Hiding Squarks and gluinos

SUSY Plenary meeting (Apr. 05, 2017)

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We know that if nature at a fundamental level really obeys supersymmetry,[1] then the supersymmetry must be spontaneously broken. However, we do not know whether the vacuum expectation values involved in this breakdown are of an "ordinary" energy scale, say of order 300 GeV, like those involved in the breakdown of the electroweak gauge symmetry, or whether they are much larger, perhaps as high as the Planck mass. One reason to suspect that supersymmetry is broken only at ordinary energies arises from the hierarchy problem:[2] if supersymmetry is unbroken at higher energies then it can protect some scalar fields from getting enormous masses in the spontaneous breakdown of whatever symmetry connects strong with electroweak interactions; these scalars would then survive to provide a second stage of symmetry breaking, in which the electroweak gauge symmetry and supersymmetry are both spontaneously broken at ordinary energies.

Weinberg - 1982

Gluinos

- Color octet superpartners of the gluon Maiorana fermions
- Flavour blind coupling to (s)quarks and gluons
- Largest cross-section at the LHC
- Typical signature: jets (b-jets) +lepton + E_T^{miss}

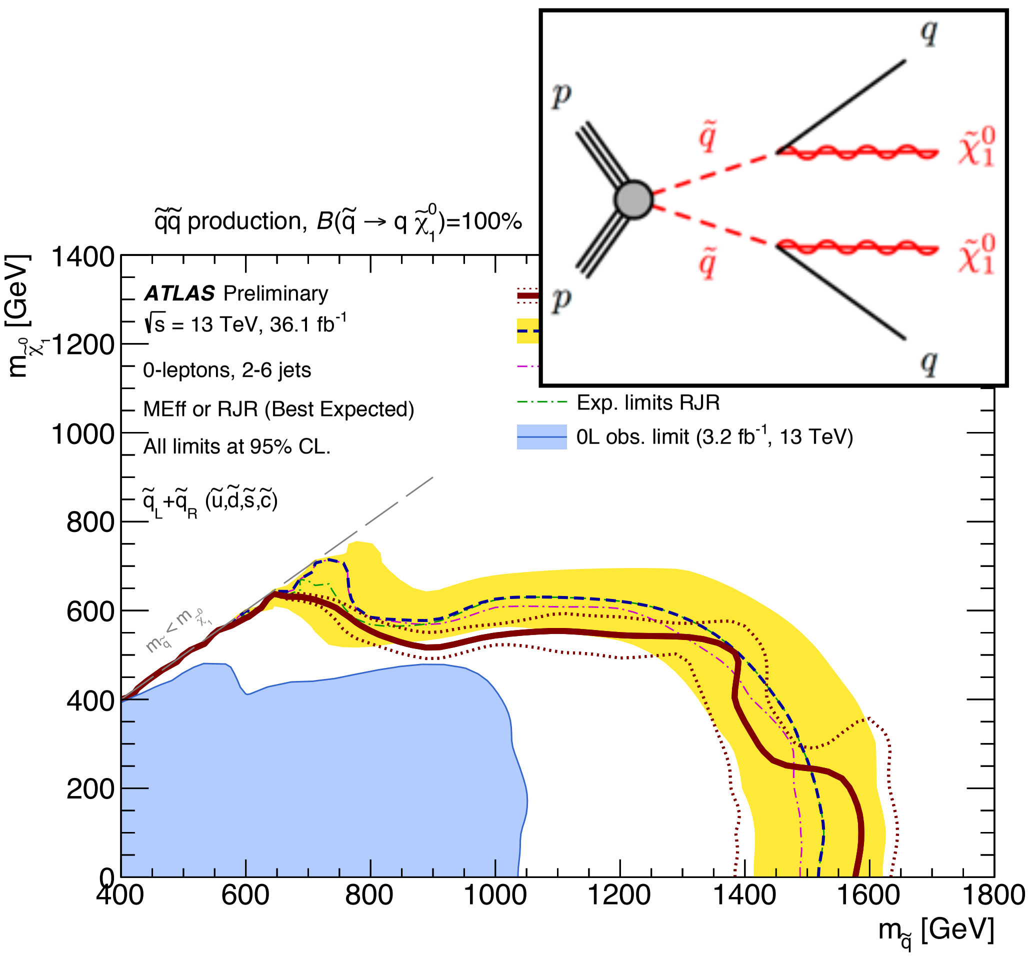
Squarks

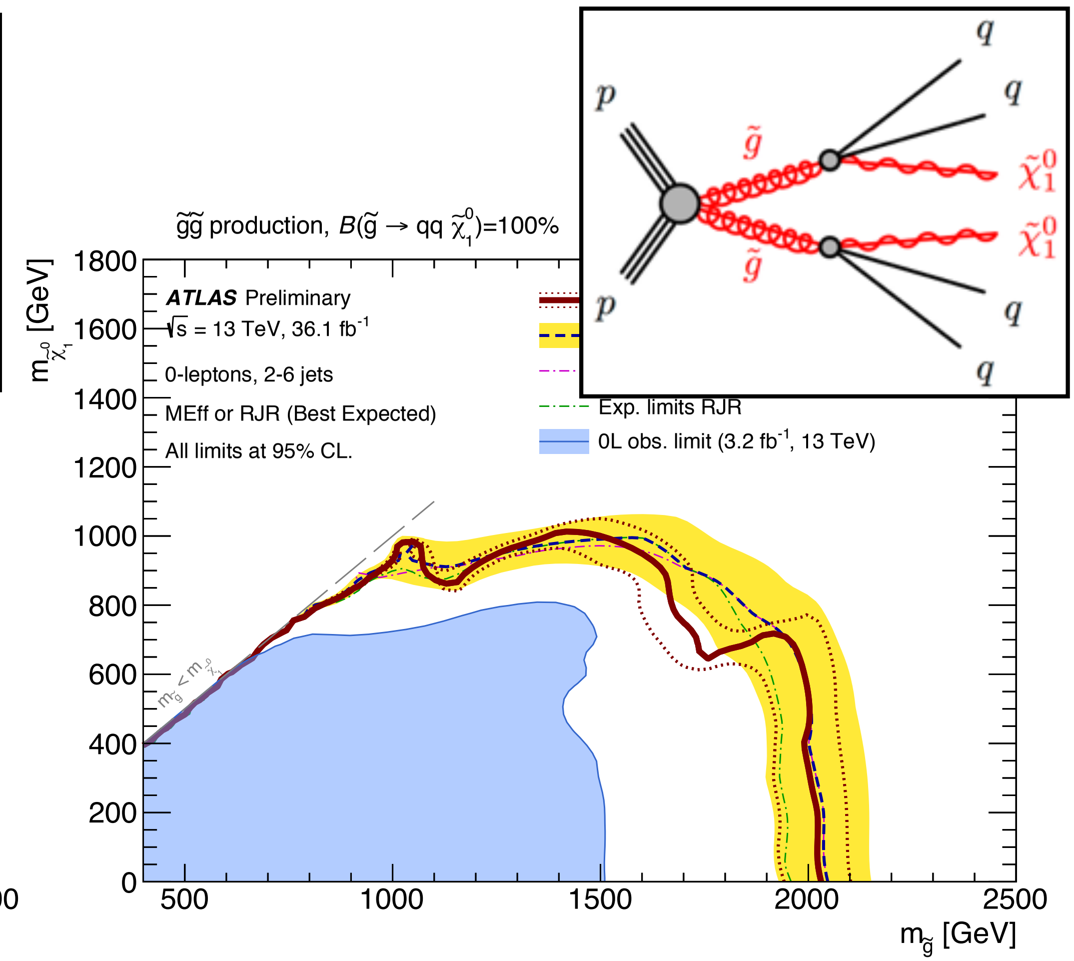
- Scalar (spin-0) partners of the SM quarks
- Any scalar with the same electric charge, R-parity and color charge will mix, physical states by diagonalising 6x6 matrices
  - With flavour-blind soft parameters, the mixing will be small, but for third generation multiplets (substantial mixing in pairs)
  - 2st/2nd generation squarks nearly degenerate
- Also large cross-section (for 1st/2nd generation)

CURRENT LIMITS

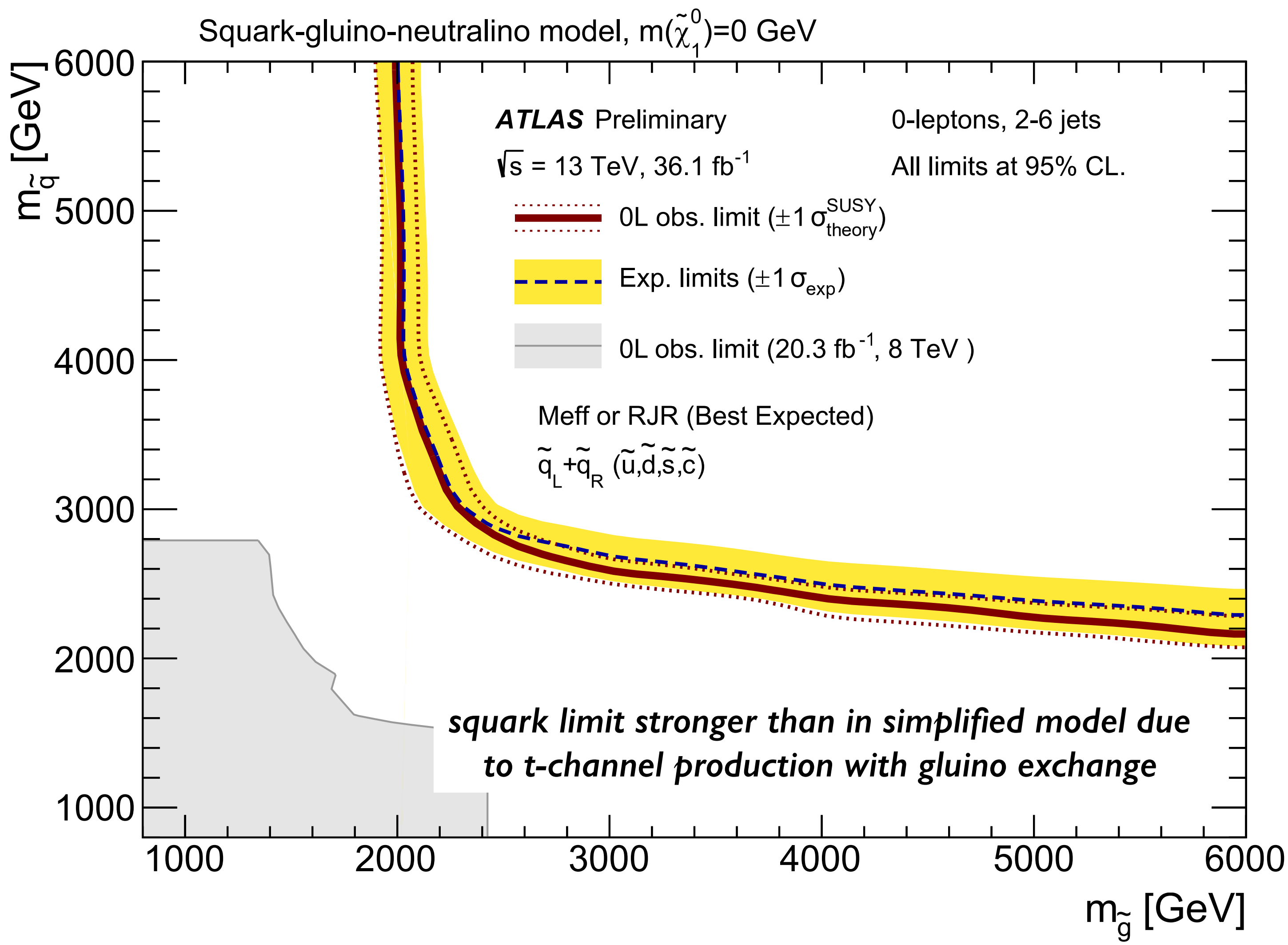
	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.85 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ 1.57 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$ 608 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0)$<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.02 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.01 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	13.2	$\tilde{g}$ 1.7 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	2 e,μ (SS)	0-3 jets	Yes	13.2	$\tilde{g}$ 1.6 TeV	$m(\tilde{\chi}_1^0)$ <500 GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$ 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$ 1.8 TeV	$m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$ 1.92 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$ 1.97 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600

$\sqrt{s}$ = 7, 8 TeV　$\sqrt{s}$ = 13 TeV

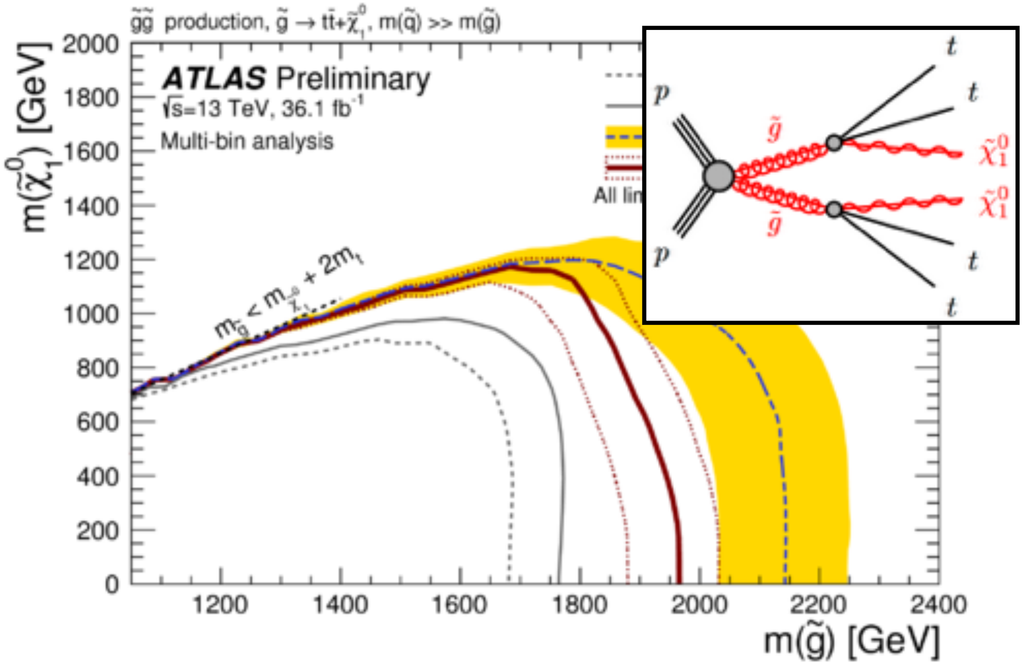


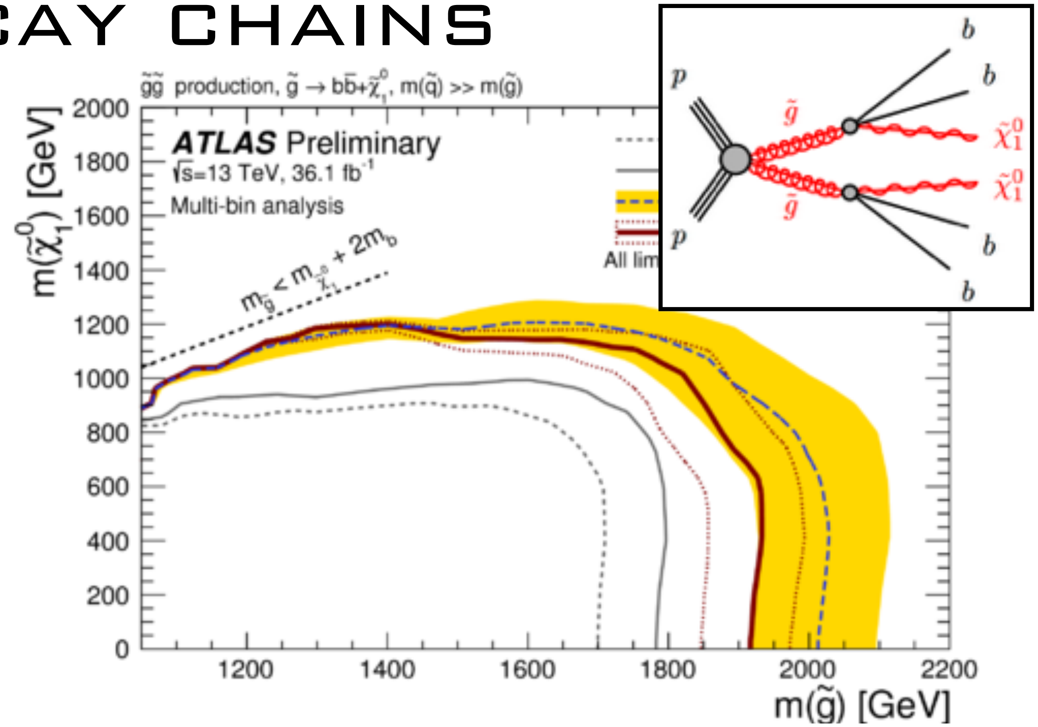


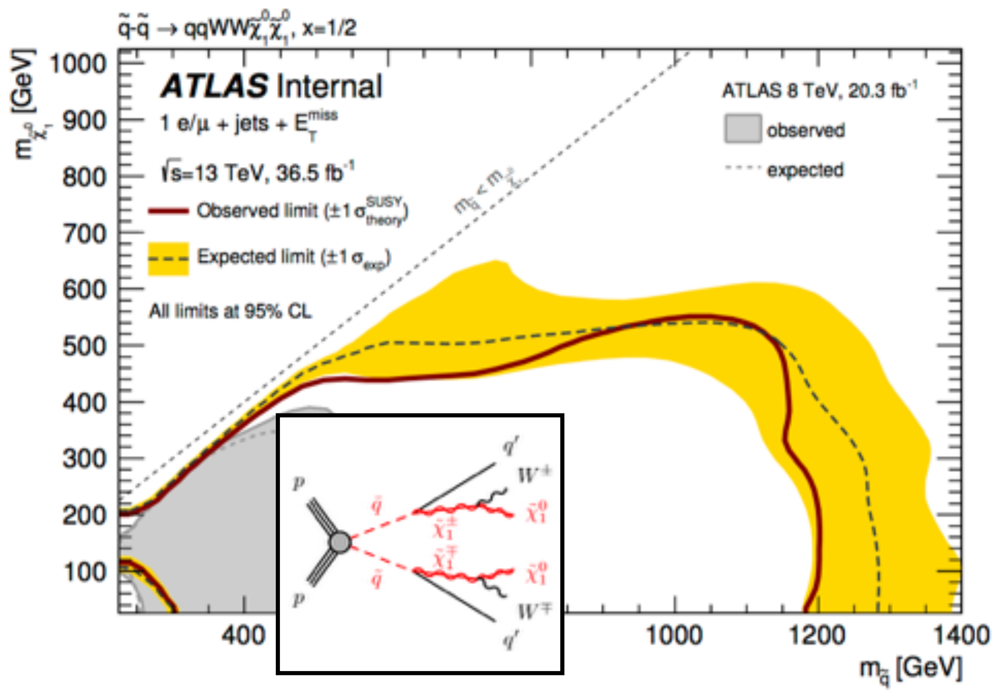
SQUARK-GLUINO-NEUTRALINO

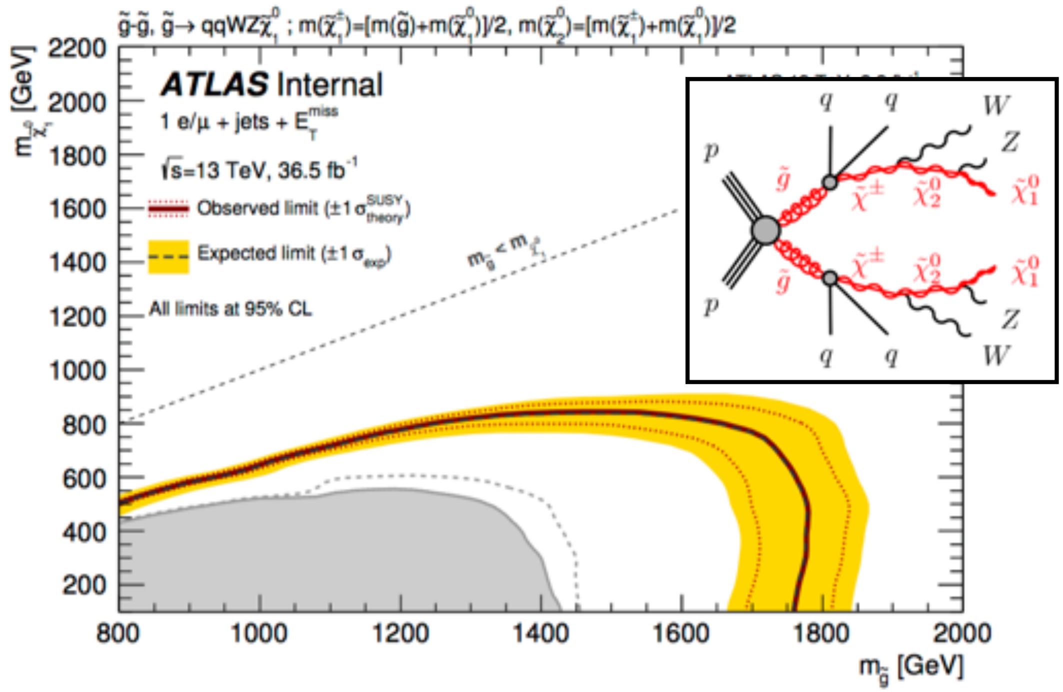


3rd Generation mediated and long decay chains









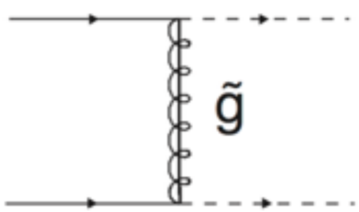
“In addition to the gluinos we have already considered, now to be called orthogluinos, λ, we introduce a second color-octet of spinorial particles which we call paragluinos, ζ, with opposite R-transformation properties. Both λ and ζ are octets of Majorana spinors. The construction of a massive Dirac gluino field from λ and ζ is compatible with R-invariance.”

Fayet - 1978

Dirac gauginos

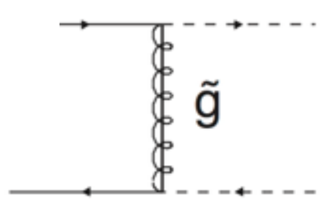
0808.2410

- In the MSSM the gluino is a Maiorana particle
- However in non-minimal SUSY extensions we can give a Dirac mass to the gluino
  - In D-term SUSY breaking, continuous R-symmetries or N=2 SUSY
- Interesting consequences for phenomenology
  - Dirac gluinos are naturally higher than scalars, relax naturalness bounds
  - The squark production cross-section is decreased due to the heavy gluinos; t-channel gluino exchange cancels between right- and left-handed squarks

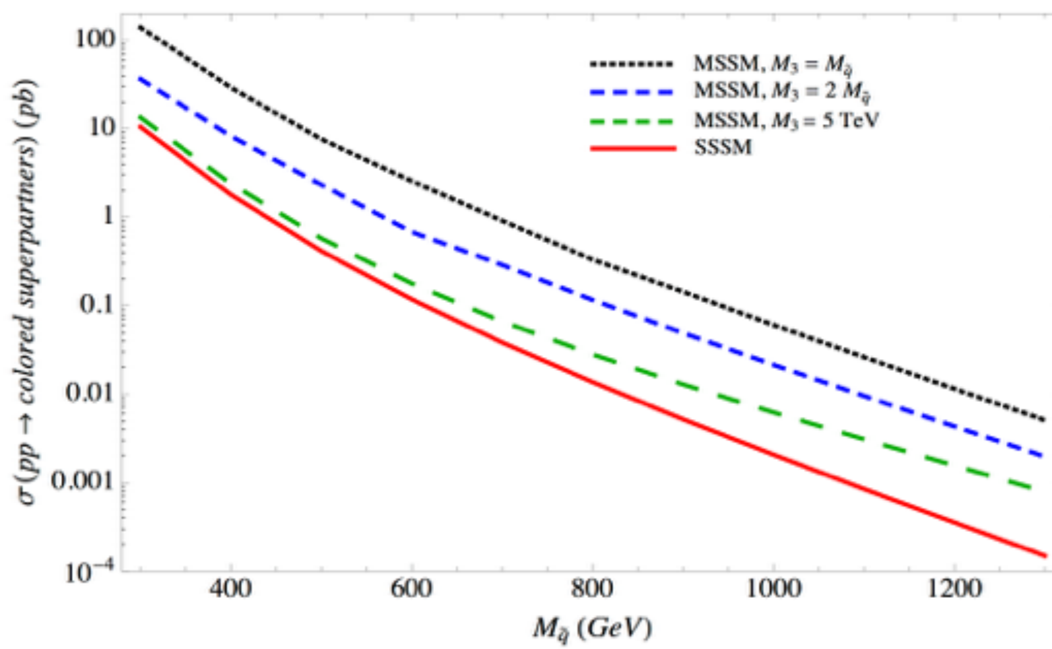


LL, RR absent

LR suppressed $1/M^2$



suppressed $1/M^2$ & PDFs



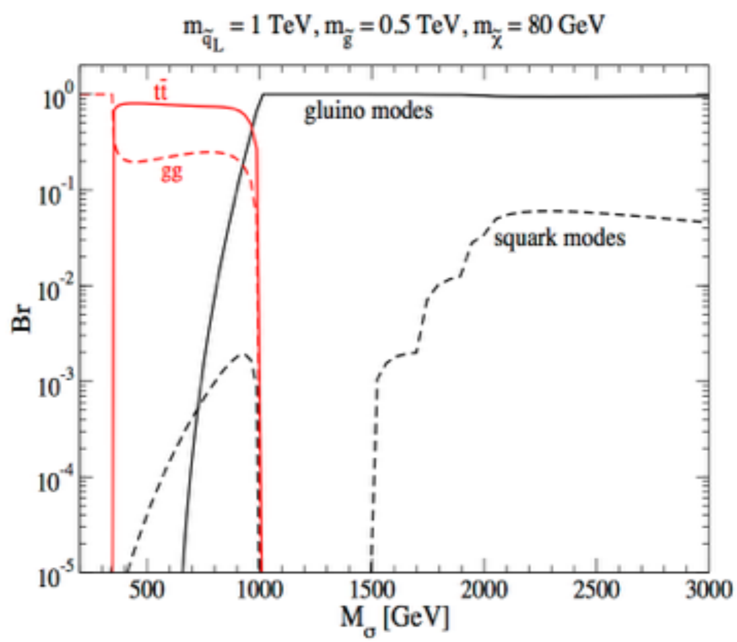
Dirac Gauginos

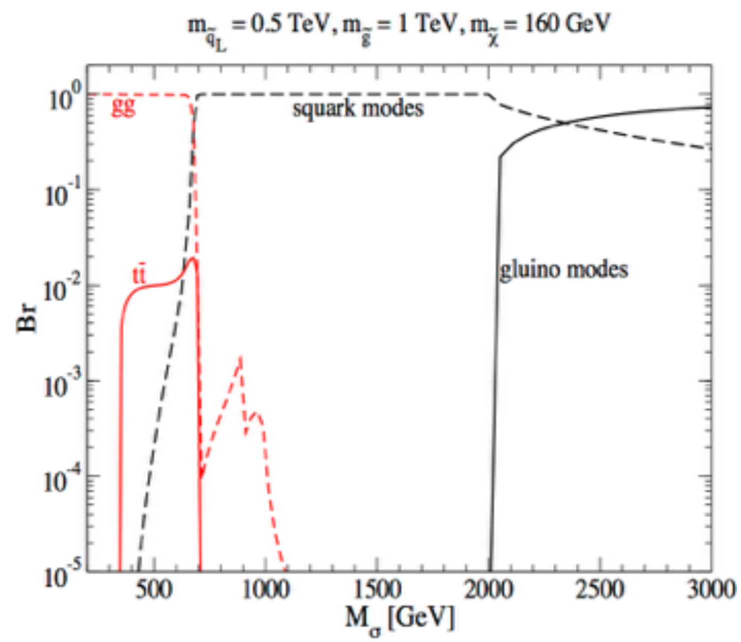
- Dirac gaugino masses require extending the MSSM with new chiral adjoint superfields (one per gauge group)
  - The color octet scalar gluon (sgluon) can also be produced at the LHC

$$\begin{cases} A_j & j = 1 \ldots 8 & \text{color octet} \\ A_j & j = 1 \ldots 3 & \text{weak triplet} \\ A_j & j = 1 & \text{singlet} \end{cases}$$

- Depending on the spectrum the sgluon decays into two-gluons/ quarks or to two top-quarks

  - Constraints exists from paired dijets and four-top searches



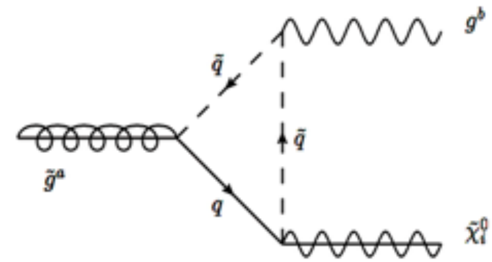


In sect. 2, we review the "standard" gluino decay modes previously discussed in the literature, namely $\tilde{g} \to q\bar{q}\tilde{\gamma}$ (and $\tilde{g} \to g\tilde{G}$ if the goldstino $\tilde{G}$ exists) [2, 3, 5] where the photino $\tilde{\gamma}$ is assumed to be the lightest supersymmetric particle. These decays imply certain experimental signatures of gluinos which we summarize. We then compare these "standard" decay modes with two modes which have not previously been considered. First is the charge conjugation (C) violating decay $\tilde{g} \to g\tilde{\gamma}$. We show that this mode could be competitive with $q\bar{q}\tilde{\gamma}$ if there is sufficient mass splitting between the scalar partners ($\tilde{q}_L, \tilde{q}_R$) of the left- and right-handed quarks (for any flavor). Since the two-body mode will have a much cleaner signature than decays with three or more particles, the existence of the $g\tilde{\gamma}$ mode could greatly improve detection possibilities.

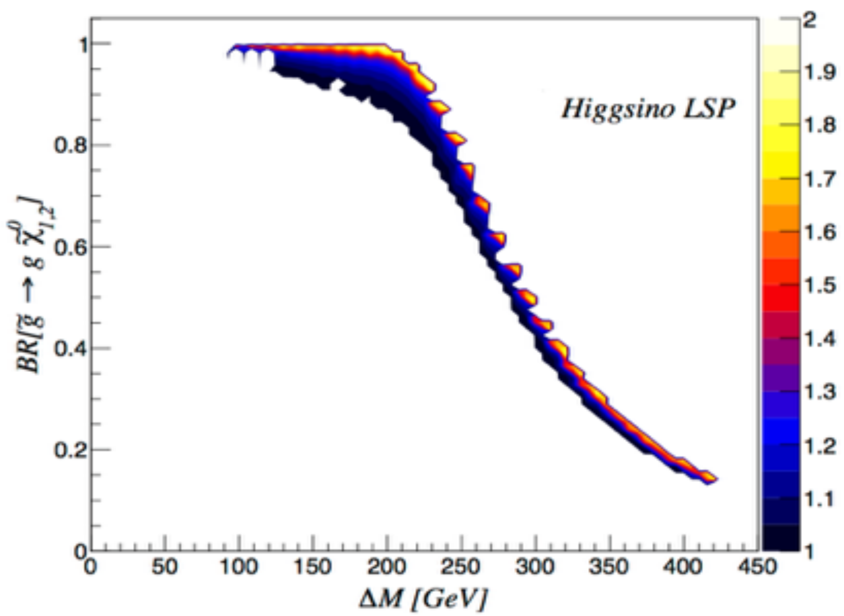
Haber, Kane - 1984

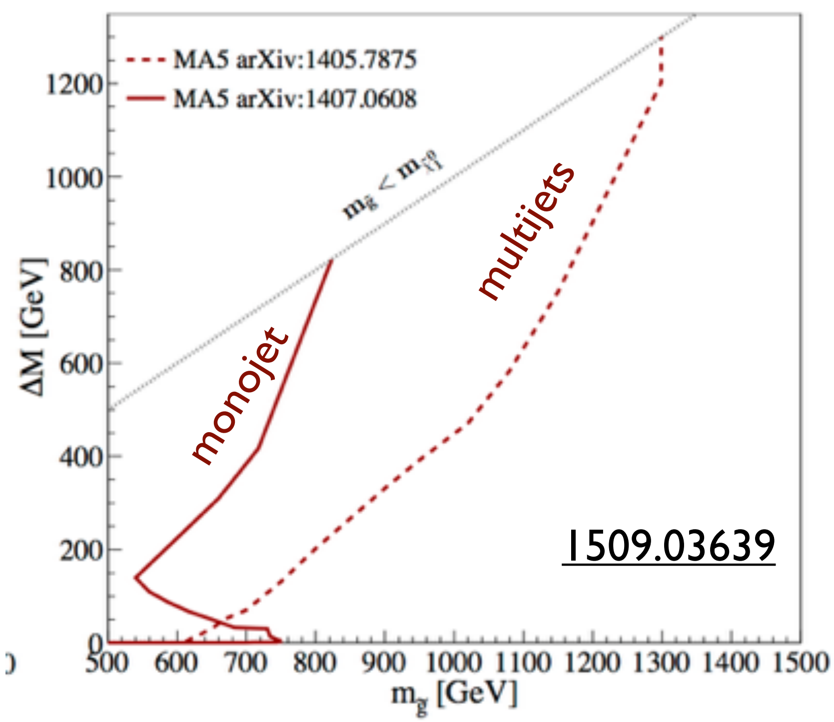
Radiative gluino decays

- If the gluino-neutralino spectrum is compressed the gluino radiative decay into a neutralino and a gluon can be the dominant one



- A spectrum with decoupled scalars and light gauginos is expected in (mini) split-SUSY, spread SUSY, NUSUGRA or gravity mediation
  - If the scalar states have a mass lower than ~10^4 TeV the gluino lifetime is small, and the gluino decays promptly





The Gluino ($\tilde{g}$), the Majorana spin ½ supersymmetric partner of the gluon, behaves like a new quark flavor which is a color octet. In analogy with quarkonium, there should exist a spectrum of $\tilde{g}\tilde{g}$ bound states which we will call gluinonia. The large color charge leads to enhanced production rates (in both singlet and octet gluinonia states) in gluon-gluon scattering processes. We compute the rate for observing gluinonium in quarkonium decay and in high energy hadronic collisions.

Goldman, Haber - 1978

*Pronounced as glōō´-ēn-ōn´´-ēə.

Gluino bound states

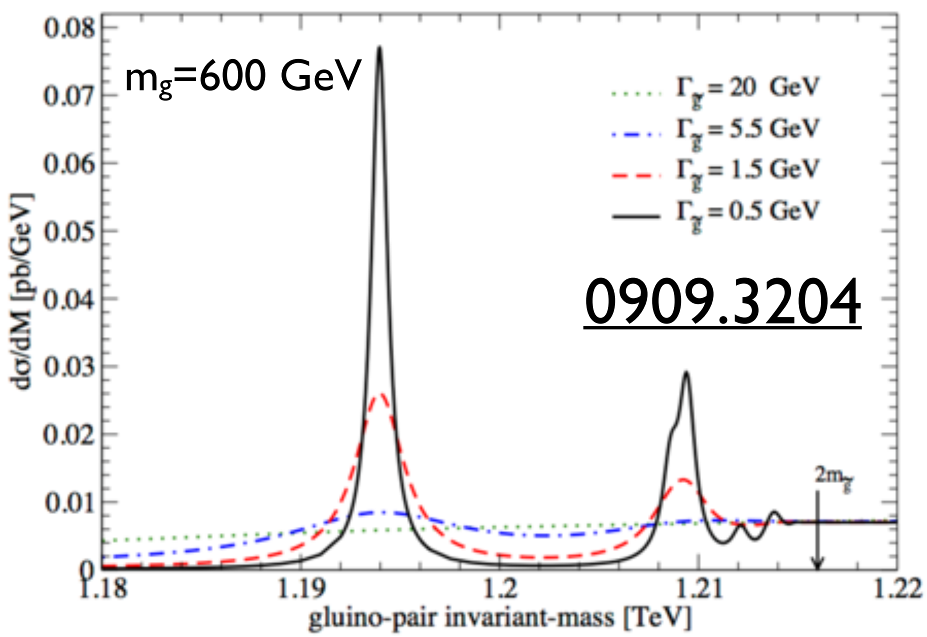
- Gluino have both a large mass and color charge (octet), we can expect bound-state effects to be large

color	symmetric $(\mathbf{1}, \mathbf{8_S}, \mathbf{27})$	anti-symmetric $(\mathbf{8_A})$
$\tilde{g}\tilde{g}$	${}^1S_0, {}^3P_{0,1,2}, {}^1D_2, \cdots$	${}^3S_1, {}^1P_1, {}^3D_{1,2,3}, \cdots$
$i = gg$	${}^1S_0, {}^3P_{0,\ 2}, {}^1D_2, \cdots$	${}^1P_1, {}^3D_{1,\ 3}, \cdots$
$i = q\bar{q}$	${}^3P_{\ 1,2}, \quad \cdots$	${}^3S_1, \quad {}^3D_{1,2,3}, \cdots$

gluinonium spectra

- Attractive Coulomb force between a pair of gluinos give:
  - *Corrections to the cross-section* above the mass threshold
  - *Formation of bound states* below threshold, ***gluinonium with 2m_g mass***

- For a gluino width of 1.5 GeV about 80% of the resonance events would decay into gluon jets
  - If gluiness have lower masses than squarks the gluino decay width is tiny, gluinonium spectra are sharp and more than two resonances are expected



Quirks in folded SUSY

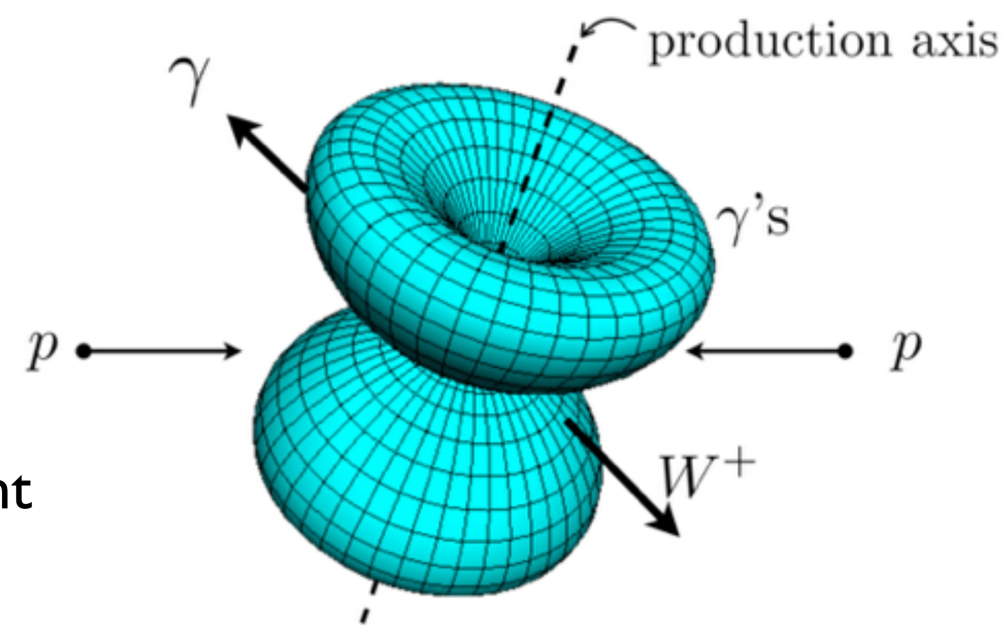
- Pair-produced particles charged under a new strong force and confined to a highly excited mesonic bound state
- QCD and QCD' related by a Z_2 symmetry
- The bound state will emit soft radiation and decay to its ground state
- The ground state can then annihilate into hard objects (e.g. Wgamma)

coloured fermion quirk

0810.3948

	$SU(N)_{QCD'}$	$SU(N)_{QCD}$	$SU(2)_L$	$U(1)_Y$
$\tilde{g}'$	$\mathbf{N}$	$\bar{\mathbf{N}}$	$\mathbf{1}$	0

- Not a new idea, apparently proposed already before the Tevatron times
- Suggest to look into new physics in the properties of the underlying event



Apart from kinematic terms and gauge couplings, the most general renormalizable supersymmetric SU(3) X SU(2) X U(1)- invariant interaction among the quark and lepton superfields is a linear combination of the trilinear F terms

$$[L_L L_L E_R^*]_F \qquad [L_L Q_L D_R^*]_F \qquad [D_R^* D_R^* U_R^*]_F \tag{3}$$

with SU(3) and SU(2) indices contracted in an obvious way. There are three conspicuous things wrong with such a theory:

Weinberg - 1982

The MSSM lagrangian

- For a minimal SUSY extension of the SM we need to include the following matter terms:

$$W_{MSSM} = h_u Q H_u u^c + h_d Q H_d d^c + h_e L H_d e^c + \mu H_u H_d$$

- However, is possible to add additional holomorfic renormalizable dim=4 couplings to the MSSM lagrangian:

45 independent parameters

$$W_{RPV} = \underbrace{\lambda_{ijk} L_i L_j e^c_K + \lambda'_{ijk} Q_i L_j d^c_k}_{\text{L-violating}} + \underbrace{\lambda''_{ijk} u^c_i d^c_j d^c_k}_{\text{B-violating}} + m_i L_i H_u$$

This bilinear term can be rotated away, adding contributions to the two L-violating operators

$j \leftrightarrow k,\ \lambda''_{ijk} = -\lambda''_{ikj}$

The udd coupling is antysymmetric, with a non-trivial color-structure

$i, j, k = 1, 2, 3$

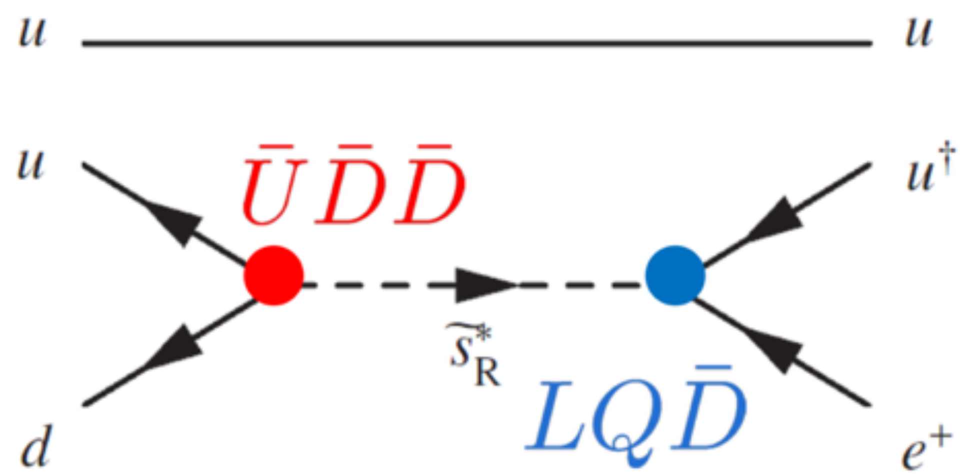
Generation indices

- Here *L* and *Q* are the lepton and quark $SU(2)_L$ doublet superfields. **e**, ***d***, ***u*** are the electron, down- and up-quark $SU(2)_L$ singlet superfiels

Proton Decay

- The combination of lepton- and baryon-number violating couplings leads to a rapid proton decay

$$p \rightarrow e^+ \pi^0$$



$$\tau \sim \frac{(9 \times 10^{-13}\,\mathrm{s})}{|\lambda'_{112}\lambda''_{112}|^2} \left(\frac{m_{\tilde{s}_R}}{1\,\mathrm{TeV}}\right)^4$$

Present limits o the proton lifetime put a constraint on RPV couplings of:

$$\lambda'_{ilk}\lambda''_{jlm} \leq 10^{-24}$$

- Proton stability can only be preserved by adding new symmetries
- In the MSSM this is done by including a "matter parity" which eliminates both couplings, with profound consequences on phenomenology
  - The MSSM conserves R-parity: $R_p = (-1)^{3B+L+2S}$ S=spin
    All the SUSY partners are R-parity odd, while SM particles are R-parity even
  - As a result the new SUSY states can only be produced in pairs and decay into SM particles. The LSP is stable, giving rise to E_T^{miss} signatures at colliders, and is a candidate to explain DM

R-PARITY

- But ***R-parity is not necessary***, other symmetries can protect the proton decay equally well
  - Forbid B-violation, with baryon-parity: only LQD, LLE operators are allowed

$$(Q_i, \bar{U}_i, \bar{D}_i) \to -(Q_i, \bar{U}_i, \bar{D}_i), \quad (L_i, \bar{E}_i, H_1, H_2) \to (L_i, \bar{E}_i, H_1, H_2).$$

  - Forbid L-violation with lepton parity (and $m_{LSP} > m_p$): only UDD exists

$$(L_i, \bar{E}_i) \to -(L_i, \bar{E}_i), \quad (Q_i, \bar{U}_i, \bar{D}_i, H_1, H_2) \to (Q_i, \bar{U}_i, \bar{D}_i, H_1, H_2)$$

- All these symmetries are included ad-hoc, and the models share the same minimal particle content and symmetries
- ***R-parity is also not sufficient*** for matter stability, higher order operators are not forbidden:

$$W_5 \supset \frac{\hat{q}\hat{q}\hat{q}\hat{L}}{\Lambda} + \frac{\hat{u}^c\hat{u}^c\hat{d}^c\hat{e}^c}{\Lambda}$$

- There is no a priori argument to prefer the RPC over RPV SUSY
  - Bonus: RPV can easily relax the experimental bounds

Both should be looked for experimentally!

Constraints on RPV couplings

- Precision experiments place many indirect bounds on RPV couplings:

$\lvert\lambda'_{ijk}\lambda''_{i'j'k'}\rvert < 10^{-9} \Leftarrow$ Proton decay	$\lvert\lambda_{13k}\rvert < 3\times10^{-2} \Leftarrow \mathrm{BR}(\tau^-\to\nu\nu e^-/\nu\nu\mu^-)$
$\lvert\lambda^*_{i12}\lambda'_{i11}\rvert < 2\times10^{-8} m^2_{\tilde\nu} \Leftarrow \mu\to e$ (Ti)	$\lvert\lambda'_{111}\rvert < 3.3\times10^{-4} \Leftarrow \nu$-less $\beta\beta$ decay
$\lvert\lambda^*_{i21}\lambda'_{i31}\rvert < 2\times10^{-5} m^2_{\tilde\nu} \Leftarrow B^0_d \to e^\pm\mu^\mp$	$\lvert\lambda'_{22k}\rvert < 10^{-1} \Leftarrow \mathrm{BR}(D^0\to K^-\mu^+\nu/K^-e^+\nu)$
$\lvert\lambda'^*_{i31}\lambda'_{i13}\rvert < 3\times10^{-8} m^2_{\tilde\nu} \Leftarrow B\bar B$ mixing	$\lvert\lambda''_{312}\rvert < 2.1\times10^{-3} \Leftarrow n\bar n$ oscillation
$\lvert\lambda''^*_{i23}\lambda''_{i12}\rvert < 6\times10^{-5} m^2_{\tilde u_{iR}} \Leftarrow B^+\to\phi\pi^-$	$\lvert\lambda''_{223}\rvert < 1.25 \Leftarrow$ RG evolution

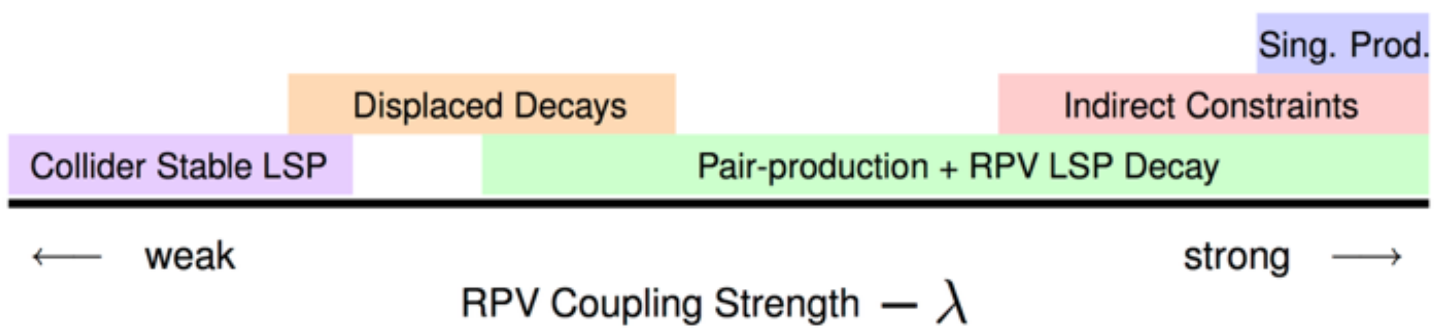
… and many more

$$\lambda_{1G\,max} \ll \lambda_{2G\,max} \ll \lambda_{3G\,max}$$

Indirect constraints ⇨ Not all couplings can be large

Third generation dominance *or* *Small universality*

$\lambda_{RPV} \sim 1$	$\lambda_{RPV} \ll 1$
Decays are prompt	Decays can be prompt
2-, 3- and 4-body decays	or *displaced*
Single production possible	or *detector stable*



The RPV-MSSM

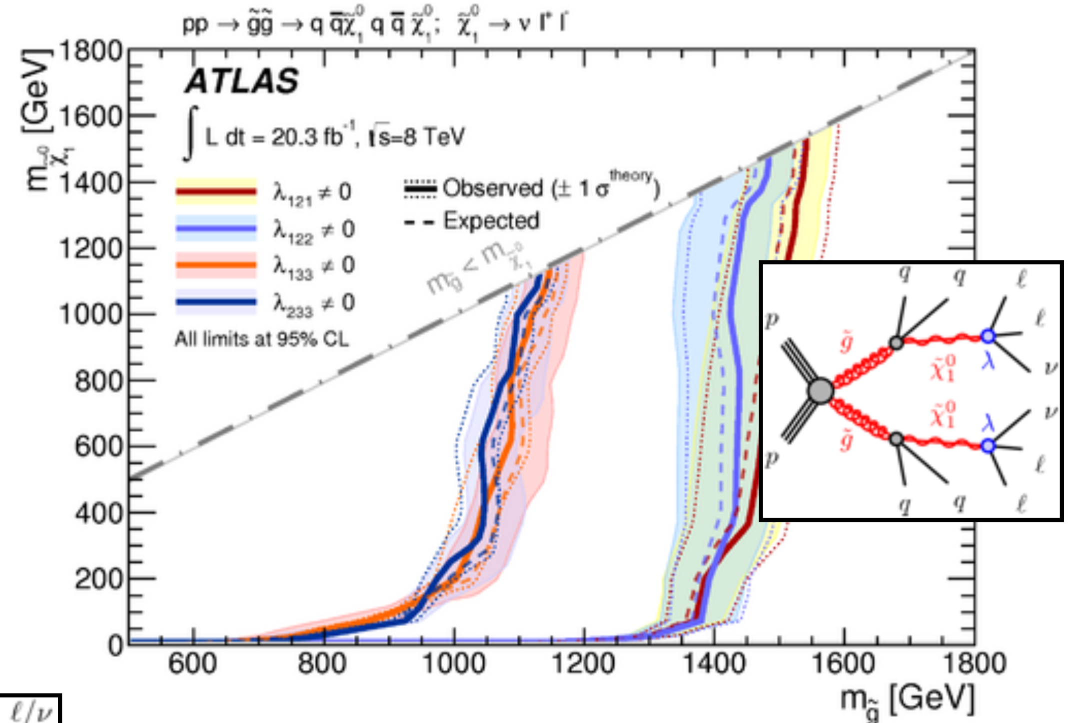
- Two types of collider signatures:
  - {All pair-produced SUSY topologies} × {RPV decays of the LSP}
  - {Single production (through RPV) + RPC decays} × {RPV decays of the LSP}
- The RPV-MSSM is an effective *signature generator*

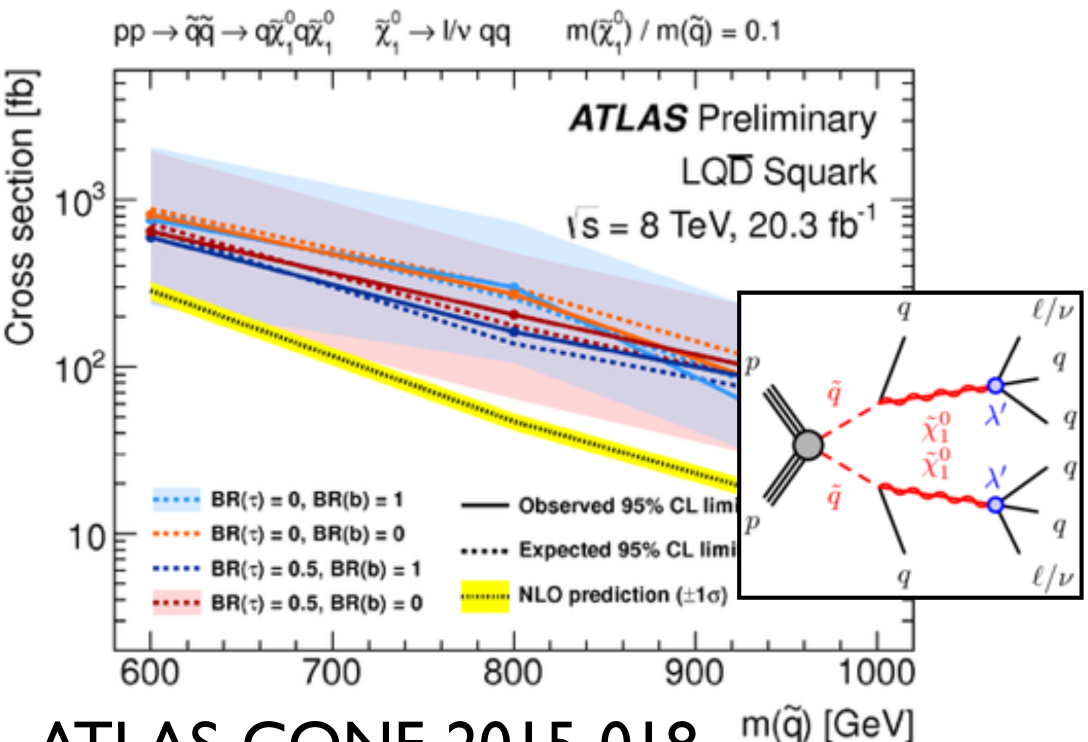
A much more complicated structure than in the RPC-MSSM

- Leptonic RPV give rise to ***multilepton final states***, which are typically at least as constrained as their RPC counterpart
- ***Displaced decays*** are also surprisingly better covered than prompt
- Gluinos are easy to find, even in the RPV case, as they typically give rise to ***high object multiplicity*** final states
- Direct RPV decays are typically less constrained. They contain ***less objects*** in the final state, without the smoking gun of large E_T^{miss}.
  - Baryonic RPV with direct decays particularly challenging, due to the overwhelming background from multijet production

Leptonic RPV

- Our inclusive four-lepton search is very powerful in constraining signatures of leptonic RPV (***LLE***, ***LQD***)
  - The large lepton and jet multiplicities make a gluino hard to hide
  - And can constrain electroweak production without problems



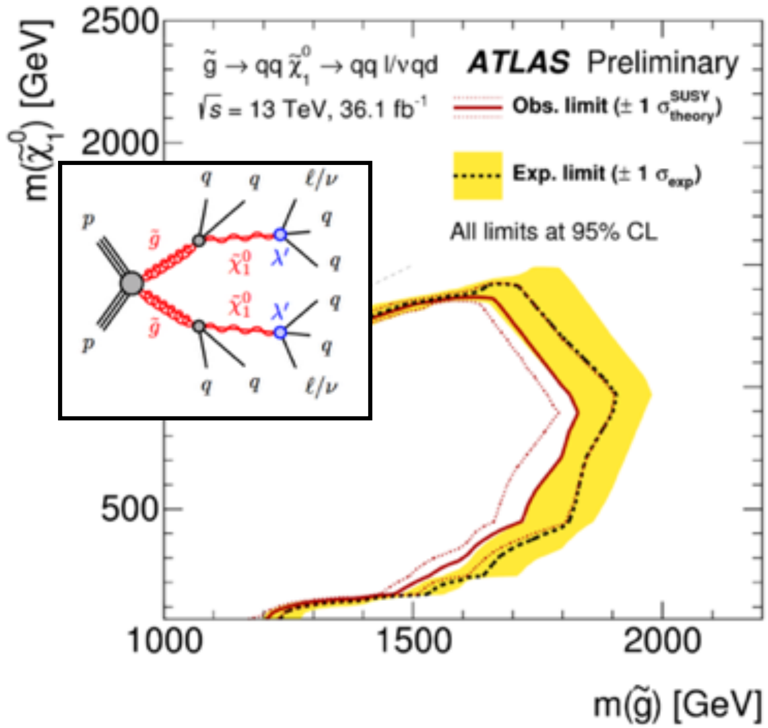


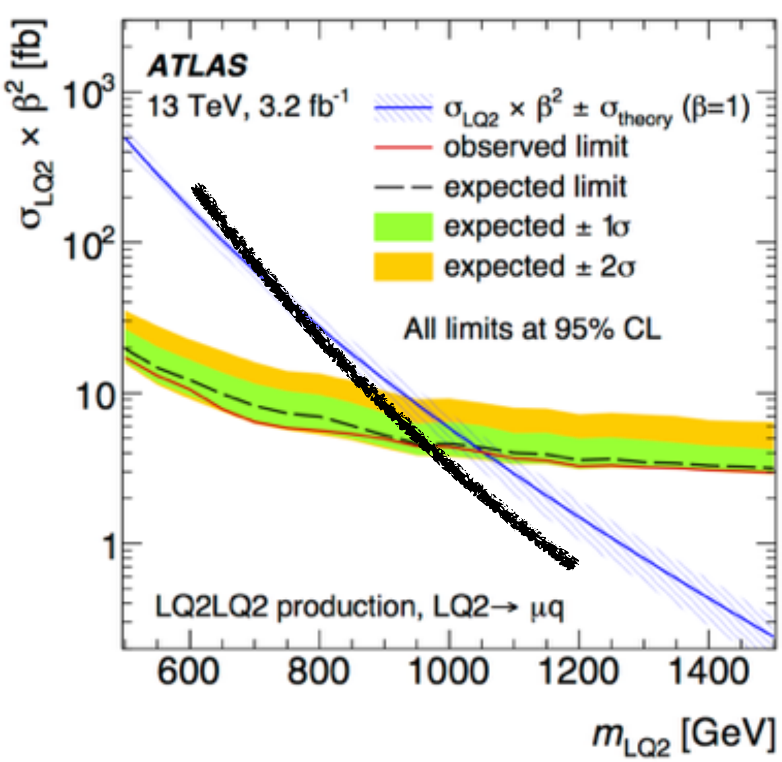
ATLAS-CONF-2015-018

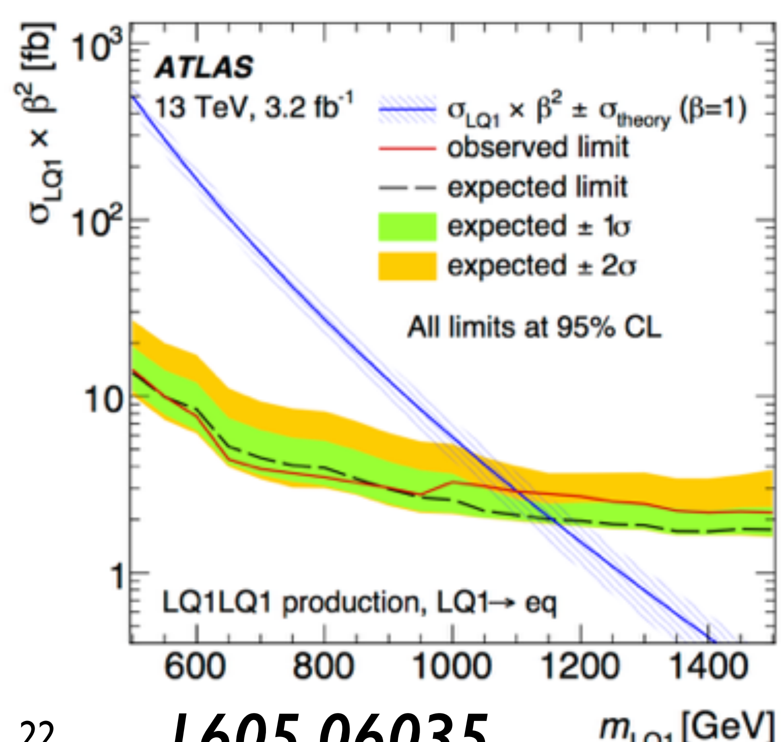
- However a ***loophole for squark*** production in the case of decays through LQD couplings
- The ***ljj*** resonance from the neutralino decay is highly boosted, ***lepton isolation kills the signal***

Squarks with LQD

- Gluino decay chains with *LQD* should be all covered by the 1L+multijet search
  - *What about decays into taus?* **1403.7197**
- For squark direct production limits from scalar leptoquark searches apply







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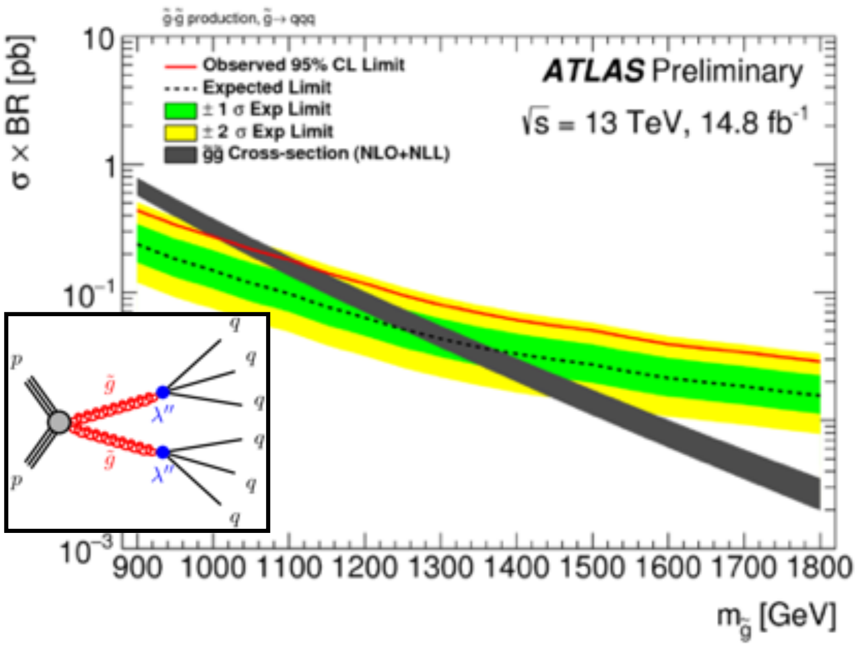
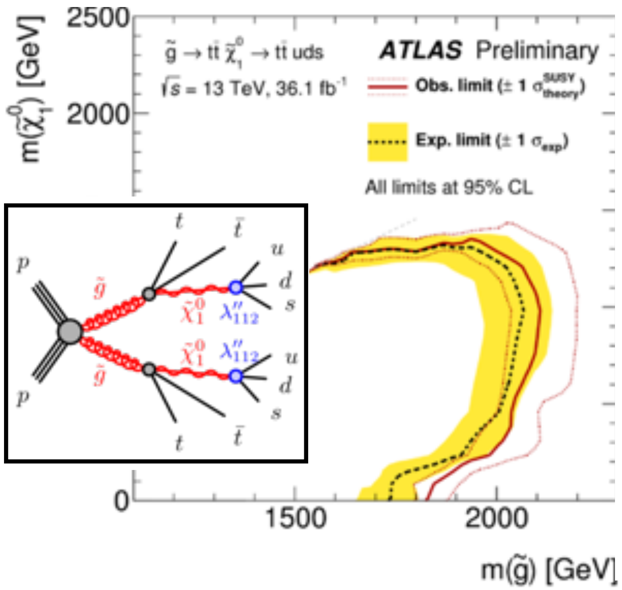
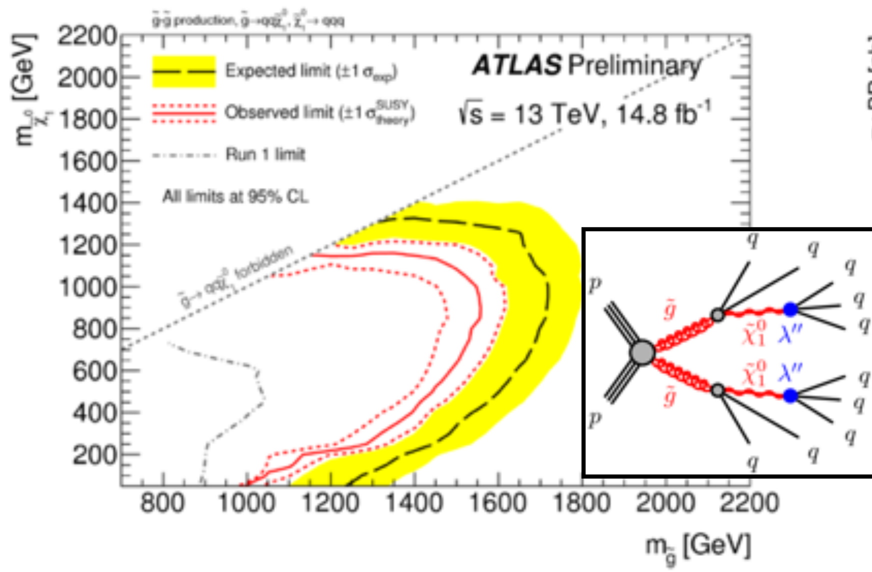
Baryonic RPV

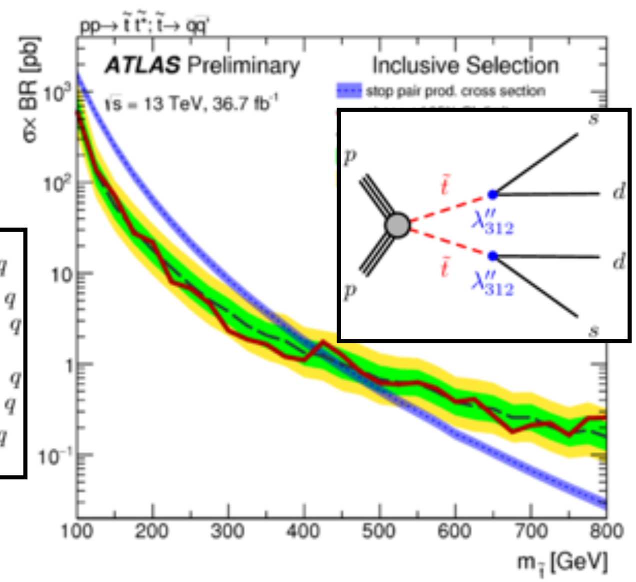
- Generic signature of multi jet resonances, *up to 18 jets!*
  - Gluino cascade decays are well covered by our RPV-multijet search



- For gluino decays involving tops even stronger constraints from the 1L+multijets
- Less sensitivity for gluino direct decays to three jets, marginal increase in sensitivity over Run1
- Squarks direct decay into two-jets with limits reaching only ~450 GeV
- *Squark decays to q+N$_1$, N$_1$->qqq uncovered!*





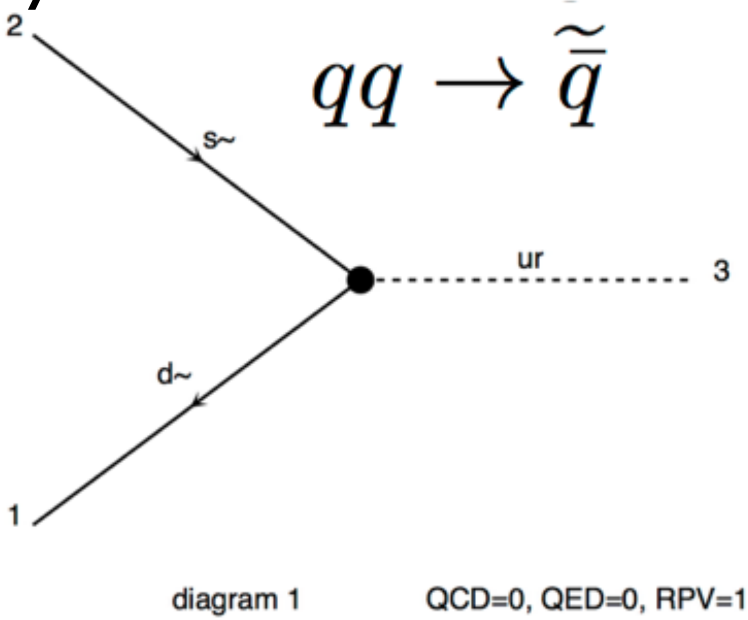


RESONANT PRODUCTION

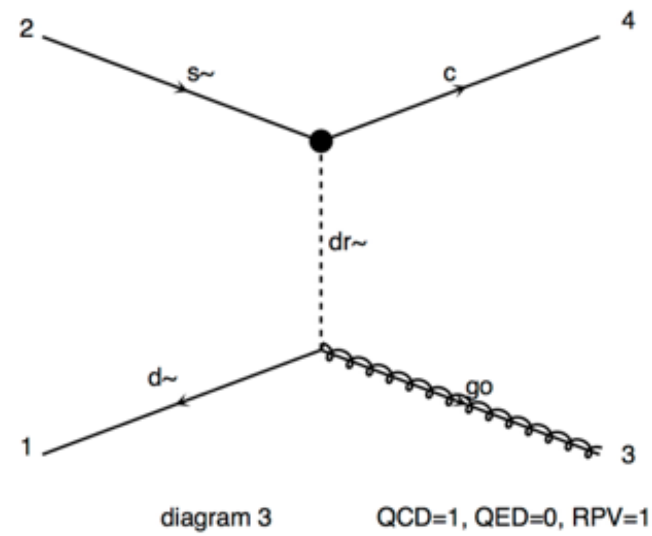
- If the R-parity violating couplings are large supersymmetric particles can be ***singly produced*** at colliders, with cross-sections larger than pair-production
  - For sfermions ***s-channel*** single production
  - For gauginos, ***t-channel sfermion exchange*** in association with an SM fermion

Baryonic RPV:

$$qq \rightarrow \tilde{\bar{q}}$$



$$qq \rightarrow (\tilde{N}_i \text{ or } \tilde{C}_i \text{ or } \tilde{g}) + q$$



Leptonic RPV:

$$q\bar{q} \rightarrow \tilde{\nu} \text{ or } \tilde{\ell}$$

LFV sneutrino resonance already searched for

$$q\bar{q} \rightarrow (\tilde{N}_i \text{ or } \tilde{C}_i \text{ or } \tilde{g}) + (\ell \text{ or } \nu)$$

The R-hadrons

The gluinos, which are flavor singlets and belong to a color SU(3) octet, interact strongly with the octet of gluons and may combine with quarks, anti-quarks and gluons in much the same way as quarks presumably do, giving new hadronic states carrying one unit of R, which we call R-hadrons. Combined with qqq, $q\bar{q}$ or simply gluons, gluinos lead, respectively, to new bosonic states (R-baryons) and new fermionic states (R-mesons, R-glueballs) which are color-singlets with a flavor multiplet structure similar to ordinary baryons, mesons and glueballs.

Farrar, Fayet - 1978

Long-lived particles

- In supersymmetry displaced decays can occur in different scenarios
  - R-parity violation if the couplings are very small

$$c\tau_{\rm RPV} \sim 0.1\text{mm}\left(\frac{100\ \text{GeV}}{\tilde{m}}\right)\left(\frac{10^{-6}}{\lambda}\right)^2$$

  - In gauge mediated SUSY models

SUSY breaking scale, displaced if > O(100 TeV)

$$c\tau_{\rm GMSB} \sim 0.1\text{mm}\left(\frac{100\ \text{GeV}}{\tilde{m}}\right)^5\left(\frac{\sqrt{F}}{100\ \text{TeV}}\right)^4$$

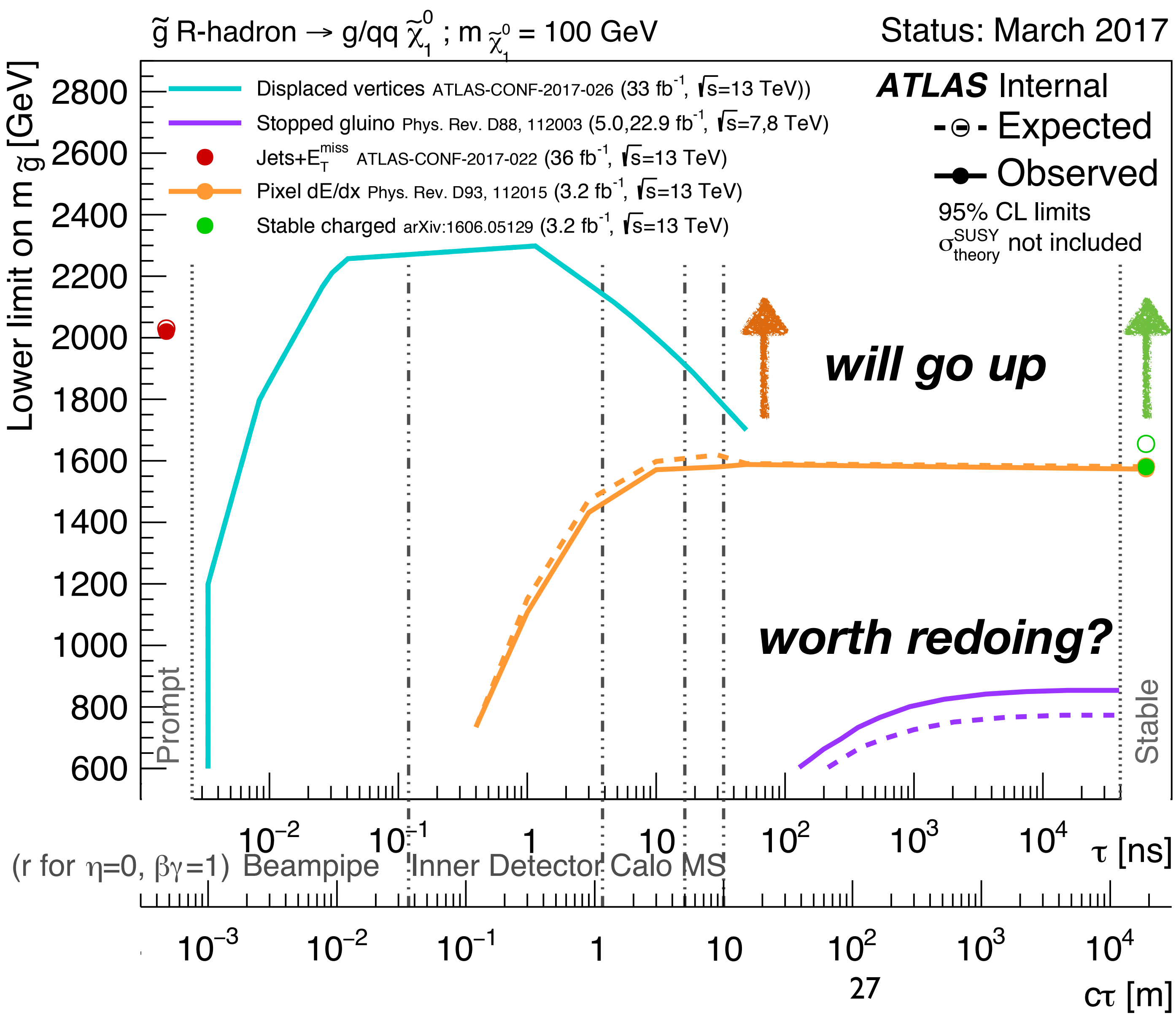
  - In mini-split SUSY if all squarks are at very high masses (PeVs)

$$c\tau \approx 10^{-5}\ \text{m}\left(\frac{m_{\tilde{q}}}{\text{PeV}}\right)^4\left(\frac{\text{TeV}}{m_{\tilde{g}}}\right)^5$$

- Particles in the bulk of the detector are extremely rare
  - Very low (or no) backgrounds yet retaining good signal efficiency

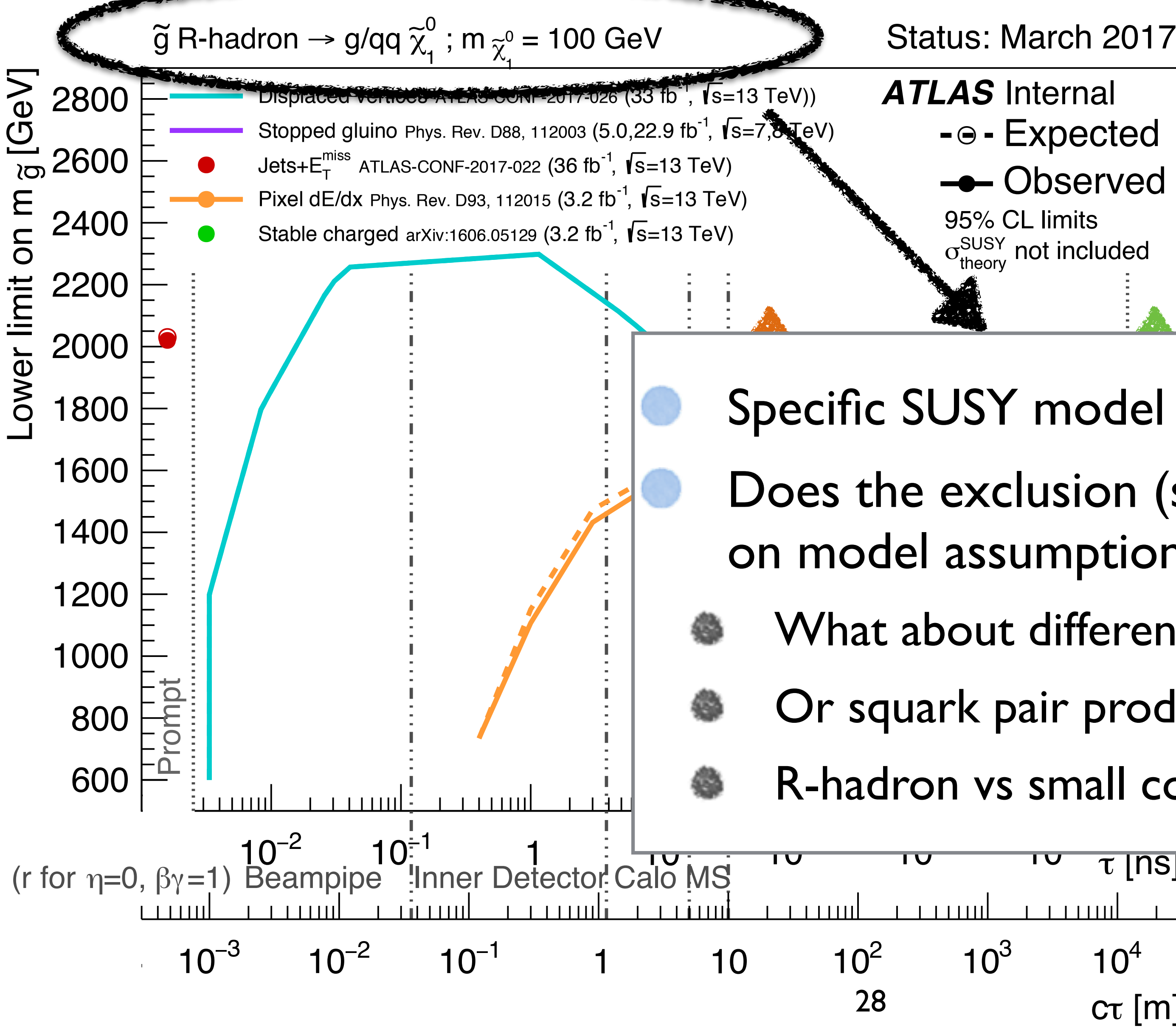
Long-lived status

- Typically, scenarios with long-lived particles are better constrained than the case of prompt decays



Long-lived status

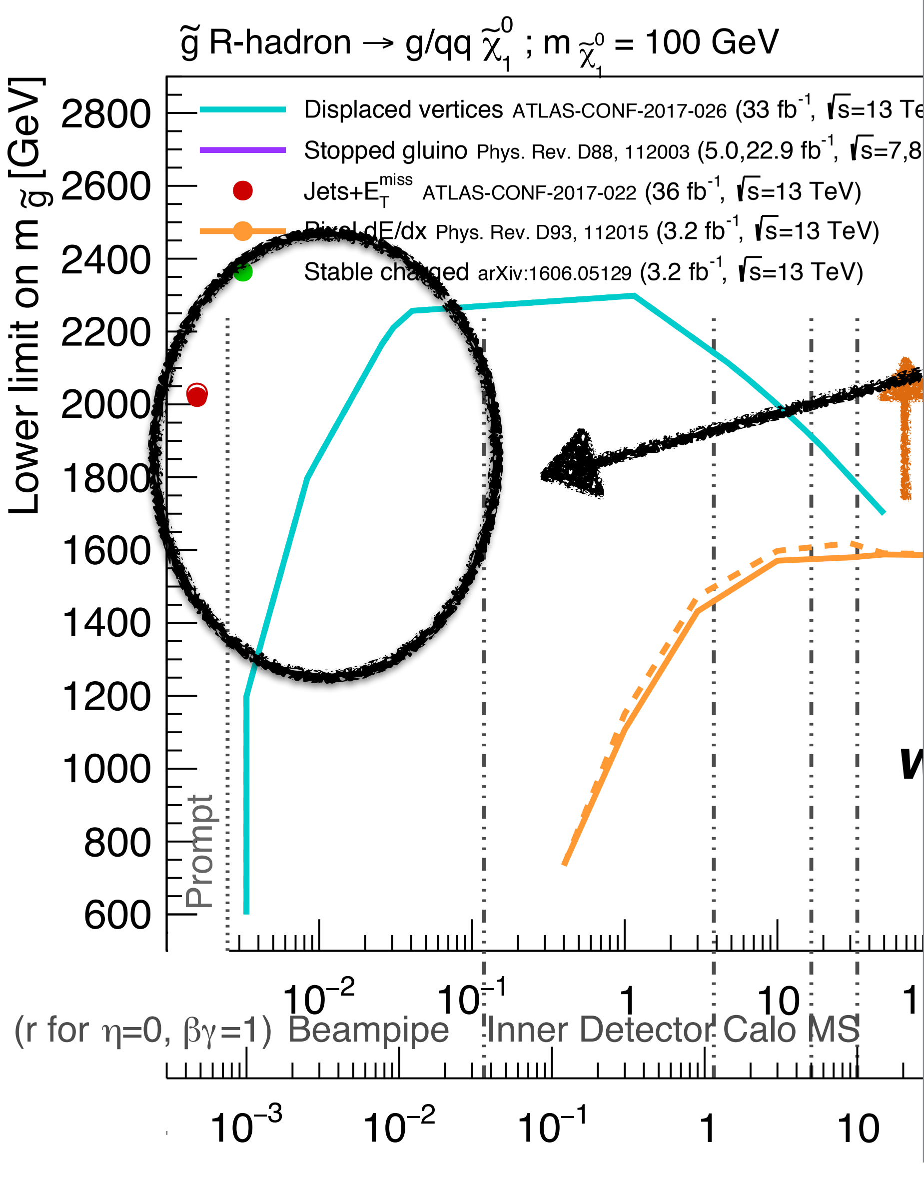
- Typically, scenarios with long-lived particles are better constrained than the case of prompt decays



- Specific SUSY model considered
- Does the exclusion (strongly) depends on model assumptions?
  - What about different decay modes?
  - Or squark pair production?
  - R-hadron vs small couplings

Long-lived status

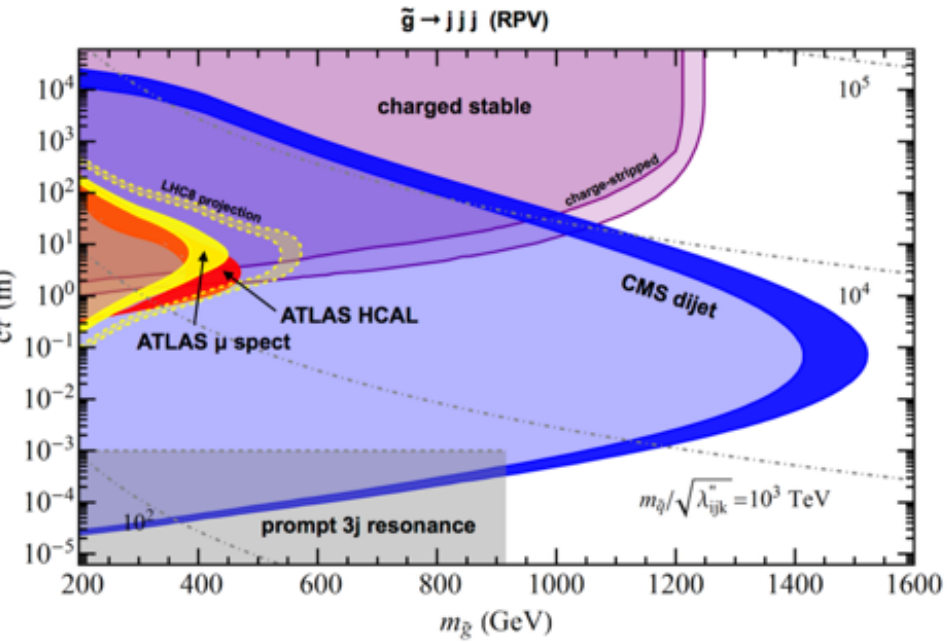
- Typically, scenarios with long-lived particles are better constrained than the case of prompt decays

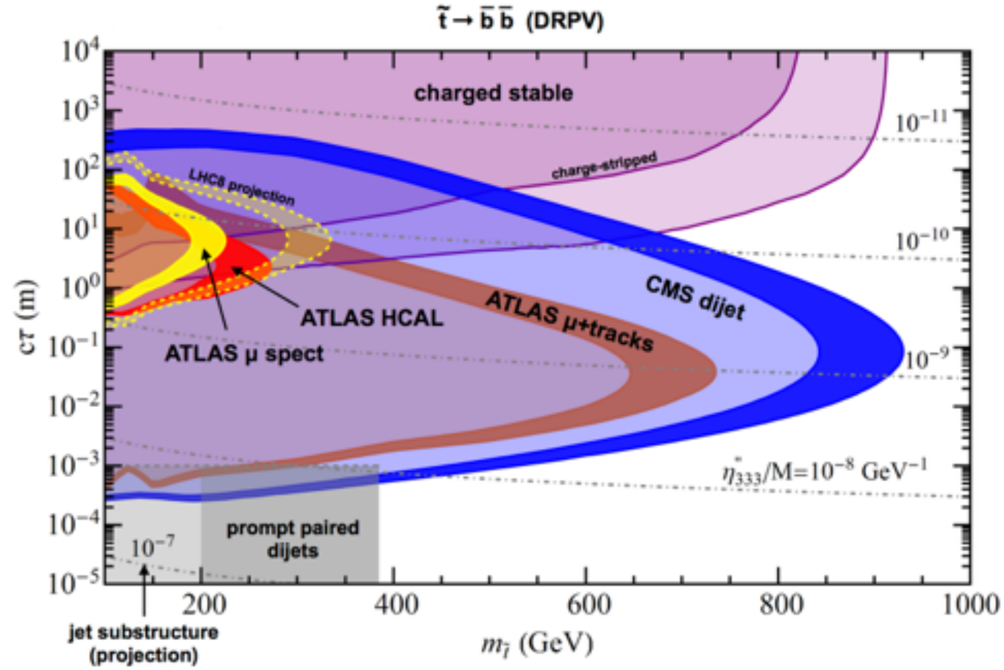


- Gap between the sensitivity of long-lived searches and the prompt decays
- Likely to be covered by the prompt searches if we would extrapolate their exclusion
  - Care needed with cleaning cuts
  - For gluino R-hadrons Run1 CONF: ***ATLAS-CONF-2014-037***
- Can we do such interpretations more systematically?
  - Need to put some work into evaluating the effect and uncertainties on our cosmic/jet/event cleaning, JVT, …

BARYONIC RPV

1503.05923

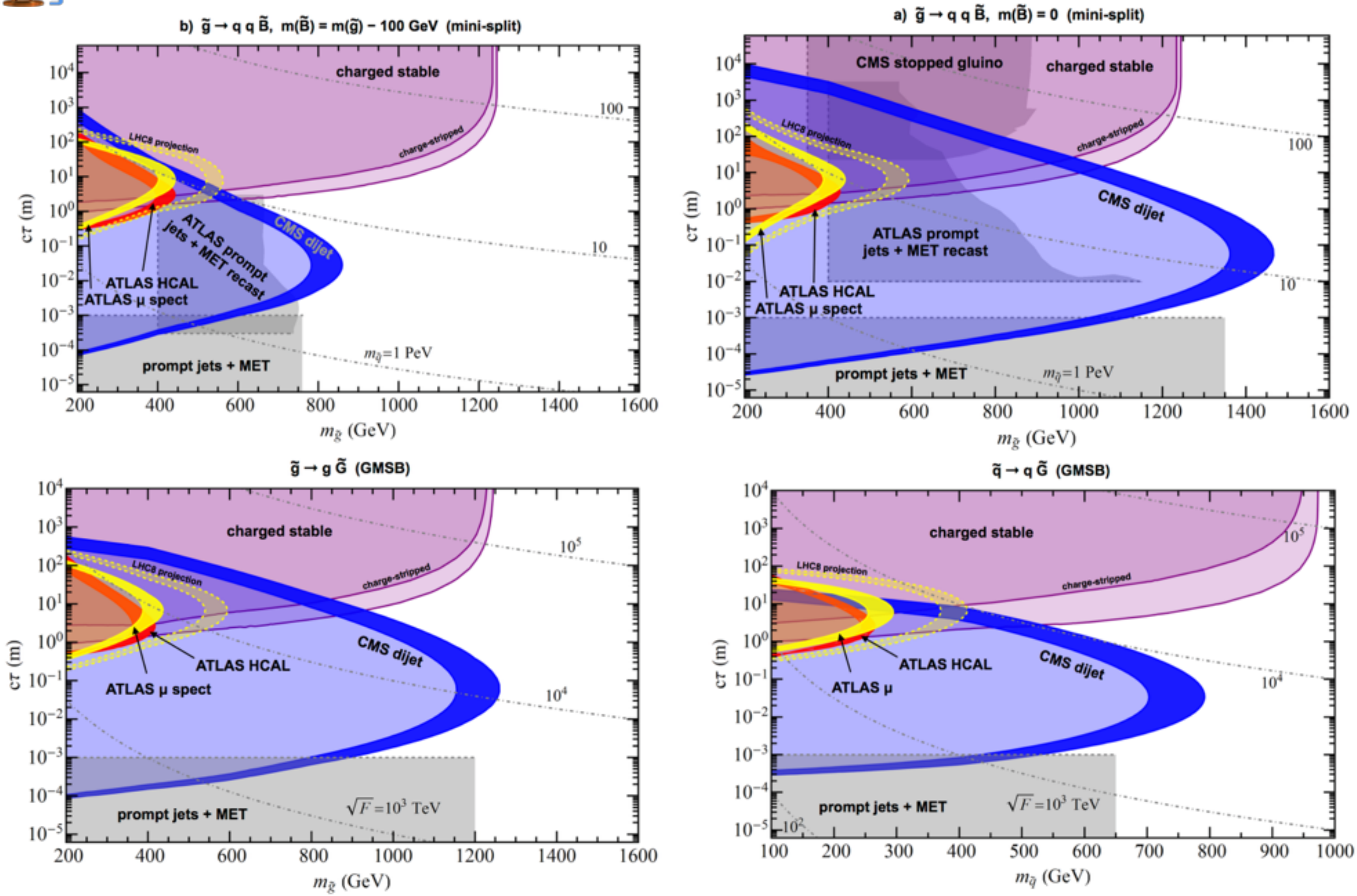




- Searches for displaced dijets or stable massive particles have been shown to be extremely powerful in constraining a variety of SUSY models
- But theorist reinterpretation required lots of work (and guesses)
- From an experimental point of view, prompt (or slightly prompt) decays become more interesting

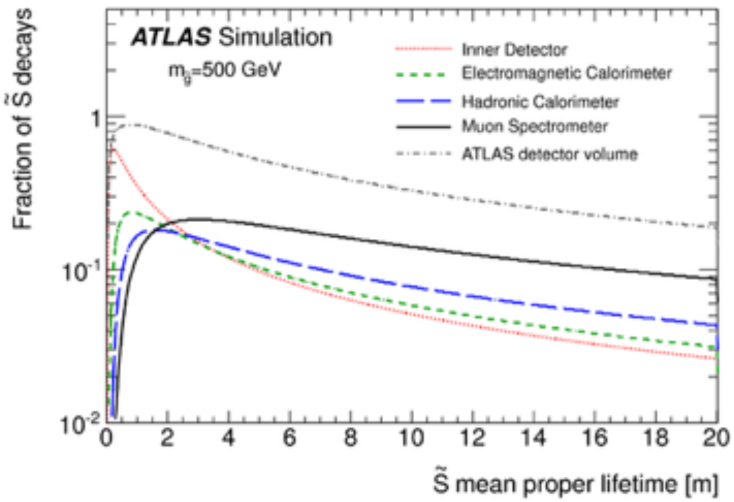
MINI-SPLIT/GMSB

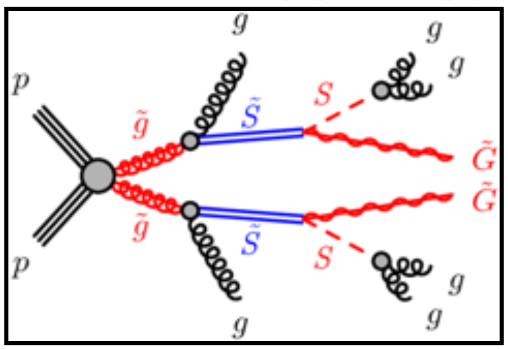
1503.05923



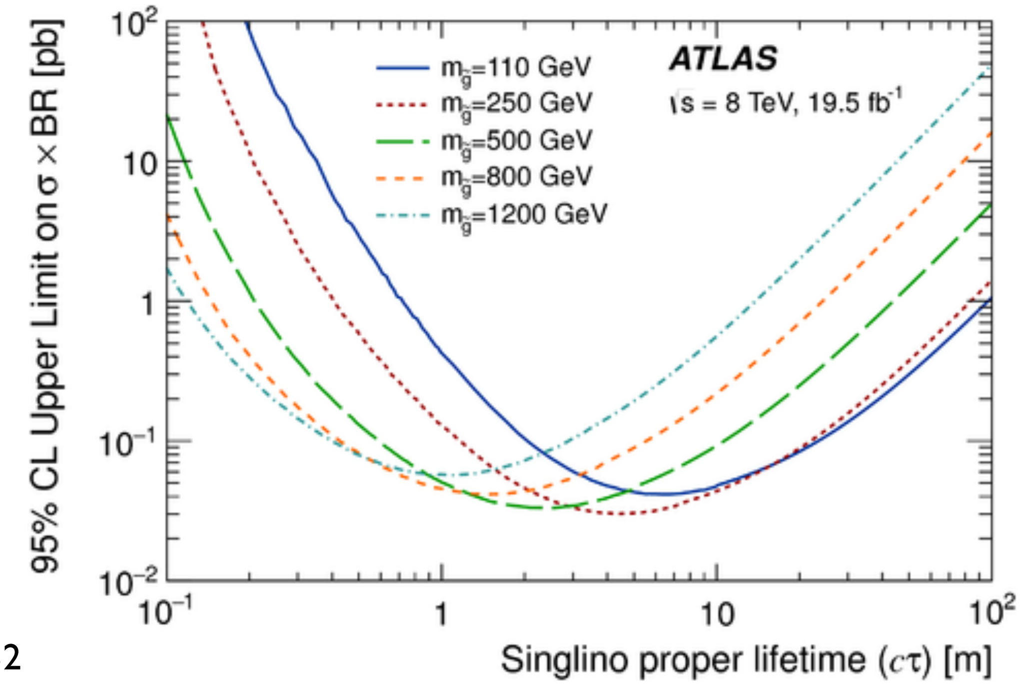
ATLAS Displaced jets

- The ATLAS displaced dijets search is interpreted in a SUSY hidden sector (stealth) model





- The MSSM is augmented with a light hidden sector which only feels SUSY breaking weakly
  - The simplest option a gauge singlet super field S at the weak scale with a nearly degenerate singlino super partner
  - Superpartners decay through the hidden sector, ETmiss is reduced through degeneracy



- Hidden fermions decays to the scalar and the LSP (axino or gravitino)
- High multiplicity final states with softer decay products (prompt or LL)

AXINO AND GRAVITINO

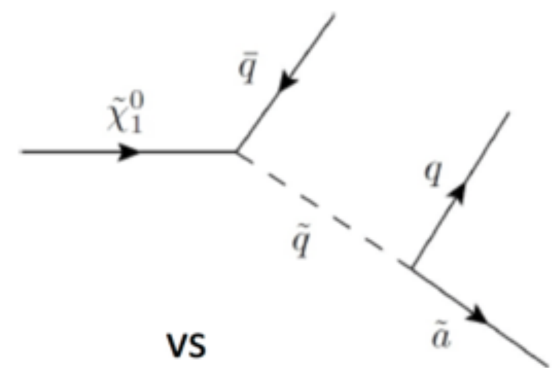
- Gravitino always the LSP $m_{3/2} = F/\sqrt{3}M_{\mathrm{P}}$
- Phenomenology determined by the NLSP
- The NLSP has a universal 2-body decay to SM partner + gravitino

$$\Gamma(\tilde{x} \to x\tilde{G}) = \frac{m_x^5}{16\pi(\sqrt{3}M_{\mathrm{P}}m_{3/2})^2}$$

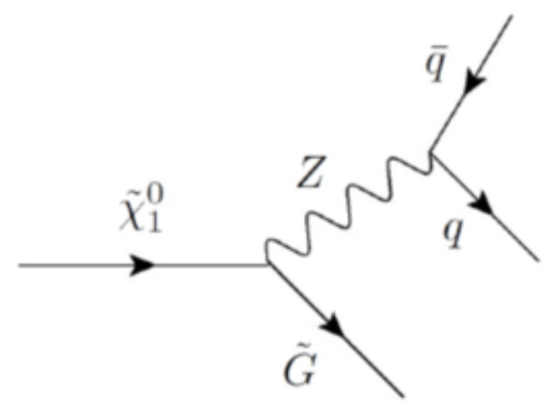
can be prompt or long-lived

- If we take neutralinos LSP

$$\widetilde{N}_1 \to Z\widetilde{G},\ h^0\widetilde{G},\ A^0\widetilde{G},\ \text{or}\ H^0\widetilde{G}$$



vs



- Another possibility is to have an axino LSP
  - Similar phenomenology, but expect harder jets and less E_T^{miss}

Summary

- For a naturally light LSP (< 500 GeV) basically ***all possible gluino decays*** are excluded up to ~2 TeV
  - Gluino decays contain either large E_T^{miss}, top quarks, or high object multiplicity final states
  - Some contrived and not very motivated exceptions exist

- For 1st/2nd generation squarks the situation is more complicated
  - For long decay chains and compressed spectra limits can be significantly relaxed
  - Similar situation if we consider RPV decays, in this case some topologies are still uncovered

Backup