Searches for SUSY in R-parity violating and long-lived signatures with the ATLAS detector

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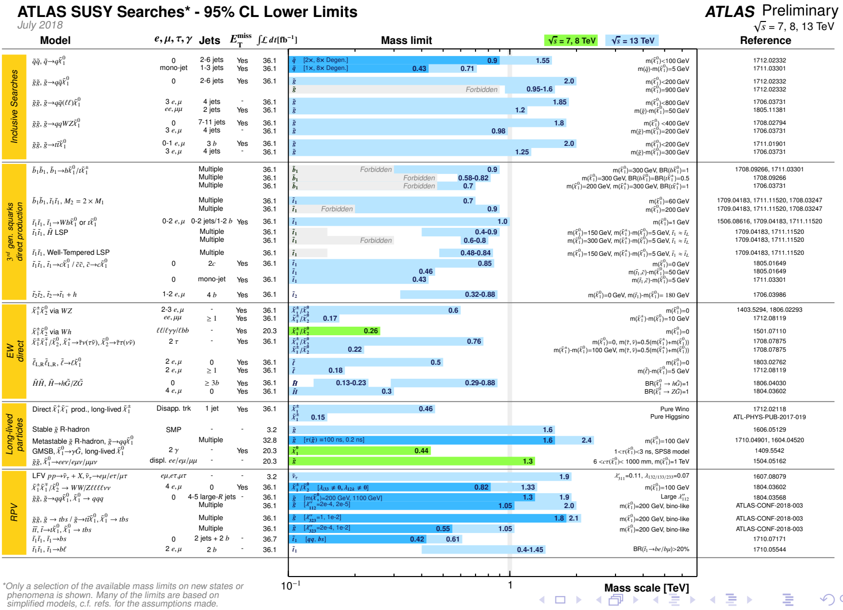
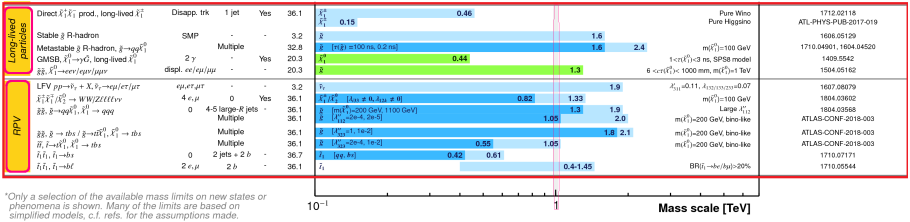
Searches for SUSY with the ATLAS detector

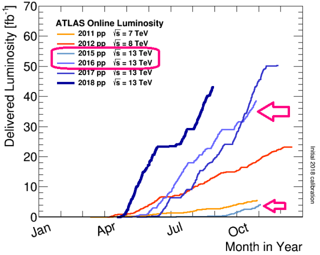


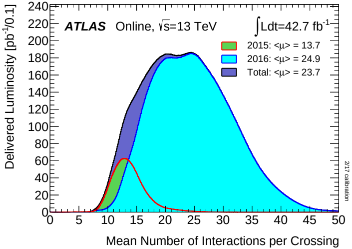
R-parity violating and long-lived signatures

In this talk focus only on searches for long-lived (LL) particles and R-parity violating signatures



- Data collected in (2015 &) 2016 by ATLAS at $\sqrt{s} = 13$ TeV energy in the center of mass
- Only a selected list of results presented, based on an integrated luminosity of 32-36 fb^{-1}
- All Supersymmetry group public results here (all ATLAS results here)





Short lived particles: RPV SUSY models

- Results are interpreted using SUSY simplified models, where particles not involved in production or decays are decoupled
- Values of the coupling are large enough to ensure prompt decays of the lightest SUSY particle (LSP)

RPV Supersymmetry (SUSY)

Supersymmetry, a fundamental theory which unifies fermions (matter) and bosons (forces)

→ Extends the Standard Model (SM) by introducing supersymmetric (heavy) partners for every SM particle with identical quantum numbers except for a half-unit difference in spin

- R-parity, $(-1)^{3(B-L)+2S}$: *protects* the baryon number and lepton number conservation
  - → In SM R=+1, in SUSY R=-1
- If R-parity conserved (RPC): SUSY particles produced/annihilated in pairs, lightest SUSY particle (LSP) stable and a potential Dark Matter (DM) candidate
- If R-parity violated (RPV): allows the possibility of some RPV couplings to be non-zero
  - LSP unstable and decays in SM particles
  - → The LSP lifetime depends on the RPV coupling strength & masses of the sfermions involved in the decay
  - Can have resonant sparticle production with long-lived particles (LLP) in the cascade decay

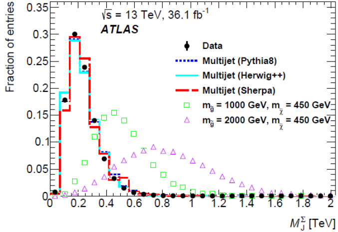
- Today: focus on only few experimental signatures predicted by selected RPV SUSY simplified models

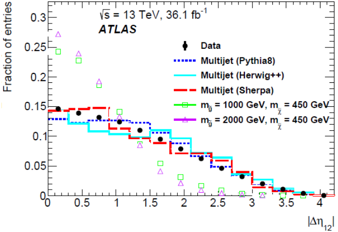
RPV SUSY with multi-jet final states

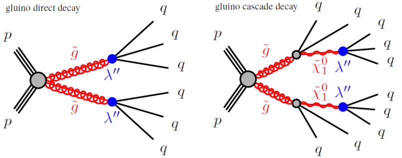
Results with 36.1 fb^{-1} of 13 TeV ATLAS data published in Phys. Lett. B. (arxiv/1804.03568)

- Final state formed by jets (≥ 6 or ≥ 10): multi-jets background dominates

→ Events are selected with a H_T trigger (H_T = sum of all jets p_T)







* all quark generations allowed in the final state

- Key variable to separate the (potential) signal from the bkg: the reconstructed "mass" of the heavy particle, which is the total jet mass defined as

$$M_J^{\Sigma} = \sum_{\substack{p_T > 200\text{ GeV} \\ |\eta| < 2.0 \\ j=1-4}} m_{jet}^{j}$$

- Other variables → the pseudorapidity difference between the two leading large-R jets, $|\Delta\eta_{12}|$

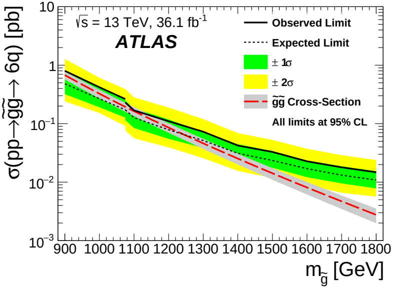
→ number of ($b-$) jets in the event and the leading jet p_T

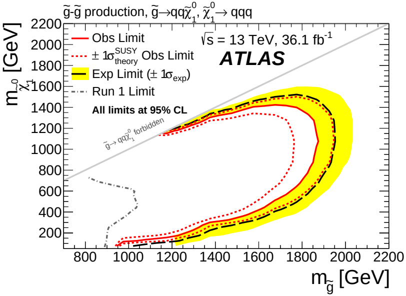
Results

Five signal regions defined to look for new physics

- No significant excess observed in any of the SRs: place exclusion limits at 95% CL on the production of gluinos

→ Gluino direct decay and cascade decay models in the UDD scenarios of RPV SUSY





LHS Gluino direct decay model: signals with a x-section as small as 0.8 fb ($m_{glu\tilde{i}no} = 900$ GeV) - 0.011 fb ($m_{glu\tilde{i}no}$=1.8 TeV) are excluded at 95% CL

RHS Gluino cascade decay model: gluinos with masses below 1 TeV and 1.9 TeV are excluded at 95% CL, depending on the neutralino mass

RPV SUSY WITH MULTI-LEPTON FINAL STATES

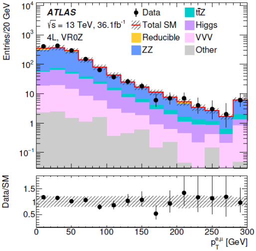
Results with 36.1 fb^{-1} of 13 TeV ATLAS data published in PRD (arxiv/1804.03602)

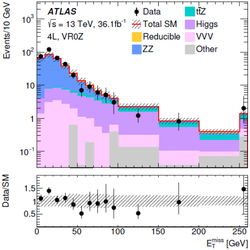
- Lepton number violating coupling (λ): neutralino (the LSP) decays through a virtual slepton or sneutrino

→ To ensure prompt decays, LSP mass restricted to 10 GeV $\leq m_{\mathrm{LSP}} \leq m_{\mathrm{NLSP}}$ -10 GeV

→ Final state formed by $\geq$ 4 charged leptons (electrons, muons or hadronically decaying tau)

- Signal regions dominated by ZZ, $t\bar{t}Z$, VVV and Higgs production, and fake leptons
- Key discriminant variables: missing transverse energy (E_T^{miss}) and effective mass of the event (m_{eff}, scalar sum of E_T^{miss}, p_T of all leptons and p_T of all jets with $p_T > 40$ GeV)



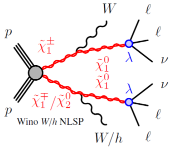


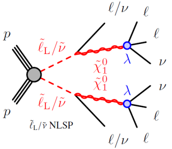
Results

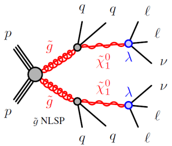
Data observations are consistent with the SM expectations in all designed signal region

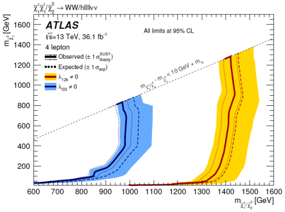
Sample	SR0A	SR0B	SR0C	SR0D	SR1	SR2
Observed	13	2	47	10	8	2
SM Total	10.2 ± 2.1	1.31 ± 0.24	37 ± 9	4.1 ± 0.7	4.9 ± 1.6	2.3 ± 0.8
p_0	0.23	0.25	0.15	0.011	0.13	0.61
Z	0.75	0.69	1.0	2.3	1.2	0

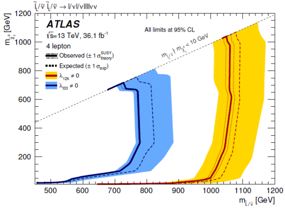
- Maximum local significance of the data-bkg disagreement around 2.3σ

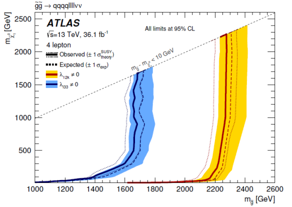






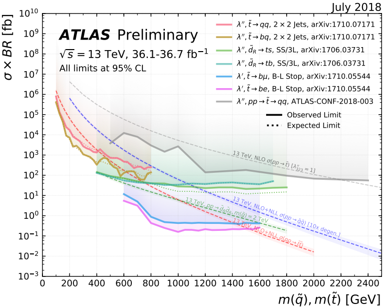


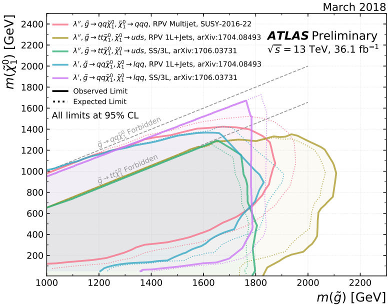




ATLAS RPV SEARCHES: SUMMARY

Limits on squark and gluino masses using simplified SUSY models:





- Several results from different teams/final states → complementary of the ATLAS searches

→ Depending on the considered RPV model, only one of the λ' or λ'' couplings are non-zero and all the remaining couplings are set to 0

  - The choice of having only one non-zero baryonic coupling is made for simplicity and the availability of a theoretical upper limit

Long Lived Particles (LLP)

- Results are interpreted using SUSY simplified models, where particles not involved in production or decays are decoupled
- When RPV SUSY: if small RPV couplings and/or large sfermion masses the LSP can become long-lived

Long-lived particles

Simplest definition for the long-lived particles (LLP):

→ Neutral particles decaying a macroscopic distance from the interaction point (IP)

→ Charged particles that decay as above or are quasistable on the detector scale

LLP can be (only few examples!):

- Supersymmetric (SUSY) models

→ Long-lived gluinos ($\tilde{g}$) due to very heavy squarks, or $\tilde{g}$-Bino co-annihilation

→ Long-lived charginos ($\tilde{\chi}$): Wino/Higgsino Lightest Stable Particle (LSP)

→ Long-lived neutralino/LSP ($\tilde{\chi^0}$): Gravitino LSP, R-parity violation, Wino-Bino co-annihilation

- Hidden/dark sector scenario

→ Long-lived dark photon: Higgs portal model

→ Long-lived neutral scalar: Heavy neutral boson portal model

- Others

→ Long-lived right-handed neutrino: Left-right symmetry extension of SM

→ Long-lived multi-charged particle: Monopole, Q-ball

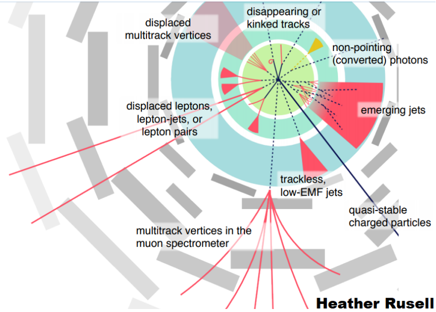
Long-lived particles (cont'd)

- LL particles can be light or heavy
- Experimental signature: LLP itself if it's stable, otherwise its decay products (jets, ℓ, etc)
- Can have an unique signature (lifetimes in the pico to nanoseconds range), for example:

→ Meta-stable LL charged particles: travel all the detector components, like muons but with a very different signature (interactions with the detector material)

→ Non-stable charged LLP: Disappearing or kinked tracks → presence of secondary (kinked) track dependent on the phase space of the decay vertex

→ LLP can decay to leptons: can look for displaced leptons or for displaced di-lepton vertices (with no track pointing back to the IP)



- Usually lower Standard Model (SM) background than in the traditional BSM searches
  - Cannot relay on MC simulations, and most of the time a fully data-driven background estimation is used
- Requires a deep understanding of the detector!

Search for massive charged LLP using an ionisation measurement

Results with 36.1 fb^{-1} of 13 TeV ATLAS data submitted to Phys. Lett. B (arxiv/1808.04095)

- The LLP are expected to travel with a velocity significantly below the speed of light

⇒ have a specific (higher) ionisation distinguishable from SM particles

- Key variable: ionisation energy loss (dE/dx) of all reconstructed charged particles

→ measured with the ATLAS pixel sub-detector

- Search for excesses in the mass distribution of reconstructed tracks with high transverse momentum (p_T) and large dE/dx

→ Two signal regions designed to look for meta-stable and stable R-hadrons produced in pairs:

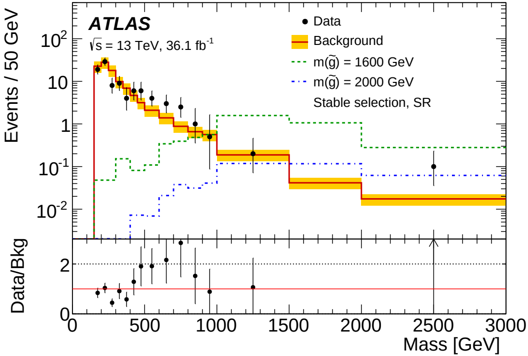
	SR	VR	p-CR		dE/dx-CR	
			for SR	for VR	for SR	for VR
Track Momentum [GeV]	>150	50–150	>150	50–150	>150	50–150
E_T^{miss} [GeV]	>170		>170		<170	
Ionisation [MeV g^{-1} cm^2]	> 1.8		< 1.8		–	

Events are selected with a trigger based on E_T^{miss}, with a threshold which varies from 70 GeV to 110 GeV

1) Meta-stable: Decay before muon spectrometer, $c\tau_{\mathrm{Lab}}$(R-hadron) $\lesssim$ 4 m (muon veto)
2) Stable: Decay outside detector or not at all, $c\tau_{\mathrm{Lab}}$(R-hadron) $\gtrsim$ 4 m (tighter isolation)

Results in the signal regions

- Background: tracks from SM processes like vector boson, top-q and multi-jet production
  - → Characterized by high dE/dx



- When looking at the results in the two signal region:
- Data observation is consistent with the background estimation ...

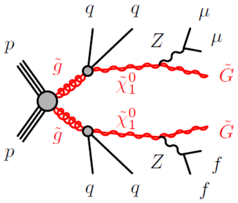
→ Largest deviation from the bkg-only hypothesis has a local significance of 2.4σ

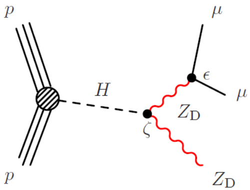
→ Stable R-hadron SR, around 500–800 GeV for the reconstructed mass of candidate tracks

LLP SEARCHES WITH DISPLACED DIMUON VERTICES

Results with 32.9 fb^{-1} of 13 TeV ATLAS data submitted to Phys. Rev. D. (arxiv/1808.03057)

- Signature: displaced (several cm from IP) pair of muons with opposite-sign electric charge
- Target specific BSM models:





LHS LL neutralino ($\tilde{\chi}_1^0$) decay in a Gauge-mediated supersymmetry (GGM) scenario

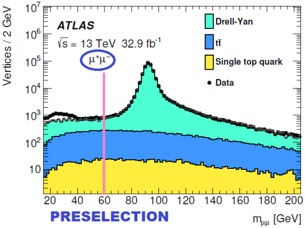
- Neutralino NLSP: heavy, long-lived
- High pT muons

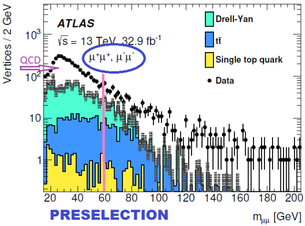
RHS LL dark photons Z_D produced from Higgs boson decay (dark-sector gauge boson model)

- Z_D is lighter than half the H mass
- Small Z-ZD coupling: long-lived
- Low pT muons

Search strategy and results

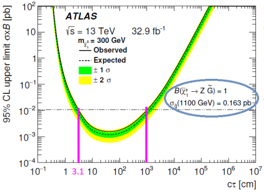
- Define low $m_{\mu\mu}$ mass (15 - 60 GeV) and high $m_{\mu\mu}$ mass (> 60 GeV) regions
  - → Events selected with E_T^{miss} and muon triggers
  - → Two displaced (1-400 cm from IP) muons of opposite sign (same-sign for bkg CRs)

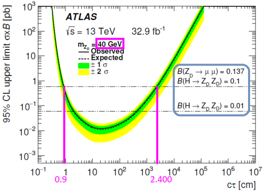




Yield	SR_{low}	SR_{high}
N^{bkgd}	13.8 ± 4.9	$0.50^{+1.42}_{-0.07}$
N^{obs}	15	2

- No significant excess of vertices over the SM background expectation



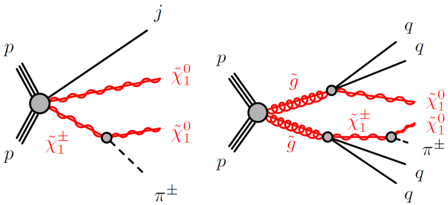


→ Place upper limits (95% CL) on the signal event yields and production x-sections for different values of the LLP proper decay distance $c\tau$

LL $\tilde{\chi}^{\pm}$ SEARCHES WITH DISAPPEARING-TRACK

Results with 36.1 fb^{-1} of 13 TeV ATLAS data published in JHEP (arxiv/1712.02118)

- Aims for SUSY models with a LL chargino ($\tilde{\chi}^{\pm}$) and neutralino ($\tilde{\chi}^{0}$) nearly mass-degenerate
- Sensitive to $\tilde{\chi}^{\pm}$ lifetimes from 10 ps to 10 ns (maximum sensitivity for lifetimes $\sim$1 ns)
  - $\rightarrow$ $\tilde{\chi}^{\pm}$ lifetime is nearly uniquely determined only by the $\tilde{\chi}^{\pm}$ mass



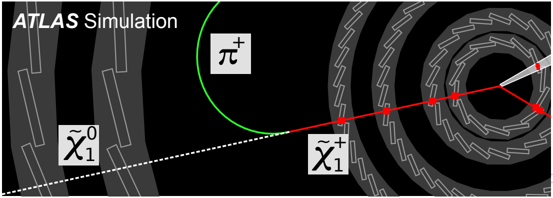
Experimental signature:

$\rightarrow$ Emitted pion has very low momentum and it's not reconstructed in the detector

$\rightarrow$ $\tilde{\chi}^{0}$ passing through the detector without interacting

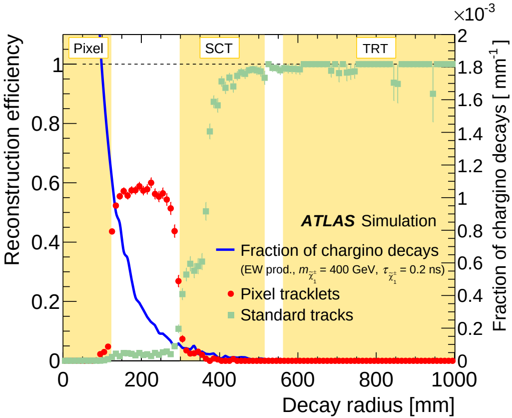
$\Rightarrow$ Track from the LL $\tilde{\chi}^{\pm}$ can therefore *disappear*

- Leave hits only in the innermost layers (no hits in the detector at higher radii)



Chargino reconstruction efficiency

Compared to other searches, it uses tracklets
(tracklet = very short track, $p_T > 5$ GeV, should have hits in all 4 Pixel layers and no holes)
→ Allows the reconstruction of charginos decaying at radii from about 12 cm to 30 cm



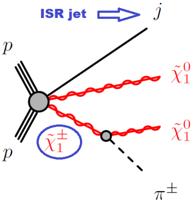
RED Reconstruction efficiency of pixel tracklets before applying the fake-rejection criteria
GREEN Reconstruction efficiency for standard tracks
BLUE Distribution of the decay radius for charginos with a lifetime of 0.2 ns

→ Extends the sensitivity to smaller chargino lifetimes

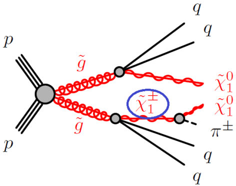
Event selection

≥ 1 isolated tracklet with $p_T > 20$ GeV, within $0.1 < |\eta| < 1.9$ and with hits in all 4 pixel layers

- In electroweak-gaugino production: one ($p_T > 140$ GeV) ISR jet present/required in the event
  - $\rightarrow$ Leads to high E_T^{miss} (> 90 GeV) in the event



- $\tilde{g}\tilde{g}$ production: expect at least four jets in the event
  - $\rightarrow$ Requite ≥ 1 high p_T jet (> 100 GeV) and ≥ 2 additional softer jets ($p_T > 50$ GeV)
  - $\rightarrow$ $E_T^{miss} > 100$ GeV

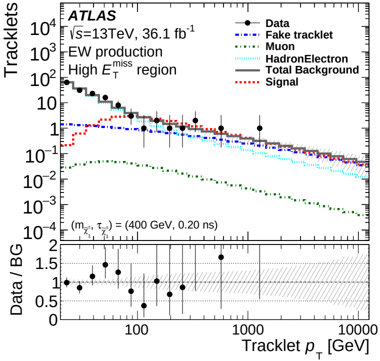


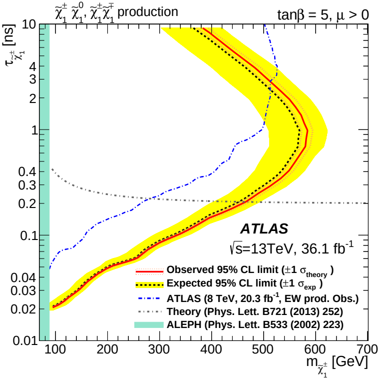
- Lepton veto applied suppress bkg events from W/Z + jets and top-pair production processes
- Cuts on $\Delta\varphi$ between the missing transverse momentum and each of the four highest-p_T jets ($p_T > 50$ GeV)

RESULTS

After selection: look for an excess of candidate events in the p_T distribution of pixel tracklets

→ No excess observed in any of the SRs: place exclusion limits at 95% CL





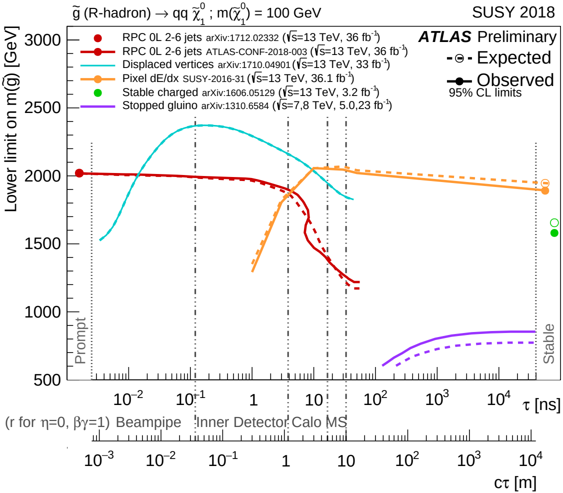
- Electroweak production: LL $\tilde{\chi}^\pm$ (0.2 ns life-time) are excluded below 460 GeV

→ Pure wino LSP model; mass-splitting between the charged and neutral wino of 160 MeV

- Results can be interpreted also using other SUSY simplified models, e.g. pure-higgsino

ATLAS LLP SEARCHES: SUMMARY

Limits on the gluino mass-vs-lifetime plane for a split-supersymmetry simplified model with the gluino R-hadron decaying into a gluon or light quarks and a neutralino with mass of 100 GeV:



- Several results from different teams/final states → complementary of the ATLAS searches

BACKUP

SUSY

		Proper states in		Spartners	Proper states in	
		interaction term	mass term		interaction term	mass term
$\begin{pmatrix} \nu \\ L \end{pmatrix}, l$	Leptons $S = 1/2$	$\begin{pmatrix} \nu_e \\ e_L \end{pmatrix}, e_R$		Sleptons $S = 0$	$\begin{pmatrix} \tilde{\nu}_e \\ \tilde{e}_L \end{pmatrix}, \tilde{e}_R$	
		$\begin{pmatrix} \nu_\mu \\ \mu_L \end{pmatrix}, \mu_R$			$\begin{pmatrix} \tilde{\nu}_\mu \\ \tilde{\mu}_L \end{pmatrix}, \tilde{\mu}_R$	
		$\begin{pmatrix} \nu_\tau \\ \tau_L \end{pmatrix}, \tau_R$			$\begin{pmatrix} \tilde{\nu}_\tau \\ \tilde{\tau}_L \end{pmatrix}, \tilde{\tau}_R$	$\tilde{\tau}_1, \tilde{\tau}_2, \tilde{\nu}_\tau$
$\begin{pmatrix} U \\ D \end{pmatrix}, u, d$	Quarks $S = 1/2$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R$		Squarks $S = 0$	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}, \tilde{u}_R, \tilde{d}_R$	
		$\begin{pmatrix} c_L \\ s_L \end{pmatrix}, c_R, s_R$			$\begin{pmatrix} \tilde{c}_L \\ \tilde{s}_L \end{pmatrix}, \tilde{c}_R, \tilde{s}_R$	
		$\begin{pmatrix} t_L \\ b_L \end{pmatrix}, t_R, b_R$			$\begin{pmatrix} \tilde{t}_L \\ \tilde{b}_L \end{pmatrix}, \tilde{t}_R, \tilde{b}_R$	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$
	Gauge Bosons $S = 1$	$W^\pm, W^0, B, g$	$W^\pm, Z^0, \gamma, g$	Gauginos $S = 1/2$	$\widetilde{W}^\pm, \widetilde{W}^0, \widetilde{B}, \widetilde{g}$	Gluino $\widetilde{g}$ Neutralinos $\widetilde{\chi}_1^0, \widetilde{\chi}_2^0, \widetilde{\chi}_3^0, \widetilde{\chi}_4^0$ Charginos $\widetilde{\chi}_1^\pm, \widetilde{\chi}_2^\pm$
H_u, H_d	Higgs Boson $S = 0$	$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$h^0, H^0, A^0, H^\pm$	Higgsinos $S = 1/2$	$\begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix}$	
G	Graviton $S = 2$	G		Gravitino $S = \frac{3}{2}$	$\tilde{G}$	