Third Generation SUSY Searches at ATLAS and CMS
$(\tilde{t}, \tilde{b}, \tilde{g}, \tilde{q})$

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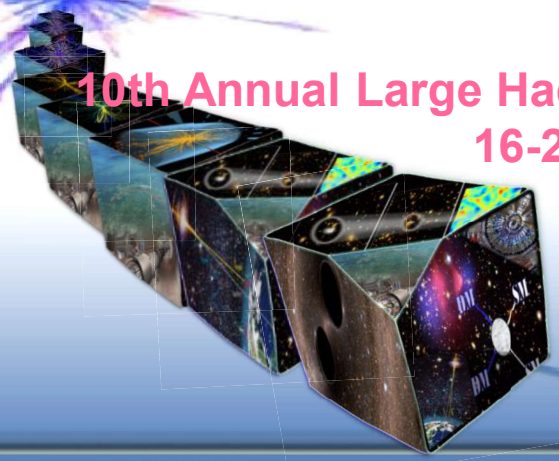


10th Annual Large Hadron Collider Physics Conference (LHCP2022),
16-21 May 2022, Virtual (Taiwan)

OUTLINE

I. Introduction: SUSY sector

II. ATLAS and CMS search results on 3rd generation squarks

III. Summary

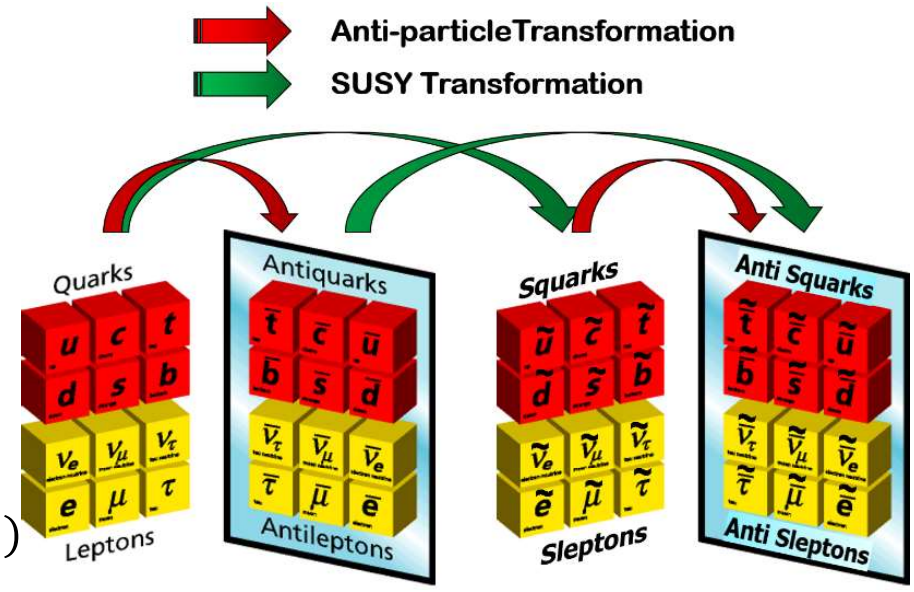
links

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS#Run_2_Summary_plots_13_TeV
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-013/

"SUSY + Another Higgs" Menu

- (Non-)MSSM Higgs (e.g., $A, H^{\pm}, \ldots$)
- **QCD Sectors**
  - Heavy $\tilde{g}$, 1st/2nd generation $\tilde{q}$?
  - **Lighter 3rd generation squarks ($\tilde{t}$, $\tilde{b}$)?**
- Charginos & Neutralinos, decaying into leptons, Higgs, W, Z

  $\tilde{\chi}_1^0 \in (\widetilde{B}, \widetilde{W}, \widetilde{H}_d, \widetilde{H}_u)$; $\tilde{\chi}_1^+ \in (\widetilde{W}^+, \widetilde{H}_u^+)$; $\tilde{\chi}_1^- \in (\widetilde{W}^-, \widetilde{H}_d^-)$



- Sleptons
  - Mass degenerate $\tilde{e}_{R,L}$, $\tilde{\mu}_{R,L}$?
  - Light $\tilde{\tau}_1$?

Compressed scenarios

- Lightest SUSY Particle (LSP)
  - $\tilde{\chi}_1^0$: Bino-like, Wino-like, Higgsino-like, Bino-Higgsino-like. [Example] Higgsino-like $\Longrightarrow \chi_1^{\pm}$ and χ_2^0 below 200 GeV, with mass splittings of order 10 GeV.
  - $\tilde{G}$: $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$, $\tilde{G}Z$, $\tilde{G}H$,
- Displaced Tracks, Long-Lived (LL)
- R-Parity violation (RPV)
- **Supersymmetric Y (e.g., Y = hidden sector)**

LHC SUSY Exploration Map

Cascade decay: $pp \to \tilde{X}\tilde{X} \to (\tilde{Y}\tilde{Y}) \to \tilde{Z}\tilde{Z}$ + SM particles

Triggers:
1) energetic jets (+ p_T^{miss})
2) leptons
3) photons
4) timing
5) ISR jet(s)
6) VBF dijet

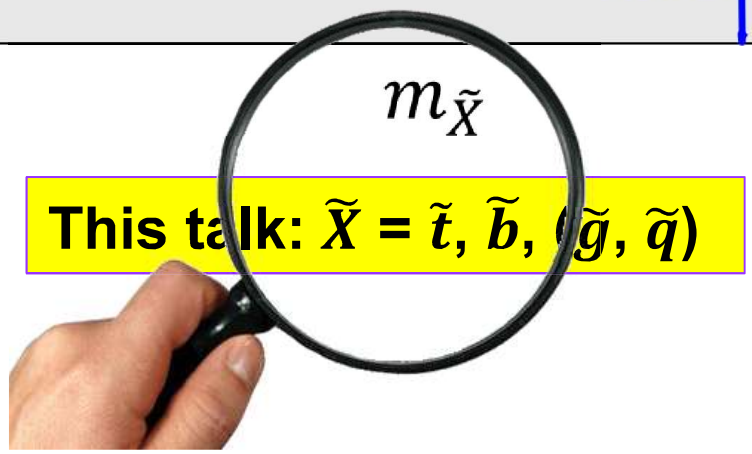
Analysis
1) Blind analysis (SRs, CRs)
2) Particle-flow ID
3) Neural-Net, Machine Learning

$m_{\tilde{Z}}$

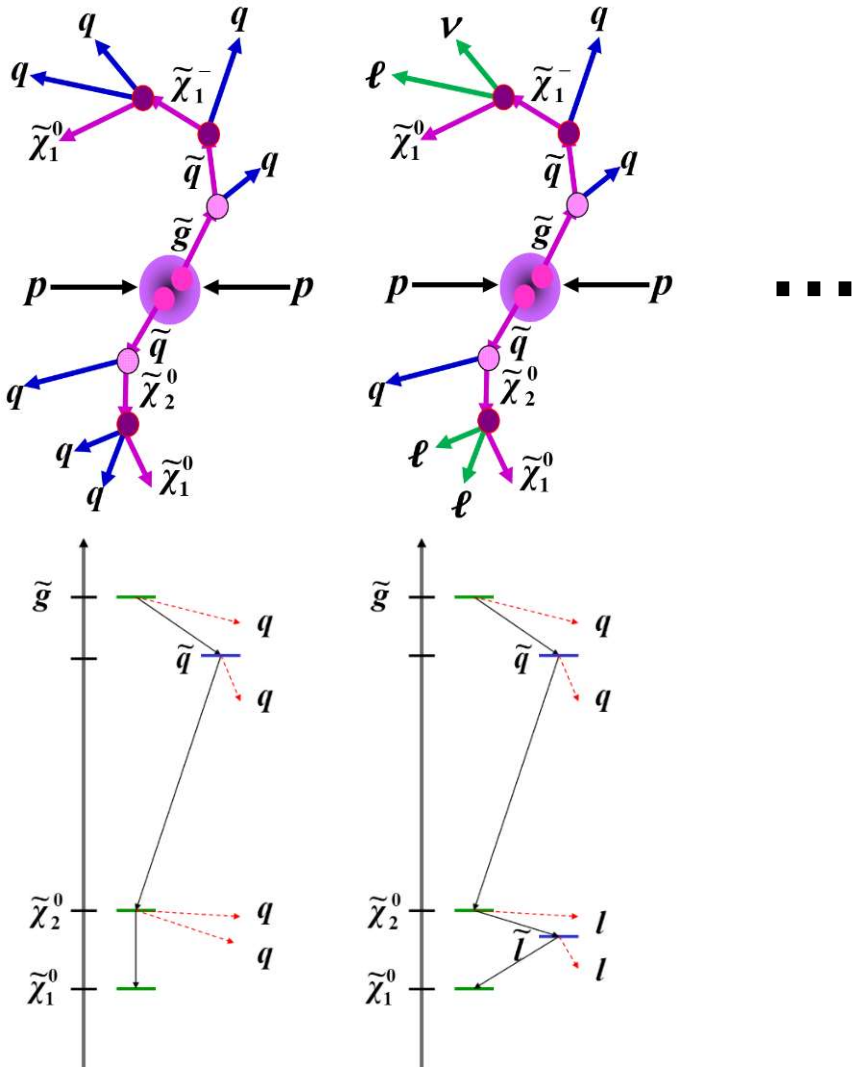
Compressed Mass Scenario

Low p_T objects

Boosted objects



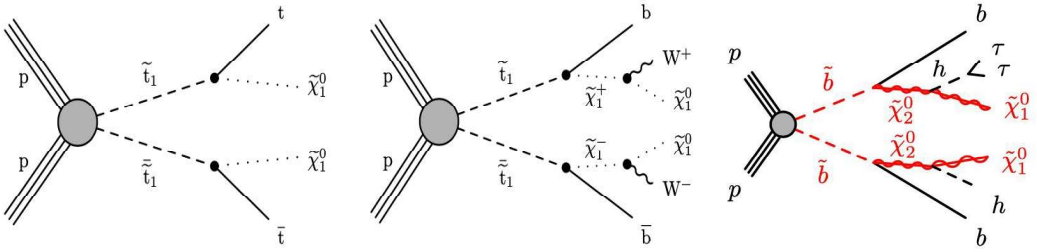
This talk: $\tilde{X}$ = $\tilde{t}$, $\tilde{b}$, ($\tilde{g}$, $\tilde{q}$)

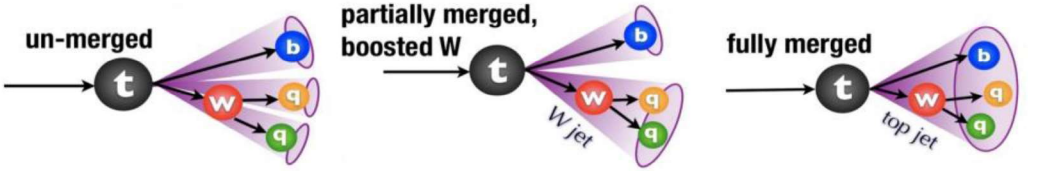


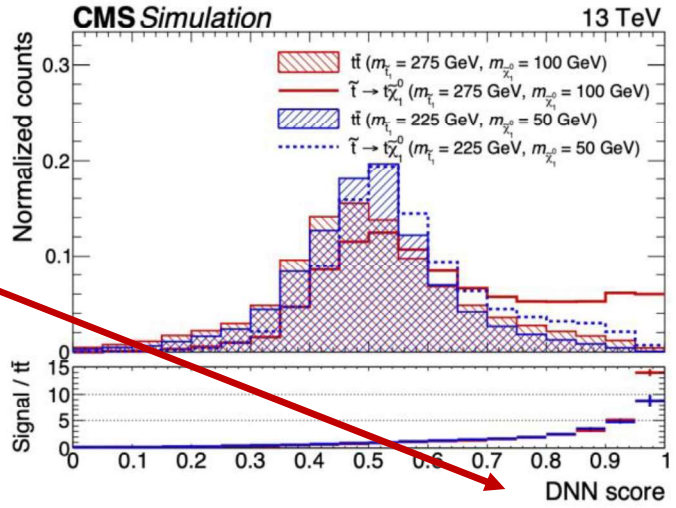
Key: Final states and branching fractions depend on the nature of cascade decays.

Analysis Flow

1) Advanced particle ID (e.g., particle flow, ML/DL, boosted objects): top, b, $h \to bb$, $h \to \tau\tau$, $W \to jj$
2) Full detector simulation
3) Signal Regions (SRs) and Control Regions (CRs)
4) Blind analysis: data in CRs must be fully understood before analysis of the data in SRs.
5) Maximize sensitivity (e.g., NN)
6) Observed and expected yields (with uncertainties) in SRs.







Note: particle flow ID

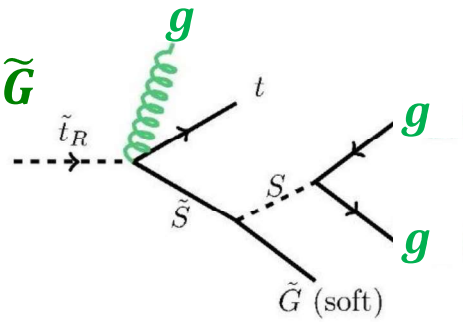
- Electrons, muons from ~5 GeV, τ_h ~20 GeV, jets ~30 GeV, b ~20 GeV, p_T^{miss} ~30 GeV, photon ~10 GeV
- See, for example, CMS: **JINST 12 (2017) P10003**, ATLAS: **Eur. Phys. J. C 77 (2017) 466**

SUSY QCD 3rd Generation Sector

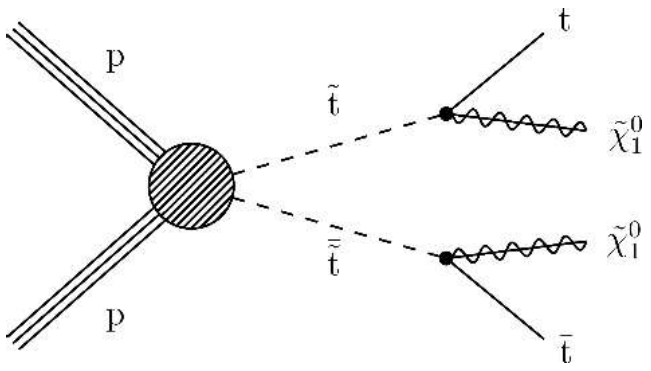
- The SUSY scale could be beyond the LHC kinematical limit a few TeV (see backup slides on the $\tilde{g}$ and 1st/2nd generation $\tilde{q}$).
- If the $\tilde{g}$ and 1st/2nd generation $\tilde{q}$ would be ultra heavy, the search program for lighter 3rd generation $\tilde{q}$ ($\tilde{t}$, $\tilde{b}$) is important.
  - R-parity conserving (RPC) SUSY
  - No or little P_T^{miss}
    - ✓ RPV: see "*Searches for RPV SUSY in ATLAS, CMS and LHCb*" by Saikat Karmakar (Tata Inst. of Fundamental Research (IN))
    - ✓ RPC "Stealth SUSY" with $\tilde{G}$ (LSP) + near-mass degenerate between scalar singlet S and fermion singlino $\tilde{S}$ (in hidden sector): $\tilde{t} \to \tilde{S} \to \tilde{G}$
    - ✓ …

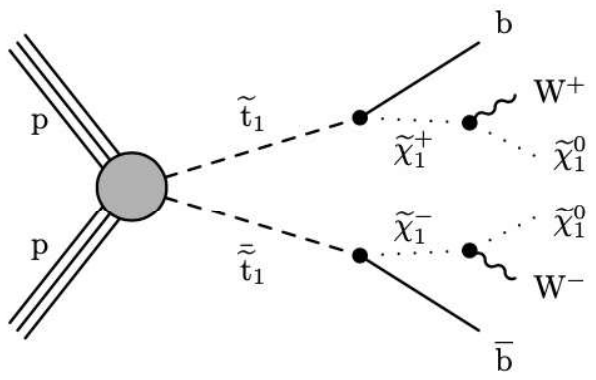
Hadron Collider ($\sqrt{s}$)	$\tilde{g}$ /$\tilde{q}$ Mass Reach (M)	M/$\sqrt{s}$
Tevatron (2 TeV)	~400 GeV	0.20
LHC (8 TeV)	~1.7 TeV	0.21
LHC (13 TeV)	**~2.2 TeV**	**0.17**
FCC (100 TeV)	~20 TeV*	0.20*

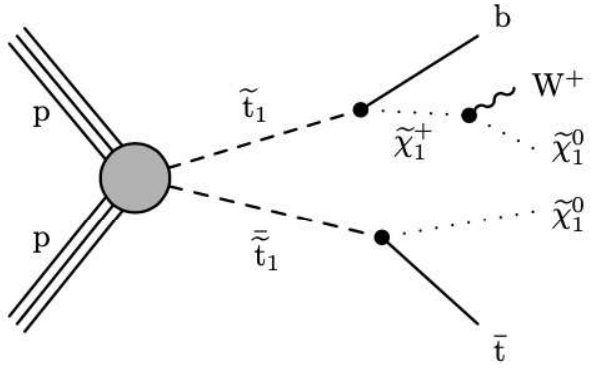
(*) just use a naïve scaling

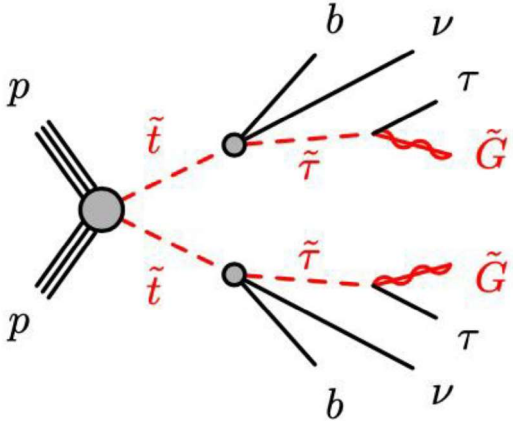


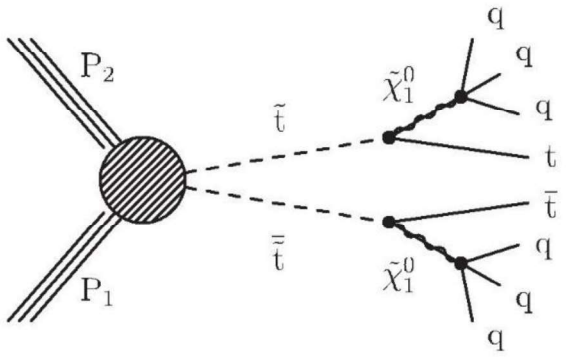
"SUSY $\tilde{t}$, $\tilde{b}$" Menu

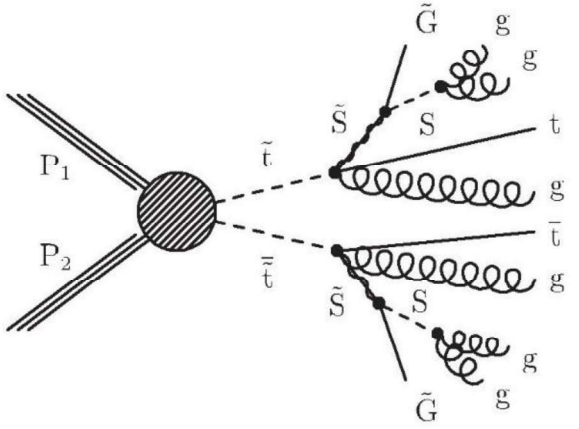


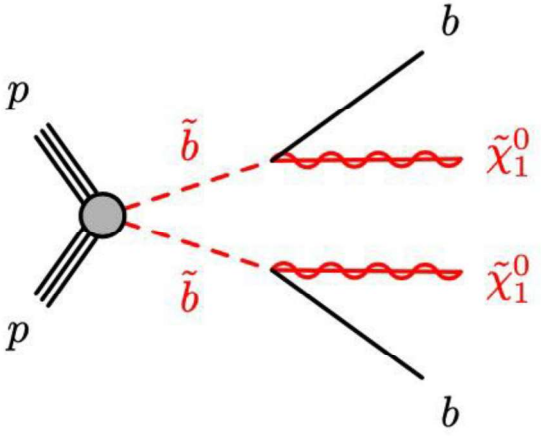


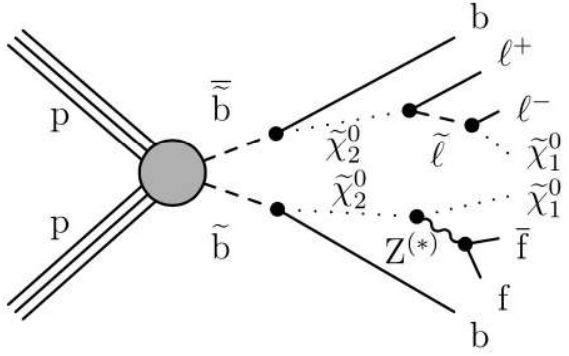


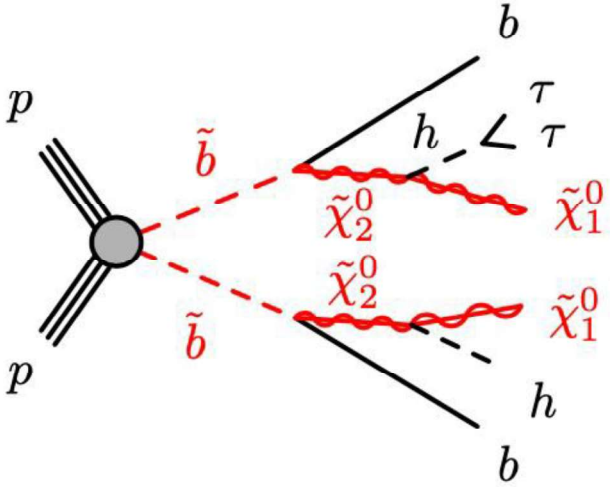




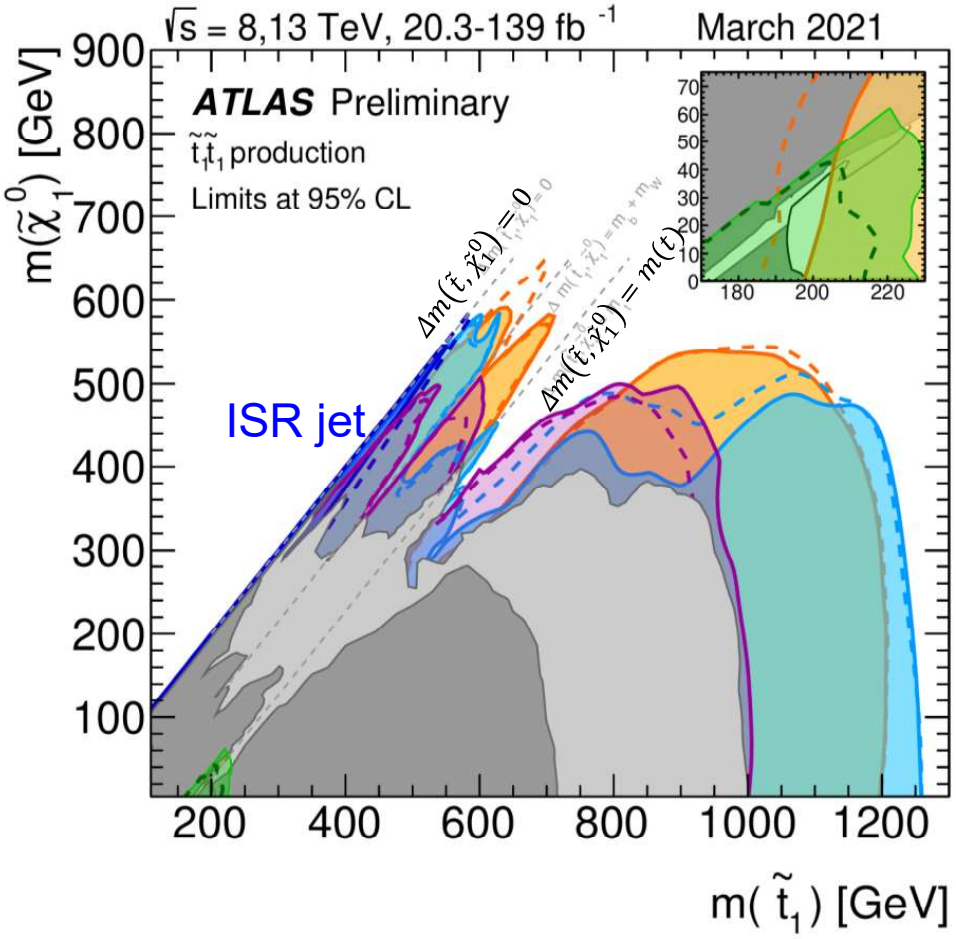


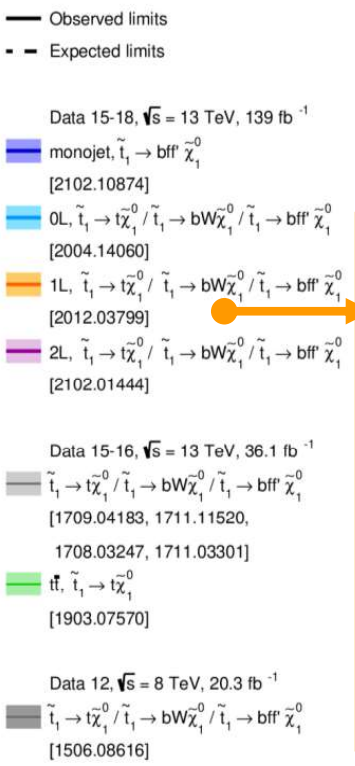




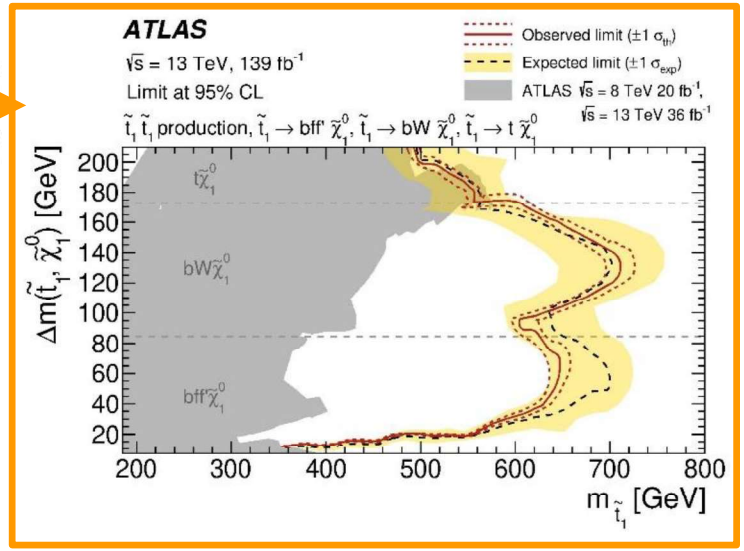


ATLAS $\tilde{t} \to t\tilde{\chi}_1^0$, $bW\tilde{\chi}_1^0$, $bff'\tilde{\chi}_1^0$





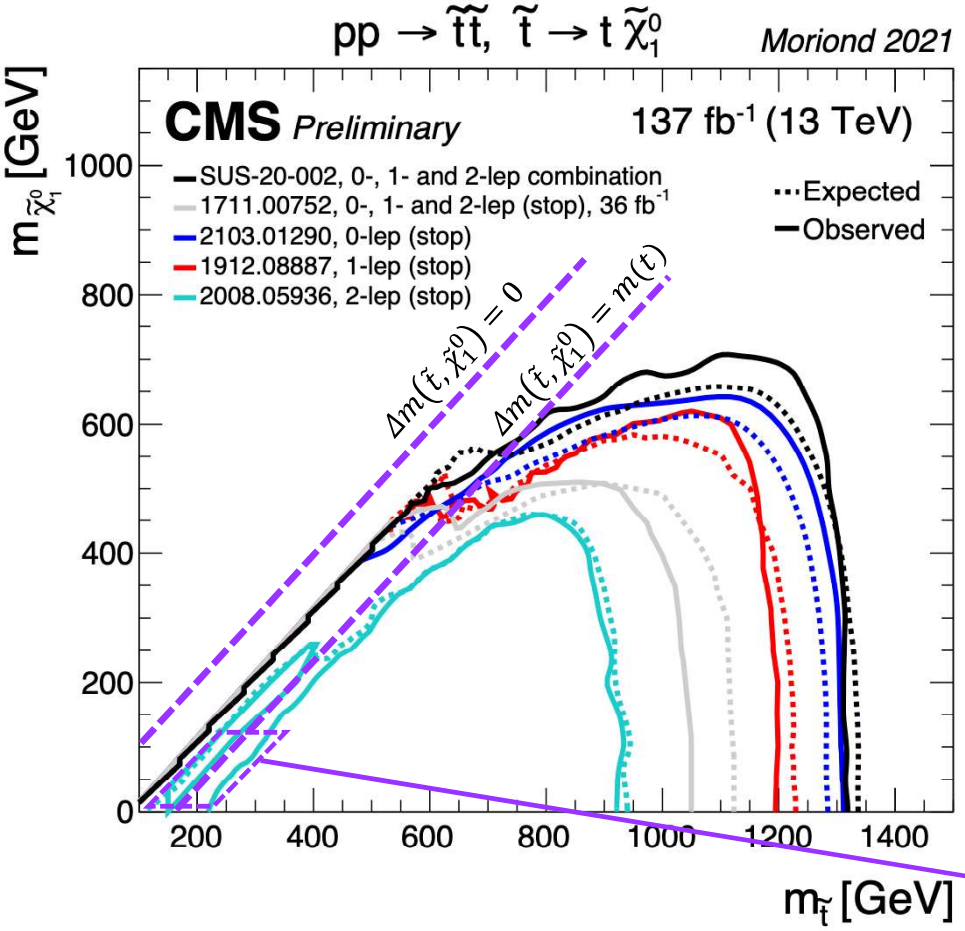
- $\Delta m(\tilde{t}, \tilde{\chi}_1^0) > m(t)$: $\tilde{t} \to t\tilde{\chi}_1^0$
- $m(t) > \Delta m > m(W)$: $\tilde{t} \to bW\tilde{\chi}_1^0$
- $m(W) > \Delta m > 0$: $\tilde{t} \to bff'\tilde{\chi}_1^0$



In the corridor ($\Delta m(\tilde{t}, \tilde{\chi}_1^0) = m(t)$), 2 complementary approaches: (i) measurement of differential cross-sections for ATLAS, (ii) DNN techniques for CMS,

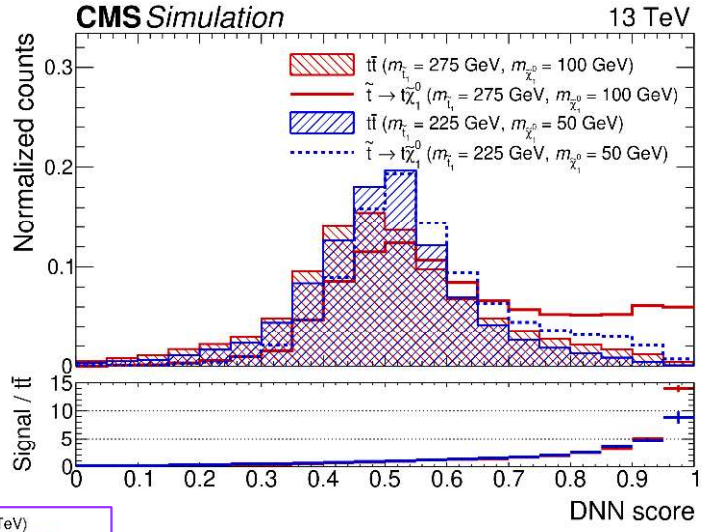
- ❑ Stop: Up to ~1250 GeV
- ❑ Weaker limits for compressed mass spectra
- ❑ Access to ultra compressed-mass scenario (small $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$) via ISR jet

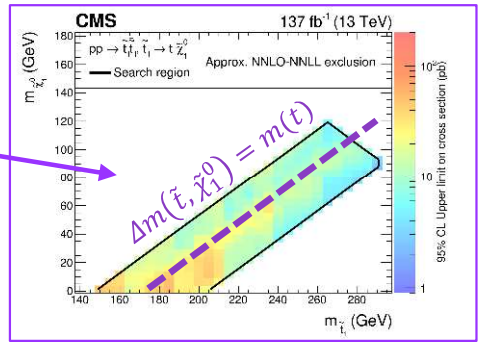
CMS $\tilde{t} \to t\tilde{\chi}_1^0$



SUS-20-002 (stop combination + corridor)

Corridor ($\Delta m(\tilde{t}, \tilde{\chi}_1^0) = m(t)$): (i) Combination of 9 channels: (ii) 3 data-taking period x 3 lepton flavor pairs; (iii) binned DNN



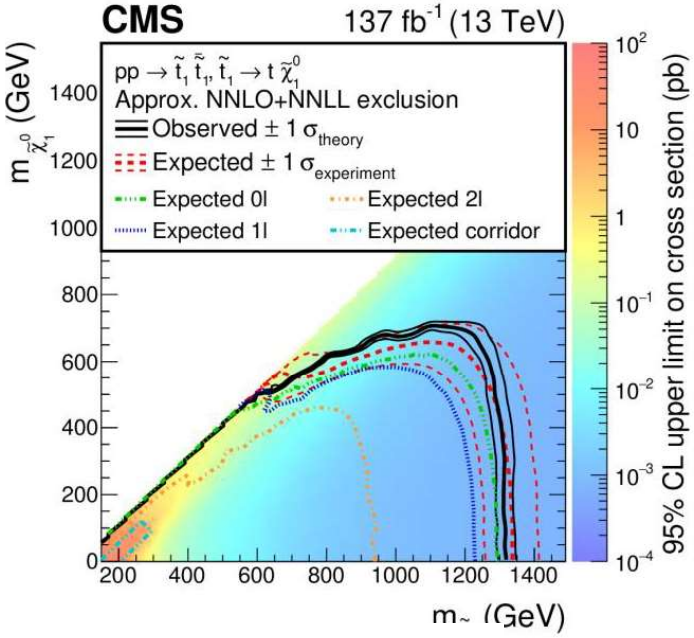


Good discrimination at high DNN score

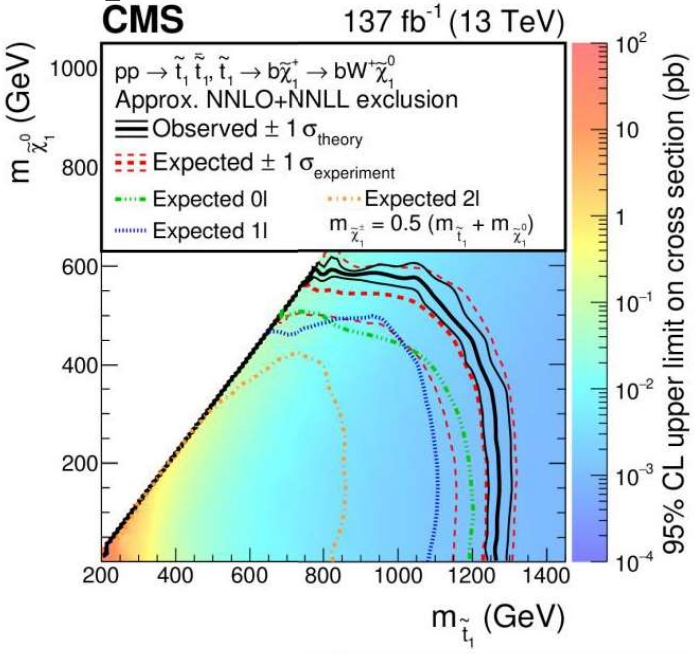
- Stop: Up to ~1300 GeV for $0\ell, 1\ell, 2\ell$ (combination)
- Weaker limits for 2ℓ
- CMS ~ ATLAS for $\Delta m(\tilde{t}, \tilde{\chi}_1^0) > m(b) + m(W)$

CMS $\tilde{t} \to t\tilde{\chi}_1^0$, $b\tilde{\chi}_1^{\pm}$

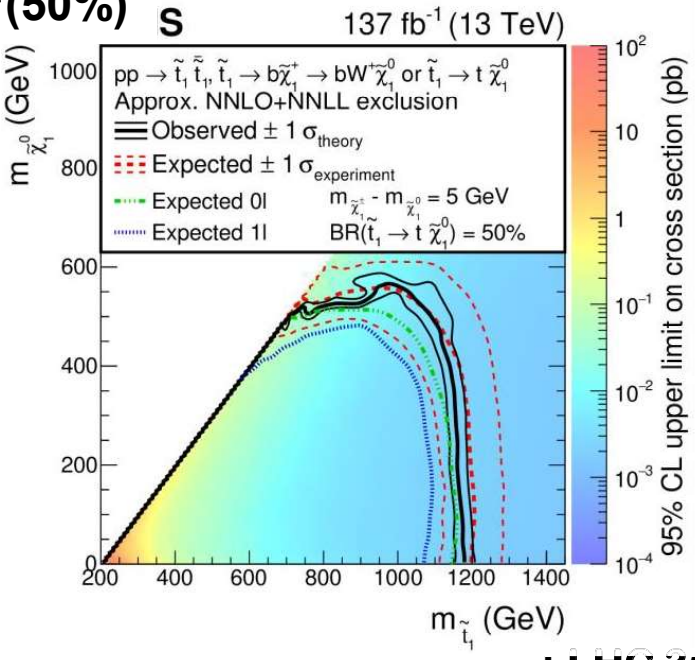
$t\tilde{\chi}_1^0$ (100%)



$b\tilde{\chi}_1^{\pm}$(100%)



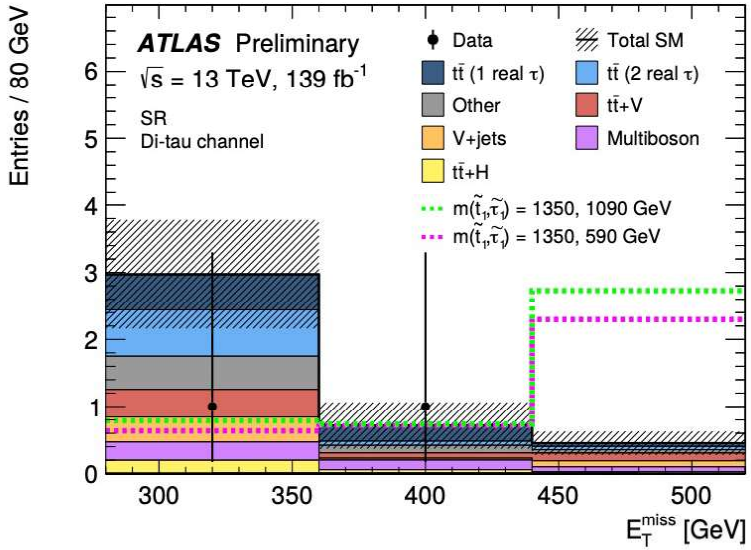
$t\tilde{\chi}_1^0$ (50%), $b\tilde{\chi}_1^{\pm}$(50%)

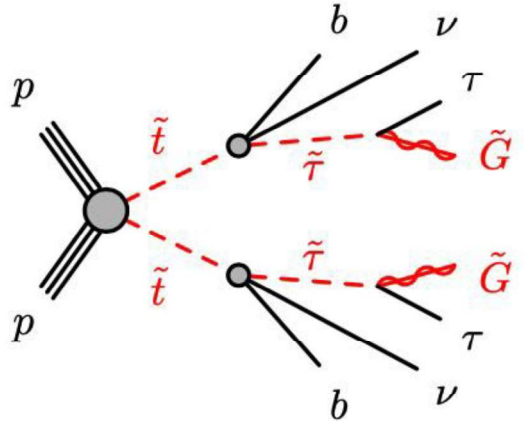


SUS-20-002 (stop combination + corridor)

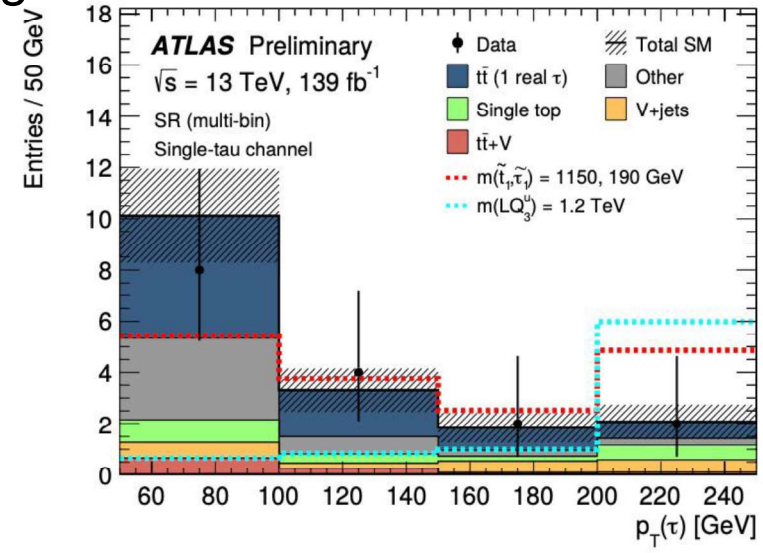
ATLAS $\tilde{t} \to b\tilde{\chi}_1^{\pm *} \to b\nu\tilde{\tau}$

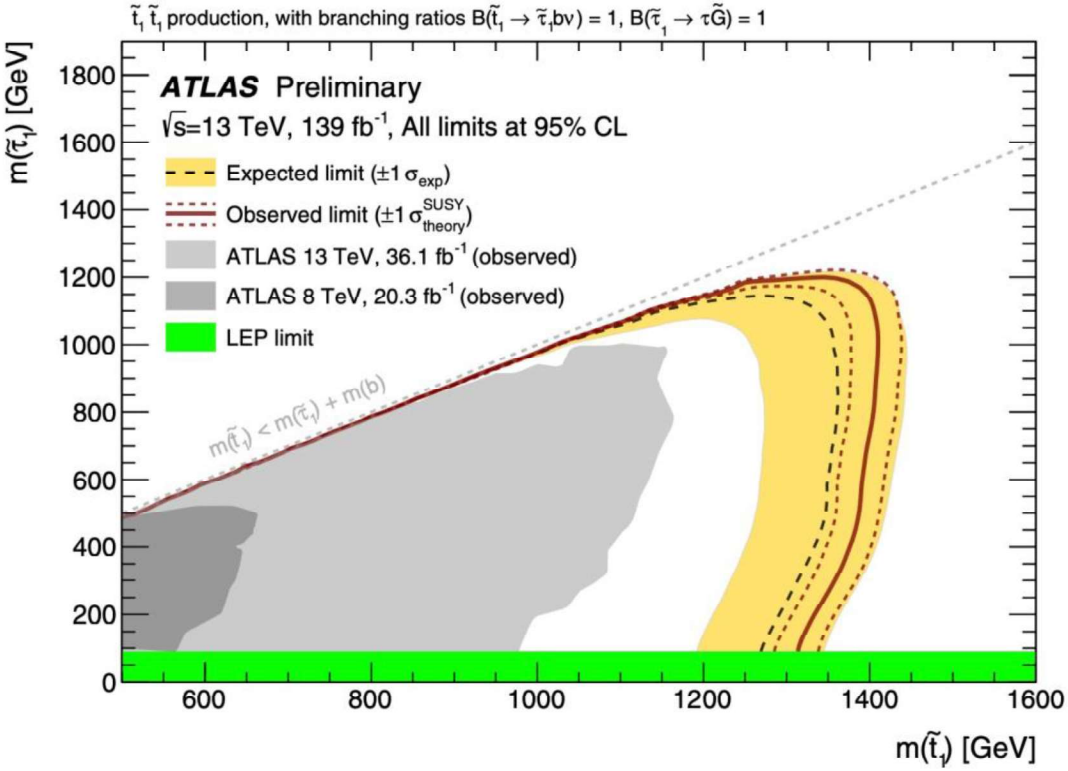
Heavy $\tilde{\tau}$ - $\tau\tau$ channel





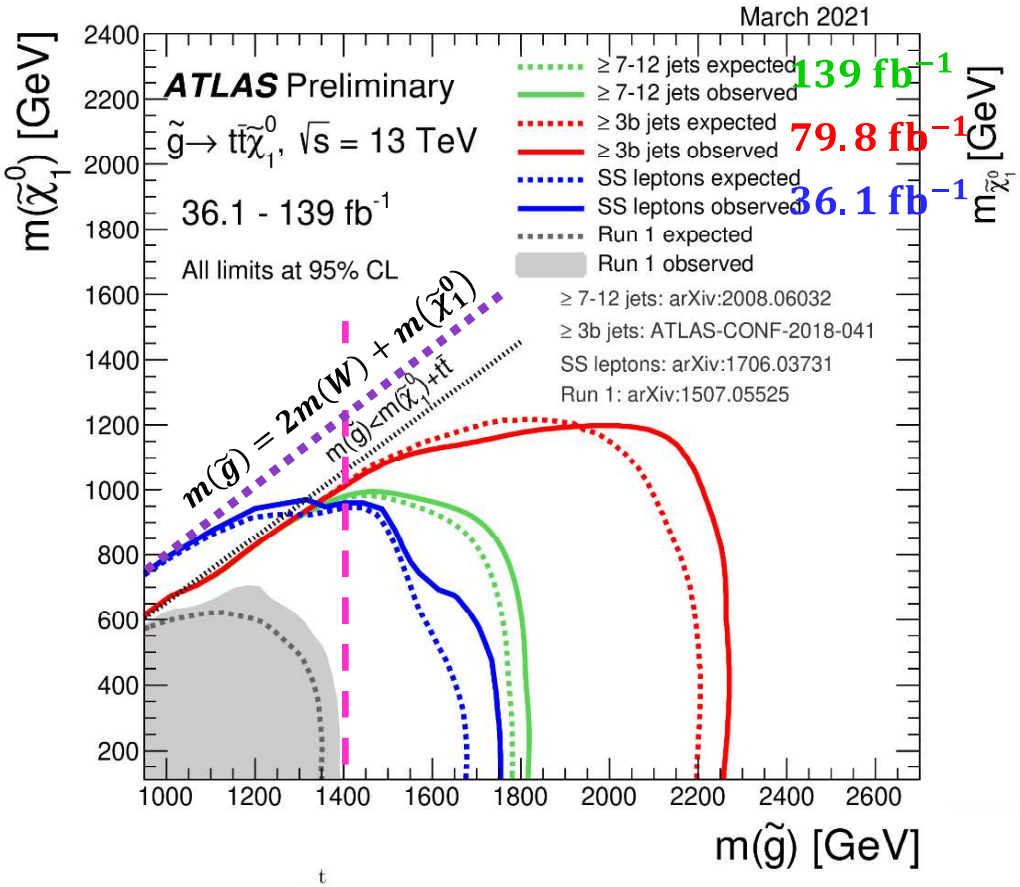
Light $\tilde{\tau}$ - 1τ channel

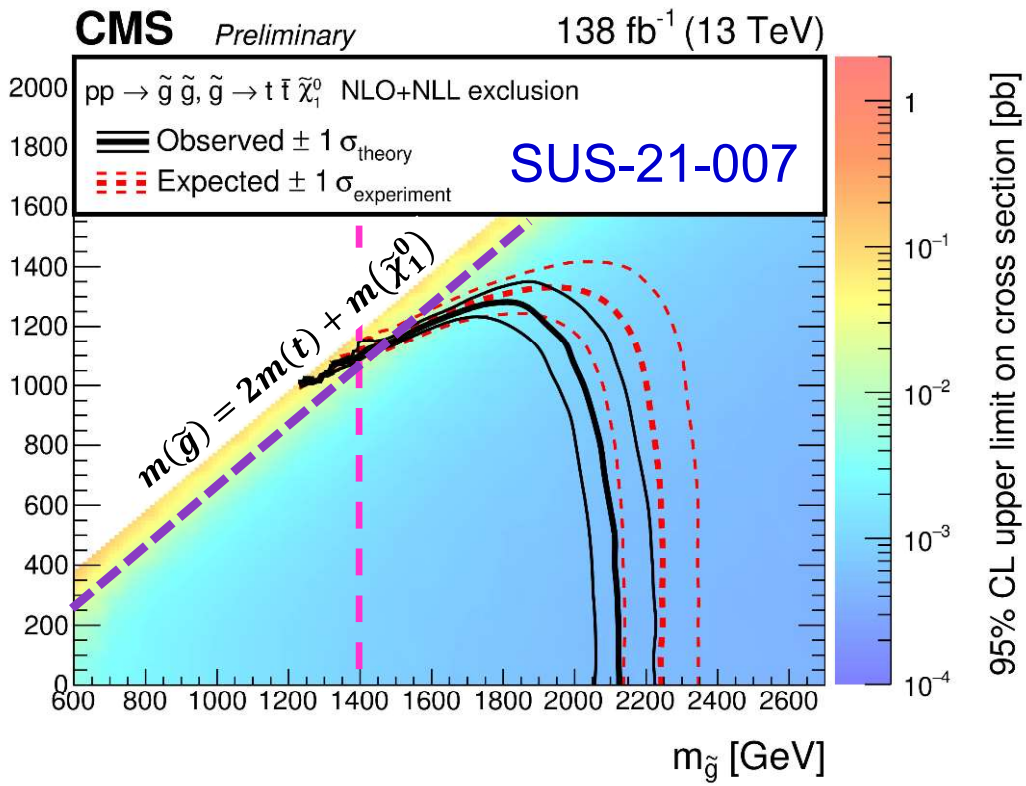


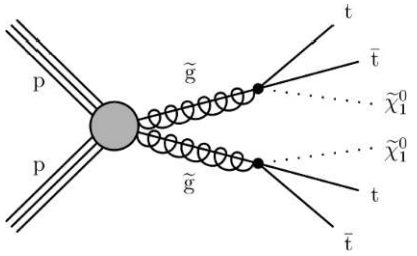


- Stop: Up to ~1400 GeV

$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$





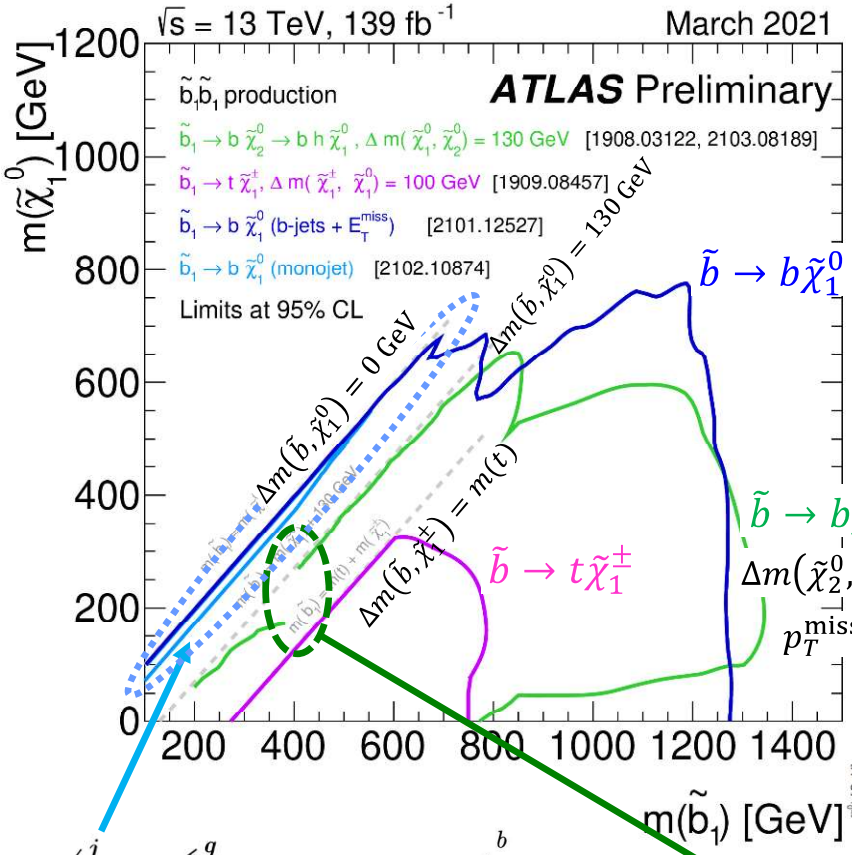


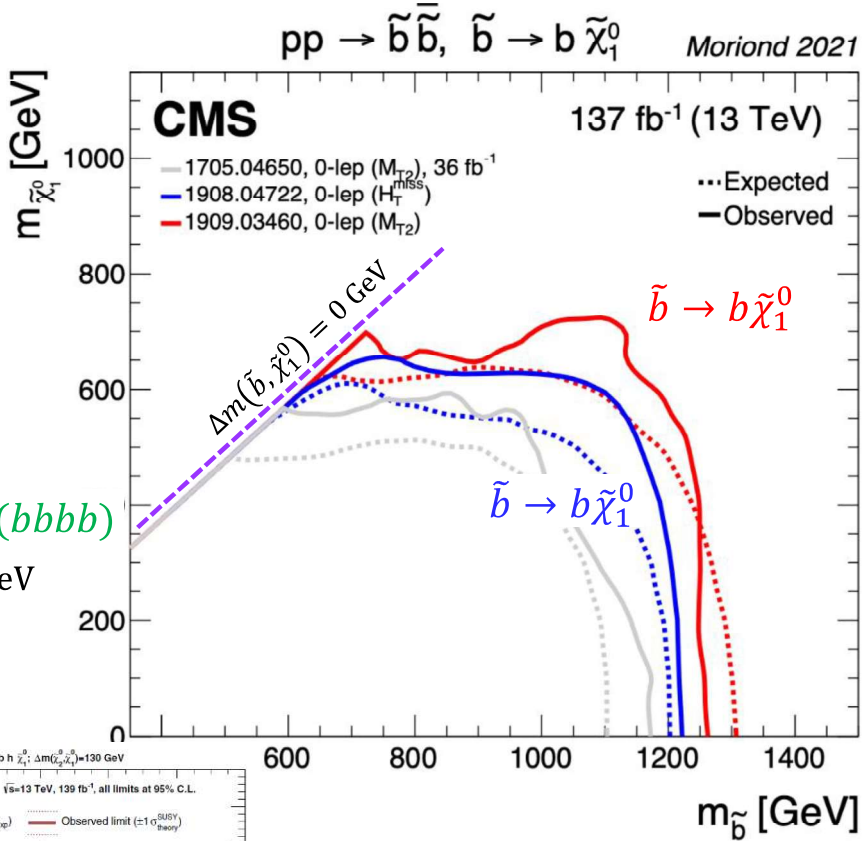
Also see SUS-19-007

Multijets, $N(b) \geq 3$, , SS $\ell\ell$, $\Delta\varphi(\ell, W_{reco})$, top and W tagings

- Gluino: Up to ~2200 GeV
- Weaker limits for multijets and SS dilepton
- Access to compressed-mass scenario vis SS dilepton

$\tilde{b} \to b\tilde{\chi}_1^0, \tilde{b} \to b\tilde{\chi}_2^0, \tilde{b} \to t\tilde{\chi}_1^-$

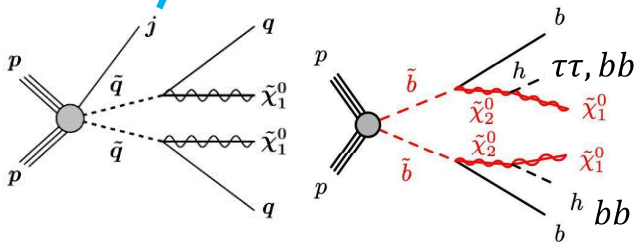


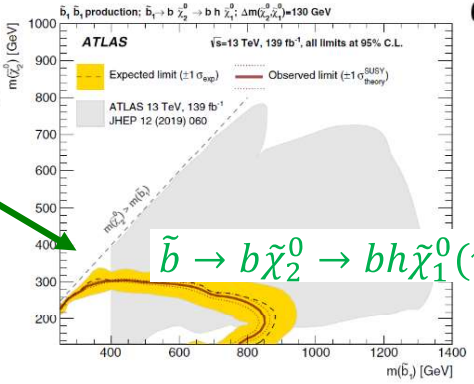


$\tilde{b} \to b\tilde{\chi}_2^0 \to bh\tilde{\chi}_1^0(bbbb)$

$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV

$p_T^{\text{miss}} > 350$ GeV



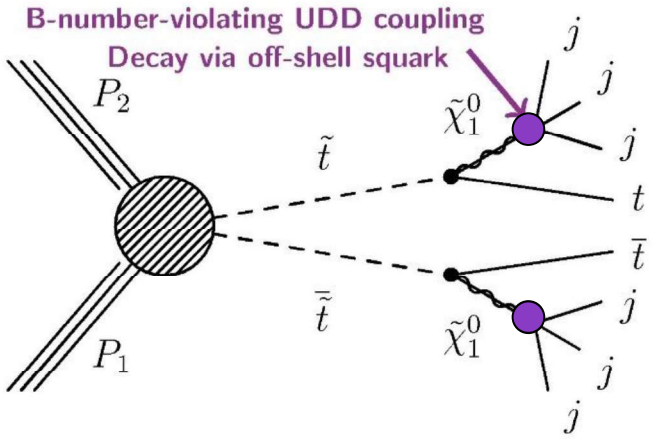


$\tilde{b} \to b\tilde{\chi}_2^0 \to bh\tilde{\chi}_1^0(\tau\tau bb)$

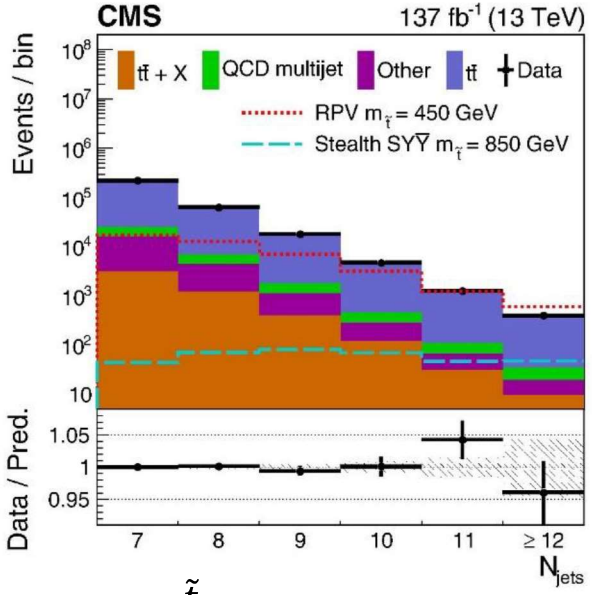
- $\tilde{b} \to b\tilde{\chi}_1^0, b\tilde{\chi}_2^0$: ~1300 GeV; Powerful to access to $\Delta m(\tilde{b}, \tilde{\chi}_{2,1}^0) \sim 0$ GeV with ISR jet
- Weaker limits for $\tilde{b} \to t\tilde{\chi}_1^-$

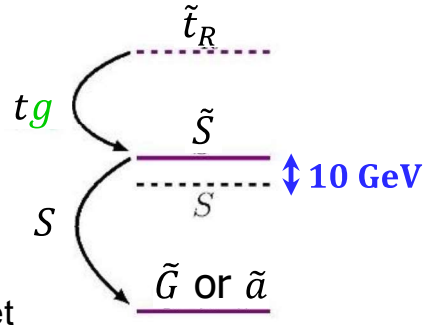
$\tilde{t}$ + $\tilde{\chi}_1^0$ RPV or Stealth Sector

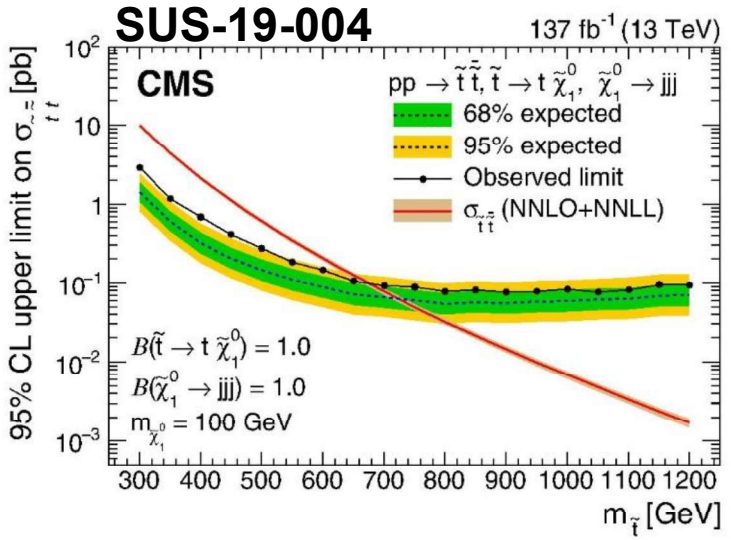
RPV



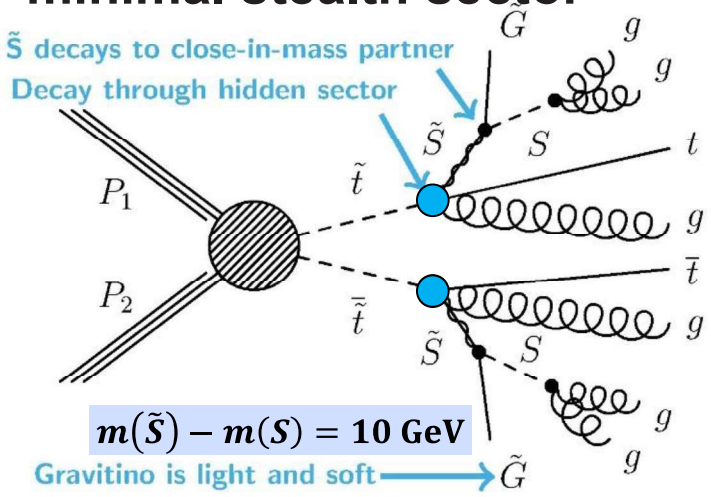
Two t quarks, 4-6 extra jets, and no or little p_T^{miss}

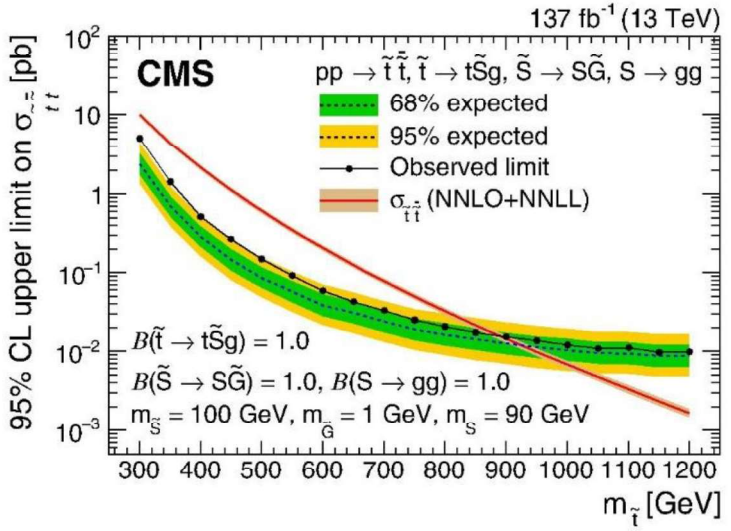






minimal stealth sector

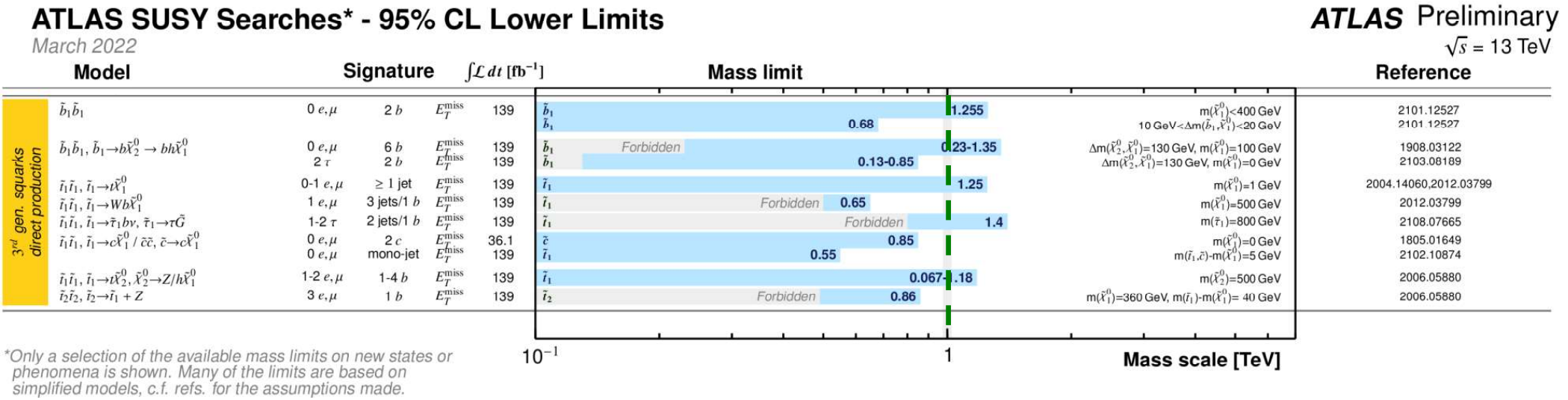


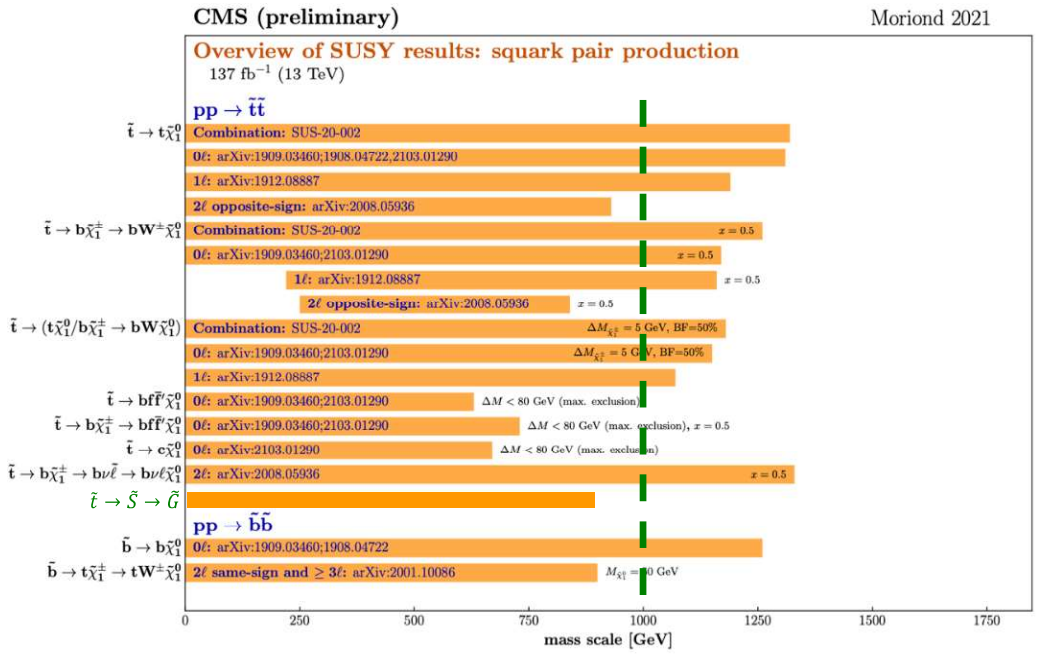


Near-mass degenerate between scalar singlet S and fermion singlino $\tilde{S}$ (in hidden sector):

- Stop: ~900 GeV for $m(\tilde{S}) - m(S) = 10$ GeV ($\tilde{G}$ from $\tilde{S}$ decay are soft ⇒ little P_T^{miss})

Summary: Run 2 ⇒ Run 3

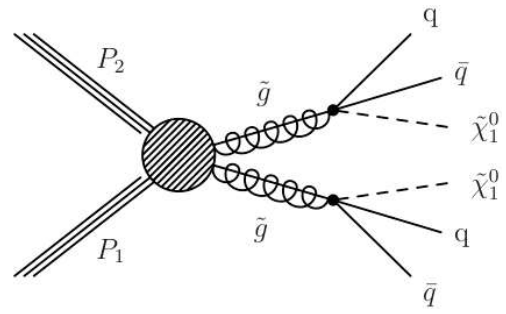


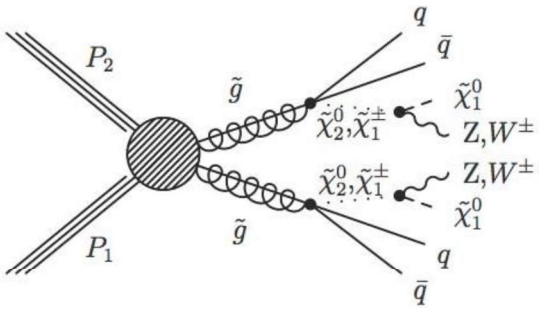


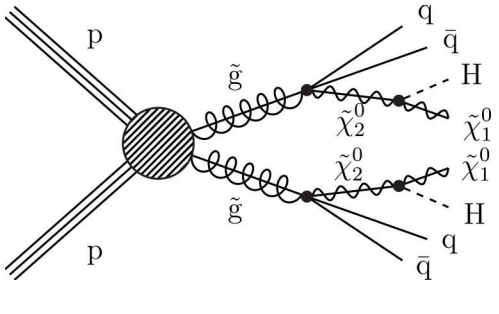
- **LHC Run-2 (140 $\mathbf{fb^{-1}}$):** Stringent limits of ***O*(1 TeV)** in very diverse search scenarios.
- **More results** are in the pipeline and will become public throughout the remainder of the year, and **more data** in **Run 3** is critical to develop **new ideas & techniques** and to open new avenues for constraining SUSY parameter space.

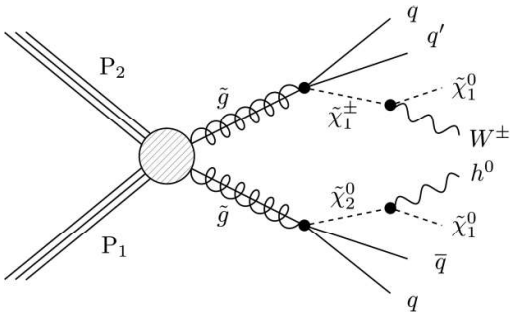
Backups

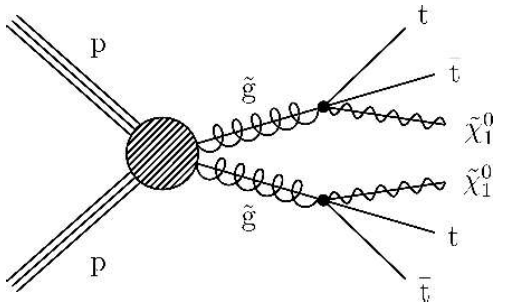
Quick Review: "SUSY $\tilde{g}$, $\tilde{q}$" Menu

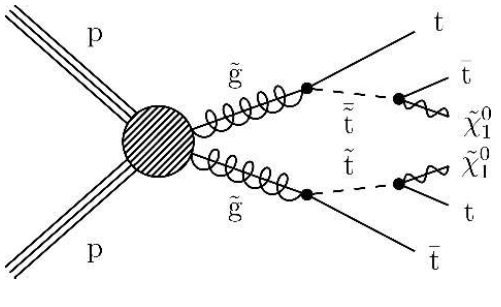


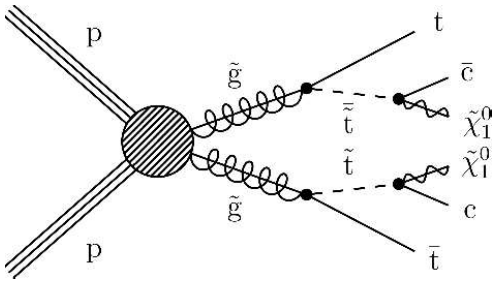


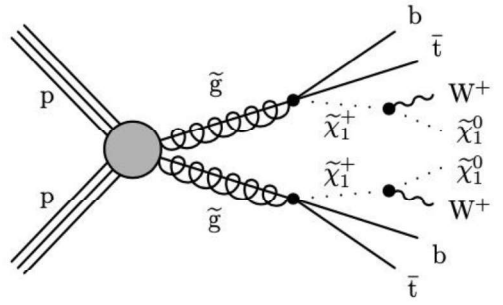


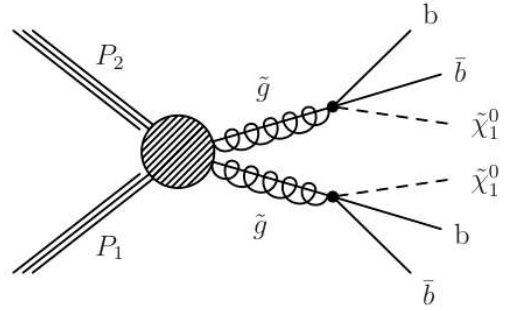


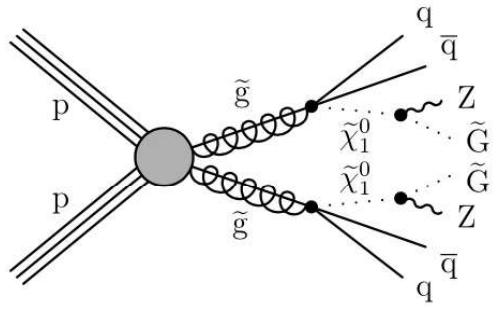


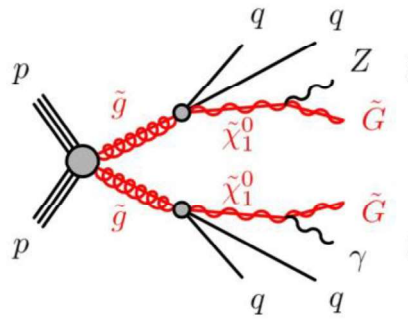




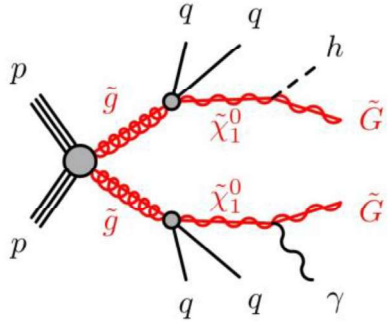




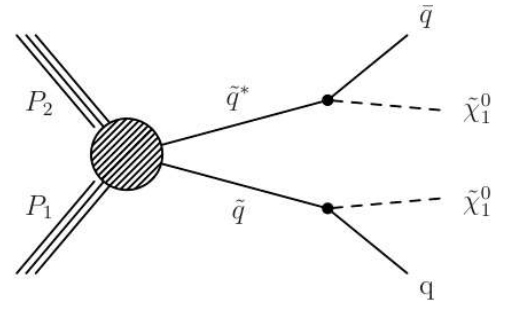


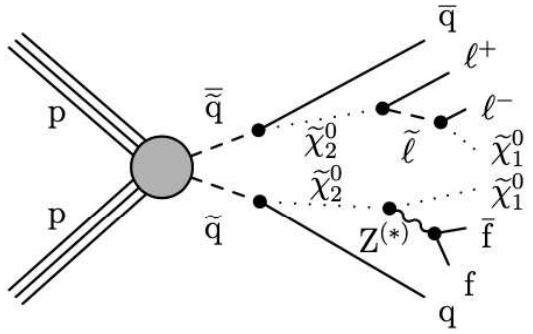


(a) γ/Z model

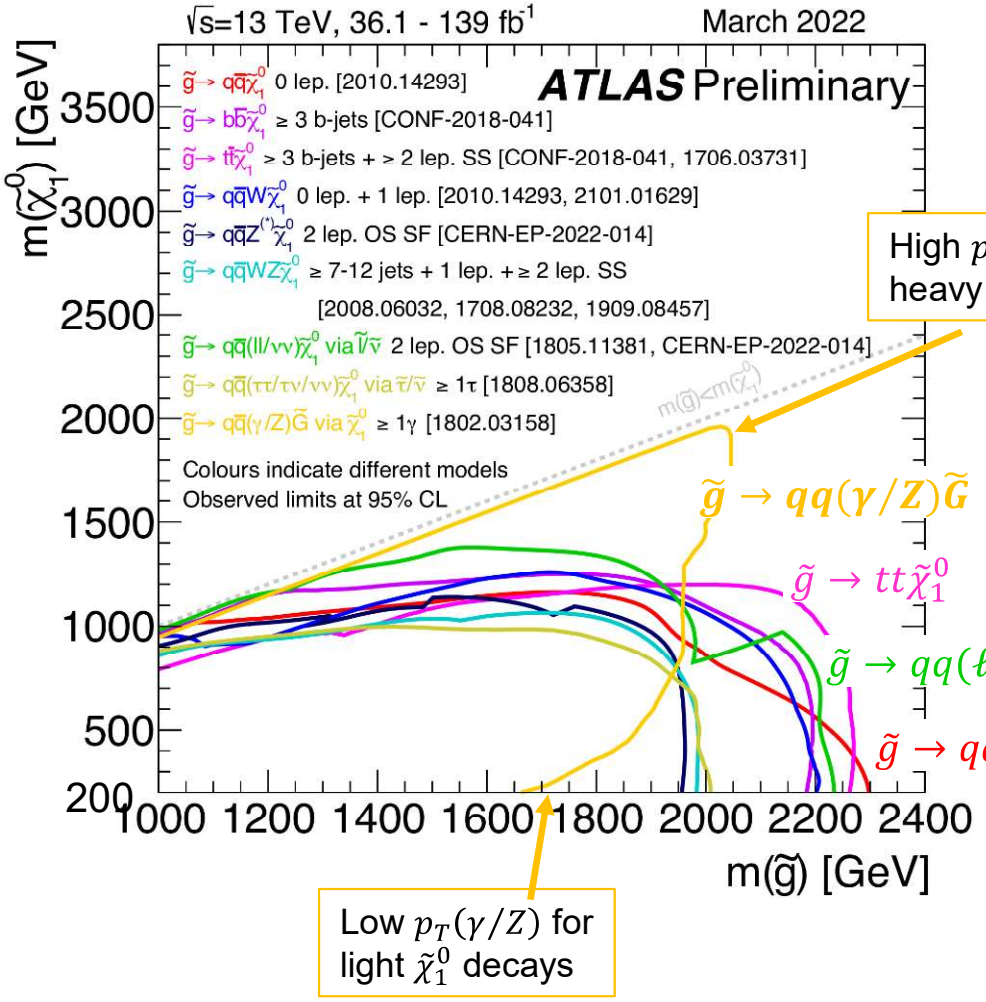


(b) γ/h model





Quick Review: $\tilde{g}$ Limits with $\tilde{\chi}_1^0$ or $\tilde{G}$



High $p_T(\gamma/Z)$ for heavy $\tilde{\chi}_1^0$ decays

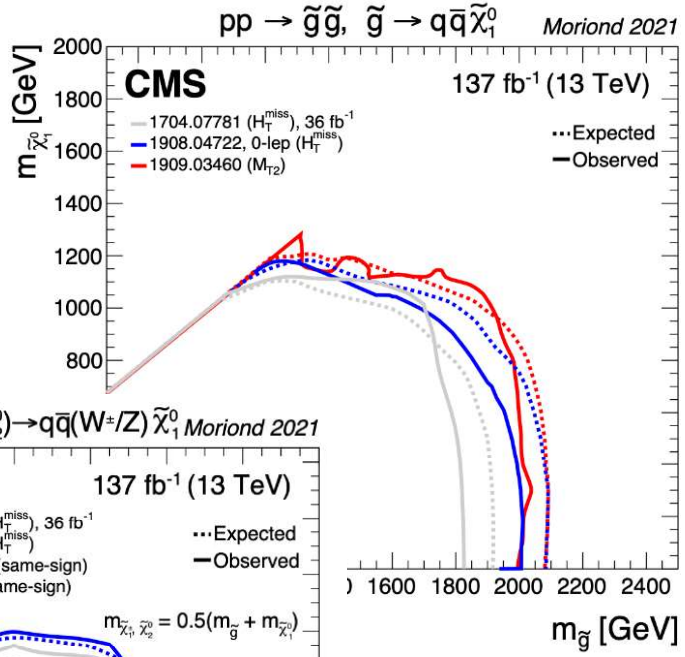
$\tilde{g} \to qq(\gamma/Z)\tilde{G}$

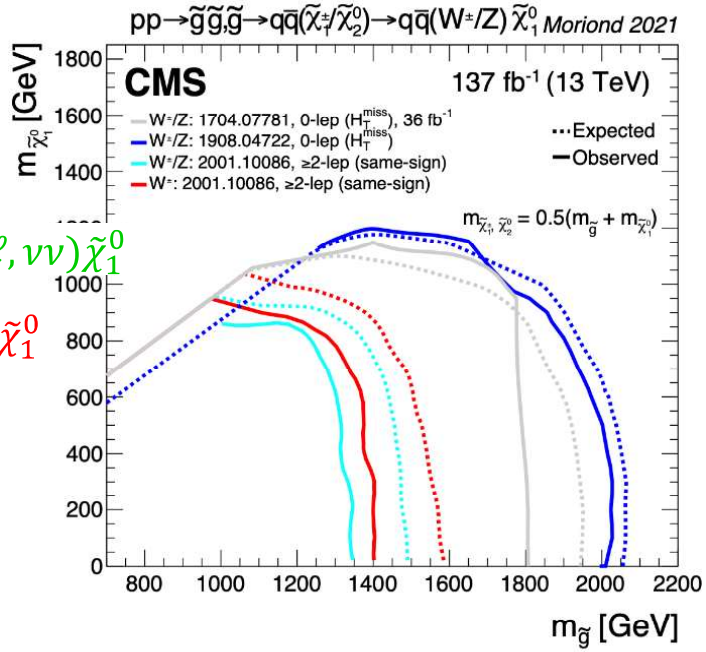
$\tilde{g} \to tt\tilde{\chi}_1^0$

$\tilde{g} \to qq(\ell\ell,\nu\nu)\tilde{\chi}_1^0$

$\tilde{g} \to qq\tilde{\chi}_1^0$

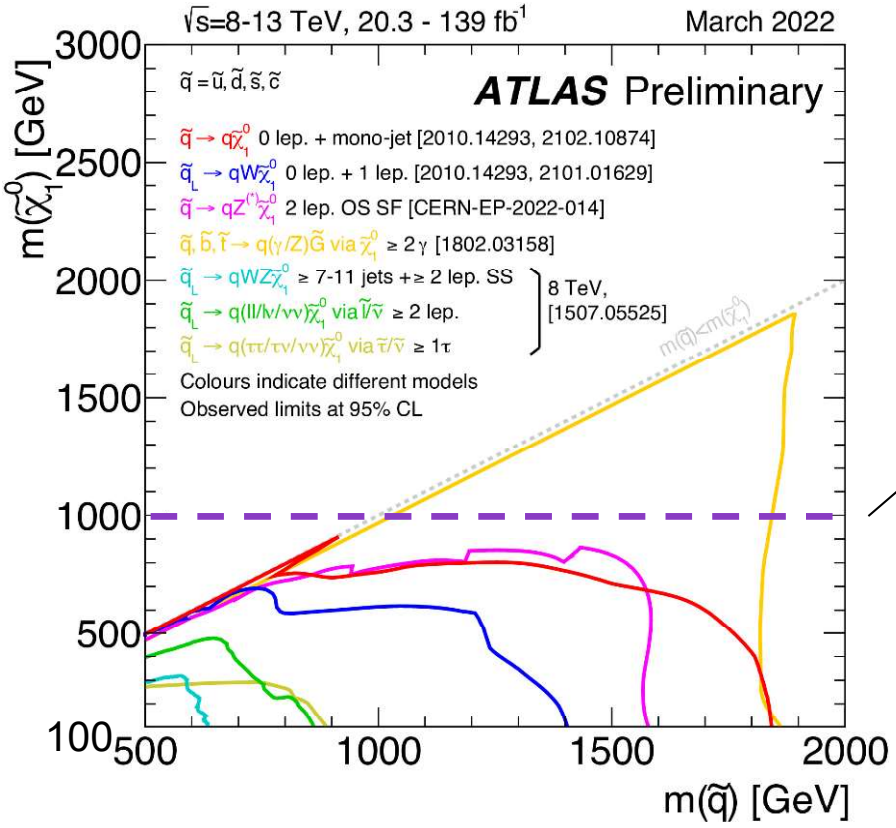
Low $p_T(\gamma/Z)$ for light $\tilde{\chi}_1^0$ decays

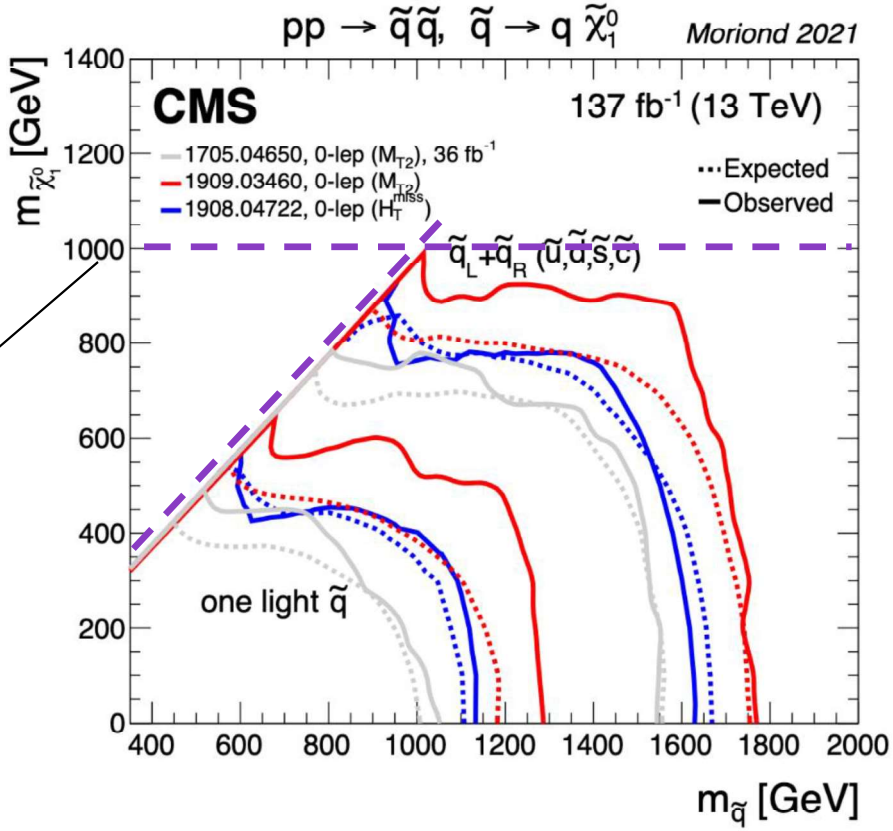


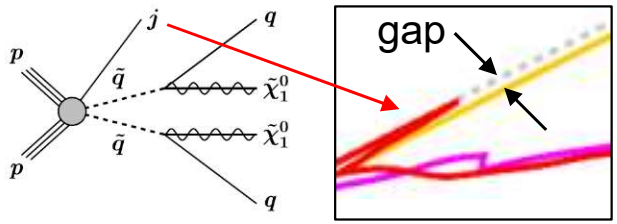


- Gluionos: Up to ~2200 GeV for $\tilde{g} \to qq\tilde{\chi}_1^0$, $bb\tilde{\chi}_1^0$, $tt\tilde{\chi}_1^0$, $qqW\tilde{\chi}_1^0$, $qq(\ell\ell,\nu\nu)\tilde{\chi}_1^0$
- Weaker limits for $\tilde{g} \to qqZ\tilde{\chi}_1^0$, $qqWZ\tilde{\chi}_1^0$, $qq(\tau\tau,\tau\nu,\nu\nu)\tilde{\chi}_1^0$
- 1600-2050 GeV for $\tilde{g} \to qq(\gamma/Z)\tilde{G}$ by $\tilde{\chi}_1^0 \to (\gamma/Z)\tilde{G}$

Quick Review: $\tilde{q}$ Limits with $\tilde{\chi}_1^0$ or $\tilde{G}$







- Squarks: Up to ~1800 GeV with 4-degenerate flavor $\tilde{q}$; ~1200 GeV for one flavor $\tilde{q}$
- Weaker limits: cascade cays via $\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm}, \tilde{\ell}$
- Powerful technique for small mass difference (compressed mass spectra) with ISR jet