RPV + stealth SUSY (LLP + unconv. signatures)

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On behalf of ATLAS and CMS

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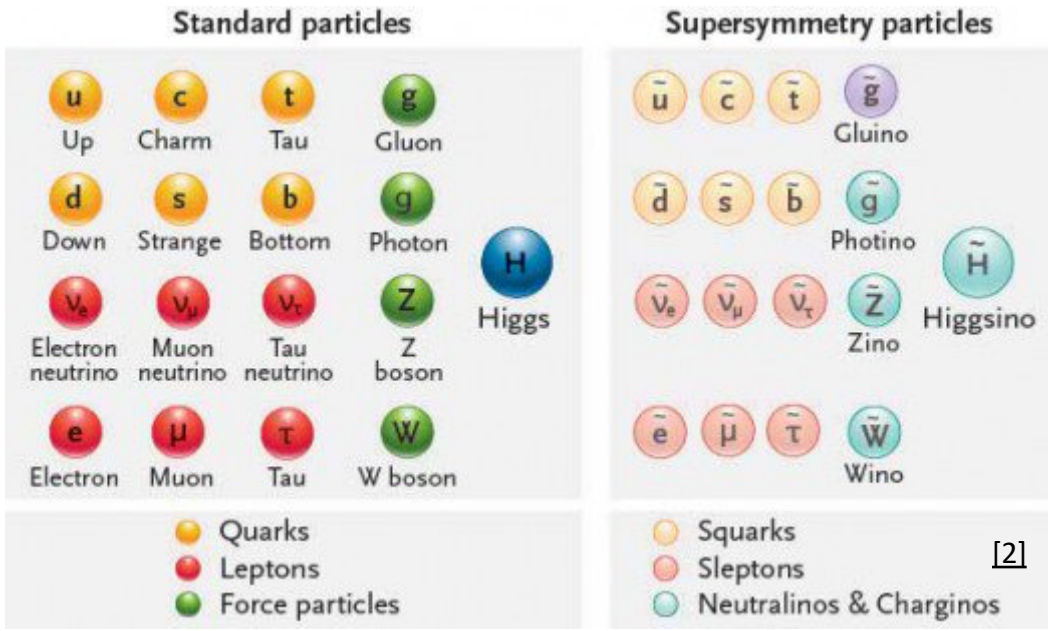
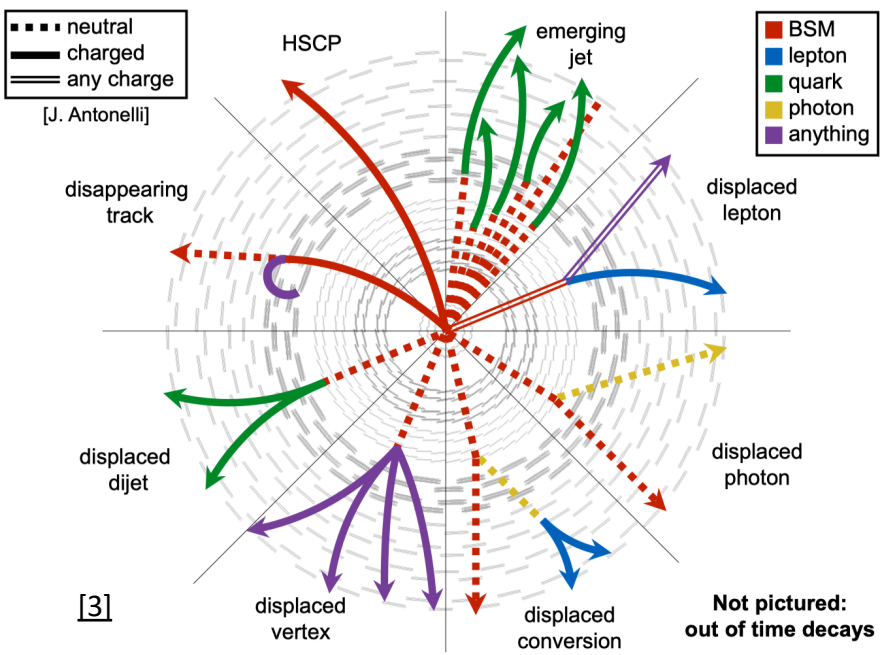
Motivation

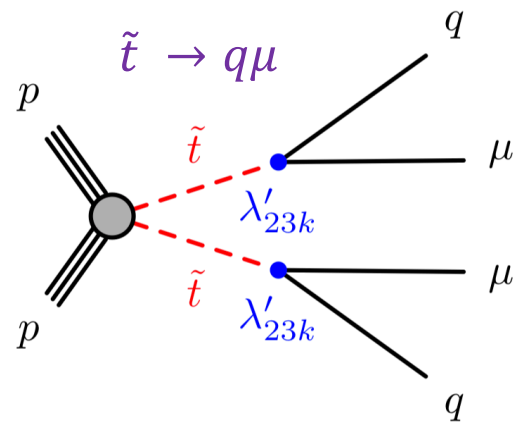
- More traditional supersymmetry searches so far have not come up with any new particles.
- Naturally, ask what non-standard signatures have we not covered in standard SUSY searches?





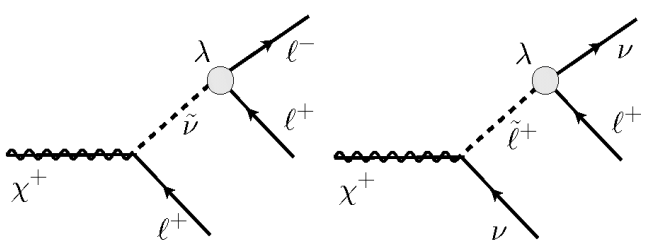
- A wide variety of non-standard SUSY models: R-parity violating, "compressed" spectra, stealth, split, hidden sector, etc…
- Many models have particles that have a longer lifetime.
- Requires clever techniques in analysis to reconstruct these particles and to suppress SM backgrounds

RPV Supersymmetry

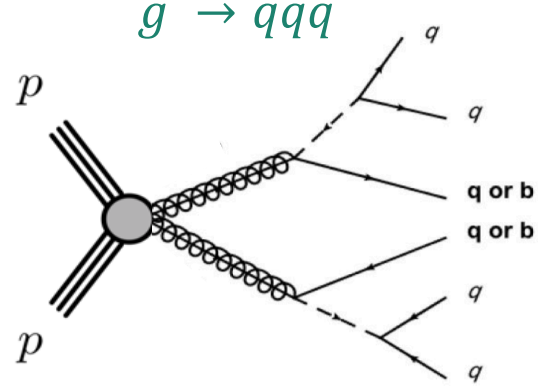


$$W_{\not{R}_p} = \boxed{\tfrac{1}{2}\,\lambda_{ijk} L_i L_j E^c_k} + \boxed{\lambda'_{ijk} L_i Q_j D^c_k} + \boxed{\tfrac{1}{2}\,\lambda''_{ijk} U^c_i D^c_j D^c_k}$$

$\tilde{\chi}^{\pm} \rightarrow l^{\pm} l^{\mp} l^{\pm}$



$\tilde{g} \rightarrow qqq$



RPV Supersymmetry

	λLLE	$\lambda' LQD$	$\lambda'' UDD$
Direct RPV decays			
$\tilde{\nu}$	Z′ $\ell^+\ell^-$	$d\bar{d}$	—
$\tilde{\ell}^-$	W′ $\ell^-\nu$	$\bar{u}d$	—
$\tilde{u}$	—	$\ell^+ d$	$d\bar{d}$
$\tilde{d}$	—	$d\nu$, $\ell^- u$	$\bar{u}\bar{d}$
$\tilde{\chi}^0$	$\ell^+\ell^-\nu$	$\ell^+\bar{u}d$, $\ell^- u\bar{d}$, $\nu d\bar{d}$	udd, $\bar{u}\bar{d}\bar{d}$
$\tilde{\chi}^+$	$\ell^+\ell^+\ell^-$, $\ell^+\nu\nu$	$\ell^+ d\bar{d}$, $\ell^+ u\bar{u}$, $\nu u\bar{d}$	uud, $\bar{d}\bar{d}\bar{d}$
Indirect RPV decays			
$\tilde{u}_i \to u_i\tilde{\chi}^0$	$u_i\ell^+\ell^-\nu$	$u_i\ell^+\bar{u}d$, $u_i\ell^- u\bar{d}$, $u_i\nu d\bar{d}$	$u_i udd$, $u_i\bar{u}\bar{d}\bar{d}$
$\tilde{u}_i \to d_i\tilde{\chi}^+$	$d_i\ell^+\ell^+\ell^-$, $d_i\ell^+\nu\nu$	$d_i\ell^+ d\bar{d}$, $d_i\ell^+ u\bar{u}$, $d_i\nu u\bar{d}$	$d_i uud$, $d_i\bar{d}\bar{d}\bar{d}$
		...	
$\tilde{g} \to u_i\tilde{u}_i$	—	$u_i\ell^+ d$	$u_i d\bar{d}$
$\tilde{g} \to u_i\bar{u}_i\tilde{\chi}^0$	$u_i\bar{u}_i\ell^+\ell^-\nu$	$u_i\bar{u}_i\ell^+\bar{u}d$, $u_i\bar{u}_i\ell^- u\bar{d}$	$u_i\bar{u}_i udd$
		$u_i\bar{u}_i\nu d\bar{d}$	$u_i\bar{u}_i\bar{u}\bar{d}\bar{d}$
		...	

single sparticle production: dijet resonance, Z′, W′

pair production: paired dijets, excited tops

pair prod: leptoquarks

pair production: all-hadronic + resonances

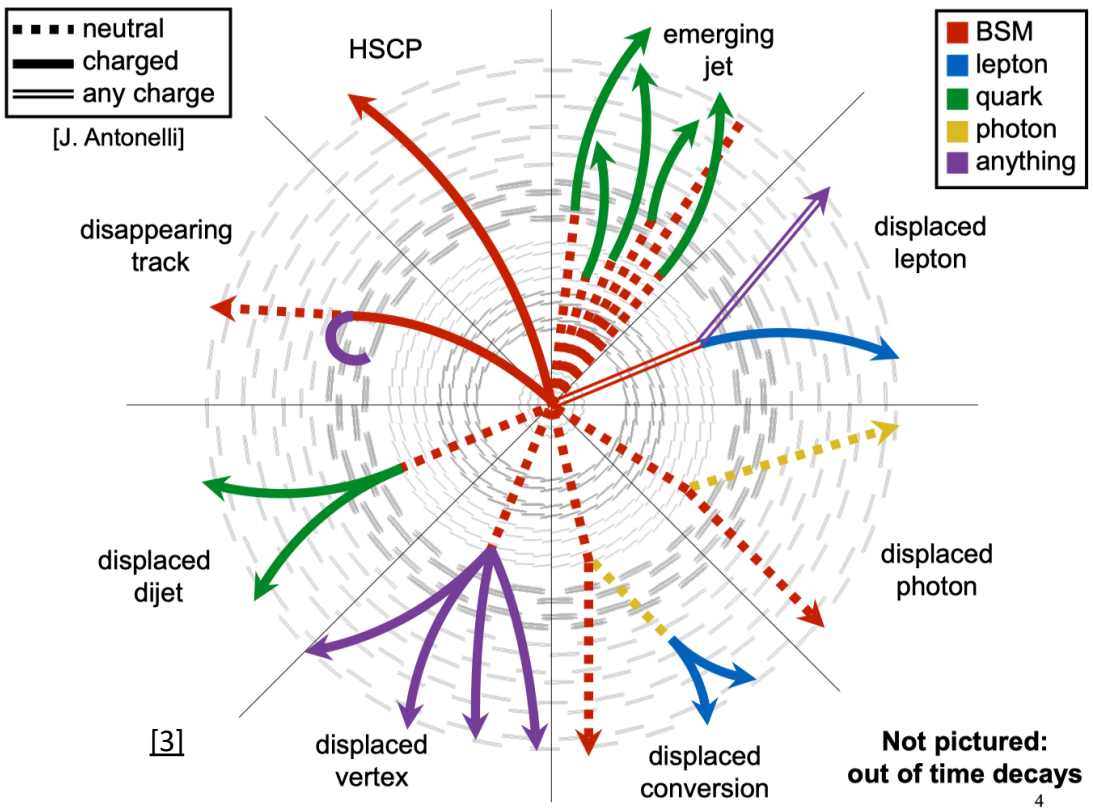
2ℓ SS + jets

2ℓ OS, 4ℓ, 6ℓ with low or no MET

Inclusive 1ℓ, high jet multiplicity with low or no MET

Table by Ana Ovcharova

Many Long-Lived Searches



- ATLAS: LLP in displaced jets with muon spectrometer: Phys. Rev. D **99**, 052005
- ATLAS: LLP in displaced jets with CALO: arXiv:1902.03094
- ATLAS: Long-lived multi-charge particles: arXiv:1812.03673
- ATLAS: HIP/monopole
- ATLAS: Higgs -> Z + LLP: Phys. Rev. D 99, 052003
- CMS: Search for new particles decaying to a jet and an emerging jet: JHEP02(2019)179
- CMS: search for prompt HNL: Phys. Rev. Lett. **120**, 221801
- CMS: long-lived (disappearing track) component of the SUSY MT2 search: CMS-SUS-19-005
- CMS: LLP using delayed jets and missing transverse momentum: EXO-19-001-PAS
- LHCb: dark photon search Phys Rev. Lett. **120**, 061801
- LHCb: Search for a dimuon resonance in the Y mass region: JHEP09(2018)147

Just a subset of long-lived searches – definitely more than can be covered in one talk!

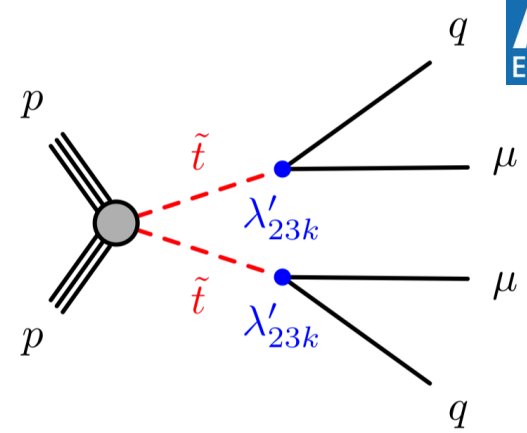
Searches for long-lived particles and other unconventional signatures (Martino Borsato)

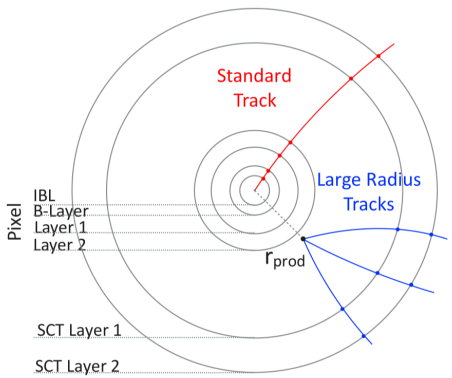
Searches for LLP in ATLAS (Sascha Mehlhase) and **Searches for LLP in CMS** (Malgorzata Kazana)

Search with Displaced Vertex and Muon

ATLAS-CONF-2019-006

- Full Run II Result!! (136 fb^{-1}, 2016 -2018)
- Pair production of stop LSP, followed by $\tilde{t} \rightarrow q\mu$ with small λ'_{23k} coupling
- Range of lifetimes ~ 0.01 ns to 100 ns (3 mm to 30 m)





- Large radius tracking – extends number of tracks by relaxing req. for impact parameter and number of shared hits.
- Displaced secondary vertex algorithm – only tracks with transverse impact parameter > 2 mm and p_T > 1 GeV considered

- Dedicated vetoes for three major backgrounds:
  - Cosmic muons
  - Fake muons from random hit combinations
  - Semileptonic decays of SM hadrons

Object Selection:

Selection level	Muon selection	Displaced vertex selection
Preselection	$p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$, 2 mm $< \lvert d_0\rvert <$ 300 mm, $\lvert z_0\rvert < 500$ mm	$r_{DV} < 300$ mm, $\lvert z_{DV}\rvert < 300$ mm, $\min(\lvert\vec{r}_{DV} - \vec{r}_{PV}\rvert) > 4$ mm, $\chi^2/N_{DoF} < 5$, Pass material map veto
Full selection	Pass cosmic-muon, fake-muon, and heavy-flavor vetoes	$n^{DV}_{Tracks} \geq 3$, $m_{DV} > 20$ GeV

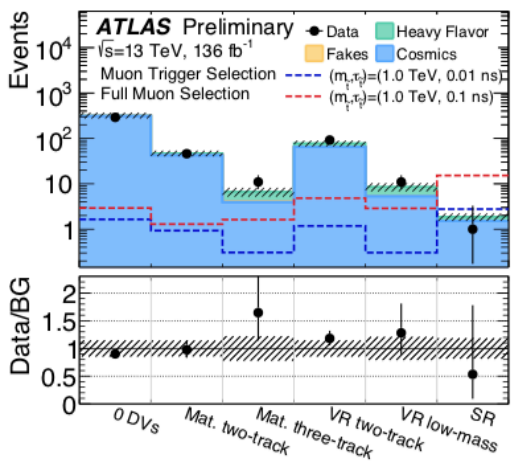
Search with Displaced Vertex and Muon

ATLAS-CONF-2019-006

- Two Triggers:
  - missing E_T ($E_{T,miss} >$ 180 GeV)
  - muon ($p_T^{\mu} > 60$ GeV, $E_{T,miss} < 180$ GeV)

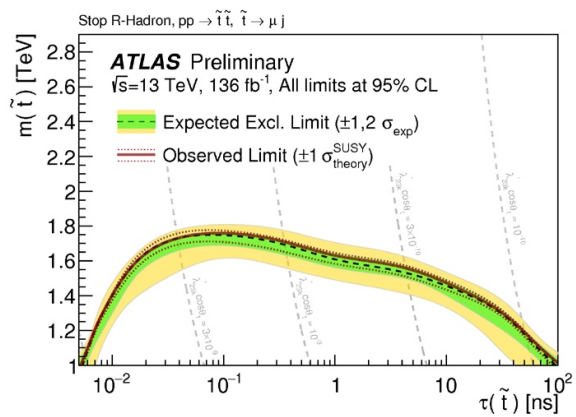
Event Selection:

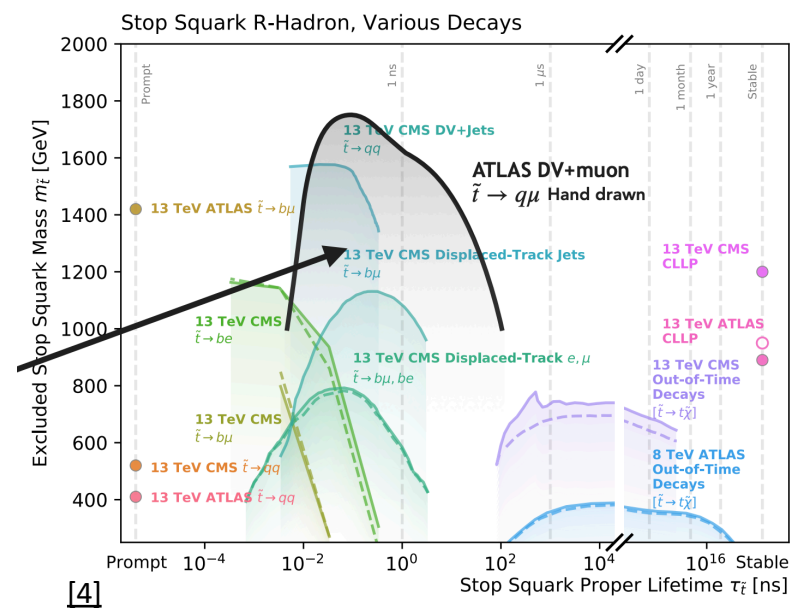
Selection level	E_T^{miss} Trigger SR	Muon Trigger SR
Preselection	Selected by E_T^{miss} trigger, Cluster-based E_T^{miss} > 180 GeV, Selected PV, preselected muon,	Selected by muon trigger, Cluster-based E_T^{miss} < 180 GeV, Selected PV, preselected muon, Highest-p_T muon matches trigger muon
Full selection	≥ 1 full-selection muon, ≥ 1 full-selection DV	



Signal Region	Expected	Observed
E_T^{miss} trigger	0.43 ± 0.16 (stat.) ± 0.16 (syst.)	0
Muon trigger	1.88 ± 0.20 (stat.) ± 0.28 (syst.)	1

- Background estimation comes from transfer factors in regions that do not pass the full-selection.





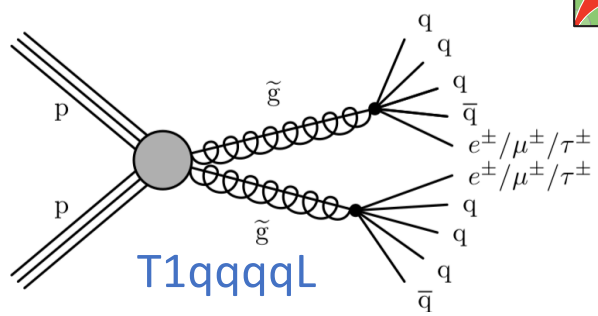
[4]

- Limits set for $m_{\tilde{t}}$ as function of $c\tau$

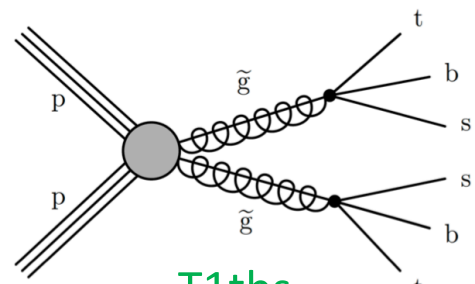
Two same-sign leptons or at least three leptons and jets

CMS-SUS-19-008-PAS

- Full Run II Result!! (137 fb^{-1}, 2016-2018)
- Mostly an RPC SUSY search, but have RPV interpretations:
  - dedicated low missing E_T search region (= 2 leptons, $p_T > 25$ GeV and missing $E_T < 50$ GeV).
- Pair production of $\tilde{g}$, followed by one of two decay cascades:
  - T1qqqqL: $\tilde{g} \to \tilde{q}q, \tilde{q} \to q\tilde{\chi}_1^0 \to qq\bar{q}l$
  - T1tbs: $\tilde{g} \to tbs$



T1qqqqL



T1tbs

Low missing E_T search bins:

N_b	N_{jets}	$H_T \in [300, 1125]$ GeV	$H_T \in [1125, 1300]$ GeV	$H_T > 1300$ GeV
0	2-4	SR1	SR8 ($N_{jets} < 5$)	SR10 ($N_{jets} < 5$)
	5+	SR2		
1	2-4	SR3		
	5+	SR4		
2	2-4	SR5	SR9 ($N_{jets} \geq 5$)	SR11 ($N_{jets} \geq 5$)
	5+	SR6		
≥ 3	2+	SR7		

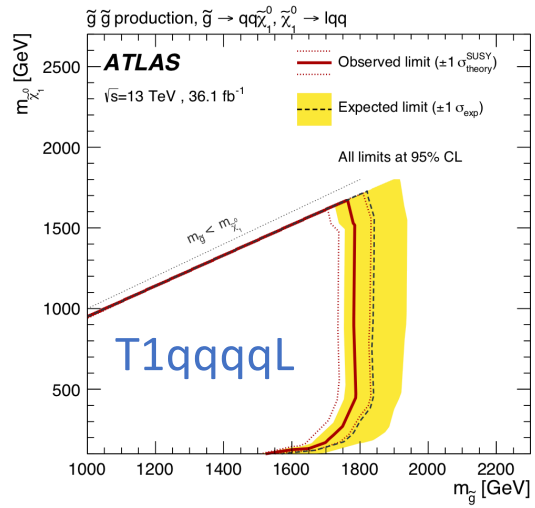
- Triggers:
  - Two isolated leptons
    - $p_{T,1}^l > 17 - 23$ GeV
    - $p_{T,2}^l > 8 - 12$ GeV
  - Two non-isolated leptons
    - $p_{T,1}^l, p_{T,2}^l > 8$ GeV
    - $H_T > 300 - 350$ GeV

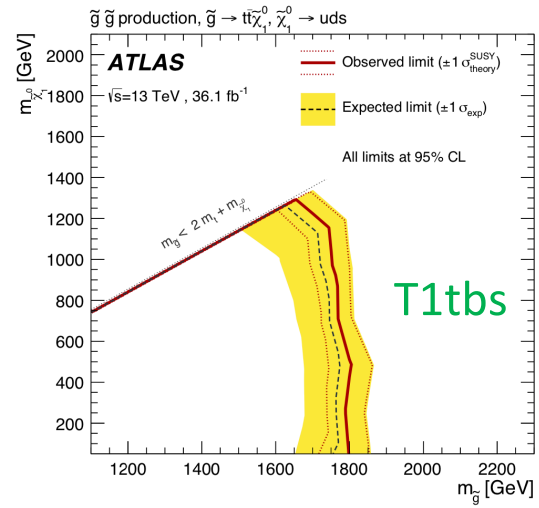
Two same-sign leptons or at least three leptons and jets

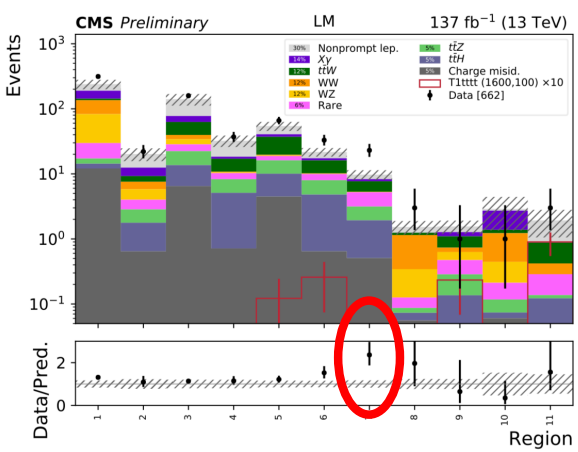
- Backgrounds include:
  - Multiple EW bosons production modes (in top quark decays, for example) – estimated using simulation
  - "Non prompt lepton" – misidentified hadron or its decay product. Estimated from "tight-to-loose" method
  - Charge mismeasurement

CMS-SUS-19-008-PAS

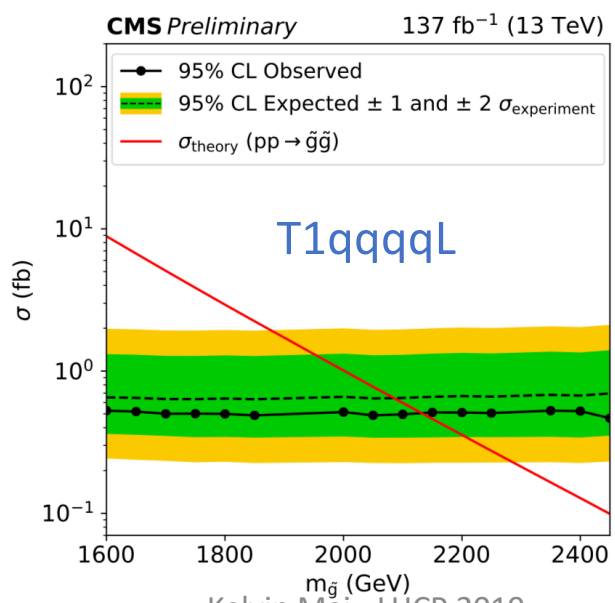
JHEP 09 (2017) 084

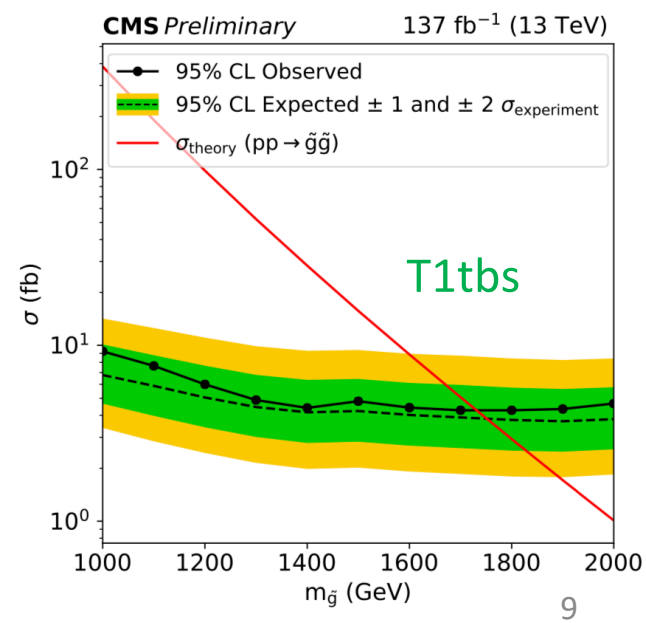






2.3σ excess in one bin!





Heavy charged long-lived particles

arXiv:1902.01636 (submitted to Phys. Rev. D)

- 2015 -2016 Run II Result (36.1 fb^{-1})
- Not RPV, but both gluinos and squarks can be long lived (split SUSY)
- Other models include charginos (mAMSB) and stau direct production (GMSB)

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Two main observables:

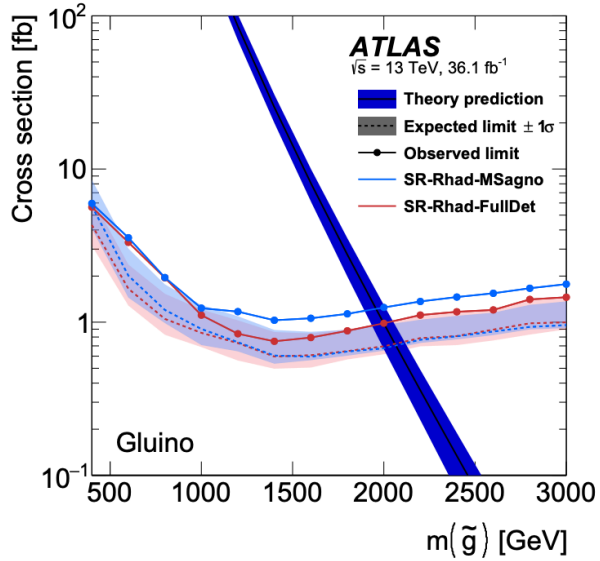
- dE/dx – R-hadrons and the other SUSY LLP tend to have larger masses and will move slower through the detector, having larger ionization energy losses
  - Corrected for η dependence and run-by-run.
- Time of Flight – Since the R-hadrons are moving slower, the time of flight is also longer
  - Measured in the MDTs, the tile calorimeter, and the RPCs and a weighted average using the uncertainties are used.
  - High p_T muons are used for a series of custom calibrations.

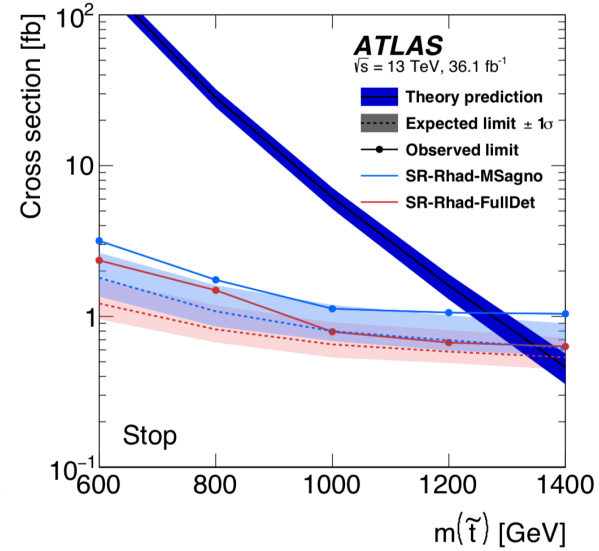
Heavy charged long-lived particles

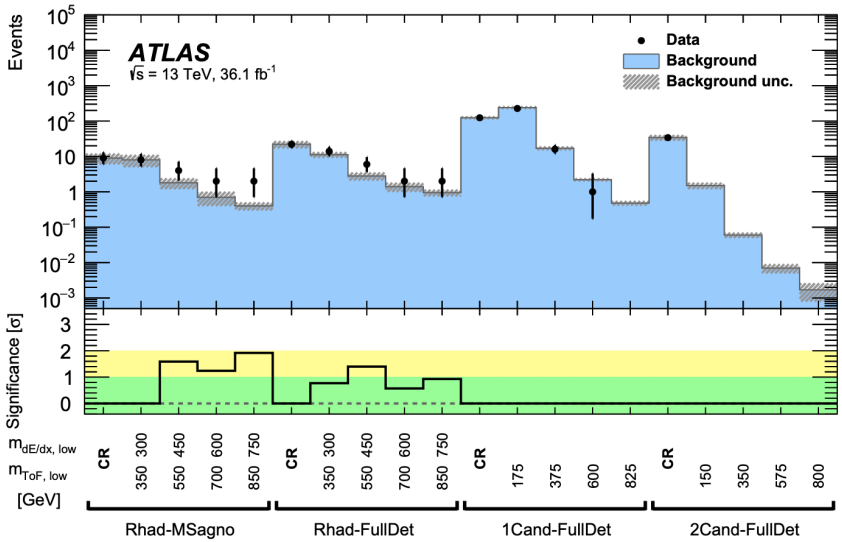
arXiv:1902.01636 (submitted to Phys. Rev. D)

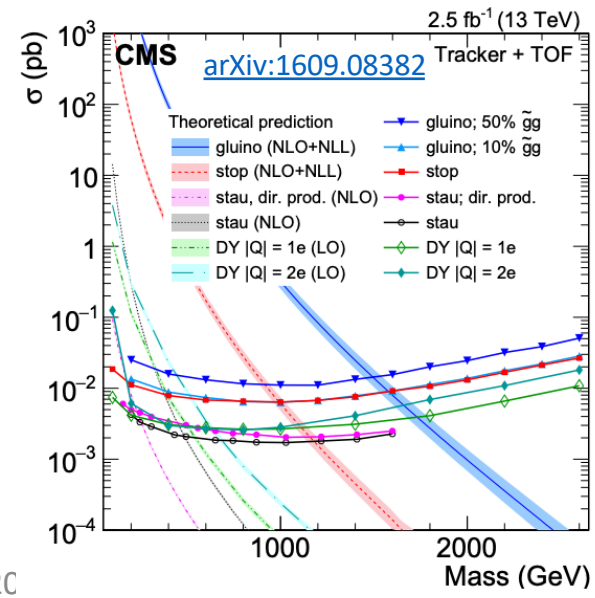
Divided into 5 mutually exclusive regions

- MS agnostic – do not use information in MS (R hadron-calorimeter interaction agnostic)
- Candidate selection using ID+ calo selection, loose, or tight determination (η and p)





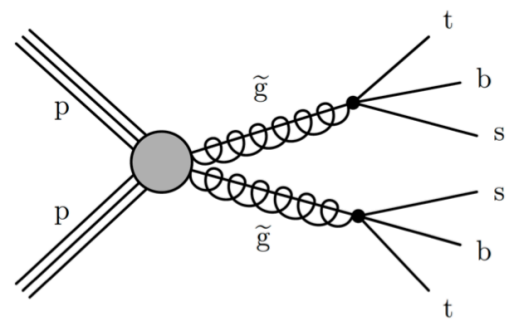


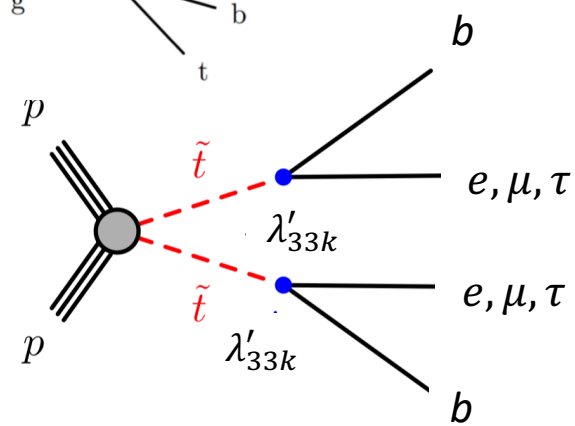


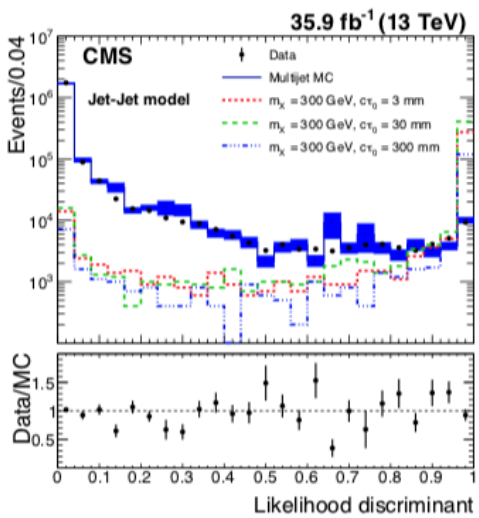
Long-lived particles to displaced jets

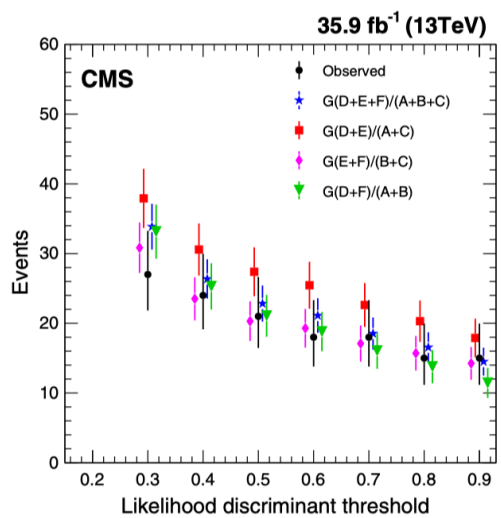
Phys.Rev. D 99 (2019) 032011

- 2016 Result (35.9 fb^{-1})
- RPV SUSY with MFV (λ''_{323}): $\tilde{g} \to tbs$
  - $1200\ \mathrm{GeV} < \mathrm{m}_{\tilde{g}} < 3000\ \mathrm{GeV}$, $1\ \mathrm{mm} < c\tau < 10\ \mathrm{m}$
- RPV SUSY (λ'_{33k}): $\tilde{t} \to bl$
  - $200\ \mathrm{GeV} < \mathrm{m}_{\tilde{t}} < 1600\ \mathrm{GeV}$, $1\ \mathrm{mm} < c\tau < 1\ \mathrm{m}$
- Long-lived gluino model (GMSB): $\tilde{g} \to g\tilde{G}$
  - $800\ \mathrm{GeV} < \mathrm{m}_{\tilde{g}} < 2500\ \mathrm{GeV}$, $1\ \mathrm{mm} < c\tau < 10\ \mathrm{m}$
- Simplified jet-jet model (two scalar neutral X particles)
  - $50\ \mathrm{GeV} < \mathrm{m}_X < 3000\ \mathrm{GeV}$, $1\ \mathrm{mm} < c\tau < 10\ \mathrm{m}$









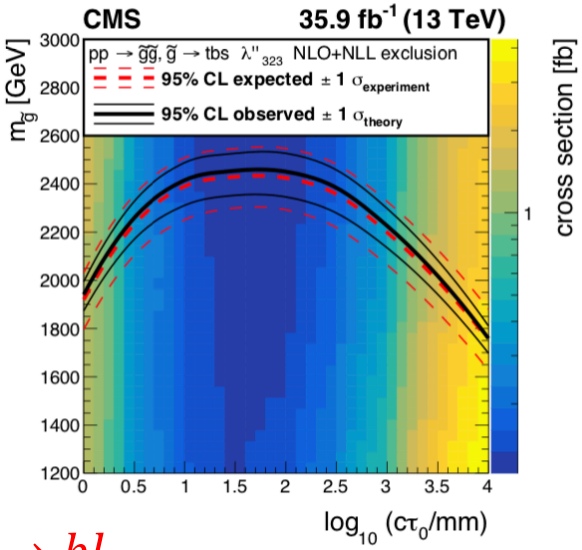
Selection:

- Derives a likelihood discriminant using vertex track multiplicity, vertex L_{xy} significance, and cluster RMS.
- Contains 9 regions (expanded ABCD method) with 3 selection criteria to cross-check all background estimation methods.

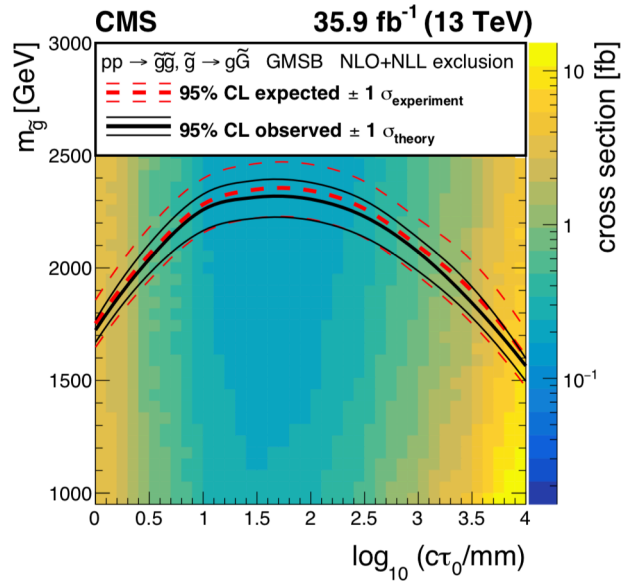
Long-lived particles to displaced jets

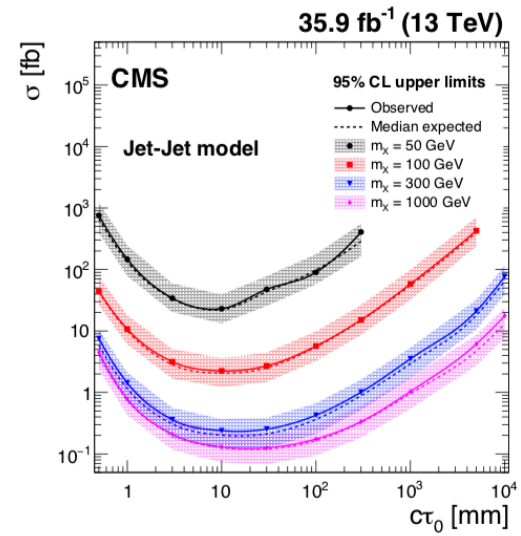
$\tilde{g} \to tbs$

Phys.Rev. D 99 (2019) 032011

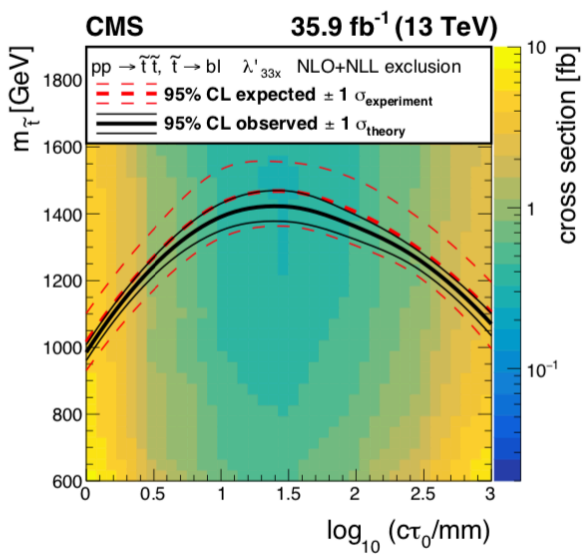


$\tilde{g} \to g\tilde{G}$

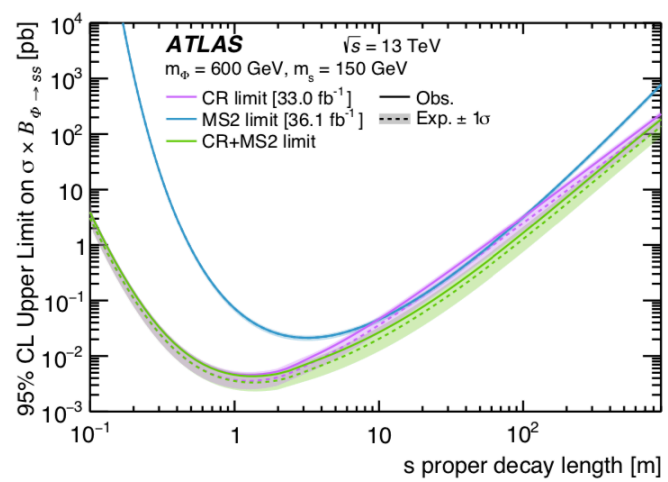




$\tilde{t} \to bl$



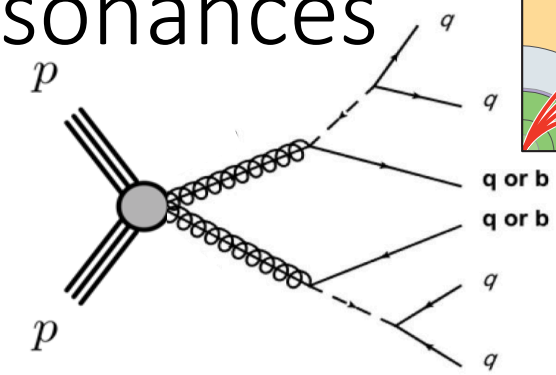
ATLAS has a similar displaced jets search, but without a RPV interpretation (covered in Martino's talk).



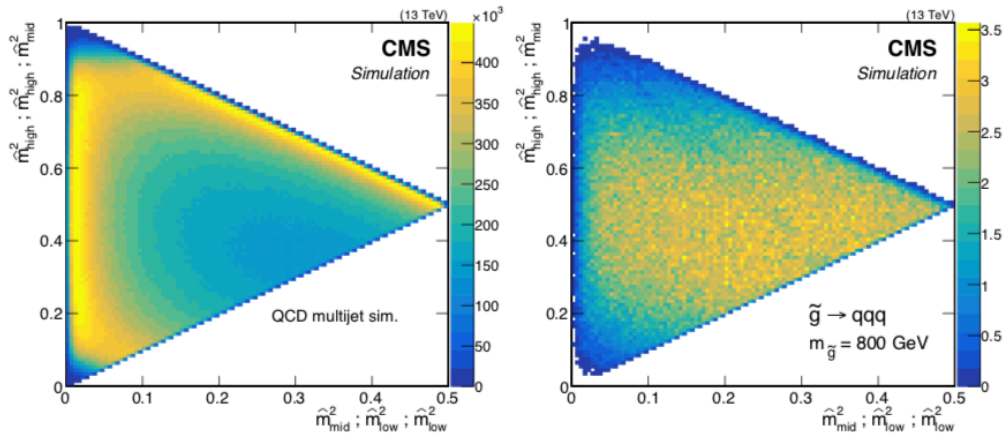
arXiv:1902.03094

Pair produced three jet resonances

Phys.Rev. D 99 (2019) 012010



- 2016 Data Set (35.9 fb^{-1})
- Pair production of gluinos, followed by $\tilde{g} \to qqq$ or qqb with λ''_{udd} coupling
- 200 GeV $< m_{\tilde{g}} <$ 2 TeV



- Dalitz Variables: signal more likely to have uniform jets, QCD more likely to be asymmetric

$$D^2_{[3,2]} = \sum_{i>j} \left(\hat{m}(3,2)_{ij} - \frac{1}{\sqrt{3}} \right)^2$$

$$D^2_{[(6,3)+(3,2)]} = \sum_{i<j<k} \left(\sqrt{\hat{m}(6,3)^2_{ijk} + D^2_{[3,2],ijk}} - \frac{1}{\sqrt{20}} \right)^2$$

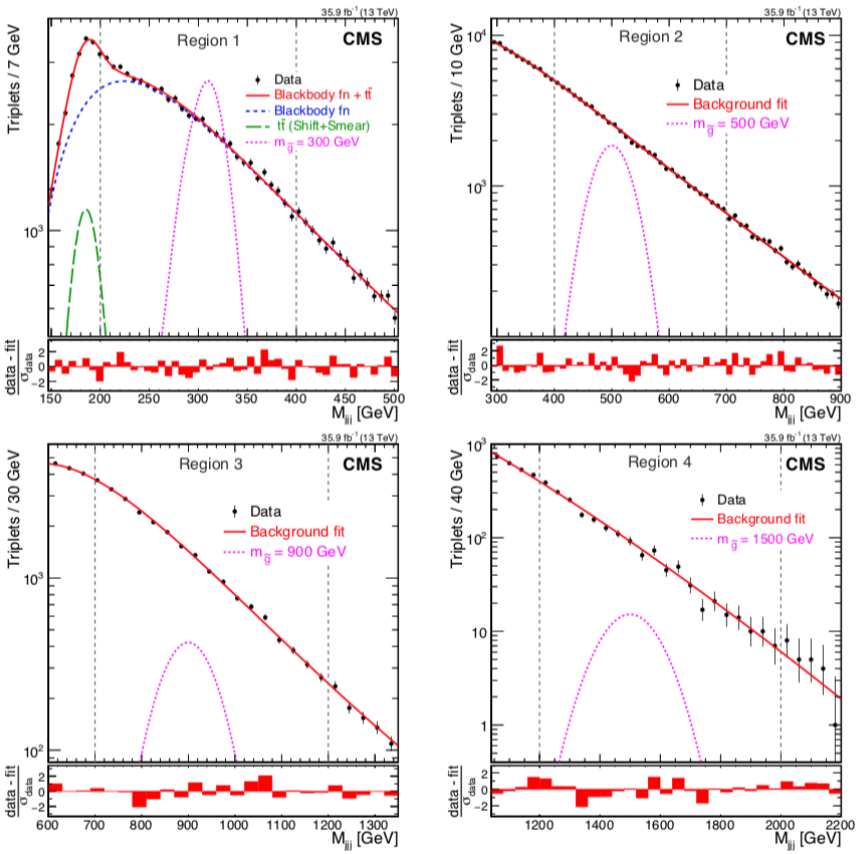
Triggers:

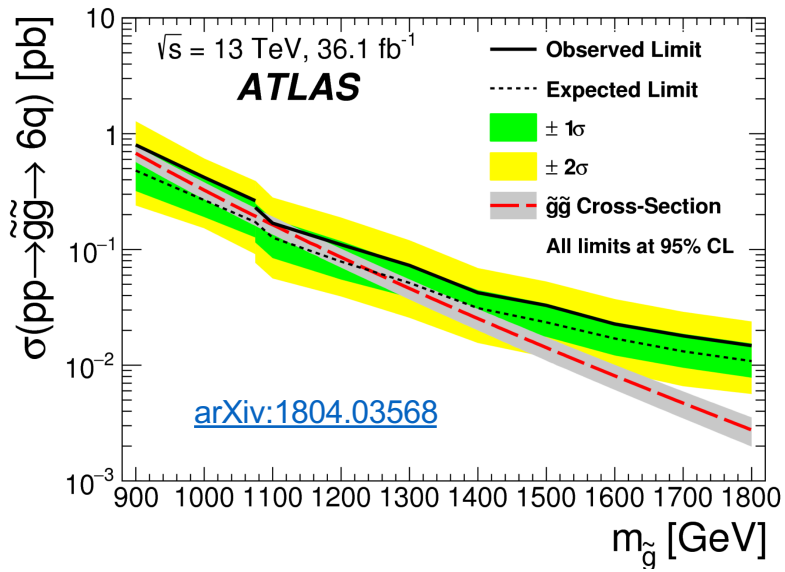
- High mass ($m_{\tilde{g}} > 700$ GeV):
  - H_T($p_{T,j}$> 40 GeV) $\geq$ 800 GeV
  - $H_T \geq$ 750 GeV, $N_{j(p_T>70\ \mathrm{GeV})} > 4$
- Low mass ($m_{\tilde{g}} \leq 700$ GeV):
  - **PF Scouting trigger: H_T($p_{T,j}$> 20 GeV) $\geq$ 410 GeV**

Region	Gluino mass range	Jet p_T	H_T	sixth jet p_T	$D^2_{[(6,3)+(3,2)]}$	A_m	Δ	$D^2_{[3,2]}$
1	200–400 GeV	>30 GeV	>650 GeV	>40 GeV	<1.25	<0.25	>250 GeV	<0.05
2	400–700 GeV	>30 GeV	>650 GeV	>50 GeV	<1.00	<0.175	>180 GeV	<0.175
3	700–1200 GeV	>50 GeV	>900 GeV	>125 GeV	<0.9	<0.15	>20 GeV	<0.2
4	1200–2000 GeV	>50 GeV	>900 GeV	>175 GeV	<0.75	<0.15	>-120 GeV	<0.25

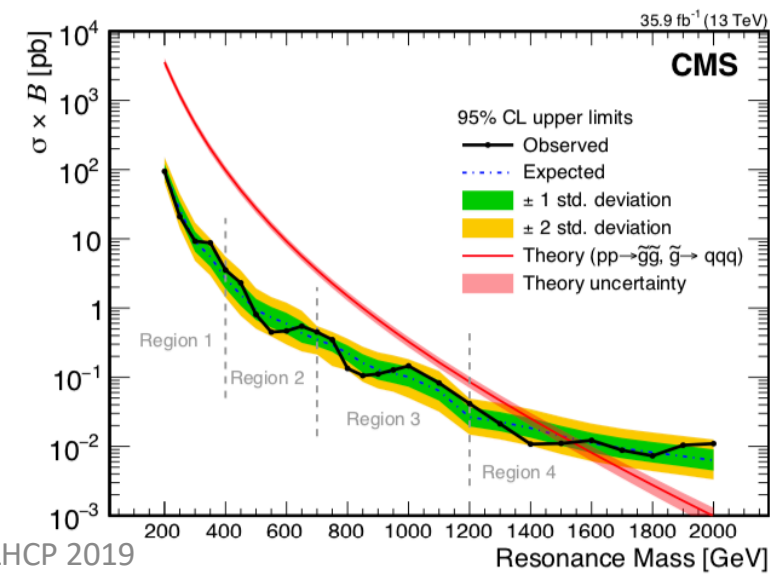
Pair produced three jet resonances

Phys.Rev. D 99 (2019) 012010



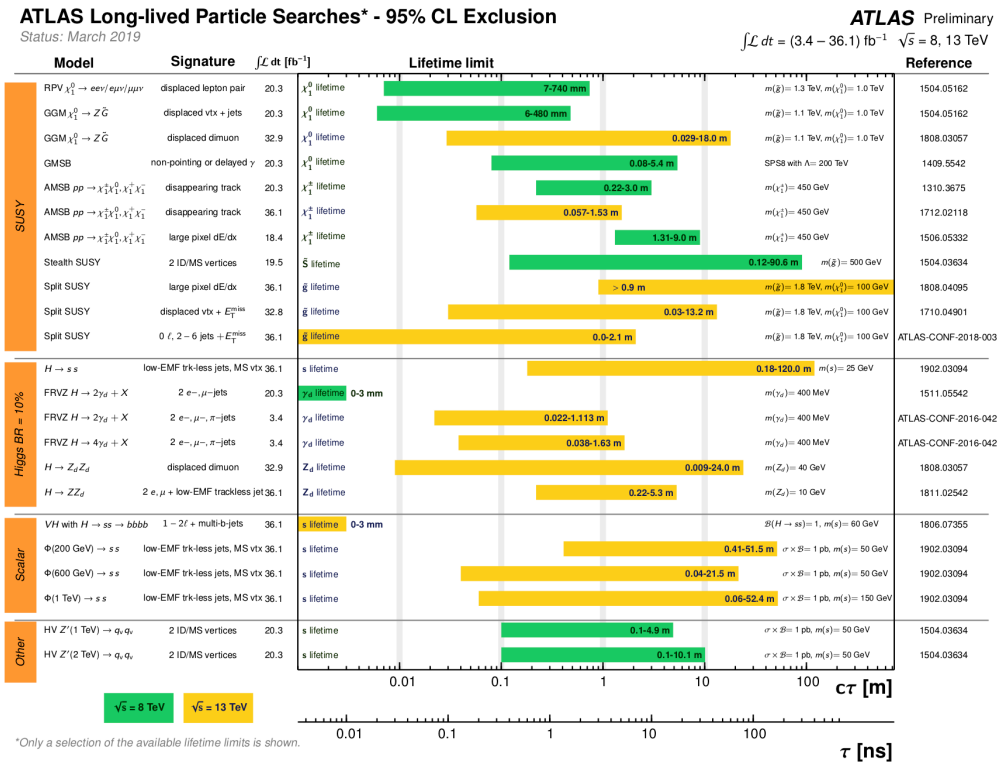


Sets limit for gluino masses below 1.5 TeV!



- Background Estimation:
  - Region 1: $$\frac{dN}{dx} = \frac{1}{(x+c)^{5+d\ln\frac{x}{\sqrt{s}}}} \frac{a}{e^{\frac{b}{x+c}} - 1},$$
  - Regions 2 – 4: $$\frac{dN}{dx} = p_0 \frac{\left(1-\frac{x}{\sqrt{s}}\right)^{p_1}}{\left(\frac{x}{\sqrt{s}}\right)^{p_2+p_3\ln\frac{x}{\sqrt{s}}}},$$

*Region 4 sets $p_3 = 0$



Summary

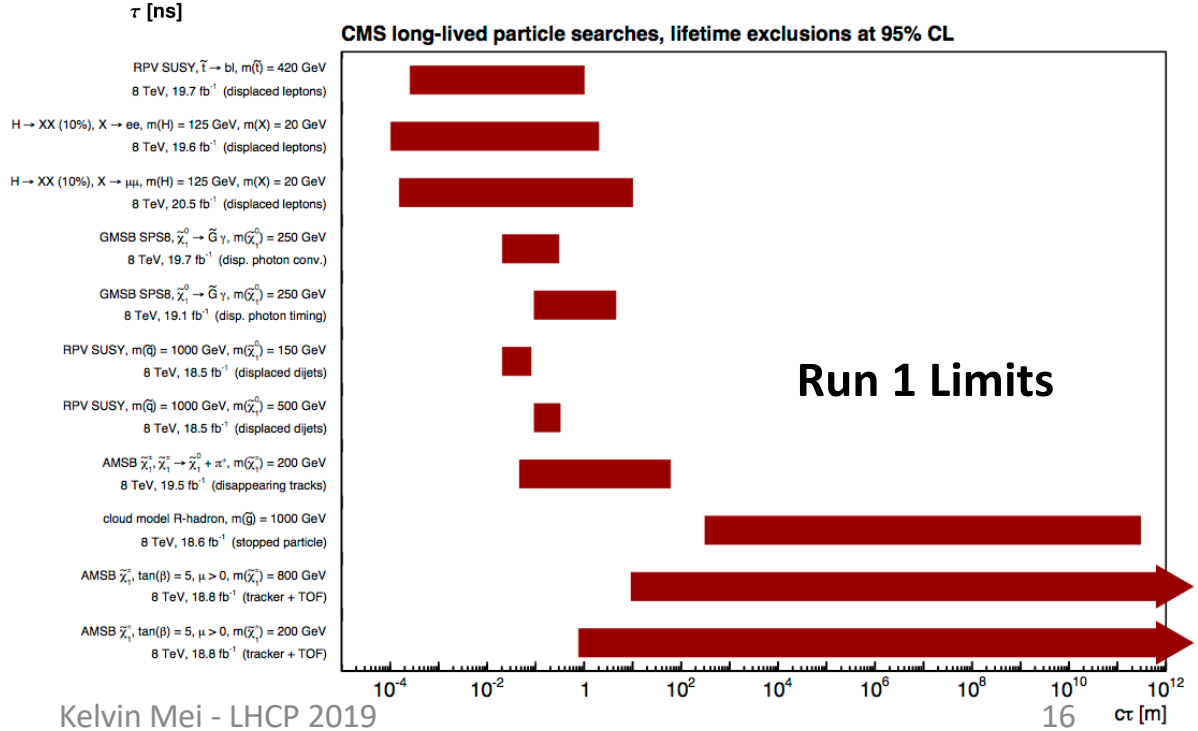
- So far, still no sign of SUSY 😢

ATLAS Public Results

CMS Public Results

- However, full Run 2 results are very much on the way, some of which were presented here!

- Many novel methods are being explored to take advantage of the full dataset!

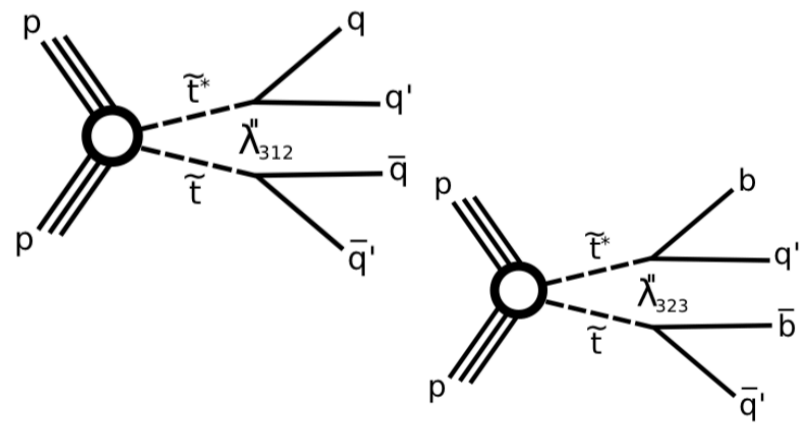


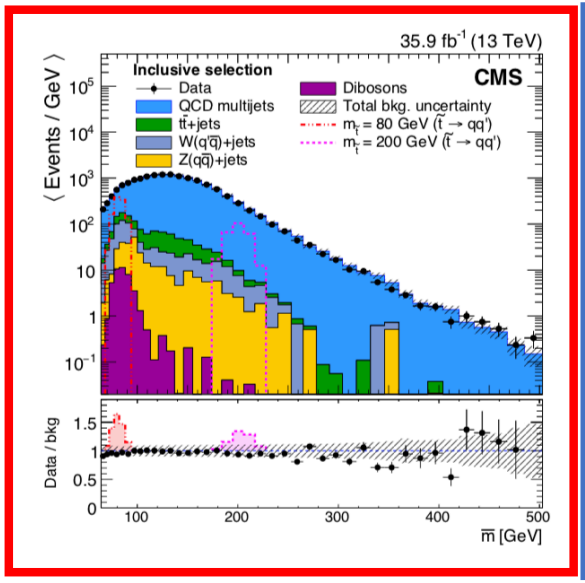
Appendix

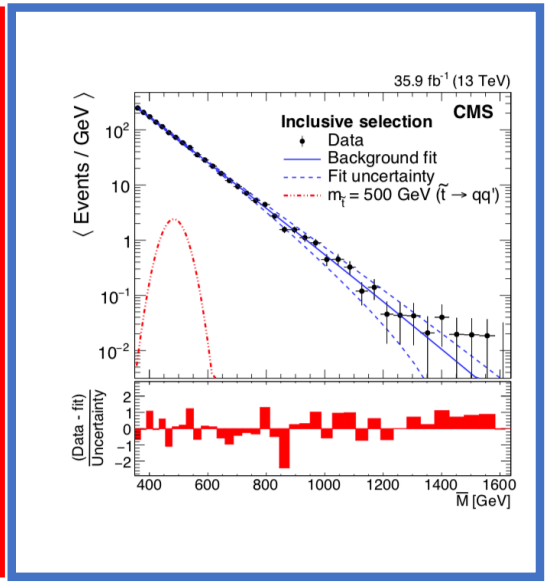
Pair produced quark pair resonances

Phys. Rev. D 98 (2019) 112014

- 2016 Data Set (35.9 fb^{-1})
- Pair production of stop LSP, followed by $\tilde{t} \rightarrow qq'$or bq′ through λ''_{312} or λ''_{323} coupling
- 80 GeV $< m_{\tilde{t}} <$ 1.5 TeV
- Two search regions: boosted and resolved



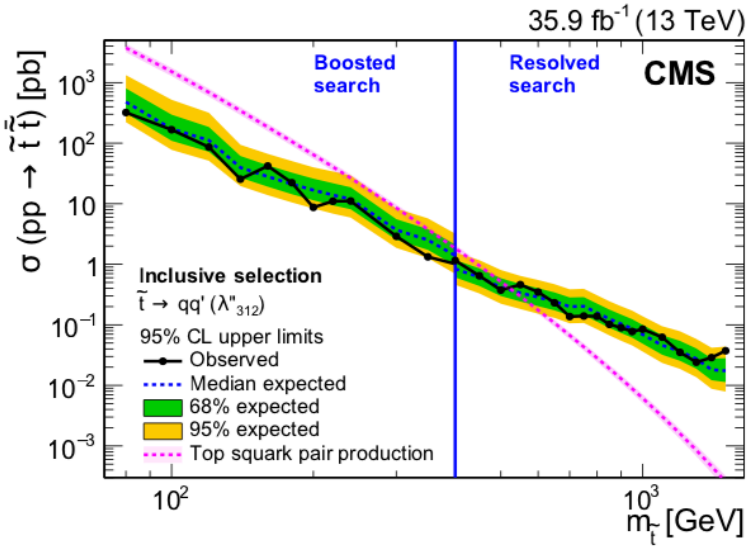


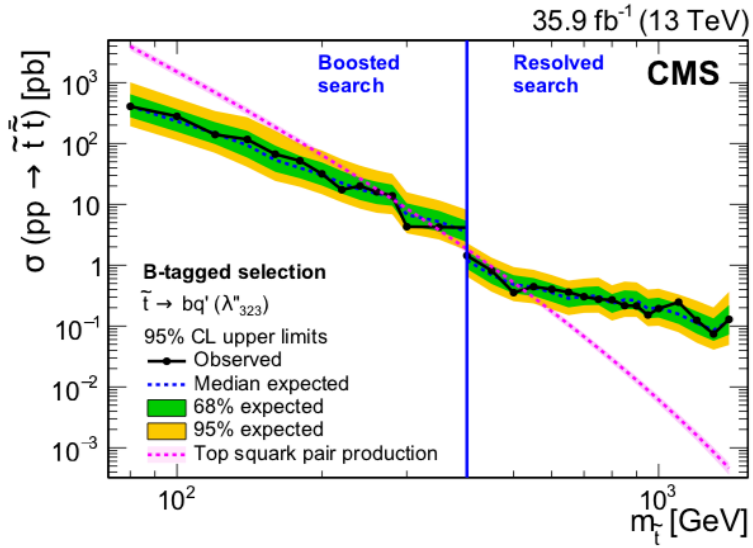


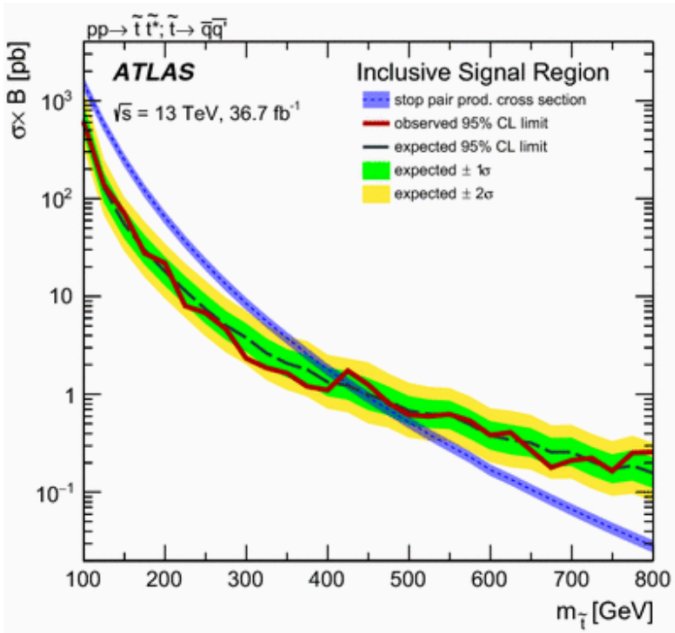
Selection	Boosted search	Resolved search
	$60 < \overline{m} < 450$ GeV	$\overline{M} > 350$ GeV
	$(80 \leq m_{\tilde{t}} < 400$ GeV)	$(m_{\tilde{t}} \geq 400$ GeV)
Inclusive and b-tagged	AK8 jets	AK4 jets
	jet $p_T > 150$ GeV	jet $p_T > 80$ GeV
	jet $\lvert\eta\rvert < 2.5$	jet $\lvert\eta\rvert < 2.5$
	Number of jets ≥ 2	Number of jets ≥ 4
	$H_T^{AK8} > 900$ GeV	$H_T^{AK4} > 900$ GeV
	$m_{asym} < 0.1$	$M_{asym} < 0.1$
	$\tau_{21} < 0.45$	$\Delta\eta_{dijet} < 1.0$
	$\tau_{32} > 0.57$	$\Delta > 200$ GeV
	$\Delta\eta < 1.5$	
b-tagged	two loose b-tagged jets	two loose b-tagged jets

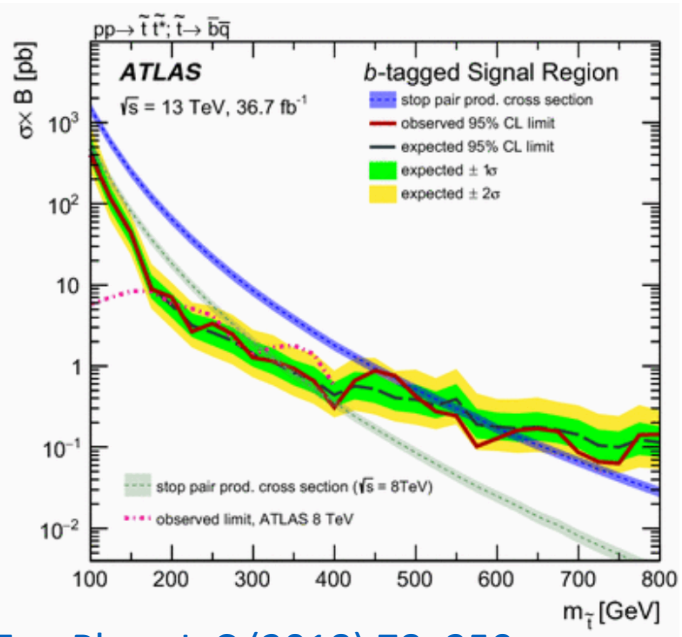
Pair produced quark pair resonances

Phys. Rev. D 98 (2019) 112014









Eur. Phys. J. C (2018) 78: 250