ATLAS searches for non-minimal, compressed and long-lived SUSY scenarios

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ATLAS EXPERIMENT

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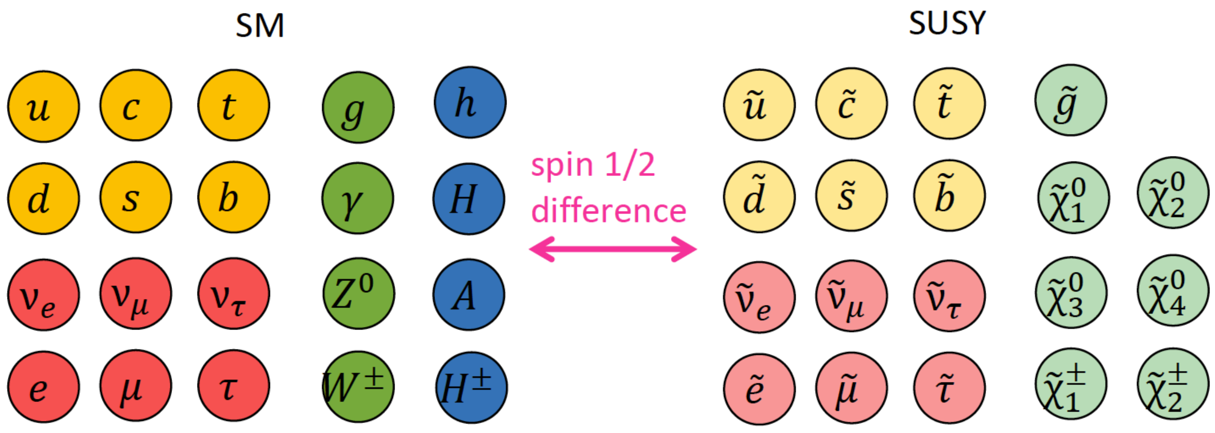
Introduction

- SUSY is a framework introducing a symmetry between fermions and bosons to extend the Standard Model.



candidate four-top-quark event

- Major SUSY models searched in ATLAS:
  - Simplified, minimal models (i.e. few free parameters, production/decay modes) → **Compressed** scenarios
  - **R-parity** conservation, where the lightest SUSY particle (LSP) is stable
  - **Long lived** Particles
  - **Non-Minimal** scenarios, that may include flavour violation
- Most of the studies calls for optimized reconstruction techniques: this is a real challenge for these searches.

Outline

Electroweak supersymmetry with compressed spectra

- Low-p_T displaced tracks
- 0L VBF signature

Searches for Long-Lived SUSY

- Displaced leptons
- High pixel ionization and β

Searches for Non-minimal SUSY

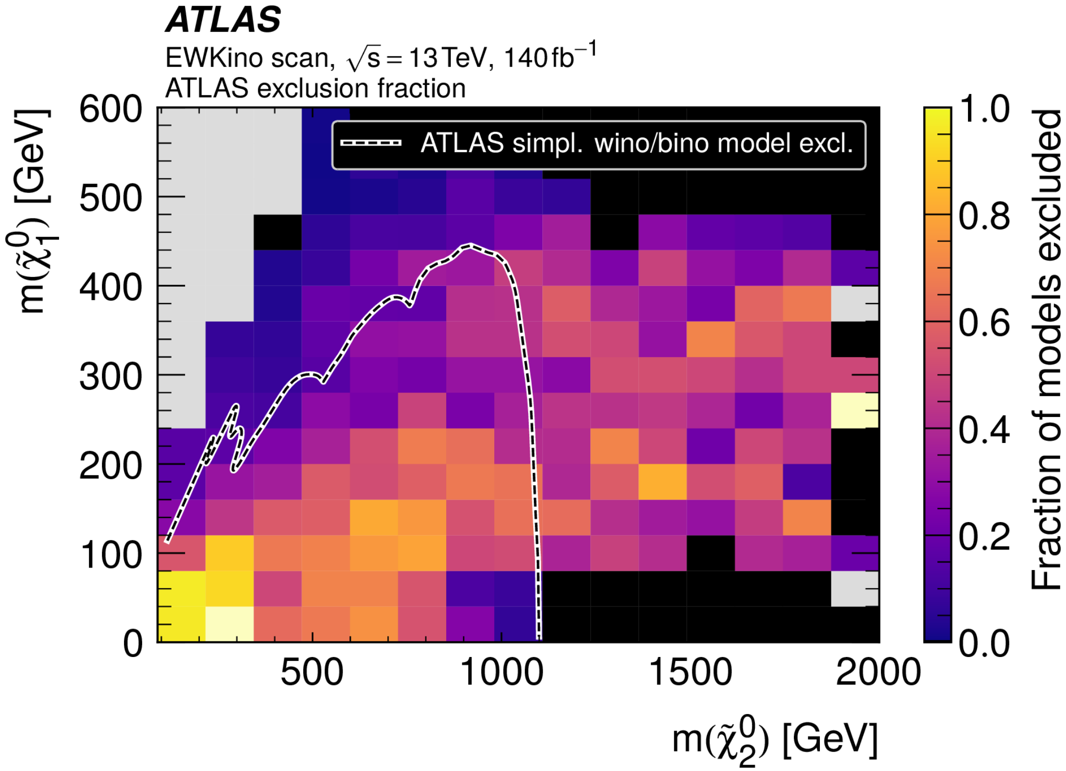
- Stop pairs in Top/Charm

Electroweak supersymmetry with compressed spectra

A compressed scenario is generated when the mass splitting between the chargino and neutralinos is small.

- They form a nearly mass-degenerate triplet of Higgsino-like mass eigenstates $(\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$

- Interesting as it is not well covered yet by the searches.
- Experimentally it induces **weak signals**, making **detection challenging. It relies on** identifying **low p_T pions** or **leptons** in the final state.

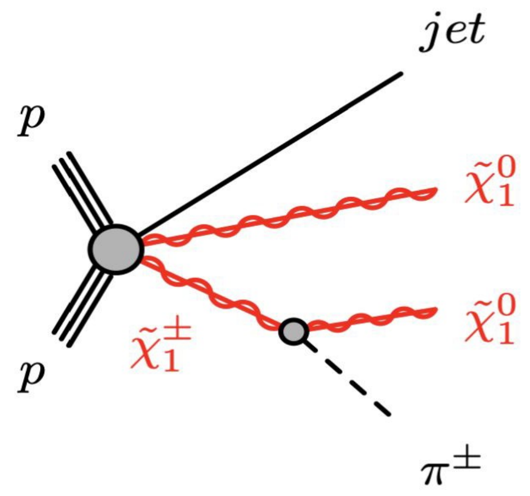


The fraction of EWKino scan models excluded by ATLAS Run 2 results. JHEP 2024 (2024) 106

Higgsinos LSP with Displaced Track

Phys. Rev. Lett. 132 (2024) 221801

- Search for nearly mass-degenerate Higgsinos
  - With $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{0}) \approx 0.3 - 1$ GeV, the chargino is nearly degenerate with the neutralino, producing low p_T pions
- Chargino travel distance
  - Chargino travels ~0.1 to 1 mm from the proton collision vertex → exploring **challenging parameter space between long-lived and prompt decays**
  - This distance allows the chargino to decay in the detector, leaving a **displaced track**
- Discrimination using $S(d_0)$:
  - $S(d_0)$, the ratio of **transverse impact parameter** to its resolution, is key discriminator for identifying this decay



Important selections to define the Signal Region

- ISR leading **jet** (pT > 250 GeV)
- E_T^{miss} > 600 GeV (rejects SM background)
- **Low p_T** track: 2 GeV < p_T < 5 GeV
- **S(d0)** > 8 (identifies displaced tracks)
- **Two SRs** in $S(d_0)$ (sensitive to Δm changes)

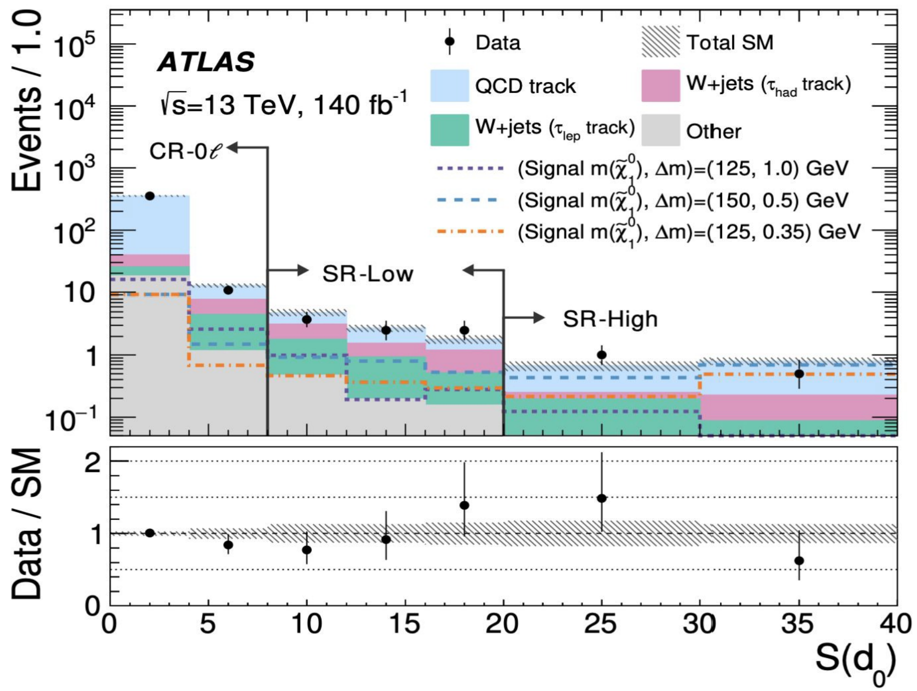
Background (back-up)

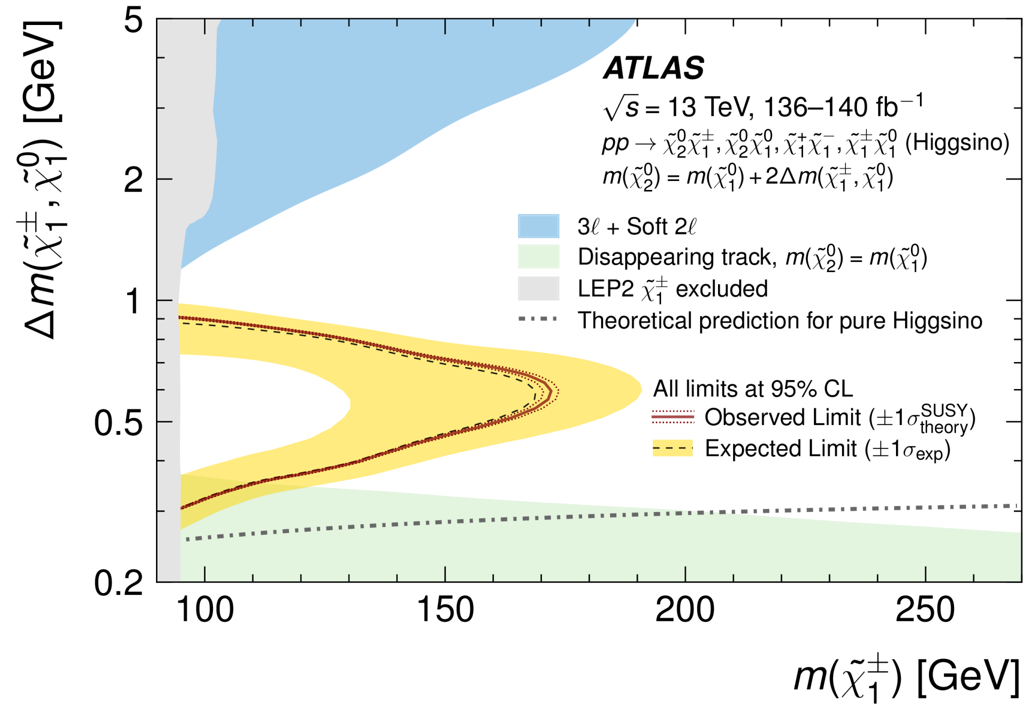
- QCD tracks → ABCD method
- Tau tracks → Montecarlo

Compressed scenarios

Results and Interpretation

[Phys. Rev. Lett. 132 (2024) 221801]



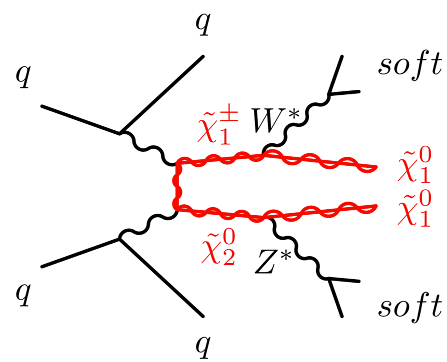


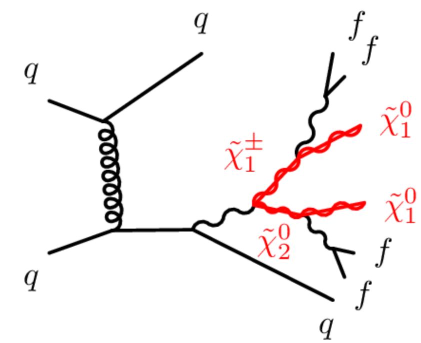
- Data match with SM predictions, showing no significant excess or evidence of new physics:
  - Limits set on Higgsino simplified models
- Data Exclusion limits for mass splittings:
  - 0.3 GeV < $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ < 0.9 GeV
- Search **sensitivity peaks** at $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ = 0.6 GeV, excluding $m(\tilde{\chi}_1^\pm)$ up to ~170 GeV

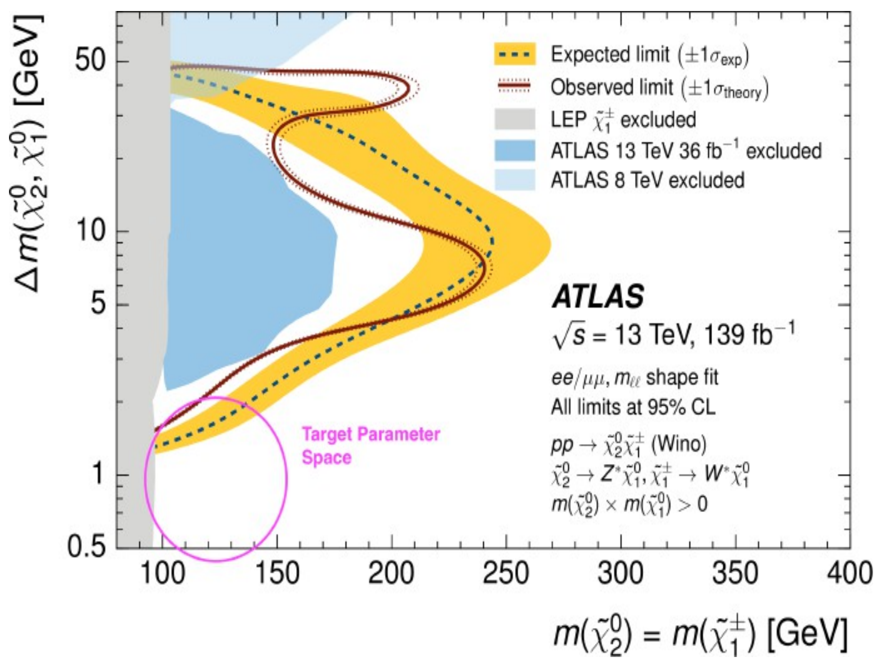
SUSY in vector boson fusion signatures

ArXiv 2409.18762

- Search chargino-neutralino pair production with **small mass splitting**: models with $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) < 2$ GeV have evaded exclusion with the strongest constraints still coming from **LEP**.
- Leptons are expected to be too soft to be identified/reconstructed: require **zero leptons**.
- **Vector boson fusion** topology to further distinguish signal and background;
  - **first** instance of **0L VBF** signature for SUSY in ATLAS.
- The strength of the VBF analysis also lies in being **independent on the decay products** of the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ decays, since it's looking at E_T^{miss} and the jets from the VBF production.







SUSY in vector boson fusion signatures

ArXiv 2409.18762

- Analysis strategy
  - Select events satisfying E_T^{miss} > 250 GeV, and **two jets passing VBF** criteria.
  - **BDT** trained to classify between signal and background;
  - **Analysis regions** defined based on BDT score and lepton multiplicity; each region further split into two channels N_{jets}= 2 and $N_{jets} \geq 3$
  - **Dominant backgrounds** from
    - ***V* + jets** estimated in signal region based on simultaneous fit including 1L/2L control regions;
    - **Multi-jet** background modeled using data-driven ABCD method.

Feature	CR−Z	VR−Z	CR−W	VR−W	VR−0L	Multi-bin SR	Single-bin SR
N_{leptons}	2		1		0		
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z\rvert < 30$ GeV		–		–		
$E_{\text{T}}^{\text{miss}}/\sqrt{\Sigma E_{\text{T}}}$	–		$E_{\text{T}}^{\text{miss}}/\sqrt{\Sigma E_{\text{T}}} > 5\ \sqrt{\text{GeV}}$		–		
BDT score	[0.50, 0.84)	[0.84, 1.0]	[0.50, 0.84)	[0.84, 1.0]	[0.4, 0.6)	[0.6, 1.0]	[0.88, 1.0]
BDT score bins	1	2	1	2	5	8	1

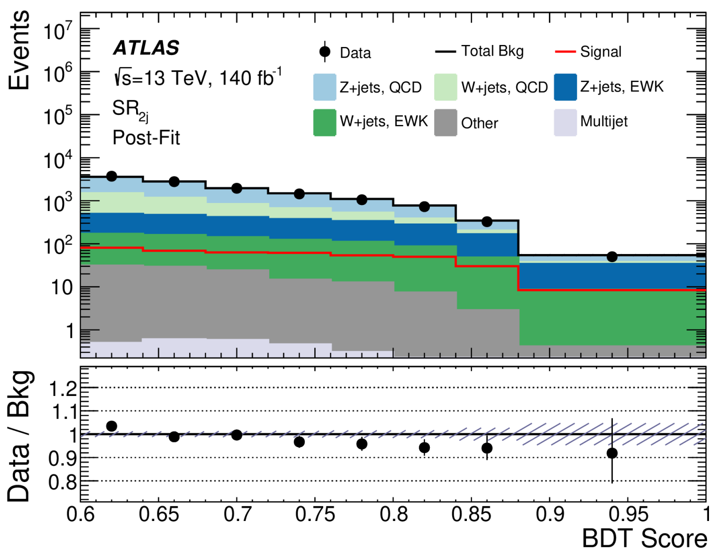
BDT = *Boosted Decision Tree*

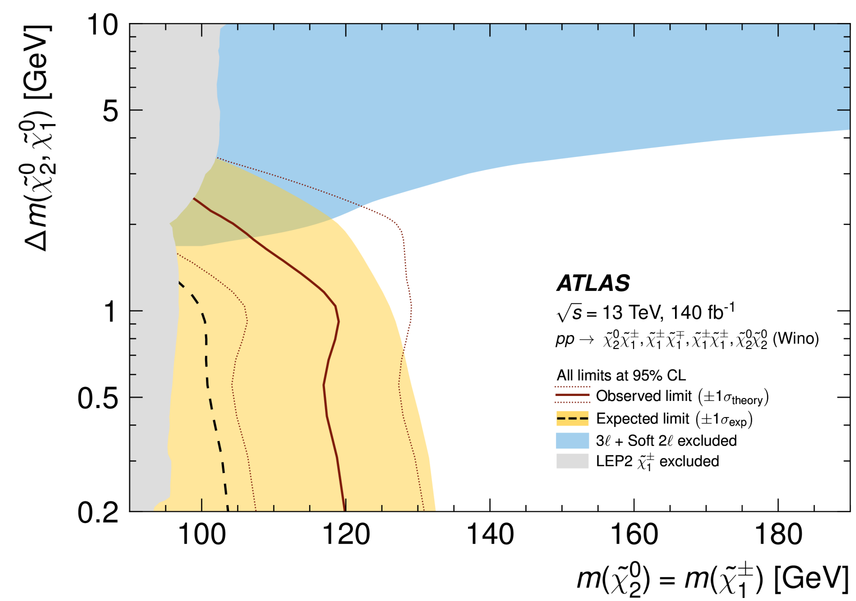
SUSY in vector boson fusion signatures

ArXiv 2409.18762

- Results
  - Background-only fit with single-bin discovery SRs requiring BDT score > 0.88 and CRs: no significant excesses seen and model-independent limits evaluated
  - Model-dependent results from exclusion fit: data consistent with the SM prediction and observed lower limit of $m(\tilde{\chi}_2^0)$ ~ 119 GeV for $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ = 1 GeV

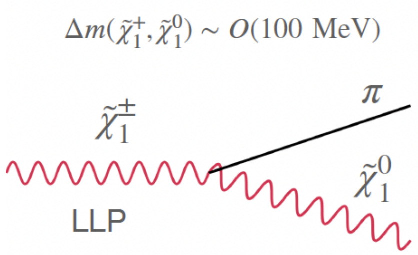
Single-Bin Region	N_{obs}	N_{exp}	$\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}	$p(s=0)$
SR_{2j}	50	55.9 ± 3.7	0.09	13	18^{+7}_{-5}	0.50
$\text{SR}_{\geq 3j}$	44	39.8 ± 4.3	0.18	25	19^{+9}_{-6}	0.19



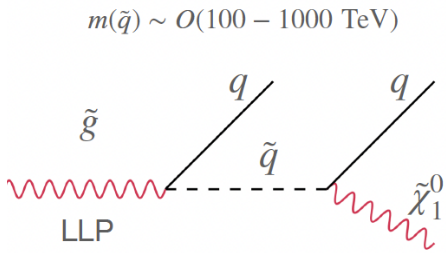


Long-lived SUSY

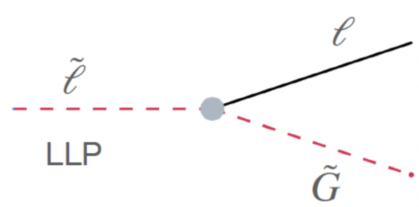
- Long-lived particle can naturally arise in many SUSY models. Mainly 3 mechanisms:



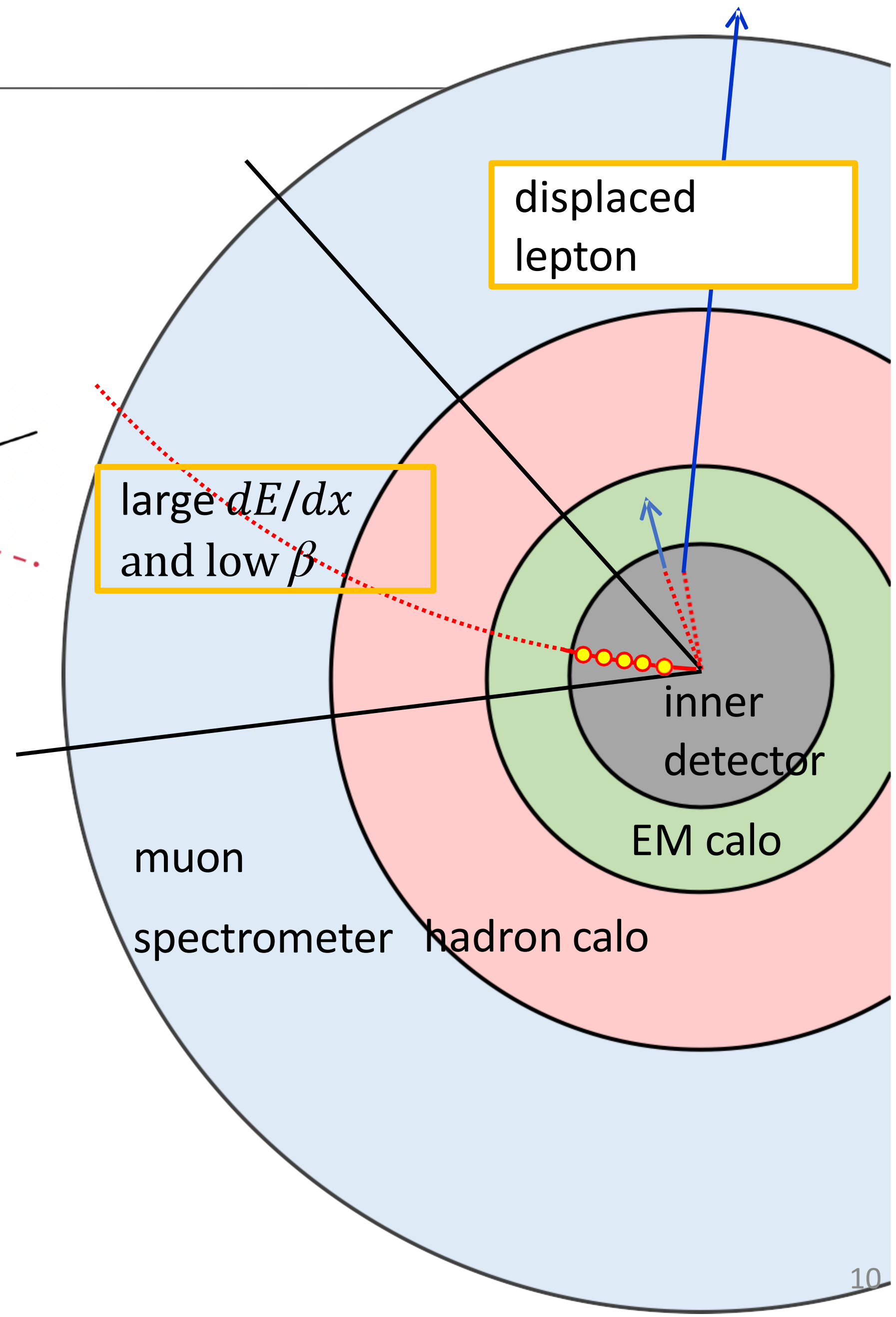
Compressed spectrum



Heavy (off-shell) mediator



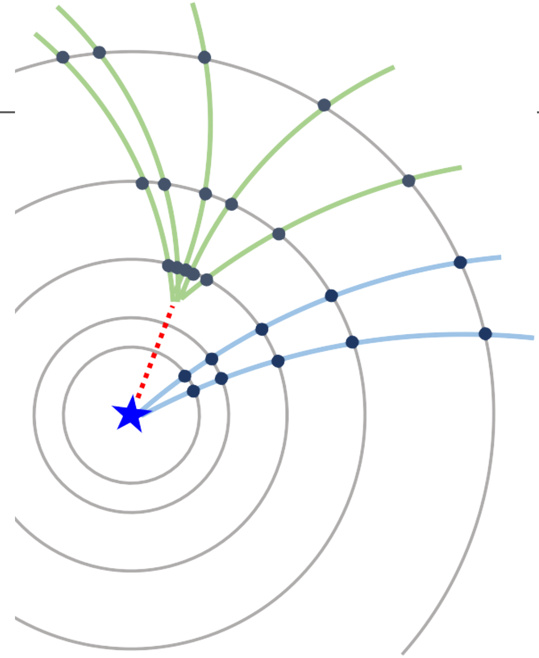
Small couplings



- LLP signature depends on
  - Lifetime, charged or neutral, decay mode
  - → Needs various special reconstructions.
- Experimental background events (**BG**s) are dominant.
  - → Data-driven estimation

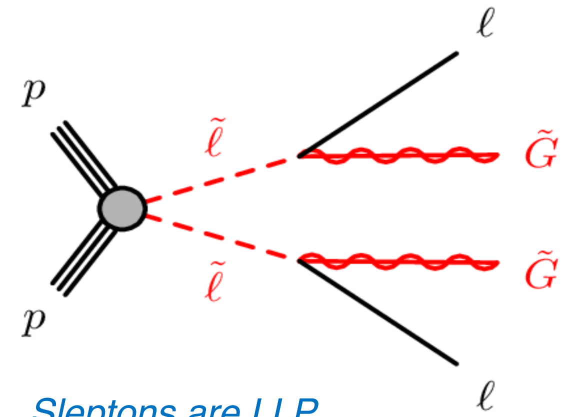
Long-Lived

Displaced Leptons

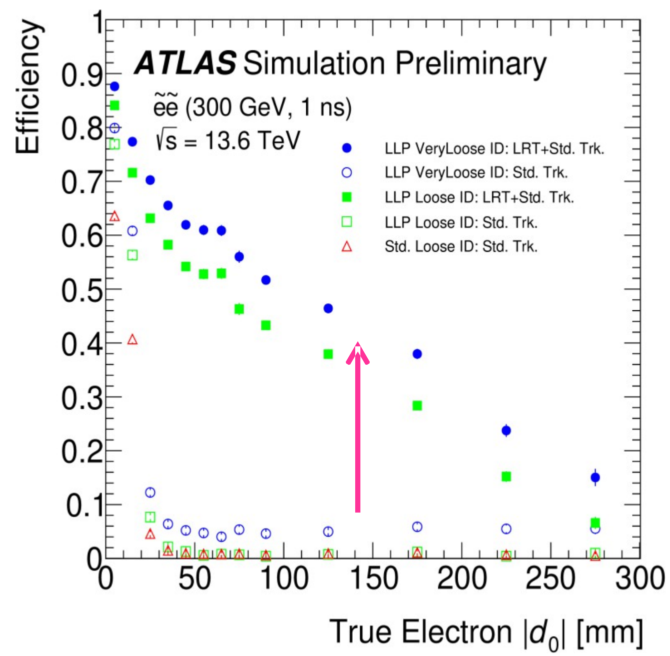


ATLAS-CONF-2024-011

- Search for electrons and muons displaced from the primary interaction vtx (Run 2 and part of Run 3)
  - Results are interpreted in the context of gauge-mediated supersymmetry breaking model with pair-produced long-lived sleptons.
- Exploits:
  - **Large radius tracking (LRT)** reconstructs tracks with large impact parameters using unused hits after standard tracking. Novel **triggers** introduced in Run 3 use LRT to reconstruct displaced tracks with low momentum (back-up).
  - **Photon** reconstruction and **multivariate** techniques are employed to broaden sensitivity to channels with large background rates or highly displaced electrons, respectively.



Sleptons are LLP, resulting in displaced leptons, LSP is a nearly massless gravitino



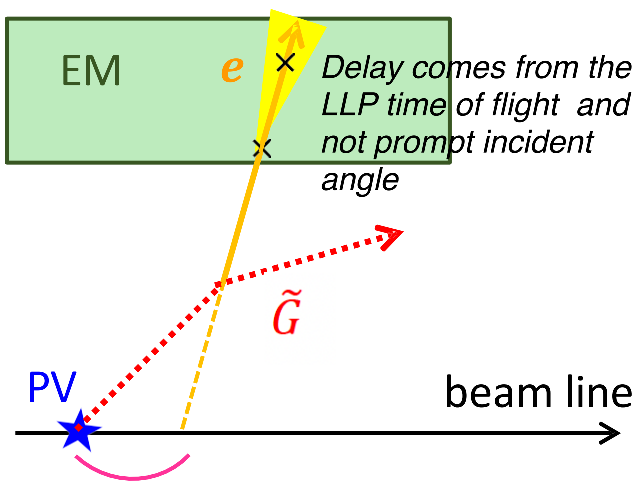
Improvement of reconstruction efficiency of LLP objects using LRT.

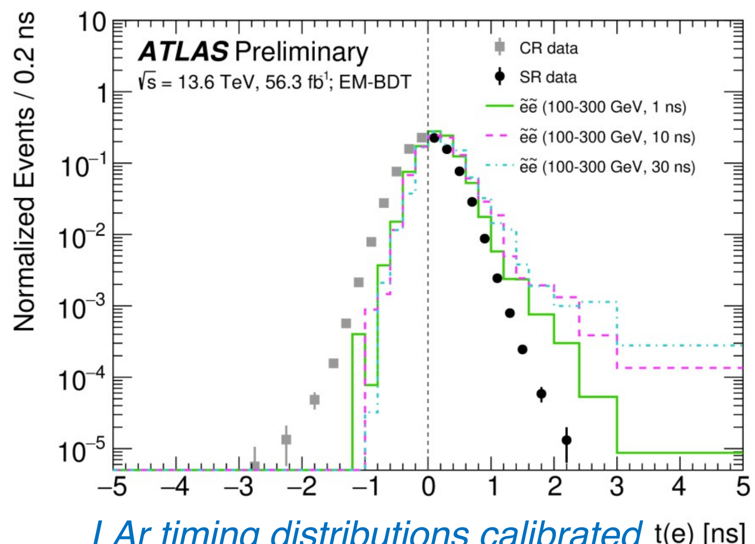
Displaced Leptons

[ATLAS-CONF-2024-011](#)

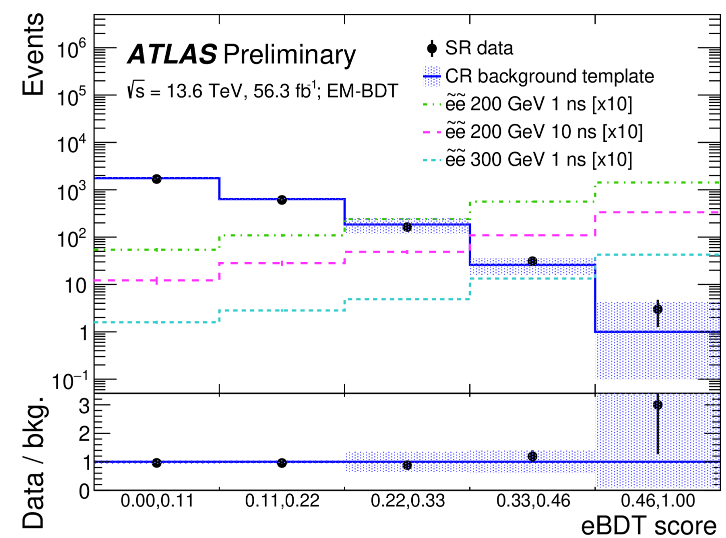
- Strategy 1: ABCD analysis focusing on *dilepton events* (back-up).
- Strategy 2 (only for Run 3): using LAr and BDT selection for expanded sensitivity to single electron and photon-reconstructed (if decay too far) events.
  - Photon or LRT lepton triggers
  - BDT using $ee/\gamma\gamma$ information
  - **SR**: High BDT score + leading e/γ with $t > 0$
  - **BGs**: Prompt objects → Estimate using events with e/γ with $t < 0$.

- eBDT: Leading e's track info, EM timing and displacement, etc.
- γBDT: Two γs' EM timing and displacement, etc.





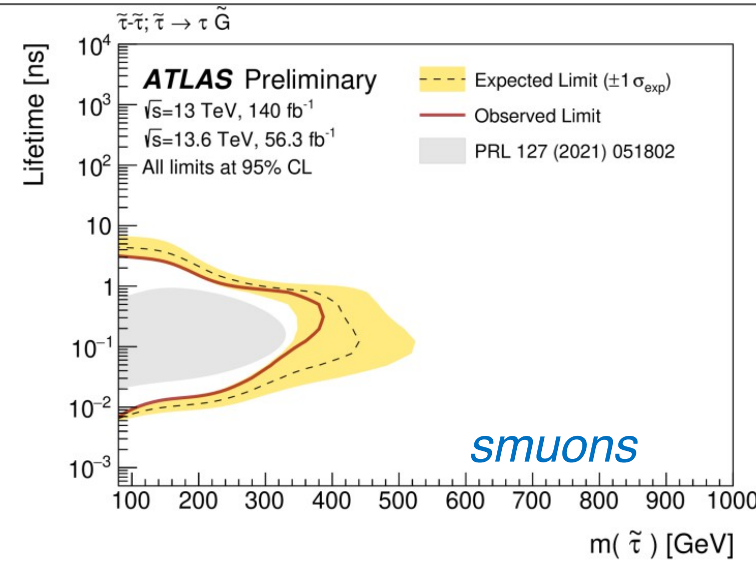
LAr timing distributions calibrated to 0 for prompt β=1 particles

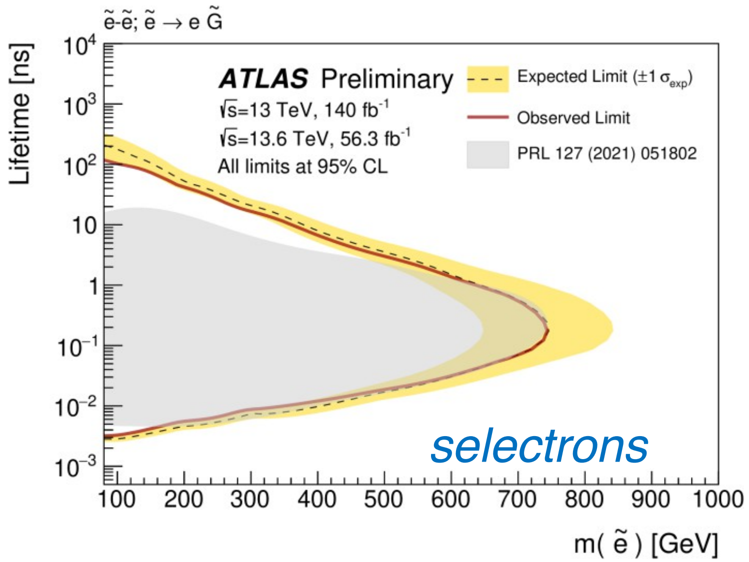


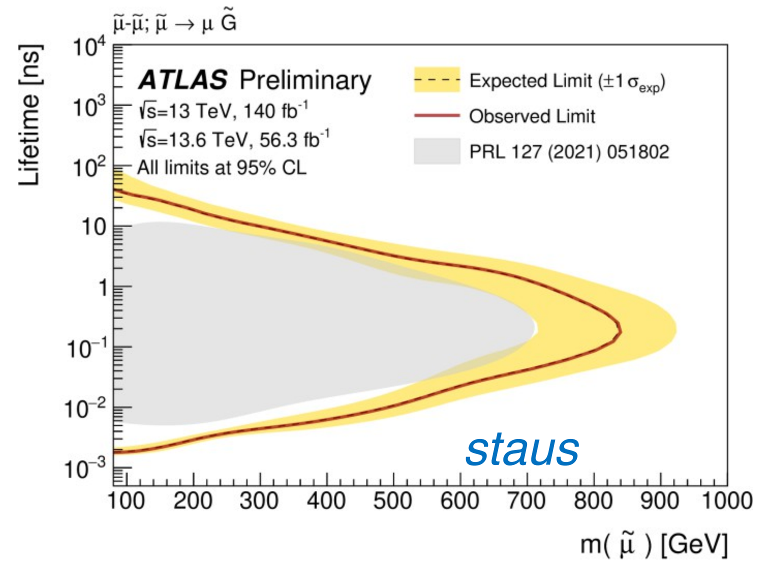
Displaced Leptons: Results

[ATLAS-CONF-2024-011]

- As no excess is found, exclusion limits are set on sleptons as a function of lifetime.
- The BDT-based analysis improved the sensitivity in the long lifetime region.



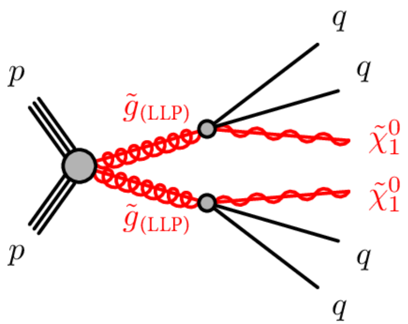


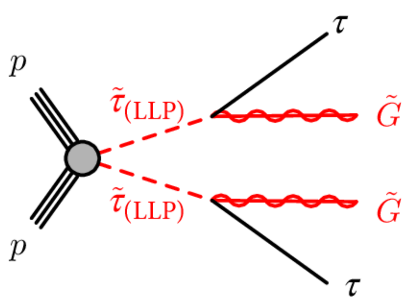


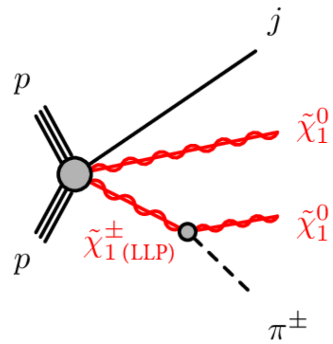
Meta-stable Charged Particles

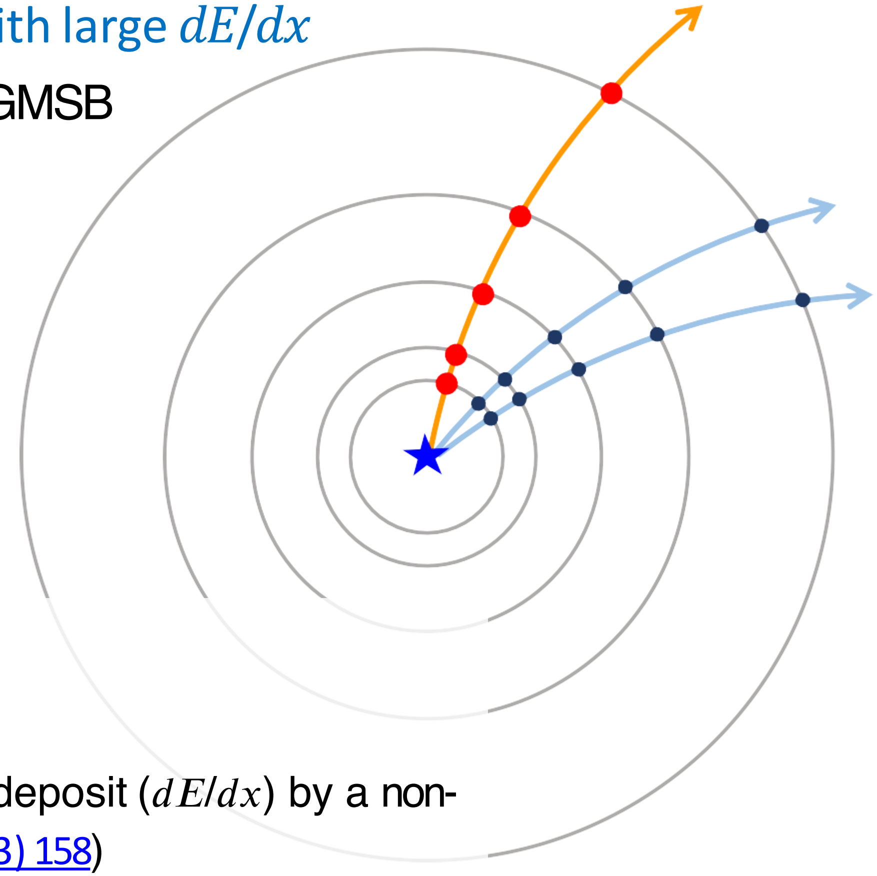
[ATLAS-CONF-2023-044](#)
[ATL-PHYS-PUB-2024-009](#)

- Search for heavy charged particles with high p_T track with large dE/dx
  - Results are interpreted in the context of Mini-split SUSY, GMSB







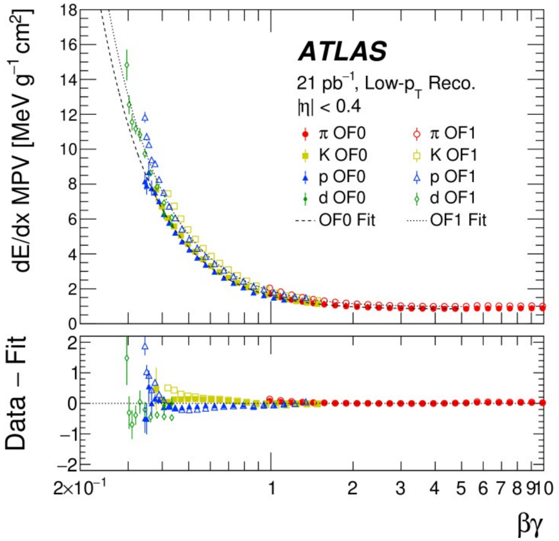


- Signatures
  - Missing transverse momentum (E_T^{miss}) from LSPs
  - Tracks with high transverse momentum (p_T) and large pixel energy deposit (dE/dx) by a non-relativistic LLP → 3.3σ excess in the previous analysis ([JHEP 06 (2023) 158](#))
  - If it comes from an LLP, the time of flight (ToF) at the calorimeter should be consistent. Done a reinterpretation of the results, and to improve result robustness two independent mass measurements have been performed (one from pixel dE/dx and one from β_{calo})

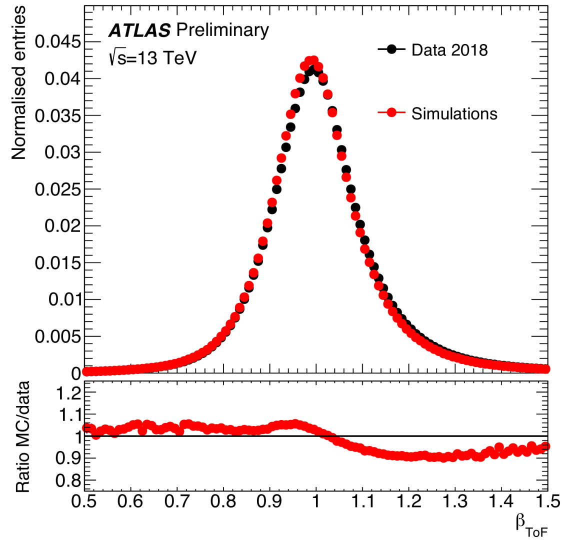
Meta-stable Charged Particles

ATLAS-CONF-2023-044
ATL-PHYS-PUB-2024-009

- Measurement relies on detector calibrations
  - **Pixel** dE/dx-$\beta\gamma$ calibration
    - Most provable value (MPV) of the dE/dx is corrected based on the period and η
    - Calibrate dE/dx-$\beta\gamma$ relation using low- momentum SM particles
  - **Tile** β measurement in the calorimeter (β_{ToF})
    - Measurements in i-th calorimeter cell: $\beta_i = 1/(1 + ct_i/l_i)$
      (t_i: measured timing, l_i: distance from the PV)
    - β_{ToF}: Weighted average of β_i in calorimeter cells



JHEP 06 (2023) 158



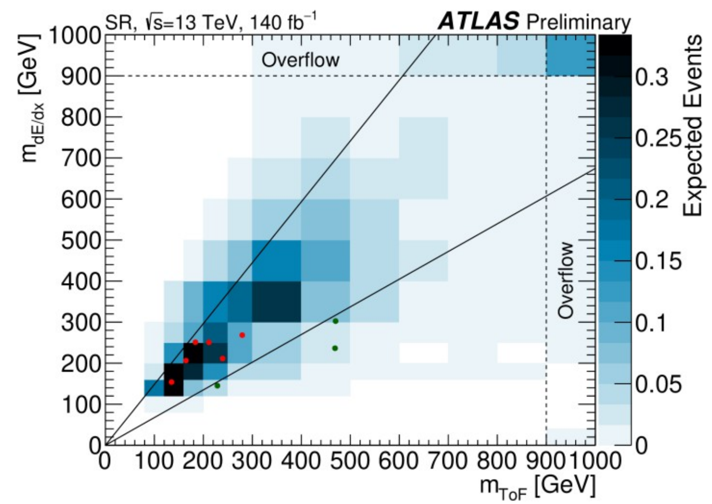
- Analysis Strategy
  - SR: $E_T^{\mathrm{miss}} > 170$ GeV + $\beta_{\mathrm{ToF}} < 1 - 2\sigma_{\mathrm{ToF}}$ + Track with $dE/dx >$ 1.8 MeV/g^{-1} cm^2 and $p_{\mathrm{T}} > 120$ GeV
  - BGs: Estimate using toys sampled from a control region

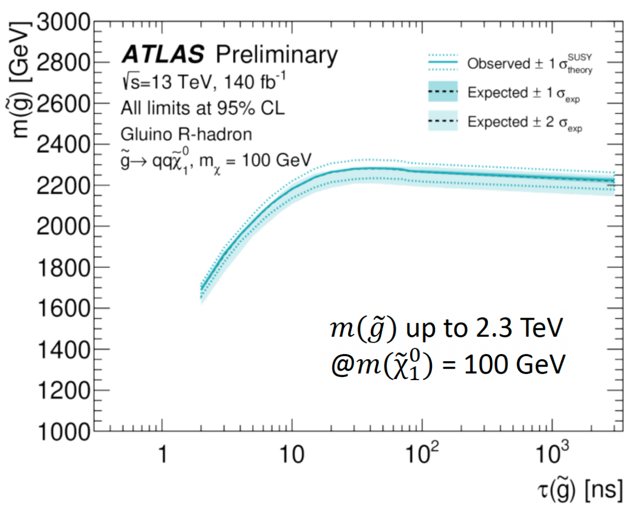
Meta-stable Charged Particles: Results

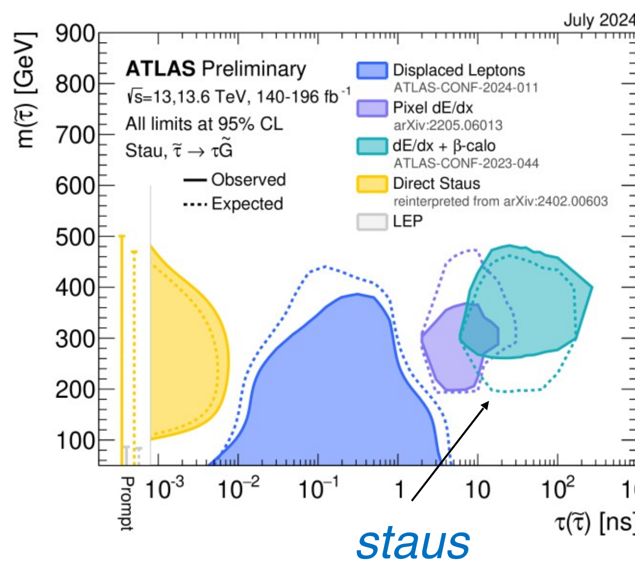
ATLAS-CONF-2023-044
ATL-PHYS-PUB-2024-009

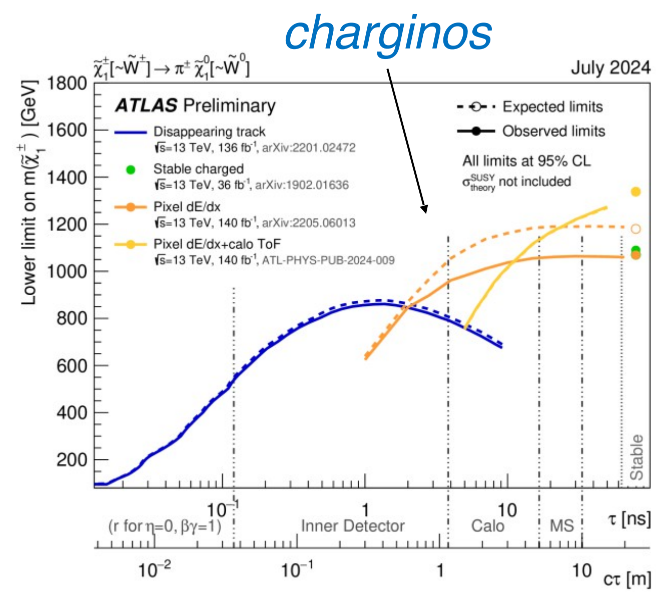
- Results are in agreement with expectations:
  - 9 events are found in the SR while 5.1 ± 0.5 are expected.
  - 6 of them have $m_{dE/dx}$ compatible with $m_{\beta\text{ToF}}$

  (est. 3.7 ± 0.4) → 1.8σ excess in 200 GeV mass window
- Exclusion limits are set on each target model.
  - Large sensitivity to R-hadron, staus and charginos.





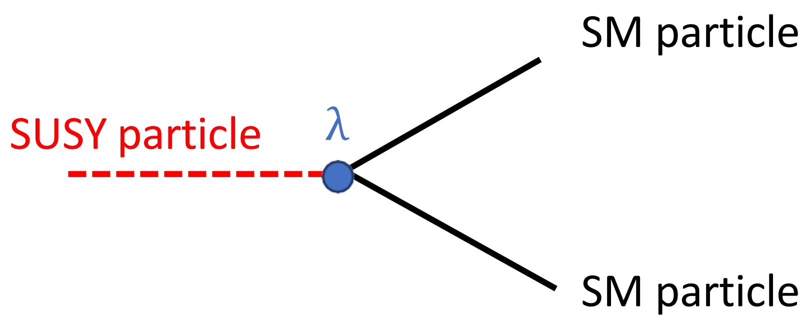




Non-minimal SUSY (Prompt)

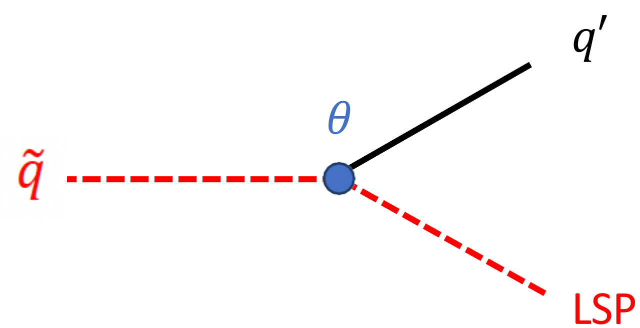
- Several non-minimal SUSY models with prompt SUSY particles have been searched in the ATLAS.

< RPV >



The LSP decays to the SM particles with RPV coupling constant λ.
→ No significant E_T^{miss}

< Flavour mixing >



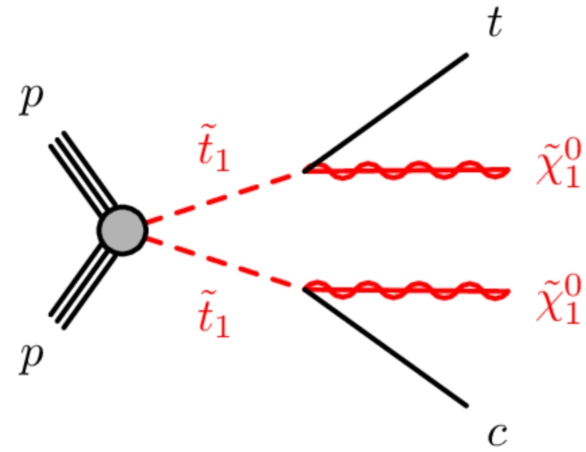
The SUSY particle decays to the SM particle in different generation through mixing angle θ.

Stop to Top or Charm

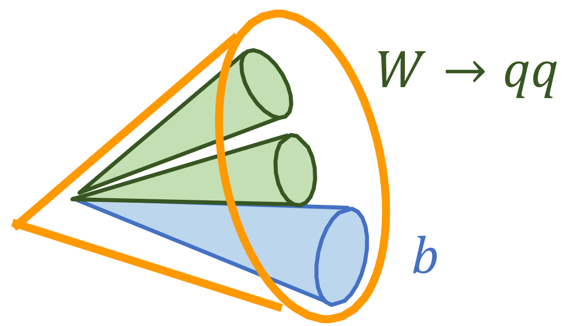
JHEP 07 (2024) 250

- Search for top-squark pair production in final states with a top quark, a charm quark and missing transverse momentum
  - Motivation: Flavour mixing of 2nd and 3rd generation squarks

- Analysis strategy
  - Full Run 2 data analysis
  - $Br(\tilde{t} \rightarrow t\tilde{\chi}_1^0) = Br(\tilde{t} \rightarrow c\tilde{\chi}_1^0)$ is at 50% when mixing is maximum
  - Use **boosted top quark hadronically decaying** and identify them via **DNN top-tagger**:
    - identifies a large-R jets with multi boosted and collimated small-R jets by looking at jet substructure
  - Strategy
    - High E_T^{miss} + multi-jets (≥ 1 b-tagged & ≥ 1 c-tagged)
    - Use top-tagger and analysis-specific c-tagger



Stop pair decaying into two possible decay modes, Decays into pairs of top quarks or charm quarks are also taken into account.



large-R jet from top decay

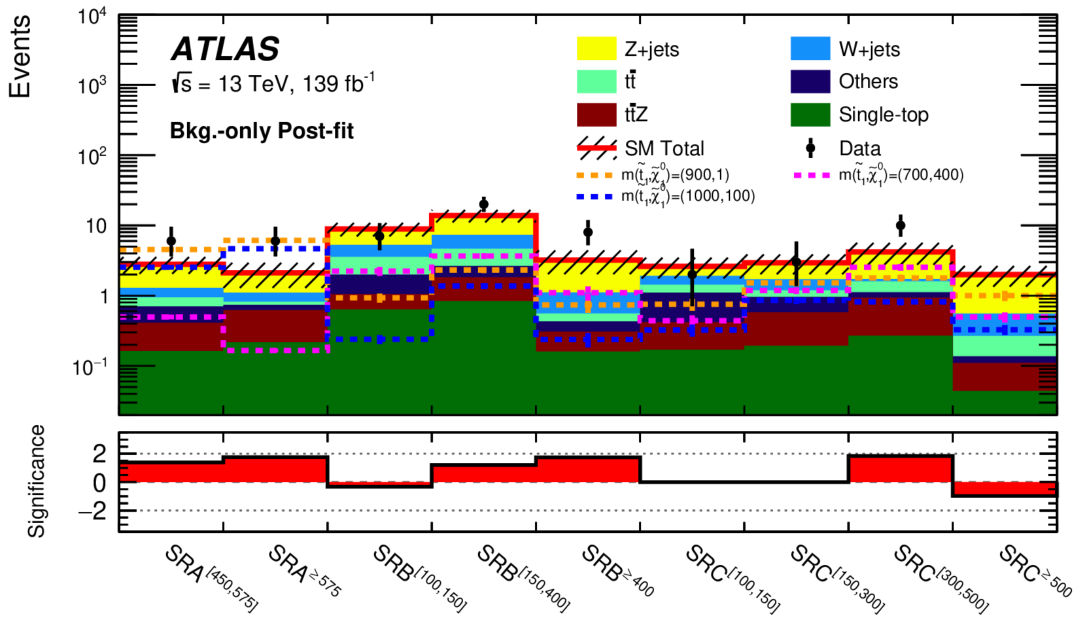
DNN = *Deep Neural Network*

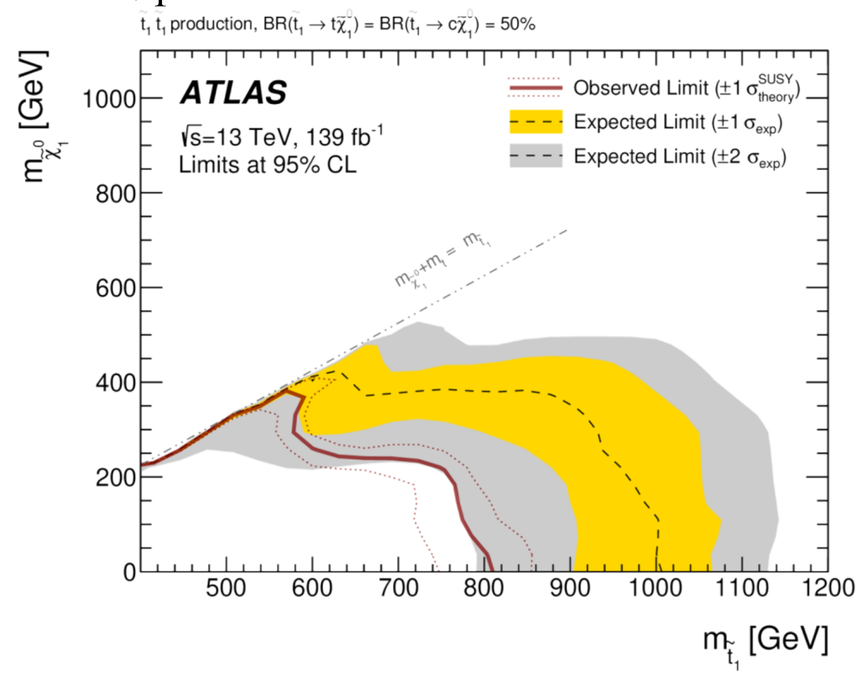
Non-minimal scenarios

Stop to Top or Charm

JHEP 07 (2024) 250

- Signal regions: Multiple SRs are defined depending on target model
  - Small $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$: Initial radiation state jet + high DNN score to distinguish signal and BG
  - Large & intermediate $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$: top-tagged large-$R$ jet
- Backgrounds: Z/W+jets, single- t, $t\bar{t}$-pairs
- Results:
  - **Mild** excess close to 2σ in SRs for large & intermediate $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$. Exclusion limits on stop mass are set.





Background-only post-fit SM yields and statistical significance: the largest deviation between the post-fit expectation and the observed data is close to 2σ in three regions.

Conclusions

- **Various searches** targeting SUSY models including compressed scenarios, LLP or non-minimal assumptions have been performed in the ATLAS.
- **Special reconstructions and analysis** methods are used for each target model to capture **unconventional** signals.
- **No evidence** of new physics was found so far, but those results gives the **constraints to the parameter space**.
- Several full Run 2 analyses are in preparation for new results, and many partial Run 3 analyses are also progressing.
- Run 3 is on-going and will improve sensitivity thanks to **more statistics and new techniques.**

Back up

Backgrounds and Validation Regions

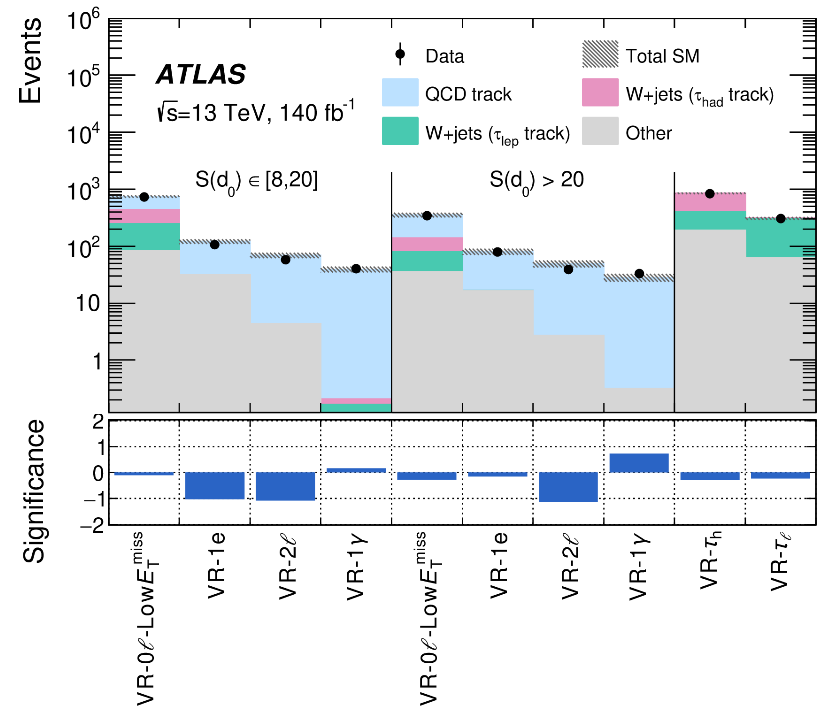
Phys. Rev. Lett. 132 (2024) 221801

Standard Model Backgrounds

- QCD tracks
  - Originates from W/Z + jets events where the signal candidate tracks originate from long lived hadrons decays, pileup jets
  - Estimated via data-driven ABCD method
- Tau tracks
  - Originates from W($\rightarrow \tau\nu$) + jets events where a pion or lepton from a low pT τ-lepton decay is tagged as the signal candidate track
  - Estimated via MC simulation, normalized to data

Validation Regions

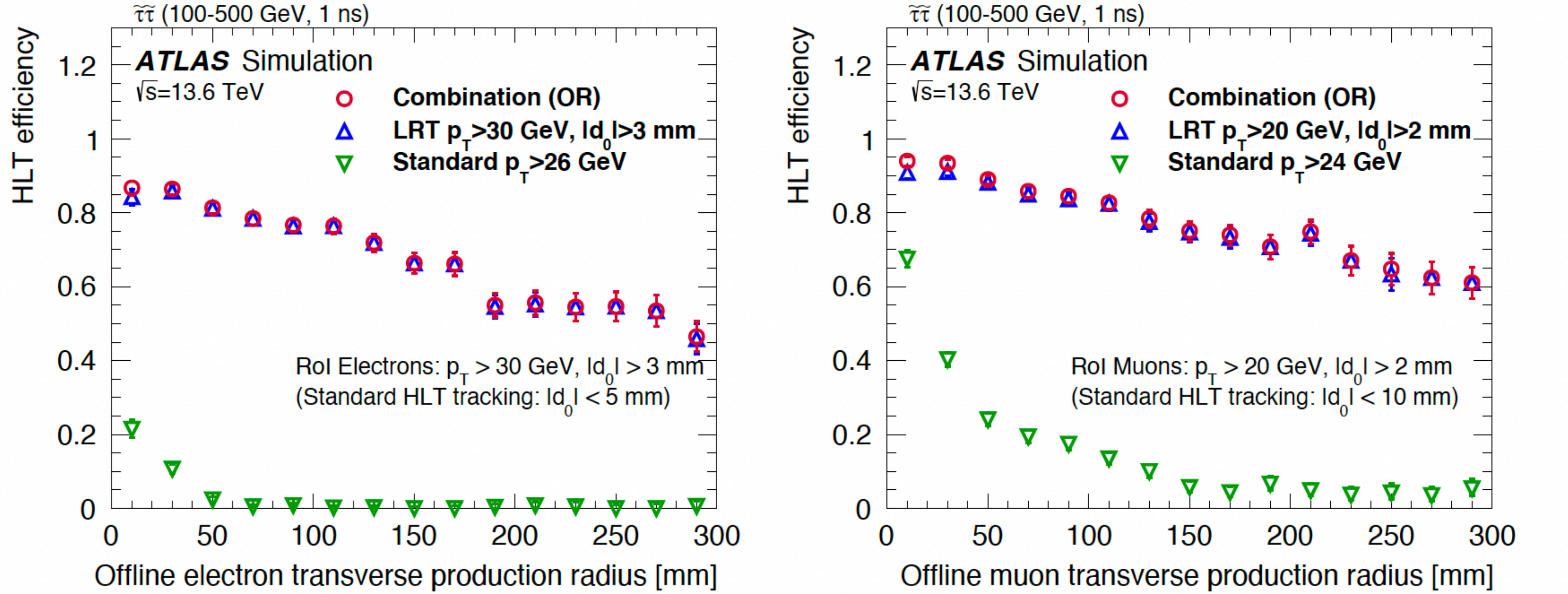
- Defined with similar backgrounds as the SRs in addition with different lepton or photon content
- A shifted E_T^{miss} range (300 GeV- 400 GeV) increases data yield and reduces signal contamination



LRT Trigger in Run 3

JINST 19 (2024) P06029

- The improvement at low masses (and therefore low momentum leptons) is from the new Large Radius Tracking trigger.



Displaced (left) electron and (right) muon trigger efficiencies with respect to their L1 seeds versus the offline reconstructed lepton production radius (LRT, open triangles). The efficiencies for the isolated primary single electron and muon triggers (Standard), are shown as inverted triangles. A logical OR between the LRT and standard triggers (Combination) is marked with open circles. Only statistical uncertainties are shown.

Long-Lived

Displaced Leptons

Spare? Add few info in others?

ATLAS-CONF-2024-011

- Strategy 1: ABCD analysis focusing on *dilepton events*
  - Photon, muon, or LRT lepton triggers (Run 3 only)
  - LRT and looser lepton identification requirements
  - Signal region (SR): Displaced $ee/e\mu/\mu\mu$
  - Background (BG): Fake leptons, leptons from heavy flavour decay, cosmic muons
    - → Estimate using ABCD method.

Overview plots

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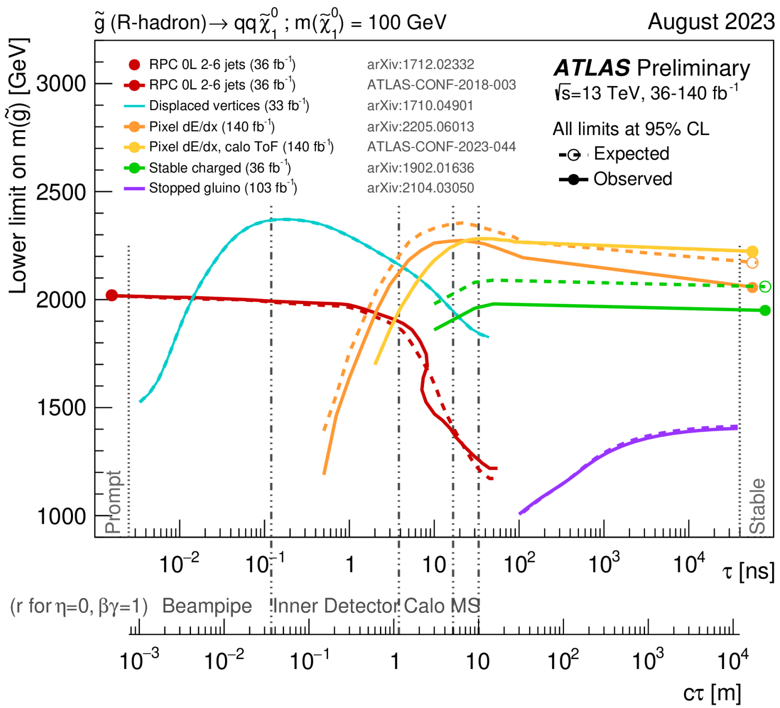
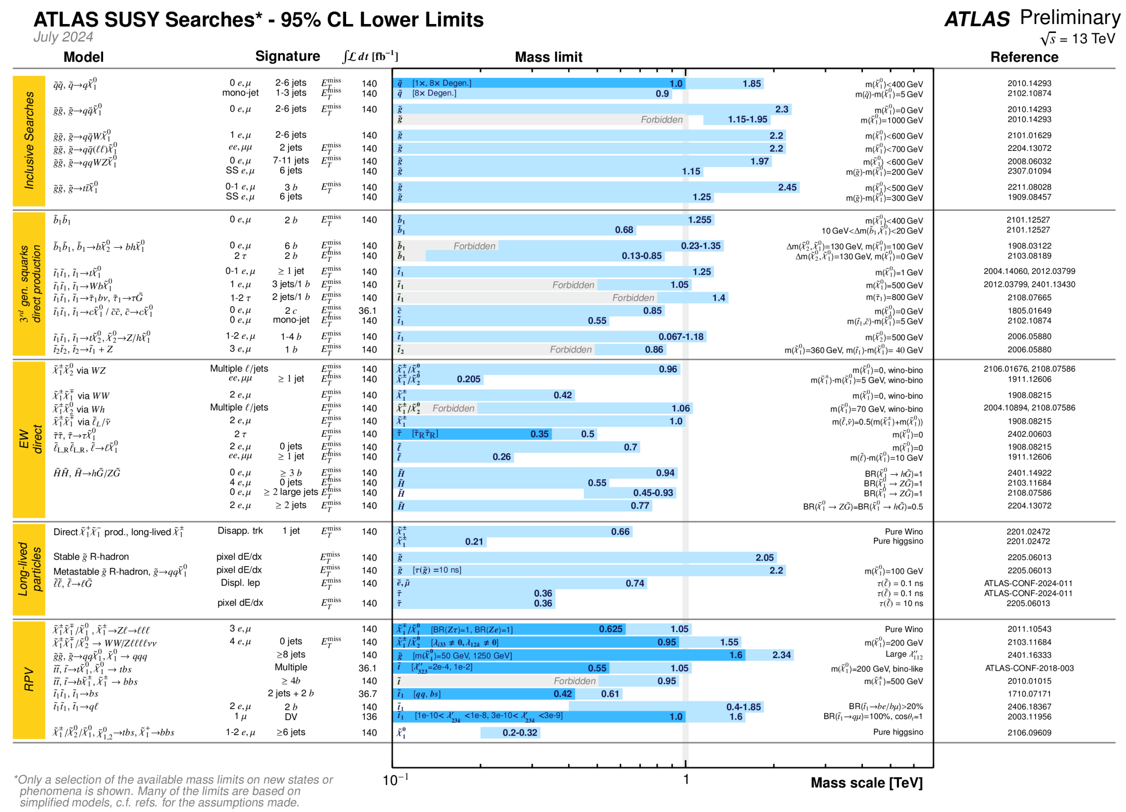


Constraints on the gluino mass-vs-lifetime plane for a split-supersymmetry model with the gluino R-hadron decaying into a gluon or light quarks and a neutralino with mass of 100 GeV



Mass reach of the ATLAS searches for Supersymmetry. A representative selection of the available search results is shown.