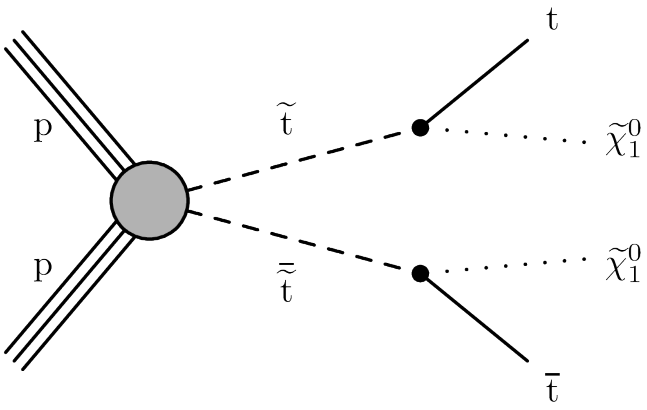
Searches for third generation squarks with the CMS detector

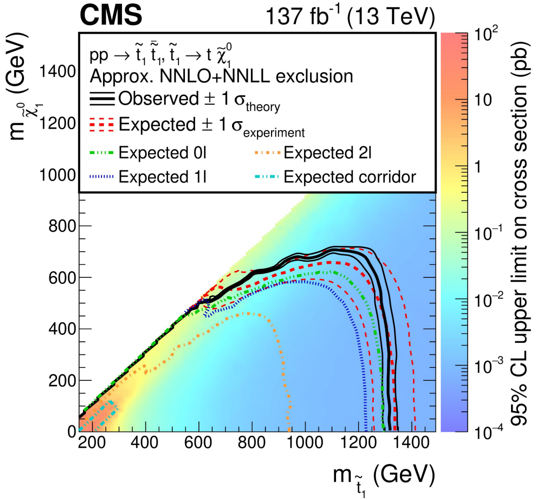


SUSY 2021

Caleb Smith (KU)

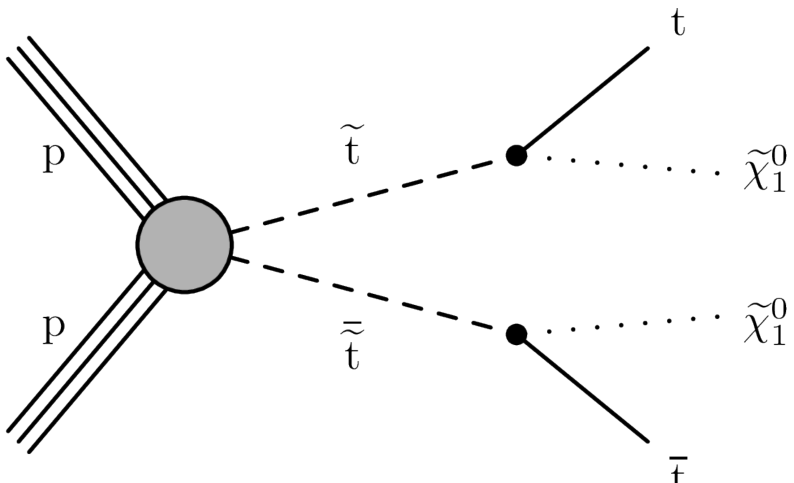
August 23, 2021

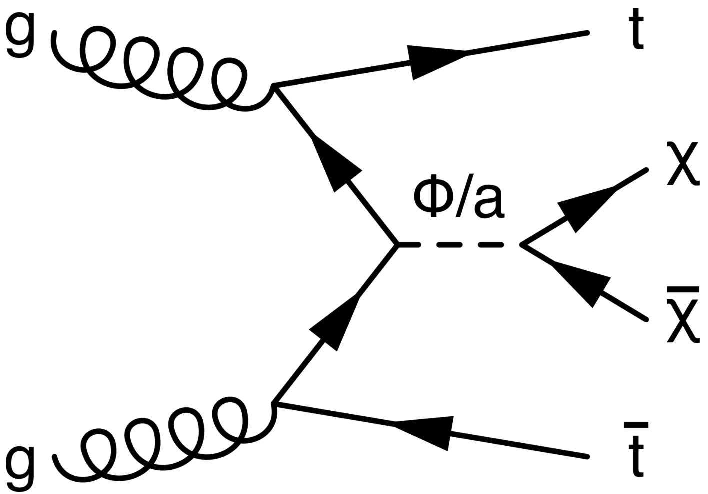
Link to indico



Outline

- CMS searches using the LHC Run 2 (137 fb^{-1}) dataset.
- Top squark searches
  - All hadronic (no charged leptons) final state.
  - Combined (0, 1, and 2 charged leptons) final state.
  - Top corridor study.
- Dark matter search
  - Scalar or pseudoscalar mediators that couple to quarks and dark matter.





Supersymmetry (SUSY)

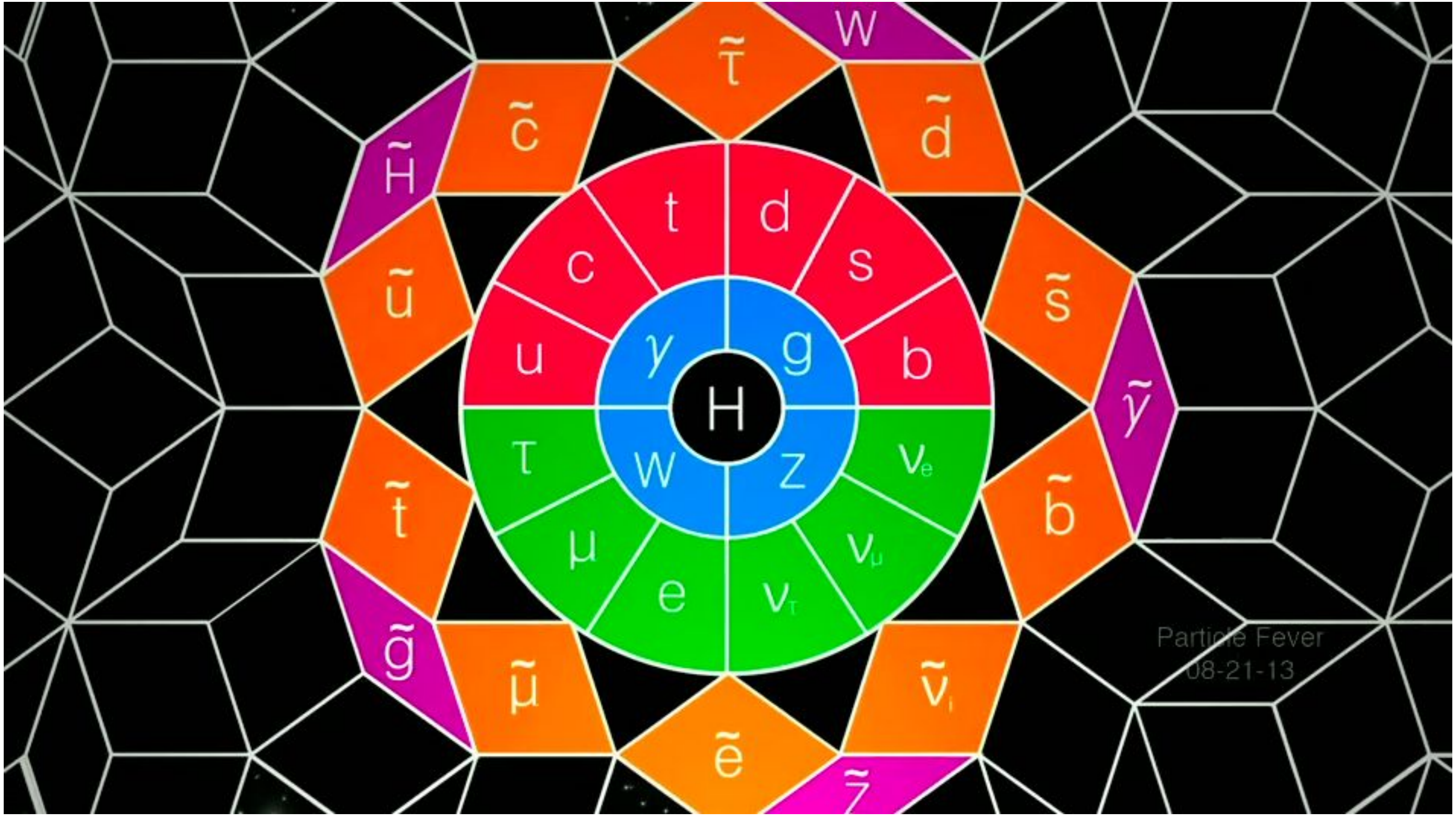
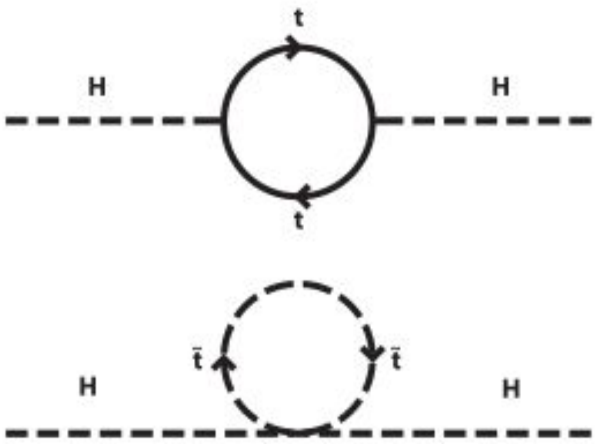


Image from Particle Fever

Supersymmetry (SUSY)

- SUSY can resolve the hierarchy problem and offers a dark matter candidate.
- Regulates divergent terms in the Higgs mass calculation: important for third generation quarks.
- Cancellation works best for lighter stops.



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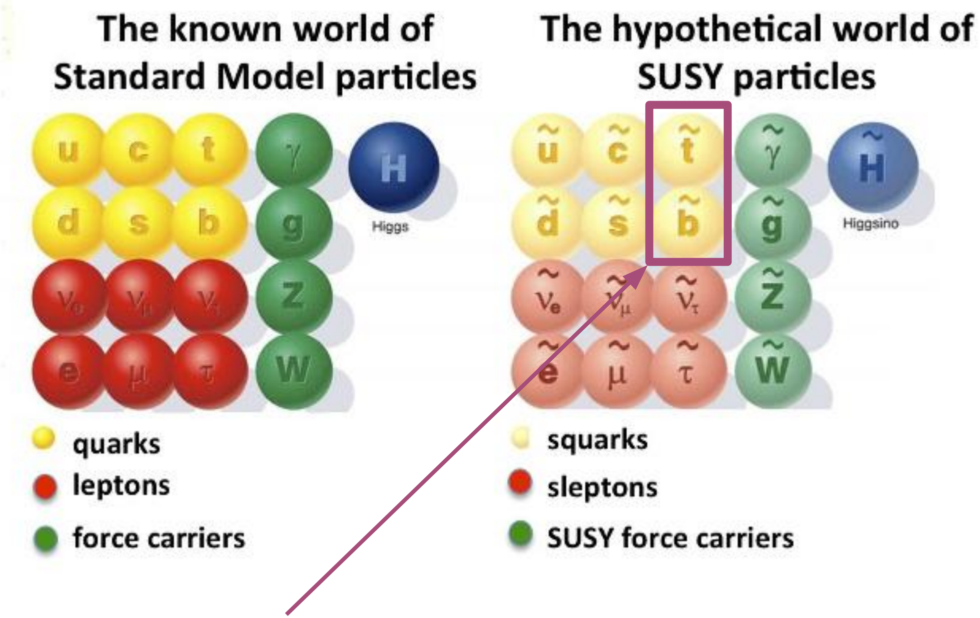
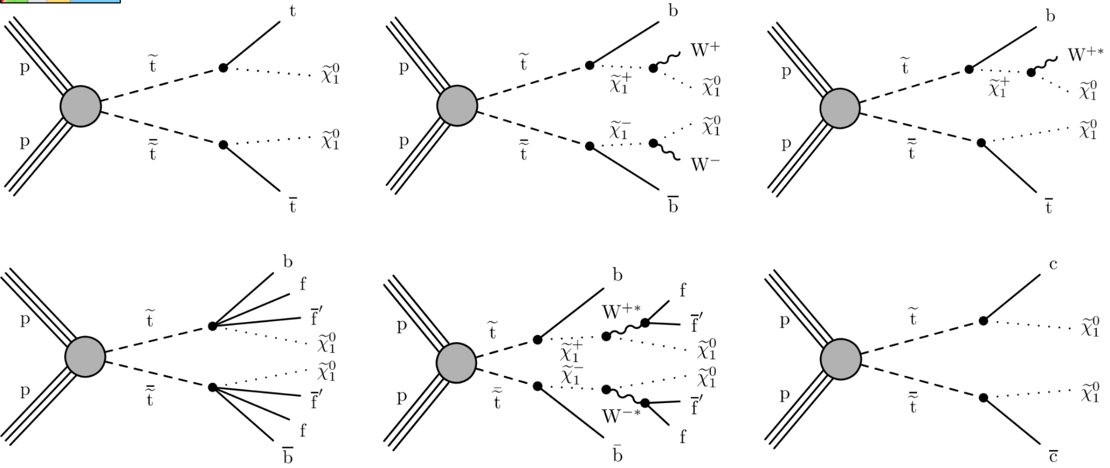
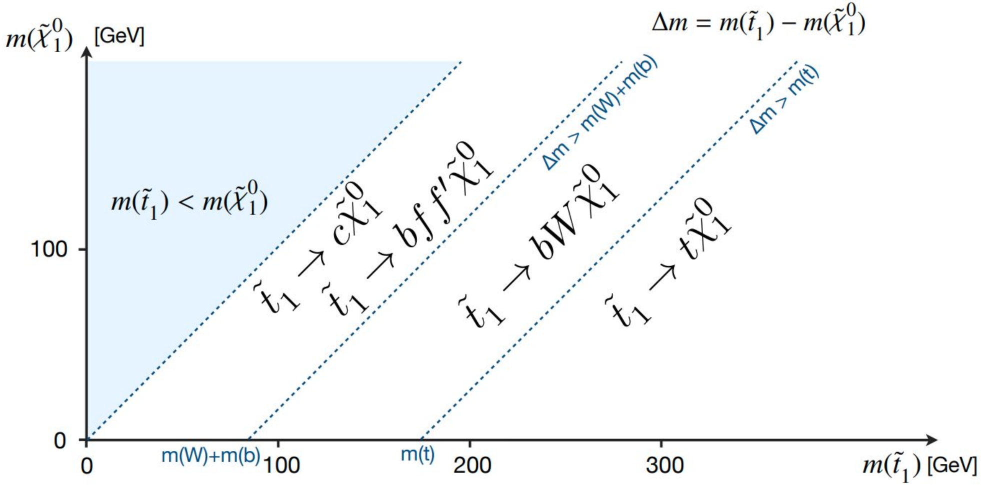


- Low mass third generation squarks are accessible at the LHC.

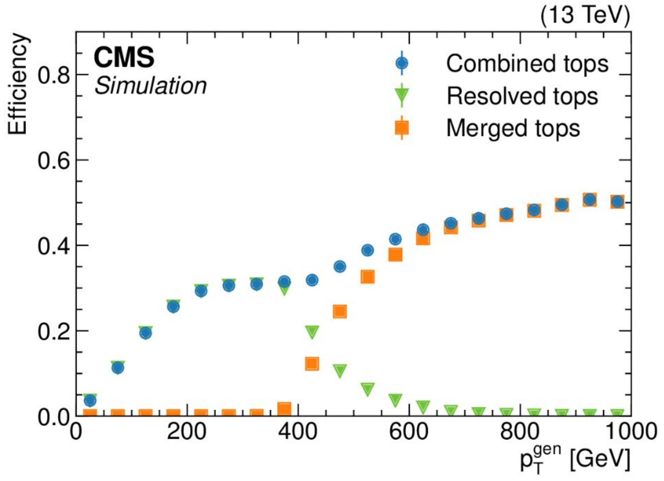
All Hadronic Stop Search

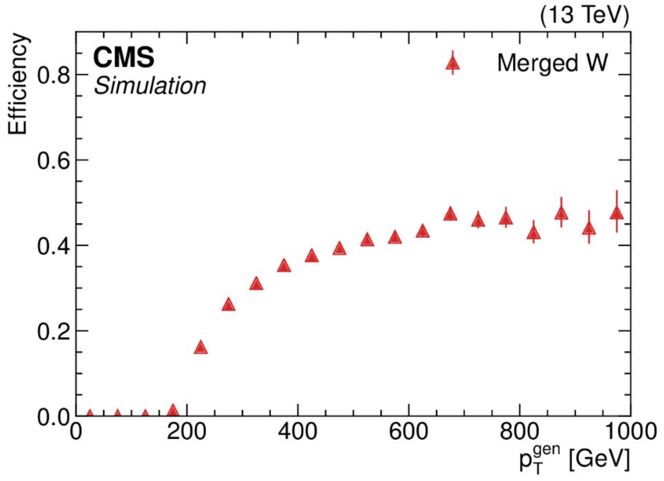


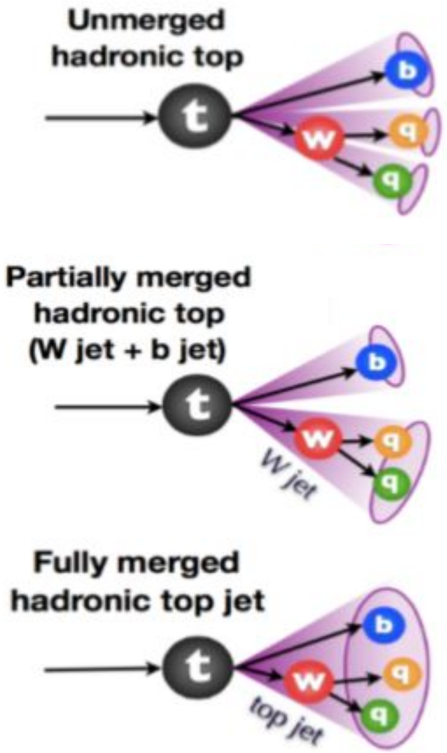


- All hadronic final state: arXiv:2103.01290
- Direct top squark production models.
- Final states determined by Δm: mass difference between top squark and neutralino.
- Analysis targets both compressed (low Δm) and uncompressed (high Δm) regions.
- Final states have jets, missing p_T, tops, bottoms, and Ws.
- Veto charged leptons.

Identifying Top Quarks and W Bosons

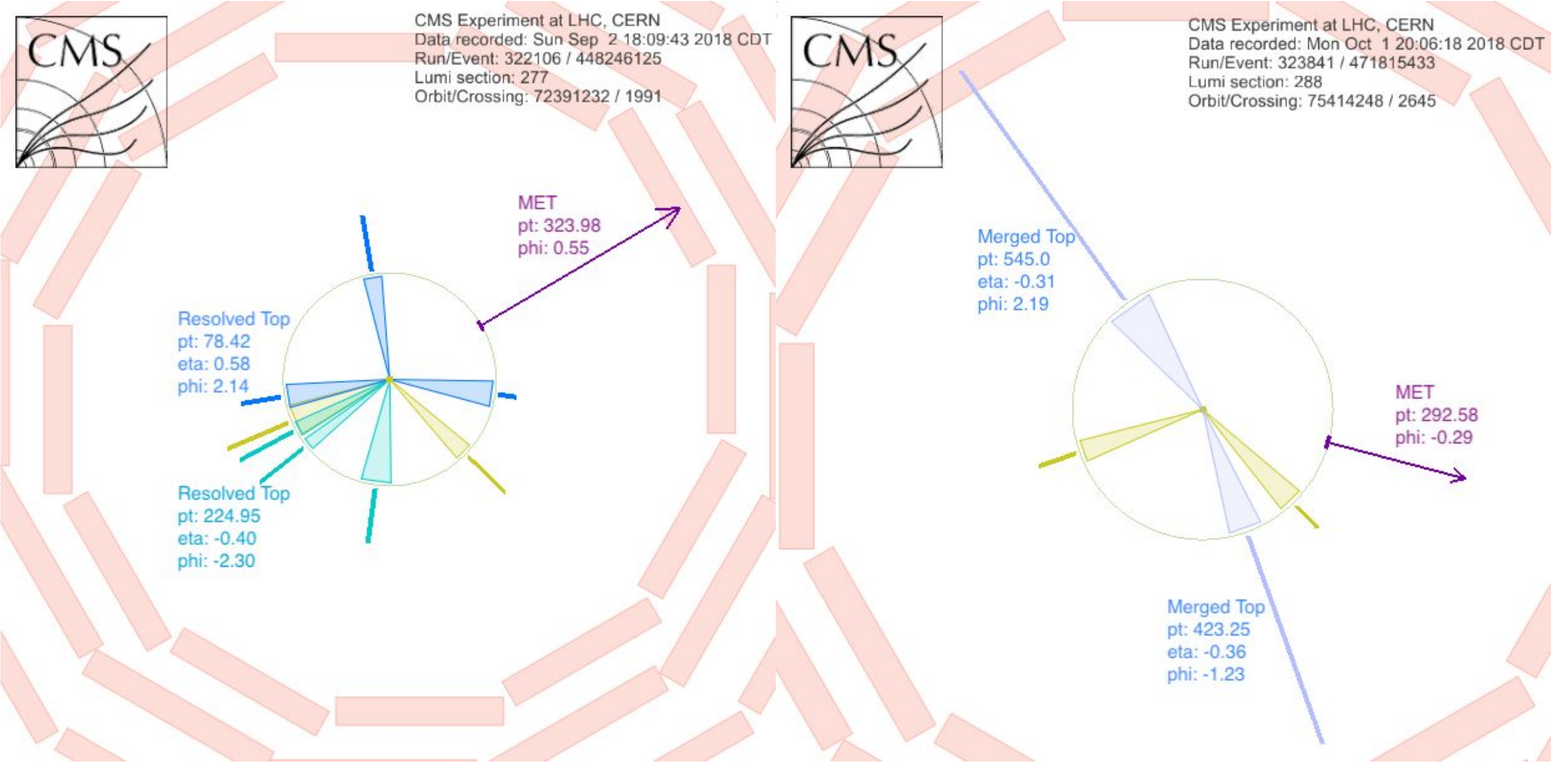






- DNNs used to identify hadronically decaying top quarks and W bosons.
- Resolved and merged top taggers provide high efficiency for low and high p_T tops.
- Bottom quarks identified with low and high p_T b taggers.

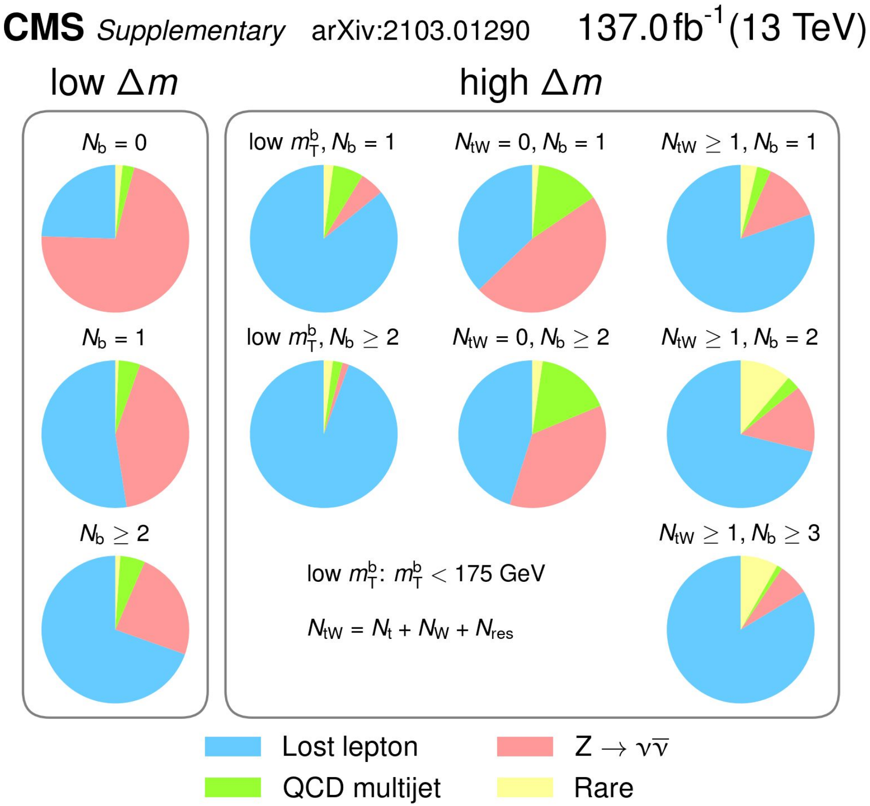
CMS Event Displays



Top tagging algorithms in action for data events in the search region. Event with two identified resolved top quarks (left). Event with two identified merged top quarks (right).

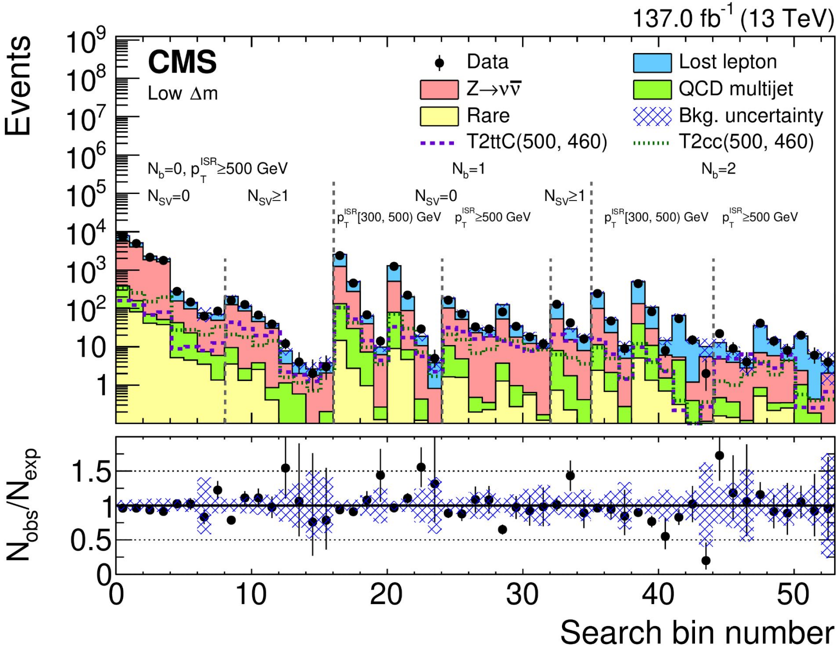
All Hadronic Stop Search

- Search regions
  - Compressed (low Δm)
  - Uncompressed (high Δm)
- Primary backgrounds
  - "Lost Lepton": tt, W + jets, etc. where lepton is not reconstructed
  - Z (to neutrinos) + jets
  - QCD multijet
- Data driven background predictions.
  - Derived from signal depleted control regions.
  - Monte Carlo simulation used to extrapolate control region data to signal region.

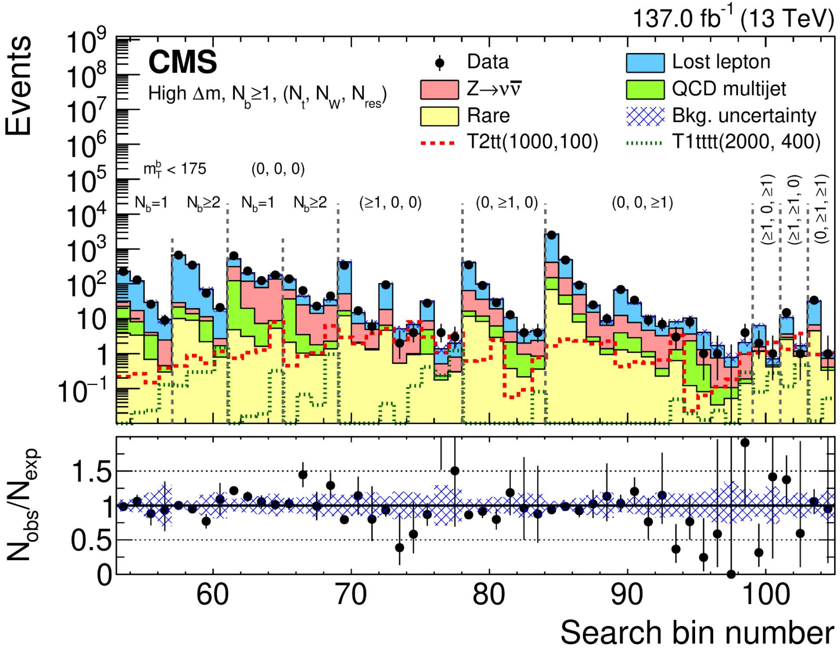


All Hadronic Stop Search

Compressed (low Δm)



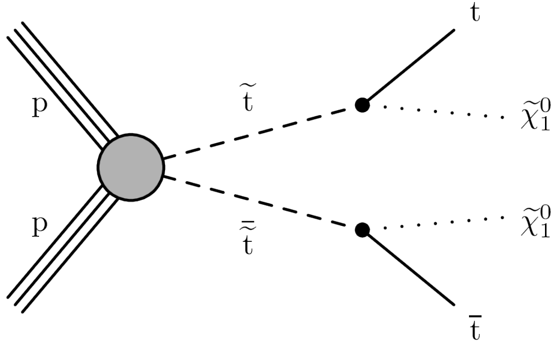
Uncompressed (high Δm)

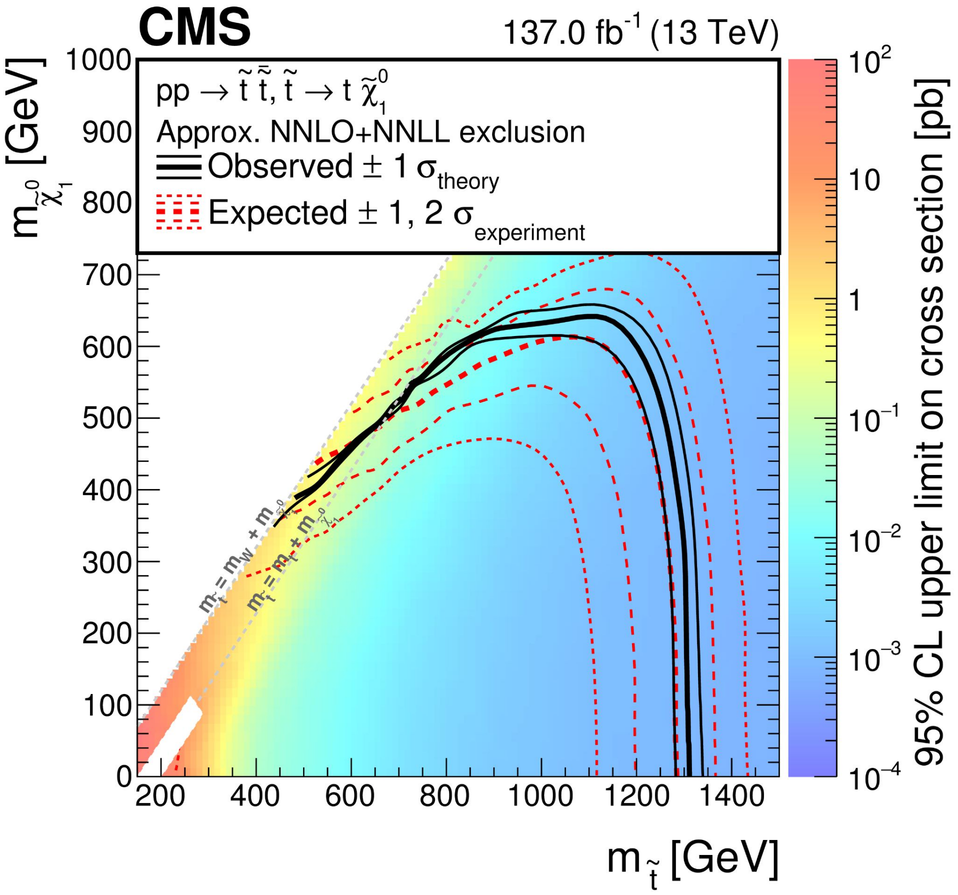


- Subset of 183 search bins.
- Bin in H_T, missing p_T, number of jets and bottoms.
- Low Δm: veto tops and Ws. High Δm: bin in number of tops and Ws.
- No excess in data beyond SM background prediction.

All Hadronic Stop Search

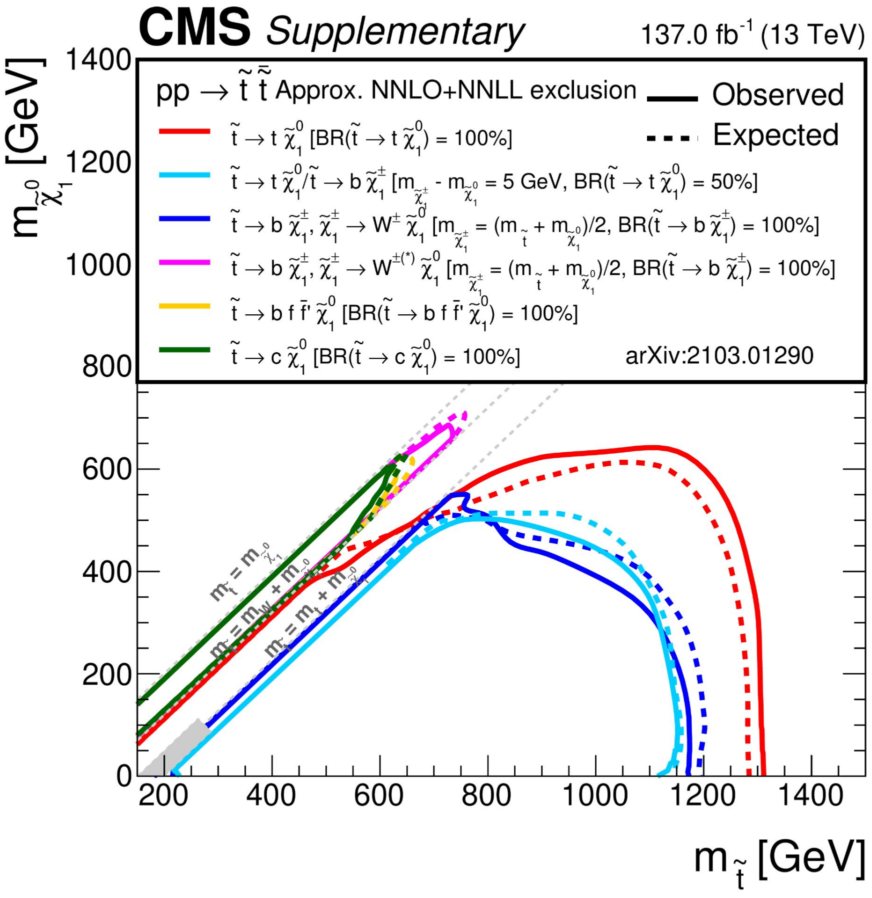
- All hadronic final state: [arXiv:2103.01290]
- Extends stop mass limit up to 1310 GeV.
  - Larger data set.
  - Optimized search bins.
  - Improved object tagging.
- Only one model shown here.
- Does not consider top corridor.





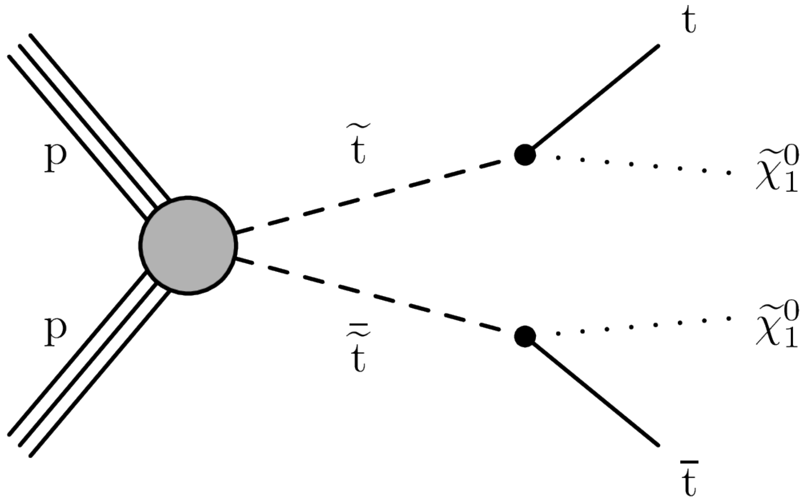
All Hadronic Stop Search

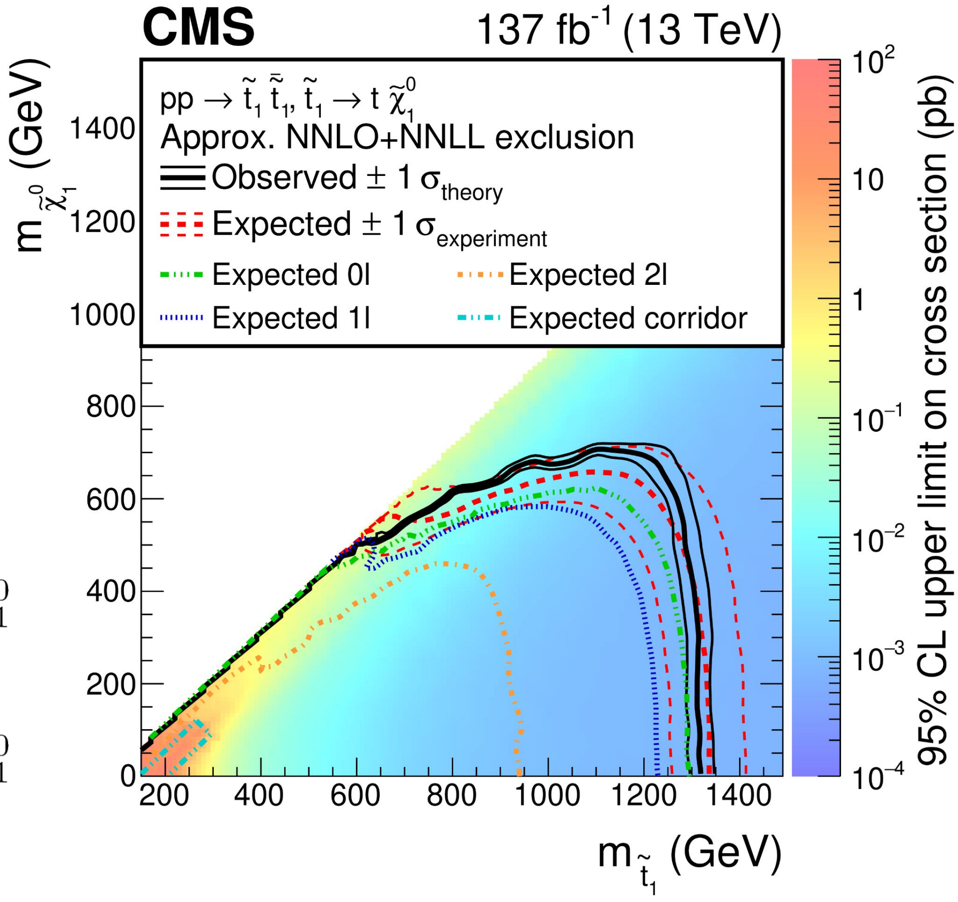
- All hadronic final state: [arXiv:2103.01290](https://arxiv.org/abs/2103.01290)
- Excluded regions for direct stop production models.
- Extends limits in compressed and uncompressed regions.
- Does not consider top corridor.



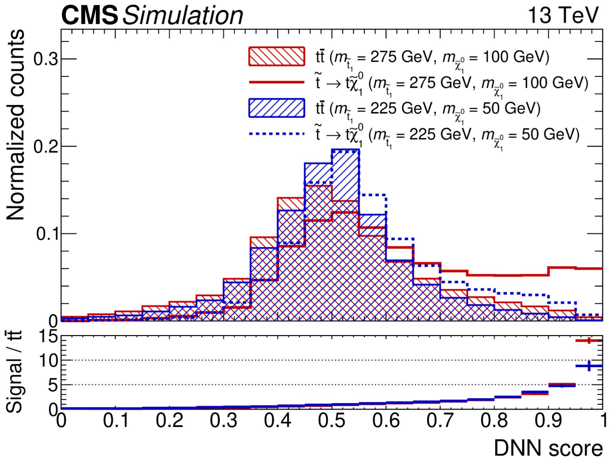
Combined Stop Search

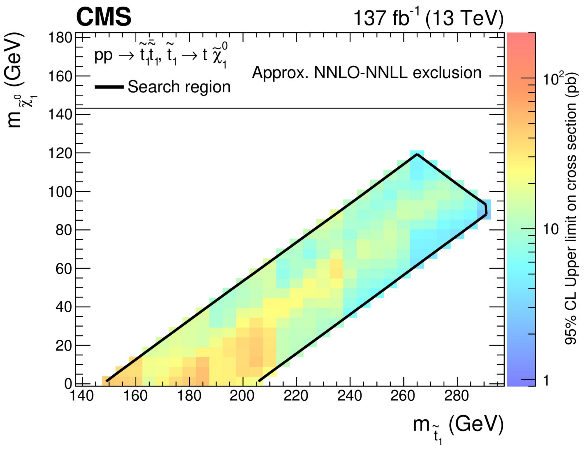
- Limit on stop production from combination of 0, 1, and 2 lepton final state searches.
- Only one model shown here.
- arXiv:2107.10892





Top Corridor Region





- Dedicated top corridor region analysis: [arXiv:2107.10892]
- Challenging region due to similarity between signal and tt background.
- Top corridor region:
  - $\Delta m_{cor} = |m_{stop} - m_{neutralino} - 175\text{ GeV}|$
  - $\Delta m_{cor} < 30$ GeV
  - $m_{stop} < 275$ GeV (approx.)
- Require two opposite charge leptons, missing $p_T > 50$ GeV, and other cuts to reduce tt, tW, and DY backgrounds.
- DNN used to increase signal sensitivity by distinguishing signal from tt background.

Dark Matter

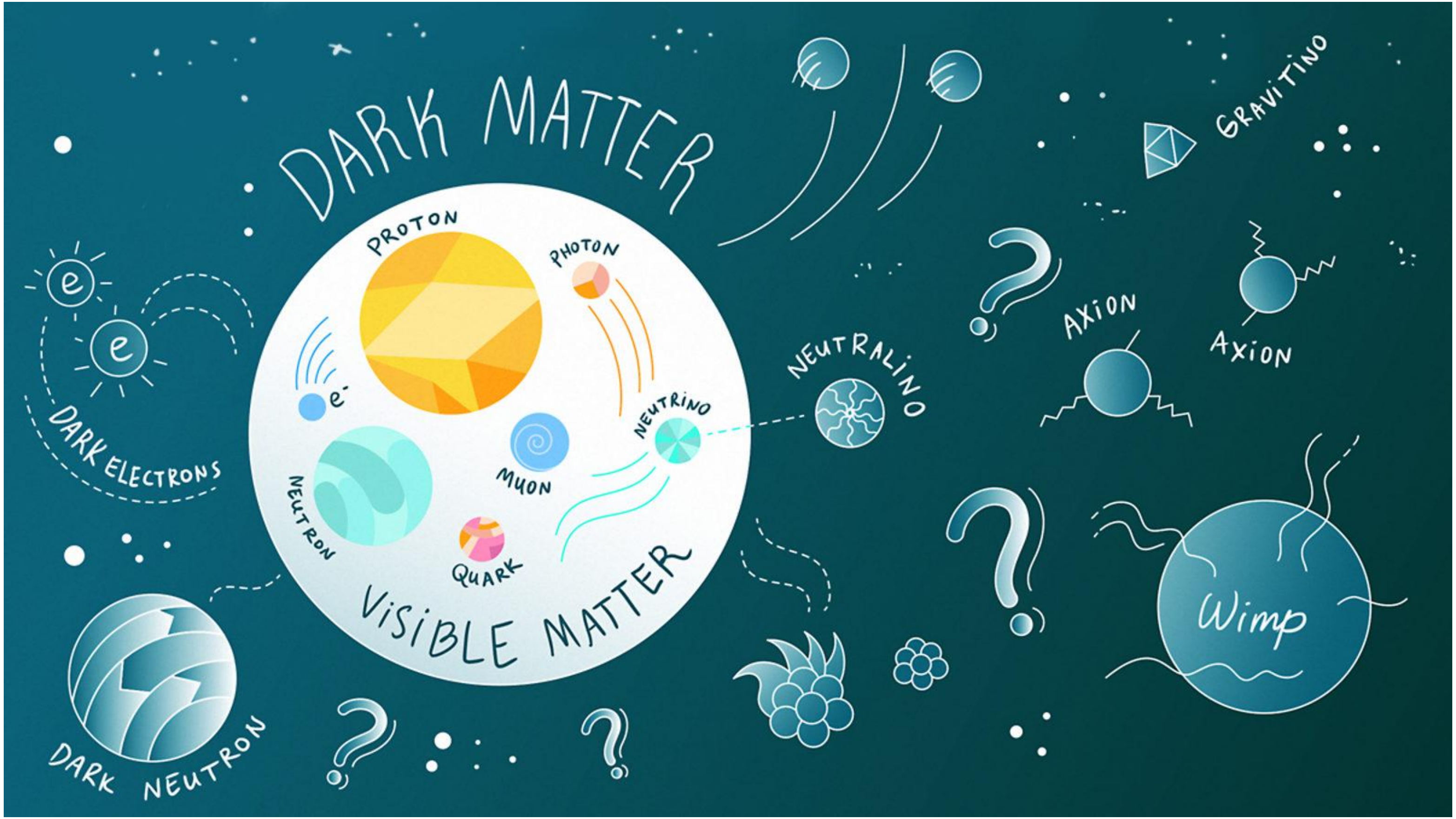
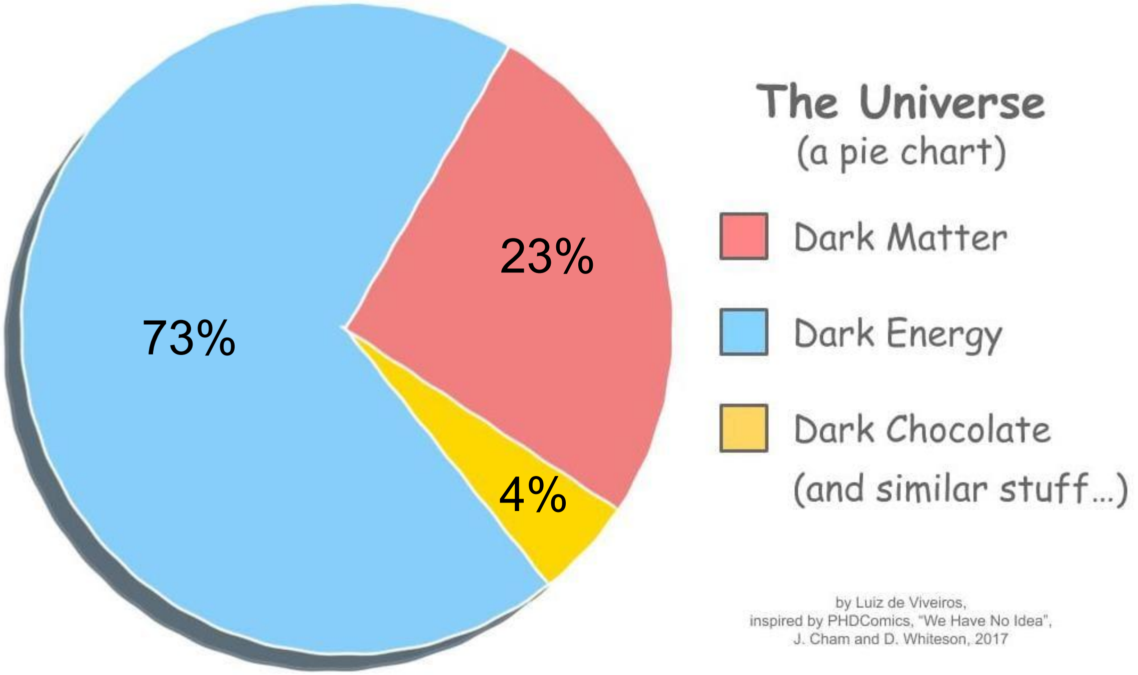


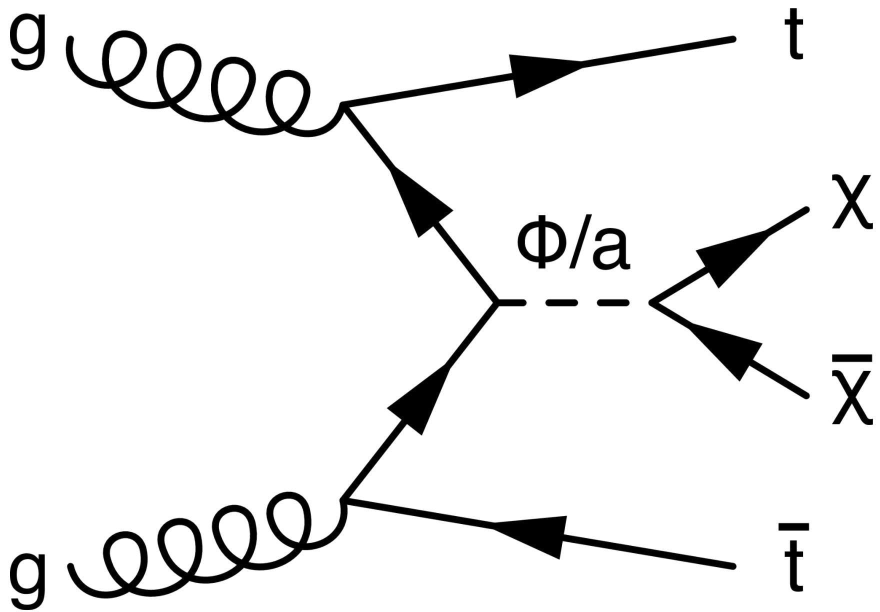
Image from Symmetry Magazine

Dark Matter

- Dark matter accounts for a large portion (~23%) of the energy in the universe, but is not explained by the SM!
- The lightest supersymmetric particle (LSP) is a potential candidate for dark matter.
- Dark matter can take other forms and couplings with the SM.

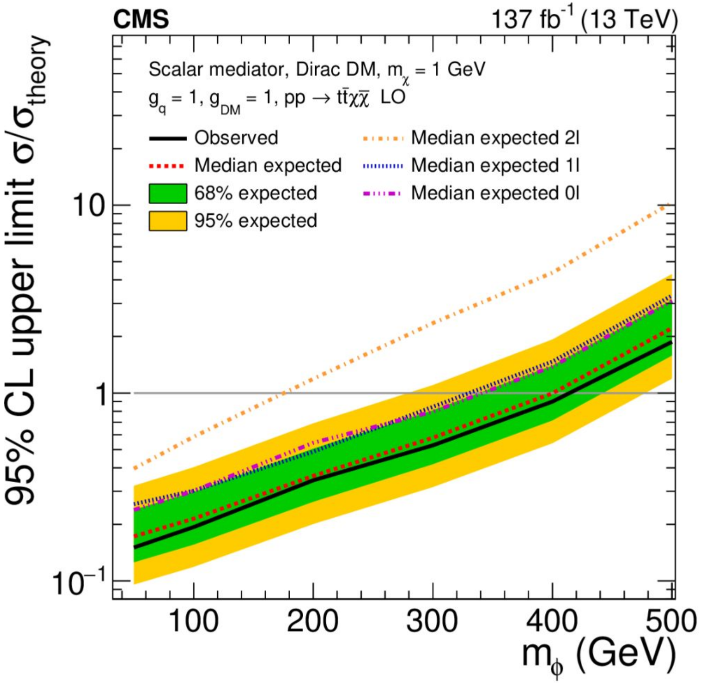


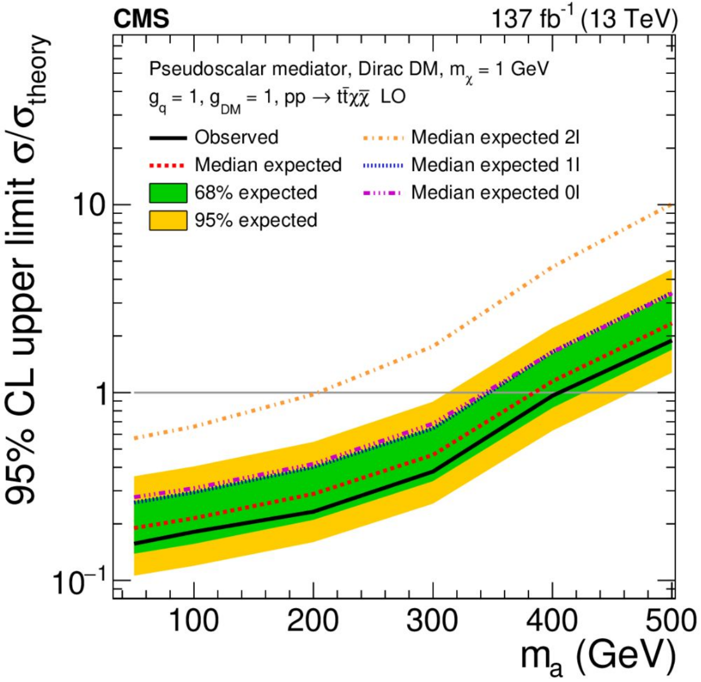
Dark Matter Production



- Dark matter production model: arXiv:2107.10892
- Couples to the top quark through a scalar (φ) or pseudoscalar (a).
- Dark matter (X) results in missing transverse energy in the final state.
- Kinematics of this model are similar to some direct stop production models.
- Use inclusive final state (0, 1, and 2 charged leptons).

Limits on Dark Matter Models

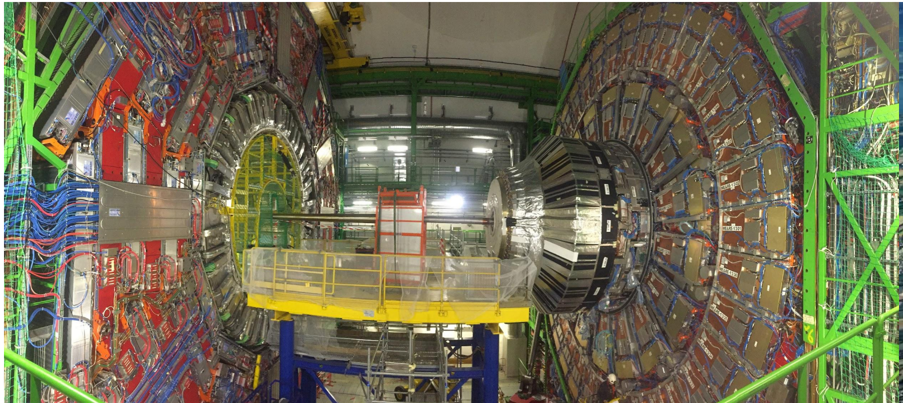




- Mediator couplings to quarks and dark matter set to 1.
- Scalar mediator (φ): m_φ excluded up to 400 GeV for m_X = 1.
- Pseudoscalar mediator (a): m_a excluded up to 420 GeV for m_X = 1.

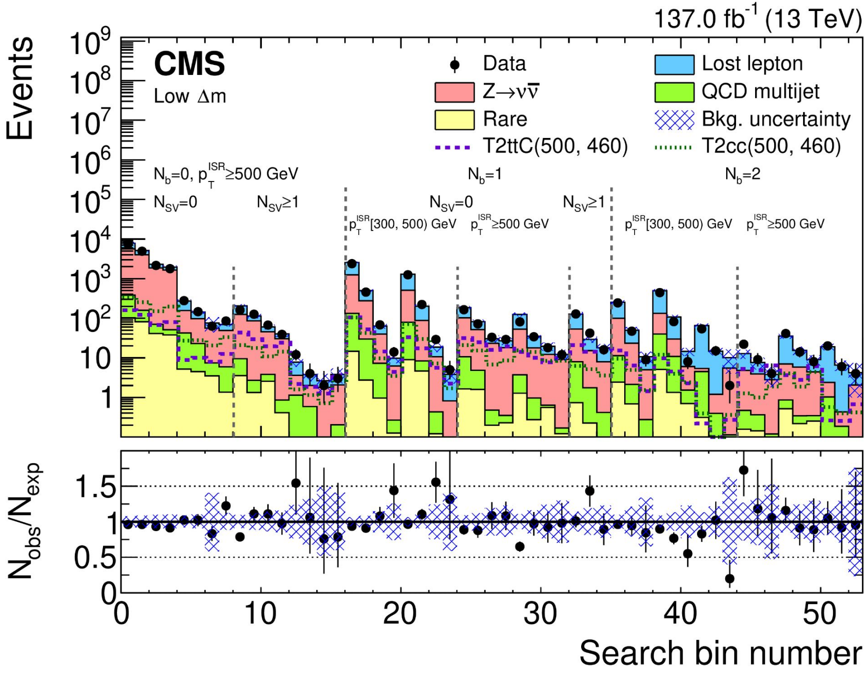
Conclusions

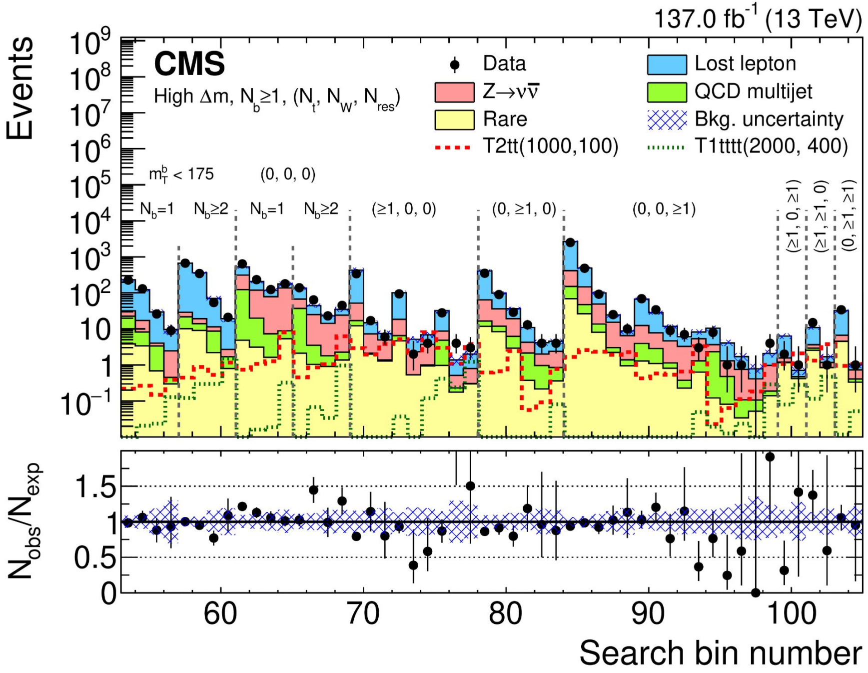
- LHC Run 2 (137 fb^{-1}) stop searches extend mass limit by ~200 GeV.
- CMS combination excludes stops up to 1325 GeV.
- Full top corridor region excluded for the first time.
- Dark matter mediators excluded up to 420 GeV.
- Sbottom masses up to 1600 GeV excluded by CMS: [arXiv:2012.08600](https://arxiv.org/abs/2012.08600)
- LHC Run 3 (2022–2024) projecting 300 fb^{-1} integrated luminosity! The hunt continues...



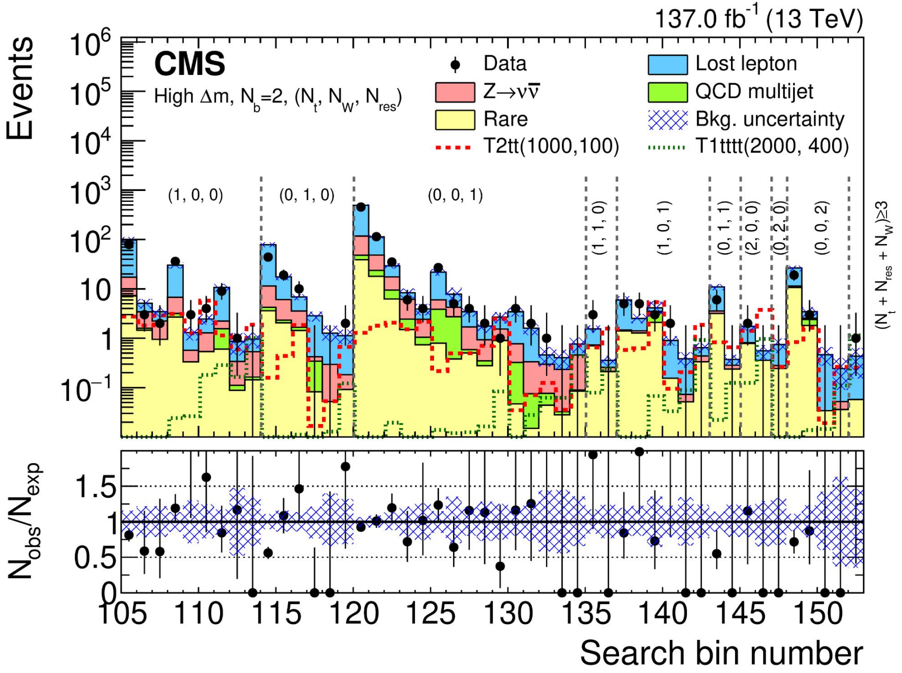

Backup Slides

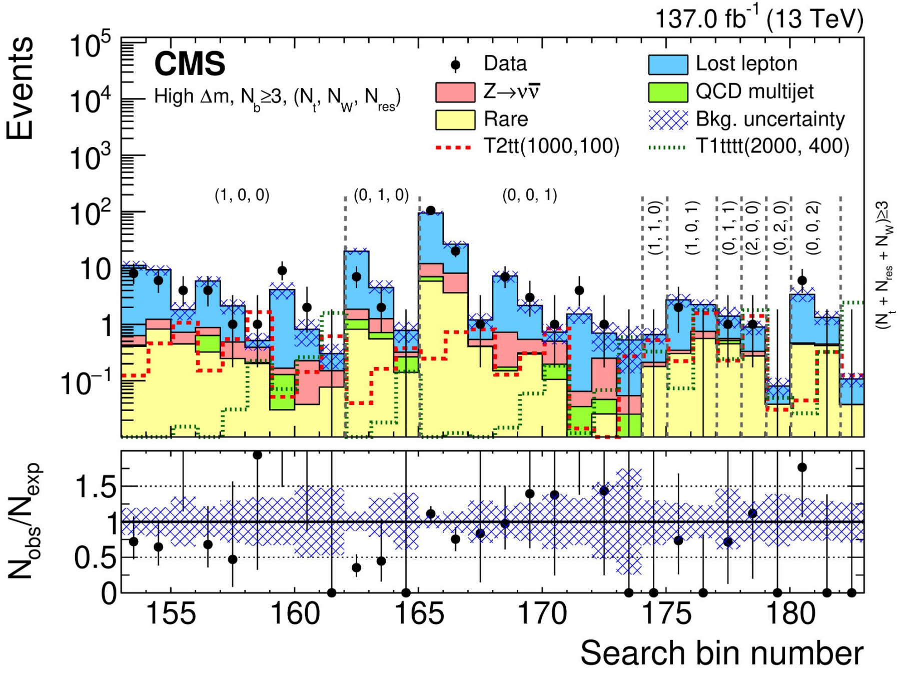
All Hadronic Stop Search





All Hadronic Stop Search





All Hadronic Stop Search

Baseline selection	
Jets	$N_{\mathrm{j}} \geq 2$ ($R = 0.4$), $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$
H_{T}	$H_{\mathrm{T}} > 300\,\mathrm{GeV}$
$p_{\mathrm{T}}^{\mathrm{miss}}$	$p_{\mathrm{T}}^{\mathrm{miss}} > 250\,\mathrm{GeV}$ $\Delta\phi\left(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{j}_1\right) > 0.5$ $\Delta\phi\left(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{j}_2\right) > 0.15$ $\Delta\phi\left(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{j}_3\right) > 0.15$ (when applicable)
Veto electron	$p_{\mathrm{T}} > 5\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$, $p_{\mathrm{T}}^{\mathrm{sum}} < 0.1\, p_{\mathrm{T}}$
Veto muon	$p_{\mathrm{T}} > 5\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$, $p_{\mathrm{T}}^{\mathrm{sum}} < 0.2\, p_{\mathrm{T}}$
Veto τ_{h}	$p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$, $m_{\mathrm{T}} < 100\,\mathrm{GeV}$
	PF charged candidates, $\lvert\eta\rvert < 2.5$, $m_{\mathrm{T}} < 100\,\mathrm{GeV}$
Veto track	$p_{\mathrm{T}} > 5\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\mathrm{sum}} < 0.2\, p_{\mathrm{T}}$ for electron and muon tracks $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\mathrm{sum}} < 0.1\, p_{\mathrm{T}}$ for charged-hadron tracks
Low Δm baseline selection	
N_{t}, N_{W}, N_{res}	$N_{\mathrm{t}} = N_{\mathrm{W}} = N_{\mathrm{res}} = 0$
$m_{\mathrm{T}}^{\mathrm{b}}$	$m_{\mathrm{T}}^{\mathrm{b}} < 175\,\mathrm{GeV}$ (for events with $N_{\mathrm{b}} \geq 1$)
ISR jet	$N_{\mathrm{j}}(\mathrm{ISR}) = 1$ ($R = 0.8$), $p_{\mathrm{T}}^{\mathrm{ISR}} > 200\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$ $\Delta\phi\left(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{j}_{\mathrm{ISR}}\right) > 2$
$p_{\mathrm{T}}^{\mathrm{miss}}$	$p_{\mathrm{T}}^{\mathrm{miss}} / \sqrt{H_{\mathrm{T}}} > 10\,\sqrt{\mathrm{GeV}}$
High Δm baseline selection	
Jets	$N_{\mathrm{j}} \geq 5$ ($R = 0.4$), $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$
b tagging	$N_{\mathrm{b}} \geq 1$
$p_{\mathrm{T}}^{\mathrm{miss}}$	$\Delta\phi\left(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{j}_{1,2,3,4}\right) > 0.5$

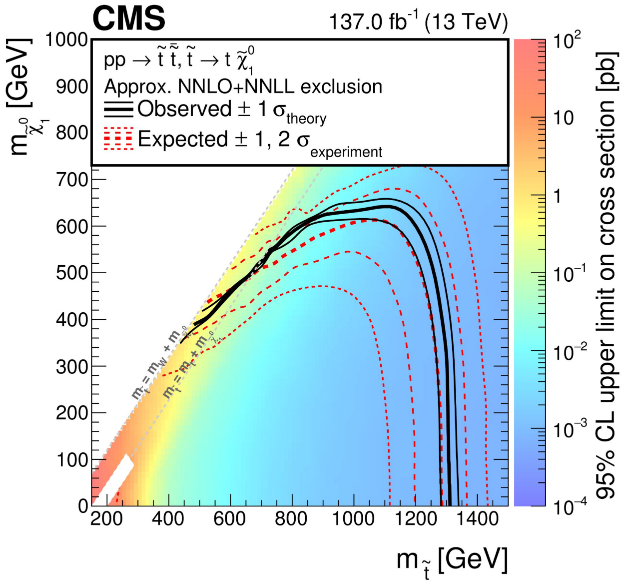
All Hadronic Stop Search

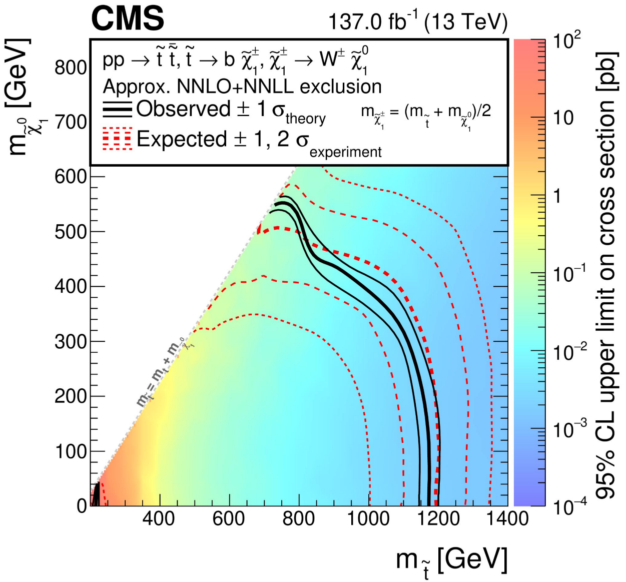
N_j	N_b	N_{SV}	m_T^b [GeV]	p_T^{ISR} [GeV]	p_T^b [GeV]	p_T^{miss} [GeV]	Bin number
2–5	0	0	—	>500	—	[450, 550, 650, 750, ∞]	0–3
≥ 6	0	0	—	>500	—	[450, 550, 650, 750, ∞]	4–7
2–5	0	≥ 1	—	>500	—	[450, 550, 650, 750, ∞]	8–11
≥ 6	0	≥ 1	—	>500	—	[450, 550, 650, 750, ∞]	12–15
≥ 2	1	0	<175	300–500	20–40	[300, 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

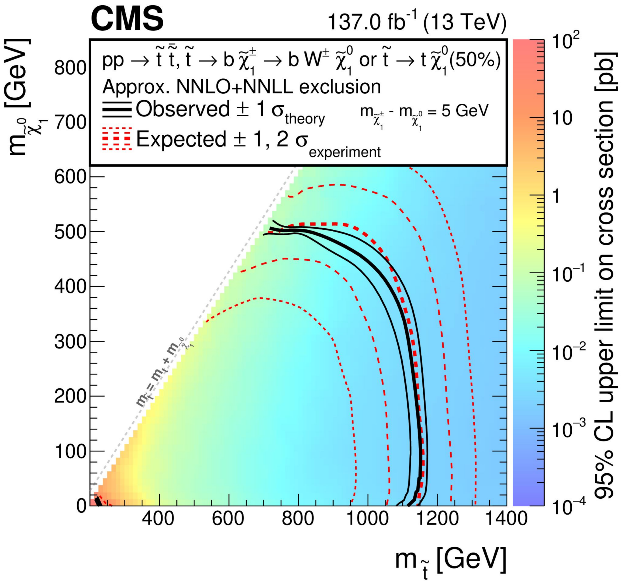
All Hadronic Stop Search

m_T^b [GeV]	N_j	N_b	N_t	N_W	N_{res}	H_T [GeV]	p_T^{miss} [GeV]	Bin number
<175	≥7	1	≥0	≥0	≥1	>300	[250, 300, 400, 500, ∞]	53–56
<175	≥7	≥2	≥0	≥0	≥1	>300	[250, 300, 400, 500, ∞]	57–60
>175	≥5	1	0	0	0	>1000	[250, 350, 450, 550, ∞]	61–64
>175	≥5	≥2	0	0	0	>1000	[250, 350, 450, 550, ∞]	65–68
>175	≥5	1	≥1	0	0	300–1000	[250, 550, 650, ∞]	69–71
>175	≥5	1	≥1	0	0	1000–1500	[250, 550, 650, ∞]	72–74
>175	≥5	1	≥1	0	0	>1500	[250, 550, 650, ∞]	75–77
>175	≥5	1	0	≥1	0	300–1300	[250, 350, 450, ∞]	78–80
>175	≥5	1	0	≥1	0	>1300	[250, 350, 450, ∞]	81–83
>175	≥5	1	0	0	≥1	300–1000	[250, 350, 450, 550, 650, ∞]	84–88
>175	≥5	1	0	0	≥1	1000–1500	[250, 350, 450, 550, 650, ∞]	89–93
>175	≥5	1	0	0	≥1	>1500	[250, 350, 450, 550, 650, ∞]	94–98
>175	≥5	1	≥1	≥1	0	>300	[250, 550, ∞]	99–100
>175	≥5	1	≥1	0	≥1	>300	[250, 550, ∞]	101–102
>175	≥5	1	0	≥1	≥1	>300	[250, 550, ∞]	103–104
>175	≥5	2	1	0	0	300–1000	[250, 550, 650, ∞]	105–107
>175	≥5	2	1	0	0	1000–1500	[250, 550, 650, ∞]	108–110
>175	≥5	2	1	0	0	>1500	[250, 550, 650, ∞]	111–113
>175	≥5	2	0	1	0	300–1300	[250, 350, 450, ∞]	114–116
>175	≥5	2	0	1	0	>1300	[250, 350, 450, ∞]	117–119
>175	≥5	2	0	0	1	300–1000	[250, 350, 450, 550, 650, ∞]	120–124
>175	≥5	2	0	0	1	1000–1500	[250, 350, 450, 550, 650, ∞]	125–129
>175	≥5	2	0	0	1	>1500	[250, 350, 450, 550, 650, ∞]	130–134
>175	≥5	2	1	1	0	>300	[250, 550, ∞]	135–136
>175	≥5	2	1	0	1	300–1300	[250, 350, 450, ∞]	137–139
>175	≥5	2	1	0	1	>1300	[250, 350, 450, ∞]	140–142
>175	≥5	2	0	1	1	>300	[250, 550, ∞]	143–144
>175	≥5	2	2	0	0	>300	[250, 450, ∞]	145–146
>175	≥5	2	0	2	0	>300	>250	147
>175	≥5	2	0	0	2	300–1300	[250, 450, ∞]	148–149
>175	≥5	2	0	0	2	>1300	[250, 450, ∞]	150–151
>175	≥5	2	$N_t + N_W + N_{res} \geq 3$			>300	>250	152
>175	≥5	≥3	1	0	0	300–1000	[250, 350, 550, ∞]	153–155
>175	≥5	≥3	1	0	0	1000–1500	[250, 350, 550, ∞]	156–158
>175	≥5	≥3	1	0	0	>1500	[250, 350, 550, ∞]	159–161
>175	≥5	≥3	0	1	0	>300	[250, 350, 550, ∞]	162–164
>175	≥5	≥3	0	0	1	300–1000	[250, 350, 550, ∞]	165–167
>175	≥5	≥3	0	0	1	1000–1500	[250, 350, 550, ∞]	168–170
>175	≥5	≥3	0	0	1	>1500	[250, 350, 550, ∞]	171–173
>175	≥5	≥3	1	1	0	>300	>250	174
>175	≥5	≥3	1	0	1	>300	[250, 350, ∞]	175–176
>175	≥5	≥3	0	1	1	>300	>250	177
>175	≥5	≥3	2	0	0	>300	>250	178
>175	≥5	≥3	0	2	0	>300	>250	179
>175	≥5	≥3	0	0	2	>300	[250, 350, ∞]	180–181
>175	≥5	≥3	$N_t + N_W + N_{res} \geq 3$			>300	>250	182

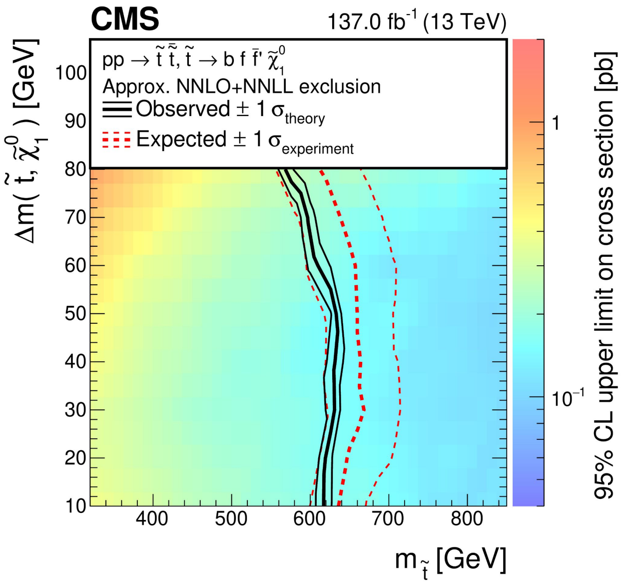
All Hadronic Stop Search

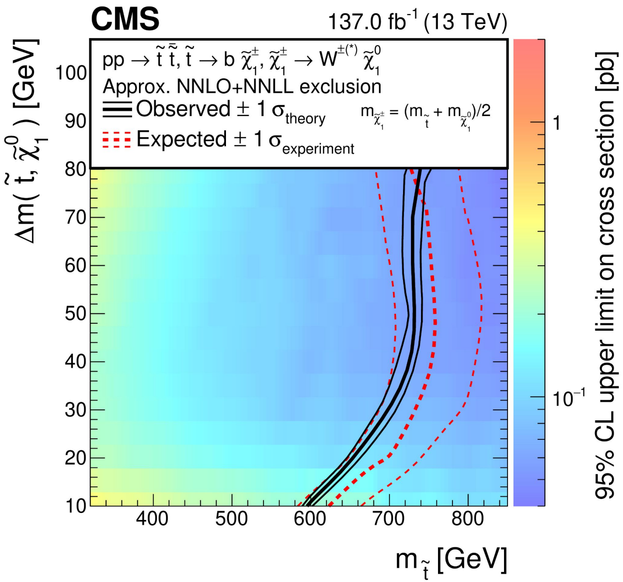


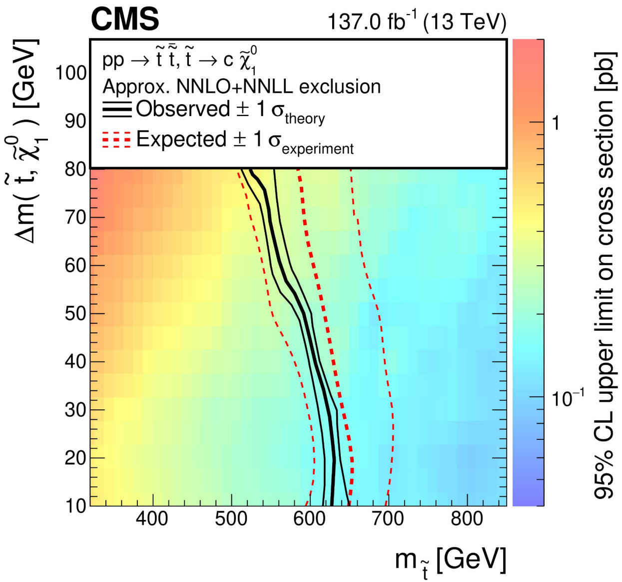




All Hadronic Stop Search







Combined Stop Search