Digging Deeper Into SUSY Parameter Space With the CMS Experiment

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on behalf of the CMS Collaboration

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University of Minnesota

Outline

- Introduction to Unconventional SUSY
- Presentation of recent CMS Results
  - RPV/Stealth SUSY Top Squark Search
  - Soft τ Lepton Compressed SUSY Spectrum Search
- Summary & Conclusions

Unconventional SUSY Models

- No convincing evidence from traditional SUSY searches
  - Most efforts focused on high p_T, high MET signatures
  - What if we've been looking in the wrong places?
  - Consider **less conventional** parts of the SUSY phase space
- R-parity violating (RPV) SUSY
  - Smaller RPV couplings to SM: LSP decays to SM particles, leaving **no MET**
- Stealth SUSY
  - New hidden stealth sector weakly coupled to SUSY-breaking sector but with finite couplings to the visible sector
  - Stealth particles and their superpartners are nearly degenerate and thus can decay to SM particles while leaving **little MET**
- SUSY with compressed spectra
  - Small mass splittings among sparticles lead to **soft decay products** that require dedicated techniques to achieve sensitivity
  - See upcoming talk by Diogo Bastos: "Searches for top squarks in compressed scenarios"
- Recent CMS to be presented:
  - RPV/Stealth Top Squark Search: Phys. Rev. D 104, 032006
  - Soft τ Lepton Compressed Spectrum Search: Phys. Rev. Lett. 124, 041803

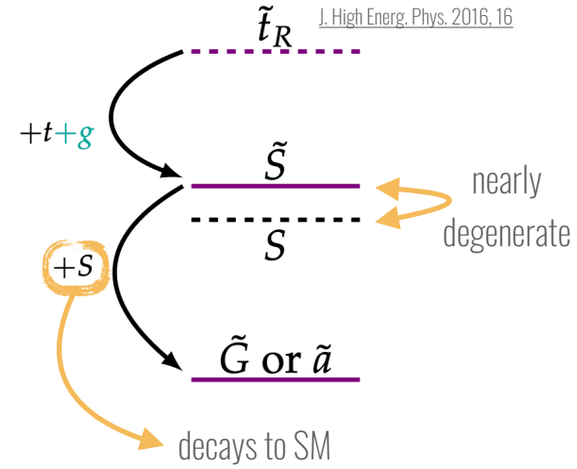
RPV Superpotential Terms

$$W_{RpV} = \epsilon_{ab}[\lambda_{ijk} L_i^a L_j^b \bar{E}_k + \lambda'_{ijk} L_i^a Q_j^b \bar{D}_k + \kappa_i L_i^a H_u^b] \quad \not{L}$$

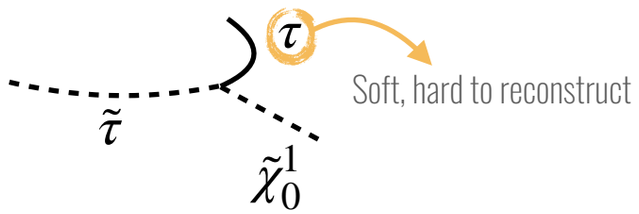
$$+\lambda''_{ijk} \epsilon_{xyz} \bar{U}_i^x \bar{D}_j^y \bar{D}_k^z \quad \not{B}$$

H. Dreiner

Stealth SUSY Spectrum



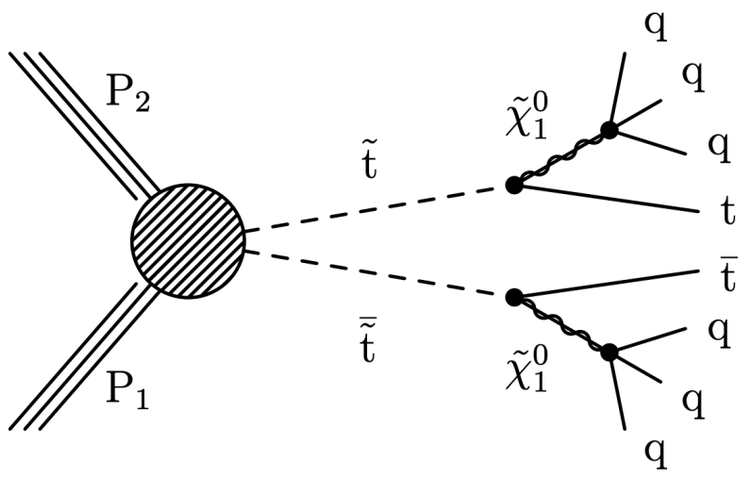
Compressed SUSY Spectrum Decay



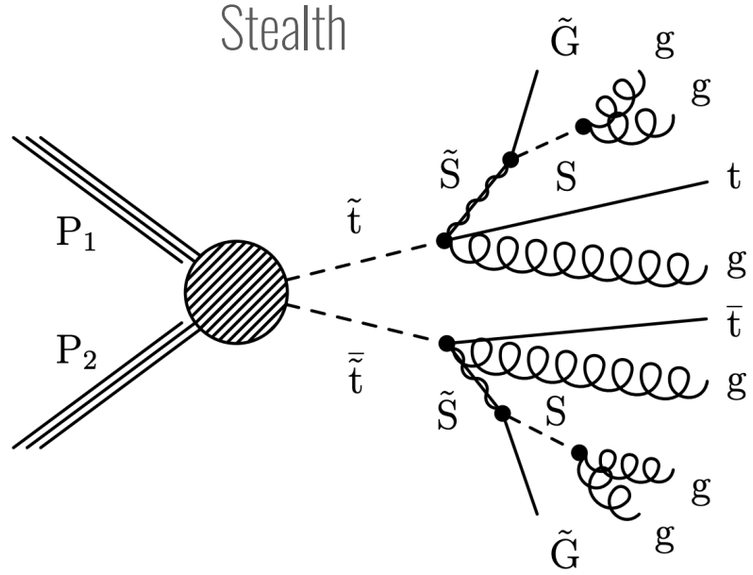
RPV/Stealth Top Squark Search

- Search for top squarks in the context of RPV and stealth SUSY models with 137 fb^{-1} (Run 2)
  - RPV: neutralino LSP from top squark decays to light jets via UDD coupling
  - Stealth: minimal stealth model ($\mathrm{SY\overline{Y}}$)
    - One scalar particle S, its superpartner $\tilde{\mathrm{S}}$, and a portal mediated by a messenger field Y
    - S and $\tilde{\mathrm{S}}$ are nearly degenerate, decay of $\tilde{\mathrm{S}}$ to S and light $\tilde{\mathrm{G}}$ leaves little MET
  - Both models lead to high jet multiplicity and low MET
- Target final state: $\mathrm{t\bar{t}} + \mathrm{jets} + 1\ell$
  - No MET
  - Lepton from top decay suppresses QCD background
- Previously unexplored phase space at the LHC for low-mass stops and light-flavor jets

RPV

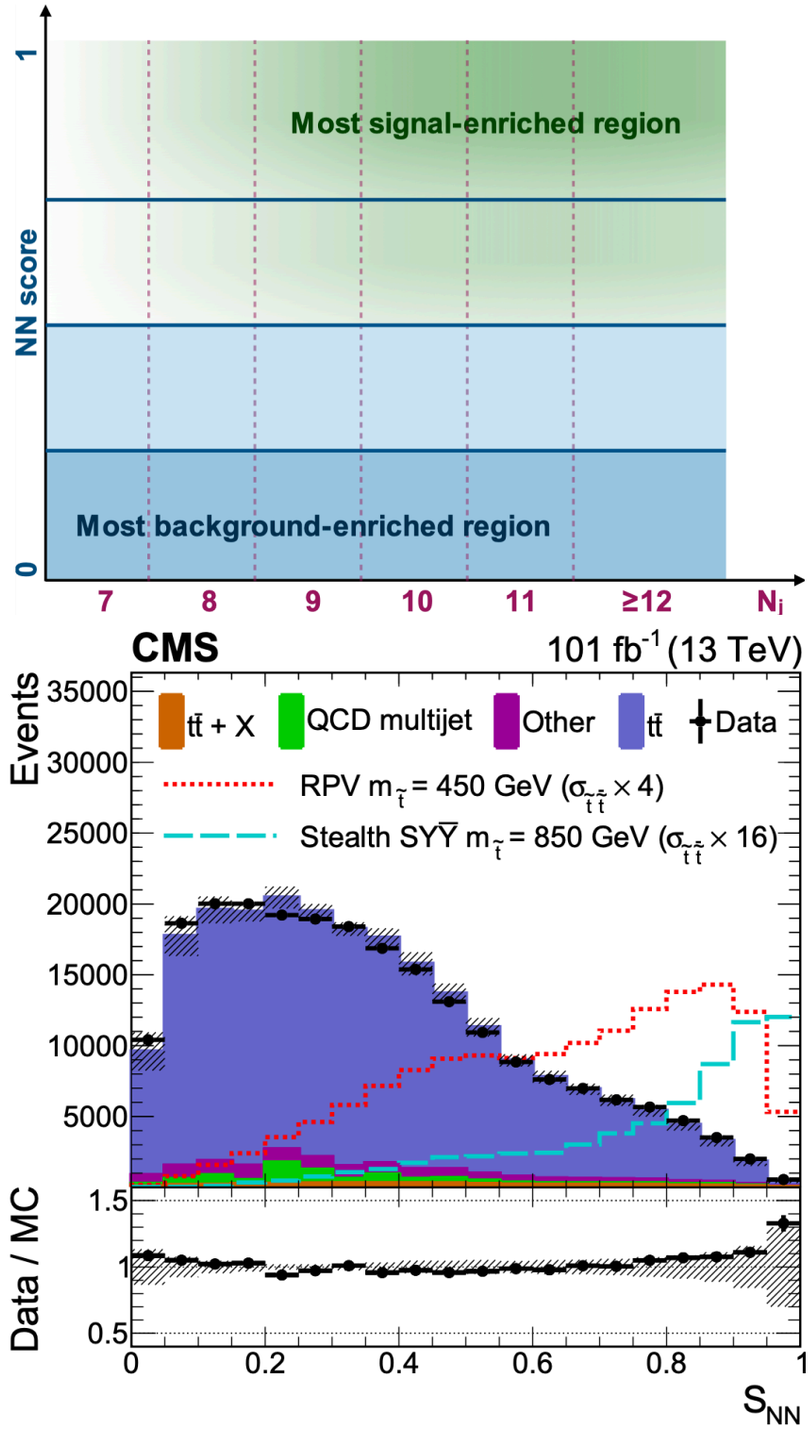


Stealth



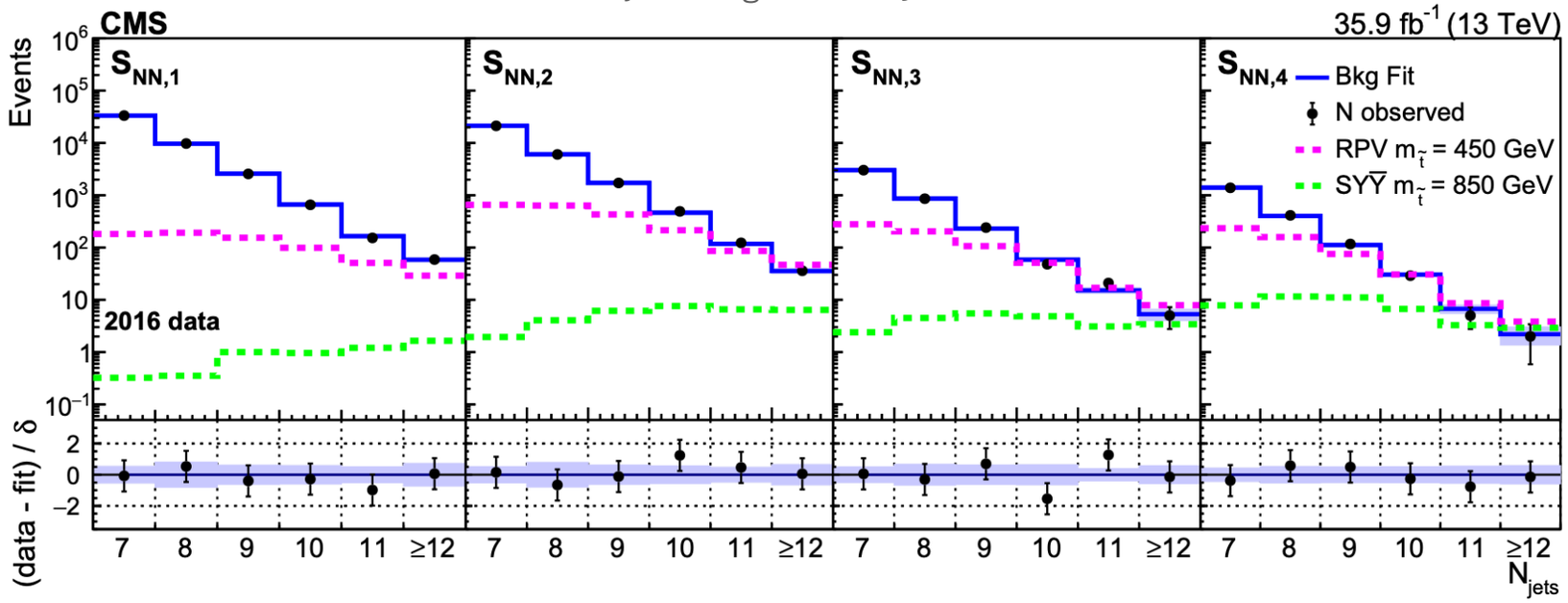
RPV/Stealth Search: Analysis Strategy

- Primary discriminating variables: N_{jets} and S_{NN}
  - N_{jets}: jet multiplicity (higher for signal)
  - S_{NN}: neural network (NN) score
    - NN trained to separate signal from dominant, irreducible $t\bar{t}$ + jets background
    - Events separated into 4 bins based on NN score (S_{NN})
    - Gradient reversal technique minimizes dependence on N_{jets}
- N_{jets} distribution is fit using a parametrization from theory
  - Simultaneous fit over all S_{NN} bins
  - $t\bar{t}$ N_{jets} shape constrained to be the same in each S_{NN} bin
- Background estimation
  - $t\bar{t}$ (~87%): predicted from N_{jets} distribution in data using S_{NN}
  - QCD (~4%): estimated from CR enriched in QCD multi-jet events
  - $t\bar{t} + X$ and other minor backgrounds (~8%): estimated from MC



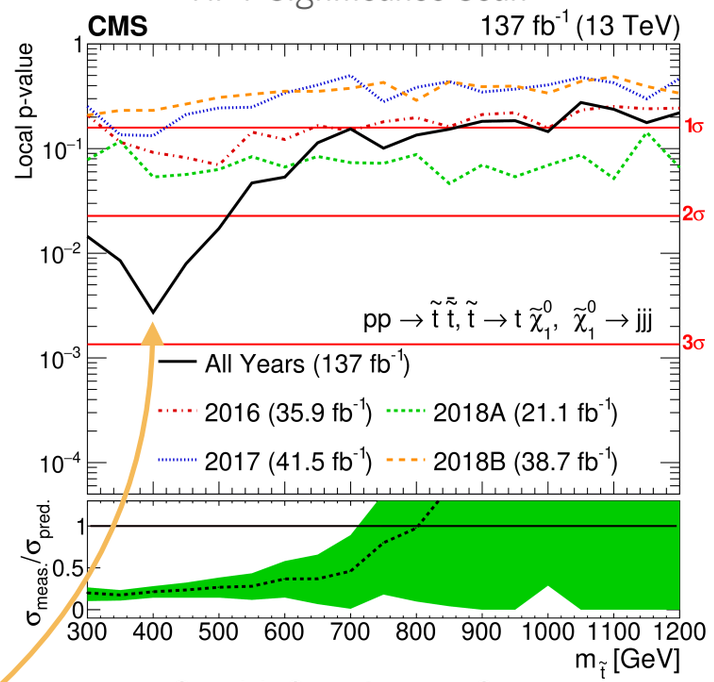
RPV/Stealth Search: Results

Nj_{ets} Background-Only Fits

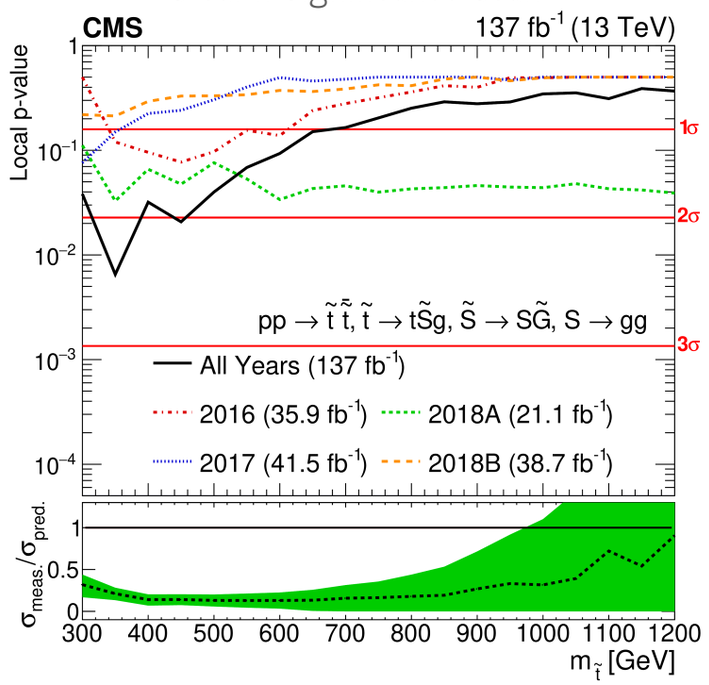


- Largest observed local significance:
  - 2.8σ for RPV model with $m_{\tilde{t}}$ = 400 GeV

RPV Significance Scan

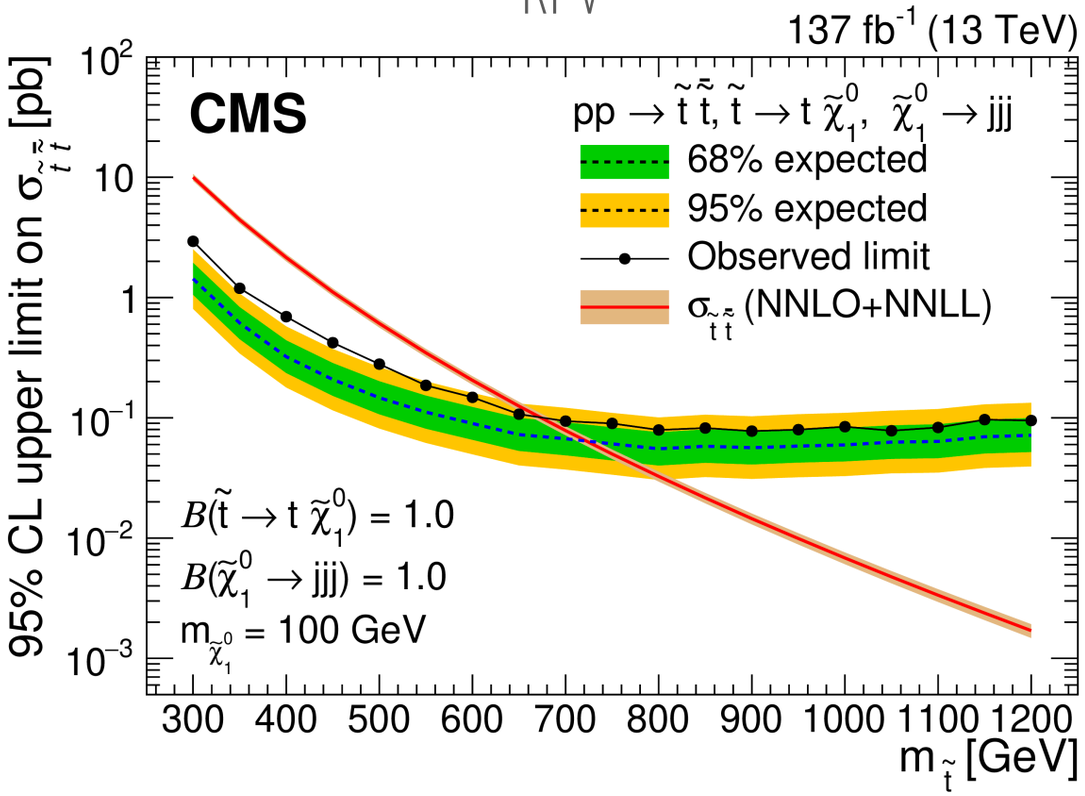


Stealth Significance Scan



RPV/Stealth Search: Limits & Conclusions

RPV



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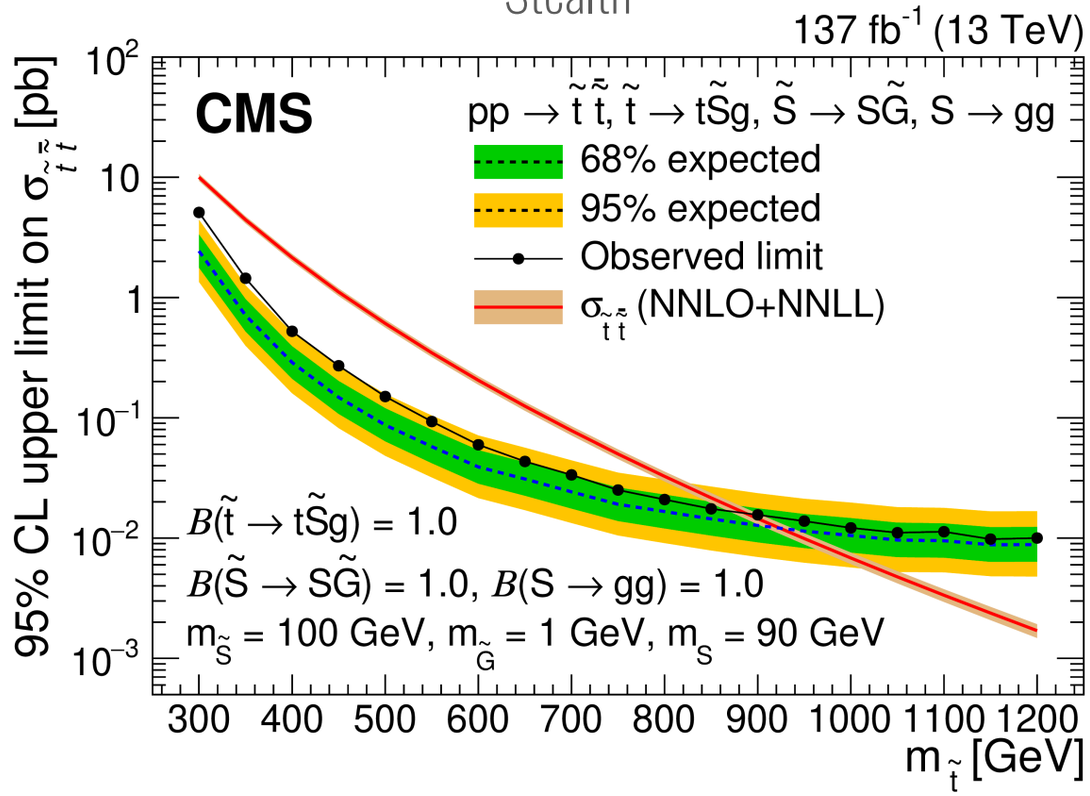
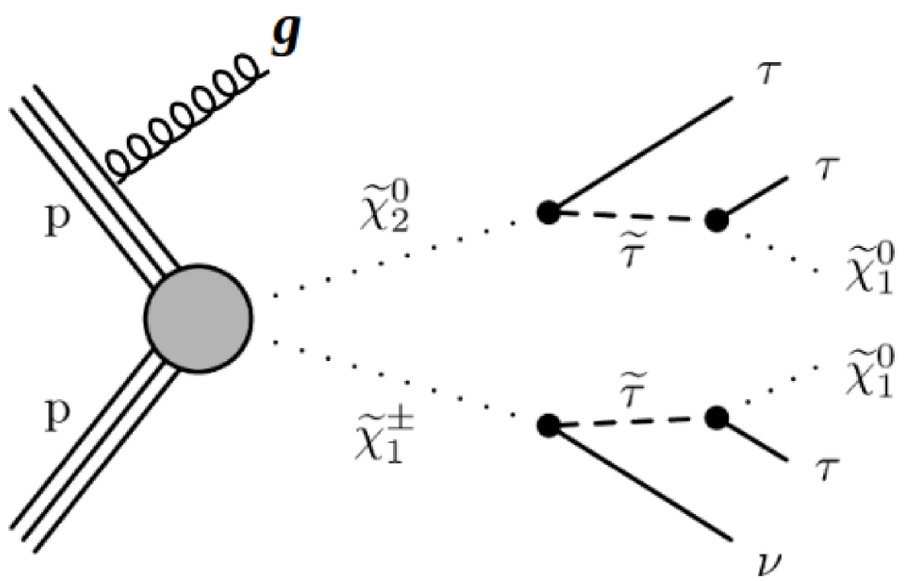


- 95% CL exclusion limits set for stop masses below:
  - 670 GeV in the RPV scenario
  - 870 GeV in the stealth ($\mathbf{SY\overline{Y}}$) scenario
- Analysis is systematics dominated
  - Primary uncertainties include modeling of H_T, jet mass, and jet p_T in $t\bar{t}$ MC and statistical uncertainties on non-$t\bar{t}$ background MC
- Ongoing CMS analyses seek to significantly mitigate the impact of systematic uncertainties and investigate other final states

Soft τ Lepton Compressed Spectrum Search

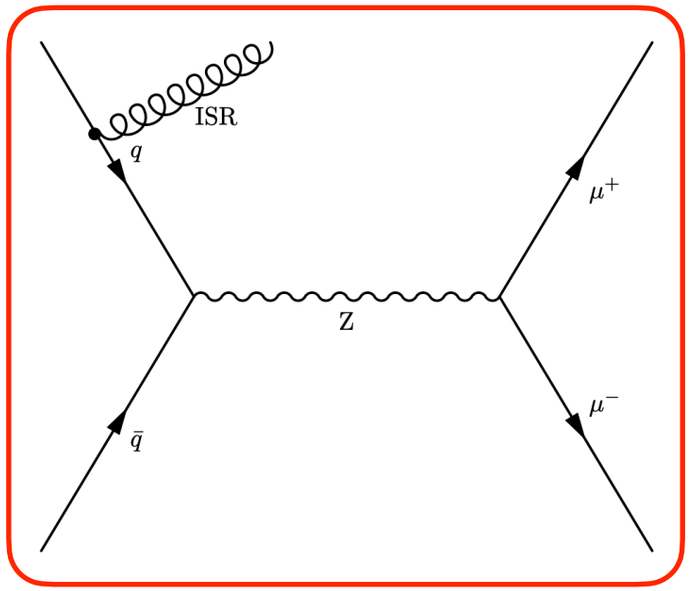
- Dark matter (DM) relic density motivation
  - For a density consistent with measurements, coannihilation (CA) between neutralino LSP and stau to normal matter can be introduced
  - DM relic density very sensitive to $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$ with $\sigma_{\mathrm{CA}} \propto e^{-\Delta m}$
  - Observed DM relic density can be achieved in compressed scenarios with $\Delta m \lesssim 50$ GeV
- Search for soft, hadronic tau (τ_{h}) from $\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm}$, and/or $\tilde{\tau}$ decays in a compressed SUSY spectrum with 77.2 fb^{-1} (2016-2017 from Run 2)
  - Initial state radiation (ISR) jet (p_T > 30 GeV) provides boost that improves acceptance of τ_{h}
  - Compressed spectrum also leads to high MET from neutrinos (require MET > 230 GeV)
  - Require exactly one soft τ_{h} candidate (20 < p_T < 40 GeV) and veto b-jets



Soft τ Compressed Search: Background Estimation

$$N_{\mathrm{SR}} = \sigma \cdot L_{\mathrm{int}} \cdot \epsilon_{\tau_{\mathrm{h}}} \cdot \epsilon_{E_{\mathrm{T}}^{\mathrm{miss}}} \cdot \epsilon_{\mathrm{ISR}} \cdot \epsilon_{\mathrm{b-jet}}$$

- $Z \to \mu\mu + \mathrm{ISR}$ control region (CR) to understand ISR jet efficiency
  - Boost weights derived to correct for mismodeling of ISR jet based on study of Z p_T
- $W \to \mu\nu + \mathrm{ISR}$ validation region (VR) to understand MET efficiency
  - Boost weights validated in region with real MET
  - Good modeling of ISR jet activity and MET are confirmed
- $Z \to \tau\tau(\to \tau_{\mathrm{h}}\tau_{\mathrm{h}}) + \mathrm{ISR}$ CR to understand τ_{h} ID efficiency
  - Good modeling of τ_{h} ID is observed and a systematic uncertainty is derived for residual differences
- 4 $t\bar{t}$ CRs to understand b-jet modeling
  - Different regions differentiated by: $N_{\mathrm{b-jets}}$, τ_{h} ID, number of τ_{h} charged particle tracks
  - Good modeling of b-jets is observed and a residual systematic uncertainty is derived
- QCD CR to develop a data-driven estimate of QCD contribution in SR due to fake τ_{h}
  - Define a transfer factor based on different ID requirements using data from an additional $W \to \mu\nu + \tau_{\mathrm{h}}(\mathrm{fake})$ CR
  - Achieves the proper normalization and m_{T} shape for QCD events



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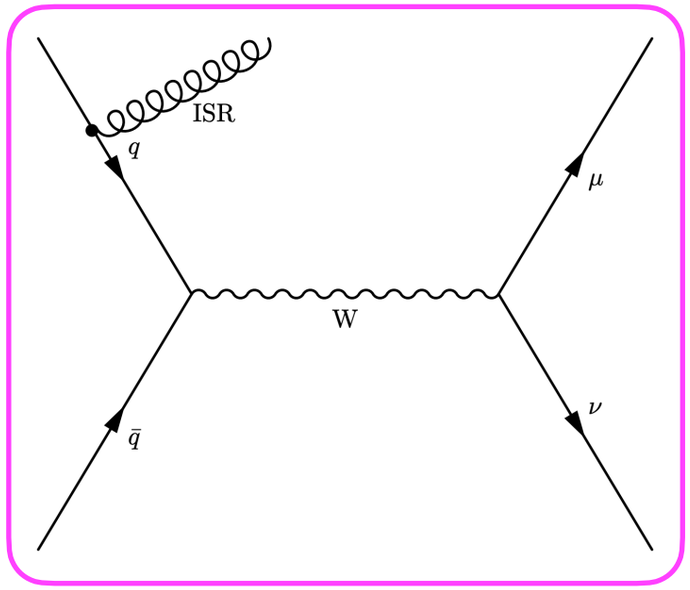

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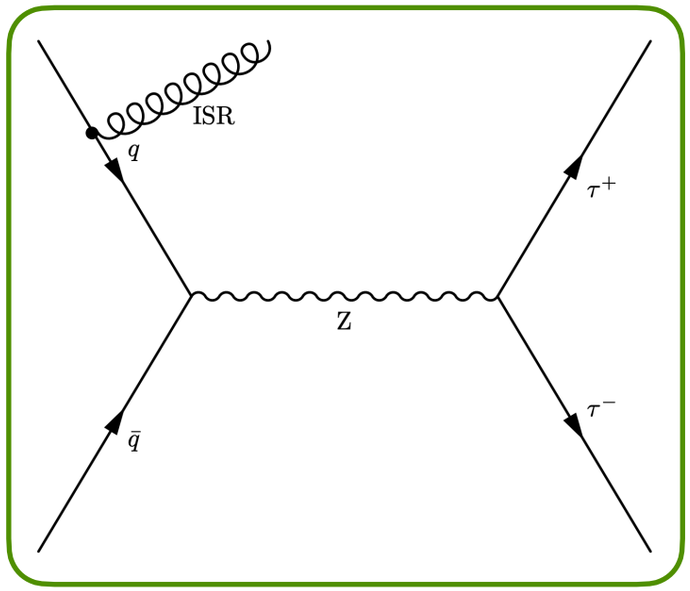

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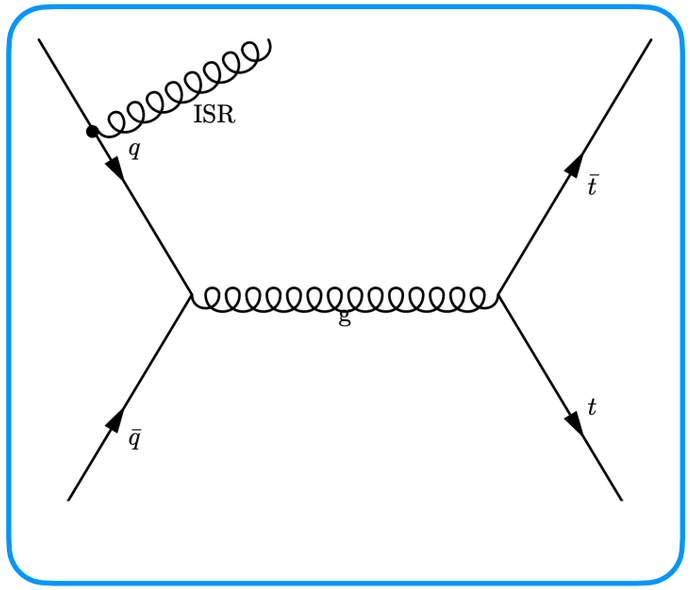

Soft τ Compressed Search: Results

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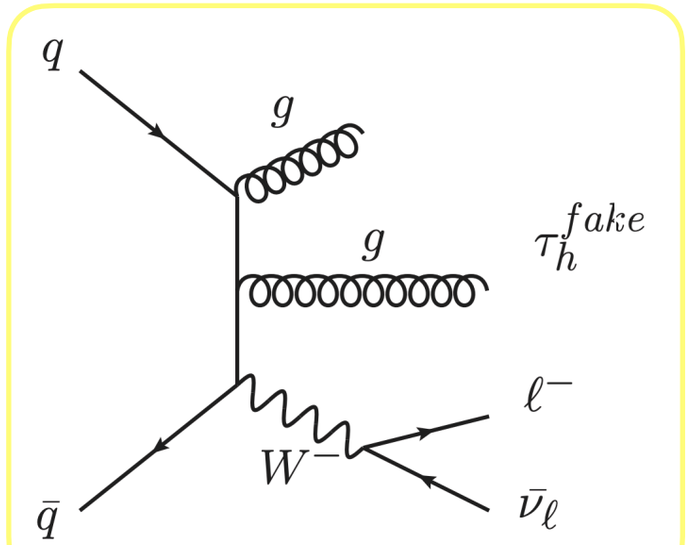
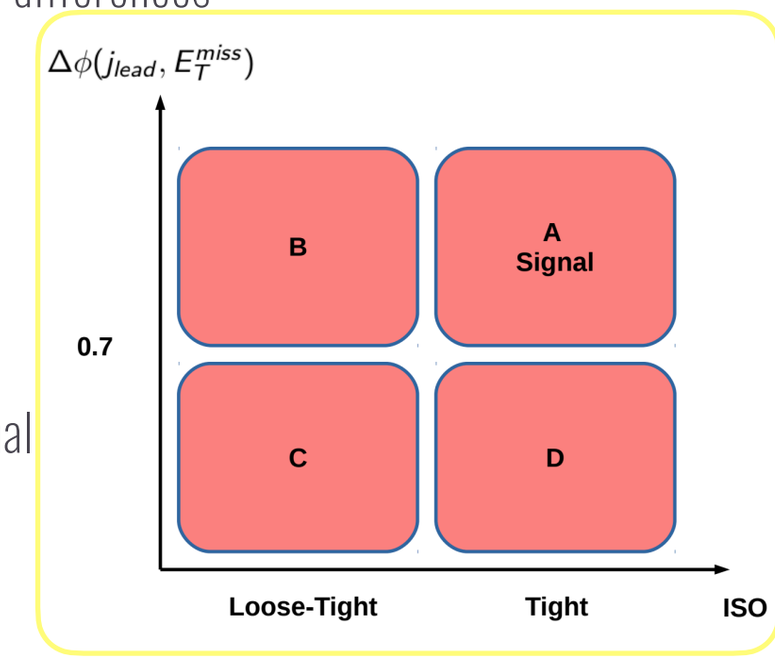
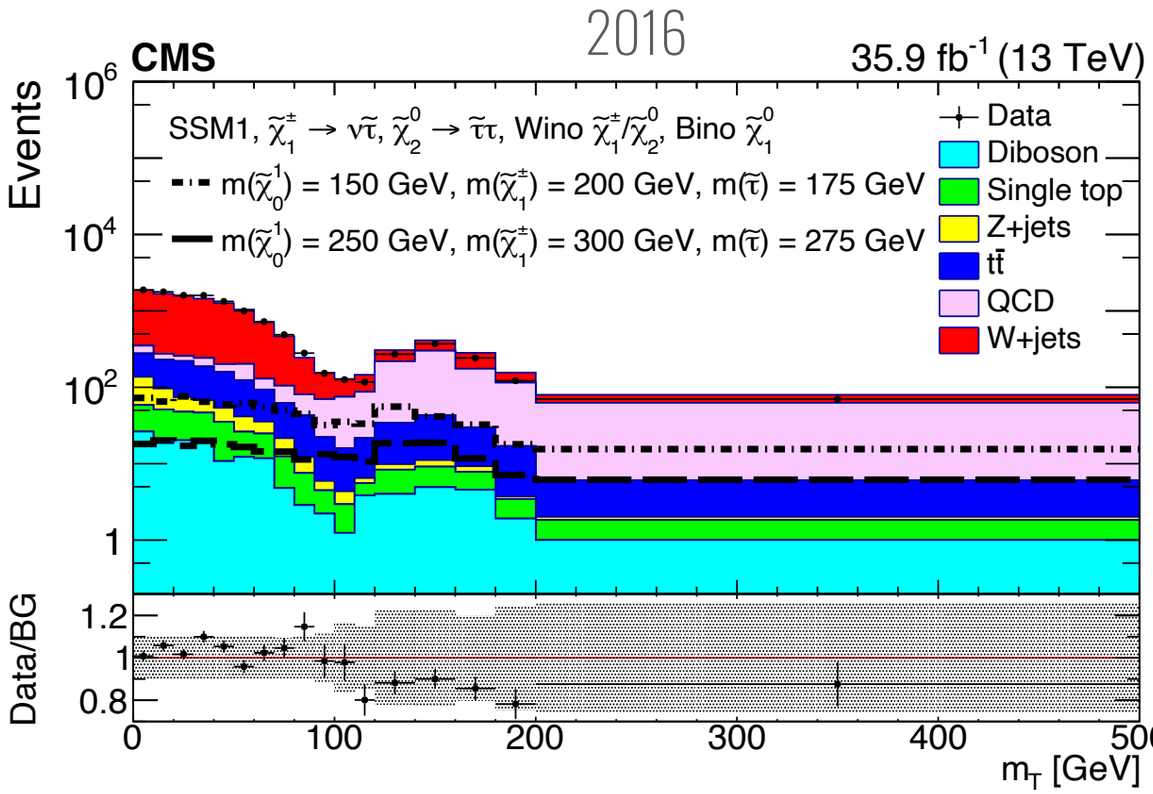
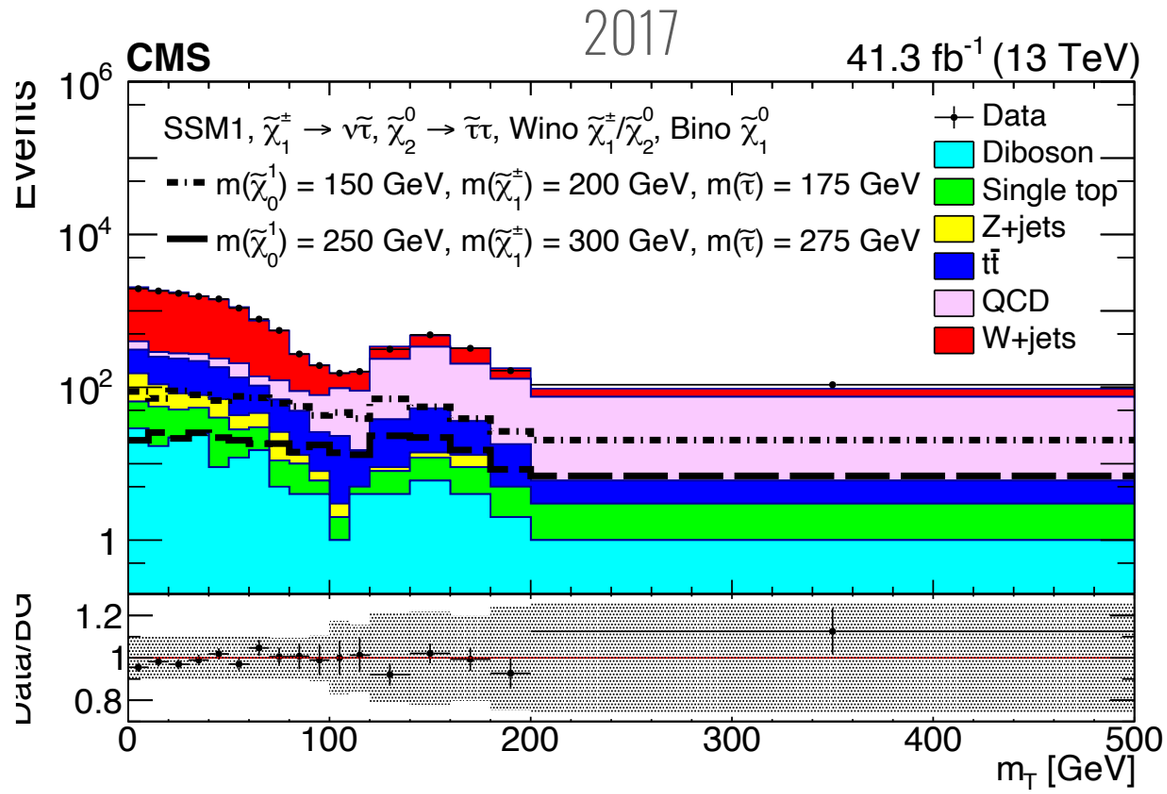




Soft τ Compressed Search: Results

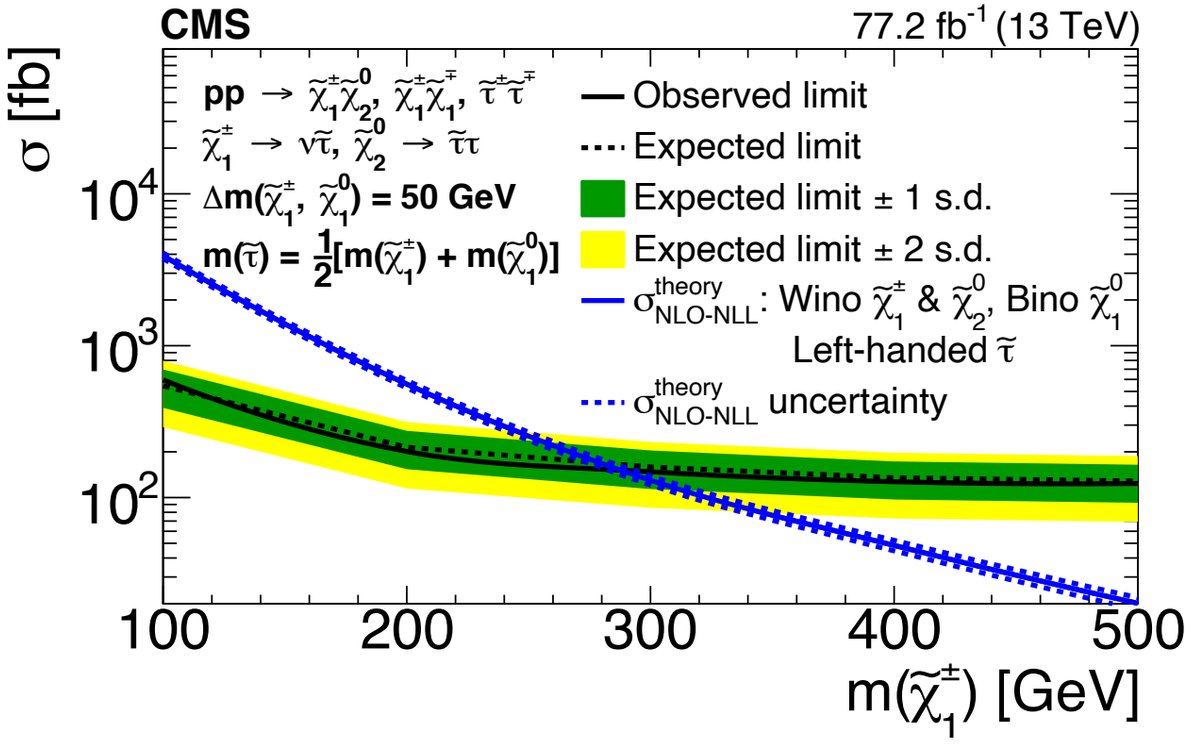




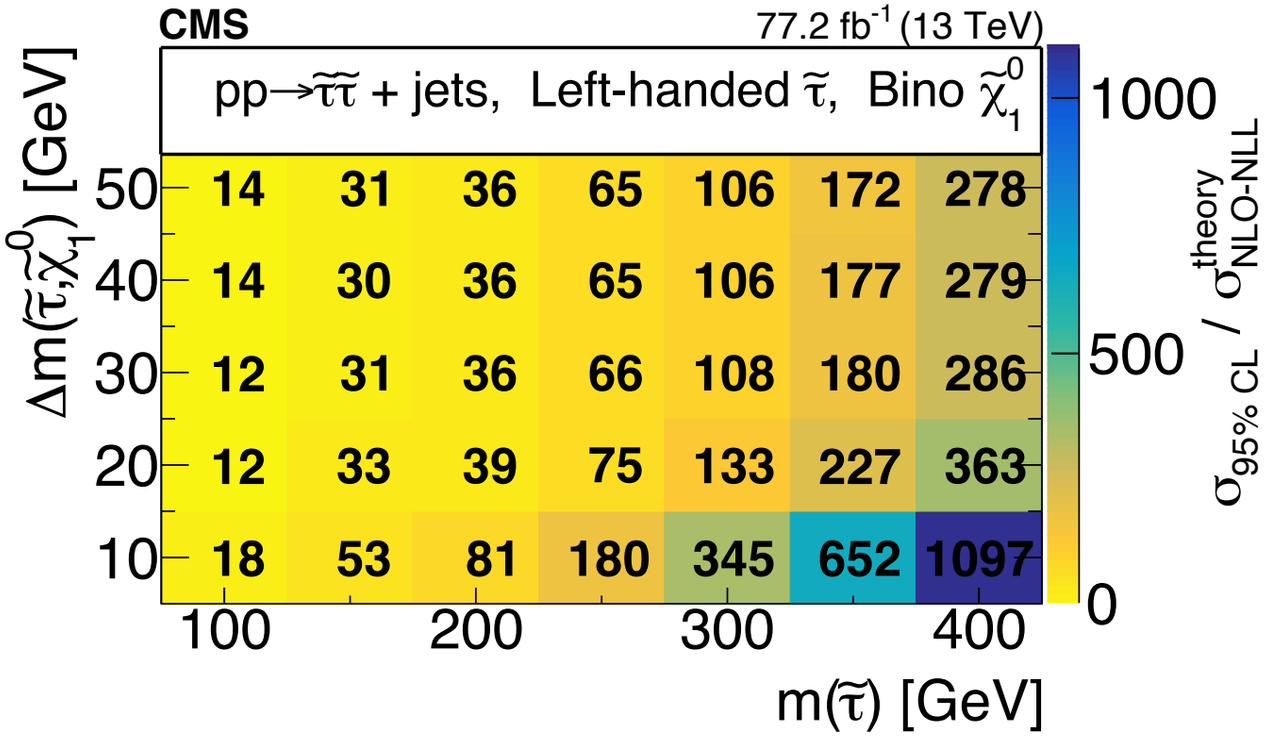
- Observed SR data is consistent with SM background

Soft τ Compressed Search: Limits & Conclusions

Inclusive $\tilde{\tau}$ Production Modes



Direct $\tilde{\tau}$ Production



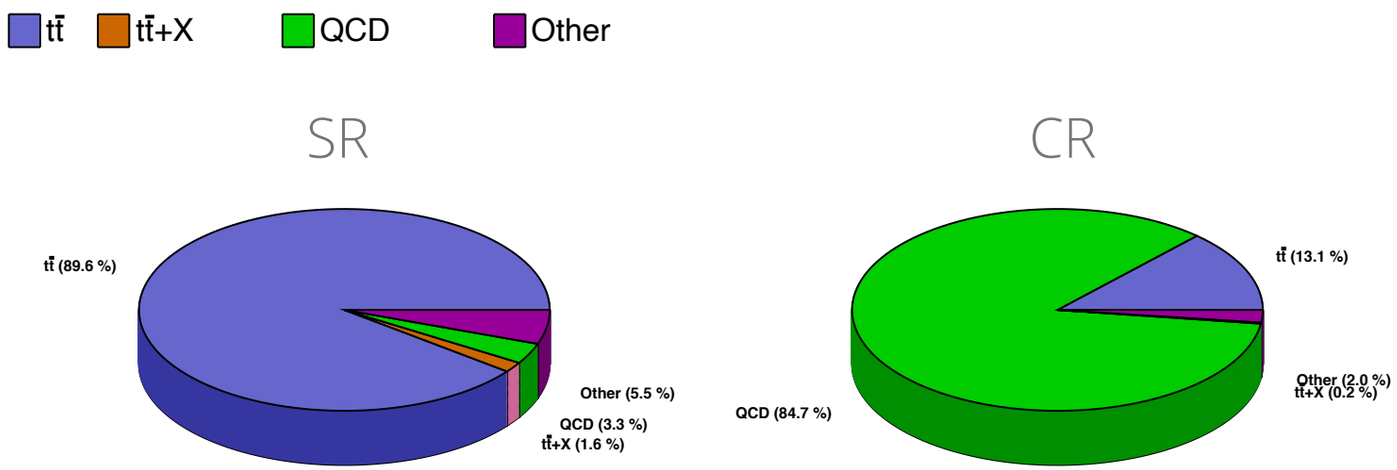
- 95% CL exclusion limits on $\tilde{\chi}_2^0/\tilde{\chi}_1^{\pm}$ mass set at 290 GeV for $\Delta m(\chi_1^{\pm}, \chi_1^0)$ = 50 GeV
  - Exceeding previous exclusions of ~100 GeV (LEP)
- Cross section exclusions computed for direct stau production
  - For comparisons to previous searches and for reinterpretations

Summary & Conclusions

- Presented two recent CMS searches in unconventional corners of the SUSY parameter space
- RPV/Stealth SUSY Top Squark Search
  - 2.8σ local significance for RPV model with $m_{\tilde{t}}$ = 400 GeV
  - Limits set at $m_{\tilde{t}}$ = 670 GeV (870 GeV) in the RPV (stealth) scenario
  - New limits in previously unexplored phase space
- Soft τ Lepton Compressed SUSY Spectrum Search
  - Limits set at $m_{\tilde{\chi}_2^0/\tilde{\chi}_1^\pm}$ = 290 GeV for $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ = 50 GeV, greatly extending beyond previous limits from LEP at ~100 GeV
  - For $m_{\tilde{\tau}}$ = 100 GeV, observed cross section limit is ~10 times theory for $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$ = 25 GeV
- Novel searches and ~200 fb^{-1} of anticipated new data from Run 3 will significantly extend the reach of CMS's SUSY search program

Backup

RPV/Stealth Search: Event Selection



- Signal region (SR):
  - Optimized to maximize signal significance
  - Selection:
    - ≥7 jets
    - H_T > 300 GeV
    - ≥1 b-jet
    - 1 e/μ
    - 50 < $m_{b,l}$ < 250 GeV
- Control region (CR):
  - Optimized to be enriched in QCD multi jet events
  - Used to estimate QCD contribution in SR and to validate independence of N_{jets} shape and S_{NN}
  - Selection:
    - ≥7 jets
    - H_T > 300 GeV
    - 0 b-jets
    - 1μ with p_T > 55 GeV

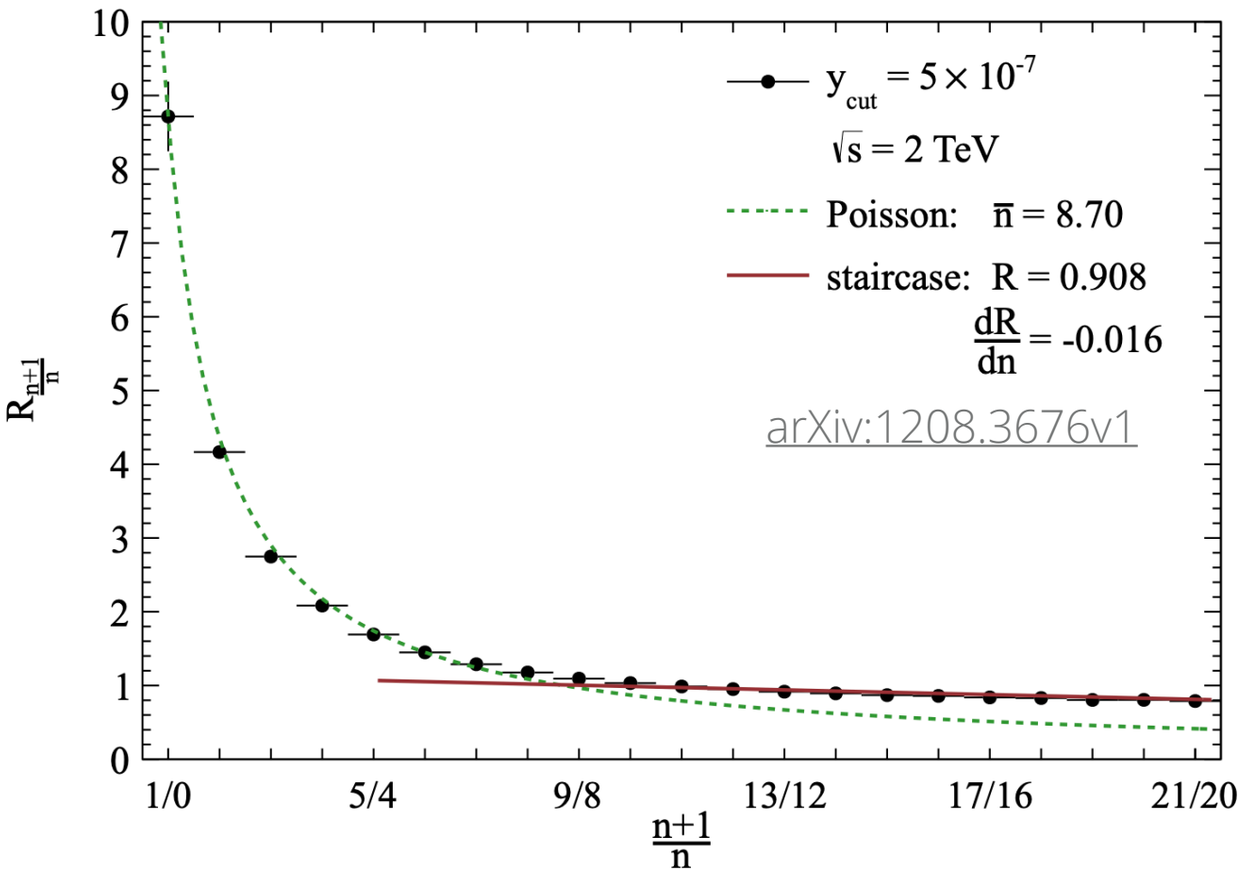
RPV/Stealth Search: Systematic Uncertainties

- Dominant uncertainties:
  - Modeling of H_T, jet mass, and jet p_T in $t\bar{t}$ simulation
  - Statistical uncertainties on simulated non-$t\bar{t}$ backgrounds
- Analysis is systematics dominated

Source of uncertainty	$t\bar{t}$ background	Minor background	RPV signal
PDFs	0–1 (2)	0–1 (8)	0–2 (7)
(μ_R, μ_F) scales	0–2 (5)	1–8 (18)	0–3 (4)
ISR	0–4 (15)	—	—
FSR	0–8 (27)	—	—
Color reconnection	0–10 (44)	—	—
ME-PS	0–14 (82)	—	—
UE tune	0–7 (100)	—	—
Pileup	0–2 (7)	0–7 (28)	0–2 (4)
JES	0–4 (18)	5–21 (100)	1–11 (31)
JER	0–2 (10)	1–15 (100)	0–6 (14)
b tagging	0–1 (3)	0–2 (12)	0–2 (2)
Lepton efficiencies	0–1 (1)	3–5 (5)	3–4 (4)
H_T primary	0–5 (17)	—	—
H_T validation	0–1 (4)	0–6 (10)	—
H_T H_T-parameterization	0–2 (9)	—	—
H_T N_{jets}-parameterization	0–7 (27)	—	—
Jet p_T	0–4 (15)	—	—
Jet mass	0–4 (15)	—	—
N_{jets} shape invariance	0–12 (37)	—	—
Integrated luminosity	—	2.3–2.5	2.3–2.5
Theoretical cross section	—	30	—

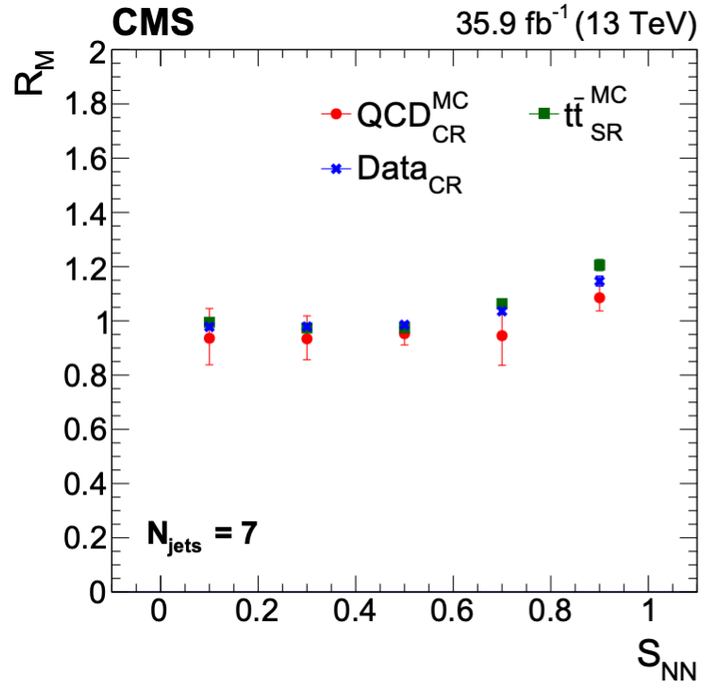
RPV/Stealth Search: N_{jets} Modeling

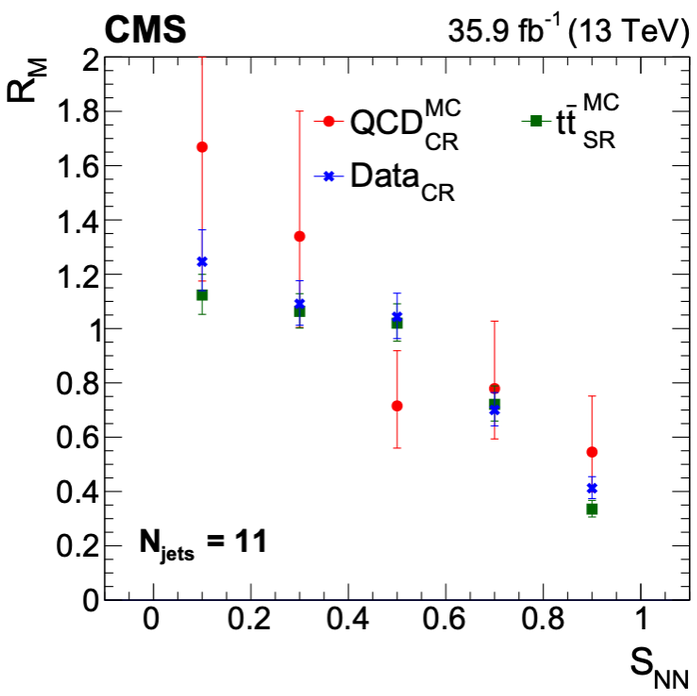
N_{jets} Parametrization



$$f(i) = a_2 + \left[\frac{(a_1 - a_2)^{i-7}}{(a_0 - a_2)^{i-9}}\right]^{1/2}$$

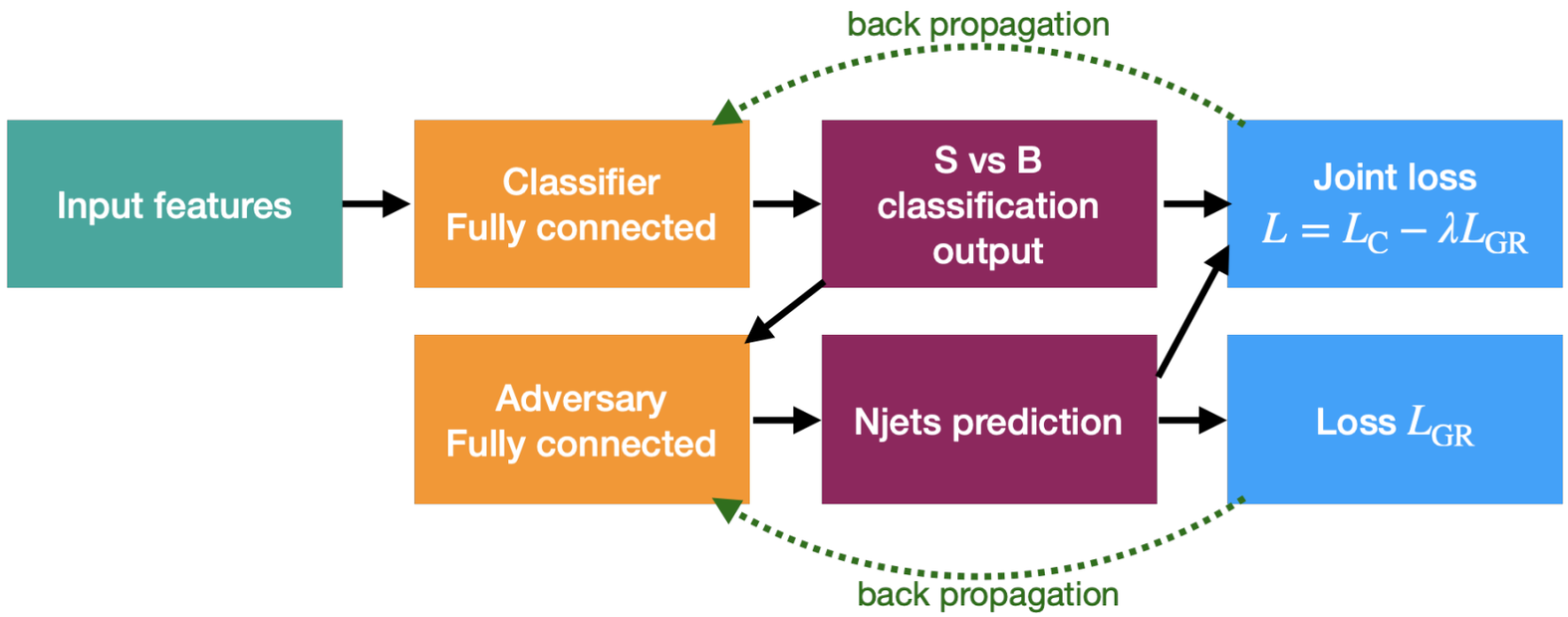
Njets-SNN Dependence Modeling

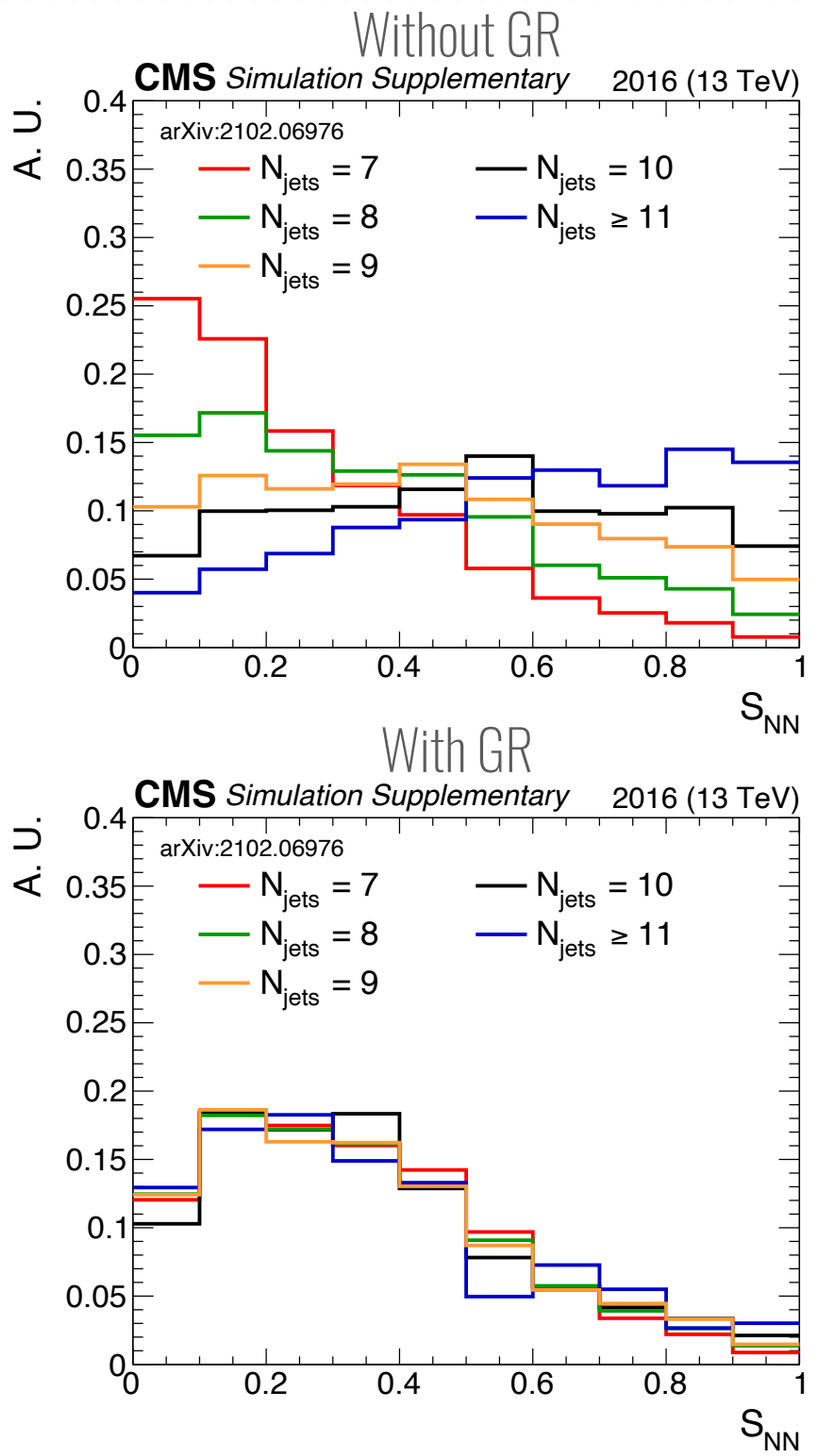




$$R_M = \frac{1}{\mu_i}\frac{M_{all}}{M_i}$$

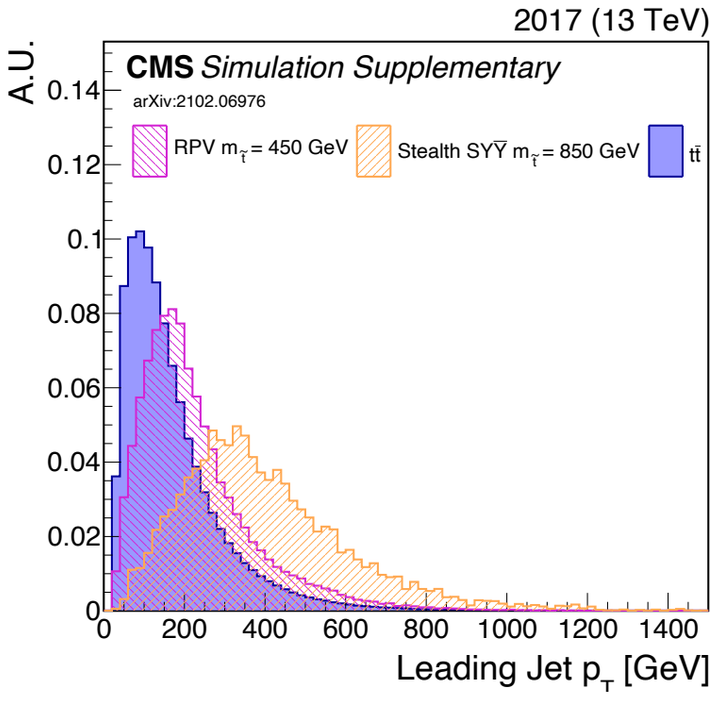
RPV/Stealth Search: NN Structure

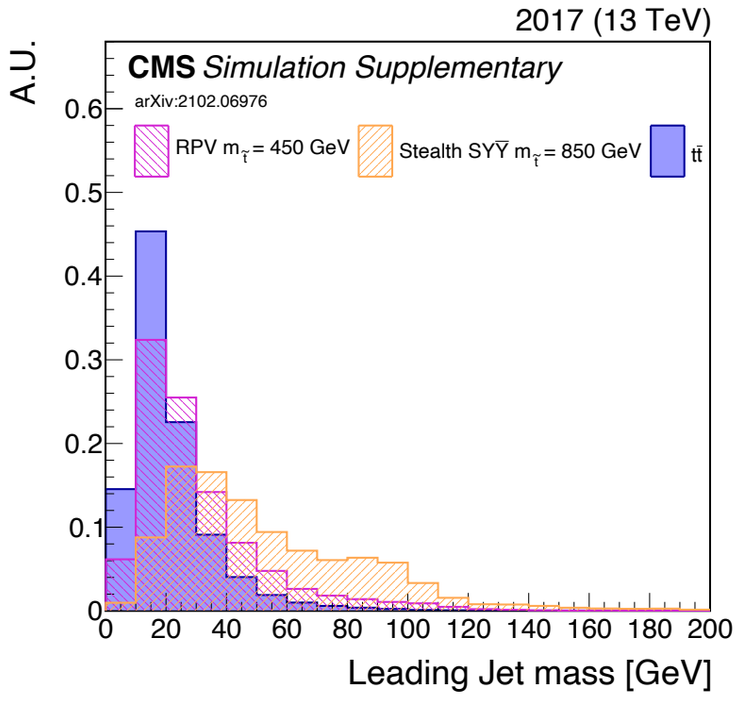


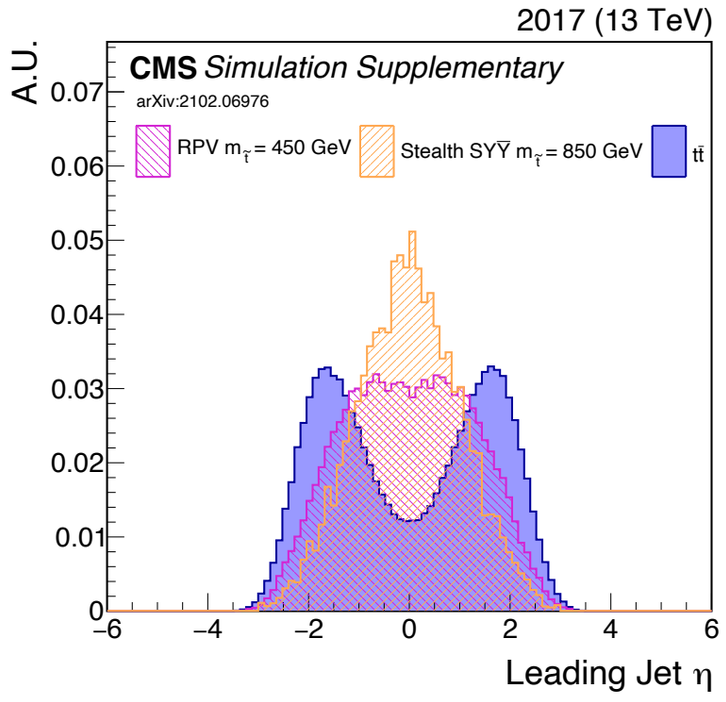


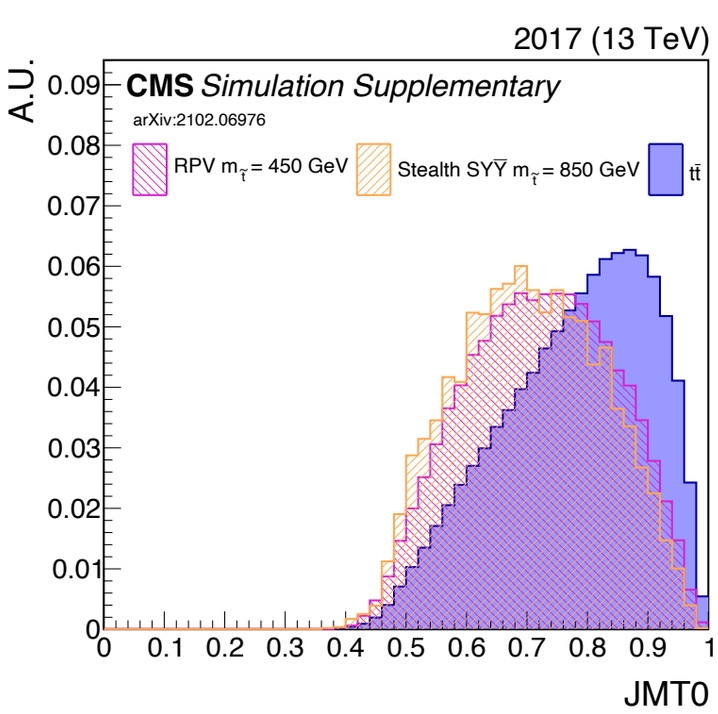
- NN classifier with gradient reversal (GR) to mitigate N_{jets} dependence
- NN inputs:
  - 4-vectors of 7 highest p_T jets and lepton
  - Jet energy-momentum tensor eigenvalues and Fox-Wolfram moments
- Training sample: $t\bar{t}$ as background, all models as signal

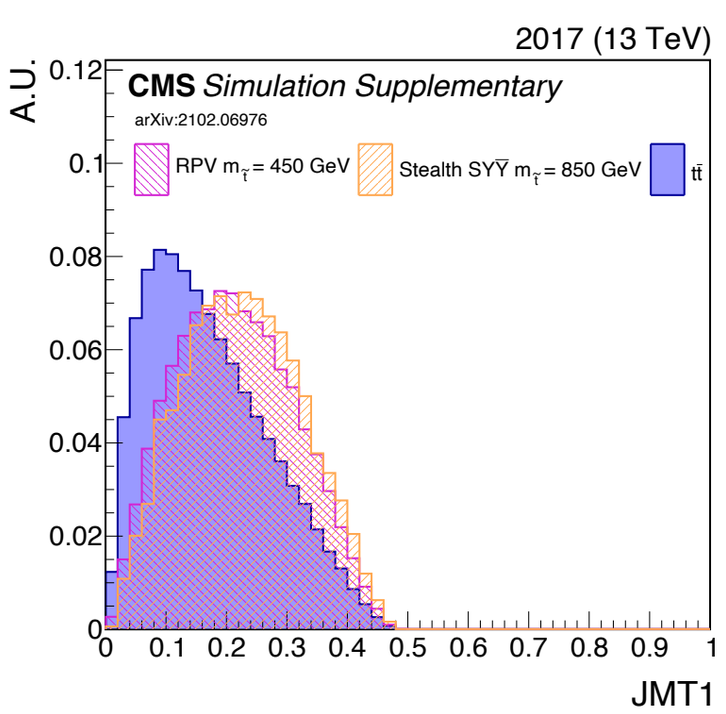
RPV/Stealth Search: NN Input Variable Shapes

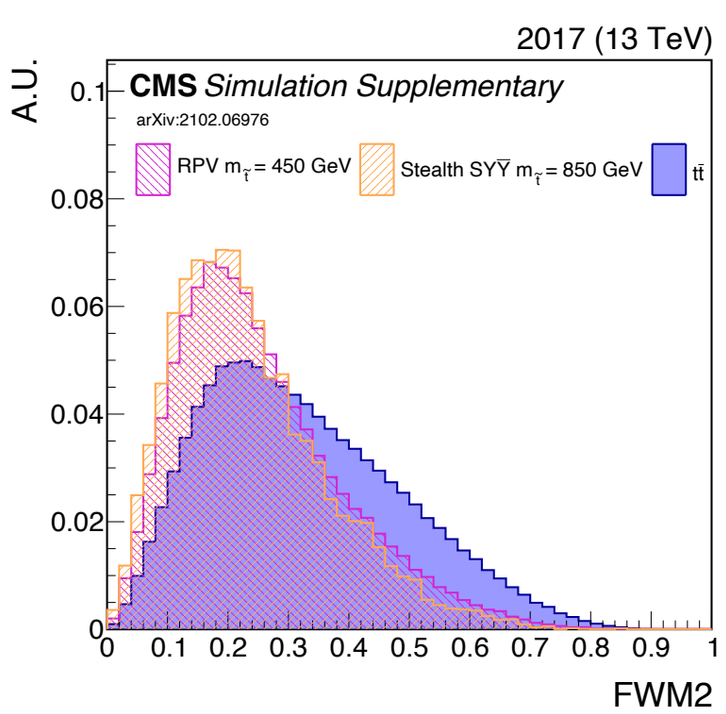








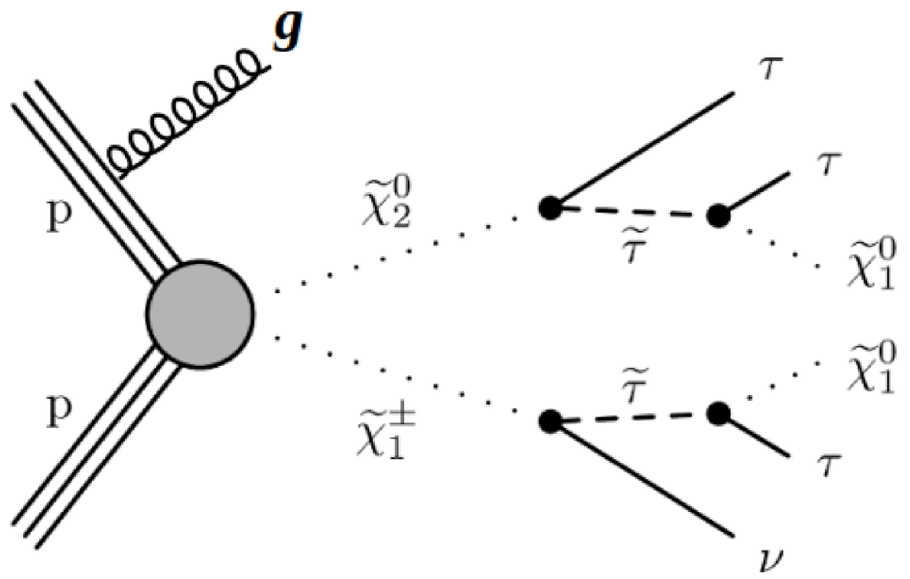




Soft τ Compressed Search: Event Selection

Event Selection

- Basic Selection and Event Cleaning
  - noise filters, good primary vertex, etc.
  - MET filters
- $\geq$ 1 jet with $p_T(j) > 30$ GeV
  - $|\eta(j)| < 2.4$ & "Loose" (2016) or "Tight" (2017) ID
  - $p_T^{ISR}(j) = p_T^{lead}(j) > 100$ GeV
- jet cross-cleaned with τ_h ($\Delta R(j, \tau_h) > 0.3$)
- $E_T^{miss} > 230$ GeV
  - PFMet with HF and type-1 corrections, MET-v2 in 2017
- $N(\tau_h) == 1$, $20 < p_T(\tau_h) < 40$ GeV, $|\eta(\tau_h)| < 2.1$
- QCD rejection: $|\Delta\phi(j_{lead}, E_T^{miss})| \geq 0.7$
- 1 prong requirement for τ_h + "Tight" MVA isolation
- Veto b-jets: $p_T > 30$ GeV and $|\eta| < 2.4$
- Veto other leptons ("Tight" for μ and "Loose" cut-based for e)
- Trigger: MET trigger ($> 99\%$ efficiency w.r.t to our selections)



Phenomenology Reference:
Phys. Rev. D 94, 073007

Soft τ Compressed Search: Systematic Uncertainties

Source	W	DY	$t\bar{t}$	VV	QCD	Signal
Lumi	2.5	2.5	2.5	2.5	–	2.5
μ ID	< 1	< 1	< 1	< 1	–	1
e ID	< 1	< 1	< 1	< 1	–	1
τ_h ID	6	8	9	9	–	9
Trigger	3	3	3	3	–	3
b ID	2	2	7	2	–	2
JES	s	s	s	s	–	s
TES	s	s	s	s	–	s
MMS	< 1	< 1	< 1	< 1	–	< 1
EES	< 1	< 1	< 1	< 1	–	< 1
Pileup	5.0	5.0	5.0	5.0	–	5.0
PDF	4.8	4.2	4.2	3.5	–	6.0
bin-by-bin stat.	s	s	s	s	–	s
Closure+Norm.	2	8	6	–	23	–
ISR	s	s	–	–	–	s
Prefiring	–	–	–	–	–	s
$Ratio^{Tight}_{Loose}$	–	–	–	–	s	–
Gen. Scale	1	1	3.5	–	–	2
Fast Sim.	–	–	–	–	–	s

Values are given as percents

"s" indicates a shape uncertainty