Search for supersymmetry in compressed scenarios with the CMS detector

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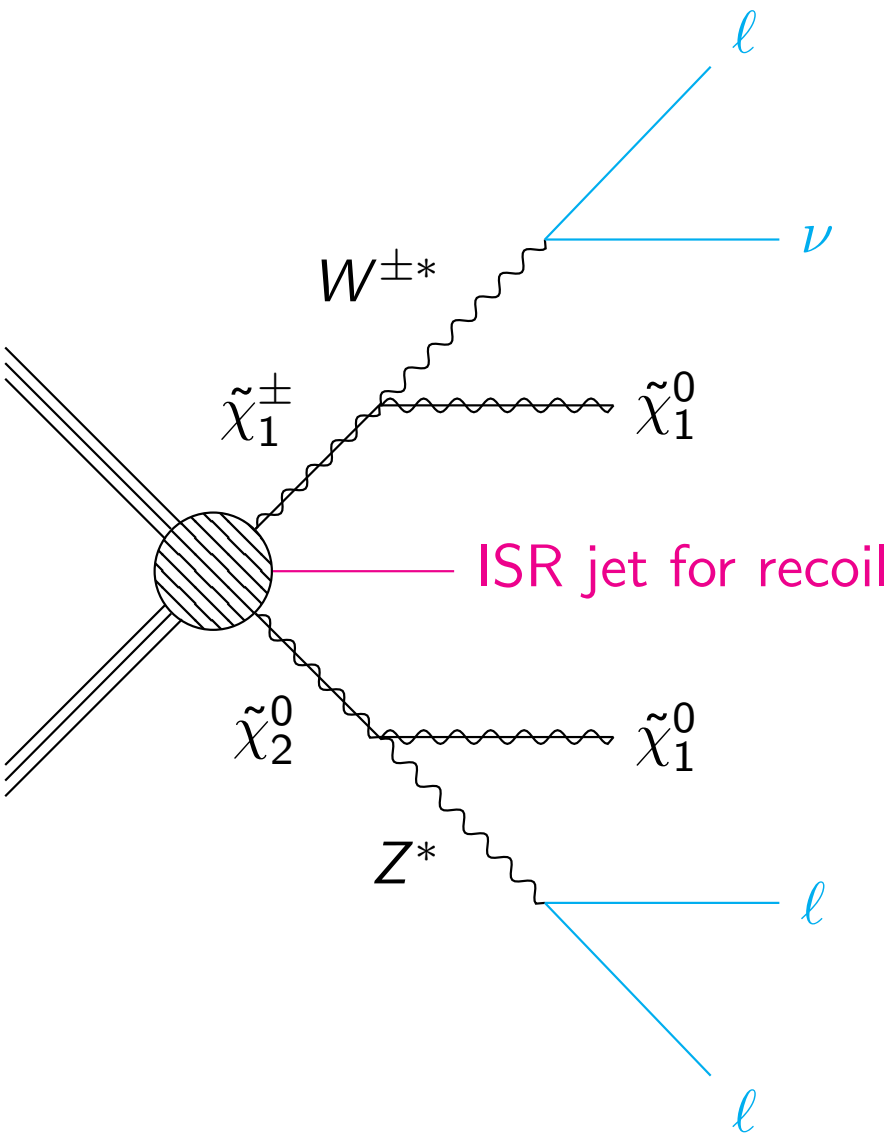
Introduction to compressed SUSY



- General feature: Small mass-gap between sparticles in decay chain
- Limited visible energy in the event for direct production

→ Need ISR jet or VBF production to trigger such events

- Identifying soft objects from the primary vertex reliably is experimental challenge

- soft final state objects from sparticle decays

Advances in compressed SUSY searches at CMS

- This talk covers examples of applying:

Soft b-tag algorithm

- CMS-SUS-20-002 - Combined searches for the production of supersymmetric top quark partners in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$
- CMS-SUS-19-010 - Search for top squark production in fully-hadronic final states in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

Non-prompt lepton rejection

- CMS-PAS-SUS-18-004 - Search for physics beyond the standard model in final states with two or three soft leptons and missing transverse momentum in proton-proton collisions at 13 TeV
- CMS-SUS-19-012 - Search for electroweak production of charginos and neutralinos in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

- Among various improvements and optimizations

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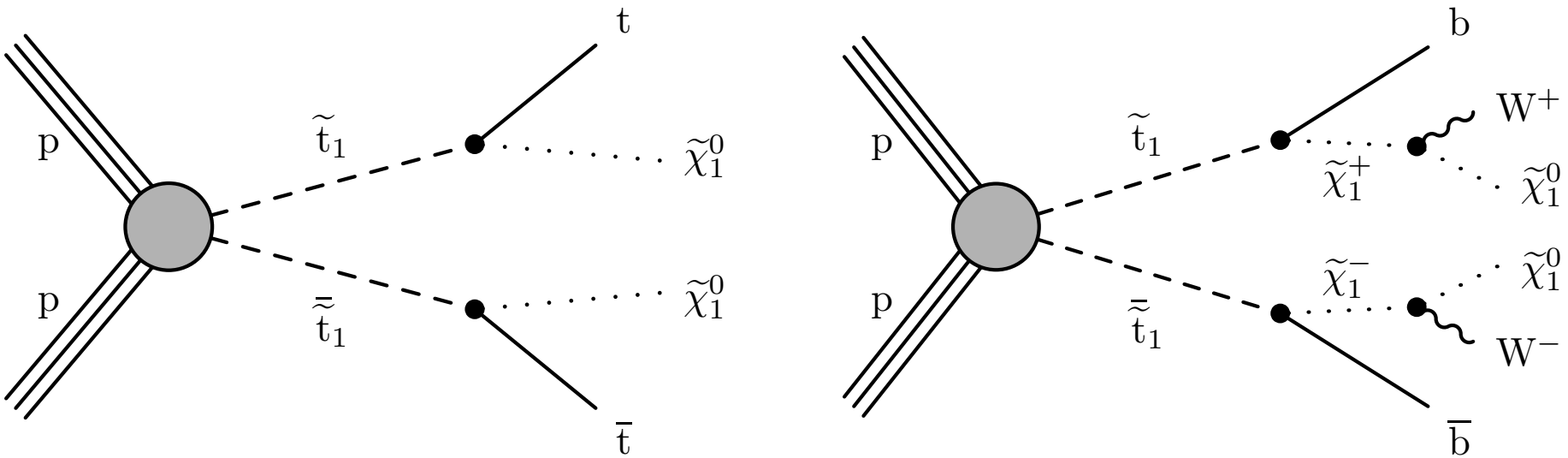
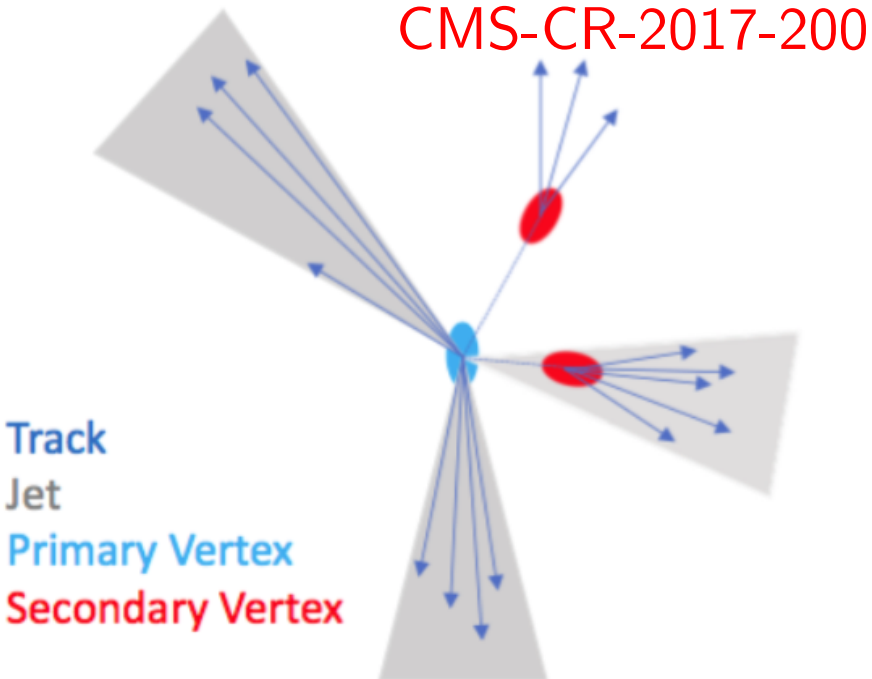
Stop search with 0, 1, or 2 leptons

CMS-SUS-20-002



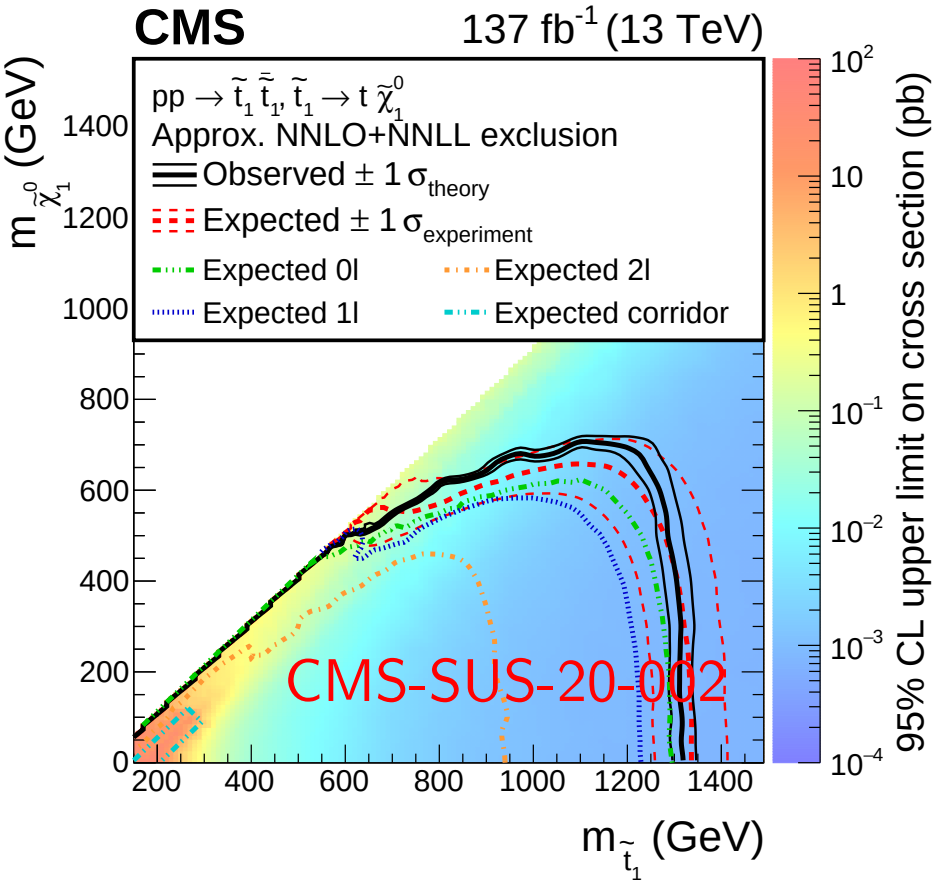
- All simplified models assume 100% branching ratios
- Size of mass gap determines observed decay mode
- Mass gap around and larger than standard model (SM) top mass $\rightarrow$ top decays
- Intermediate chargino mass $\rightarrow$ bW production
- Chargino mass determines softness of b or W

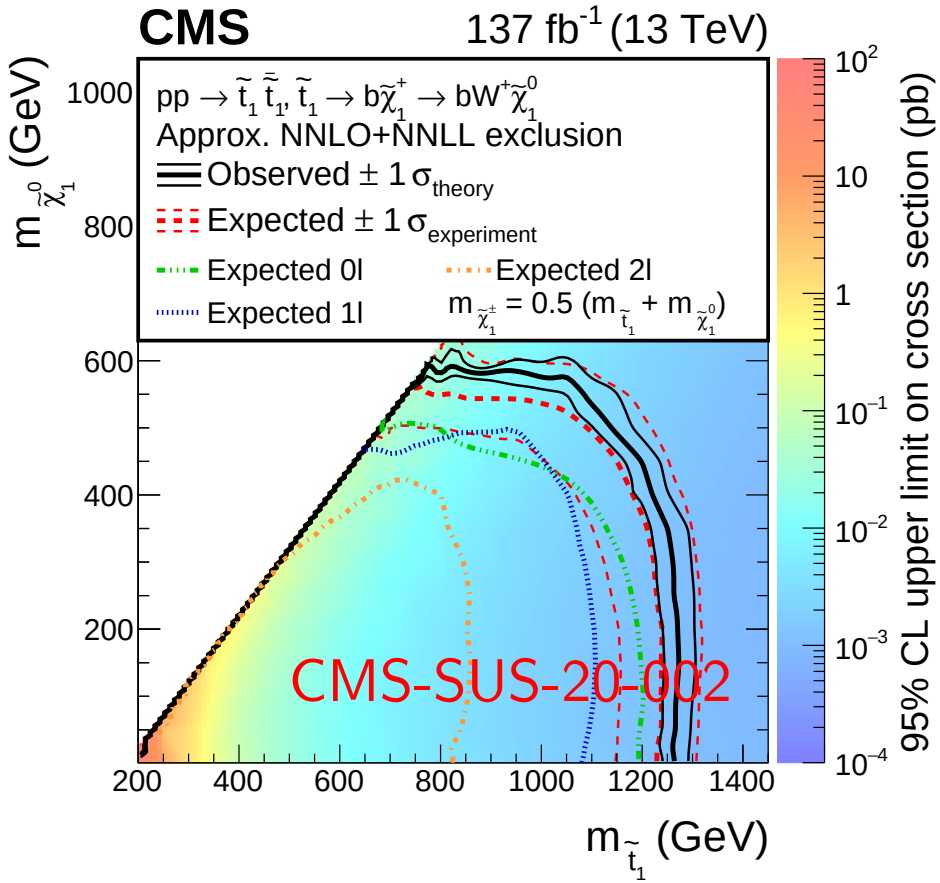
Compressed stop selection



- 0ℓ Large $p_{\mathrm{T}}^{\mathrm{miss}}$
- 1ℓ Non-b-tagged ISR jet and $p_{\mathrm{T}}^{\mathrm{miss}}$ close to lepton
- In case of $\Delta m(\tilde{\mathrm{t}}_1, \tilde{\chi}_1^0) \approx m_{\mathrm{W}}$, require ≥ 1 soft b tag (first used in SUS-16-008)
  - Aimed at b-quarks with $p_{\mathrm{T}} < 25\,\mathrm{GeV}$ not clustered into any jets
  - Efficiency $\approx 20\%$
  - Misidentification rate $< 1\%$
- 2ℓ not specifically sensitive to compressed scenarios

Combined 0-2 lepton top squark limits

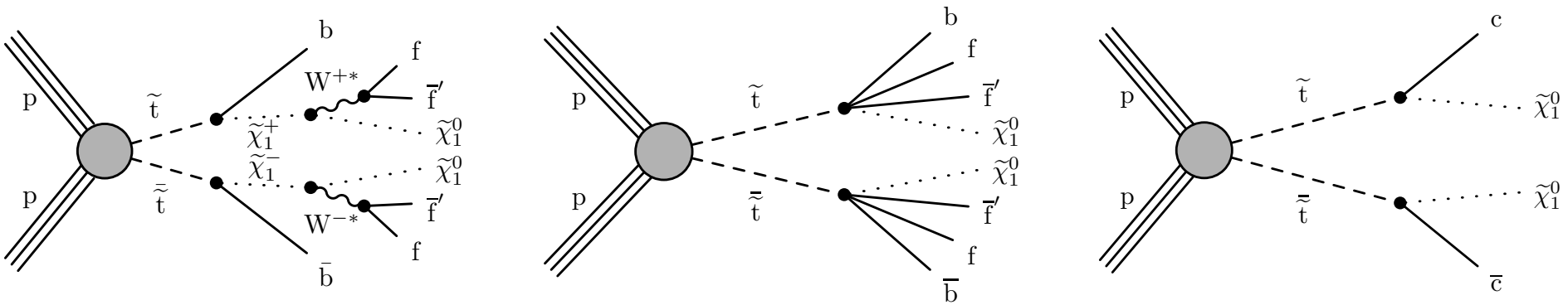




- Combination of 183 exclusive signal regions (all-hadronic) and 39 exclusive signal regions (1ℓ) contribute most to compressed regions
- Main background is $\mathrm{t\bar{t}}$ ($> 95\%$)
- Selection with Deep Neural Network (DNN)
- DNN improvements least for degenerate case $\Delta m(\tilde{\mathrm{t}}_1, \tilde{\chi}_1^0) \approx m_{\mathrm{t}}$

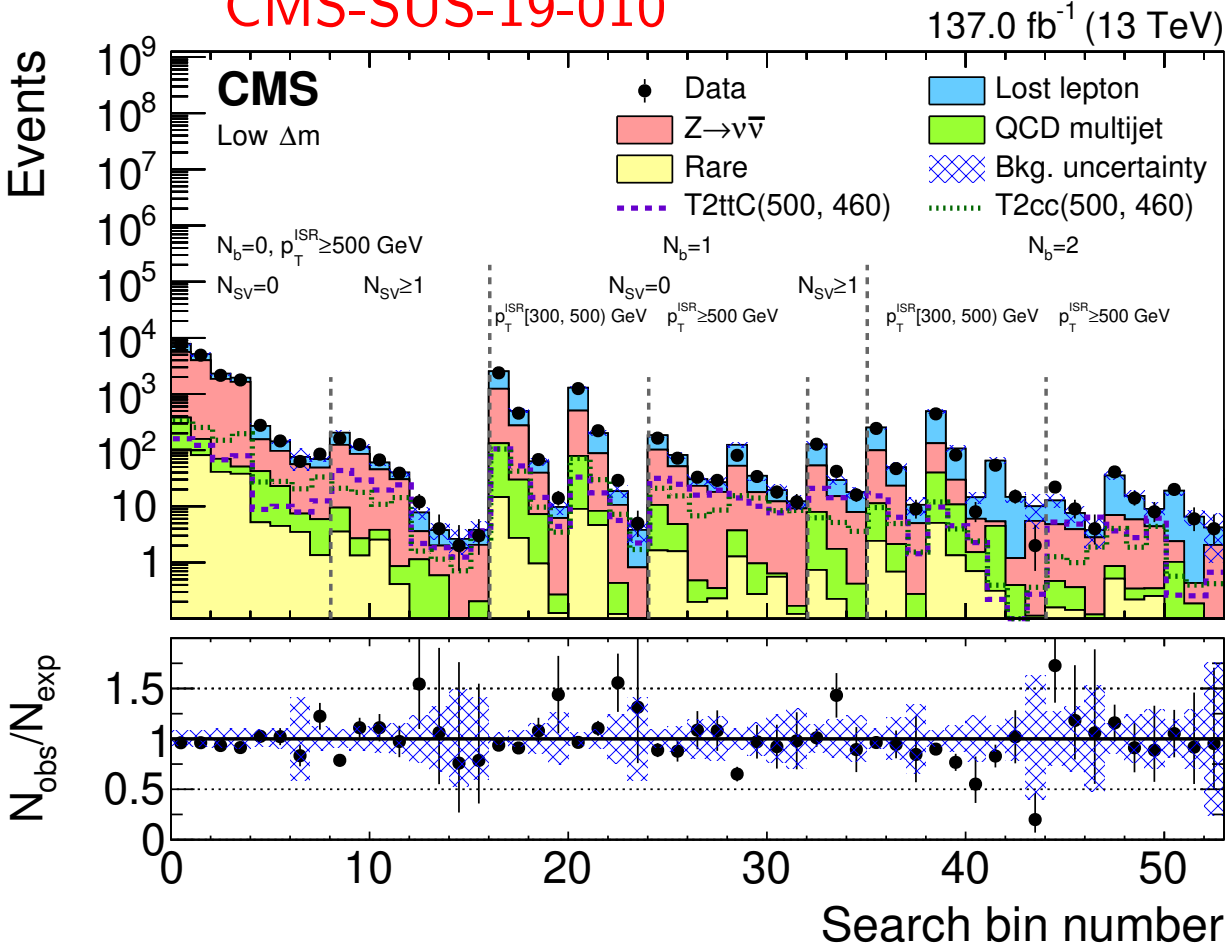
Stop search all-hadronic with δm below W mass

CMS-SUS-19-010



- Models with even more compressed scenarios where $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m_W$ lead to:
  - Virtual W decays (left)
  - Effective four-point interactions (middle, named "T2ttC")
  - Loop-induced flavour-changing neutral current charm production (right, named "T2cc")
- Still benefit from b- or c-tagging improvements and soft b tagging

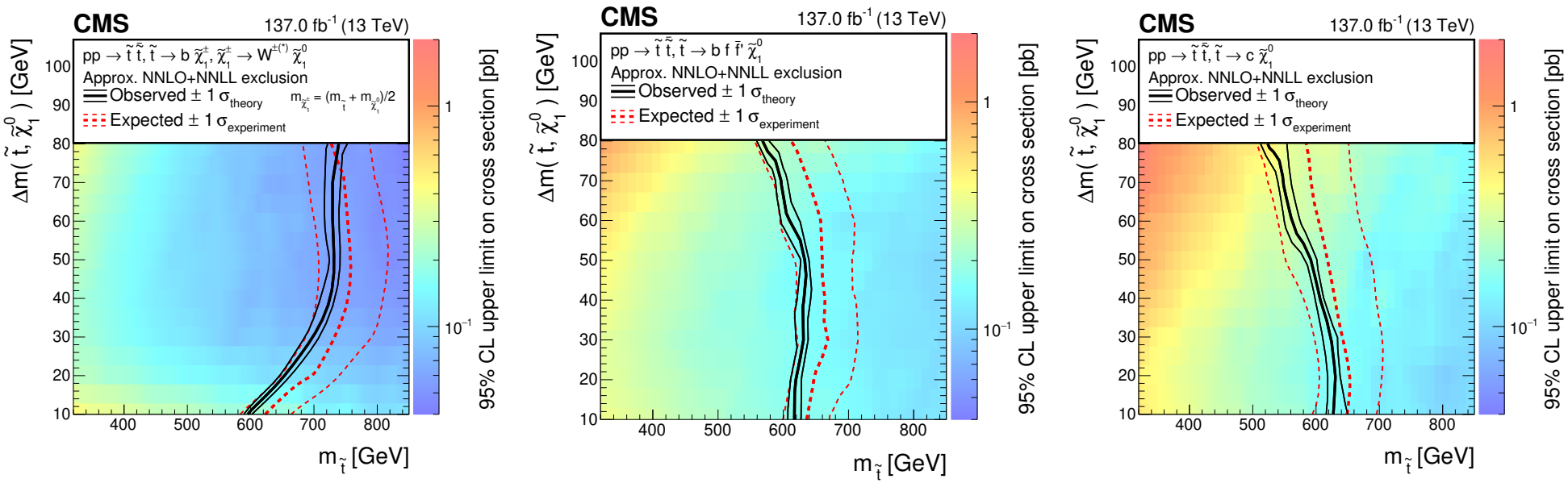
All-hadronic selections with δm below W mass



- High p_{T} ISR jet required, $p_{\mathrm{T}}^{\mathrm{miss}}$ trigger
- Many sensitive bins only accessible with soft b tag(s) (denoted as $\mathrm{N_{SV}}$)

All-hadronic limits with δm below W mass

CMS-SUS-19-010



- Limits could be set down to extremely low $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \geq 10\,\text{GeV}$ for top squark masses of at around 600 GeV
- Low p_T b-tagging, whether in jets or as standalone SVs is very useful in this regimen!

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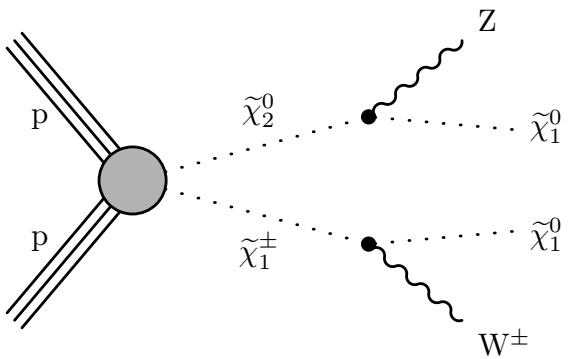
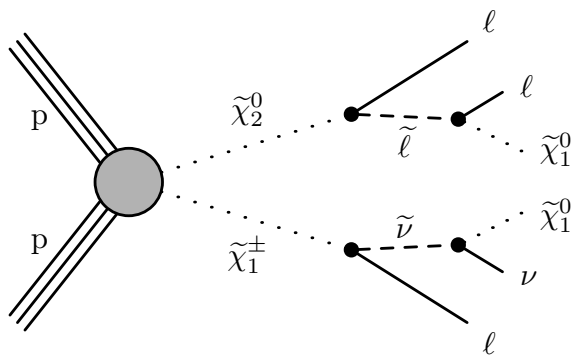
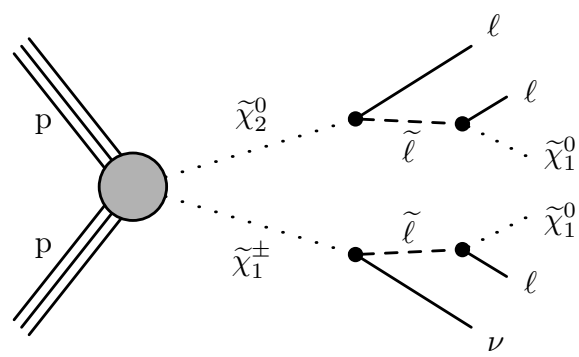
2-4 (soft) leptons (and τ_{h}) and large $p_{\mathrm{T}}^{\mathrm{miss}}$

CMS-PAS-SUS-18-004



CMS-SUS-19-012





- EWKINO production lends itself to looking at various multiplicites of soft leptons
- Subject to various backgrounds, depending on the bin definitions
- Troublesome source of soft leptons: non-prompt production from hadron decays

Identifying non-prompt soft leptons

- Gradient boosted decision tree (BDT)
- Distinguishes prompt from nonpromt light leptons
- Uses properties of jet that contains the lepton

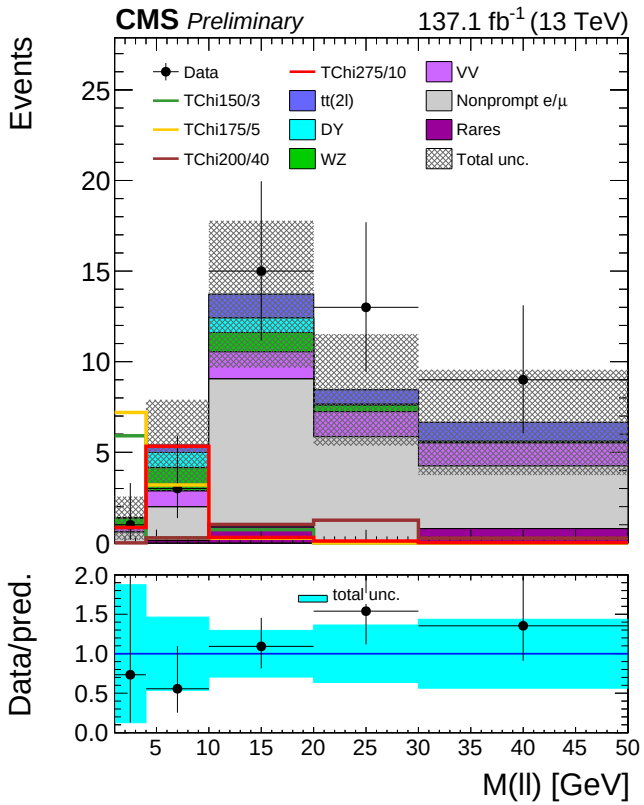
List of variables in BDT

- DeepFlavor b-tagging score
- ratio of lepton to jet p_{T}
- jet momentum transverse to lepton momentum
- p_{T}, η, $I_{\mathrm{rel}}^{\mathrm{mini}}$, d_0, d_z, $|d_{3D}|/\sigma(d_{3\mathrm{D}})$

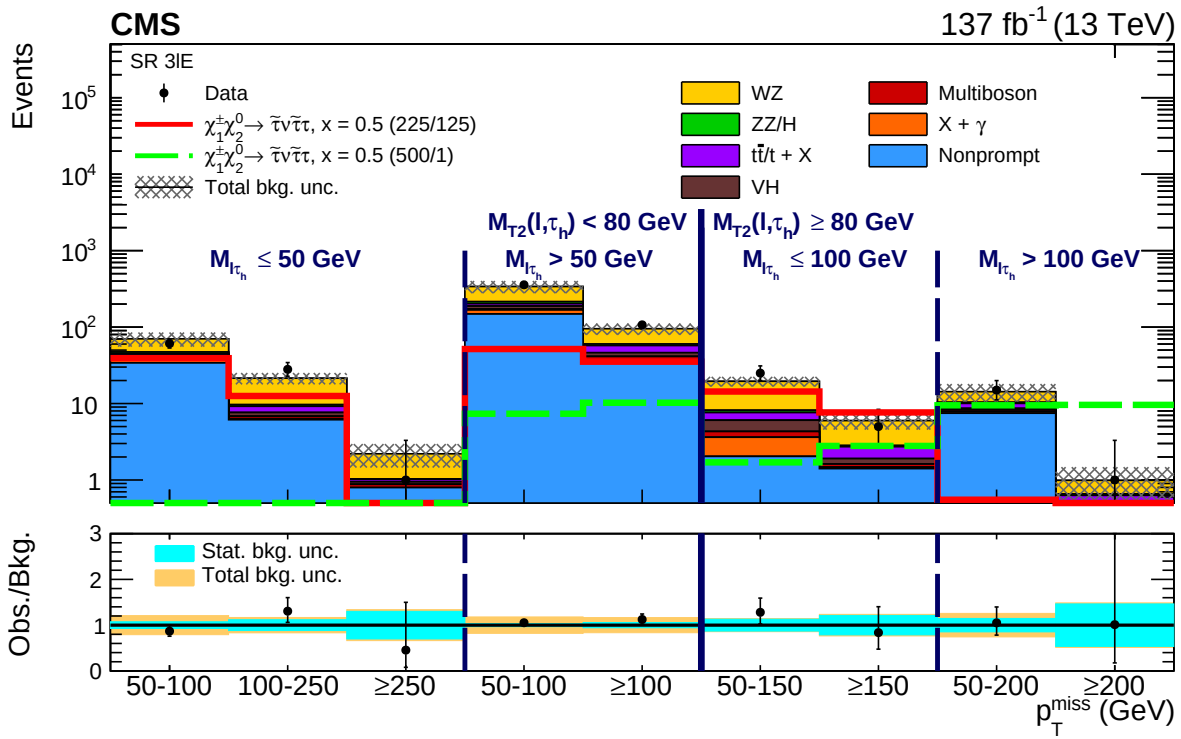
- BDT output selection tightness varies with lepton category
- E.g. CMS-SUS-19-012 uses tighter criterium for 2 same-sign (SS) leptons than for ≥ 3 leptons

Signal bin examples

CMS-PAS-SUS-18-004

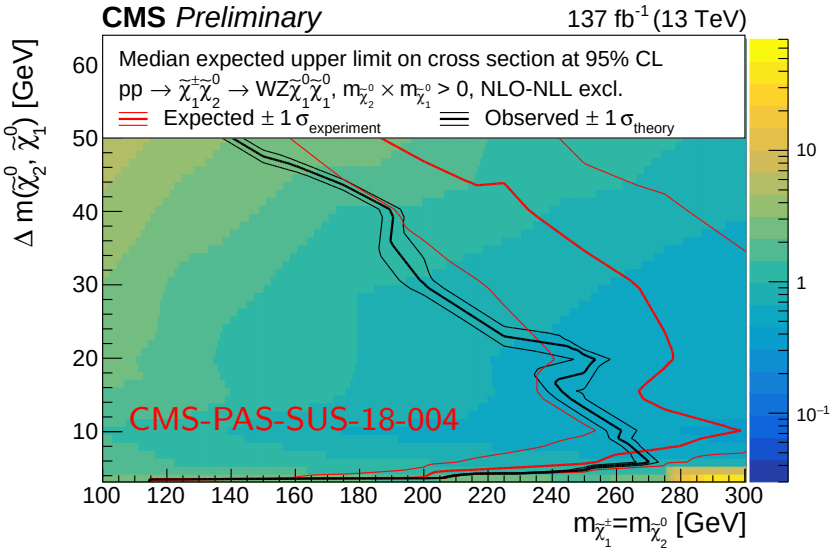


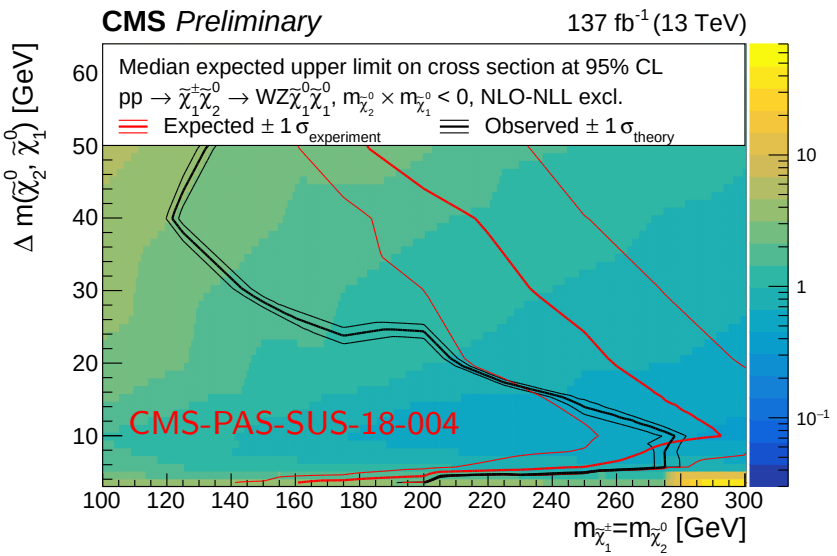
CMS-SUS-19-012

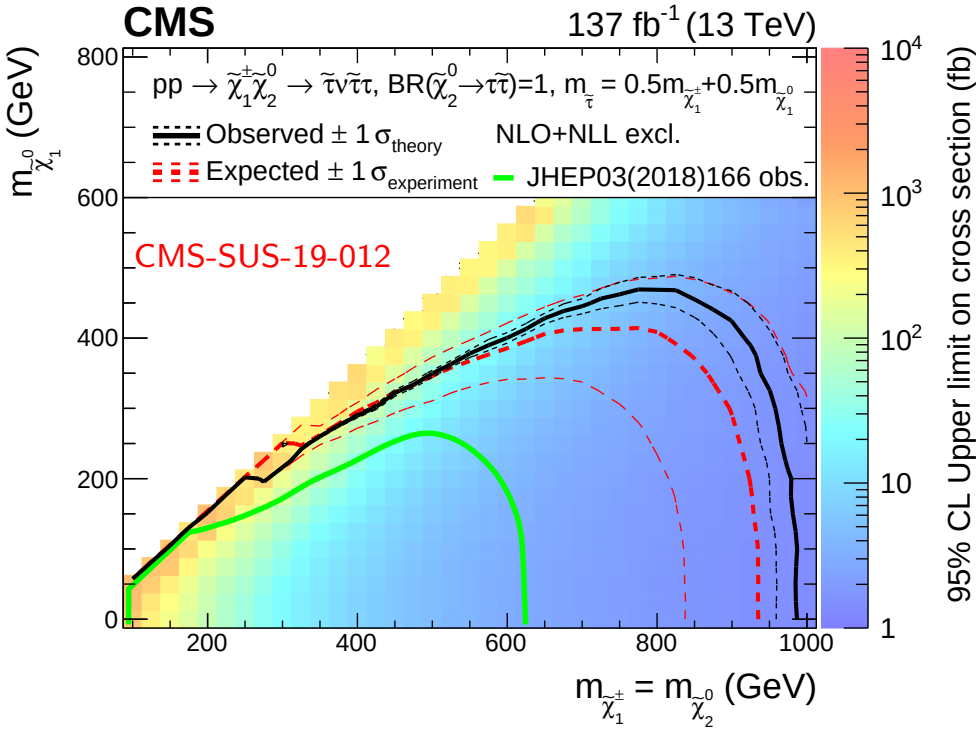


- Left 2ℓ electroweak search region with $p_{\mathrm{T}}^{\mathrm{miss}} > 290\,\mathrm{GeV}$
- Signal model is WZ production with $(m_{\mathrm{NLSP}}/\Delta m(\mathrm{NLSP,LSP}))$
- Right 3ℓ search bins with decay chain containing staus $(m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0})$
- Non-prompt leptons contribute large reducible backgrounds

Limits in compressed EWKINO and slepton sectors







- Some limit examples among various interpretations
- Non-prompt lepton suppression aids the exploration of compressed parameter space

Conclusions

- Presented some up-to-date analyses with the CMS detector exploring compressed SUSY scenarios
- Need energetic ISR or VBF jets to trigger
- Reconstruction of soft objects facilitates these challenging searches
- No hint of any kind of SUSY also in compressed scenarios, yet
- As always, more analyses with Run2 data still await $\rightarrow$ we'll keep looking

Thank you for your attention!

soft b tag specifics

1. Aimed at b-quarks with $p_{\mathrm{T}} < 25\,\mathrm{GeV}$
2. Secondary vertex (SV) reconstructed with inclusive vertex finder (IVF)
3. SV and primary vertex (PV) within 3 cm in transverse plane
4. > 2 tracks associated with SV
5. Significance of distance > 4
6. Cosine of pointing angle defined by scalar product of $\overrightarrow{\mathrm{SV,PV}}$ and $\vec{p}_{\mathrm{SV}}$ (total three-momentum of tracks associated with SV) direction > 0.98
7. Distance ΔR of SV > 0.4 to any jets
8. Transverse component of $p_{\mathrm{SV}} < 25\,\mathrm{GeV}$
9. $\approx 20\%$ efficiency, $< 1\%$ misidentification of b hadrons

SUS-20-002 DNN specifics

1. training with TENSORFLOW using KERAS interface
2. Final DNN structure sequential: 7 hidden layers with a RelU activation function (300,200, 100, 100, 100, 100, 10 neurons)
3. Output 2 neurons with softmax normalization function
4. Selected optimizer corresponds to Adam with learning rate of 0.0001%
5. Out of 40% events used for DNN implementation, 60% used for training, 15% for validation, leftovers for guarding against overfitting

SUS-19-010 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

- Search bin definitions specifically for compressed scenarios