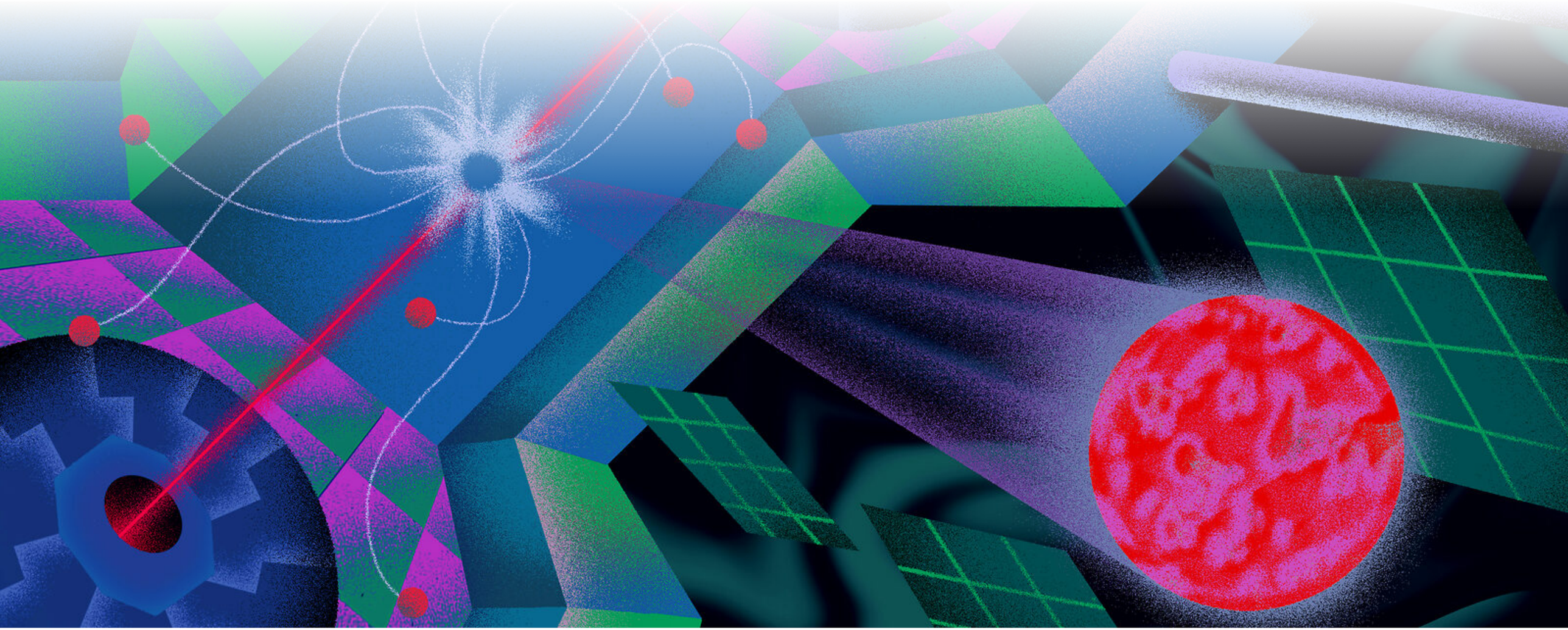
Probing the Lifetime Frontier at the LHC and Beyond



SFU
SIMON FRASER UNIVERSITY

Jackson Burzynski

Physics Potential of Future Colliders Workshop
19 September 2024

ATLAS EXPERIMENT

The Lifetime Frontier

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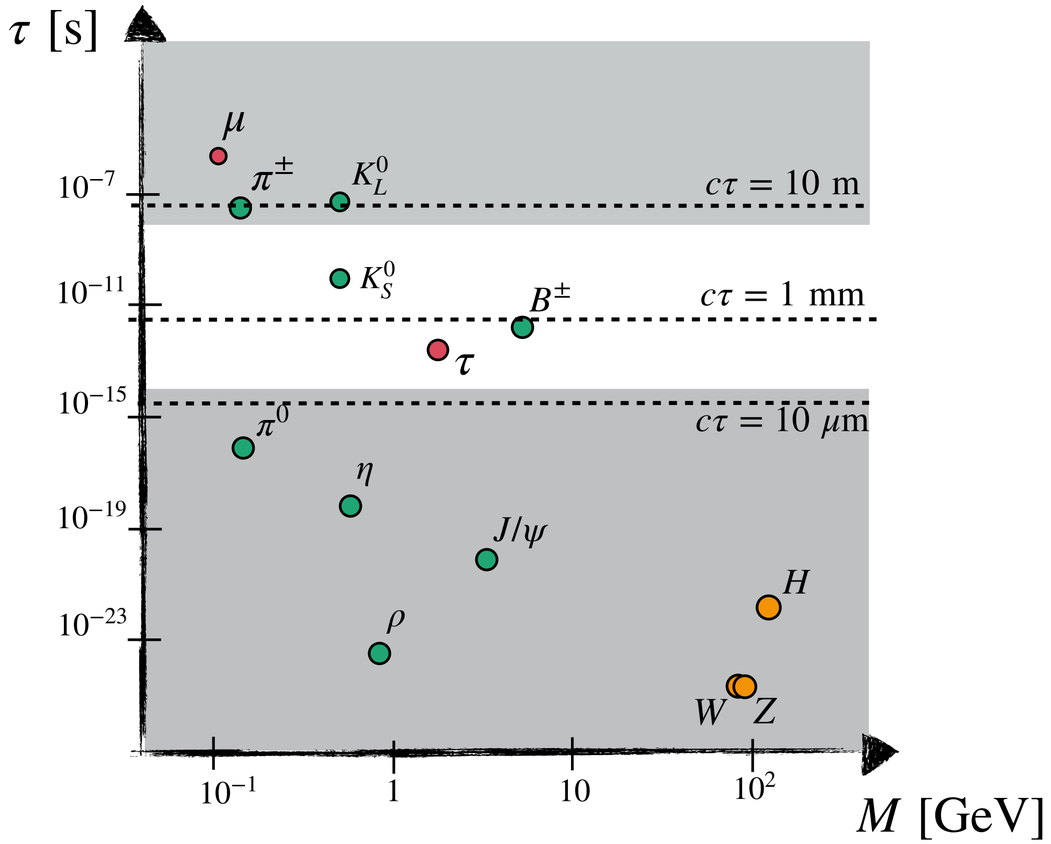

Figure adapted from arxiv:1810.12602

Lack of evidence of new physics in LHC Run 2 data motivates an increasing focus on **weakly coupled new particles** and **exotic signatures**

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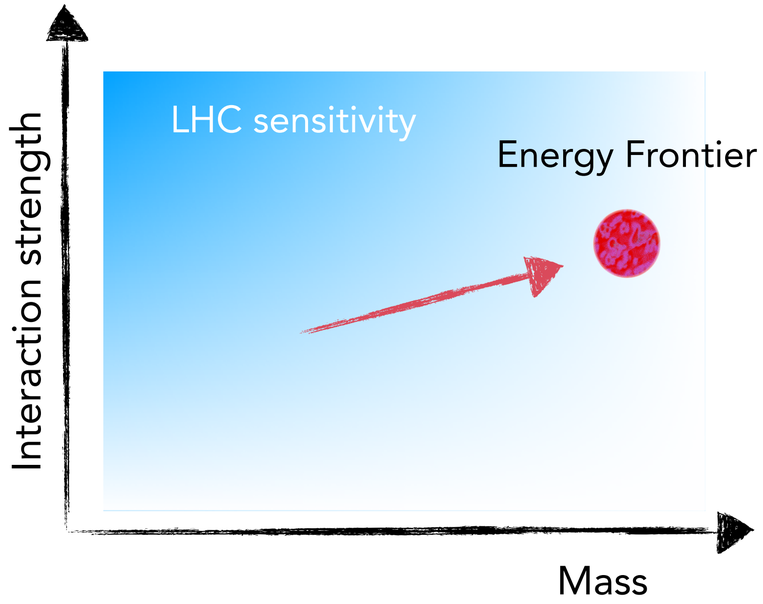

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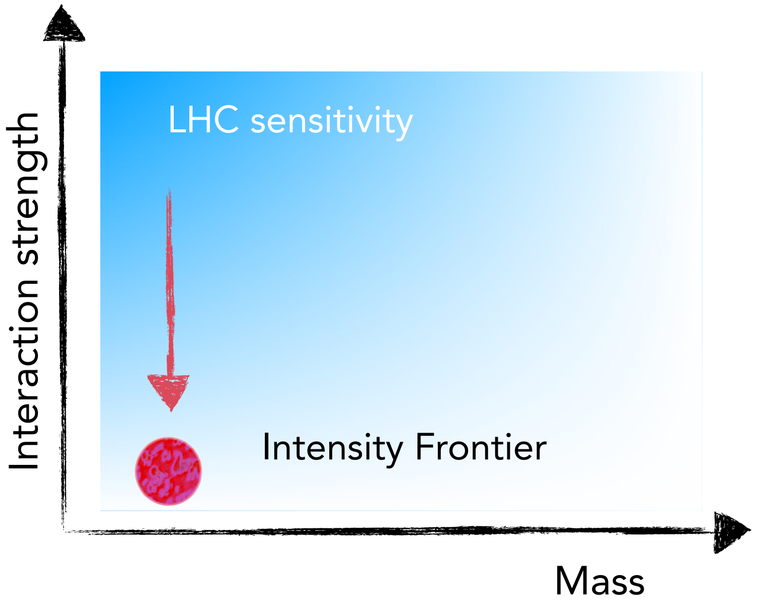

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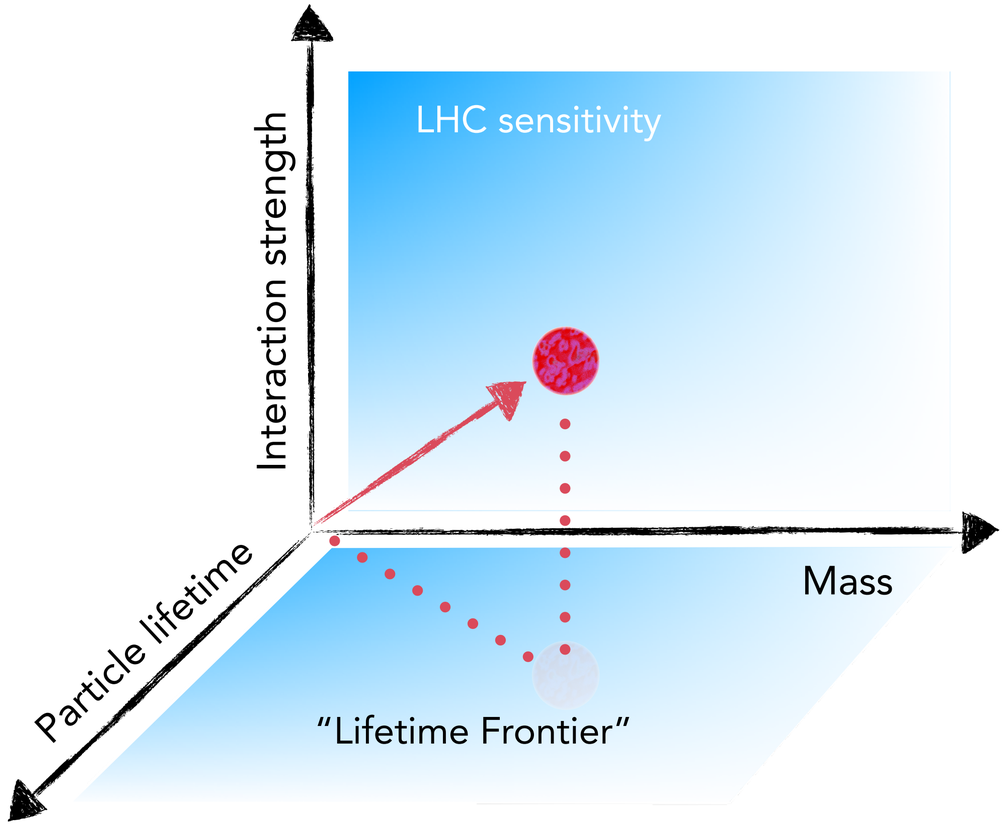

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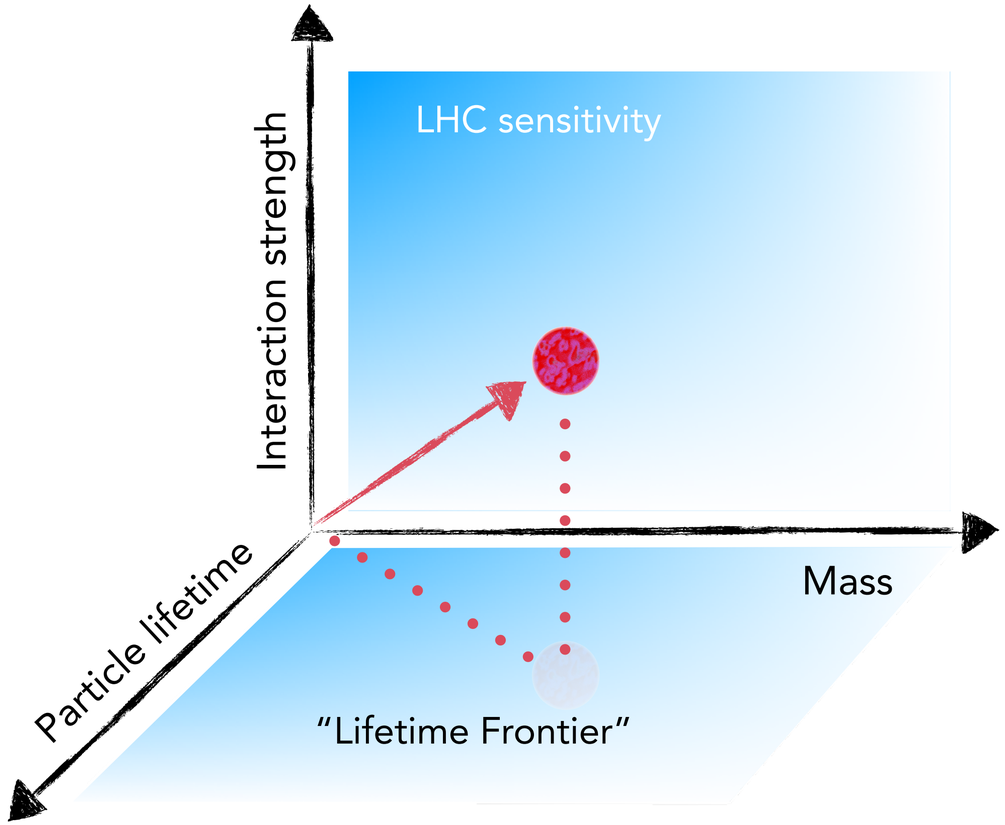

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To maximize the discovery potential of the BSM search program, we need to also probe the **“lifetime frontier”**

Overview

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Summary of recent LLP search results from ATLAS

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HL-LHC prospects for LLPs

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HiLumi HL-LHC PROJECT

LLPs at Future Colliders

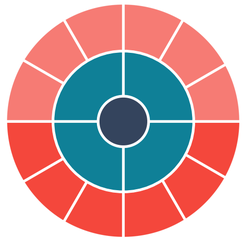
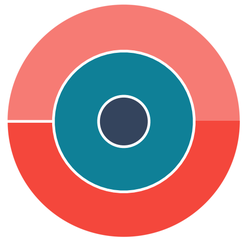
FUTURE CIRCULAR COLLIDER

LLP searches in ATLAS

Higgs portal scalars

Benchmark scenario: Higgs portal dark sector

- Bottom-up motivation as one of three renormalizable portal interactions to dark sector
- Top-down motivation from models of Neutral Naturalness

Visible sector  $-\,-\,-\left(\mu S + \lambda S^2\right) H^\dagger H\,-\,-\,-$  Dark sector

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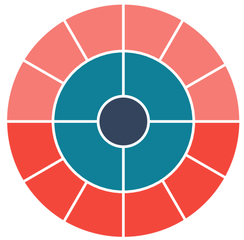
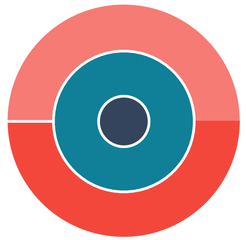
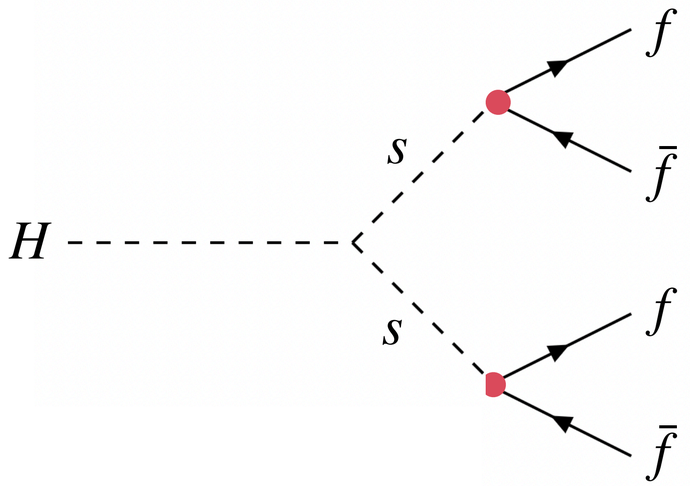
Visible sector  $-\,-\,-\left(\mu S + \lambda S^2\right) H^\dagger H\,-\,-\,-$  Dark sector

Gives rise to exotic decays of the Higgs boson

- Long-lived mediators → displaced hadronic signatures



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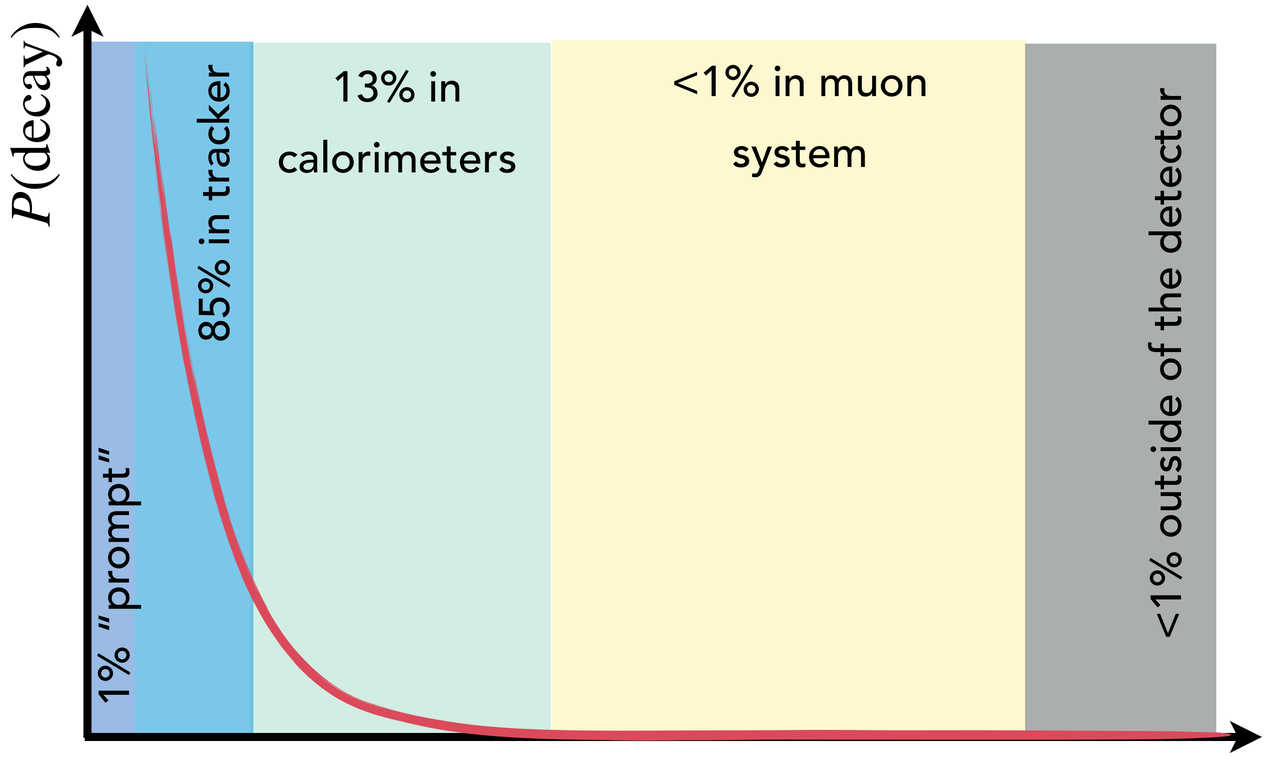

e.g. for $c\tau = 100$ mm, $\beta\gamma \sim 5$

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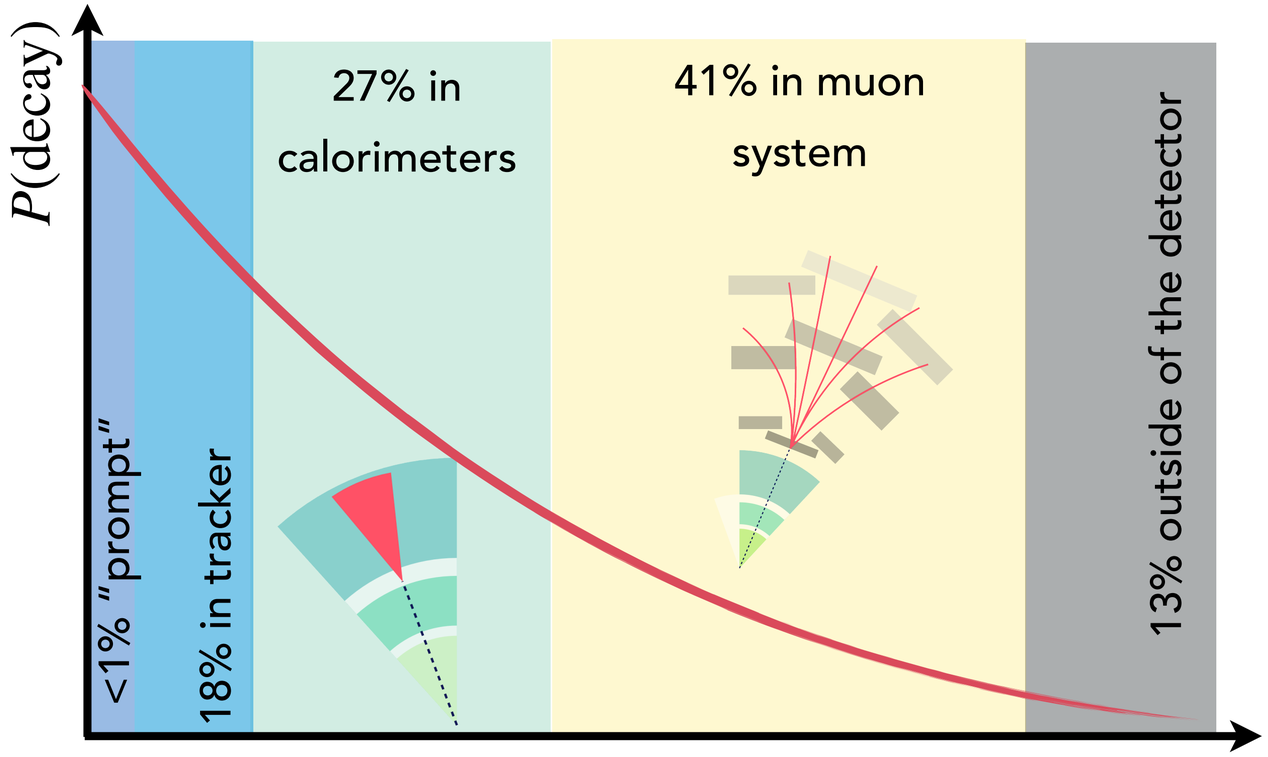
- ATLAS has a robust search program for displaced jets in each subsystem



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Displaced vertices in the ID

EXOT-2021-32

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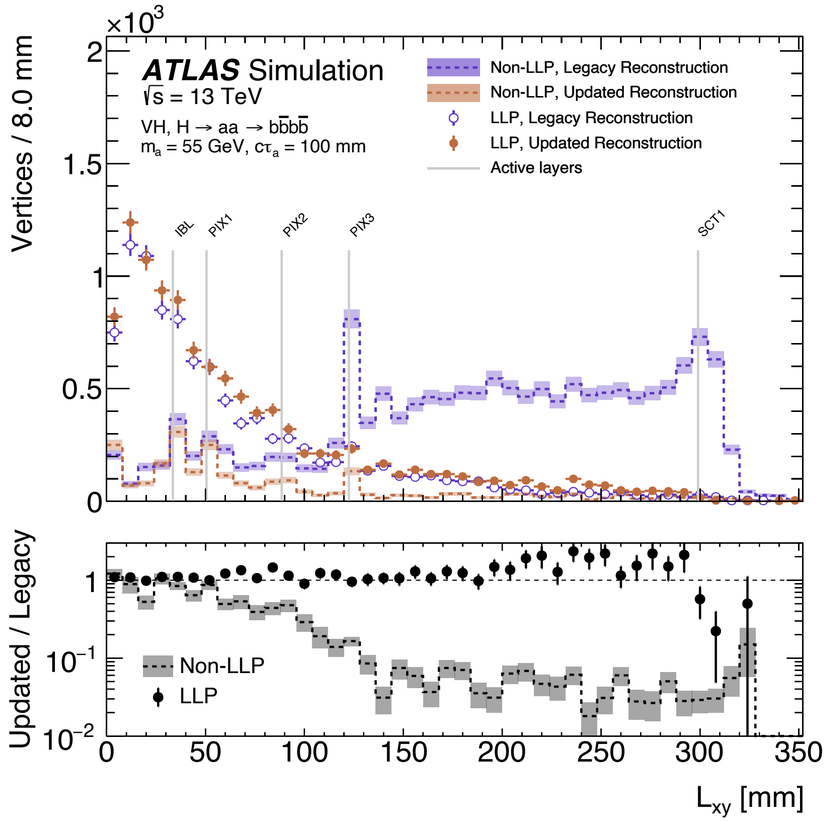

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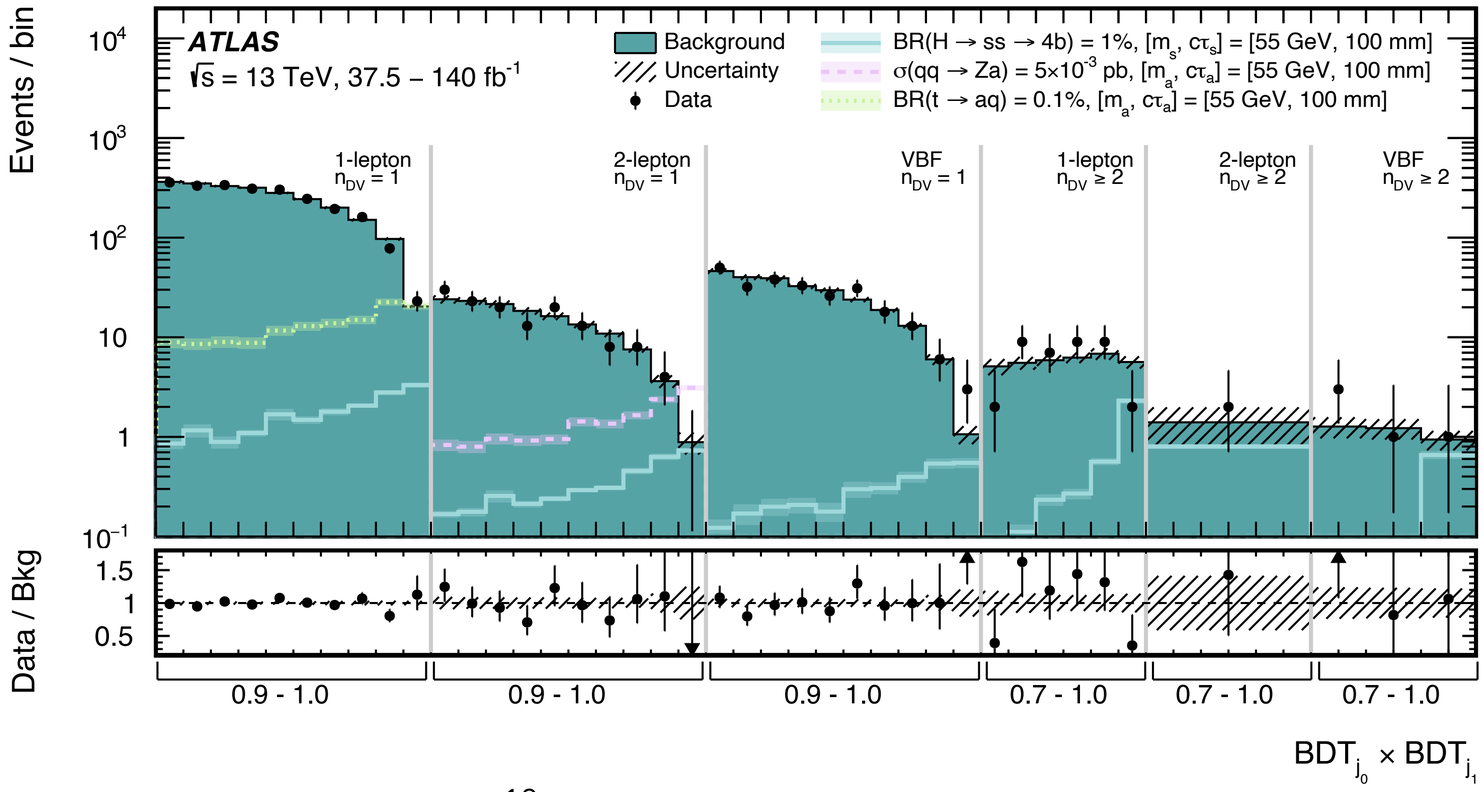

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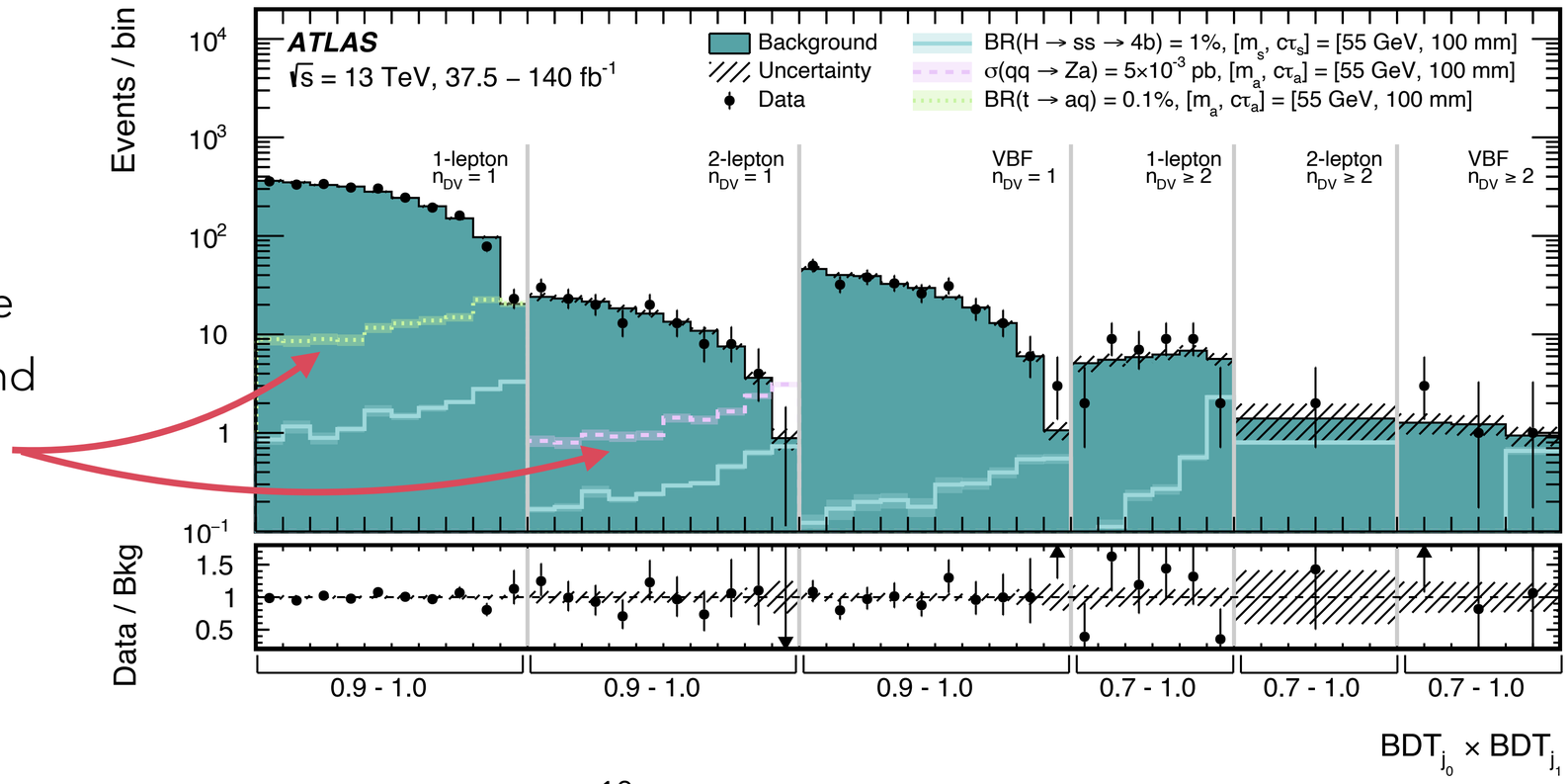
Sensitivity also to axion-like particles from top decays and vector boson couplings



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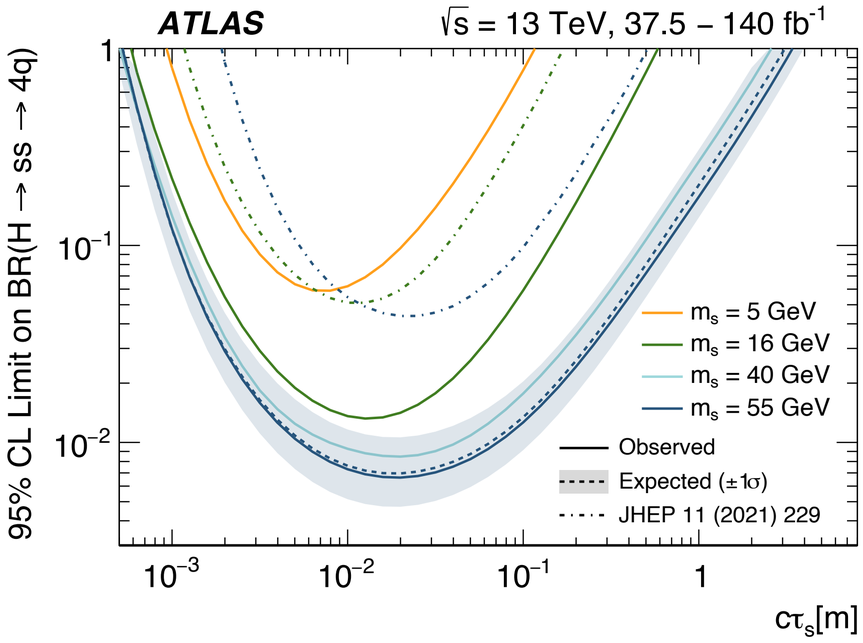
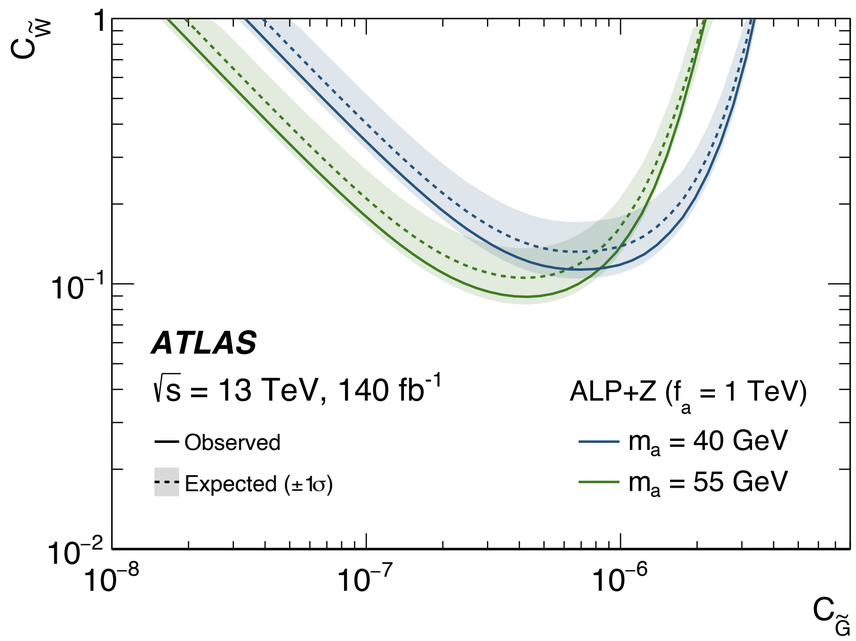
- 10x improvement w.r.t. previous ATLAS Run 2 results using the same data, first limits on both ALP models





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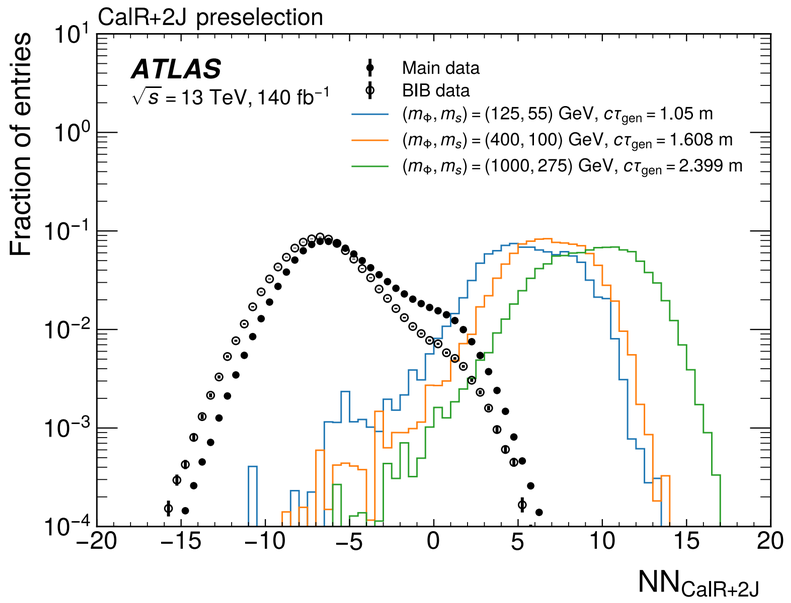
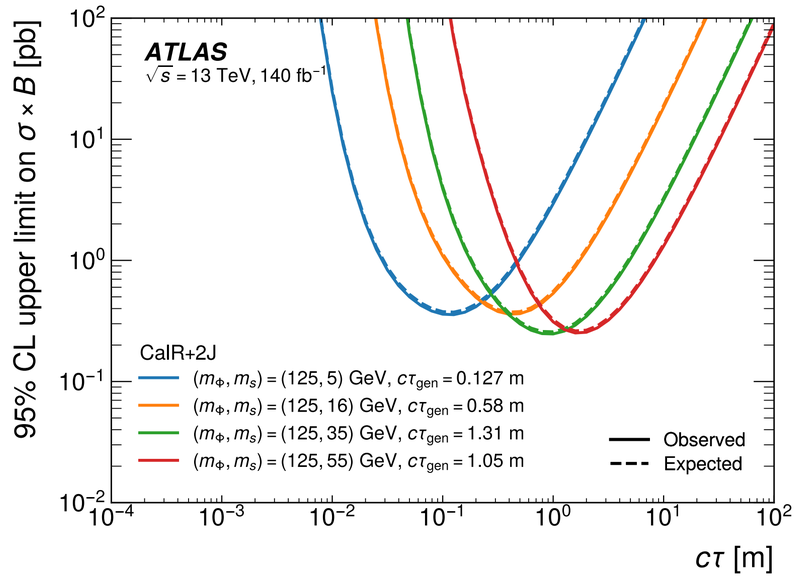
Displaced jet + 2 prompt jet analysis uses dedicated displaced jet trigger and a NN to reject QCD and BIB

- Improves sensitivity at shorter lifetimes w.r.t. 2 displaced jet search





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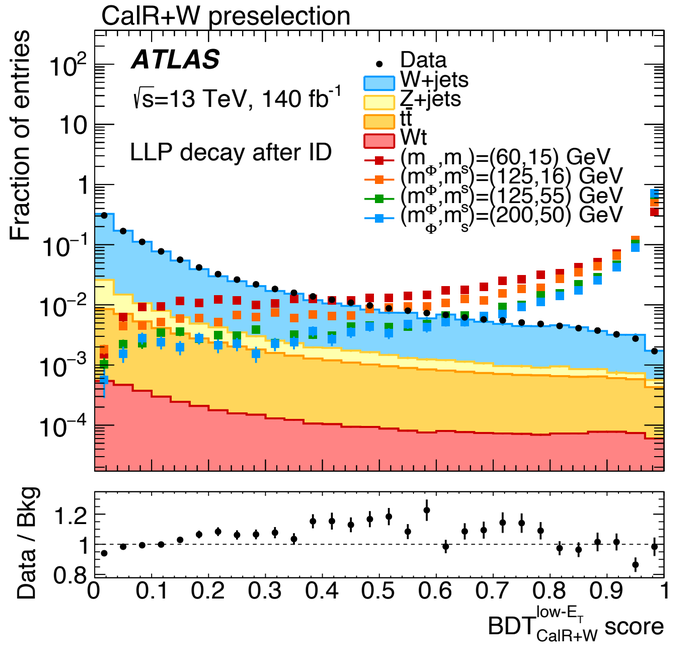
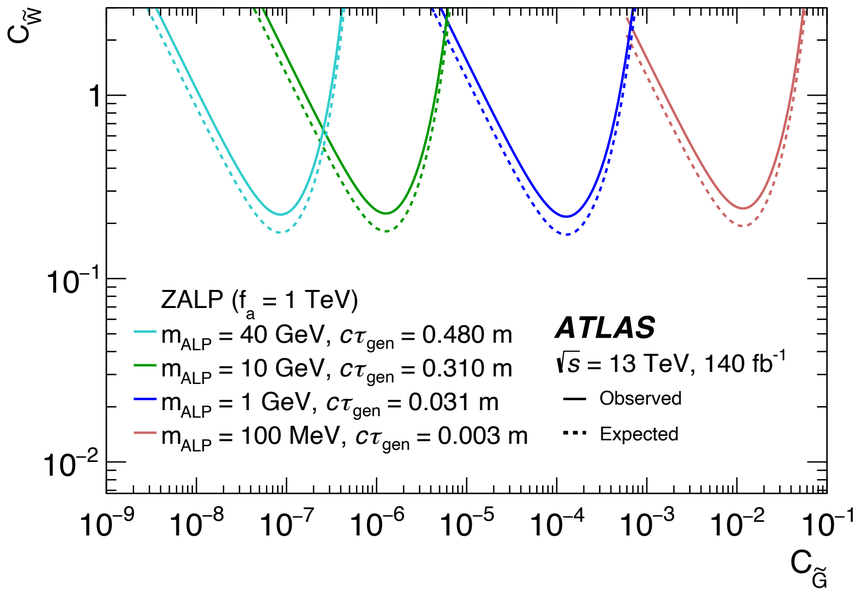
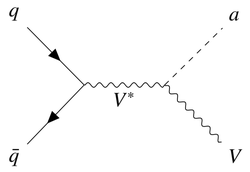
Displaced jet + lepton channel uses lepton triggers and a BDT to separate signal and background

- Complementary sensitivity to Va ALP production as ID-based search







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EXOT-2019-24

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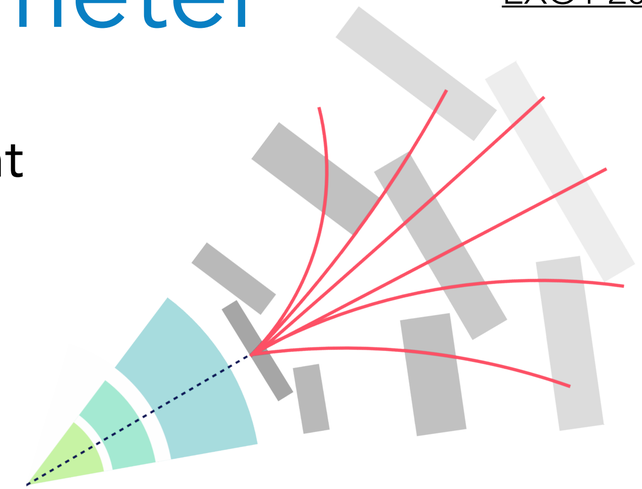

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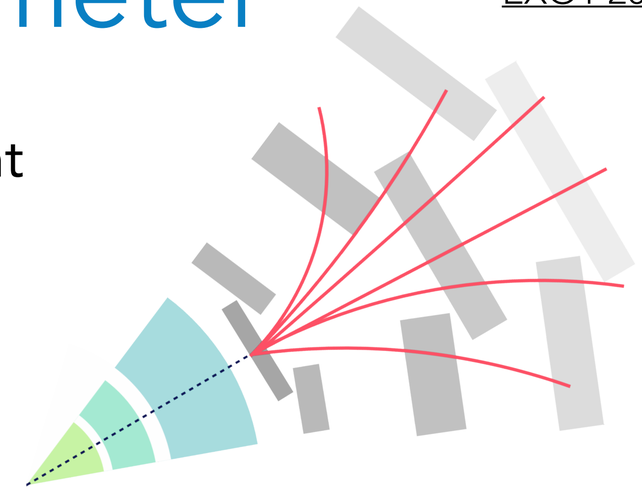

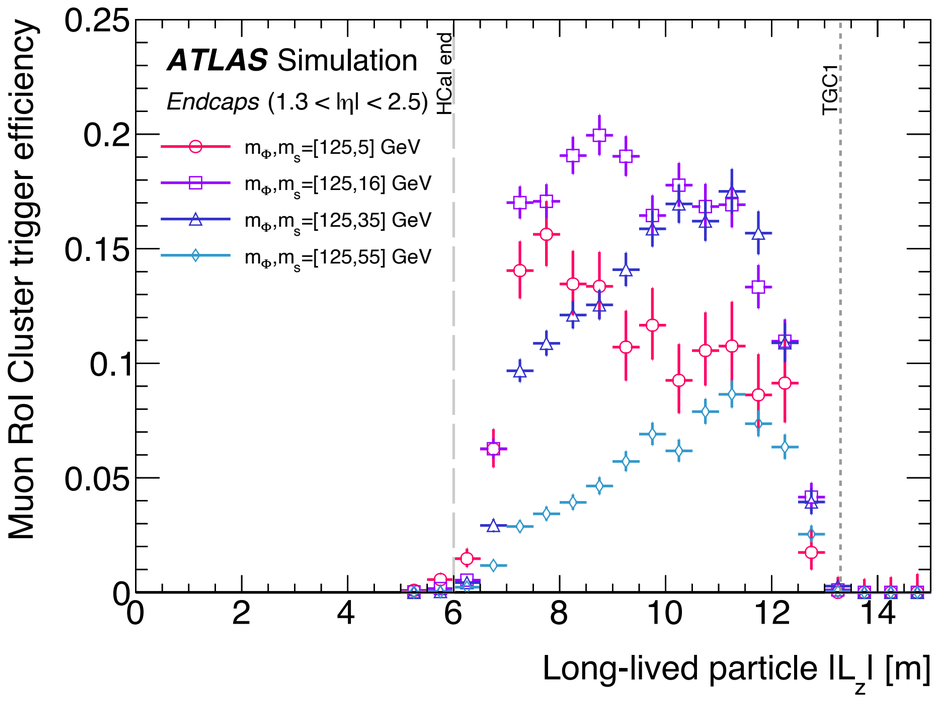

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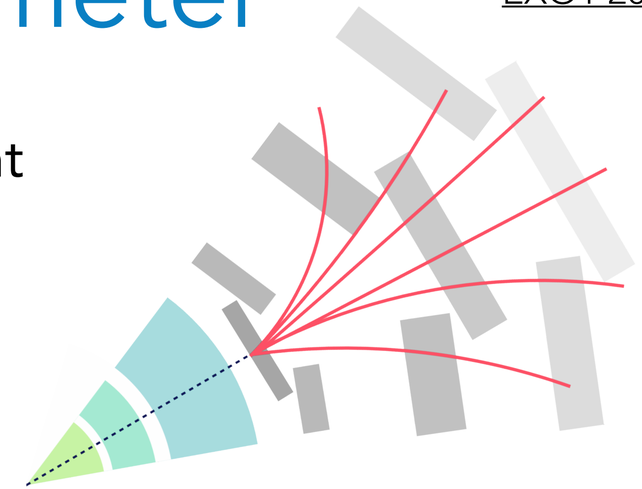

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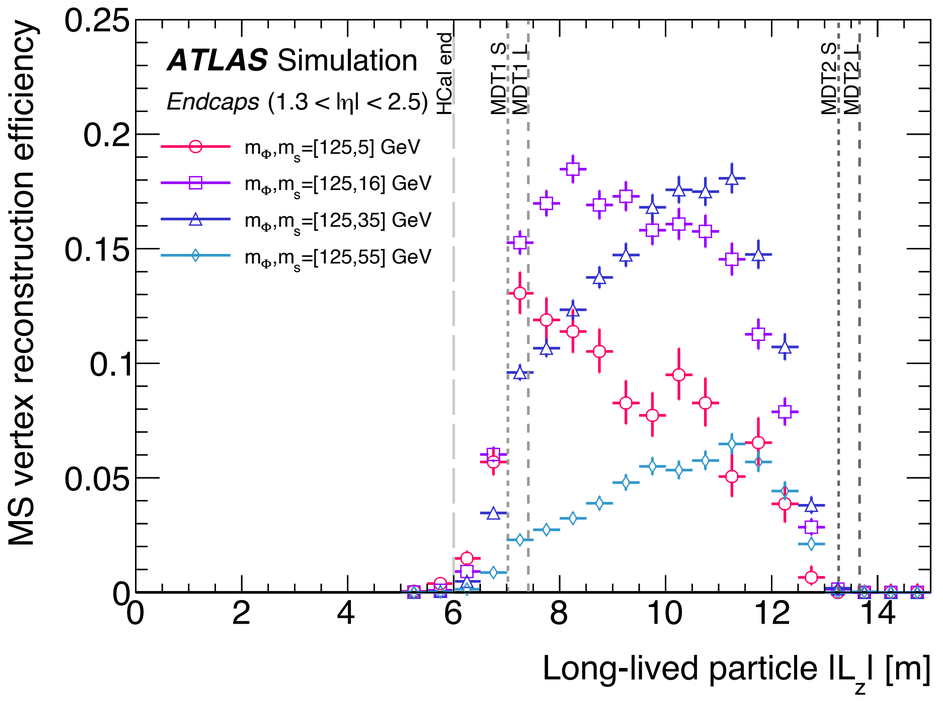

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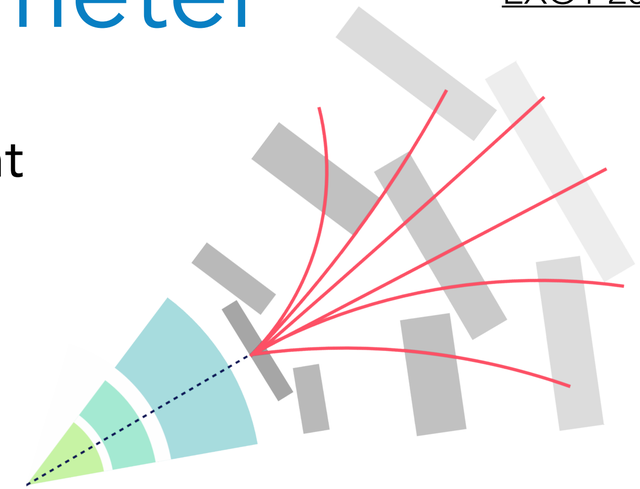

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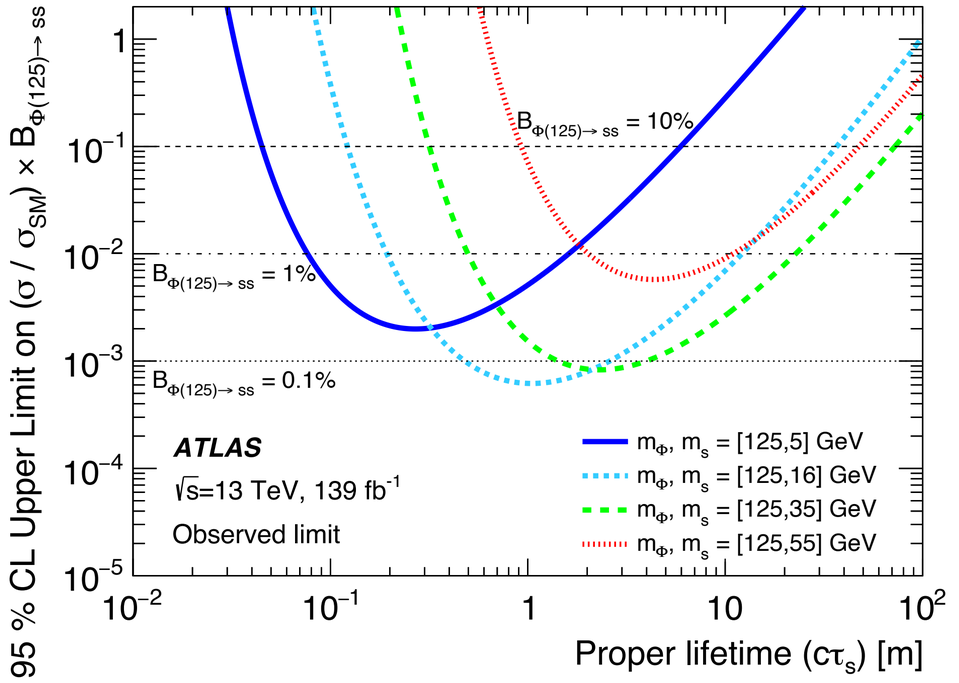

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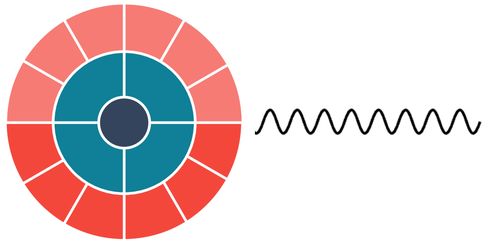
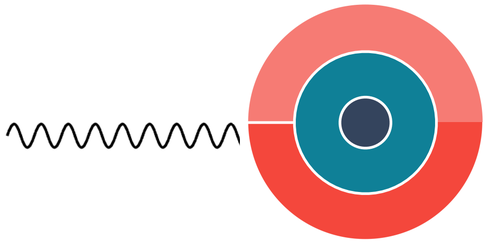
Visible sector  $F_{\mu\nu}F_D^{\mu\nu}$  Dark sector

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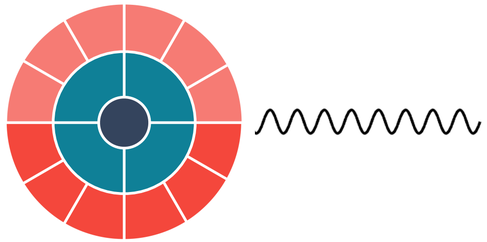
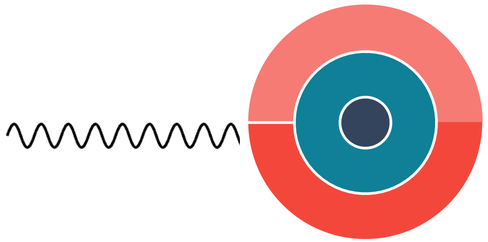
Visible sector  $F_{\mu\nu}F_D^{\mu\nu}$  Dark sector

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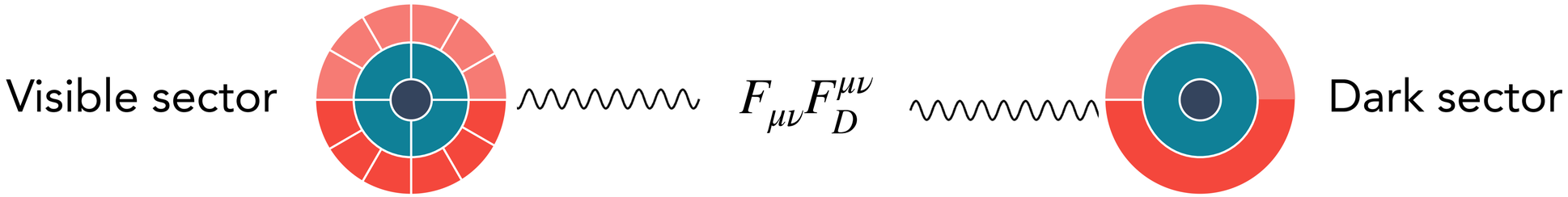

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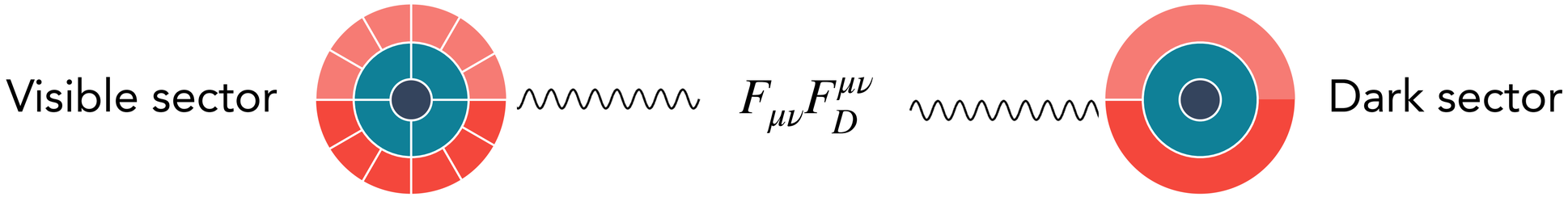

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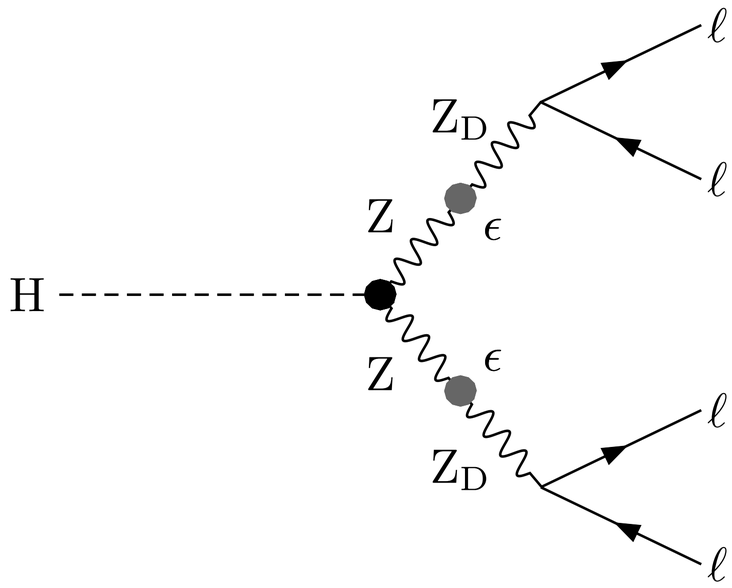

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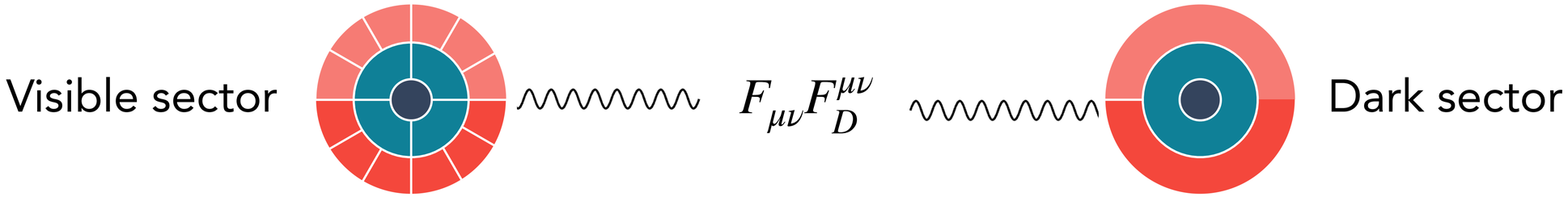

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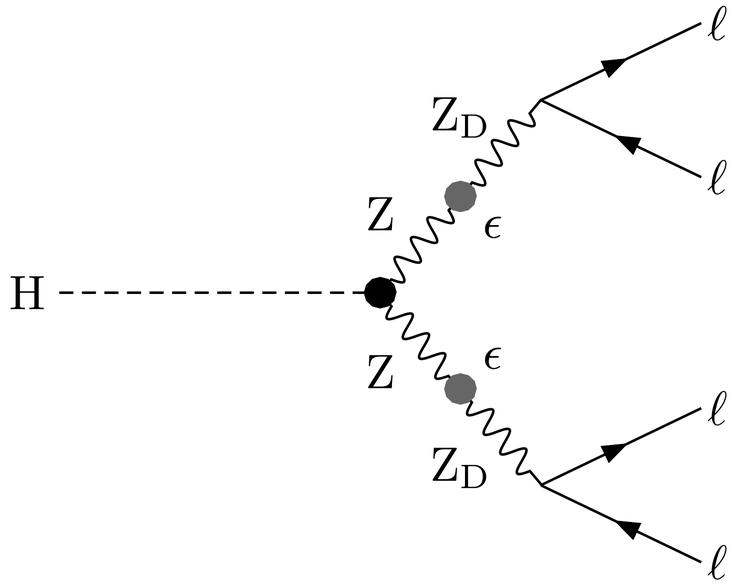

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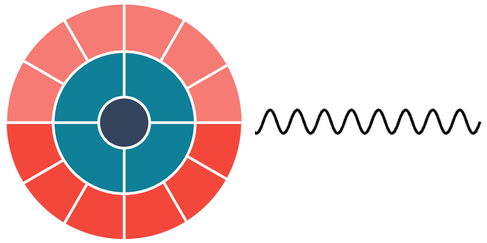
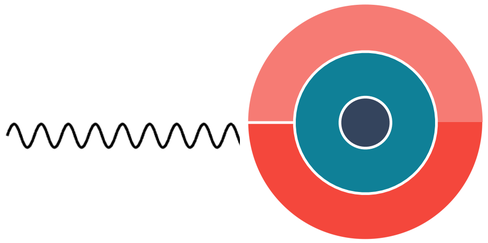
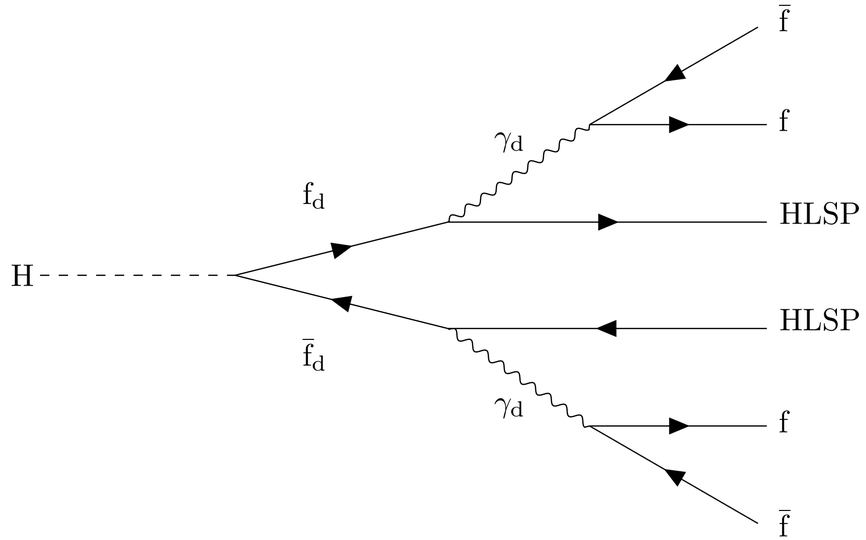
Visible sector  $F_{\mu\nu}F_D^{\mu\nu}$  Dark sector

Two benchmark models:

1. **Hidden Abelian Higgs Model (HAHM)**
   - Dark photon production via $H \to Z_D Z_D$
2. **Falkowski–Ruderman–Volansky–Zupan (FRVZ) model**
   - Dark photon production via intermediate dark fermion f_D



Dark photons

EXOT-2019-05 EXOT-2022-15

Dark photons

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ATLAS probes long-lived dark photons via collimated displaced leptons/hadrons: "**dark photon jets**" (DPJs)

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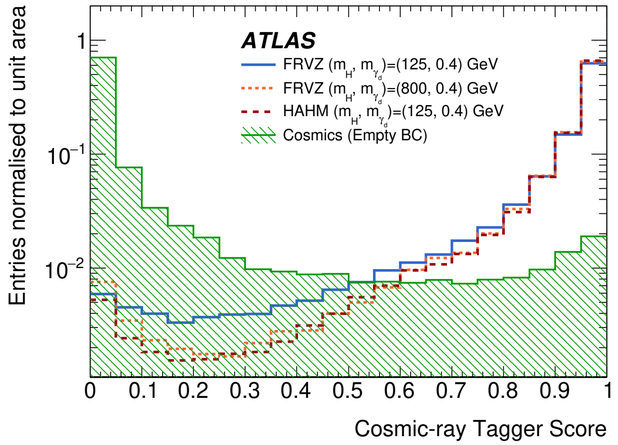

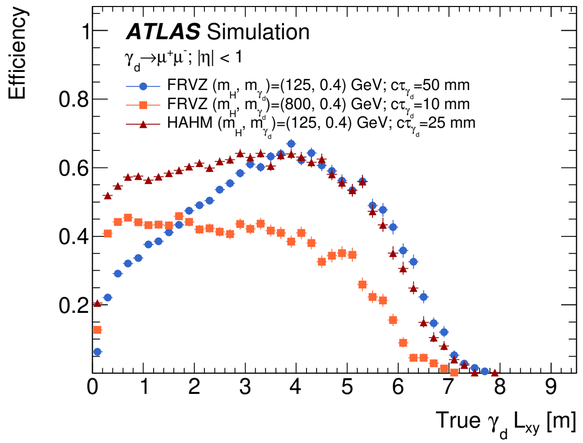

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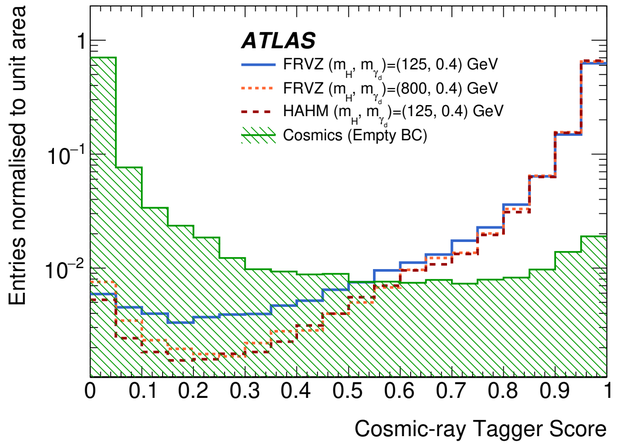
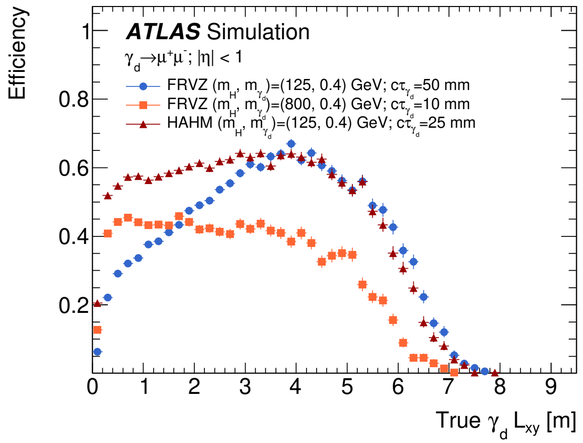
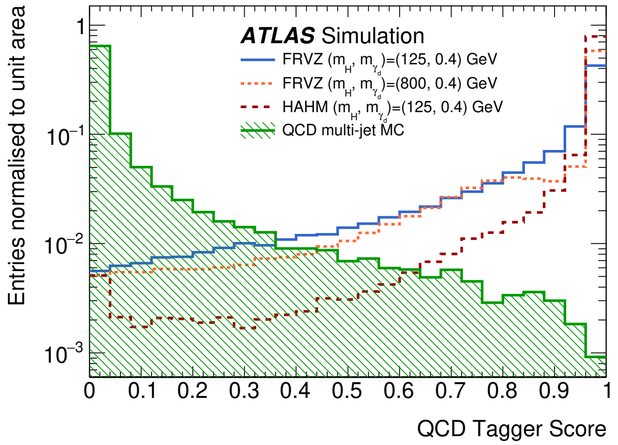
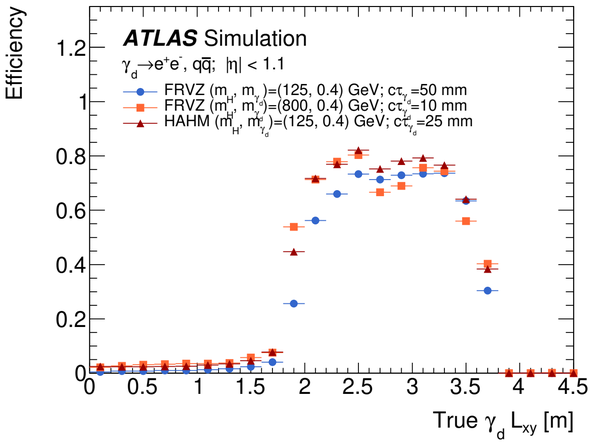




Calorimeter DPJs

- Two separate discriminators used for QCD and BIB
- CNN trained on three-dimensional representations of energy deposits associated to the jet





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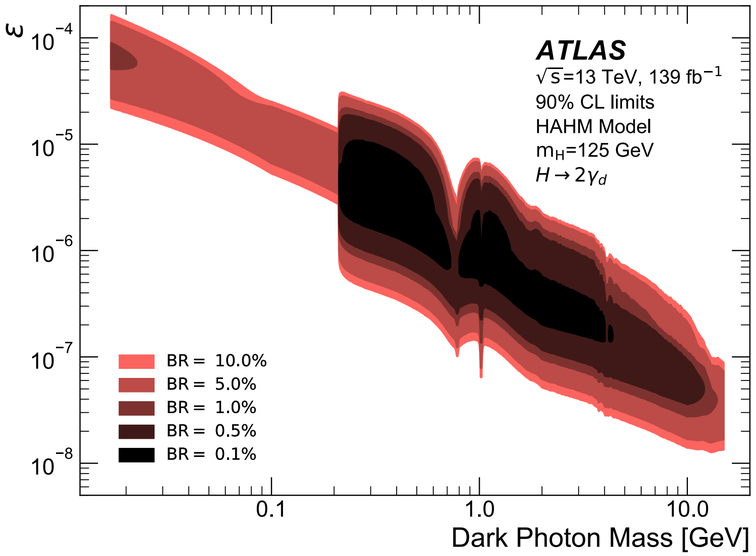

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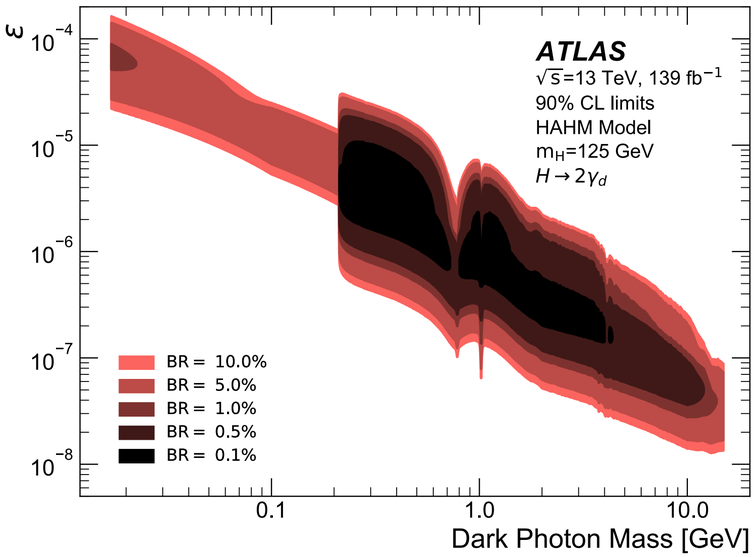

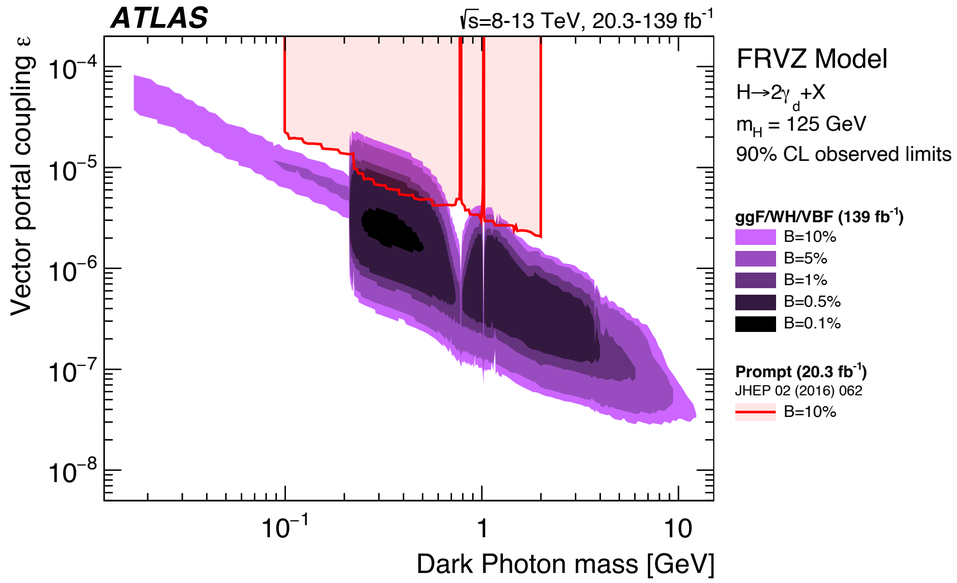

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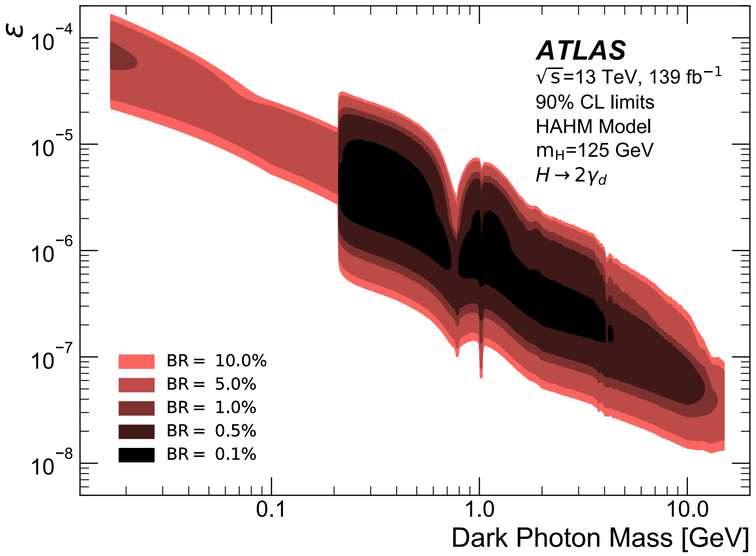
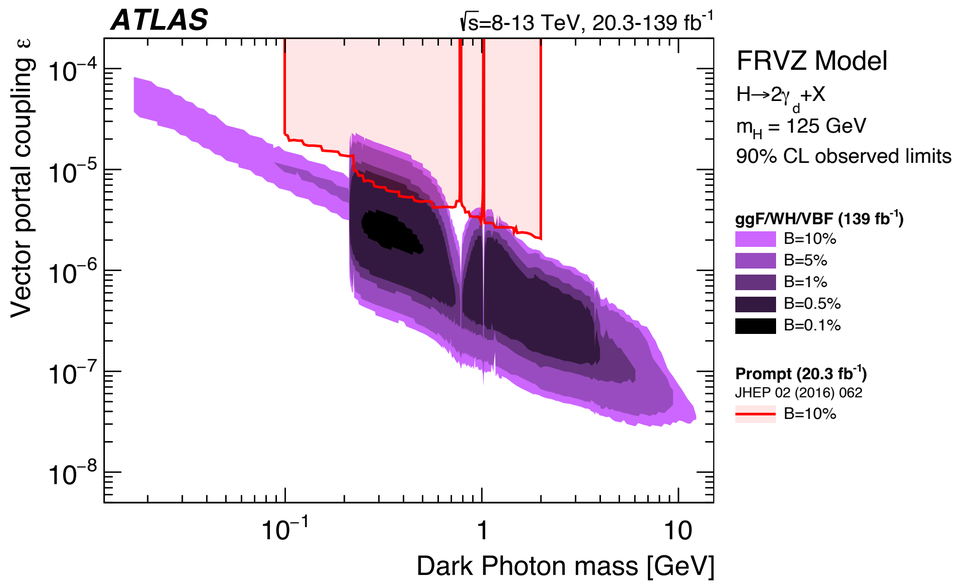
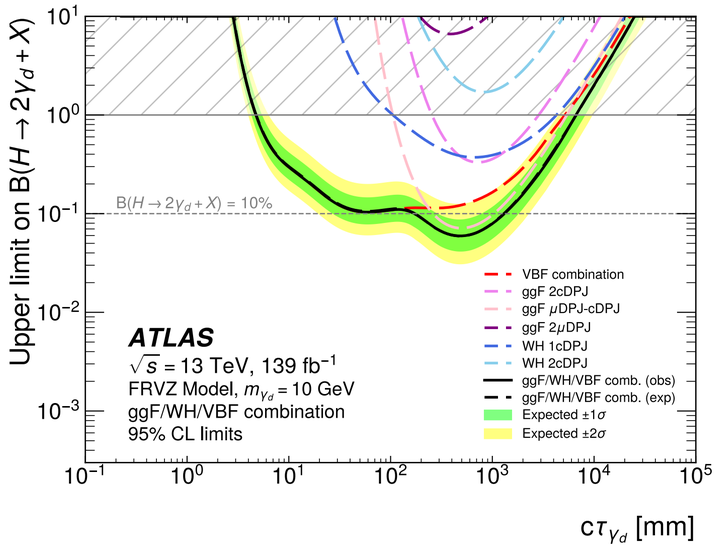
- VBF channel dominates sensitivity at low lifetimes due to trigger on prompt objects







Heavy Neutral Leptons

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Extension of SM with right-handed neutrinos can simultaneously explain **neutrino masses**, **baryon asymmetry**, and **dark matter**

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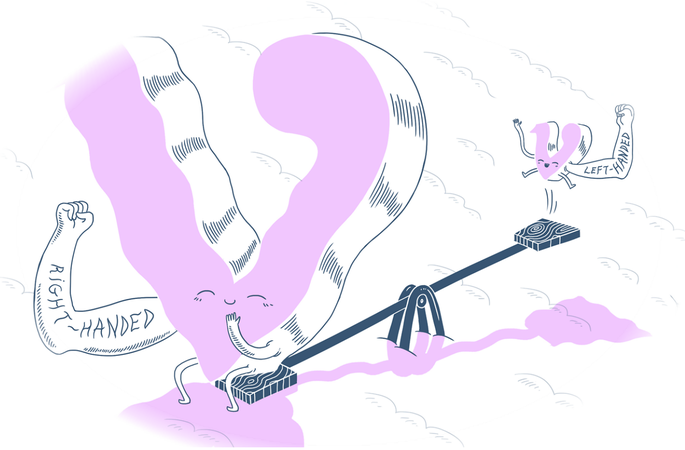
- e.g. Type-I seesaw mechanism



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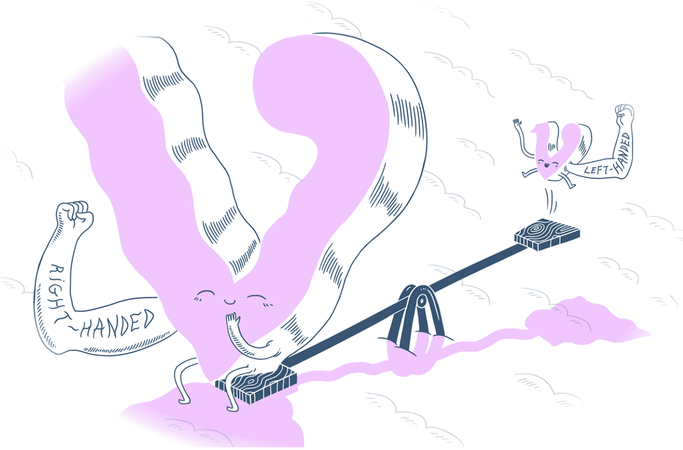

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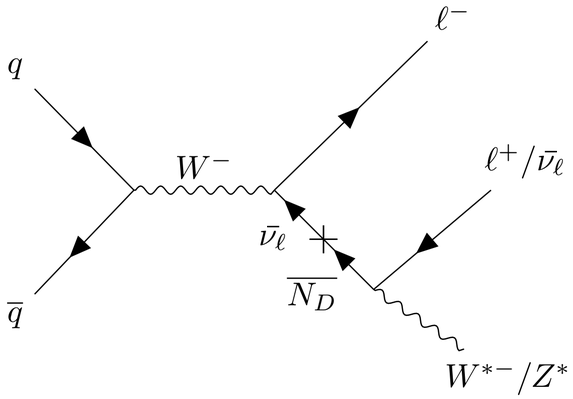
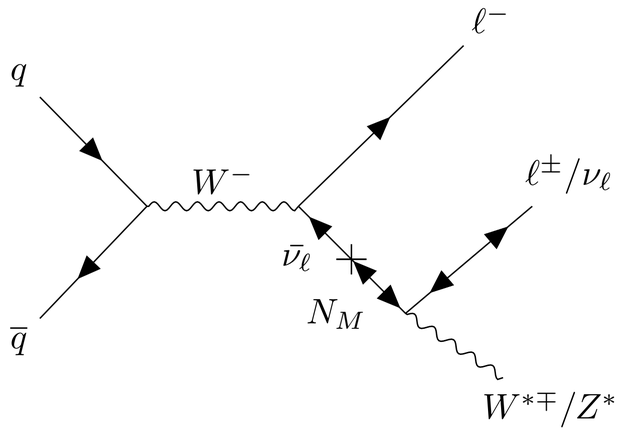
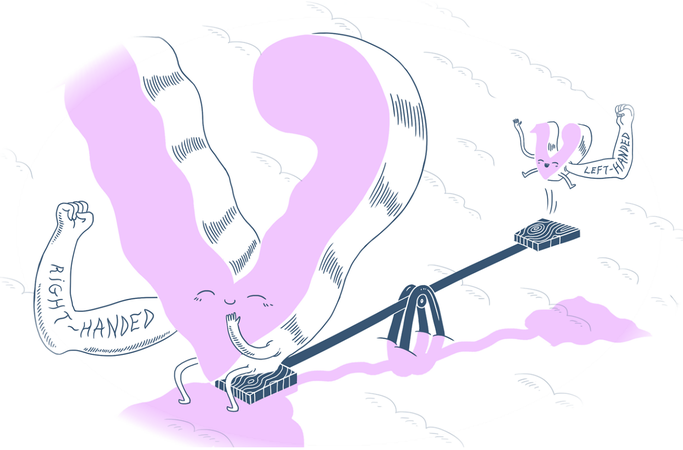
Dirac





Maiorana

Heavy Neutral Leptons



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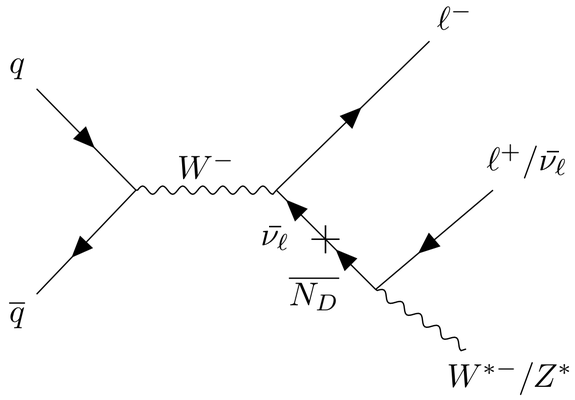
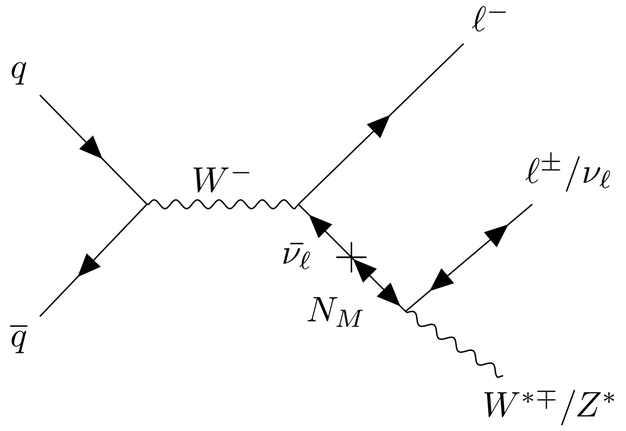




Maiorana

Lifetime driven by mixing angle between SM neutrino and HNL and HNL mass

- Natural to expect long-lived HNLs

$$\tau_N \propto \frac{1}{m_N^5 |U_\alpha|^2}$$

Leptonic HNL decays

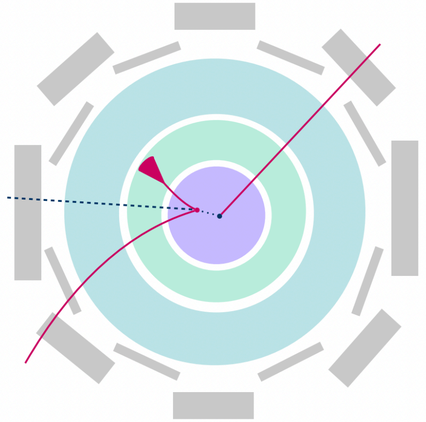
EXOT-2019-29

Leptonic HNL decays

EXOT-2019-29

Clean channel of displaced dilepton vertex in the inner detectors

- Background dominated by random crossings of two lepton tracks



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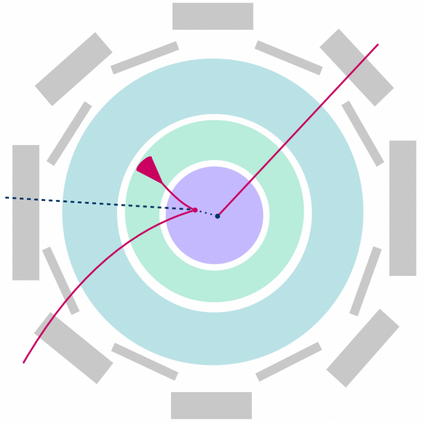
EXOT-2019-29



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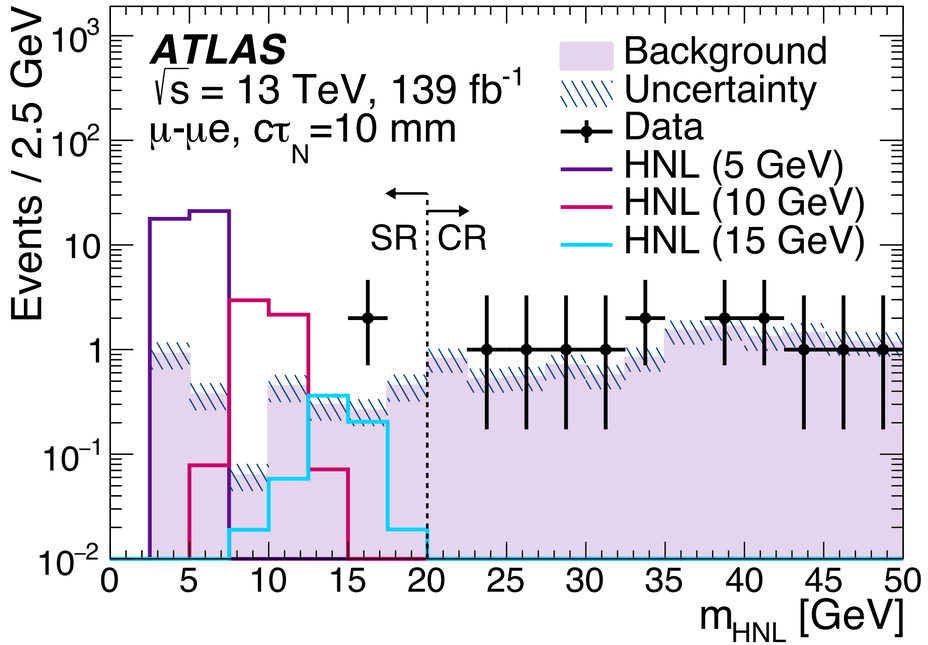
Reconstruct mass of HNL using energy momentum conservation

- Background shape template derived and normalized in control region



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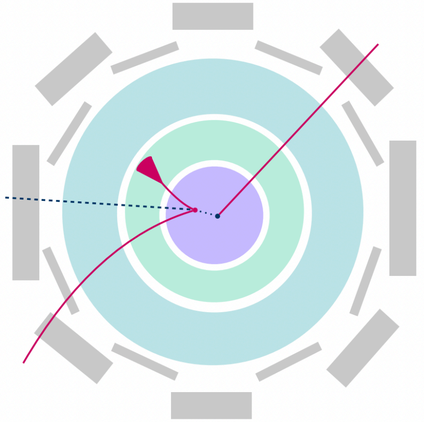

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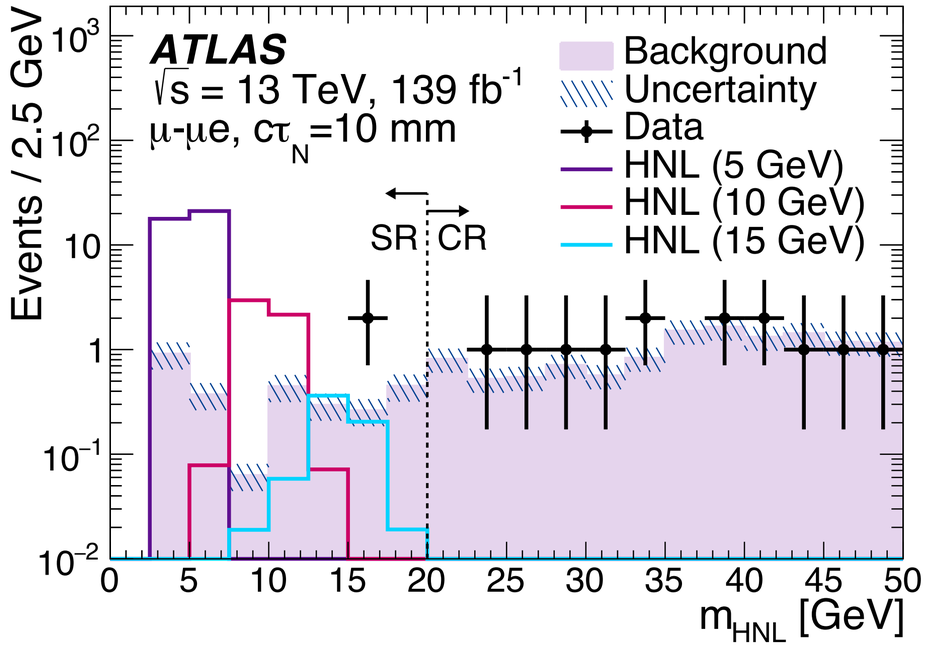
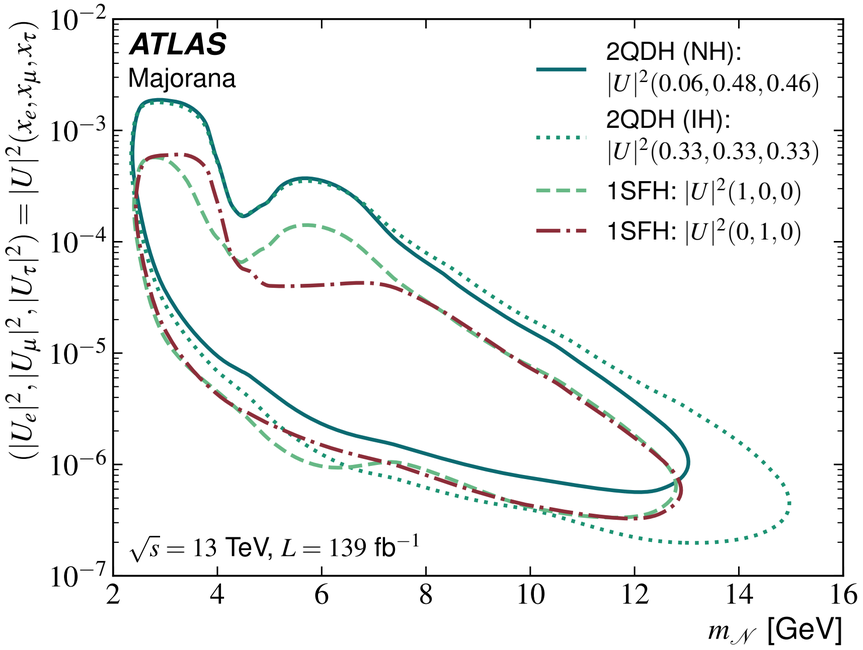
First search to target models with two quasi-degenerate HNLs (2QDH) with multi-flavour mixing

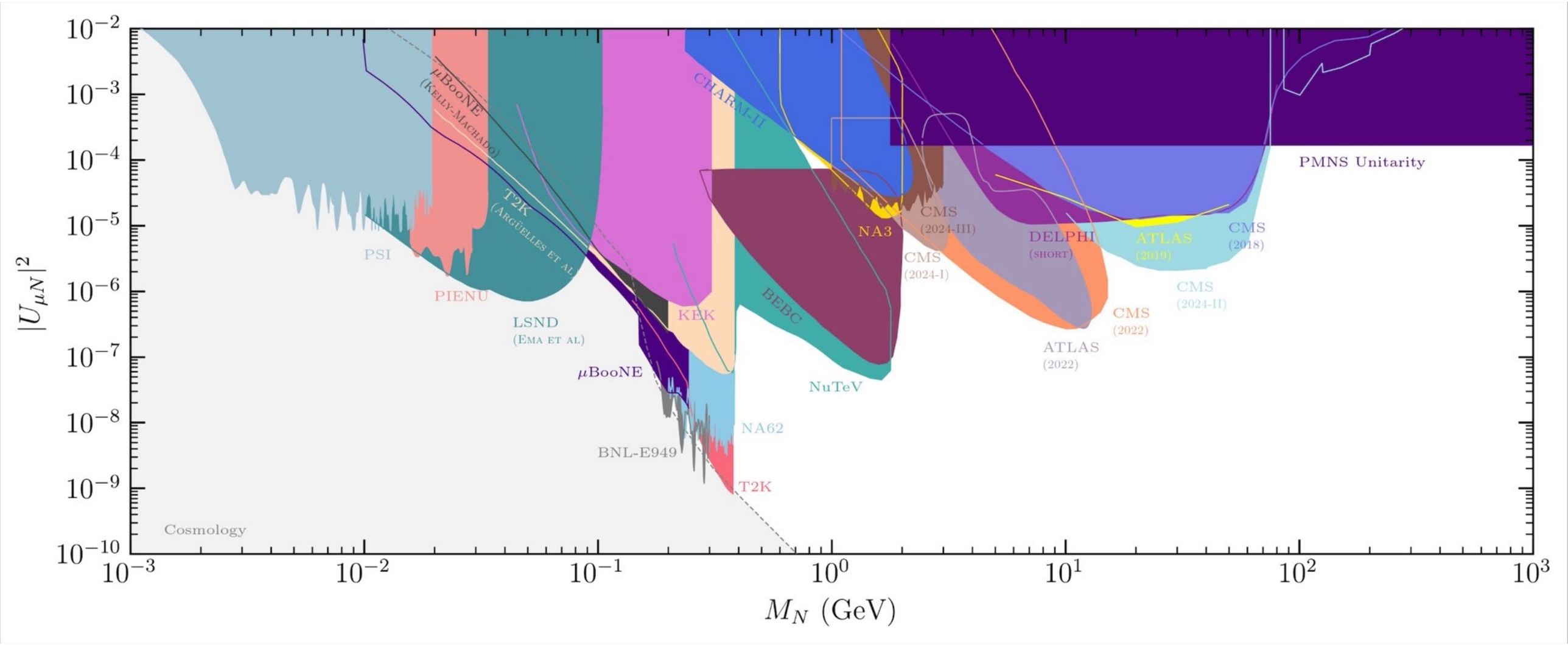




Similar results obtained by CMS: EXO-20-009

Current HNL landscape

Together, LHC searches are considerably expanding our reach into unexplored phase space



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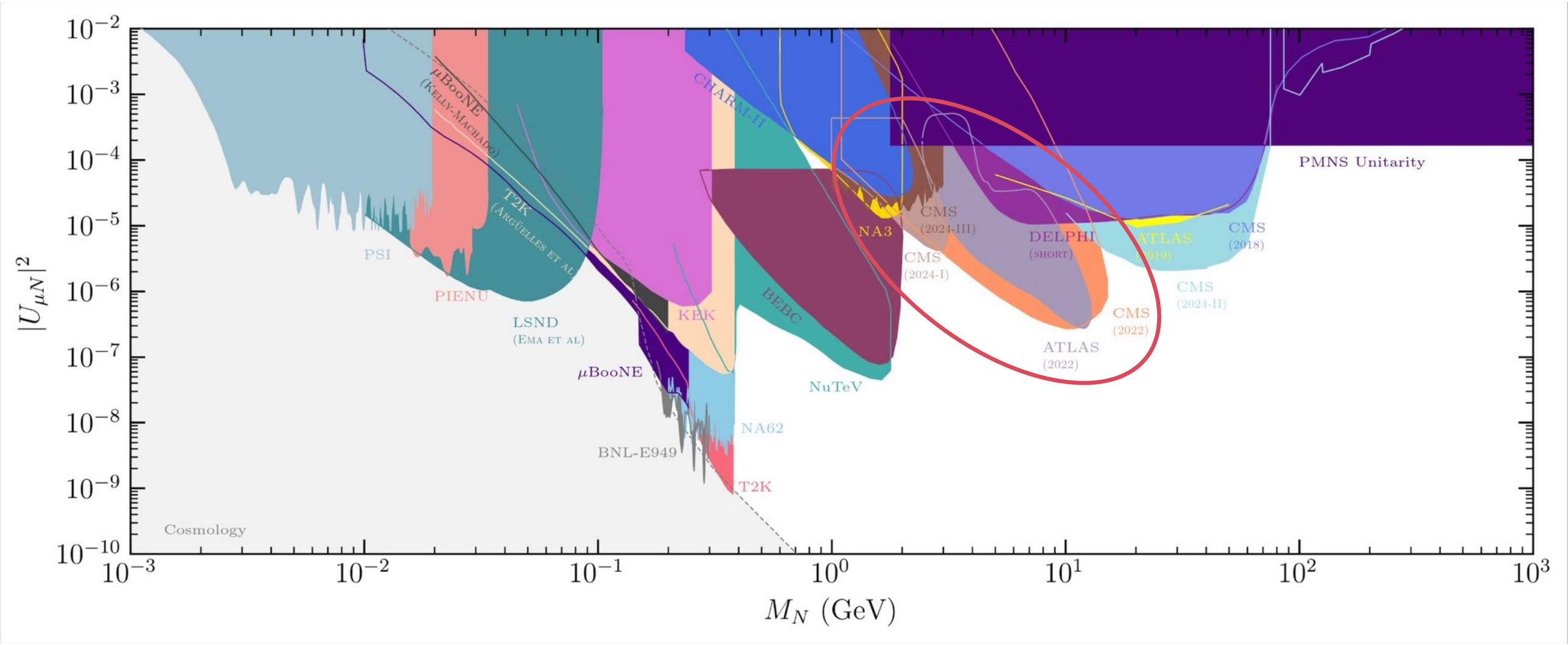


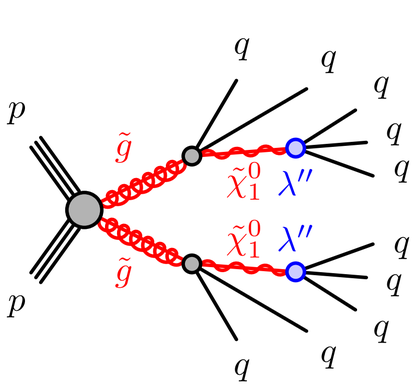
Long-lived SUSY

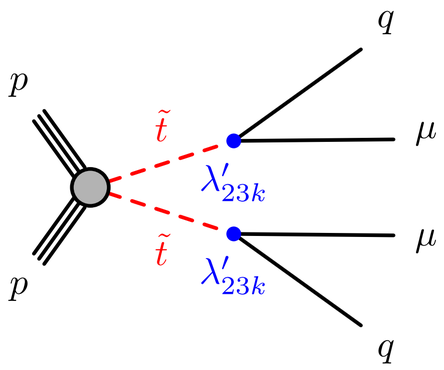
LLPs are also ubiquitous in various SUSY scenarios:

<u>R-parity violating:</u>

$$\mathscr{W}_{\mathrm{RPV}} = \mu_i \ell_i h_u + \lambda_{ijk} \ell_i \ell_j \bar{e}_k + \lambda'_{ijk} \ell_i q_j \bar{d}_k + \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

Small λ values suppress decays of SUSY particles leading to long lifetimes



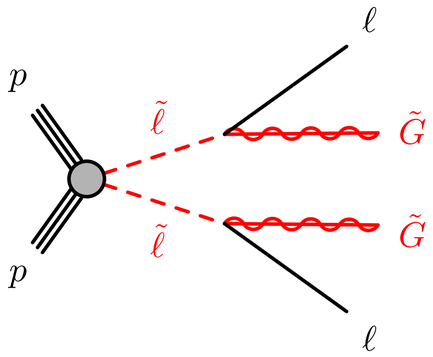


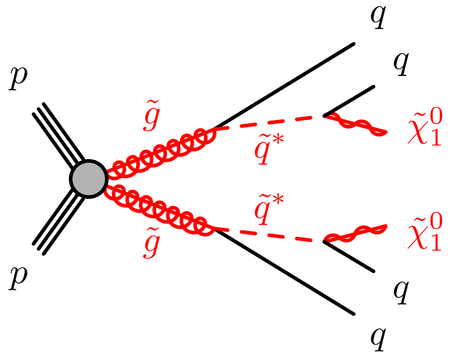
<u>R-parity conserving:</u>

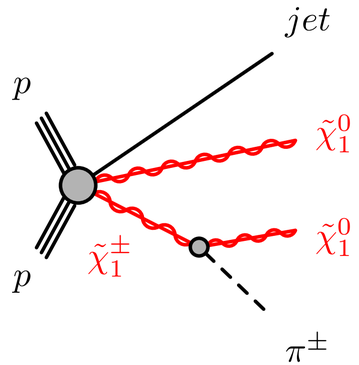
<u>GMSB</u>: weak coupling between NLSP and LSP

<u>Split SUSY</u>: heavy intermediate particles

<u>Compressed SUSY</u>: small phase space







Displaced vertices + jets in ATLAS

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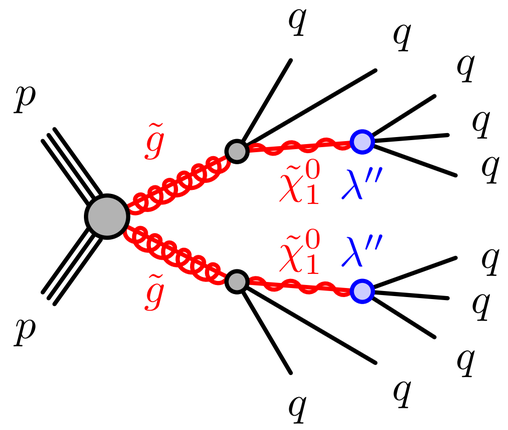
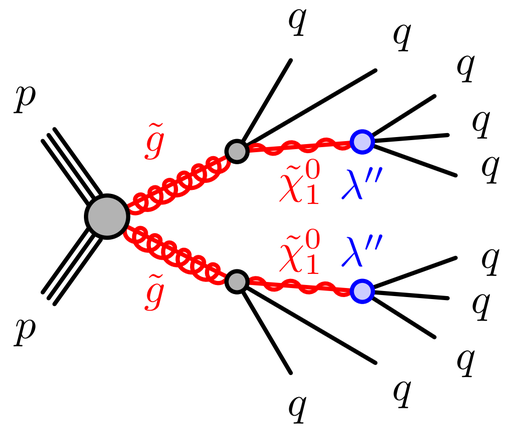


Search for a heavy, multitrack displaced vertex in the ATLAS Inner Detector

- Targeting λ'' RPV coupling

Displaced vertices + jets in ATLAS



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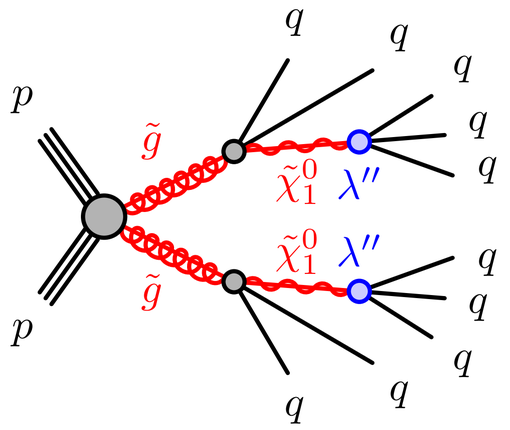

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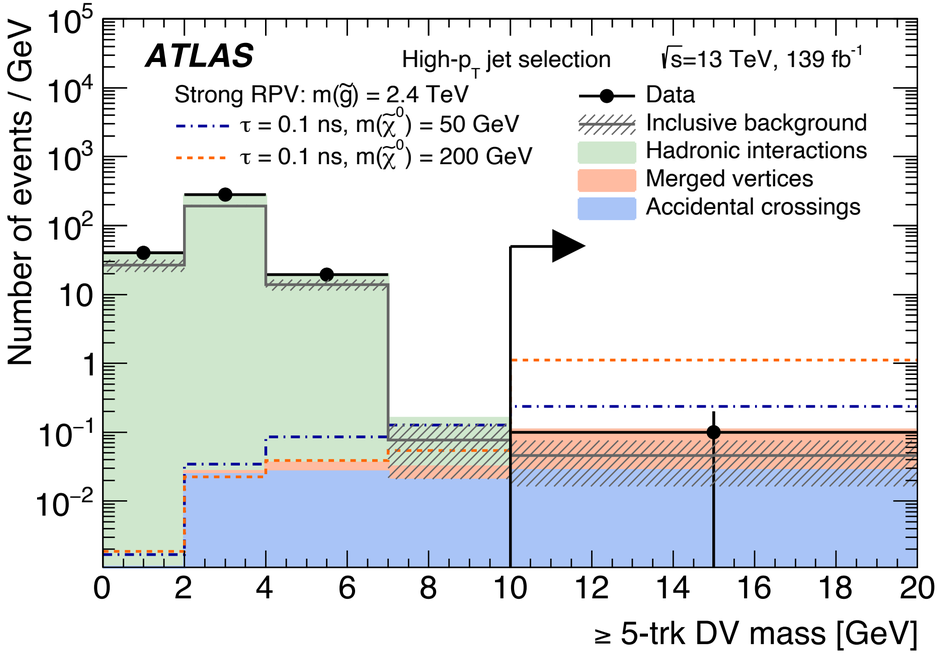

SUSY-2018-13

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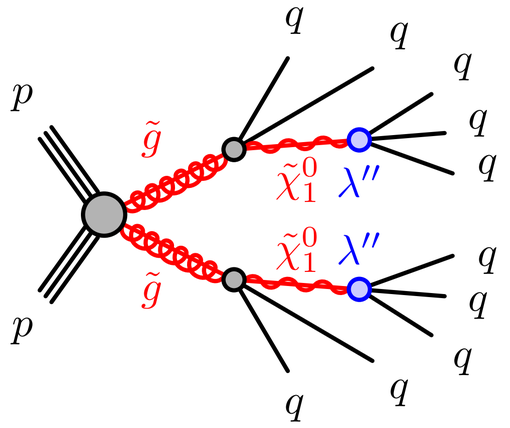

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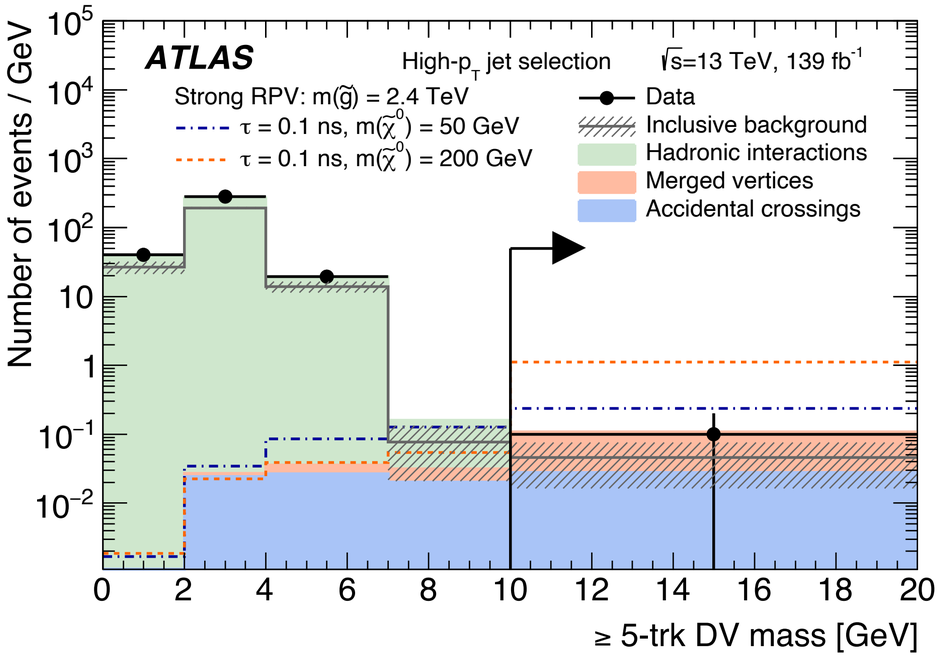
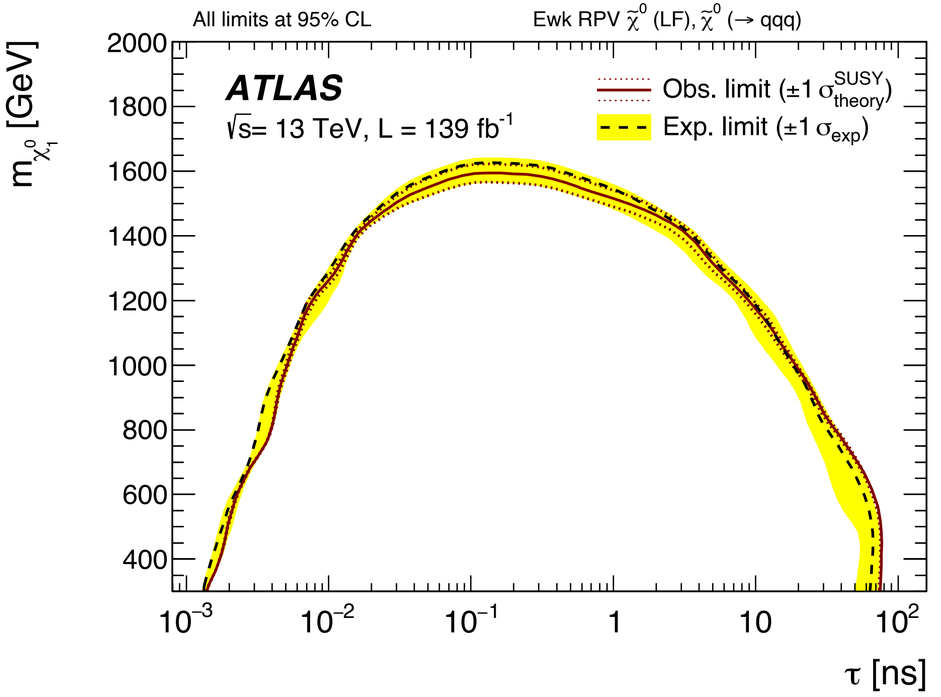




Displaced leptons

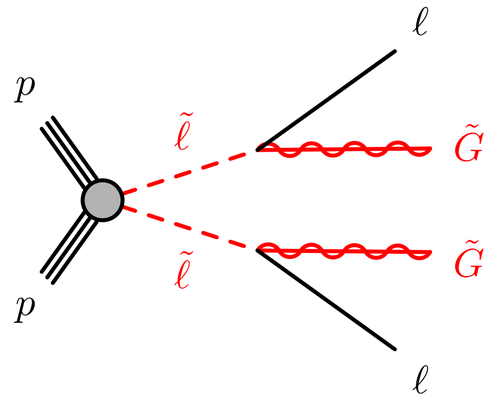
ATLAS-CONF-2024-011

Displaced leptons

ATLAS-CONF-2024-011

Search for long-lived sleptons in GMSB model

- First ATLAS Run 3 search results! Combined with Run 2 data



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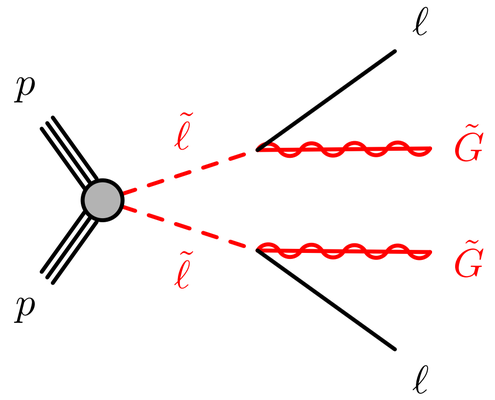

Displaced leptons

ATLAS-CONF-2024-011

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Major improvements over Run 2 analysis:

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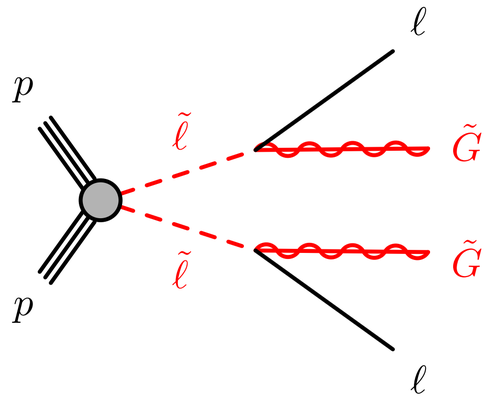

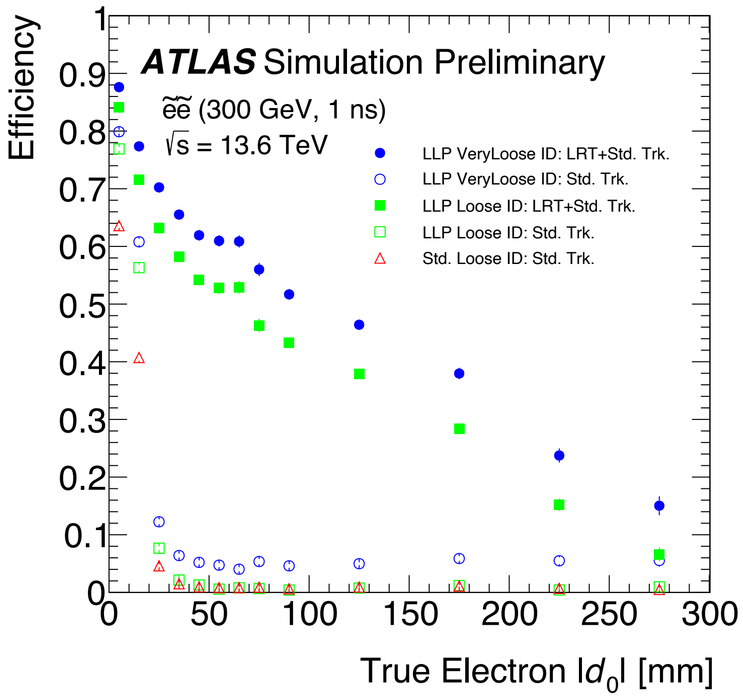

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ATLAS-CONF-2024-011

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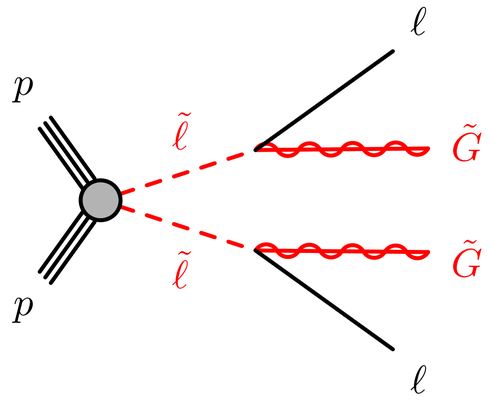

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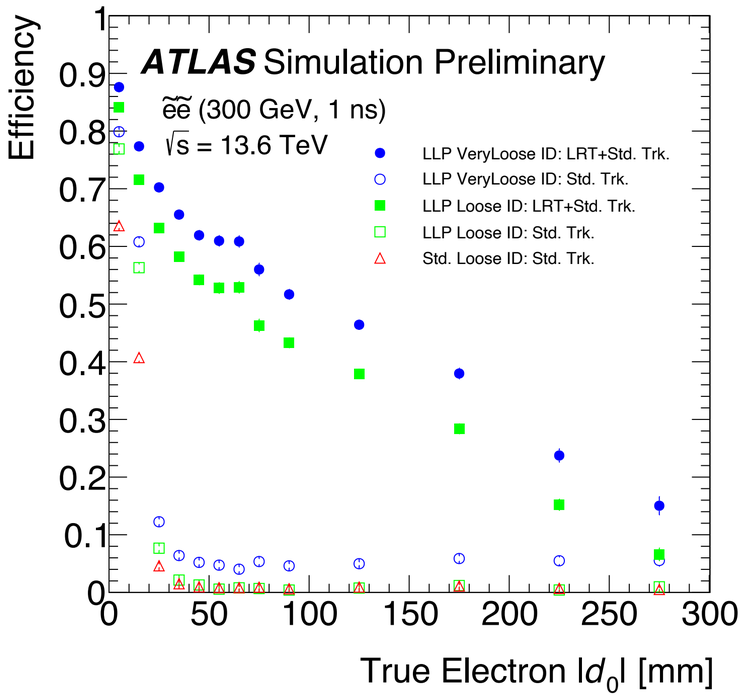

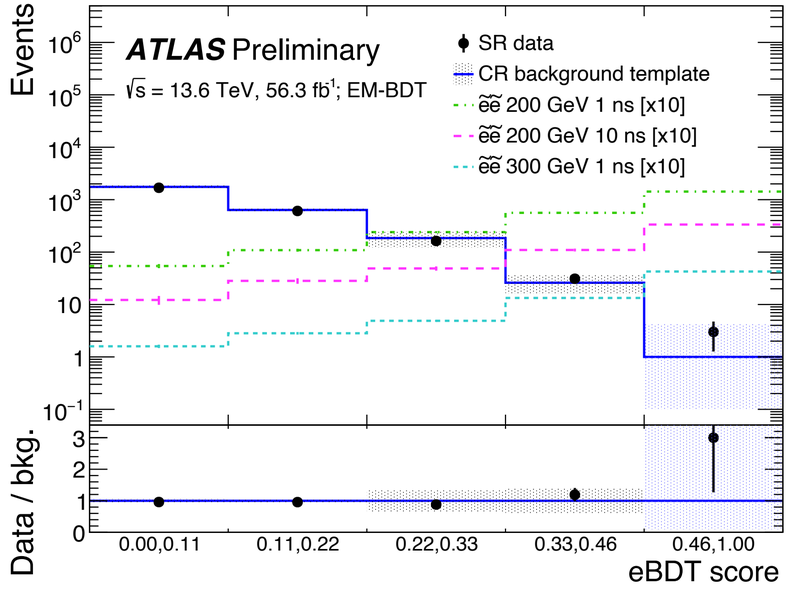

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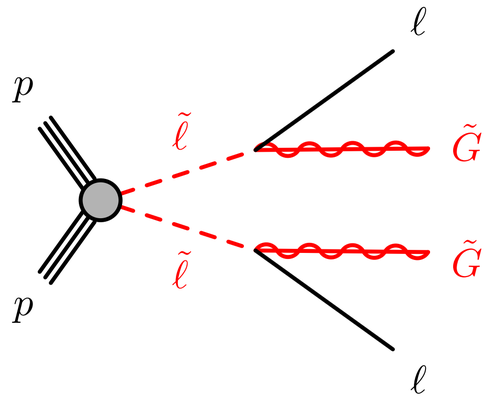

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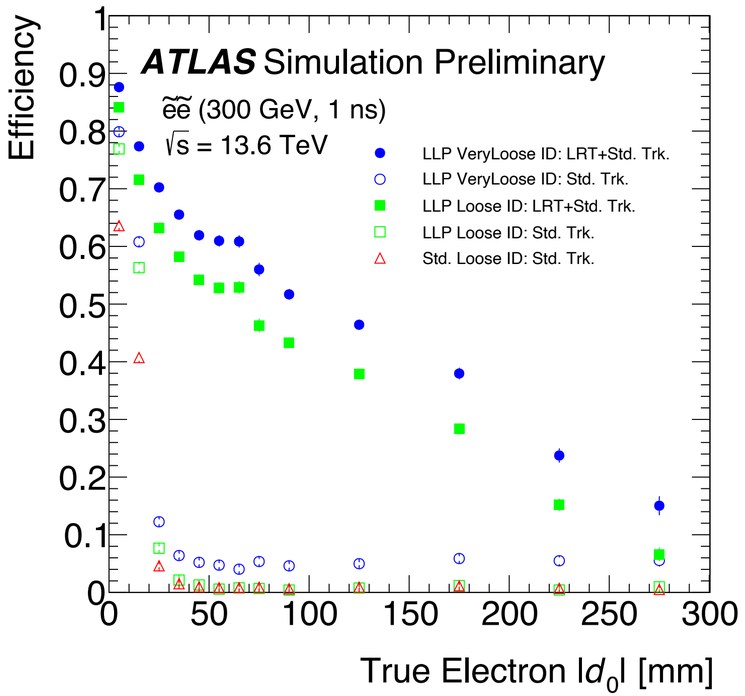

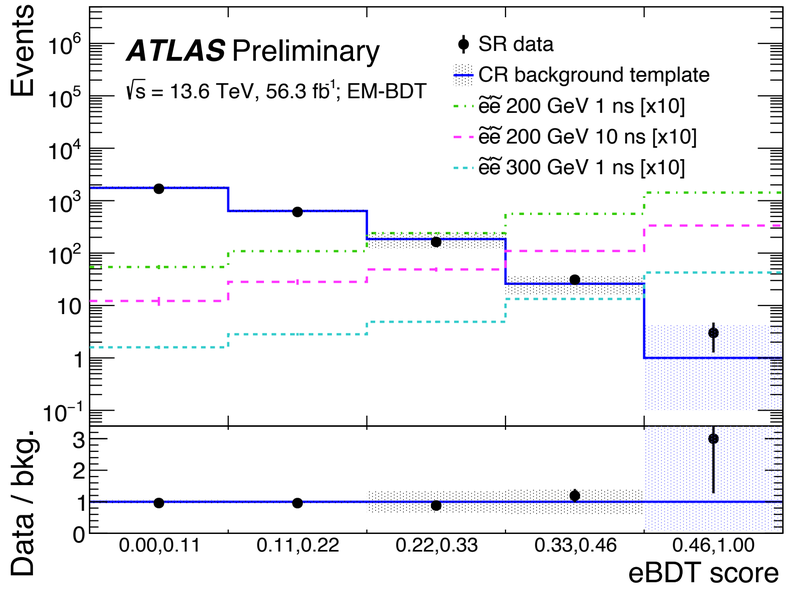

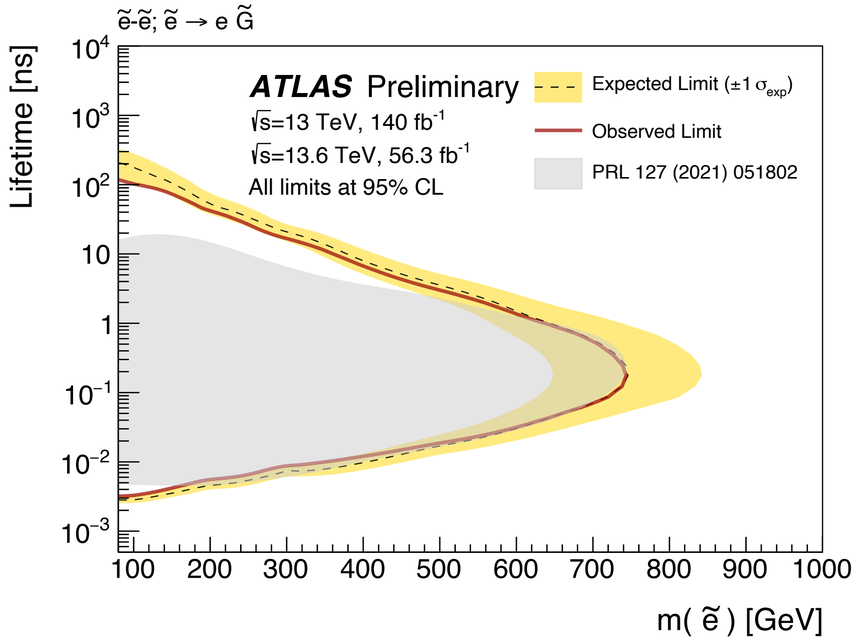

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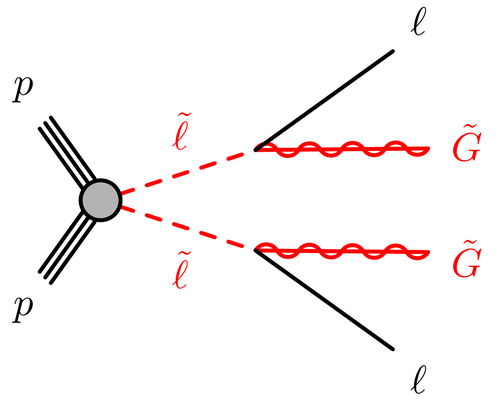

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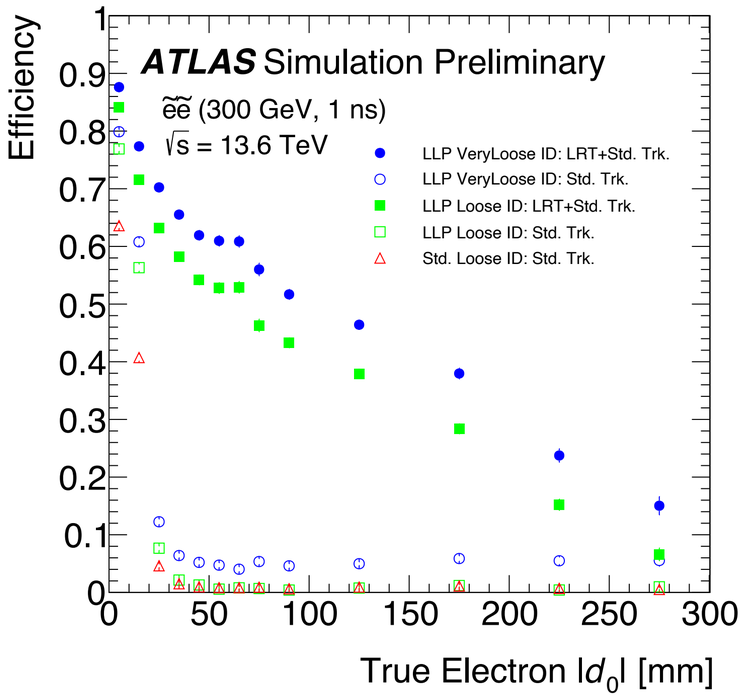

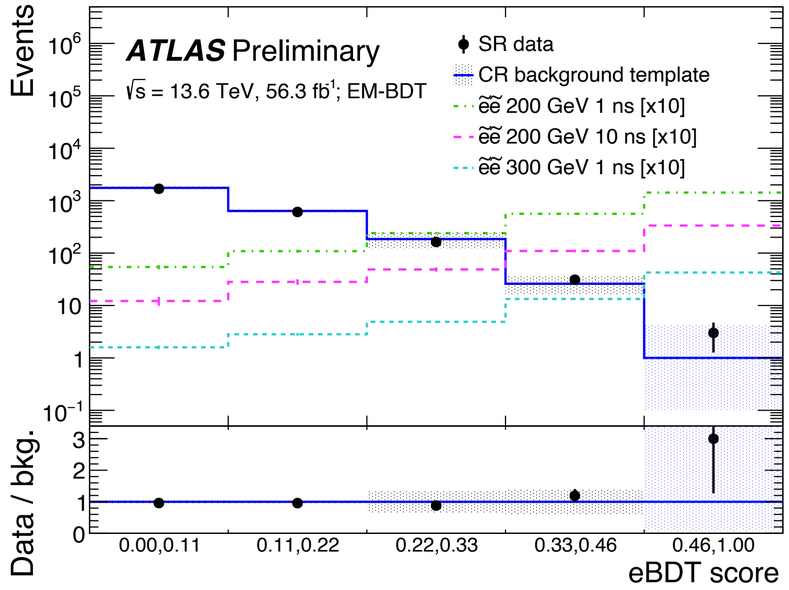

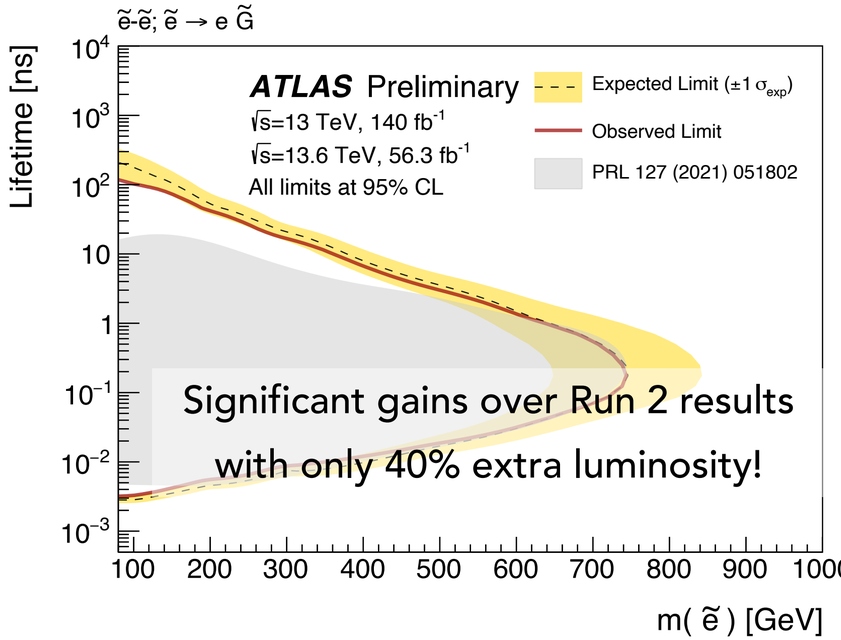

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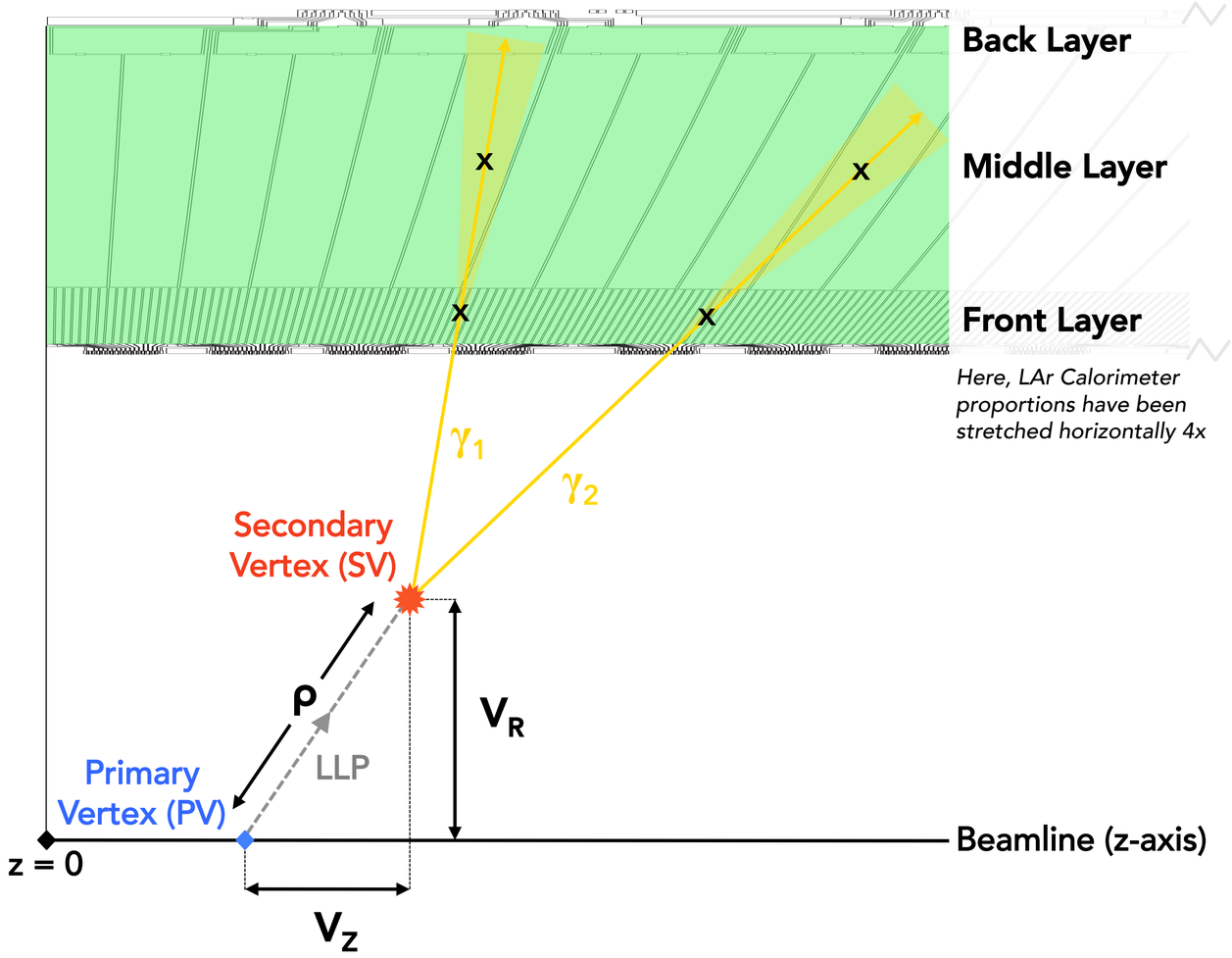

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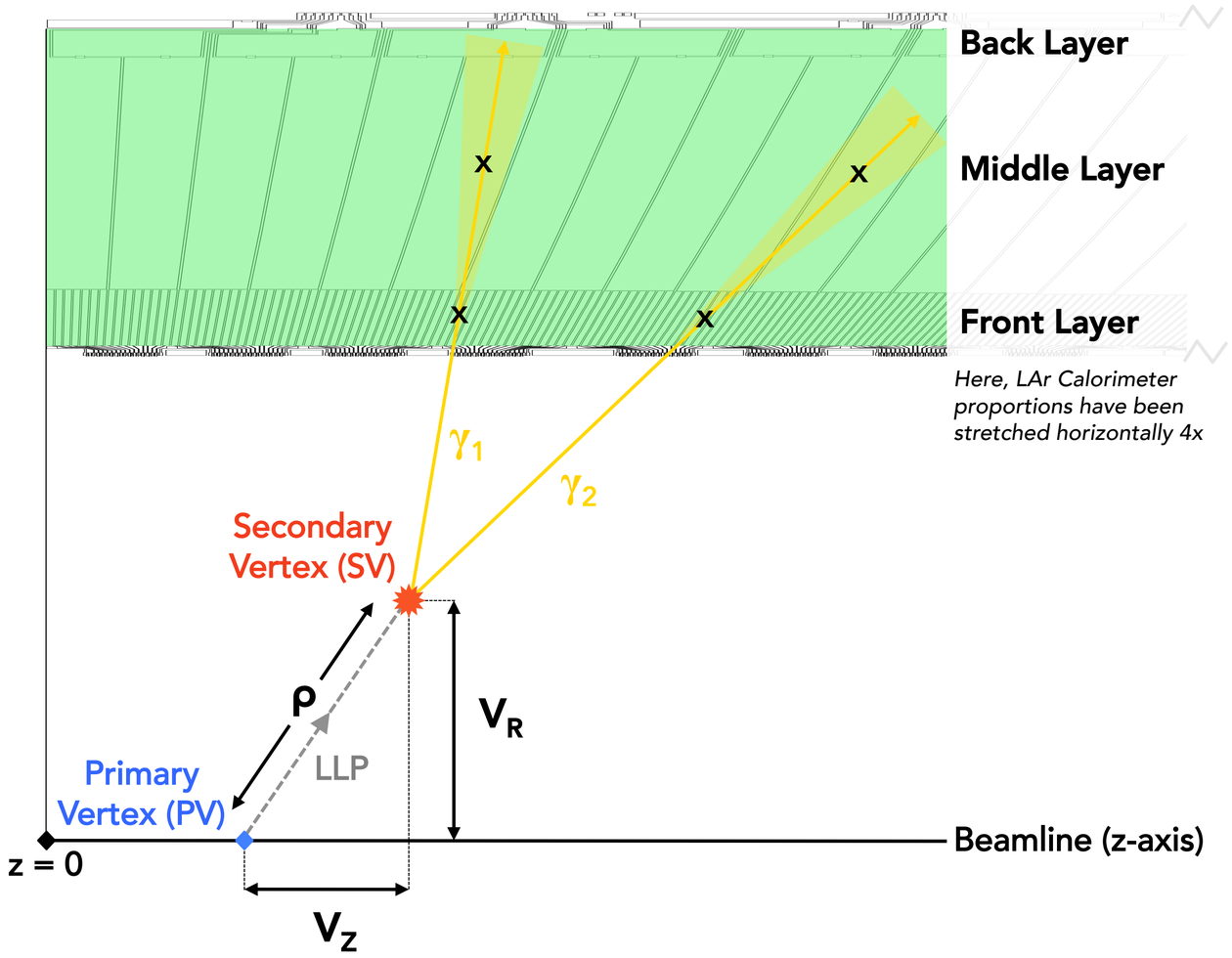

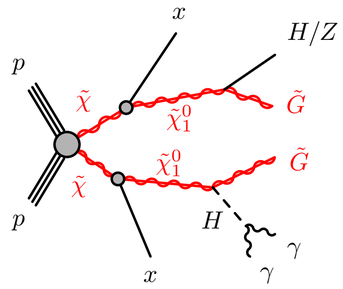

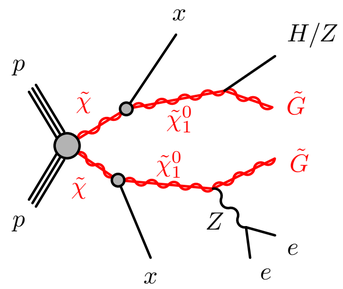

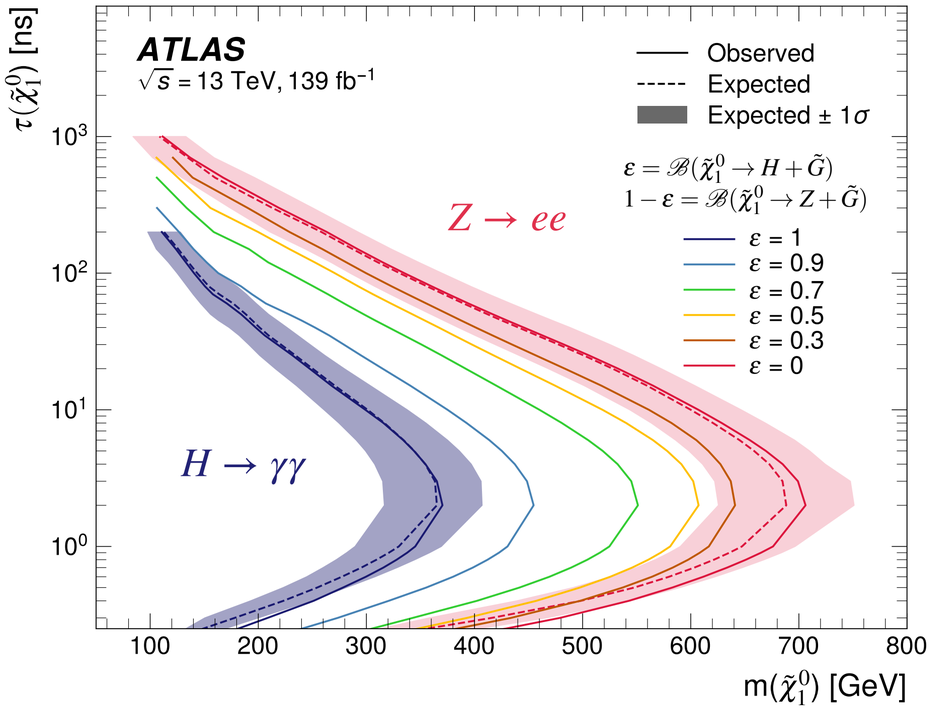

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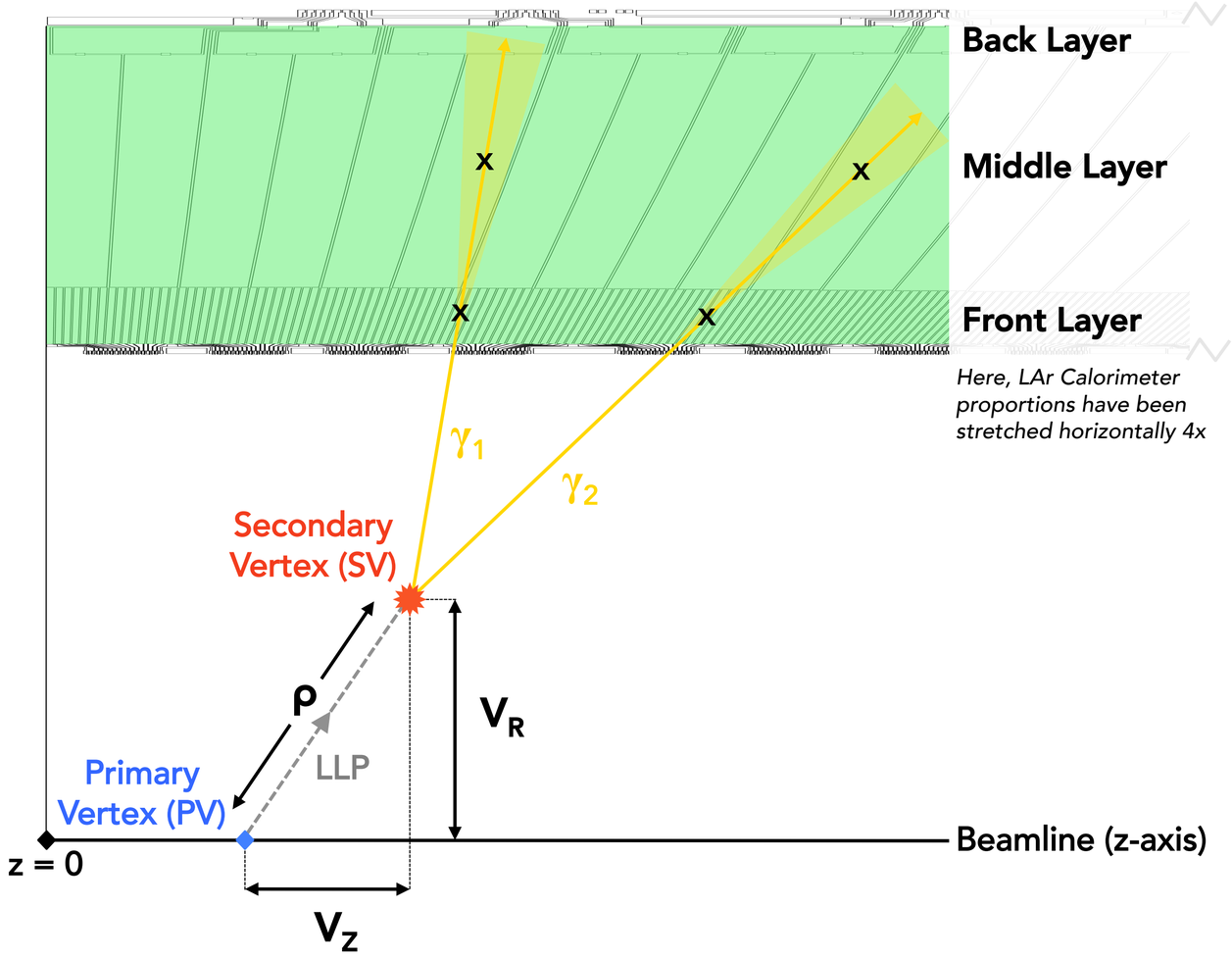

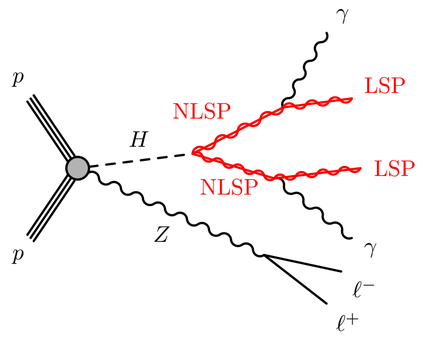

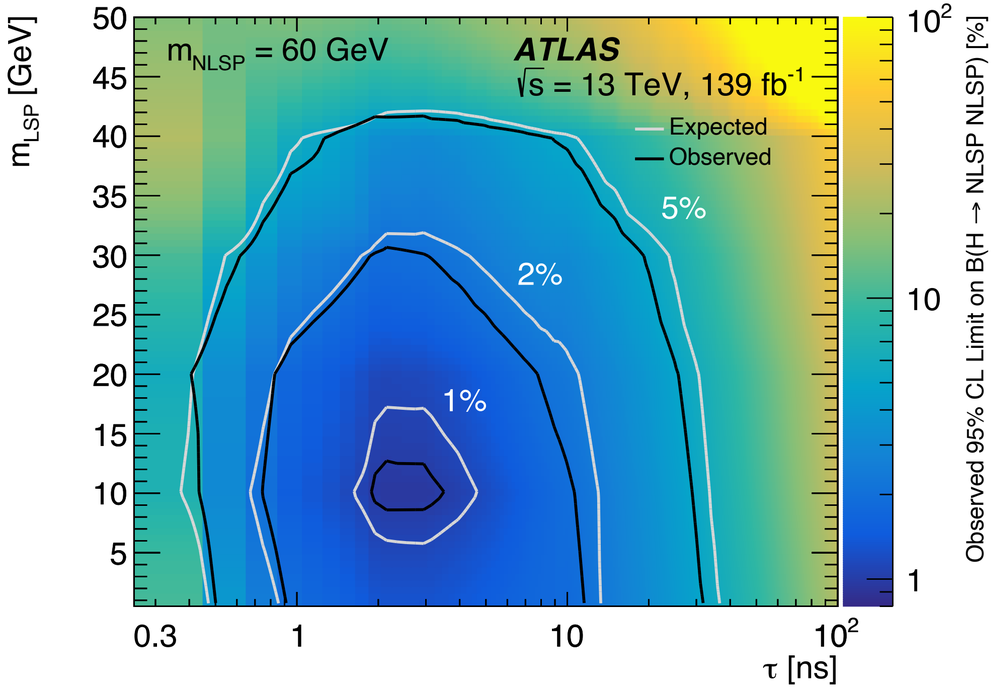

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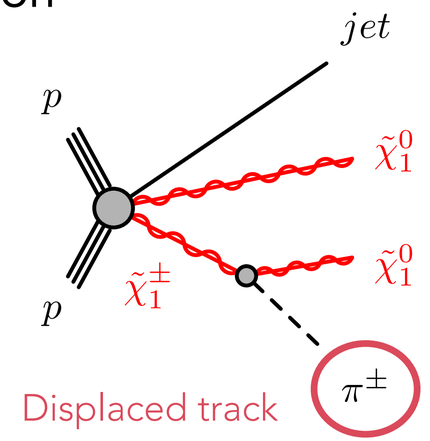

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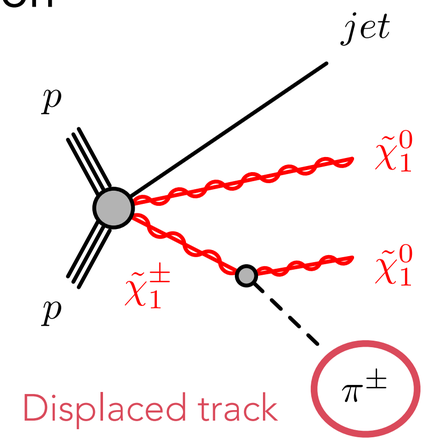

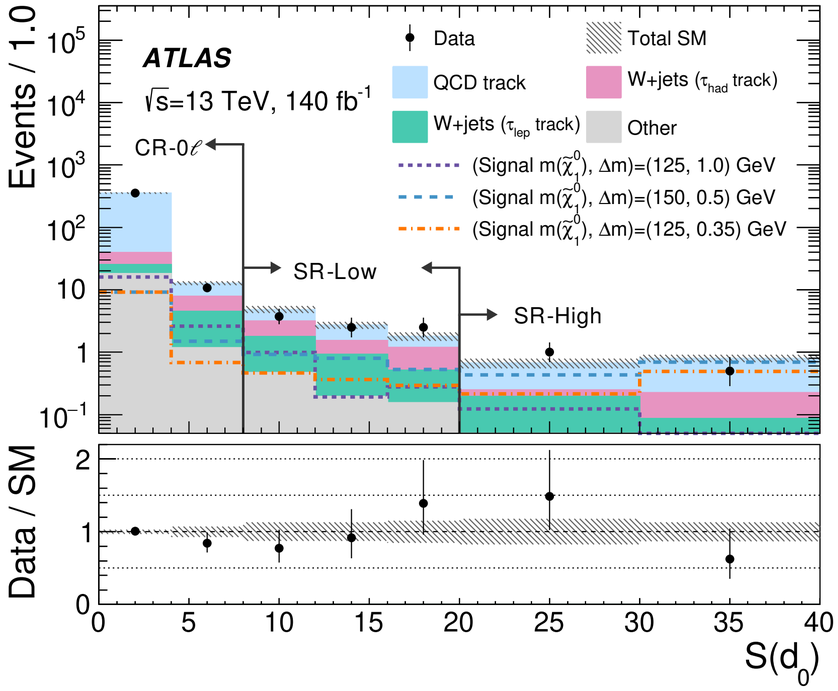

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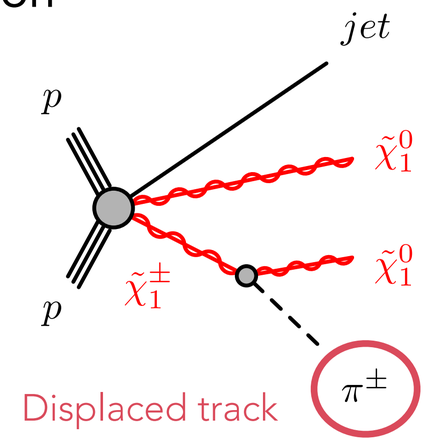
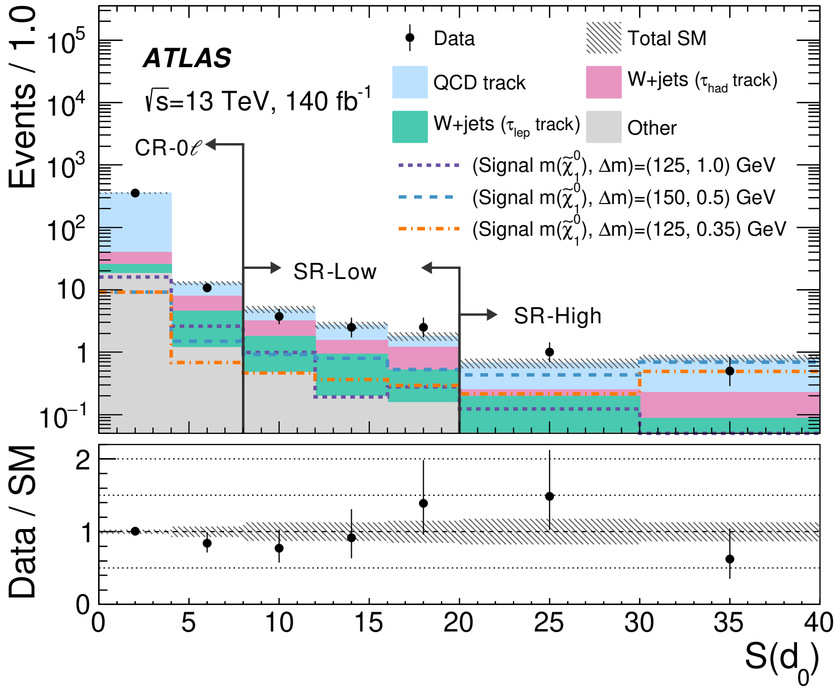
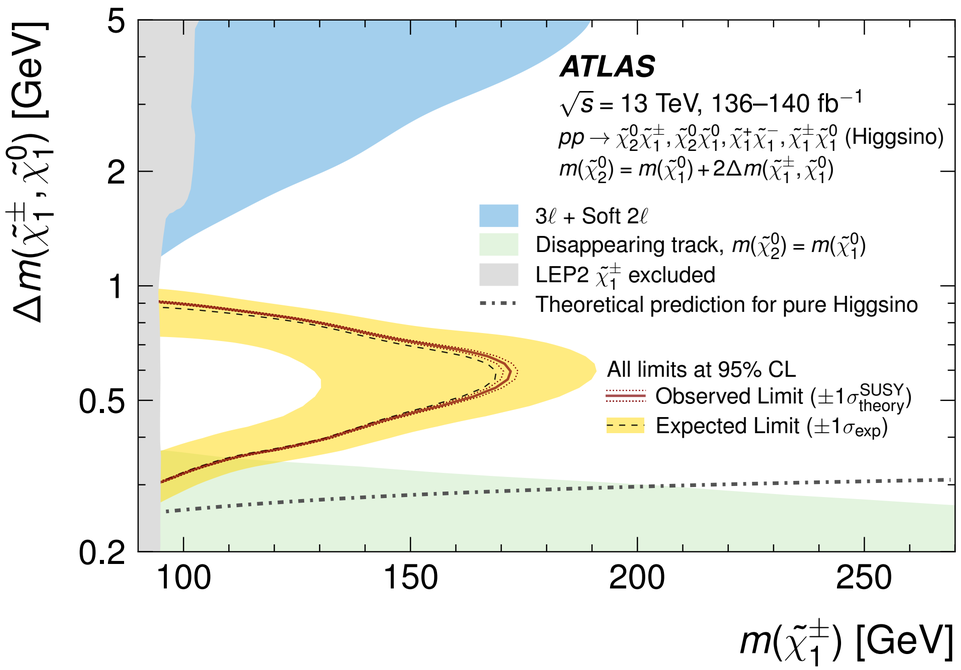
Sensitive to mass splittings of $\mathcal{O}(0.5)$ GeV







Disappearing tracks

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Longer-lived charginos may interact directly with the pixel detector, but decay before reaching SCT

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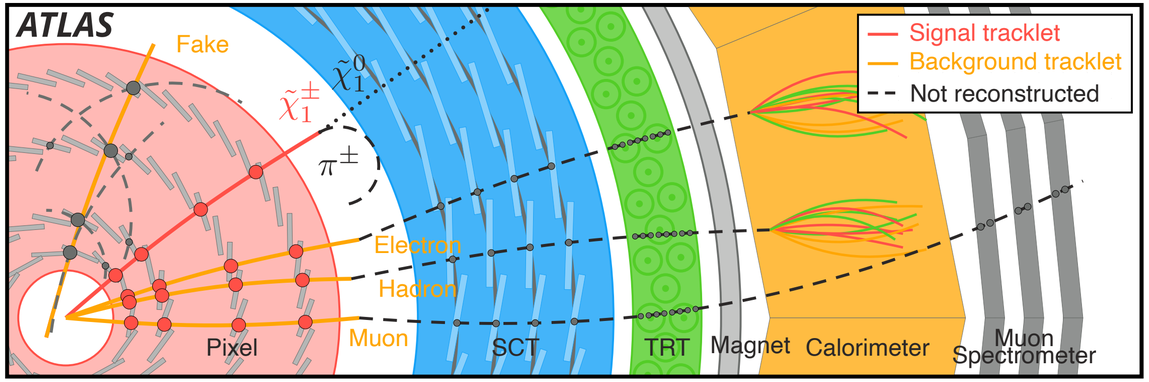

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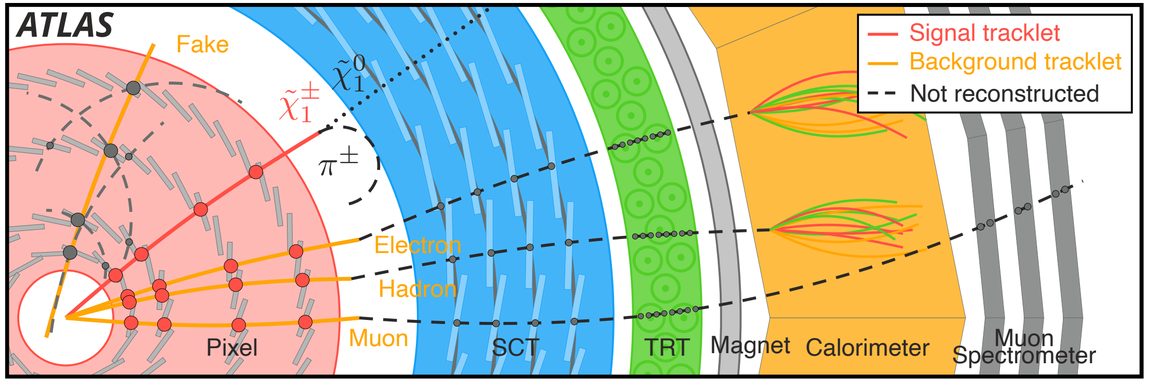

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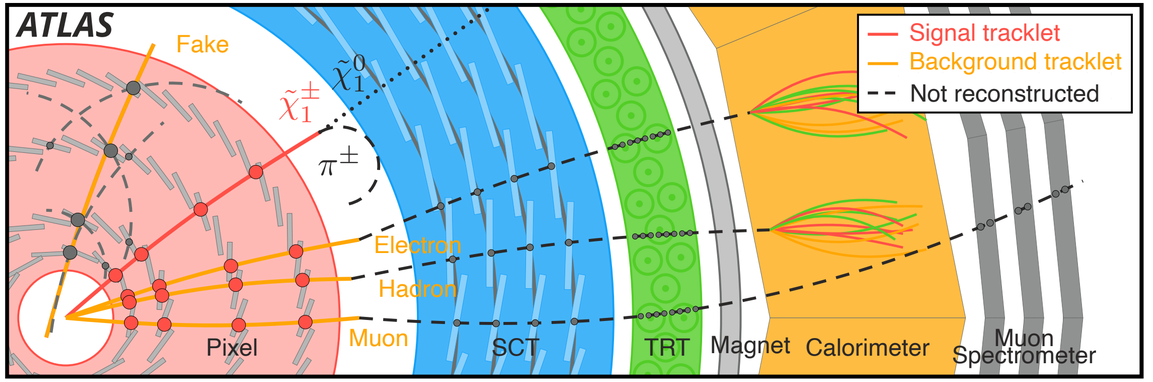

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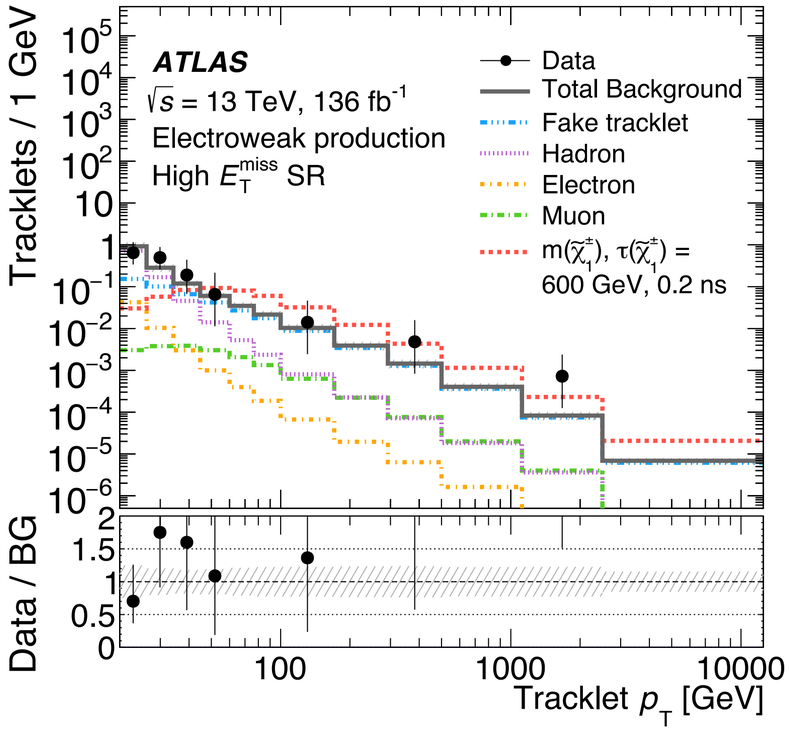

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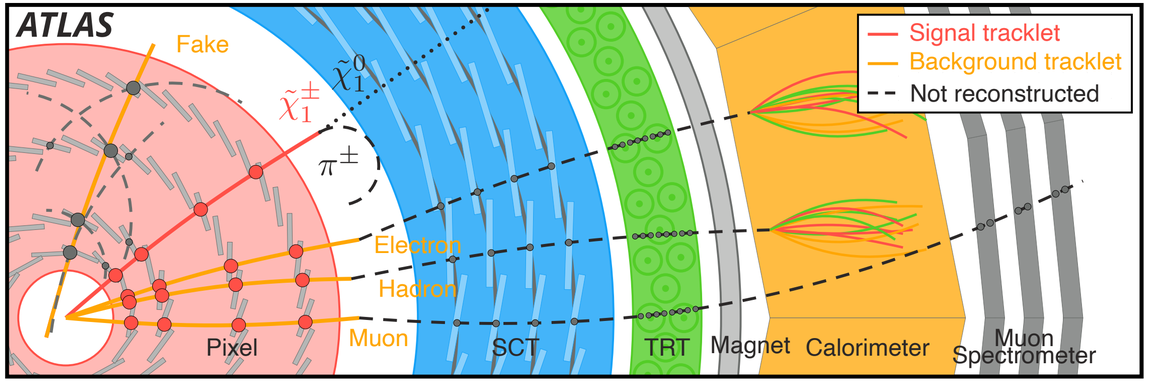

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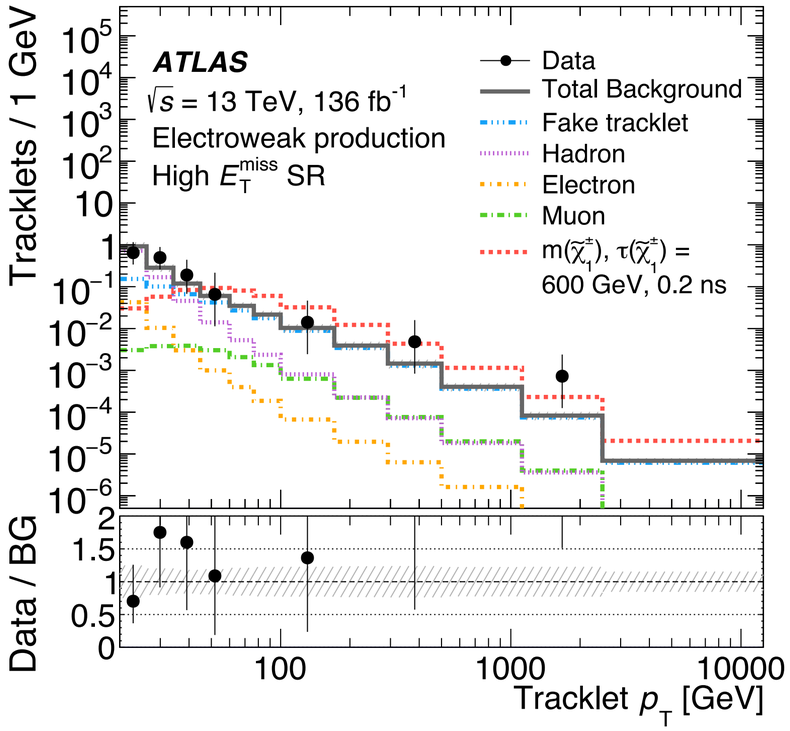

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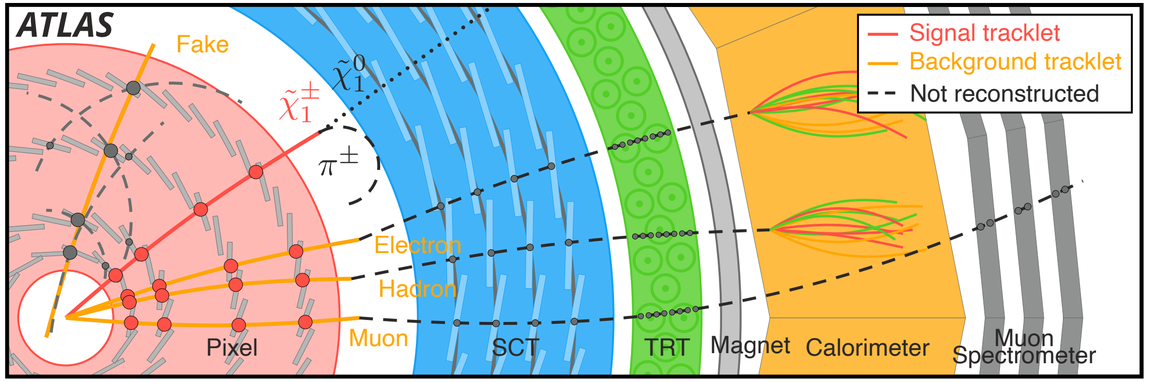

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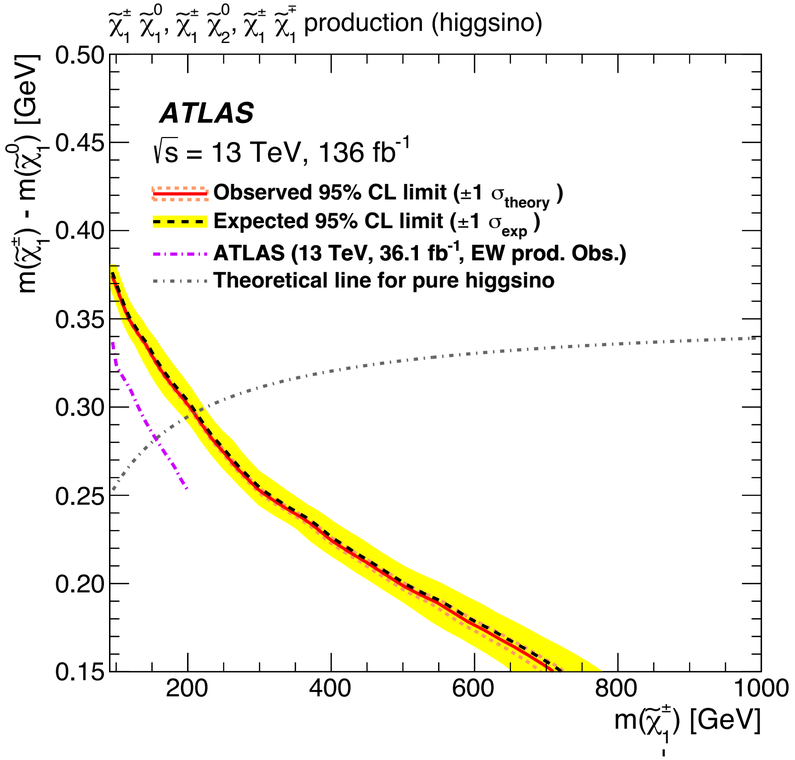

Direct LLP detection

SUSY-2018-42 ATLAS-CONF-2023-044

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SUSY-2018-42 ATLAS-CONF-2023-044

Longer-lived charginos will leave anomalous energy deposits in the detector

- Measure dE/dx in silicon tracker based on charge collected
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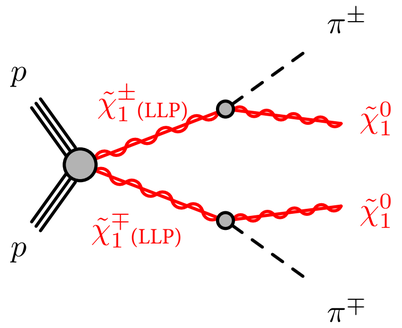

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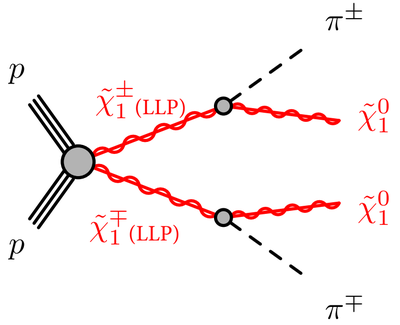

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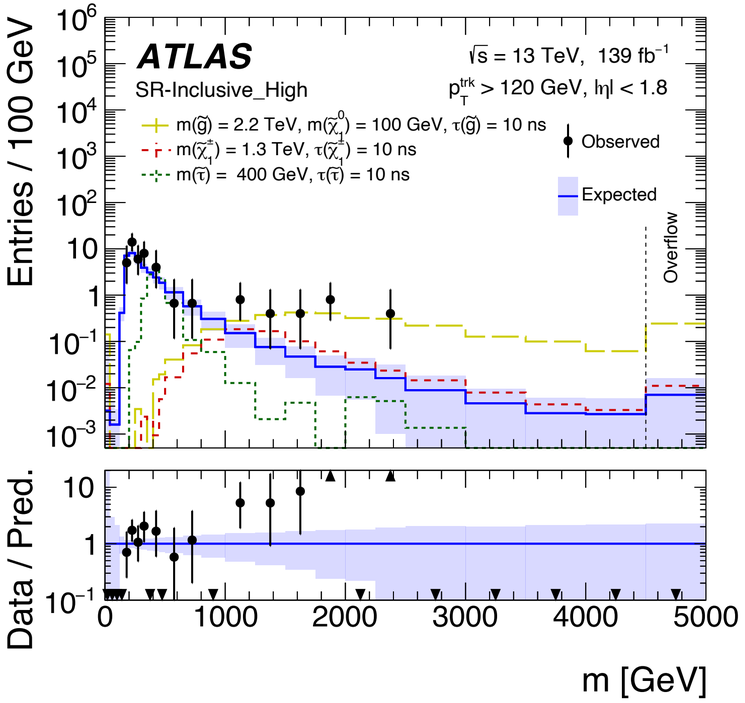
ATLAS search observed 3.3σ global excess

- Consistent with $\beta = 1$ from calo & MS ToF



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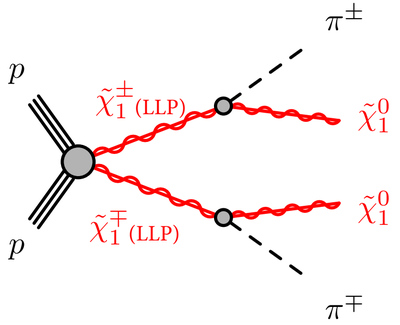

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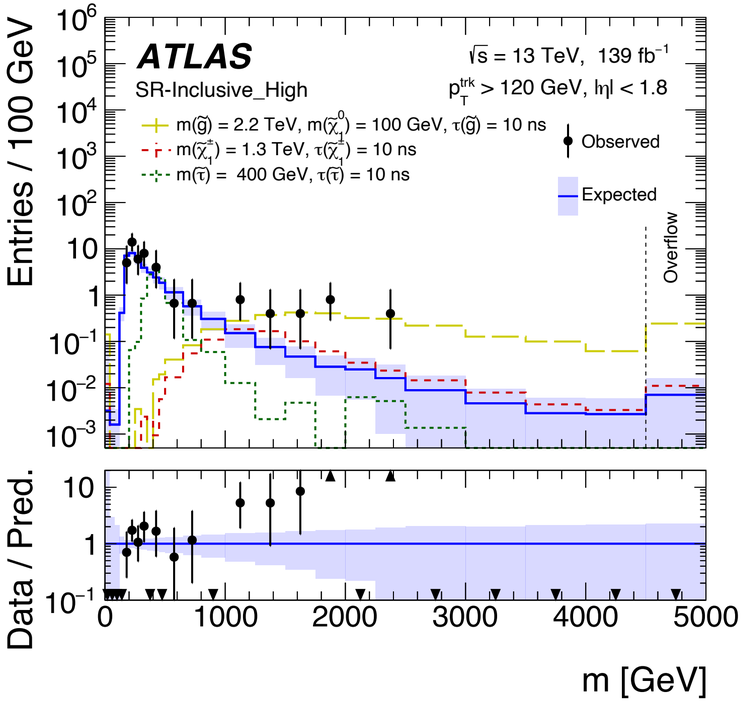
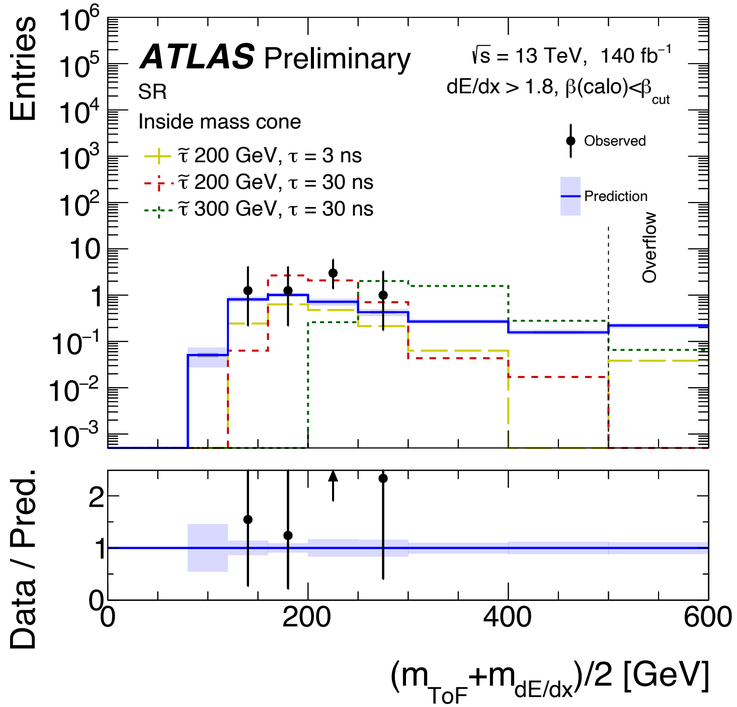
Follow-up analysis requiring $\beta < 0.9$ showed no excess





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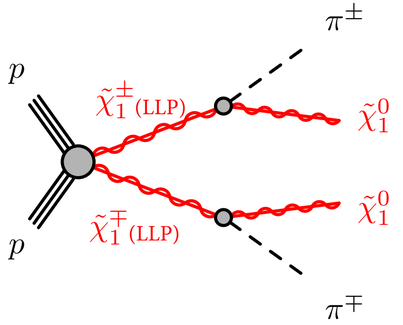

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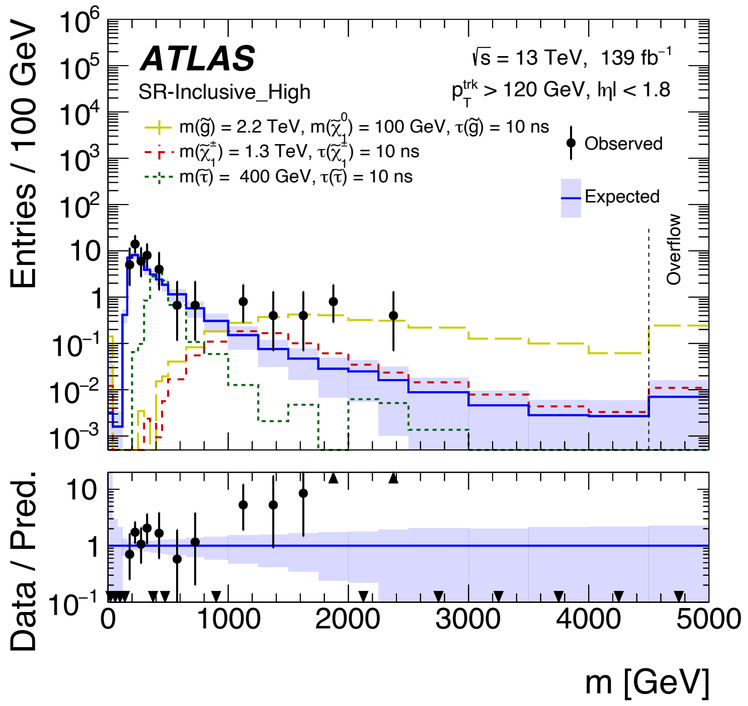
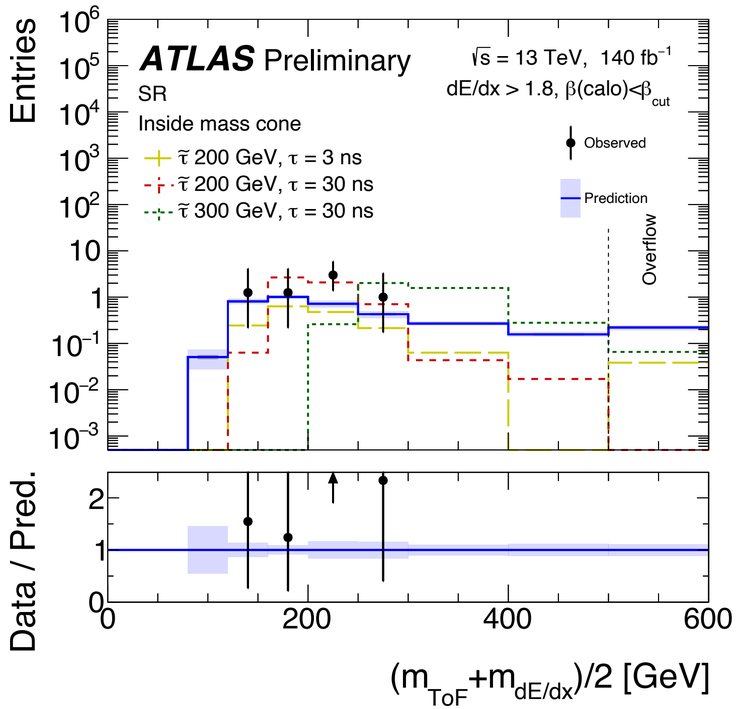
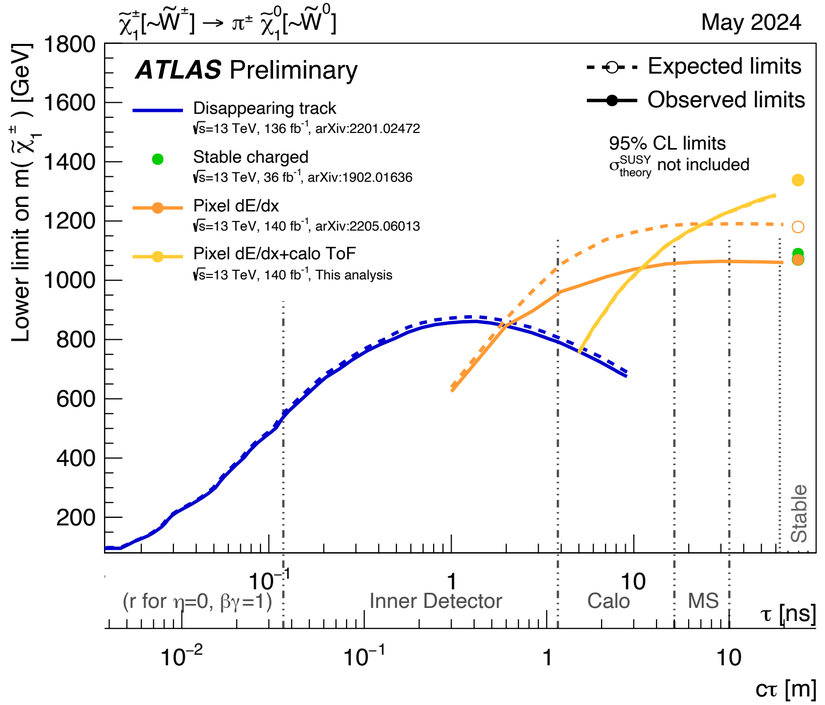
Add complementary sensitivity to disappearing track results







The potential of the HL-LHC

ATLAS Inner Tracker upgrade

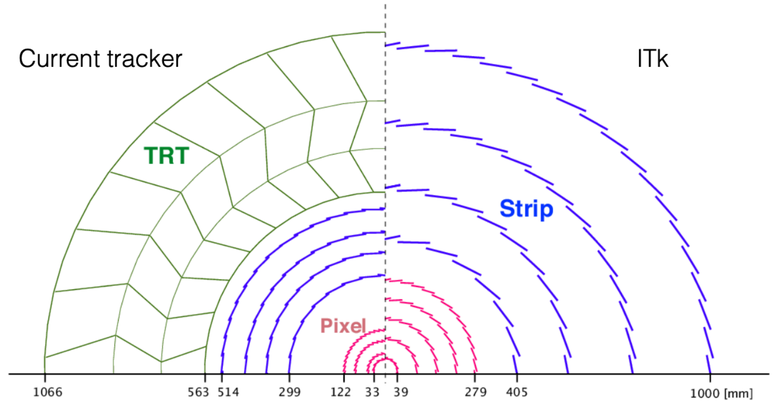
ATL-PHYS-PUB-2018-033

ATLAS Inner Tracker upgrade

ATL-PHYS-PUB-2018-033

ATLAS Phase-II upgrades include a brand new inner tracking detector (ITk)

- improved geometry
- larger silicon volume
- lower material budget



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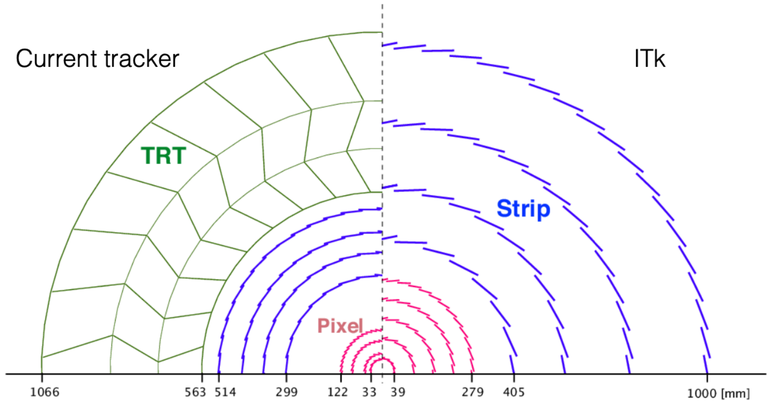
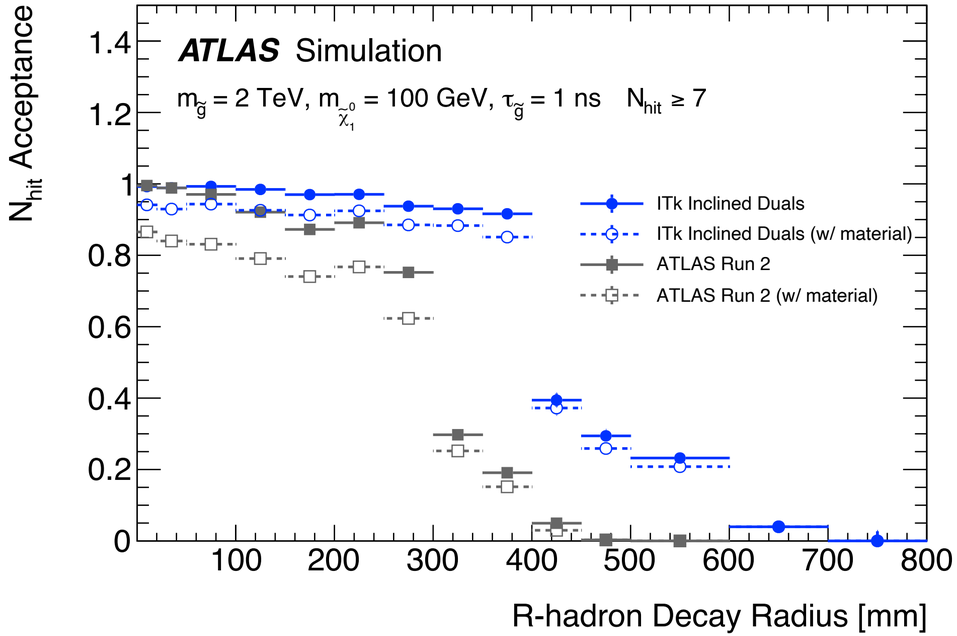


Improved efficiency for displaced vertex signatures



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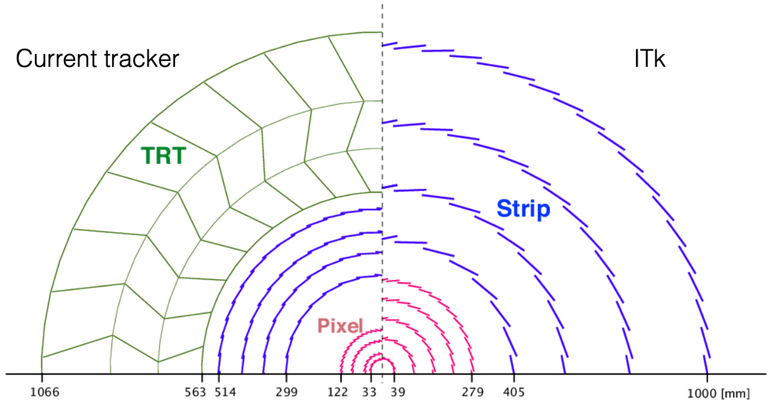
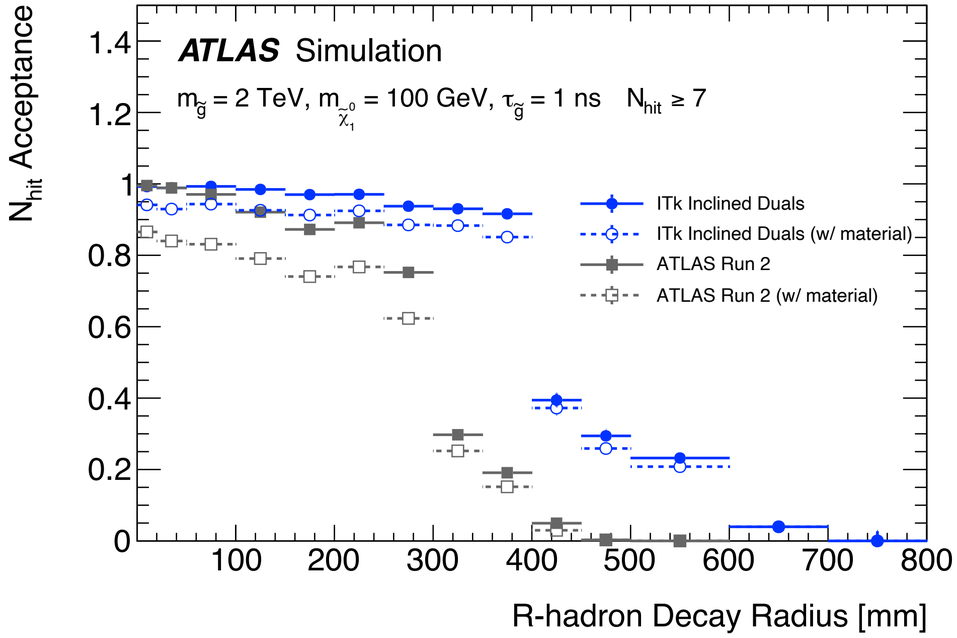
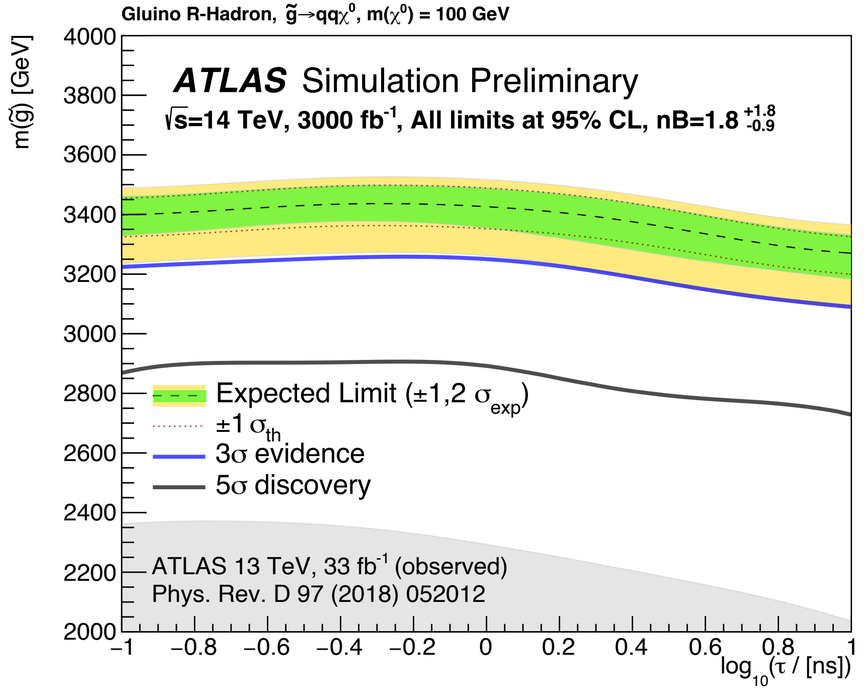


Translates to significantly improved sensitivity for LLP decays in the tracker





Timing information

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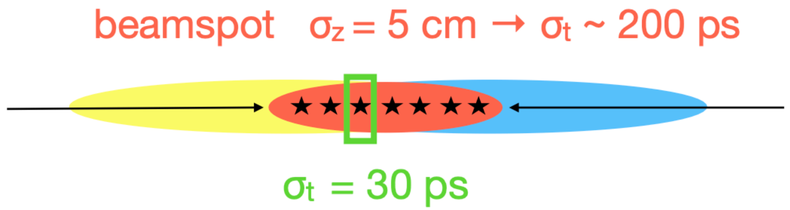

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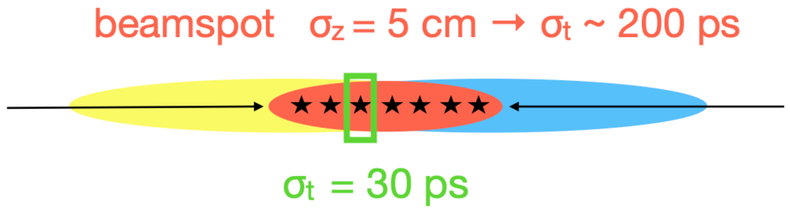

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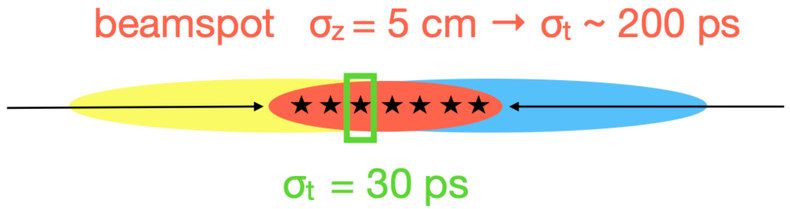

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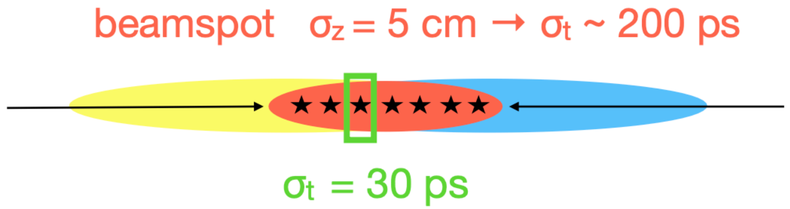

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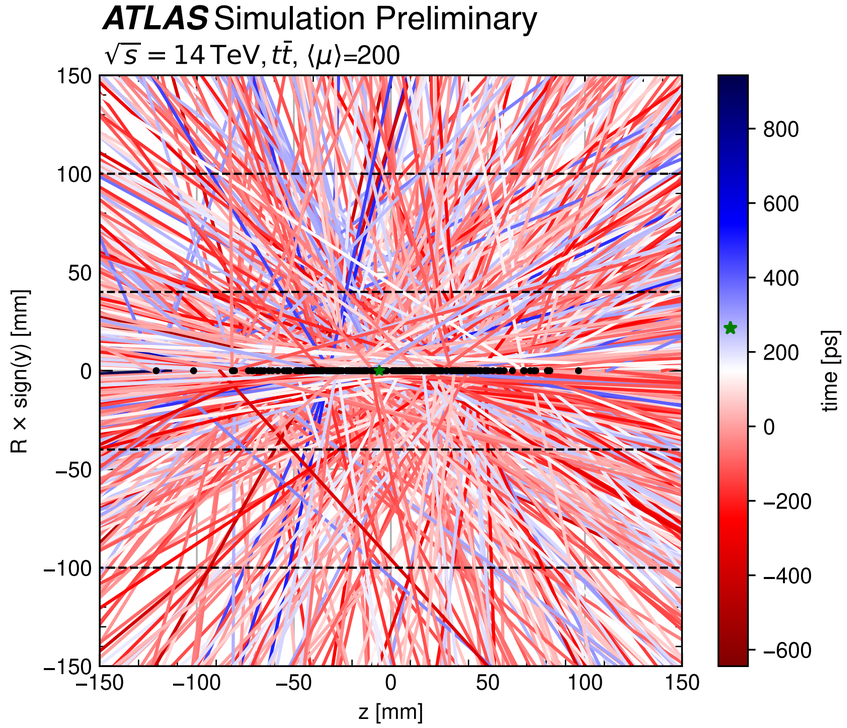

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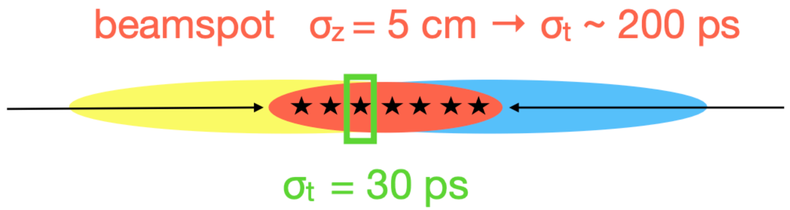

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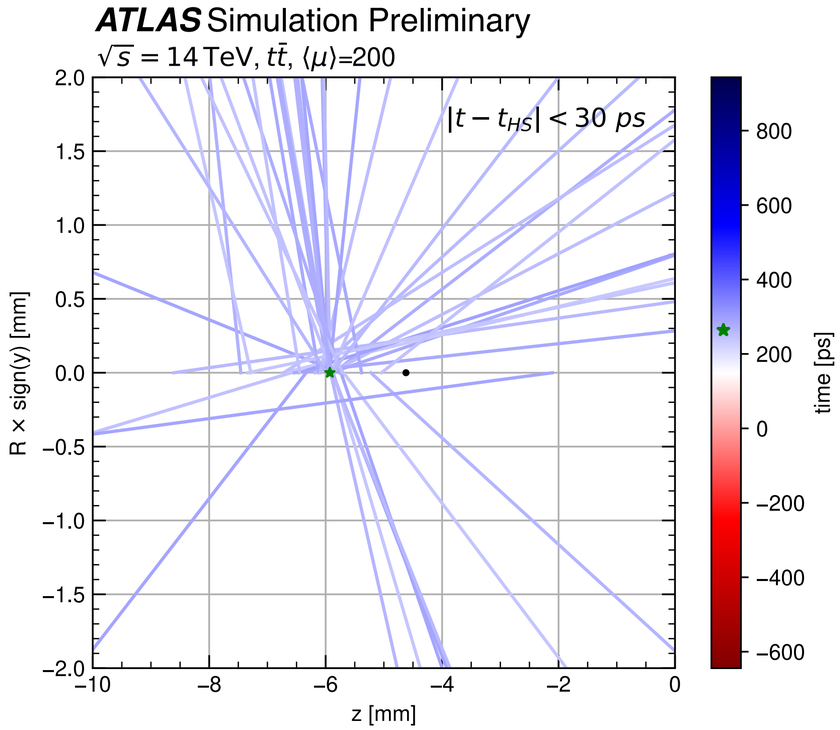

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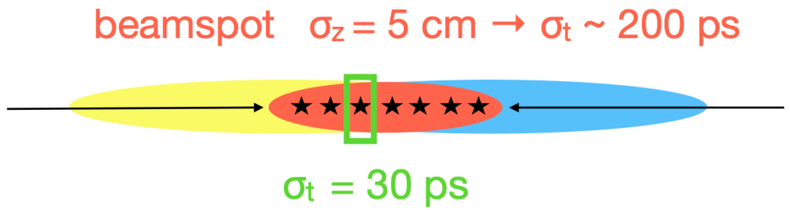

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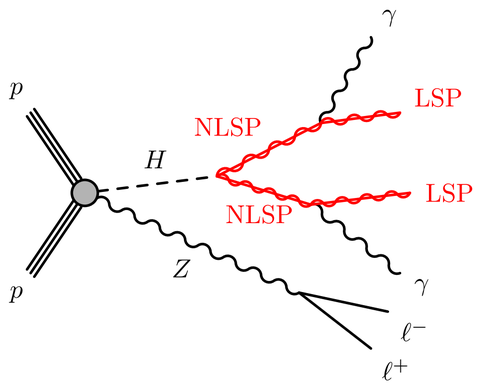
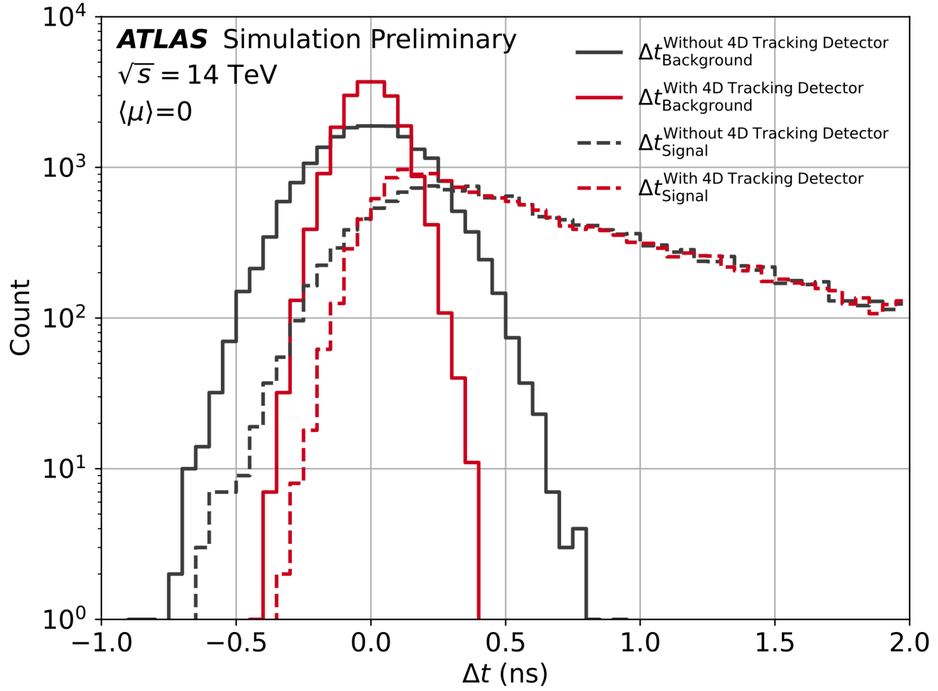
Case study: displaced diphotons in GMSB





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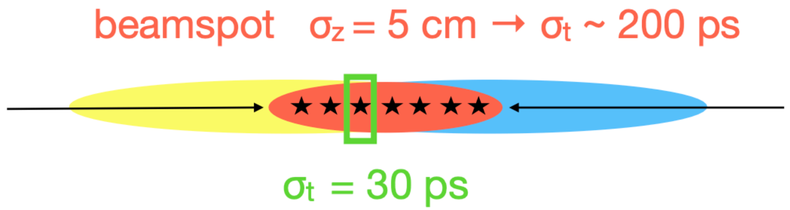

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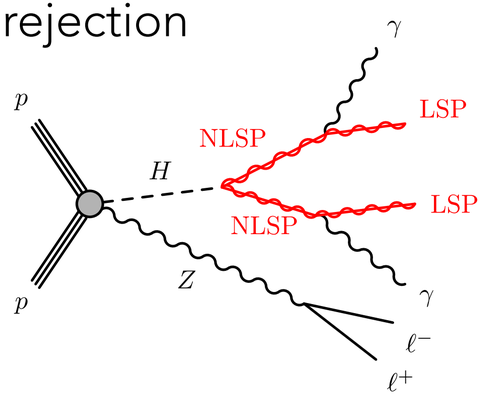
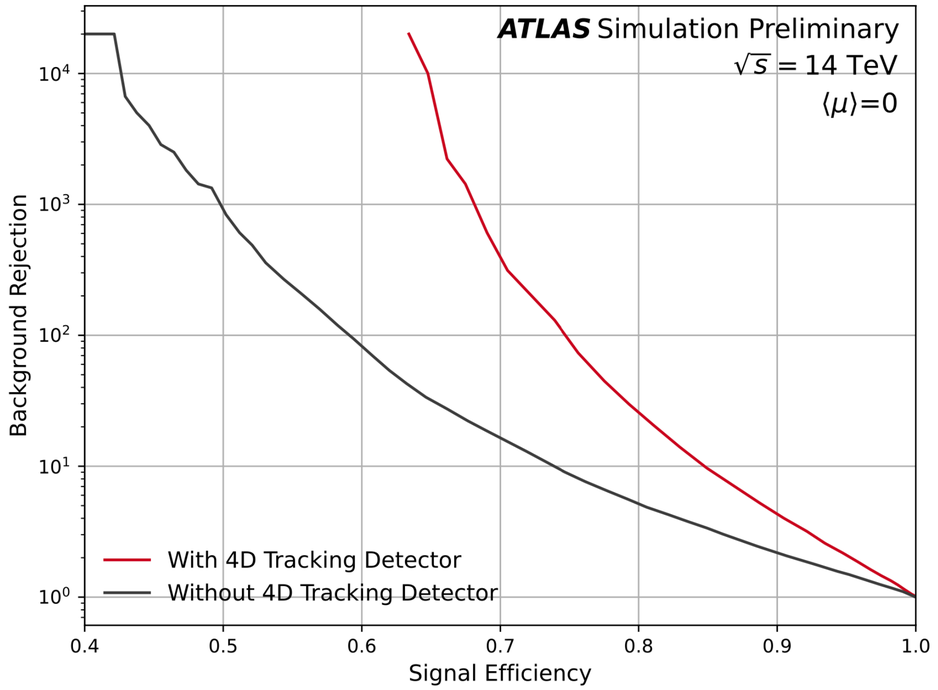
- 4D tracking can improve background rejection by more than a factor 10





Dedicated LLP detectors

There are a number of existing or proposed **dedicated LLP search experiments**

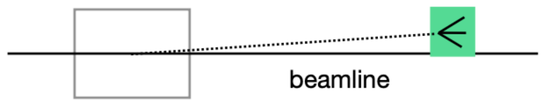
Fixed target experiments and forward detectors to probe low-mass scenarios

FASER

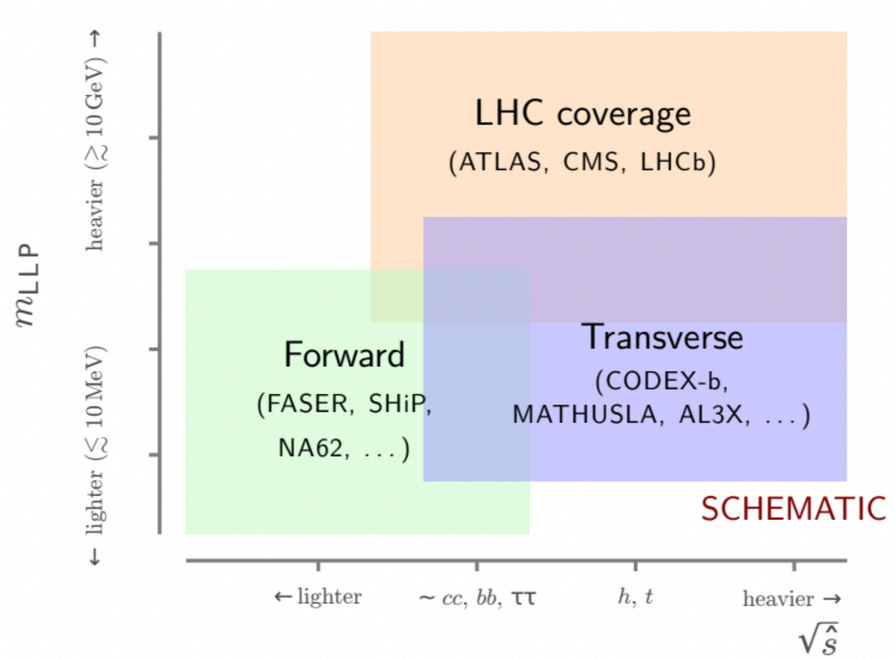
NA64

SHiP
Search for Hidden Particles

new experiment



ATLAS/CMS/LHCb



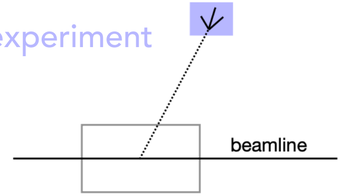
Transverse detectors searching for higher-mass LLPs at larger angles

MATHUSLA

ANUBIS

CODEX–b

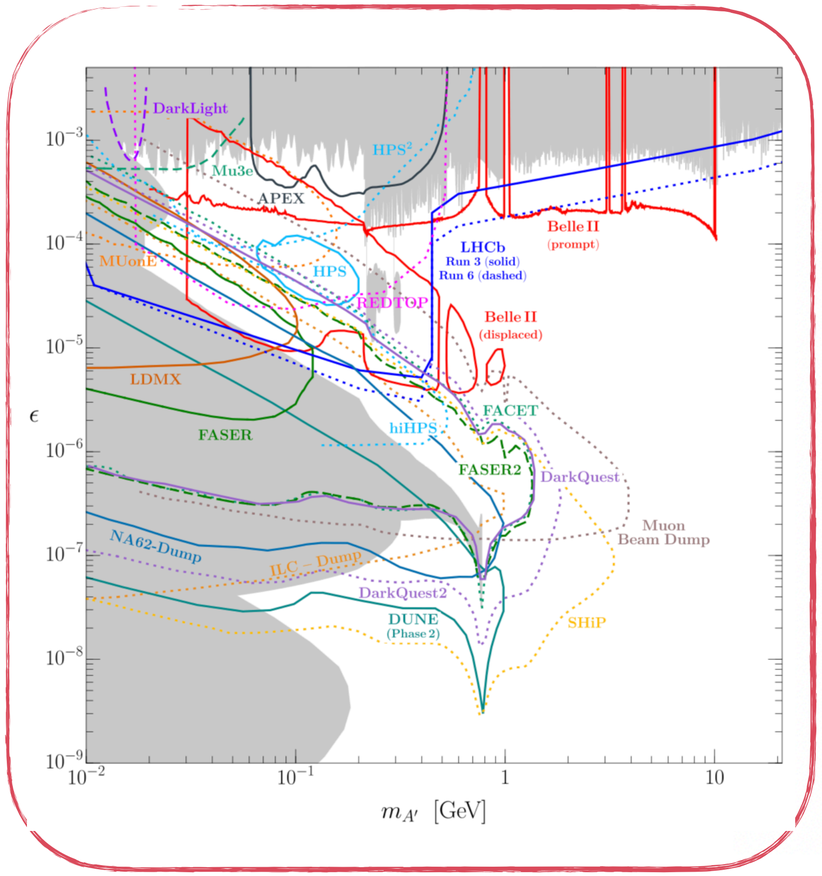
new experiment

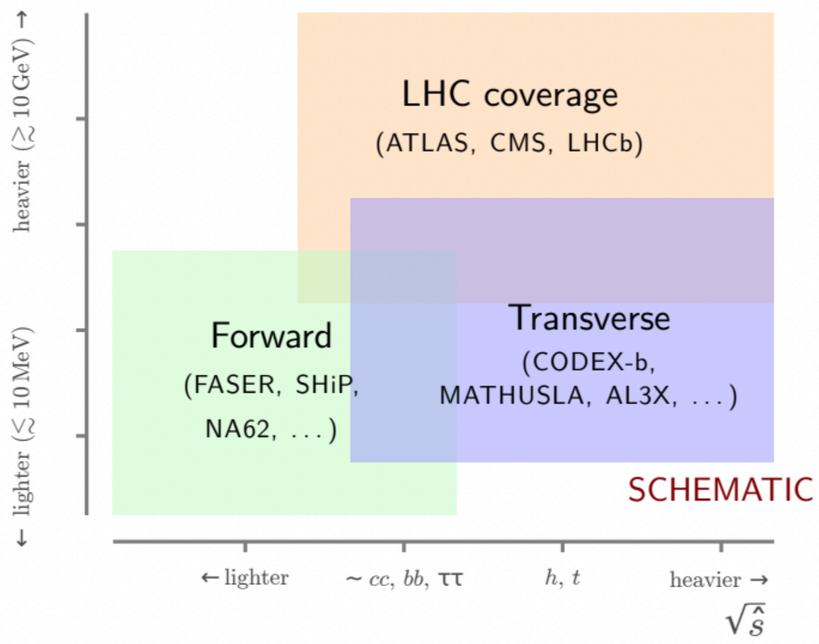


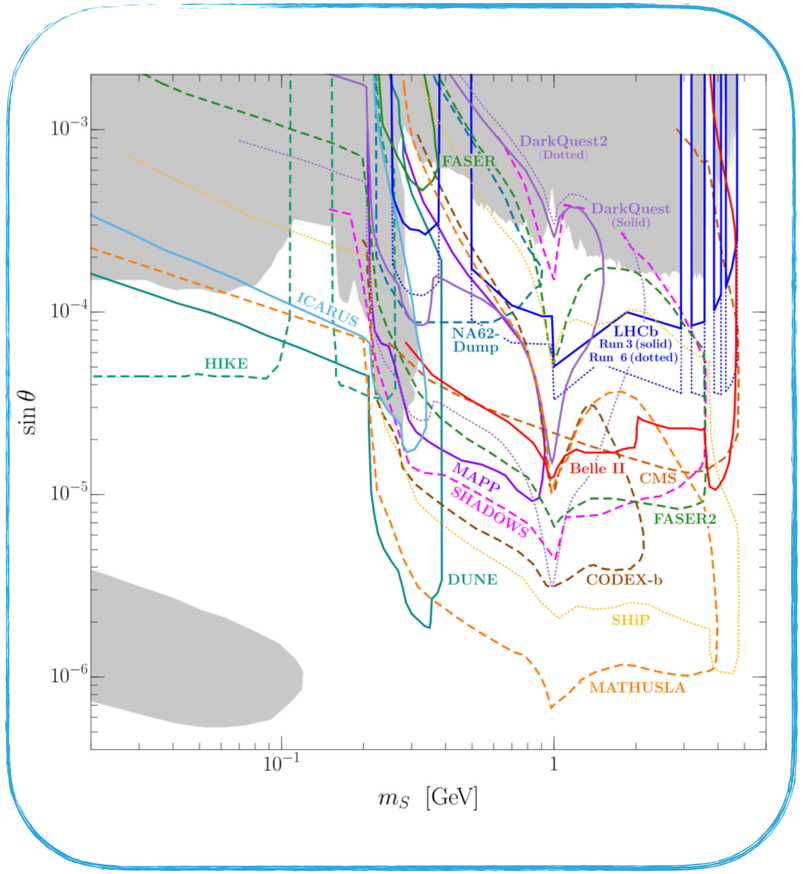
ATLAS/CMS/LHCb

Slide inspired by Giuliano Gustavino

Dedicated LLP detectors







Potential to significantly expand sensitivity beyond searches at general purpose detectors

2207.06905

LLPs at Future Colliders

LLPs at Higgs factories

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Higgs factories are LLP factories!

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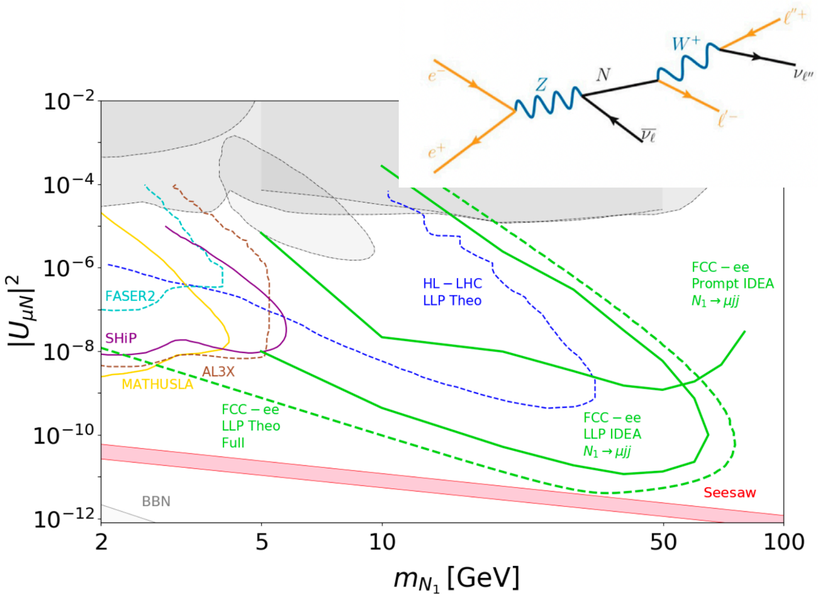
HNLs

- From Z- mediated processes



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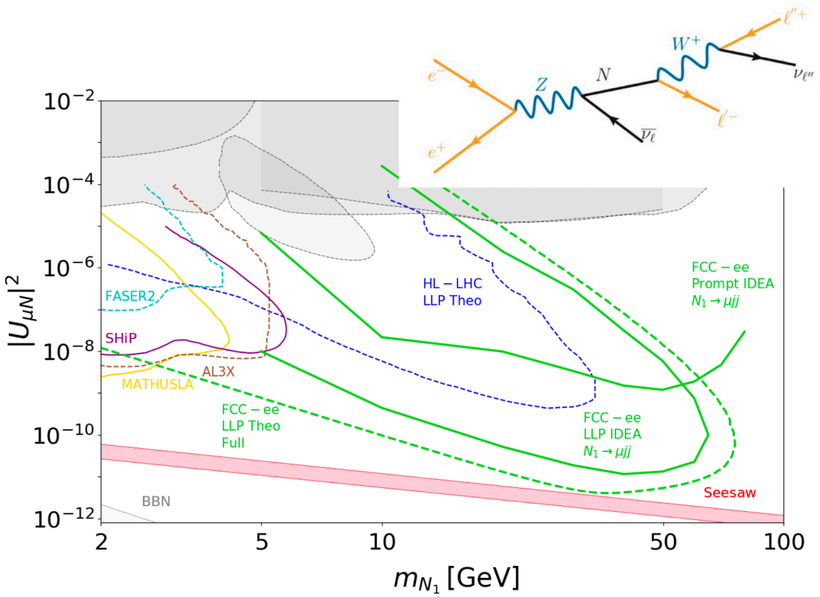
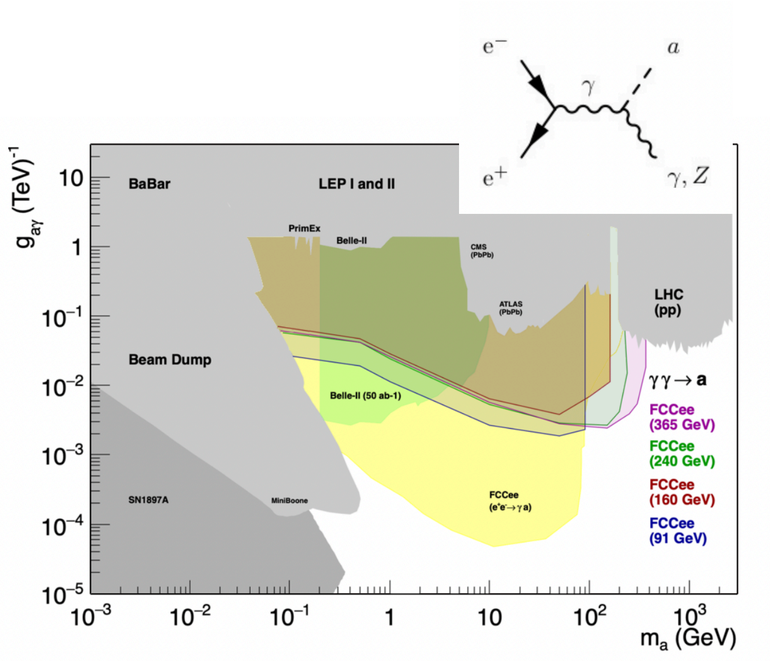


ALPs

- $e^+e^- \to a\gamma$ dominates sensitivity



2310.17270

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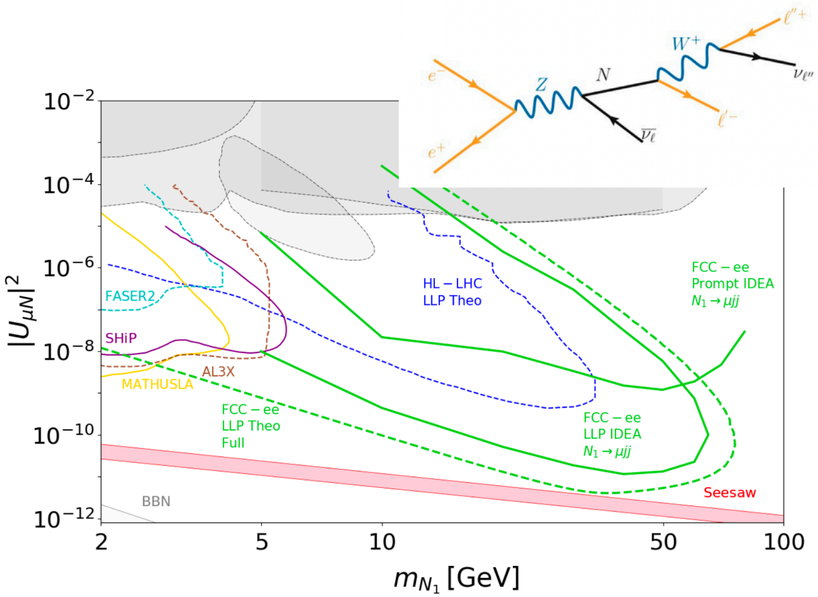

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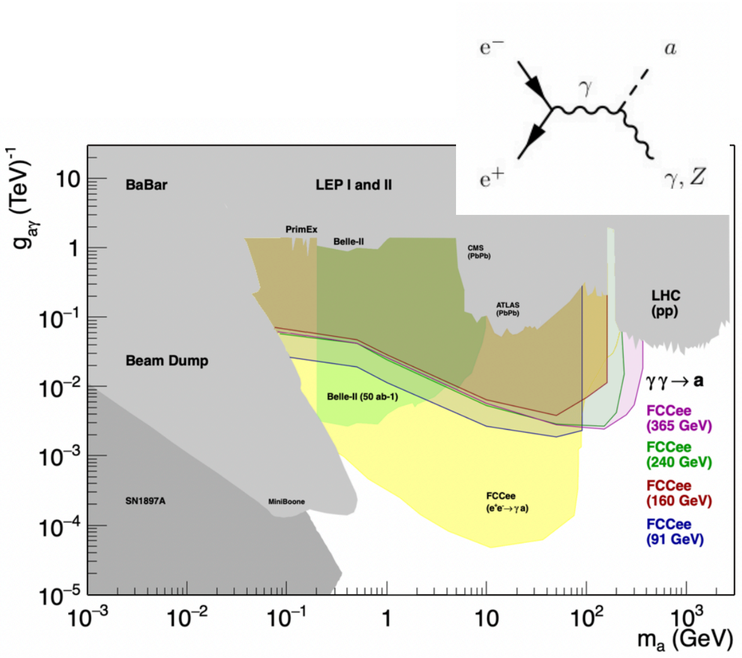

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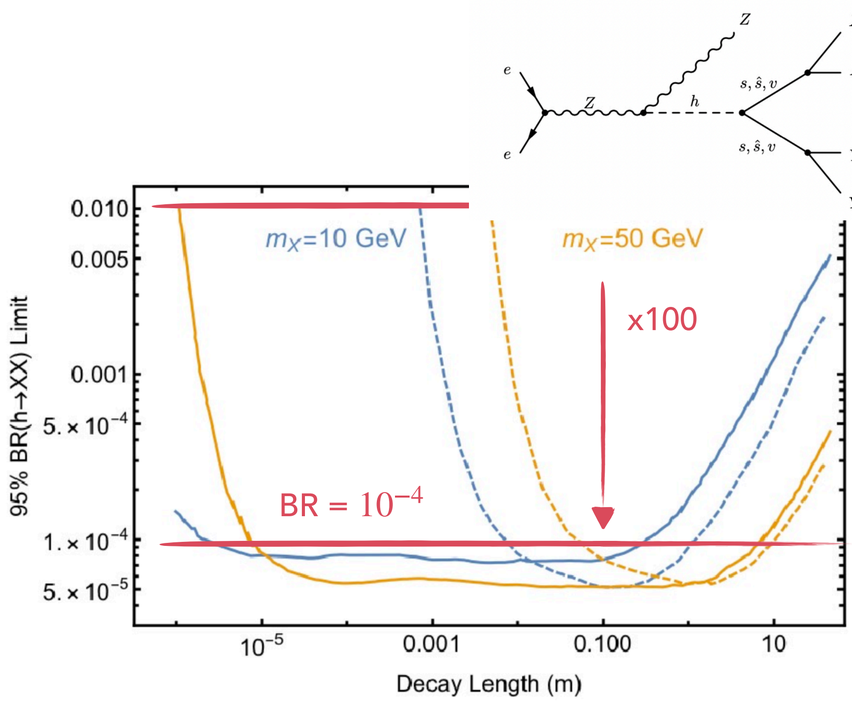
Higgs portal scalars

- From $ZH, H \to ss$



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Muon Colliders

2301.02602

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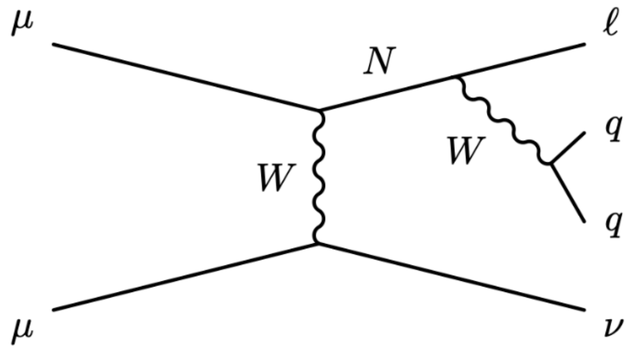

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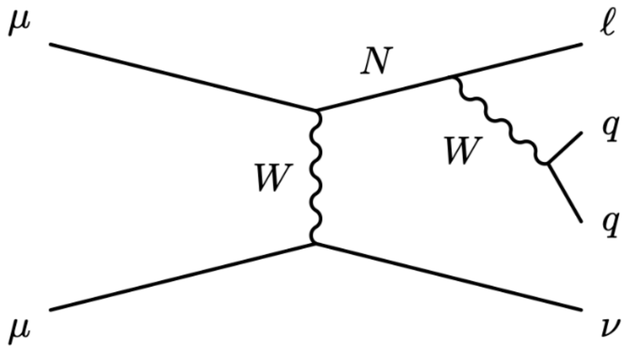
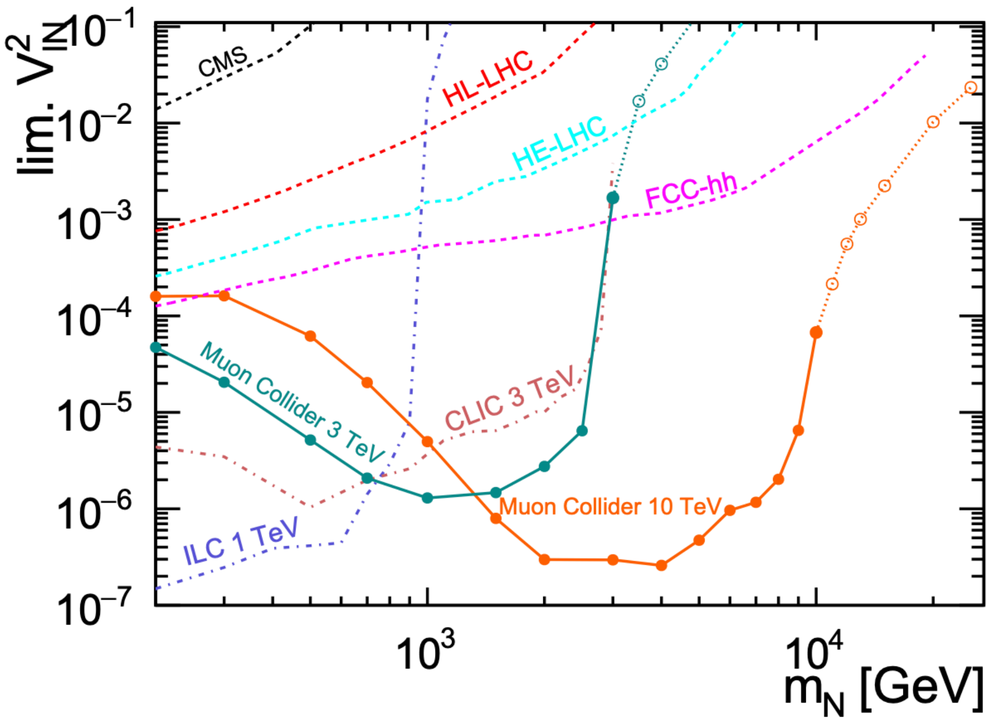


Probe TeV-scale HNLs at mixing angles **~4 orders of magnitude smaller** than FCC-hh



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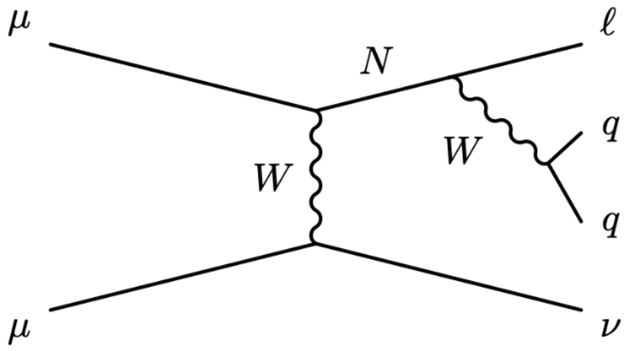

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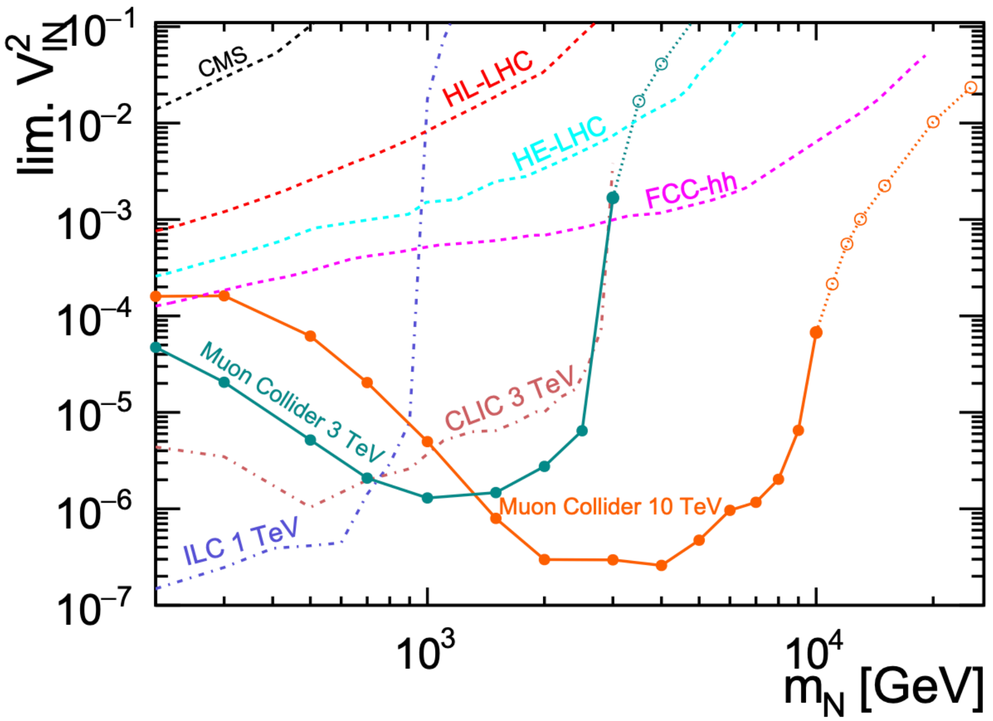

Note: sensitivity projections for prompt HNLs, but similar gains possible for LLPs at lower masses

Summary

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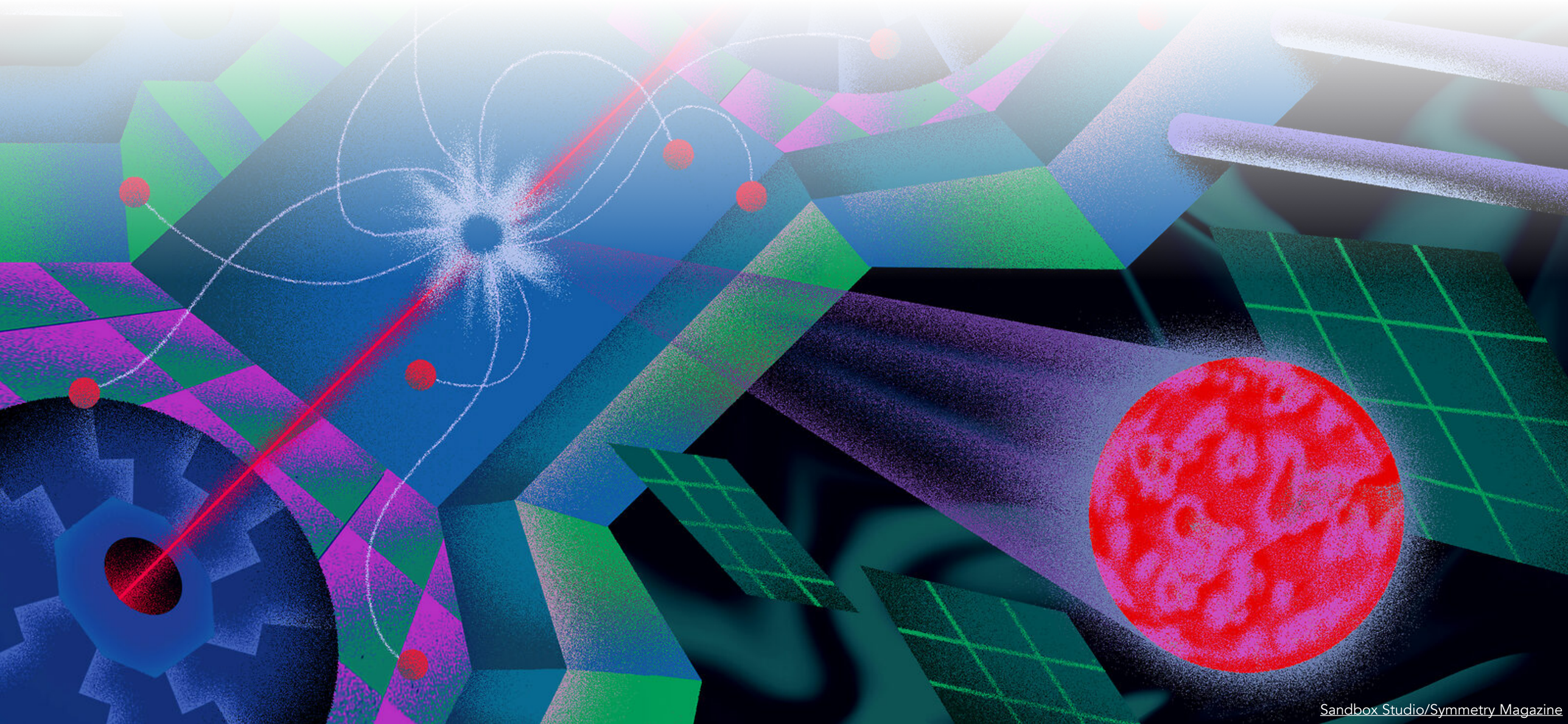
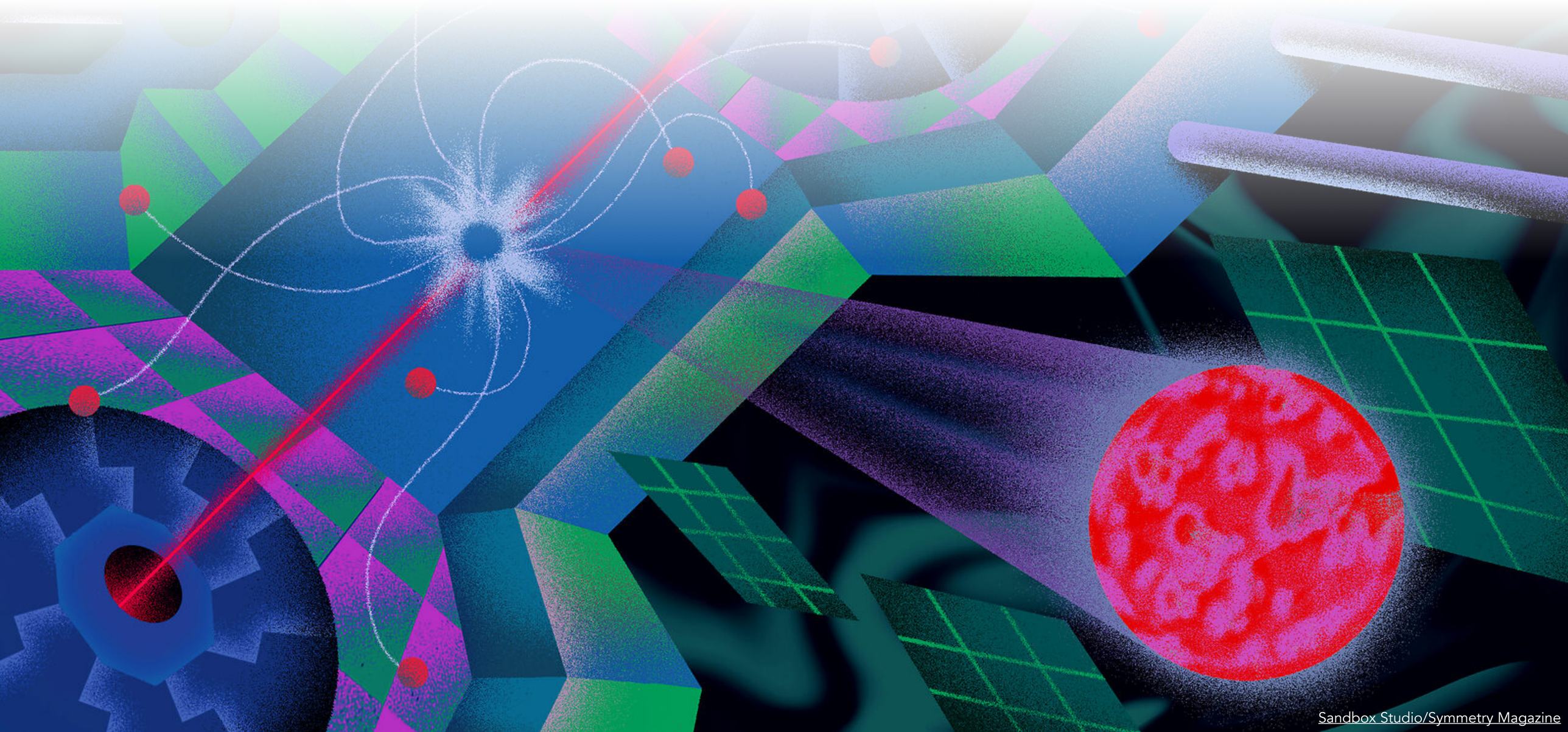
There is an exciting future ahead at the **lifetime frontier!**

Thank you for your attention! Questions?



Sandbox Studio/Symmetry Magazine

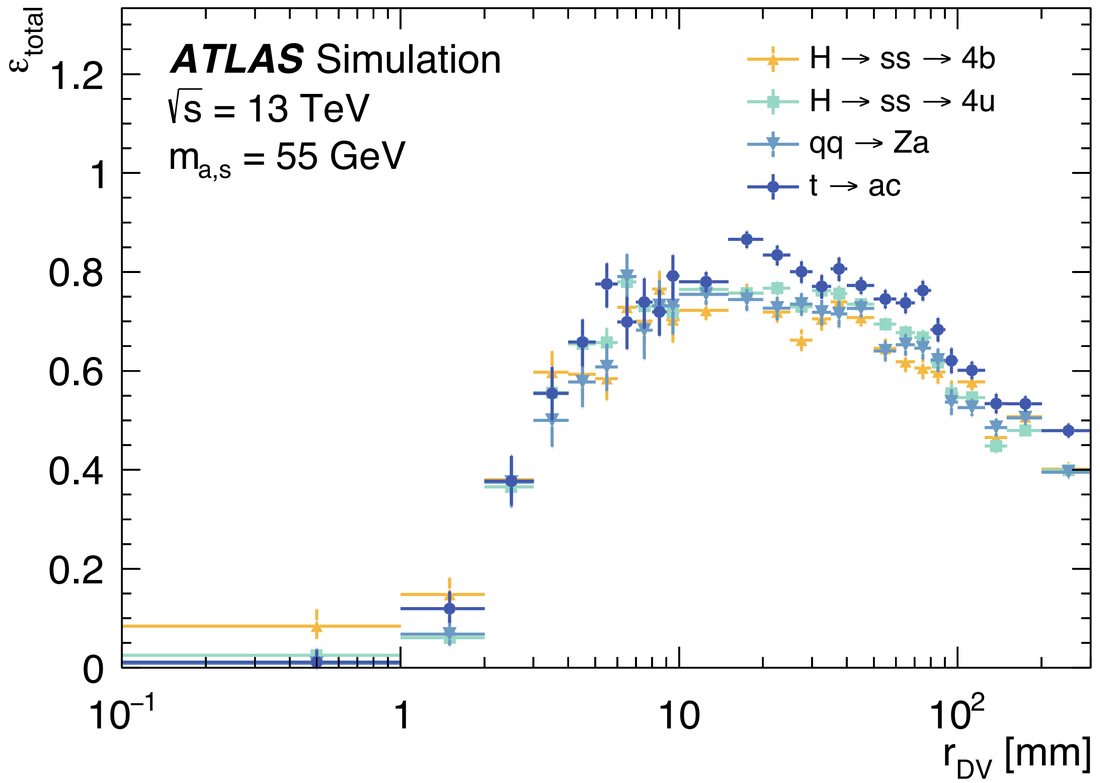
Backup

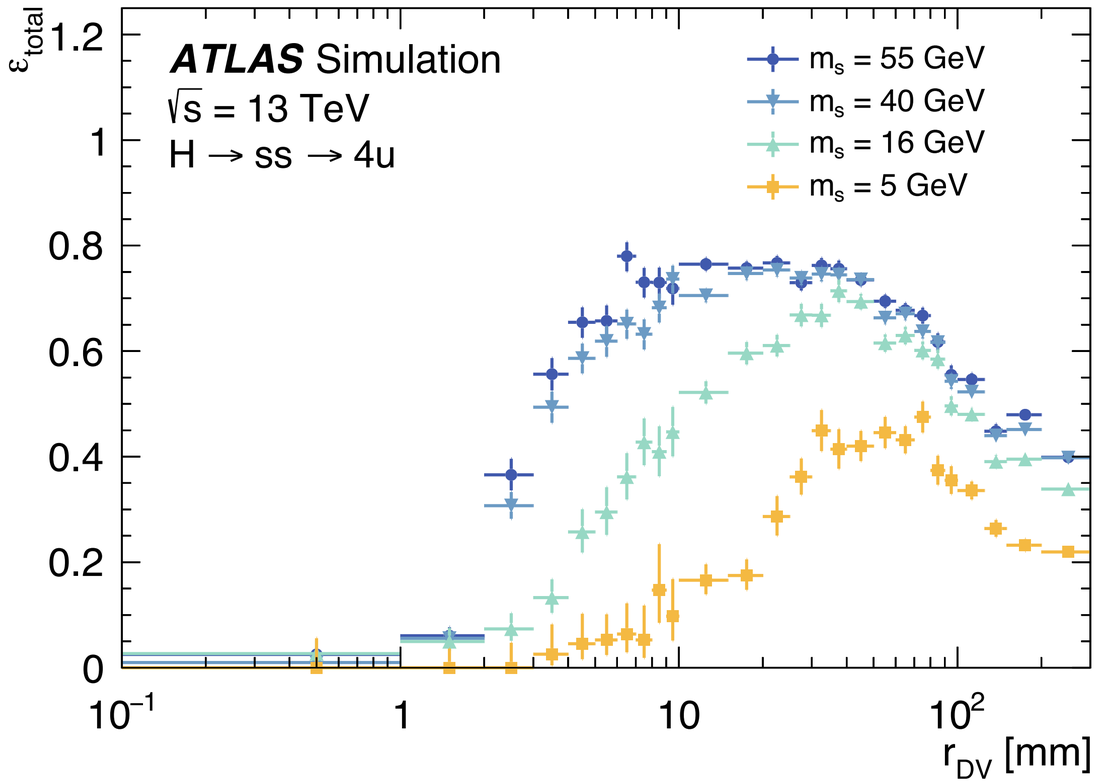


Sandbox Studio/Symmetry Magazine

Hadronic vertices in ATLAS

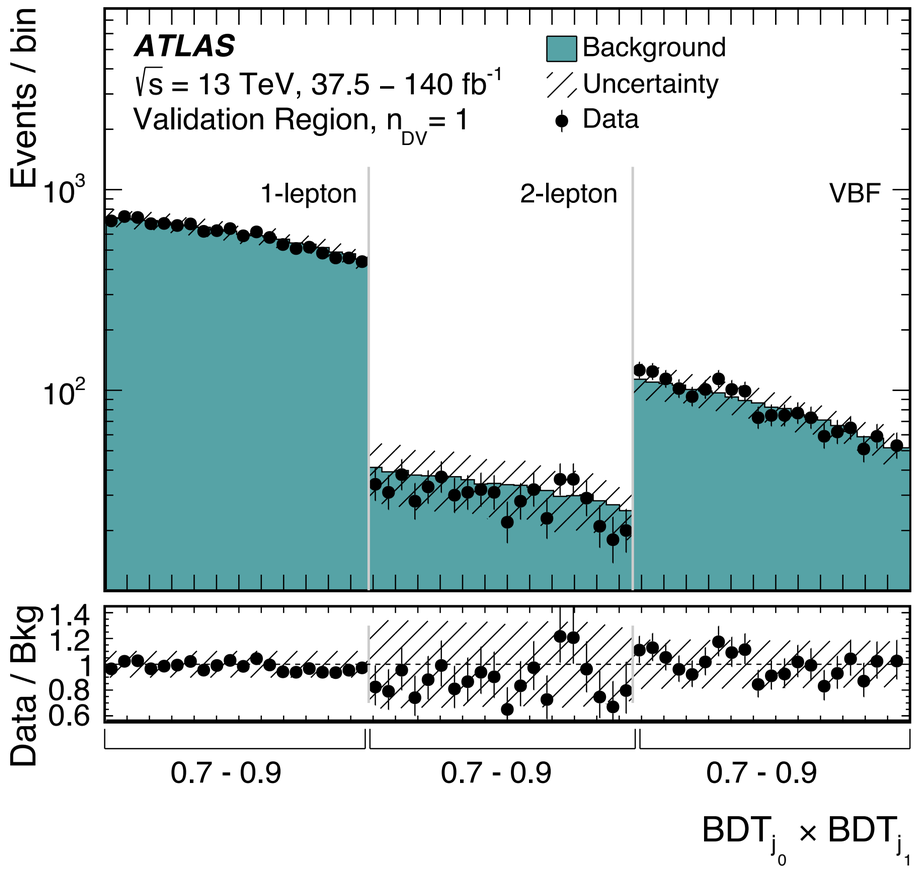
Vertex reconstruction efficiency for different models

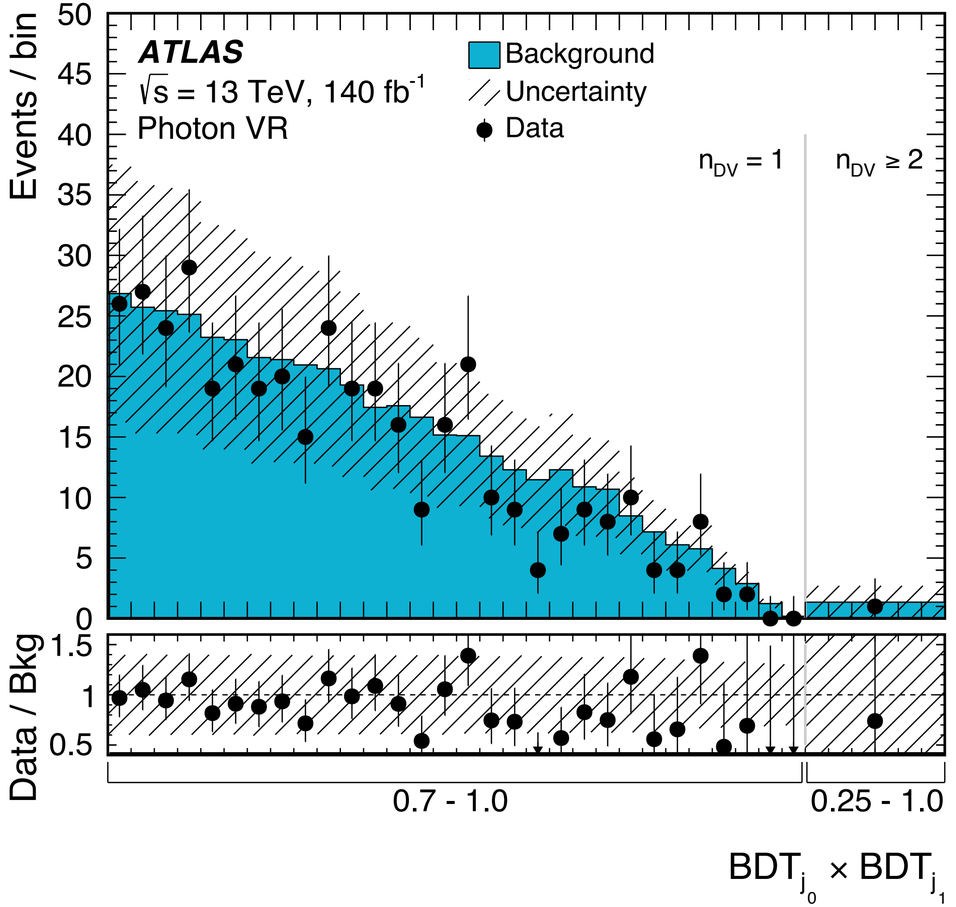




Hadronic vertices in ATLAS

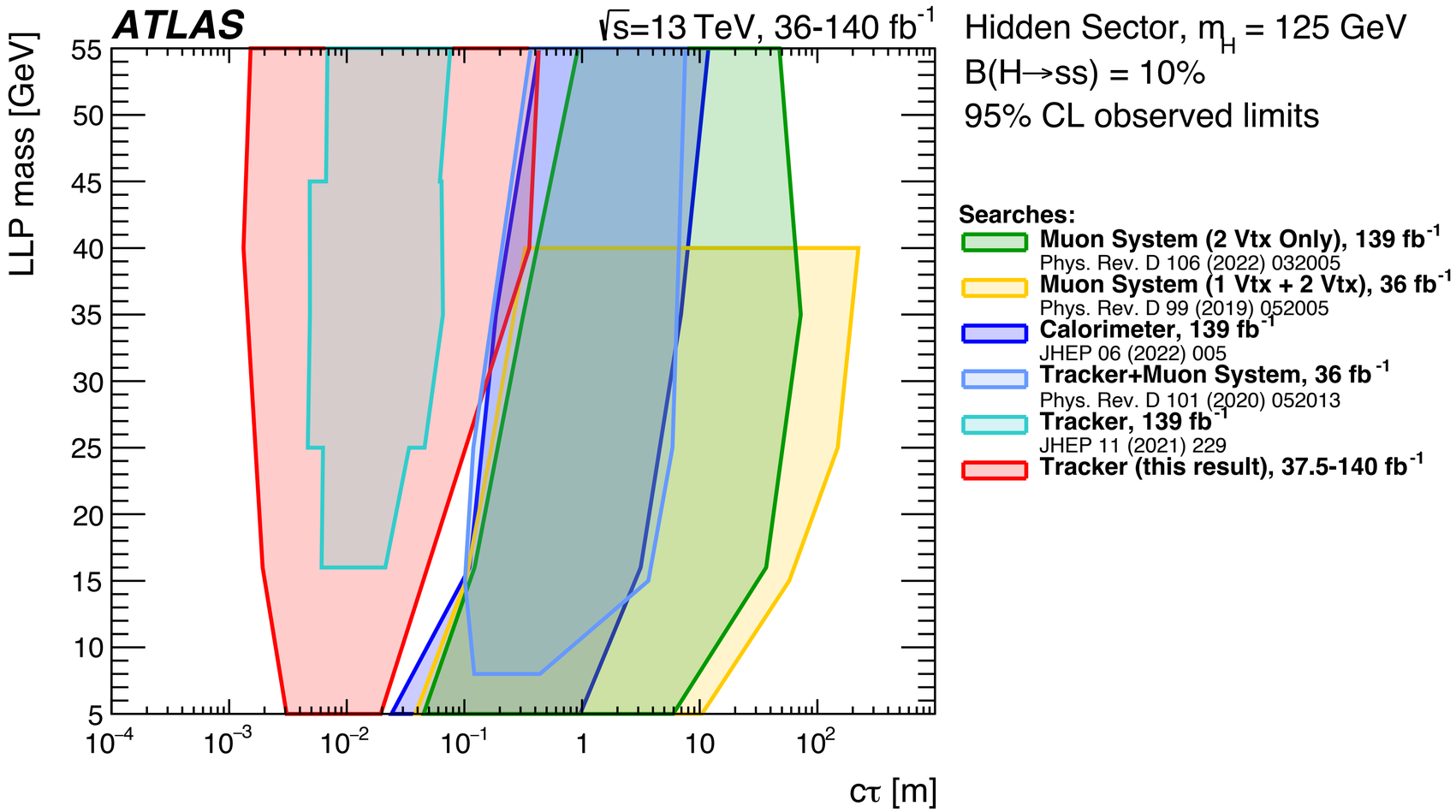
Background estimate validated in CRs with intermediate event-level discriminant values and dedicated γ+jets region





Hadronic vertices in ATLAS

Excluded regions for $\mathrm{Br}(H \to ss) = 10\,\%$



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Exclusion limits on $\mathrm{Br}(H \to ss)$