LLPs at ATLAS: Recent Results & Perspective

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ATLAS Experiment

Outline

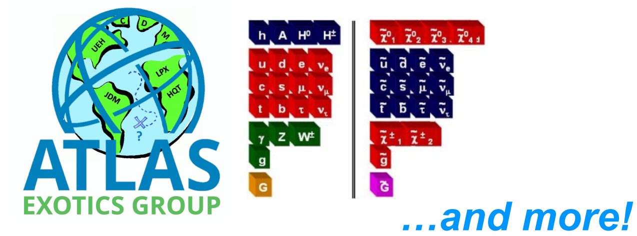
1. Overview of the ATLAS LLP search program

2. Recent Run 2 public results
   - Disappearing track
   - Exotics Higgs to LLPs
   - Stopped particles
   - Displaced vertices in the muon spectrometer

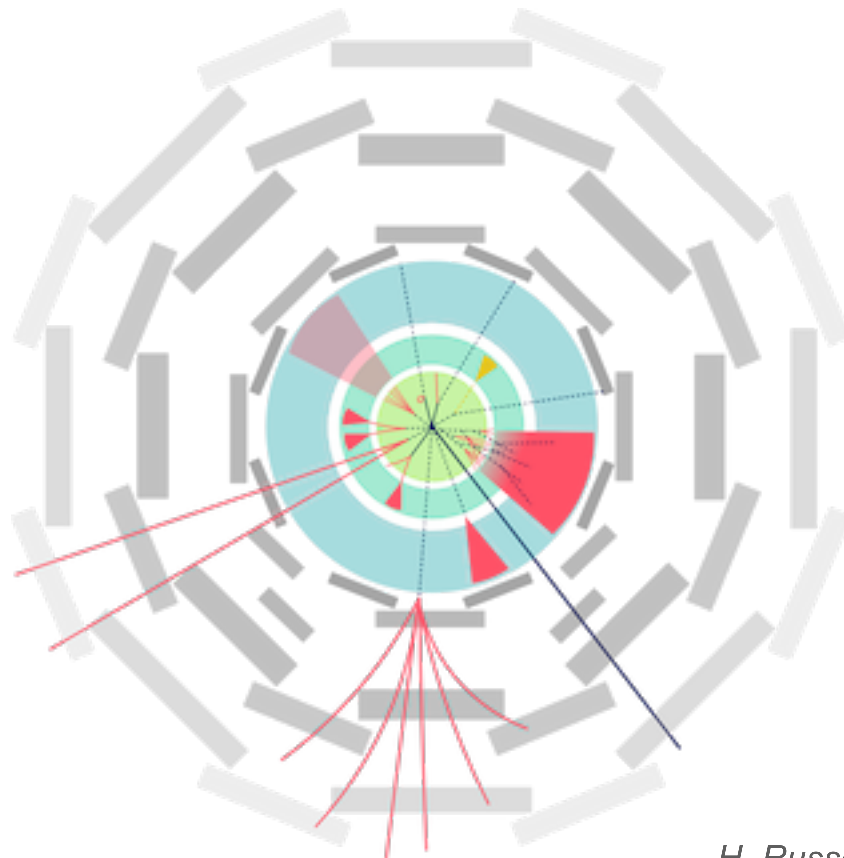
3. Looking forward
   - Combinations
   - Search ideas
   - Run 3 & HL-LHC

LLP Searches at ATLAS

- Organization of analyses:
  - SUSY group: R-parity violating/long-lived (RPVLL)
  - Exotics group: Unusual signatures and Exotic Higgs (UEH)



- Key signatures that we need to recognize:
  - Displacements: single objects or vertices
  - Timing
  - Ionization (non-MIP particles)
- Key exclusion parameters:
  - LLP mass(es)
  - LLP lifetime
  - Production cross section (parent branching ratio)



H. Russell

LLP Searches at ATLAS

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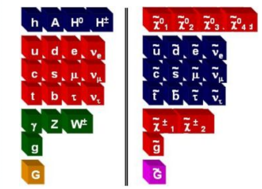
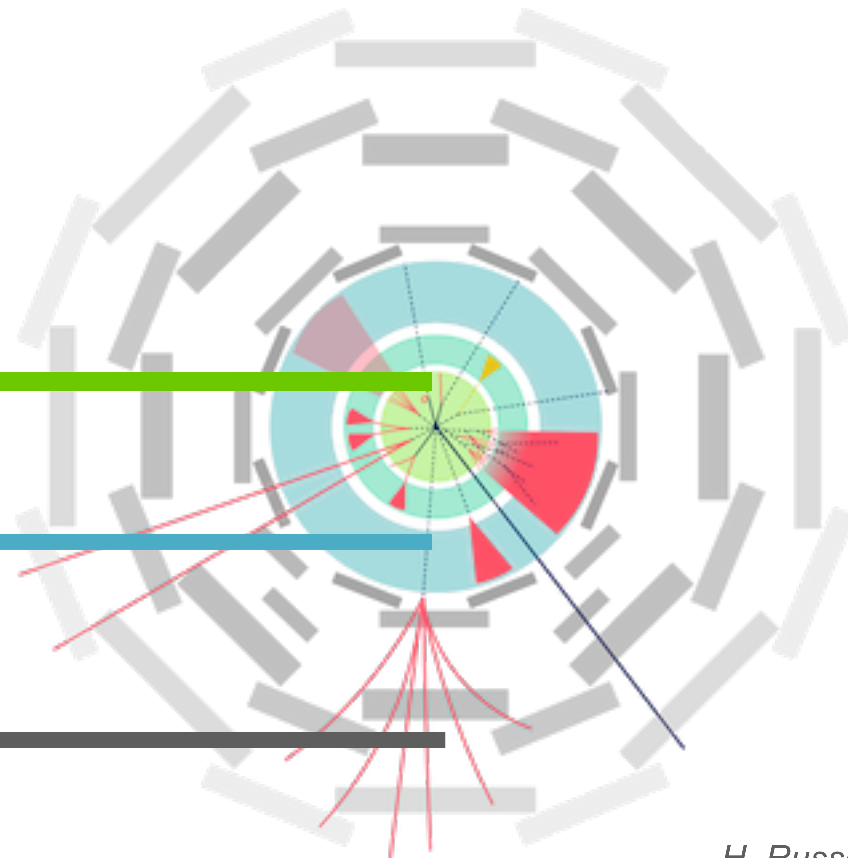


…and more!

ID:
1. Disappearing track
2. Exotic Higgs

Calorimeters:
3. Stopped particles

Muon spectrometer:
4. DV in MS



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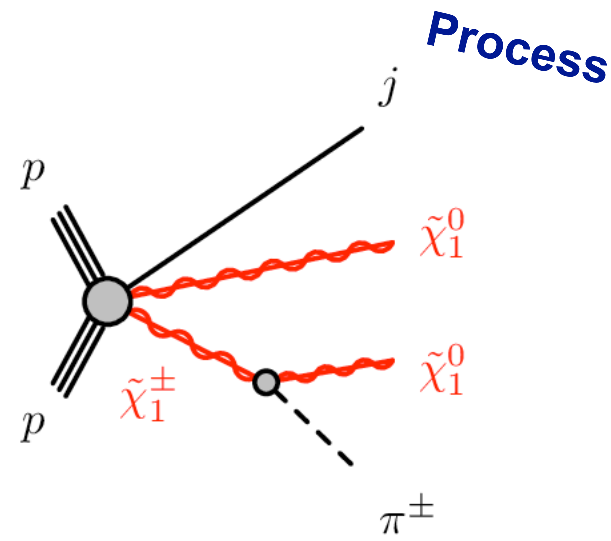
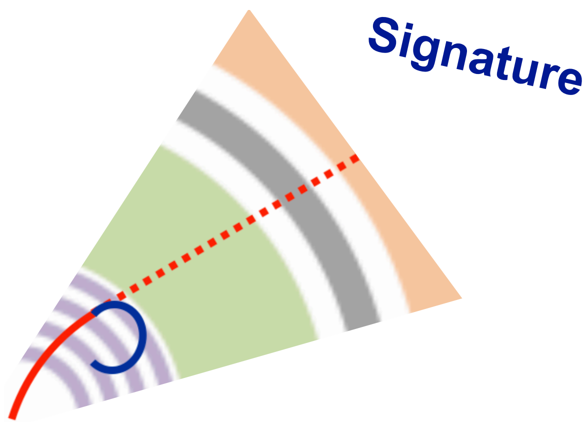
Disappearing Tracks

➡ *"Search for long-lived charginos based on a disappearing-track signature using 136 fb-1 of pp collisions at √s = 13 TeV with the ATLAS detector"* [Moriond, March 2021]

- **Physics target:** strong or electroweak production of long-lived chargino
  - Mass: O(100s GeV)
  - Lifetime: O(ps - ns), from small mass splittings between χ± and χ0
- **Signature**: soft pion that is indistinguishable above background, leaving charged track from chargino → invisible





Disappearing Track Analysis

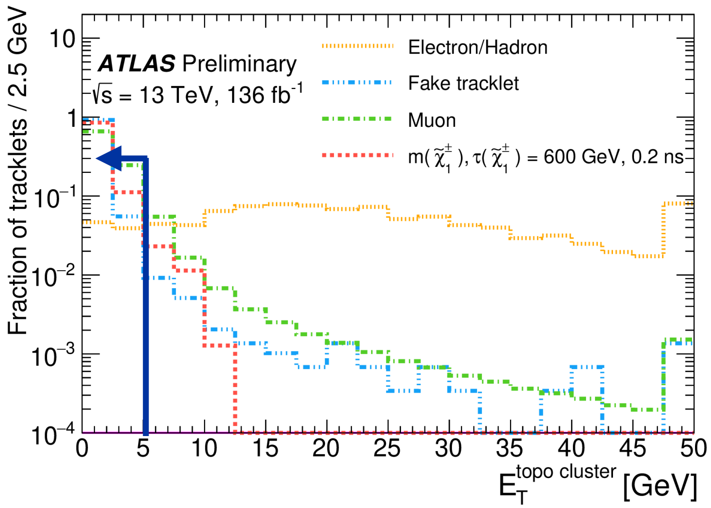
- Key strategy: ≥1 pixel tracklets
  - At least 4 hits in consecutive pixel layers (gain sensitivity to short lifetimes)
  - p_T >20 GeV, 0.1<|η|<1.9
  - **Veto on SCT Hits**
  - **No significant calorimeter energy in tracklets' trajectory**
  - High E_T^{miss}

➡ *new in Run 2!*

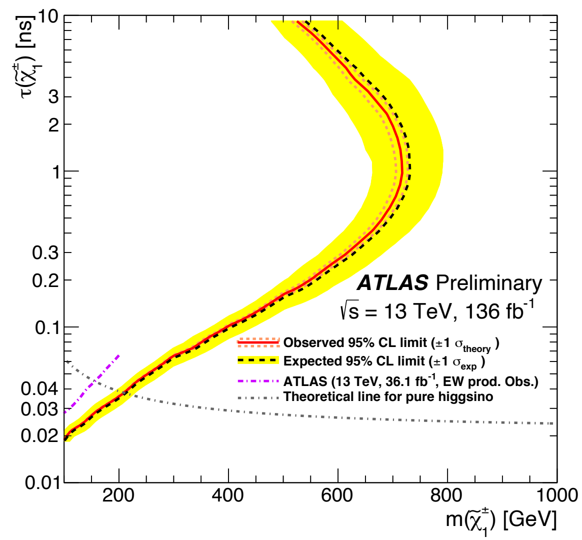
- Background: data-driven
  - Processes: charged lepton scattering/reversal, fakes from random hit combinations
  - Pixel tracklet pT templates from CRs: low-E_T^{miss}, mid-E_T^{miss}, high E_T^{miss} lepton scattering

- **Results:** strong improvement from lumi + tracklet E^{topo} cut
  - Mass of pure wino (higgsino) charginos > 660 (210) GeV
    - > 1.4 TeV for Δm = 50 GeV
  - Strongly produced in cascade decay of heavy gluino: m_g > 2.1 TeV for $m_{\chi\pm}$ 300 GeV

Tracklet E^{topo}



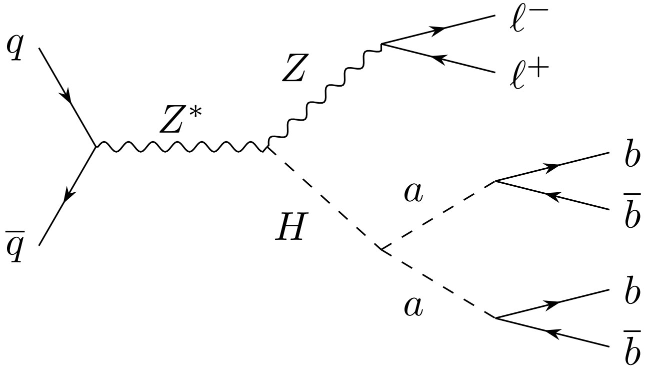
Higgsino τ vs. mass



Exotic Higgs Decays to LLPs

➡ *"Search for exotic decays of the Higgs boson into long-lived particles in pp collisions at $\sqrt{s}$ = 13 TeV using displaced vertices in the ATLAS inner detector"* [arXiv:2107.06092, July 2021]

Process



- Physics target: exotics Higgs to scalar *a*
  - Higgs to BSM branching ratio: existing constraint < 21% (ATLAS+CMS)
  - Mass: *a* ~ O(10s GeV)
  - Lifetime: O(1-100s mm)

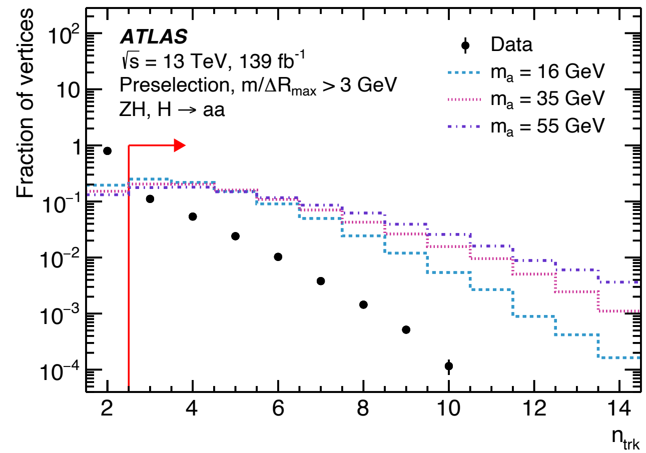
Signature

- **Signature**: two displaced vertices with high mass and track multiplicity

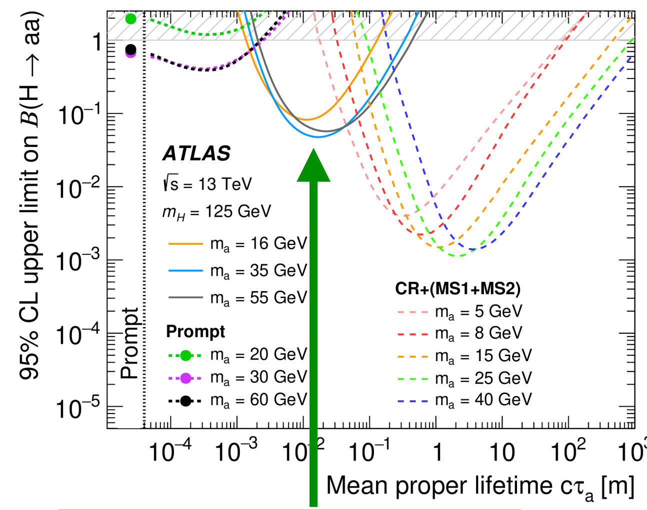
Higgs → LLPs Analysis

- Key strategy: large radius tracking
  - Looser track-to-vertex association on d0/z0
  - At least 2 displaced vertices (DVs)
  - Trigger on Z decay products (2 OSSF leptons in Z m_{ll} window)
- Background: data-driven
  - CR defined with # DVs < 2
  - Probability of DV reweighted across jet pT and DL1 b-tag score
  - Validated in ɣ+jets
- Results:
  - BR < 10% for LLP 4 < $c\tau$ < 100mm
  - m_{LLP} < 40 GeV: most stringent constraint in this lifetime regime

DV Track Multiplicity



H → BSM BR vs. cτ

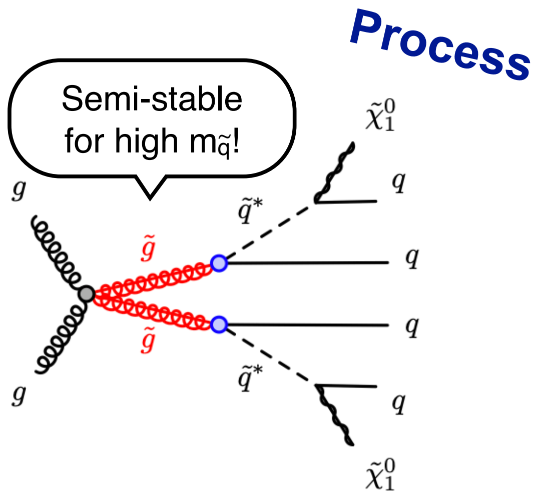


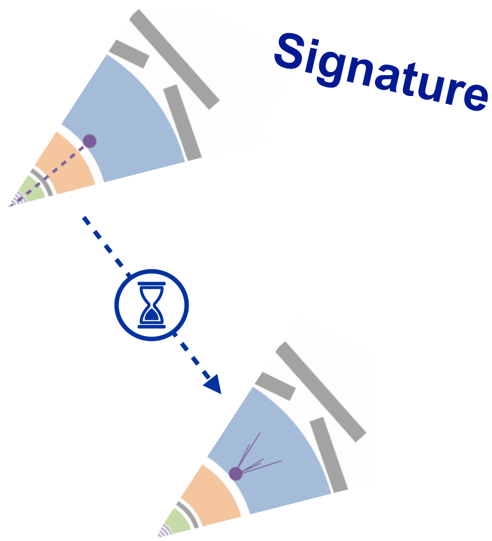
Fills gap in coverage at O(cm) decay lengths

Stopped Particles

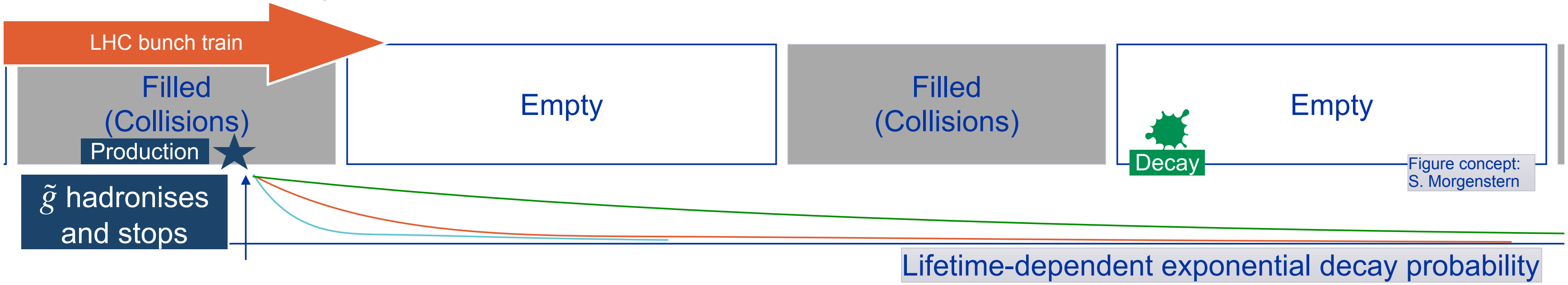
➡ *"A search for the decays of stopped long-lived particles at $\sqrt{s}$ = 13 TeV with the ATLAS detector"* [JHEP 07 (2021) 173, July 2021]

- Physics target: suppressed gluino decay due to heavy off-shell squark (R-hadrons)
  - Mass: O(TeV)
  - Lifetime: O(10^{-5} - 10^{3} sec)
- **Signature**: cluster of calorimeter energy when no *pp* collision occurs





Stopped Particles Analysis

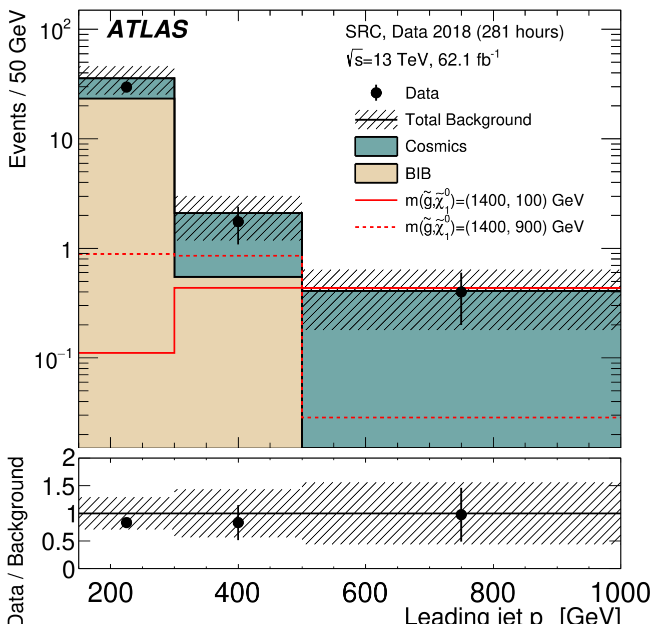


- 2017 dataset: 49.0/fb filled BXs, 298h empty BXs
- 2018 dataset: 62.1/fb filled BXs, 281h empty BXs (different bunch train configuration)

- Key strategy: empty bunch crossings (BXs) [100-150 ns buffer with collisions]
  - Signal scales with lumi and *live time* (when trigger selects/ accepts signal-like events in empty BCs)
  - Signal is isotropic in decay, high pT jet, no primary vertex
- Background: jet pT templates in non-collision CRs
  - Cosmics: dedicated 2016 dataset with no circulating beams
  - Beam-induced background: unpaired bunches (only one beam)
  - Cavern background
- **Results:** gluinos masses up to 1.4 TeV excluded for lifetimes from 10μs to 1 day

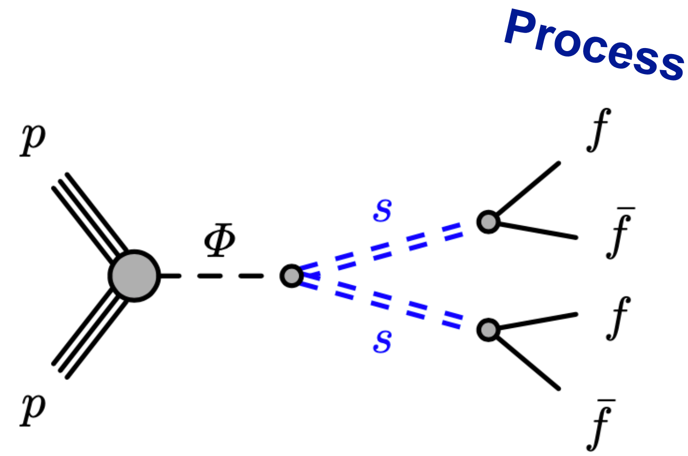
➡First of its kind! Previous exclusion 832 GeV in this τ range

$$N^{SR}_{events} = L^{int} \times \sigma_{\tilde{g}\tilde{g}} \times 2 \times \epsilon^{SR} \times f_{stopping} \times (\text{live fraction})$$



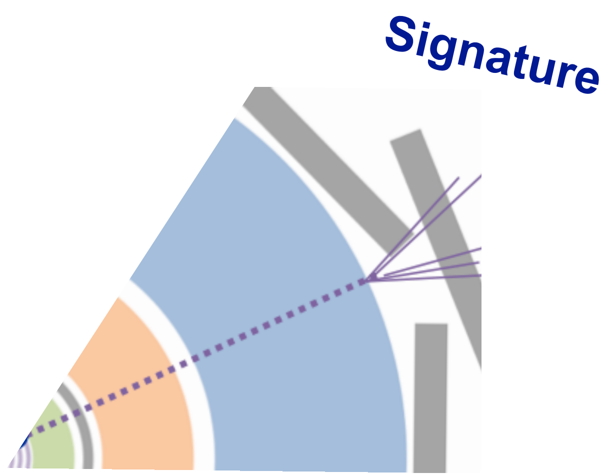
Displaced Vertices in Muon Spectrometer

➡ *"Search for events with a pair of displaced vertices from long-lived neutral particles decaying into hadronic jets in the ATLAS muon spectrometer in pp collisions at √s = 13 TeV"* [EPS, July 2021]



- Physics target:
  - Mass: *s* ~ O(10s GeV), ϕ~ O(100s GeV) [including SM Higgs]
  - Lifetime: O(0.1-1000s mm)

- Signature: narrow, high-multiplicity hadronic showers in muon detector



DV in MS Analysis

- Key strategy:
  - Dedicated HLT trigger [JINST 8 (2013) P07015]
  - Dedicated vertexing algorithms [JINST 9 (2014) P02001]
  - 2 isolated MS vertices outside of transition regions with $\Delta R > 1$, matched to trigger clustering
- Background: punch-through QCD jets + residual
  - Validated in non-isolated VR

$$N_{2\mathrm{Vx}} = N^{1\mathrm{cl}} \cdot P^{\mathrm{Vx}}_{\mathrm{noMStrig}} + N^{2\mathrm{cl}}_{1\mathrm{UMBcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Bcl}} + N^{2\mathrm{cl}}_{1\mathrm{UMEcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Ecl}}$$

674775 | 4.6×10^{-7} | 3 | 3.2×10^{-3} | 0 | 3.53×10^{-2}

= 0.32 ± 0.05 (statistical errors)

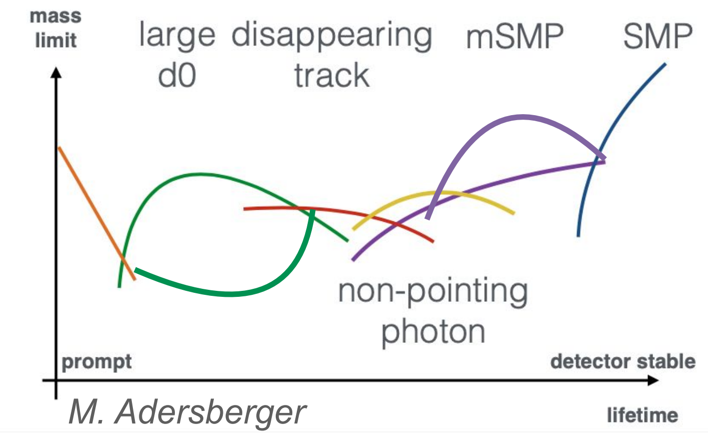
0 events observed in data

- Results:
  - H→BSM BR < 10% for LLP 4 cm < $c\tau$ < 71.3 m
  - First ATLAS exclusion for LLPs → ttbar in the MS

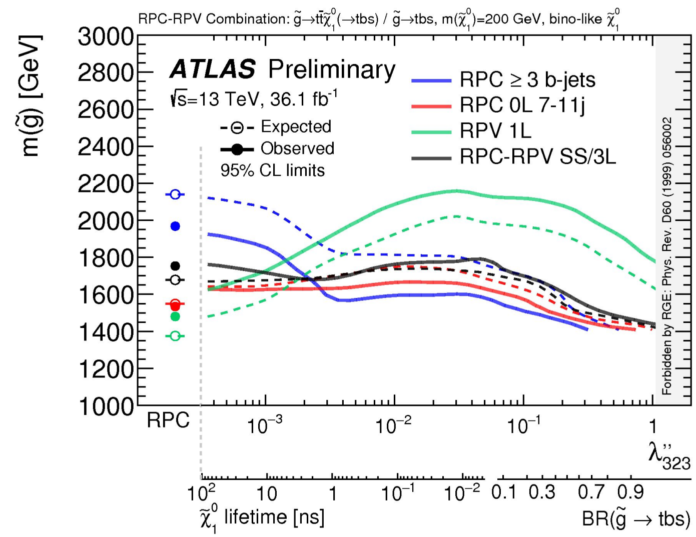
➡ ***See Audrey's talk tomorrow!***

Putting It All Together

- **Lifetime coverage:** ~17 decades! b-tagging [ps] — O(1 day)
  - Be sure to integrate prompt searches in summaries!
- **Many Run 2 displaced objects/vertices searches:**
  - Inner detector: ✔ DV+μ, displaced leptons, dilepton DV, DV+jets
  - Ecal: ✔ e/ɣ vertex
  - Hcal: ✔ calorimeter ratio
  - Muon spectrometer: ✔ DV in MS
- **Higgs to LLP decays:** B(H → aa → 4b) reaches a few % for lifetimes around ~1 ns for LLP masses of 35—55 GeV
- **Ionization:**
  - Milli/fractional-charged particles
  - Multi-charged/highly ionizing searches (pixel dE/dx, stable MS TOF)
- **Dark sector:** emerging/semi-visible jets
- Notes on summaries/combinations:
  - RECAST-ability: lifetimes → model couplings?



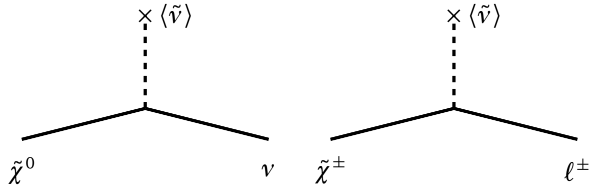
Strong Summary vs. Coupling



Future Search Considerations

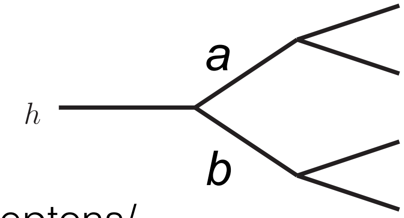
➡ Be sure to well-cover areas of phase space of interest for current anomalies/mysteries

- Muon g-2 & LHCb **flavor anomalies** imply possible new couplings to leptons; could be explained for ex. by RPV SUSY with 3rd generation super partners [2106.15647]
- **Neutrino masses**: neutrino/neutralino mixing from bilinear RPV couplings → 100μm lower bound on decay lifetime. Many possible decays/reinterpretations [0712.2156]



➡ Unusual/uncovered/unexpected… ?

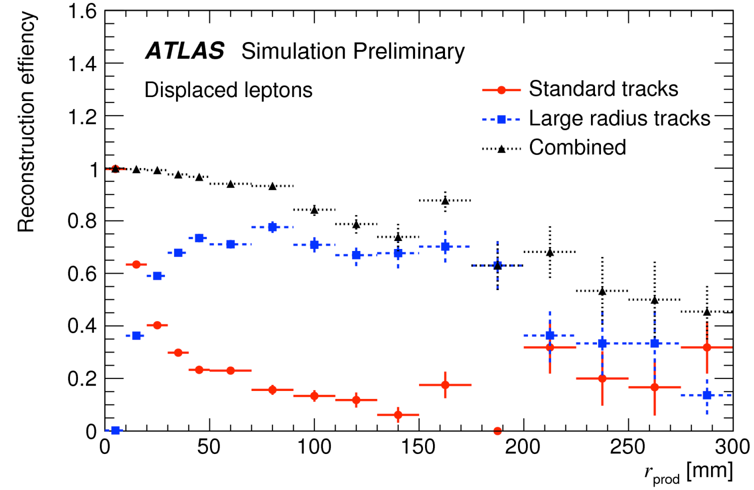
- Exotics Higgs:
  - Decays to LLPs where daughters have different masses ?
  - VBF topology triggers for LLP searches in signatures without leptons/MET/energetic jets?
- Role of anomaly detection: model-independence through very careful background characterization



Towards Run 3 & HL-LHC

- **Large radius tracking**: run over hits leftover from standard tracking [ATL-PHYS-PUB-2017-014]
  - Reprocessing of full Run 2 dataset
  - Run 3: 95% reduction in fakes with only 10-15% reduction in efficiency [ATL-PHYS-PUB-2021-012]

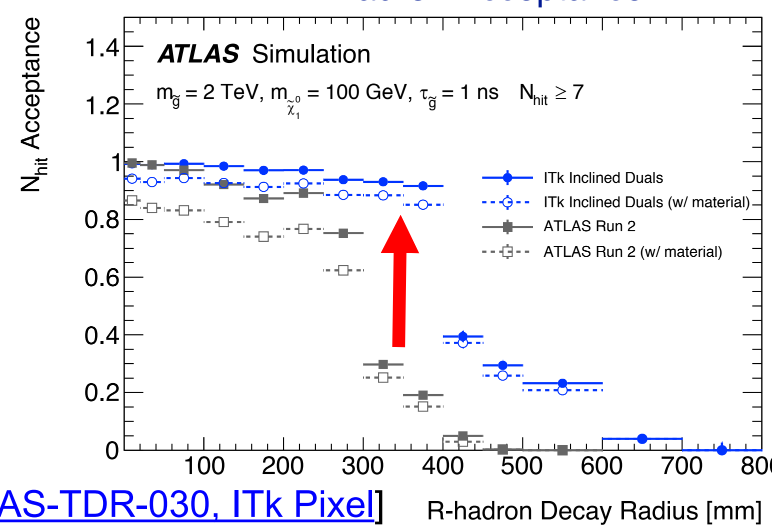
LRT Displaced Lepton Reco Efficiency



- **New displaced e/μ object triggers**: extend production radius

- **Phase-II Upgrades:**
  - Inner detector: expect DV increased efficiency due to new Si Inner Tracker (ITk)
  - High Granularity Timing Detector (HGTD): σ_t ~ 30 ps/track

ITk R-Hadron Acceptance



[ATLAS-TDR-030, ITk Pixel]

Conclusions

- Broad and exciting LLP search program at ATLAS!
  - Many important theoretical interfaces: SUSY, dark sector, flavor anomalies…
- LLP searches are the place to be for Run 3:
  - Large radius tracking → increased displaced track efficiency
  - Many yet-to-be-covered signatures of interest
- Long-term program through HL-LHC lifetime
  - Important complementarity with eg. MATHUSLA, FASER, milliQan, etc.

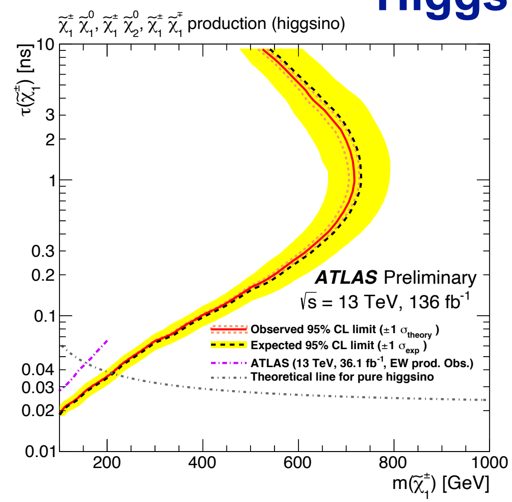
➡ Integration & connectivity are crucial! Detector expertise, interpretations/combinations all overlapping in LLP searches

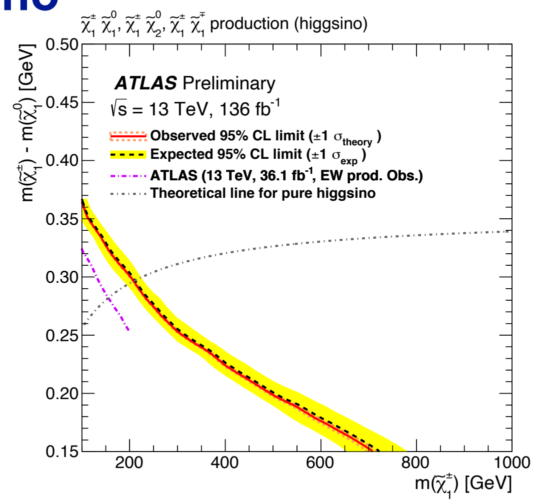
Backup

Disappearing Track Results

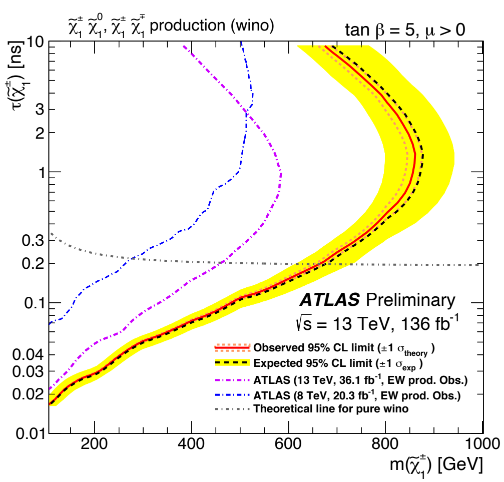
	Electroweak channel	Strong channel
	High-$E_{\mathrm{T}}^{\mathrm{miss}}$ SR	
Fake	2.6 ± 0.8	0.77 ± 0.33
Hadron	0.26 ± 0.13	0.024 ± 0.031
Electron	0.021 ± 0.023	0.004 ± 0.004
Muon	0.17 ± 0.06	0.049 ± 0.018
Total Expected	3.0 ± 0.7	0.84 ± 0.33
Observed	3	1
p_0 (Z)	0.5 (0)	0.38 (0.30)
Observed $\sigma_{\mathrm{vis}^{95\%}}$ [fb]	0.037	0.028
Expected $\sigma_{\mathrm{vis}^{95\%}}$ [fb]	$0.038\ ^{+0.014}_{-0.009}$	$0.024\ ^{+0.009}_{-0.003}$

Higgsino

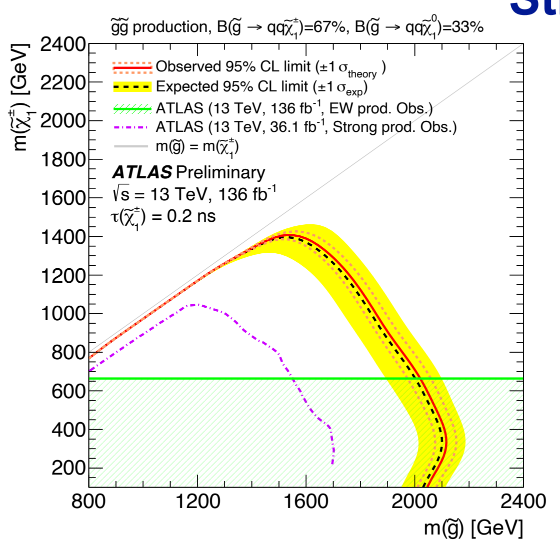


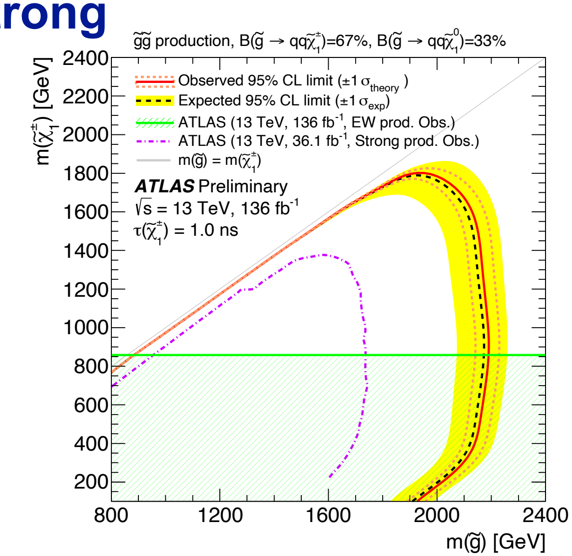


Wino



Strong



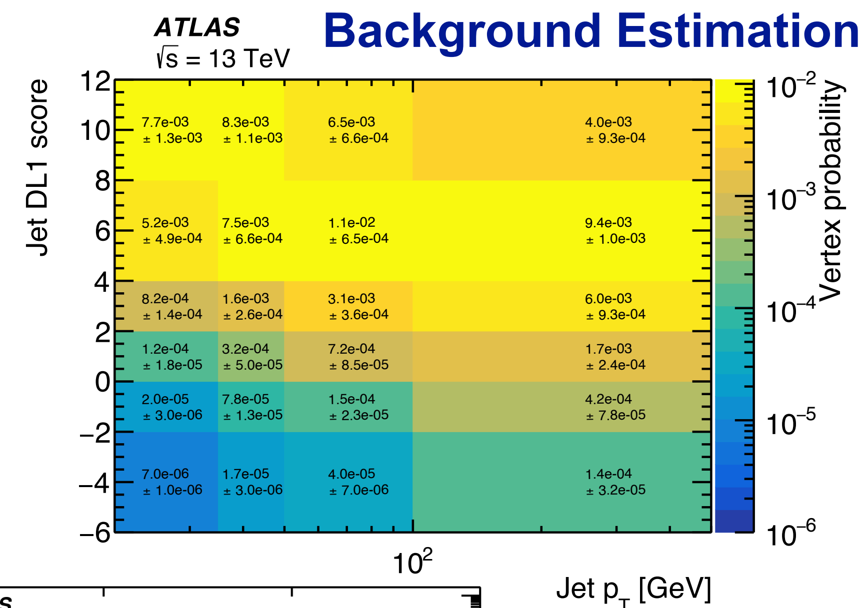


Exotics Higgs to LLP

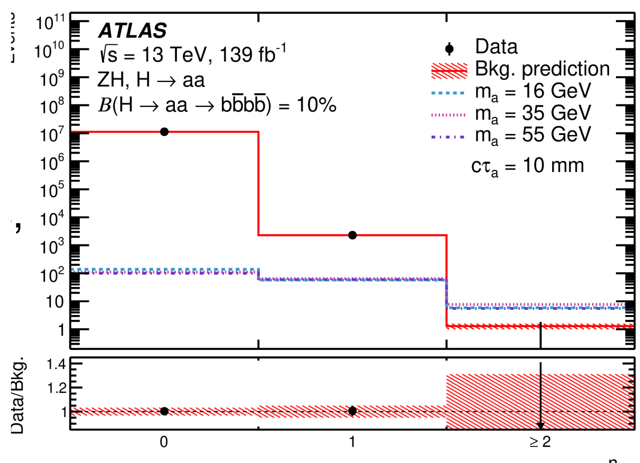
Table 1: The full set of selection criteria applied to DVs.

Selection type	Requirement
Track pruning	$\|d_0^{DV}\| < 0.8$ mm
	$\|z_0^{DV}\| < 1.2$ mm
	$\sigma(d_0^{DV}) < 0.1$ mm
	$\sigma(z_0^{DV}) < 0.2$ mm
Vertex preselection	$\chi^2/n_{DoF} < 5$
	$r < 300$ mm
	$\|z\| < 300$ mm
	pass material veto
Vertex selection	$n_{trk} > 2$
	$m/\Delta R_{max} > 3$ GeV
	$r/\sigma(r) > 100$
	$\max(\|d_0\|) > 3$ mm
	$\Delta R_{jet} < 0.6$

Background Estimation



Unblinded SR



Predicted events: 1.30 ± 0.08 (stat.) ± 0.27 (syst.)
Observed events: 0

Stopped Particles Regions

Search/ background samples

Data sample (purpose)	**Bunch structure**	**Trigger requirements**	**Offline requirements**
Search sample	Empty	HLT jet $p_{\mathrm{T}} > 55$ GeV HLT $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV HLT jet $\lvert\eta\rvert < 2.4$	Leading jet $p_{\mathrm{T}} > 90$ GeV Leading jet $\lvert\eta\rvert < 2.4$
Cosmic sample	–	L1 jet $p_{\mathrm{T}} > 12$ GeV	Leading jet $p_{\mathrm{T}} > 90$ GeV Leading jet $\lvert\eta\rvert < 2.4$
Beam-induced background sample	Unpaired	L1 jet $p_{\mathrm{T}} > 12$ GeV or L1 jet $p_{\mathrm{T}} > 50$ GeV	Leading jet $p_{\mathrm{T}} > 90$ GeV Leading jet $\lvert\eta\rvert < 2.4$
Cavern background sample	Empty	Random	–

VRs

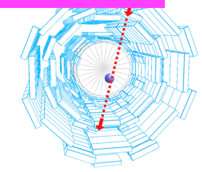
Region	**Data sample**	**Number of muons**	**Leading jet p_{T} [GeV]**	α	**Leading jet w_{ϕ}**	**Leading jet $\lvert\eta\rvert$**
Central validation regions						
VRC-α		**≥ 1 ($\lvert\eta\rvert$ < 1.4)**		> 0.2	> 0.02	
VRC-bib	Search sample	0	> 150	> 0.2	**0.01–0.02**	< 0.8
VRC-w_{ϕ}		0		**< 0.2**	> 0.02	
Inclusive validation regions						
VRIncl-α		**≥ 1 ($\lvert\eta\rvert$ < 1.4)**		> 0.2	> 0.02	
VRIncl-bib	Search sample	0	> 150	> 0.2	**0.01–0.02**	< 2.4
VRIncl-w_{ϕ}		0		**< 0.2**	> 0.02	
Central BIB normalisation regions						
NRC-α		≥ 1 ($\lvert\eta\rvert$ < 1.4)		> 0.2	> 0.02	
NRC-bib	Search sample	0	**90–150**	> 0.2	0.01–0.02	< 0.8
NRC-w_{ϕ}		0		< 0.2	> 0.02	
Inclusive BIB normalisation regions						
NRIncl-α		≥ 1 ($\lvert\eta\rvert$ < 1.4)		> 0.2	> 0.02	
NRIncl-bib	Search sample	0	**90–150**	> 0.2	0.01–0.02	< 2.4
NRIncl-w_{ϕ}		0		< 0.2	> 0.02	

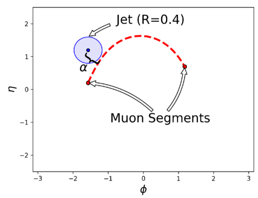
L.Corpe

Stopped Particles

Background Estimation

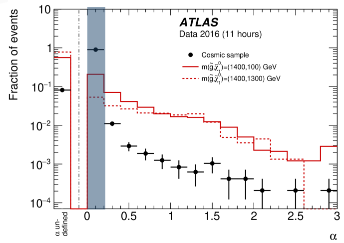
Cosmics





Dedicated cosmic run in 2016: data taken with no beams

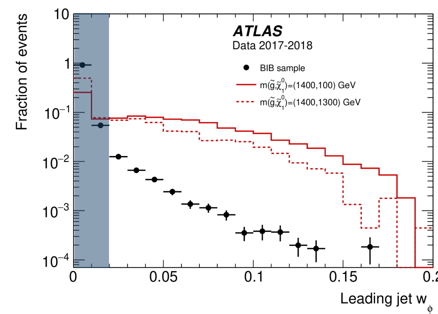
α represents geometrical distance between leading jet and candidate cosmic track: veto small values

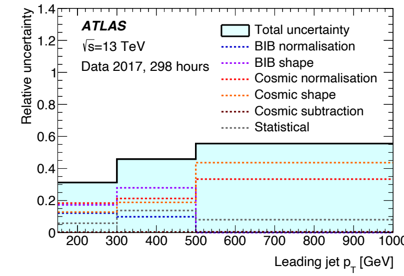


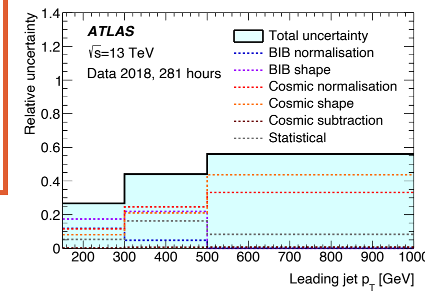
BIB Data from "unpaired" BXs (beam on one side only)

w_Φ represents width of jet in Φ (p_T-weighted average ΔΦ between jet axis and each cluster)
>> Veto small values

$$w_\phi = \frac{\sum_i p_T(i) \cdot |\Delta\phi(\text{jet}, i)|}{\sum_i p_T(i)}$$

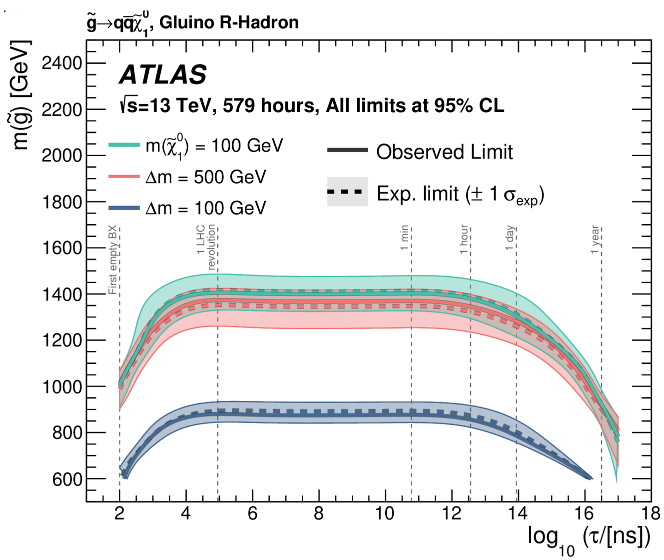


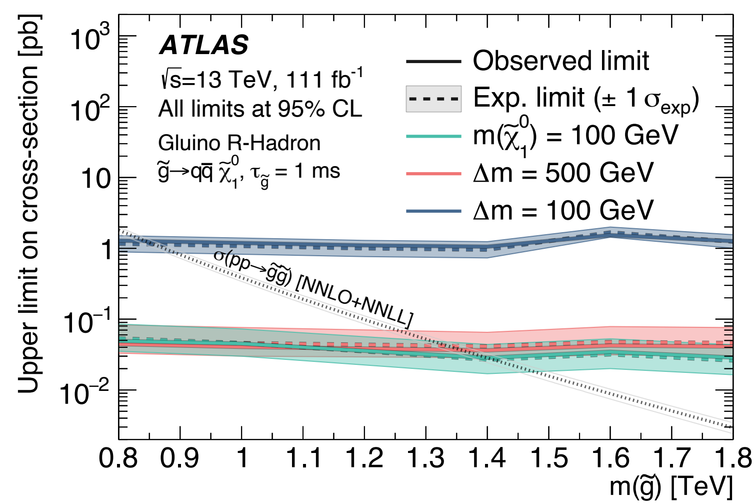




L.Corpe

Limits

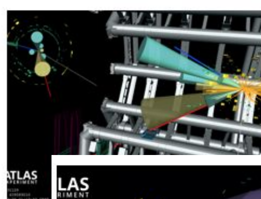




RPVLL Public Results

	Disappear.	Pixel dE/dx	SMP	DV+MET	DV+Jets	DV+mu	Dilepton DV	Disp.Leptons	Photons	Stoppped
7TeV	2011	2011	2011	2011						2012
	2012	2012		2012					2013	
8TeV	2013	2015	2014	2015	-	2015	2015		2014	2013
2015		2016	2016							
2016	2017	2018	2019	2017	-	-	2019			
Full Run2	2021(CONF)	Draft1	R&D	R&D	post-PAR	2020	R&D	2020	Unblinded	2021
2nd wave	R&D	Being discussed						micro-displaced	photon DV R&D	

ATLAS Physics Briefings



The hunt for higgsinos reaches new limits

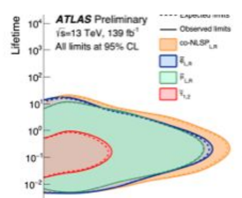
The ATLAS Collaboration has released three new searches for "higgsinos" - the super-partner of the Higgs boson.

Physics Briefing | 10th June 2021

Better late than never: ATLAS searches for late-decaying new particles

A new result from the ATLAS Collaboration – debuted at the virtual Moriond Electroweak conference – sets itself apart from more traditional LHC searches. Typically, physicists will look for new particles produced in LHC collisions that immediately decay to known or invisible particles. This analysis, in contrast, looks for new particles that live for roughly a hundred nanoseconds or more before decaying.

Physics Briefing | 23rd March 2021



Leptons at a distance: a new search for long-lived particles

ATLAS researchers are broadening their extensive search programme to look for more unusual signatures of unknown physics, such as long-lived particles. A theory that naturally motivates long-lived particles is supersymmetry (SUSY). A new search from the ATLAS Collaboration – released this week for the 5th International Conference on Particle Physics and Astrophysics (ICPPA-2020) – looks for the superpartners of the electron, muon and tau lepton

Physics Briefing | 7th October 2020