ATLAS searches for supersymmetry with long-lived particles

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on behalf of the ATLAS collaboration

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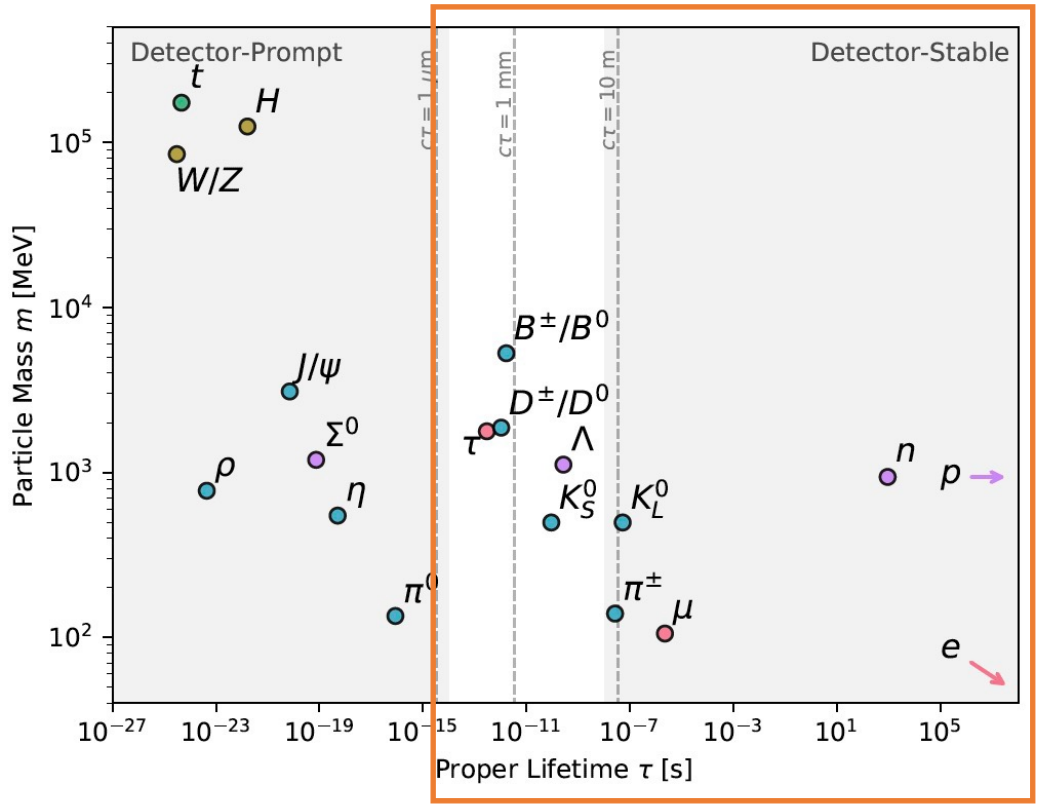
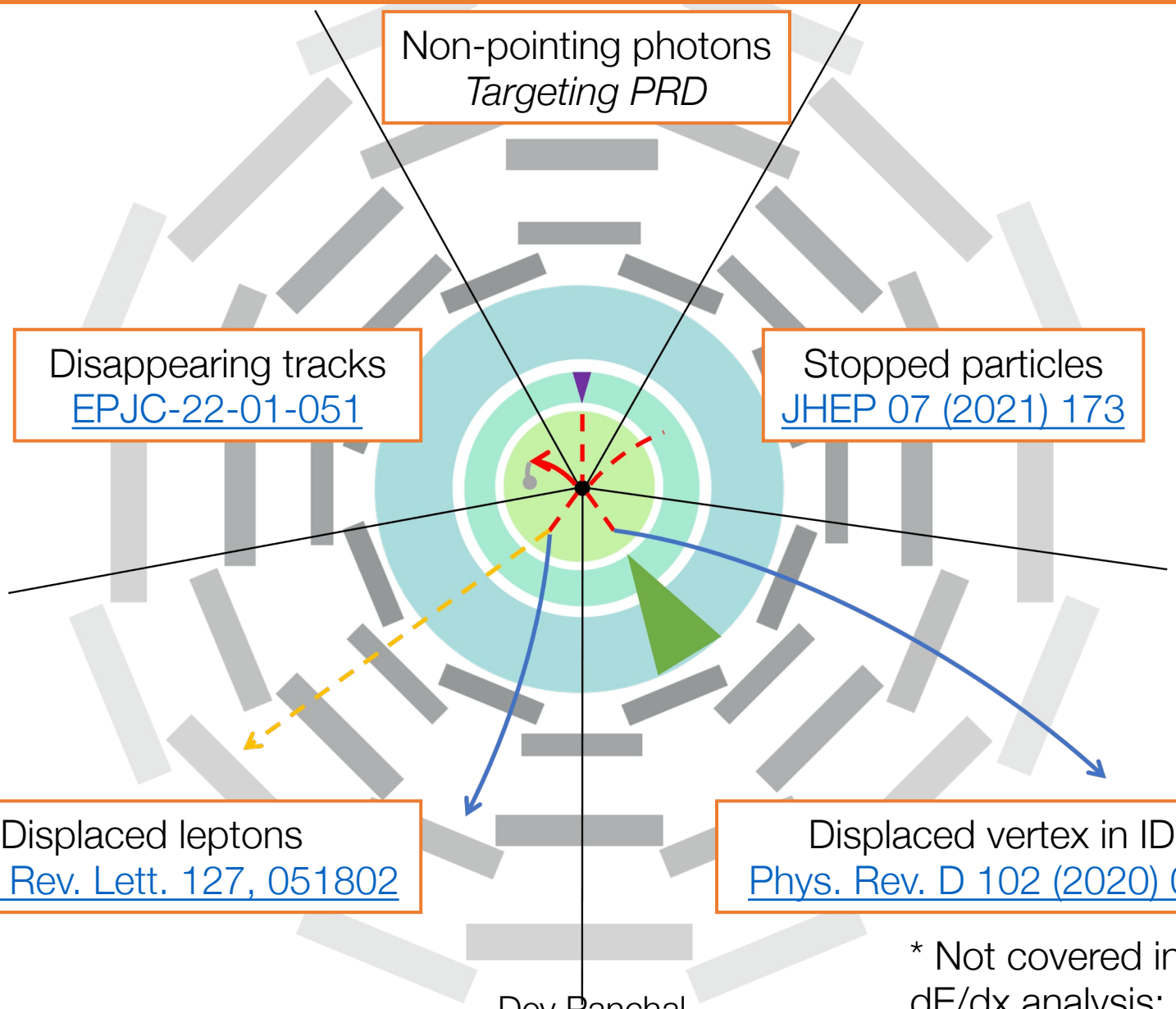
Long-lived particles

- Long-lived particles (LLPs) are abundant in the Standard Model (SM) and well-motivated in Supersymmetry (SUSY) extensions.
- SUSY models such as the Gauge-Mediated SUSY Breaking (GMSB), Minimal Supersymmetric Standard Model (MSSM), R-parity violation, etc. predict LLPs.
- LLPs give rise to an experimentally unique signatures and unusual backgrounds.
  - Require dedicated triggers, dedicated reconstruction, excellent knowledge detector & its performance, …
- LLP searches are signature-driven—depend on the LLP mass, lifetime, and charge.



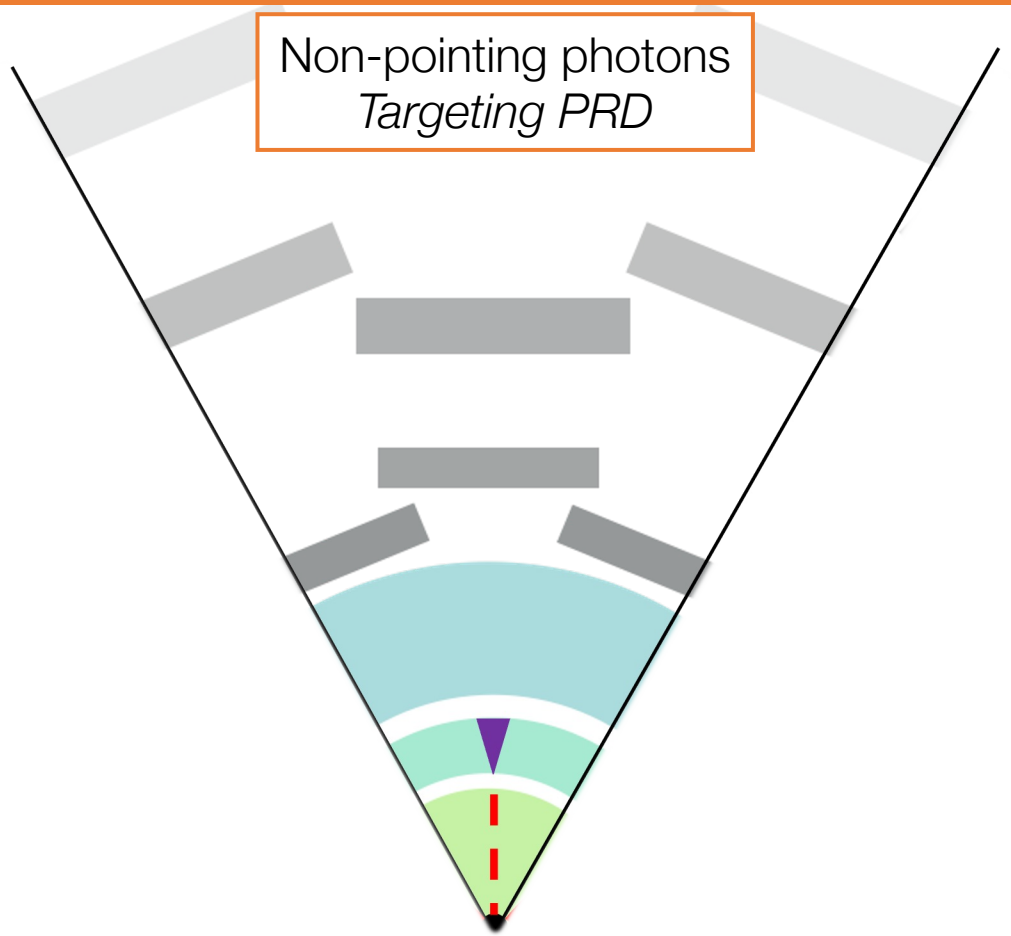
arXiv: 1810.12602

Search program for LLPs in SUSY at ATLAS



* Not covered in this talk is the pixel dE/dx analysis; see Leonardo's talk

Search program for LLPs in SUSY at ATLAS



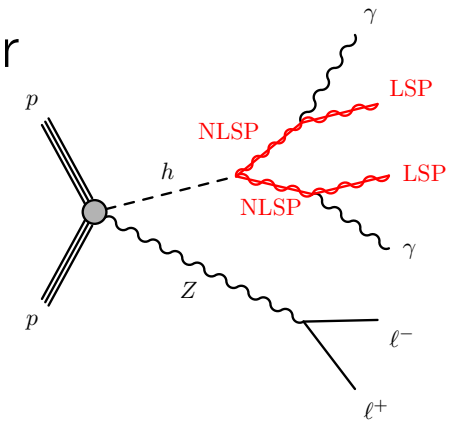
Lepton
Anything
BSM
Jet
Photon

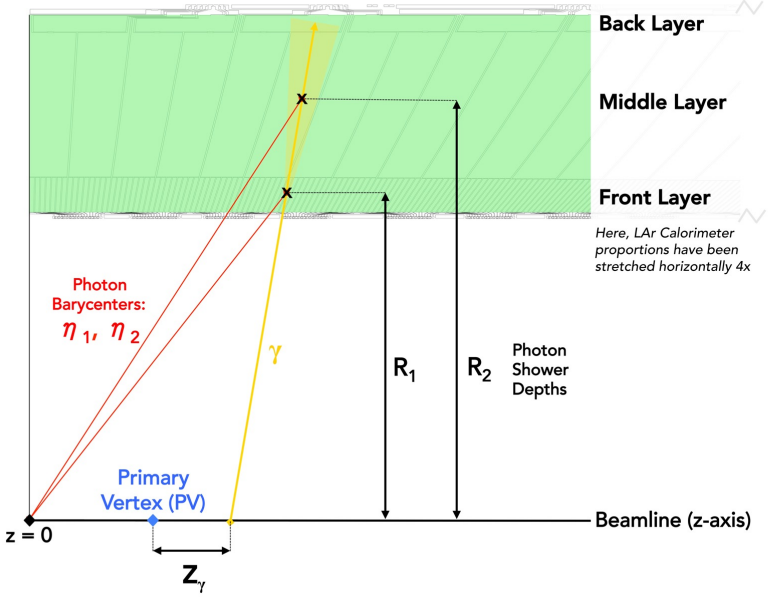
Non-pointing photons

Search for delayed and non-pointing photons originating from displaced decay of a neutral LLP

Motivation:

- Electrically neutral NLSP could avoid direct detection as it travels through the detector before decaying, with a prominent decay to a γ + LSP.
- Photons produced in this decay will be delayed (compared to prompt γ) and non-pointing due to the opening angle between the γ and LSP.
- Fully exploits the fine-segmentation of the calorimeter to measure pointing (z_γ)—exclusive to ATLAS.
- Targeted signal: $\mathrm{H} \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ (\mathrm{LLP}) \to \gamma\gamma + \tilde{G}\ (\mathrm{LSP})$ plus associated W/Z/$t\bar{t}$ for trigger.
- Take advantage of potential Higgs to BSM branching ratio (~13%). Higgs Yellow Report





Schematic showing the calculation of the photon "pointing" value using LAr calorimeter layers' barycenter information.

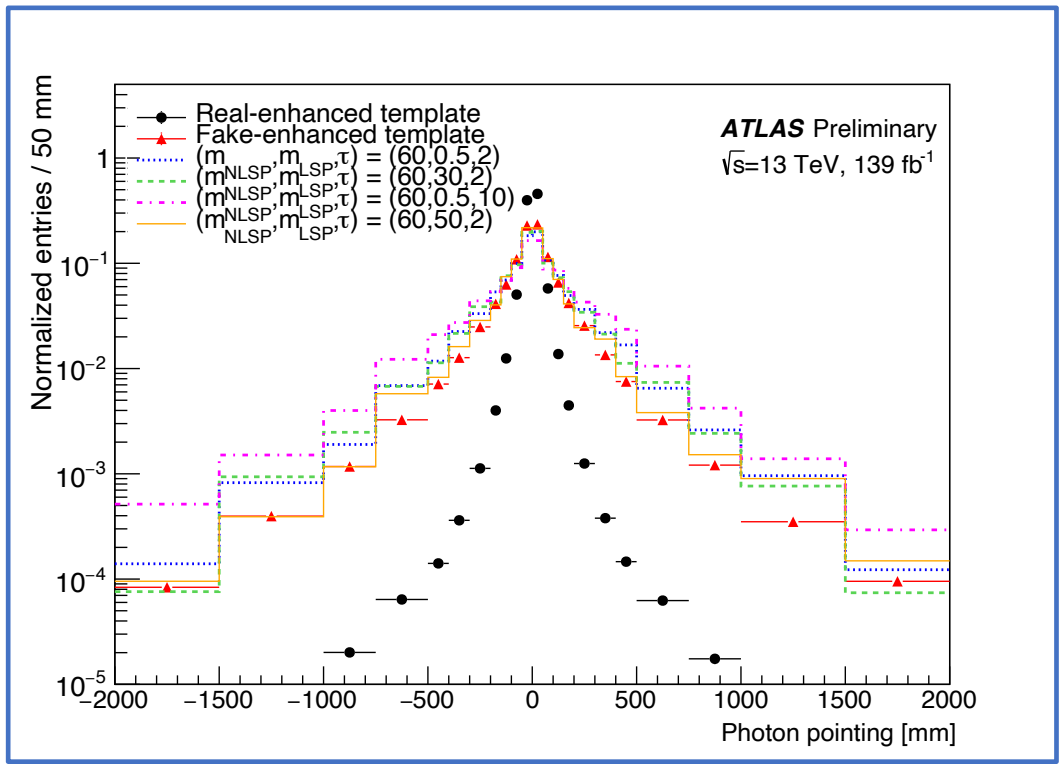
Non-pointing photons—Analysis Strategy

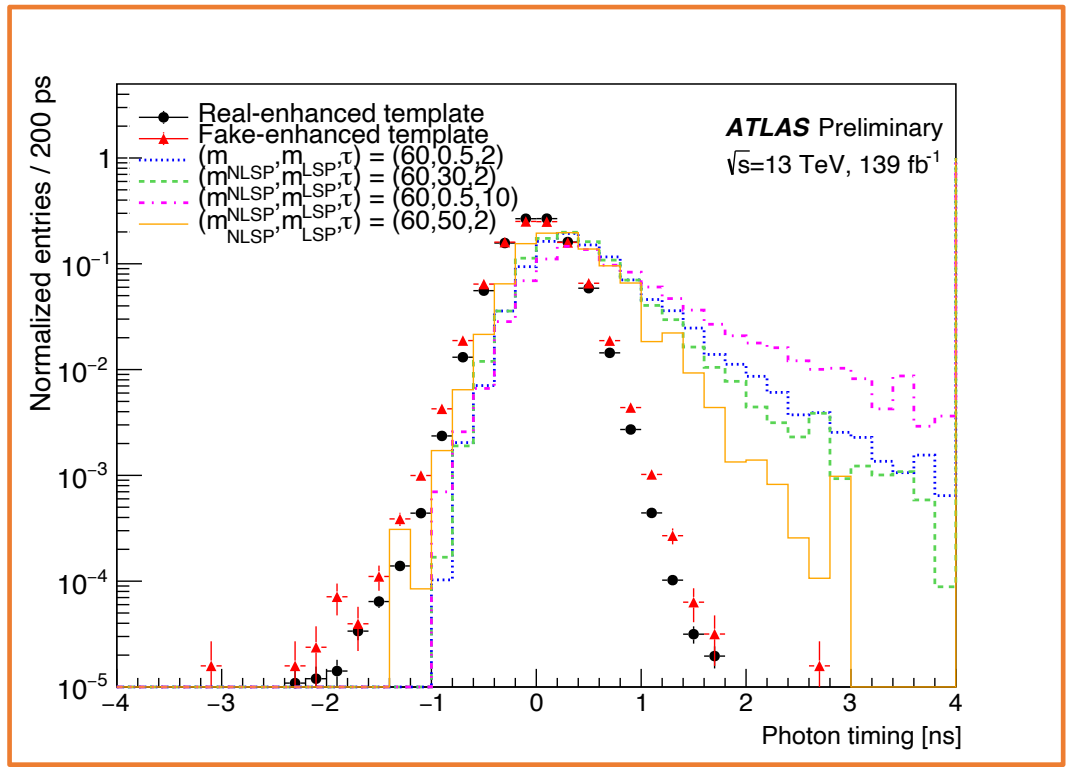
- Key discriminants are pointing and timing measurements from the LAr calorimeter.

Calculate the photon pointing using information from the multiple layers of the LAr EM calorimeter.

LAr timing measurement obtained using optimal filter coefficients (OFCs). **Offline timing calibration** provides a 200 ps resolution.

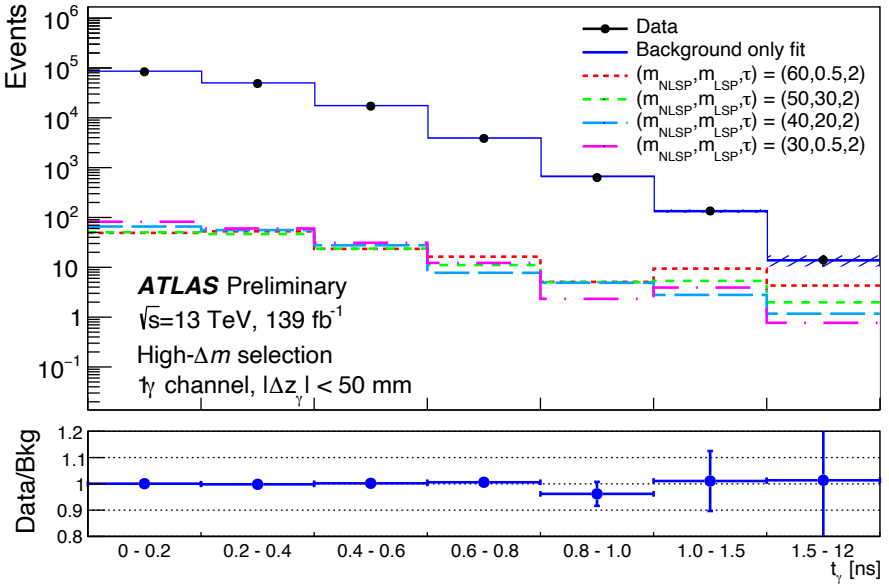
Signal events are delayed ⇒ broader timing distribution compared to prompt events.





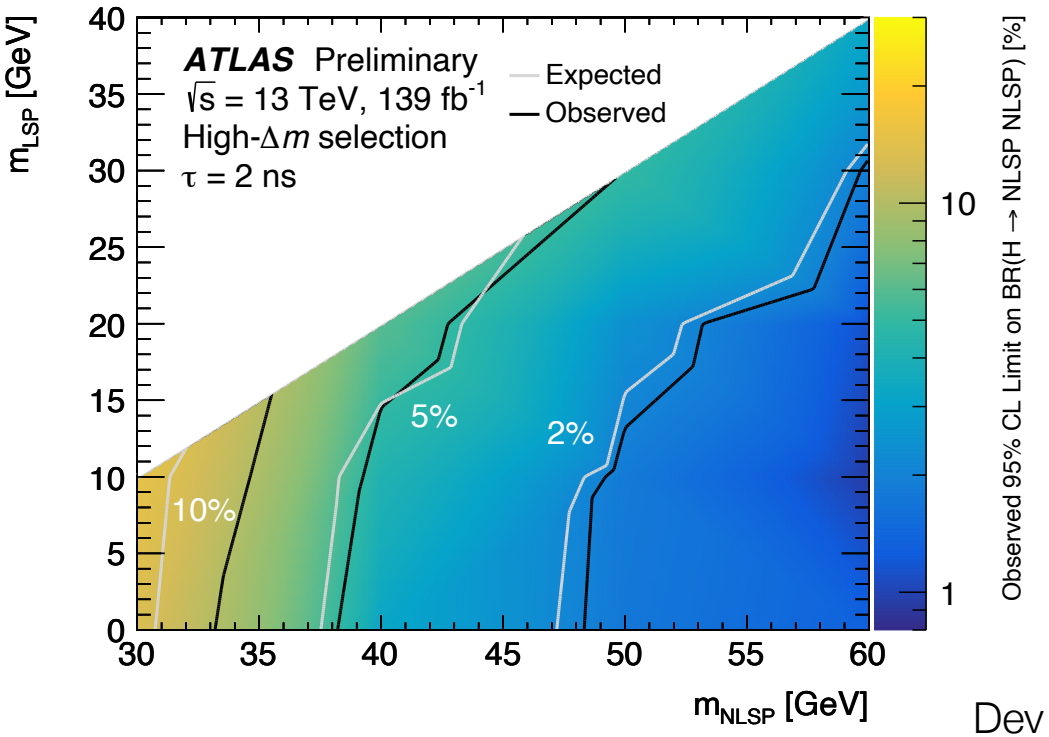
Non-pointing photons—Background Estimation

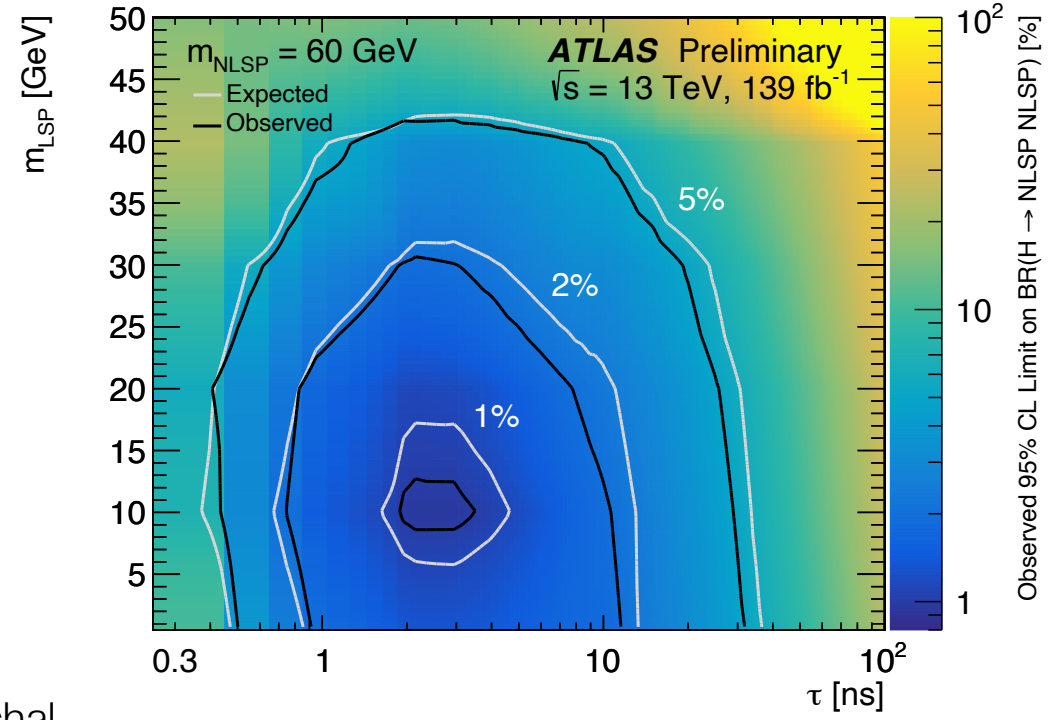
- Analysis regions are selected in categories of E_T^{miss}: CR ∈ [0, 30) GeV, VR ∈ [30, 50) GeV, SR ∈ [50, ∞) GeV.
  - SR has high- E_T^{miss} from the LSPs.
- Data-driven background estimation with two templates summed with an ad-mixture parameter α.
  - Real-enhanced photon (mis-measured prompt γ): low- E_T^{miss} `Medium/Tight` photons + photons from $Z \rightarrow \ell\ell\gamma$ events (ℓ = e, μ)
  - Fake-enhanced photon (electron, jets): low- E_T^{miss} `Loose-Not-Medium/Tight` photons.
- Photon pointing distributions sliced in exclusive bins of pointing and shape fits performed.
  - Background modeling tested with VR data.
  - Fit procedure tested by performing signal injection tests—observe good linearity between injected and extracted signal strength.



Non-pointing photons—Results

- No significant excess observed over background expectation.
- Results interpreted in the GMSB model.
  - 95% C.L. upper limits set on $\mathcal{B}(\mathrm{H} \to \mathrm{NLSP}\ \mathrm{NLSP})$ assuming $\mathcal{B}(\mathrm{NLSP} \to \mathrm{LSP} + \gamma) = 100\%$
- Results interpreted in a model-independent production of displaced photons with large values of pointing and timing.





Search program for LLPs in SUSY at ATLAS

Disappearing tracks
EPJC-22-01-051

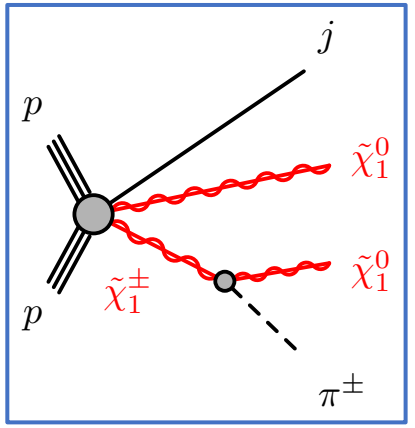
Lepton
Anything
BSM
Jet
Photon

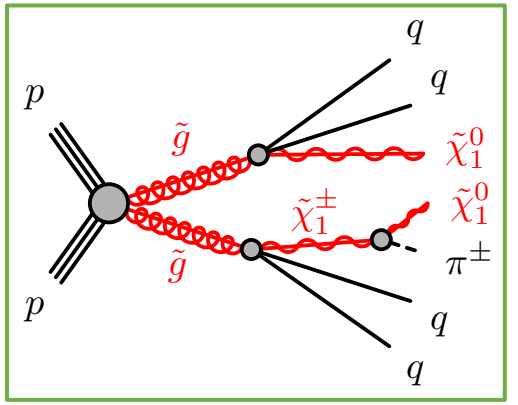
Disappearing tracks EPJC-22-01-051

Search for long-lived charginos with a distinct signature of a short and then a disappearing track

Motivation:

- Scenarios where the LSP is Wino-like, $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \sim 100$ MeV. Several 'natural' SUSY models also predict a light Higgsino LSP with a mass as light as the electroweak scale.
- Probe Higgsino dark matter model with this signature.
- In both wino and Higgsino scenarios, the chargino can be produced with large momentum and be **long-lived to traverse multiple layers of the pixel detector before decaying**.
- Targets both the electro-weak and strong production; with sensitivity to **short lifetime tracks** ($O(10^{-2} - 1)$ ns).





Analysis Strategy:

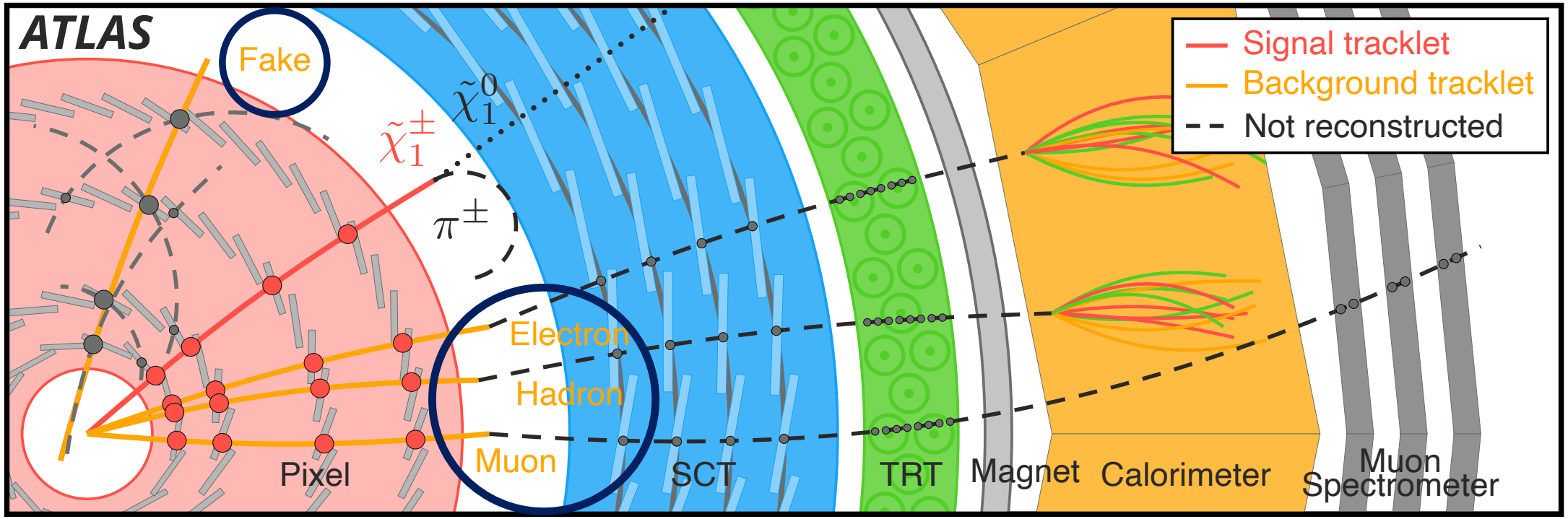
- Select events with E_T^{miss} triggers.

Disappearing track:

  - Reconstruct pixel tracklets which are tracks seeded by 4 hits in pixel layer.
  - Signal pixel tracklets should not have hits in the SCT and no associated calorimeter activity.
- Signal events have a distinctive signature of disappearing track and large E_T^{miss}.

Disappearing tracks—Background Estimation

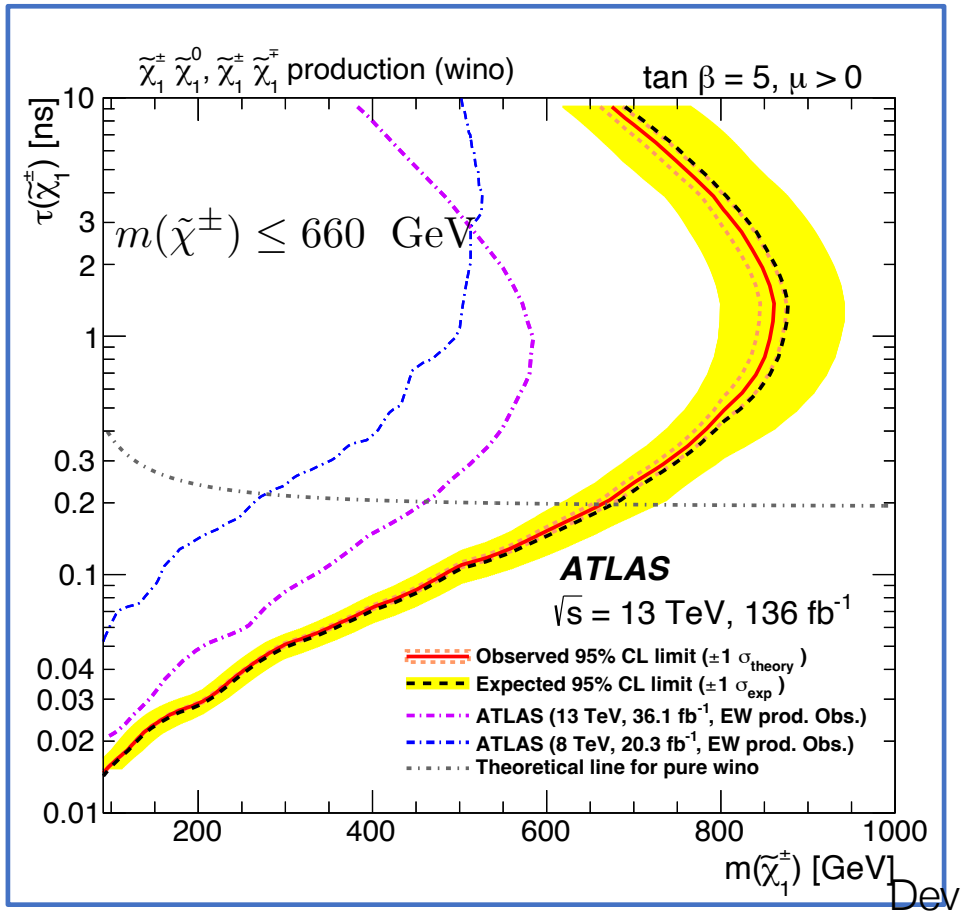
- Sources of disappearing tracks:

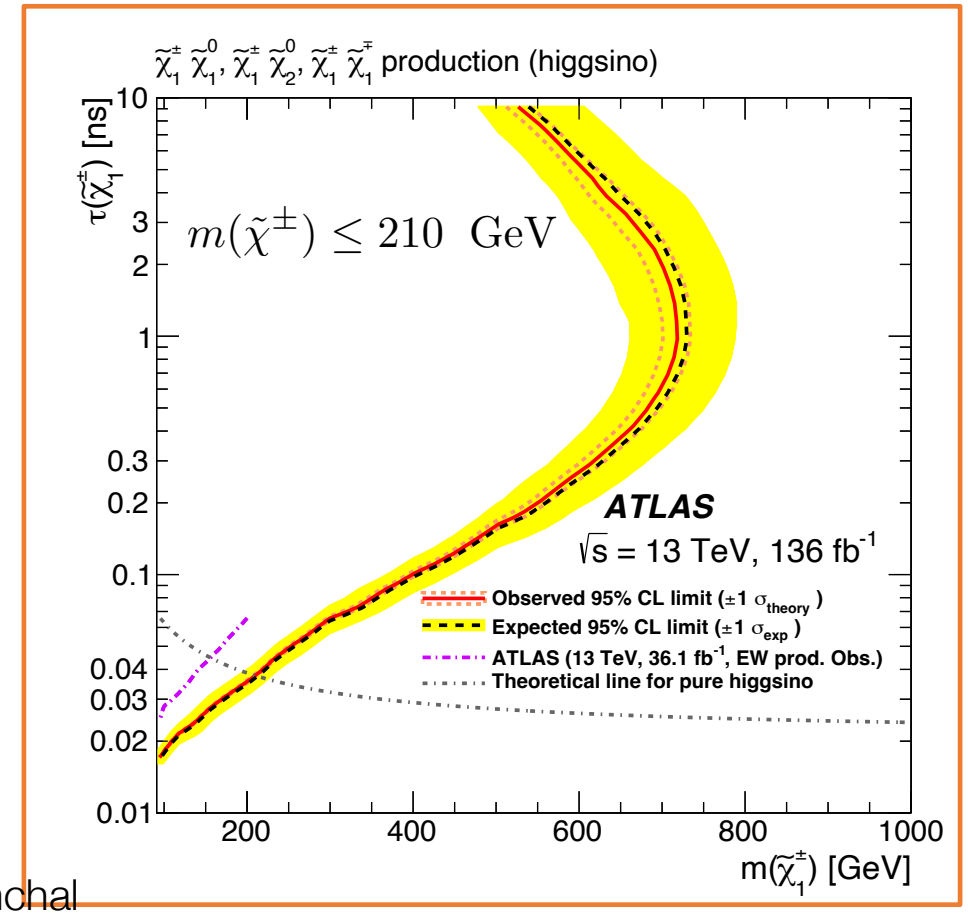


- Data-driven background templates for tracklet p_T spectrum derived from control regions.
- Derive transfer functions to extrapolate to validation/signal regions.
- Apply momentum smearing function to account for p_T resolution differences.

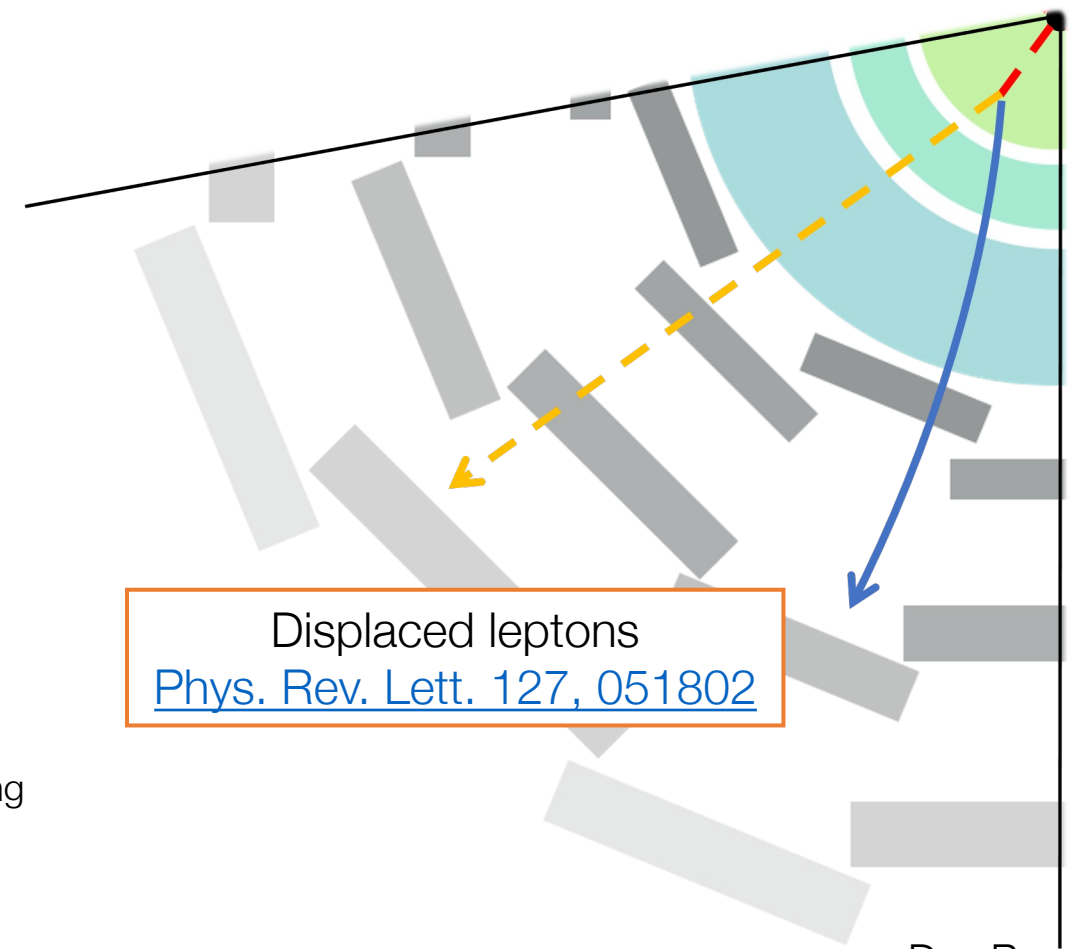
Disappearing tracks—Results

- No significant excess over background expectation.
- 95% C.L. exclusion limits set on the production of pure winos or pure higgsinos as a function of the chargino lifetime and mass.





Search program for LLPs in SUSY at ATLAS



Displaced leptons
Phys. Rev. Lett. 127, 051802

Lepton
Anything
BSM
Jet
Photon

Displaced leptons

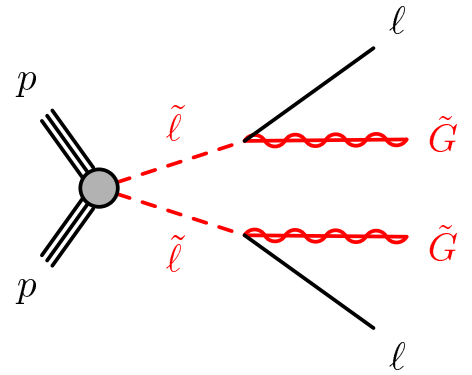
Phys. Rev. Lett. 127, 051802

Search for charged leptons with large impact parameters using 139 fb^{-1} of ATLAS data

First ATLAS result for this model

Motivation:

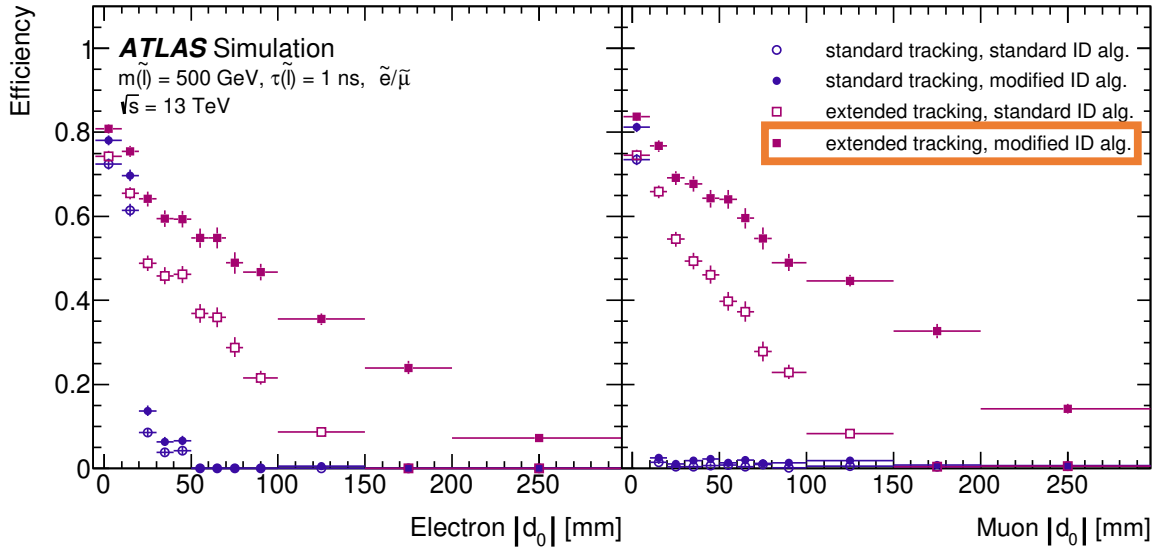
- Explore GMSB model where long-lived sleptons decay to a massless gravitino and a lepton of the same flavor as the parent slepton.
- No sensitivity to signatures with same-flavor displaced leptons in previous LHC searches.



Analysis strategy:

- Select electrons using photon triggers and use only the MS info. to identify muons.
- Select events with two high-p_T leptons with $p_T > 65$ GeV and 3 mm < $|d_0|$ < 300 mm.
- Search utilizes dedicated reconstruction algorithms:

1. **Large-radius tracking:** reconstructs displaced tracks with unused hits after the standard tracking algorithm.
2. **Modified lepton identification:** remove $|d_0|$ and hit requirements on track.



Dedicated reco. algorithms improve efficiency

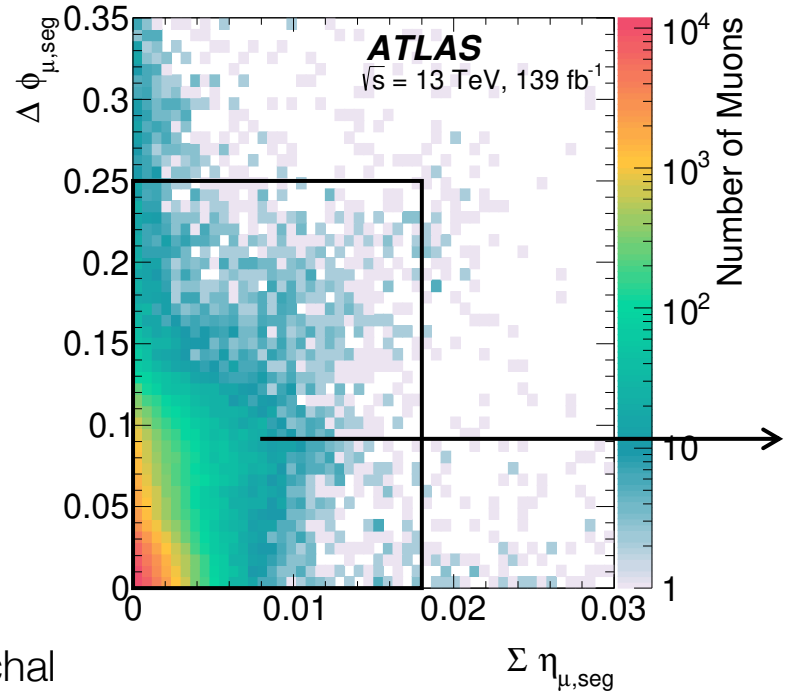
Displaced leptons—Background Estimation

Sources of displaced leptons:

1. Fake leptons: mismatch of the ID track to photon or MS track.
   Use ABCD method to estimate the number of fake and heavy-flavor leptons in the signal region.

	VR-ee-fake	VR-ee-heavy-flavor	VR-$e\mu$-fake	VR-$e\mu$-heavy-flavor
Estimate	1356 ± 49	23.5 ± 1.9	$1.9^{+1.8}_{-1.0}$	$0.38^{+0.37}_{-0.32}$
Observed	1440	26	2	1

2. Cosmic ray muons:
   veto events with cosmic tagged muons;
   use an ABCD-like method for mismeasured MS tracks.



> 99% of cosmic-tagged muon events vetoed

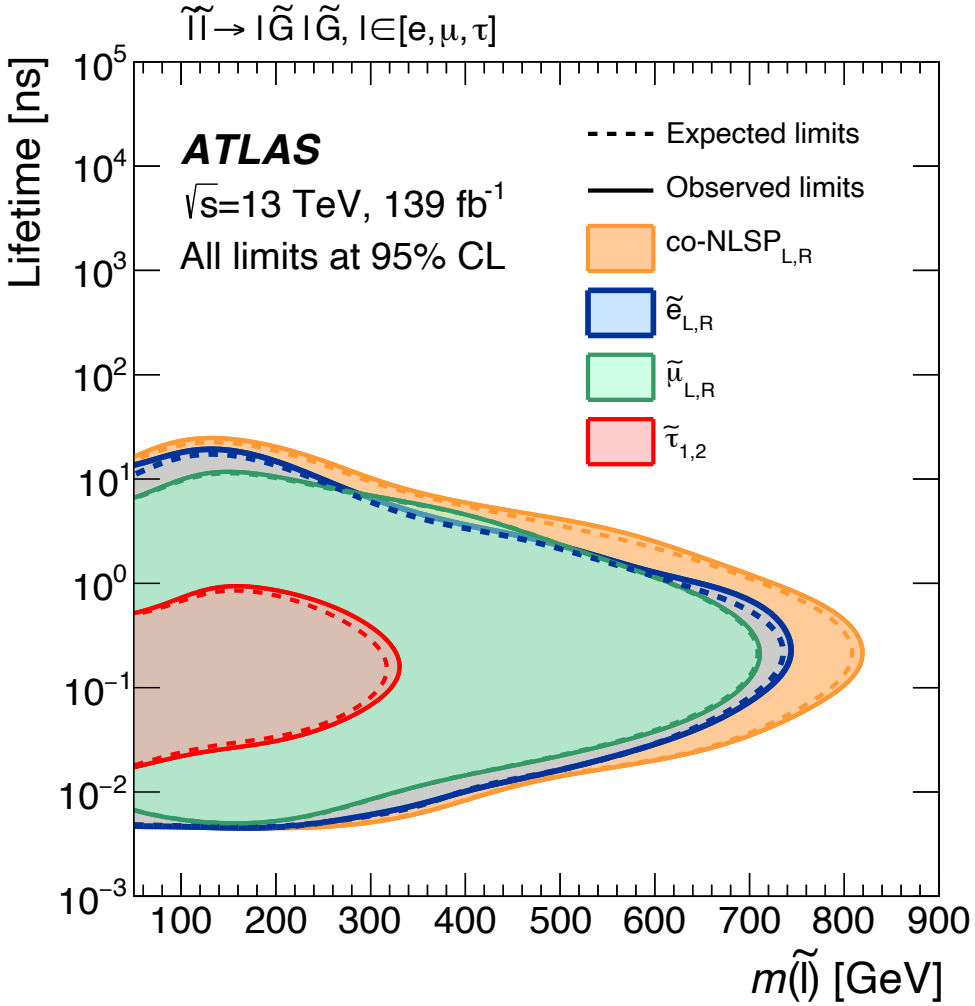
Displaced leptons—Results

- No significant excess over background expectation.

Region	SR-ee	SR-$\mu\mu$	SR-$e\mu$
Fake + heavy-flavor	0.46 ± 0.10	$< 10^{-4}$	$0.007^{+0.019}_{-0.007}$
Cosmic-ray muons	–	$0.11^{+0.20}_{-0.11}$	–
Expected background	0.46 ± 0.10	$0.11^{+0.20}_{-0.11}$	$0.007^{+0.019}_{-0.007}$
Observed events	0	0	0

- Results interpreted with GMSB model.

For 0.1 ns lifetime, the co-NLSP scenario is excluded for slepton mass up to 820 GeV.



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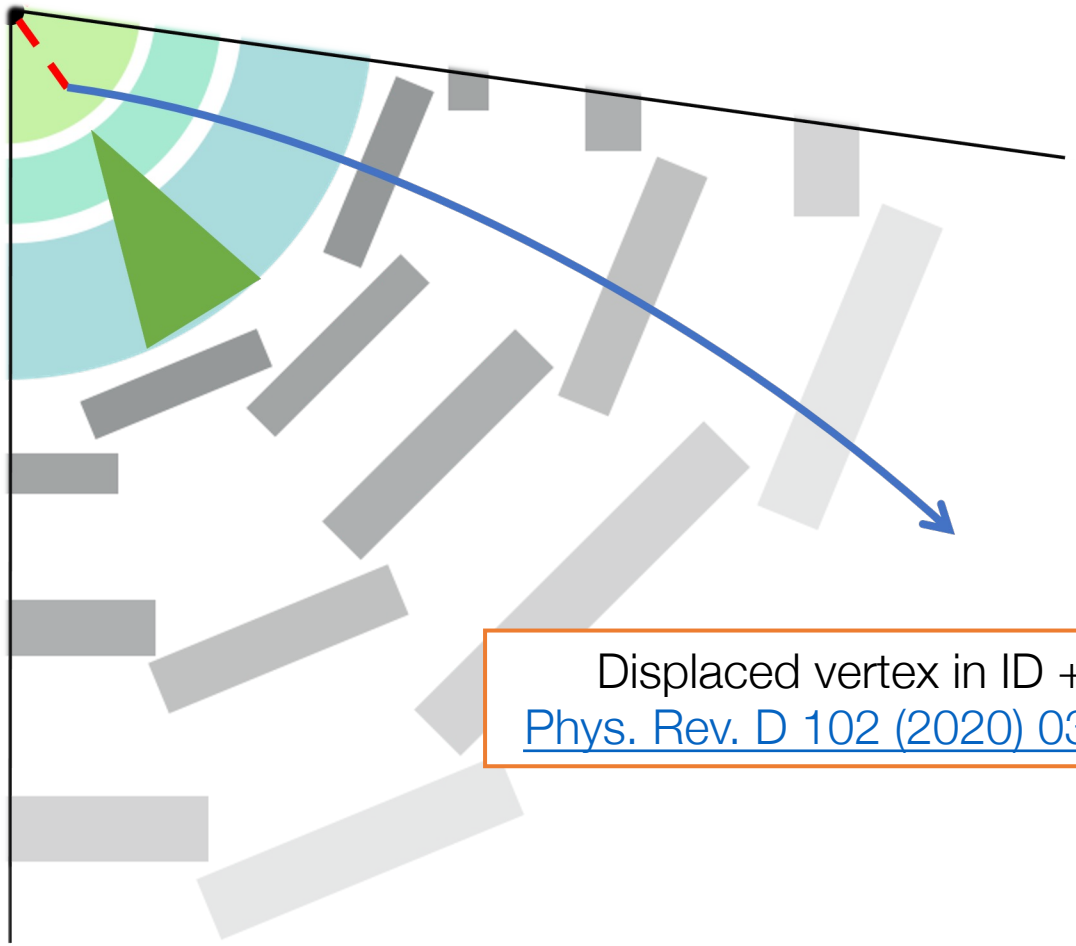


Displaced vertex in ID + μ
Phys. Rev. D 102 (2020) 032006

Lepton
Anything
BSM
Jet
Photon

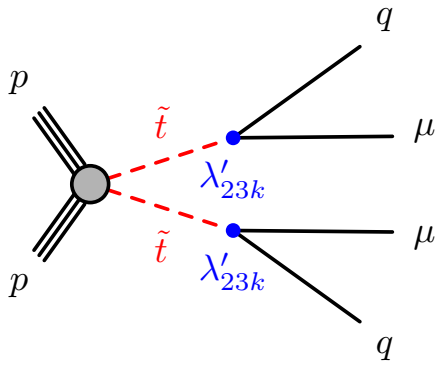
Displaced vertices in ID + μ

Phys. Rev. D 102 (2020) 032006

Search for a displaced muon and a displaced vertex

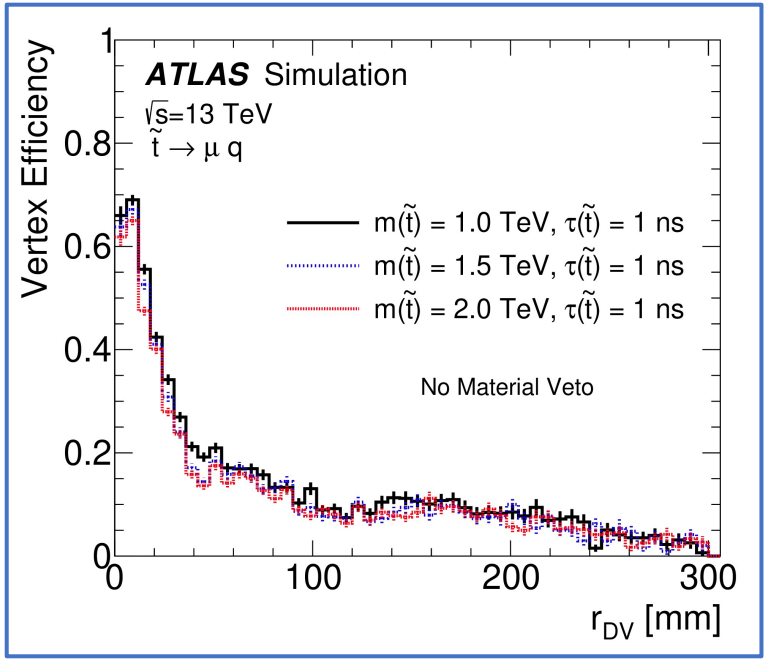
Motivation:

- Non-zero λ'_{23k} value would allow a top squark to decay into a muon and kth-generation down-type quark.
- If λ'_{23k} is sufficiently small and the top squark is the LSP, the top squark is long-lived.
- Strongest constrain on λ'_{23k} coupling comes from partial-width measurements of the Z boson at LEP.



Analysis Strategy:

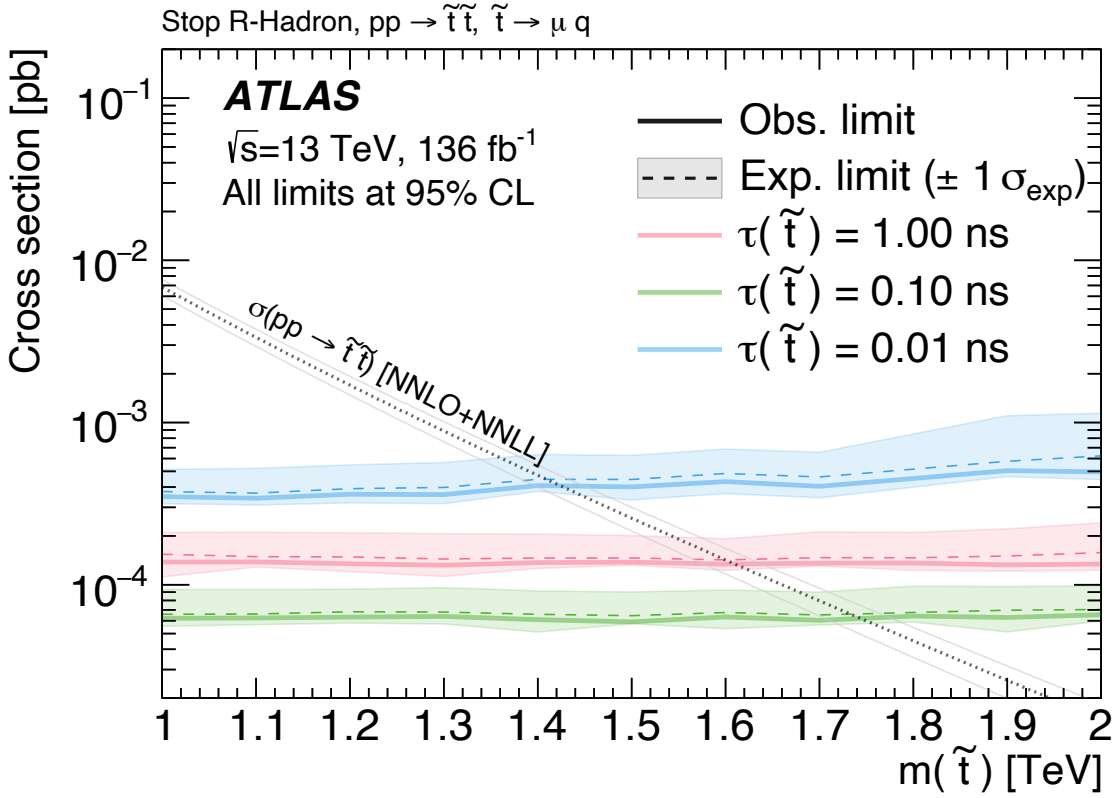
- Select events with E_T^{miss} triggers and muons with MS information.
- Reconstruct displaced tracks with large radius tracking (LRT).
- Displaced vertices should have $n_{tracks} \geq 3$ and $m_{DV} > 20$ GeV.
- Background from cosmics, heavy-flavour decays, hadronic interactions, etc. are estimated using dedicated CRs.

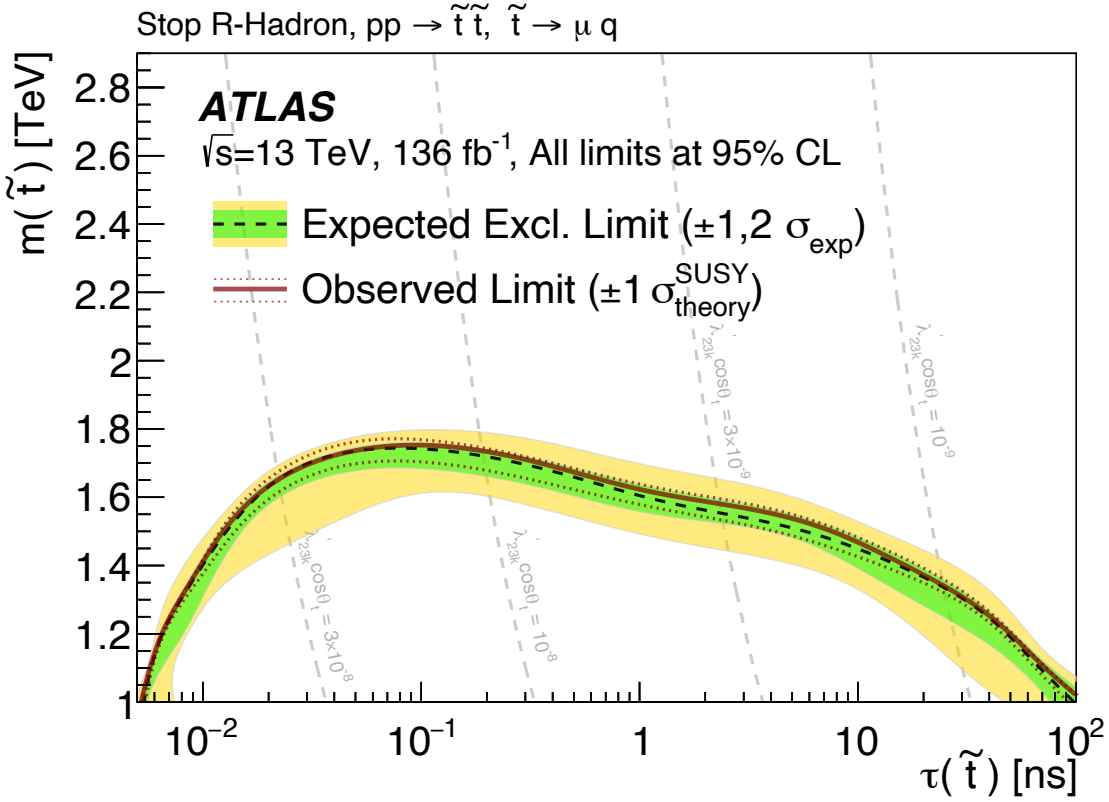


Vertex efficiency for DVs with the LRT algorithm

Displaced vertices in ID + μ—Results

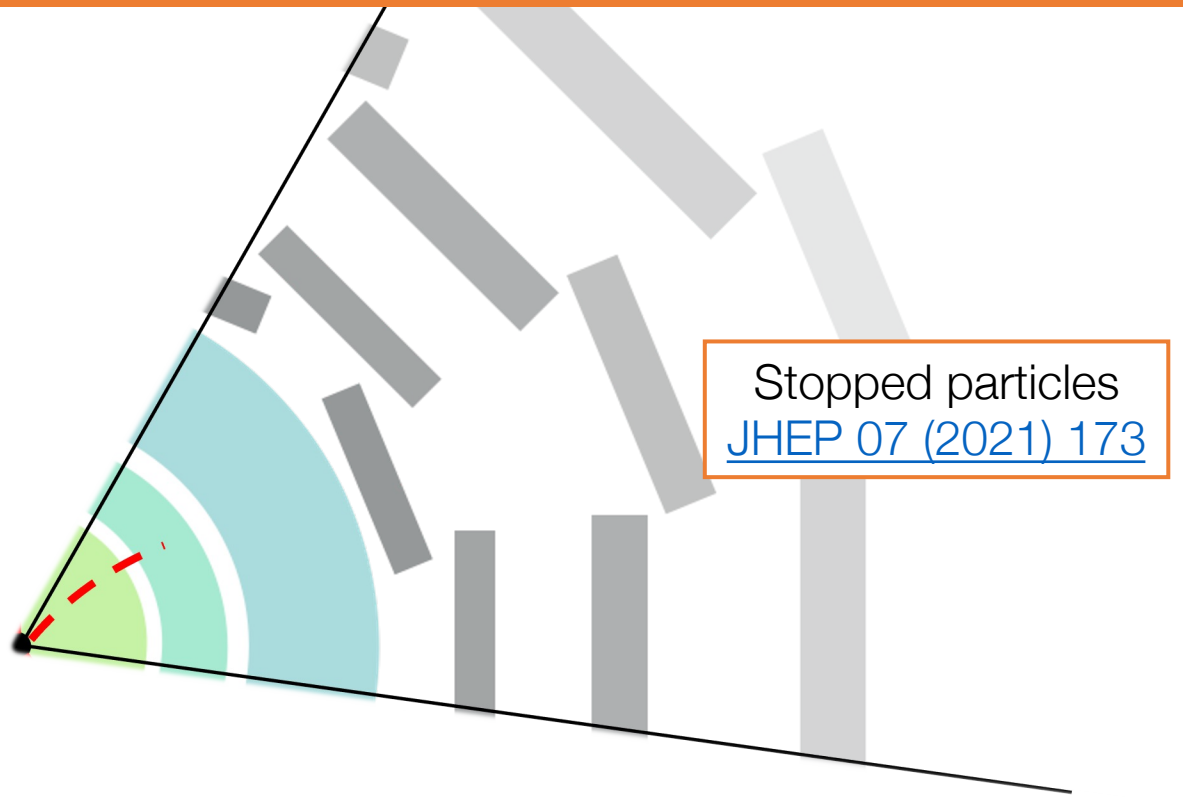
- No significant excess above background expectation.
- Results interpreted in context of stop pair production model.





Exclude stop mass below 1.7 TeV for 0.1 ns lifetime

Search program for LLPs in SUSY at ATLAS



Stopped particles
JHEP 07 (2021) 173

Lepton
Anything
BSM
Jet
Photon

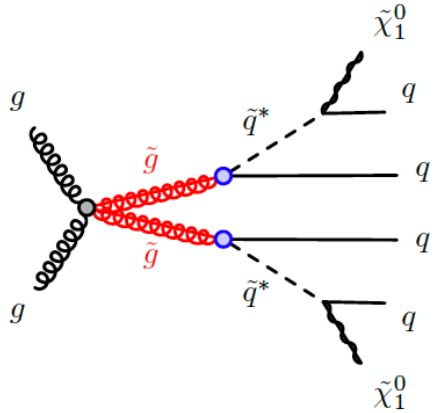
Stopped particles

JHEP 07 (2021) 173

Search for LLPs which have come to rest within the ATLAS calorimeters and decay later when no proton–proton (pp) collisions occur

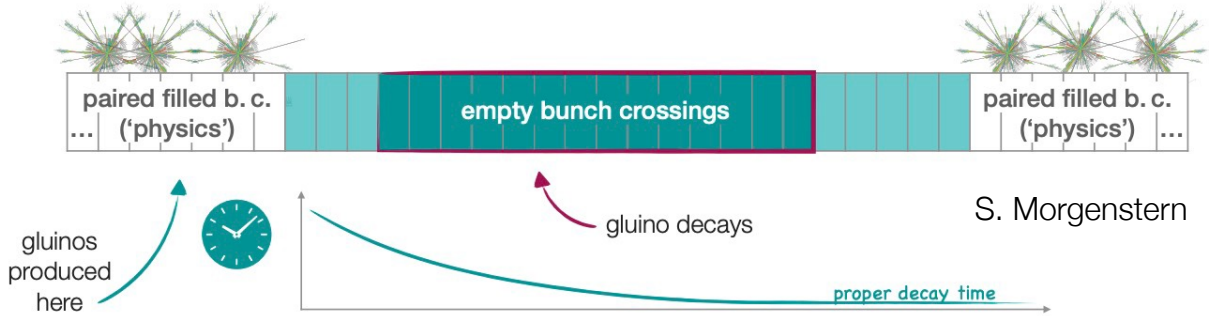
Motivation:

- Strongly interacting LLP can be produced in pp collisions which hadronizes into SM quarks and gluons.
- LLP can traverse the detector and loose enough energy to come to rest; "stopped" particle could then decay significantly later then the bunch crossing in which it was produced.
- Searching for **late decays to hadronic jets**; targeting lifetimes from **μs to years**.



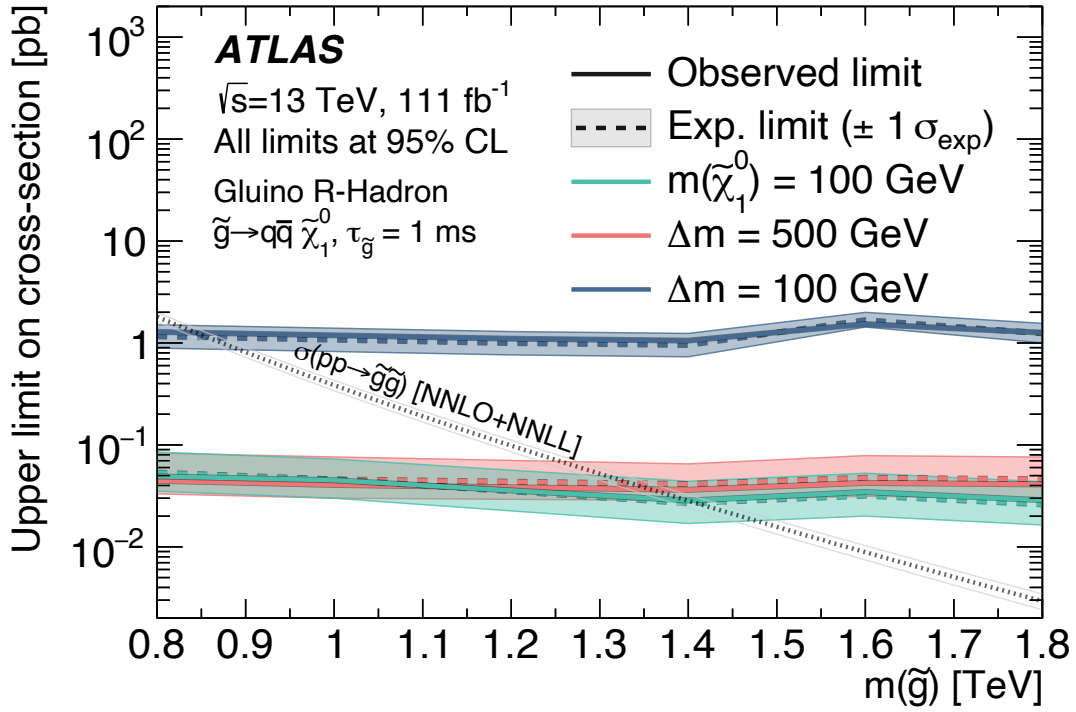
Analysis strategy:

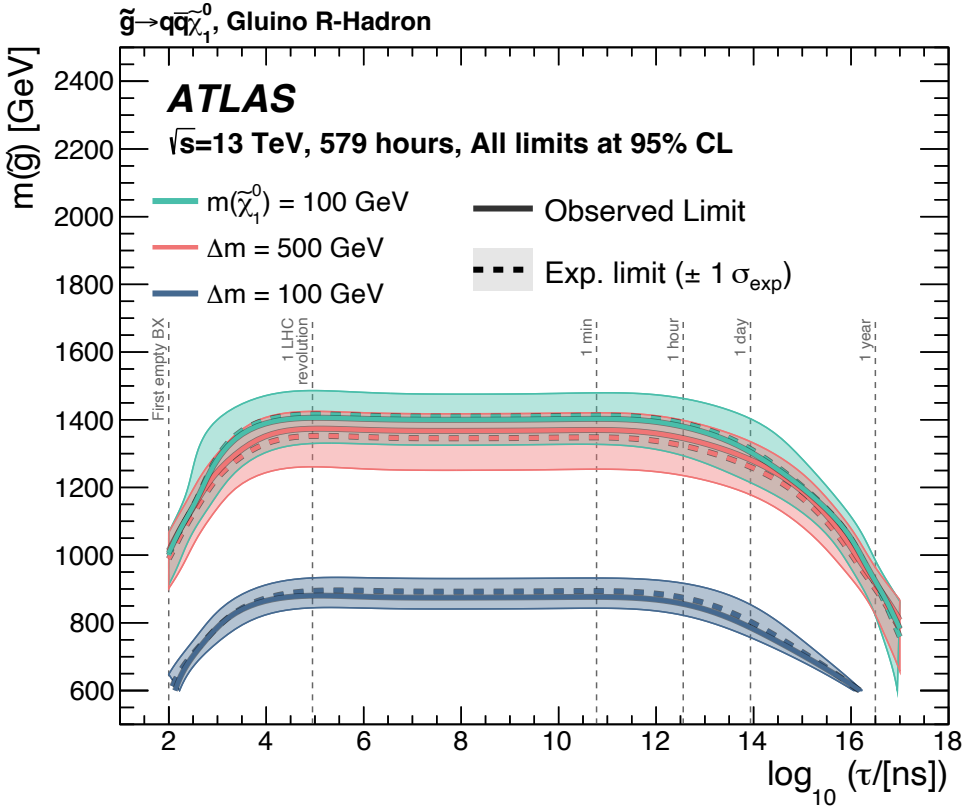
- Search for delayed decays in empty bunch crossings (BCs) ⇒ clean environment without background from pp collisions.
- Select events with at least one jet with $p_T > 90$ GeV.
- Background from cosmics and beam induced background (BIB) are estimated with data-driven techniques in dedicated CRs.



Stopped particles—Results

- No significant excess over background expectation.
- Results interpreted with split-SUSY simplified model with long-lived gluino, assuming $\mathcal{B}(\tilde{g} \to q\bar{q}\tilde{\chi}_1^0) = 100\%$

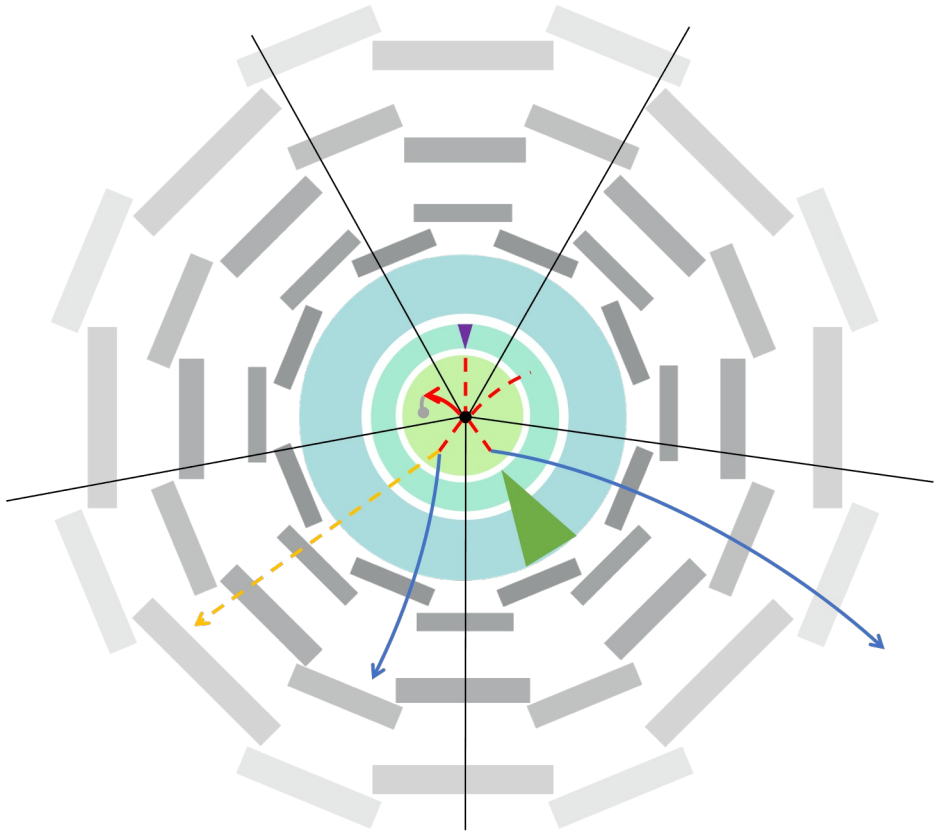




Gluino masses excluded up to 1.4 TeV for lifetime in range 10^{-5} – 10^{3} seconds.

Summary

- Comprehensive ATLAS search program for LLPs producing unique and unusual signatures.
- Several new results based on Run 2 dataset with more analyses in progress.
- Set strong constraints to-date on various parameters and simplified models.
- No evidence of LLPs yet, but lots to explore with Run 2 dataset and in Run 3.
- Substantial phase space still unexplored with exciting opportunities for new discoveries!

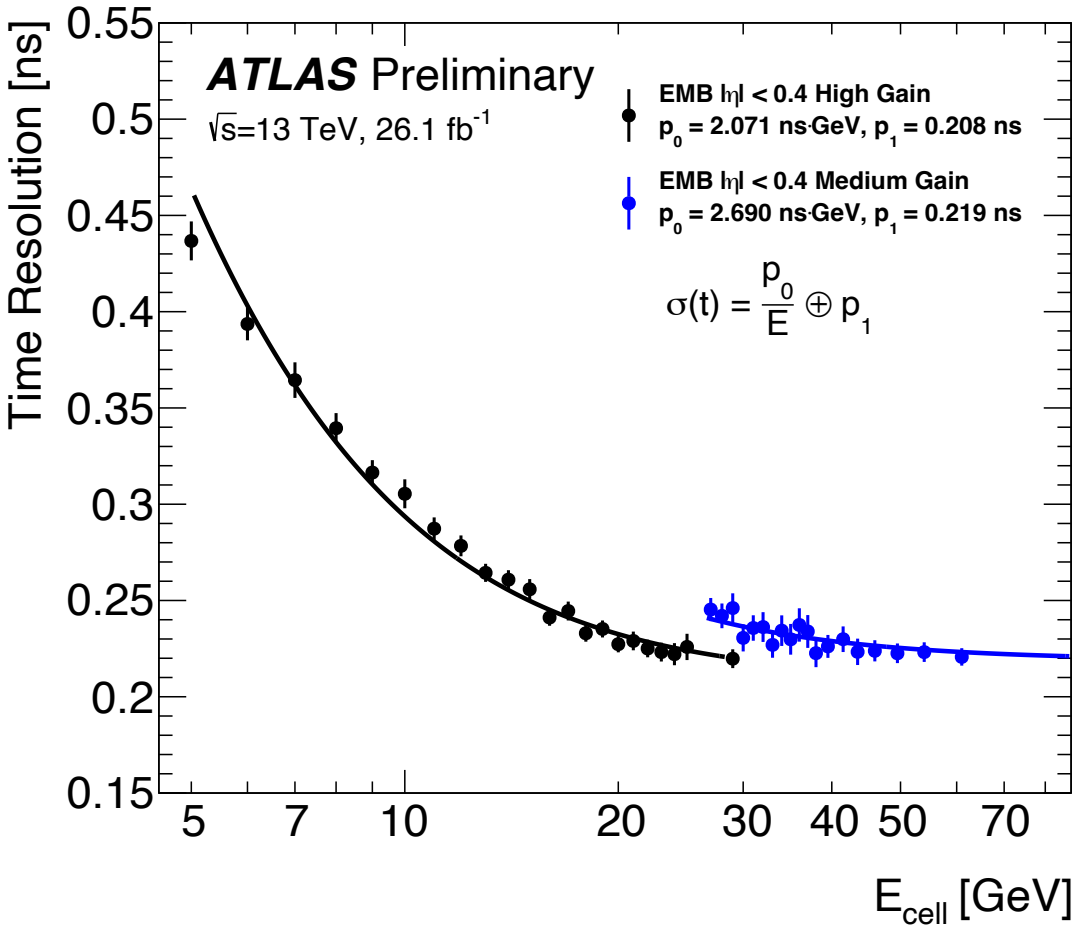


*Mittelhorn-Schreckhorn-Eiger panorama

Backup Slides

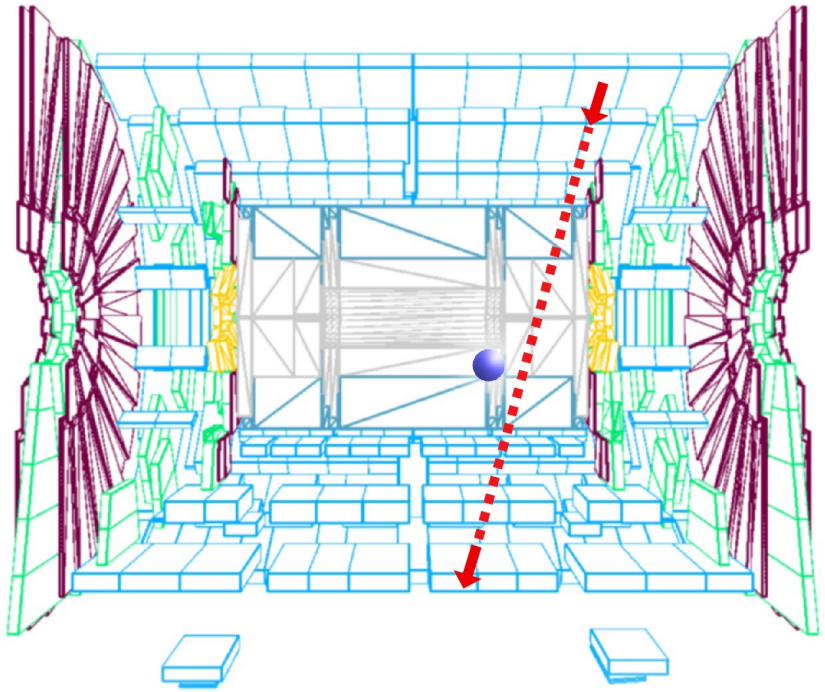
Non-pointing photons—Timing calibration

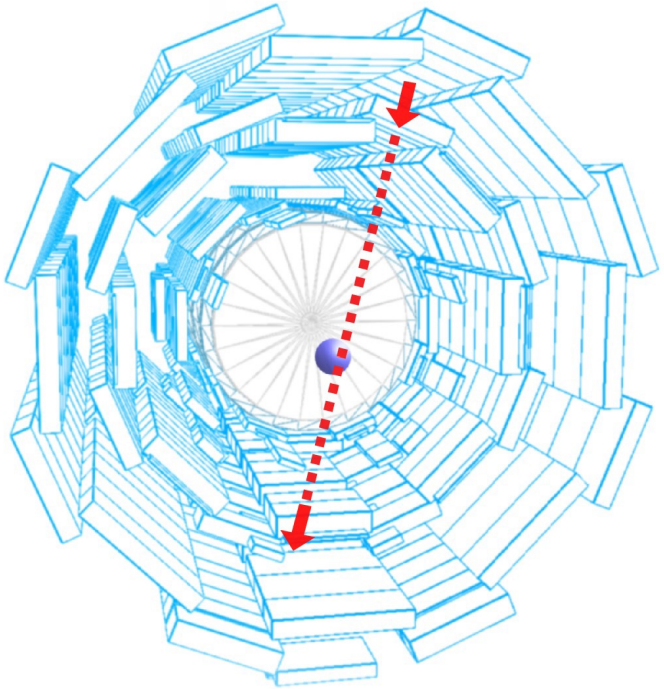
- Timing calculated using LAr optimal filtering coefficients (OFCs).
- Determined by the cell in the middle layer with maximum energy deposit (E_{cell}^{max}).
- Achieve ~1 ns online resolution; calibrate offline using $W \rightarrow e\nu$ / $Z \rightarrow ee$ to reach ~200 ps resolution (dominated by the beamspread).
- Dedicated offline timing tool to correct & smear EM timing in MC.

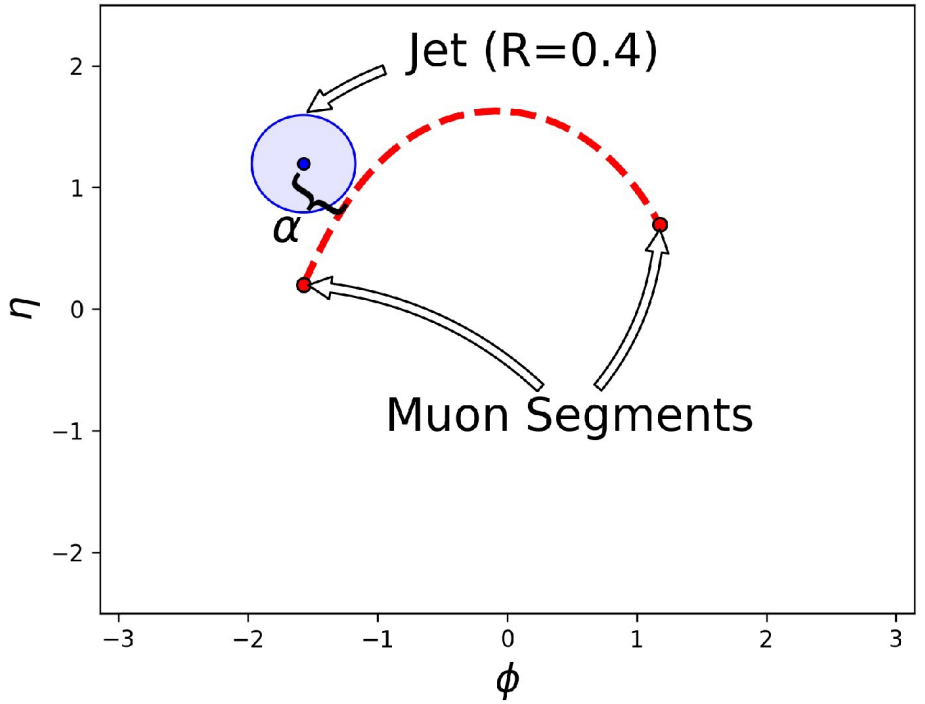


Stopped particles

- Schematic overview of the cosmic veto α:





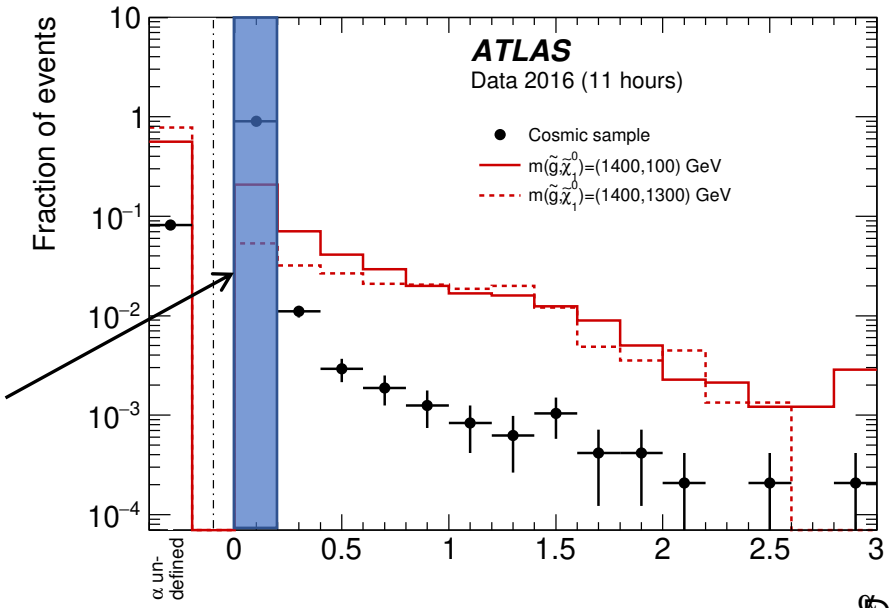


Stopped particles—Background Estimation

1. Cosmic rays: Traversing muon induces an energetic jet in the calorimeter.
2. Beam induced background (BIB): Beam protons interact with material upstream from detector.

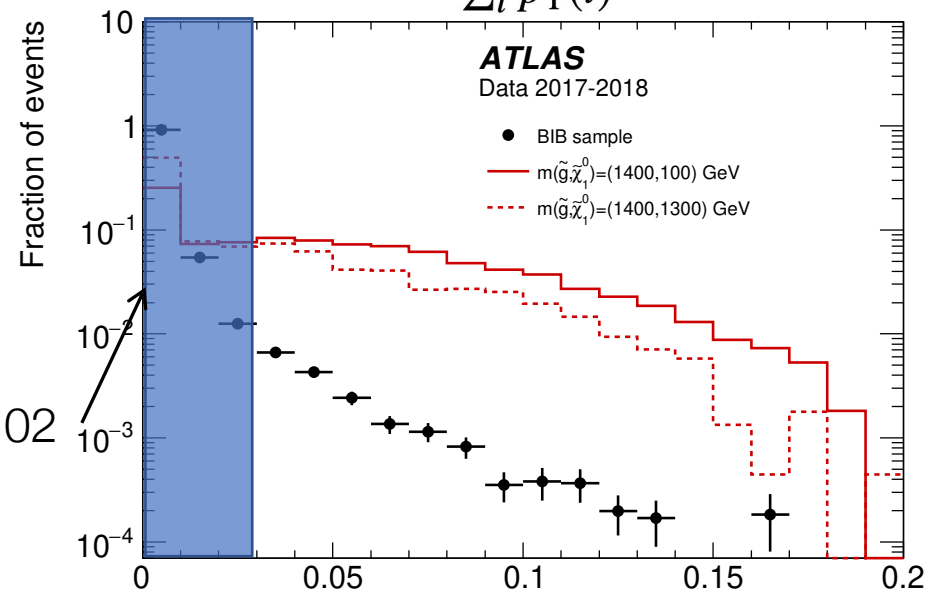
Construct templates of cosmic & BIB jet p_T from control regions.

α := minimum spatial distance between muon segment pairs and leading jet



veto α < 0.2

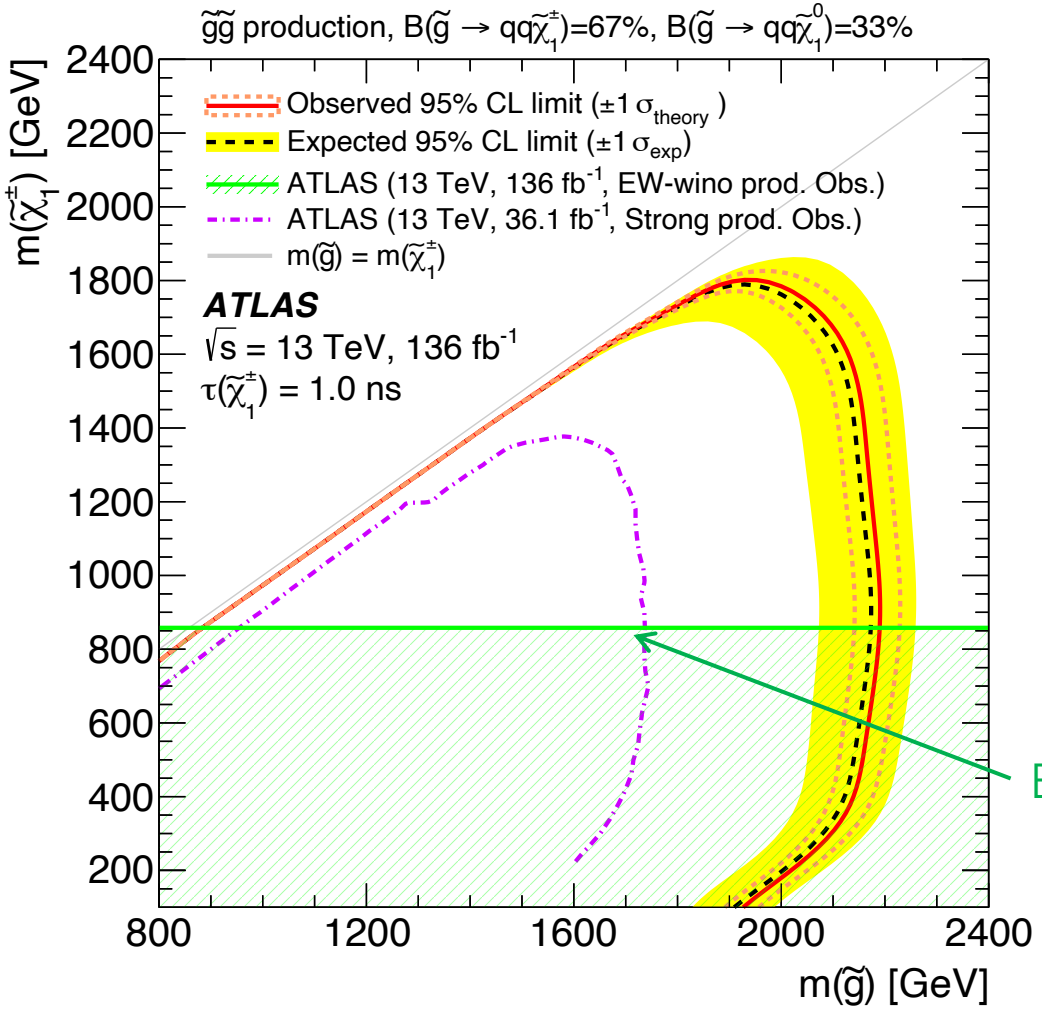
$$w_\phi = \frac{\sum_i p_T(i) \cdot |\Delta\phi(\text{jet}, i)|}{\sum_i p_T(i)}$$



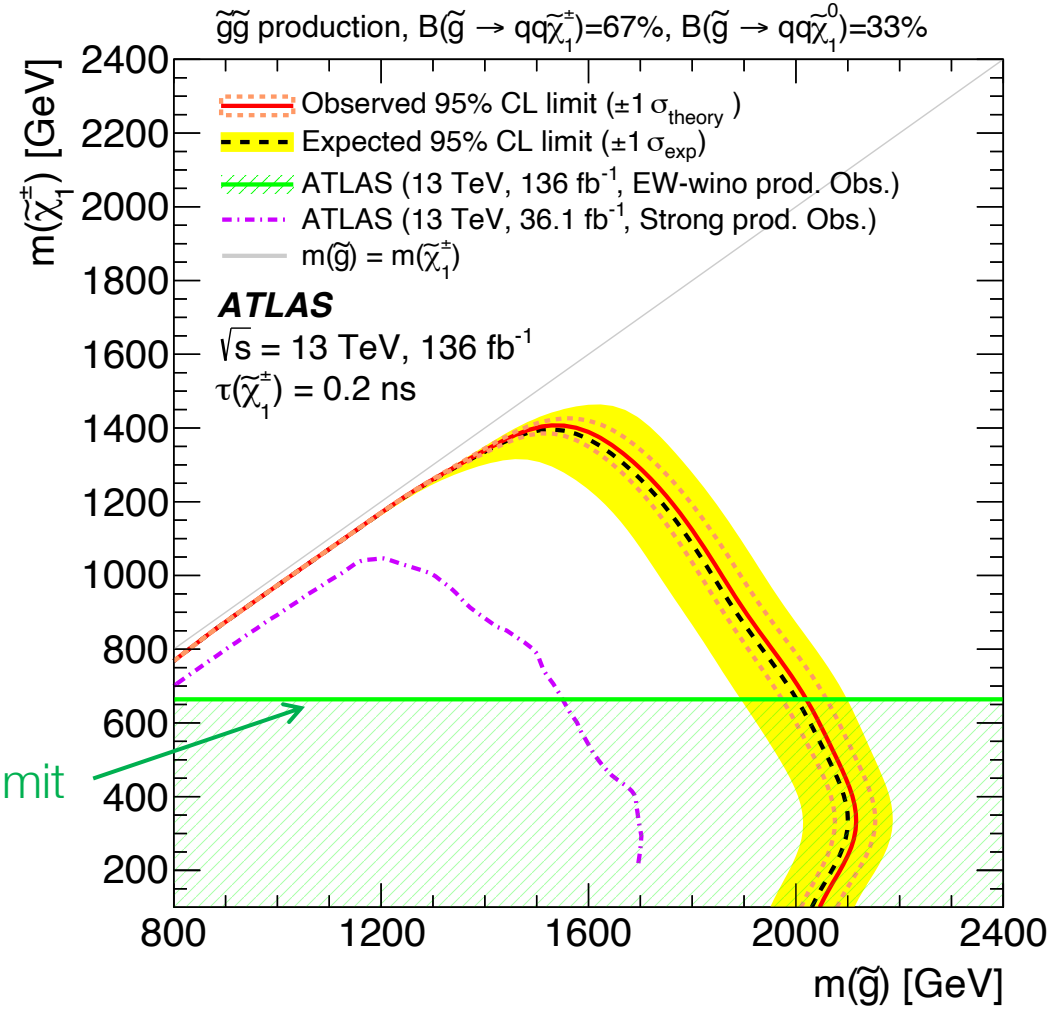
veto w_ϕ < 0.02

Disappearing tracks—Results

Exclusion limits on the strong production

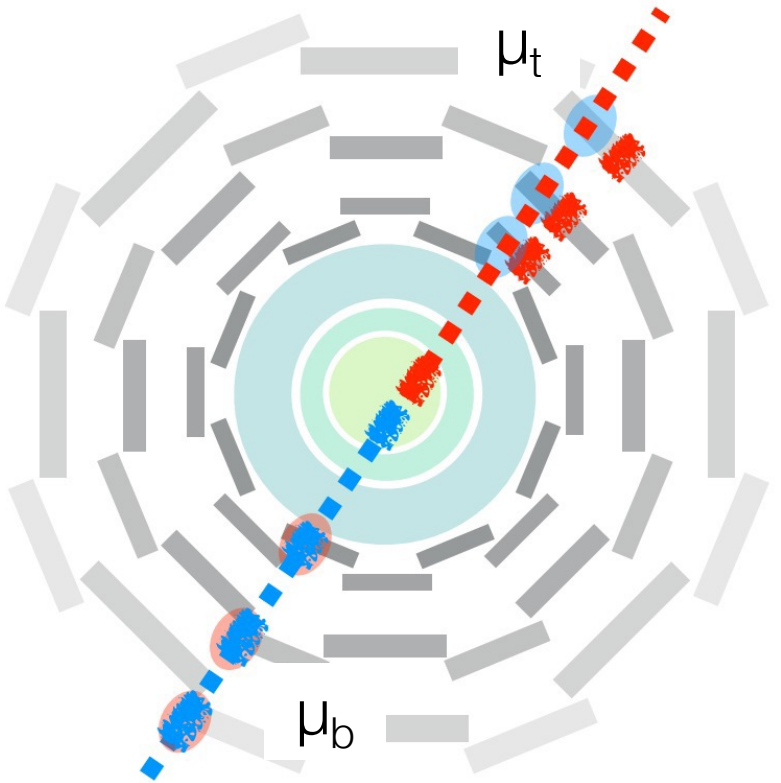


EW prod. obs. limit



Displaced Leptons

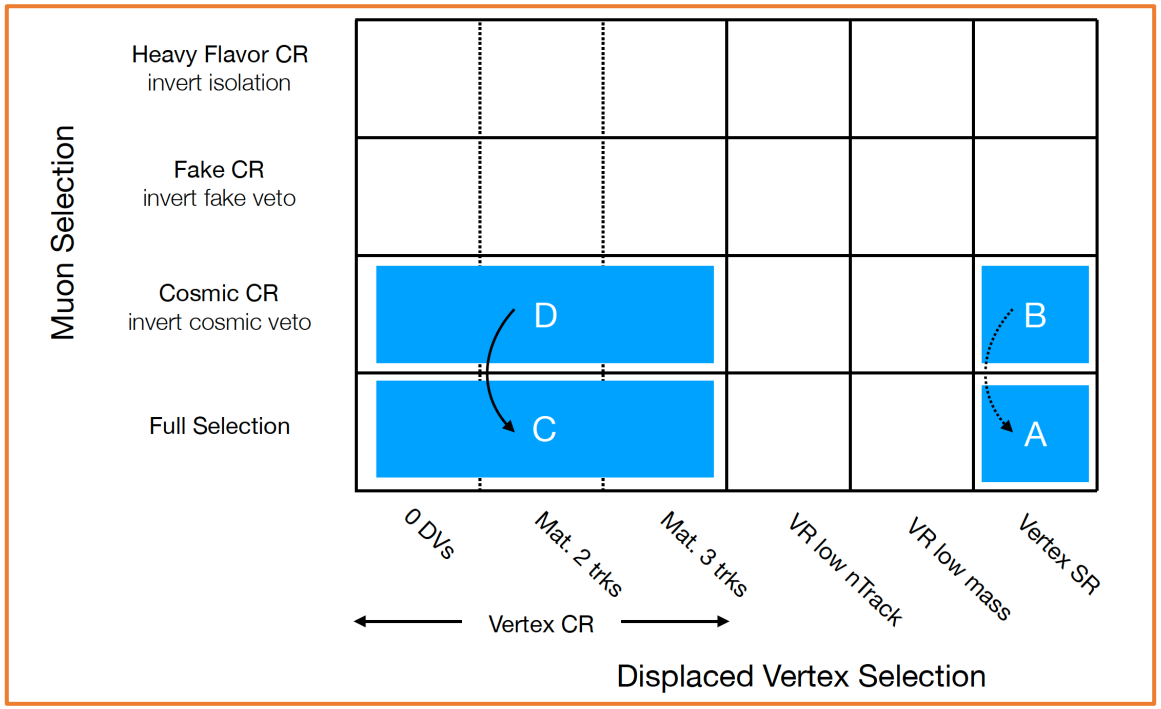
- To measure rate of mismeasured tracks in the SR-μμ channel,
  a scaling R_{good} is defined.
  - R_{good} is calculated for events where μ_t is cosmic tagged.
  - R_{good} = # events μ_t passes quality cuts / # events μ_t fails quality cuts
- Number of background events in SR-μμ:
  R_{good} x # events fail μ_t cosmic tag and fail at least one quality cut

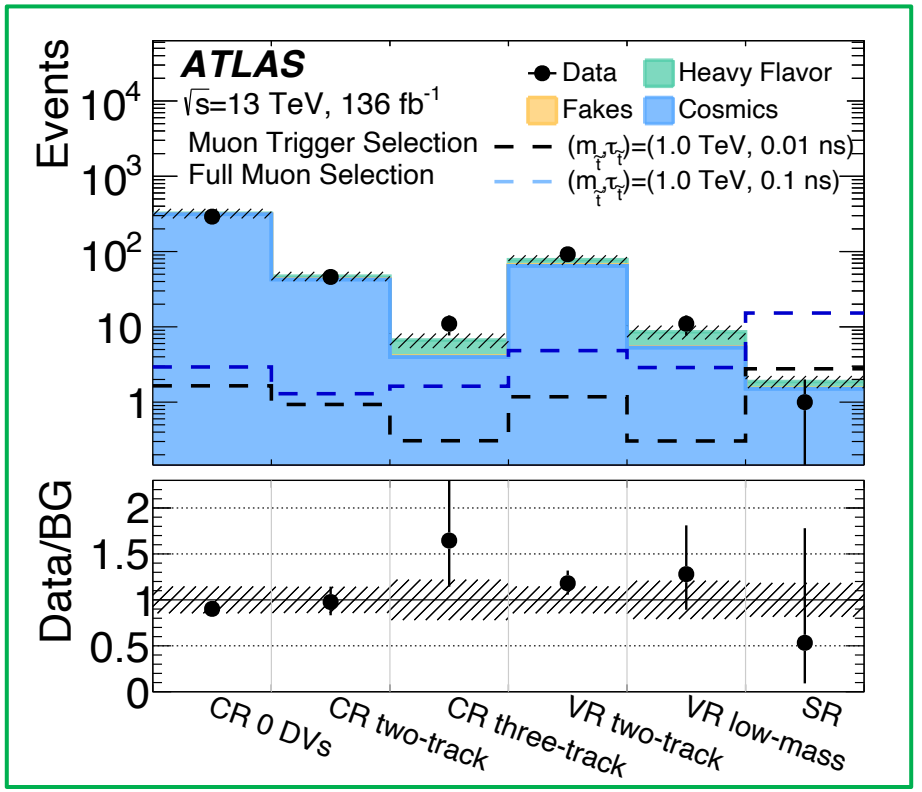


L. Horyn

Displaced vertices in ID + μ—Background Estimation

- Sources of muons: cosmics, heavy-flavor decays, fakes.
- Sources of DVs: hadronic interactions, random crossings, etc.
- Dedicated control regions for each background source to derive transfer functions using ABCD-like method.

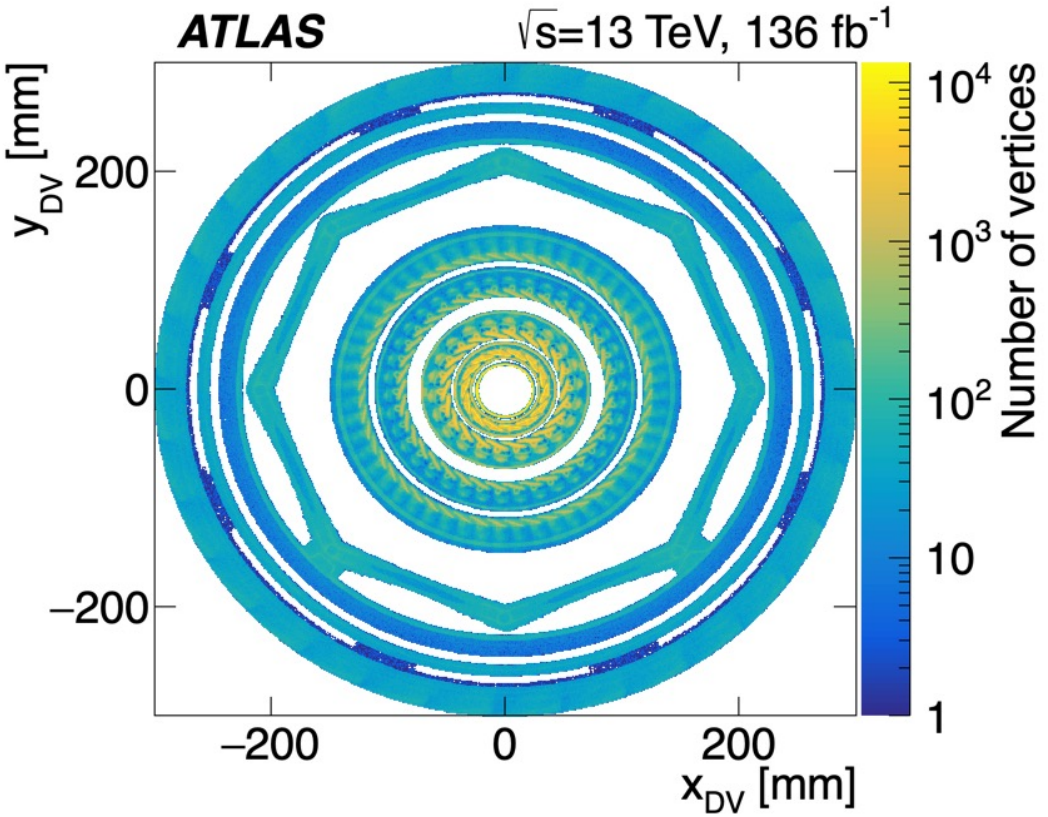




Good modelling of the DV and muon backgrounds

Displaced vertices in ID + μ

Veto DVs inside material



Background modeling in good agreement in the E_T^{miss} trigger selection