

SEARCHES FOR BSM PHYSICS USING CHALLENGING AND LONG-LIVED SIGNATURES WITH THE ATLAS DETECTOR

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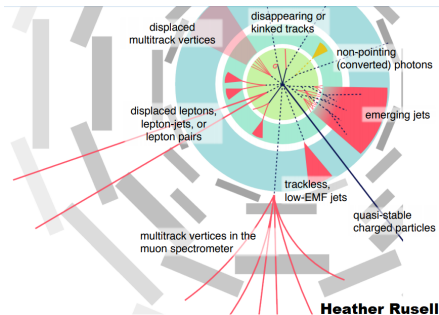
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[DIS2022: Deep-Inelastic Scattering and Related Subjects](#)

LONG-LIVED PARTICLES

- Experimental signature: LLP itself if it's stable, otherwise its decay products (jets, leptons)
- Can have an unique/unusual signature (lifetimes in the pico to nanoseconds range), e.g:

- LLP can decay to leptons: can look for displaced leptons or for displaced di-lepton vertices (with no track pointing back to the IP)
- Non-stable charged LLP: Disappearing or kinked tracks
- Meta-stable LL charged particles: travel all the detector components, like muons, but with a very different signature (interactions with the detector material)

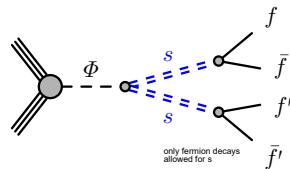


- Usually lower Standard Model background than in the traditional BSM searches
 - Dominant background: beam-induced, instrumental noise
 - Cannot rely on MC simulations, and most of the time a fully data-driven background estimation is used
- Requires a deep understanding of the detector!

SIGNATURE: DISPLACED HADRONIC JETS

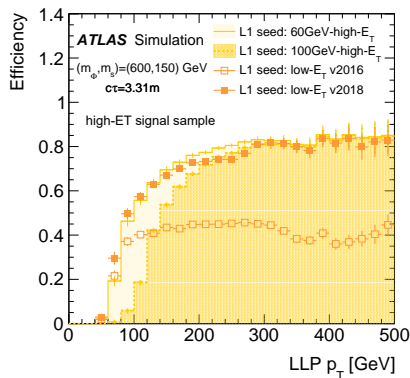
SEARCH FOR DECAYS OF PAIR-PRODUCED NEUTRAL LLPs ([arXiv:2203.01009](https://arxiv.org/abs/2203.01009))

- Simplified Hidden Sector (HS) model, where SM and HS are connected via a heavy neutral boson (Φ)
- Φ decays to two long-lived neutral scalar bosons (s)
- Φ has masses in the 60 GeV – 1 TeV interval, and s in the 5 GeV – 475 GeV range
- BR depends on s mass: largest (lightest) s mass = top (charm) final states dominant



TWO DISPLACED HADRONIC JETS IN THE FINAL STATE:

- LLP decays in the calorimeters → f and \bar{f} collimated → only one hadronic jet reconstructed
- Two analysis selections: low- E_T^{miss} (high- E_T^{miss}) models for Φ masses \leq ($>$) 200 GeV



TYPE OF BACKGROUNDS:

- **Main background:** multi-jet production

A) with jets composed mainly of neutral hadrons

B) or where some of the tracks are mis-reconstructed

- **Other backgrounds:**

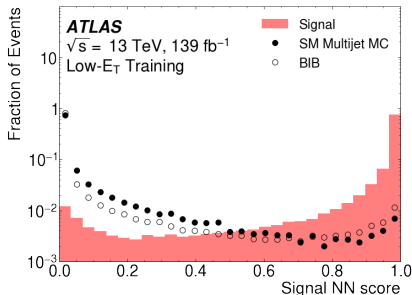
C) jets reconstructed from non-collision background consisting of cosmic rays

D) and beam-induced background (BIB)

- Key variables: $\Delta R(\text{jet}, \text{closest track associated to PV})$, number of displaced jets

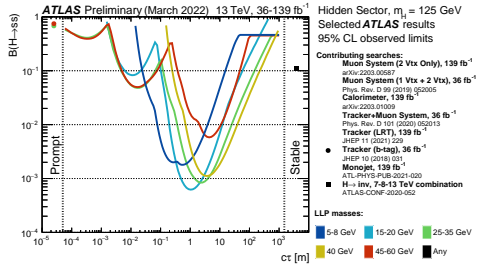
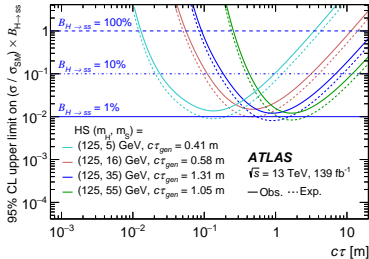
- **Neural network (NN)** trained on a per-jet basis to discriminate signal from bkg

→ Trained on SM multi-jet MC, a BIB dataset, a combination of the HS signal



STATISTICAL INTERPRETATION ([ARXIV:2203.01009](https://arxiv.org/abs/2203.01009) AND [ATL-PHYS-PUB-2022-007](https://arxiv.org/abs/2203.01009))

- No excess seen in any of the defined signal regions
- place expected and observed limits on the $\Phi \rightarrow ss$ branching ratio (vs the decay length)



LEFT SM Higgs boson mediator $\Rightarrow H \rightarrow ss$ BRs above 10% excluded between 20 mm and 10 m

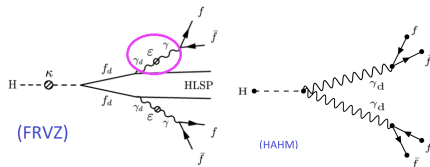
SIGNATURE: LEPTONS OR LIGHT HADRONS

SEARCH FOR (DISPLACED) LONG-LIVED DARK PHOTONS ([ATLAS-CONF-2022-0019](#))

- Model: dark photon (γ_D) from Higgs portal, decays through vector portal to (collimated) leptons or light hadrons
- γ_D and γ mix kinetically; **small mixing term ϵ ($< 10^{-5}$)** allows macroscopic distances from the IP, and γ_D masses in the (> 10) MeV - GeV range

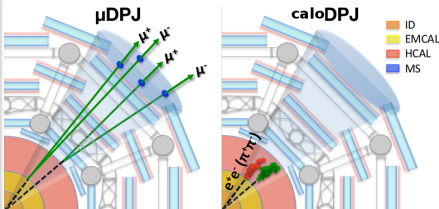
PRODUCTION MODES:

- gluon-gluon Fusion:**
- dedicated triggers for (displaced) LLP
- Higgs associated prod with W :**
- triggering on prompt lepton from W
- ≤ 3 jets, 0 b -jets to remove $t\bar{t}$



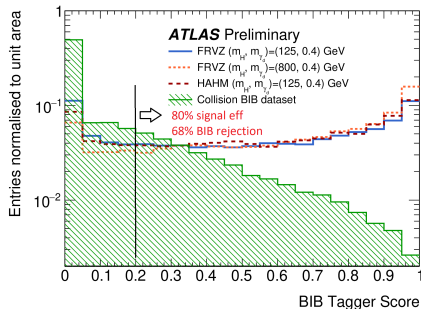
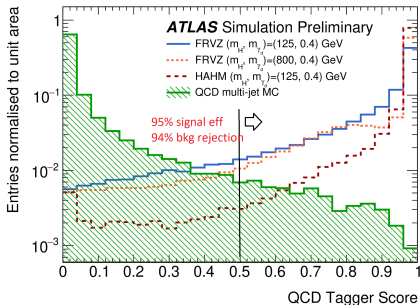
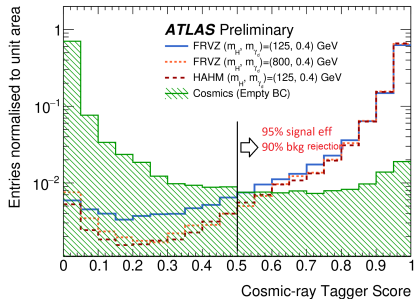
FINAL STATES: JET-LIKE STRUCTURES

- Di-muons:** no jets or tracks in ID
- A displaced electron, or di-jets:** most of energy deposit in the calorimeters

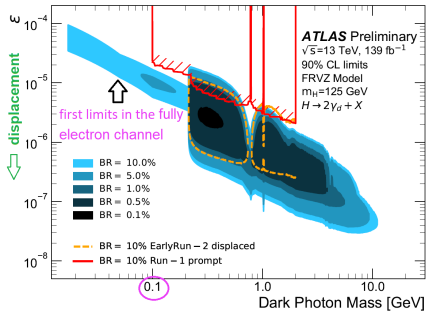
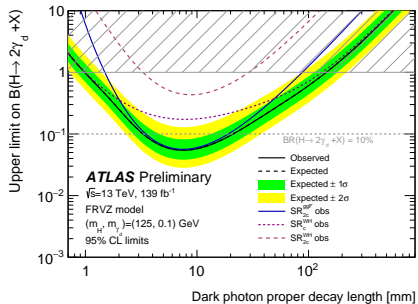


TYPE OF BACKGROUNDS (DATA ESTIMATION):

- **Di-muons** (Low- p_T $\mu \rightarrow$ hard to trigger): Cosmic-ray muons, separated from signal with a NN tagger exploiting timing, angular direction and impact param info
- **A displaced electron, or di-jets**: QCD events, BIB; NN tagger exploiting 3D images produced using angular direction and calorimeter cluster info



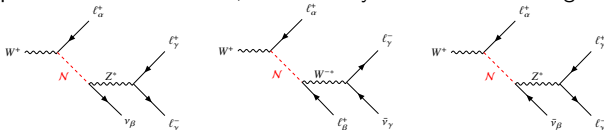
STATISTICAL INTERPRETATION



SIGNATURE: DILEPTON DISPLACED VERTEX

SEARCH FOR LL HEAVY NEUTRAL LEPTONS IN DECAYS OF W BOSONS ([EXOT-2019-29](#))

- Model: “type-I seesaw”, predicting heavy neutral leptons (HNL, N)
- Each HNL state carries a small admixture of the left-handed neutrino of flavor $\{e, \mu, \tau\}$
- can participate in weak interactions, controlled by dimensionless mixing coefficients U_α



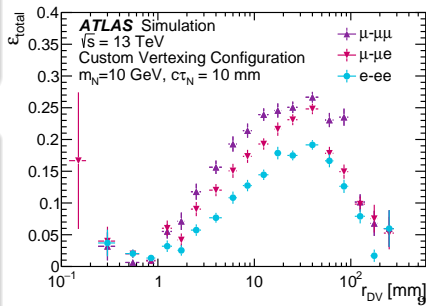
EVENT SELECTION:

- Single lepton triggers ($p_T > 20$ -26 GeV)
- Key: 1) prompt lepton reconstruction and 2) **displaced vertex reconstruction**

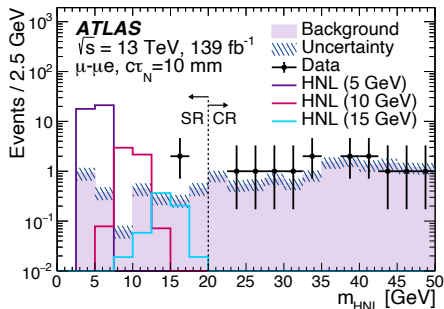
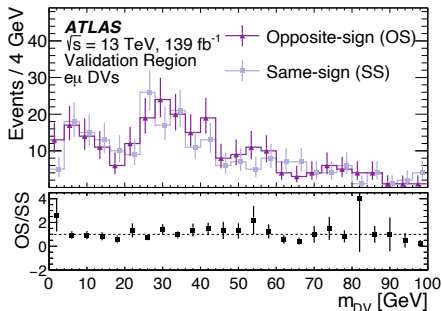
TYPE OF BACKGROUNDS:

- DVs from particle interactions with detector material;
- DVs from random crossings of ℓ tracks;
- Decays of metastable SM particles;
- $Z \rightarrow \ell\ell$; Cosmic-ray muons

total displaced vertex reconstruction efficiency versus the displaced vertex radius:



DATA VS BACKGROUND ESTIMATION AGREEMENT:



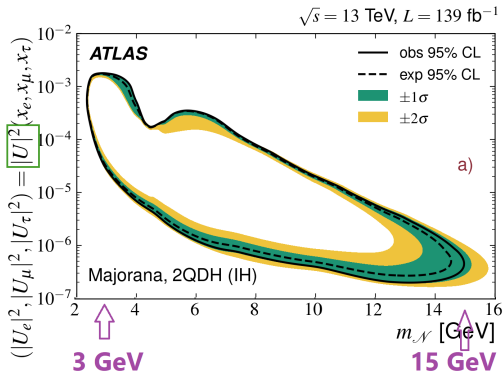
- Left: Distribution in validation regions, of opposite and same-sign displaced $e\mu$ vertex mass
- Right: Heavy neutral lepton (HNL) mass distribution in a signal region (SR) and control region (CR); **three signal points also shown**

NOTE Dominant source of background (also in SRs): random lepton crossings

YIELDS IN THE SR AND CR:

Channel	Signal region		Control region	
	Background	Observed	Background	Observed
$e-ee$	0.4 ± 0.3	2	3.6 ± 1.8	2
$\mu-ee$	0.2 ± 0.1	1	1.8 ± 1.3	1
$e-e\mu$	0.9 ± 0.4	0	4.1 ± 1.9	5
$\mu-\mu e$	2.8 ± 0.8	2	12.2 ± 3.2	13
$e-\mu\mu$	1.2 ± 0.9	1	2.8 ± 1.6	3
$\mu-\mu\mu$	2.2 ± 1.4	2	8.7 ± 2.9	9
$e^\pm-e^\mp\mu^\pm$	0.6 ± 0.3	0	2.4 ± 1.4	3
$\mu^\pm-\mu^\mp e^\pm$	1.9 ± 0.6	0	8.1 ± 2.6	10

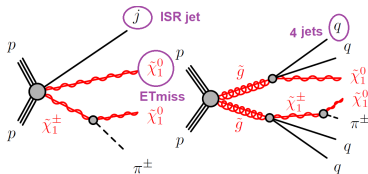
LIMITS: HEAVY LEPTON \mathcal{N} MASS VS. SQUARE OF THE DIMENSIONLESS MIXING COEFFICIENT



SIGNATURE: DISAPPEARING-TRACK

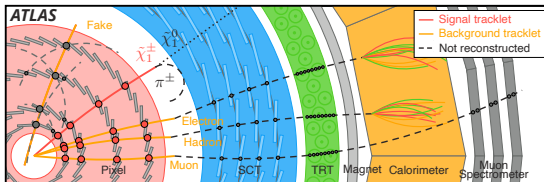
Search for LL charginos (SUSY-2018-19)

- Aims for SUSY models with a LL chargino ($\tilde{\chi}^{\pm}$) and neutralino ($\tilde{\chi}^0$) nearly mass-degenerate
- Sensitive to $\tilde{\chi}^{\pm}$ lifetimes from 0.1 ns to 10 ns (max sensitivity for lifetimes ~ 1 ns)
 - $\tilde{\chi}^{\pm}$ lifetime is nearly uniquely determined only by the $\tilde{\chi}^{\pm}$ mass



EXPERIMENTAL SIGNATURE:

- Emitted pion has very low momentum and it's not reconstructed in the detector
- $\tilde{\chi}^0$ passing through the detector without interacting
- ⇒ Track from the LL $\tilde{\chi}^\pm$ can therefore *disappear*
 - Leave hits only in the innermost layers (no hits in the detector at higher radii)
 - Must be isolated from calorimeter energy deposits

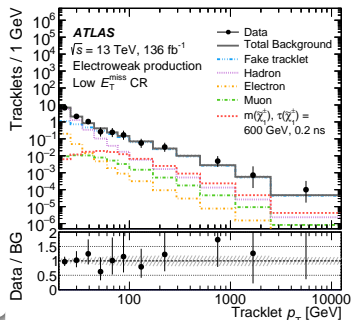


- Compared to other searches, it uses tracklets

→ tracklet = very short track, $p_T > 5$ GeV, should have hits in all 4 Pixel layers and no holes
 ≥ 1 isolated tracklet that originate from the hard-scatter interaction, with no SCT hits, and with $p_T > 20$ GeV, within $0.1 < |\eta| < 1.9$

EVENT SELECTION

- In electroweak-gaugino production:** one ($p_T > 100$ GeV) ISR jet required in the event
 → Leads to high E_T^{miss} (> 200 GeV)
- $\tilde{g}\tilde{g}$ production:** expect at least four jets in the event
 → Require ≥ 1 high p_T jet (> 100 GeV) and ≥ 2 additional softer jets ($p_T > 20$ GeV)
 → $E_T^{\text{miss}} > 250$ GeV

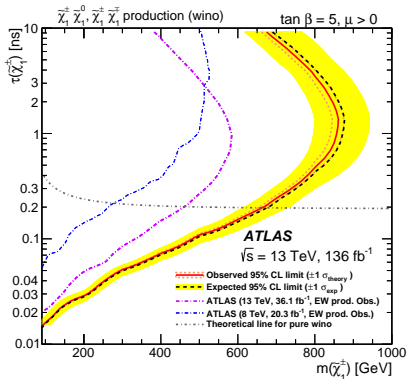
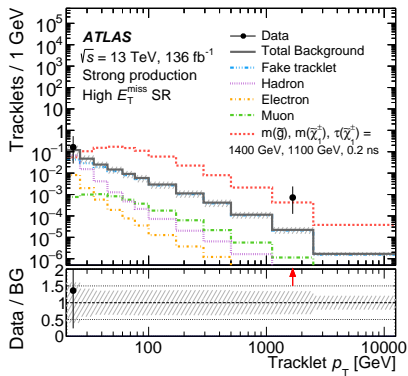


COMMON SELECTION

- Lepton veto applied suppress bkg events from W/Z + jets and top-pair production
- Cuts on $\Delta\varphi$ between the missing transverse momentum and each of the four highest- p_T jets ($p_T > 50$ GeV)

After selection: look for an excess of candidate events in the p_T distribution of pixel tracklets

→ (Left-plot) No excess observed in the SRs: (Right-plot) place exclusion limits at 95% CL



• Electroweak production: LL $\tilde{\chi}^\pm$ (0.2 ns life-time) are excluded up to 660 GeV

→ Pure wino LSP model; mass-splitting between the charged and neutral wino of 160 MeV

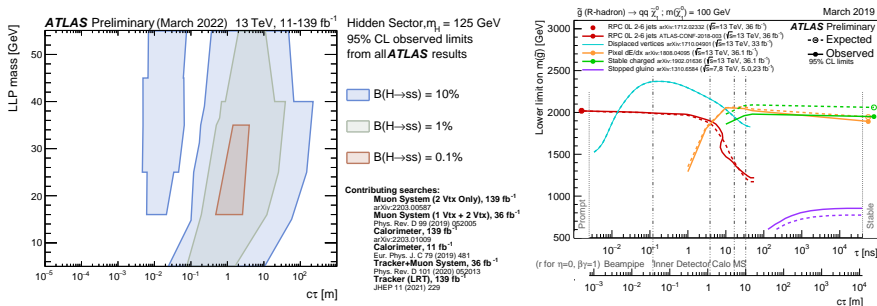
→ Results can be interpreted also using other SUSY-EW simplified models, e.g. pure-higgsino

CONCLUSIONS & MORE SUMMARY PLOTS

Many recent ATLAS results not shown in this presentation

- Please, look at the ATLAS ([link](#)) public page for all the results
- All EXOTICS (SUSY) group results [here](#) ([here](#))

ADDITIONAL HIDDEN SECTOR (LEFT) AND SUSY (RIGHT) SUMMARY PLOTS:



- **Left:** the scalar mediator H is the SM Higgs boson, which may decay to a pair of long-lived (s) neutral scalars
- **Right:** Several (2019) results from different teams/final states! showing the complementary of the ATLAS searches

BACKUP

LONG-LIVED PARTICLES

LONG-LIVED PARTICLES (LLPs), SIMPLEST DEFINITION:

- Neutral or charged, decaying a macroscopic distance from the interaction point (IP)
 - or which are quasi-stable on the detector scale
- **Long lifetimes because of:** approximate symmetries, small couplings, availability of suppressed phase space for decays, ...

PRESENT IN THE STANDARD MODEL (SM), AND PREDICTED BY MANY BEYOND SM MODELS:

Hidden/Dark sector:

- Long-lived dark photon: e.g Higgs portal model
- Long-lived neutral scalar: e.g Heavy neutral boson portal model

Supersymmetry (SUSY):

- Long-lived gluinos (\tilde{g}) due to very heavy squarks, or \tilde{g} -Bino co-annihilation
- Long-lived charginos ($\tilde{\chi}$): Wino/Higgsino Lightest Stable Particle (LSP)
- Long-lived neutralino/LSP ($\tilde{\chi}^0$): Gravitino LSP, R-parity violation, Wino-Bino co-annihilation

Others BSM models:

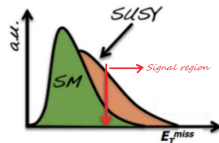
- Heavy neutral leptons (HNLs)
- Long-lived right-handed neutrino: Left-right symmetry extension of SM
- Long-lived multi-charged particle: Monopole, Q-ball

STRATEGY TO LOOK FOR BSM PHYSICS

All searches for BSM physics have some common points:

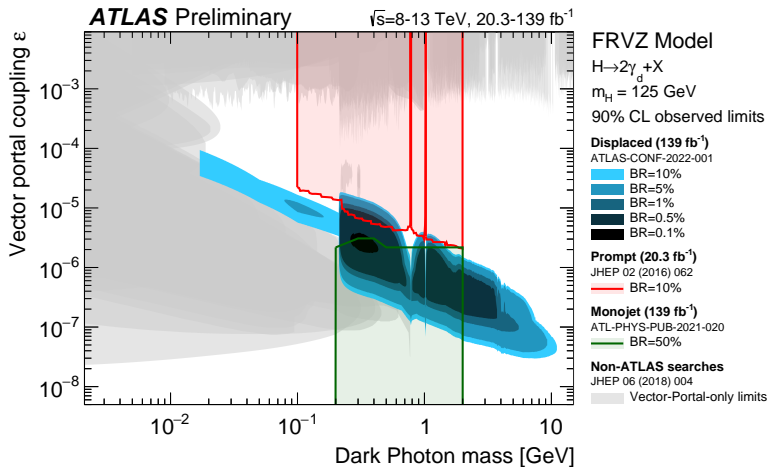
- Signal regions (SRs): regions targeting specific BSM signal models

- Defined to have the best discovery potential in the selected models
- For one model, several SRs can be defined, to cover each region of the phase-space
- In Run2: exploiting more new variables and using machine learning techniques



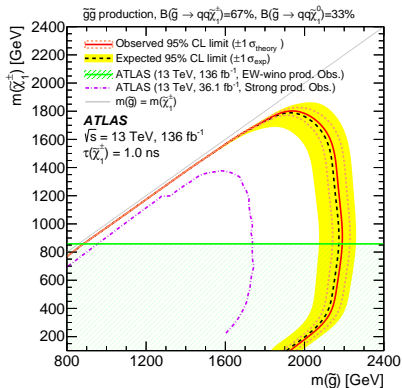
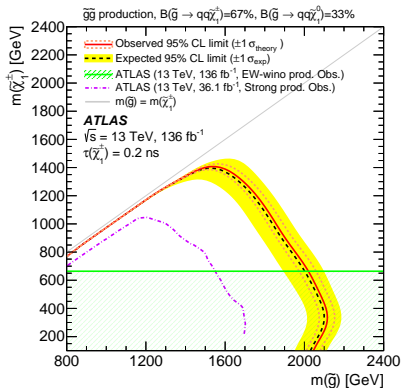
- Background (bkg): identify → understand → estimate as precise as possible → validate
 - Standard Model (SM) bkg, or Detector bkg
 - Estimated from Monte Carlo (MC) simulations, or using data control regions (CRs), or with data-based techniques, as appropriate
 - In Run 2: an increased use of data-based bkg estimates to avoid dependence on MC
- Statistical interpretation: test the compatibility between data and bkg estimation in SRs
- In case of no excess:
 - E.g: Set model dependent / independent exclusion limits

The results are interpreted using simplified models, where particles not involved in production or decays are decoupled, i.e too heavy to be produced or affect the decays of the BSM particles of interest



- Results from 3 ATLAS analyses
- different assumptions on the $H \rightarrow 2\gamma_D + X$ branching ratio, ranging between 0.1% and 50%
- Grey shaded regions → vector portal, for both production and decay of the dark photon

Search for LL charginos (disappearing track) ([SUSY-2018-19](#))



- Gluino pair production: gluinos below 2 TeV excluded for a chargino mass of 300 GeV
- Results for a chargino lifetime of (left) 0.2 ns and (right) 0.1 ns