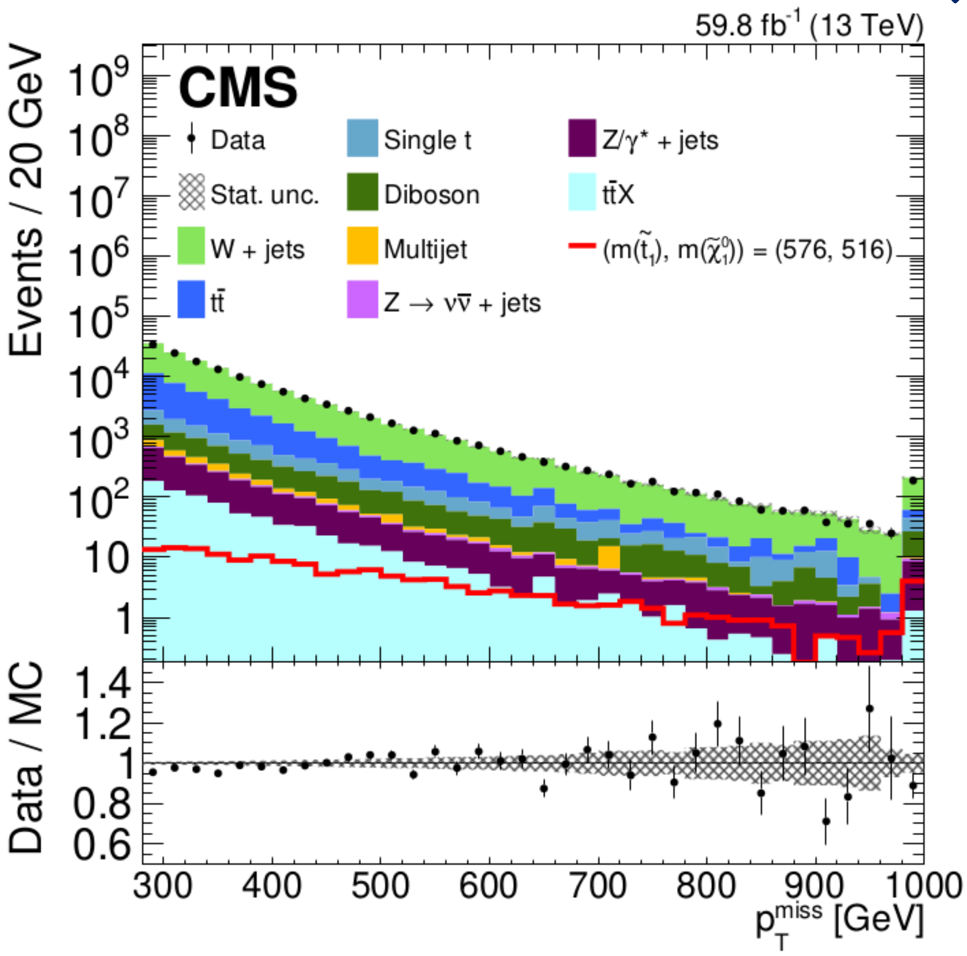

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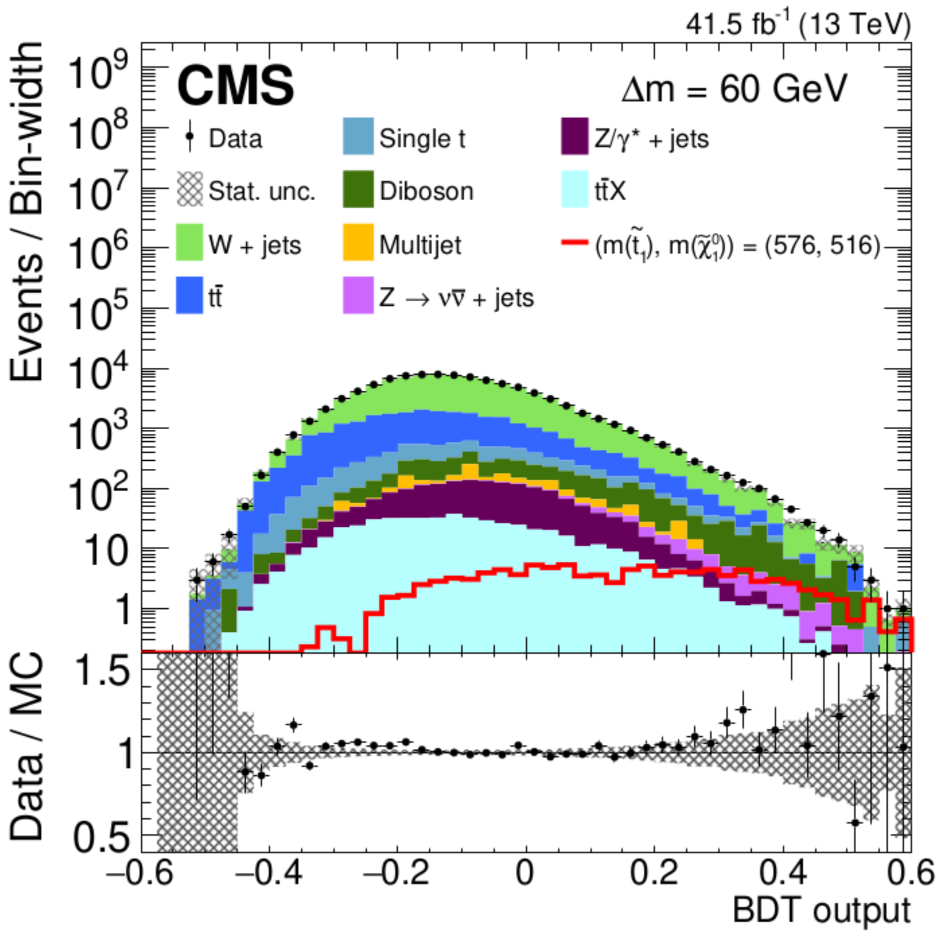

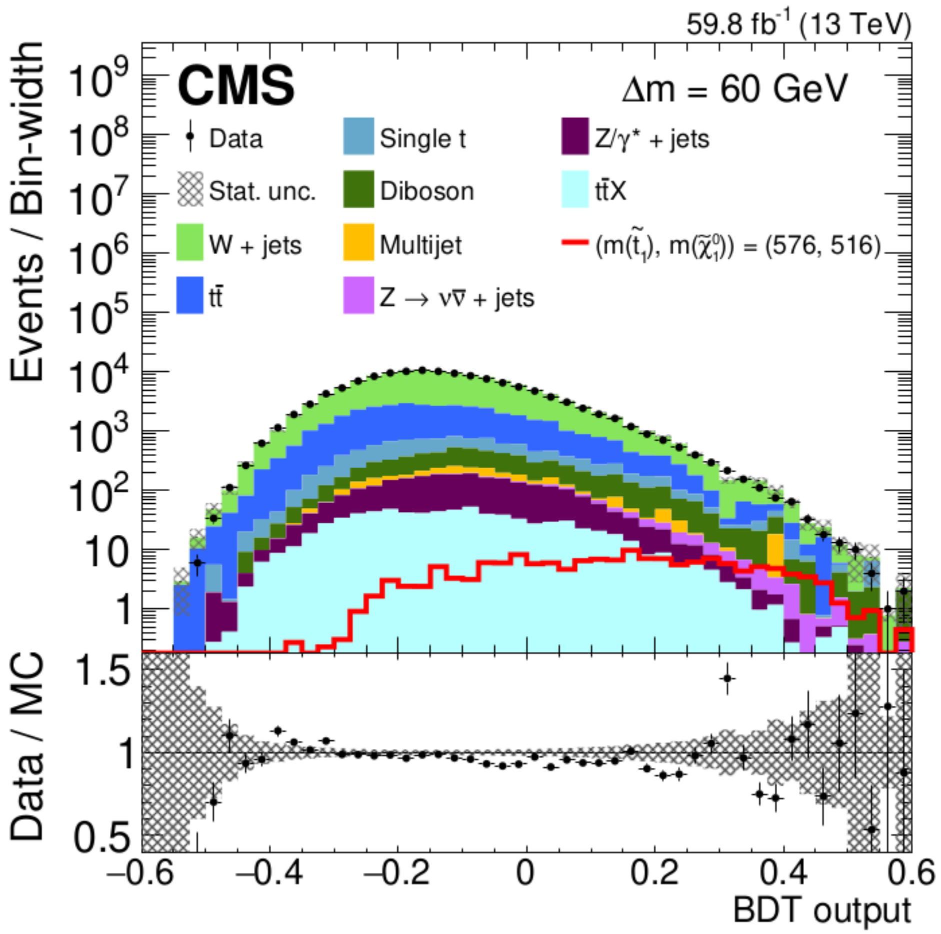

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Year	Δm (GeV)	BDT >	$Y_{\mathrm{p}}^{\mathrm{SR}}$(W+jets)	$Y_{\mathrm{p}}^{\mathrm{SR}}$($\mathrm{t\bar{t}}$)	$Y_{\mathrm{np}}^{\mathrm{SR}}$	N^{SR}(Other)	N^{SR}(Total)	N^{SR}(Observed)
2017	10	0.31	11.0 ± 2.4	2.2 ± 2.9	20.1 ± 3.5	5.4 ± 3.7	38.8 ± 6.3	49
	20	0.32	37.4 ± 4.6	3.3 ± 5.2	49.6 ± 7.0	18.4 ± 9.3	109 ± 14	116
	30	0.38	23.8 ± 3.8	0.0 ± 7.2	41.7 ± 6.1	19.4 ± 9.9	85 ± 14	86
	40	0.40	15.9 ± 2.6	0.0 ± 8.1	32.6 ± 5.5	20 ± 10	69 ± 15	66
	50	0.43	10.9 ± 2.0	0.0 ± 6.7	22.3 ± 4.0	17.9 ± 9.2	51 ± 12	48
	60	0.47	3.9 ± 0.8	0.0 ± 6.2	7.6 ± 2.2	10.3 ± 5.4	21.8 ± 8.5	23
	70	0.39	11.1 ± 2.0	8.9 ± 7.6	12.9 ± 2.9	19.7 ± 9.8	53 ± 13	50
	80	0.41	15.6 ± 4.3	10.3 ± 9.7	8.3 ± 2.2	17.1 ± 8.2	51 ± 14	51
2018	10	0.32	17.3 ± 4.3	0.0 ± 2.4	16.7 ± 3.6	7.1 ± 4.5	41.1 ± 7.6	77
	20	0.39	18.4 ± 2.8	0.3 ± 3.1	14.5 ± 3.4	6.3 ± 3.5	39.4 ± 6.4	57
	30	0.35	48.5 ± 8.1	9.1 ± 9.4	22.5 ± 4.8	33 ± 14	114 ± 19	127
	40	0.43	10.7 ± 3.1	3.4 ± 4.5	11.7 ± 2.9	12.3 ± 6.7	38.1 ± 9.1	49
	50	0.46	8.7 ± 3.0	3.4 ± 4.5	10.5 ± 2.8	10.3 ± 5.2	32.9 ± 8.0	36
	60	0.41	16.5 ± 4.7	16.2 ± 8.8	17.3 ± 3.8	22 ± 10	72 ± 15	61
	70	0.40	35.6 ± 8.7	15.2 ± 8.6	16.9 ± 5.2	30 ± 12	97 ± 18	96
	80	0.42	16.3 ± 3.7	10.9 ± 7.8	10.7 ± 4.3	21.5 ± 9.8	59 ± 14	41