Searches for top squarks in compressed scenarios with the CMS experiment

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on behalf of the CMS collaboration

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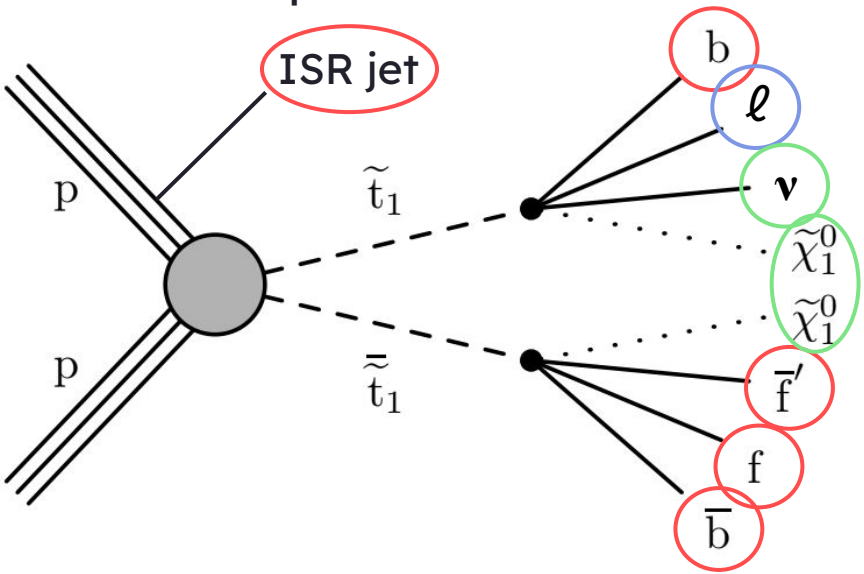
FCT Fundação para a Ciência e a Tecnologia
LIP LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS
CMS

Characteristics of the stop compressed scenario

Ex: stop 4-body decay in 1 lepton final states



$$\Delta m = m(\tilde{t}_1) - m(\tilde{\chi}_1^0) < m(W)$$

Compressed scenario:
Δm(stop,neutralino) < 80 GeV

LSP can be WIMP Dark Matter that was depleted in the early universe through co-annihilation process to match the observed DM density

- ISR jet to boost the sparticle pair
- Favors soft decay products that can be jets or leptons
- High p_T^{miss} due to Neutralino escaping undetected

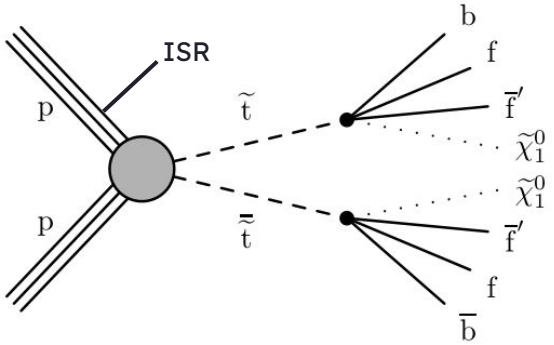
Advances in compressed stop searches at CMS

In this talk we will cover:

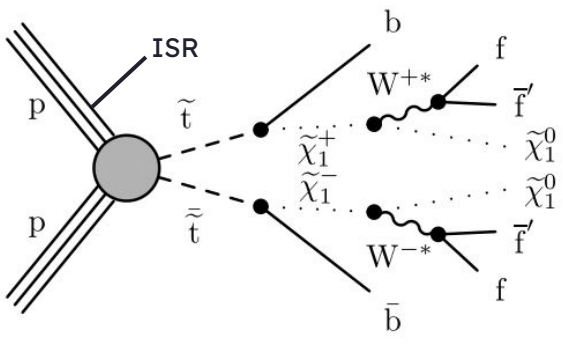
- CMS-SUS-19-010: *Search for top squark production in fully-hadronic final states in proton-proton collisions at √s=13 TeV*
  PRD 104, 052001 (2021) | end of 2021
  Strategy: **Soft b-tag algorithm**
- CMS-SUS-18-004: *Search for SUSY in final states with two or three soft leptons and missing transverse momentum in proton-proton collisions at √s=13 TeV*
  JHEP04(2022)091 | Spring 2022
  Strategy: **Opposite sign lepton pair and soft b-tagged jets**
- CMS-SUS-21-003: *Search for top squarks decaying via the four-body mode in single-lepton final states from Run 2 of the LHC*
  CMS-PAS-SUS-21-003 | Preliminary public results Summer 2022
  Strategy: **Train 1 BDT per Δm**

All-hadronic stop search

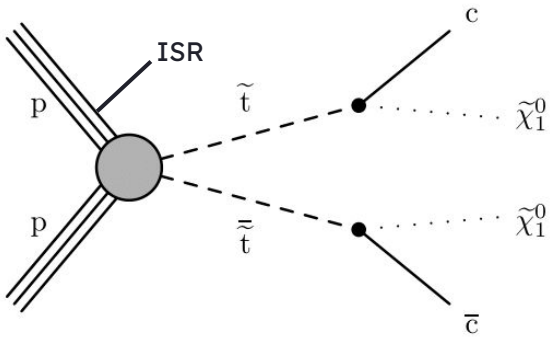
4-body decay



Chargino mediated



2-body decay

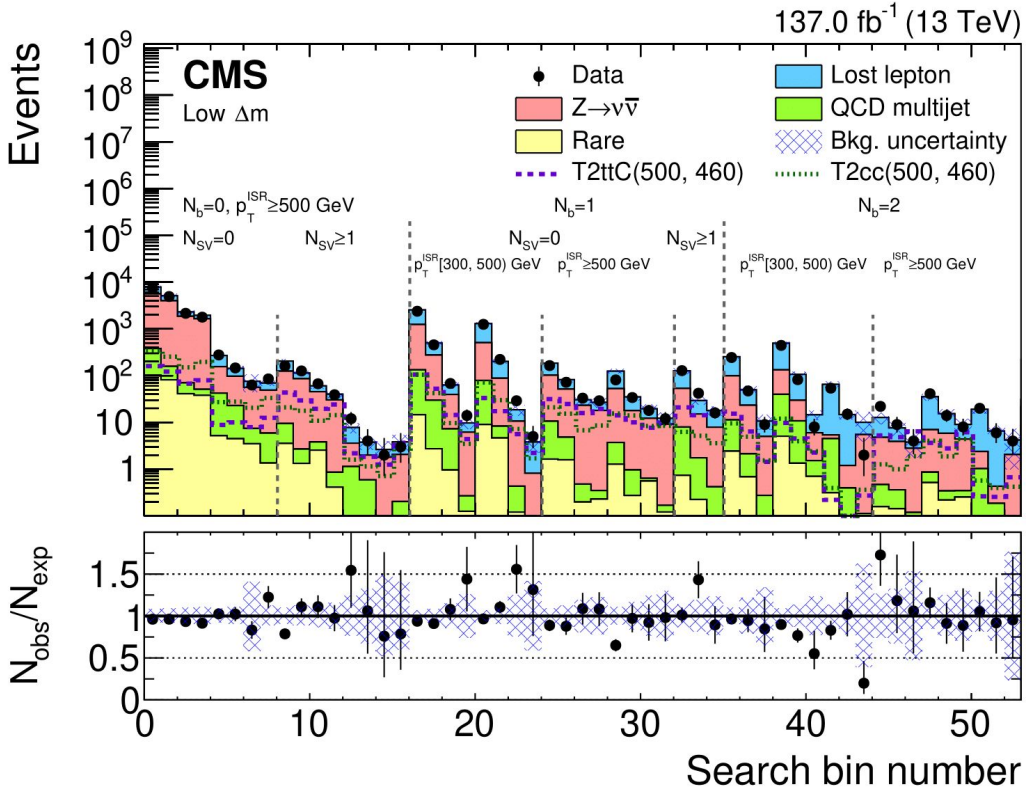


- 4bd: Effective four-point interaction
- Chg: Virtual W decays
- 2bd: Loop-induced flavour-changing neutral current charm production

Using a **cut-and-count** approach, this search takes advantage of b-/c-tagging and soft b-tagging algorithms in all-hadronic final states

PRD 104, 052001 (2021)

All-hadronic Signal Region

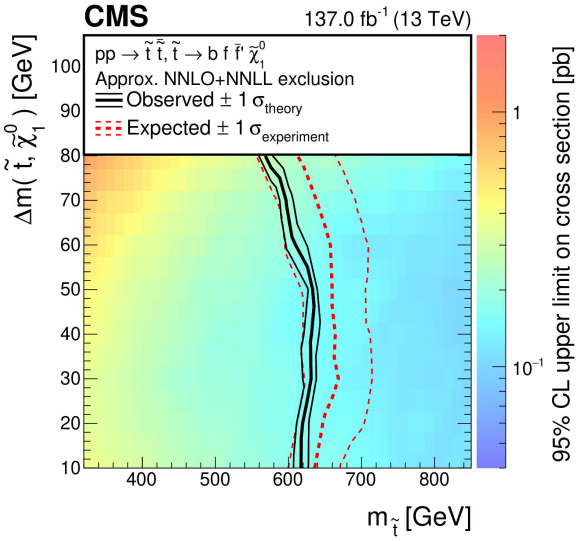


- Online trigger on p_T^{miss}
- H_T > 300 GeV
- p_T^{miss} > 250 GeV
- p_T^{ISR} > 200 GeV
- Veto leptons
- Bins only accessible through soft b-tag (N_{SV})
- SM Backgrounds estimated and validated from control regions

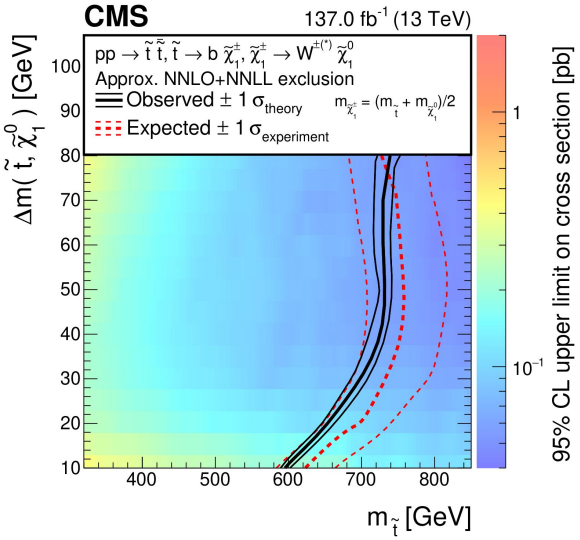
PRD 104, 052001 (2021)

All-hadronic Exclusion Limits

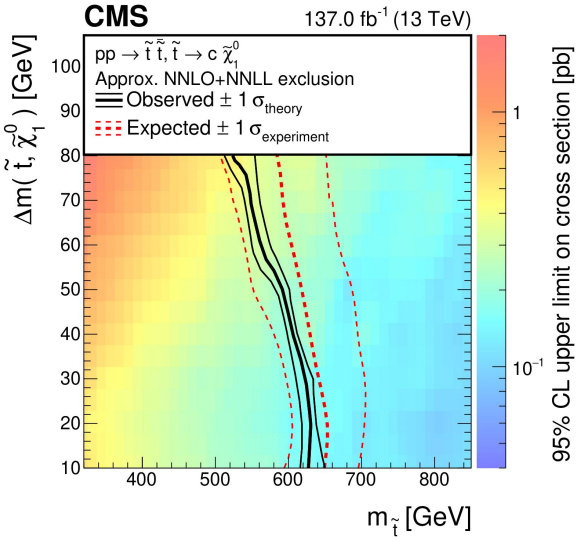
4bd



Chg



2bd



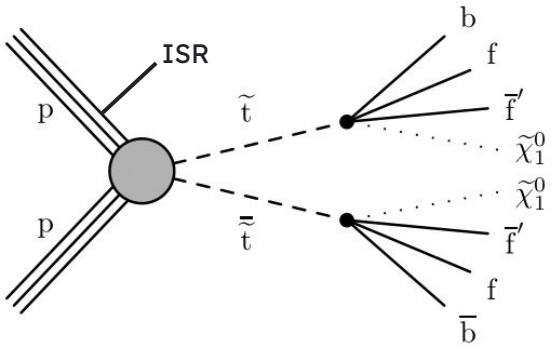
Excluded top squark masses up to:

- 640 GeV for 4bd model
- 740 GeV for Chg model
- 630 GeV for 2bd model.

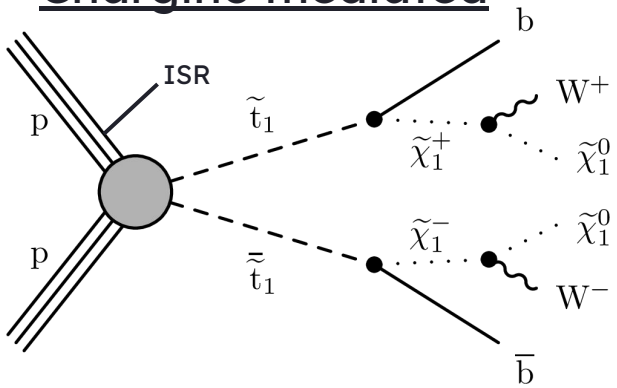
PRD 104, 052001 (2021)

Two-leptons stop search

4-body decay



Chargino mediated



- 4bd: Effective four-point interaction
- Chg: Virtual W decay

Using a **cut-and-count** approach, this search looks for opposite sign lepton pairs final states and soft be tagged jets to probe for 4-body decay and Chargino mediated signal models

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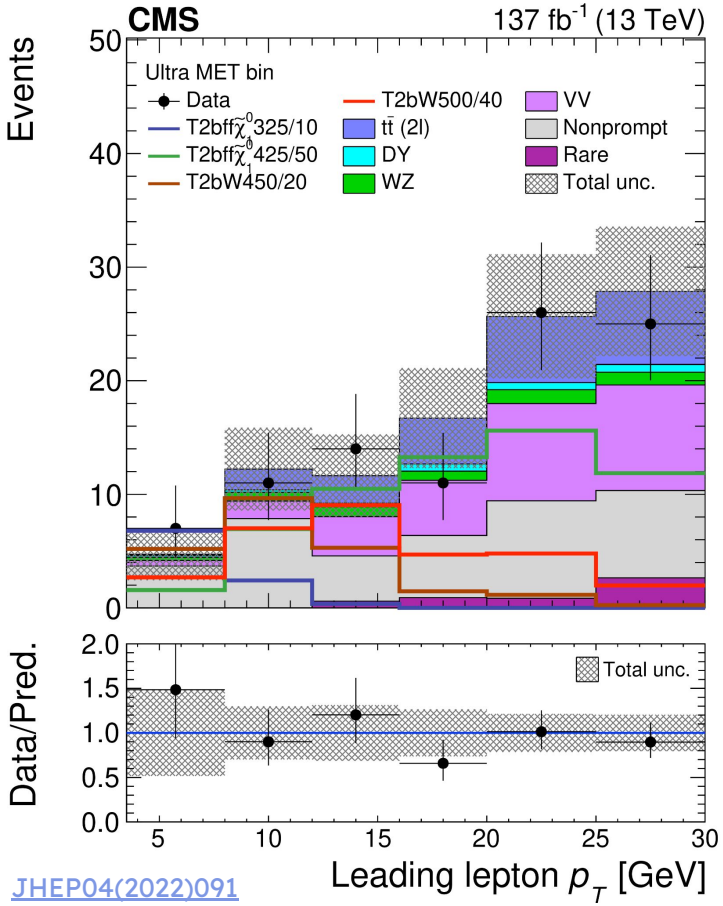
Two-leptons Signal Region



- Online trigger on p_T^{miss} or di-lep+p_T^{miss}
- Search region is first split in p_T^{miss} bins
- Soft leptons: 5(3.5) < $p_T(\ell)$ < 30 GeV for e(μ)
- H_T > 100 GeV
- 0.66 < p_T^{miss}/H_T < 1.4
- “tight lepton veto” criteria on the leading jet → realized only by ISR jet
- Veto b-tagged jet with p_T > 25 GeV
- Prompt lepton backgrounds estimated from CRs
- Non-prompt lepton backgrounds estimated from “tight-to-loose” method

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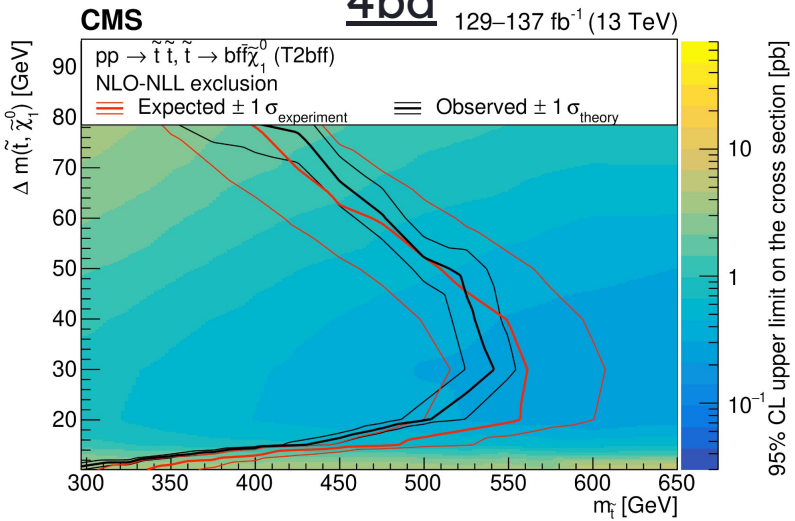
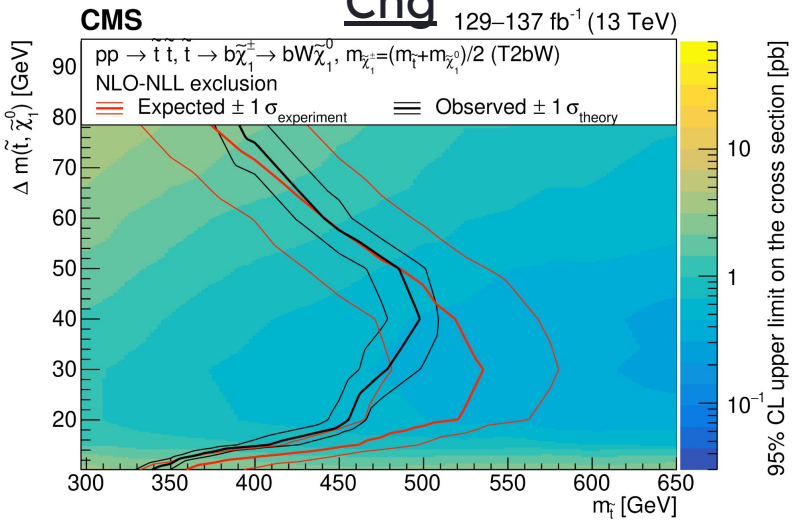
Two-leptons Exclusion Limits





Excluded top squark masses up to:

- 540 GeV for 4bd model
- 480 GeV for Chg model

This search has access to both models but is not optimized for. Used to confirm the results from other specified searches

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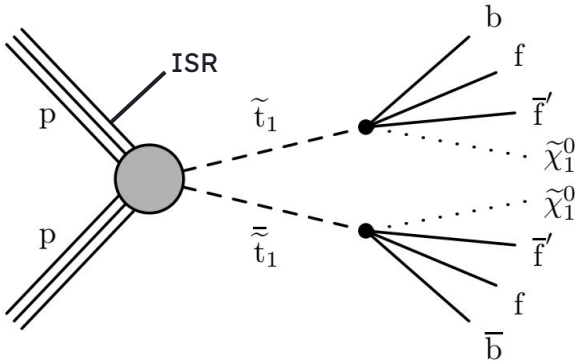
Single-lepton stop search



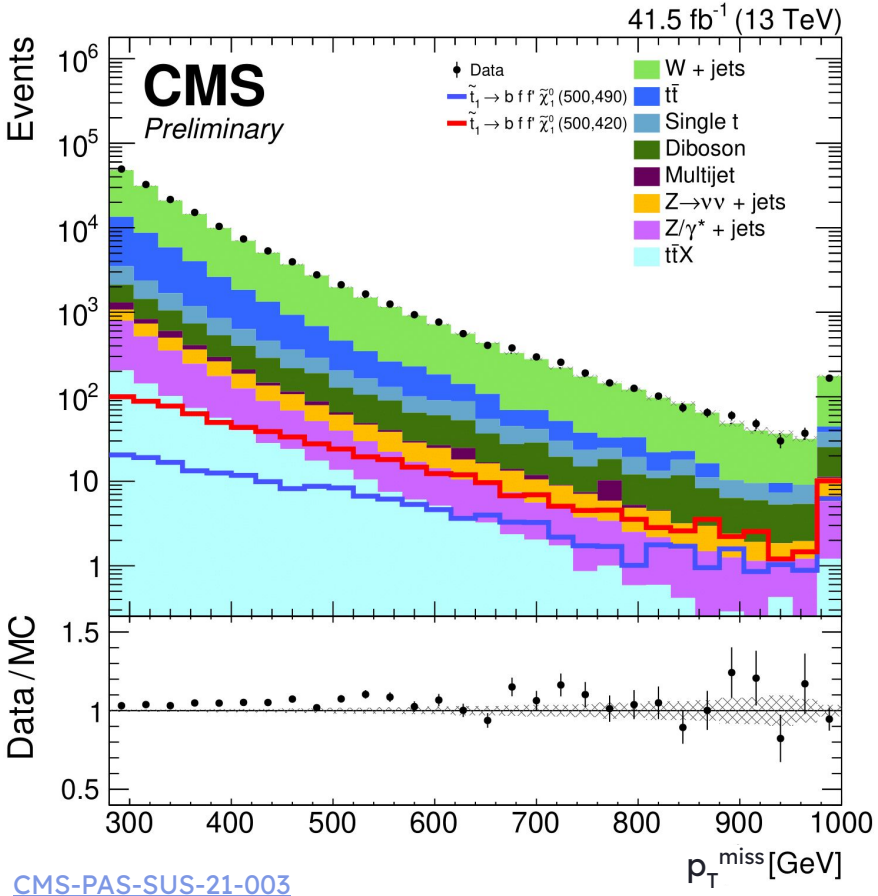
- 4bd: Effective four-point interaction

Using a multivariate approach, this search builds the SRs in 2 steps:

- Preselection region: reduce background while preserving signal
- Train a Boosted Decision Tree (BDT) per Δm region (10 to 80 GeV, in 10 GeV steps) and optimize the cut on the BDT output

CMS-PAS-SUS-21-003

Single-lepton Preselection



- Online trigger on p_T^{miss}
- Exactly 1 lepton
- Soft leptons:
  $p_T(\ell) > 5(3.5)$ GeV for e(μ)
- For $\Delta m \leq 60$ GeV: $p_T(\ell) < 30$ GeV
- $H_T > 200$ GeV
- $p_T^{miss} > 280$ GeV
- $p_T^{ISR} > 110$ GeV

CMS-PAS-SUS-21-003

BDT for the determination of the Signal Regions

1. Train a BDT per Δm (10 to 80 GeV, in 10 GeV steps):
   - Signal: All the Signal Points (SPs) with the same Δm:
     - SPs with **different Δm** have **different** kinematic distributions
     - SPs with the **same Δm** have **similar** kinematic characteristics
   - Background: WJets+TTbar normalized to XS
2. 12 Discriminant variables: p_T(lep), η(lep), chg(lep), p_T^{miss}, M_T, N_{jets}, $p_T(jet_1)$, $p_T(jet_b)$, H_T, N_{jets}(b loose), ΔR(lep, jet_b) & Disc(jet_b)
3. Check for overtraining
4. Measure signal/background separation as a function of the BDT cut: Selection = Preselection && BDT > **x**
5. The optimal **x** is going to be the cut that **maximizes** this separation
   → Thus, **Signal Region** has been determined

repeat once per Δm, per year

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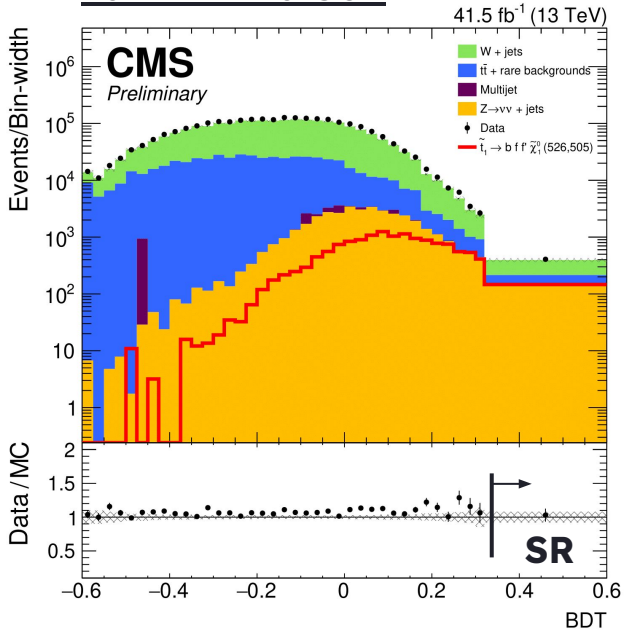
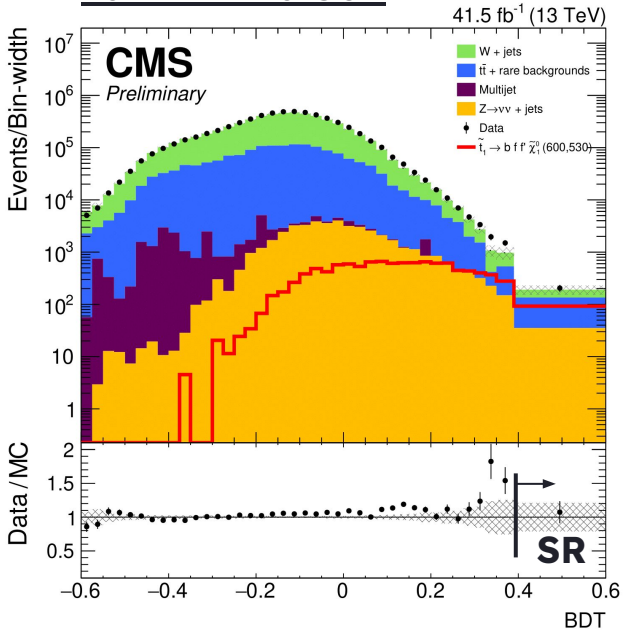
Single-lepton SRs determined by the BDT output

2017 Δm=20 GeV



2017 Δm=70 GeV

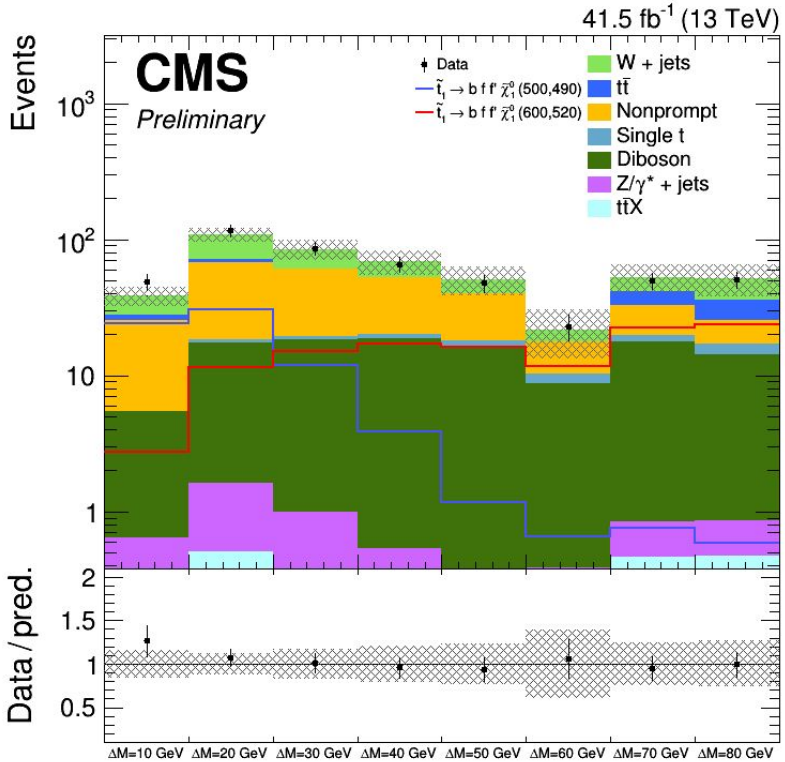


MC estimated backgrounds

BDTs transform the background/signal differences across 12 discriminant variables into a 1-D variable where a cut is set to determine the SR of the respective Δm search region.

CMS-PAS-SUS-21-003

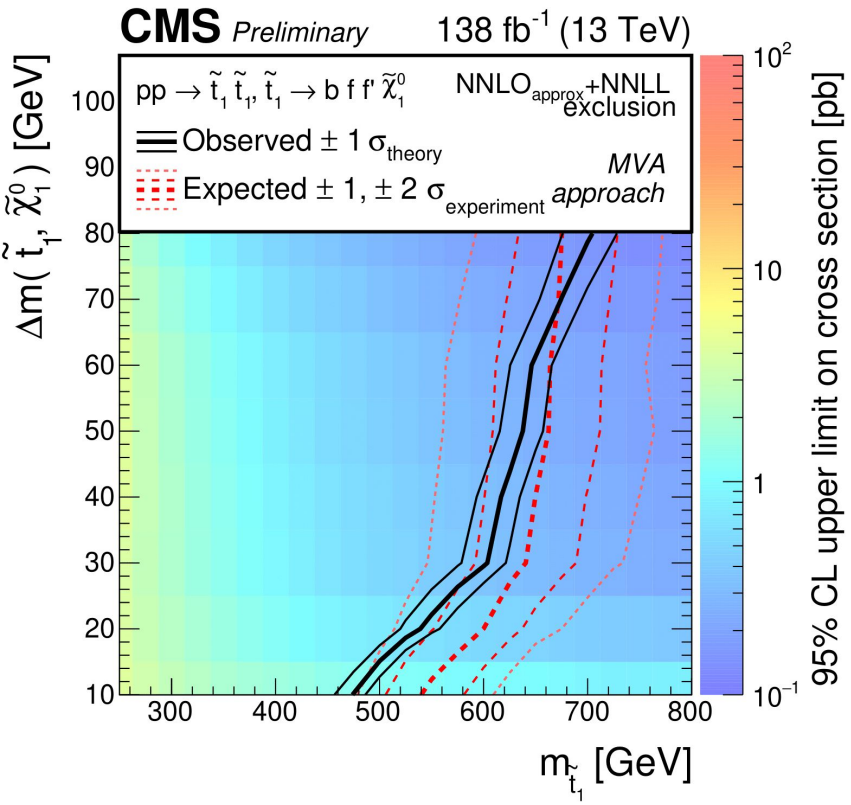
Single-lepton Signal Region



- Each signal region determined by Preselection + $BDT_{cut}(\Delta m)$
- WJets and TTbar prompt backgrounds predicted by data-driven method
- Non-prompt lepton backgrounds estimated from “tight-to-loose” method

CMS-PAS-SUS-21-003

Single-lepton Exclusion Limits



Excluded top squark masses up to:

- 480 GeV at Δm=10 GeV
- 700 GeV at Δm=80 GeV

Local significance of 2.5 standard deviations only at Δm=10 GeV region

CMS-PAS-SUS-21-003

Summary

- Presented the latest results on the searches for stop in compressed scenarios with the CMS experiment
- Covered 0-lepton (all-hadronic), 1-lepton and 2-leptons final states of the 4-body decay of stop in this regimen
- Showcased the different search strategies: soft b-tagging, cut-and-count and multivariate approaches
- No hint of SUSY in the compressed scenario, *yet*
- **Run3:** increase in luminosity, improvement of reconstruction algorithms for soft physics objects and the use of multivariate techniques → will bring interesting searches opportunities…

…Let's keep looking!

Backup

Soft b-tagging

Based on the presence of a Secondary Vertex (SV) reconstructed with inclusive vertex finder (IVF)

- The distance in the transverse plane between the SV and PV < 3 cm
- The significance of the distance between the SV and the PV is > 4
- The pointing angle, defined as $cos((\overrightarrow{PV, SV}, \overrightarrow{p}_{SV}))$ > 0.98, $\overrightarrow{p}_{SV}$ is the total four-momentum of the tracks associated to the SV
- The number of tracks associated to the SV ≥ 3
- The p_T of SV < 20 GeV
- The distance to any jet with p_T > 20 GeV ≥ 0.4 to achieve the orthogonality to the jets and b-tagged jets

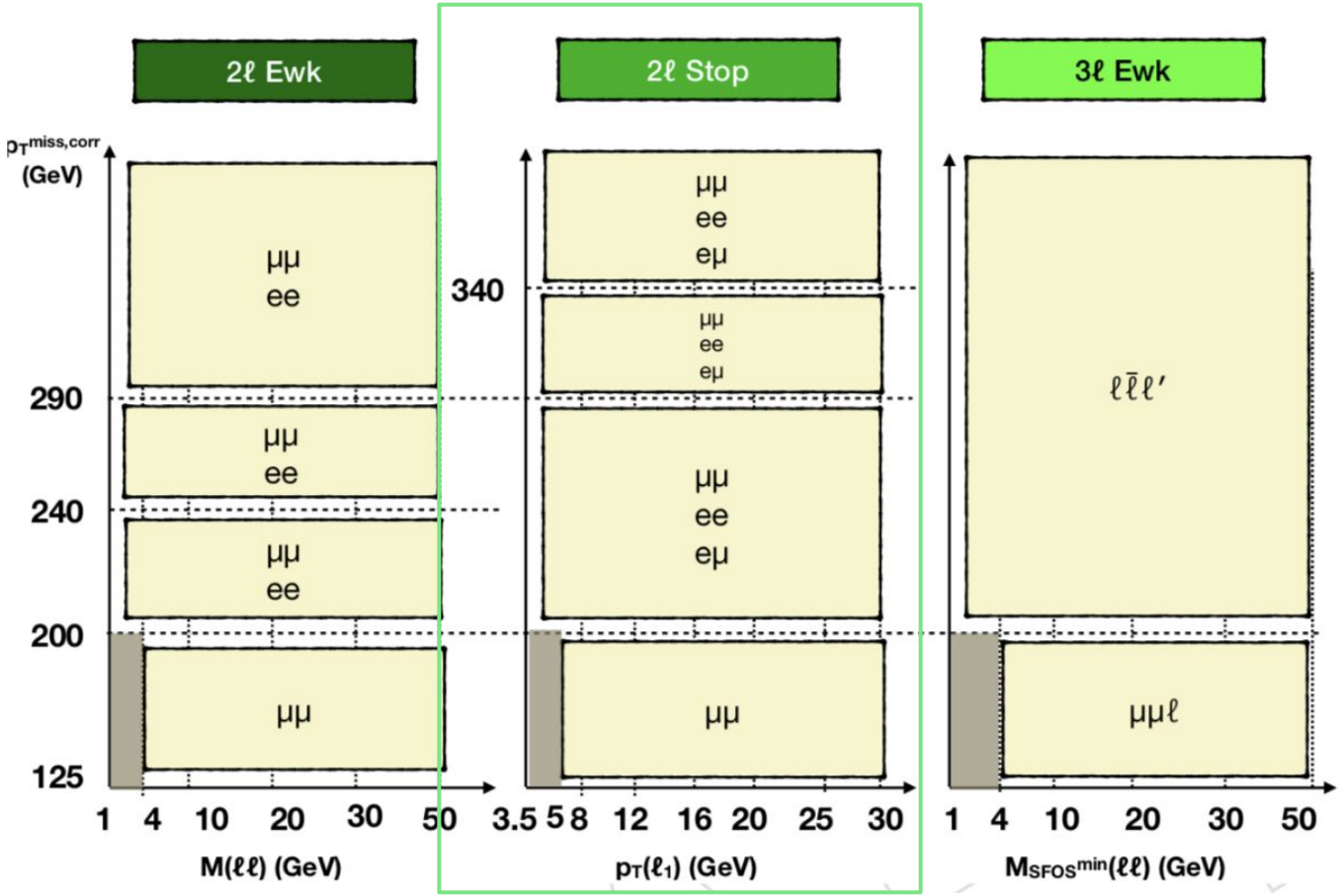
All-hadronic search bin definitions

N_j	N_b	N_{SV}	m_T^b [GeV]	p_T^{ISR} [GeV]	p_T^b [GeV]	p_T^{miss} [GeV]	Bin number
2–5	0	0	—	>500	—	[450, 550, 650, 750, ∞]	0–3
≥6	0	0	—	>500	—	[450, 550, 650, 750, ∞]	4–7
2–5	0	≥1	—	>500	—	[450, 550, 650, 750, ∞]	8–11
≥6	0	≥1	—	>500	—	[450, 550, 650, 750, ∞]	12–15
≥2	1	0	<175	300–500	20–40	[300, 400, 500, 600, ∞]	16–19
≥2	1	0	<175	300–500	40–70	[300, 400, 500, 600, ∞]	20–23
≥2	1	0	<175	>500	20–40	[450, 550, 650, 750, ∞]	24–27
≥2	1	0	<175	>500	40–70	[450, 550, 650, 750, ∞]	28–31
≥2	1	≥1	<175	>300	20–40	[300, 400, 500, ∞]	32–34
≥2	≥2	—	<175	300–500	40–80	[300, 400, 500, ∞]	35–37
≥2	≥2	—	<175	300–500	80–140	[300, 400, 500, ∞]	38–40
≥7	≥2	—	<175	300–500	>140	[300, 400, 500, ∞]	41–43
≥2	≥2	—	<175	>500	40–80	[450, 550, 650, ∞]	44–46
≥2	≥2	—	<175	>500	80–140	[450, 550, 650, ∞]	47–49
≥7	≥2	—	<175	>300	>140	[450, 550, 650, ∞]	50–52

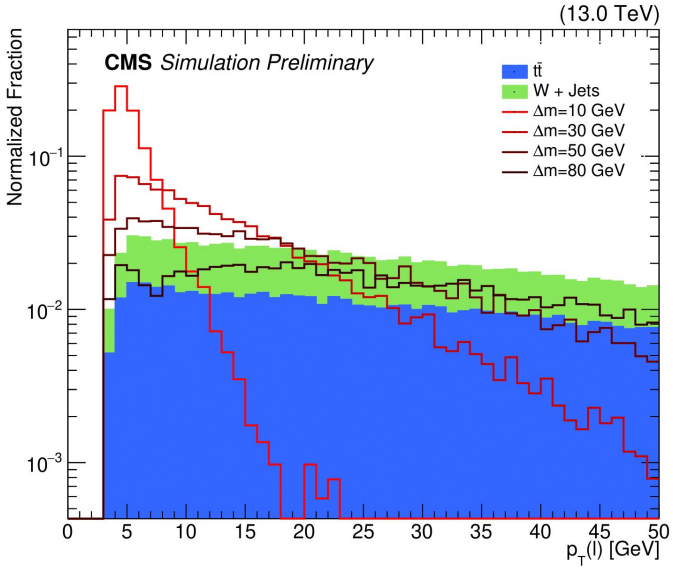
Two-leptons p_T^{miss} SR split

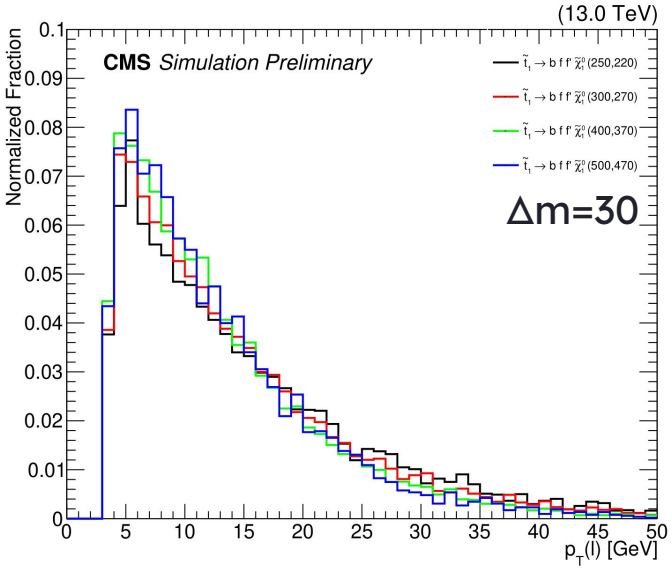
Search region	Low-MET		Med-MET	High-MET	Ultra-MET
	Raw p_T^{miss}	p_T^{miss}	p_T^{miss}	p_T^{miss}	p_T^{miss}
2ℓ-Ewk	> 125	$(125, 200]$	$(200, 240]$	$(240, 290]$	> 290
2ℓ-Stop	> 125	$(125, 200]$	$(200, 290]$	$(290, 340]$	> 340
3ℓ-Ewk	> 125	$(125, 200]$		> 200	

Two-leptons final states



BDT Training Strategy





1 - Signal points with **different Δm** have **different** kinematic distributions

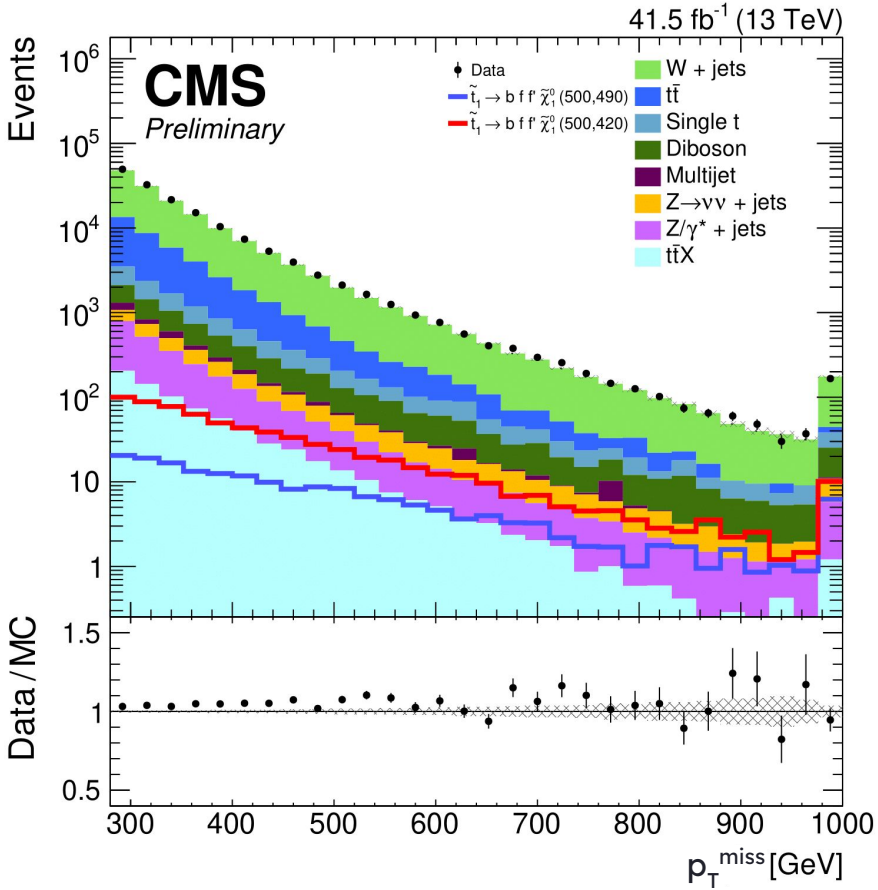
2 - Signal points with the **same Δm** have **similar** kinematic characteristics

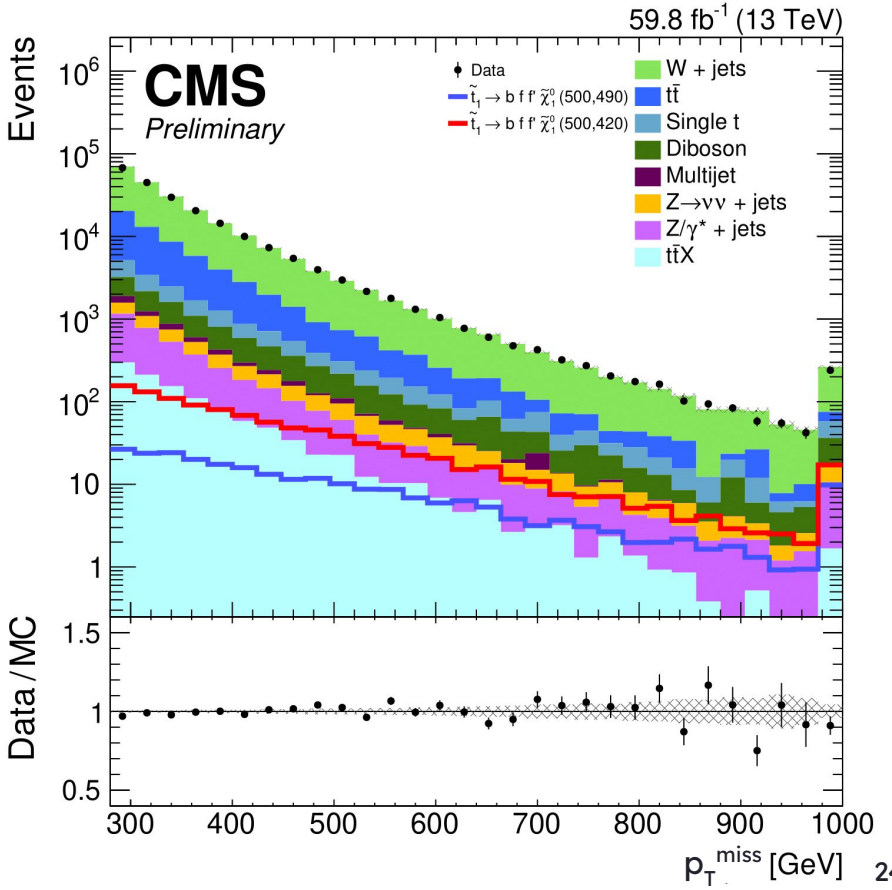
We take advantage of these 2 properties to aggregate the SPs within the same Δm to gain in stats and use them to **train a BDT per Δm** (per year).

Single-lepton training variables

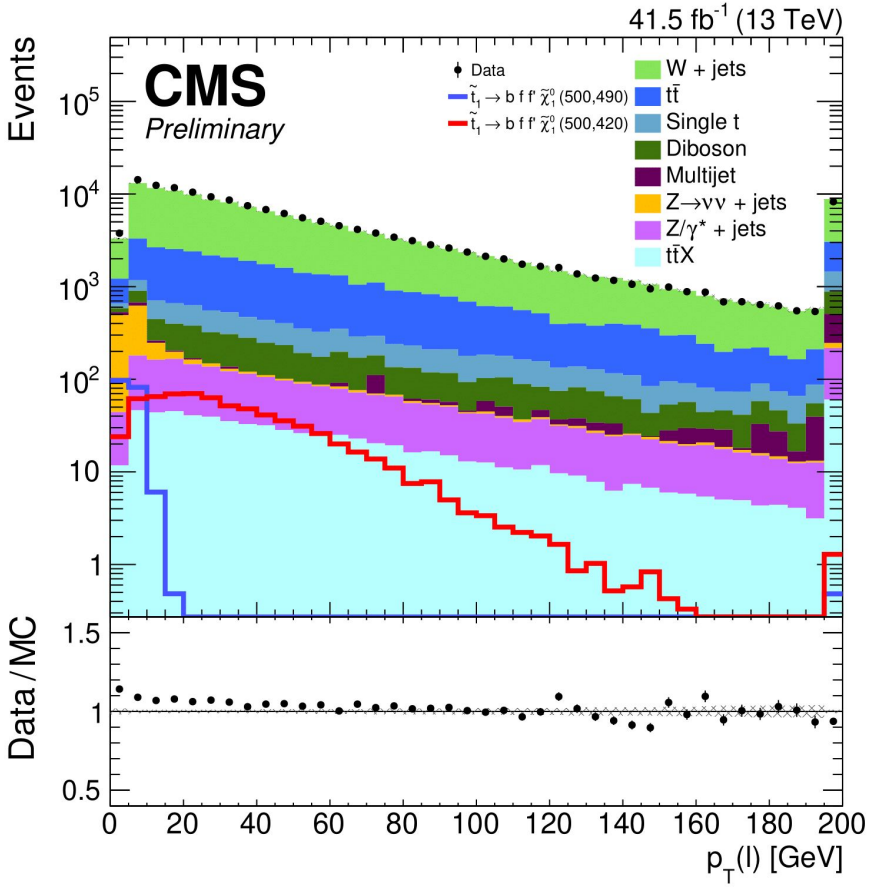
- p_T(lep): lepton (e,μ) p_T
- η(lep): lepton (e,μ) pseudo-rapidity
- chg(lep): lepton (e,μ) charge
- p_T^{miss}: Missing transverse momentum
- M_T: Transverse invariant mass of (p_T^{miss},p_T(lep)) system
- Njets: Number of jets
- $p_T(jet_1)$: Leading jet p_T
- $p_T(jet_b)$: p_T of th jet with the highest b-discriminant
- H_T: scalar sum of the p_T of all jets with $p_T > 30$ GeV
- Njets(b loose): number of loosely b-tagged jets
- ΔR(lep, jet_b): distance between the lepton and the jet with the highest b-discriminant
- Disc(jet_b): b-discriminant distribution of the jet with the highest b-discriminant

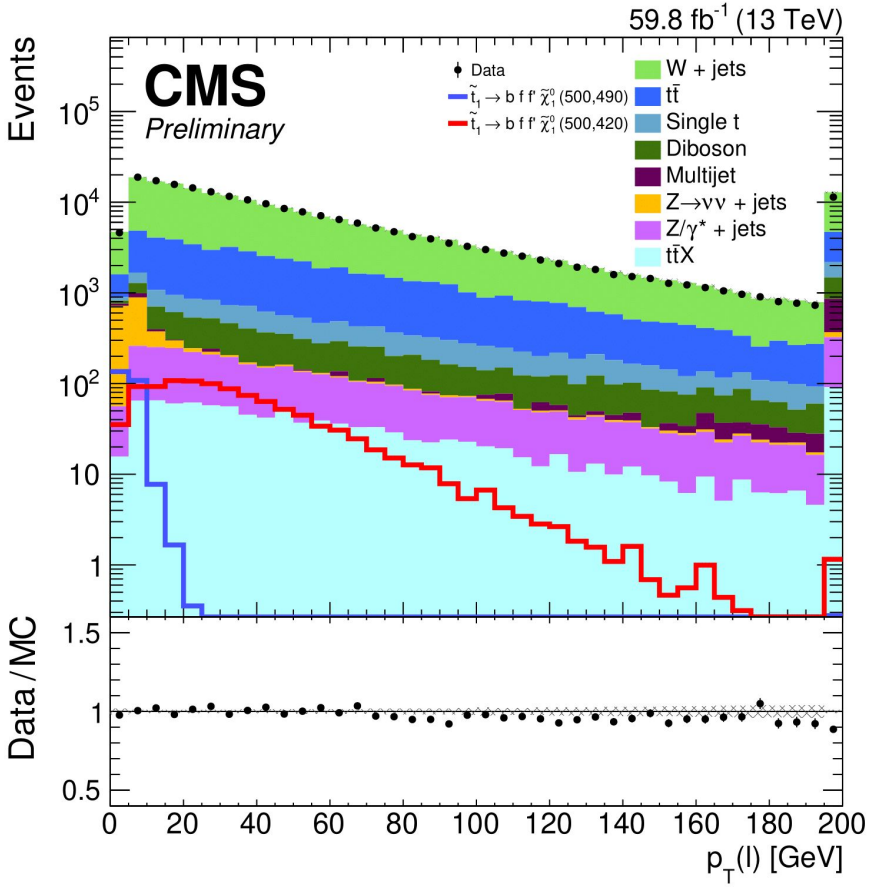
Single-lepton training variables: p_T^{miss}



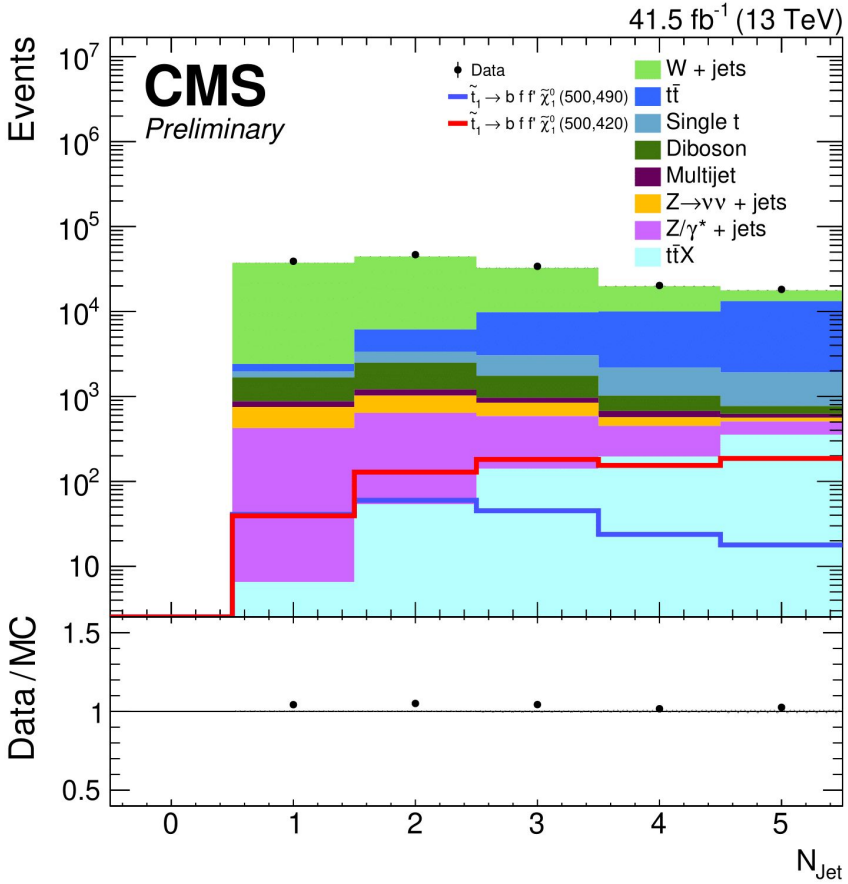


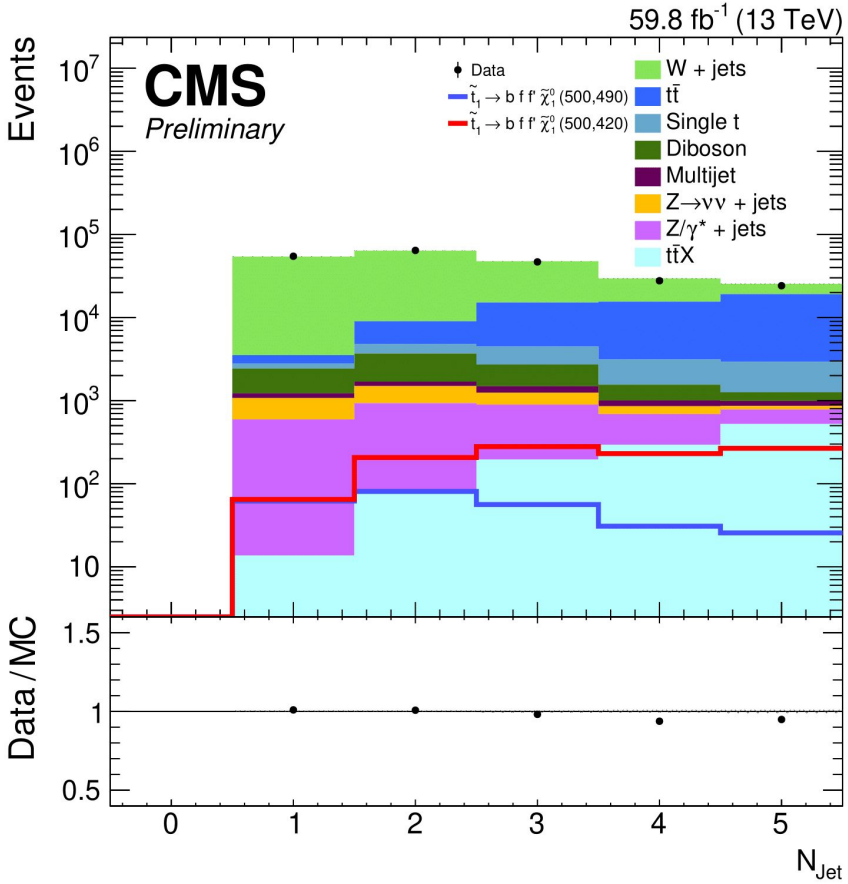
Single-lepton training variables: $p_T(l)$



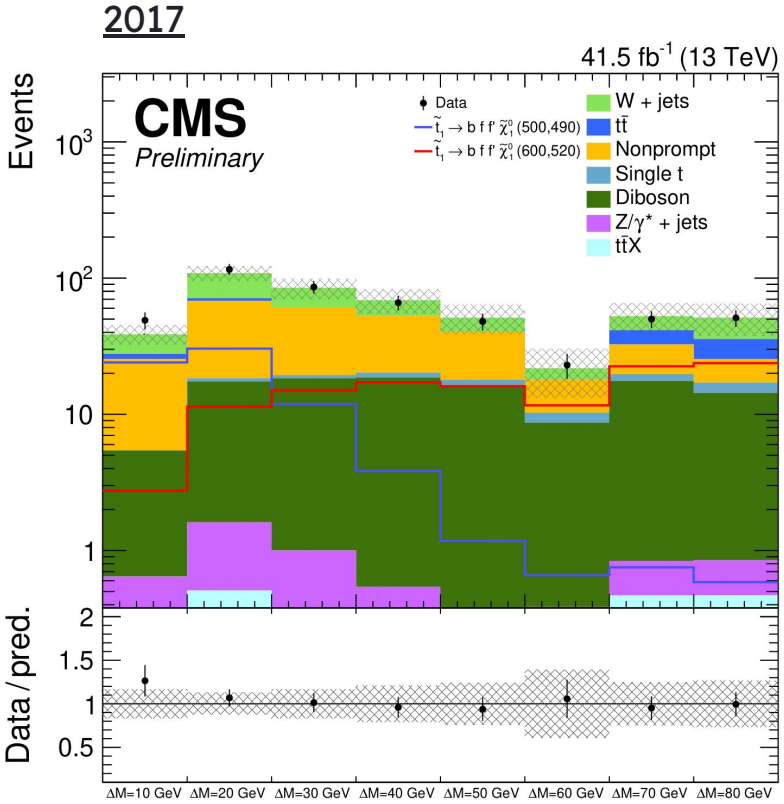


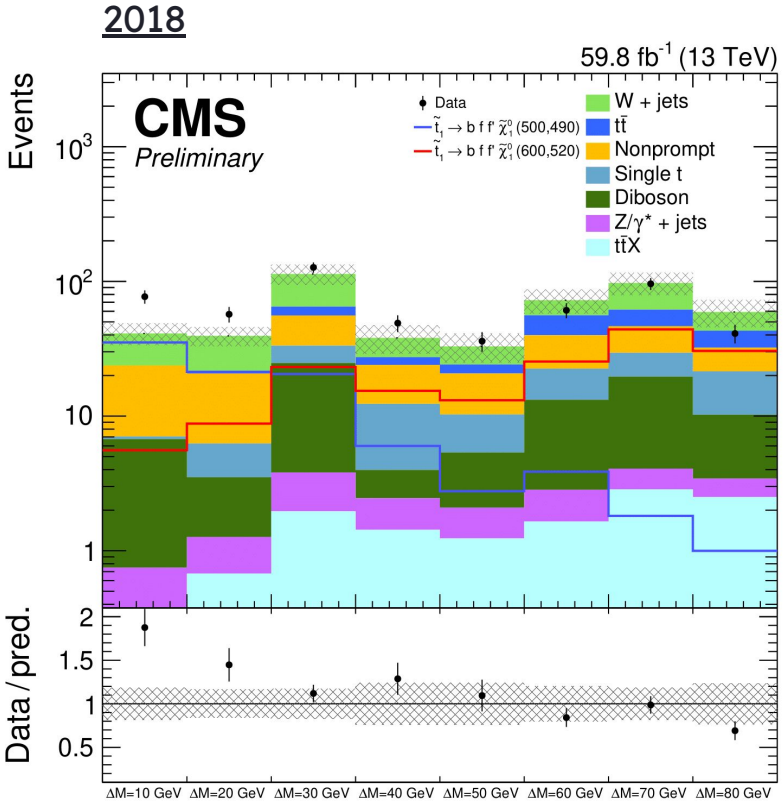
Single-lepton training variables: N_{Jet}





Single-lepton unblinded Signal Region





The 3 main backgrounds (WJets, TTbar and Nonprompt leptons) are estimated from data driven methods