

Searches for RPV SUSY with LNV at the LHC and Beyond

Ian Dyckes, University of Pennsylvania

Detector Signatures

Minimal Supersymmetric Standard Model with RPV:

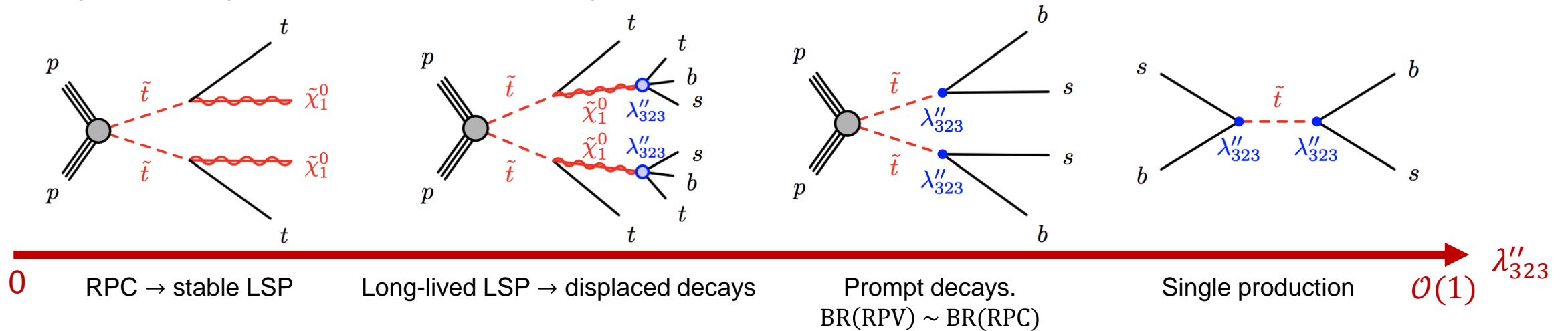
- R-parity is not a symmetry of the most general MSSM Lagrangian.

$$W_{Rp} = \left[\mu_i H_u L_i + \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c \right] + \left[\frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c \right]$$

Lepton number violating
Baryon number violating

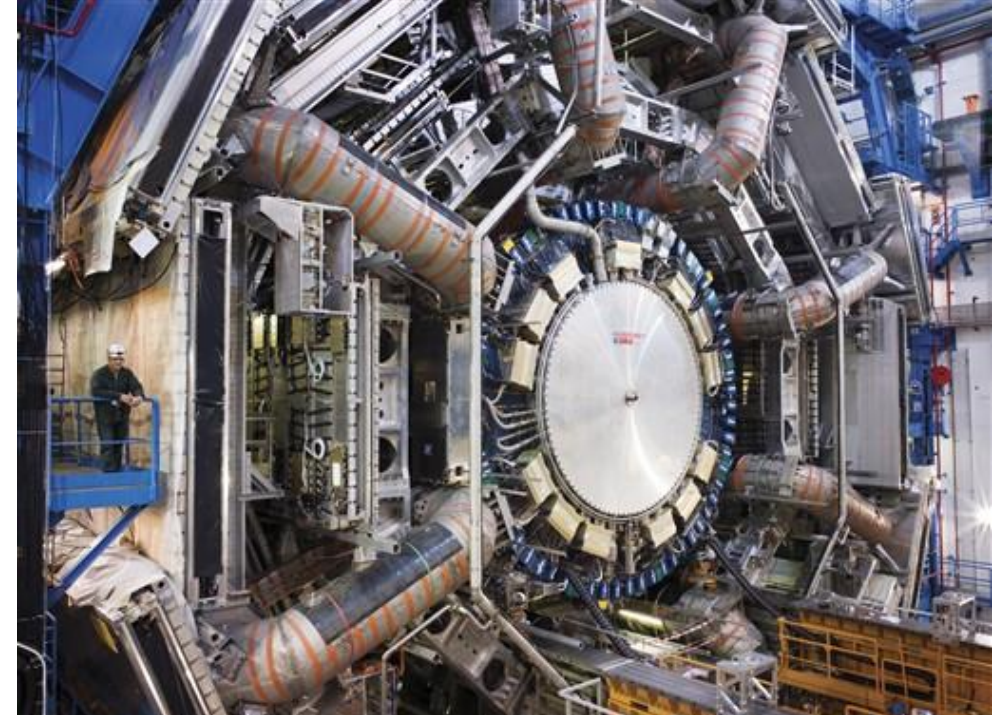
Consequences of RPV:

- LSP can carry charge and decay to SM particles.
- Strength of couplings can lead to various detector signatures.



Outline

1. Prompt searches:
 - CMS SS/3L
 - ATLAS 4L
 - ATLAS trilepton resonance
 - ATLAS stop
2. Long-lived searches:
 - ATLAS displaced vertex + muon
 - CMS displaced jets
 - CMS displaced jet tagger
 - ATLAS DV+OS
3. Setting limits on RPV coupling strengths
 - ATLAS RPC meets RPV
4. Projections for future colliders

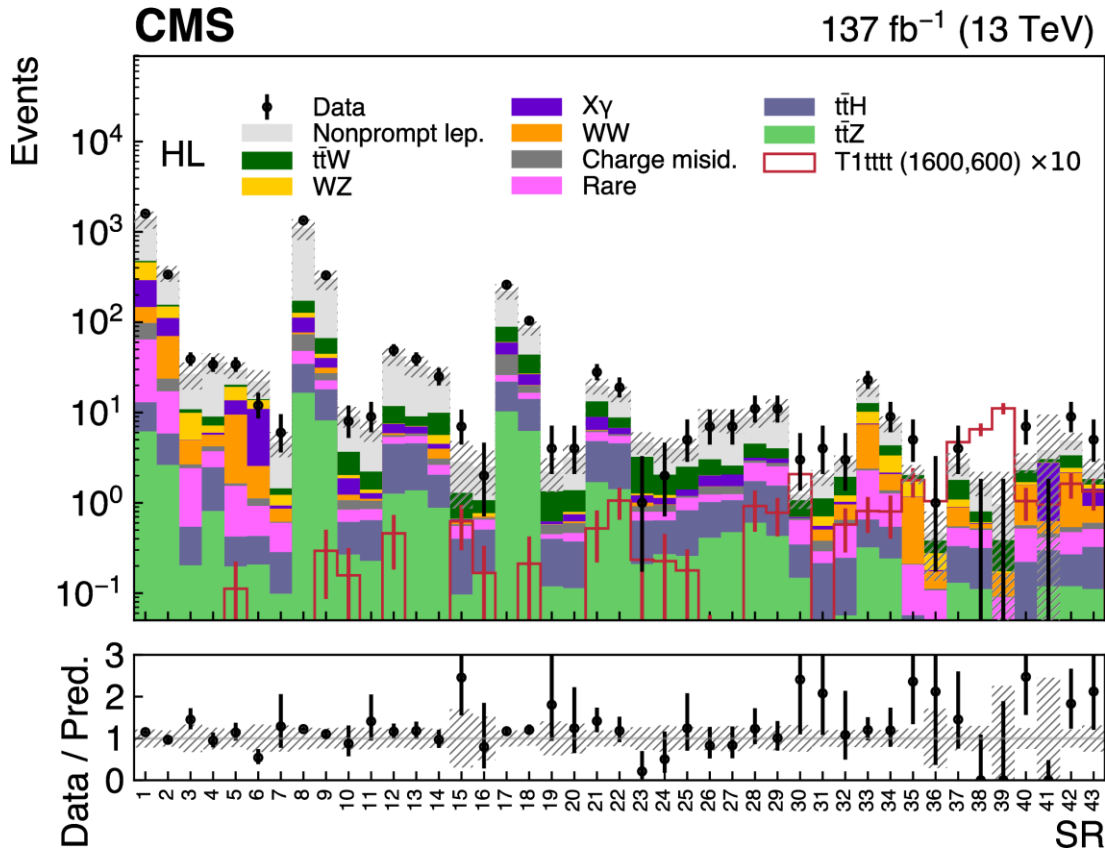
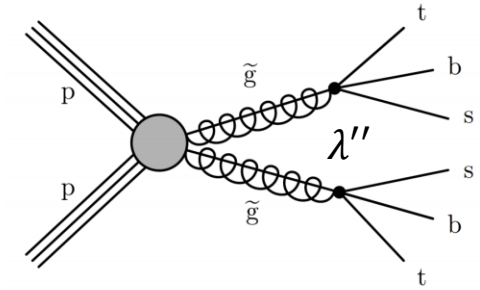
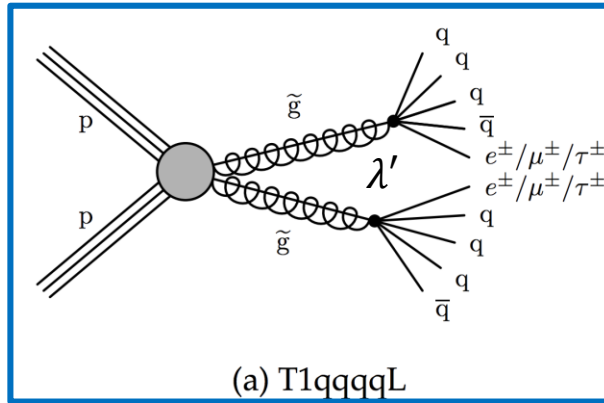


Search for BSM physics in events with jets and same-sign leptons

[arXiv:2001.10086](https://arxiv.org/abs/2001.10086)

Final State:

- Require **either** 2 same-sign leptons **or** at least 3 leptons.
 - And** at least 2 jets.
- Rarely produced by SM, but common in many BSM scenarios.



Target Models:

- Interpretations for a wide range of RPC and RPV SUSY models.
- Two RPV benchmark models with gluino LSPs:
 - 5-body decay via LQD coupling (λ').
 - 3-body decay via UDD coupling (λ'').

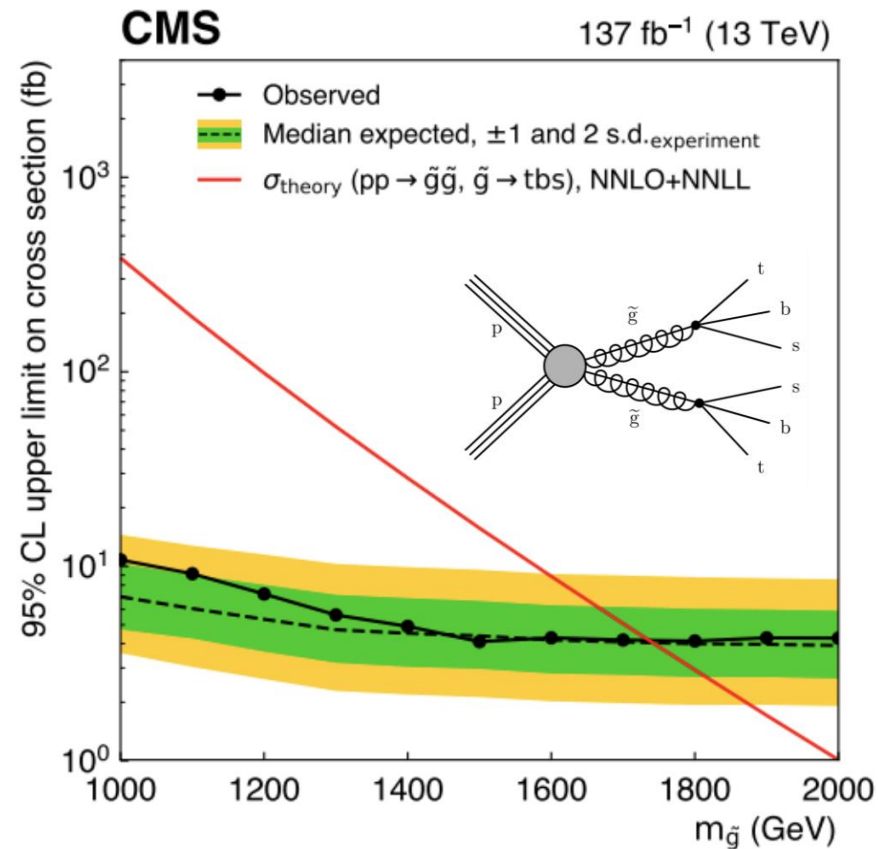
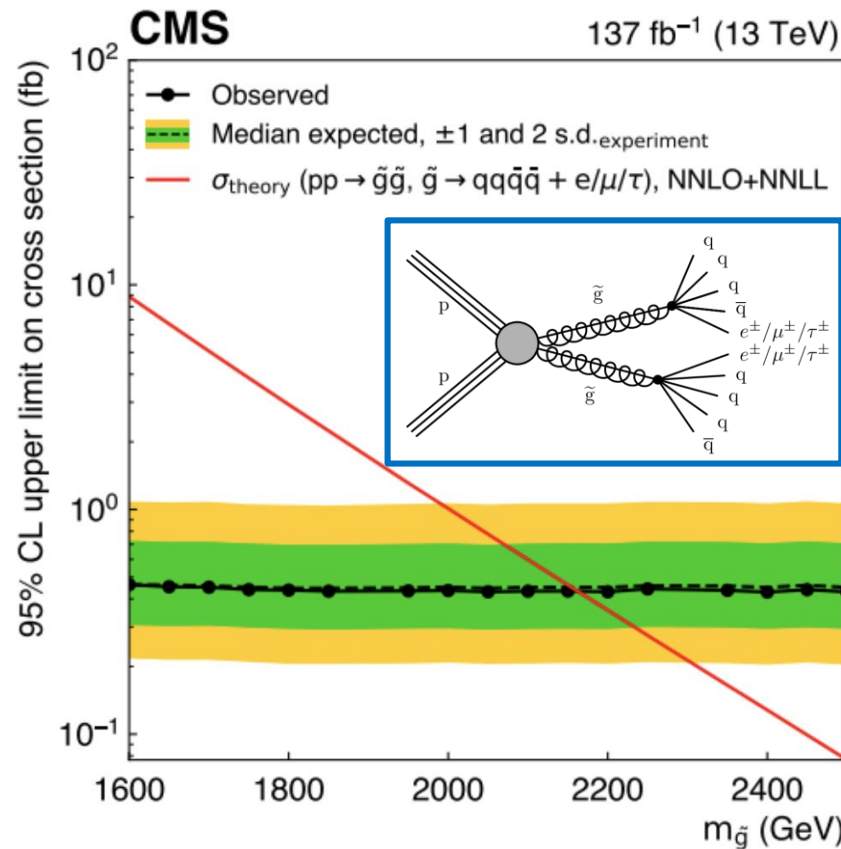
Signal Region Strategy:

- Over 150 orthogonal SRs, binned in various kinematic variables:
 - Lepton p_T , charge, multiplicity.
 - Jet and b-jet multiplicity.
 - p_T^{miss} , H_T , m_T^{min} .
 - On/off Z mass (3L SRs).



Search for BSM physics in events with jets and same-sign leptons

[arXiv:2001.10086](https://arxiv.org/abs/2001.10086)



Results:

- No significant deviation from SM seen.
- Simultaneously fit all SRs \rightarrow place exclusions on the two benchmark RPV models.
 - Exclude gluino masses up to **2.1 TeV for 5-body decay (left)** and 1.7 TeV for 3-body decay (right).

ATLAS SS/3L:

- Only has UDD interpretation, but should be sensitive to LQD as well (see backup).

Targeted RPV models:

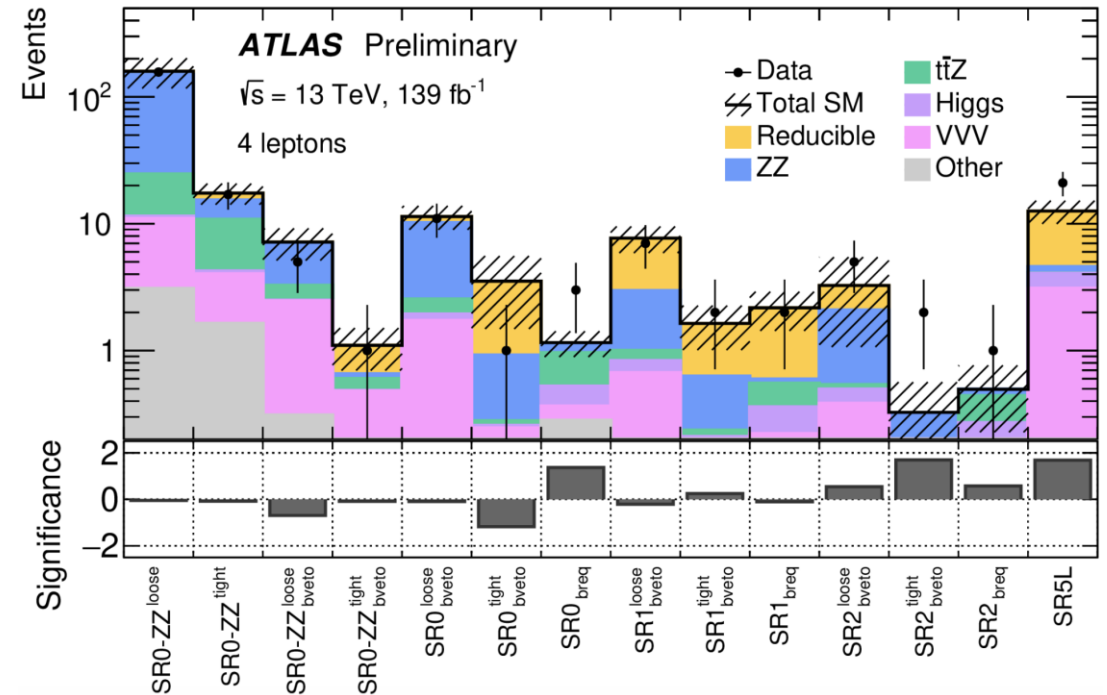
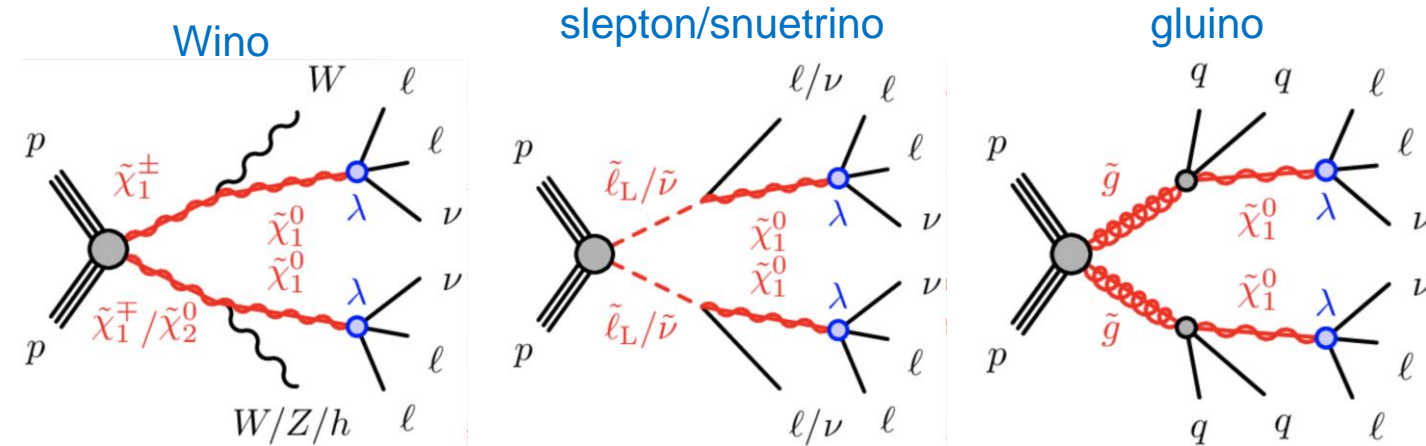
- Bino $\tilde{\chi}_1^0$ pairs decaying via LLE coupling (λ) \rightarrow 4 leptons.
 - Wino $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_2^0$, slepton, and gluino production
- Two decay scenarios:

Scenario	$\tilde{\chi}_1^0$ branching ratios
$LL\bar{E}12k$	$e^+e^-\nu$ (1/4) $e^\pm\mu^\mp\nu$ (1/2) $\mu^+\mu^-\nu$ (1/4)
$LL\bar{E}i33$	$e^\pm\tau^\mp\nu$ (1/4) $\tau^+\tau^-\nu$ (1/2) $\mu^\pm\tau^\mp\nu$ (1/4)

$i, k \in 1, 2$

SR strategy:

- Define SRs with varying $N_{e,\mu}$ & N_τ requirements.
 - Such that $N_{e,\mu} + N_\tau \geq 4$.
- Bin in N_b and $m_{\text{eff}} = \text{scalar } p_T \text{ sum of all leptons, jets, and } E_T^{\text{miss}}$.
- Dedicated inclusive SR with $N_{e,\mu} \geq 5$.



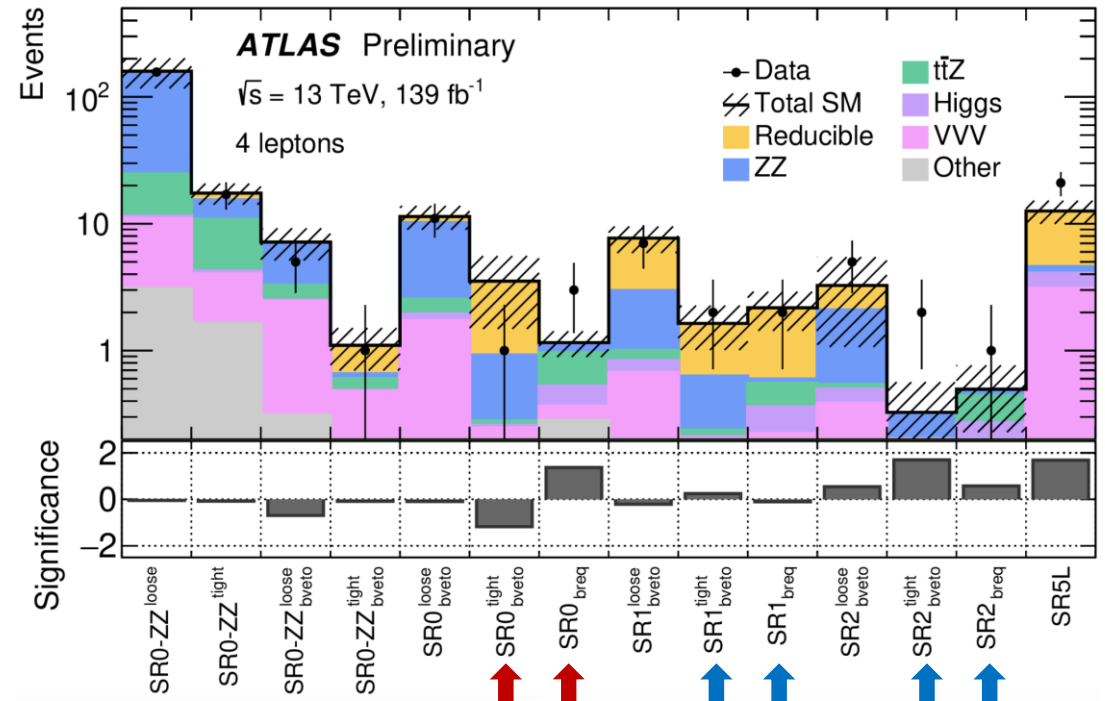
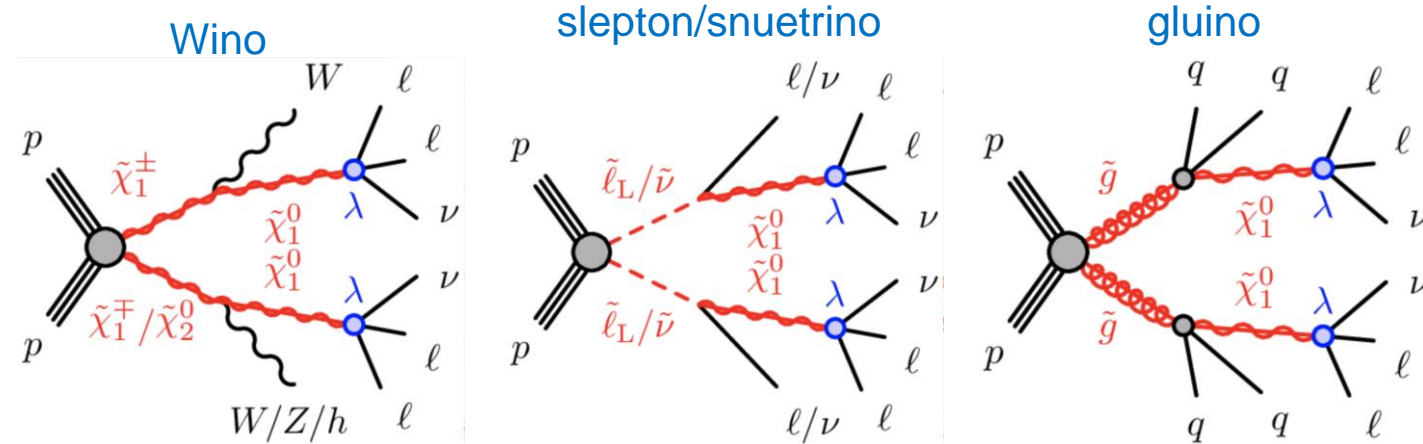
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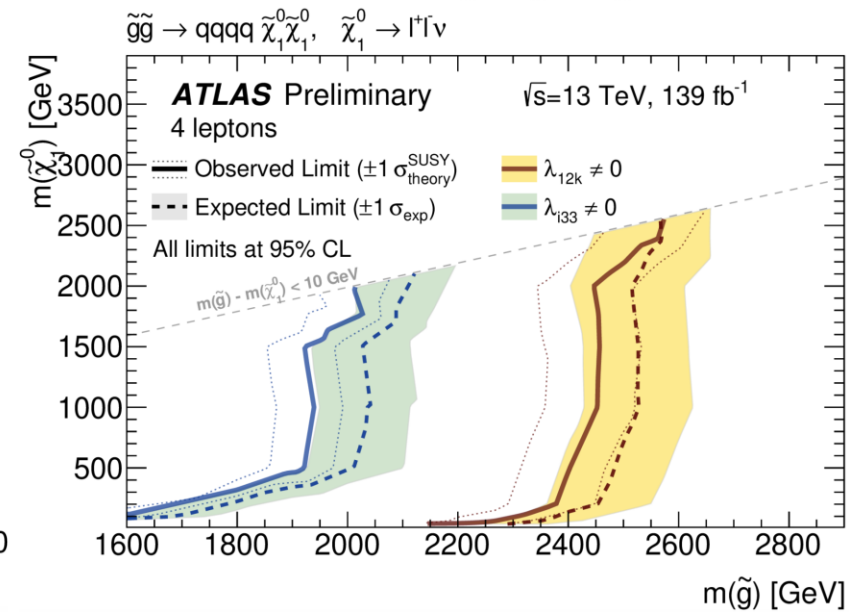
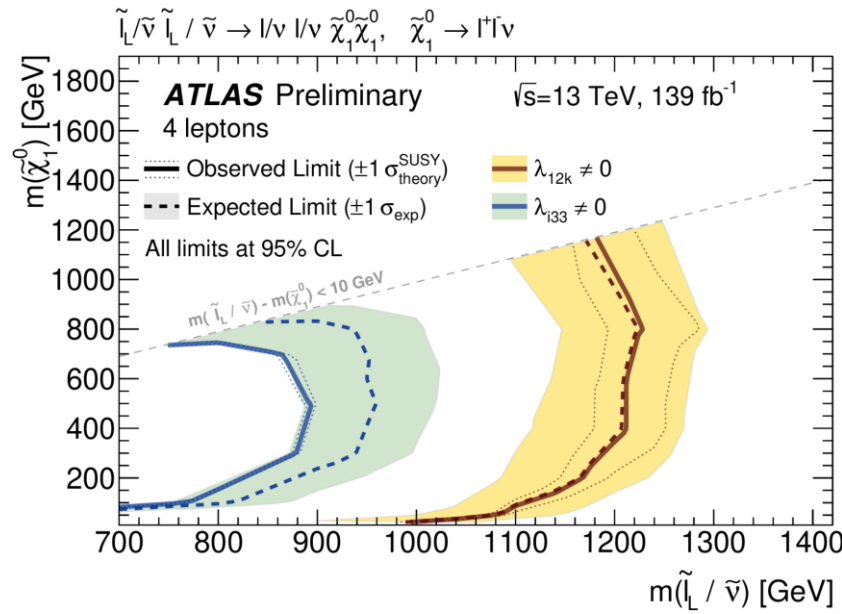
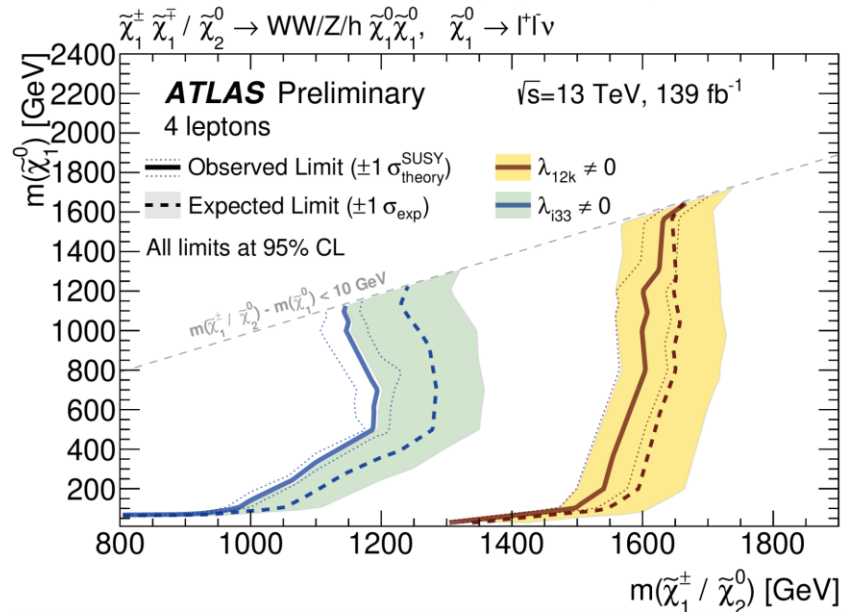
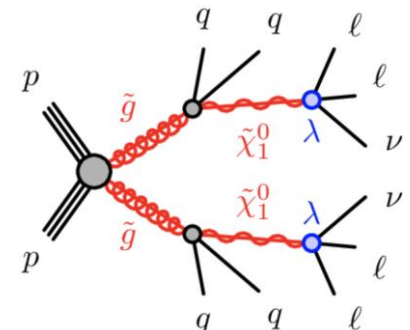
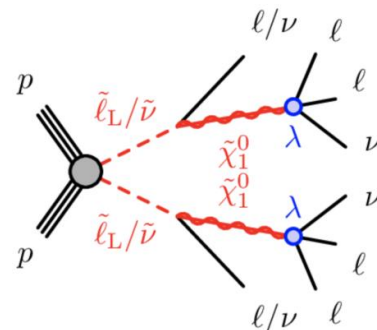
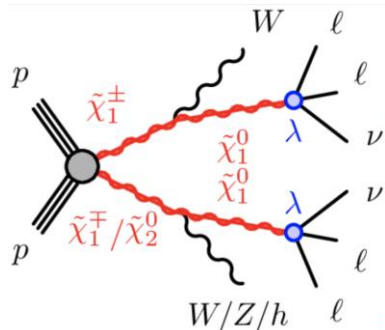
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- Bin in N_b and $m_{\text{eff}} = \text{scalar } p_T \text{ sum of all leptons, jets, and } E_T^{\text{miss}}$.
- Dedicated inclusive SR with $N_{e,\mu} \geq 5$.



Search for supersymmetry with four or more charged leptons

ATLAS-CONF-2020-040



Results:

- No significant deviation from SM seen.
- Simultaneously fit all SRs → place exclusions on [3 NLSPs] × [2 LEE coupling] scenarios.

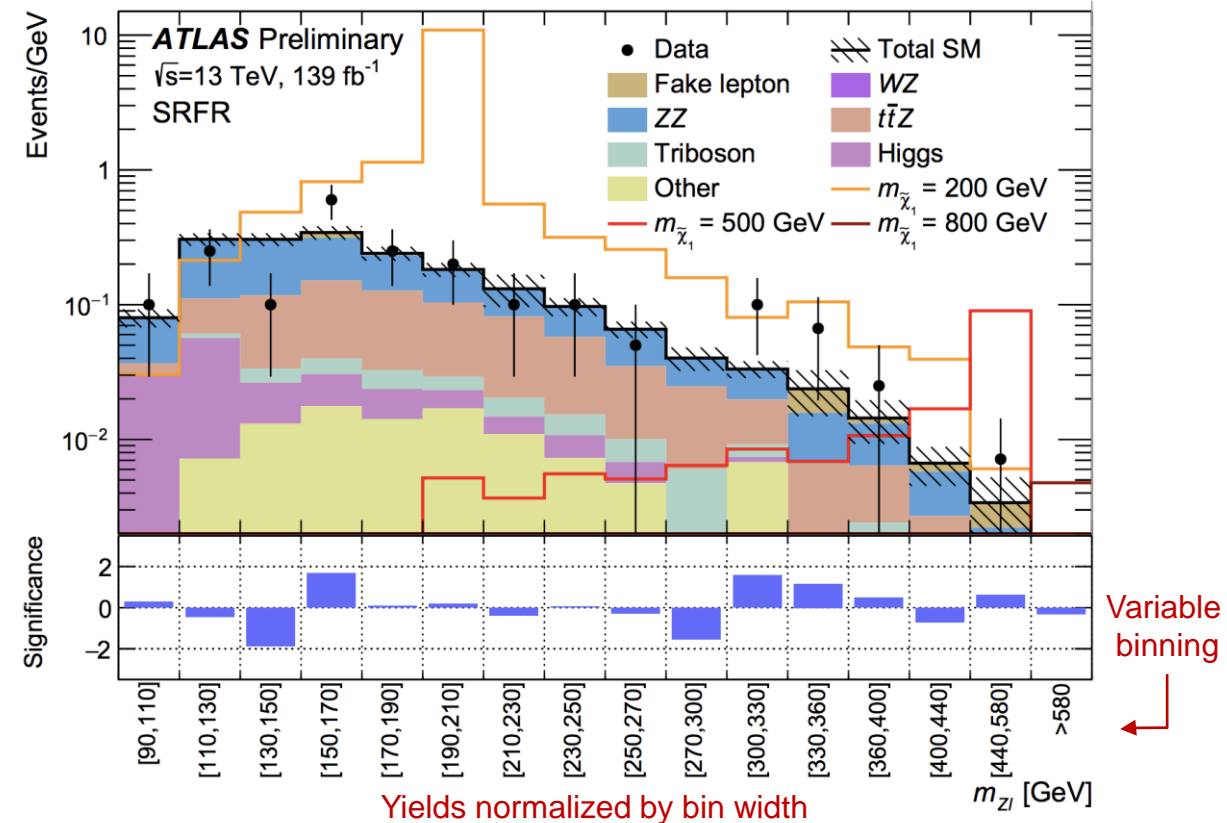
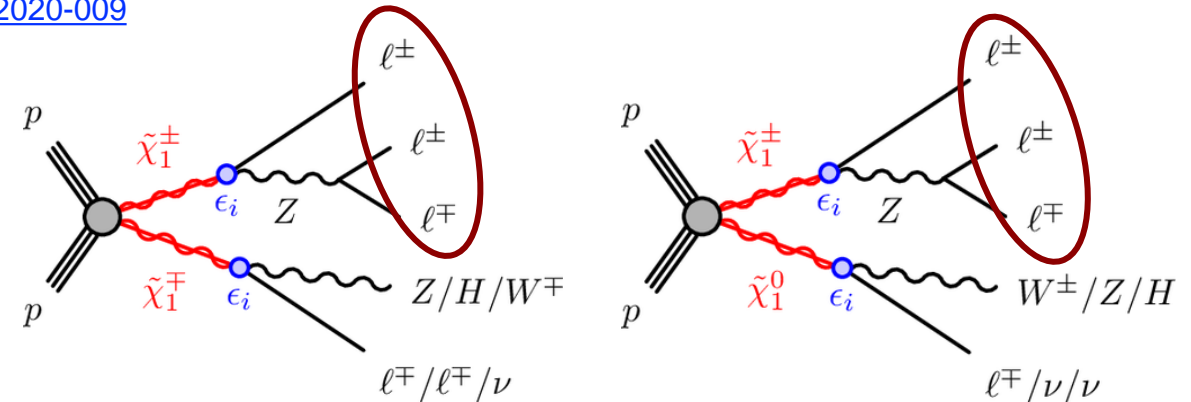
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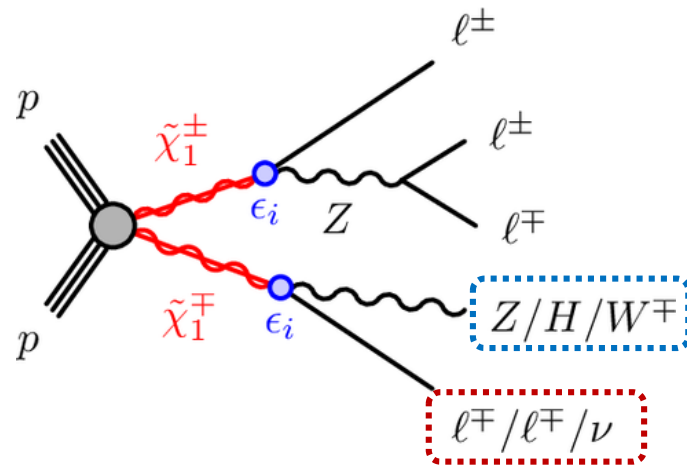
Model:

- Inspired by the $B - L$ MSSM with RPV [1][2].
 - Add $U(1)_{B-L}$ symmetry to the MSSM.
 - Break spontaneously \rightarrow R-parity and L -violation.
- Wino $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ are possible LSPs in this model.
 - Decay promptly to a SM boson and a lepton/neutrino.
 - BRs to different lepton flavors related to the neutrino hierarchy.

SR Strategy:

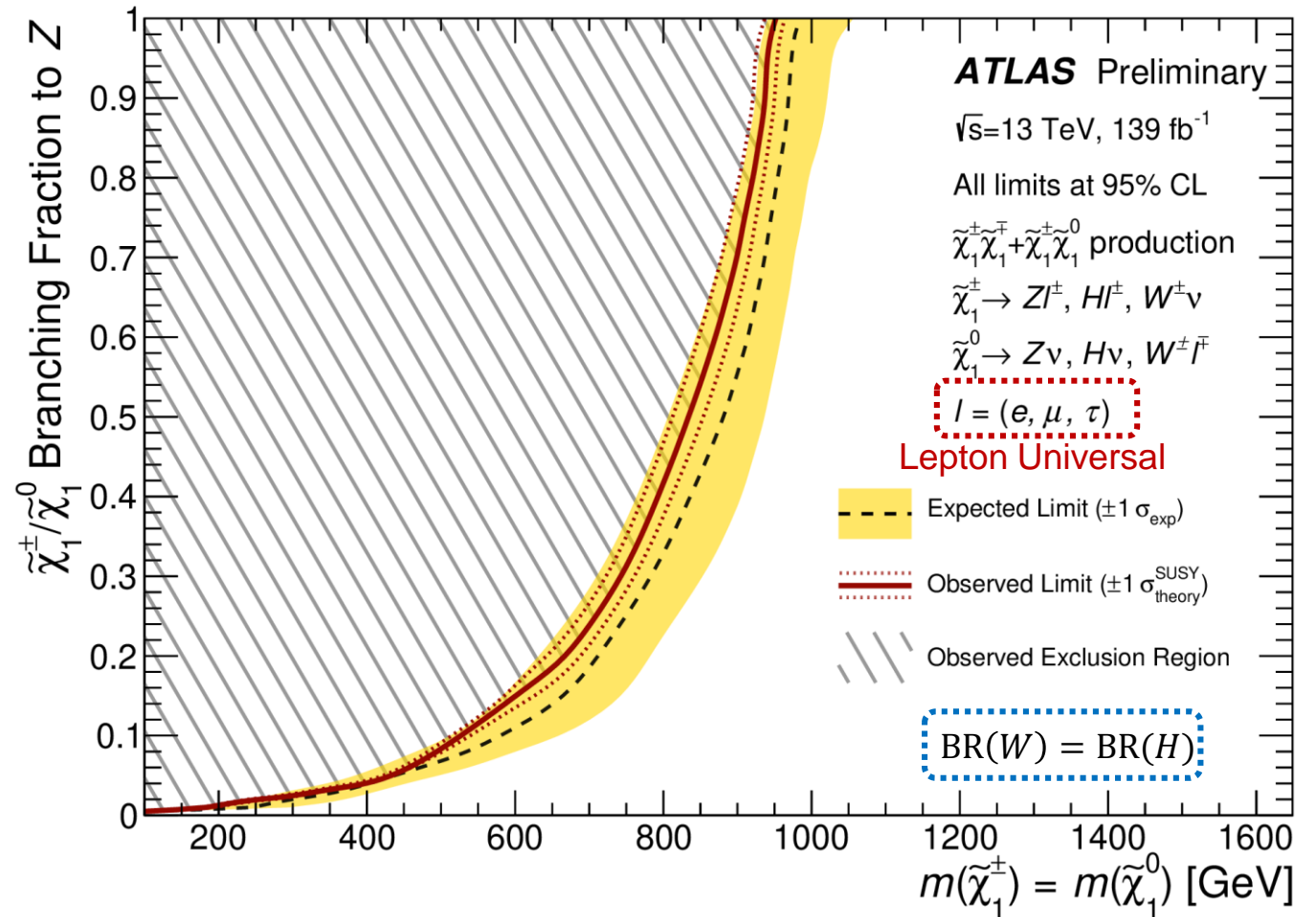
- Targets wino $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production.
 - Require one $\tilde{\chi}_1^\pm \rightarrow Zl \rightarrow ll$ decay \rightarrow trilepton resonance.
 - No constraints on the decay of the other $\tilde{\chi}_1^\pm / \tilde{\chi}_1^0$.
- Attempt to reconstruct the second wino decay.
 - Number of leptons and reconstructed bosons defines 3 SRs.





Results:

- No significant excess seen → set limits.
- Simultaneously fit the m_{Zl} distributions in the 3 SRs.
- Scan over $\tilde{\chi}_1^\pm / \tilde{\chi}_1^0$ decay BRs to **bosons** & **lepton flavors**.
 - For each sampled point in lepton BR space, limits are set on wino mass as function of BR(Z).
- Exclude wino masses up to 950 GeV for lepton universal decays.



Search for $B - L$ RPV top squark decays

[Phys. Rev. D 97 \(2018\) 032003](#)

[Marshall, Ovrut, Purves, Spinner](#)
[arXiv: 1402.5434](#)

Model:

- Also inspired by the $B - L$ MSSM with RPV [3].
 - $U(1)_{B-L}$ spontaneously broken by a RH sneutrino VEV.
- Targets $\tilde{t} \rightarrow b + l_i$ via LQD coupling (λ'_{i33}).
 - BRs to leptons related to neutrino mass hierarchy.

SR strategy:

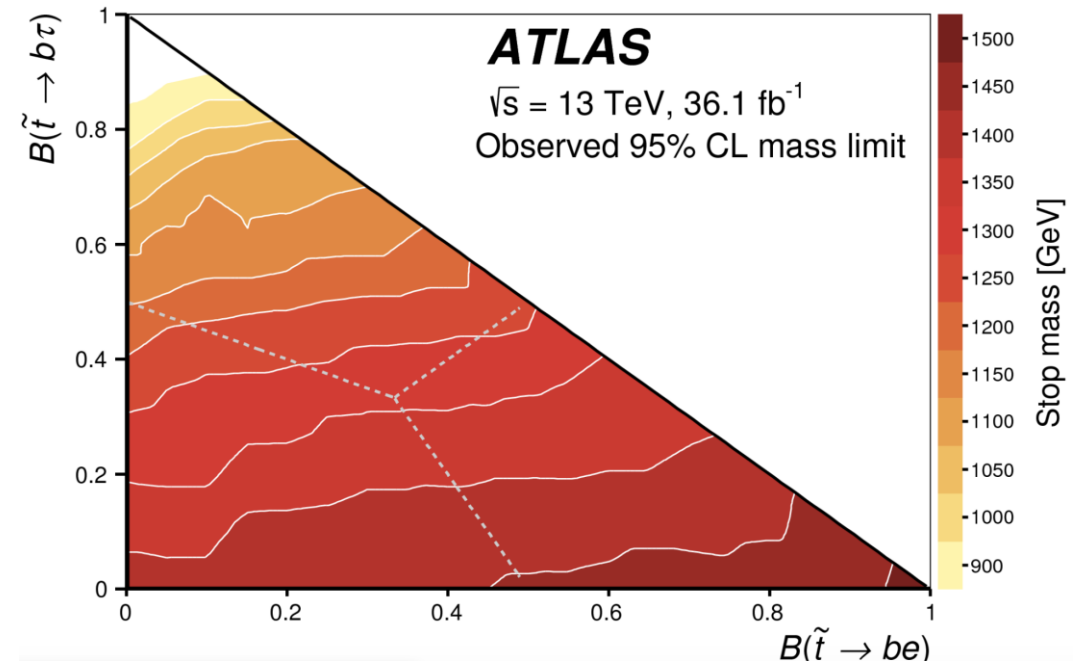
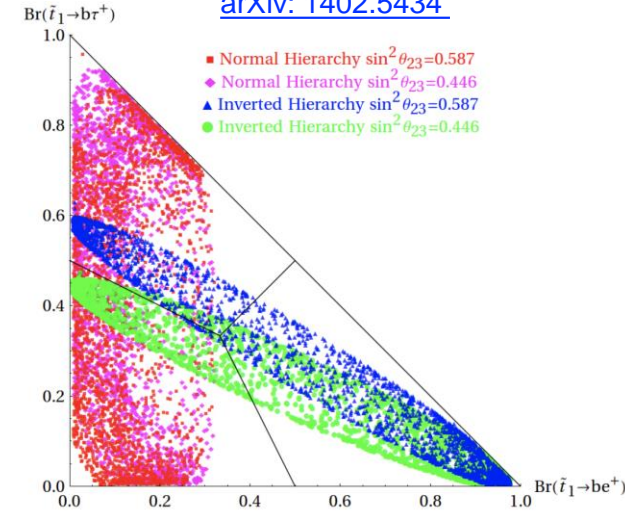
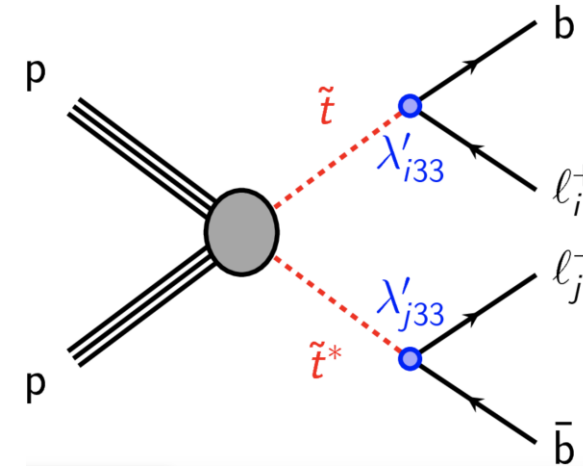
- Require at least 2 leptons and 2 jets (at least 1 b-tagged).
- Pair leptons with jets, minimizing mass asymmetry:

$$m_{bl}^{\text{asym}} = \frac{m_{bl}^0 - m_{bl}^1}{m_{bl}^0 + m_{bl}^1}$$

- Define two overlapping SRs: $m_{bl}^0 > 800, 1100$ GeV.

Results:

- No excess seen \rightarrow set limits on stop mass.
- Scan over BRs to different lepton flavors.

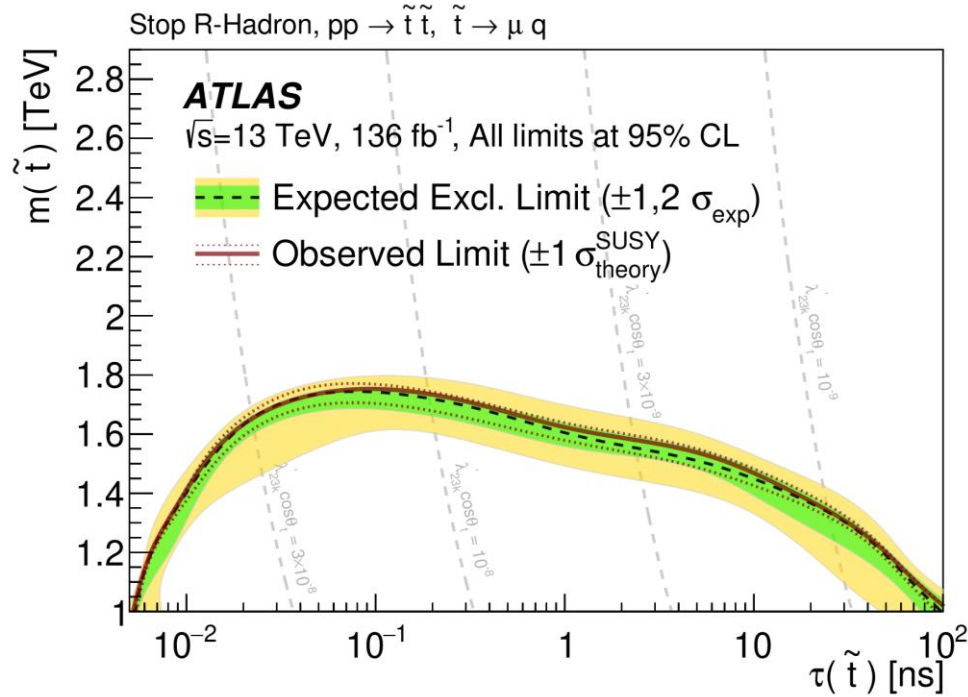
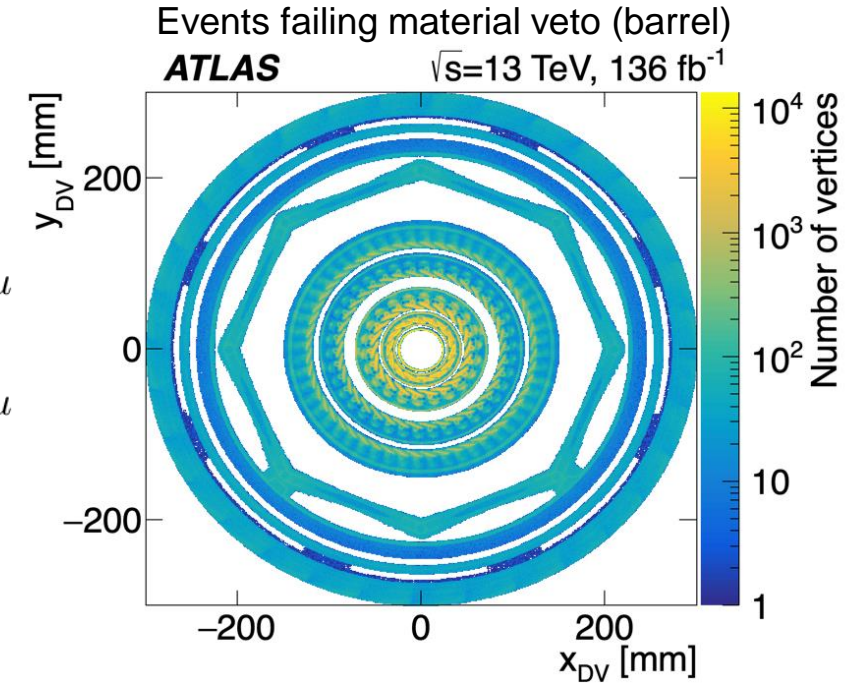
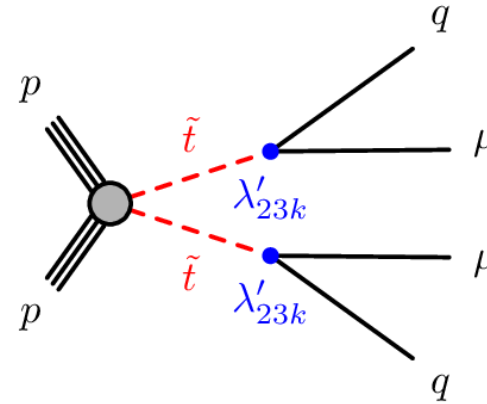


Model:

- Stop LSP decays via LQD term (λ') to muon and d/s quark.
- Small λ' \rightarrow stop hadronizes, has displaced decay.

Signature:

- Muons with large impact parameters.
- Displaced vertices with $4 \text{ mm} < r_{DV} < 300 \text{ mm}$ (before the SCT).



Managing SM background:

- Veto DVs with positions consistent with the detector (active + support/services).

Results:

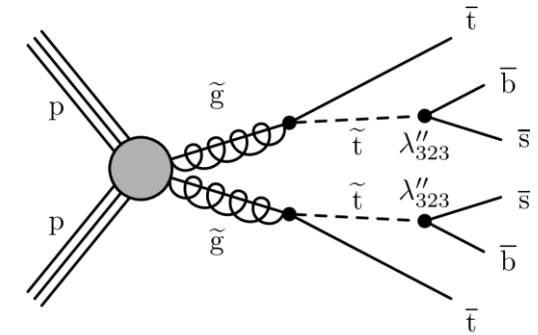
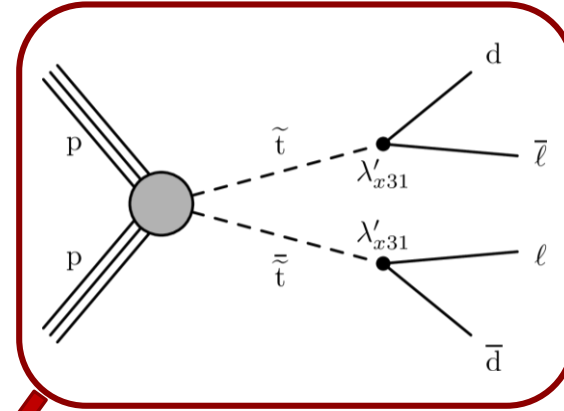
- No events above expected background.
- Set limits in the $m_{\tilde{t}}$ vs $\tau(\tilde{t})$ plane.

Searches for long-lived particles decaying into displaced jets

CMS-PAS-EXO-19-021

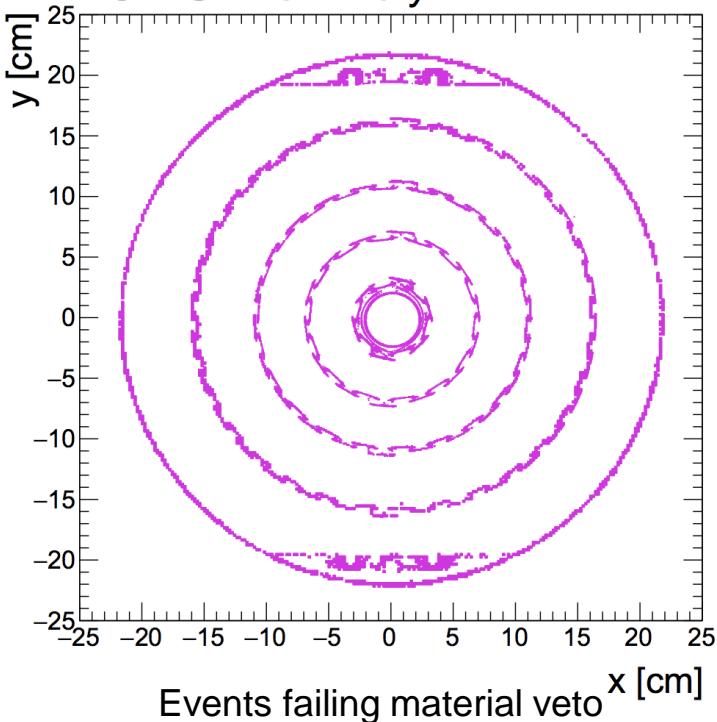
Target Models:

- Many BSM models with LLPs decaying to jets.
- RPV models:
 - $\tilde{t} \rightarrow ld_k$ via LQD (λ') and $\tilde{g} \rightarrow tbs$ via UDD (λ'').
 - $\tilde{t} \rightarrow dd$ via dynamical RPV coupling (η/M).

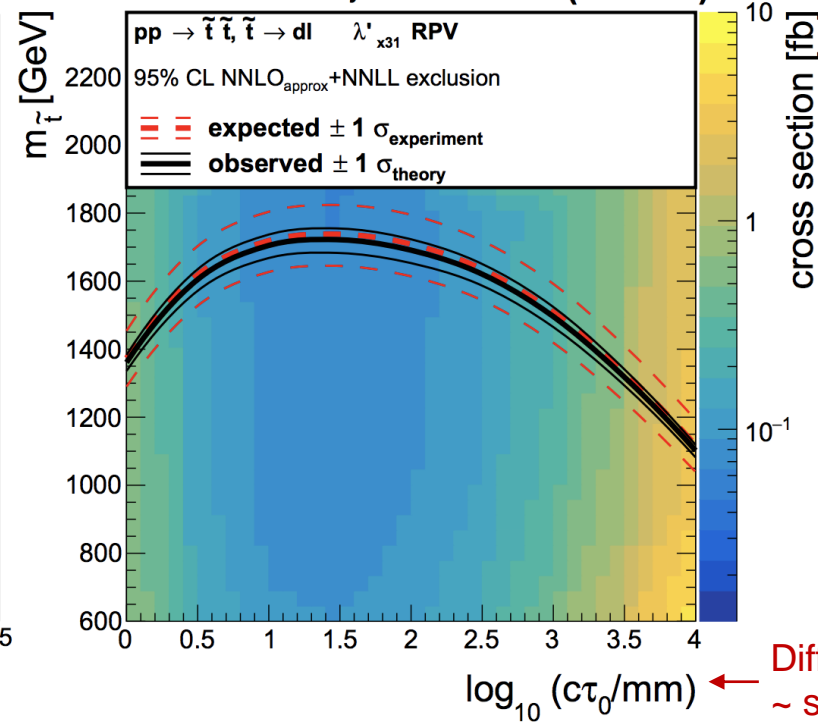


Long-lived \tilde{g} , off-shell \tilde{t} .

CMS Preliminary



CMS Preliminary 132 fb⁻¹ (13 TeV)



Different units
~ same range

Signature:

- Dijet systems matched to a displaced vertex.
 - Transverse displacements $r_{DV} \lesssim 55$ cm.
 - Before outer barrel of the silicon strip tracker.

Results:

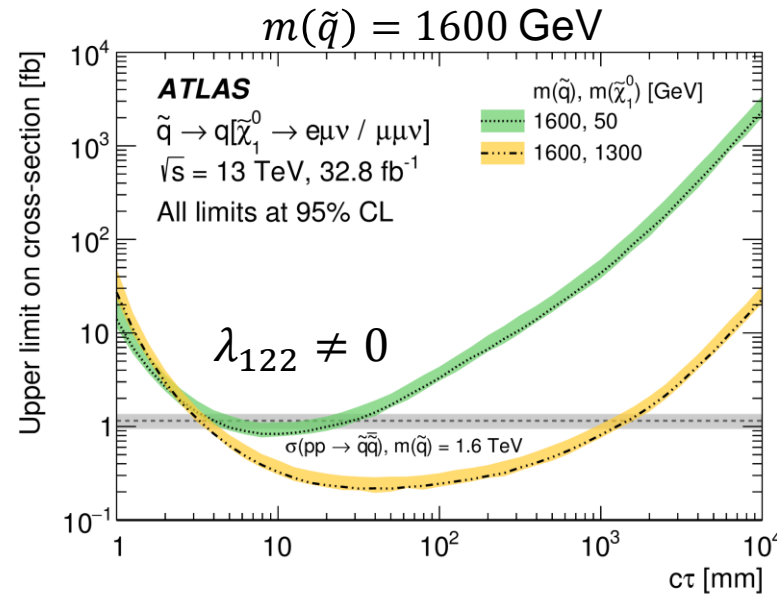
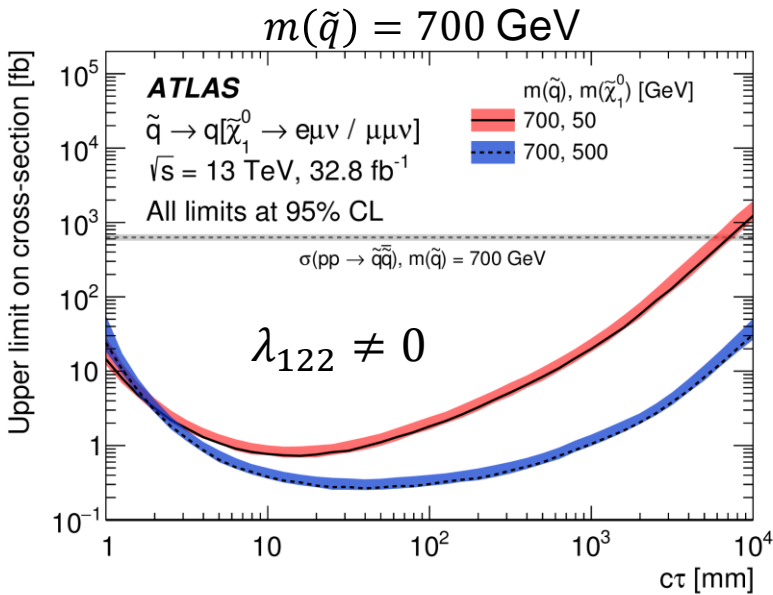
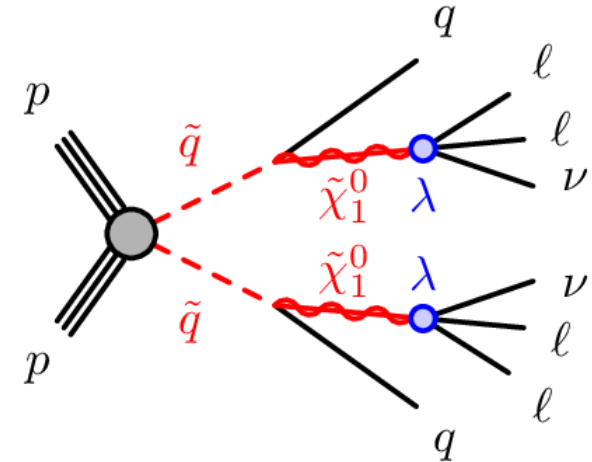
- Expected 0.75 ± 0.44 (stat) ± 0.39 (syst).
- Observed 1 event with a DV with $r_{DV} = 26$ cm.
 - Close to a silicon strip layer (within ~ 1 cm).

Model:

- Neutralino LSP decays via LLE term (λ) to 2 OS leptons + neutrino.
 - Small $\lambda \rightarrow \tilde{\chi}_1^0$ decay is displaced.

Strategy:

- Search for 2 OS leptons forming a displaced vertex.
 - $2 \text{ mm} < r_{DV} < 300 \text{ mm}$.



Results:

- No events above expected background.
- Set upper limits on cross section as function of $\tilde{\chi}_1^0$ lifetime.
- Separate interpretations for:
 - Non-zero $\lambda_{121} \rightarrow ee + e\mu$ final states.
 - Non-zero $\lambda_{122} \rightarrow e\mu + \mu\mu$ final states (shown).

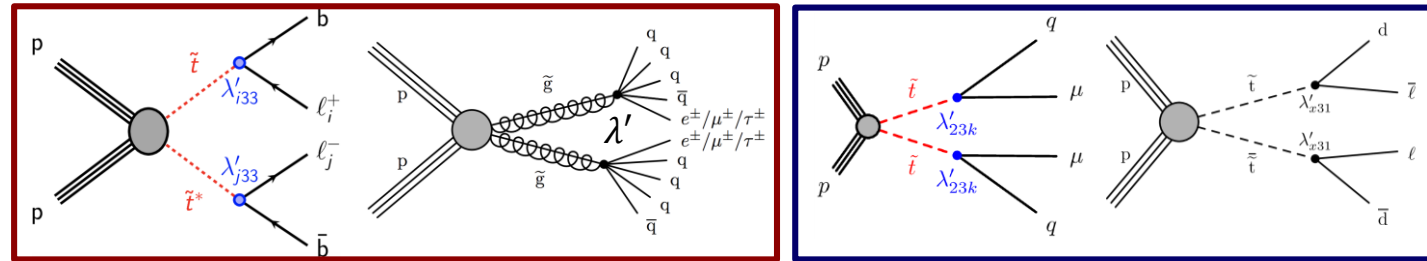
Summary of Targeted Simplified Models

Prompt
Long-lived

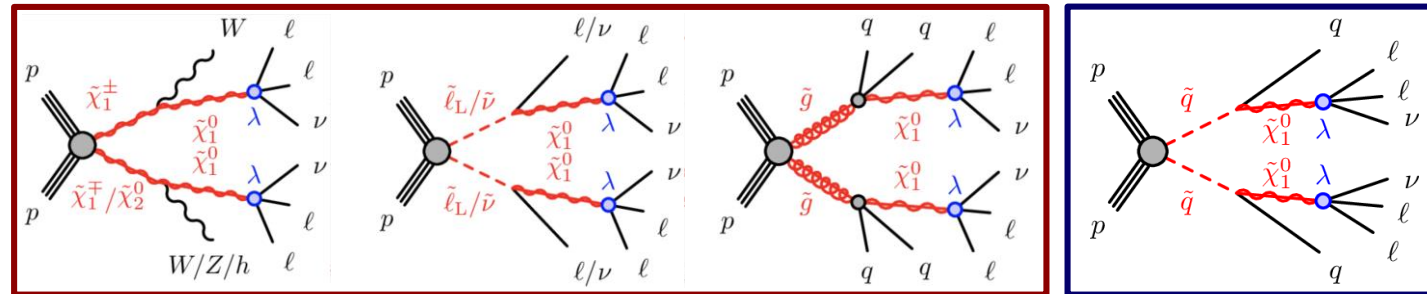
Simplified models:

- Shown many exclusion contours for simplified models.
 - Assume some (N)LSP & production mode.
 - Turn on a single RPV coupling.
- Prompt searches assume coupling is large enough for prompt decays.
 - Set limits on production xsec vs LSP mass.
 - Or perform a 2D mass scan (LSP vs NLSP).
- Long-lived searches assume coupling is small enough for a displaced decay.
 - Set limits on LSP mass vs lifetime.
- How do these exclusions translate to limits on the coupling strength?

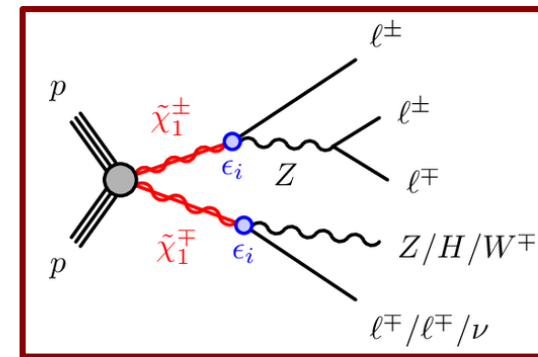
LQD (λ')



LLE (λ)



B - L Bilinear



Filling in the Gaps

ATLAS-CONF-2018-003 (36 fb⁻¹)

Setting limits on coupling strength:

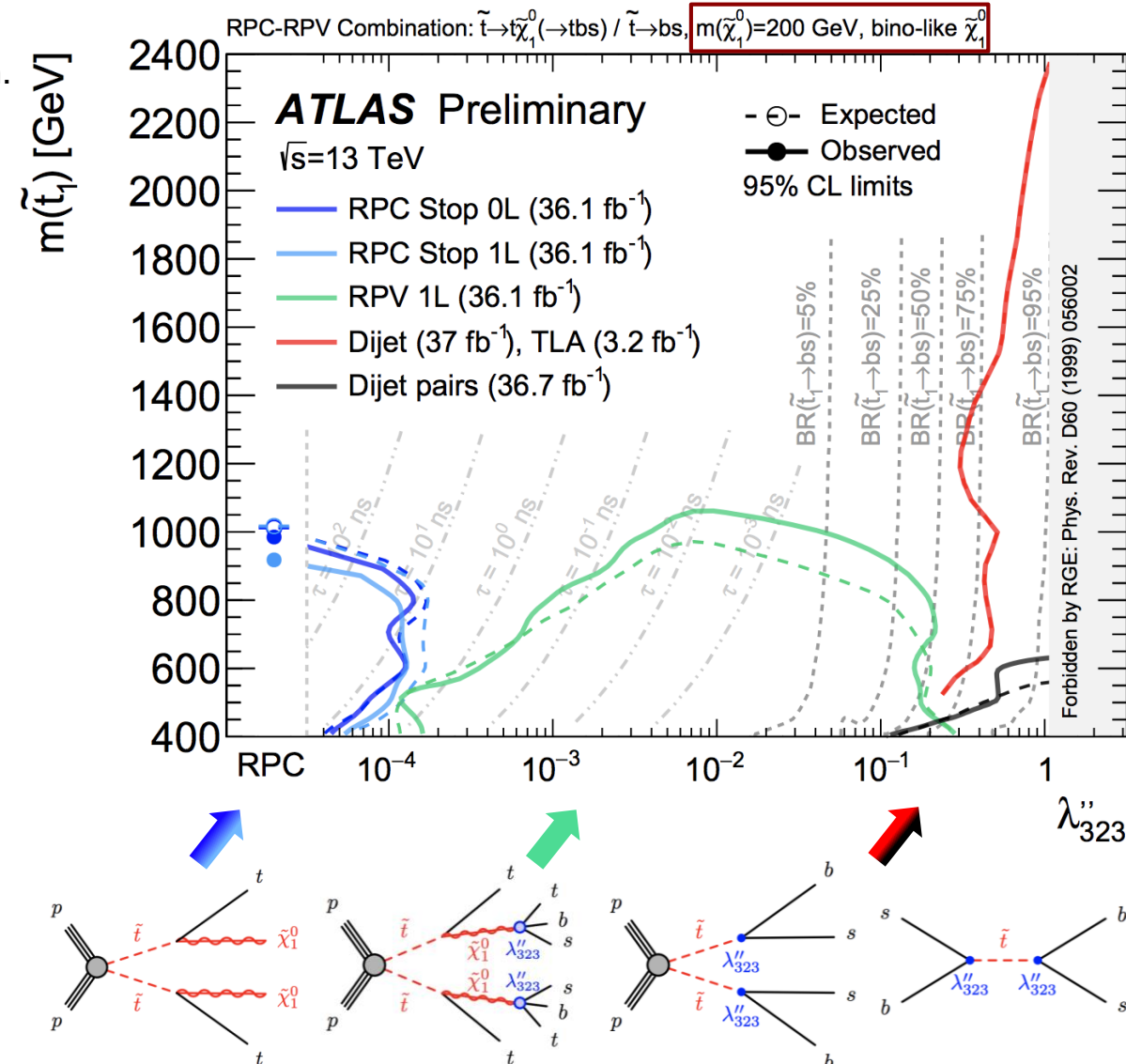
- For LL searches, can convert lifetime limits → coupling limits via an equation.
 - May depend on other parameters (virtual sparticle masses, mixings).
- For prompt searches, need reinterpretations.
 - Use RPV signals with variable coupling strengths.
 - Additional systematics for displaced signals.
- Analyses targeting RPC SUSY or other BSM may be sensitive to RPV.
 - Should reinterpret these as well!

RPC meets RPV:

- ATLAS reinterpreted prompt SUSY (RPC+RPV) and exotics searches.
 - Set limits on RPV coupling strengths in multiple **BNV** (UDD) models.
- ATLAS Run 1 summary of RPV with **LNV** (LLE, LQD, bRPV) [1].

Facilitating reinterpretations:

- CMS has published simplified likelihoods for their multi-bin analyses [2].
- ATLAS has started publishing full likelihoods using pyhf [3].
- Using CheckMATE to set limits on RPV CMSSM (LNV & BNV) [4].



Projections to Future Colliders

European Strategy Yellow Report [1] :

- LHCb had only explicit RPV projection (pg 698, more info [2]).
- Search for long-lived neutralinos.
 - $h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow \mu q q$ via LQD.
- Projected exclusion made in $\tilde{\chi}_1^0$ mass-lifetime plane for Runs 3, 4, 5.
 - For various $B(h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$.

Can other BSM projections be easily translated to RPV SUSY?

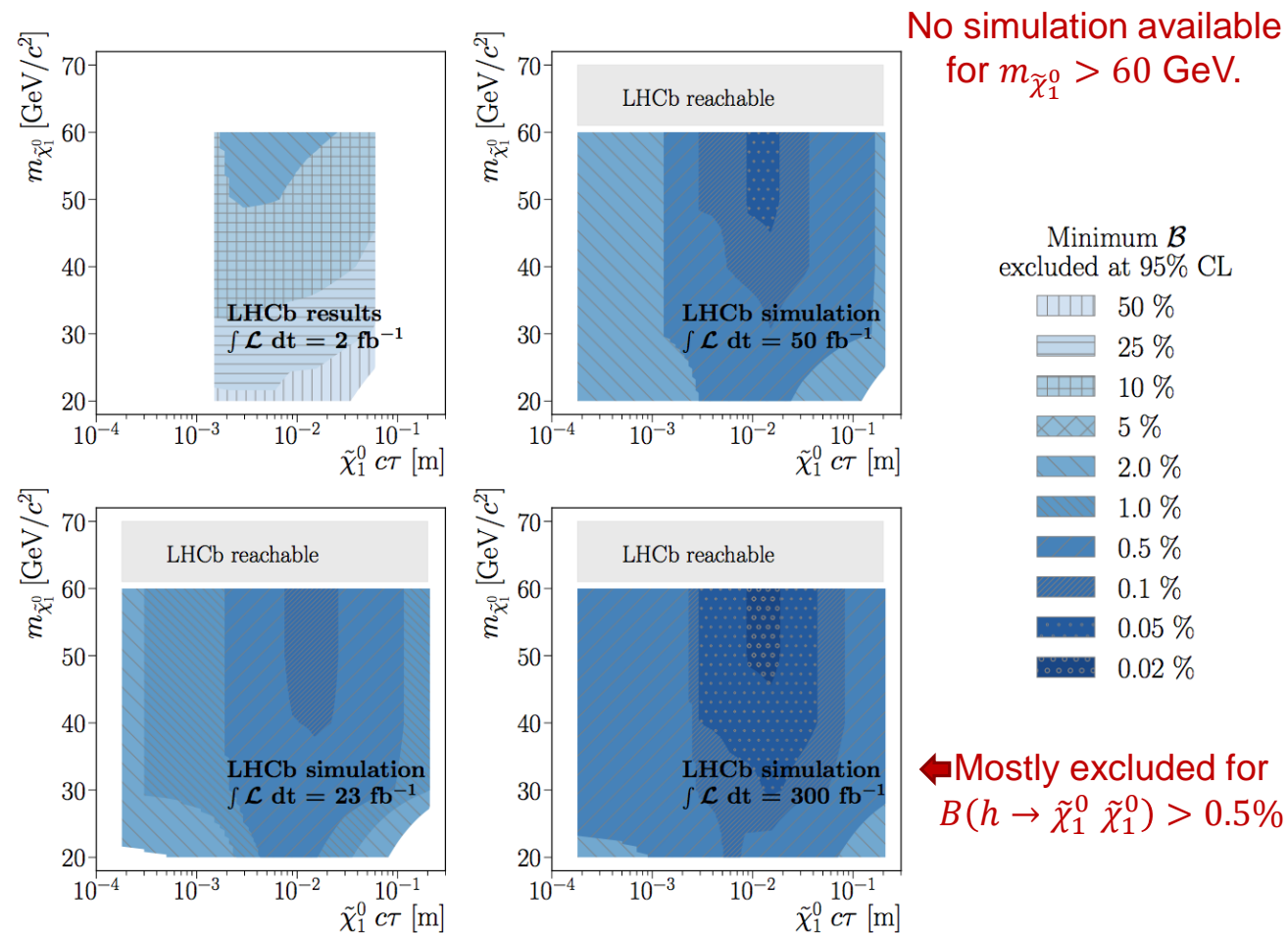
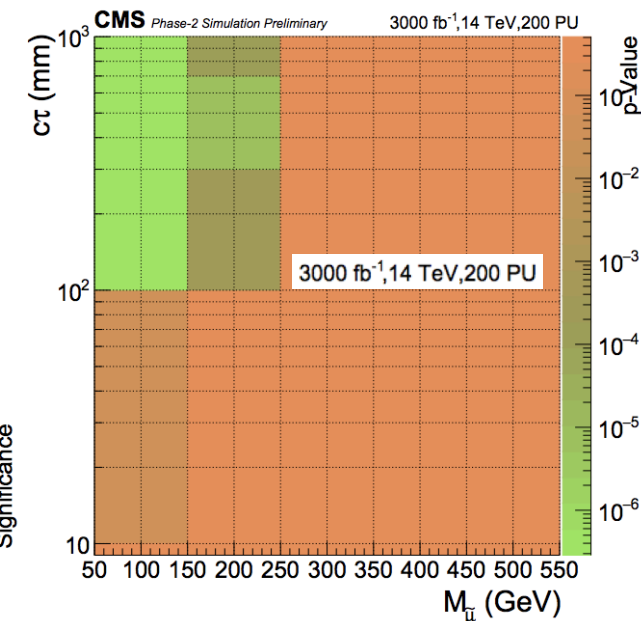
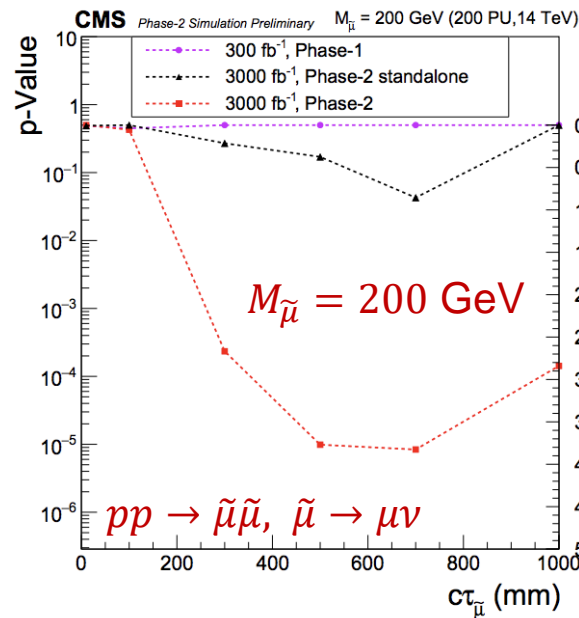
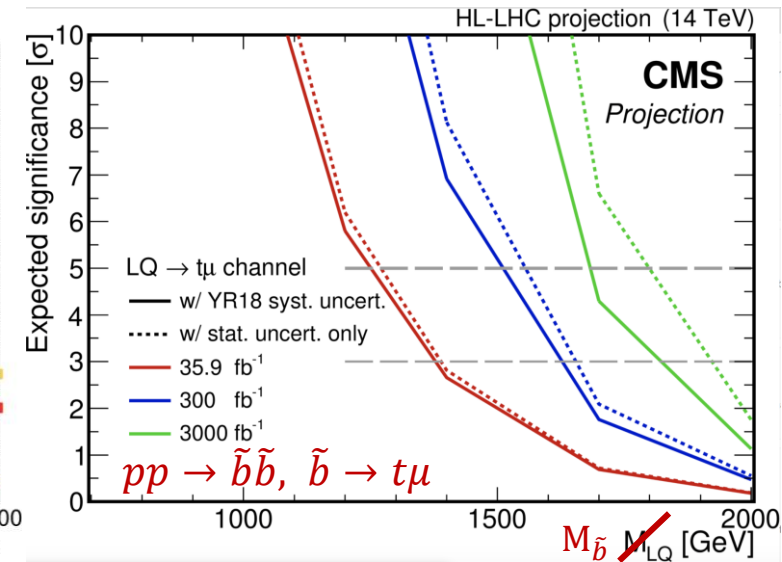
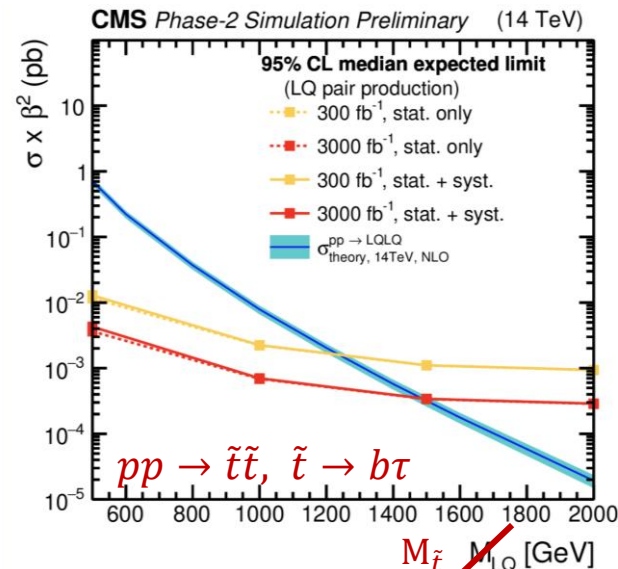


Fig. 4.2.5: Projected sensitivities of the search for RPV supersymmetric neutralinos decaying semileptonically and produced through a Higgs boson exotic decay. The results are extrapolated from Run-1 results (top left), for luminosities of 23 fb^{-1} (top right), 50 fb^{-1} (bottom left) and 300 fb^{-1} (bottom right). The results are presented in terms of the excluded parameter space of the neutralinos for different upper limits at 95% C.L. on the branching fractions of the Higgs boson decay.

Projections to Future Colliders

Can other BSM projections be easily translated to RPV SUSY?

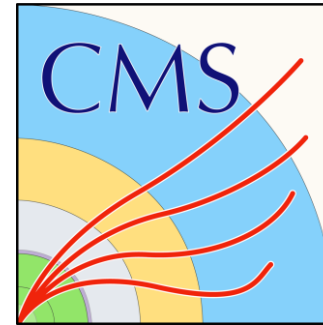
- Scalar leptoquarks \rightarrow squarks with LQD decays:
 - CMS projections to HL-LHC:
 - Pair production of LQs, decay to $t\tau/t\mu$ [1].
 - Single & pair production of LQs, decay to $b\tau$ [2].
 - Yellow report projection to HE-LHC:
 - Pair production of LQs, decay to $b\tau$ (pg 726).
- Long-lived smuons search:
 - Displaced muons with CMS at HL-LHC (pg 697, more info [3]).
 - Translate $\tilde{\mu} \rightarrow \mu + \tilde{G}$ (GMSB) to $\tilde{\mu} \rightarrow \mu + \nu$ (LLE RPV).
- Type-III seesaw heavy leptons $\rightarrow \tilde{\chi}_1^0 / \tilde{\chi}_1^\pm$ in bRPV models?



Summary

- Presented ATLAS and CMS searches for RPV SUSY with LNV.
 - Targeting both short- and long-lived LSPs.
- Variety of production modes, mass spectra, allowed couplings.
 - ➔ Diverse set of final states.
- Explicit interpretations for simplified models.
 - MSSM with trilinear RPV ($\lambda, \lambda', \lambda''$).
 - More extended frameworks ($B - L$, Dynamical RPV).
- Sensitivity of these searches to new physics extends beyond the simplified models, and even SUSY.
 - Existing analyses, targeting SUSY or otherwise, are sensitive to RPV SUSY → Need RPV (re)interpretations.
- Projections for RPV SUSY to the HL-LHC and beyond are a bit lacking.
 - It's a great time to get involved!
 - Ideas?

SnowMass2021

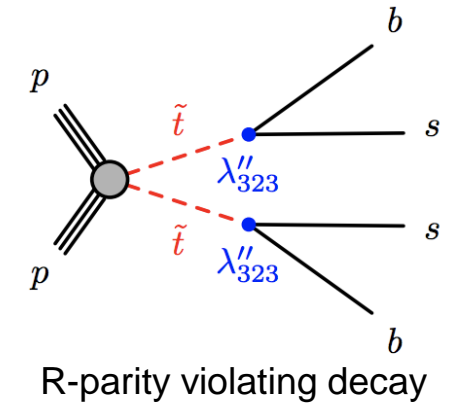
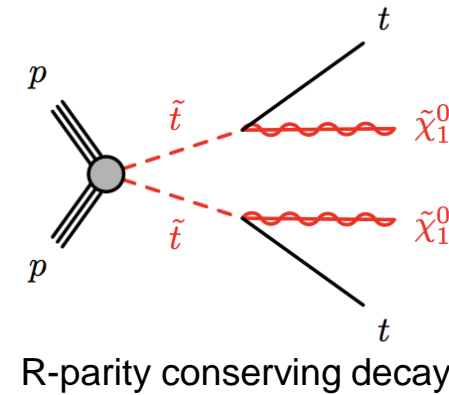


Backup

R-Parity In the MSSM

What is R-Parity?

- Multiplicative quantum number defined as $R = (-1)^{3(B-L)+2s}$.
 - $R = +1$ for SM particles.
 - $R = -1$ for supersymmetric partners.



Minimal Supersymmetric Standard Model with RPV:

- R-parity is not a symmetry of the most general MSSM Lagrangian.

$$W_{R_p} = \underbrace{\left[\mu_i H_u L_i + \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c \right]}_{\text{Lepton number violating}} + \underbrace{\left[\frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c \right]}_{\text{Baryon number violating}}$$

- Often impose R-parity conservation to prevent these terms.
 - Baryon and lepton number are conserved \rightarrow proton is stable.
 - Bonus: "SUSY-ness" is conserved \rightarrow the lightest supersymmetric particle (LSP) is neutral and stable \rightarrow dark matter candidate.

Projections to Future Colliders

European Strategy Yellow Report [1] :

- LHCb had only explicit RPV projection (pg 698, more details [2]).
 - $h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow \mu qq$ via via LQD term.
 - $\tilde{\chi}_1^0$ is long-lived.

Can other BSM search projections be easily translated for RPV?

- Scalar leptoquarks \rightarrow LQD decays of squarks.
 - CMS projections to HL-LHC:
 - Pair production, decay to $t + \tau$ or $t + \mu$ [link].
 - Single & pair production, decay to $b + \tau$ [link].
 - Yellow report projection to HE-LHC:
 - Pair production, decay to $b + \tau$ (pg 734).
- LLP searches:
 - Displaced muons with CMS at HL-LHC (pg 697, more info [link]).
 - Translate GMSB RPC $\tilde{\mu} \rightarrow \mu + \tilde{G}$ to LLE RPV $\tilde{\mu} \rightarrow \mu + \nu$?

Need more projections, especially beyond the HL-LHC!

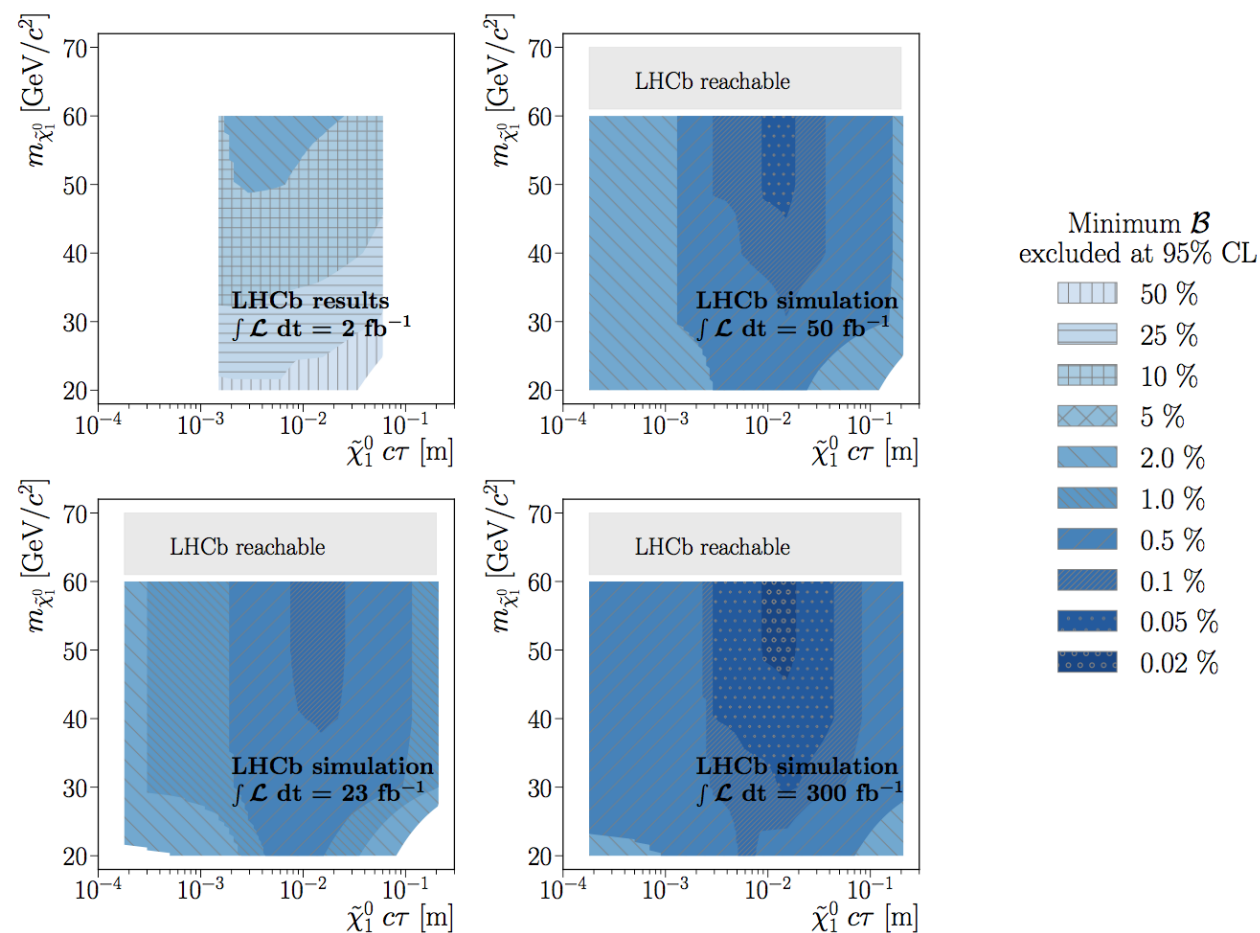


Fig. 4.2.5: Projected sensitivities of the search for RPV supersymmetric neutralinos decaying semileptonically and produced through a Higgs boson exotic decay. The results are extrapolated from Run-1 results (top left), for luminosities of 23 fb^{-1} (top right), 50 fb^{-1} (bottom left) and 300 fb^{-1} (bottom right). The results are presented in terms of the excluded parameter space of the neutralinos for different upper limits at 95% C.L. on the branching fractions of the Higgs boson decay.

RPV searches with BNV

Analysis Overview:

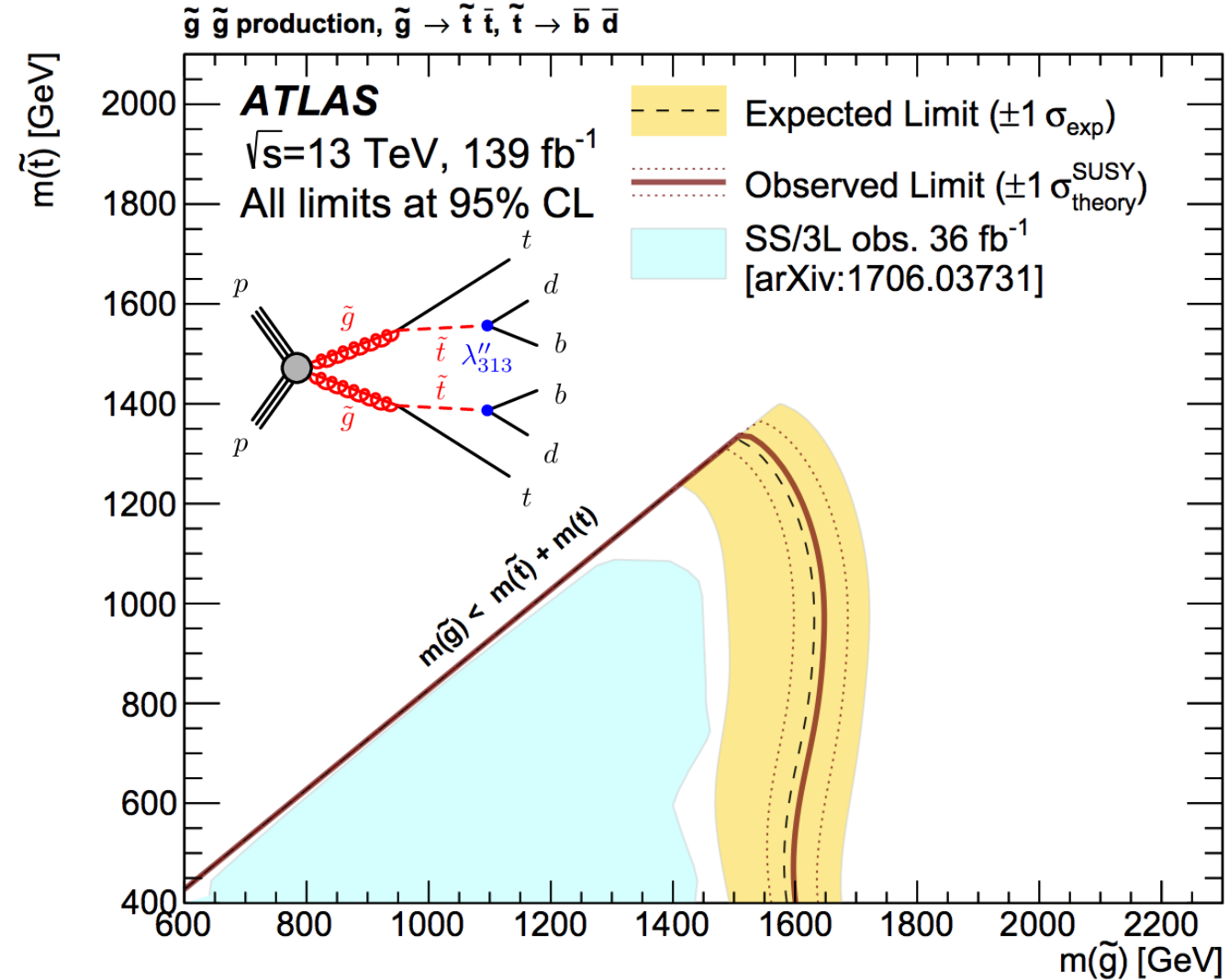
- Require 2/3 SS leptons + jets.
- Define 5 overlapping SRs, fit independently.

Dedicated RPV SR:

- Require 2 SS leptons, $N_{\text{jets}} \geq 6$, and $m_{\text{eff}} > 2.6$ TeV.
 - m_{eff} = scalar p_T sum of all leptons, jets, and the E_T^{miss} .
- Defined inclusively → sensitive to many RPV scenarios.

Results:

- No significant excess above SM background.
- Also set exclusions for $\tilde{g} \rightarrow tbs/tbd$.
 - But assume intermediate stop is on-shell → 2D mass scan.
 - Exclude gluino masses up to 1.6 TeV.



Target models:

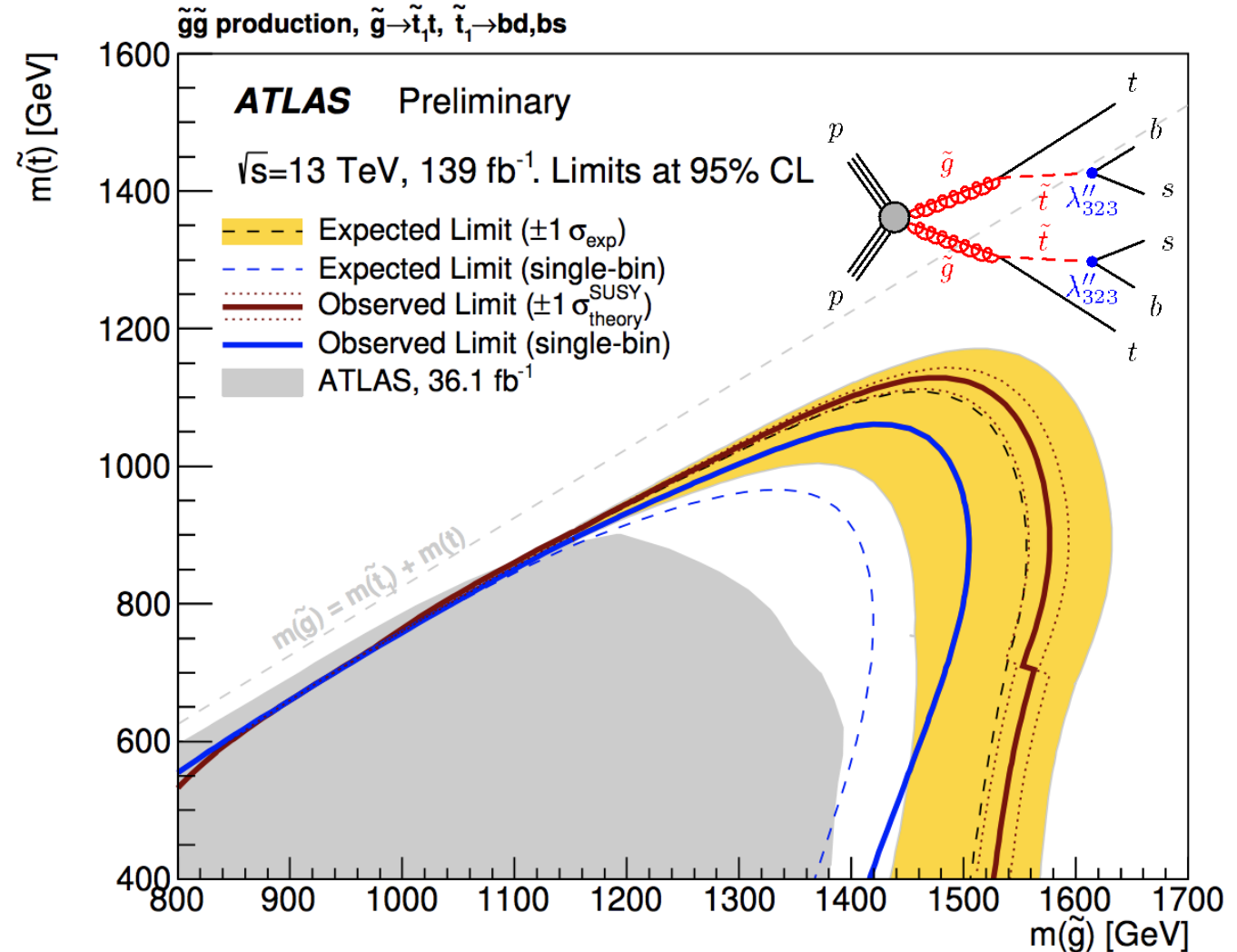
- Gluino pair production in a variety of RPC and RPV models.
 - All with large jet multiplicities and real E_T^{miss} .
- Same RPV model as ATLAS SS/3L search.
 - Real E_T^{miss} from $t \rightarrow \tau_{\text{had}} \nu + b$.

SR strategy:

- Perform 3 separate multi-bin fits, requiring $N_{\text{jets}} \geq 8, 9, 10$.
 - Further binning in $N_{b\text{-jets}}$ and $M_J^\Sigma = \sum_j m_j^{R=1.0}$.

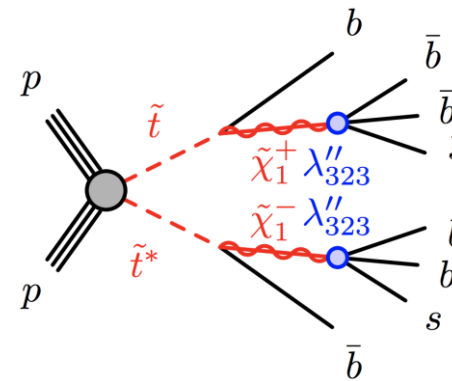
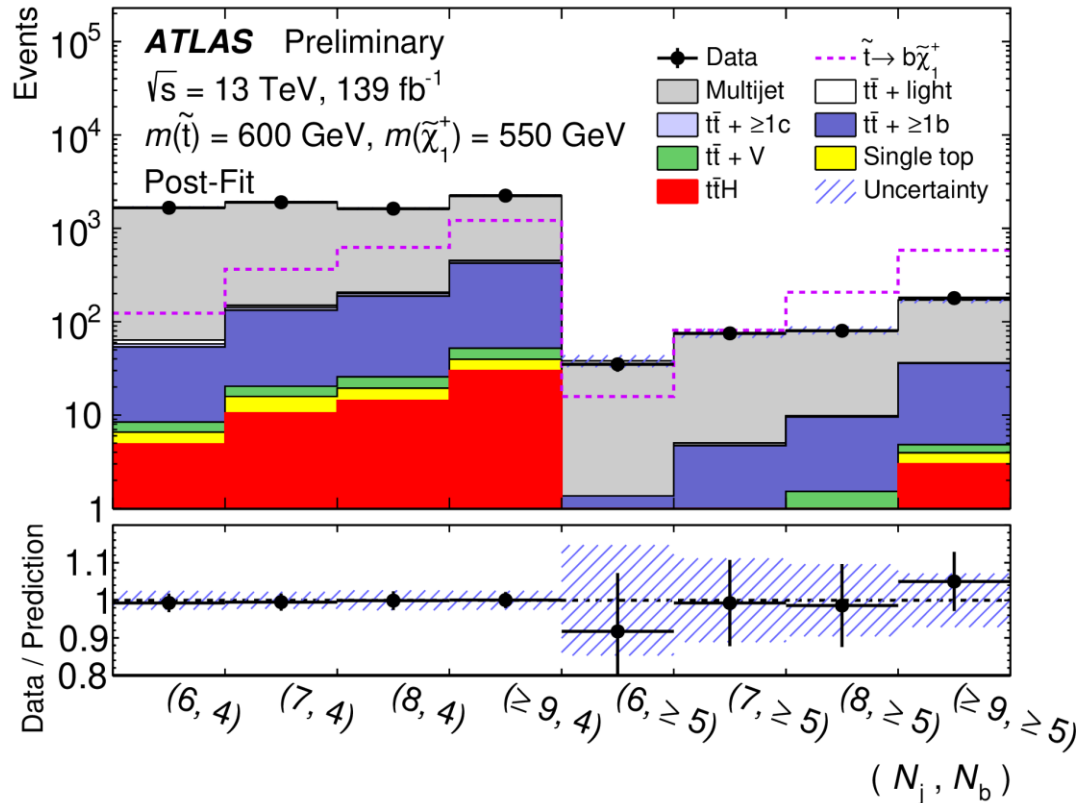
Results:

- No significant excess over SM background.
- For RPV scenario, exclude gluino masses up to 1.5 TeV.
 - Can compare with ATLAS SS/3L exclusion contours.



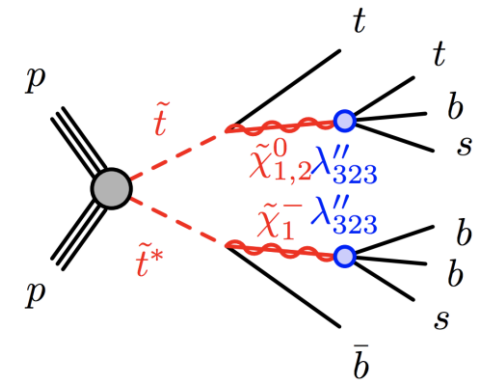
Final State:

- Large b-jet multiplicity, no leptons, and low E_T^{miss} .
- First LHC search in this final state.



$$\text{BR}(\tilde{t} \rightarrow b \tilde{\chi}_1^{\pm}) = 100\%$$

Light stop & higgsino LSPs \rightarrow natural



$$\text{BR}(\tilde{t} \rightarrow b \tilde{\chi}_1^{\pm}) = 50\%$$

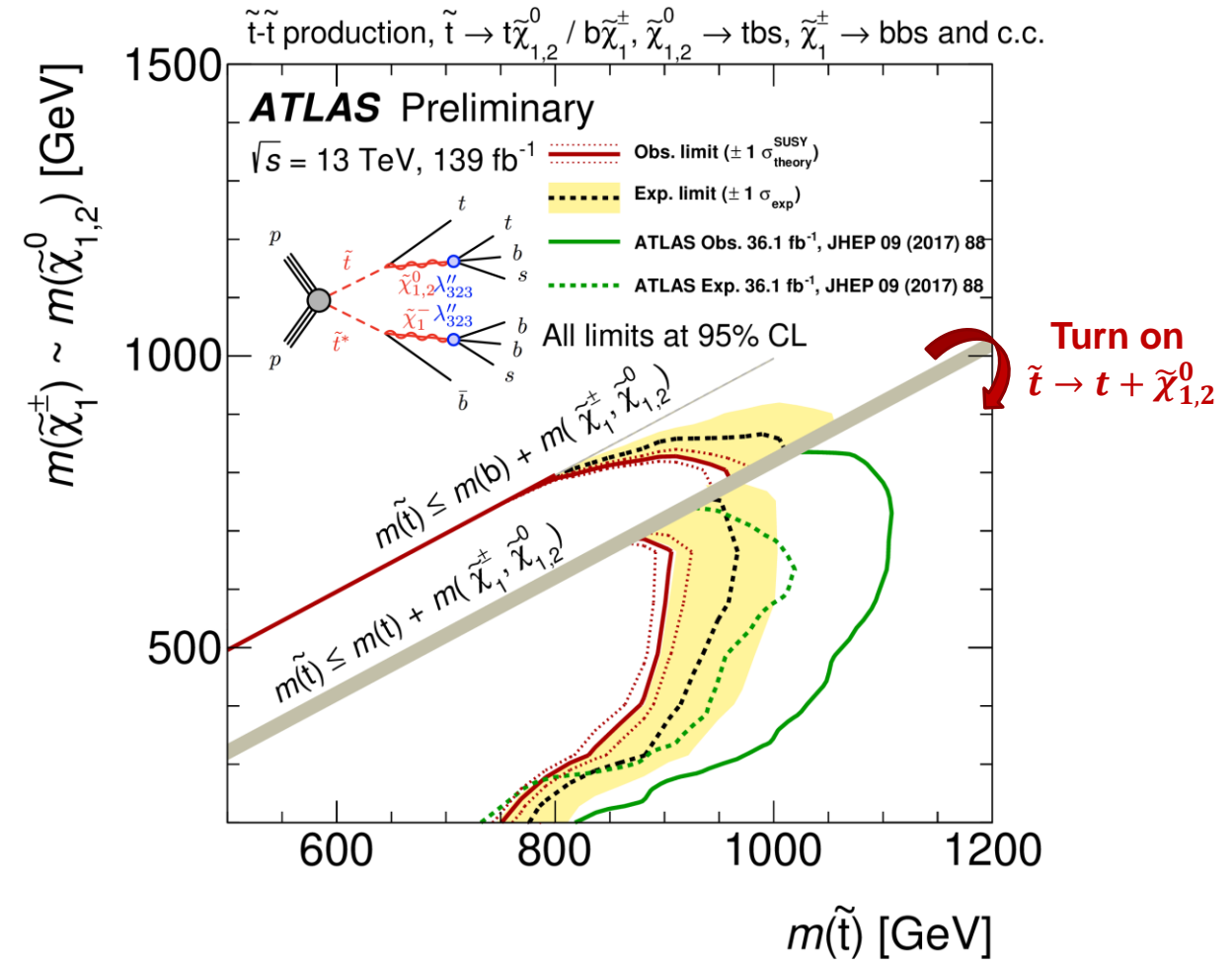
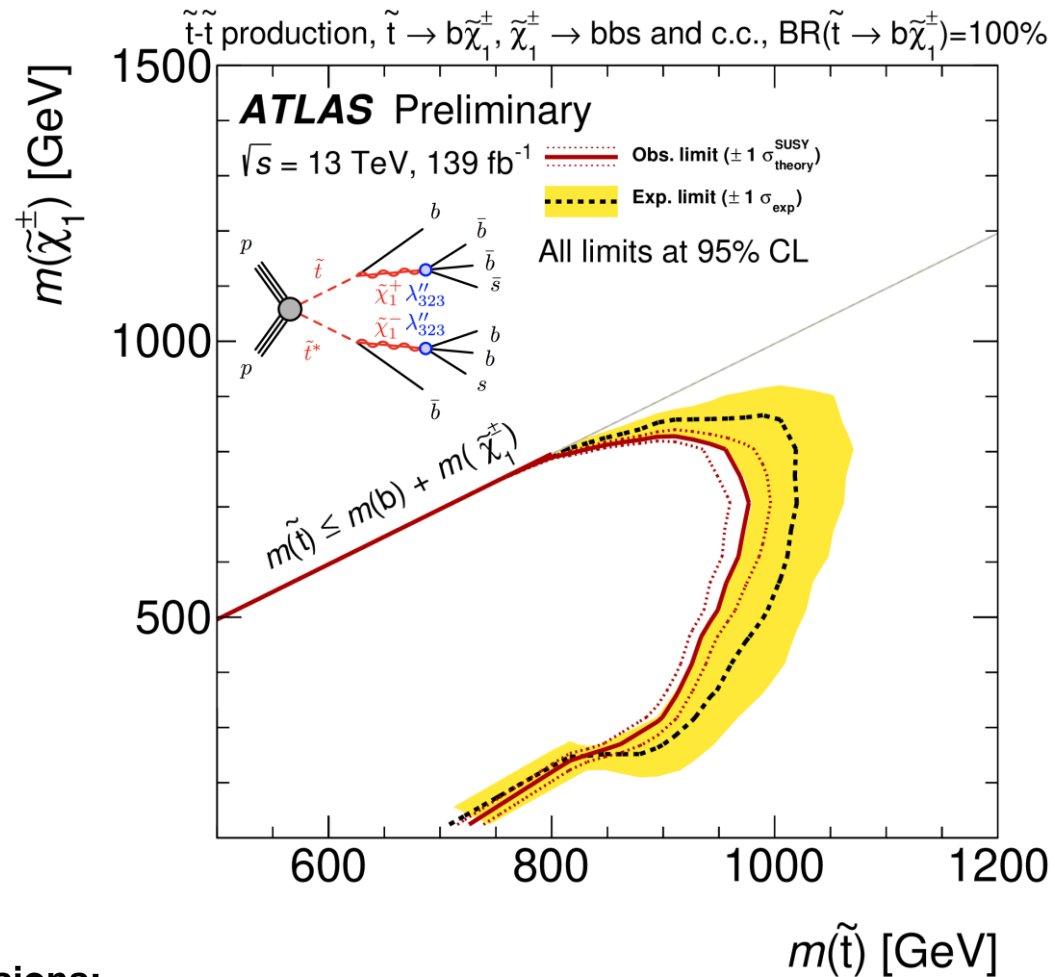
$$\text{BR}(\tilde{t} \rightarrow t \tilde{\chi}_{1,2}^0) = 50\%$$

Benchmark RPV models:

- Stop pair production with different available decay paths.
- Charginos and neutralinos decay via UDD RPV coupling (λ_{323}'').

SR Strategy:

- Simultaneously fit 8 orthogonal SRs, binned in N_j and N_b .



Exclusions:

- No observed excess over background prediction.
- Exclude stop masses up to 950 GeV in these models.

More info on CMS displaced jet tagger

Deep neural network to search for LLPs decaying to jets

[CMS-EXO-19-011](#)

Training:

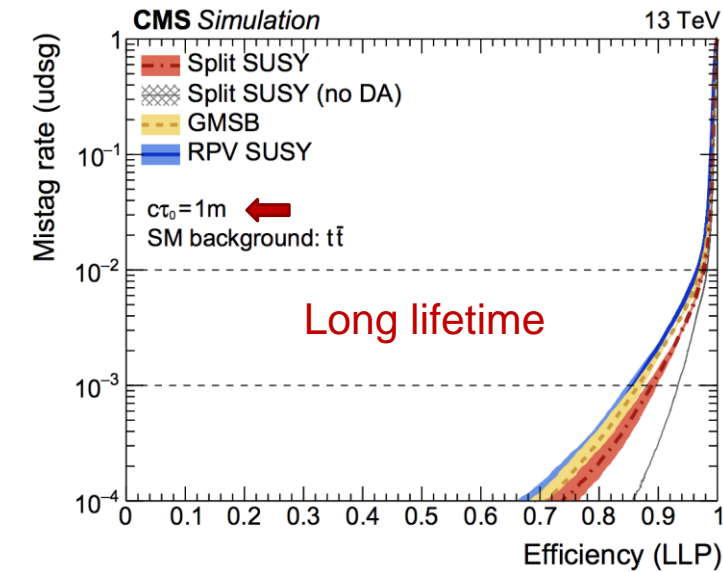
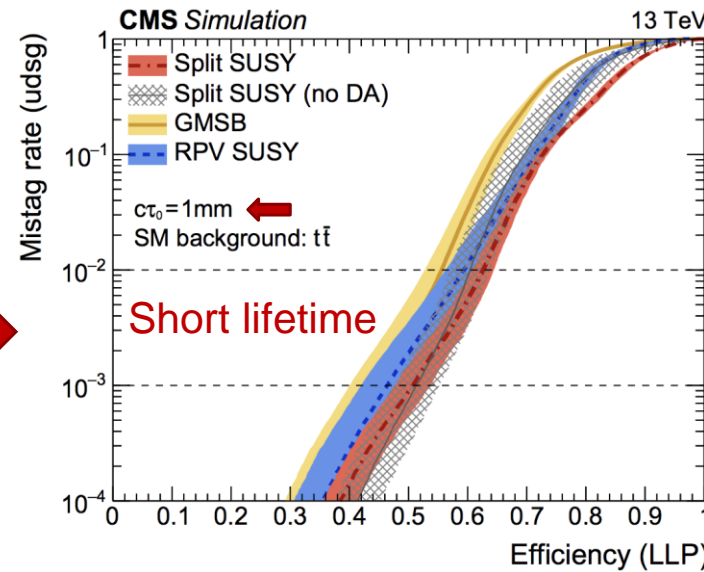
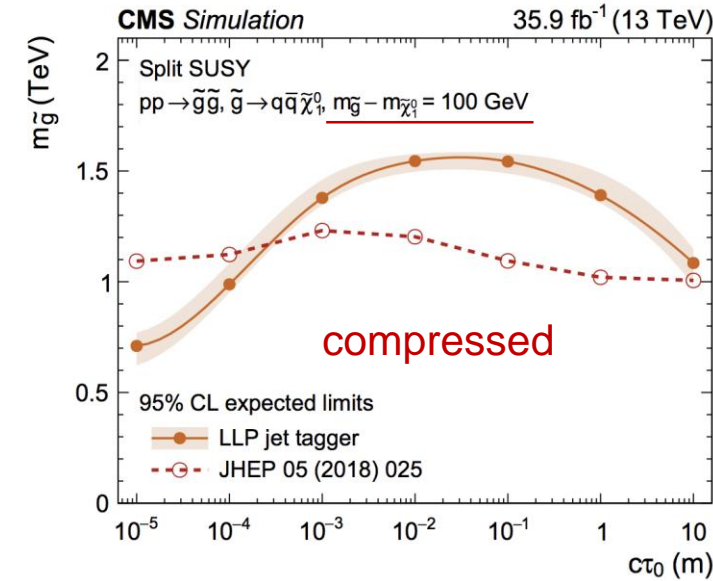
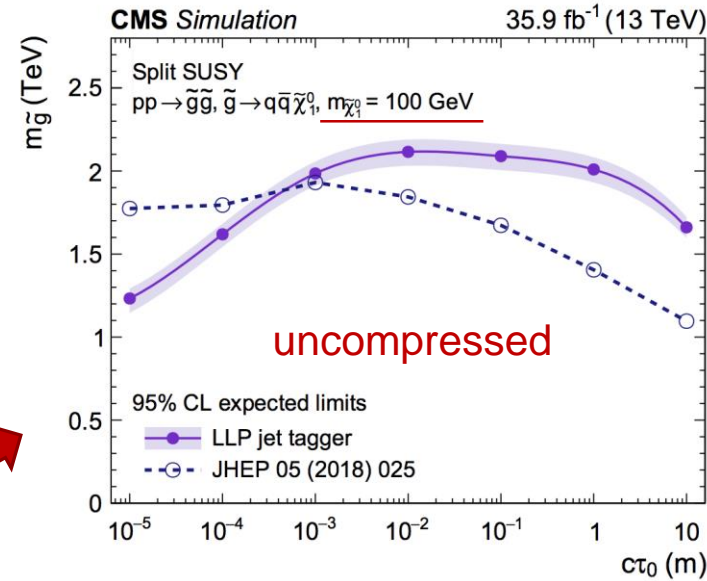
- Developed a DNN for tagging jets from LLP decays.
- Trained on split SUSY models with RPC.
 - Pair production of long-lived gluinos, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$

Evaluation:

- Calculate expected exclusions for the split SUSY model.
- Compare with a “conventional” analysis.
 - Inclusive search in final states with jets and p_T^{miss} .

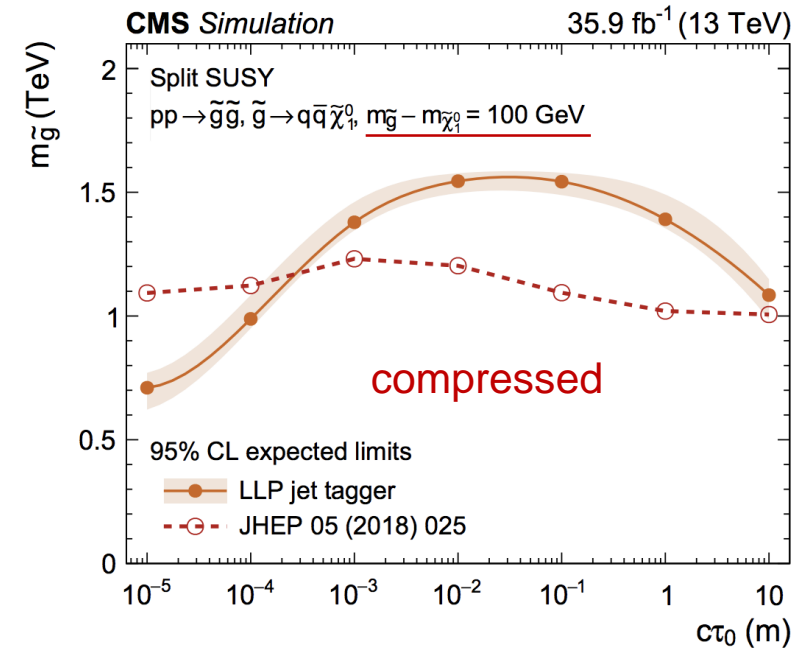
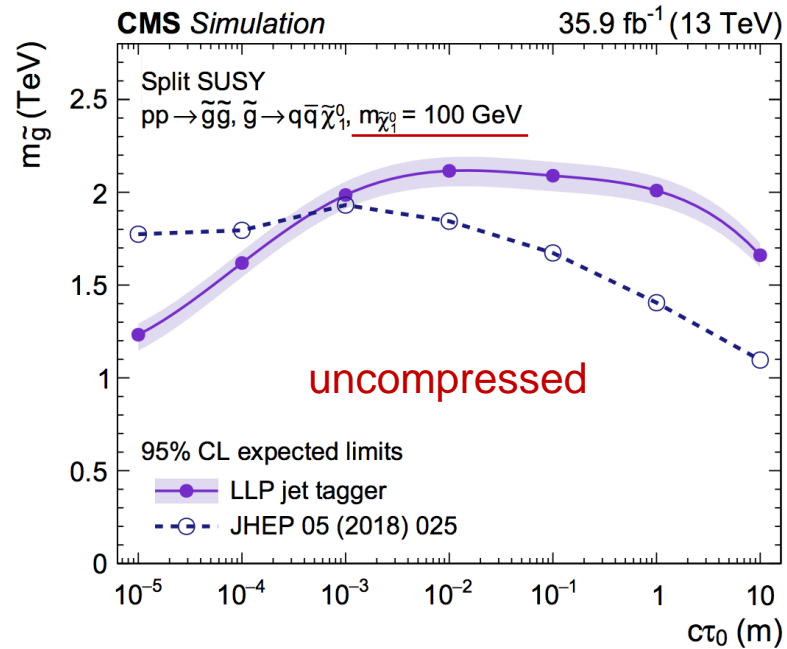
Generalizability:

- Evaluate performance on **GMSB** and **RPV** models.
 - $\tilde{t}\tilde{t}$ production, with $\tilde{t} \rightarrow bl$ via LQD term (λ').
 - $m(\tilde{t}) = 1200$ GeV.
- Similar performance across models.



Deep neural network to search for LLPs decaying to jets

CMS-EXO-19-011



Training:

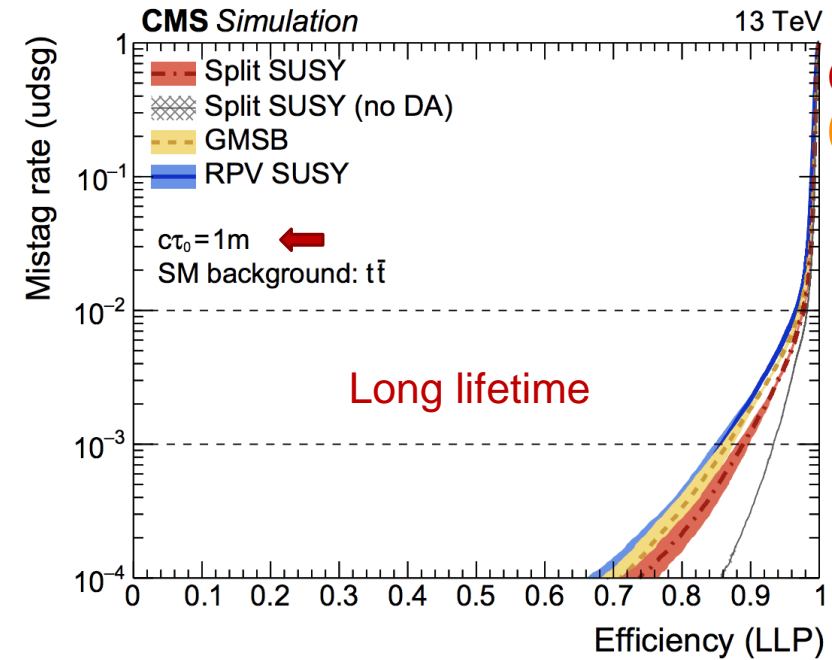
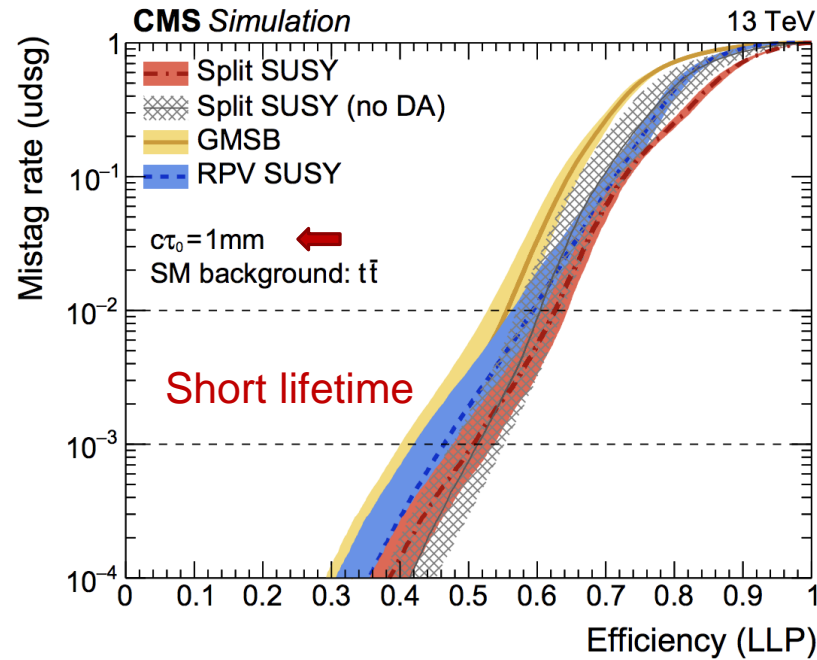
- Developed a DNN for tagging jets from LLP decays.
- Trained and evaluated on jets from split SUSY models with RPC.
 - Pair production of long-lived gluinos, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$.
 - Use variety of $m(\tilde{g})$ & $m(\tilde{\chi}_1^0) \rightarrow$ range of jet momenta.
- Detector signature strongly depends on $c\tau_0$.
 - Provide as an external parameter to DNN.
 - Perform hypo testing over wide $c\tau_0$ range with a single network.

Evaluation:

- Calculate expected CLs limits on split SUSY model.
 - Compare with inclusive SUSY search with jets and p_T^{miss} .
 - Test both large and small $\Delta M = m(\tilde{g}) - m(\tilde{\chi}_1^0)$.
- Stronger exclusions for $c\tau_0 \gtrsim 1 \text{ mm}$.
 - Lose sensitivity at low $c\tau_0$ due to proximity to primary pp interaction vertex.

Deep neural network to search for LLPs decaying to jets

CMS-EXO-19-011



$(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}) = (2000, 0)$ GeV
 $(m_{\tilde{g}}, m_{\tilde{g}}) = (2500, 0)$ GeV
 $m_{\tilde{t}} = 1600$ GeV

Generalizability:

- Evaluate performance on GMSB and RPV models.
- RPV model:
 - $\tilde{t}\tilde{t}$ production, with $\tilde{t} \rightarrow bl$ via LQD term (λ').
 - $m(\tilde{t}) = 1200$ GeV, $c\tau = 1$ mm or 1 m.
- Jet flavor composition varies significantly across models.
 - Split SUSY \rightarrow uds quarks from LL gluino decay.
 - GMSB \rightarrow gluons from LL gluino decay.
 - RPV \rightarrow b hadrons from LL stop decay.

\rightarrow Similar performance for each model.

Deep neural network to search for LLPs decaying to jets

[CMS-EXO-19-011](#)

Overview:

- Classifies jets as originating from b, c, uds, g, or LLP.
- Classification training done using jets from split SUSY (range of $m_{\tilde{g}}, m_{\tilde{\chi}}, \tau_{\tilde{g}}$), W+jets, and ttbar MC.
- Domain adaptation by backpropagation of errors \rightarrow Mitigate differences in classification performance between MC and data.

Input:

Charged PF candidates:

- Kinematic properties of associated track (absolute and relative to jet axis).
- Track quality.
- Transverse+3D impact params (and their significances).

Neutral PF candidates:

- Energy, fraction of energy deposited in ECAL and HCAL.
- Compatibility with photon, PU hypotheses.
- Collinearity with respect to jet axis and the nearest secondary vertex.

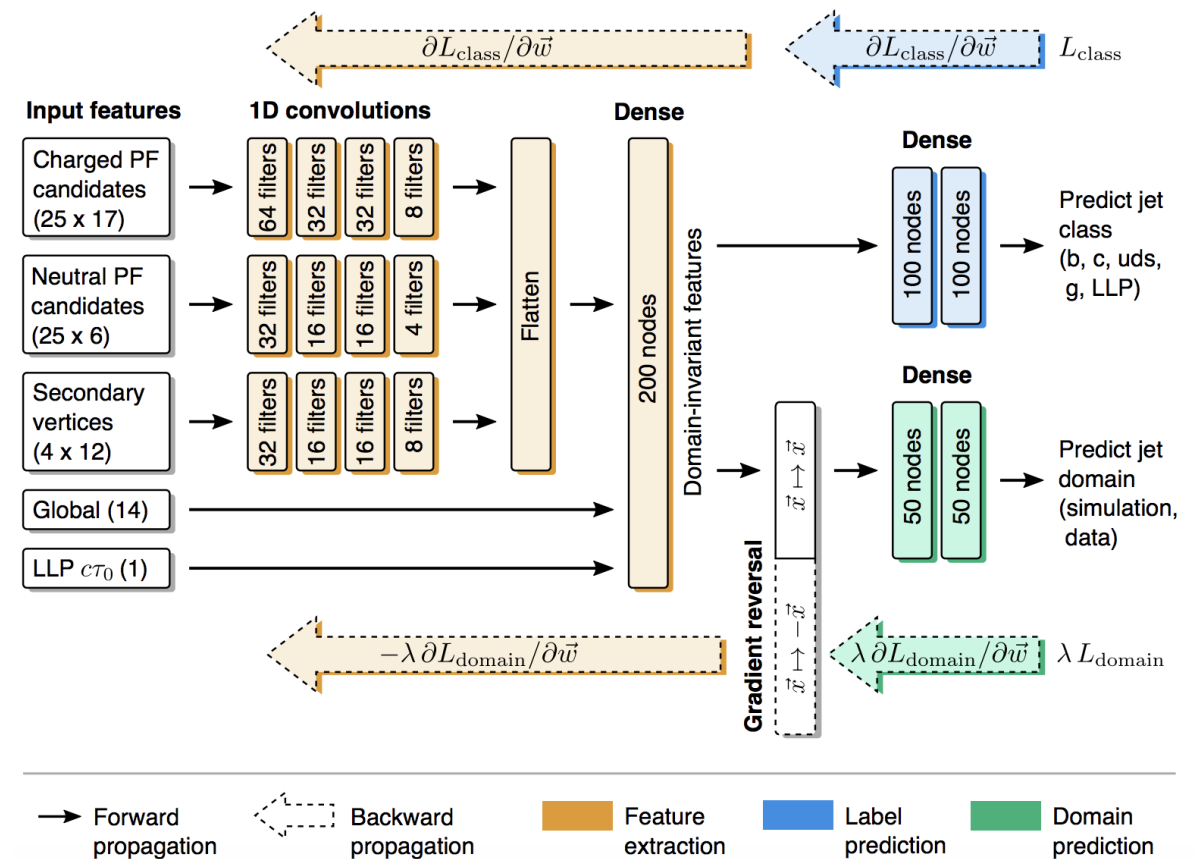
Secondary vertices:

- Kinematic properties.
- number of associated tracks.
- 3D displacement from the PV.

Global jet features:

- Jet momentum and eta
- Number of constituent PF candidates and recon. secondary vertices.
- CSV b-tagging algorithm variables.

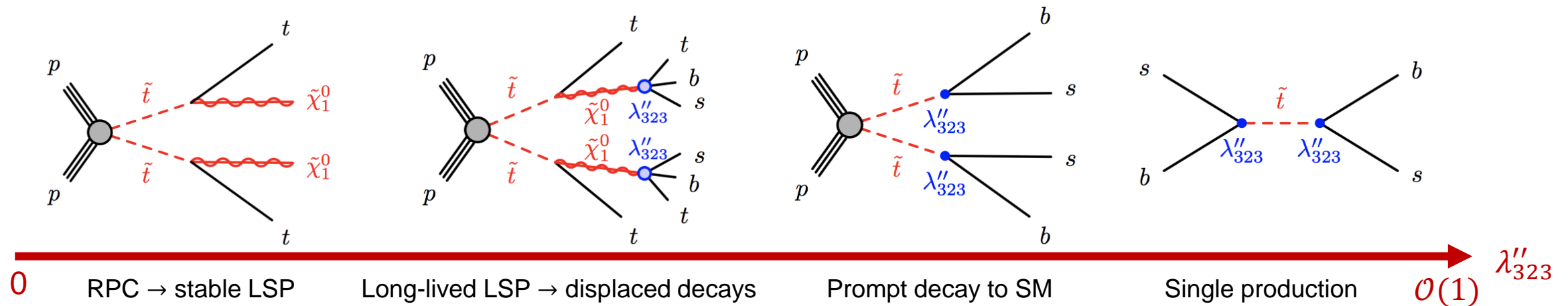
LLP lifetime hypothesis.



ATLAS RPV meets RPC

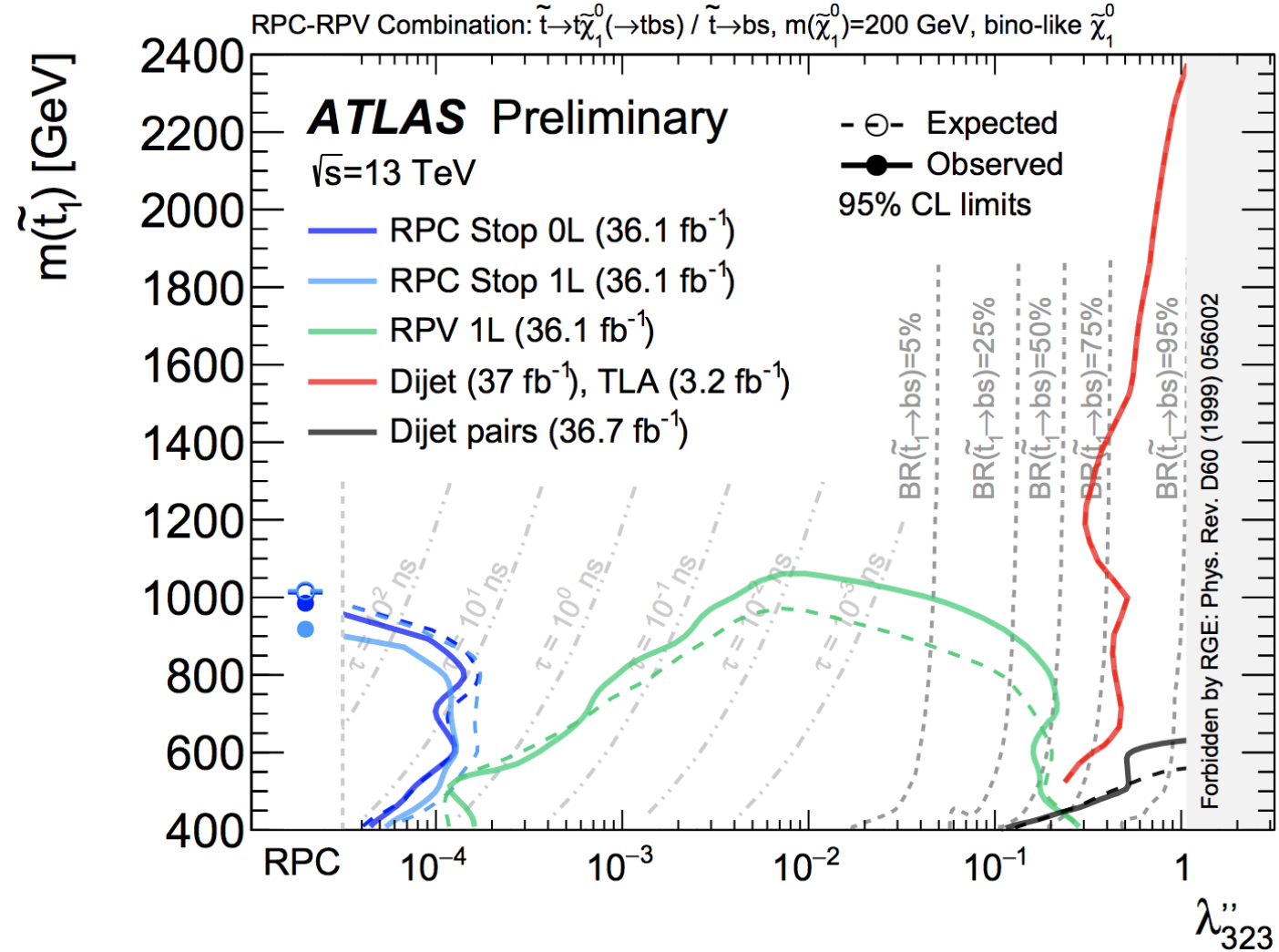
Filling in the gaps:

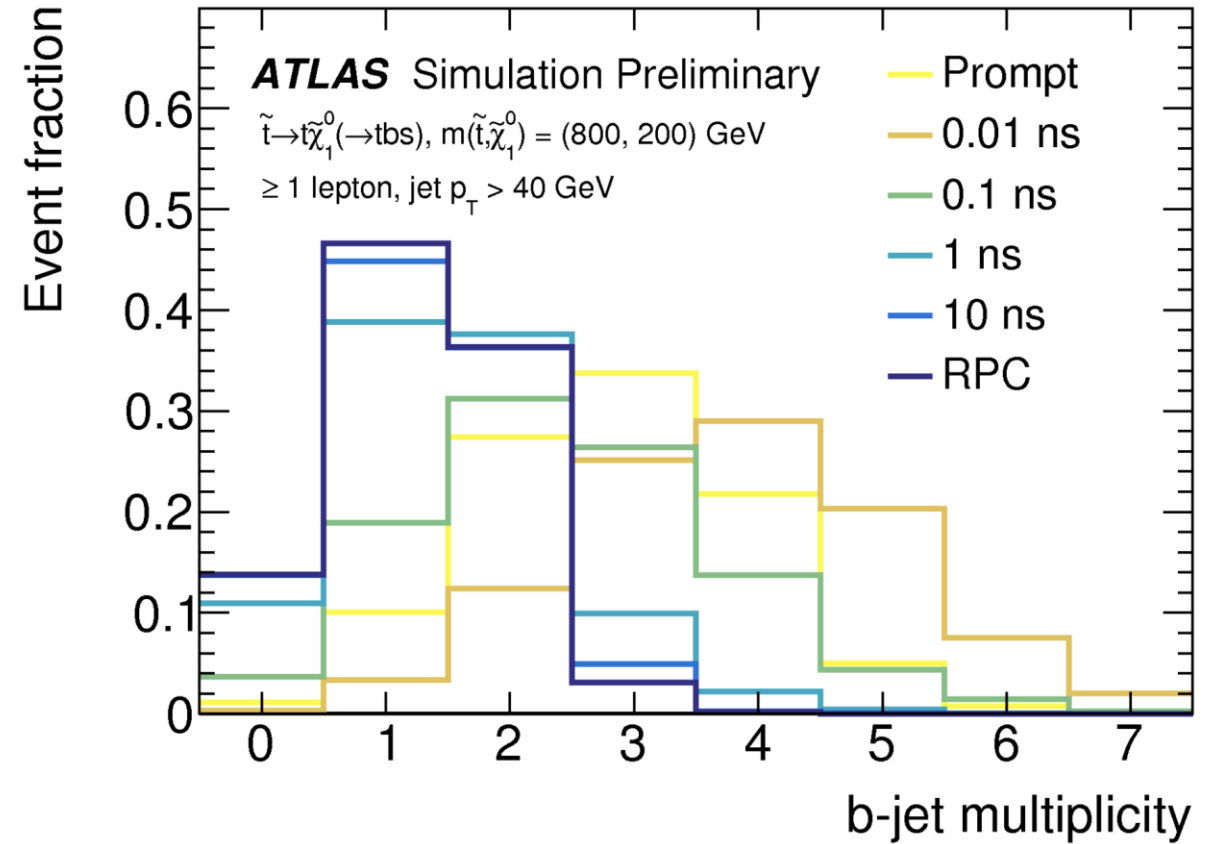
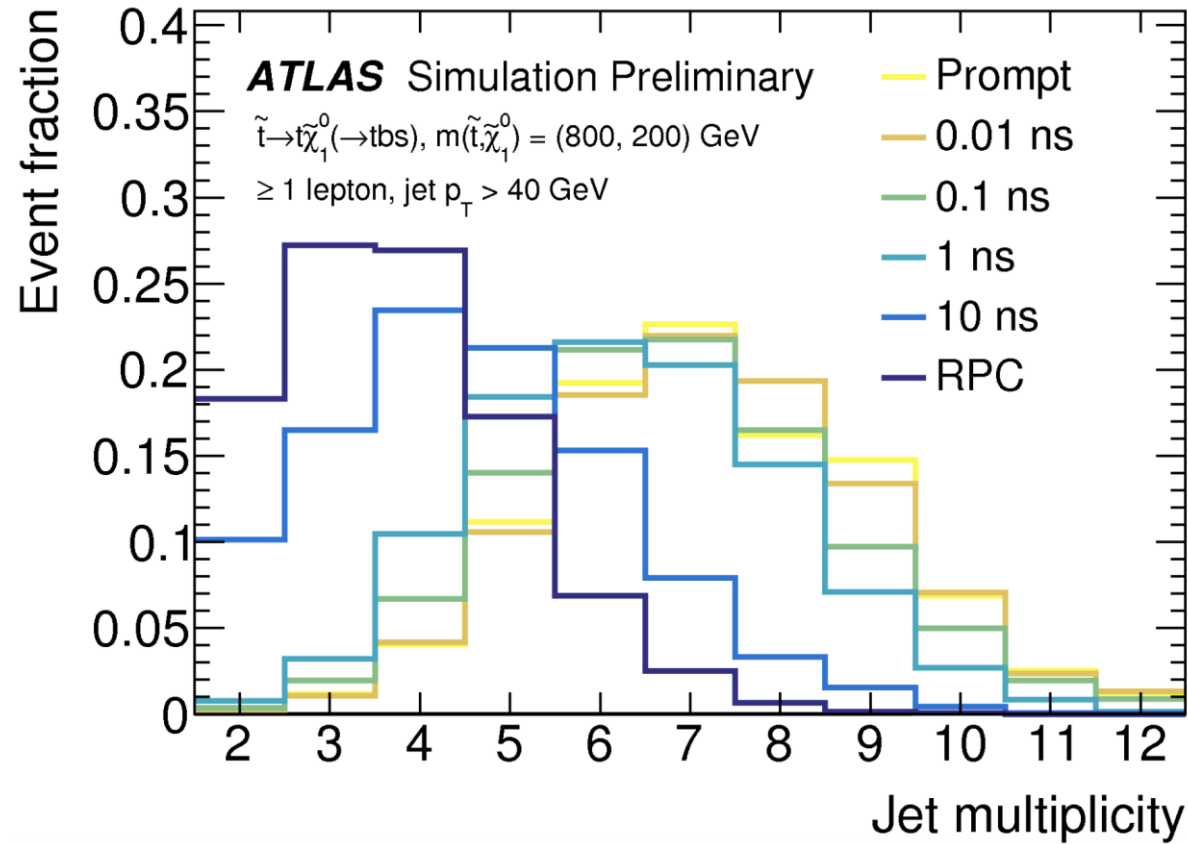
- Depending on RPV coupling strengths, LSP can be:
 - Stable (at least on collider scales).
 - Long-lived with displaced decays.
 - Short-lived with prompt decays.
- Prompt RPC and RPV analyses were reinterpreted in models with variable coupling strength.
- Multiple models considered with non-zero UDD coupling (λ''), including:



Stop decays via λ''_{323} :

- Set limits on stop mass for a wide range of λ''_{323} .
- $\tilde{\chi}_1^0$ assumed to be bino, with $m(\tilde{\chi}_1^0) = 200$ GeV.
 - Bino \rightarrow no nearby chargino \rightarrow fewer decays.
 - Also, nature of $\tilde{\chi}_1^0$ matters since decay requires off-shell stop, and higgsinos have a larger coupling to stops.
- Show contours for various \tilde{t} lifetimes and $BR(\tilde{t} \rightarrow bs)$.
 - As λ''_{323} increases:
 - \tilde{t} lifetime decrease.
 - Direct $\tilde{t} \rightarrow bs$ decay takes over $\tilde{t} \rightarrow t\tilde{\chi}_1^0 (\rightarrow tbs)$.
- Limits account for single stop production at high λ''_{323} .
 - $\frac{\sigma_{\text{single}}}{\sigma_{\text{pair}}} > 10^2$ for $m(\tilde{t}) = 500$ GeV, $\lambda''_{323} = 1$.
- Also accounts for mass of virtual stop in $\tilde{\chi}_1^0 \rightarrow tbs$ decay.





- Jet multiplicity increase as lifetime of bino LSP decreases.

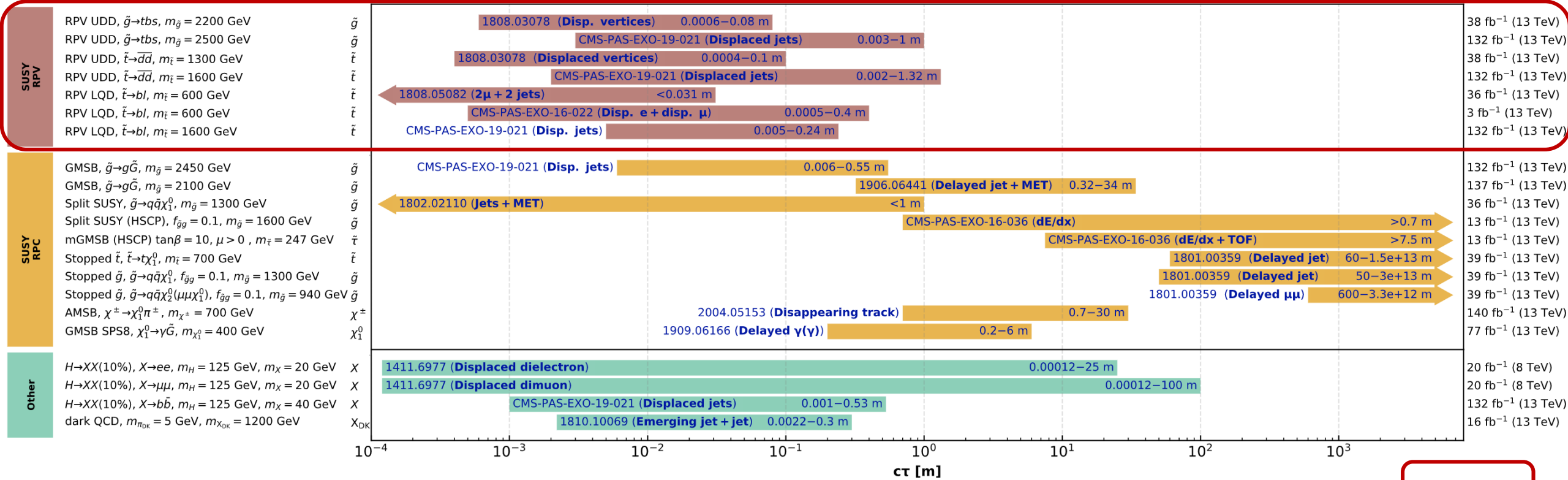
Summary plots



Overview of CMS long-lived particle searches

CMS Preliminary

3 - 140 fb⁻¹ (8, 13 TeV)



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

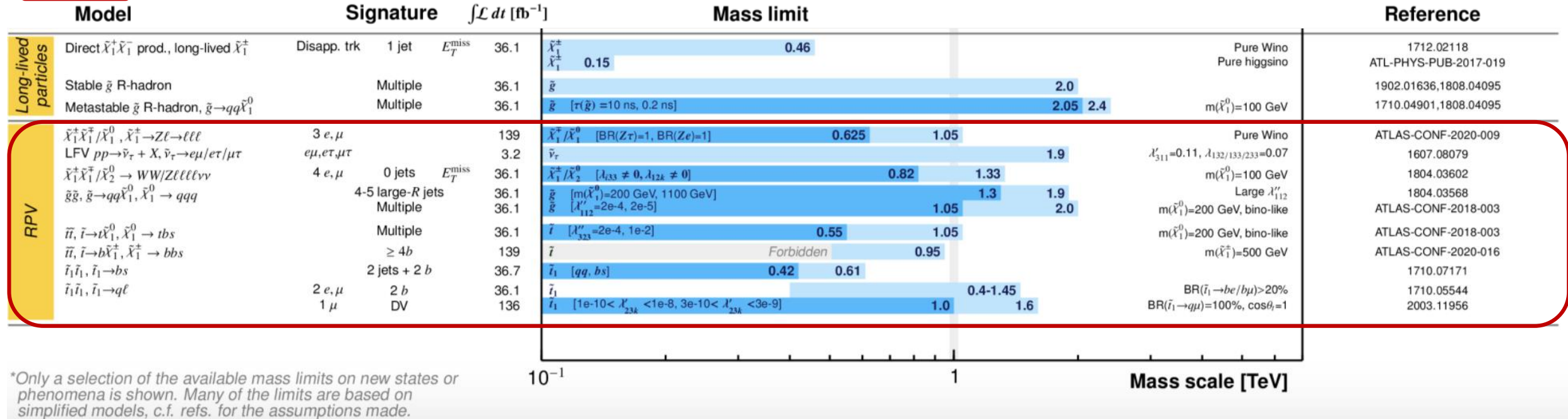
LHCP 2020

- From CMS Exotica [public results](#).

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2020

ATLAS Preliminary
 $\sqrt{s} = 13 \text{ TeV}$

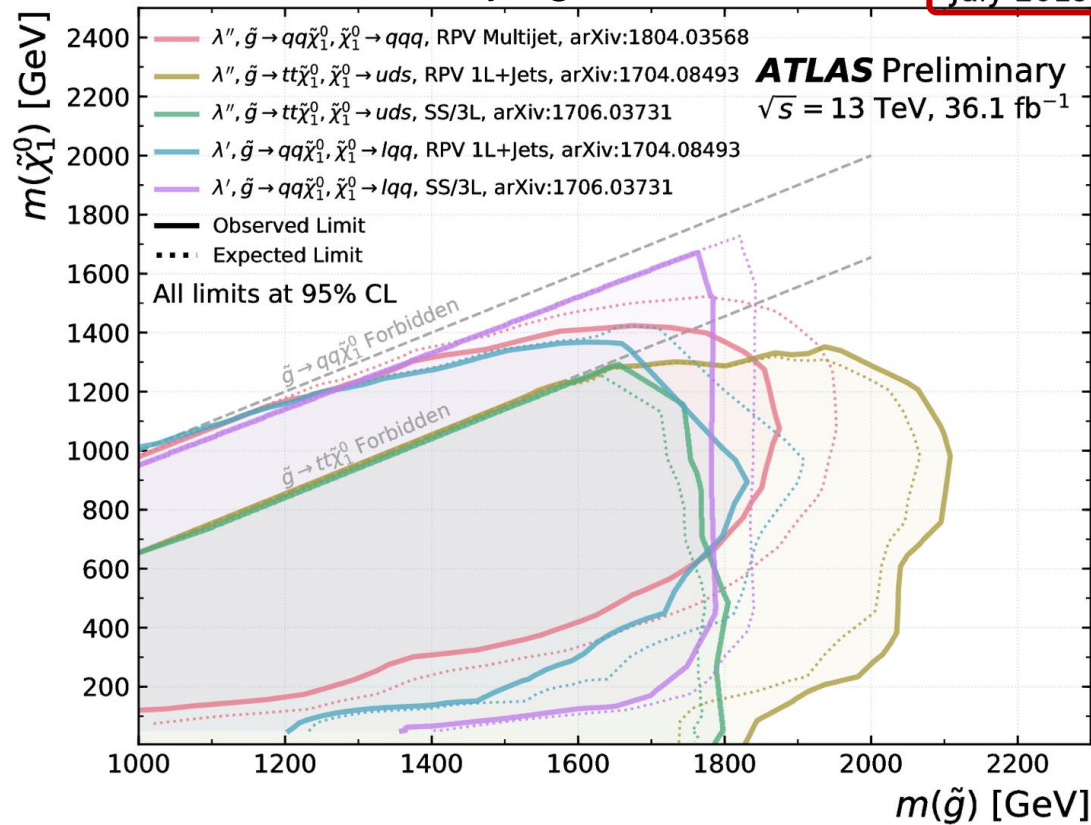


*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

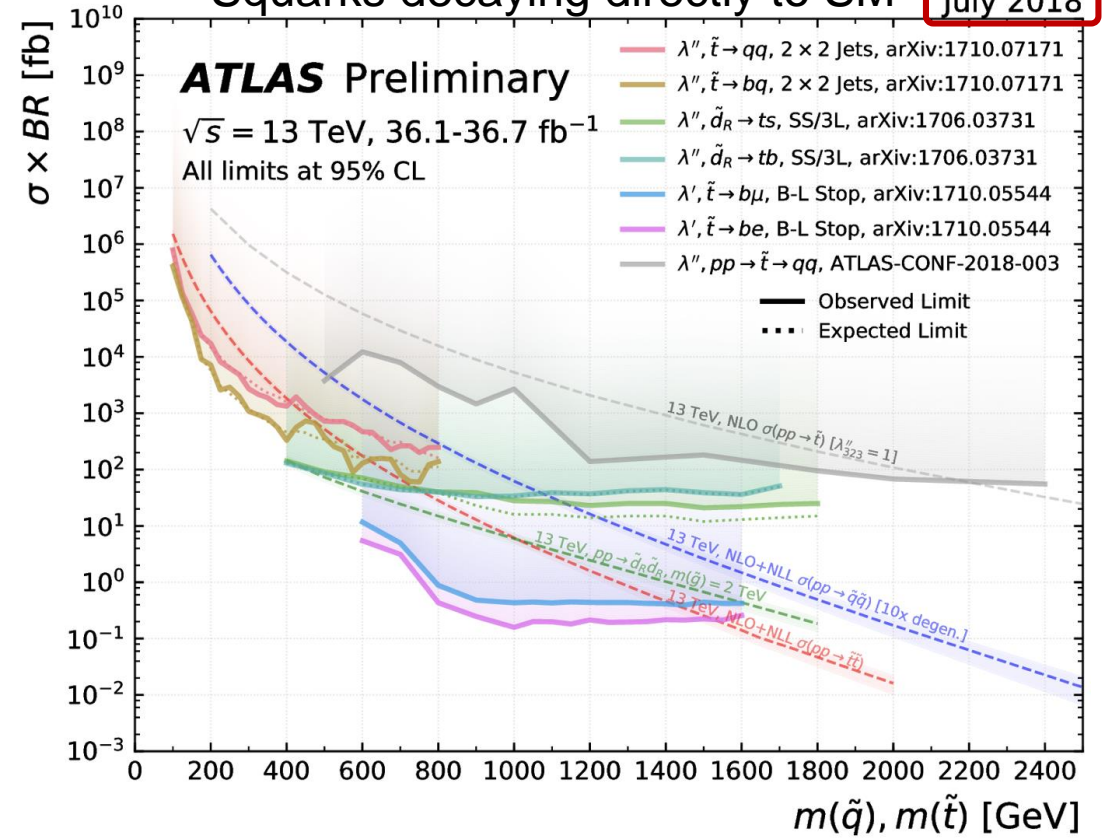
- From ATLAS SUSY [public results](#).

RPV Summary Plots

Gluininos decaying via neutralinos July 2019

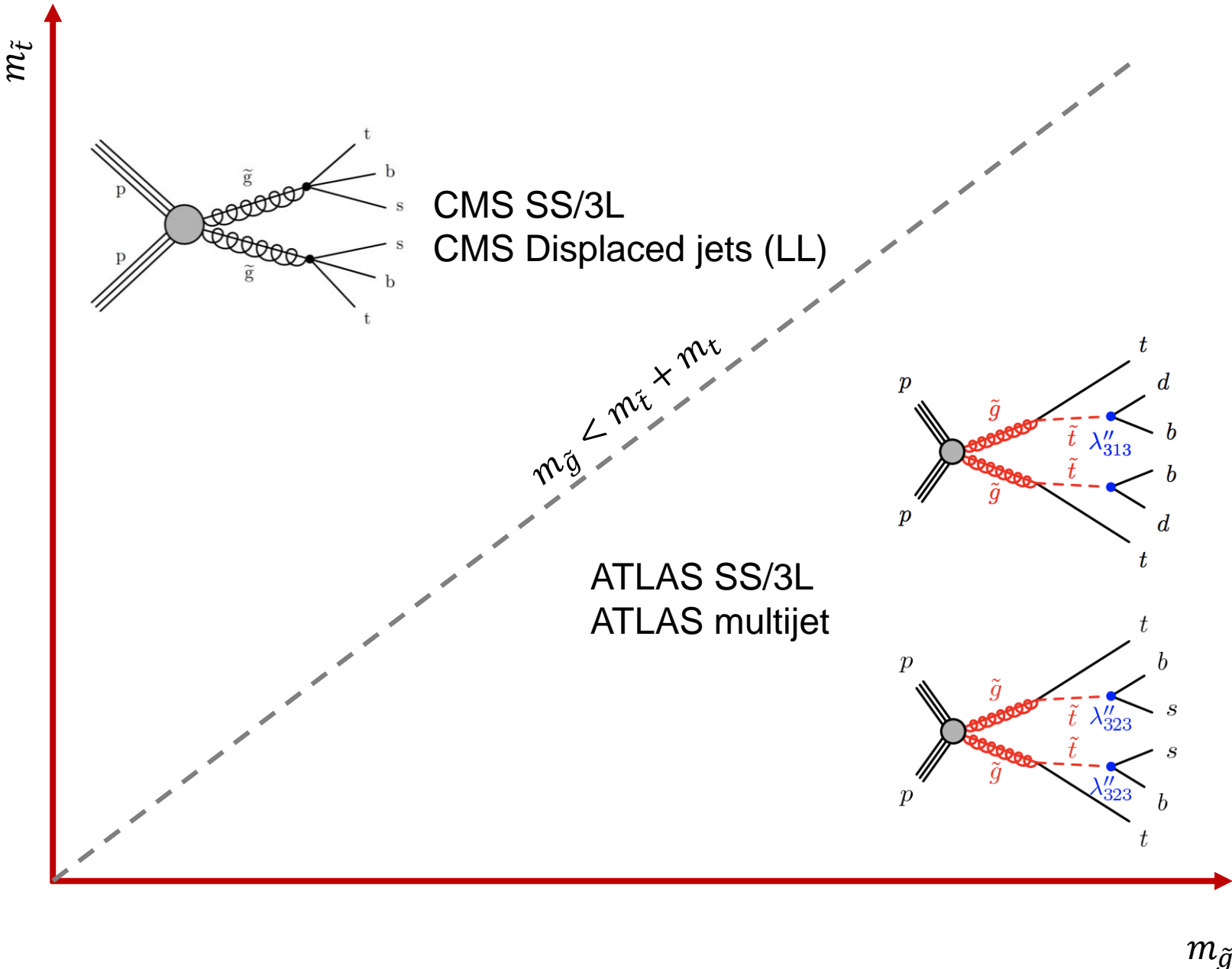


Squarks decaying directly to SM July 2018



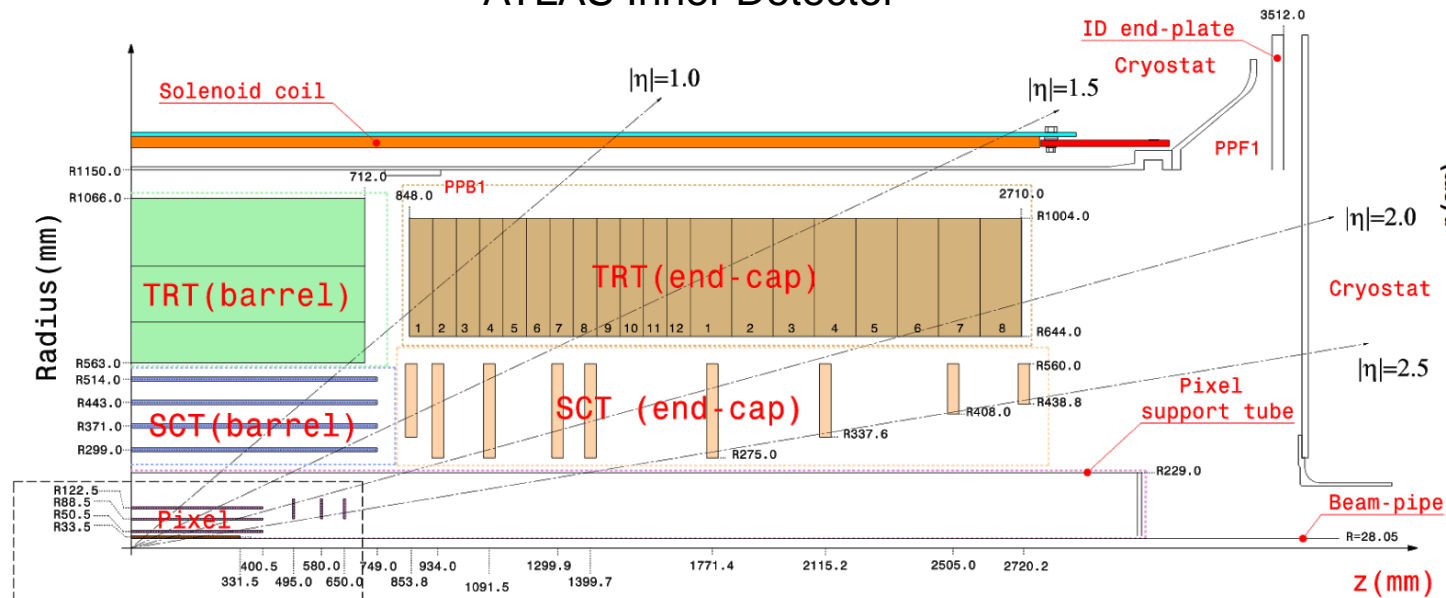
- From ATLAS SUSY [public results](#).
- Assumes decay mode listed in legend occurs with 100% BR.
- Assumes decays are prompt.

Other

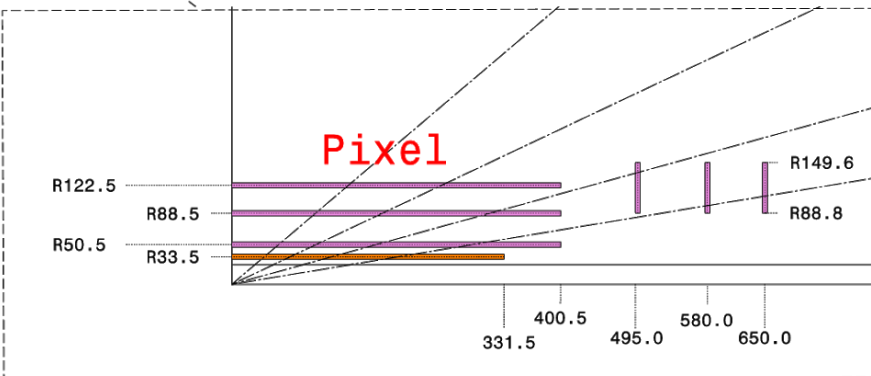
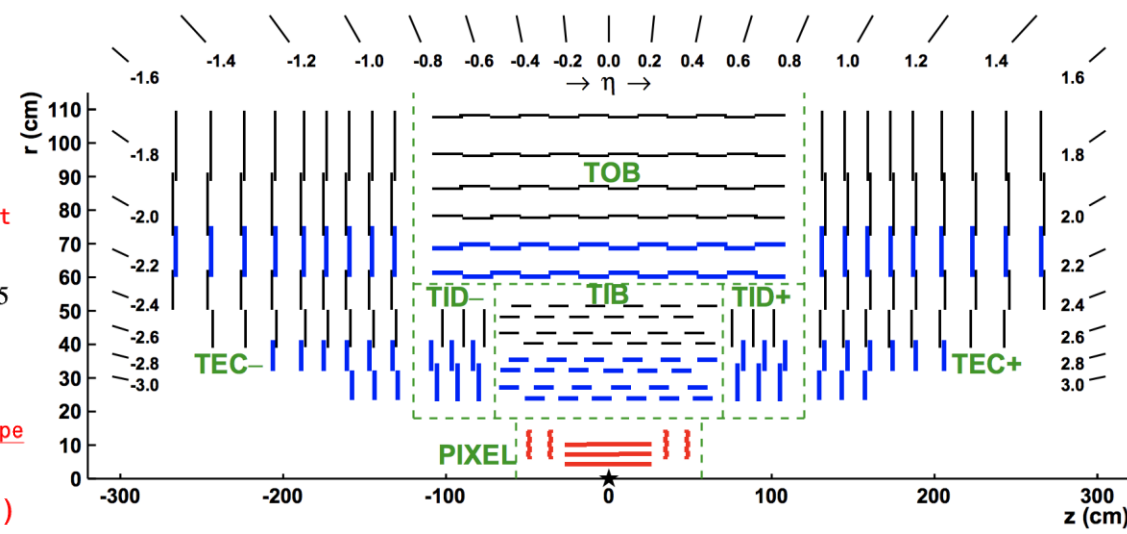


- Pair produced gluinos, $\tilde{g} \rightarrow tbs/tbd$.
 - Via RPV UDD coupling (λ'').
 - s, d indistinguishable in detector.
- Above diagonal, stop is off-shell \rightarrow 3-body decay.
 - 1 CMS search with prompt decay.
 - 1 CMS search with displaced decay.
- Below diagonal, stop is on-shell \rightarrow have to scan over stop mass as well.
 - 2 ATLAS searches with prompt decays.

ATLAS Inner Detector



CMS Tracker



Envelopes

Pixel	.....	31<R<242 (mm)
SCT barrel	.....	255<R<549 (mm)
SCT end-cap	.....	251<R<610 (mm)
TRT barrel	.....	554<R<1082 (mm)
TRT end-cap	.....	617<R<1106 (mm)