

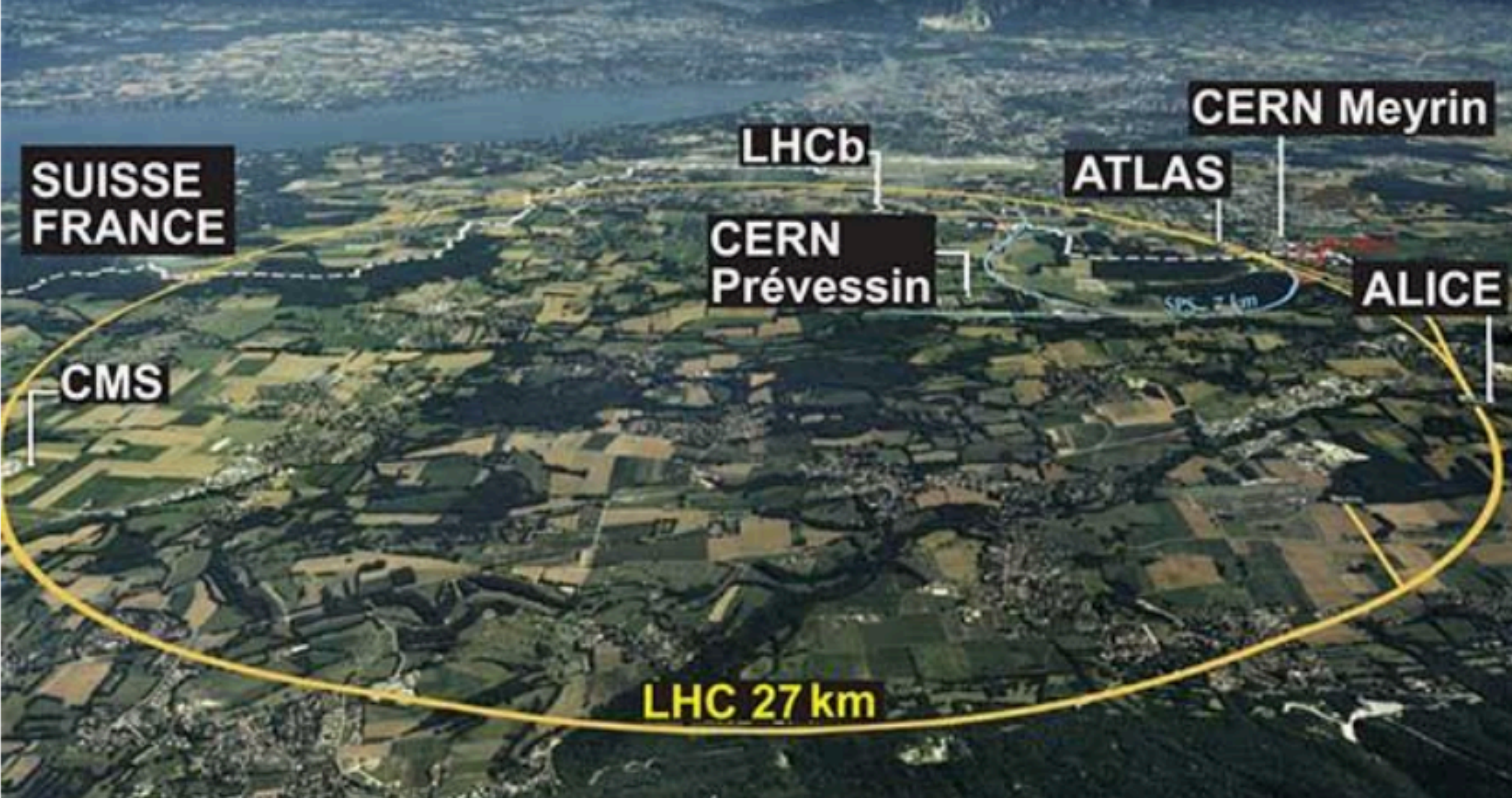
# Search for baryon number violation at the LHC

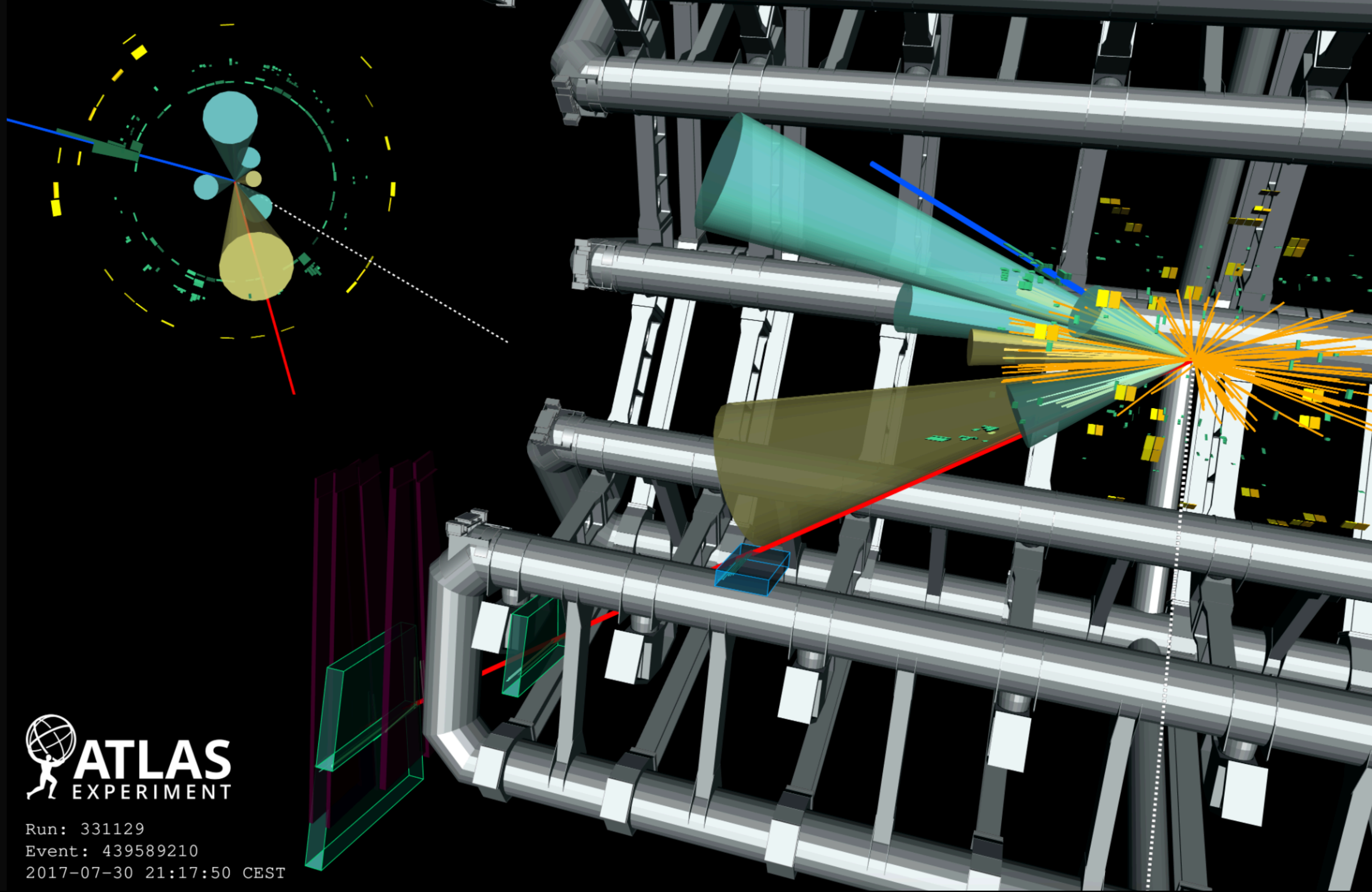
BLV, September 5, 2022

**Lauren Osojnak, University of Pennsylvania**

**On behalf of the ATLAS and CMS Collaborations**

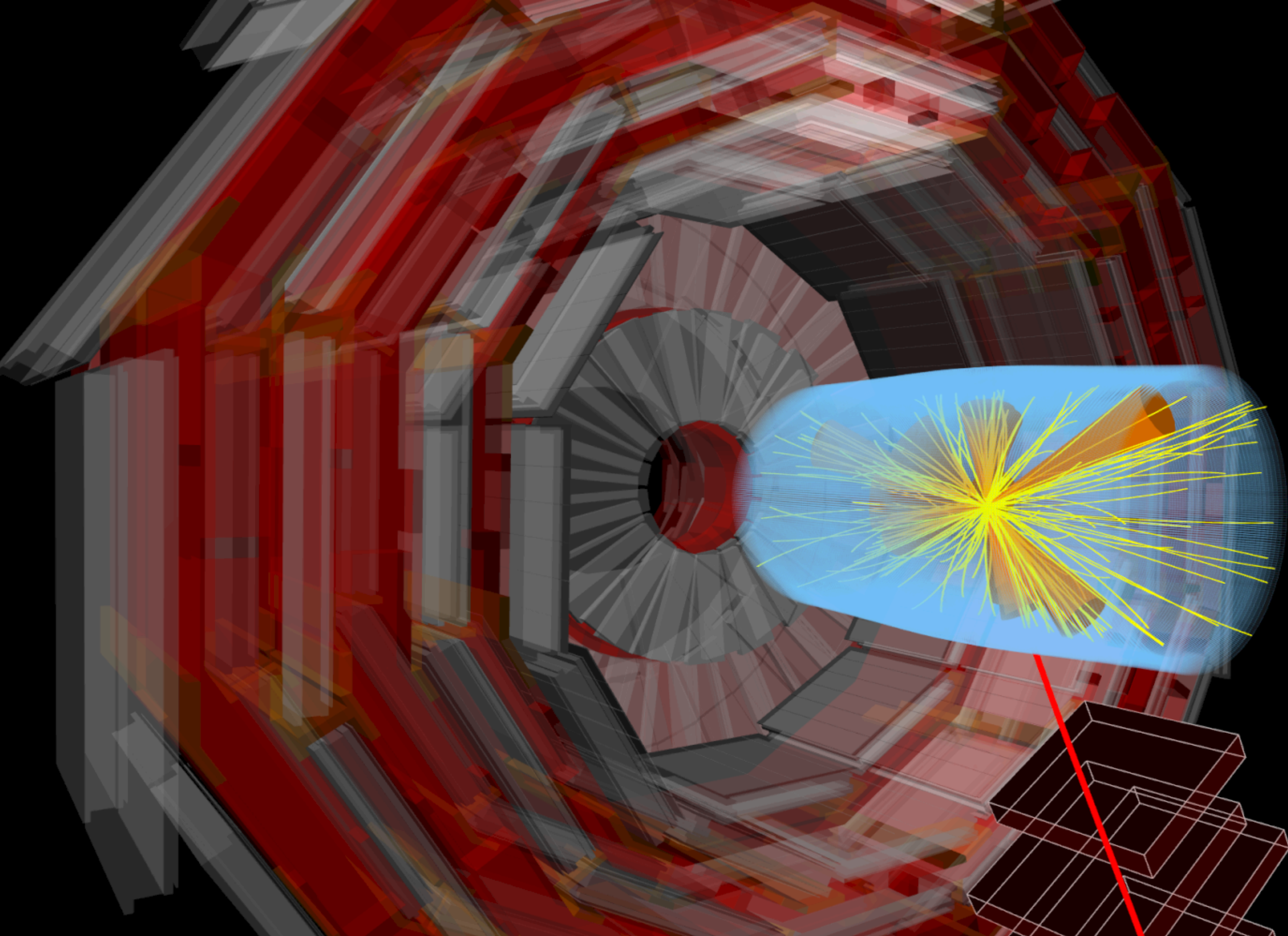






 **ATLAS**  
EXPERIMENT

Run: 331129  
Event: 439589210  
2017-07-30 21:17:50 CEST



# Outline

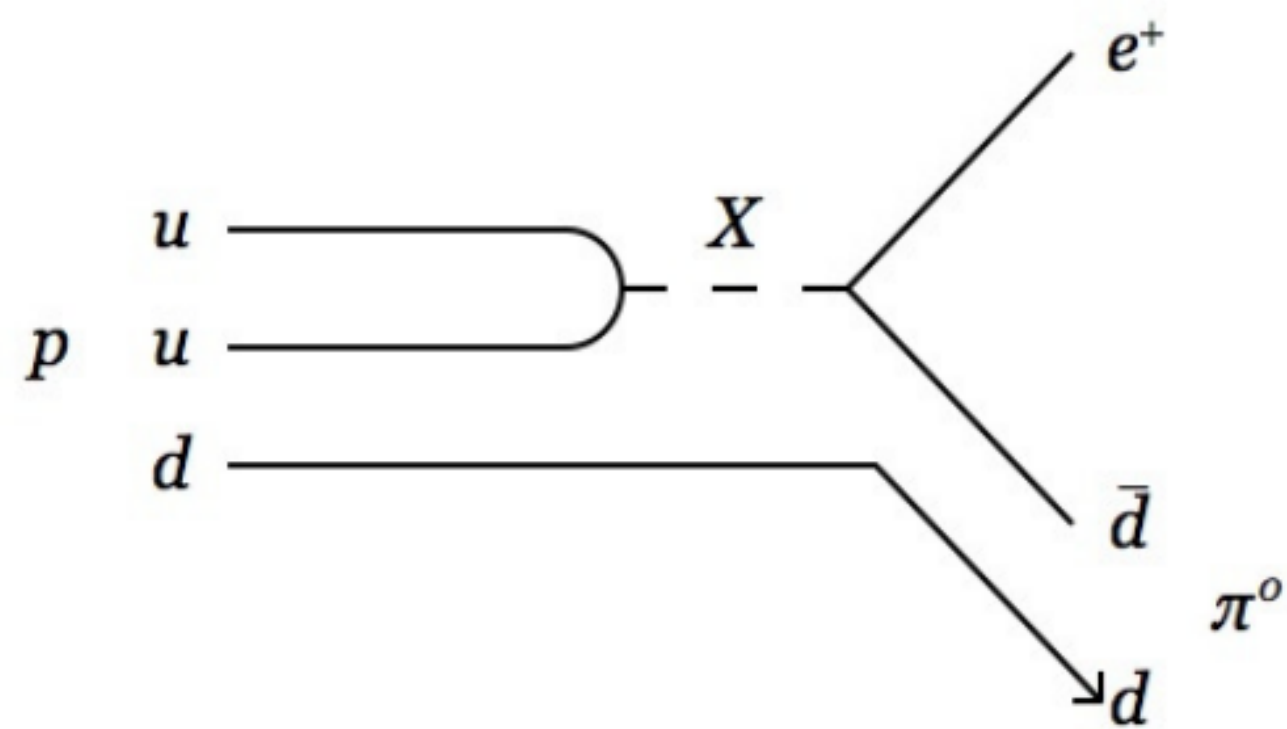
1. Introduction
2. R-parity Violation (RPV) multi lepton multi jet search ATLAS
3. Beyond Standard Model (BSM) search for 0L and multiple b-jets ATLAS
4. Search for trilepton Resonance from chargino/neutralino ATLAS
5. Stop search with 2 tops and light flavor jet final state CMS
6. Search for dijet resonance CMS
7. Long lived particle (LLP) decay to jets with displaced vertices CMS
8. Outlook

# Violation of Baryon Number

$$\Delta B \neq 0, \Delta L = 0, \Delta[B - L] \neq 0$$

$$\Delta B = 0, \Delta L \neq 0, \Delta[B - L] \neq 0$$

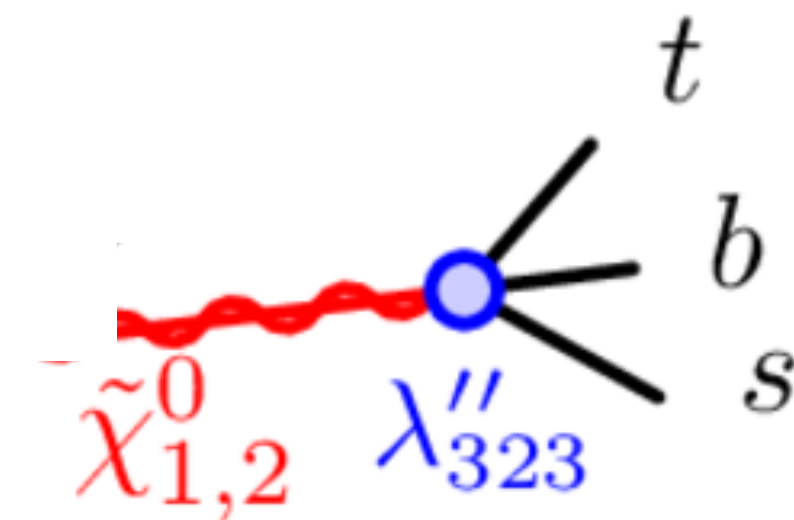
$$\Delta B \neq 0, \Delta L \neq 0, \Delta[B - L] = 0$$



**Proton decay**

$$\Delta B = \Delta L = 1$$

$$\Delta(B - L) = 0$$



**RPV coupling**

$$\Delta B = 1, \Delta L = 0$$

$$\Delta(B - L) = 1$$

# What is R-parity?

- R-parity conservation invoked in SUSY analyses to prevent Baryon # violating and Lepton # violating terms; also to prevent proton decay
- **R-parity:**  $R = (-1)^{3(B-L)+2s}$
- SUSY particles have -1 R parity
- SM particles have +1 R parity

# Why Violate it?

- The most general gauge invariant and renormalizable super potential would include violating terms
- R-Parity is proposed “ad hoc” to prevent proton decay
- If R parity = conserved -> Lightest Supersymmetric Particle (LSP) is stable
- If R parity = violated -> LSP allowed to decay into only SM particles (proton still stable)

$$W_{\mathcal{R}_p} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_2.$$

Lepton Number Violating

Baryon number violating

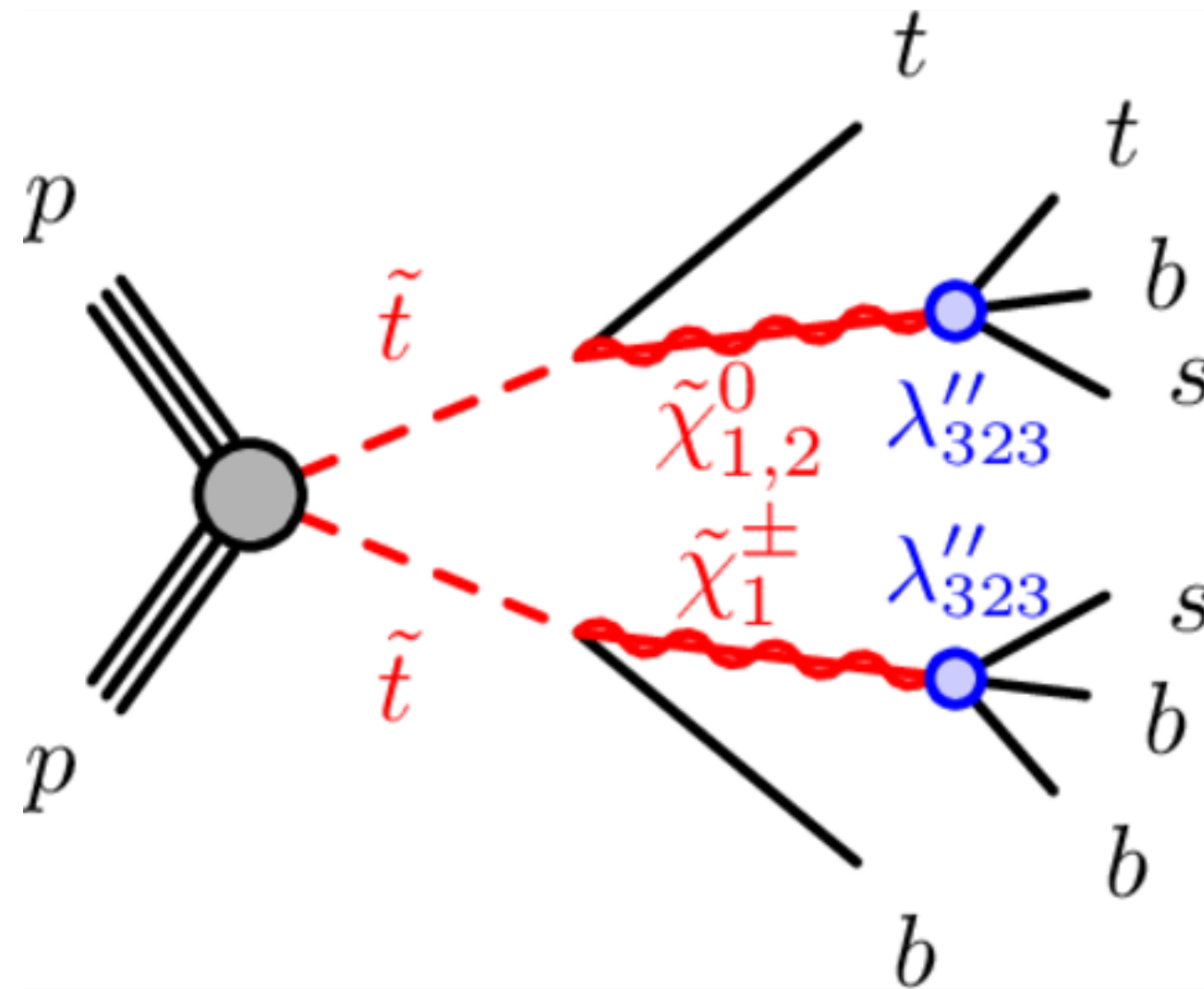
If large  $\lambda''$  -> prompt decay  
if small -> Long lived decay

If U is top quark.. decay to  
 $Wb \rightarrow lv$



# RPV search with multi lepton & multi jet final state

arXiv:2106.09609



## Model:

- RPV SUSY featuring gluino or stop production
- lightest neutralino ( $\tilde{\chi}_1^0$ ) is the LSP

## Signature:

- at least one isolated lepton
- at least 8-15 jets; several of which may contain b-tags

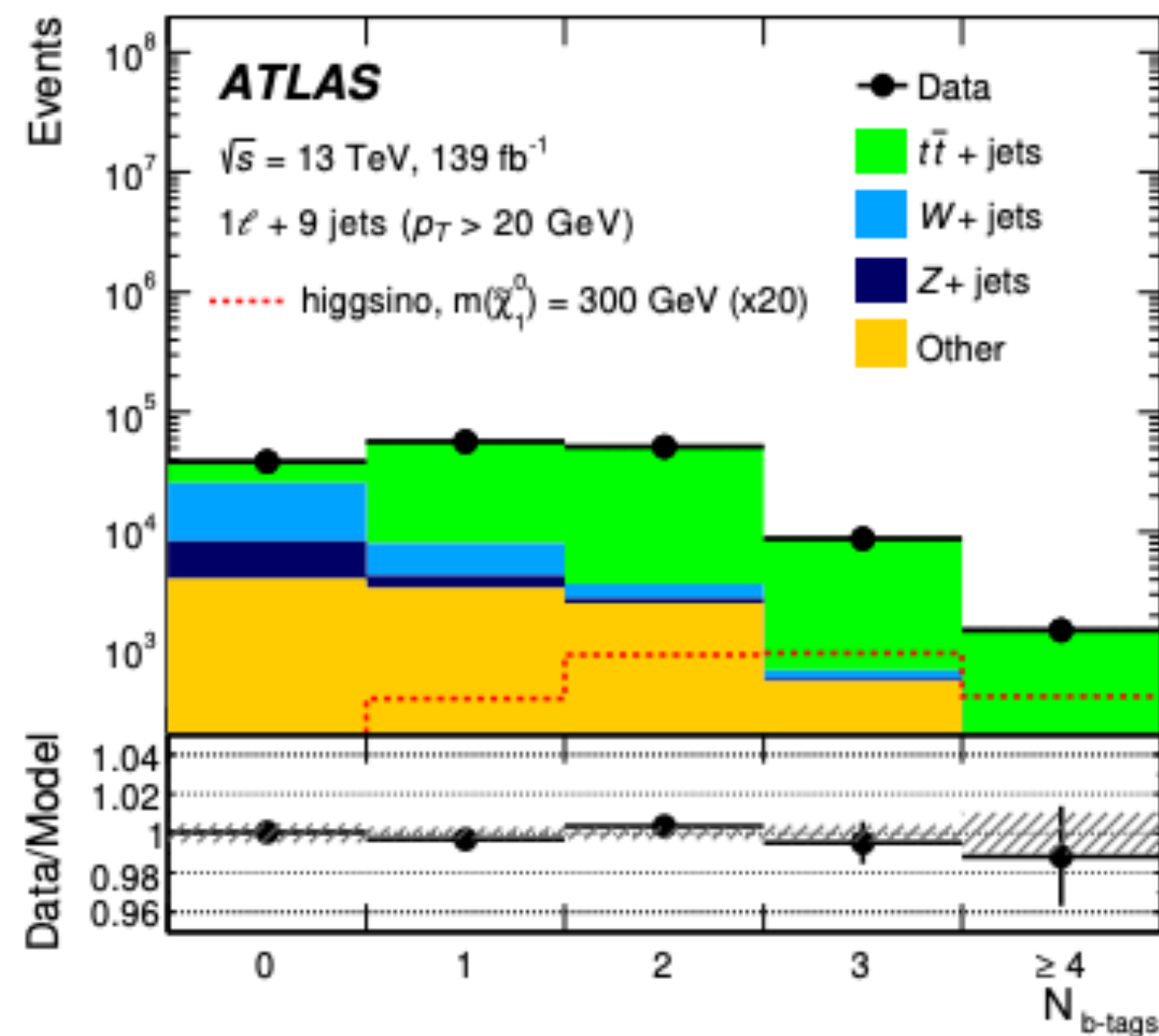
## Signal Regions:

Lepton category	Jet multiplicity	Analysis regions
1 $\ell$ category	4...7 jets	0b $\ell^-$ , 0b $\ell^+$ , 0b $m_{\ell\ell}$ , 1b, 2b, 3b, $\geq 4b$
	8... $\geq N_{\text{last}}^{1\ell}$ jets	0b, 1b, 2b, 3b, $\geq 4b$
2 $\ell^{\text{sc}}$ category	4... $\geq N_{\text{last}}^{2\ell^{\text{sc}}}$ jets	0b 3 $\ell$ , 0b, 1b, 2b, 3b, $\geq 4b$

# RPV search with multi lepton & multi jet final state

## Background Estimation:

- data-driven model based on observables at medium jet multiplicity to predict b-tag jet multiplicity at higher multiplicities used in this search
- Neural Networks used to extend data-driven estimate to shape of machine learning discriminate

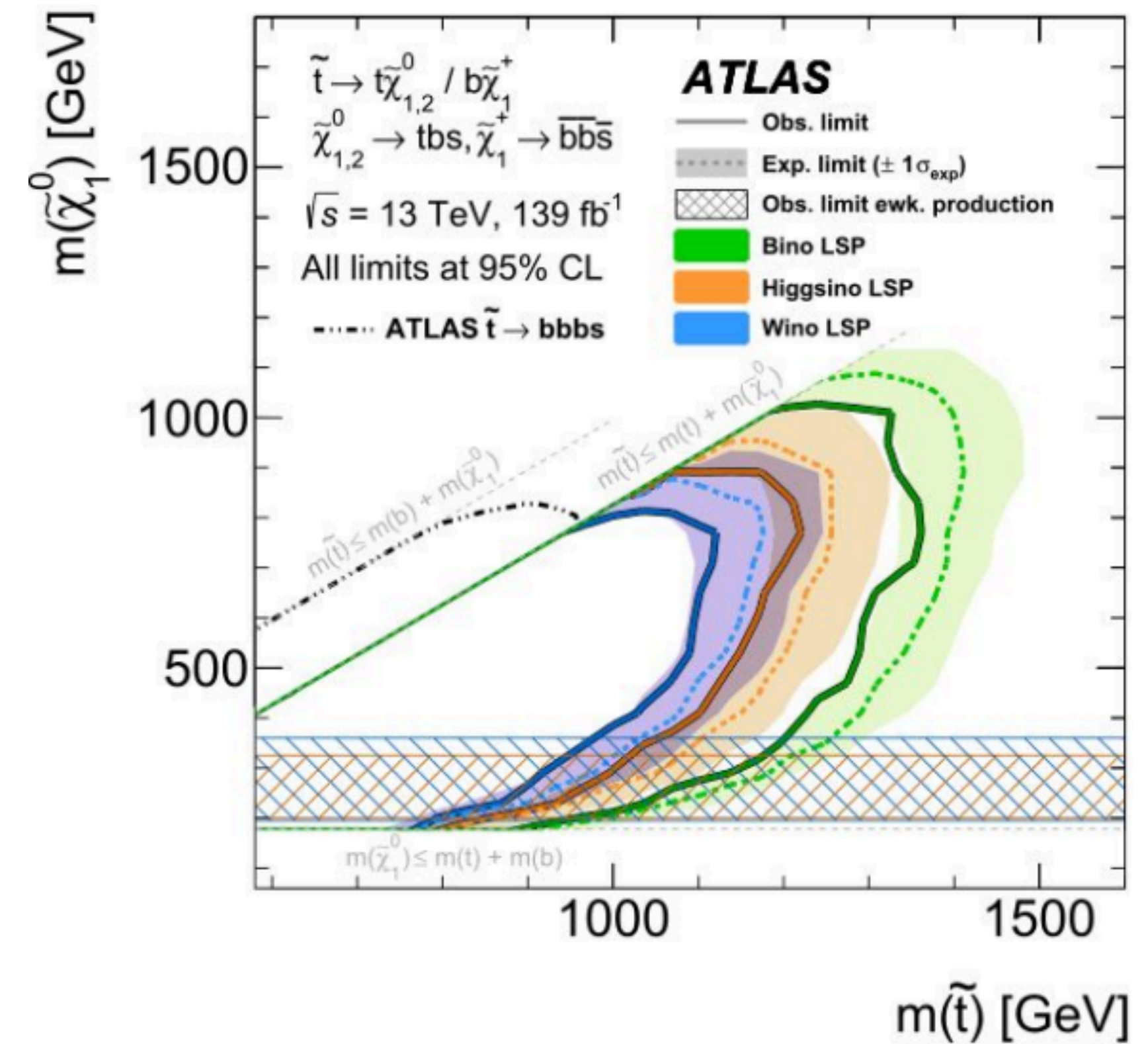


arXiv:2106.09609

## Results:

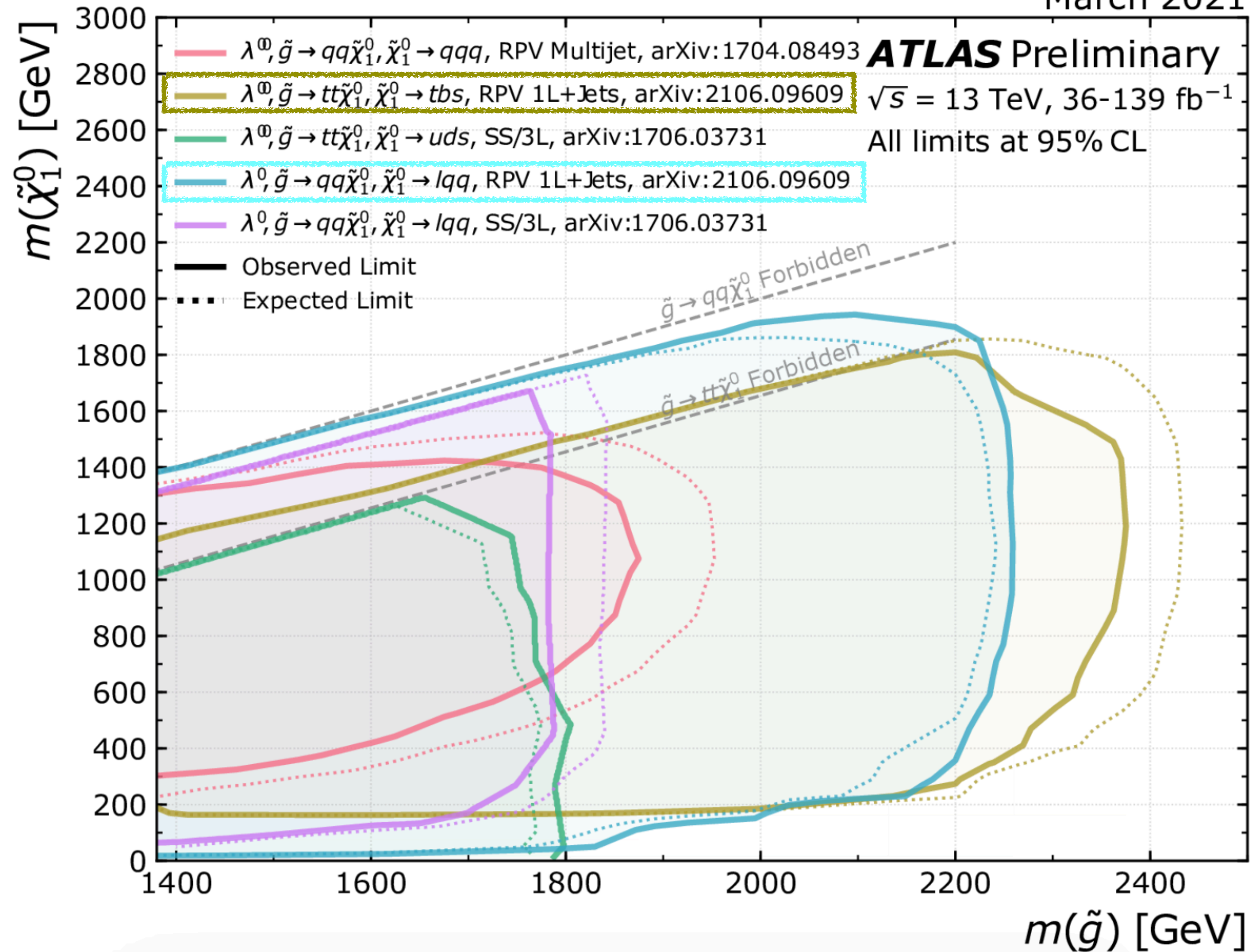
- Exclusion limits on higgsino masses between 200 GeV and 320 GeV
- Improves upon earlier search

arXiv:1704.08493



# ATLAS RPV summary plot

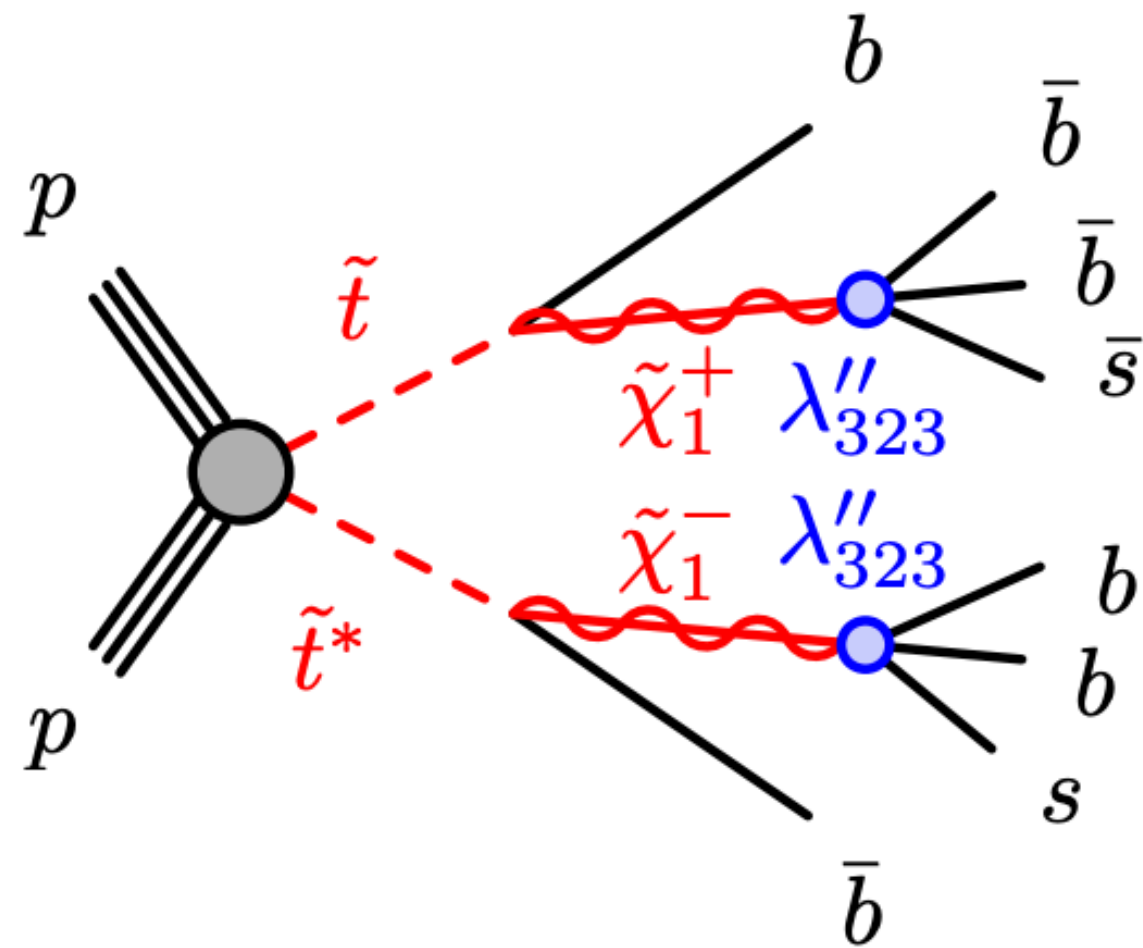
March 2021



# BSM search for multiple b-jets and 0 leptons



arXiv:2010.01015

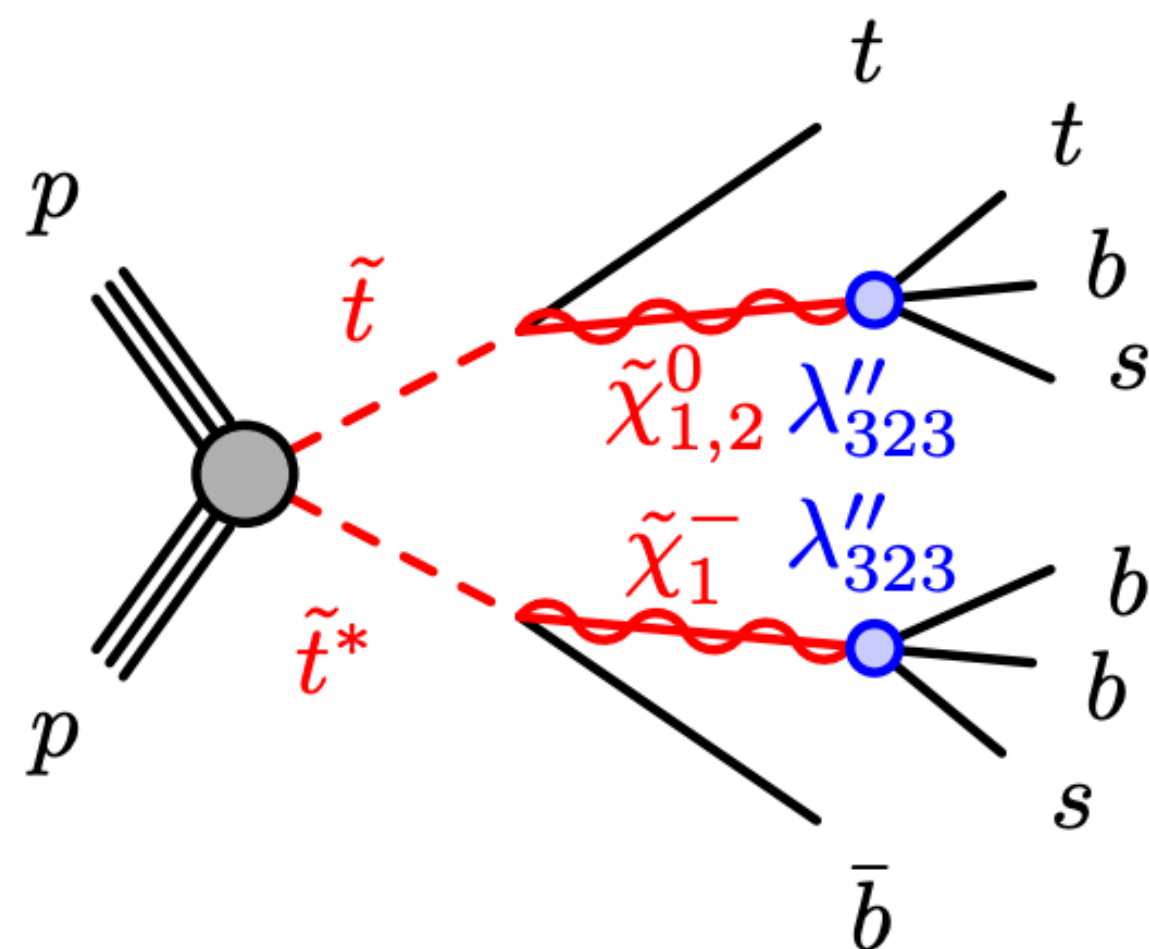


## Model:

- RPV via stop pair production
- charginos/neutralinos decay via UDD RPV coupling ( $\lambda''_{323}$ )

## Signature:

- no leptons, high jet multiplicity (6 or more),  $\geq 4$  b tagged jets
- no requirement placed on missing transverse momentum in event

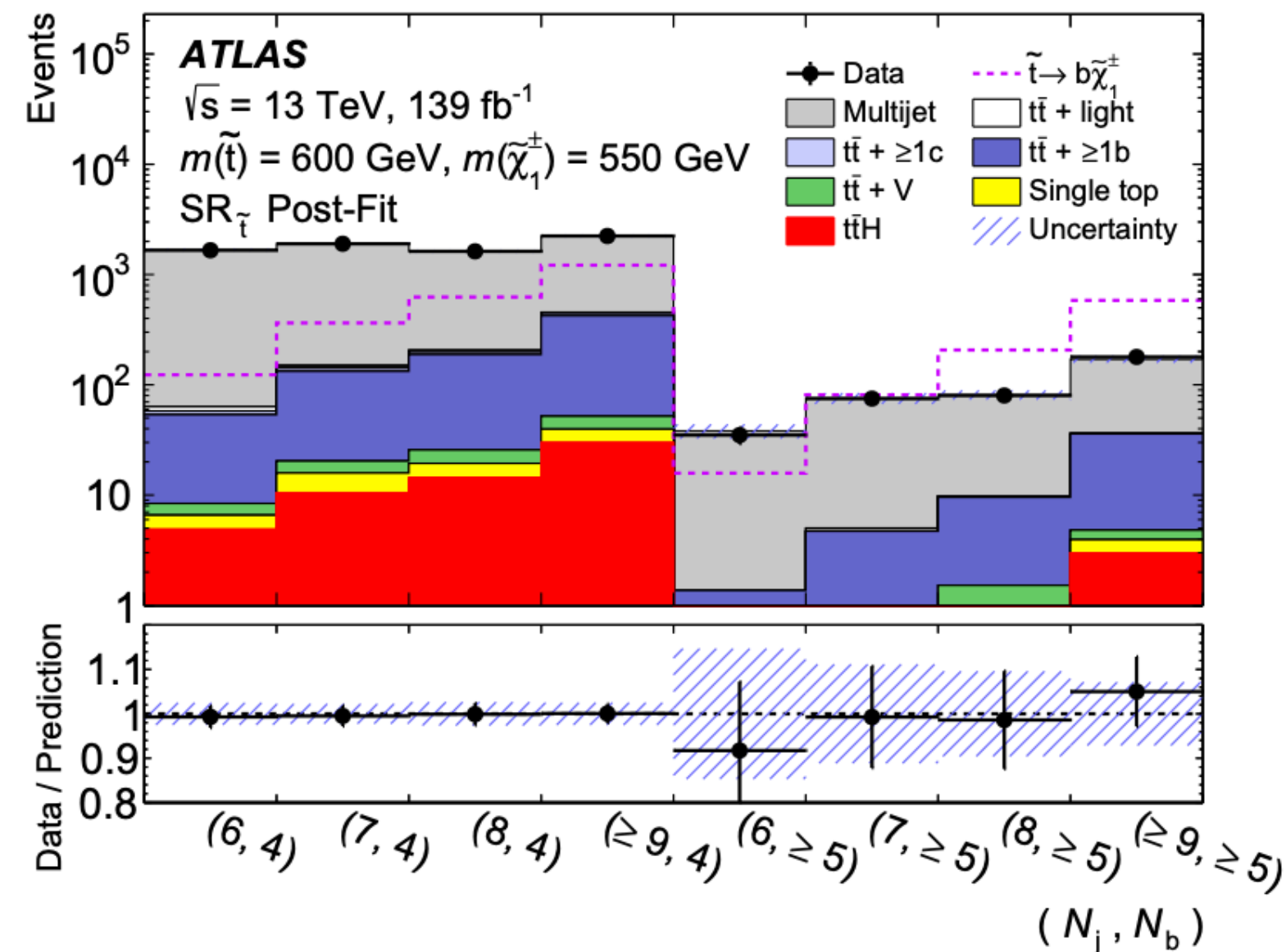


First limits from ATLAS on the production of stops that decay exclusively to a chargino and b-quark.

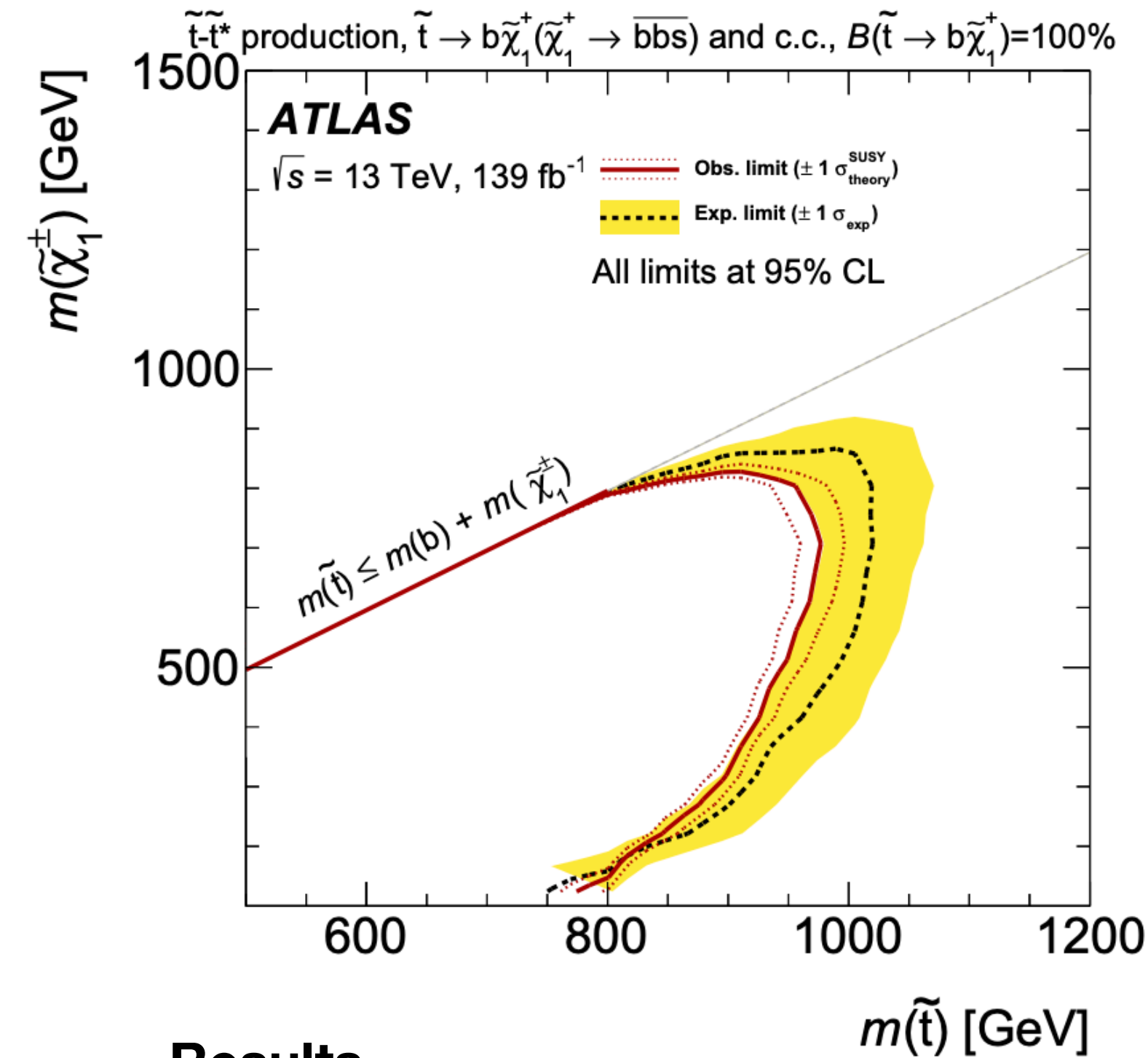
# BSM search for multiple b-jets and 0 leptons

## Analysis Strategy

- Data-driven estimation for multi-jet dominated background
- extrapolate from events with low b-jet multiplicity to high
- validate background estimates using region-dependent selection



arXiv:2010.01015



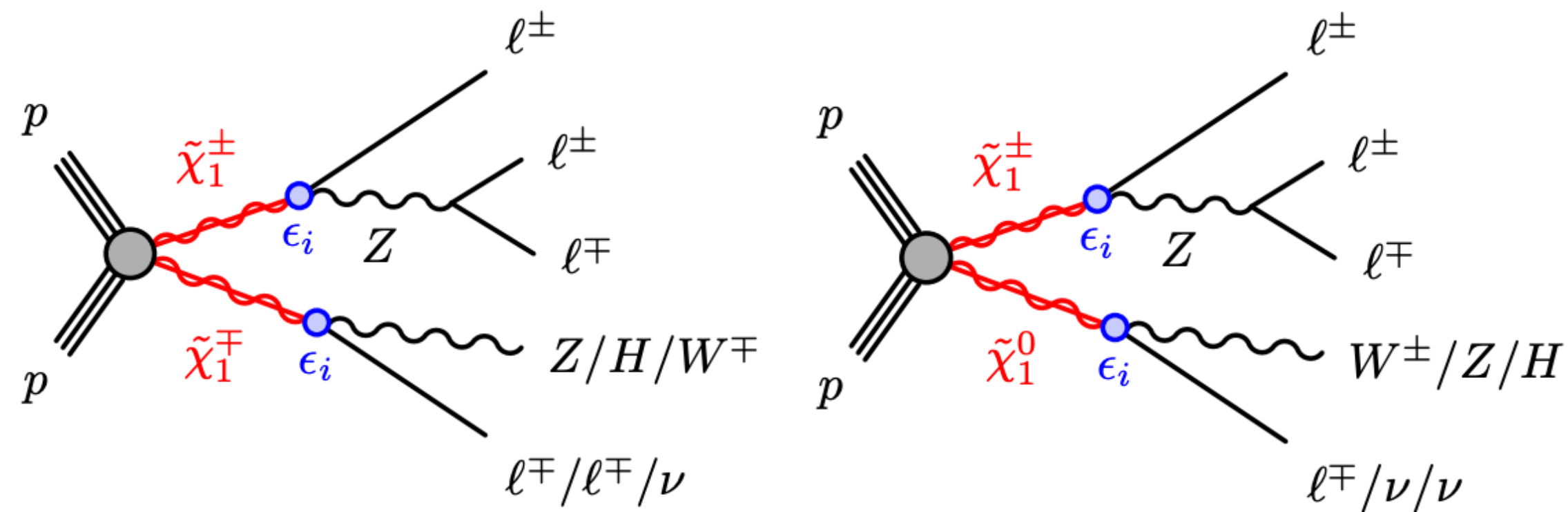
## Results

- No significant excess over SM expectation observed
- Excludes stop masses up to 950GeV in these models

# Search for 3L resonances from neutralino/chargino

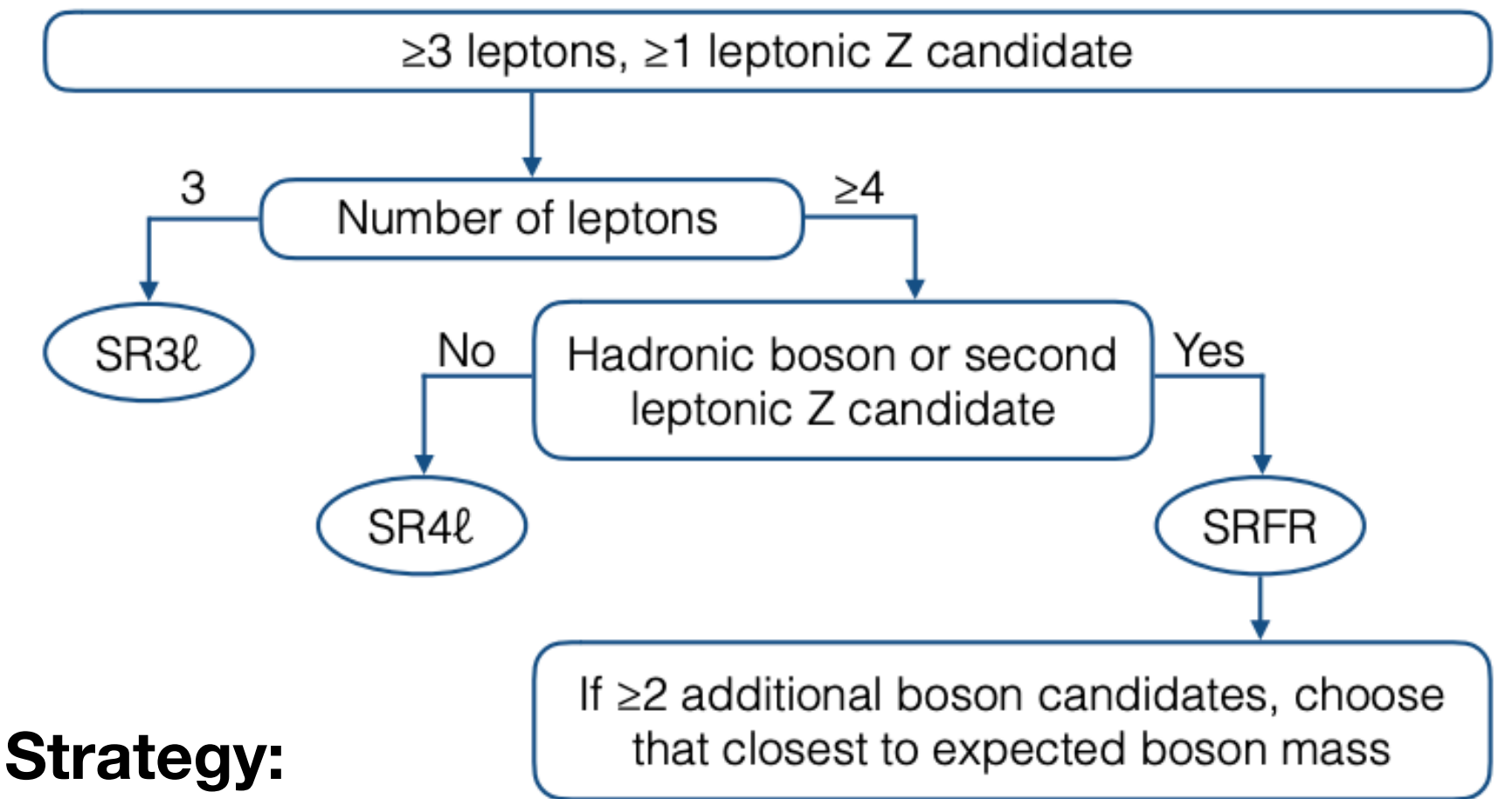


arXiv:2011.10543



## Model:

- B-L MSSM with RPV
- EWK pair production of two chargino's ( $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$ ) or a chargino/neutralino pair ( $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ )
- wino pairs promptly decay to SM bosons



## Analysis Strategy:

- No SM process naturally produces 3L resonance -> nice place to distinguish signal from background
- Decay of interest:  $\tilde{\chi}_1^\pm \rightarrow Zl \rightarrow ll$
- 3 orthogonal SRs constructed for the decay of the second unconstrained  $\tilde{\chi}_1^\pm / \tilde{\chi}_1^0$

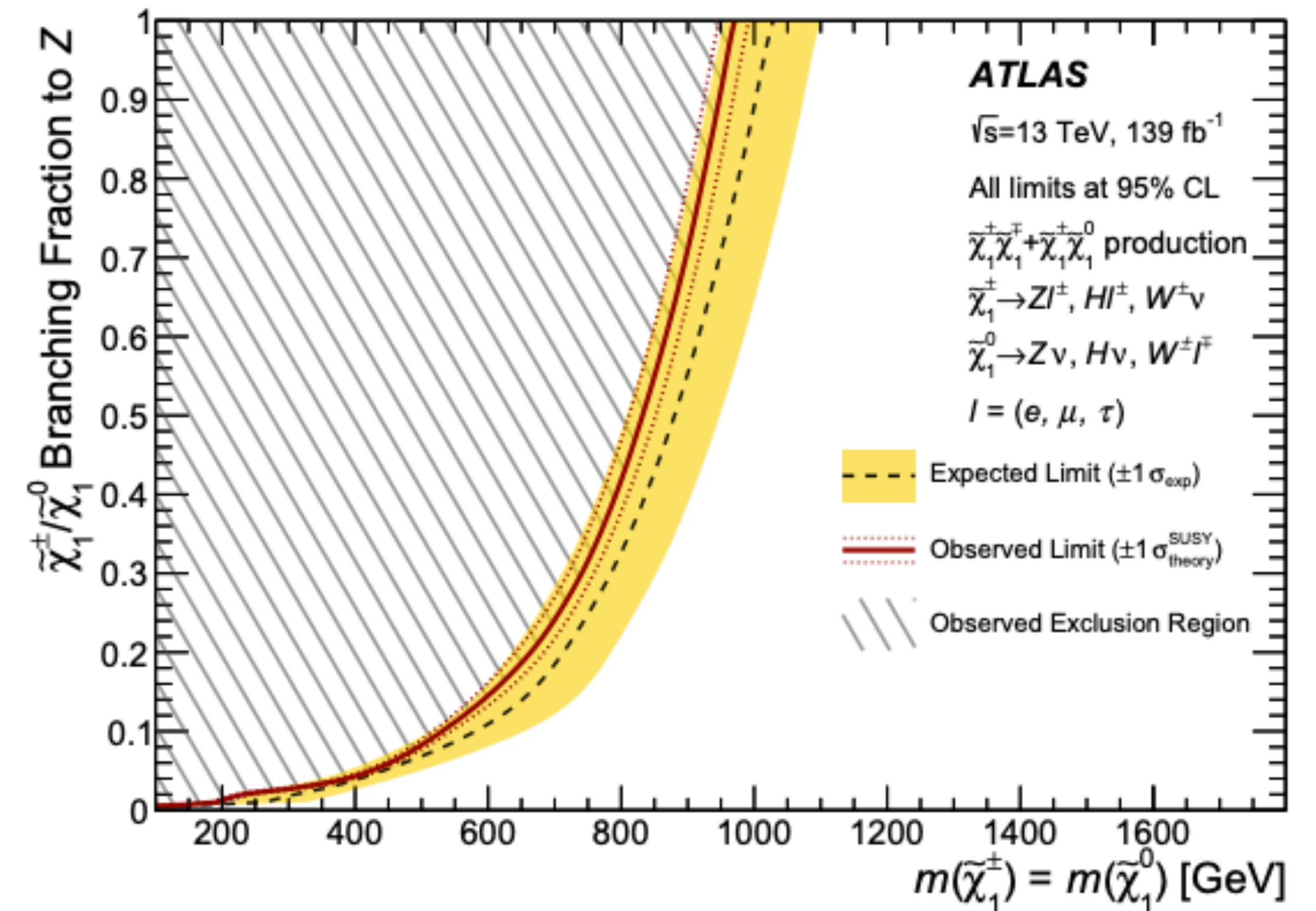
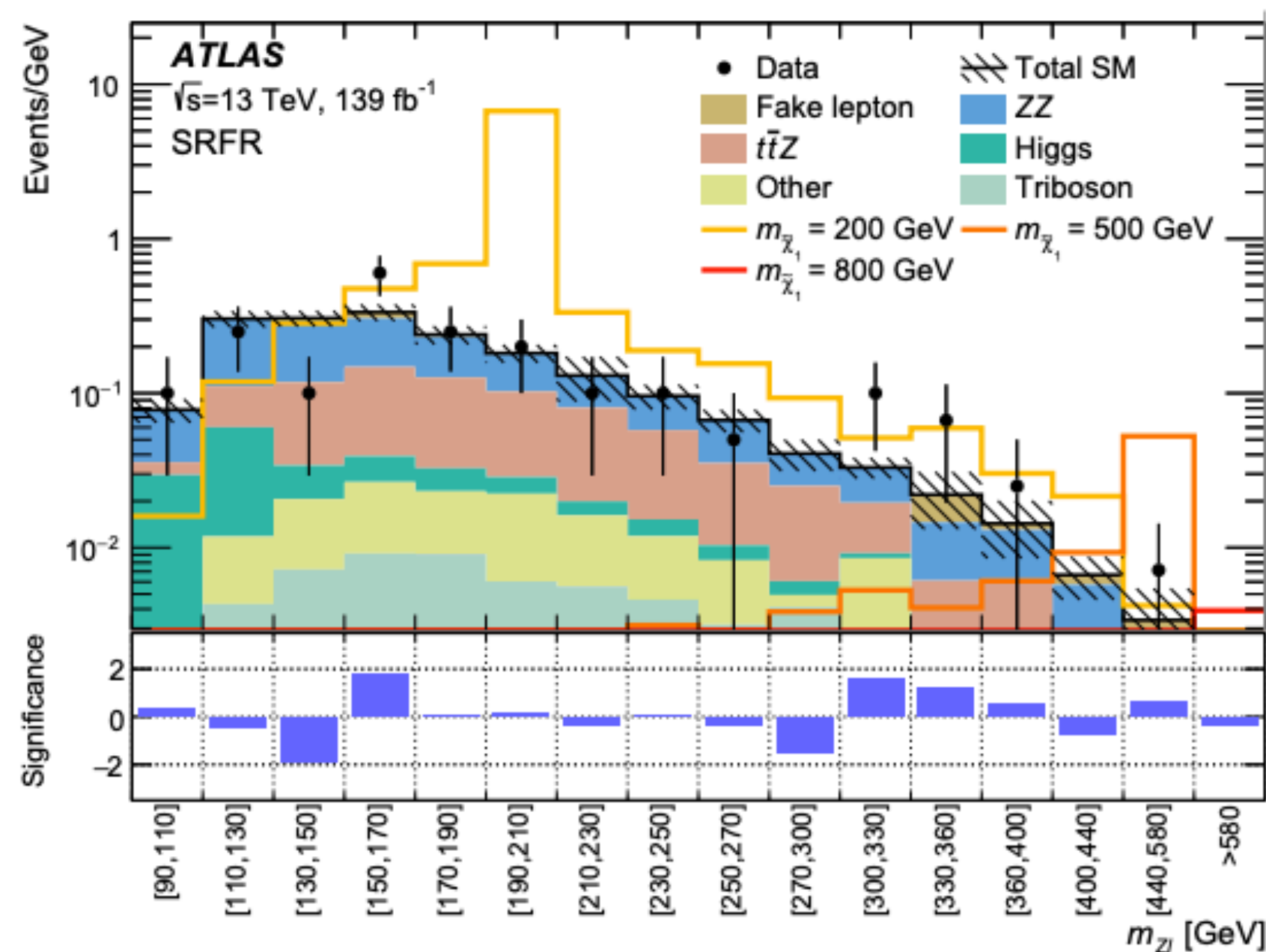
# Search for 3L resonances from neutralino/chargino



## Results:

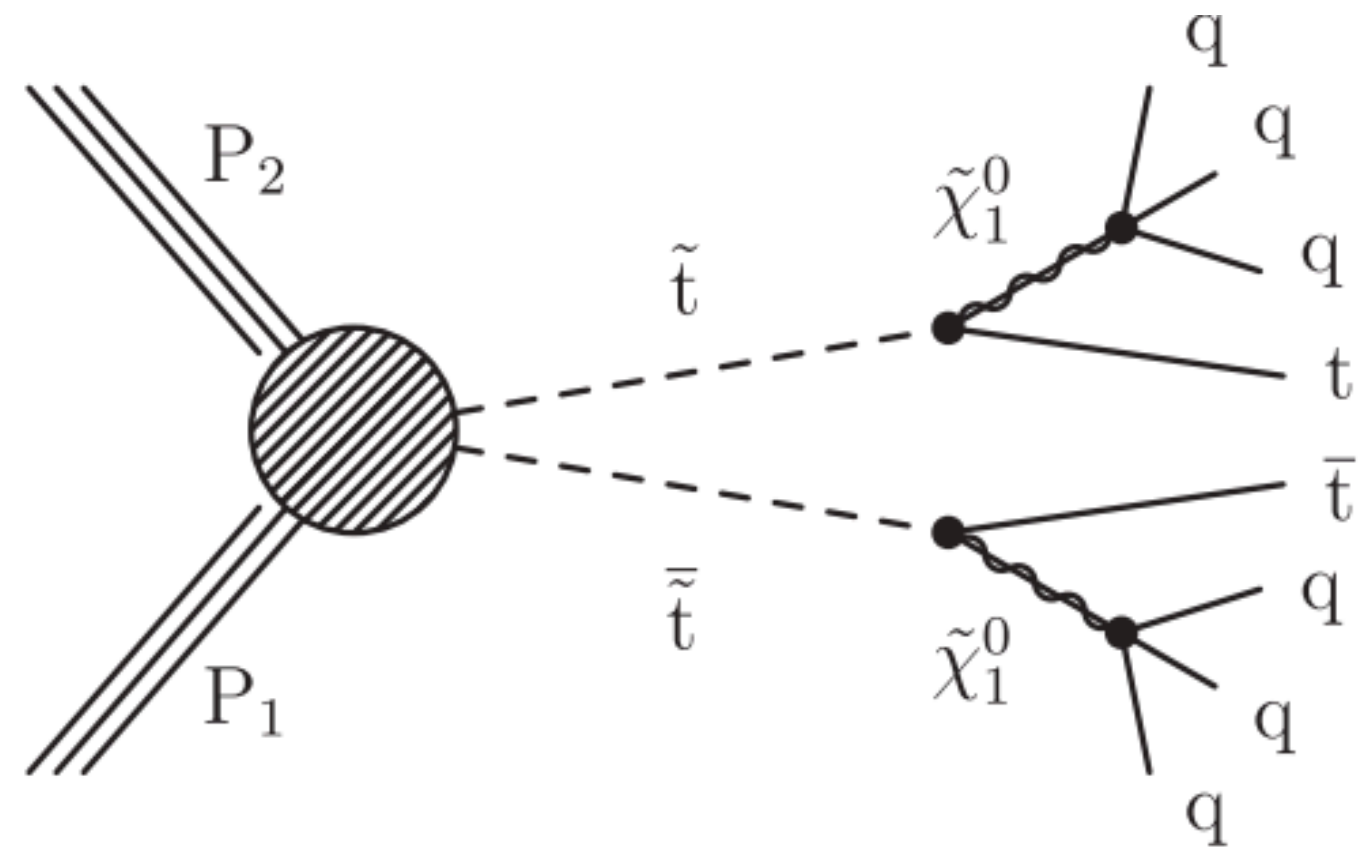
- No significant excess seen in  $m_{Zl}$  distributions of the signal regions
- Multi-bin fit is used across 3 SRs
- Limits of 625 GeV, 1050 GeV, and 1100 GeV set as lower limits for 100% BR to a Z plus a tau, muon or electron respectively.

[arXiv:2011.10543](https://arxiv.org/abs/2011.10543)



# Search for stops with final states 2 tops & light flavor jets

[arXiv:2102.06976](https://arxiv.org/abs/2102.06976)



## Model:

1. RPV SUSY
2. Stealth SUSY

## Signature:

$\geq 7$  jets

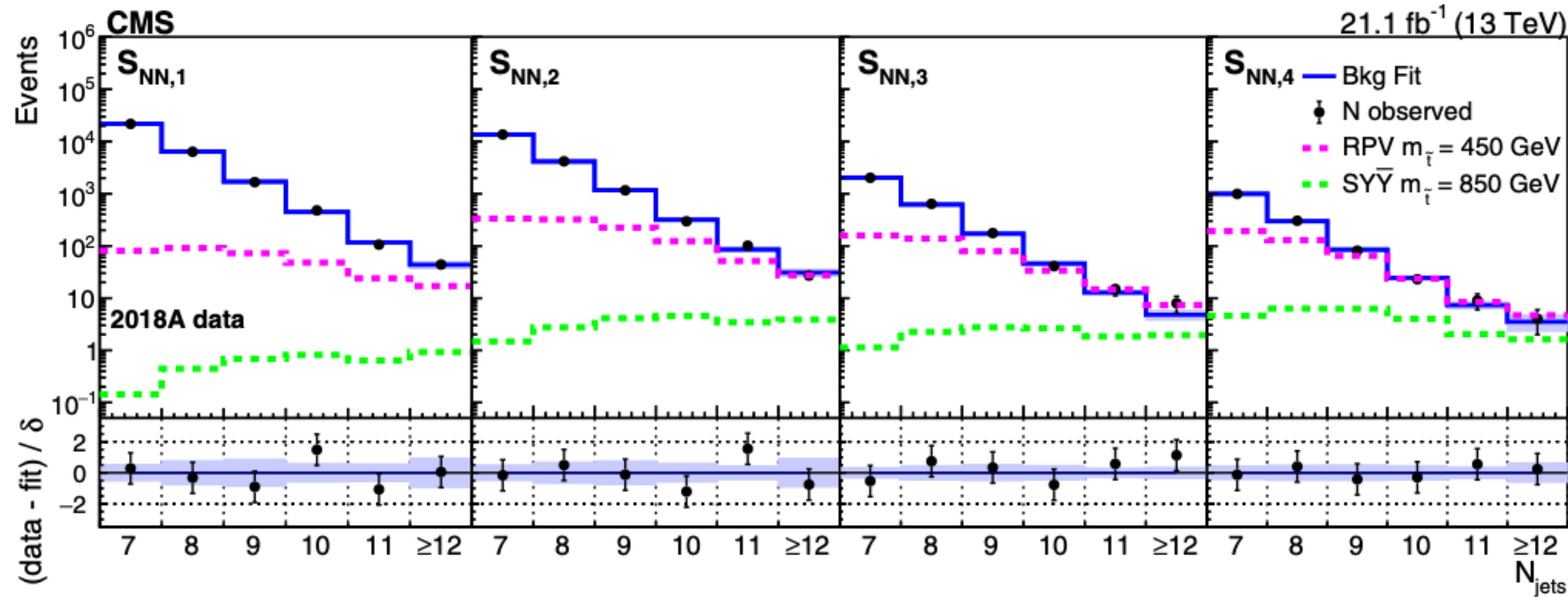
exactly 1  $e/\mu$



# Search for stops with final states 2 tops & light flavor jets



arXiv:2102.06976

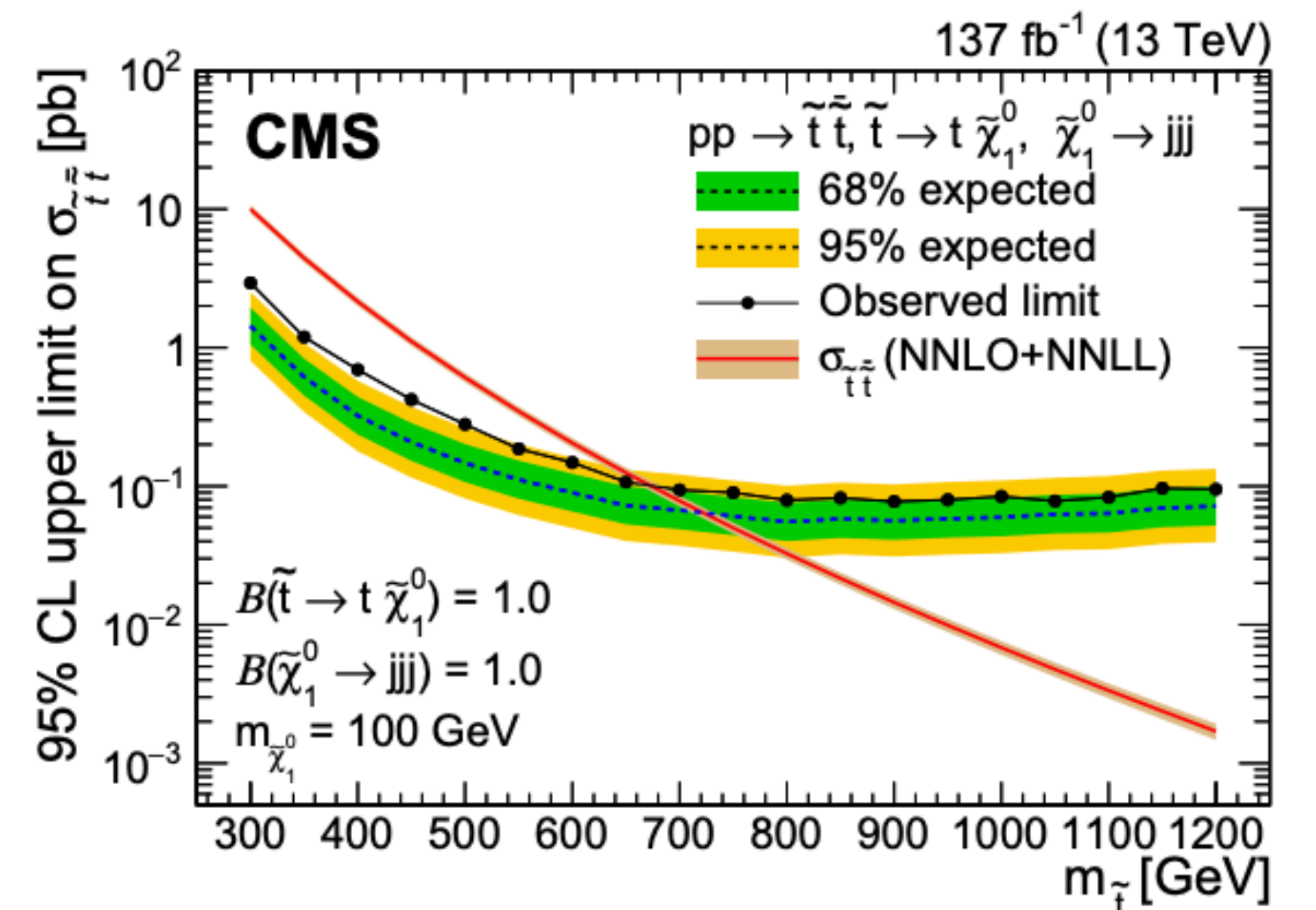


## Background Estimation:

- Neural network to distinguish signal and  $t\bar{t}$  background as well as spatial distribution of jets
- Jet multiplicity in 4 regions of NN space
- gradient reversal technique

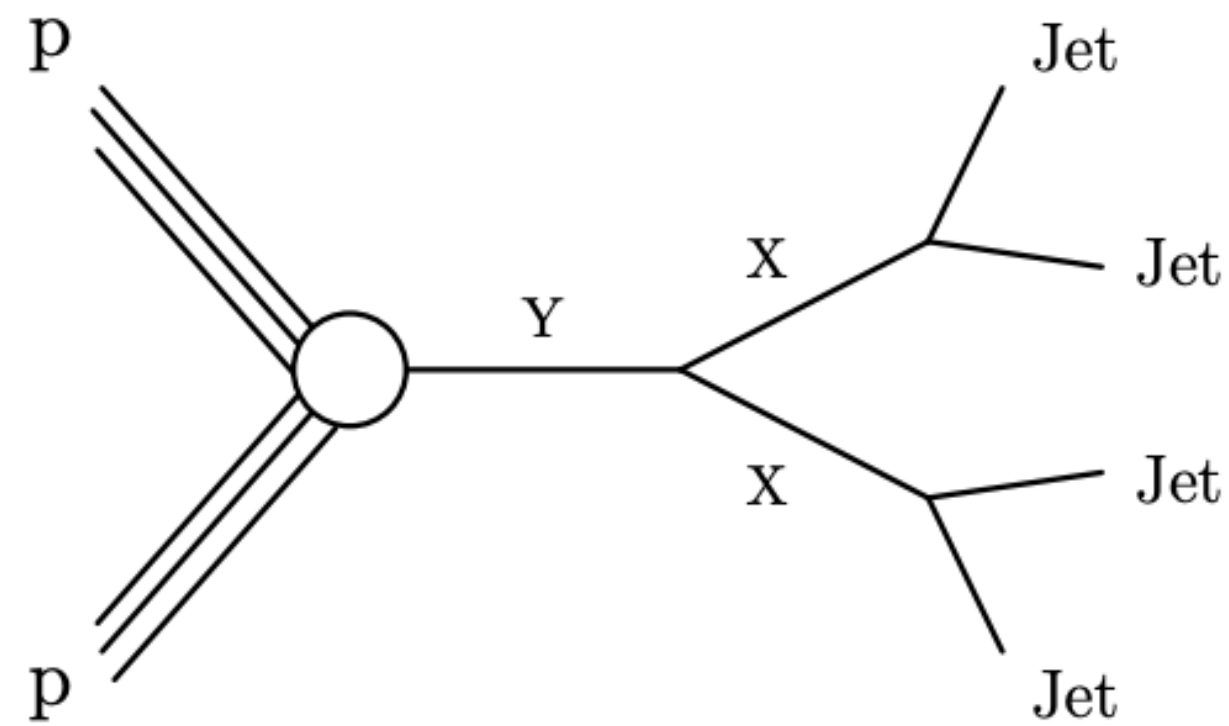
## Results:

- stop mass up to 670 (870) GeV for the RPV (stealth) scenario are excluded
- no significant signal over SM background observed



# Search for dijet resonance

[arXiv:2206.09997](https://arxiv.org/abs/2206.09997)



## Model:

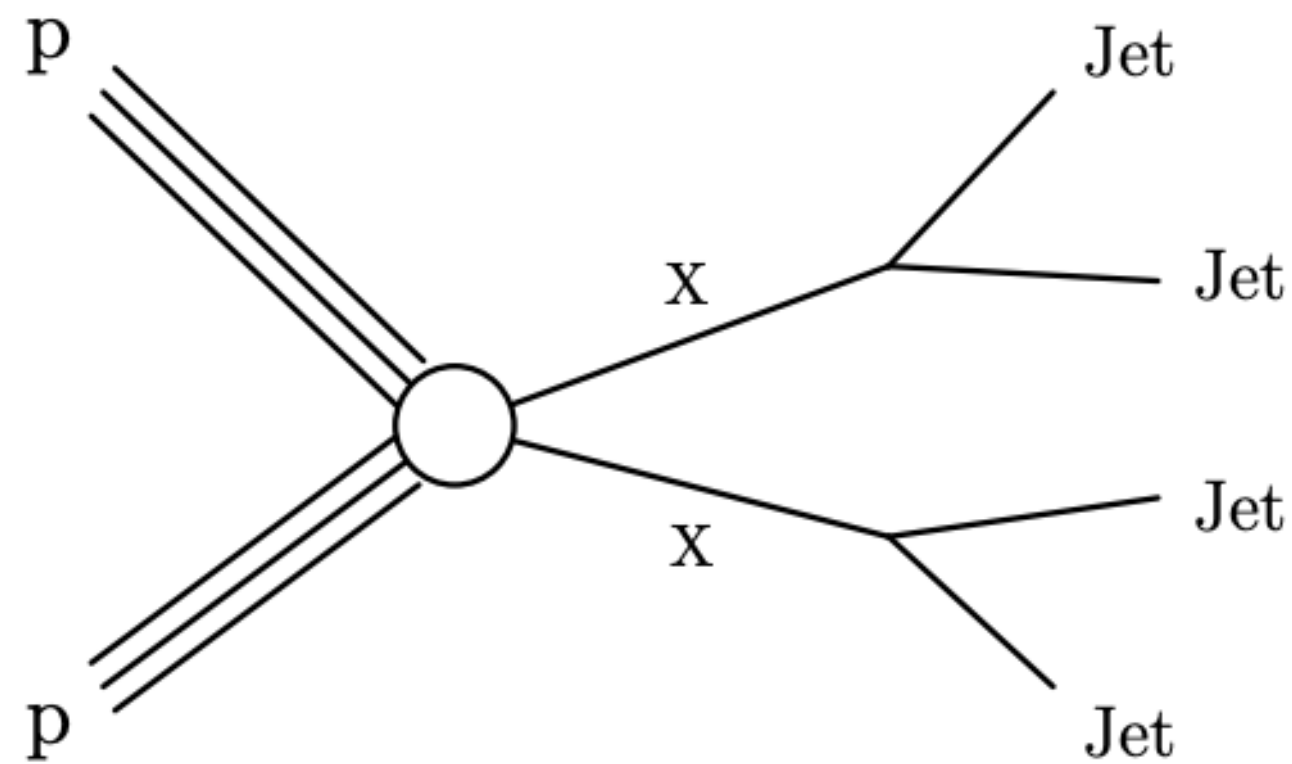
1. Scalar diquark as benchmark  $\rightarrow$  large cross section
2. RPV SUSY  $\rightarrow$  stop dijet resonance

## Signature:

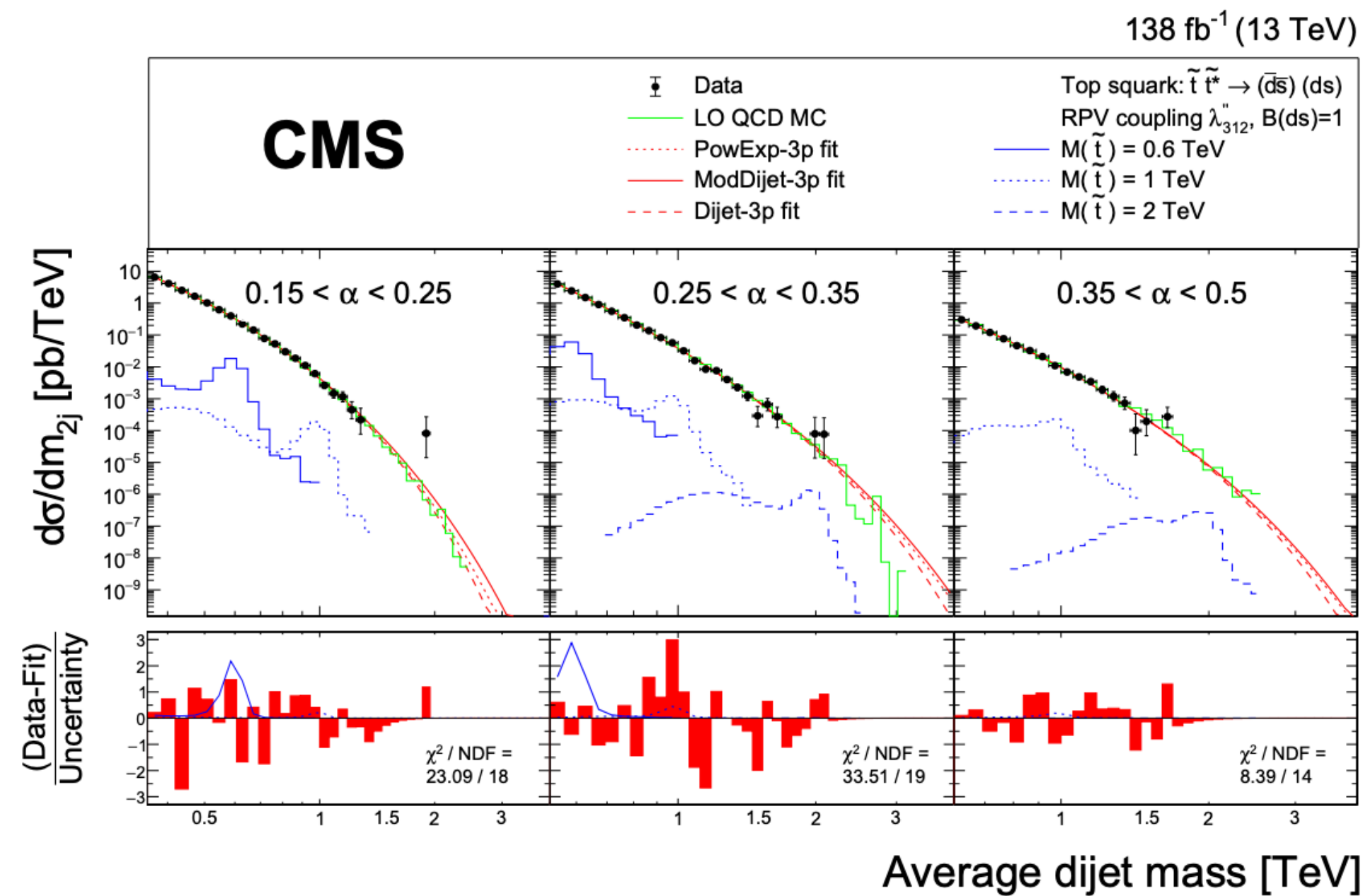
- equal mass dijet resonance
- At least 4 jet final state

1. Resonant production via a particle Y, of pairs of dijet resonance X

2. Non-resonant production



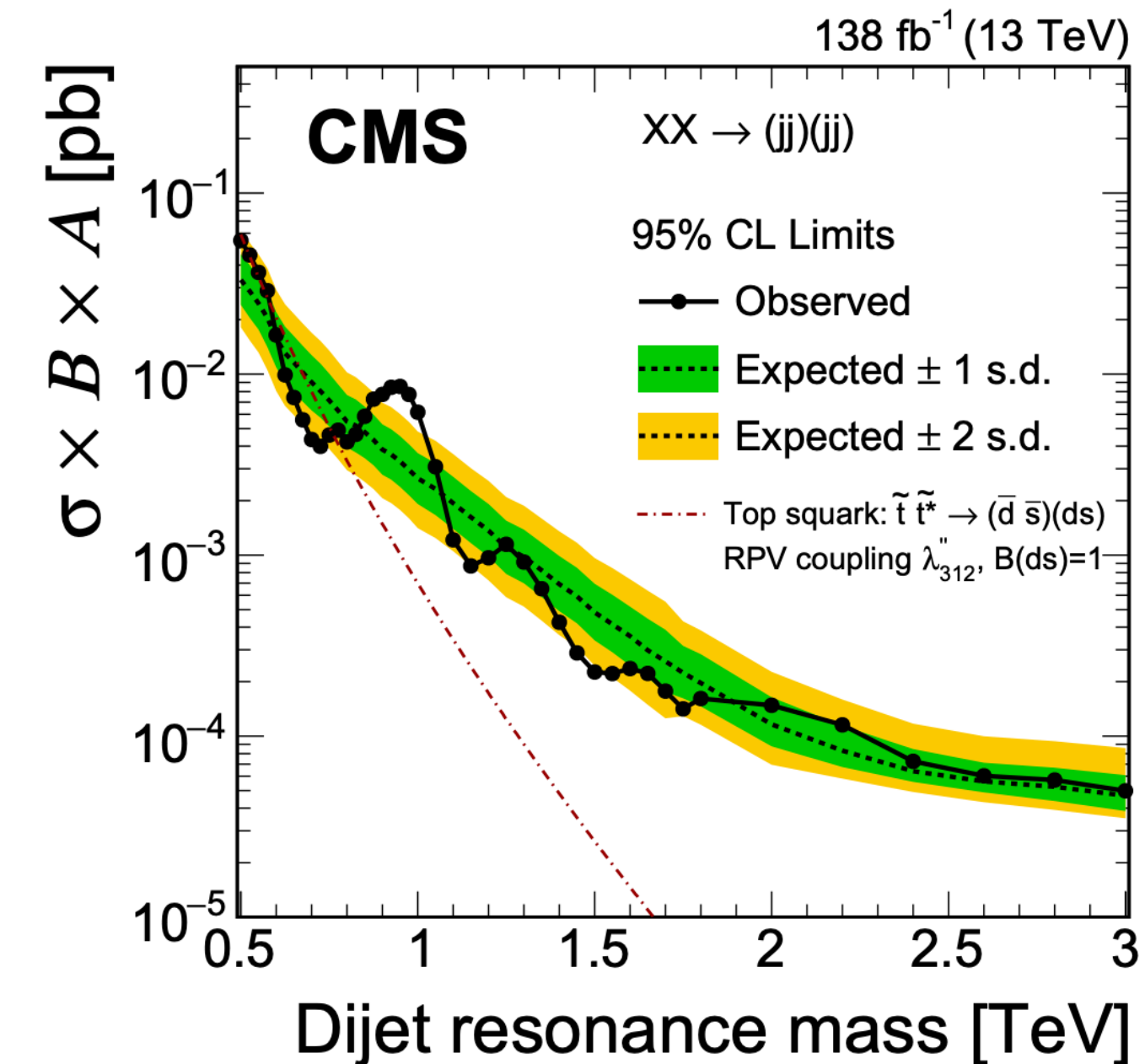
# Search for dijet resonance



arXiv:2206.09997

## Result

- Extended limits on four jet and dijet production cross sections
- 0.5TeV to 0.77TeV stop masses excluded
- <0.76TeV excluded for diquark masses

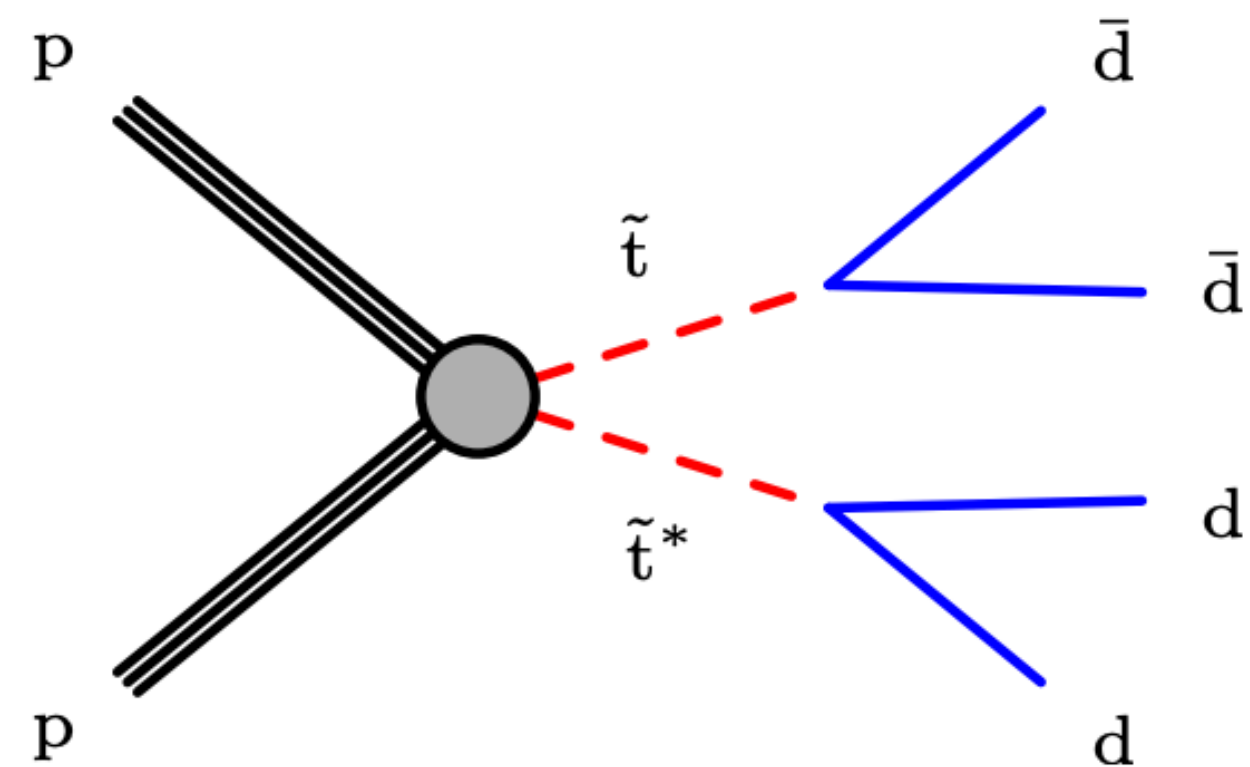
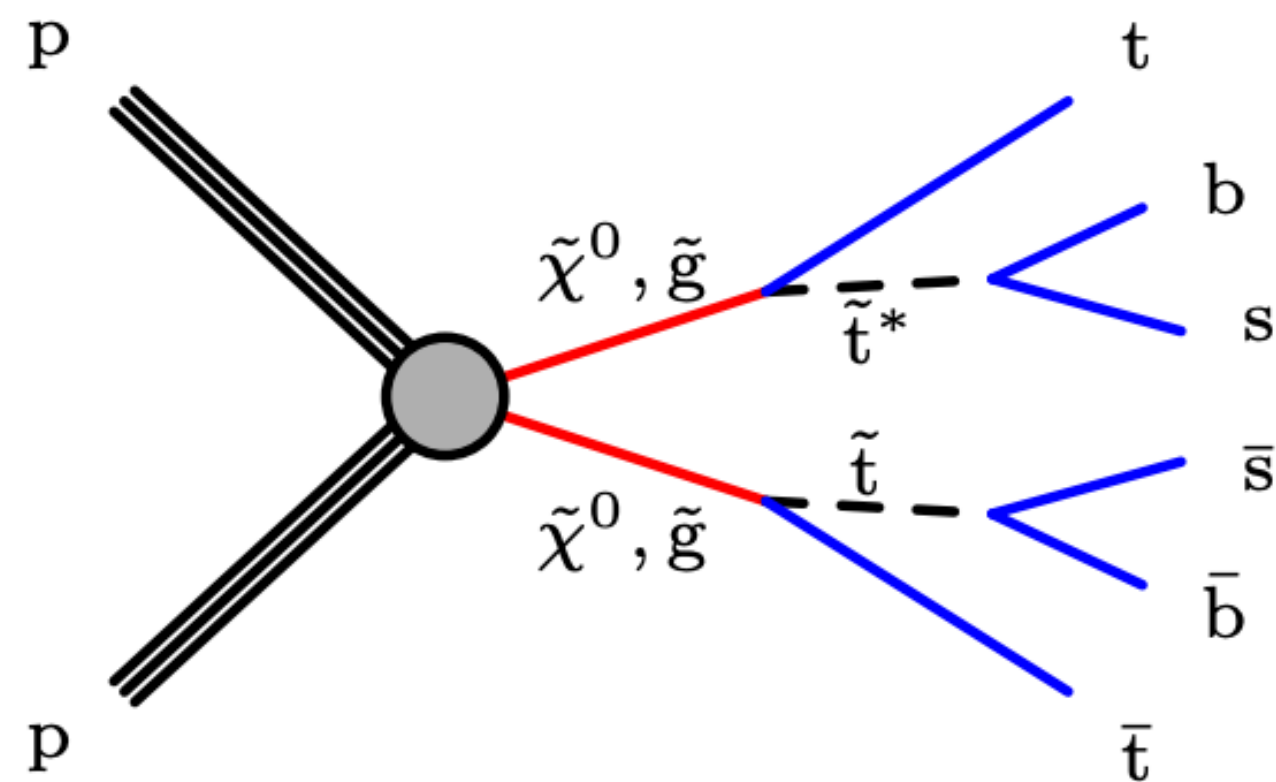


## Analysis Strategy

- $\alpha = \bar{m}_{jj}/m_{4j}$  measure of the boost of the two dijet systems
- $\alpha$  is a good variable to bin the data-> increases sensitivity
- optimize the number of  $\alpha$  bins for maximum signal sensitivity

# Search for LLPs decaying to jets with displaced vertices

[arXiv:2104.13474](https://arxiv.org/abs/2104.13474)  
[Phys. Rev. D 104, 052011 \(2021\)](https://arxiv.org/abs/2104.13474)



## Model:

1. RPV SUSY  $\rightarrow$  LSP is LLP gluino or neutralino
2. RPV SUSY  $\rightarrow$  LSP is LLP stop

Extension of previous search [arXiv:1808.03078](https://arxiv.org/abs/1808.03078)

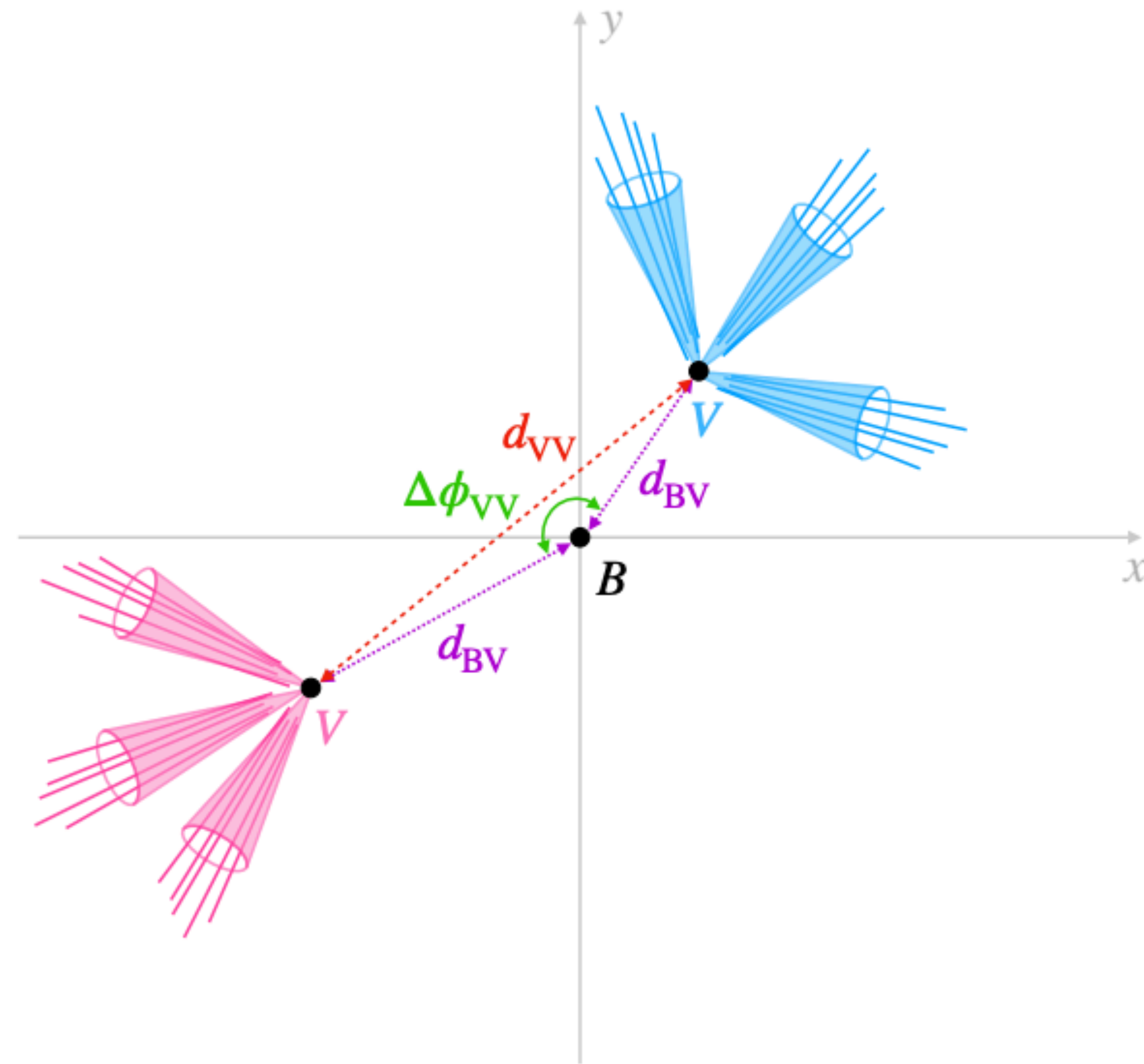
## Signature:

LLP's produced in pairs decaying to multiple jets containing charged particles ( $\geq 5$  track vertex)

2 reconstructed vertices within radius of the beam pipe

$$d_{BV} > 100\mu m \pm 25\mu m$$

# Search for LLPs decaying to jets with displaced vertices



# Search for LLPs decaying to jets with displaced vertices



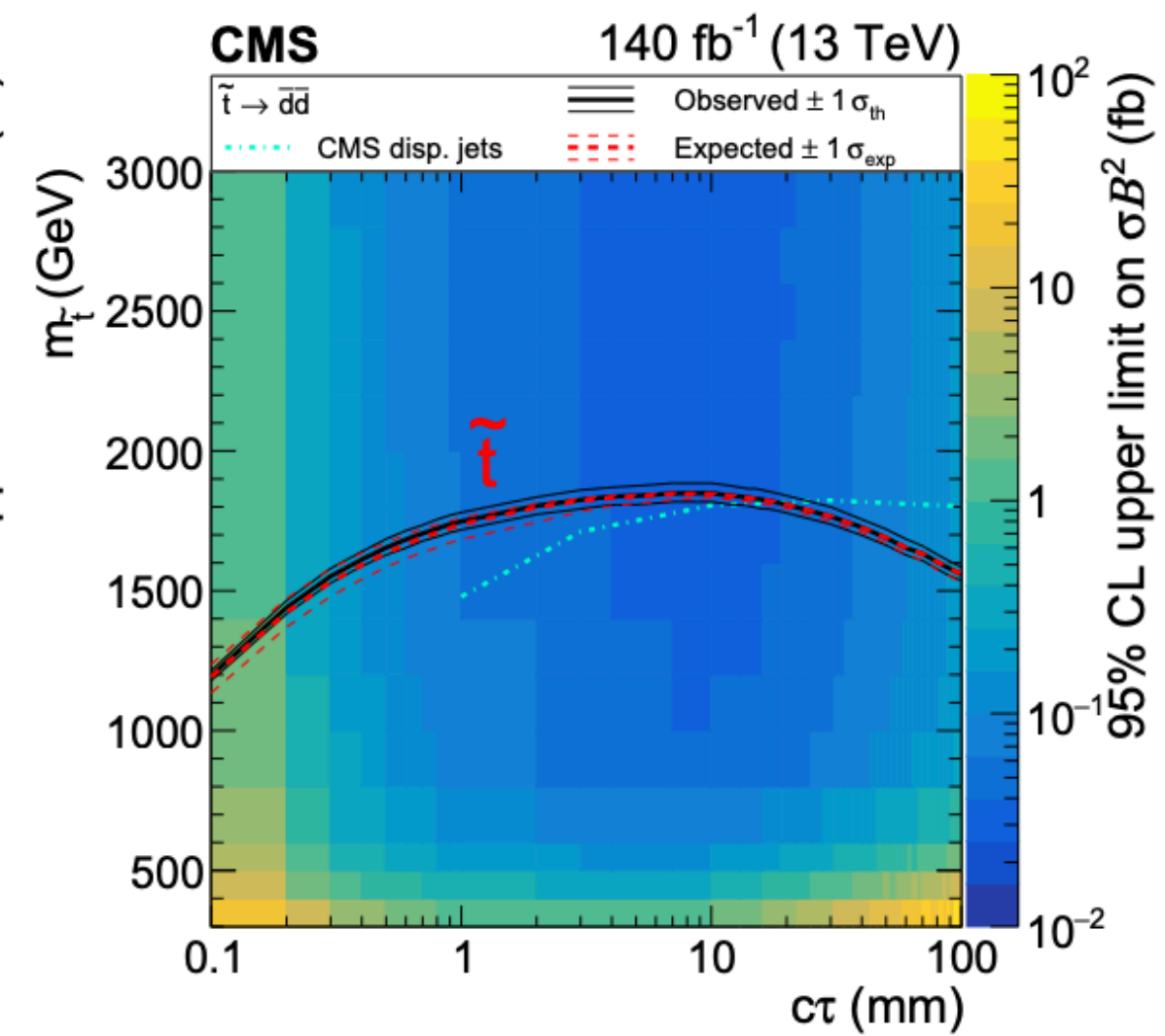
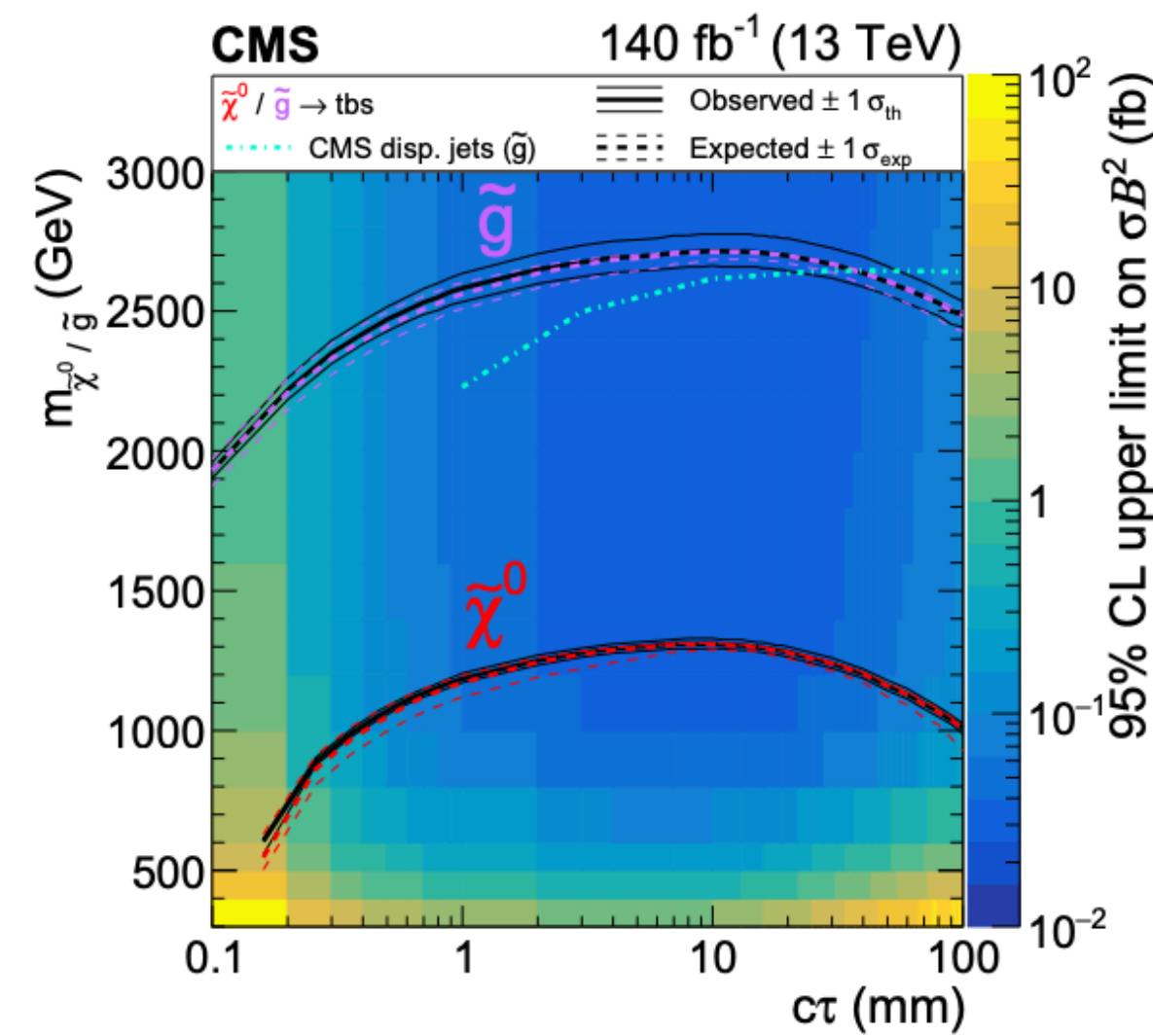
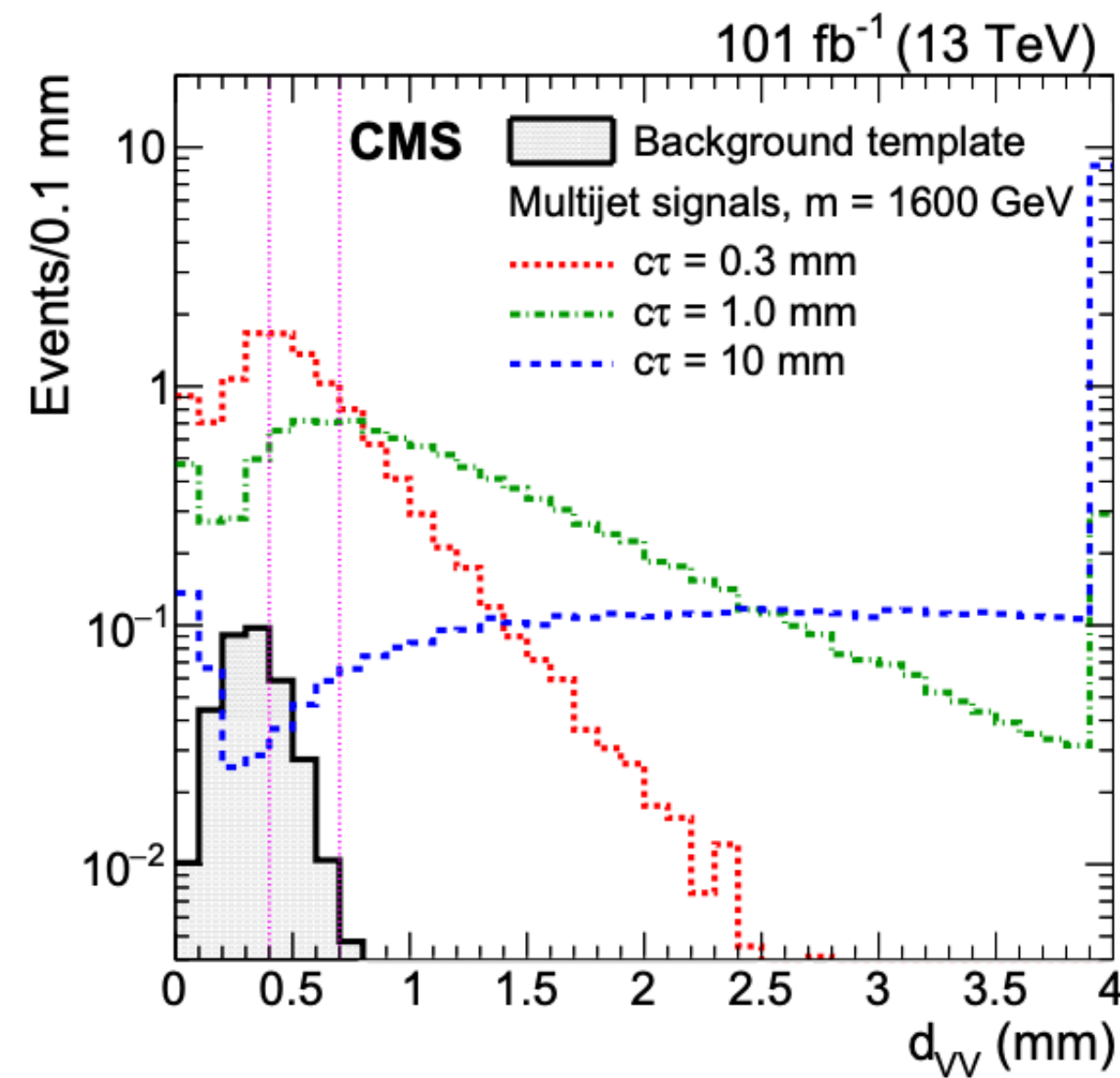
## Background Estimation

- Vertex refitting procedure removes more than 40% of background vertices due to pileup
- Three bins for distance between vertices to maximize signal significance

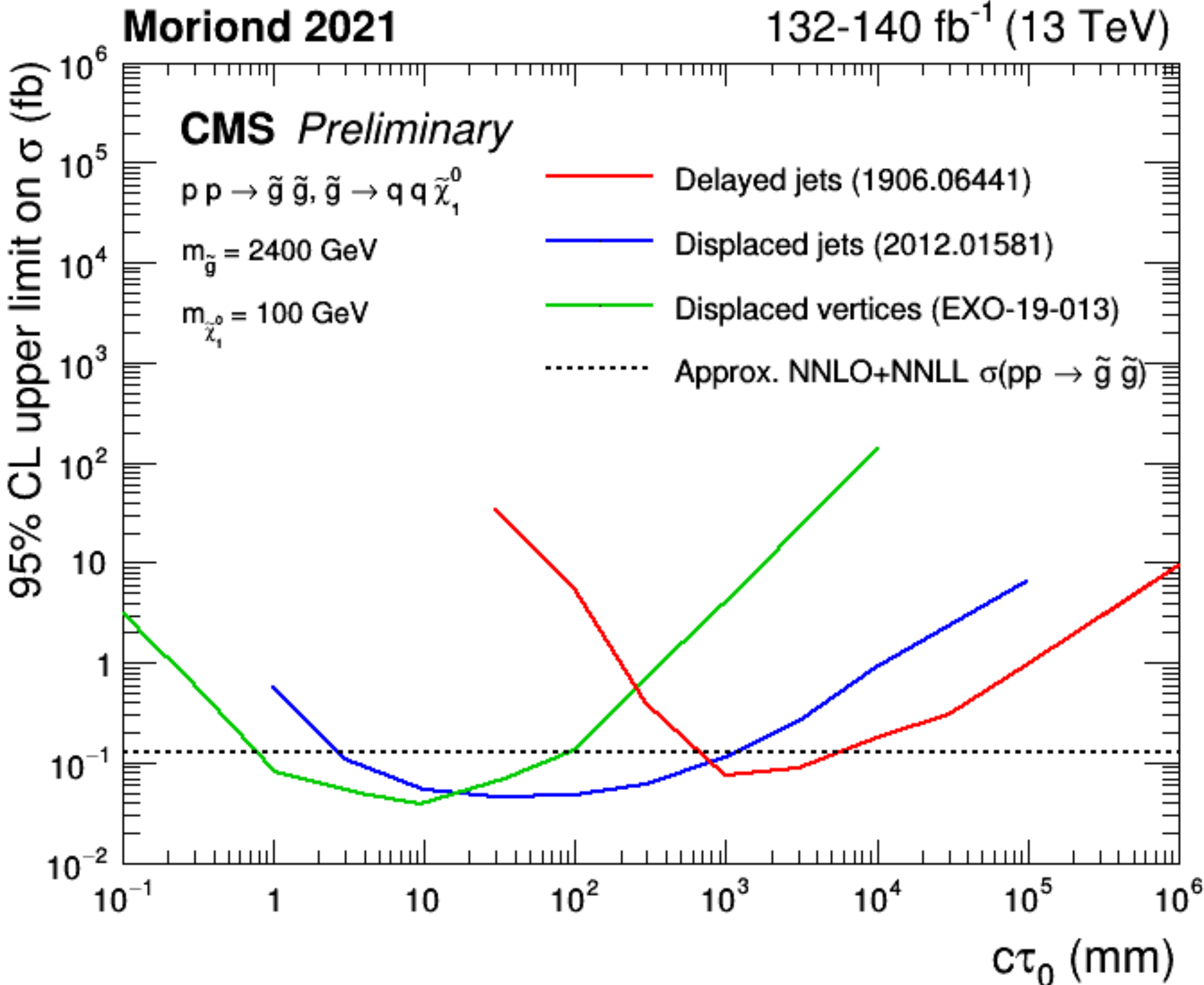
[arXiv:2104.13474](https://arxiv.org/abs/2104.13474)

## Result

- No excess over SM observed
- Upper limits set on both RPV SUSY models
- Can apply these results to other signal models



# CMS summary plot



# Conclusions

- Diverse set of final states with a variety of production modes presented for both CMS and ATLAS results
  - short and long-lived LSP decays
  - UDD and B-L RPV
- New techniques improve limits across different physics models
  - Data-driven background estimation
  - Neural Networks
- With start of Run 3 at the LHC we will have new data and hopefully new results on RPV and baryon number violating searches!



# Backup

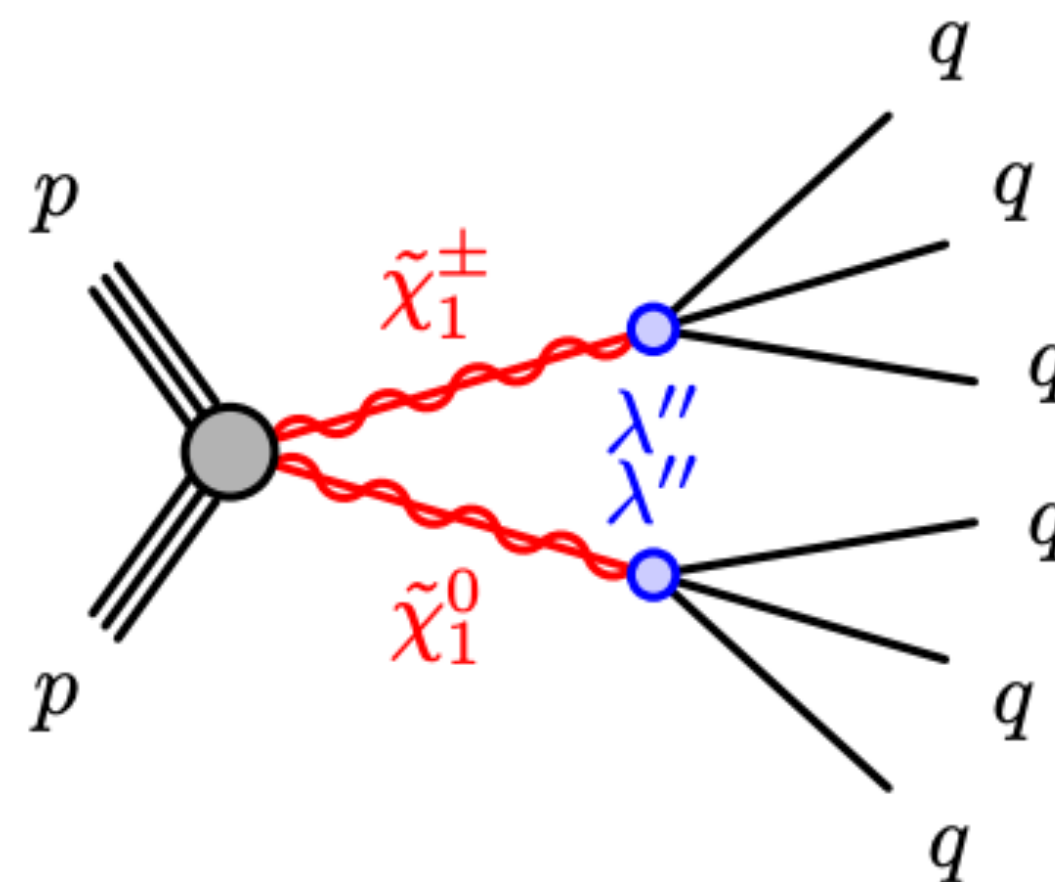
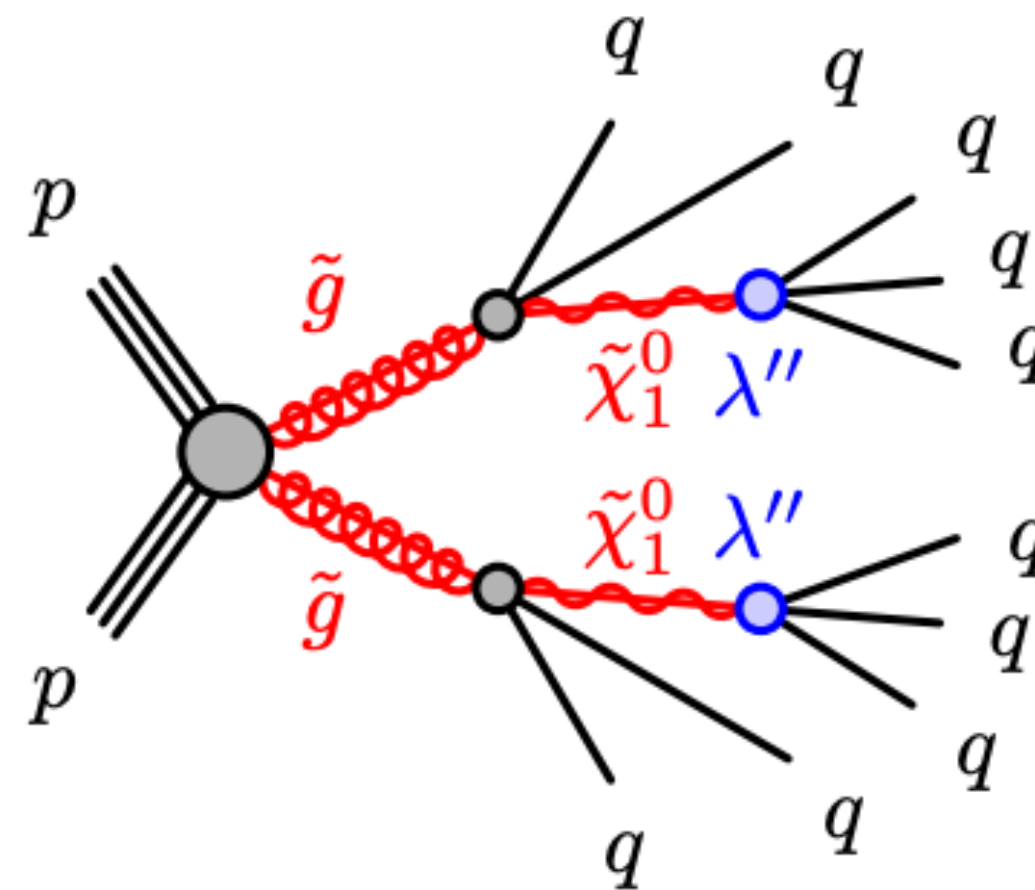
# Search for LLPs with displaced vertices + jets



## Target Models:

- Small values of RPV UDD coupling( $\lambda''$ )
- $\lambda''$  constrained experimentally to be small  $\rightarrow$  LLPs arise

ATLAS-CONF-2022-054



## Signature:

$$R_{DV} < 300\text{mm}$$

$$n_{\text{selected tracks}}^{DV} \geq 2$$

1.Strong RPV scenario

2.EWK RPV scenario

# Search for LLPs with displaced vertices + jets

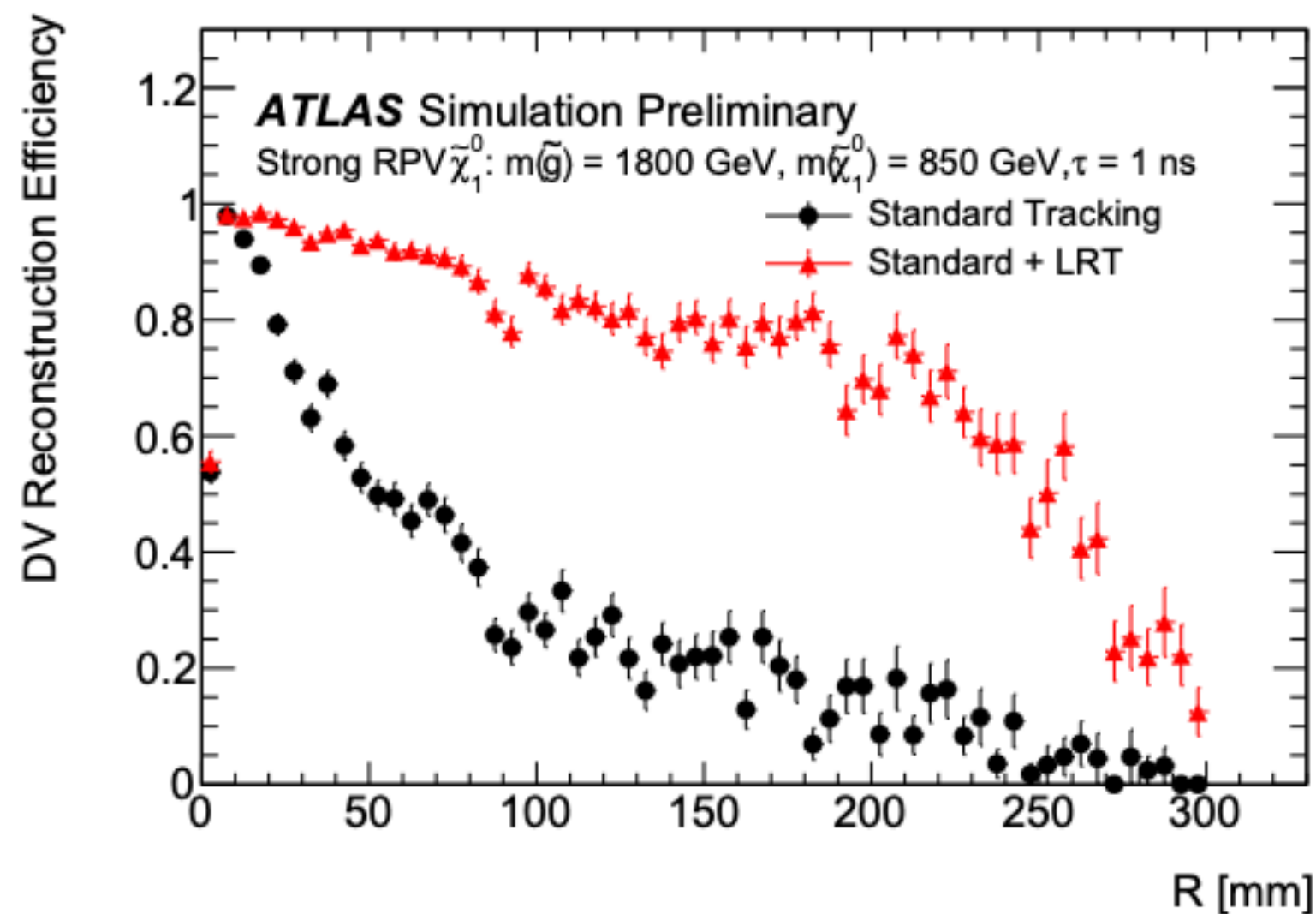


ATLAS-CONF-2022-054

## Managing SM background:

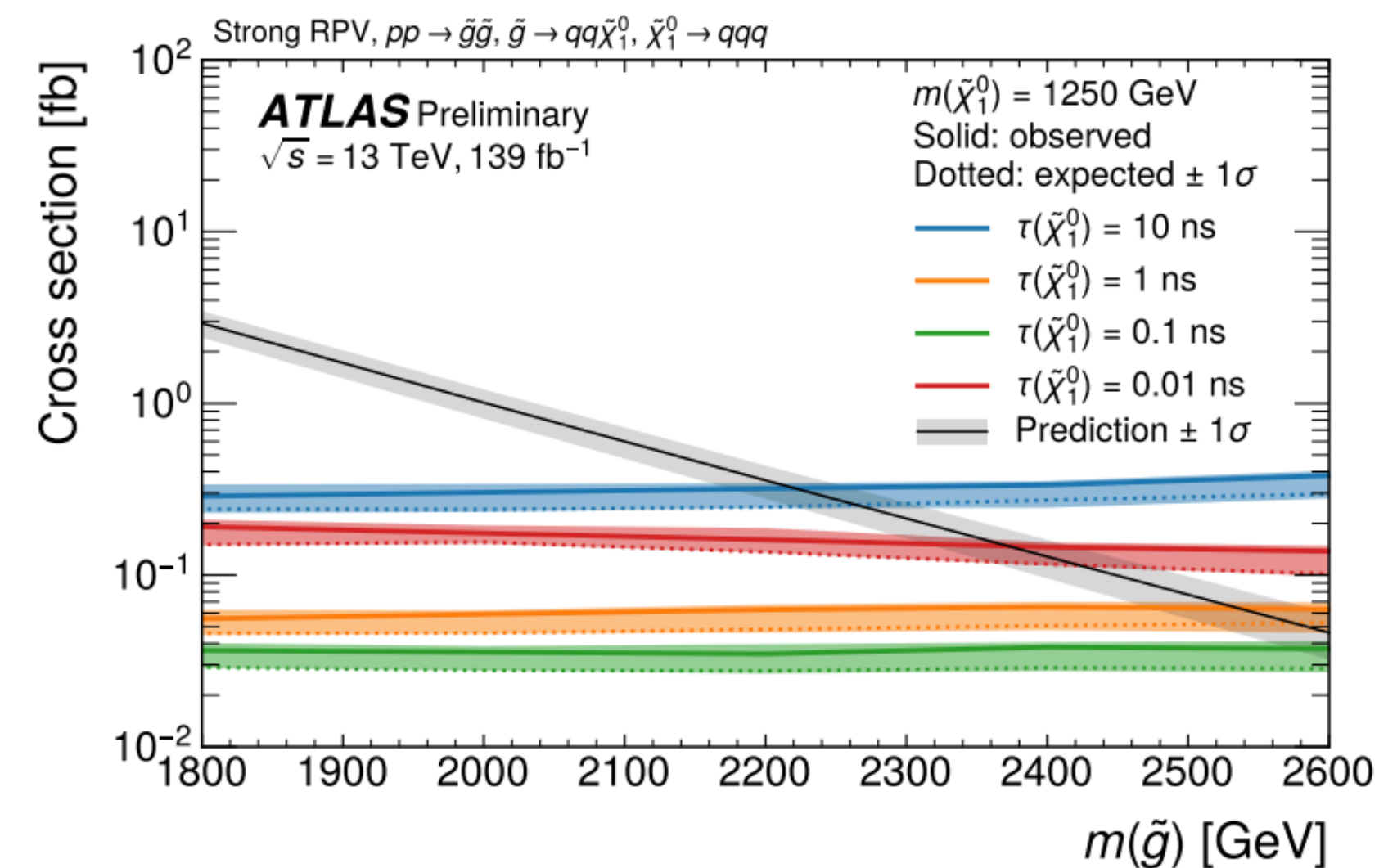
- Large radius tracking
- trackless and high pT jet filters

•



## Results:

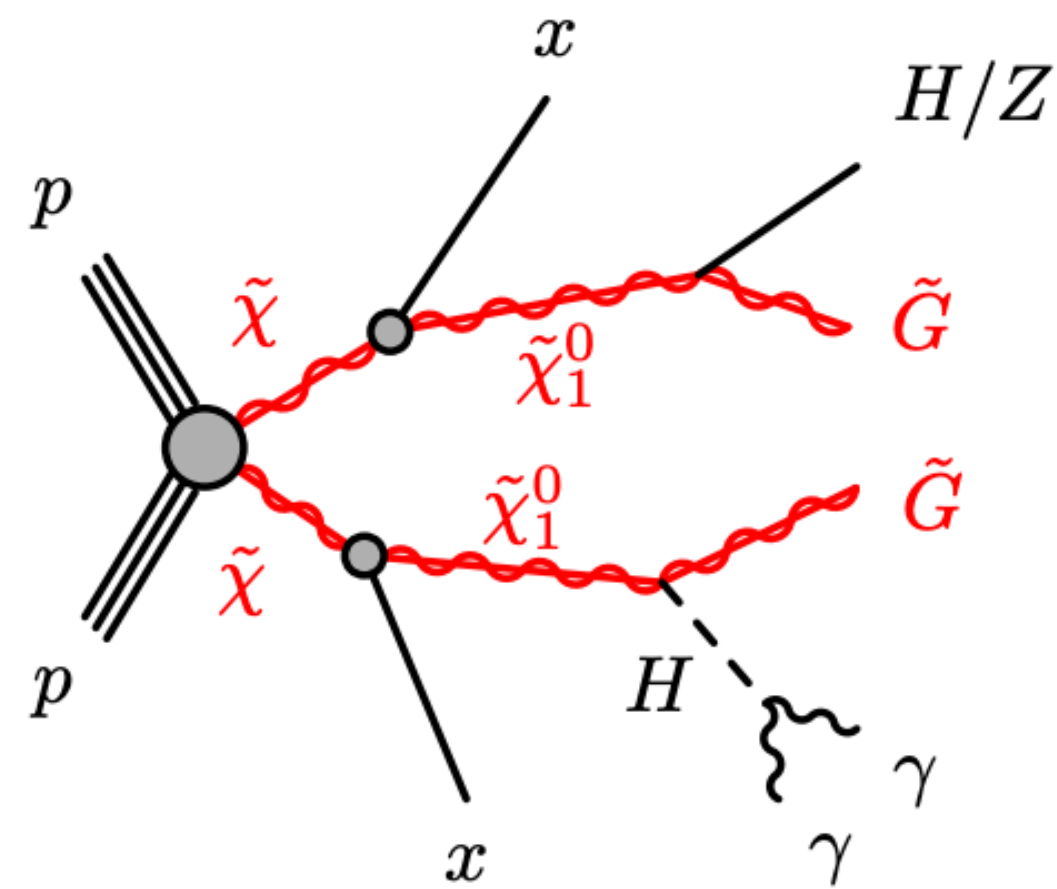
- Data agrees with background expectation
- set limits in the  $m(\tilde{\chi}_1^0)$  vs  $\tau(\tilde{\chi}_1^0)$
- set limits on sought signatures



# Search for LLPs with displaced diphoton vertices



ATLAS-CONF-2022-051

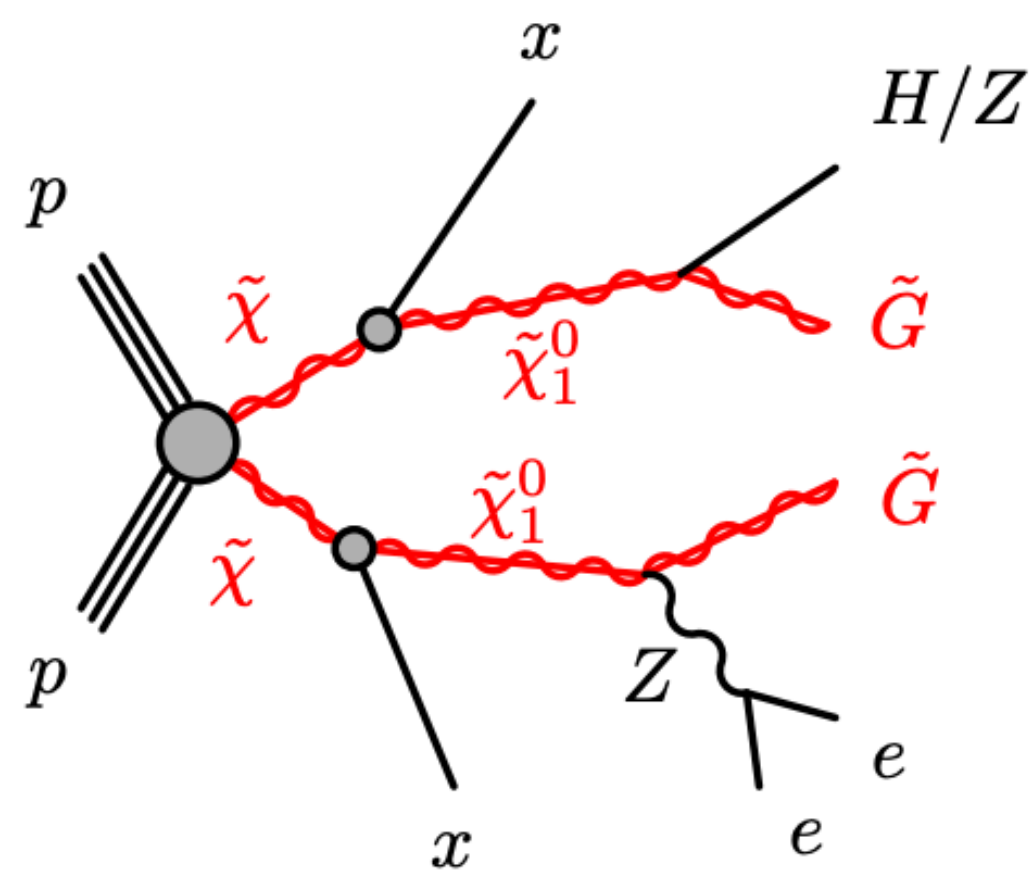


**Signature:**

- Displaced Diphoton Vertex (ee or  $\gamma\gamma$ )

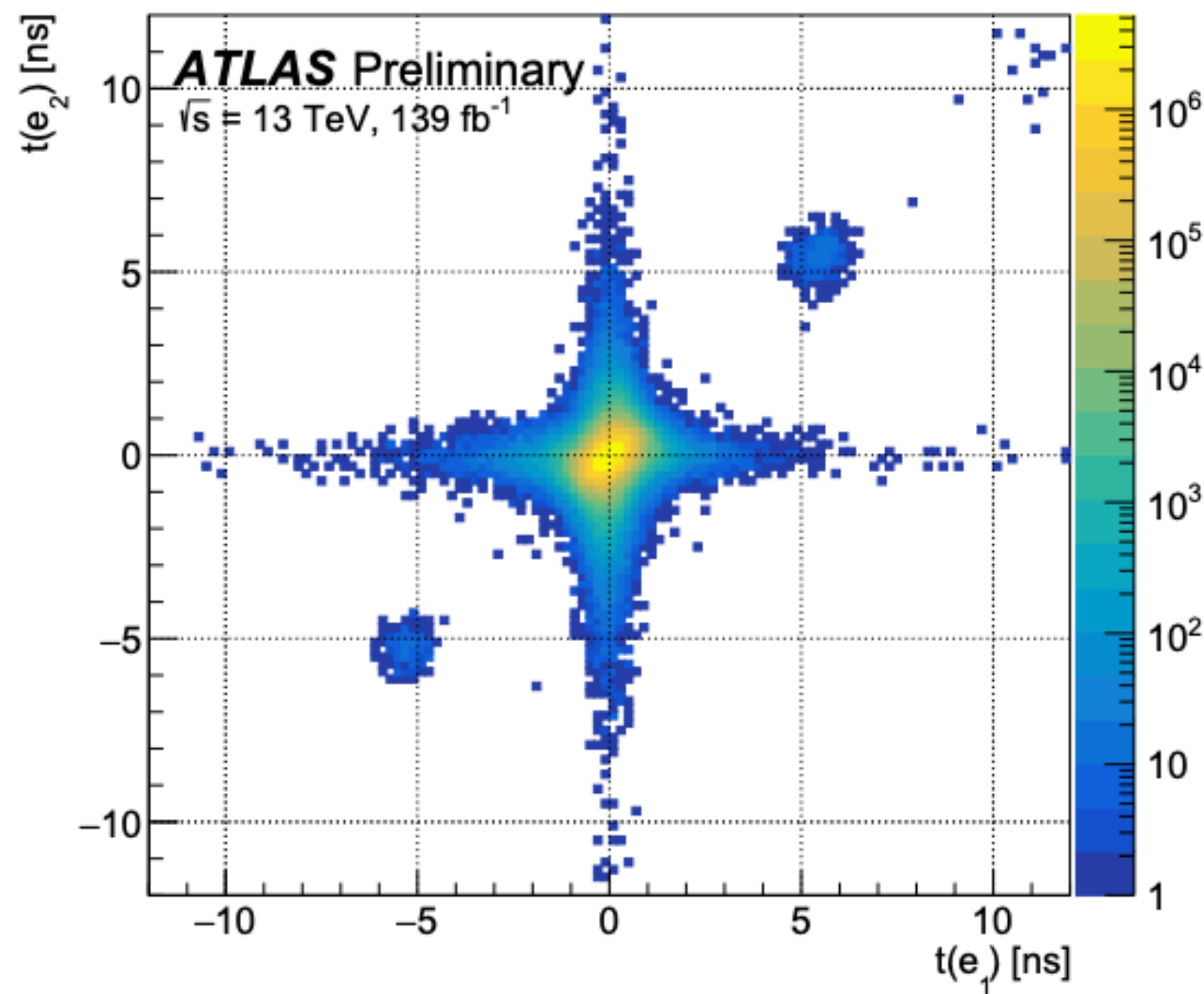
**Model:**

- Gauge mediated SUSY Breaking (GMSB)
- NLSP decays to SM particle (x)
- Displaced production of Higgs or  $Z^0$  boson from pair produced LLP



# Search for LLPs with displaced diphoton vertices

ATLAS-CONF-2022-051

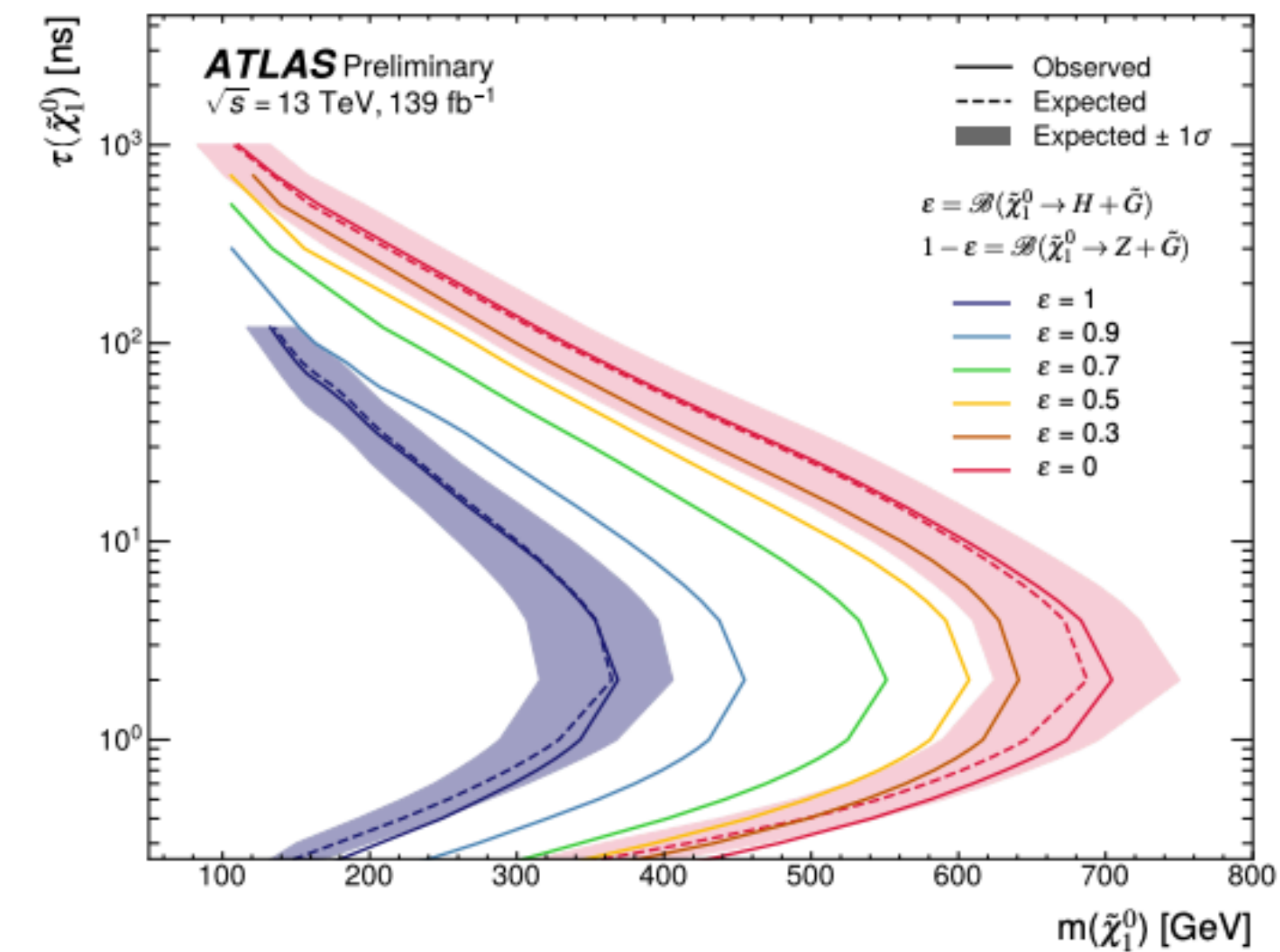


## Photon Selection:

- Utilizing LAr calorimeter
1. timing of photon signal
  2. pointing of its trajectory back to the beamline

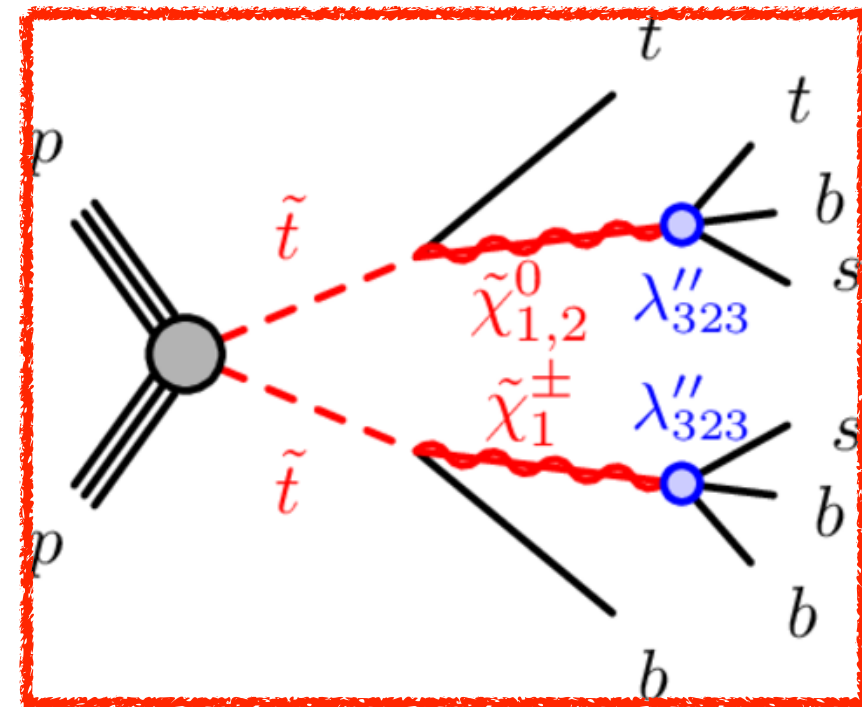
## Results:

- No excess above SM background estimation
- Limits set on GMSB models

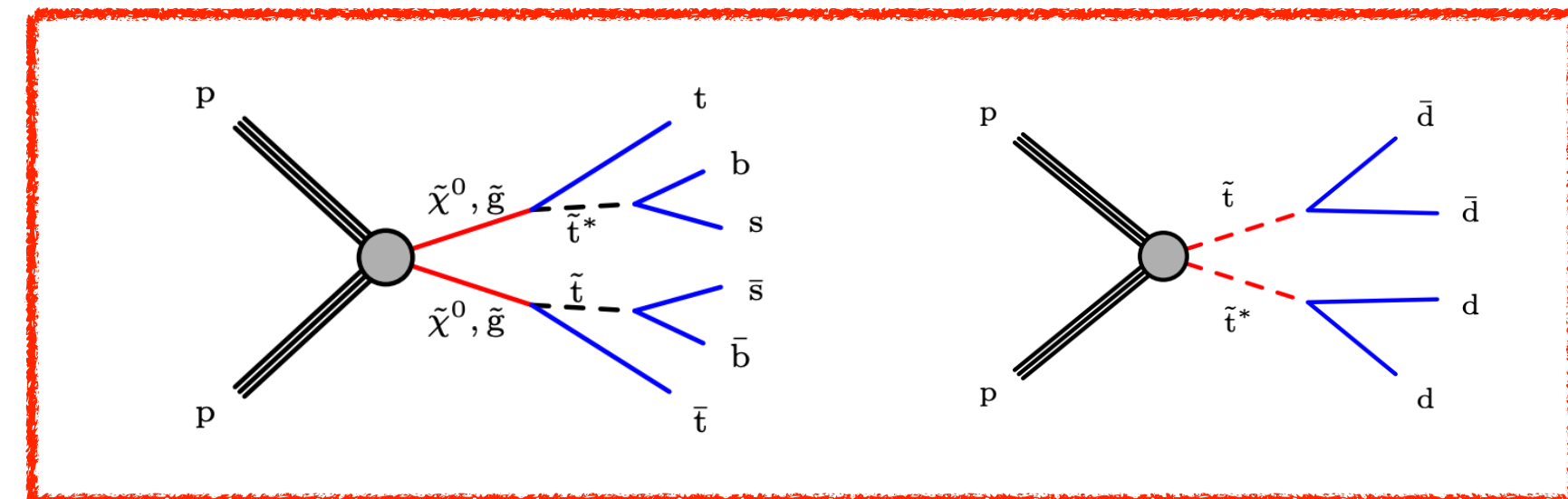
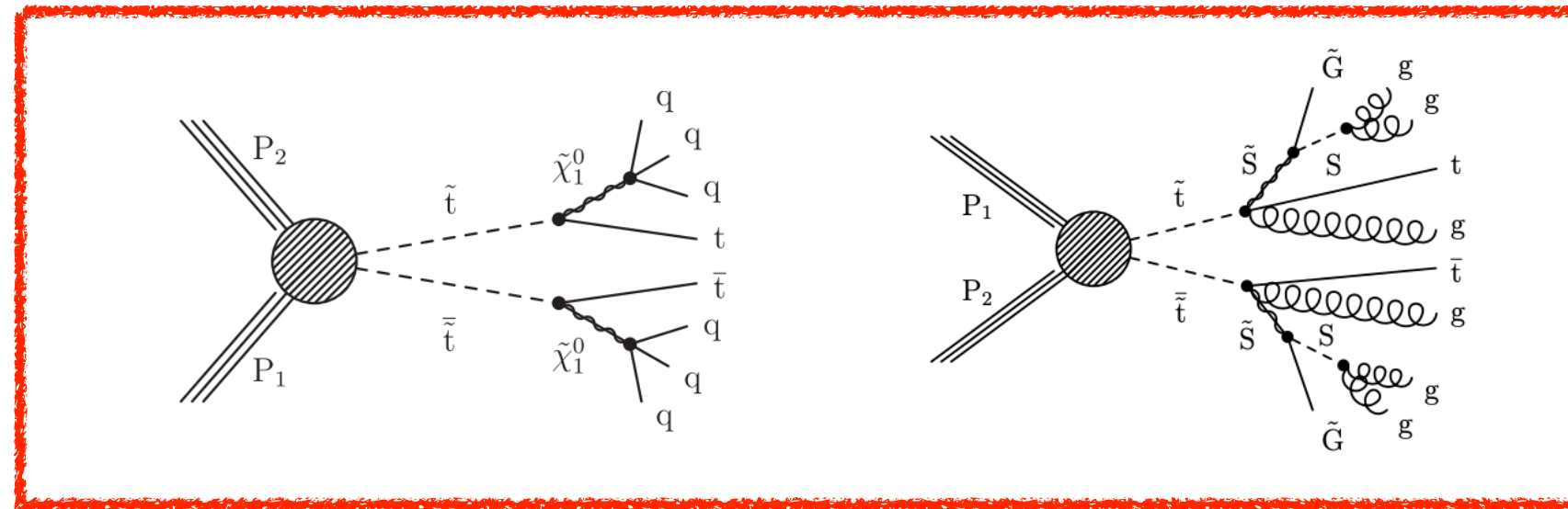
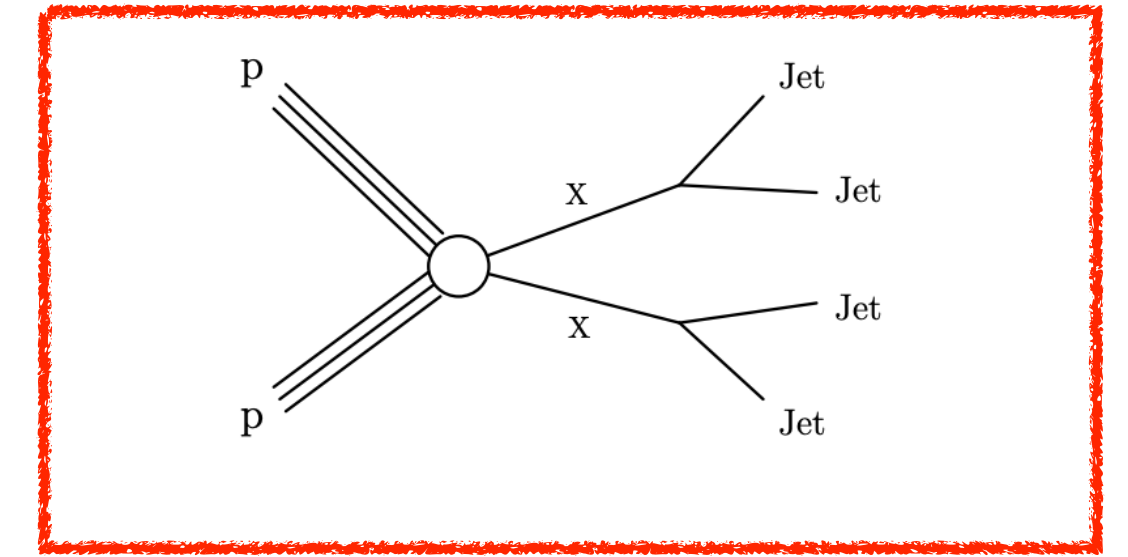
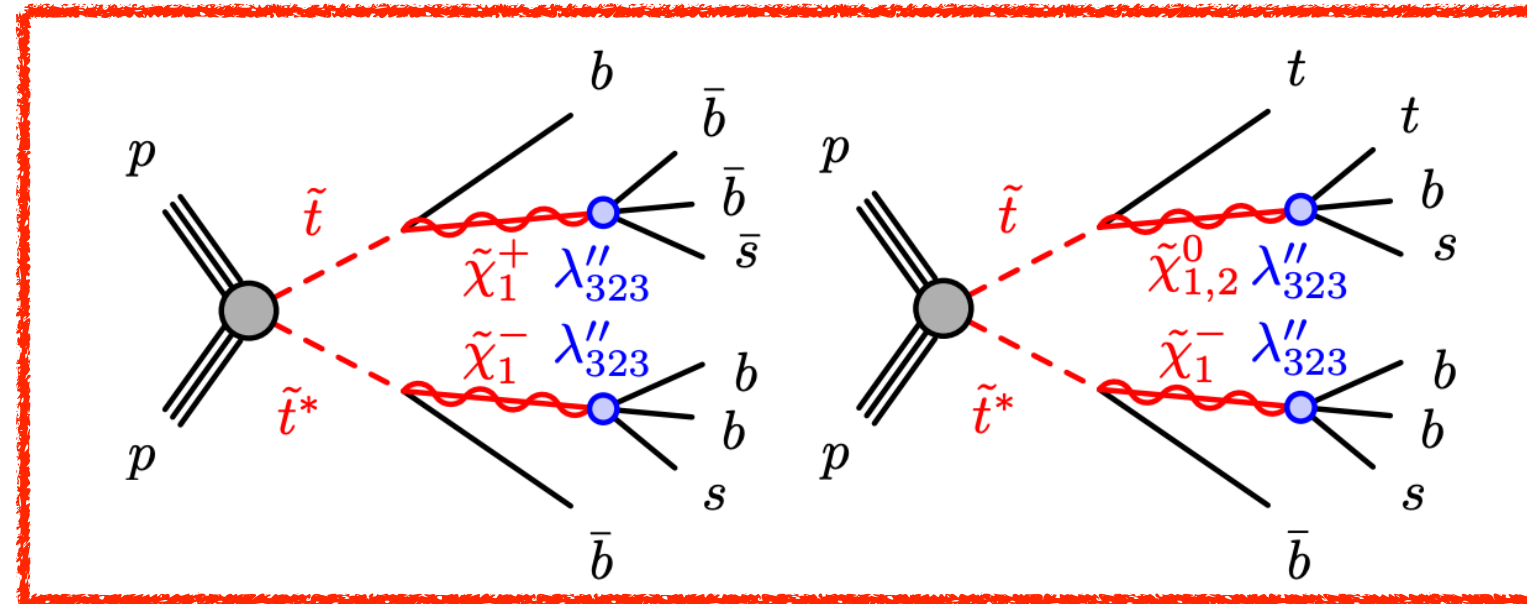


# Overview of Signatures Covered

$UDD(\lambda'')$

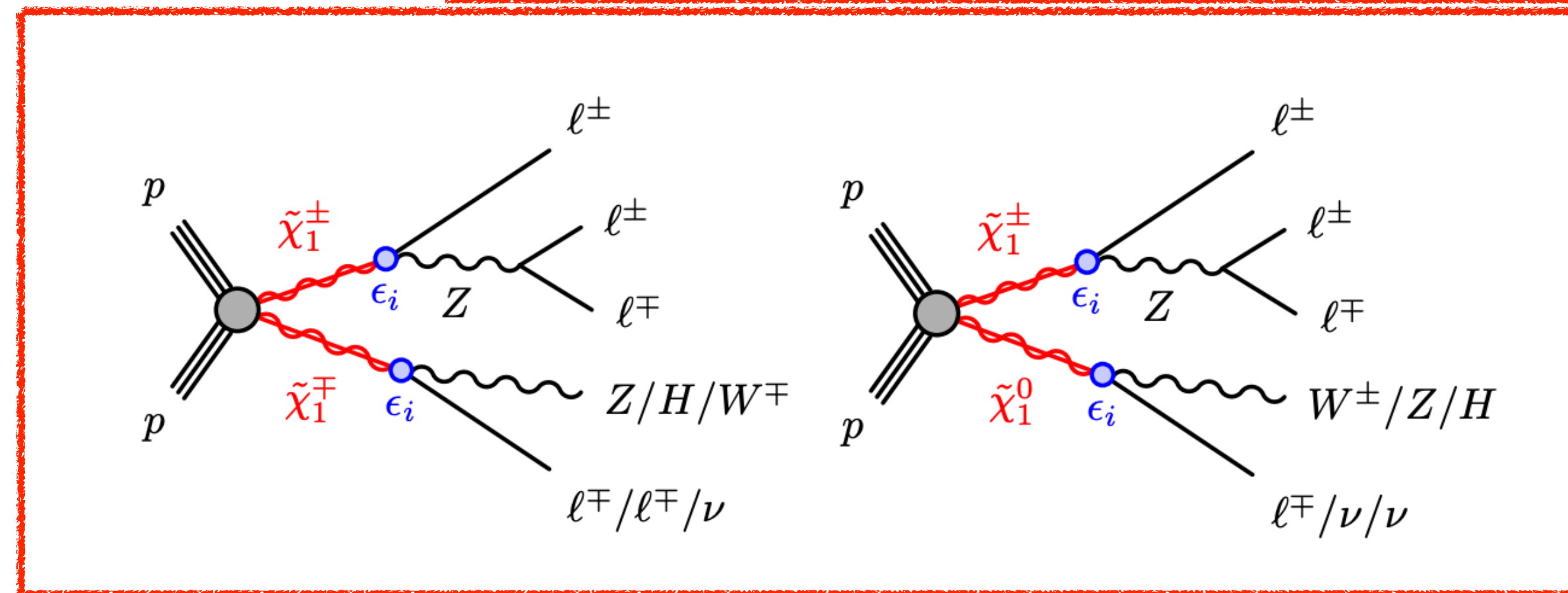


$$\Delta B \neq 0, \Delta L = 0, \Delta[B - L] \neq 0$$



$Bilinear B - L$

$$\Delta B = 0, \Delta L \neq 0, \Delta[B - L] \neq 0$$

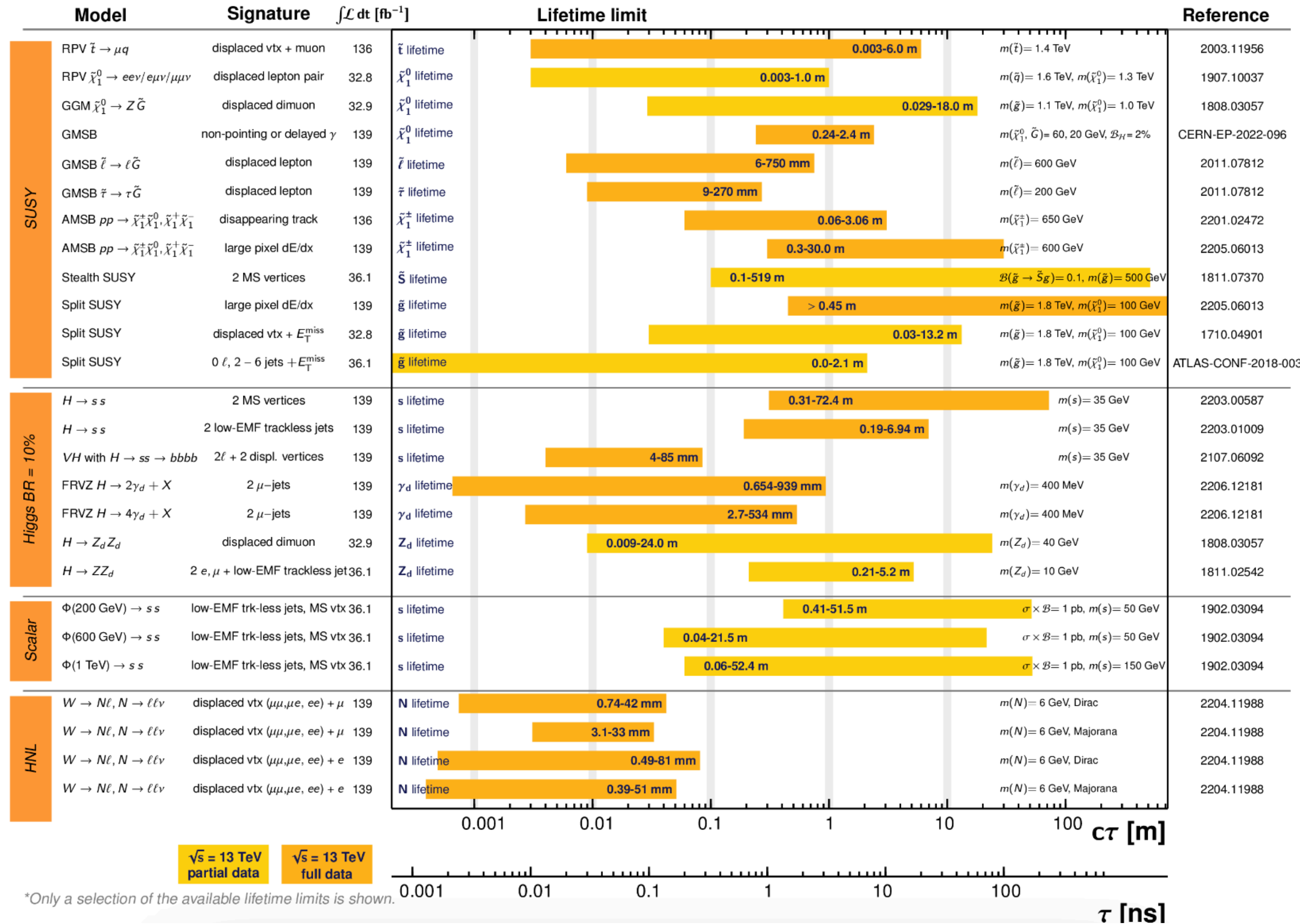


# ATLAS LLP Summary Plot

## ATLAS Long-lived Particle Searches\* - 95% CL Exclusion

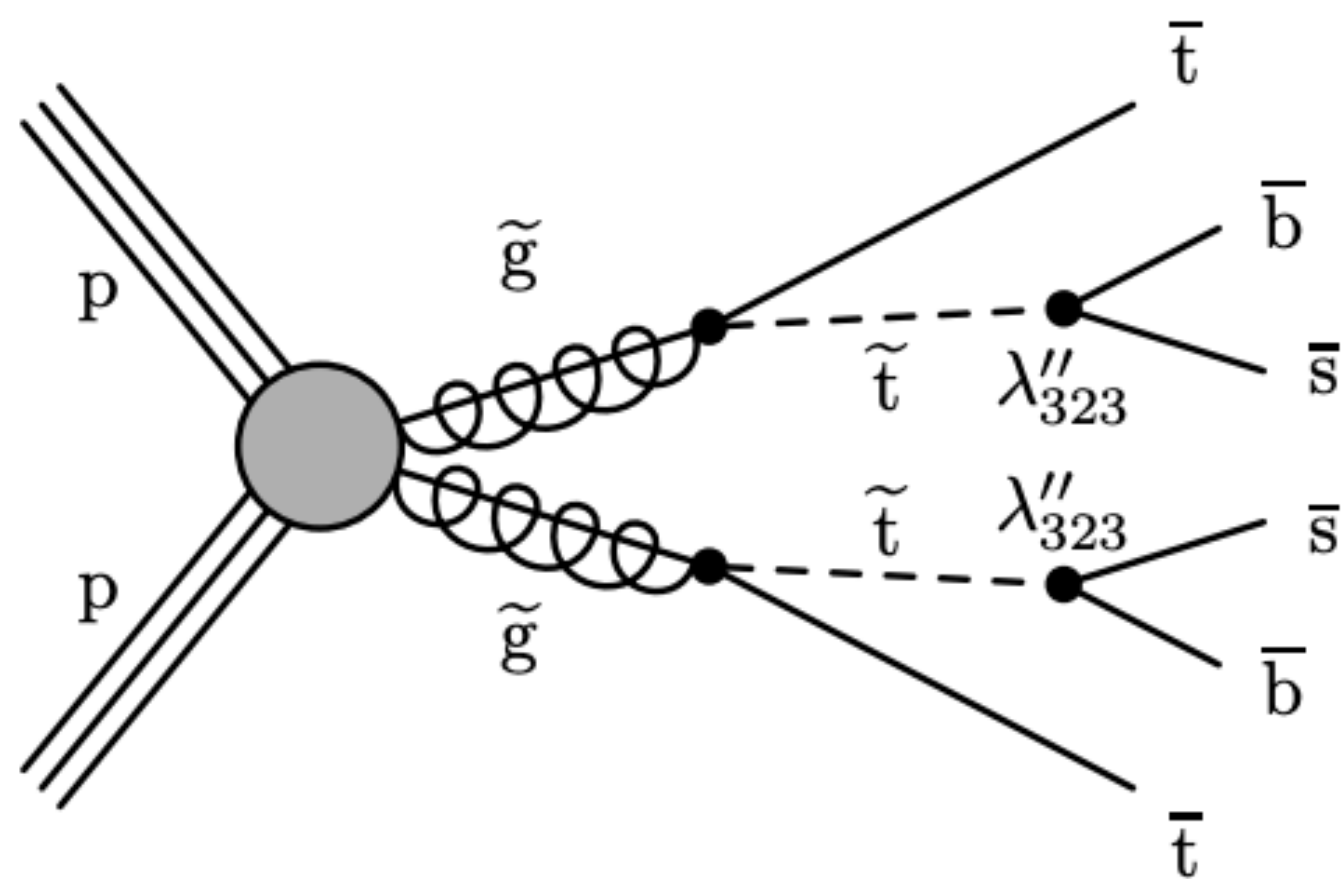
Status: July 2022

ATLAS Preliminary  
 $\int \mathcal{L} dt = (32.8 - 139) \text{ fb}^{-1}$   
 $\sqrt{s} = 13 \text{ TeV}$



# Search for LLPs using displaced jets

[arXiv:2012.01581](https://arxiv.org/abs/2012.01581)



## Models:

1. Dijet Model
2. exotic decays of SM-like Higgs boson
3. general gauge-mediation models with  $\tilde{g} \rightarrow g\tilde{G}$
4. mini-split SUSY with  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$
5. RPV SUSY with  $\tilde{g} \rightarrow tbs$
6. RPV SUSY with  $\tilde{t} \rightarrow bl$
7. RPV SUSY with  $\tilde{t} \rightarrow dl$
8. RPV SUSY with  $\tilde{t} \rightarrow \bar{d}\bar{d}$