

Searches for SUSY particles with macroscopic lifetimes using the ATLAS detector

EPS-HEP
Ghent, July 10-17, 2019

Christian Ohm, on behalf of the ATLAS Collaboration



A popular SM extension: Supersymmetry

SUSY could

- ▶ Explain Dark Matter
- ▶ Alleviate the hierarchy problem
- ▶ Allow for gauge coupling unification

How?

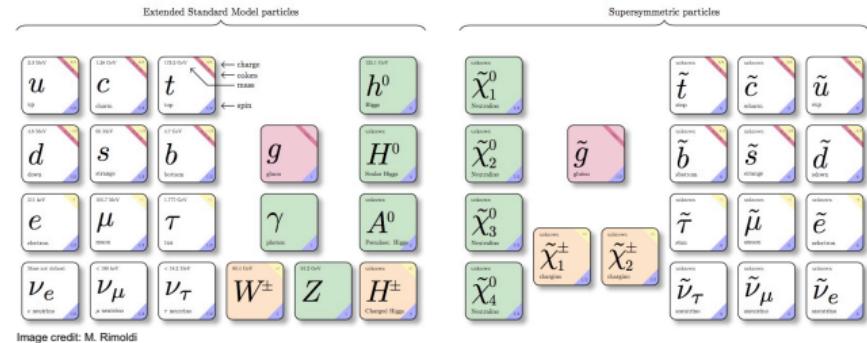
- ▶ Generalization of SM: symmetry between force and matter particles
- ▶ Introduces sfermions and gauginos
⇒ doubles particle content wrt SM

Sfermions: $q, \ell \longleftrightarrow \tilde{q}, \tilde{\ell}$

Gauginos: e.g. $g \longleftrightarrow \tilde{g}$

But...

- ▶ With ~ 100 free parameters \Rightarrow wide range of possible exp. signatures



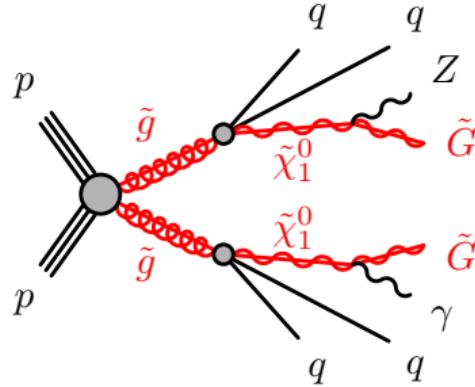
Mix of SUSY partners of electroweak and Higgs bosons is a WIMP. R -parity protects lightest SUSY particle from decaying, could be DM.

So, SUSY is *theoretically appealing, phenomenologically rich, and experimentally challenging!*

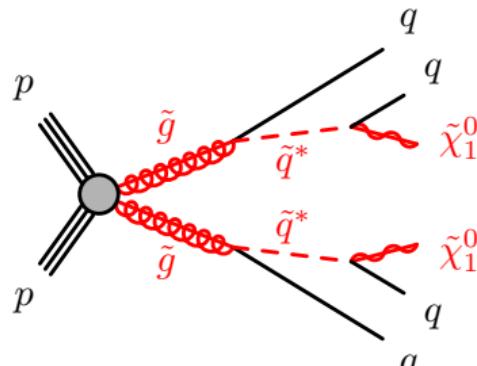
Long-Lived Particles (LLPs) in SUSY scenarios

LLPs arise if small ME and/or limited phase space for decay, i.e. for (nearly) mass-degenerate spectra, small couplings, highly virtual intermediate states (comprehensive reviews in [1810.12602](#) and [1903.04497](#))

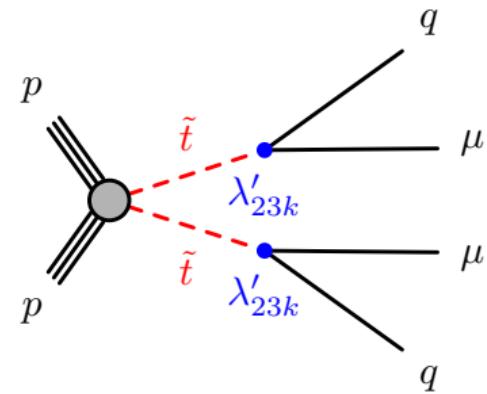
Gauge-Mediated
SUSY-Breaking: displaced Z
decays (see e.g.
[hep-ph/9601367](#))



Split SUSY \Rightarrow long-lived \tilde{g}
([hep-th/0405159](#), [1212.6971](#))



Small R -parity-violating
couplings \Rightarrow e.g. long-lived \tilde{t}
or $\tilde{\chi}^0$ ([hep-ph/0406039](#))

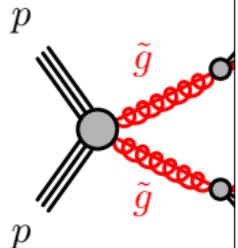


Many more not discussed here: e.g. co-annihilation scenarios $\tilde{B}-\tilde{g}$ ([1504.00504](#)), $\tilde{B}-\tilde{W}$ ([1506.08206](#)), AMSB, ... and of course many non-SUSY BSM models give rise to similar signatures!

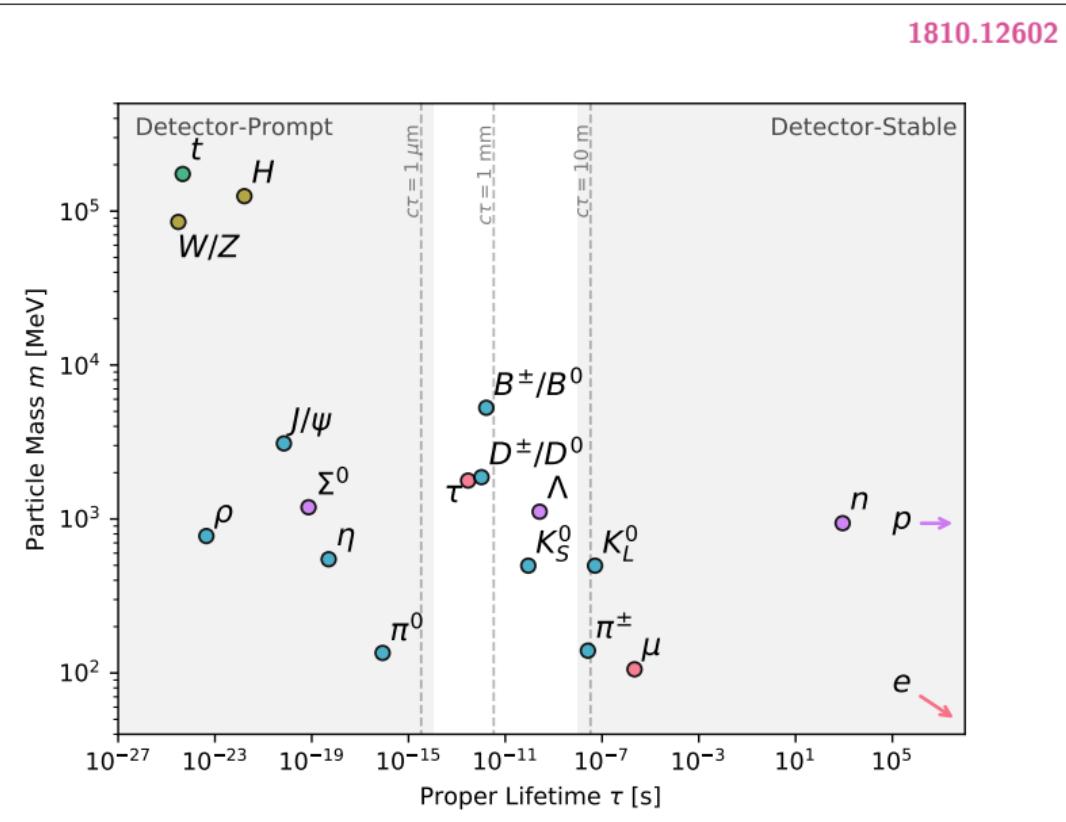
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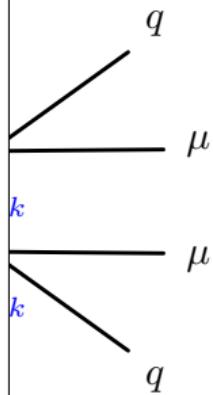


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AMSB



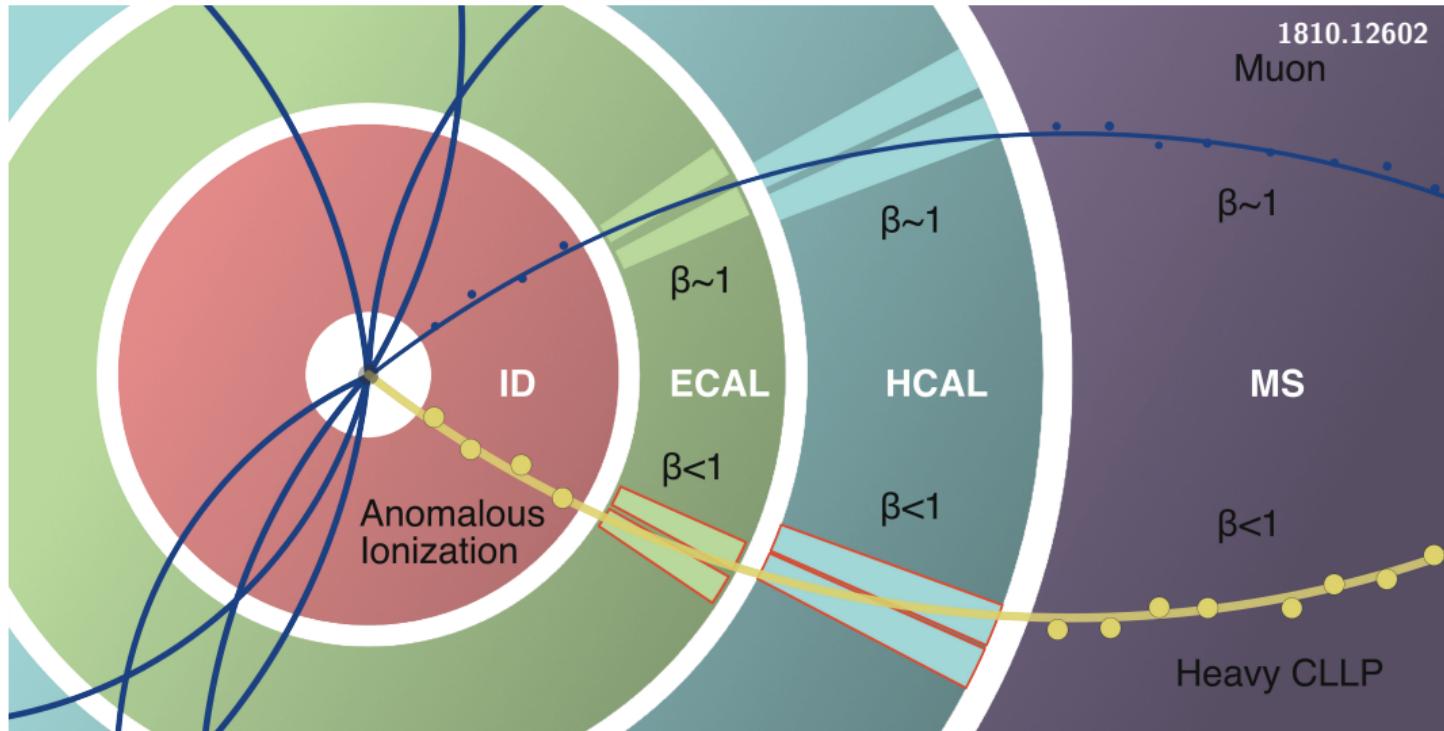
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[6039](#))



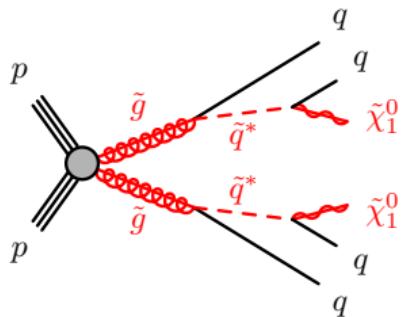
[16.08206](#)),
res!

Direct detection of Charged LLP (CLLP): $\beta < 1$ and large dE/dx



Search for heavy charged LLPs (36 fb^{-1}) (Phys. Rev. D 99 (2019) 092007)

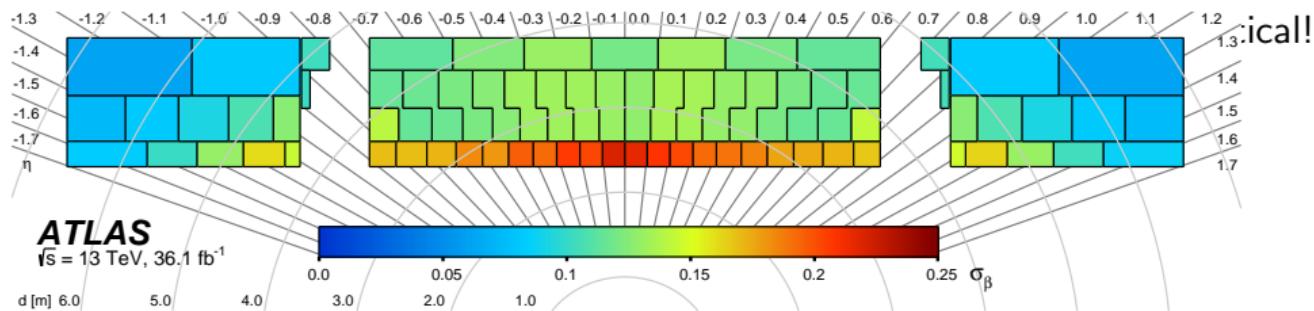
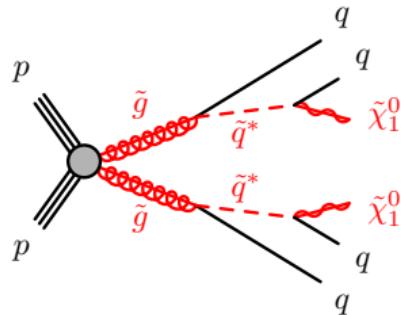
- ▶ LLP search based on direct detection
- ▶ Targets R -hadrons ($\tilde{g}, \tilde{t}, \tilde{b}$), and long-lived $\tilde{\ell}/\tilde{\chi}^\pm$



- ▶ Selection
 - ▶ Trigger: E_T^{miss} or muon
 - ▶ LLP candidate: isolated high- p_T track
 - ▶ Combine p with β (from MS and Tile) and dE/dx from Pixels for mass estimates
 - ▶ Signal region: window in 2D mass plane
- ▶ Backgrounds
 - ▶ No physics bg - only instrumental effects!
 - ▶ PDFs of variables constructed from β and dE/dx measurements extracted from side-band data \Rightarrow expected SR yield
- ▶ Low-level detector calibration critical!
 - ▶ Timing resolution with muons
 - ▶ dE/dx with low- p SM hadrons

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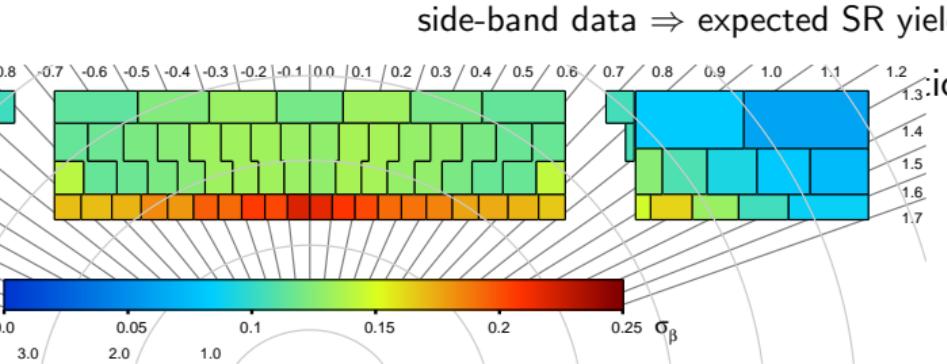
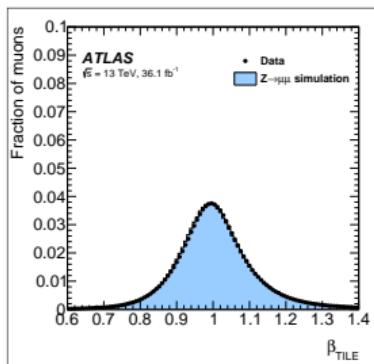
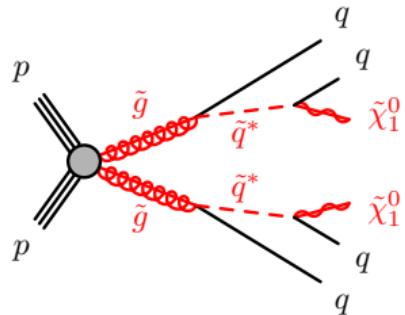
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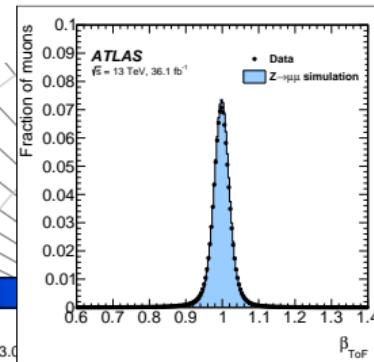
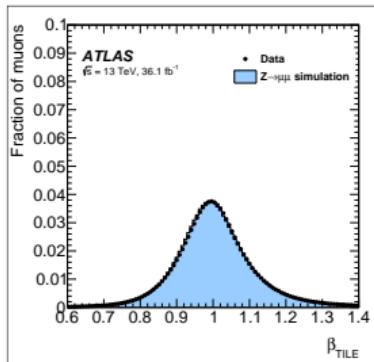
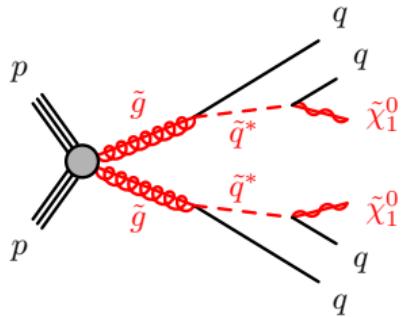
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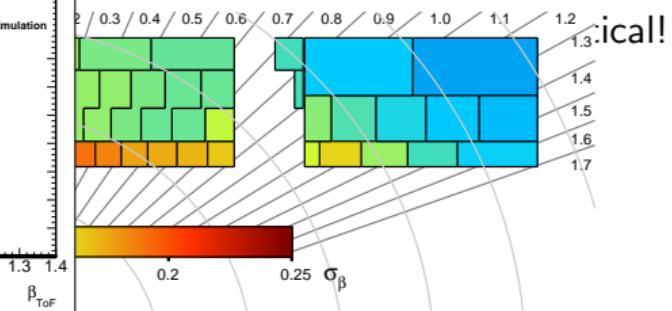


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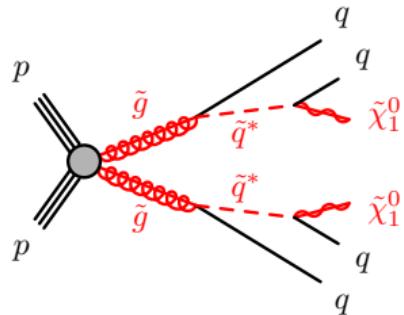
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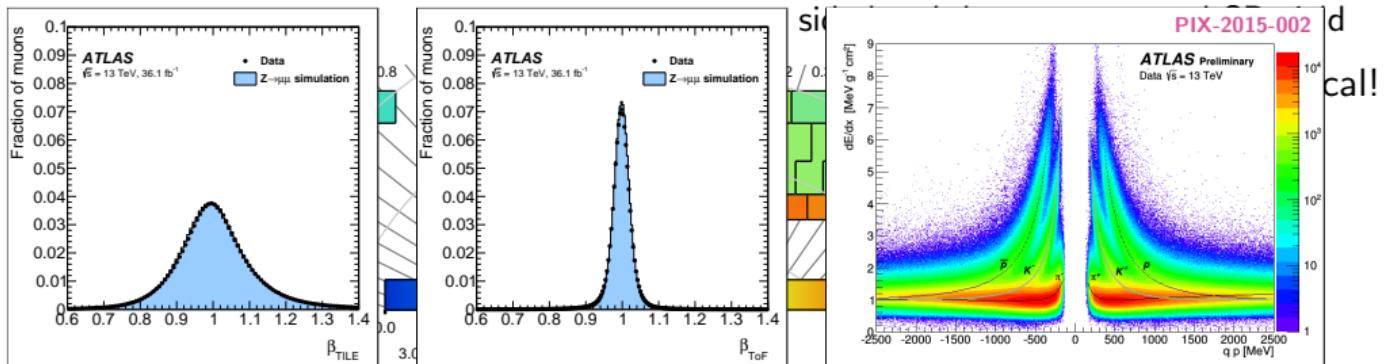


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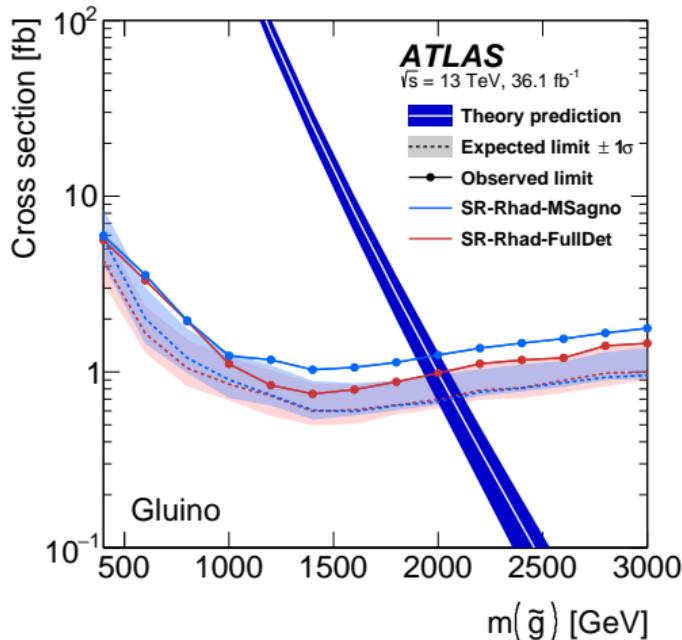
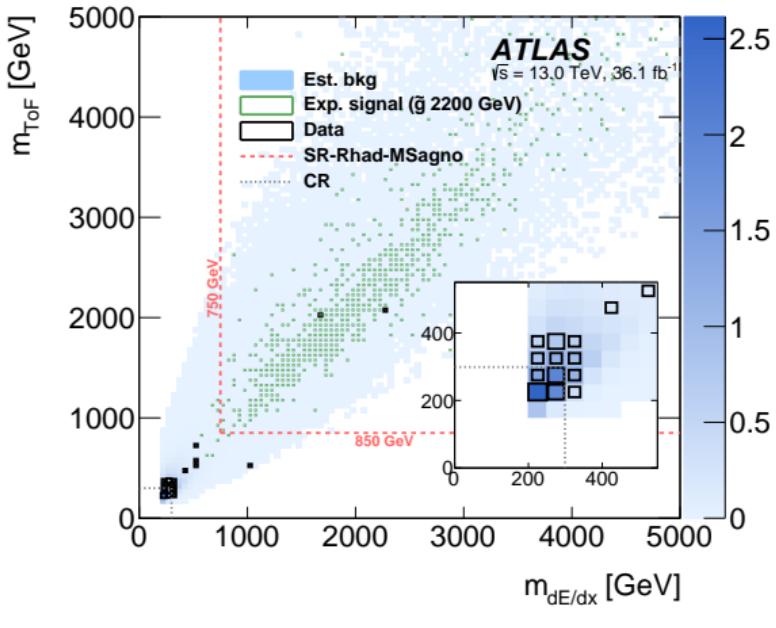
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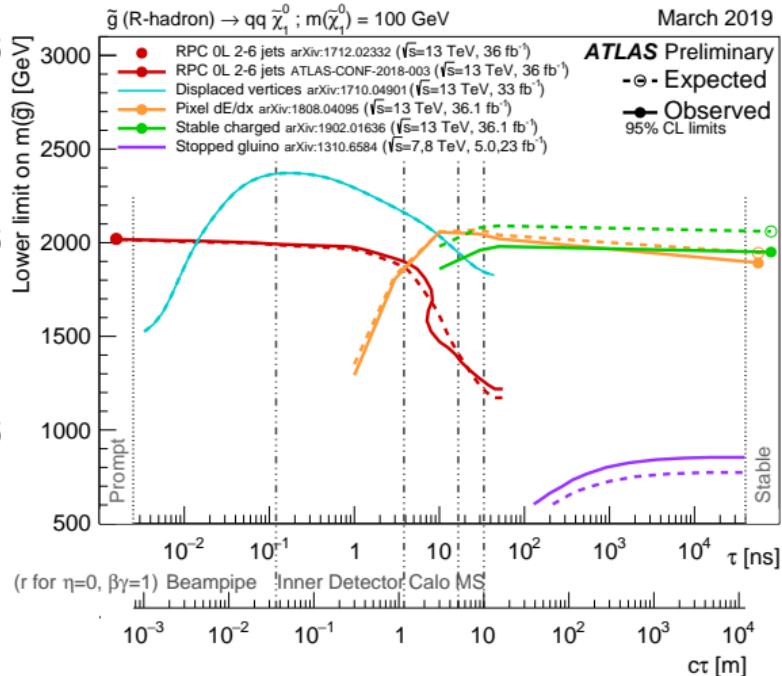
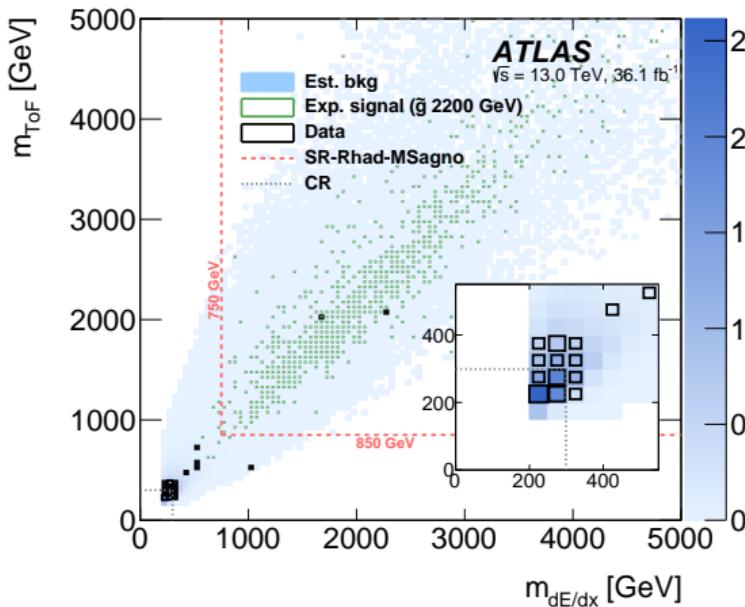


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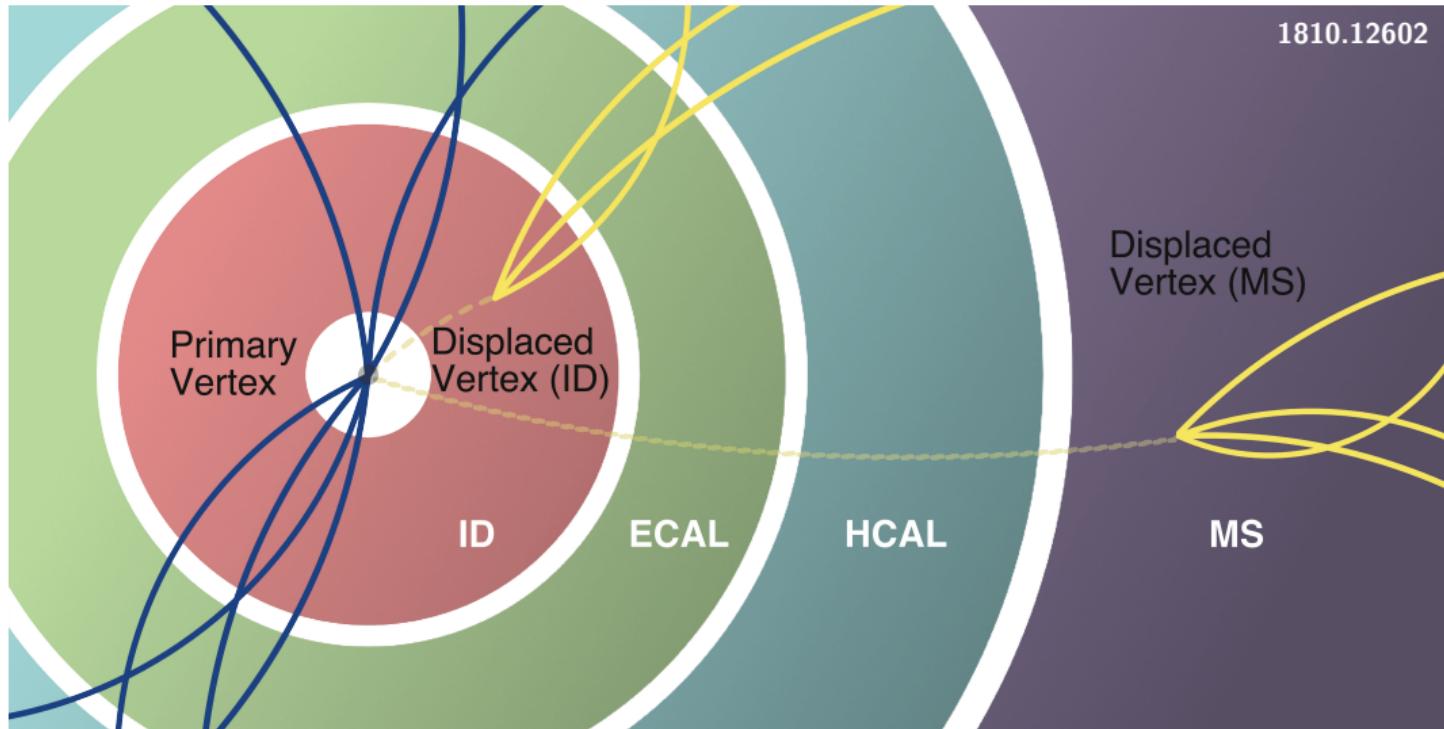
Analysis also has SRs for signature requiring signal in MS, and requiring two candidates per event excluding directly produced $\tilde{\chi}^\pm$ and $\tilde{\ell}^\pm$ below 1070 GeV and 420 GeV, respectively

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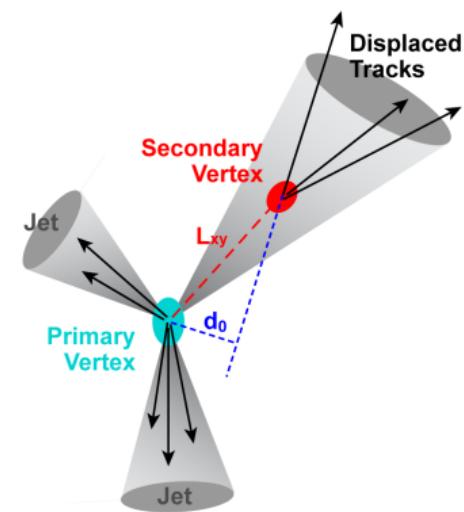
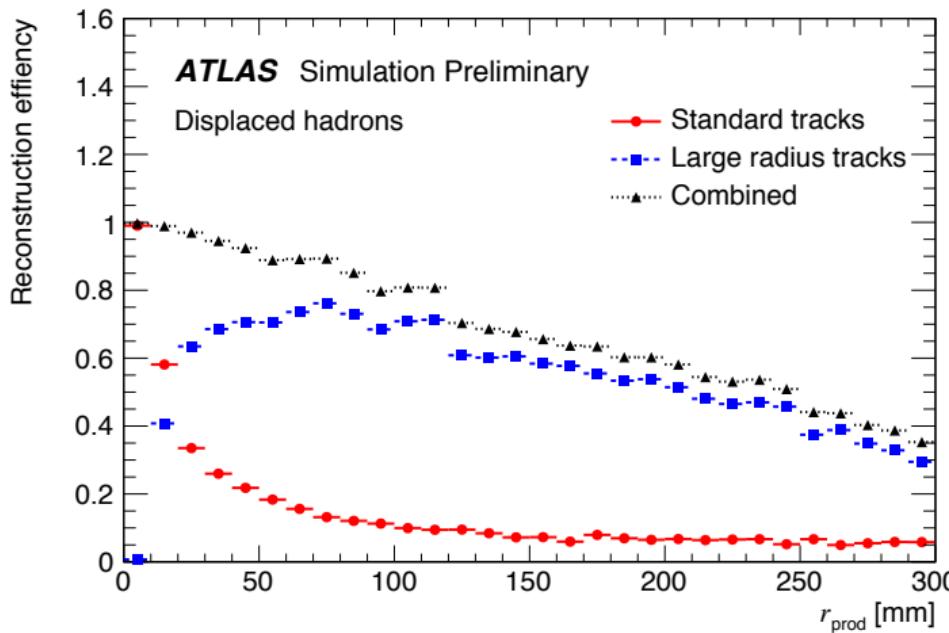
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Indirect detection of LLP: Displaced Vertex (DV)



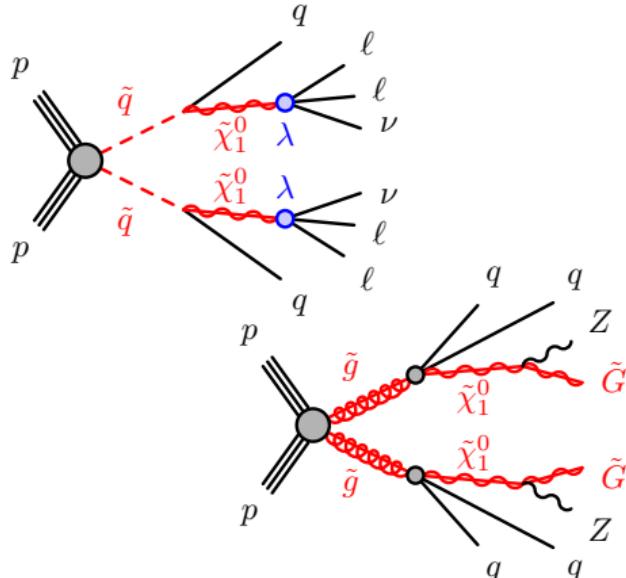
Need dedicated **track reconstruction** to exploit ID DV signature

- ▶ Dedicated second-pass “large-radius” tracking with relaxed d_0 and z_0 requirements, runs on unused hits: [ATL-PHYS-PUB-2017-014](#)
- ▶ Improves performance dramatically for displaced decays - especially for low-mass vertices.



Search for displaced dilepton decays in ID (33 fb^{-1}) (BRAND NEW!)

- Brand new search for displaced e^+e^- , $\mu^+\mu^-$ or $e^\pm\mu^\mp$ vertex in the ID!
- Designed to be model-independent, motivated by e.g. RPV and GMSB



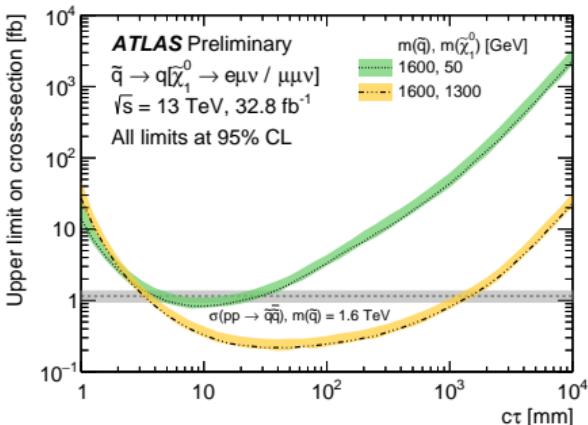
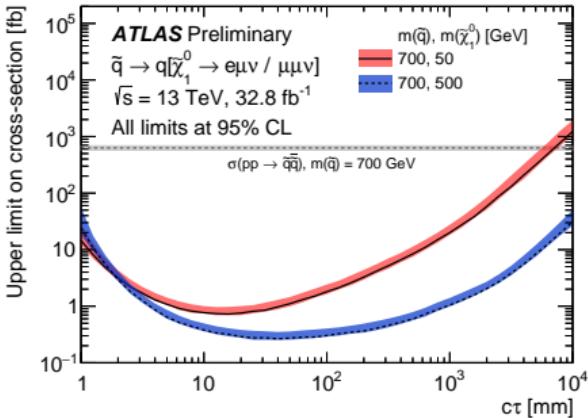
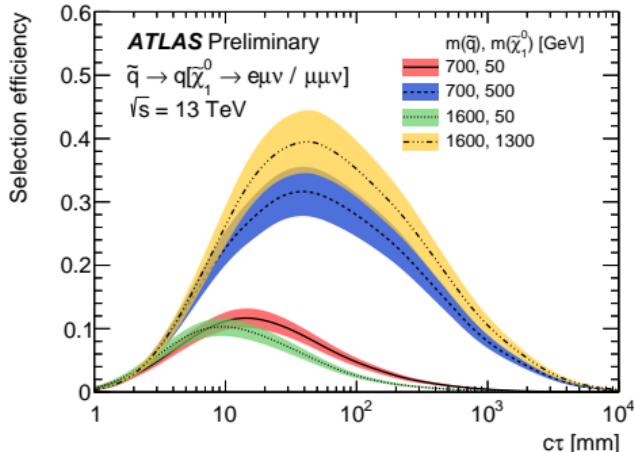
Selection outline

- Trigger: high- p_T photon or muon (no ID-track requirements)
- Two leptons w/ $p_T > 10 \text{ GeV}$ forming displaced $\ell^+\ell^-$ vertex with
 - $\Delta R_{xy} > 2 \text{ mm}$ to all PVs
 - Not inside regions with material
 - Quality requirements
 - $R_{xy} < 300 \text{ mm}$ and $|z| < 300 \text{ mm}$
 - $m_{\text{DV}} > 12 \text{ GeV}$

Backgrounds (extracted from data):

- cosmic muons (suppressed by ΔR cut)
- randomly crossing tracks in ID
⇒ total $\mathcal{O}(1)$ event expected

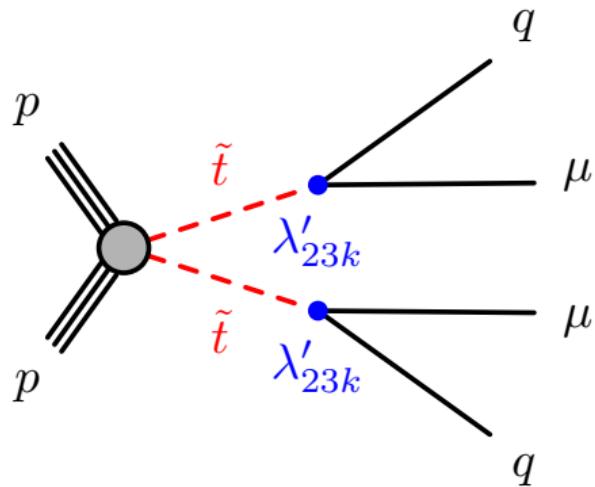
Search for displaced dilepton decays in ID (33 fb^{-1}) (BRAND NEW!)



- ▶ Acceptance \times efficiency: 10–40% (similar for $ee, e\mu, \mu\mu$)
- ▶ Sweet-spot in τ depends on mass/boost
- ▶ Larger $m_{\tilde{\chi}_1^0} \Rightarrow$ higher eff.

Displaced muon and displaced vertex (ATLAS-CONF-2019-006)

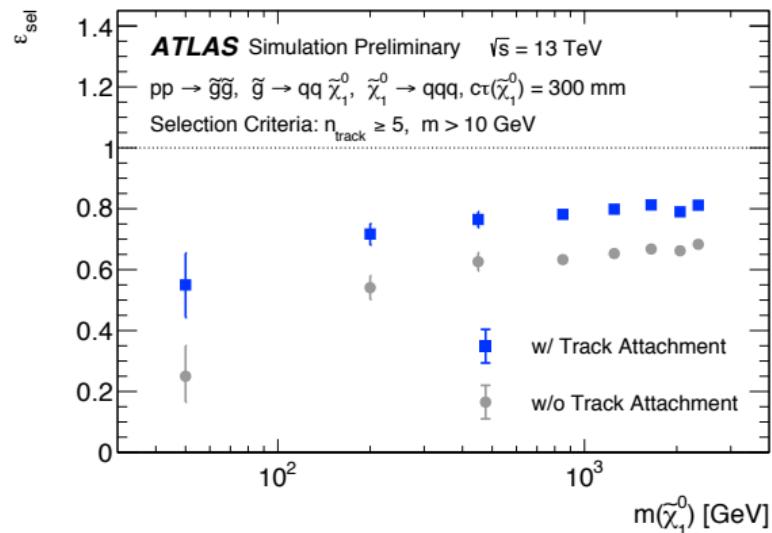
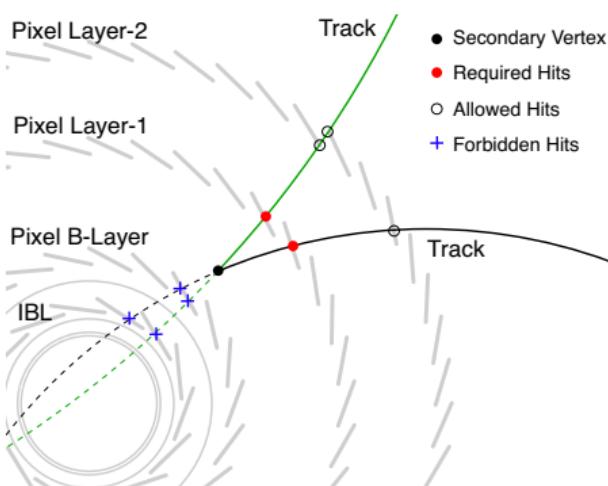
- ▶ LLP result using full Run-2 dataset (136 fb^{-1})
- ▶ Target: Long-lived \tilde{t} decaying through small RPV coupling λ'_{23k} (LQD term)
- ▶ TeV-scale stop alleviates hierarchy problem

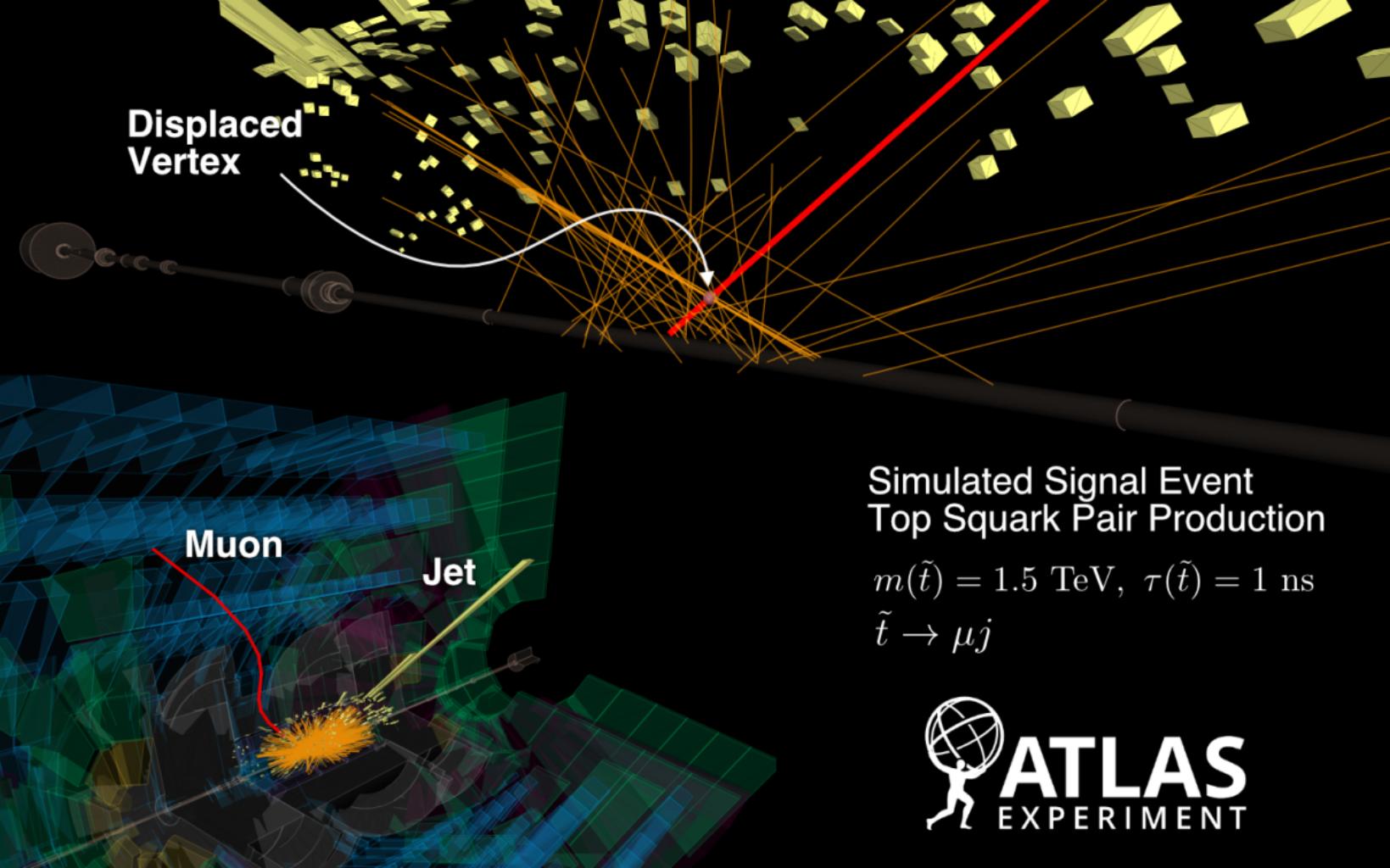


- ▶ Trigger on E_T^{miss} - muons invisible in trigger-level E_T^{miss} or MS-only muon
- ▶ Require at least one displaced muon and one displaced vertex satisfying
 - ▶ In fiducial volume:
 $R < 300 \text{ mm}$, $|z| < 300 \text{ mm}$
 - ▶ $n_{\text{tracks}} \geq 3$
 - ▶ $m_{\text{DV}} > 20 \text{ GeV}$
- ▶ Backgrounds: hadronic interactions (suppressed by material veto), randomly crossing tracks, cosmic muons, but b -jets more relevant
⇒ but here we have **two** separate handles, DV and muon - simplifies bg estimation ("ABCD" method)

Uses improved secondary vertexing algorithm (ATL-PHYS-PUB-2019-013)

- ▶ Improves performance dramatically - especially for most challenging scenarios with low-mass LLPs giving displaced vertices with low track multiplicities!





Displaced
Vertex

Muon

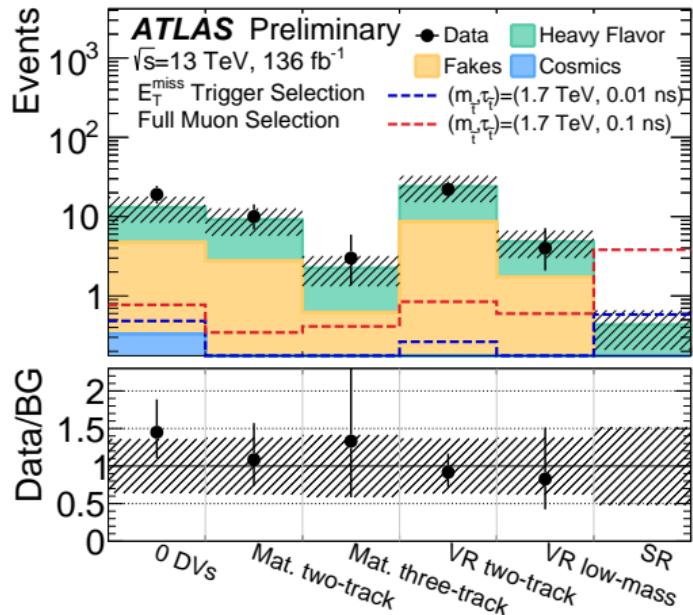
Jet

Simulated Signal Event
Top Squark Pair Production

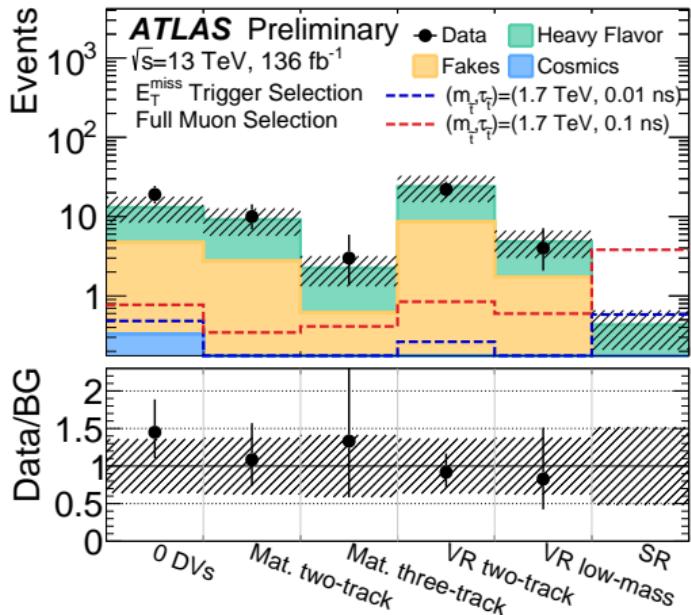
$m(\tilde{t}) = 1.5 \text{ TeV}$, $\tau(\tilde{t}) = 1 \text{ ns}$
 $\tilde{t} \rightarrow \mu j$



Displaced muon and displaced vertex (ATLAS-CONF-2019-006)

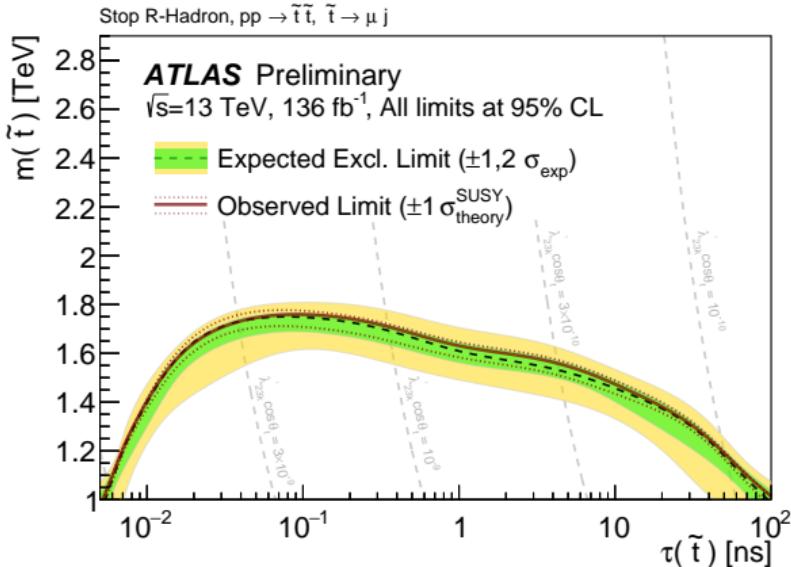


Displaced muon and displaced vertex (ATLAS-CONF-2019-006)



Long-lived stops excluded for masses up to 1.75 TeV!

$$\tau(\tilde{t}) = \frac{16\pi}{m(\tilde{t}) [\lambda'_{23k} \cos \theta_t]^2} \Rightarrow \text{limits on } \lambda'_{23k} \cos \theta_t \text{ vs. mass!}$$



Summary

- ▶ Long-lived particles give spectacular detector signatures without irreducible physics backgrounds - but challenging, the LHC experiments were not designed for LLPs
- ▶ Three recent LLP searches targeting SUSY scenarios presented here, see also Emma Torro's talk this morning for more ATLAS LLP results
- ▶ Parameterized efficiencies (becoming) available for all, allowing our pheno friends to reinterpret our results with particle-level simulations of their favorite models!
- ▶ LLP searches often require significant effort in trigger, reconstruction and simulation (see public notes on tracking, vertexing, *R*-hadron simulation used in these results)
- ▶ Beyond-SM physics with long-lived particles could have been missed in LHC searches – there is still room for significant improvements for these types of signatures and very few results using full Run-2 dataset are out already
- ▶ HL-LHC upgrades can further improve sensitivities, and improvements could be possible already in Run 3 ⇒ LLPs exciting area moving forward!

Backup slides

Theoretical motivation for long-lived particles (LLPs)

The proper lifetime of a particle, τ , is given by

$$\tau^{-1} = \Gamma = \frac{1}{2m_X} \int d\Pi_f |\mathcal{M}(m_X \rightarrow \{p_f\})|^2 \quad (1)$$

where m_X is the mass of the particle, \mathcal{M} is the matrix element for its decay into decay products $\{p_f\}$, and $d\Pi_f$ is the Lorentz-invariant phase space for the decay.

LLPs arise if there is a small ME and/or limited phase space, i.e.:

- ▶ (nearly) mass-degenerate spectra
- ▶ small couplings
- ▶ highly virtual intermediate states

(Comprehensive reviews of motivation and searches for LLPs in [1810.12602](#) and [1903.04497](#))

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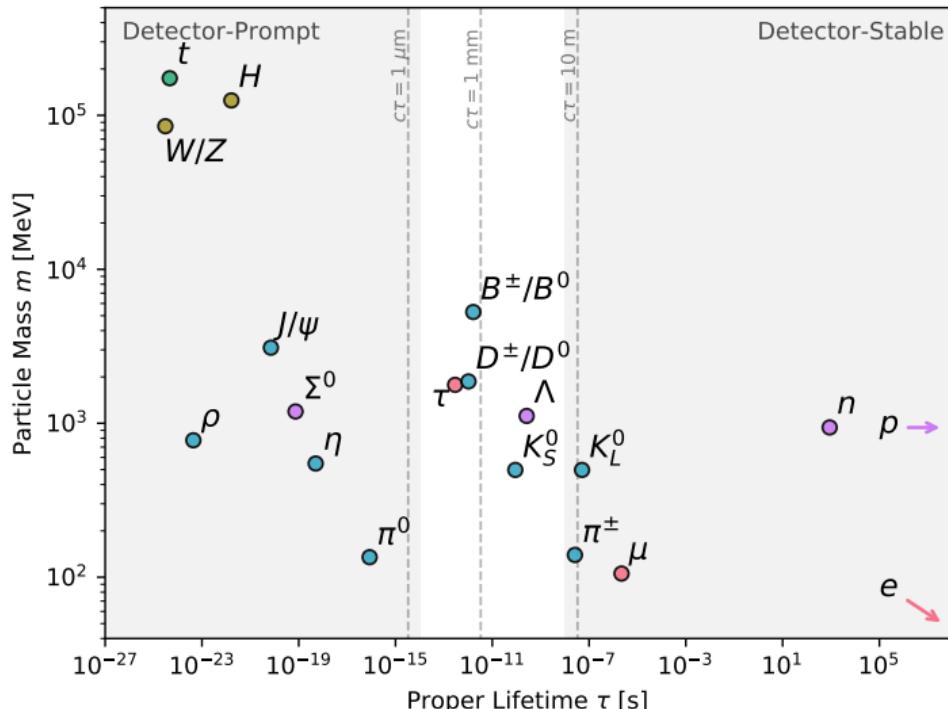
The proper

where m_X is
products $\{p\}$

LLPs arise in

- ▶ (nearly) neutral
- ▶ small couplings
- ▶ highly virialized

(Comprehe

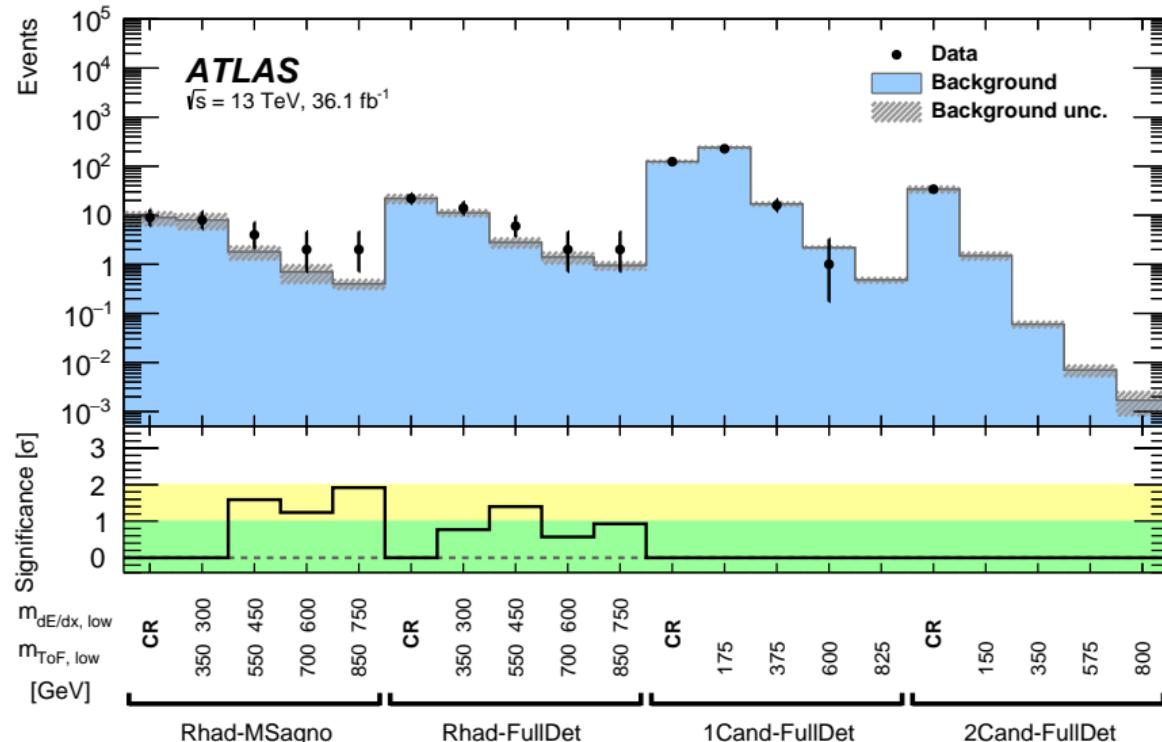


(1)

into decay

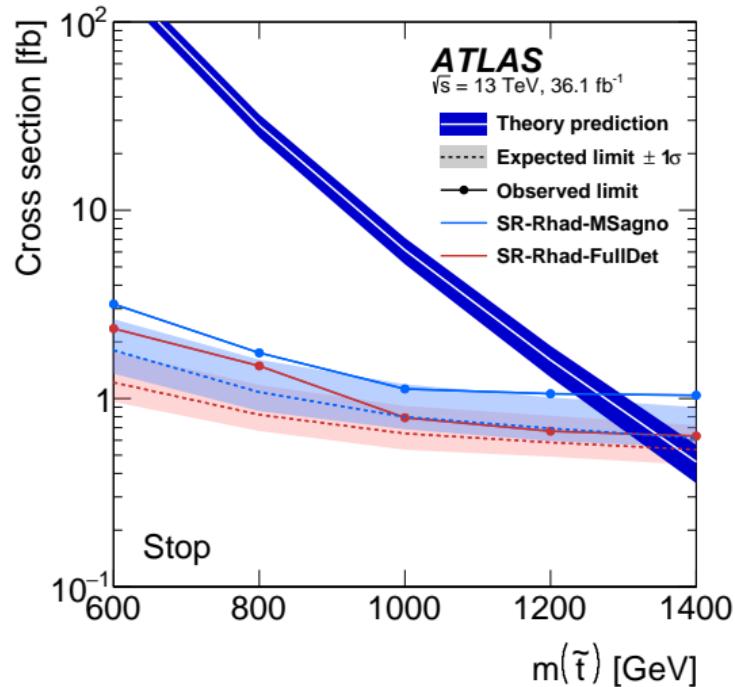
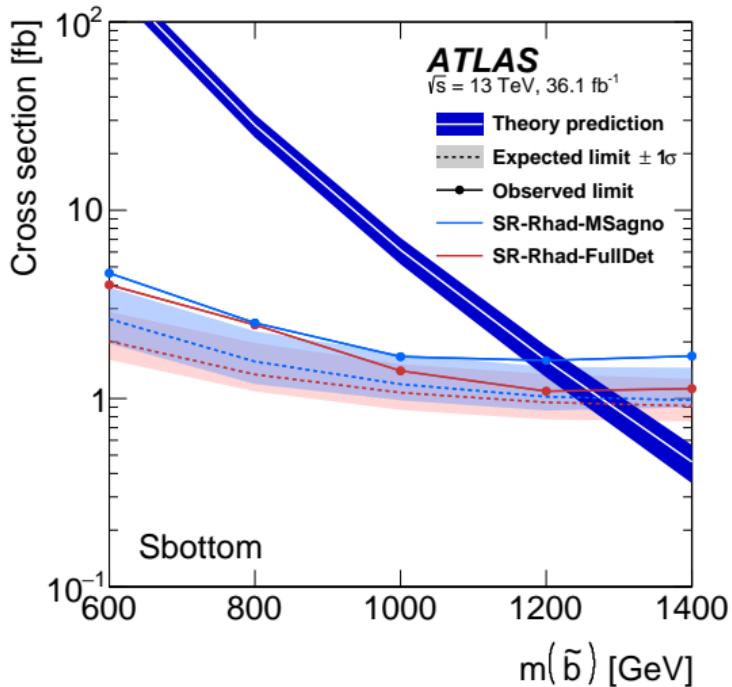
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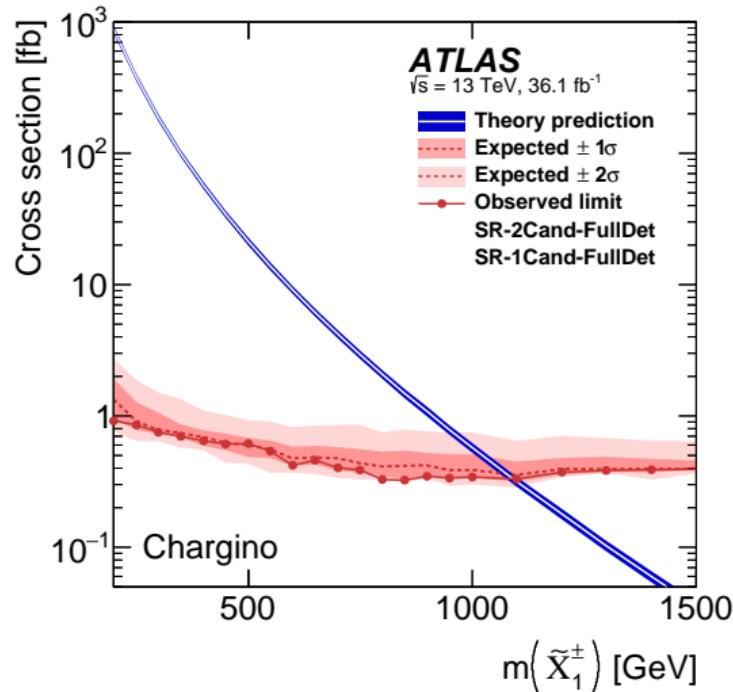
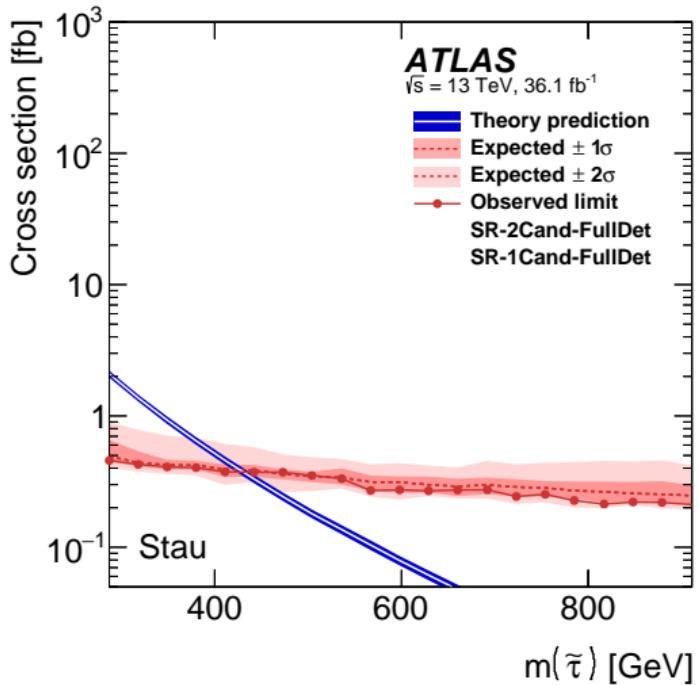
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Exclusion limits on detector-stable sbottom and stop R -hadrons

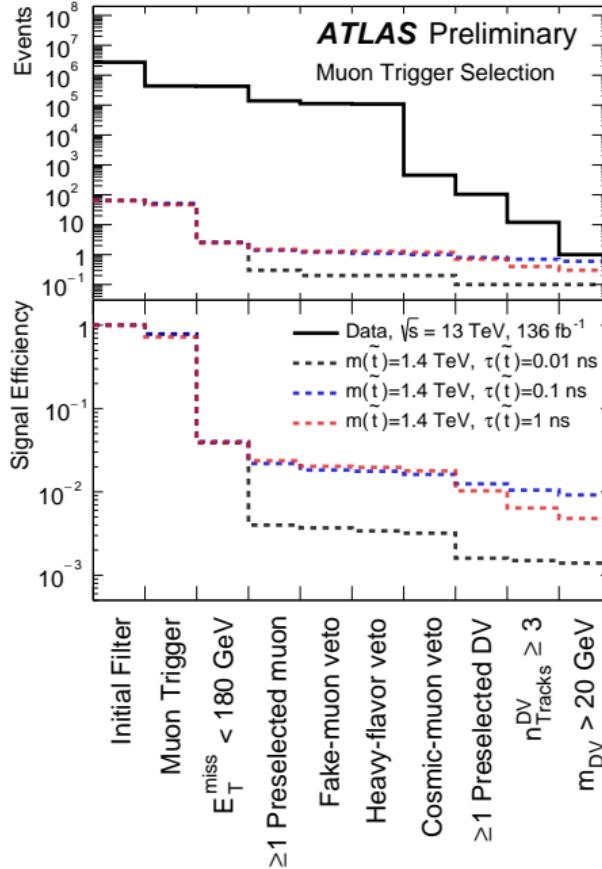
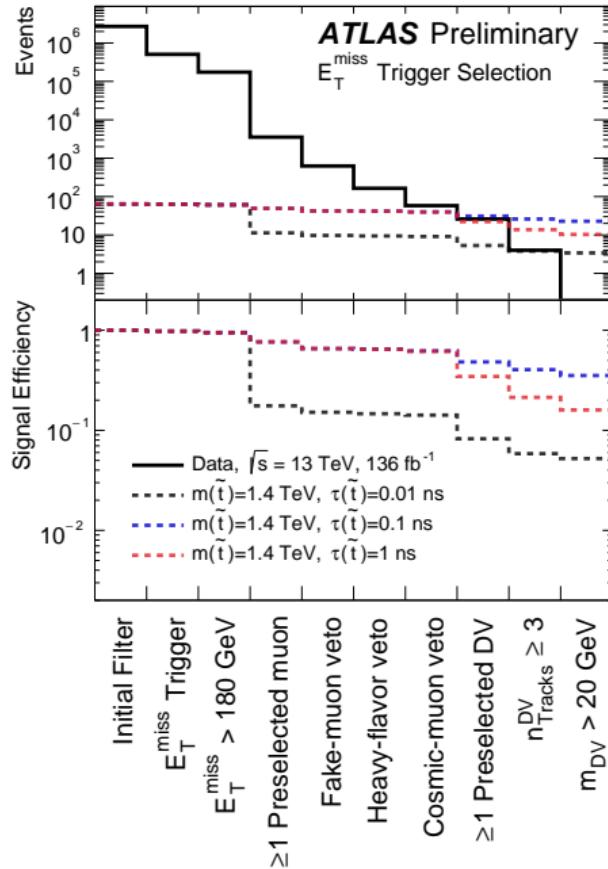


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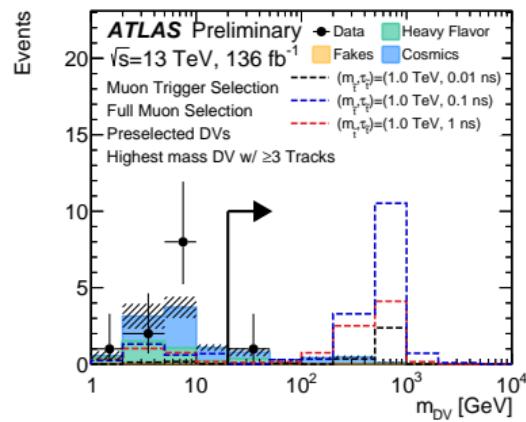
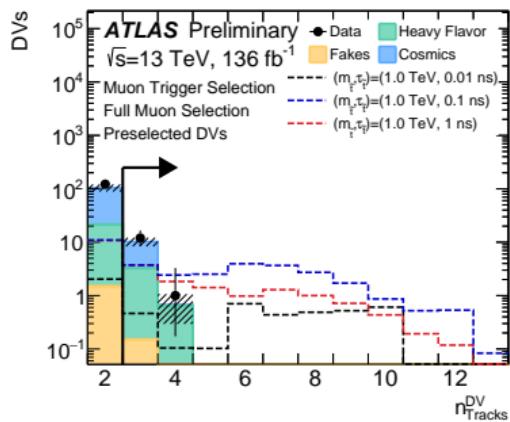
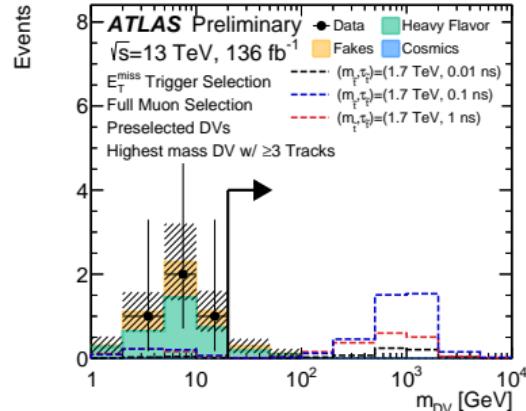
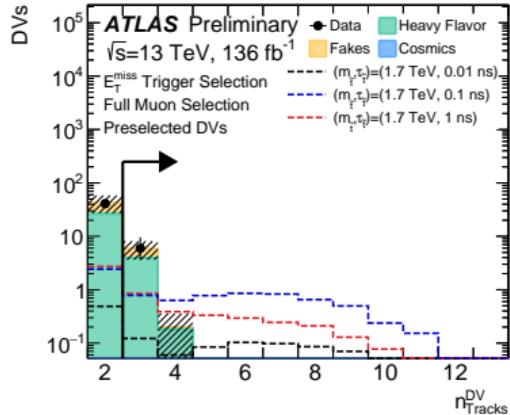
Exclusion limits on detector-stable $\tilde{\chi}^\pm$ and $\tilde{\ell}^\pm$



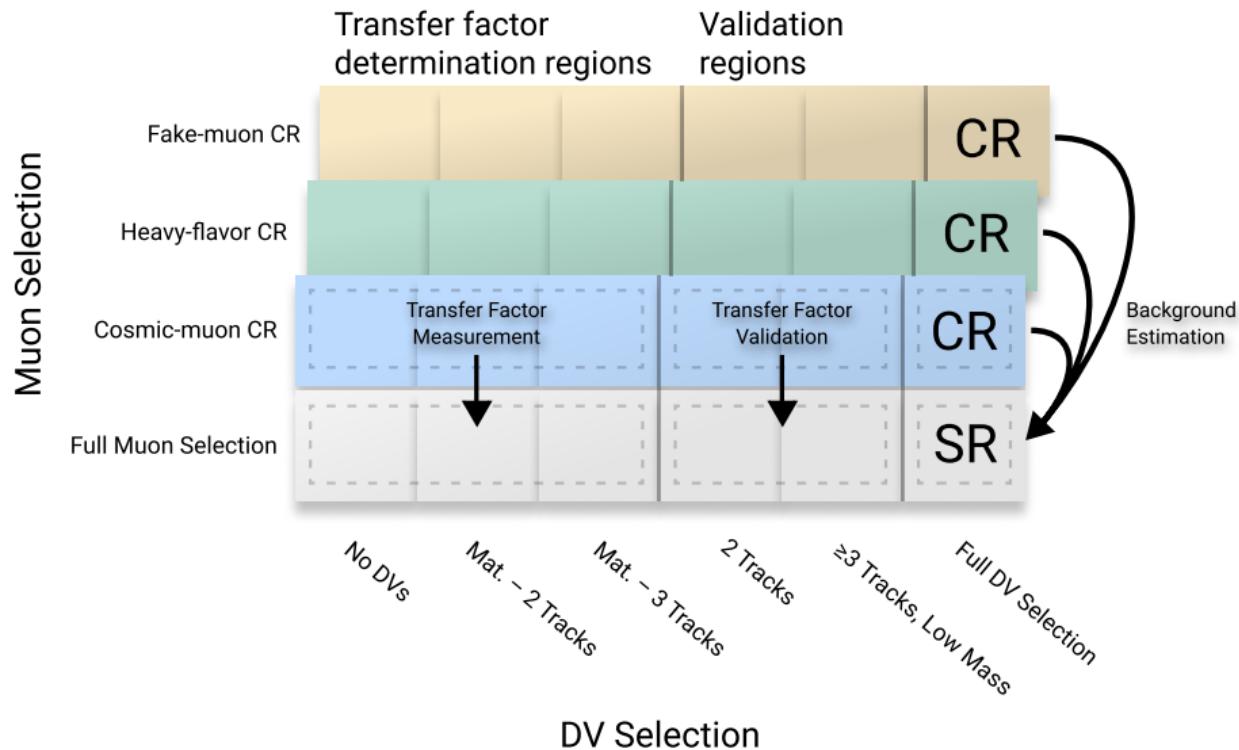
Displaced muon and displaced vertex (ATLAS-CONF-2019-006)



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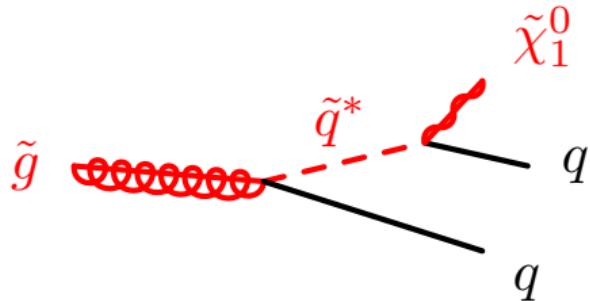


Displaced muon and displaced vertex (ATLAS-CONF-2019-006)



Displaced vertex + E_T^{miss} , 1710.04901

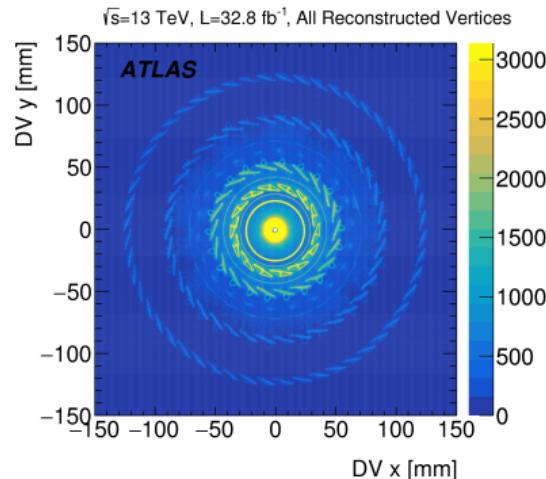
- ▶ Target: scenarios with LLPs decaying in ID to visible and invisible particles, e.g. Split-SUSY



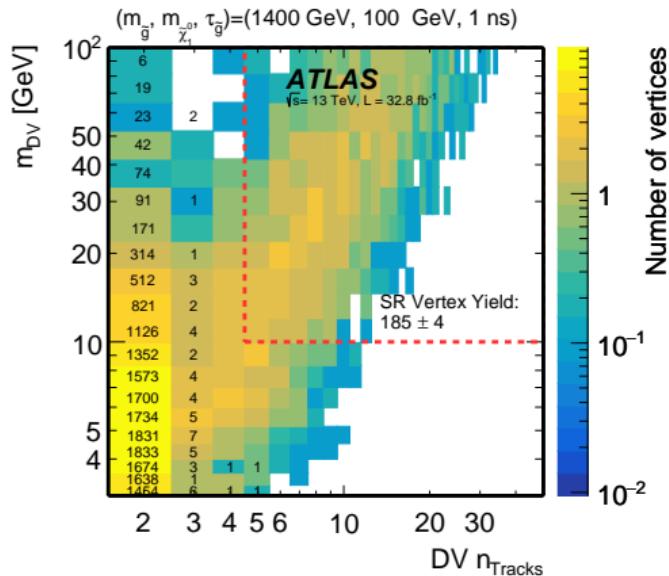
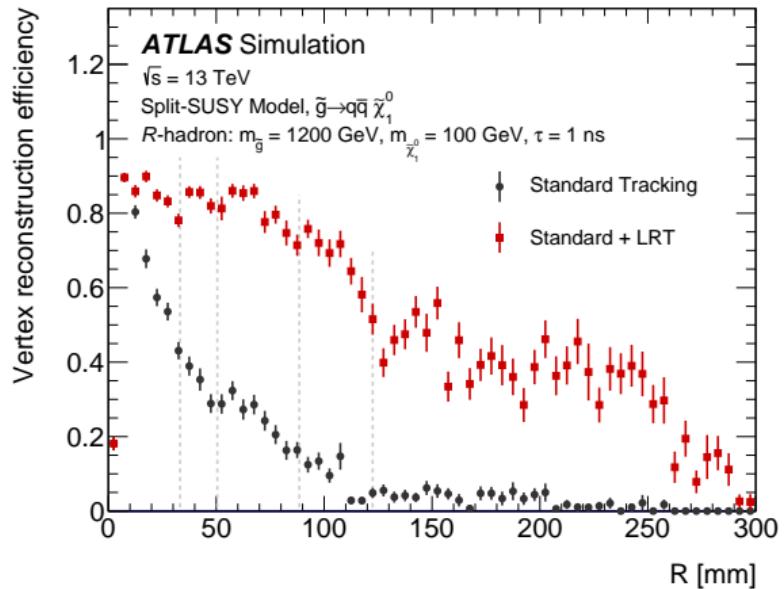
- ▶ Trigger on E_T^{miss} , cut at 250 GeV offline
- ▶ Require at least one displaced vertex (DV) satisfying
 - ▶ In fiducial volume:
 $R < 300 \text{ mm}$, $|z| < 300 \text{ mm}$
 - ▶ $n_{\text{tracks}} \geq 5$
 - ▶ $m_{\text{DV}} > 10 \text{ GeV}$

Backgrounds: 0.02 ± 0.02 events exp.

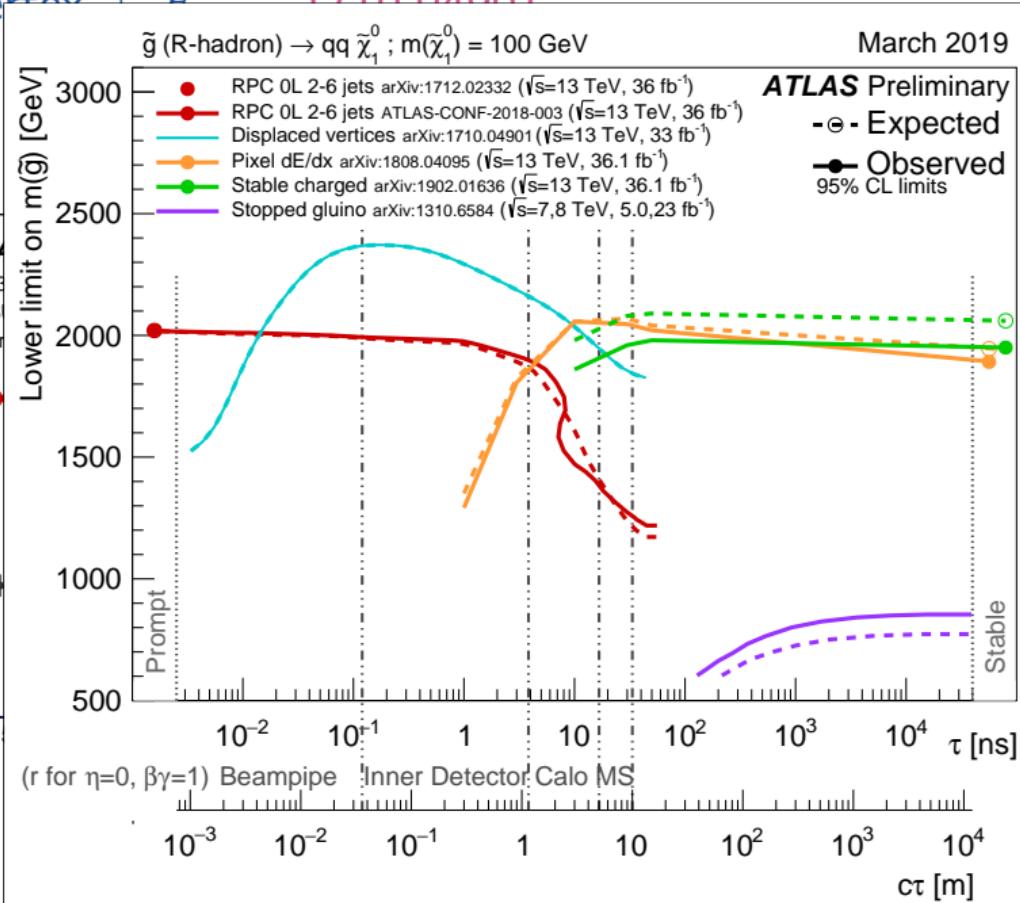
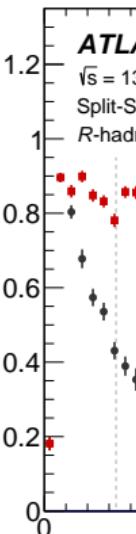
- ▶ Hadronic interactions - veto regions with material!
- ▶ Accidentally crossing tracks - promotes low-mass SM LLPs (B , K_S^0) to higher mass and n_{Tracks}
- ▶ Merged low-mass vertices



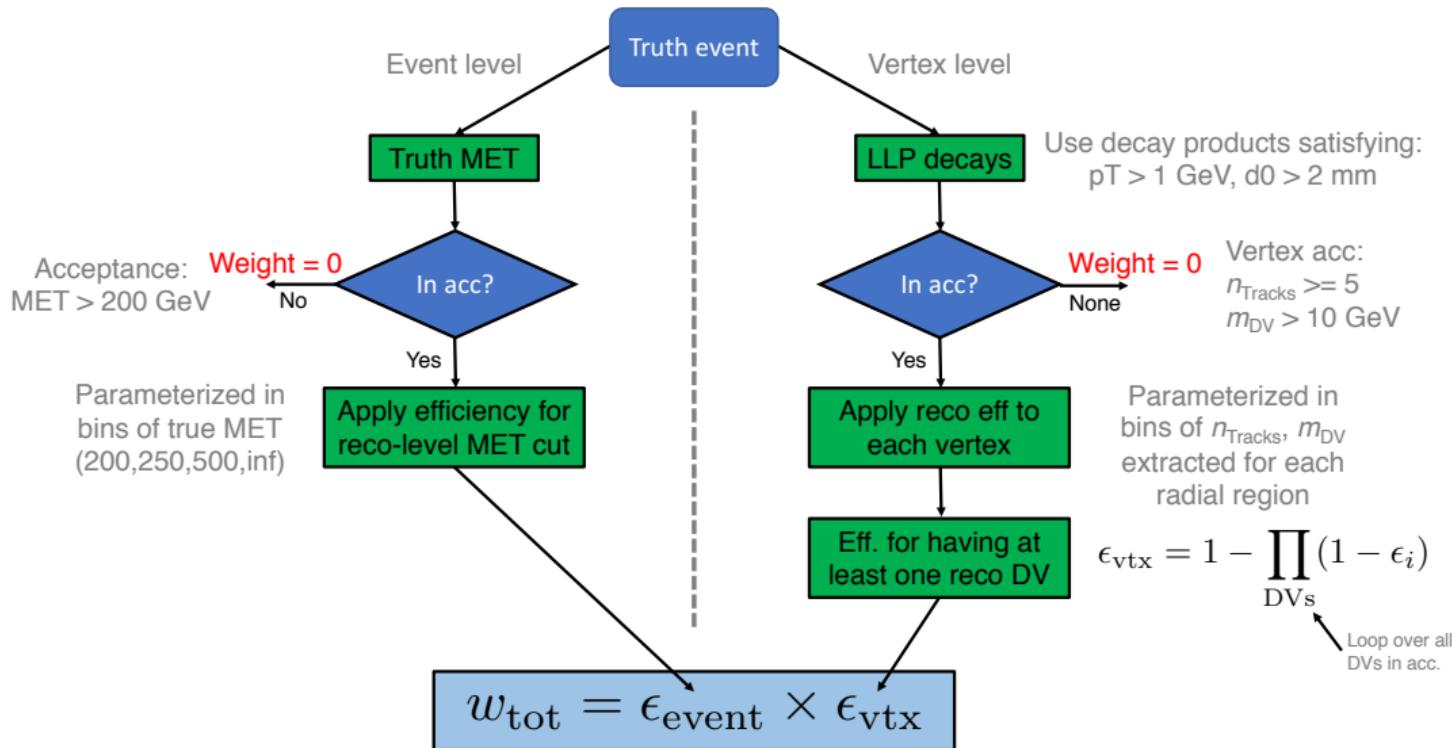
Displaced vertex + E_T^{miss} , 1710.04901



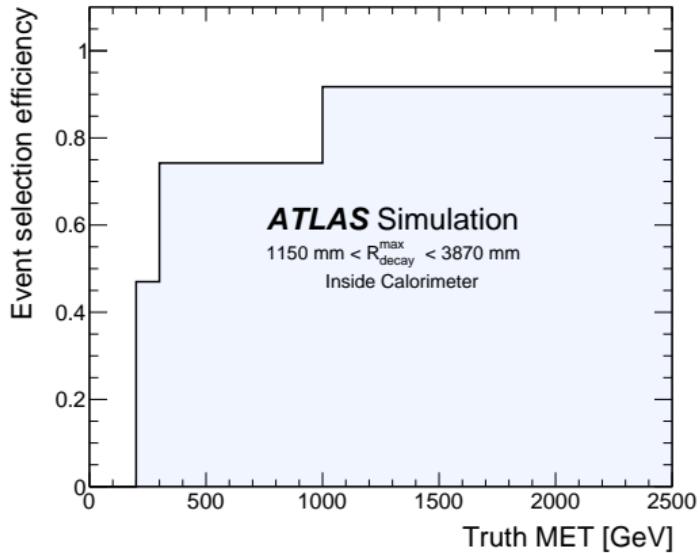
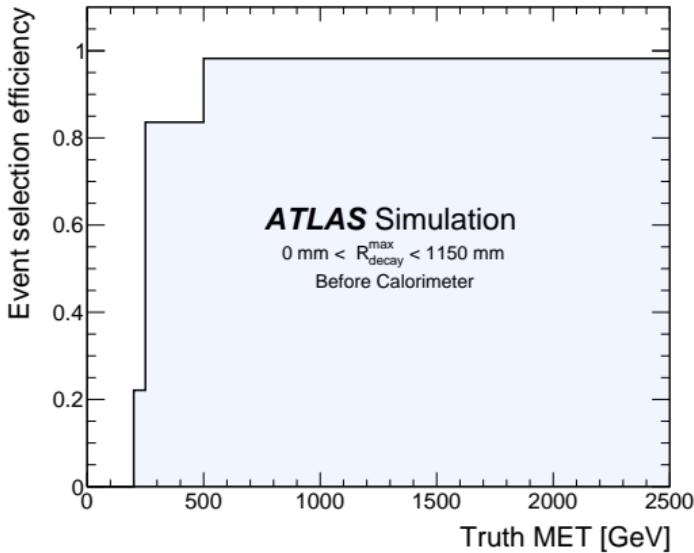
ATLAS
 $\sqrt{s} = 13$
 Split-S
 R-hadron



How a theorist can apply our result to her/his favorite model



DV+ E_T^{miss} : event-level efficiencies



DV+ E_T^{miss} : vertex-level efficiencies

