SUSY searches in ATLAS and CMS

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for the ATLAS & CMS Collaborations

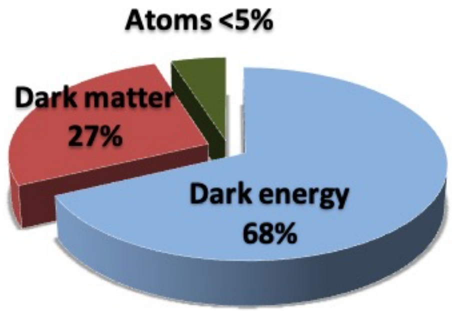
19th HELLENIC SCHOOL AND WORKSHOPS ON ELEMENTARY PARTICLE PHYSICS AND GRAVITY

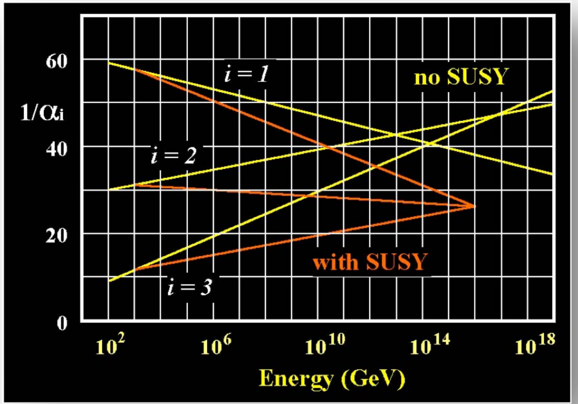
Workshop on Connecting Insights in Fundamental Physics: Standard Model and Beyond

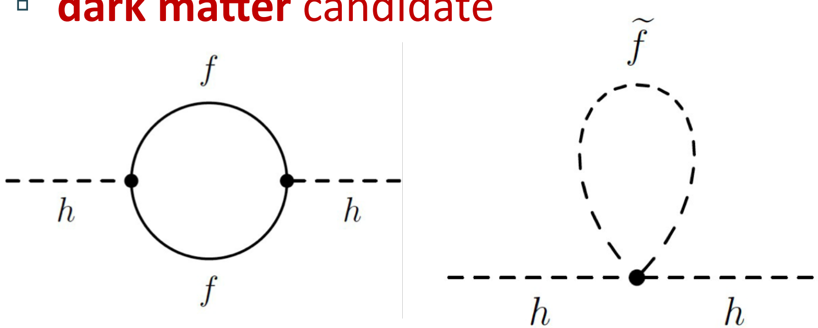
August 31 - September 11, 2019, Corfu, Greece

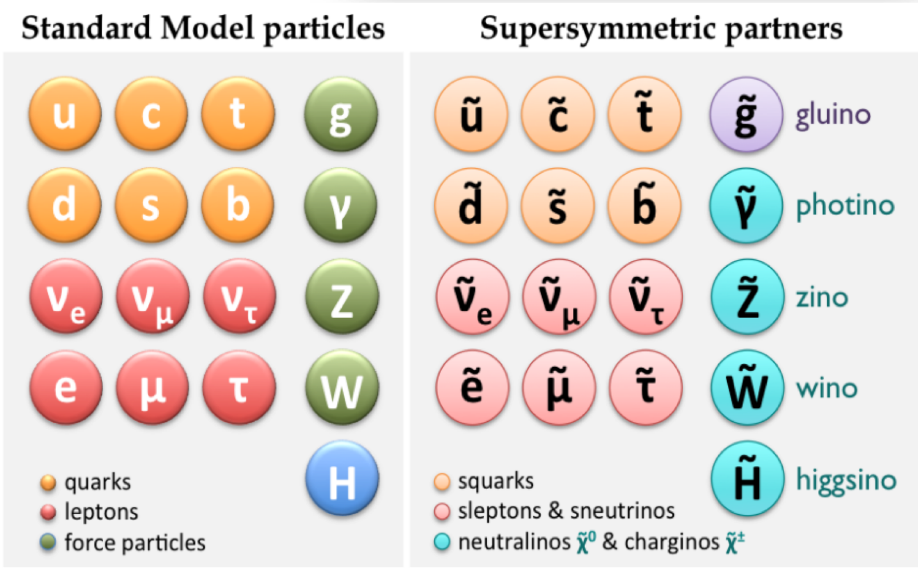
Supersymmetry

- What it is?
  - global symmetry between fermions & bosons
- Why is it attractive?
  - Higgs: predicts a below-135-GeV Higgs scalar
    - may be SM-like
    - completely solves hierarchy problem
  - **unification** of gauge couplings at a single scale
  - **dark matter** candidate

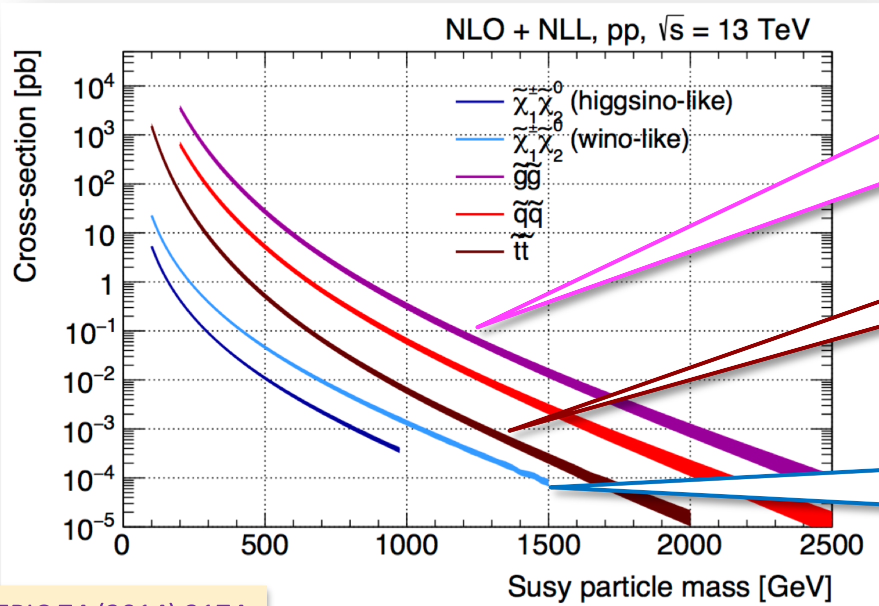








SUSY searches strategy



EPJC 74 (2014) 3174

Strong-production channels
- copious production at hadron colliders
- MET-based generic channels

Third-generation sparticles
- naturalness → mass of *O*(<TeV)
- lighter than other squarks

Electroweak production
- coloured spartners too heavy
- direct **gaugino/slepton** production
- relevant for **dark matter** searches

RPC or RPV
- RPV ⇒ more leptons/jets and less MET
- RPV → prompt or delayed LSP decay

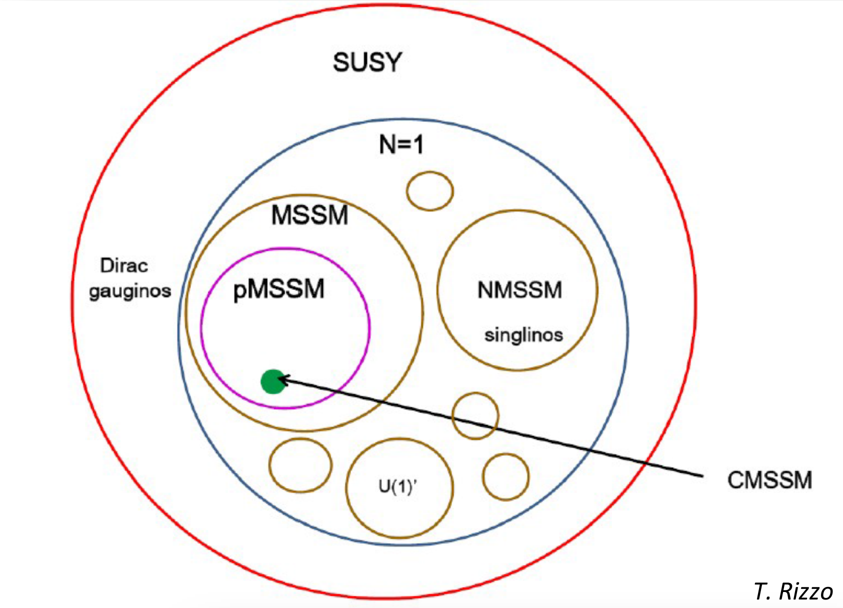
Interpretations in other BSM scenarios (including dark matter)

(Meta)stable sparticles
- suppressed (effective) coupling
- lack of phase space, e.g. mass degeneracies
- may induce non-trivial signals in detectors

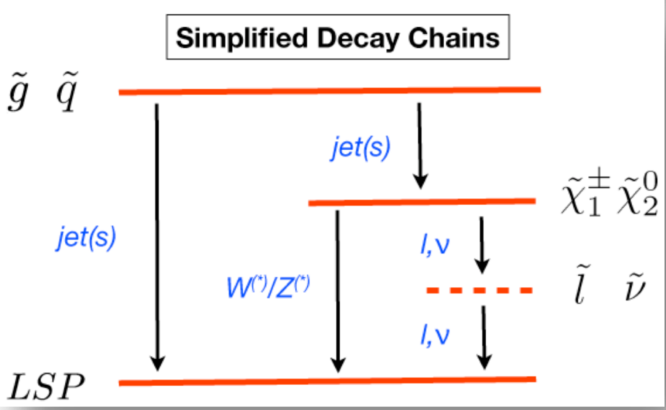
Interpretation

- Sparticle masses from SUSY breaking not fixed by theory ⇒ huge parameter space to explore
- **How to test that at LHC?**

1. Top-down approach
   - SUSY breaking mechanism ➞ different models
   - GUT scale unification ➞ few free parameters
2. Bottom-up approach
   - Phenomenological models (pMSSM, …)
     - fix mass hierarchy, mass scales and other assumptions
     - scan remaining parameters
   - Simplified topologies
     - specific decay chain
     - easy to interpret results in terms of other models

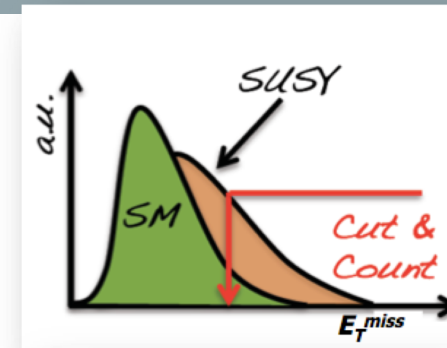


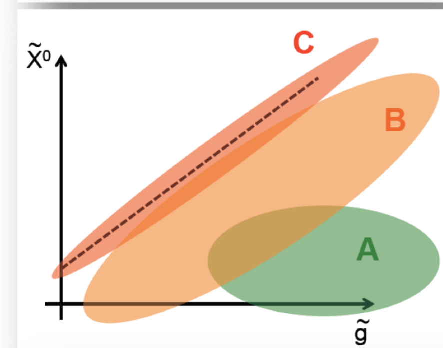
T. Rizzo

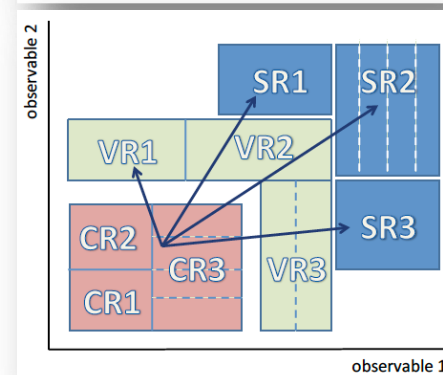


Typical SUSY search

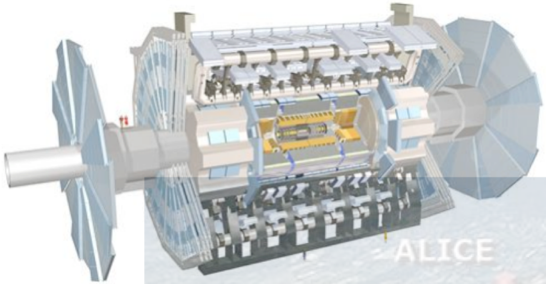
- Signal region (**SR**)
  - may be single-bin ("cut & count") or multi-bin
  - optimised for best discovery in targeted production/decay mode
  - to cover different mass hierarchies ➜ few SRs for each final state
- Data-driven background estimate
  - irreducible backgrounds estimated using control region (**CR**) data as a constraint and Monte Carlo to extrapolate from CR to SR
  - reducible background (fake/non-isolated leptons, MET from jet mis-measurement) from data
  - validation regions (**VR**) to check background estimate method and CR→SR variable modelling
- Likelihood fit of data in SRs and CRs
  - hypothesis testing of signal models ➜ 95% CL cross-section upper limits
  - background versus data ➜ model-independent upper limits at 95% CL in visible cross-section

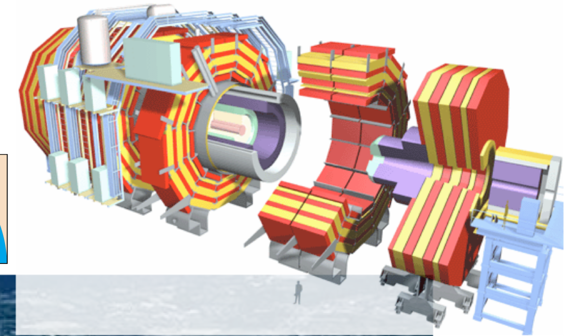


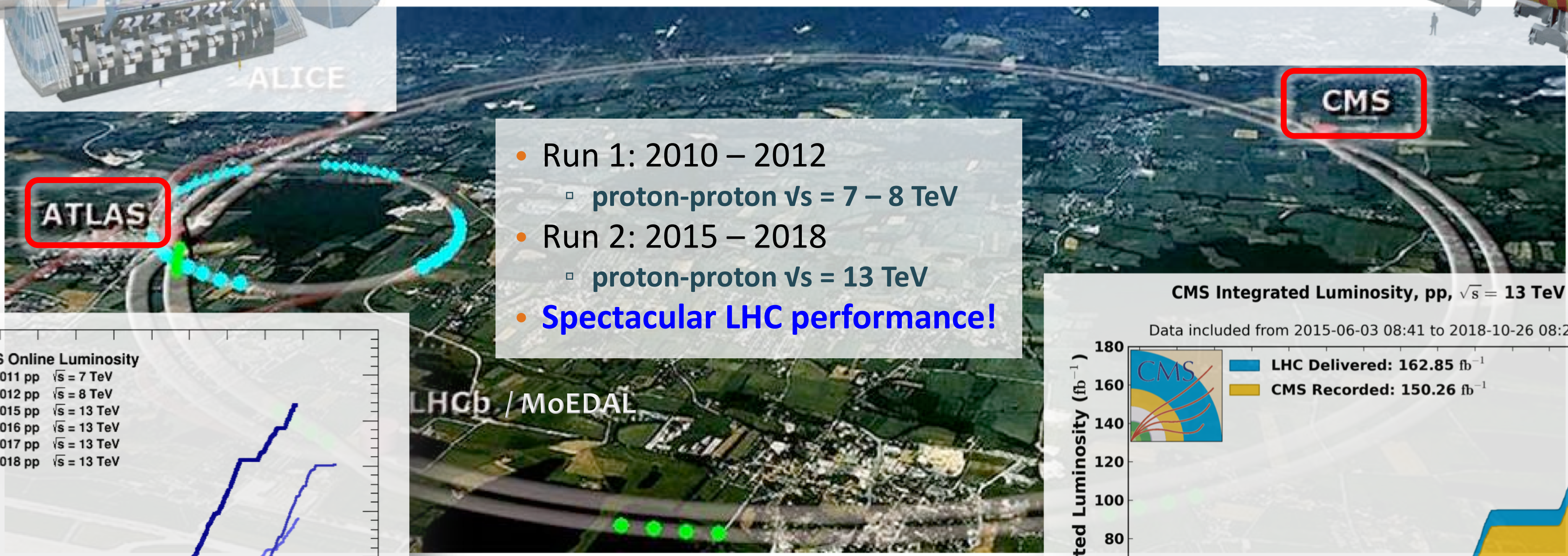




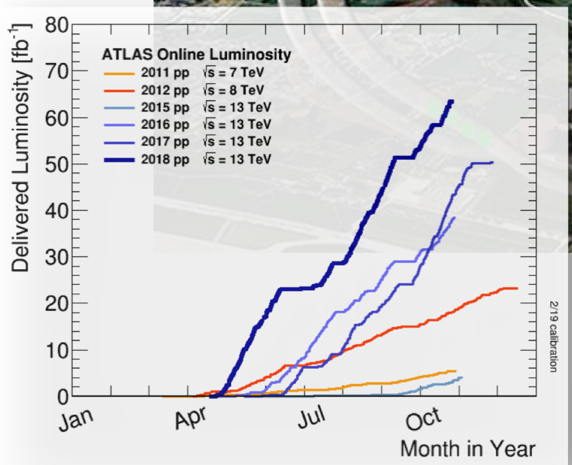
Large Hadron Collider at CERN

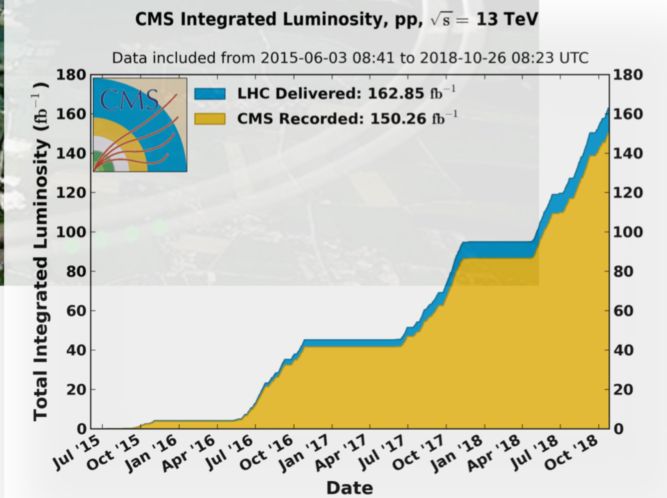






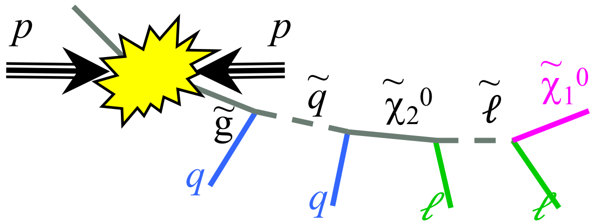
- Run 1: 2010 – 2012
  - proton-proton √s = 7 – 8 TeV
- Run 2: 2015 – 2018
  - proton-proton √s = 13 TeV
- **Spectacular LHC performance!**

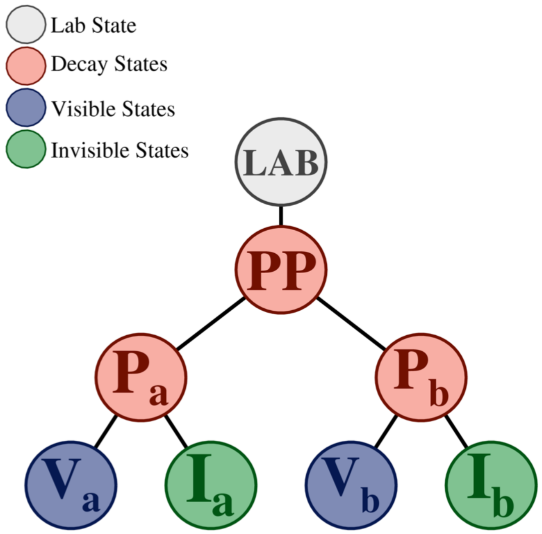




Strong production

Production of 1st and 2nd generation squarks and gluinos with subsequent cascade decay to lighter sparticles

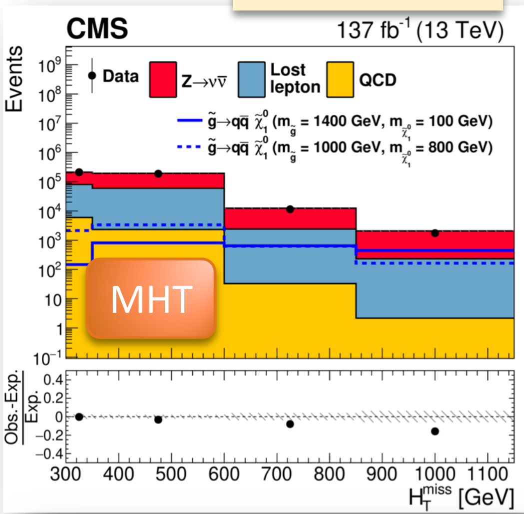


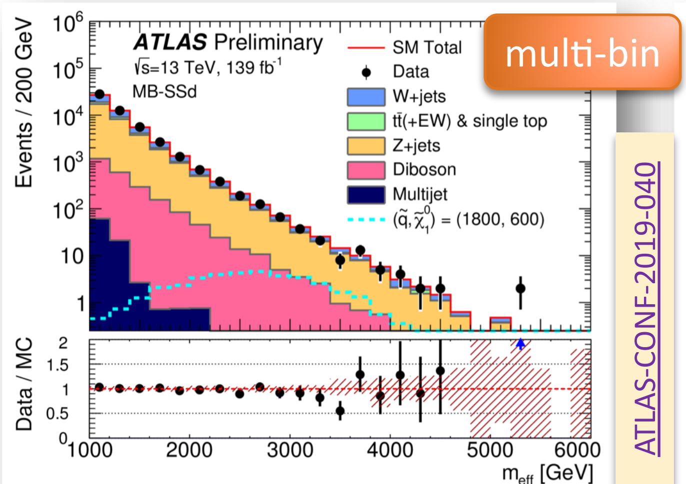


Squarks & gluinos: 0L + jets + MET

- Events with no isolated lepton (e/μ) in the final state
  ☛ relying on high MET and hadronic activity
- Various strategies:
  a) multi-bin SRs: shape of jet-related variables, e.g. $m_{\text{eff}} = \sum_{\text{jets}} p_{\text{T}}^{\text{j}}$
  b) Boosted Decision Tree (BDT) trained against SM
  c) split events into two pseudojets and compute MT2(j_1; j_2)
  d) use $\text{MHT} = \left\| - \sum_{\text{jets}} \mathbf{p}_{\text{T}}^{\text{j}} \right\|$

arXiv:1908.04722





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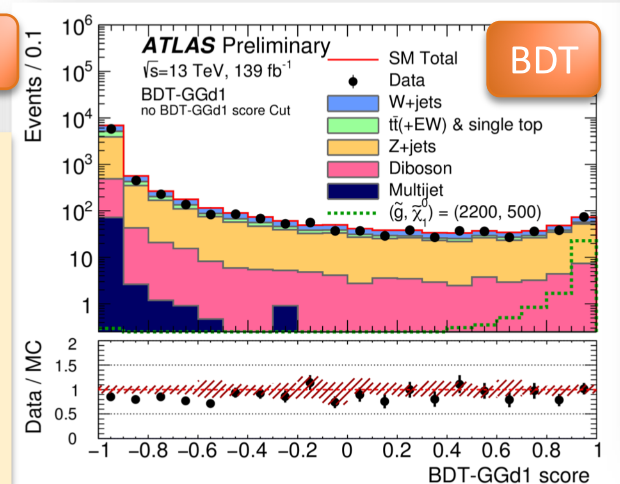
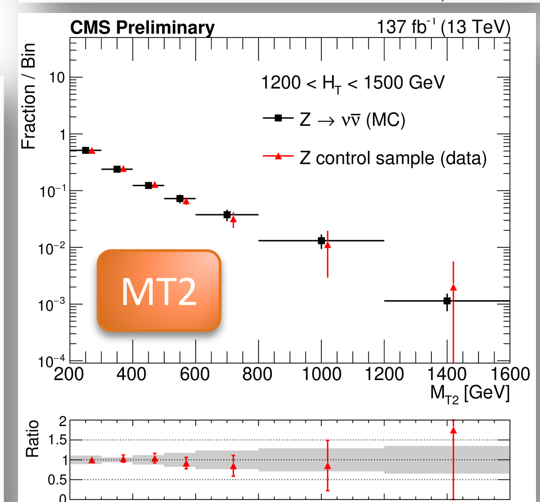
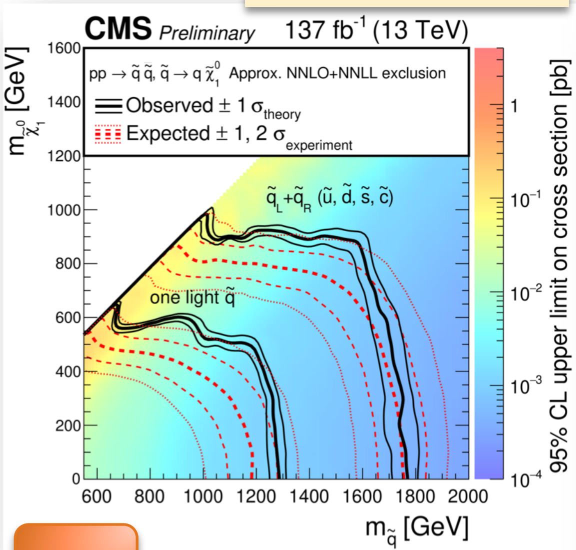




CMS-PAS-SUS-19-005

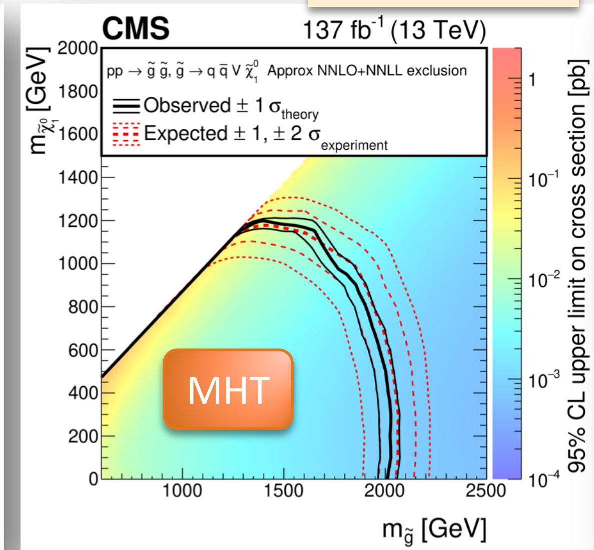
0L + jets + MET interpretation

CMS-PAS-SUS-19-005



MT2

arXiv:1908.04722



MHT

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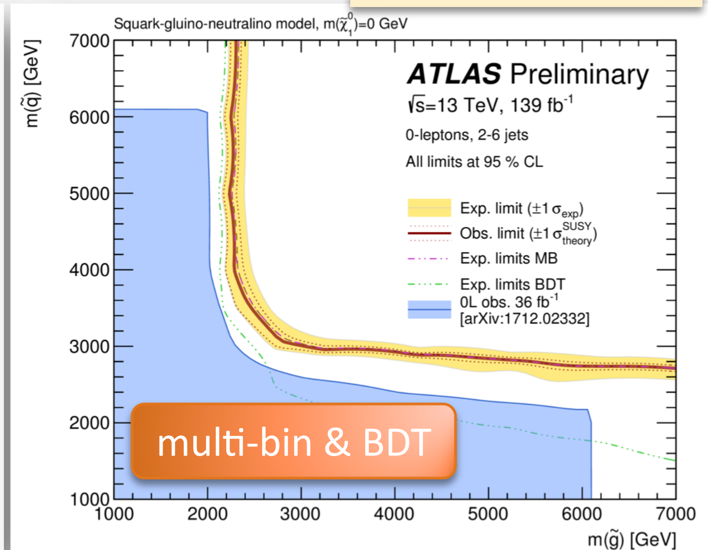
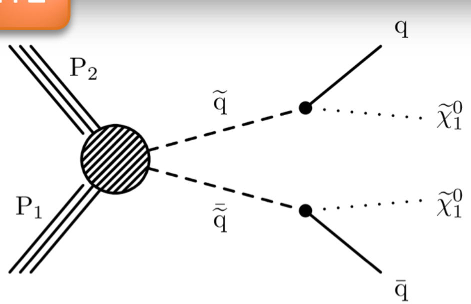
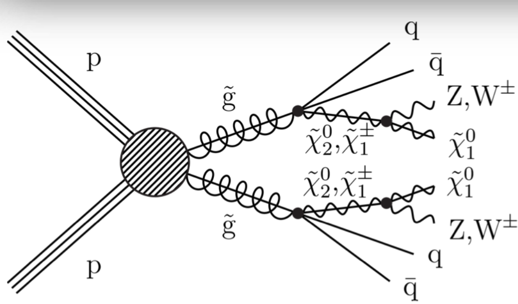


multi-bin & BDT

Combined production of $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{g}$



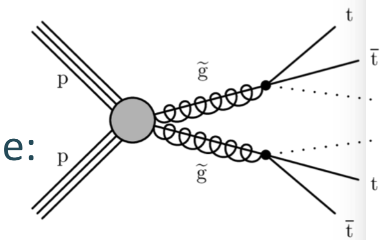


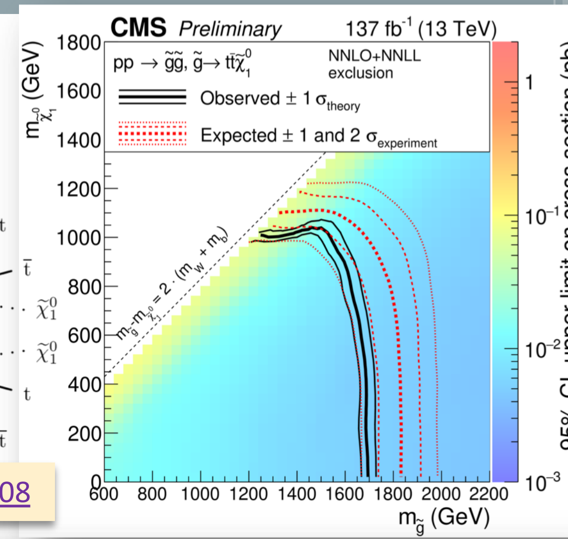
3rd generation: interpretations also for $\tilde{t}\tilde{t}$ and $\tilde{b}\tilde{b}$ and for $\tilde{g}$-mediated $\tilde{t}/\tilde{b}$ production

Same-sign 2 leptons & 3 leptons

Targets leptonic decay signals (including *R*-parity violation*)

- limited SM (irreducible) same-sign lepton backgrounds
- reducible detector backgrounds non negligible: fake/non-prompt leptons, electron charge flip, ... ➜ estimated from data





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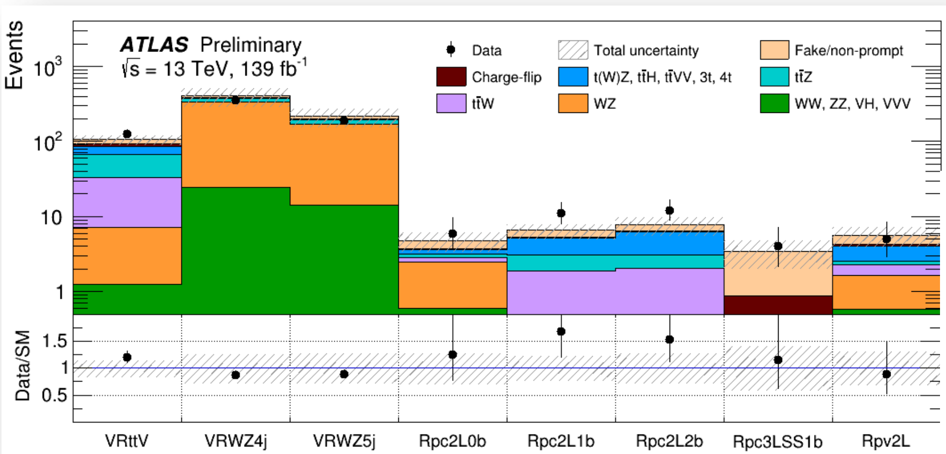

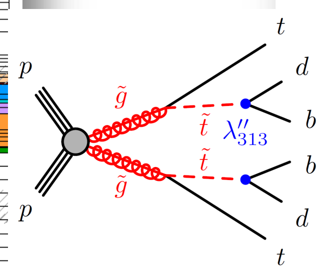

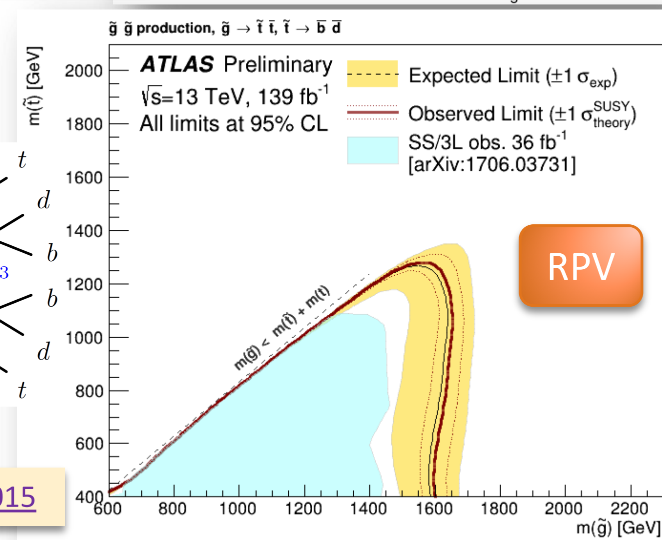

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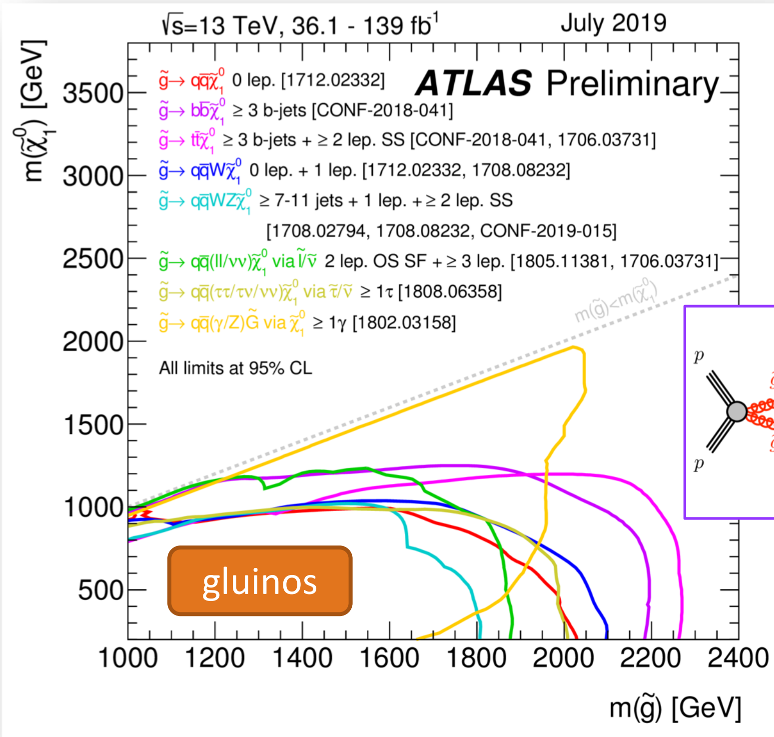
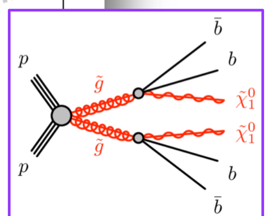
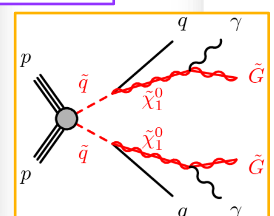
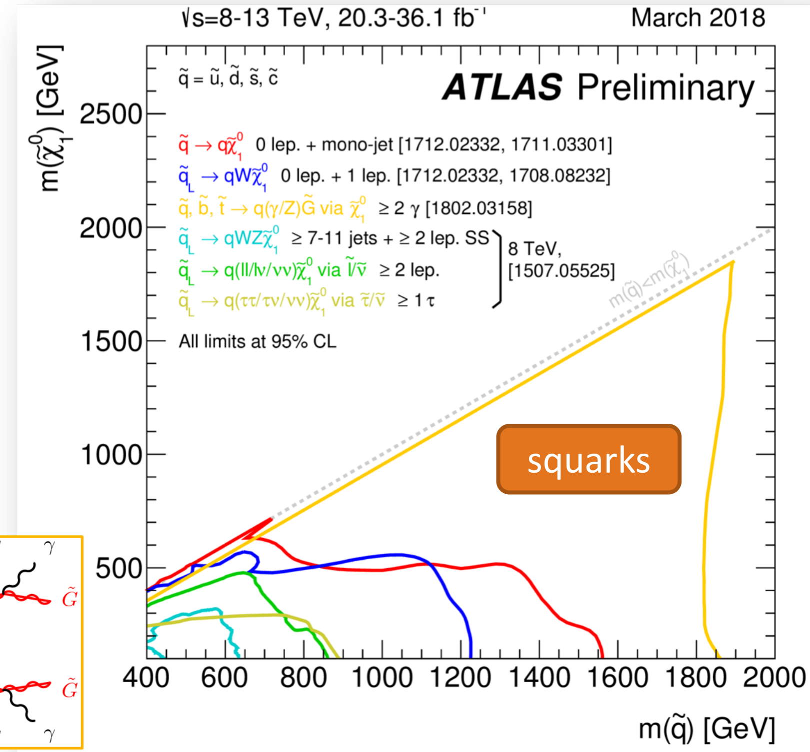
* Discussed in detail in “*R*-parity violation”

Strong production - summary







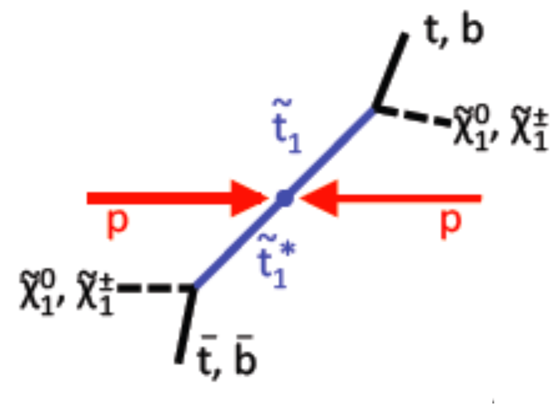


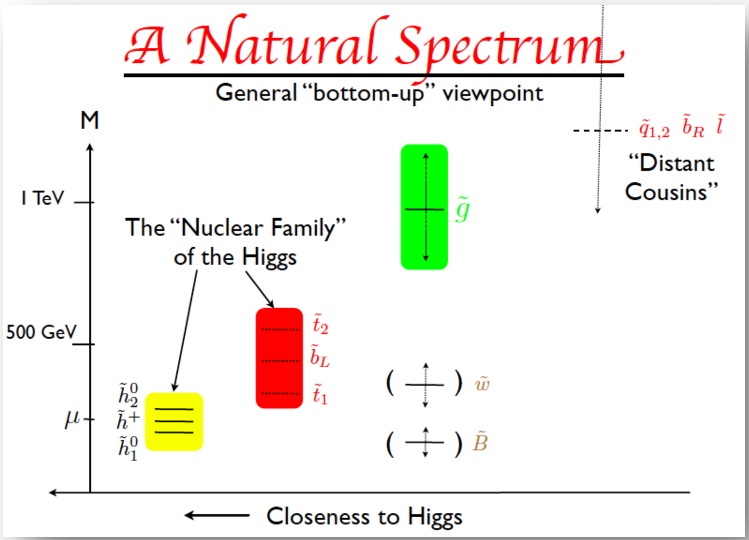
- 100% branching ratios are assumed
- Exclusion curves not necessarily directly comparable
  - — different sparticle mass hierarchies
  - — different simplified decay scenarios

ATL-PHYS-PUB-2019-022

3rd generation quarks

- Inspired by naturalness arguments
- Focuses on **stop** and **sbottom** production





L. Hall, Berkeley 2011

Stop in 1-lepton channel

- Selection: 1 ℓ (e/μ), ≥ 2 jets, large MET, large M_T, ≥1 (soft) b-jet
- New techniques to address specific regions: neural networks, modified topness variable, ...

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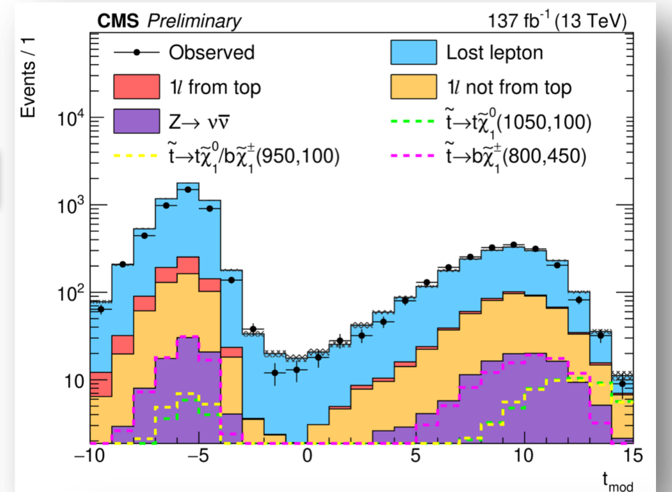
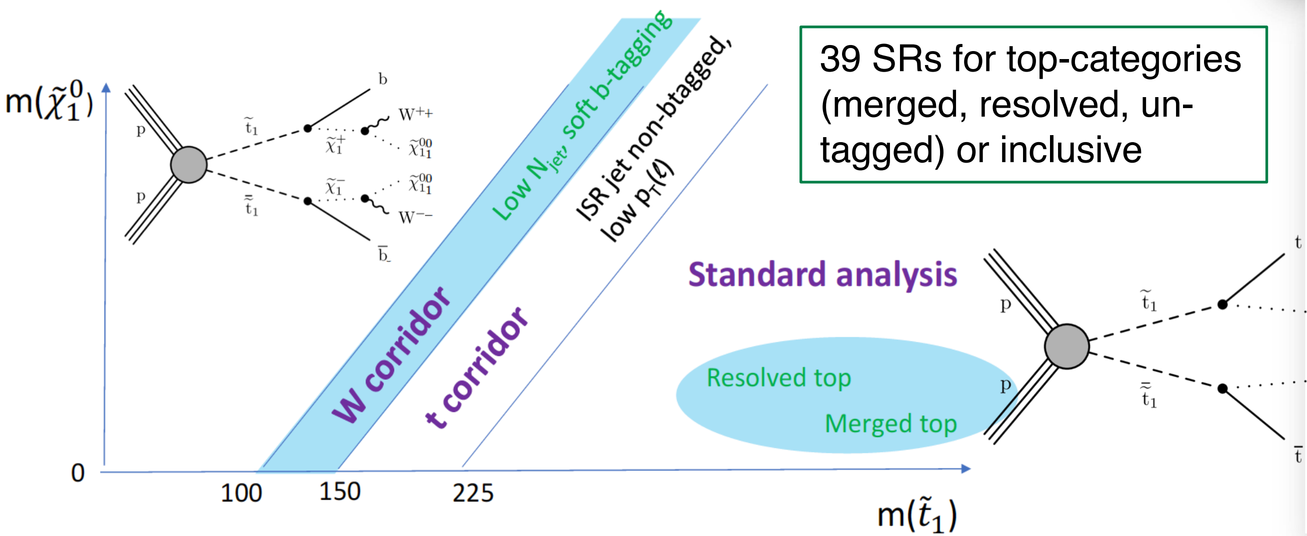
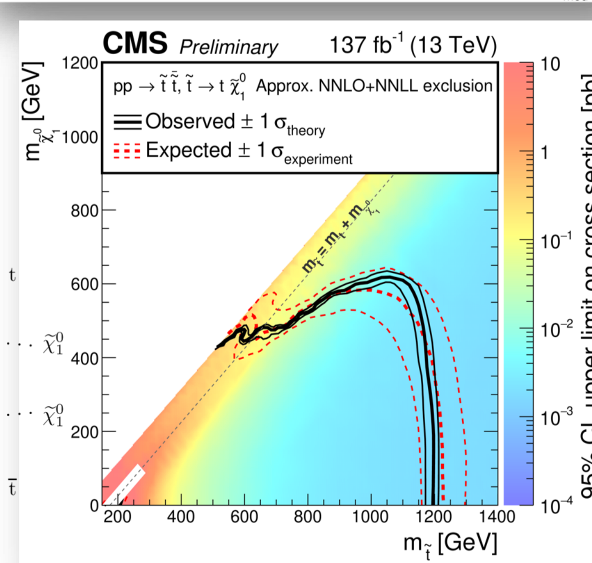


$$t_{\rm mod} = \ln(\min S),\ \text{with}\ S = \frac{\left(m_{\rm W}^2 - (p_\nu + p_\ell)^2\right)^2}{a_{\rm W}^4} + \frac{\left(m_{\rm t}^2 - (p_{\rm b} + p_{\rm W})^2\right)^2}{a_{\rm t}^4}$$

39 SRs for top-categories (merged, resolved, un-tagged) or inclusive

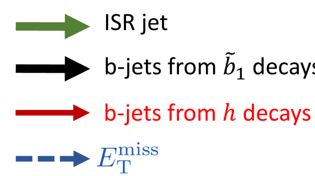


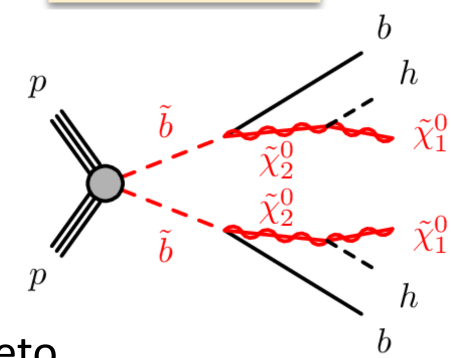


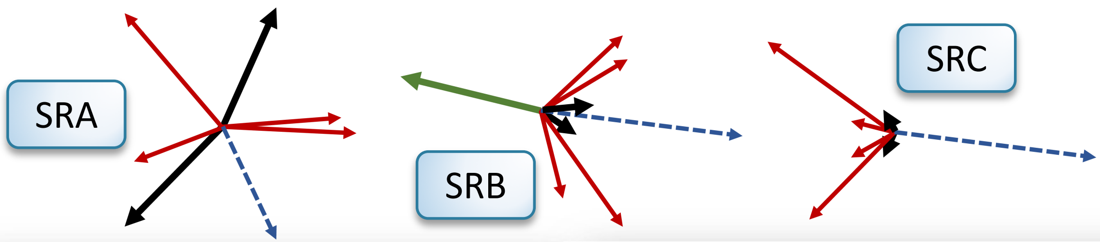
Sbottom decay to Higgs

arXiv:1908.03122

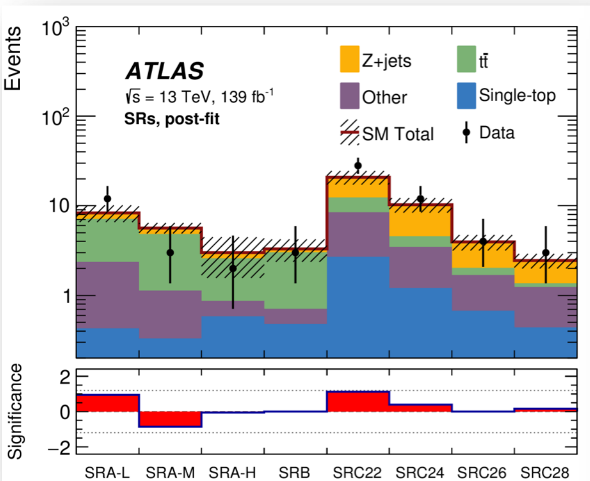
- $h \to b\bar{b}$ decay leads to multi-*b*-jets final signature
- Depending on mass splittings, *b*-jets from sbottom may have different kinematics from ones from *h*

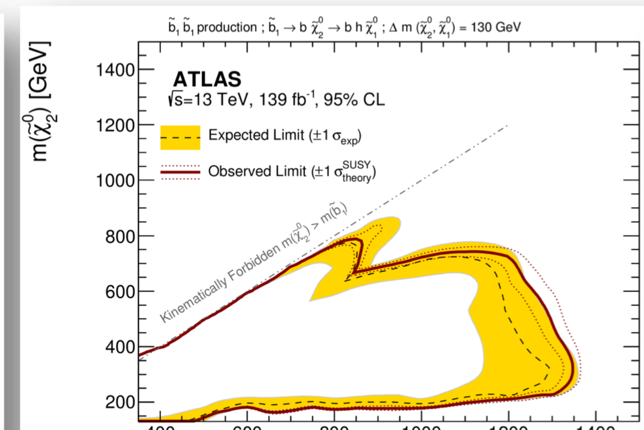




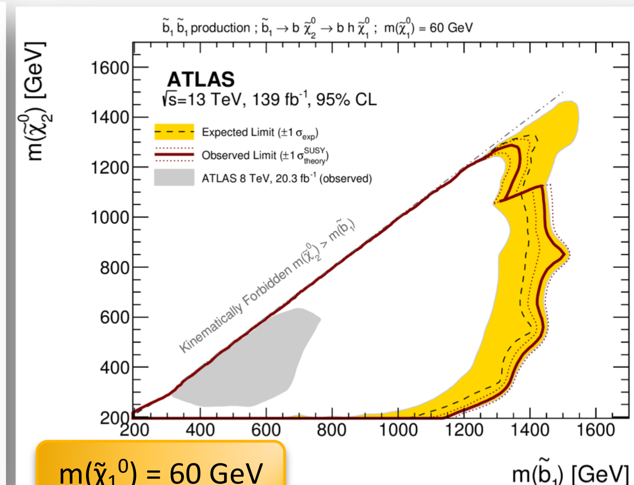


- lepton veto
- many (≥ 3 or 4) *b*-jets





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



$m(\tilde{\chi}_1^0)$ = 60 GeV

Stop production

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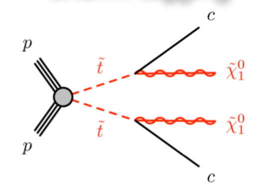
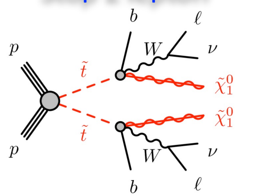
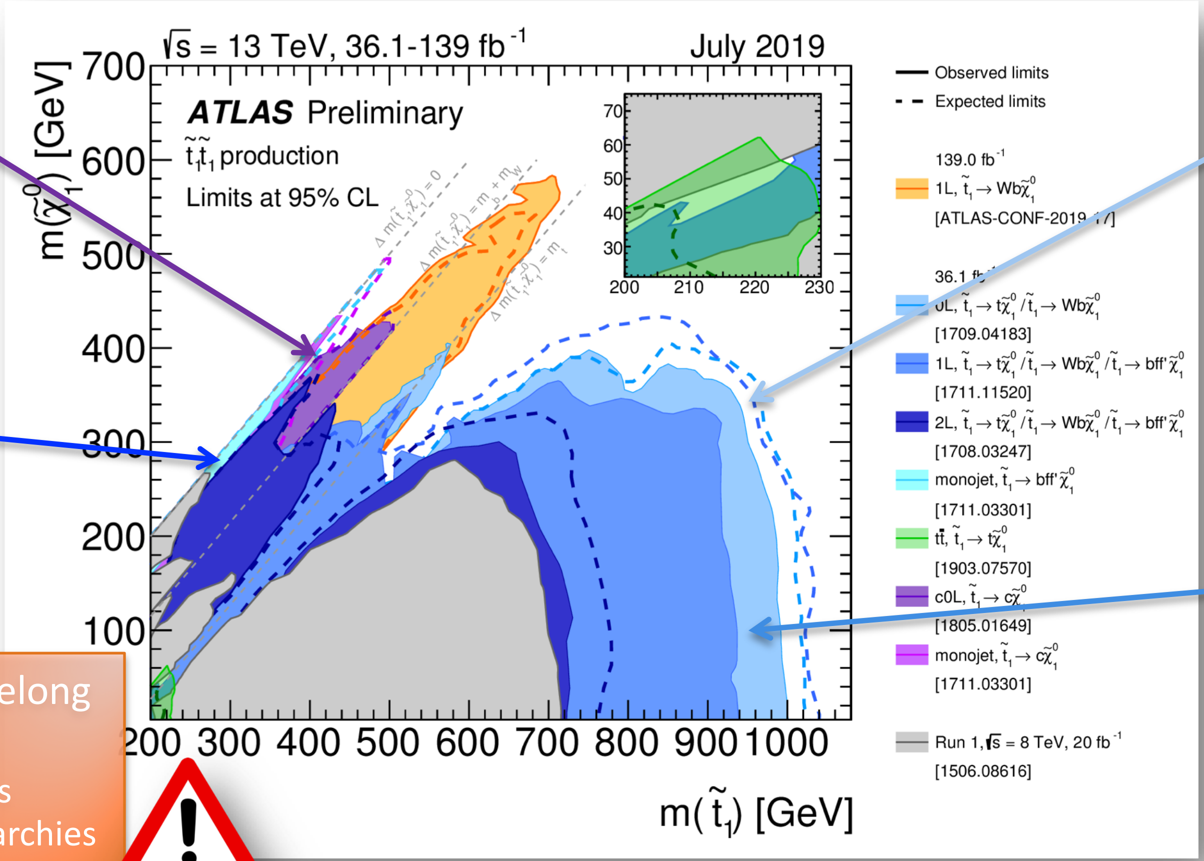
Charm tagging



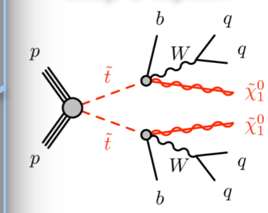
m(stop) ≲ m(top) + m($\tilde{\chi}_1^0$)

Stop 2 lepton

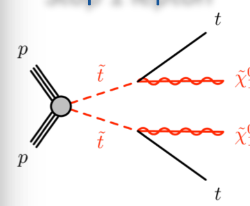




Stop 0 lepton



Stop 1 lepton



Overlaid contours belong to different:

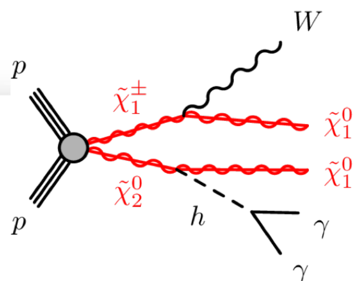
- stop decay channels
- sparticle mass hierarchies
- simplified decay scenarios

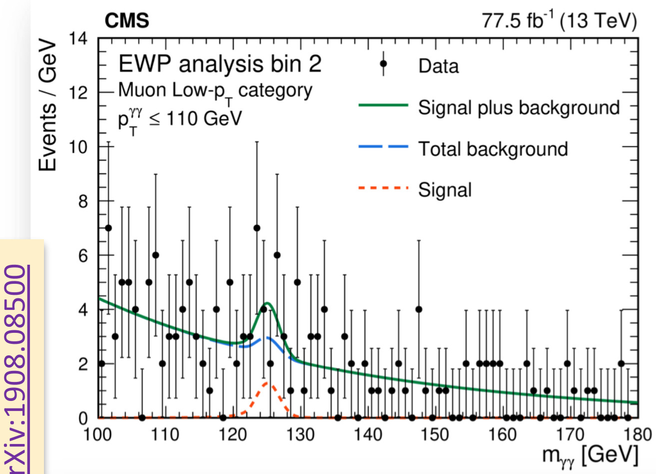
Electroweak production

- Involves **neutralino**, **chargino**, **slepton** direct production
- Results also interpreted in the context of **dark matter**

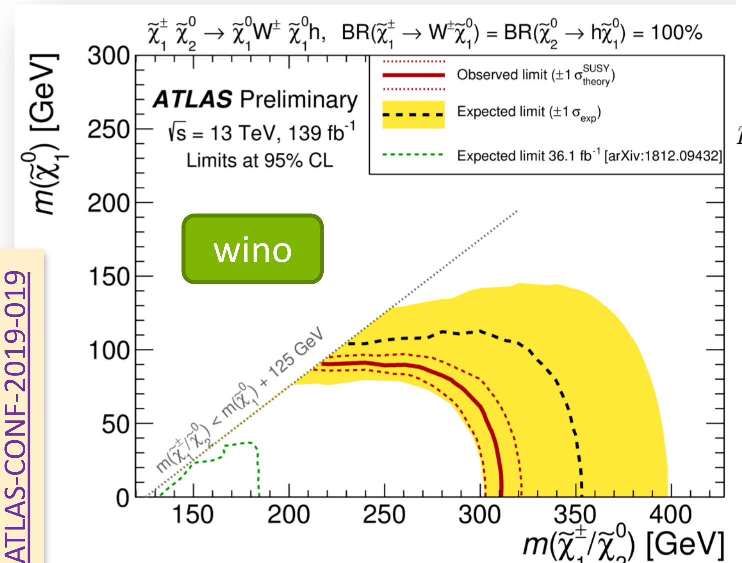
Chargino/neutralino with h→γγ

- Targetting
  - wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$
  - higgsino-like $\tilde{\chi}_1^0\tilde{\chi}_1^0$ in GMSB with $\tilde{G}$ LSP
- Selection: ≥2γ, H→γγ tag, 1 e/μ OR $e^+e^-/\mu^+\mu^-$ pair close to m(Z) OR ≥1 jet





arXiv:1908.08500



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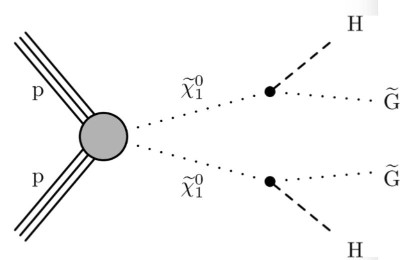
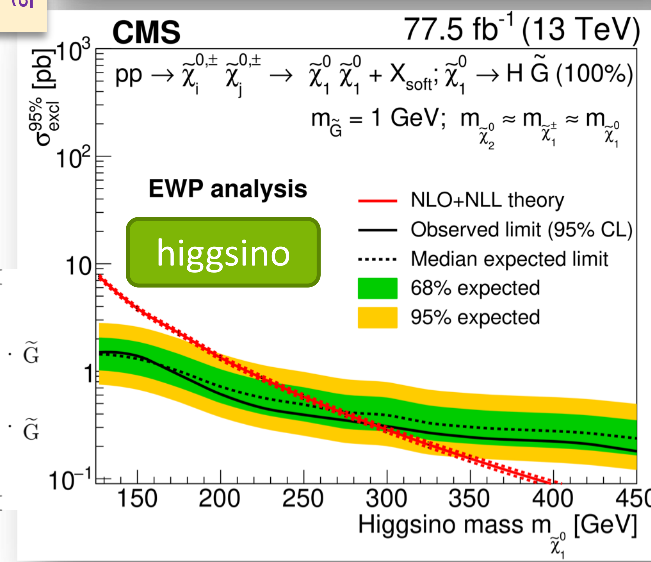
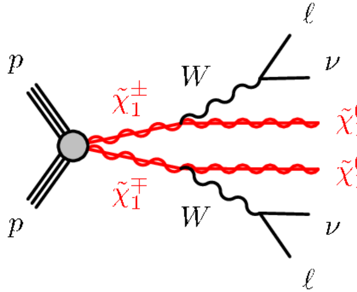
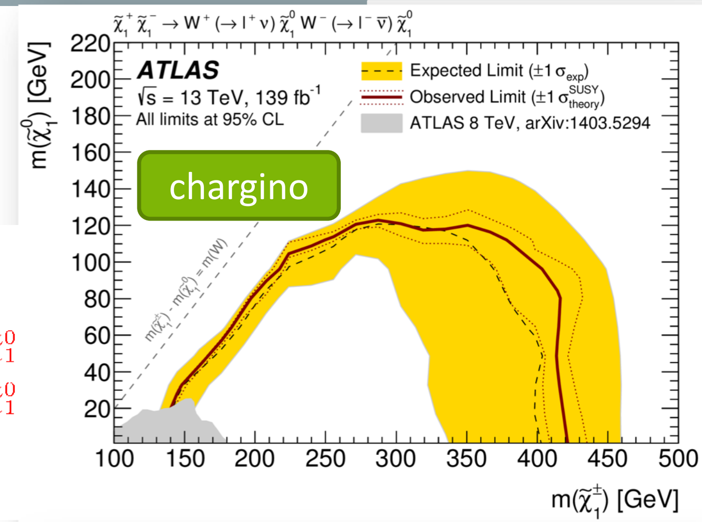


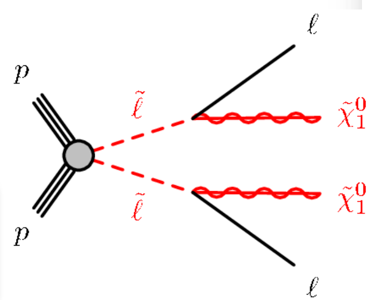


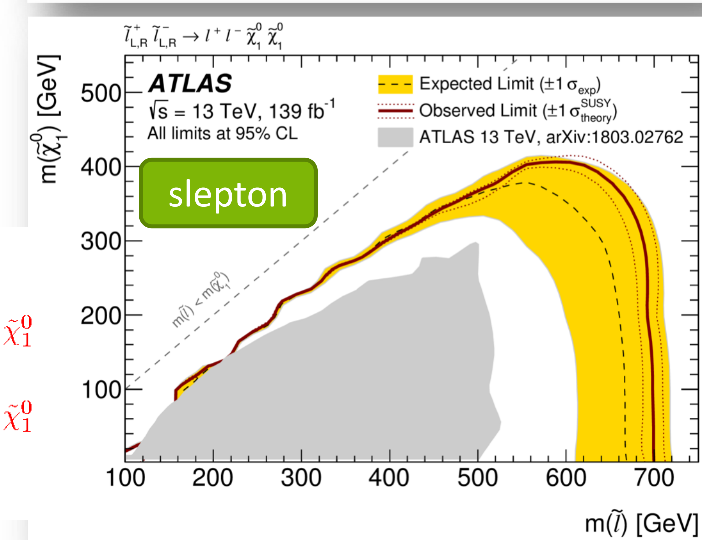
2 leptons + 0 jets

- Signature: 2ℓ opposite-sign, 0/1 jet, *b*-jet veto (to reject $t\bar{t}$)
- Analysis uses object-based missing transverse momentum significance
  - significantly reduces MET background, particularly in 1-jet events
- Binned SRs in stransverse mass m_{T2} to exploit shape differences between signal and background







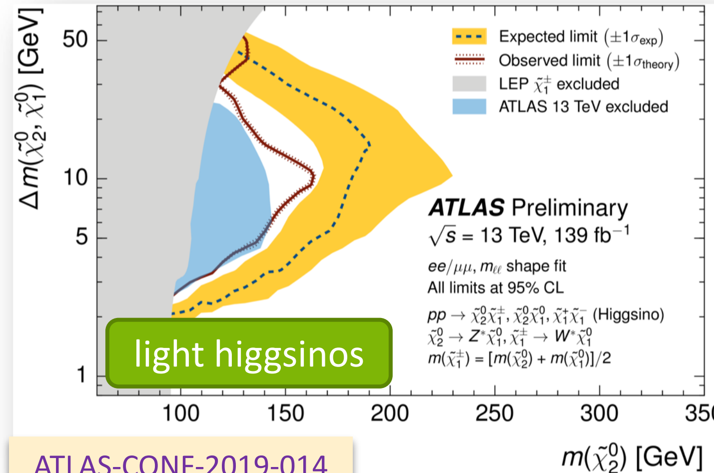


arXiv:1908.08215

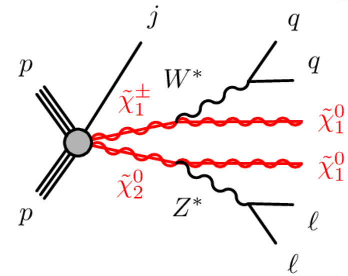
Big improvement w.r.t. Run 1 limits excluding up to 400 GeV in $\tilde{\chi}_1^{\pm}$ mass

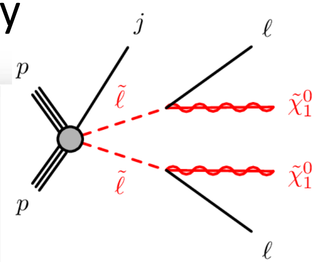
Compressed scenarios

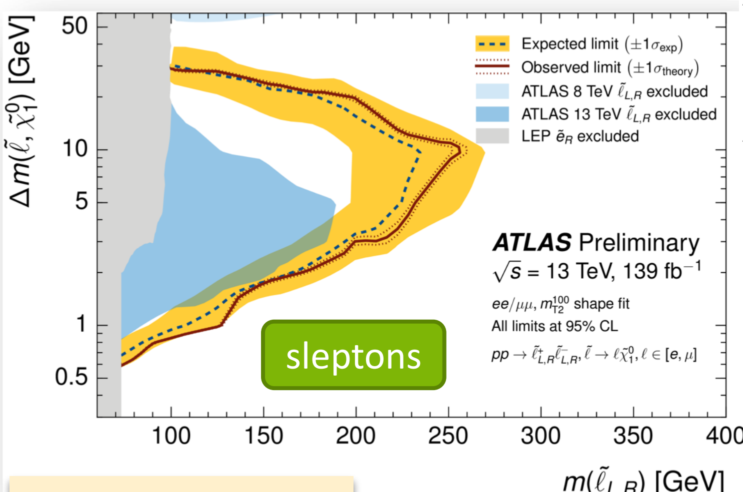
- Light higgsinos: compressed mass spectrum, i.e. $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0) \ll m(W/Z)$
  $\Rightarrow$ very low-p_T leptons (~5 GeV)
- Trigger: ISR jet or MET
- Gaugino production via vector boson fusion considered recently



ATLAS-CONF-2019-014







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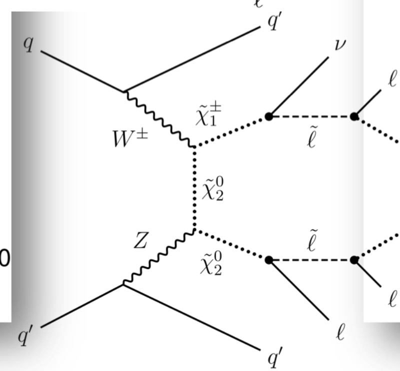
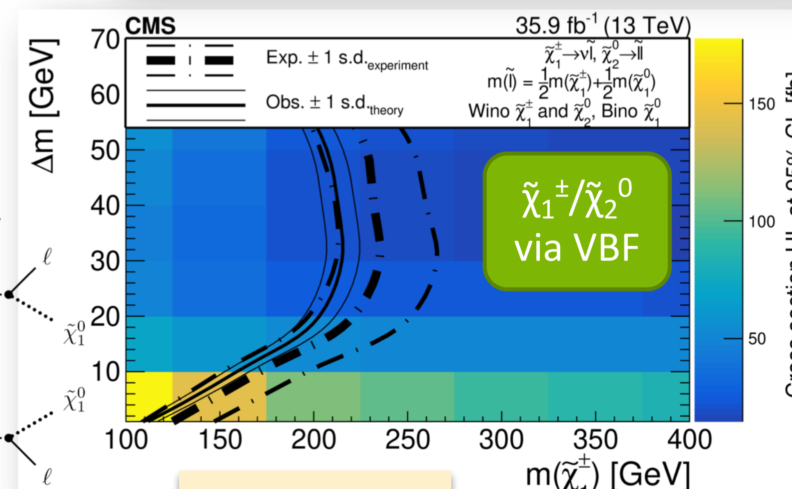
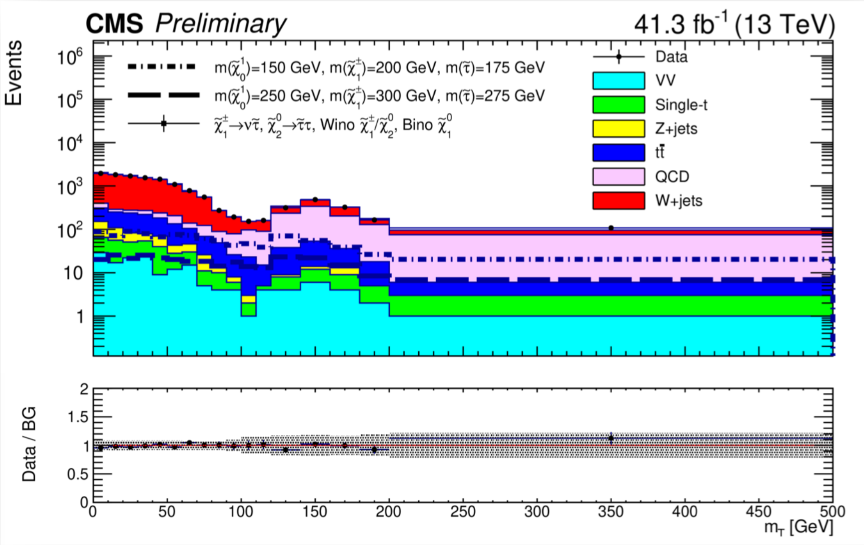


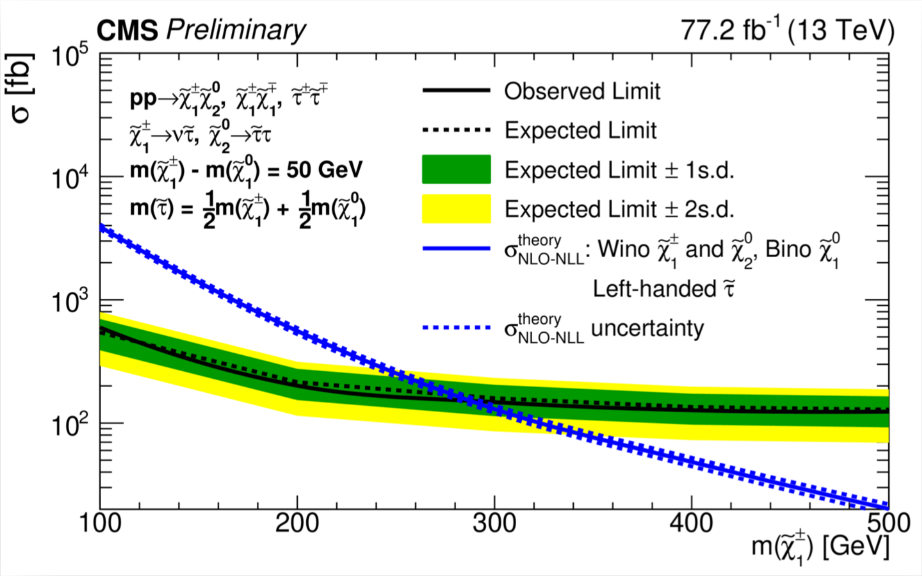


arXiv:1905.13059

Compressed scenarios with staus

- First SUSY search in events with one soft tau
  - + one energetic ISR jet and large MET
- Signal models: co-annihilation between (nearly mass degenerates) $\tilde{\tau}$ and $\tilde{\chi}_1^0$ ➜ generates "correct" dark matter relic density





Upper limits set on the $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$ and $\tilde{\tau}$ production cross sections
⇒ lower mass limit of 290 GeV on the mass of the $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$
➜ most stringent to date

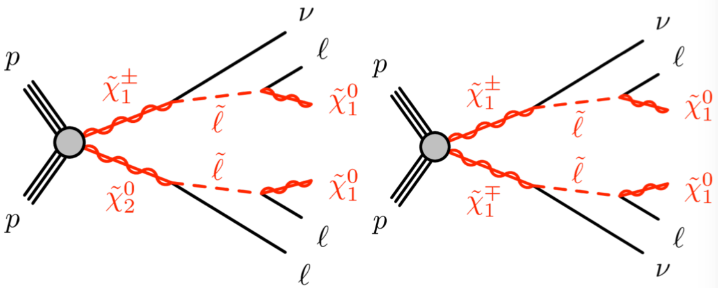
CMS-PAS-SUS-19-002

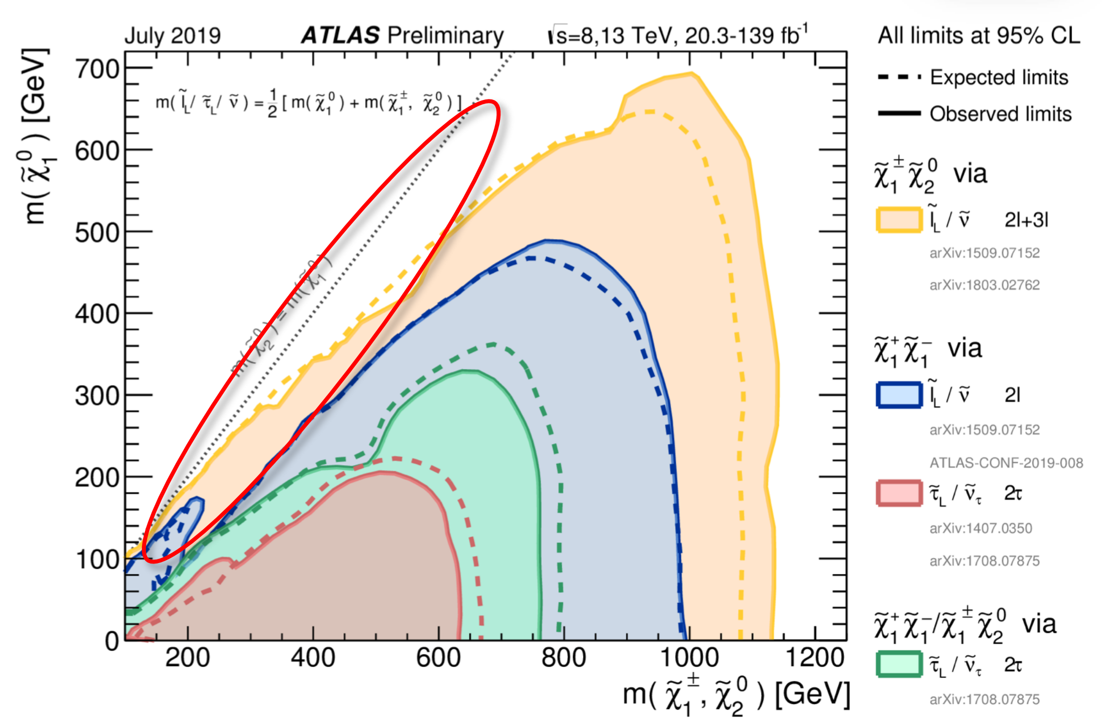
Electroweak production - summary

ATL-PHYS-PUB-2019-022

- **Neutralino, chargino, slepton** direct production
- Final states (+MET):
  - multileptons
  - hadronic taus
  - (di-)bosons
    ➔ b-jets, photons

Sensitive to details of scenario considered, e.g. nature of gaugino (bino, wino, higgsino)

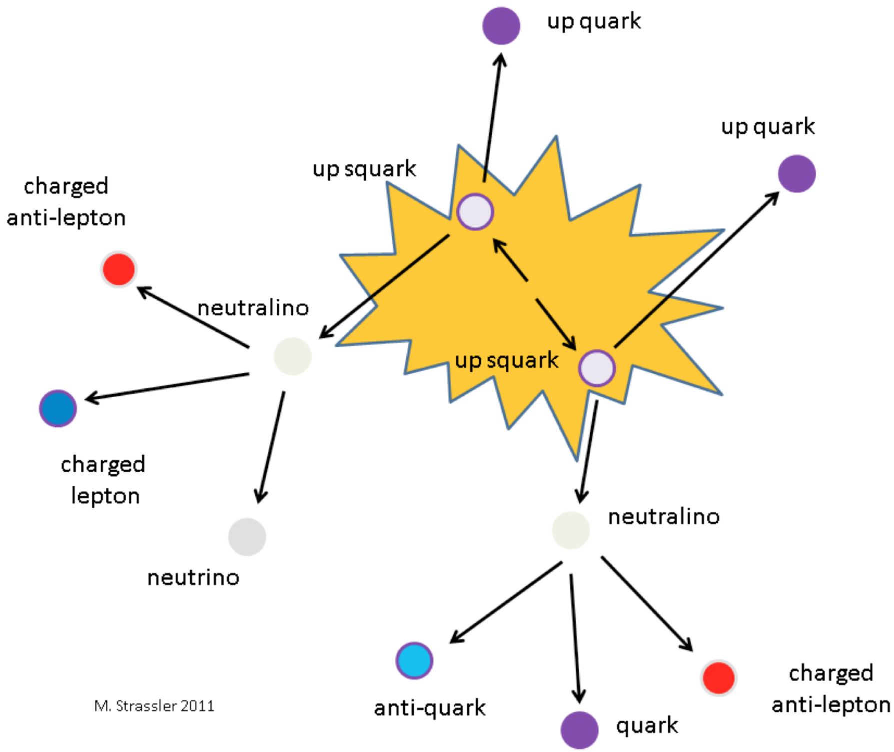




Intense effort to cover compressed-spectra region

R-parity violation

☛ *talk by Stephen F. King for connection between neutrino masses and RPV SUSY*



M. Strassler 2011

R-parity violation

$$W_{\not{R}p} = \underbrace{\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^C_k + \epsilon_i\hat{L}_i\hat{H}_u}_{L\text{-number violation}} + \underbrace{\lambda''_{ijk}\hat{U}^C_i\hat{D}^C_j\hat{D}^C_k}_{B\text{-number violation}}$$

L-number violation bilinear terms *B*-number violation

- *R*-parity conservation hinted but *not required* by proton stability
- *R*-parity conservation/violation largely define final states of SUSY events

$$R = (-1)^{3(B-L)+2s}$$

$$R = \begin{cases} +1 \text{ for SM particles} \\ -1 \text{ for superpartners} \end{cases}$$

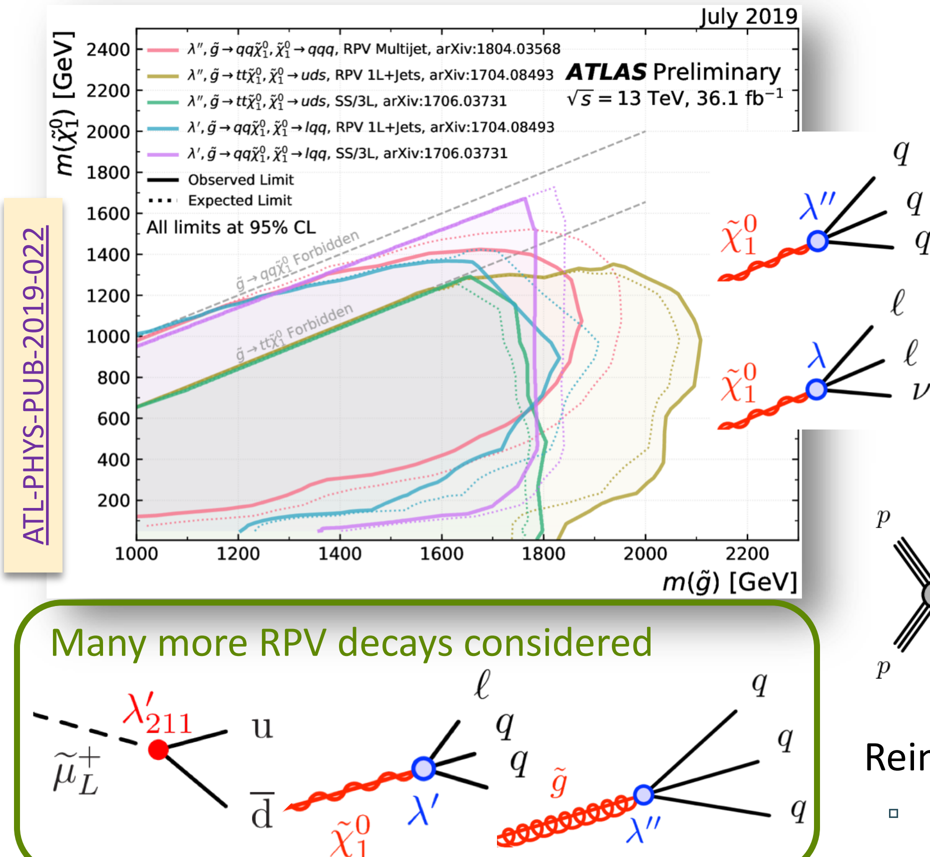
In broken *R*-parity

- LSP is *not* stable
- LSP may be charged and/or carry colour
- MET may be small ➔ "standard" SUSY searches *may miss* RPV signal
- **multi-lepton** and/or **multi-jet** inclusive final states
- **resonant LSP reconstruction** ➔ impossible in RPC SUSY
- LSP may be long-lived ➔ **displaced vertices**

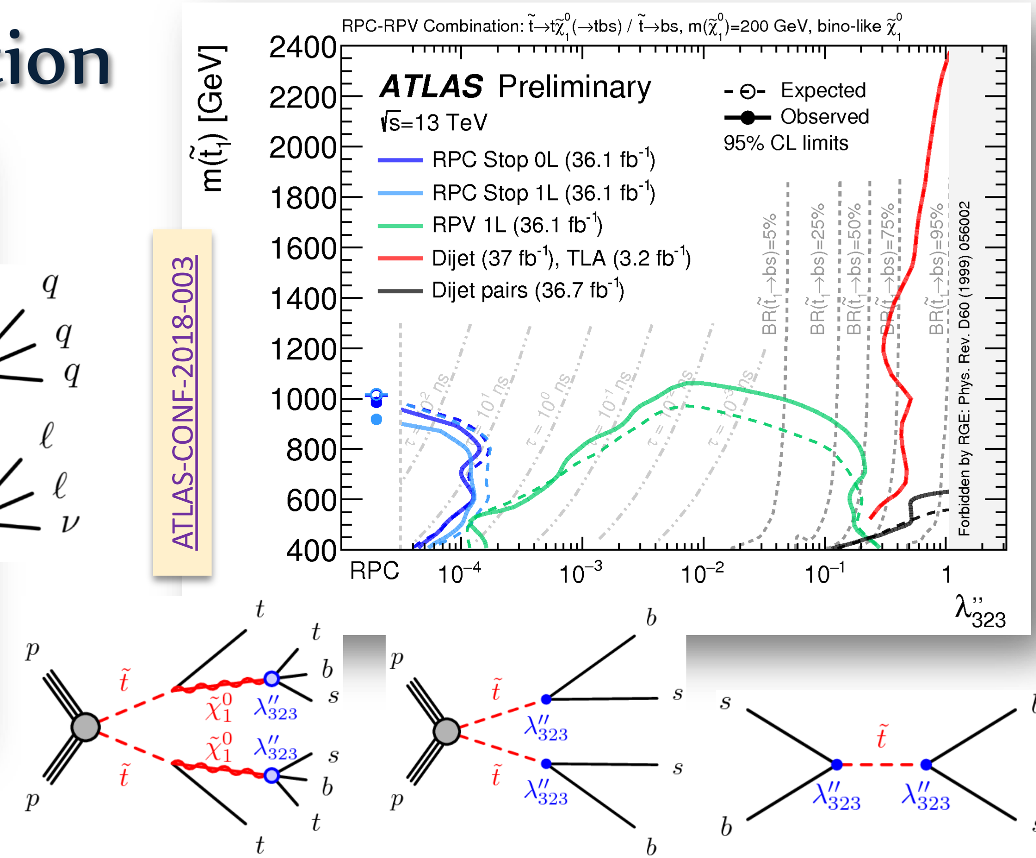
Extensive search program for RPV SUSY in both ATLAS and CMS, also inclusive searches with RPV interpretations

Prompt* R-parity violation

ATL-PHYS-PUB-2019-022



ATLAS-CONF-2018-003



Many more RPV decays considered

Reinterpreting RPC & RPV analyses in varying RPV coupling

- rich phenomenology offers full coverage
- nice complementarity between RPC and RPV searches

* More on delayed LSP decays in “Long-lived particles”

Long-lived particles

- For dedicated reviews, see:
  - Lee, Ohm, Soffer, Yu, Prog.Part.Nucl.Phys. 106 (2019) 210
  - LHC-LLP Community, arXiv:1903.04497

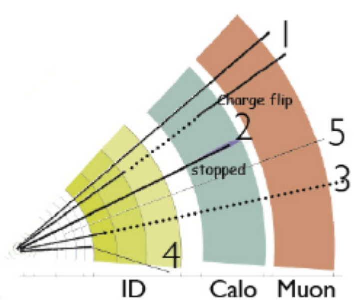
☛ *talk by Herbi Dreiner on long-lived neutralinos in RPV on Thursday afternoon*

☛ *talk by Haifa Rejeb Sfar on CMS searches for long-lived particles on Thursday afternoon*

☛ *talk by Audrey Kvam on ATLAS search for displaced hadronic jets on Tuesday Sep 10th*

Long-lived particles

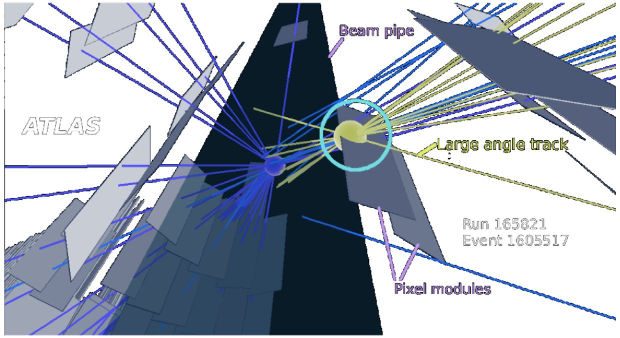
- Long-lived decays of spartners possible in several frameworks, including
  - nearly conserved symmetry
    - long-lived gluinos or squarks that hadronise before decaying → **R-hadrons in Split SUSY**
  - low coupling between the particle and the final state
    - weak **RPV** couplings or gravitational (**GMSB**)
  - mass degeneracy between the particle and the final state
    - chargino and neutralino wino in **AMSB**
    - stau and neutralino in **coannihilation** scenarios
- Depending on the lifetime, different detection techniques involving various objects: tracks, photons, leptons, displaced vertices, …



(1) Slow, large dE/dx
(2) Slow, stopped
(3) Disappearing track
(4) Kinked track
(5) displaced track

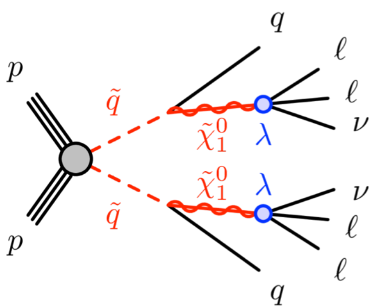
~ 1000 mm
~ 100 mm
~ 10 mm

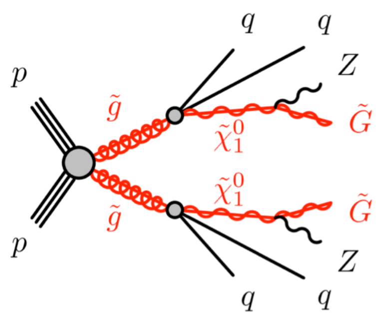
Longer lifetime



Displaced dilepton decays

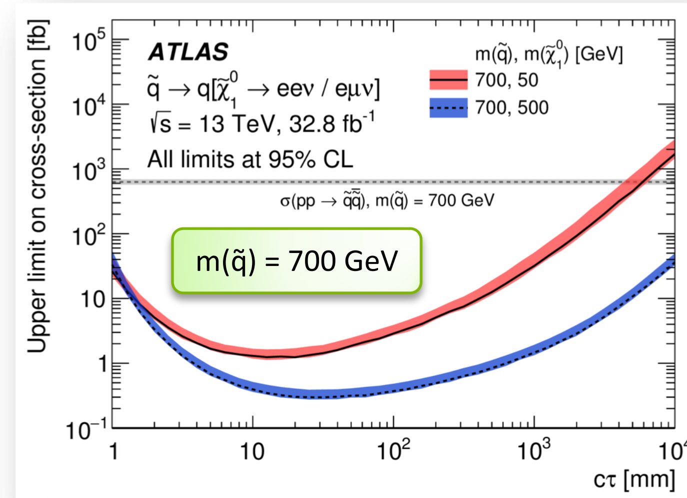
- Search for displaced e^+e^-, $\mu^+\mu^-$ or $e^\pm\mu^\mp$ vertices in the inner detector
- Analysis designed to be model-independent
  - interpreted for RPV models with λ coupling
  - also motivated by GMSB

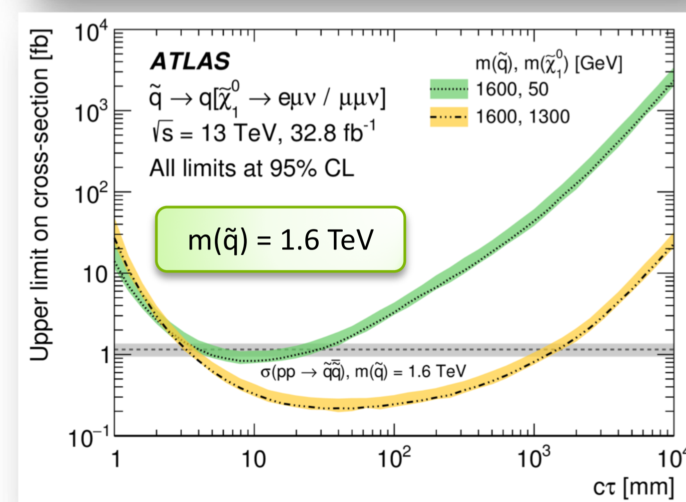




- Sensitivity in cτ depends on $\tilde{q}/\tilde{\chi}_1^0$ mass splitting (controls boost)
- Higher efficiency for large $m(\tilde{\chi}_1^0)$

[arXiv:1907.10037](https://arxiv.org/abs/1907.10037)

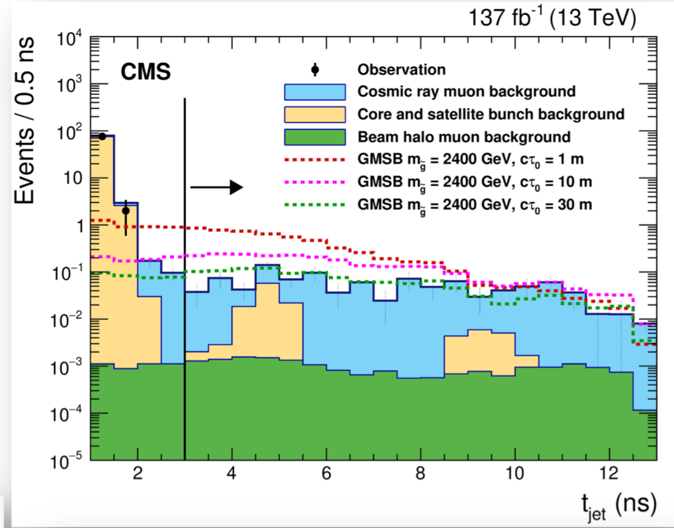


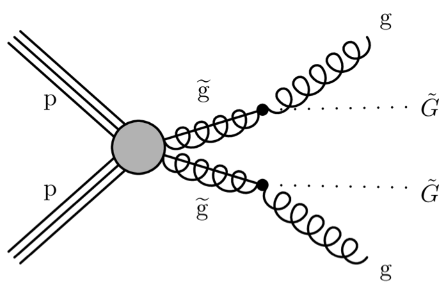


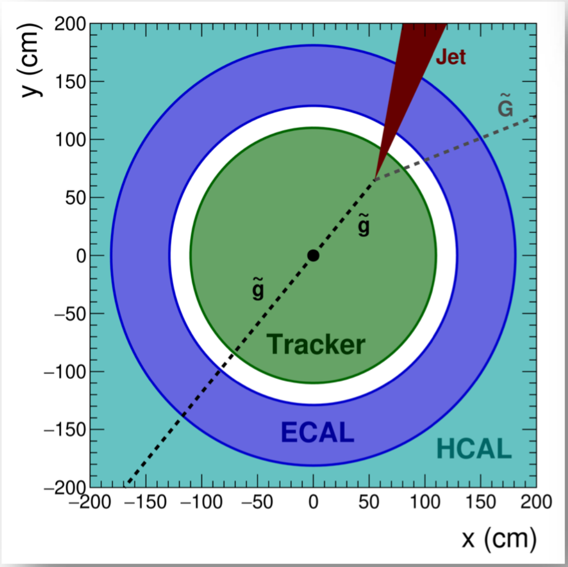
Delayed jets

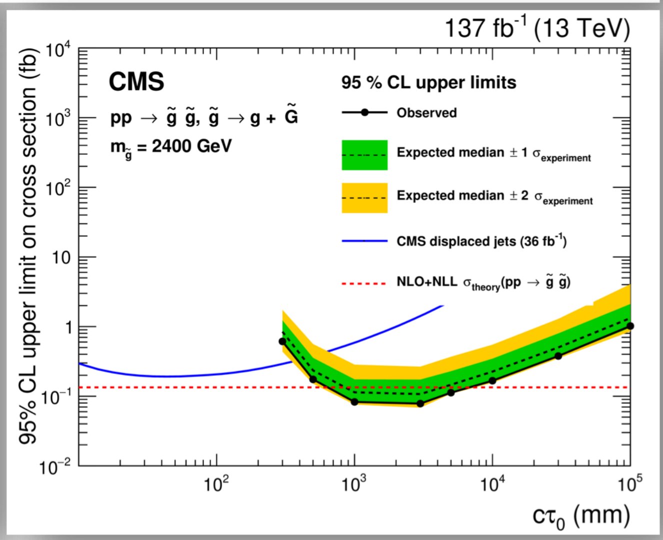
arXiv:1906.06441

- Search for LLPs decaying to hadronic jets
  - shower would arrive late at the ECAL
  - targeting decays beyond the acceptance of the tracker
- First search to use ECAL timing to tag delayed jets
- Extensive quality selections to remove hardware or cavern backgrounds
- Limits placed on long-lived $\tilde{g}$ production in the context of a GMSB model

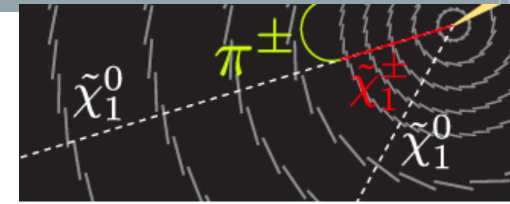






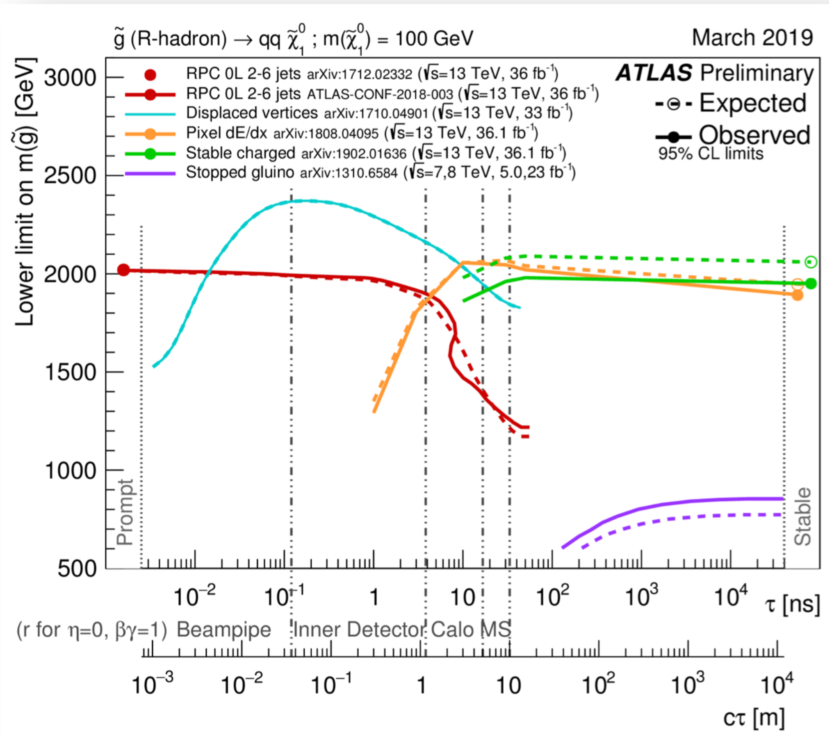


R-hadrons & long-lived charginos



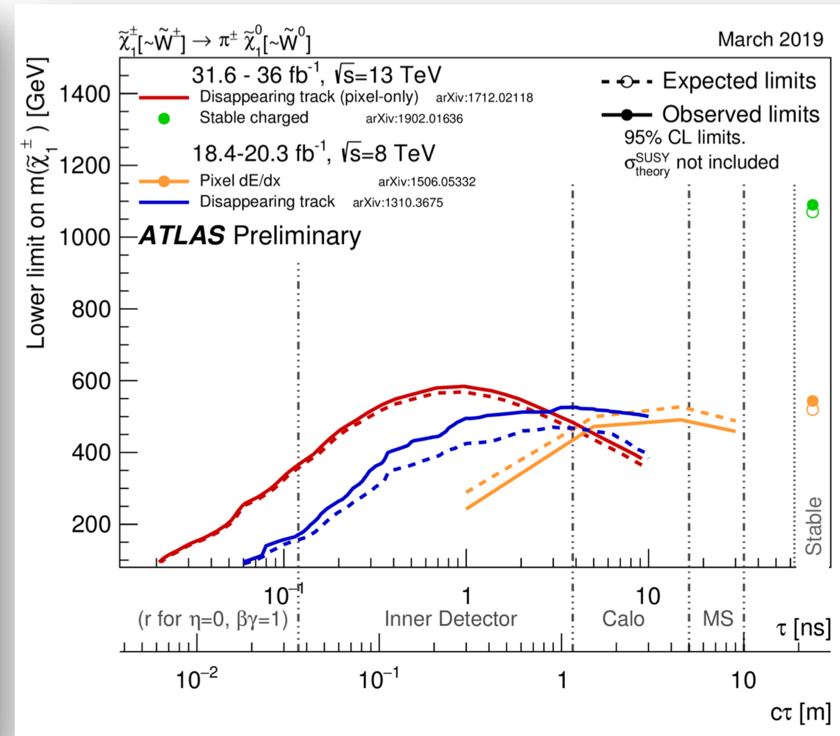
Results on R-hadrons

Split SUSY with metastable $\tilde{g} \rightarrow g/qq\ \tilde{\chi}_1^0$



Summary on disappearing track

Long lived chargino, $\tilde{\chi}_1^\pm \rightarrow \pi^\pm\ \tilde{\chi}_1^0$



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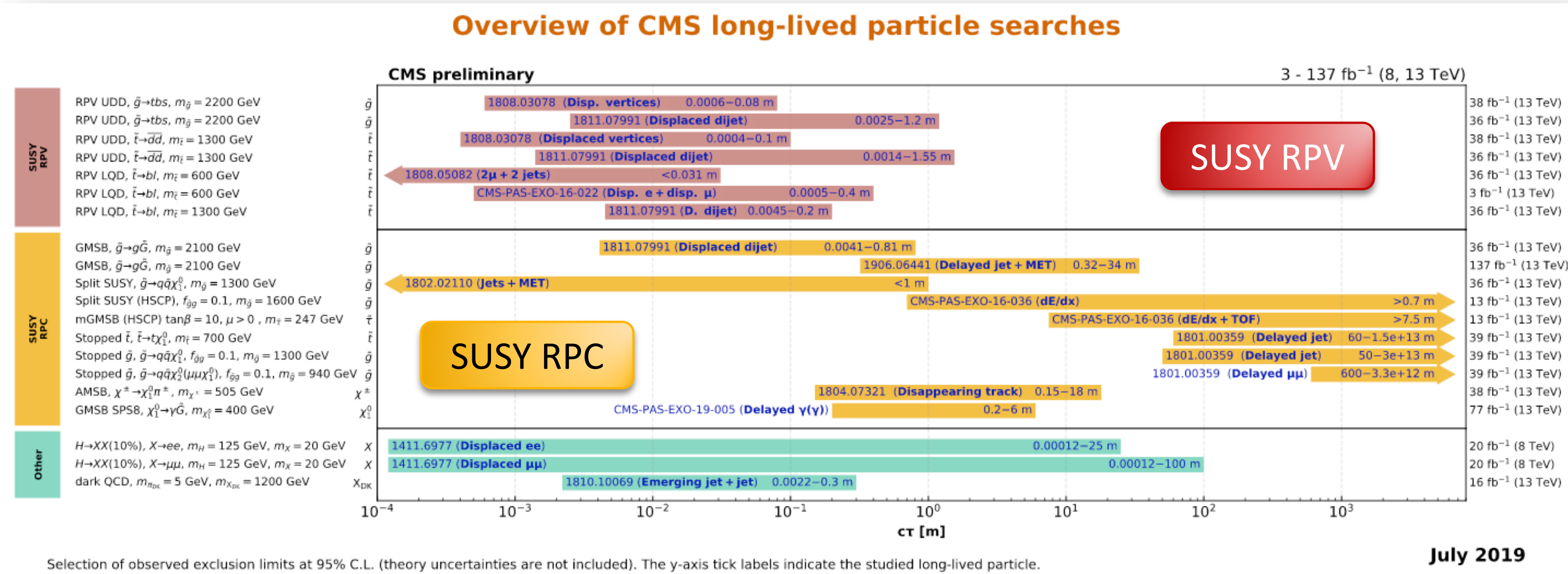
Long-lived particles – summary

Including R-parity violation



http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html

Conclusions & outlook

- ATLAS and CMS have developed a vast program to search for supersymmetry
  - many new results have just been released with the full Run 2 dataset
  - no significant excess seen so far
- Improved search methods and new reconstruction techniques have de possible the exploration of kinematic regions previously inaccessible
- More searches and updates keep coming with the full Run-2 dataset and beyond
- **Stay tuned for upcoming results !**

More results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS