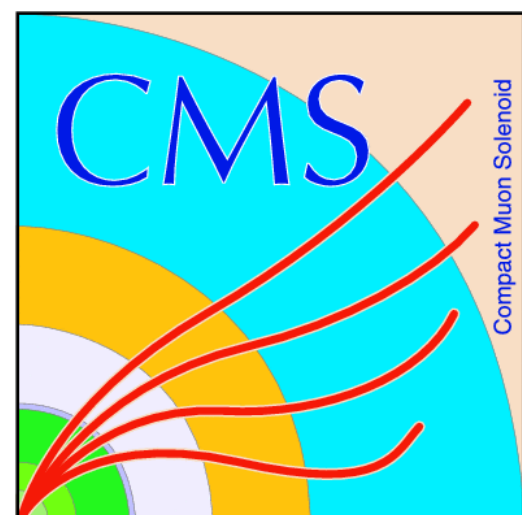


# RPV-UDD SUSY Searches at the LHC

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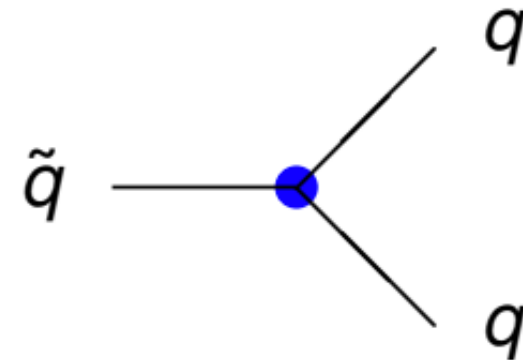


# RPV with UDD couplings

$$W_{RPV} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

UDD coupling lead to following topologies:

- single squark production
- squark direct decay to 2 quarks
- gluino decay to 3 quarks via (off-shell) squark
- neutralino/chargino decay to 3 quarks via (off-shell) squark



Usually, a single nonzero coupling is assumed (strongest indirect constraints on product of couplings)

# Effect of coupling strength

## Production:

- For pair-produced sparticles, RPV coupling strength does not enter into the production cross section
- Single squark production cross section can dominate over pair-production if coupling is large enough,  $O(1)$

## Decay:

- Coupling strength affects sparticle lifetime
- If  $\lambda$  large enough, decays are prompt, and searches are not sensitive to specific value of the coupling
  - Will focus on prompt searches in this talk
- If  $\lambda$  small ( $\sim 10^{-5}$ ), then sparticles will travel noticeable distance
  - Searches such as displaced vertices, stopped particles, HCSP, displaced jets, etc have good sensitivity

# Typical LHC signatures

UDD coupling leads to many fully hadronic final states without missing transverse momentum

⇒ Resonance searches are quite powerful:

- pair-produced 2-jet resonances
- pair-produced 3-jet resonances
- pair-produced 4/5-jet resonances

Can also end up with more complicated decay topologies:

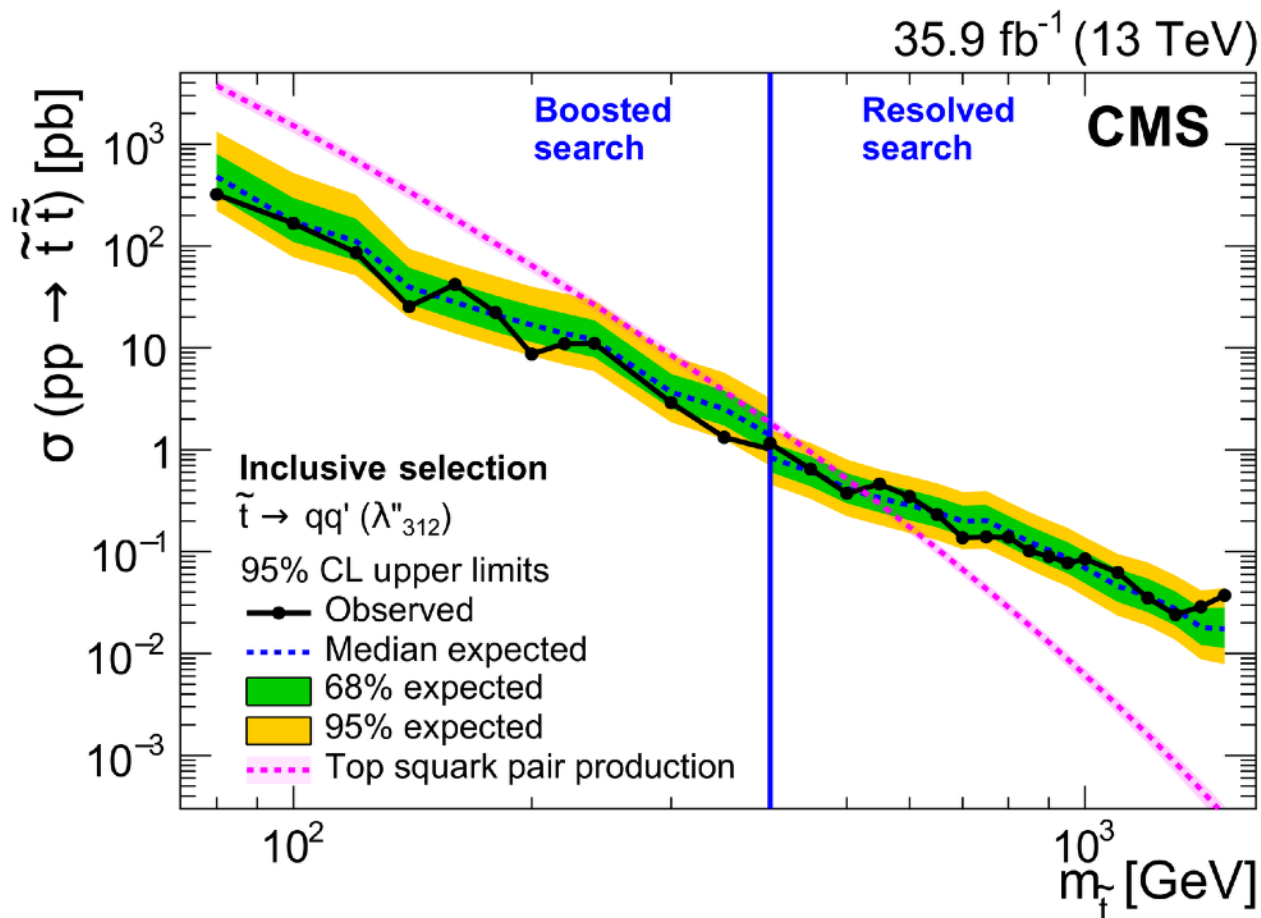
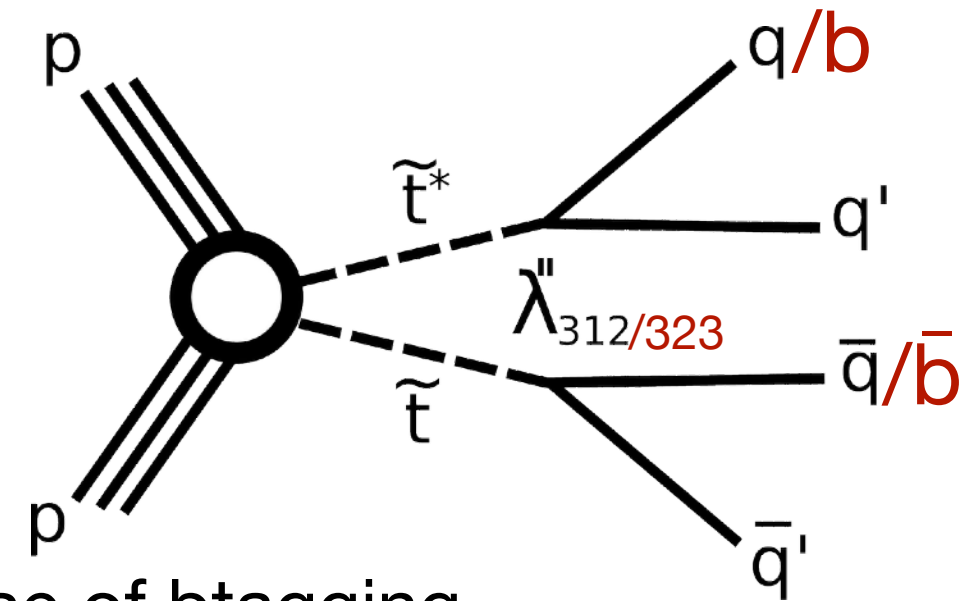
- Long cascade decays if RPV coupling is small enough that RPC decays dominate until one reaches the LSP
- Top quarks in the decay chain

⇒ Exploit large multiplicity, internal structure, etc

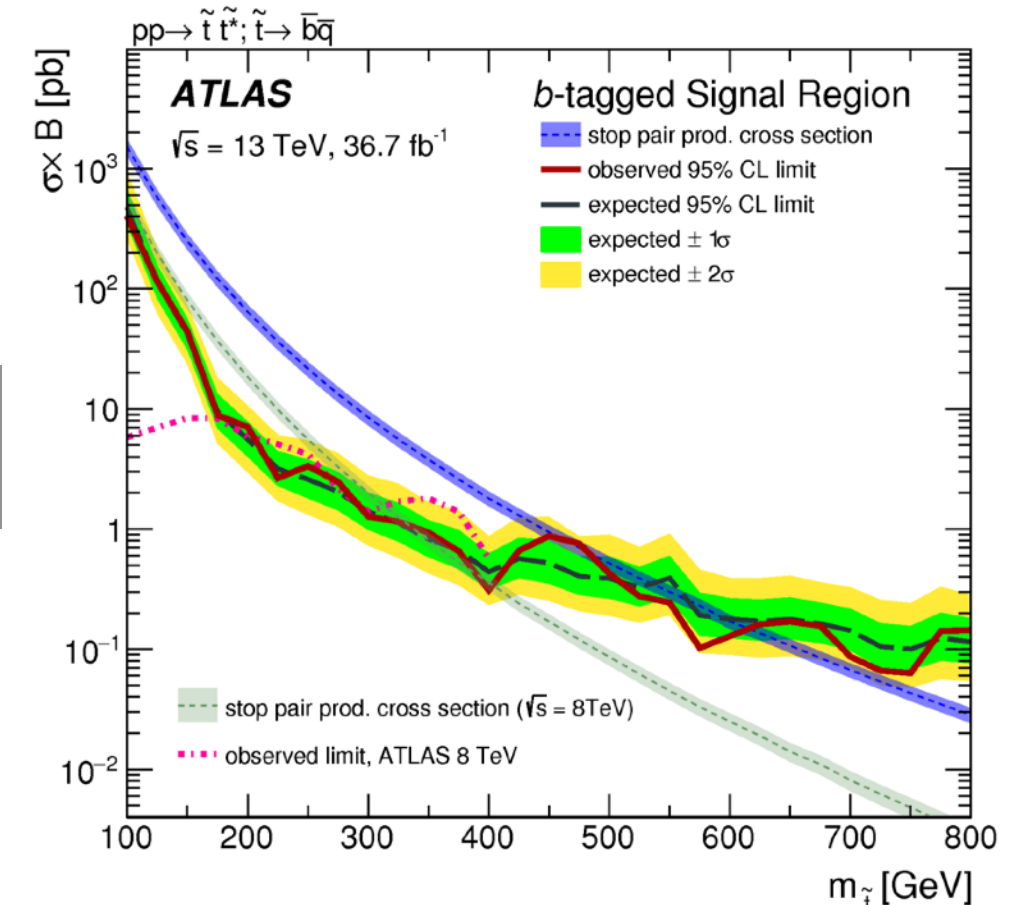
*Challenge: large QCD and/or  $t\bar{t}$  backgrounds*

# Pair-produced 2-jet resonances

- Signature: squark  $\rightarrow qq'$
- Existing searches usually interpreted in the context of top squarks with coupling  $\lambda''_{312}$ 
  - Exclude up to  $m_{\tilde{t}} = 525$  GeV
- Can extend sensitivity for  $\lambda''_{323}$  by making use of btagging
  - Exclude up to  $m_{\tilde{t}} = 640$  GeV

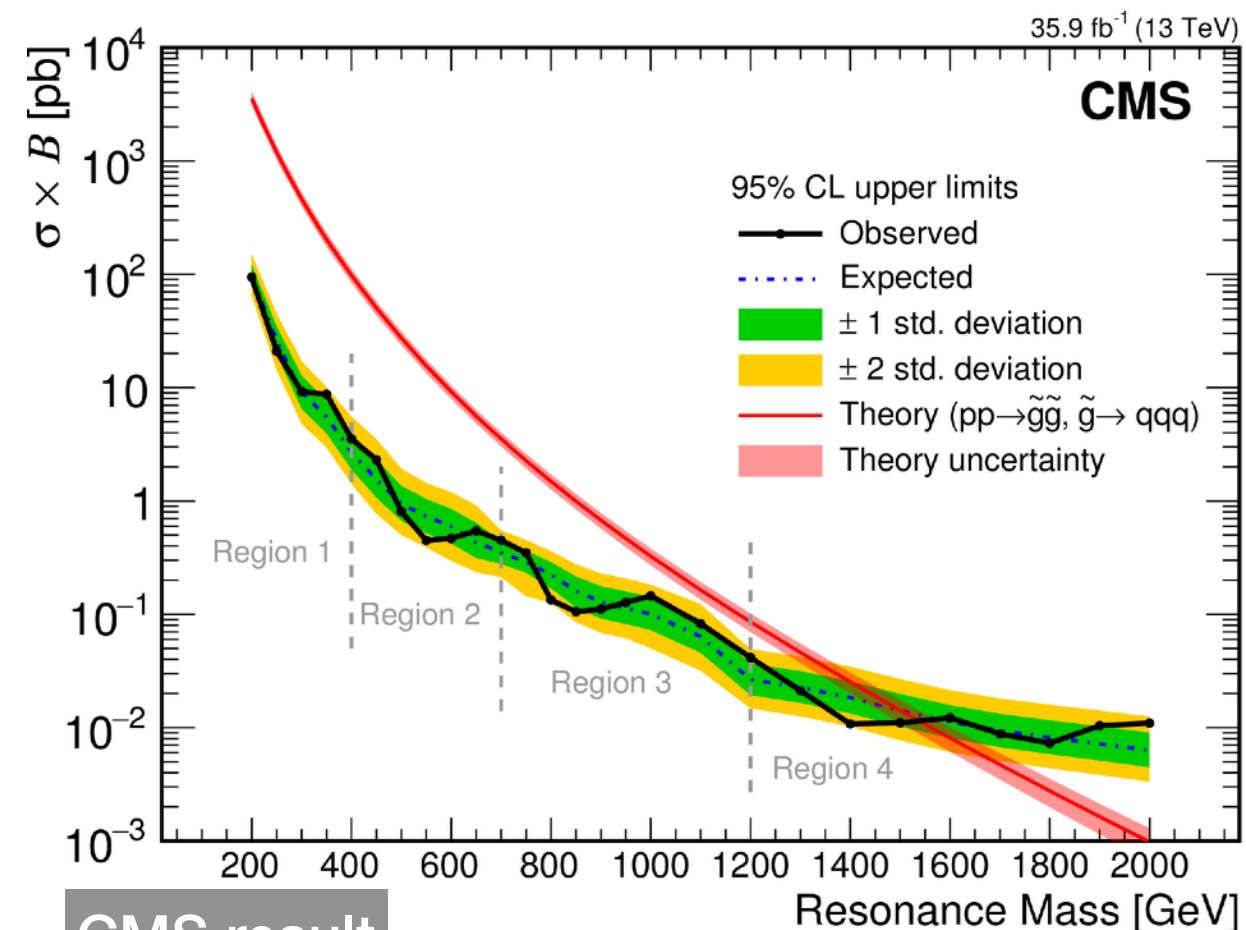
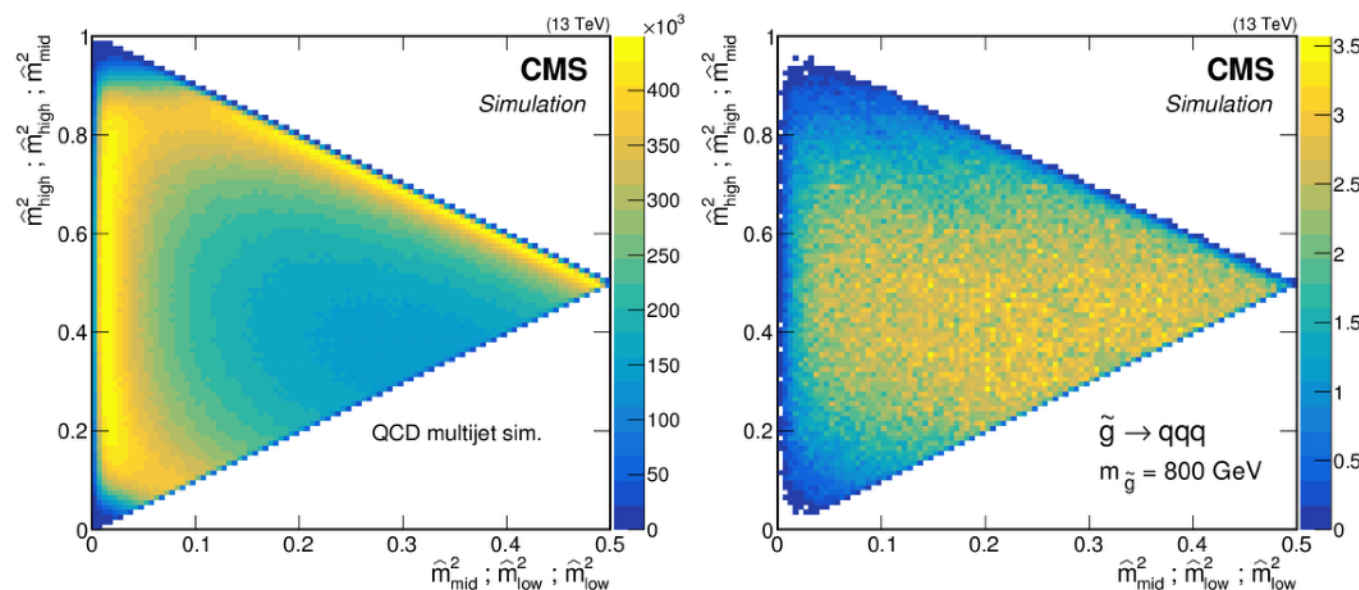
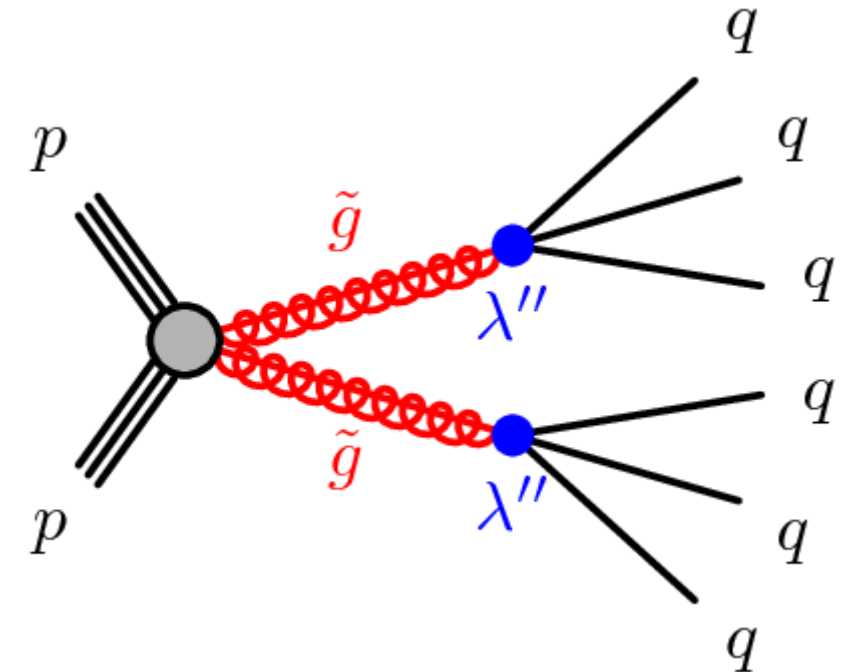


CMS result  
ATLAS result



# Pair-produced 3-jet resonances

- Signature: gluino  $\rightarrow$  qqq
- Constrains all  $\lambda''_{ijk}$  for  $i, j, k = 1, 2$
- Uses *data scouting* to access the low mass region and regular triggers for high mass region
- Uses lack of structure in the gluino decay products via Dalitz plot
- Excludes gluinos up to 1.5 TeV

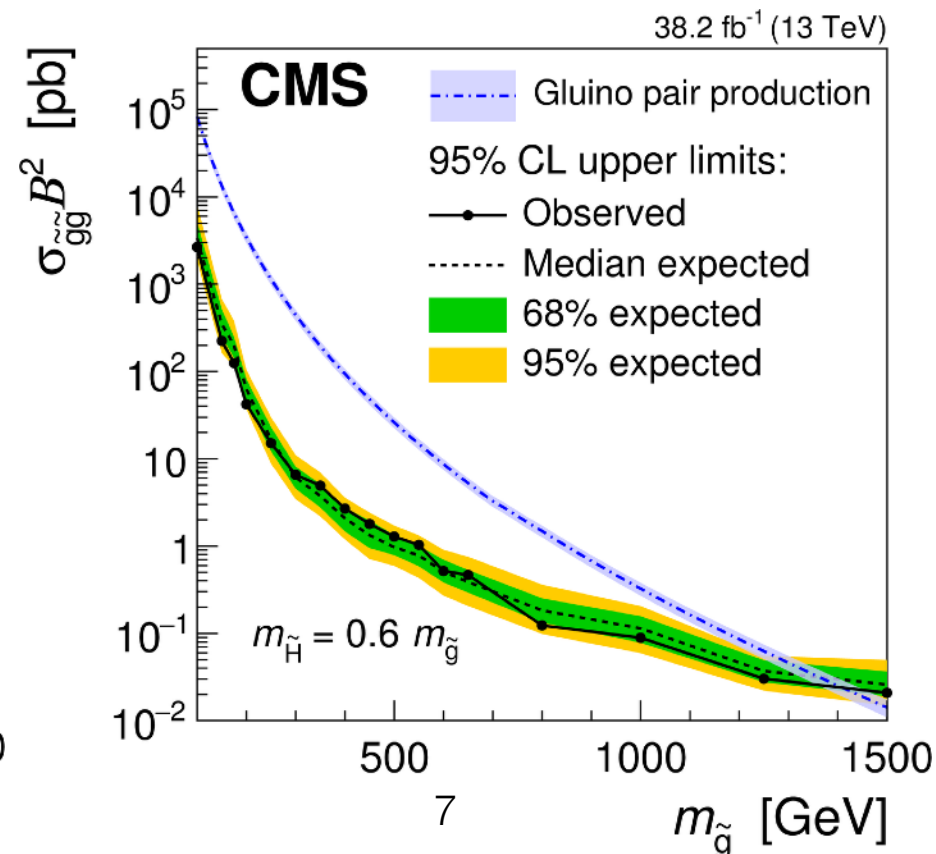
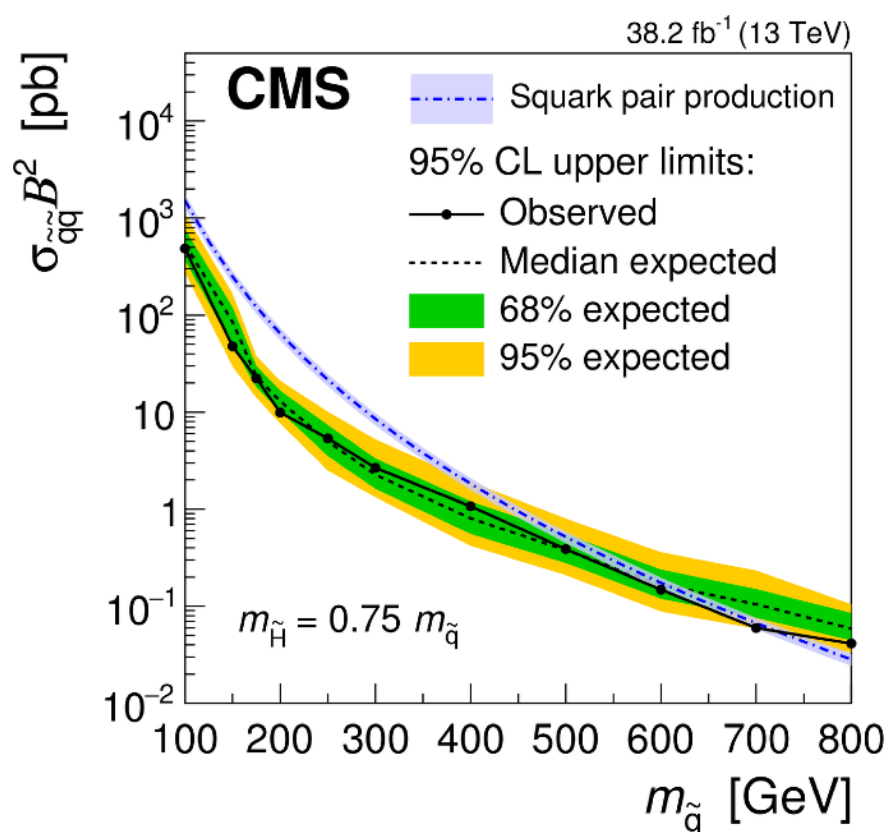
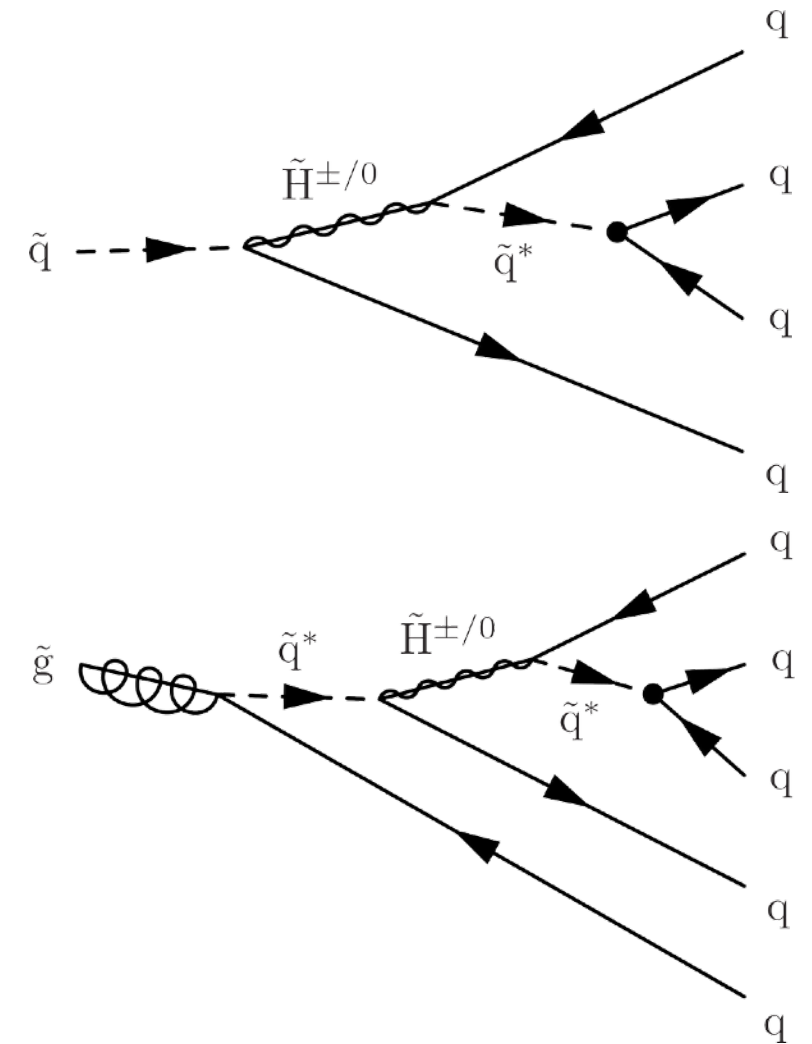


CMS result



# Pair-produced $\geq 4$ -jet resonances

- Signature: cascade decay of squark or gluino through a higgsino to 4 or 5 non-top quarks
  - Dominant if higgsino is lighter than squark/gluino and  $\lambda''$  is small
- Particles are clustered into 2 large jets that are investigated using N-subjettiness  $\tau_{42}$  and  $\tau_{43}$ , and have small mass asymmetry



Gluginos between 100–1400 GeV and squarks between 100–700 GeV (single species) are excluded

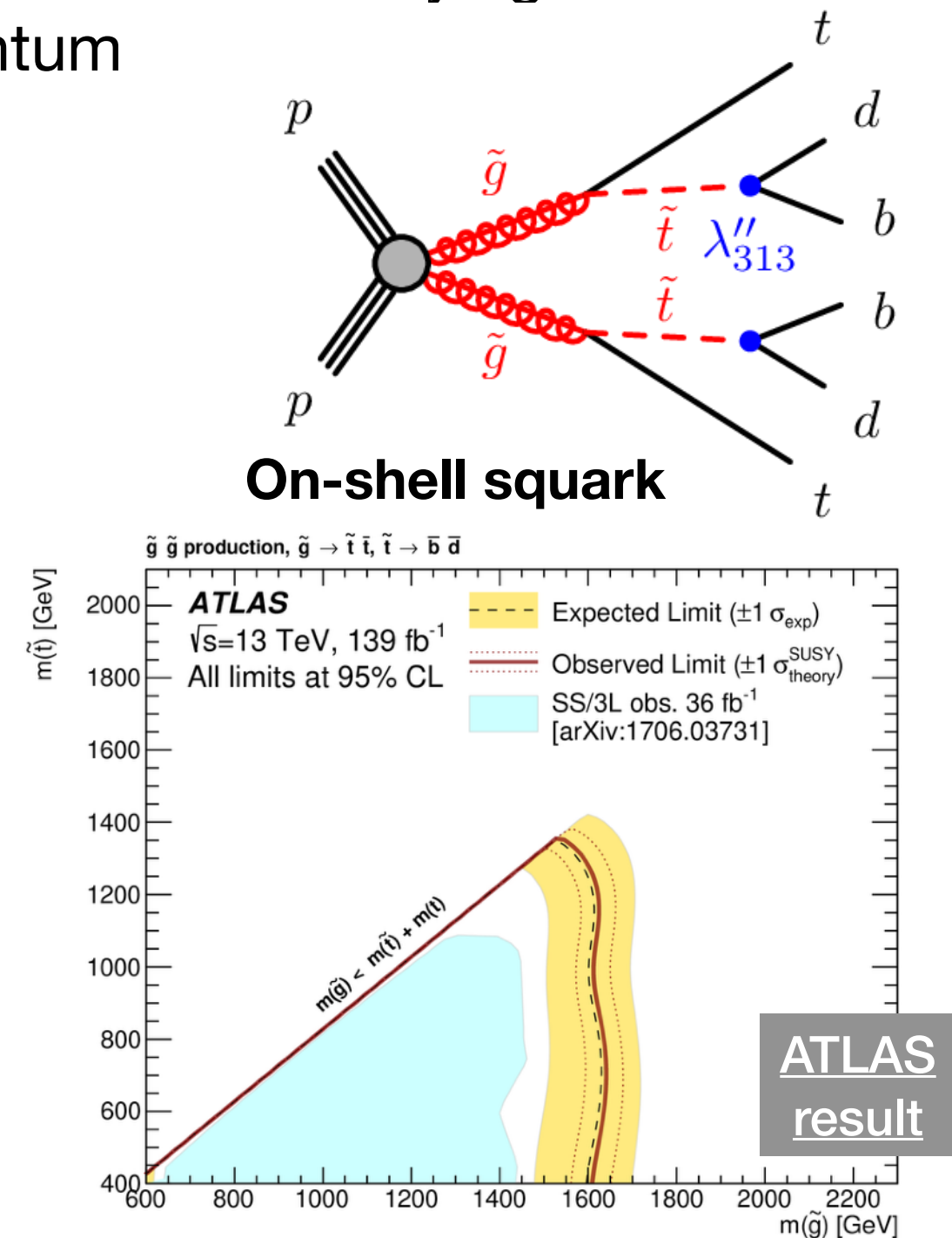
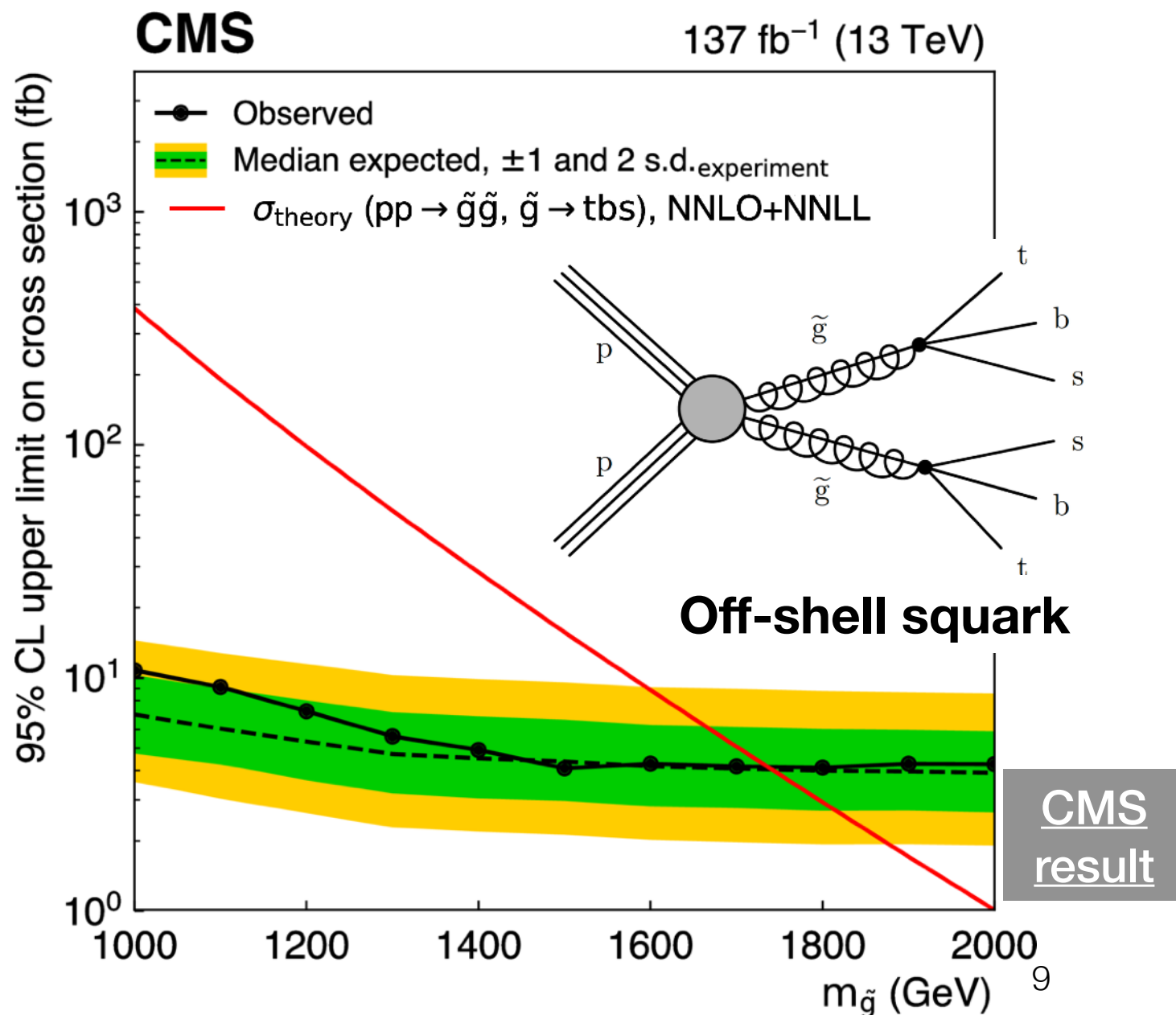
# Including top quarks

- Most of the paired N-jet resonance searches assume that the involved quarks are not top quarks
- When top quarks are involved, a few things change:
  - Leptons appear, lowering the fully hadronic branching fraction, likely resulting in a weakened limit
  - More jets can appear, which can spoil the reconstruction technique used
  - Signal can appear in  $t\bar{t}$  control regions
- Dedicated searches for RPV decays involving top quarks exist
  - For gluino decays, same sign top quarks, and thus same sign leptons can appear
  - Generally, searches exploit presence of many jets and bjets



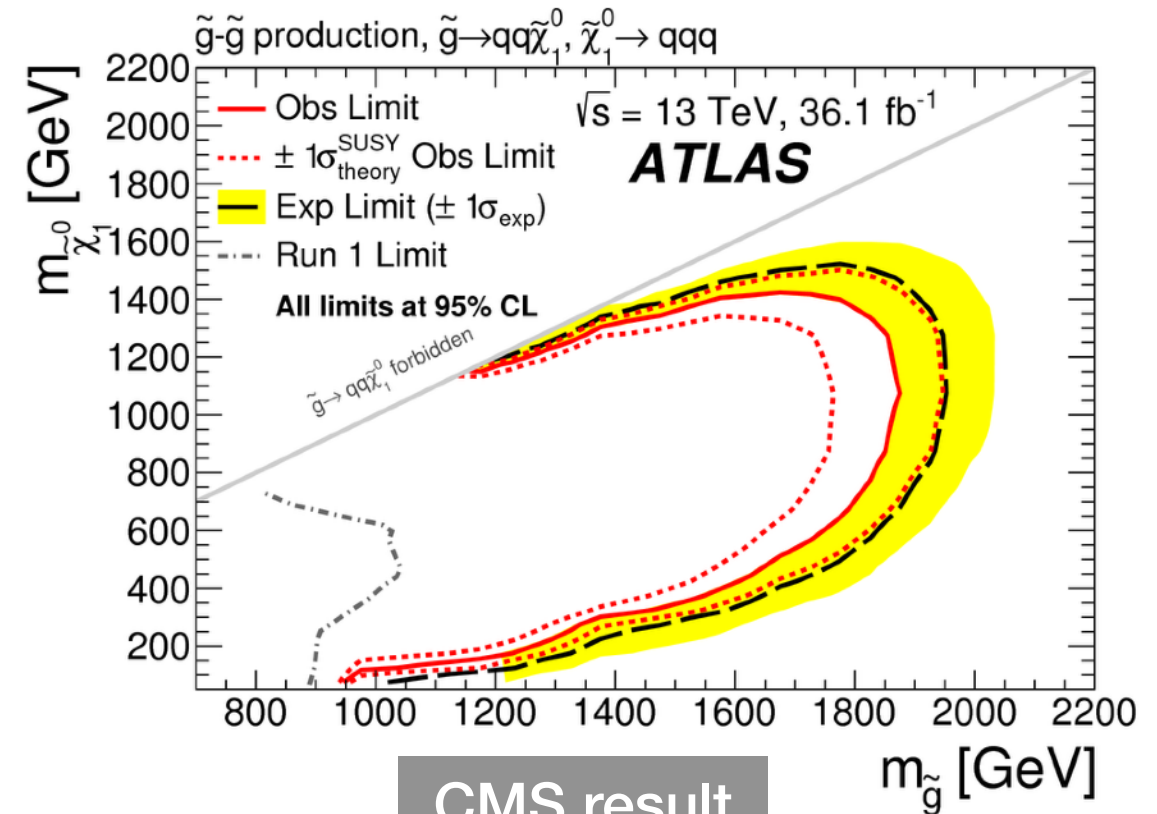
# Same-sign dilepton search

- Classic SUSY search in final state of SS dilepton and multilepton
- Very small SM background enables search without relying on presence of missing transverse momentum

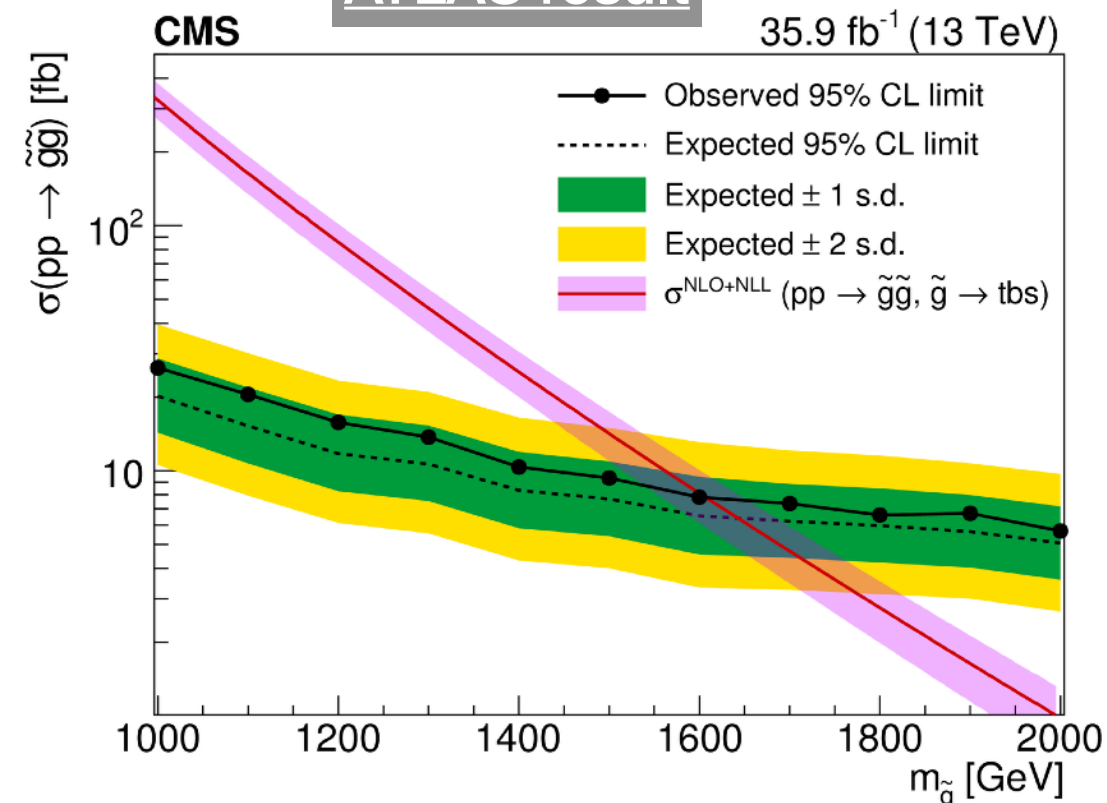
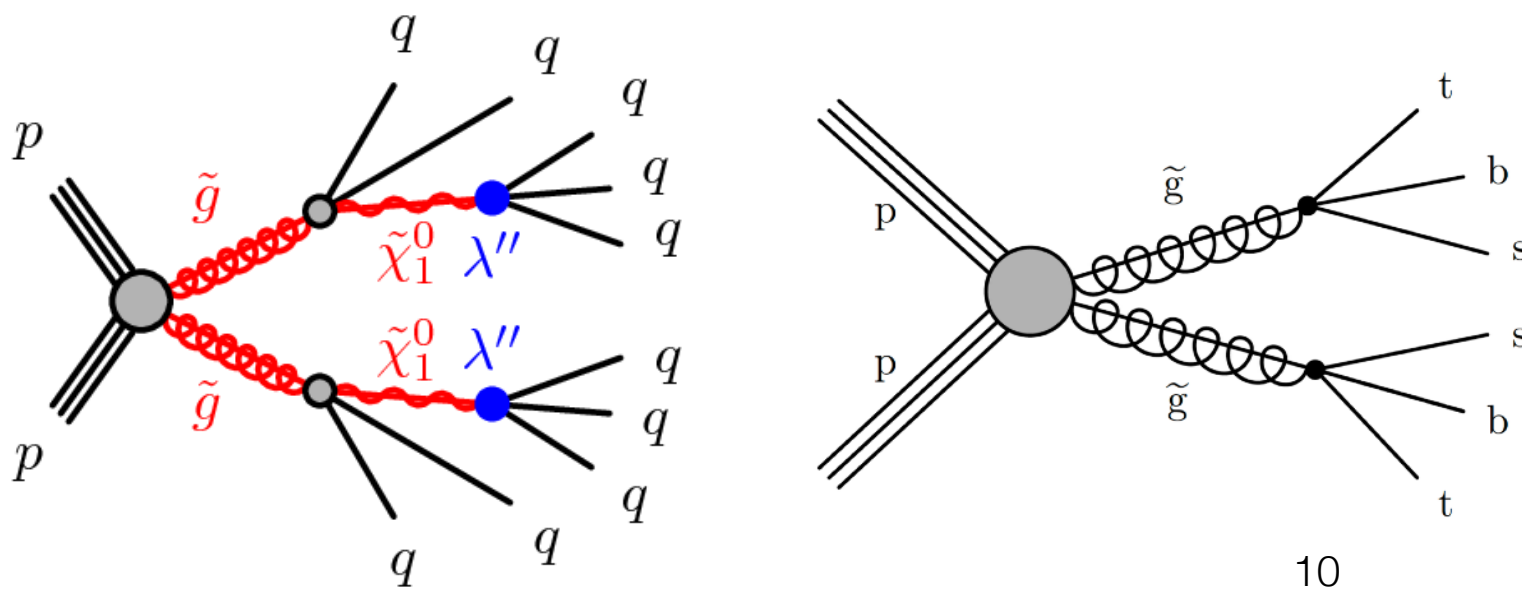


# 1-lepton search with $M_J$

- Signature:
  - CMS: gluino  $\rightarrow$  tbs via  $\lambda''_{323}$
  - ATLAS: gluino  $\rightarrow$  3q or 5q via cascade decay, all  $\lambda''_{ijk}$  equally
- Reconstructs large-R jets, and uses the sum of their masses  $M_J$  to discriminate signal from background
- Also exploit large jet and bjet multiplicity, although searches do include 0b regions as well

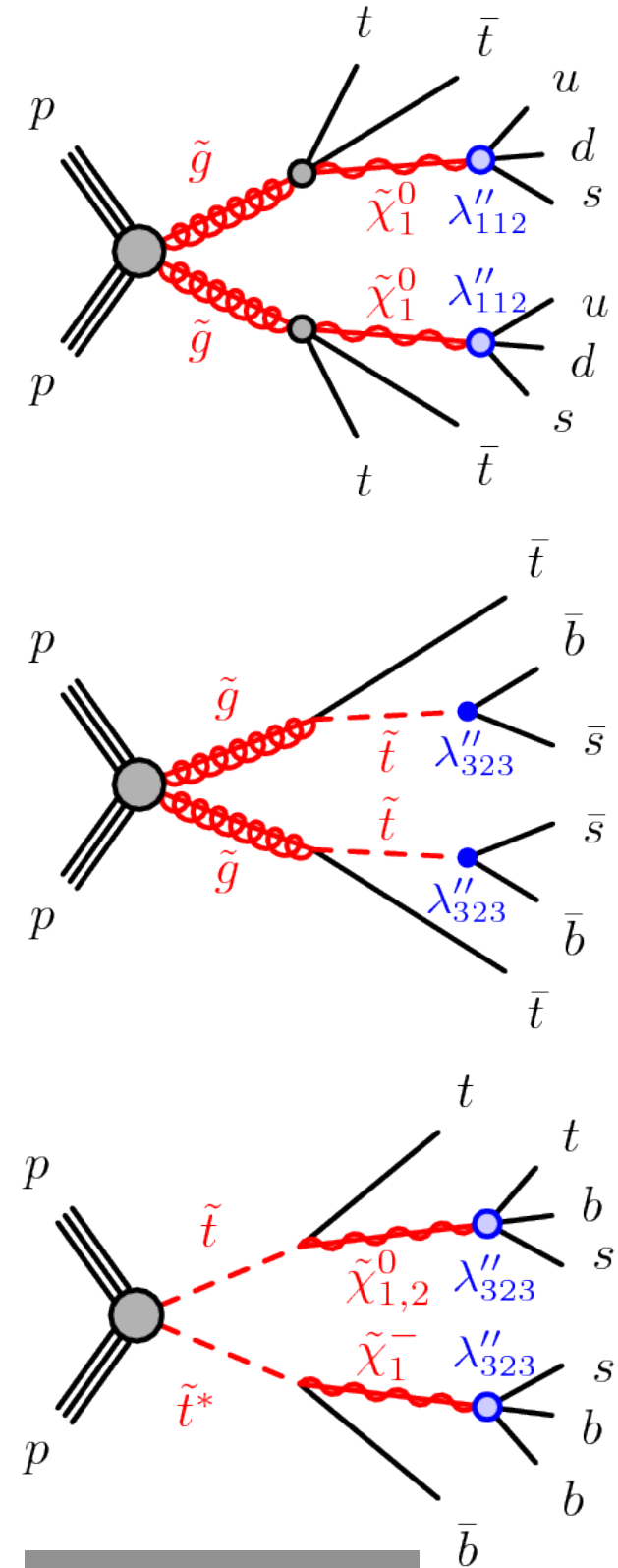
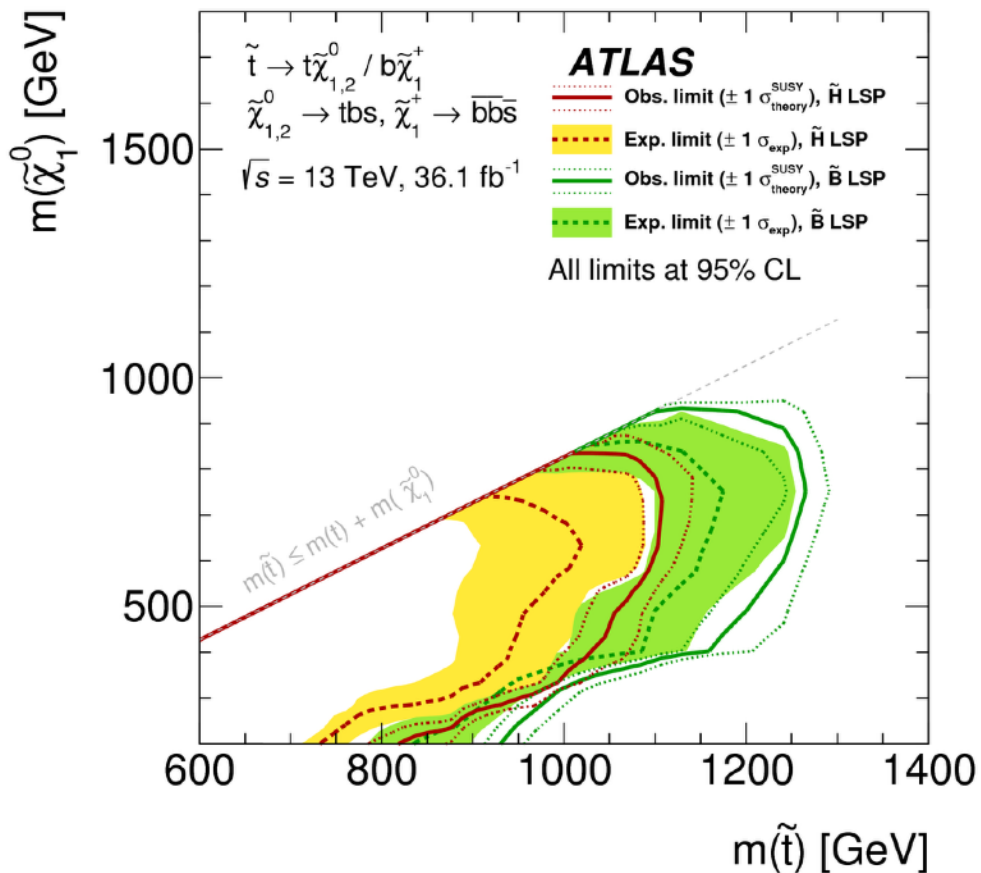
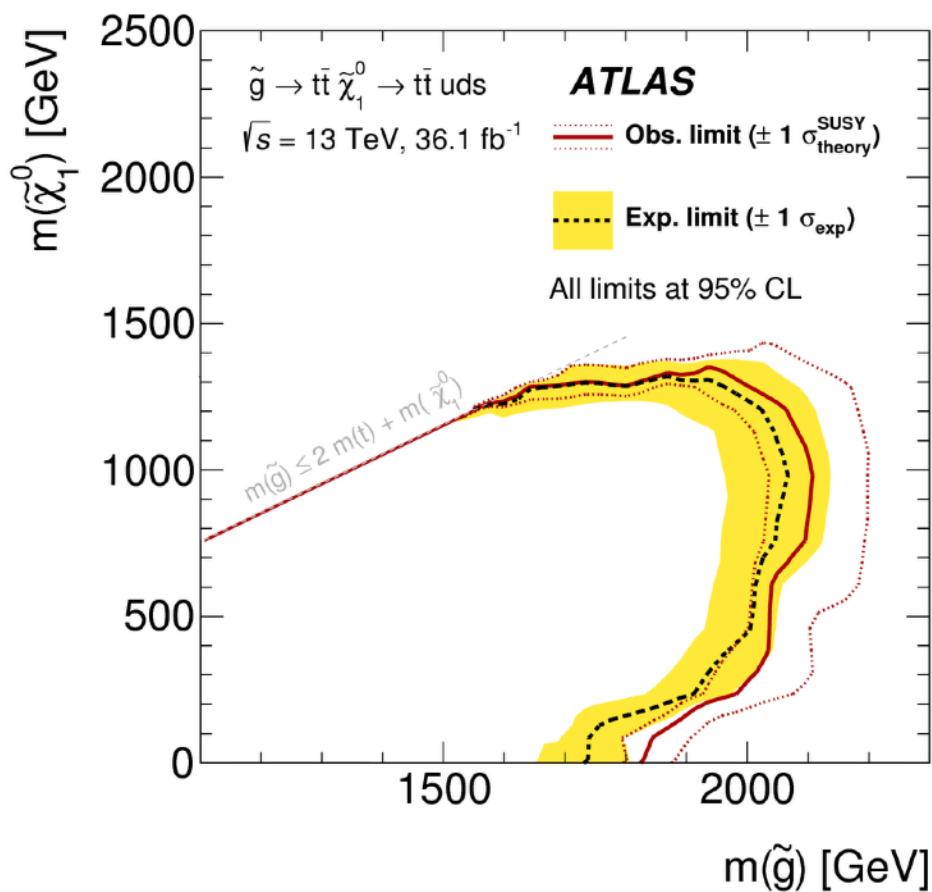


CMS result  
ATLAS result



# 1-lepton with large jet multiplicity

- Final state: 1l, many jets, either 0 or  $\geq 3$  bjets
- Targets broad range of signal models, all featuring very large jet multiplicity
- Backgrounds are modeled using parameterized extrapolations for Njets and Nbjets, based on jet scaling



ATLAS result

# Summary of current reach and prospects for future colliders

- In the above mentioned decay modes, gluinos are generally excluded up to  $\sim 1.5$  TeV, and squarks up to  $\sim 500$ - $700$  GeV, with some signatures providing stronger constraints
- **So, there is still room for TeV-scale stops with RPV UDD decays, as well as gluinos near 2 TeV**
- RPV UDD scenarios have not been as well studied in the context of future colliders compared to RPC scenarios.
  - Most recent studies from previous Snowmass (afaik)
  - Clearly an area where Snowmass 2021 can go beyond previous studies
  - *Will (any/all) future collider option be able to rule out “natural” SUSY with RPV decays?*

# Questions for discussion

- There is quite good coverage for direct RPV decays, e.g.  $\tilde{q} \rightarrow qq, \tilde{g} \rightarrow qqq$ . Does this also hold when other sparticles are within reach, resulting in more complicated cascade decay chains for small RPV couplings?
- What about RPV decays of neutralinos/charginos, in case they are the only sparticle light enough to be produced? pair-produced 3-jet resonance search should have some sensitivity, but mass reach not currently known
- What are the challenges of RPV searches at future colliders? Trigger issues? Resolution of substructure in boosted jets?

# Questions for discussion

- Has the very low stop/gluino/... mass region been fully covered for all UDD scenarios?  
If not, is this an opportunity for a lepton collider?
- Should we (re)consider resonant squark production?
  - Are the large  $\lambda''_{ijk}$  couplings needed for this production mode to dominate already excluded via other means?
  - Are there scenarios that the dijet searches would miss?
- Are there any uncovered scenarios? Could they be fully covered at the (HL)LHC, or is a future collider needed?