Searches for BSM physics using challenging and long-lived signatures with the ATLAS detector

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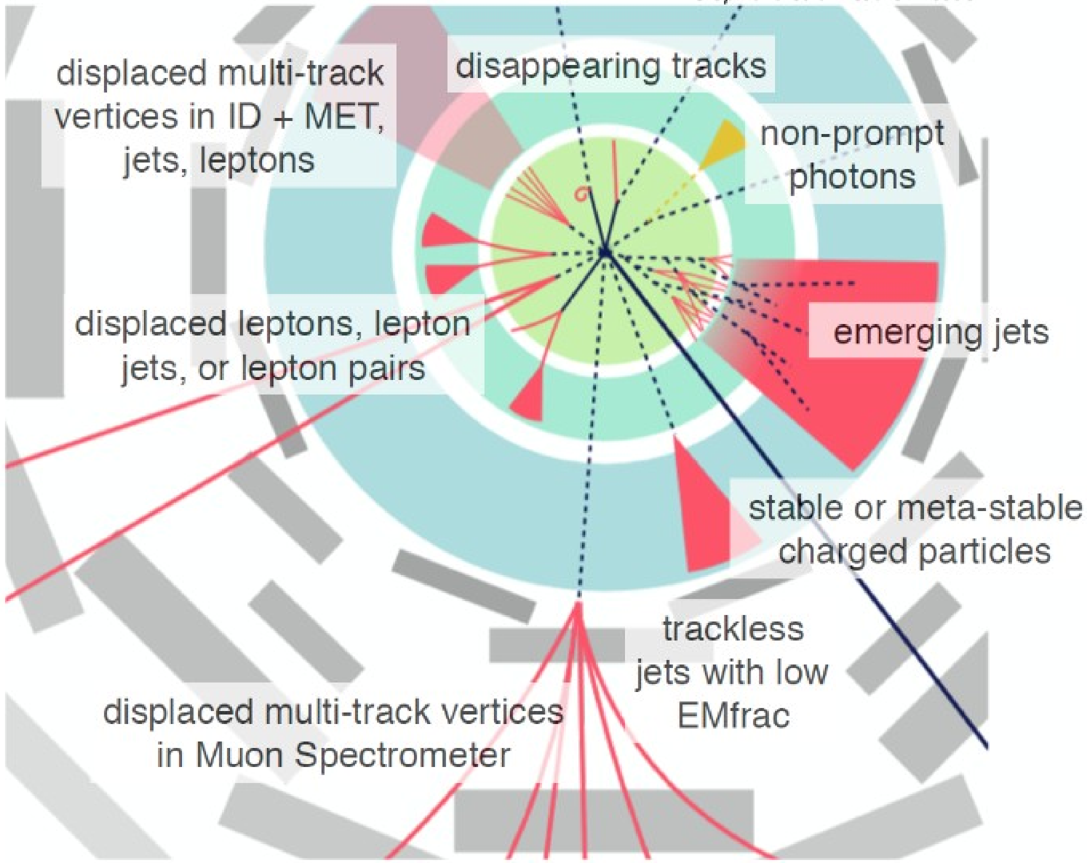
On behalf of the ATLAS collaboration

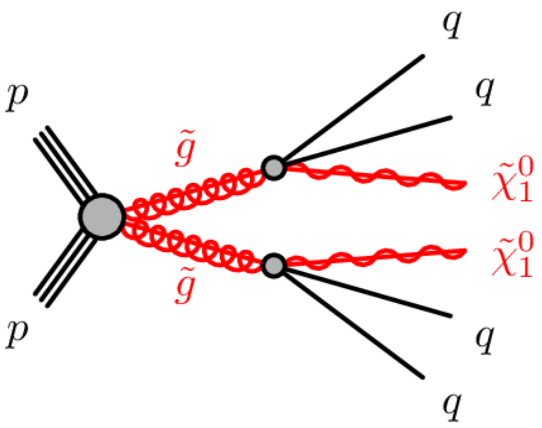
- Large ATLAS dataset collected over several years of LHC operation, along with extensive knowledge of the detector developed, now allows for a broad range of searches using unconventional signatures.
- Challenging to detect due to frequent limitations in triggering, unusual object reconstruction, and difficult background estimation.
  - Push the limits of what ATLAS is capable of to fully exploit the physics capability of the LHC
- Present here several recent ATLAS results of this kind.

Graphic credit: Heather Russell

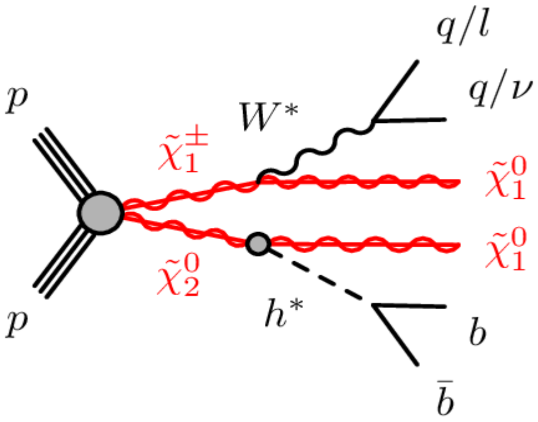


- Run 2 search using 137 fb^{-1} of data from 2016-2018
- Trigger using missing transverse momentum (MET), target models with displaced vertices in association with non-detected particles.
  - Trigger using calorimeter-based E_T^{Miss} > 50 to 70 GeV, require offline E_T^{Miss} > 150 GeV.

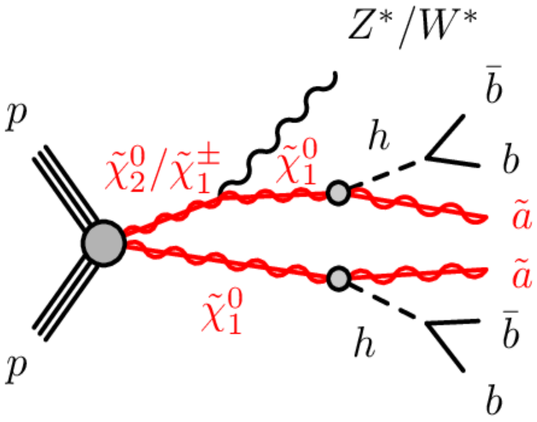
Physics Interpretations



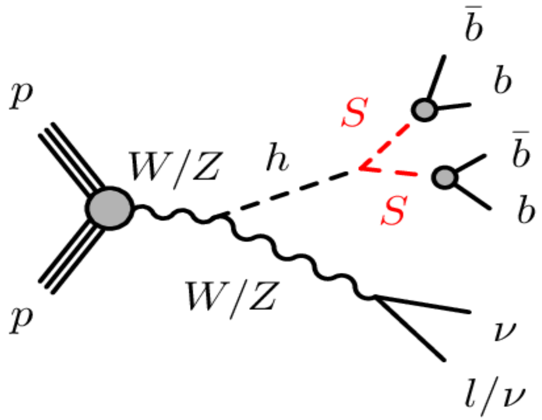
Gluino R-hadron



Bino-Wino coannihilation



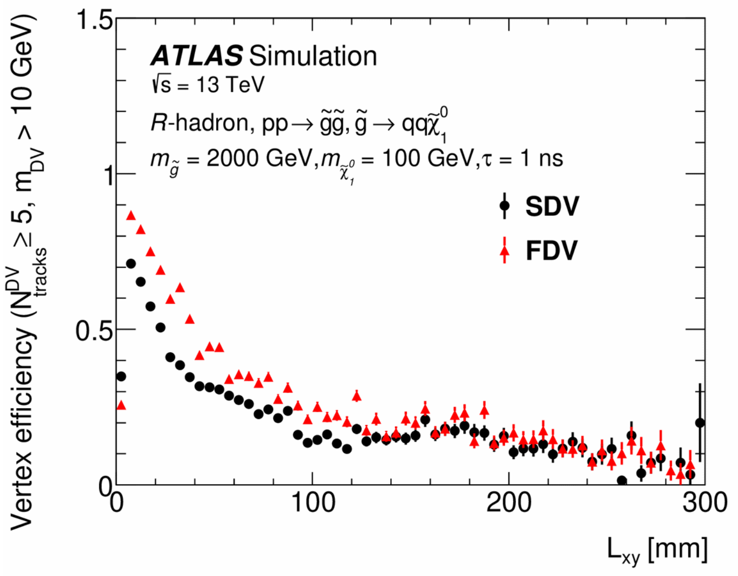
DFSZ Axino

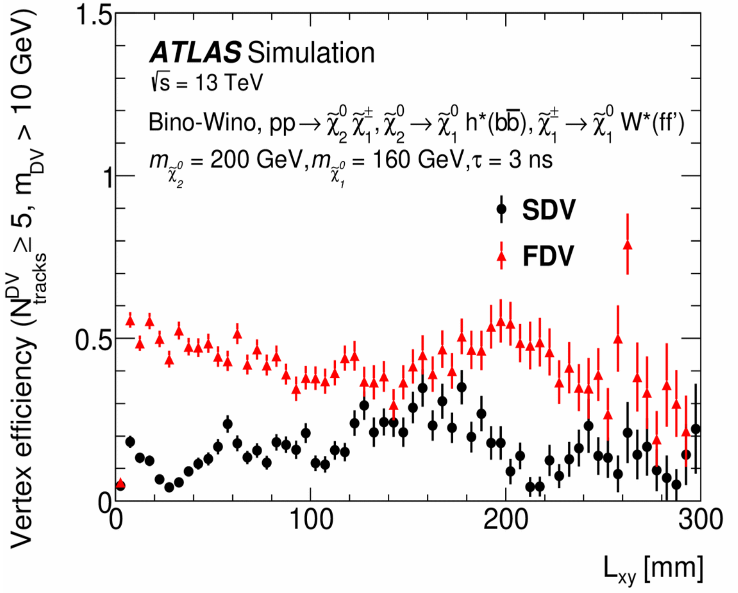


Higgs Portal Scalars

https://arxiv.org/abs/2603.12051

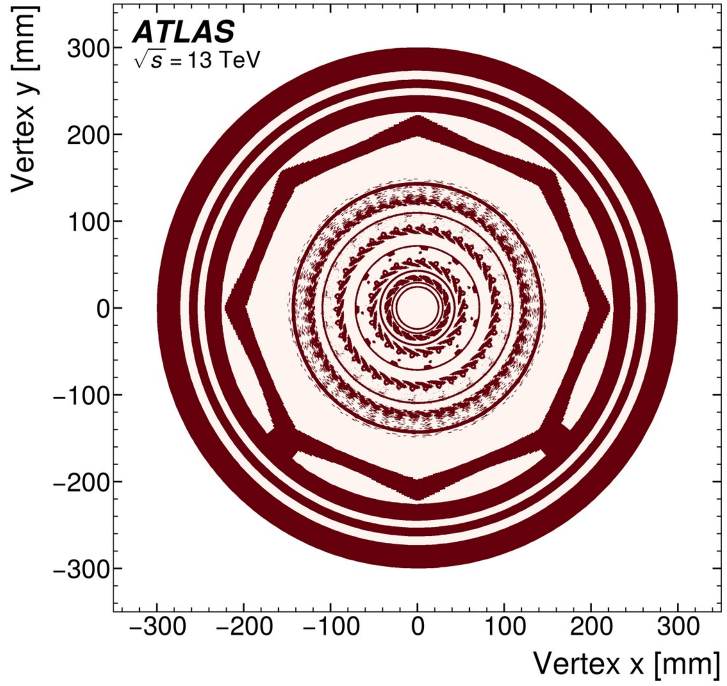
DV + MET Method





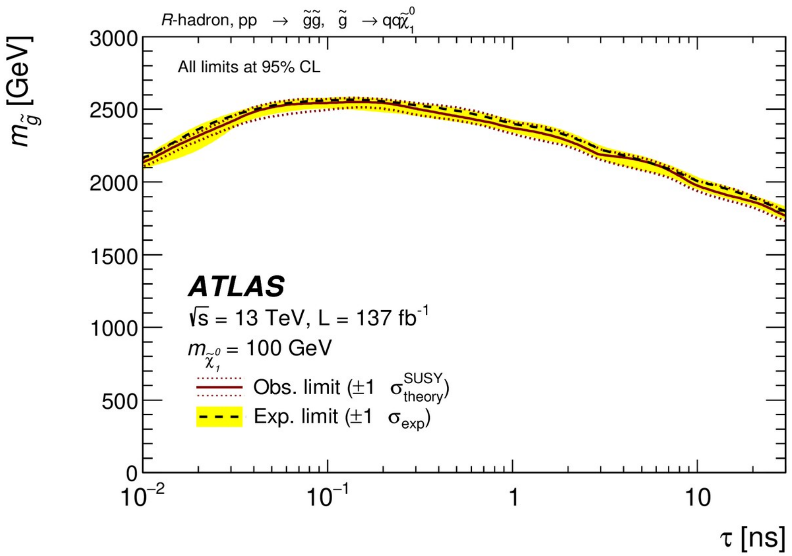
https://arxiv.org/abs/2603.12051

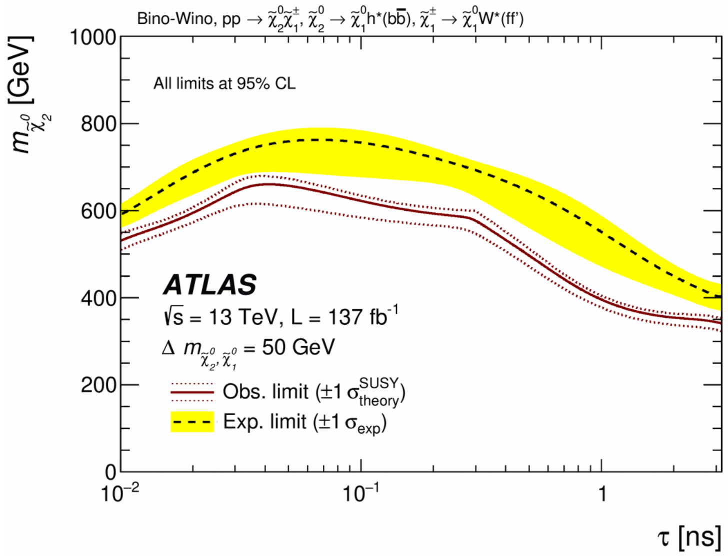
- Use new fuzzy displaced vertexing (FDV) algorithm in addition to standard vertexing (SDV)
  - Increases sensitivity to displaced decays where not all particles originate from a single point.
- Primary backgrounds from hadronic interactions, accidental crossings, and merged vertices
  - Data-driven background prediction using vtx. reco probability given the density of tracks in the event.
  - Reduce using material map veto and quality requirements for tracks+vertices.

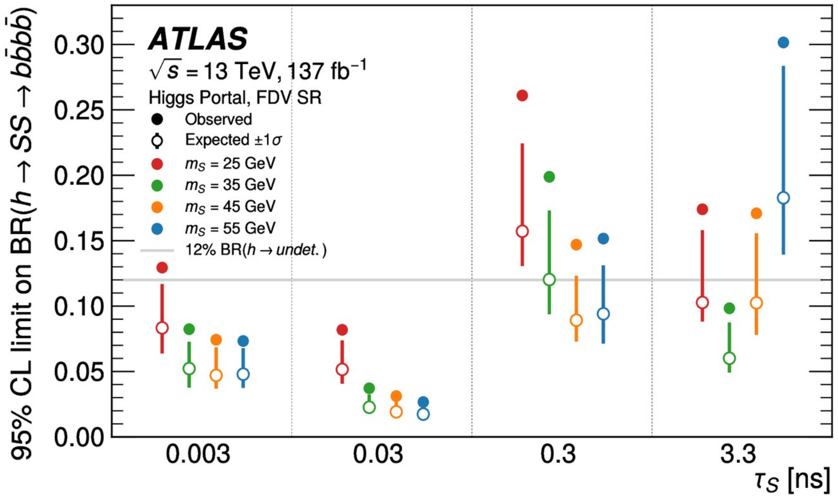


DV + MET Results

Region	Observed (Expected)	$\langle A\epsilon\sigma\rangle^{95}_{\rm obs}$ [fb]	$S^{95}_{\rm obs}$	$S^{95}_{\rm exp}$	$p(s=0)$	Z
SDV SR	1 (0.6 ± 0.4)	0.0280	3.84	$3.20^{+1.17}_{-0.05}$	0.32	0.46
1FDV SR	3 (0.8 ± 0.5)	0.0469	6.42	$3.62^{+1.53}_{-0.18}$	0.06	1.59
2FDV SR	2 (1.3 ± 0.6)	0.0353	4.83	$3.98^{+1.59}_{-0.63}$	0.31	0.50





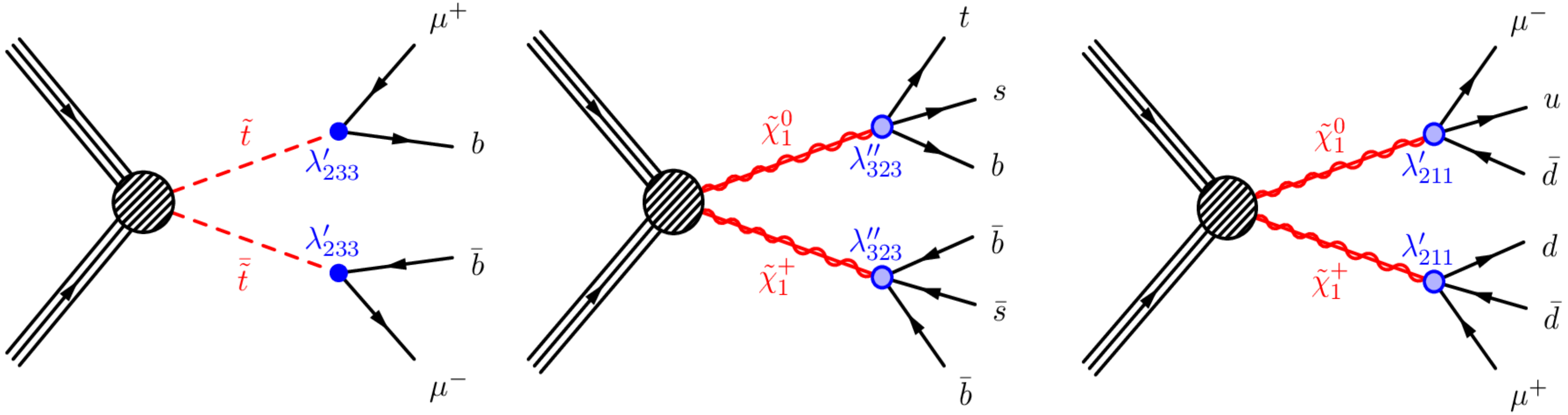


- Slight excess observed in one fuzzy displaced vertex signal region, other regions consistent with expectation.
- Model-independent limits calculated for any non-SM process independently within each signal region.

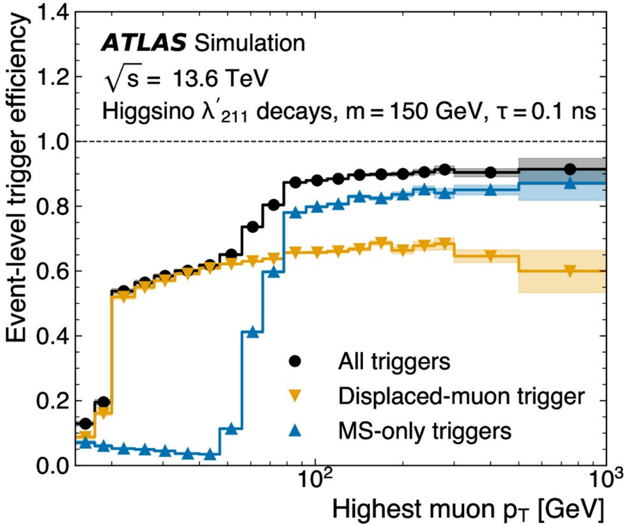
https://arxiv.org/abs/2603.12051

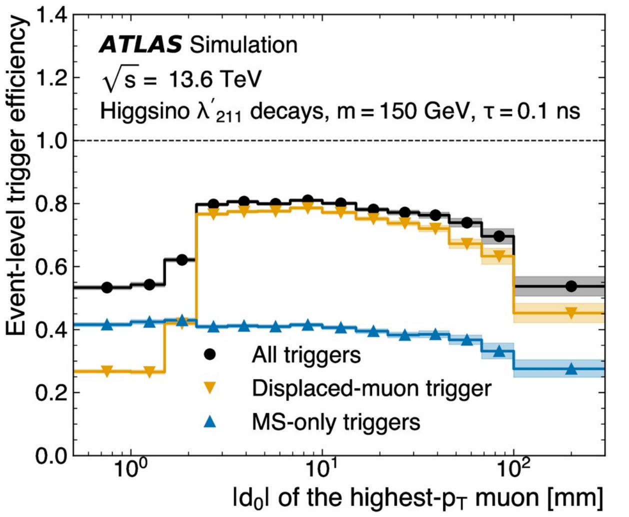
Displaced Vertices and Muons

- Partial Run 3 search using 164 fb^{-1} of data from 2022-2024
- Trigger using muons produced in association with displaced DVs
  - Add novel displaced muon trigger introduced in Run 3
  - Muons required to have large transverse impact parameters, but *not* necessarily be reconstructed with the DV.



Interpret results with three different R-parity-violating SUSY benchmark models

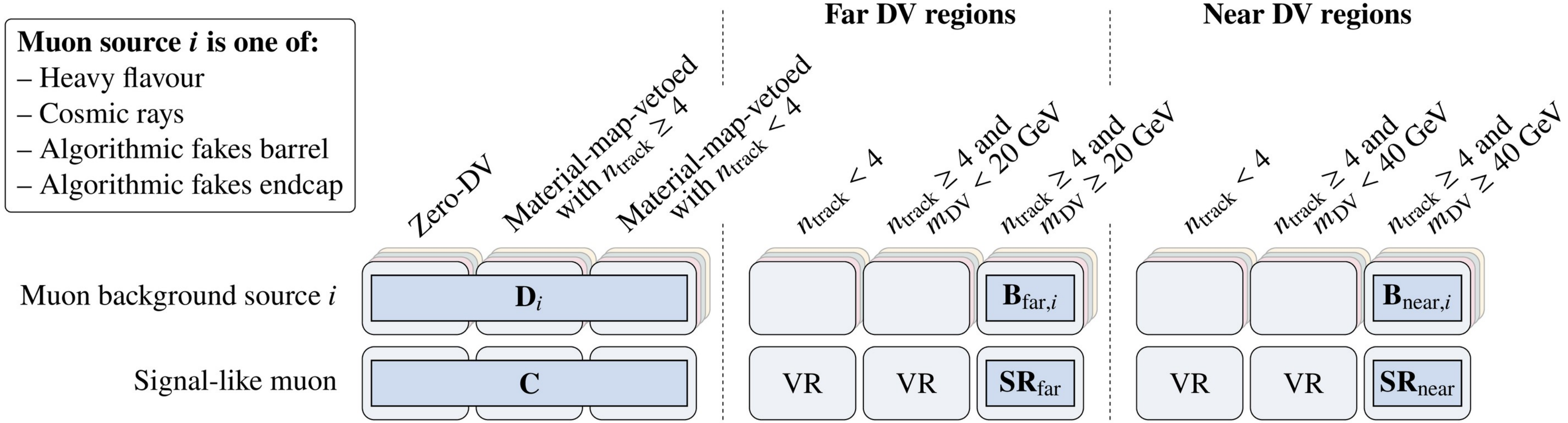




https://arxiv.org/pdf/2603.01991

DV + Muon Methods

- Two signal regions based on the position of the DV
  - *Near* DVs, with transverse distance > 1 and <4 mm
  - *Far* DVs, with transverse distance >4 mm
- Background displaced muons from heavy-flavor decays, cosmics, or algorithmic fakes
- Background DVs from random crossings or hadronic interactions
- Predict background using ABCD method, requiring separate scalings for each background source.
  - Derive transfer factors using orthogonal regions enriched in each separate source.



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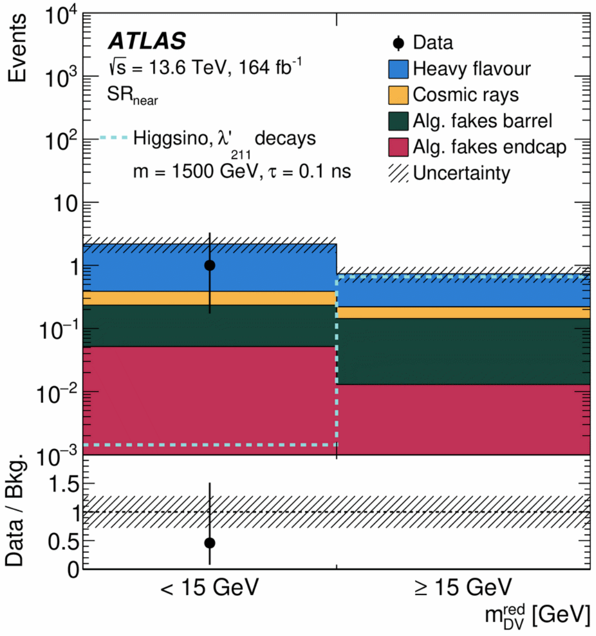
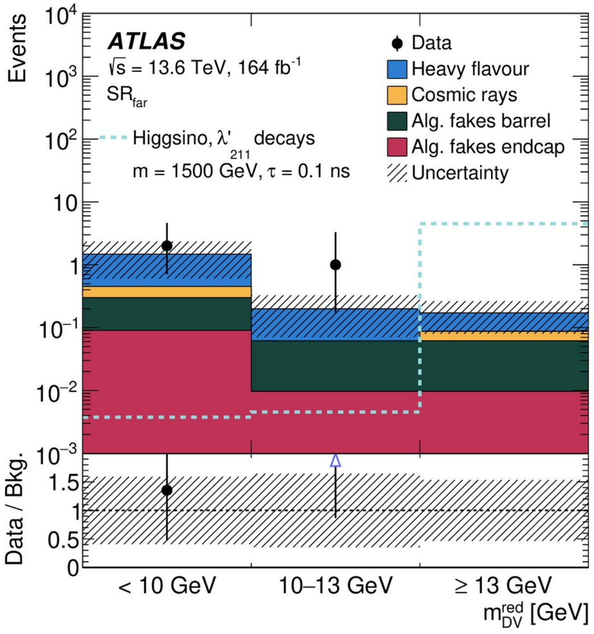
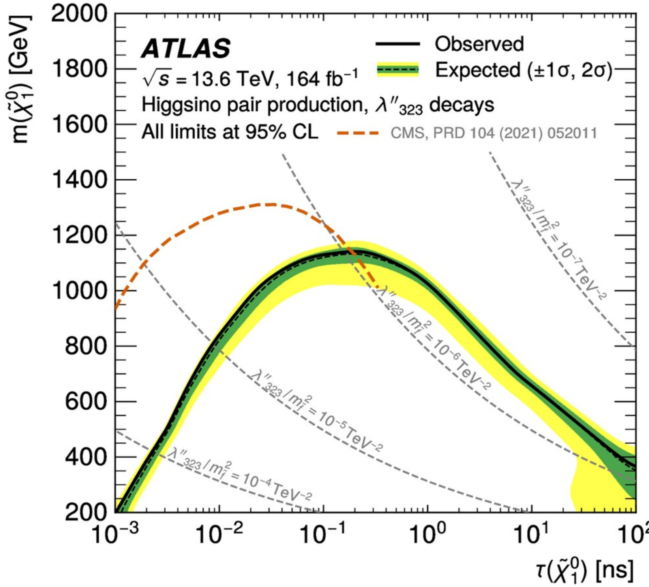
DV + Muon Results

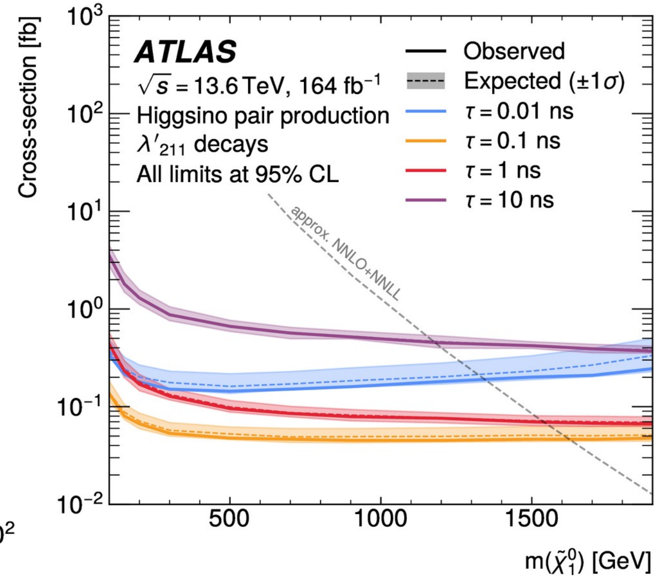




- Observed event counts consistent with background-only hypothesis.
- Produce model-independent limits for each signal region as well as exclusion plots for each of the three RPV models considered.

	Total predicted	Observed	$\langle\sigma A\epsilon\rangle^{95}_{\mathrm{obs}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}
$\mathrm{SR_{far}}$, $m^{\mathrm{red}}_{\mathrm{DV}}$ inclusive	1.8 ± 1.1	3	0.038	6.2	4.9
$\mathrm{SR_{far}}$, $m^{\mathrm{red}}_{\mathrm{DV}} \geq 10$ GeV	0.37 ± 0.20	1	0.023	3.8	3.1
$\mathrm{SR_{far}}$, $m^{\mathrm{red}}_{\mathrm{DV}} \geq 13$ GeV	0.17 ± 0.09	0	0.018	3.0	3.0
$\mathrm{SR_{near}}$, $m^{\mathrm{red}}_{\mathrm{DV}}$ inclusive	2.9 ± 0.8	1	0.021	3.5	4.7
$\mathrm{SR_{near}}$, $m^{\mathrm{red}}_{\mathrm{DV}} \geq 15$ GeV	0.73 ± 0.20	0	0.018	3.0	3.0

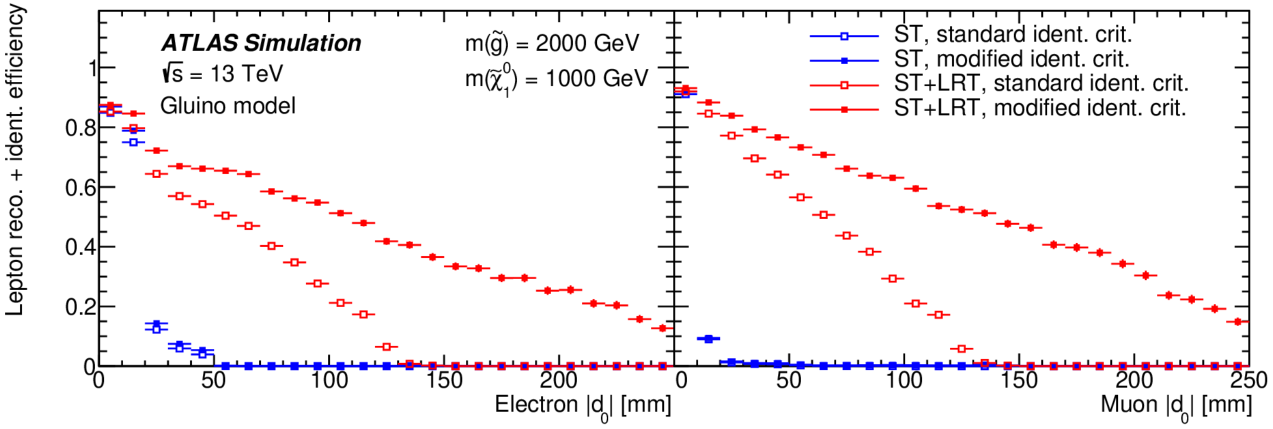




https://arxiv.org/pdf/2603.01991

Displaced Di-lepton Vertices

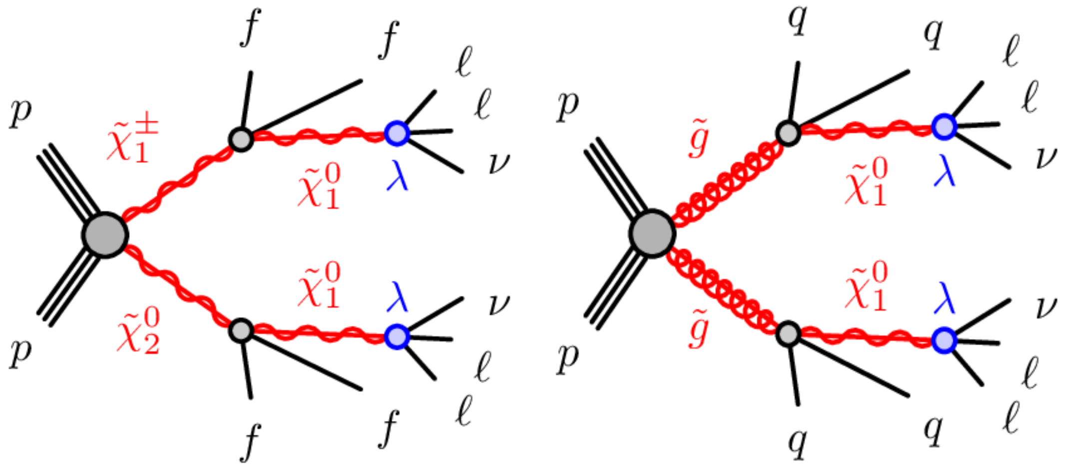
- Run 2 search using 140 fb^{-1} of data collected from 2015-2018
- Target models with decays directly producing pairs of displaced leptons.
  - Signature-driven analysis due to low backgrounds in di-lepton decays, implement as few model-dependent selections as possible.



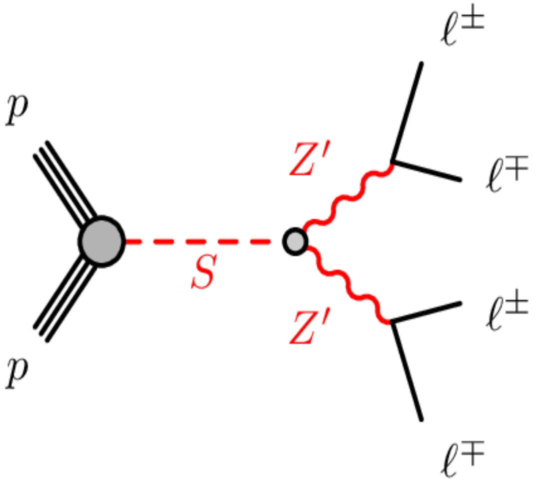
- Use large radius tracking (LRT) with selections on impact parameter and number of track hits removed to increase efficiency.

https://arxiv.org/abs/2601.05664

Benchmark Interpretations

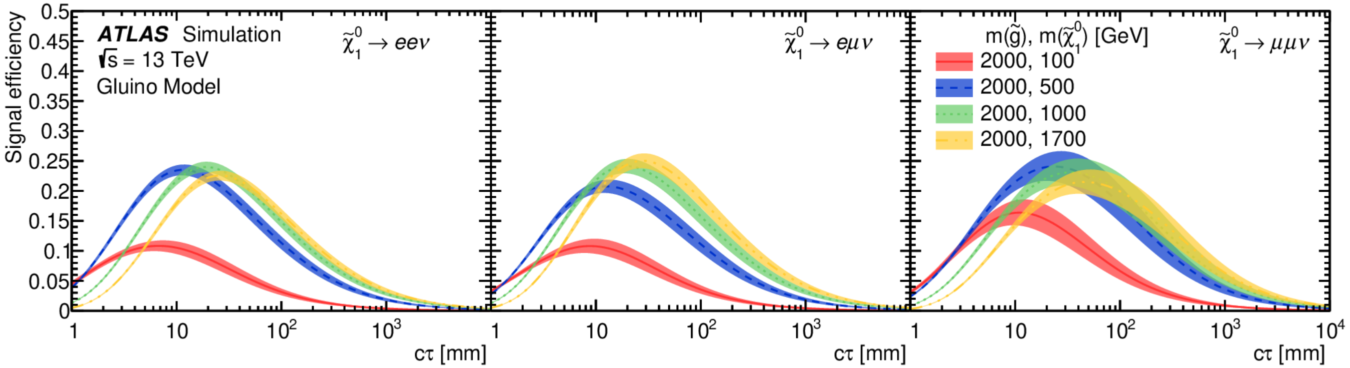


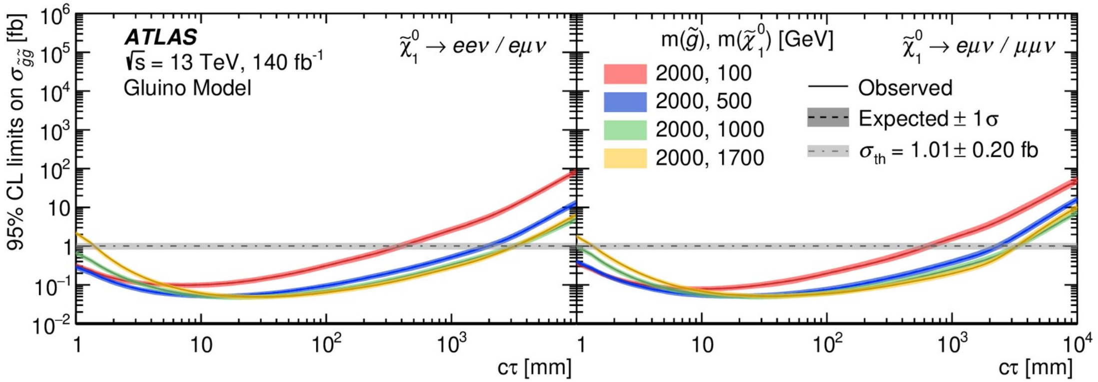
χ^0 produced via gluino (left) or electroweakino (right)

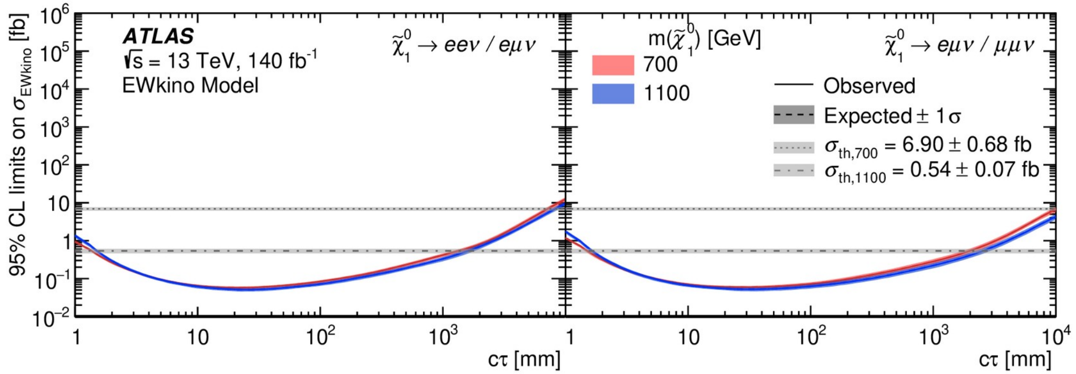


Z' production through Scalar

- Require lepton pair have invariant mass >12 GeV to remove backgrounds from SM decays
- Primary backgrounds from cosmic muons and random crossings.
  - Apply cosmic veto to reject back-to-back tracks, estimate cosmic background by extrapolating inverted veto CR.
  - Estimate random crossing probability by mixing randomly selected leptons from different events and reconstructing vertices.





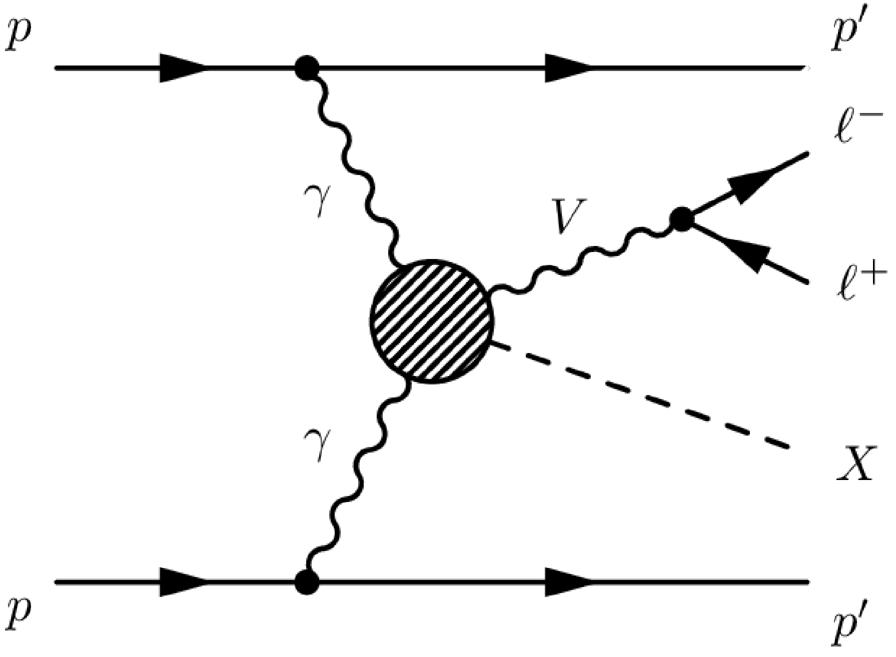


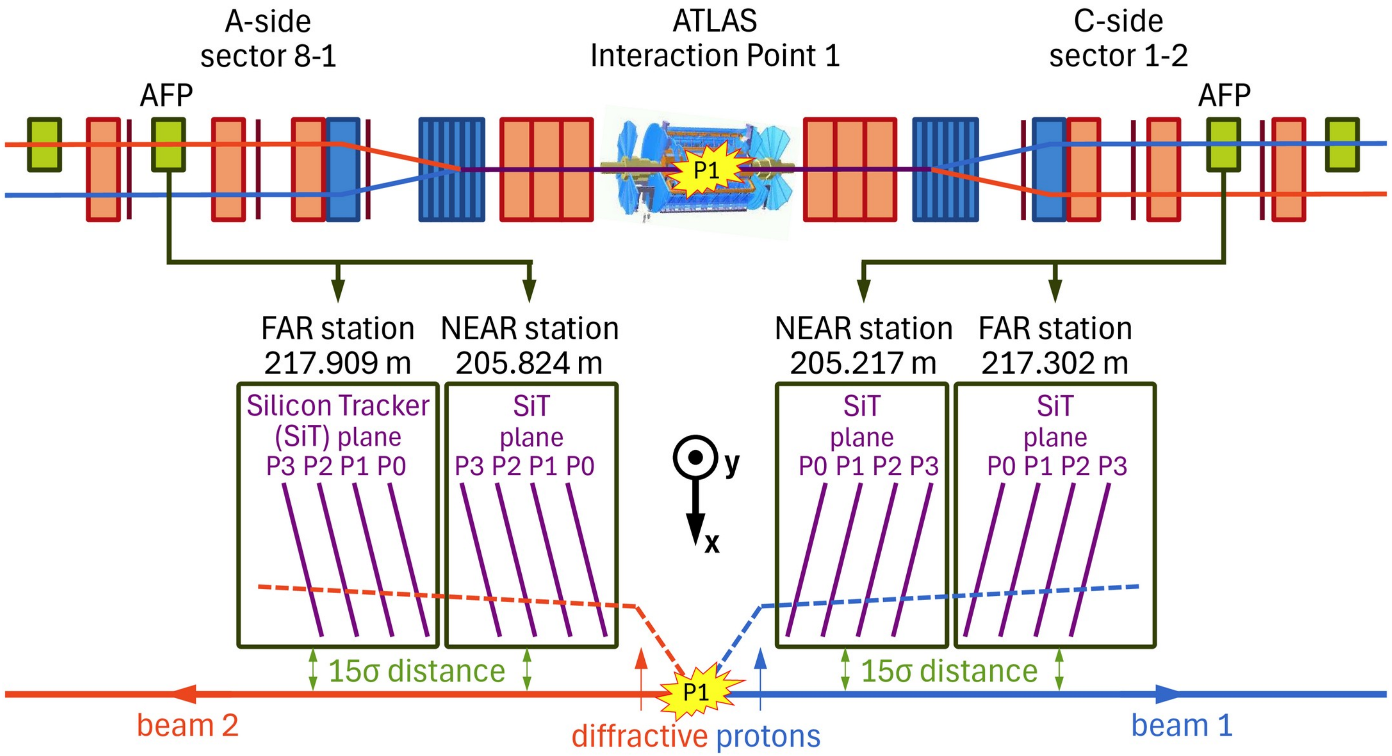
- Observe 0 events in the signal region, consistent with background-only hypothesis.

https://arxiv.org/abs/2601.05664

Missing Mass and Di-leptons in Forward-Proton-Tagged Events

- Run 2 search using 14.7 fb^{-1} of data collected in 2017
- Search for missing *mass* in events with di-lepton pairs and undetected invisible component
  - ATLAS forward proton spectrometer allows *full* photon-photon four-momentum reconstruction.





https://arxiv.org/abs/2603.20837

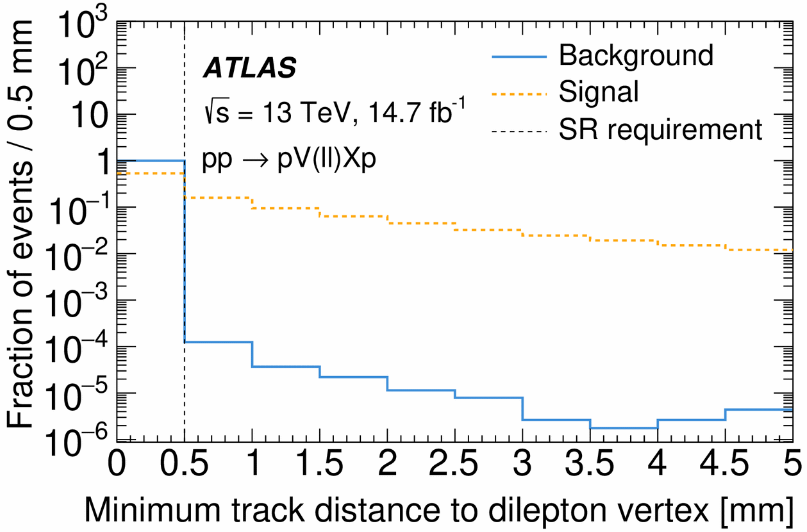
Dilepton AFP Methods

https://arxiv.org/abs/2603.20837

Feature	Criterion
Electrons	$p_T > 18$ GeV $\lvert\eta\rvert < 2.47$
Muons	$p_T > 15$ GeV $\lvert\eta\rvert < 2.4$
Dilepton system	Same flavour, opposite charge $m_{\ell\ell} > 50$ GeV $p_T^{\ell\ell} > 20$ GeV
Protons	$0.035 < \xi < 0.08$

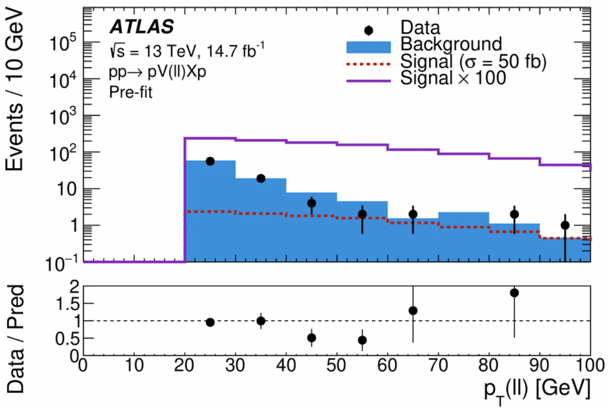
$$\xi = 1 - \frac{E_{p'}}{E_{beam}}$$

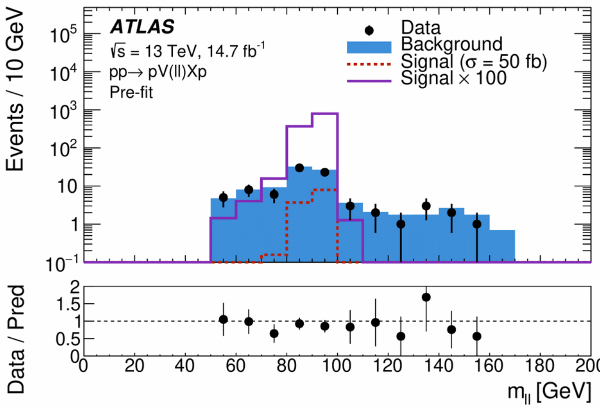
- Use single- or di-lepton triggers
- Require exactly one proton per side
- Match signal leptons to ID tracks, reject events with additional tracks near the dilepton vertex.

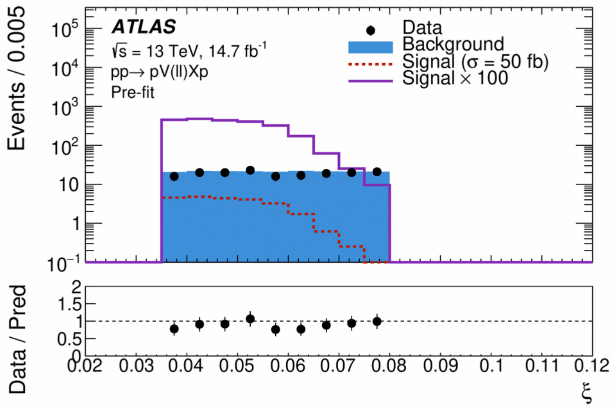


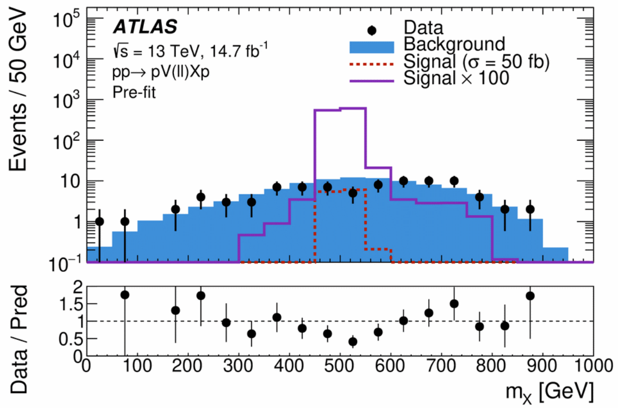
Signal mass [GeV]	Signal region [GeV]	Control region(s) [GeV]
100	0–300	300–400
200	100–300	300–400
300	200–400	0–100, 400–450
400	300–500	600–1000
500	400–600	700–1000
600	500–700	400–450, 800–1000
700	600–800	450–500, 900–1000
800	700–900	400–600
900	700–1000	400–600

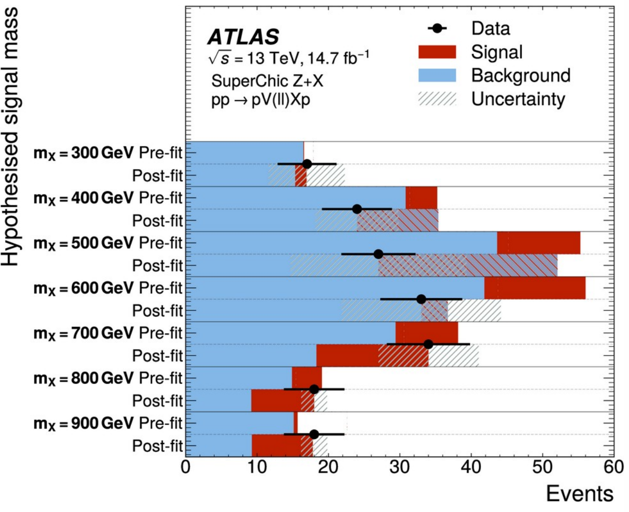
- Primary backgrounds from inclusive SM dileptons paired with protons from pileup.
  - Estimated using event mixing, combining forward protons with inclusive dileptons from other events.
- For each hypothesized mass, perform simultaneous fit using signal region near the mass and a control region far from it.

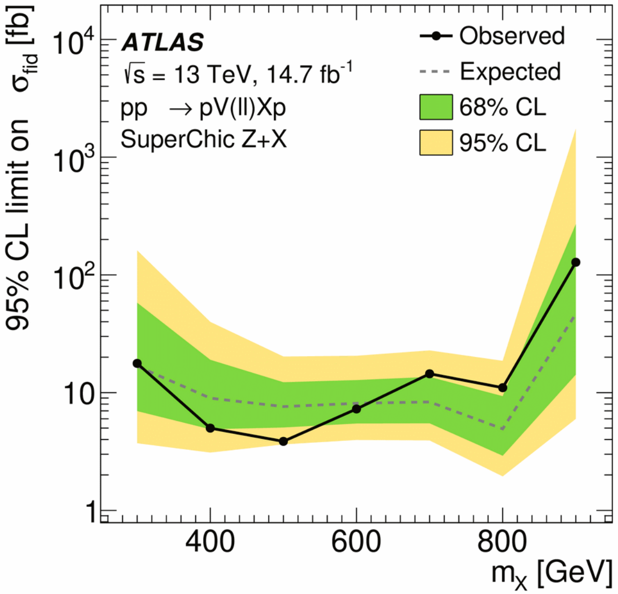


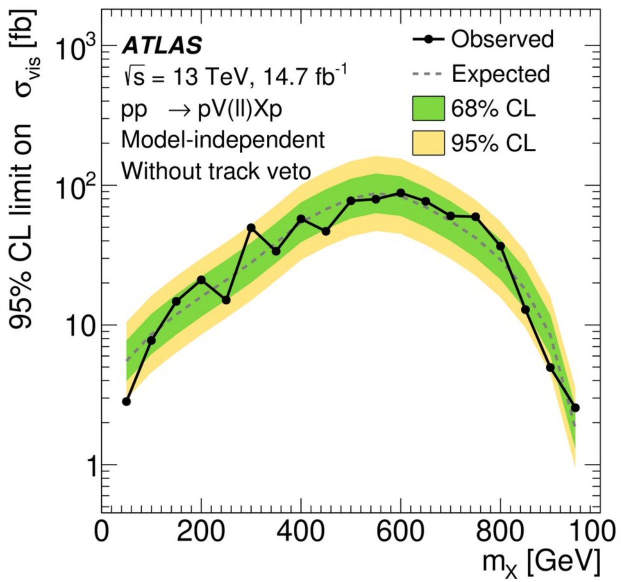


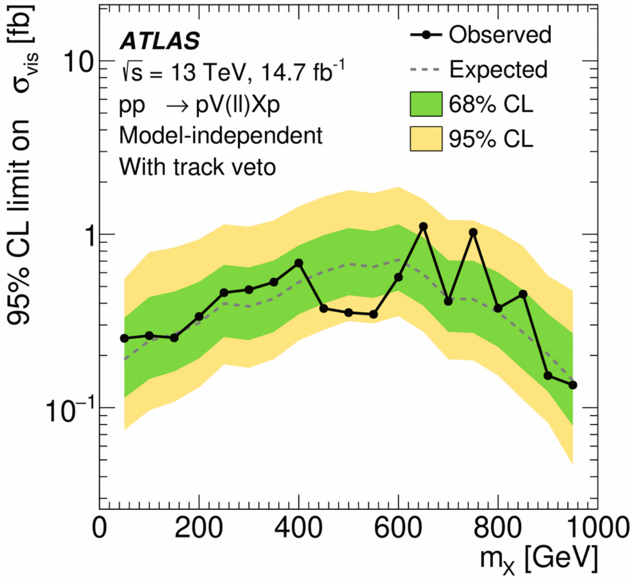










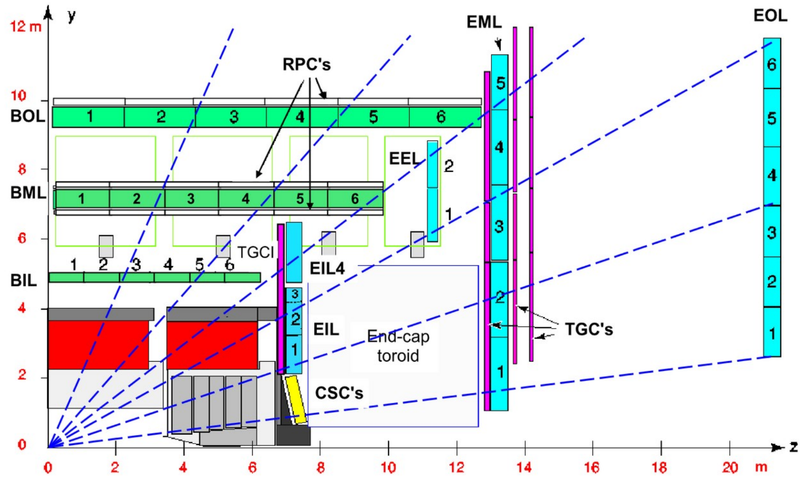


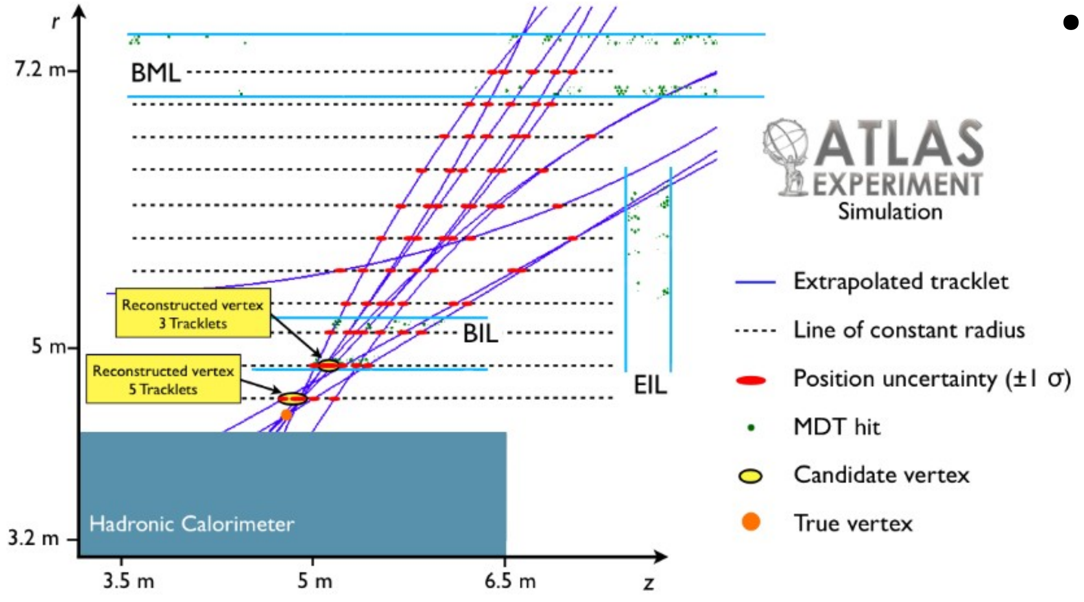
- Observations consistent with background-only hypothesis for all signal masses.

https://arxiv.org/abs/2603.20837

Displaced Vertices in the Muon Spectrometer

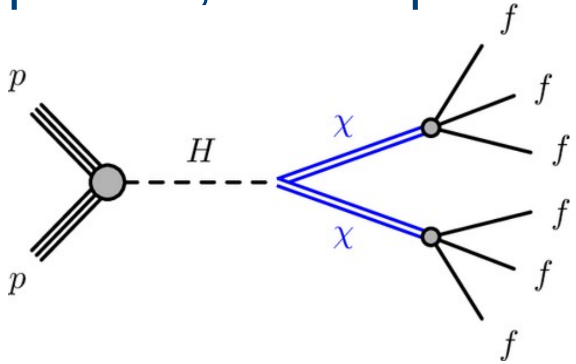
- For *really* long lifetimes, target decays in the larger volume, lower-background area of the Muon Spectrometer (MS).
- Previous ATLAS Run 2 MS DV search required two vertices, new result extends sensitivity to events with only one (Phys. Rev. D 112, 092001).

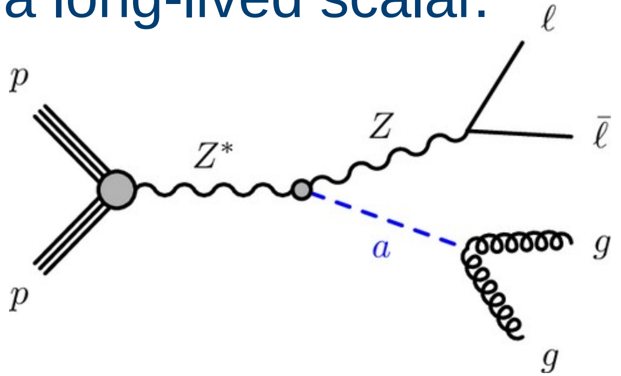




JINST 9 (2014) P02001

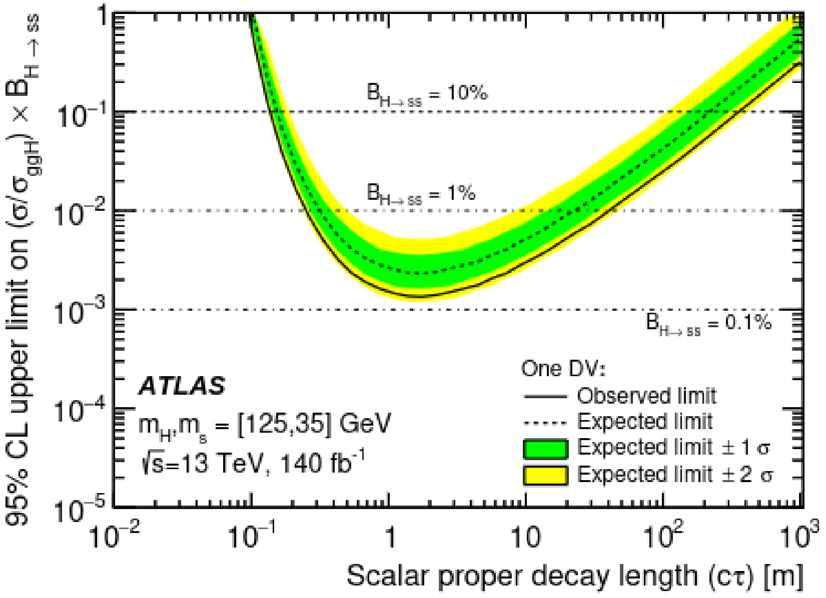
- Two analysis channels:
  - "Isolated vertex", interpreted using Higgs and Scalar portal models.
  - "Lepton-triggered", interpreted using models producing a Z boson in association with an axion-like-particle, a dark photon, or a long-lived scalar.

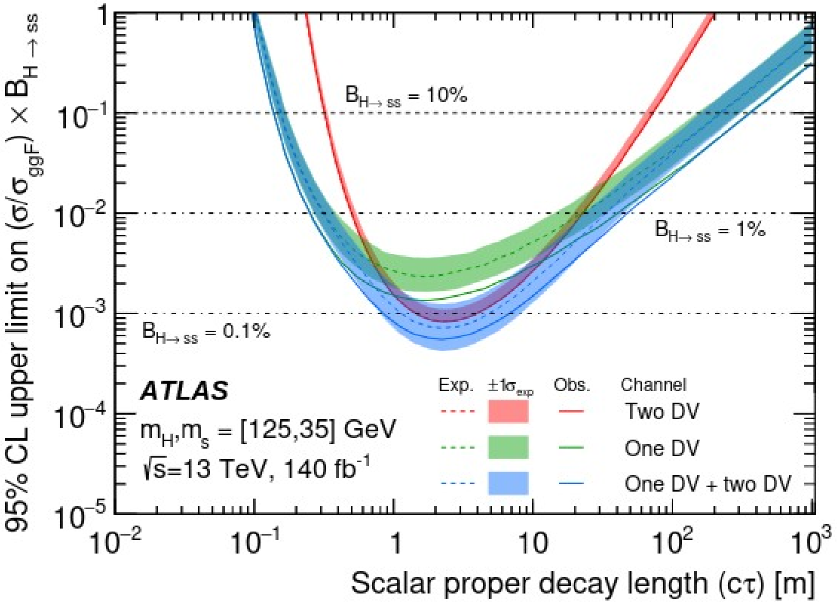


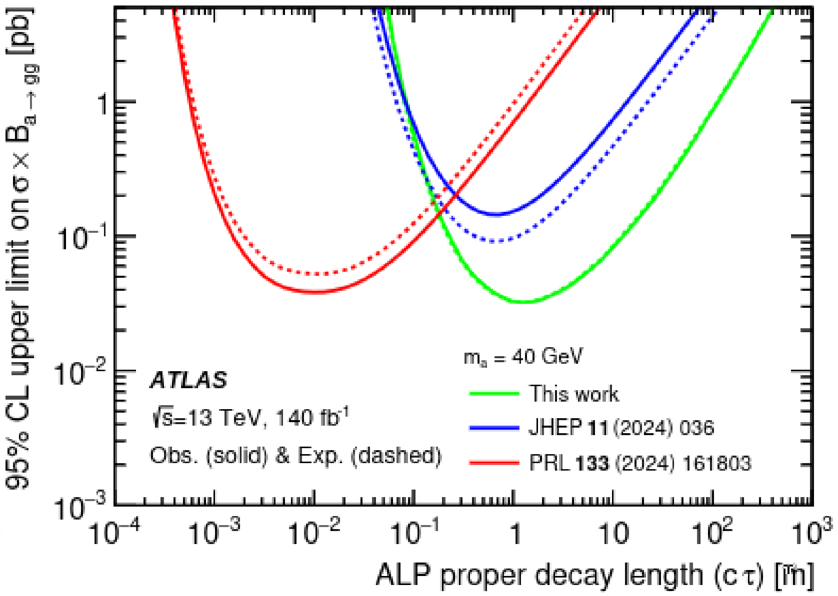


MS DV Results

- Primary backgrounds from punch-through jets
  - *Reduce* by requiring MS DVs to be isolated from tracks and jets.
  - *Predict* using data-driven ABCD method, using isolation information on one axis and vertex information on the other.
- One-vertex channel significantly increases sensitivity to shorter and longer-lived models compared to previous two vertex search (Phys. Rev. D 106, 032005).
- Strongest ATLAS limits to date for ALPs with decay lengths > O(10) m







Phys. Rev. D 112, 092001

Conclusions

- Presented recent ATLAS searches for displaced vertices and MET, muons, and dileptons, as well as missing mass in dilepton events and displaced vertices in the muon spectrometers.
- Many more unconventional and displaced analyses currently undergoing development or already published!
  - Working to fully exploit the capability of ATLAS to detect unconventional signatures in the large dataset produced with Runs 2 and 3.
- Many improvements to be made in the future, both from the improved luminosity of the HL-LHC and improvements to detector hardware, triggering algorithms, reconstruction, and analysis techniques.