Searches for BSM Physics at ATLAS

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On behalf of the ATLAS Collaboration

ASPEN 2023

Aspen, 29 March 2023

UNIVERSITY of WASHINGTON

THE ATLAS EXPERIMENT

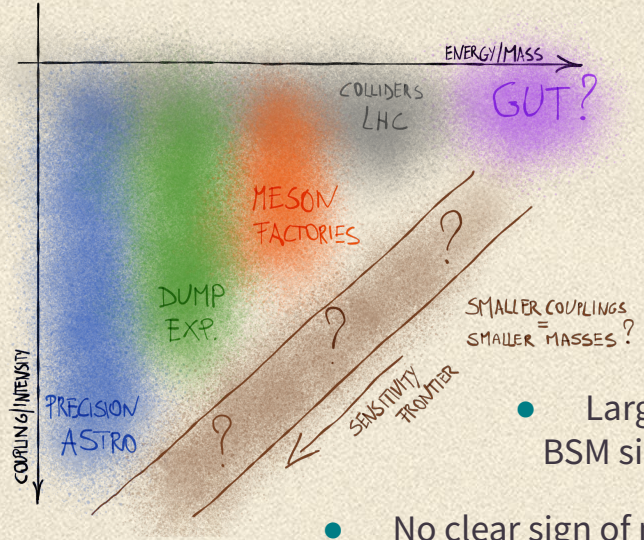
est. 2022

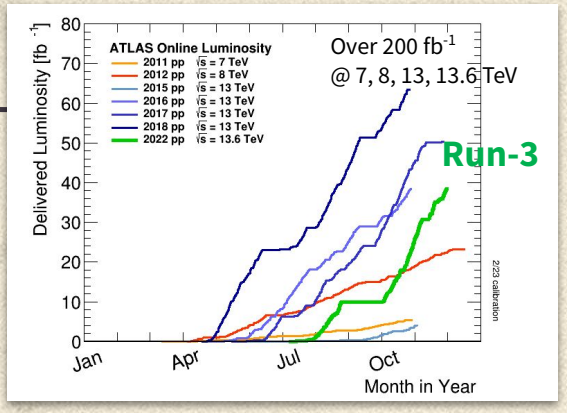
13.6 TeV

LHC RUN 3

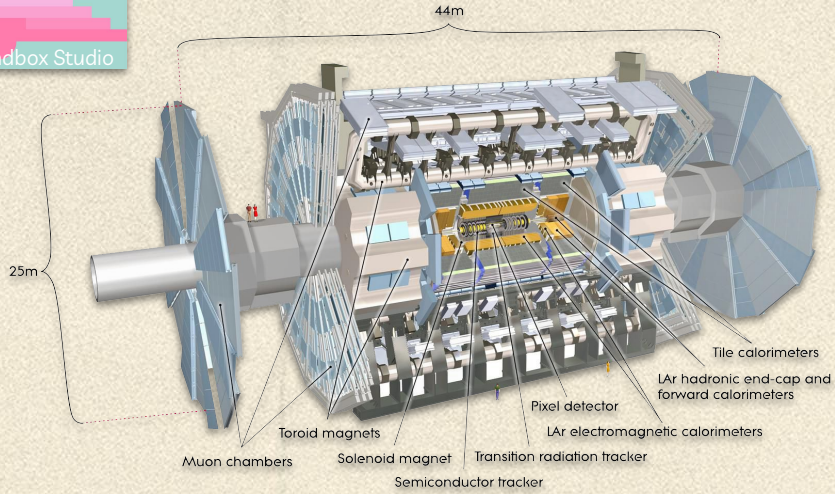
BSM? Where? How? When?

Many theories predicting heavy new states with sizeable coupling





- Large number of searches for BSM signatures done at the LHC
- No clear sign of new physics, but still a lot of unexplored models and parameter space
- **Many portals**: vector (dark photons), scalar (dark Higgs), fermion (sterile neutrino), pseudo-scalar (axions)



NB1: full set of ATLAS public results can be found in AtlasPublic
NB2: some of the latest BSM searches using ML are in Daniel's talk

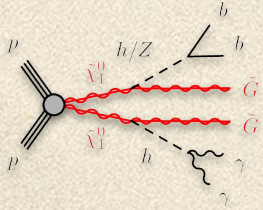
Paired Produced Higgsinos

NEW

ATLAS-CONF-2023-009

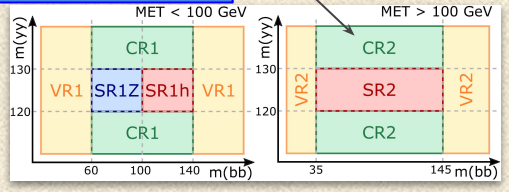
Search for Higgsinos decaying into Higgs or Z bosons

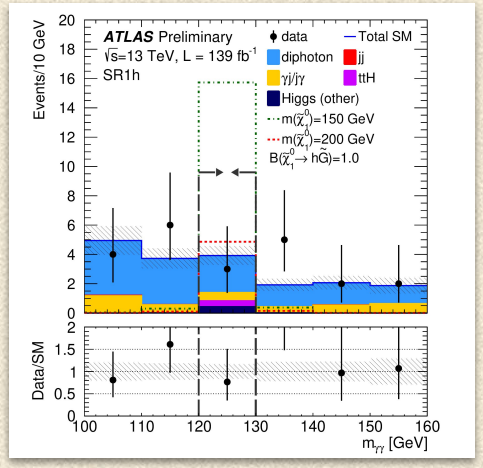
- Final states with 2γ and $2b + E_T^{miss}$ (from Gravitino)
- Three orthogonal SR to gain sensitivity to different Higgsino mass hypothesis and decay modes
- Resonant background from $H \to \gamma\gamma$ (subdominant) determined from MC
- Non-resonant background (dominant) estimated using data in the sidebands of $m_{\gamma\gamma}$ distributions

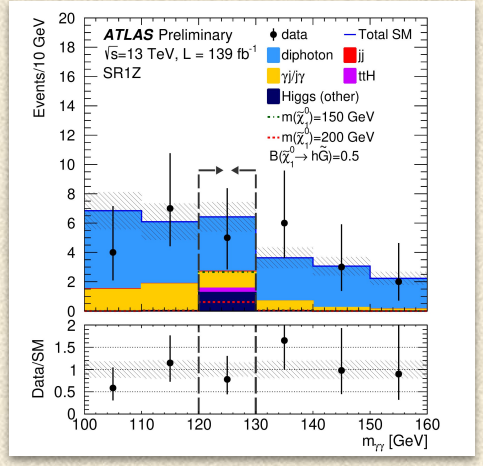


Higher-mass Higgsino decays

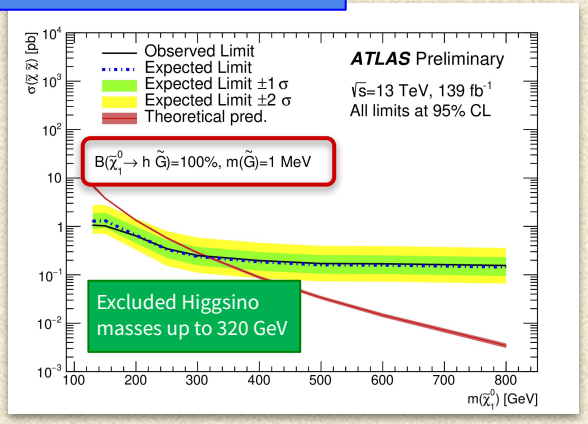
2x2D sidebar method







Statistical combination of 3 SRs



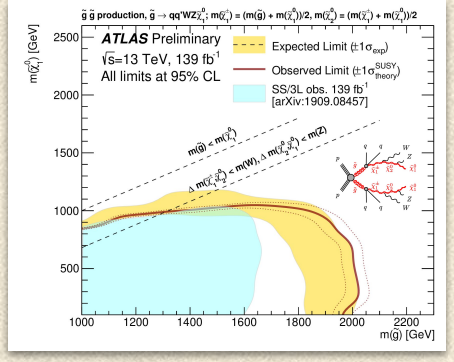
Squarks/gluinos Decaying Via Sleptons/W

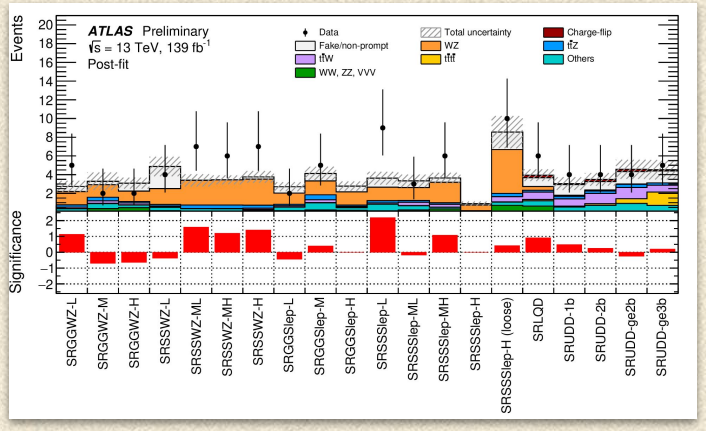
ATLAS-CONF-2023-017

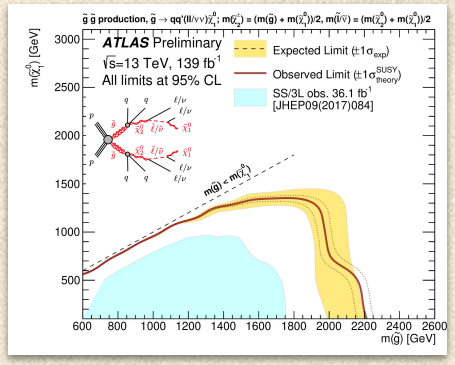
NEW

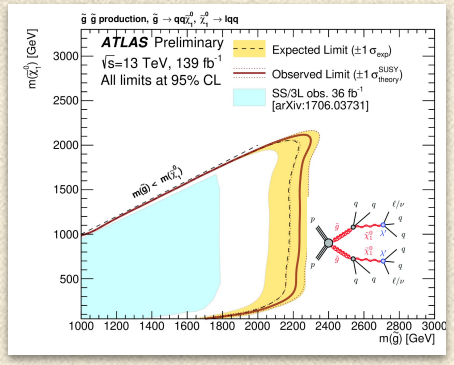
Search for squarks or gluinos in final states with leptons

- Final state with exactly 2 same-sign leptons or at least 3 leptons (no charge requirement)
- Multiple (not exclusive) SRs to maximise the sensitivity to the various signal models
  - Built on the # of leptons and their charges, and # of jets
  - Most relevant observable: $m_{\mathrm{eff}} = \sum p_{\mathrm{T}}^{\mathrm{jet}} + \sum p_{\mathrm{T}}^{\ell} + E_{\mathrm{T}}^{\mathrm{miss}}$
- Dominant same-sign lepton final states background from:
  - SM processed → estimated with MC + data control region
  - Fake/non prompt leptons or incorrect charge reco → data-driven methods







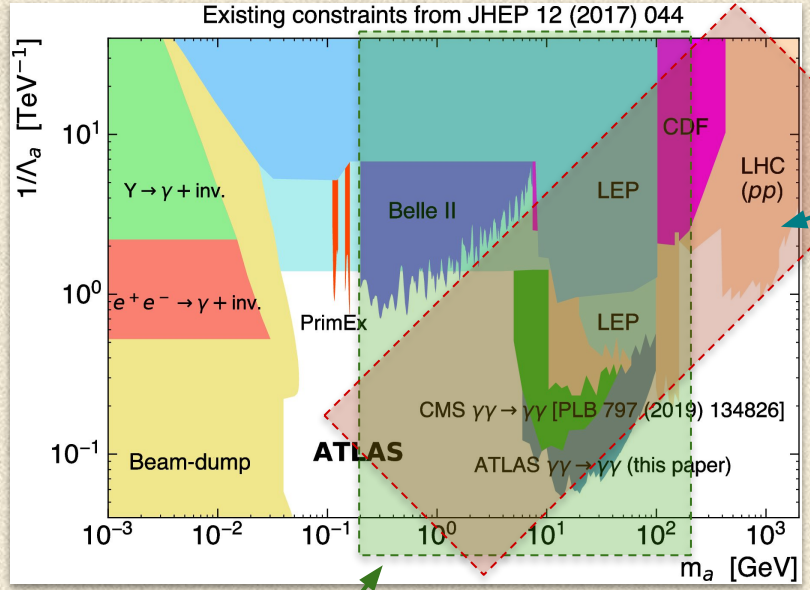


ALPs (Axion Like Particles)

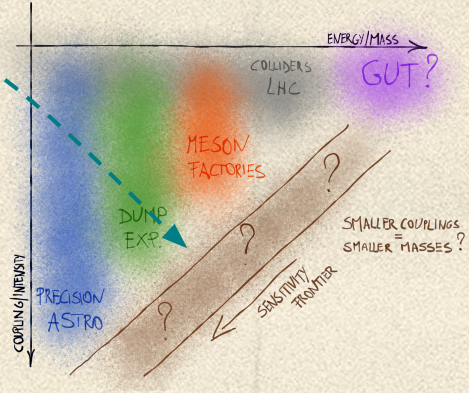
Very light (pseudo) scalar particles

- They appear in any theory with spontaneously broken global symmetry
- ALPs interactions grow with momentum

Credits: Sandbox Studio



Interesting region for $(g\text{-}2)_\mu$ anomalies



- Couplings inversely proportional to NP scale Λ_a
- Non-thermal candidates for DM, explain unclear astrophysical phenomena (e.g. TeV transparency, stellar cooling excess)

ALPs Searches with AFP

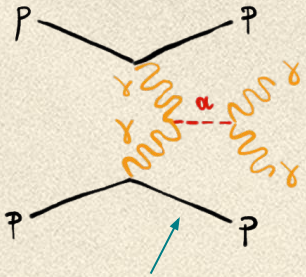
NEW

ATLAS-CONF-2023-002

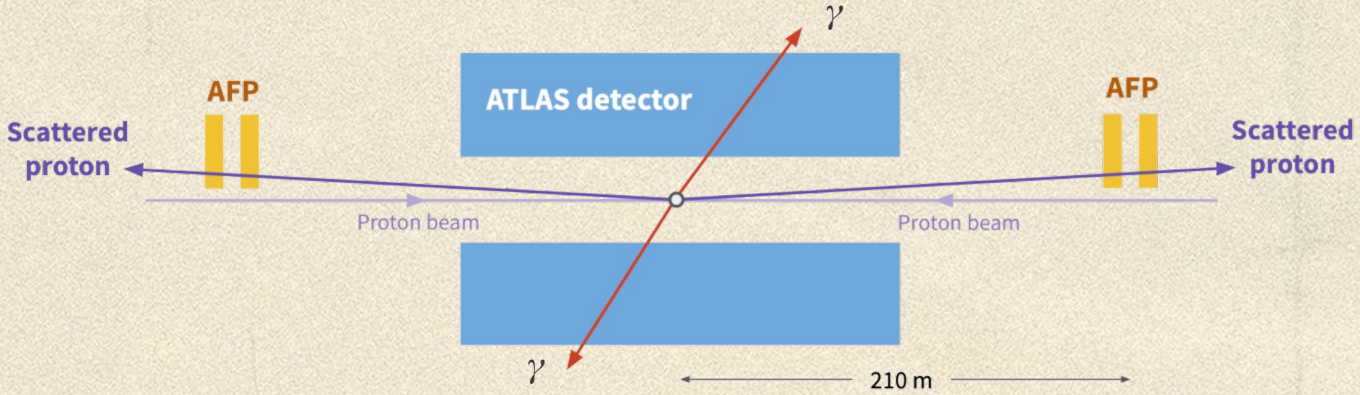
Search for forward proton scattering with light-by-light scattering

- For di-photon masses >~ 20 GeV effective $\gamma\gamma$ **luminosity in *pp* collisions higher than Pb-Pb**
- Resonance search in $m_{\gamma\gamma}$ distributions: **pair of photons in ATLAS + at least 1 proton tagged in ATLAS Forward Proton (AFP)**
- Proton-proton collision data recorded in 2017 @ 13 TeV (14.6 fb^{-1})

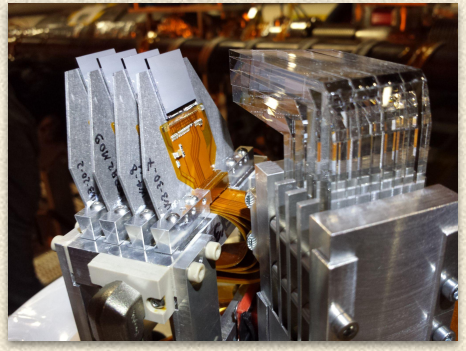
$\gamma\gamma$ cross section can be enhanced by BSM



1 or both protons can dissociate radiating a virtual photon



- AFP → Roman Pots system (ATLAS-TDR-024, ATL-PHYS-PUB-2017-012)
  - 4 tracking units located at $z = \pm 205$ m and ± 217 m
  - Each station has a silicon tracker made of four planes of edgeless silicon pixel sensors (6 μm resolution)



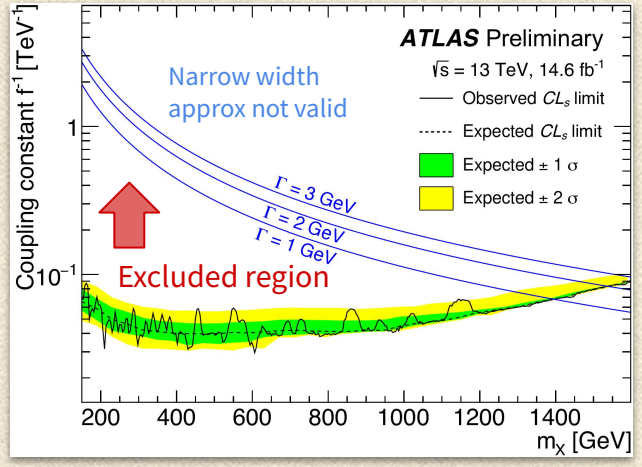
ALPs Searches with AFP

NEW

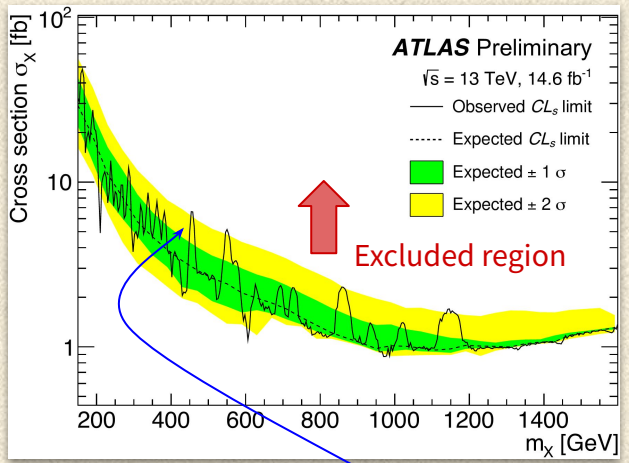
ATLAS-CONF-2023-002

Search for forward proton scattering with light-by-light scattering

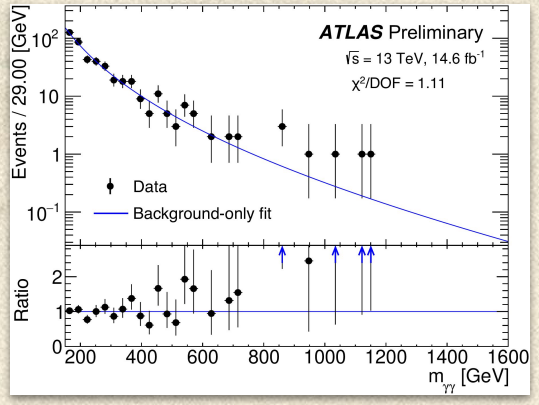
- Selection based on proton energy loss fraction: $\xi = 1 - E_{scattered}/E_{beam}$
  - Interesting events expected to have $\xi^{\pm}_{\gamma\gamma,ATLAS} \sim \xi^{\pm}_{AFP}$
- Combinatorial background from pair of photons (including fakes) + protons produced in another collision
  - Fully data-driven combinatorial background sample



Assuming 100% ALP → yy



Most significant excess at m_X = 454 GeV, 2.51 σ local significance. Global p-value for null hypothesis > 0.5

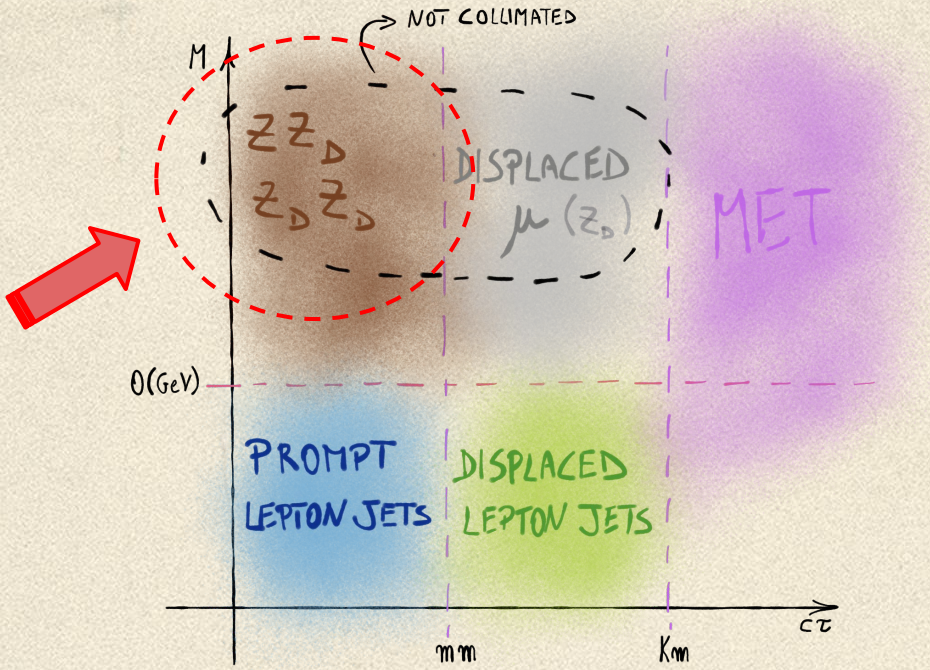


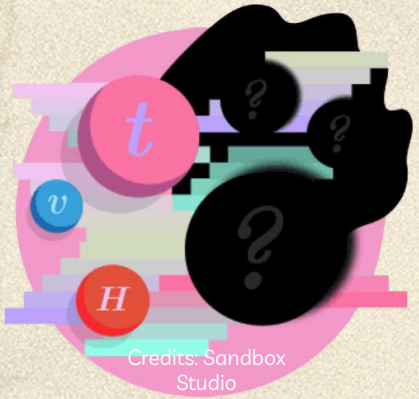
- 441 observed events
- Statistical uncertainty is dominant
- Systematics from AFP alignment
- >1 AFP proton matching increase the mass acceptance

Dark Photons

Many extensions of the SM introduce a dark/hidden sector (DS)

- DS containing a dark abelian gauge group $U(1)_D$ gives rise to "vector portal"
  → **kinetic mixing between dark photon (DP) and SM hypercharge gauge boson** ($\epsilon \sim 10^{-8}$-10^{-4})
  → If $U(1)_D$ is broken → massive DP



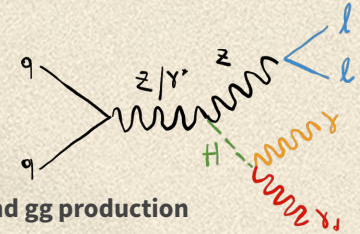


- Higgs portal: could observe deviations in some SM Higgs decay channels
- Can explain DM, some astrophysical observations (positron excess in cosmic rays), muon anomalies, …

Dark Photons via ZH

NEW

HDBS-2019-13



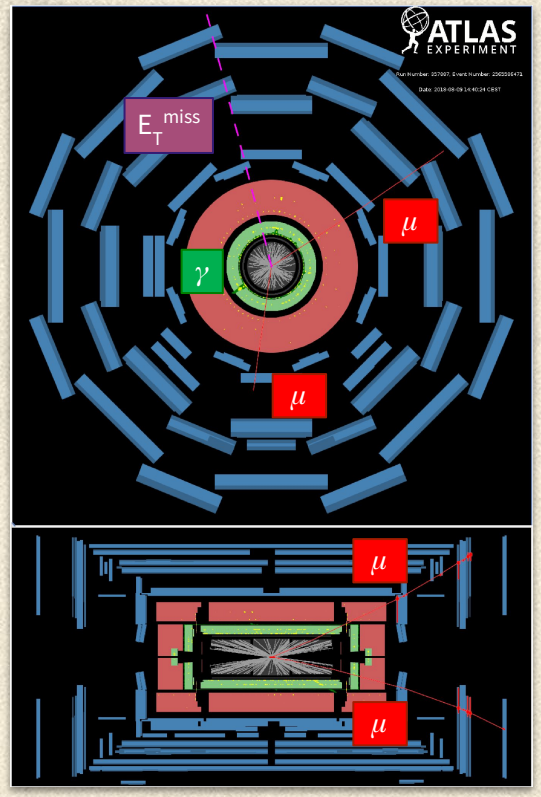
qq and gg production

Search for dark photons produced through ZH using 139 fb^{-1} of data

- Branching ratio of $H \to \gamma\gamma_d$ with values up to a few % are possible for a massless dark photon / heavy DS scenarios
- Look for
  - resonant γ+MET events (selection optimised for signal acceptance)
  - 2 same-flavour, opposite-charge electrons or muons (trigger and Z mass constraint)
- Relatively clean signal
- Signal sensitivity improved using a **BDT implemented using the XGBoost** classifier using 6 variables: E_T^{miss} significance, $m_{\ell\ell}$, p_T^{γ}, $m_{\ell\ell\gamma}$, and

$$m_T = \sqrt{2E_T^{miss} p_T^{\gamma}[1 - \cos[\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{\gamma})]]} \qquad p_T^{ratio} = \frac{|\vec{E}_T^{miss} + \vec{p}_T^{\gamma}| - p_T^{\ell\ell}}{p_T^{\ell\ell}}$$

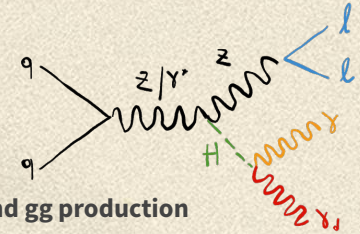
- **5-fold cross validation strategy**:
  - Samples divided into 5 subsets → **5 BDTs trained**
    - Each BDT training: 4 subsets used for training and 1 for testing
      → 5 BDT trainings = permutations of training-testing setups → used to compute BDT score of data divided into 5 subsets in the same way



Dark Photons via ZH

NEW

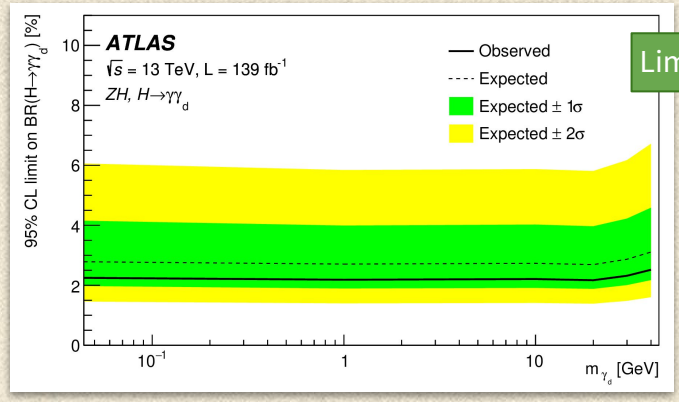
HDBS-2019-13



qq and gg production

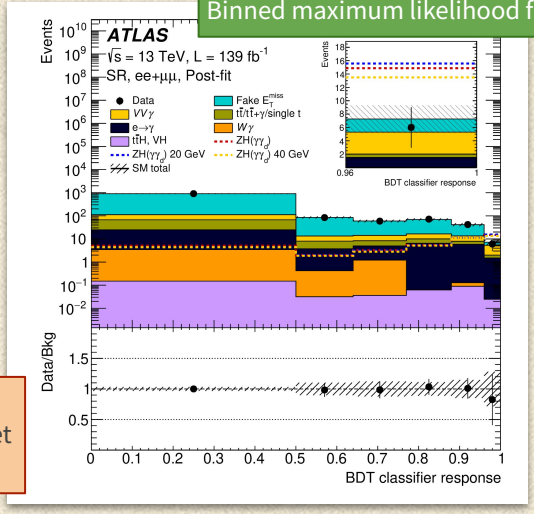
Search for dark photons produced through ZH using 139 fb^{-1} of data

- Backgrounds:
  - **Irreducible from VVγ** final states to decay leptonically
  - **Reducible**: fake E_T^{miss} (dominant), particle mis-identification (e $\rightsquigarrow \gamma$), jets not contained in the detector acceptance, t → W(→ $\ell\nu$)b
    - e $\rightsquigarrow \gamma$ estimated using a "probe-e" CR (SR selection + extra *e* required): **21.0 ± 2.4 (*ee*)** and **20.4 ± 2.1 ($\mu\mu$)**
    - Fake E_T^{miss} estimated using ABCD (CRs enriched with fake E_T^{miss}); residual E_T^{miss} (from e $\rightsquigarrow \gamma$) and background (VVγ, …) subtracted: **413 ± 50 (*ee*)** and **581 ± 64 ($\mu\mu$)** events
    - Others bkg estimated using MC simulation constrained by data in VR



Limits on BR(H → $\gamma\gamma_d$)

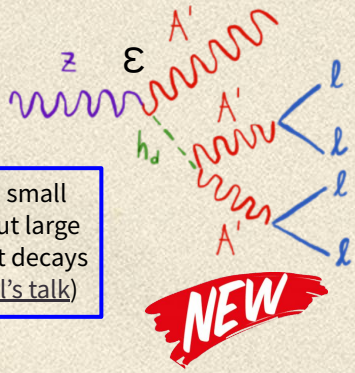
Binned maximum likelihood fit



Largest syst. in the last bin related to shape of fake E_T^{miss} (18%) and jet energy scale and resolution (13%)

Dark Photons via Rare Z Decays

ATLAS-CONF-2023-016

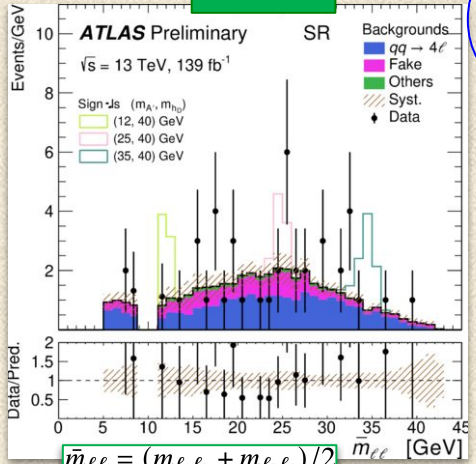


(First!) search for a dark photon and dark Higgs produced via dark Higgs-strahlung in rare Z boson decays

Considering $m_{hd} > m_{A'}$: small kinematic mixing (ε) but large enough to have prompt decays (LLP example in Daniel's talk)

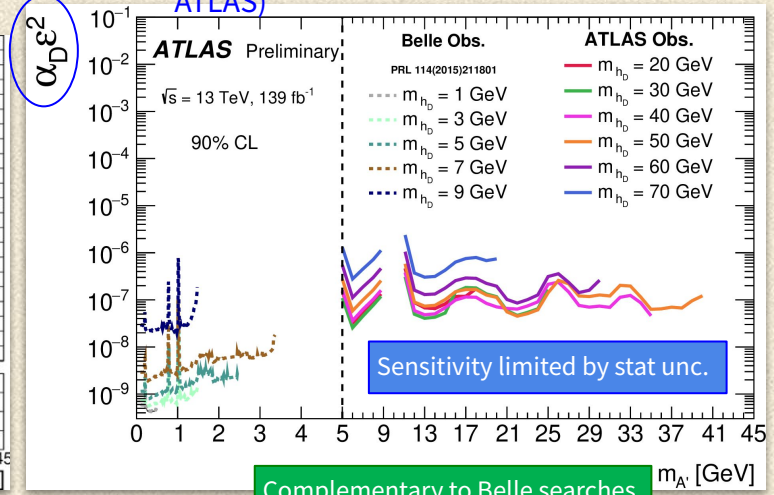
- Final state: 4ℓ (e/μ from on shell DP, same-flavour opposite-charge) + X
- Dominant background from qq → 4ℓ (modelled using MC and normalised to data)
- Subleading bkg from Z+jets, top-quark and WZjj with fake leptons, minor contributions (<5%) from ZZ → 4ℓ, tri-boson, tt + X (J/ψ, Υ(bb), b jet vetoes)
- Signal selection:
  - **$m_{4\ell} < m_Z$ - 5 GeV** (suppress qq → 4ℓ)
  - Quadruplet with smaller lepton-pair mass difference
  - **$m_{\ell\ell(\text{lower})} / m_{\ell\ell(\text{higher})} > 0.85$** (ensure originate from A' decay)
  - Same (opposite) flavored leptons required to have **ΔR > 0.1 (0.2)**
  - **$m_{\ell+\ell} > 5$ GeV**
  - Veto to suppress quarkonia bkg

ML fit in SR



$\bar{m}_{\ell\ell} = (m_{\ell_1\ell_2} + m_{\ell_3\ell_4})/2$

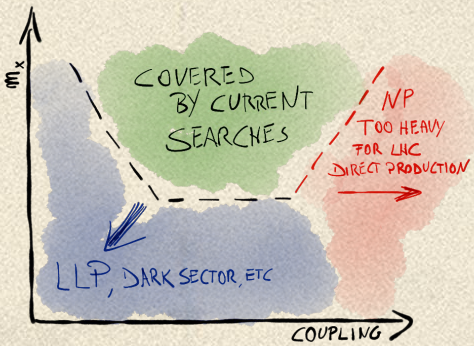
$\propto$ decay rate (1st limit on α_d and ε in ATLAS)

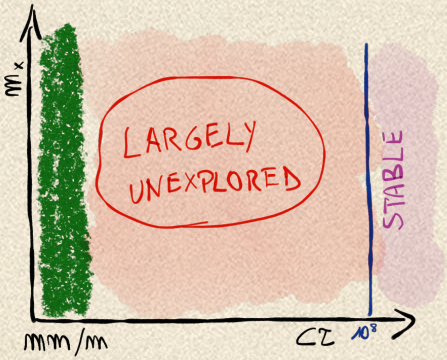


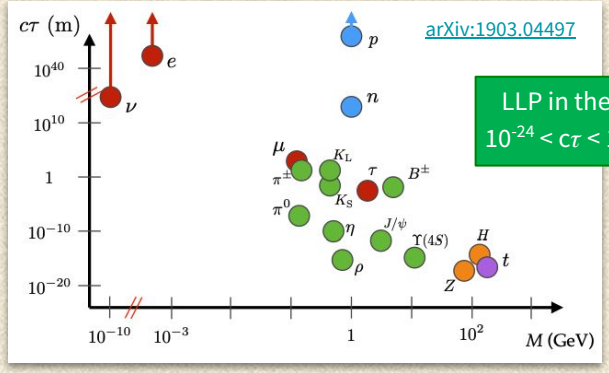
Sensitivity limited by stat unc.

Complementary to Belle searches

Long-Lived Particles

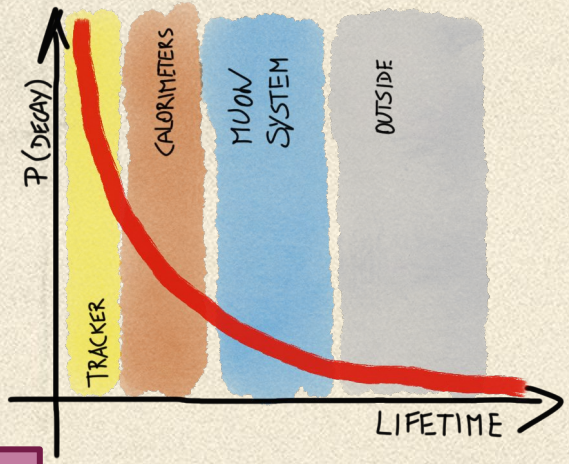






Nature is plenty of particles with macroscopic detectable decay lengths

- Not surprising that long-lived particles (LLP) might exist also beyond the SM
- New particles might more likely labelled as background
- The particle lifetime is a free parameter in the model (sampled from an exponential)
- Detector signatures strongly depend on boost/mass of the LLP

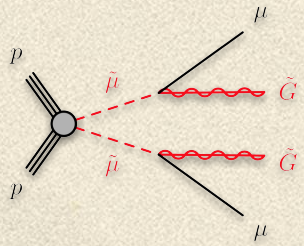


Need to adapt the search strategy!

ML heavily used in LLP searches (also with innovative approaches) - see Daniel's talk

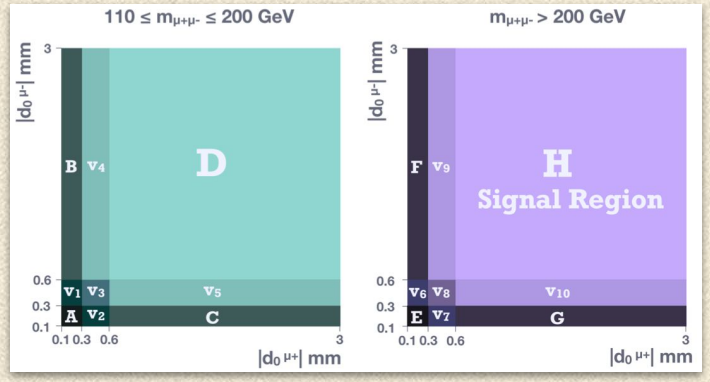
ATLAS Micro-Displaced Muons NEW

ATLAS-CONF-2023-018



Search for pairs of $\mu^+\mu^-$ with impact parameters in the *mm* range

- Target a gap in coverage *smuon* lifetime 1-10 ps between prompt and displaced slepton searches
- Selected muons with **$0.1 \leq |d_0| \leq 3$ mm** (no selection on z_0), **$m_{\mu\mu} \geq 110$ GeV** (reduce contribution of muons from Z)
- Dominant background from semileptonic B-hadron decays bb → $\mu^+\mu^-$ (Z/W+jets, top decays are negligible)
  - d_0 and $m_{\mu\mu}$ used to define 8 regions (A-H)



$$N_H^{\text{est. bkg.}} = N_A^{\text{data}} \cdot r^{d_0^+} \cdot r^{d_0^-} \cdot r^{m_{\mu^+\mu^-}}$$

where:

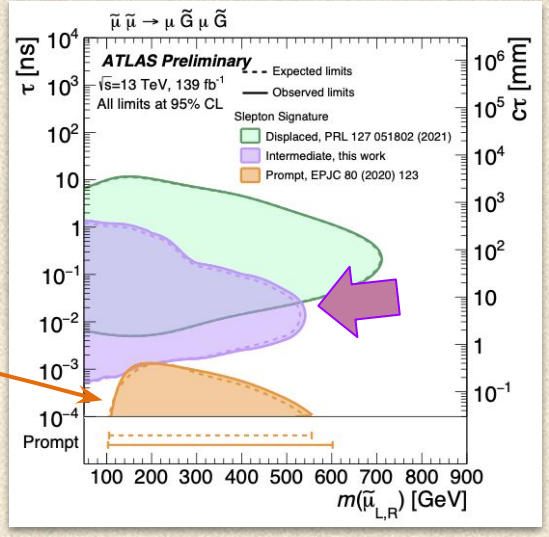
$$r^{d_0^+} = N_C^{\text{data}} / N_A^{\text{data}},$$

$$r^{d_0^-} = N_B^{\text{data}} / N_A^{\text{data}},$$

$$r^{\mu+\mu-} = N_E^{\text{data}} / N_A^{\text{data}}$$

Set of Regions	$\lvert d_0\rvert^{\text{low}}$ [mm]	$\lvert d_0\rvert^{\text{low}}$ [mm]	$\lvert d_0\rvert^{\text{high}}$ [mm]	$\lvert d_0\rvert^{\text{high}}$ [mm]	$m_{\mu^+\mu^-}$ [GeV]	Additional cut
1	≥ 0.1	< 0.3	≥ 0.6	< 3	200	-
2	≥ 0.1	< 0.3	≥ 0.6	< 3	140	-
3	≥ 0.1	< 0.3	≥ 0.6	< 1.3	125	$\Delta R_{\mu^+\mu^-}$ > 3 rad.

Strongest sensitivity to GMSB



RECAST of slepton production with prompt lepton search

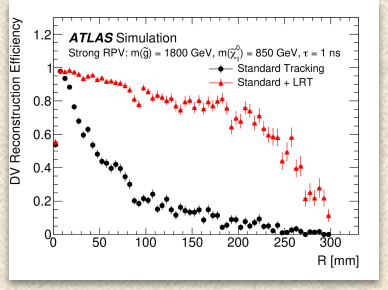
First (explicit) reinterpretation of a prompt lepton search in the LL regime!

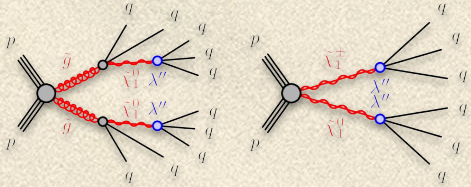
ATLAS Displaced Jets in the Tracker

SUSY-2018-13

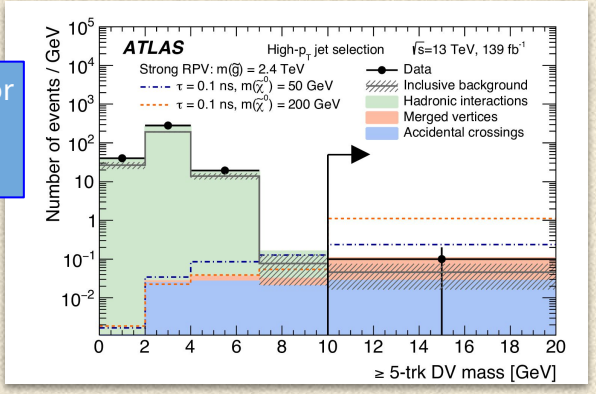
Search for LLP decaying into hadrons in events with multiple jets and a displaced vertex

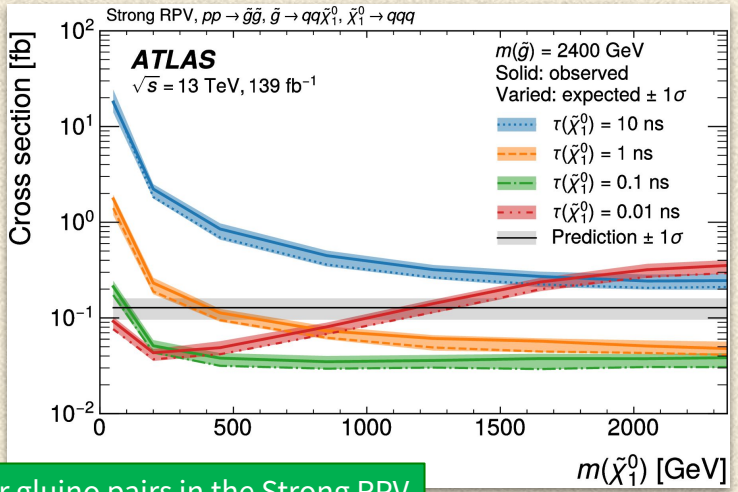
- 2-7 high-pT jets + ≥ 1 DV with ≥ 5 tracks and mass > 10 GeV
  - Additional dedicated SR for lower pT jets
- Dedicated LLP reconstruction techniques (ATL-PHYS-PUB-2017-014)
- Background from **hadronic interactions**, **accidental crossings**, and **merged vertices** estimated using an inclusive data-driven technique predicting the displaced vertices rates for all sources and validated in several VRs





Invariant mass for preselected DVs with ≥ 5 tracks

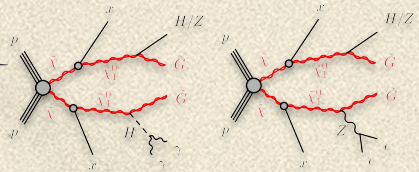




Limits for gluino pairs in the Strong RPV

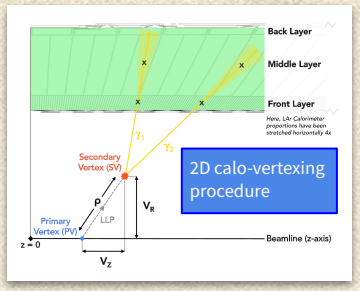
ATLAS Displaced/Delayed Photons

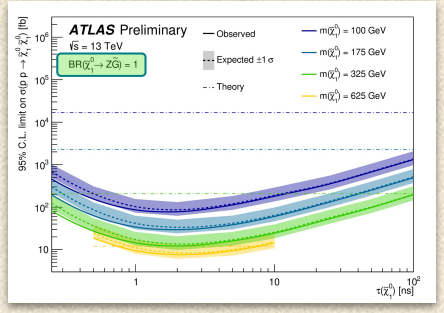
ATLAS-CONF-2022-051



Search for displaced production of H/Z from a neutral LLP

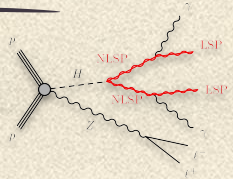
- 2γ/2e from H/Z (vertexing using only LAr precise timing info) + E_T^{miss}
- Selection using pointing/timing info
- Background: processes with real and fake photons
  - Data-driven bkg estimation using a CR with low E_T^{miss} values
- Binned profile likelihood fit of t_{avg} performed simultaneously across five ϱ categories



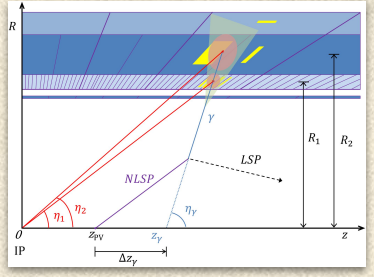


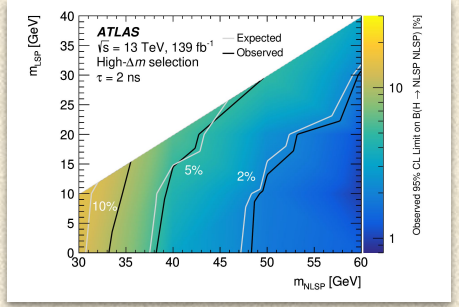
Search for delayed and nonpointing photons from LLPs

SUSY-2019-14



- 2γ + triggering on prompt leptons
- Pointing/timing info and shape fit of timing distribution
- Background from prompt γ, e/jets misidentified as photons → estimated using data control samples
- Look for lifetimes O(10 ns)
- Results interpreted in terms of m_{LSP}, m_{NLPS}, LLP lifetime



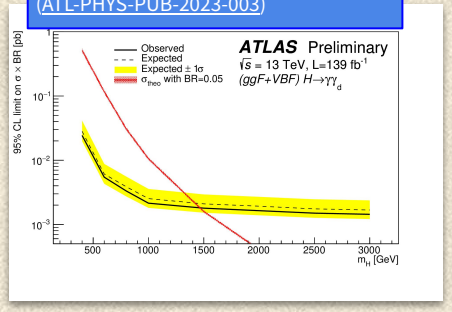


…and Many More Results!

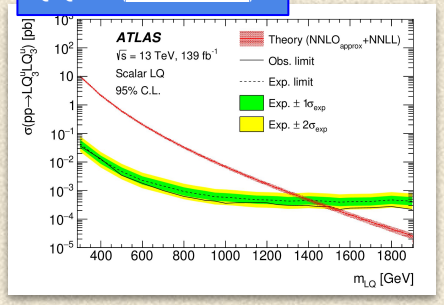
No significant excess in BSM searches has been observed yet

- More Run-2 analyses are progressing and Run-3 has just started… 😊

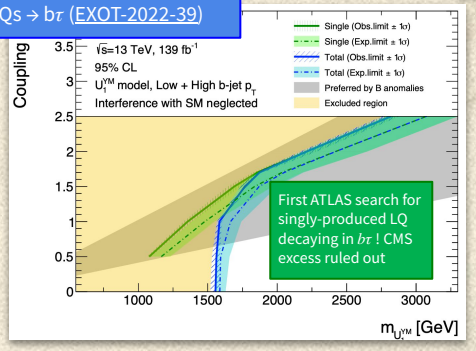
RECAST: high-mass resonances $\gamma + E_T^{miss}$ (ATL-PHYS-PUB-2023-003)



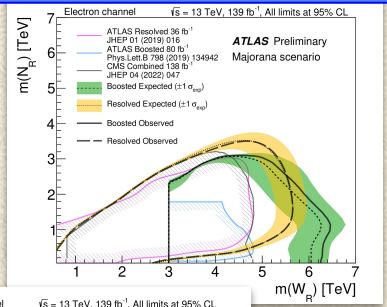
LQLQ → bτ (EXOT-2021-15)

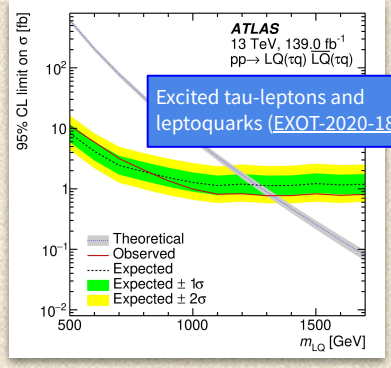


LQs → bτ (EXOT-2022-39)

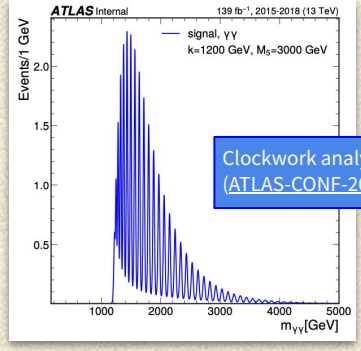


Heavy RH Majorana or Dirac neutrinos N_R and heavy RH gauge bosons W_R (EXOT-2019-39)

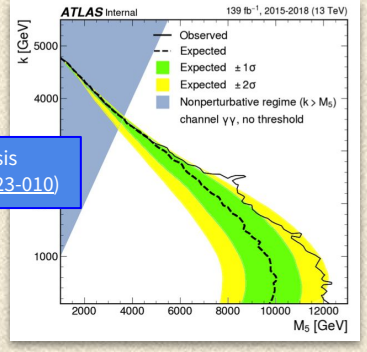


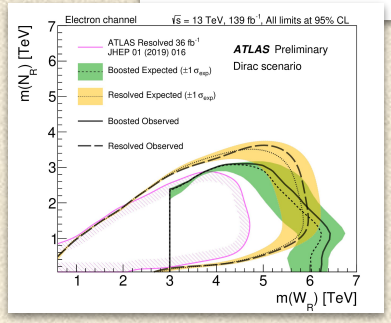


Excited tau-leptons and leptoquarks (EXOT-2020-18)



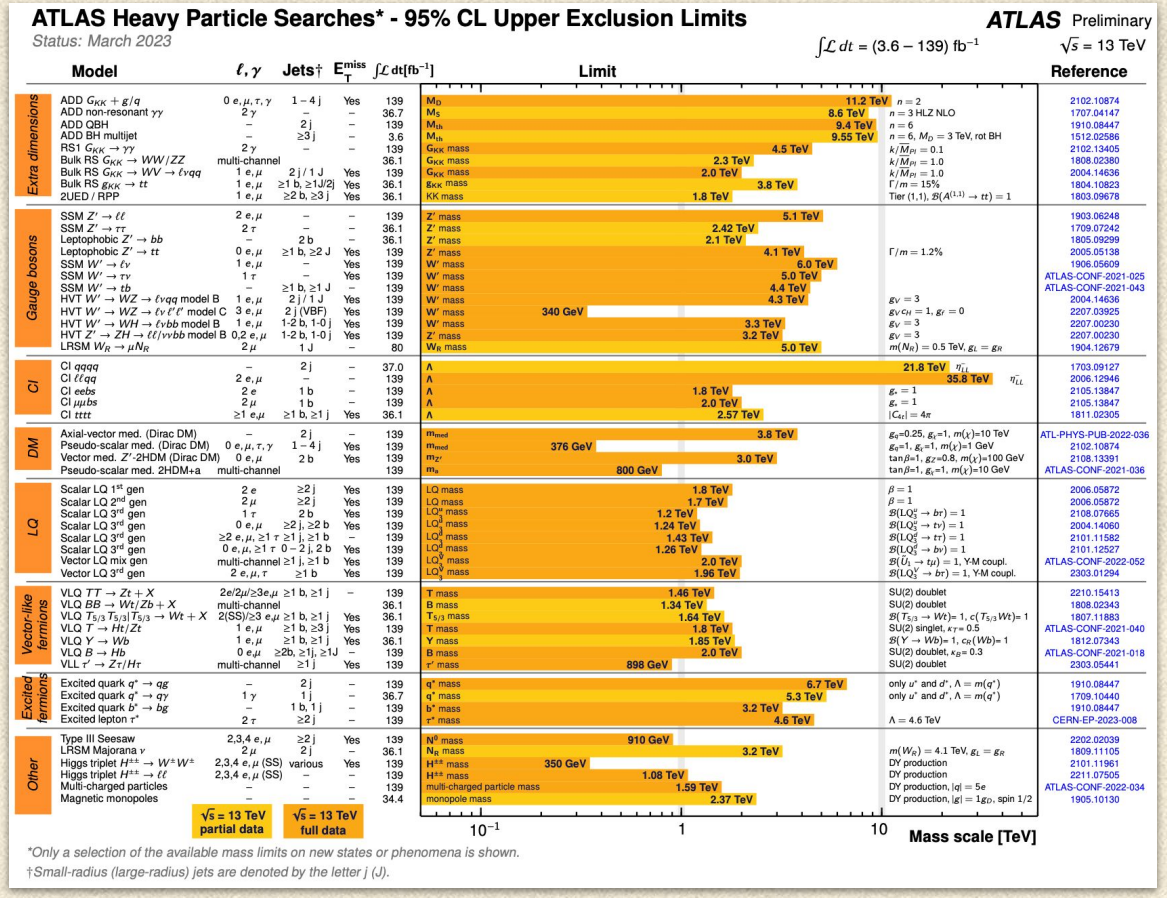
Clockwork analysis (ATLAS-CONF-2023-010)



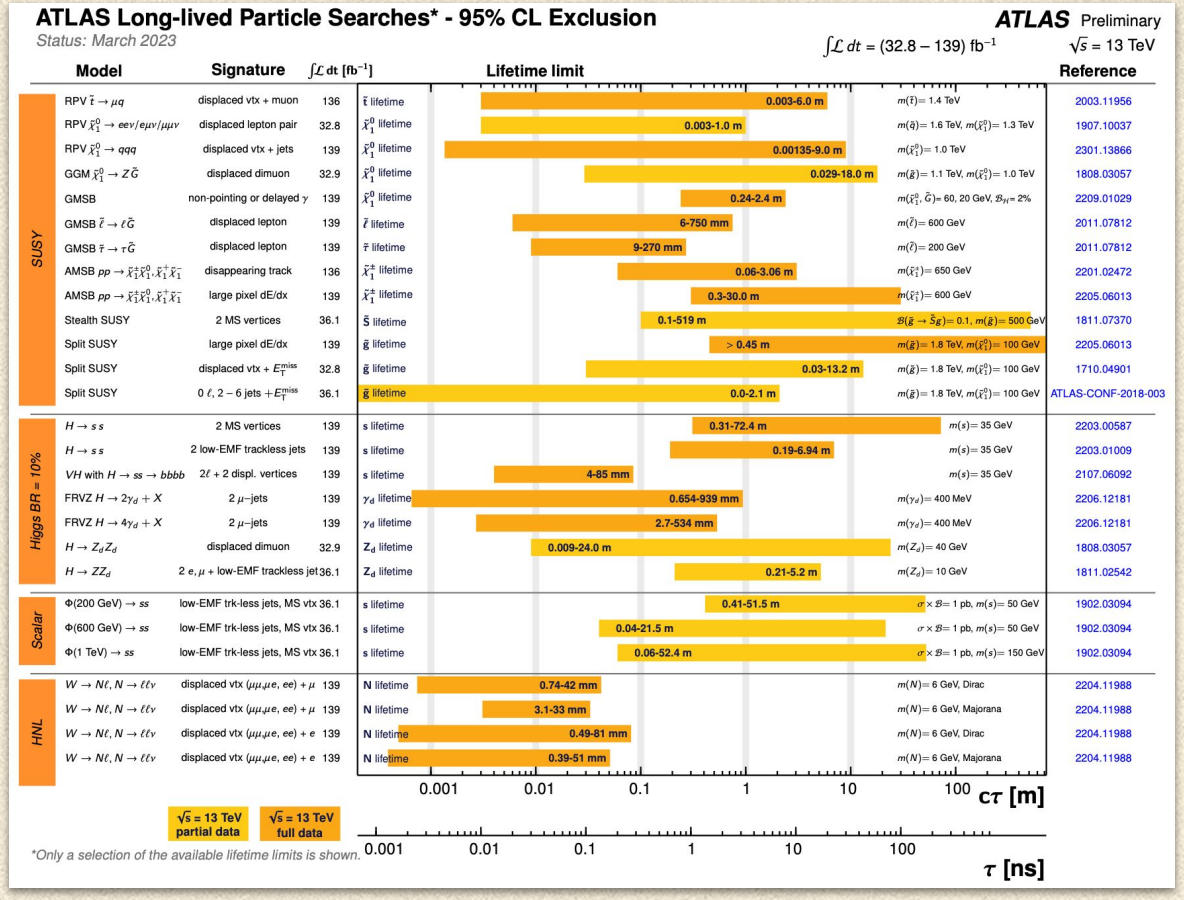


Backup

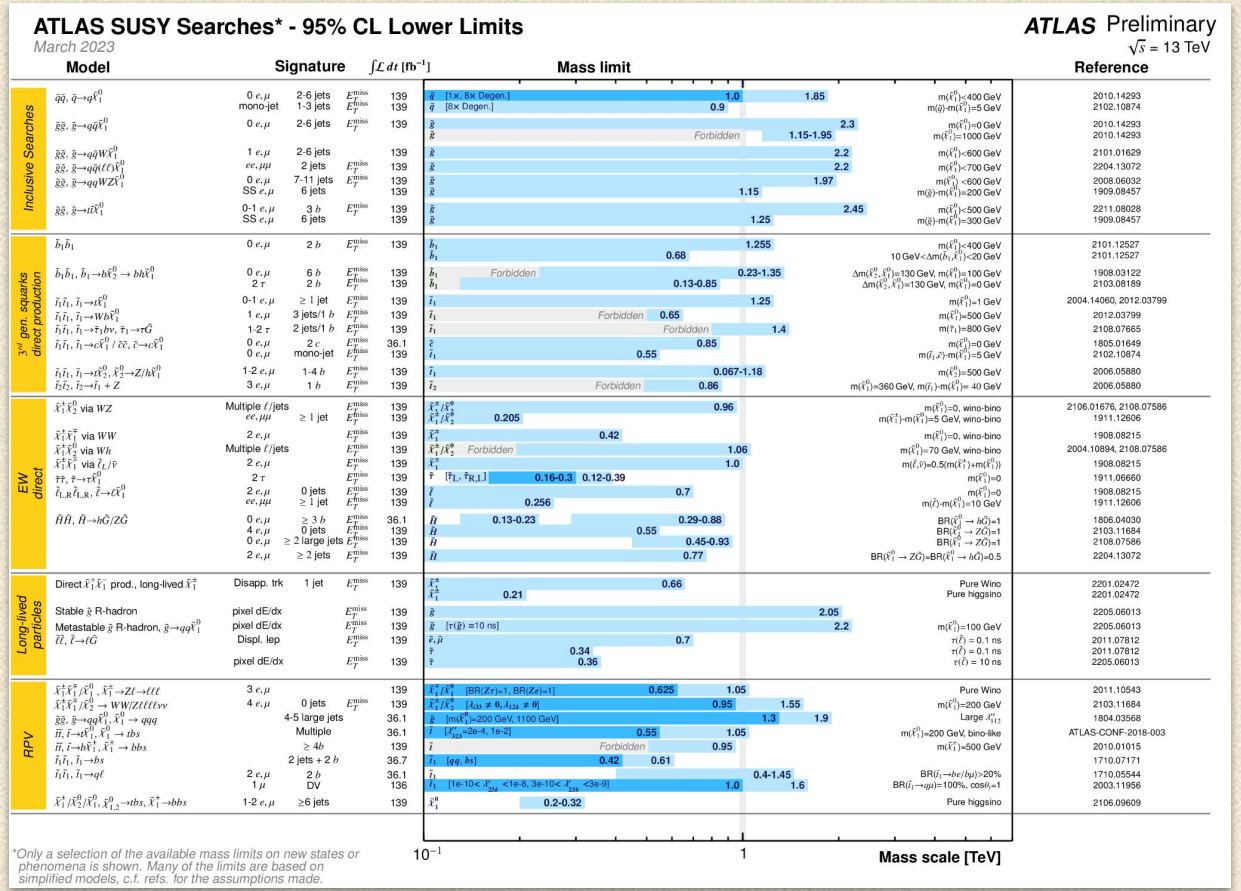
Some Summary Plots - Heavy Particles



Some Summary Plots - LLP



Some Summary Plots - SUSY



Paired Produced Higgsinos - SR Selection / Event Yield

ATLAS-CONF-2023-009

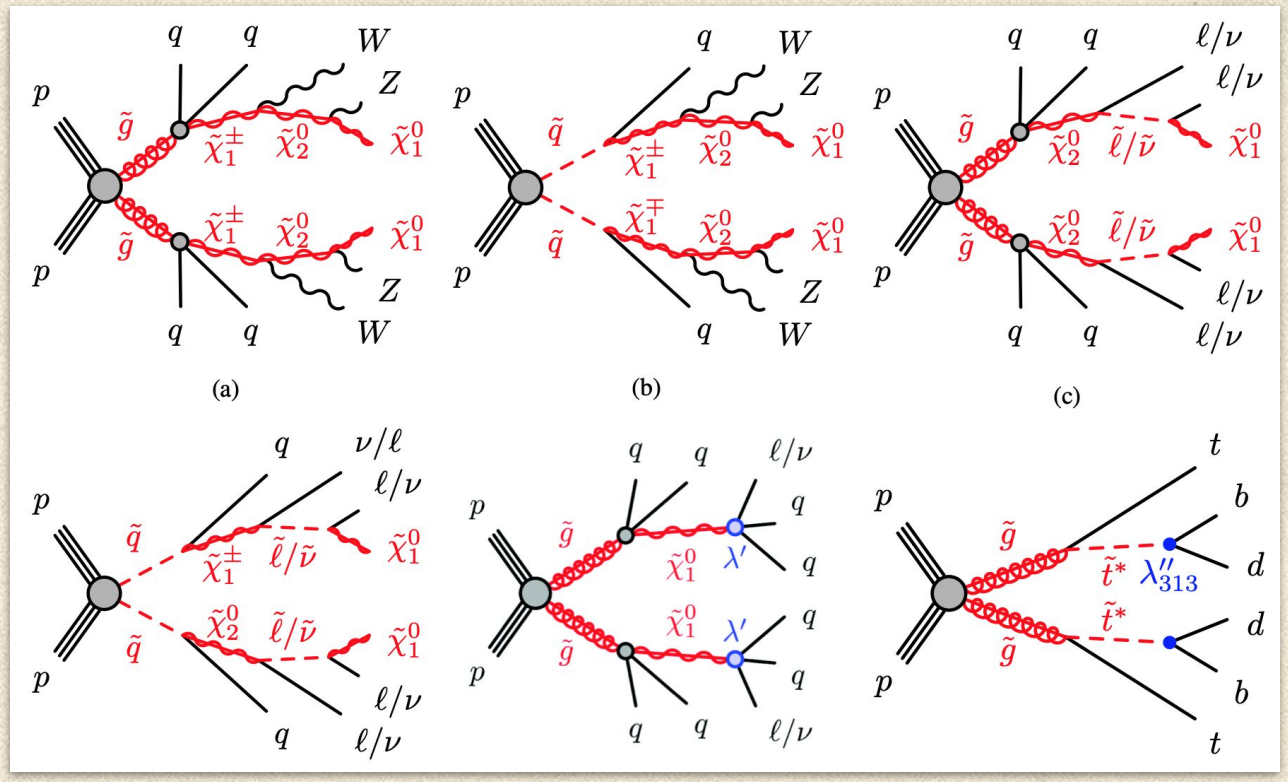
NEW

requirement	SR1h	SR1Z	SR2
$\lvert m_{\gamma\gamma} - 125\,GeV \rvert$	$< 5\,GeV$		
$E_{\mathrm{T}}^{\mathrm{miss}}$	$\leq 100\,GeV$		$> 100\,GeV$
m_{bb}	$\in (100, 140)\,GeV$	$\in (60, 100)\,GeV$	$\in (35, 145)\,GeV$
$p_{\mathrm{T}}^{\gamma\gamma}$	$\geq 90\,GeV$		-
$p_{\mathrm{T}}^{\gamma\gamma}/m_{\gamma\gamma}$	≥ 0.4		≥ 0.2

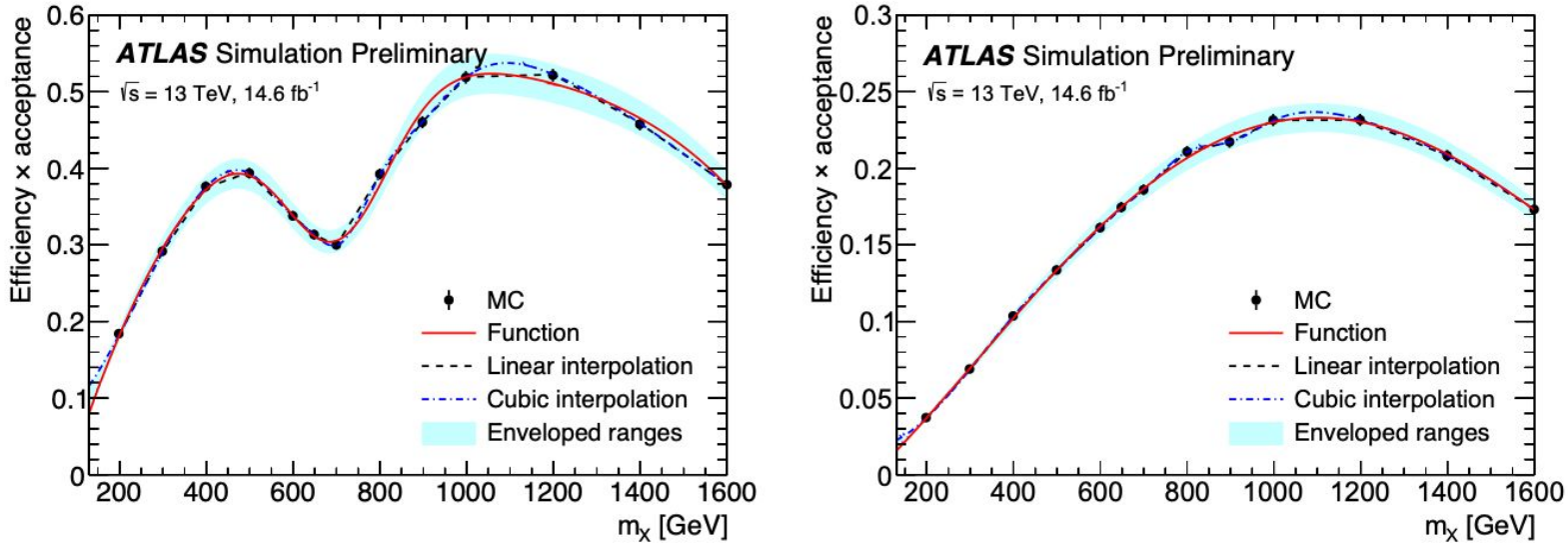
Channel	SR1h	SR1Z	SR2
Observed events	3	5	2
Total SM events	3.9 ± 0.6	6.4 ± 1.0	1.7 ± 0.7
$\gamma\gamma$ events	2.5 ± 0.5	3.7 ± 0.7	0.88 ± 0.26
γj events	0.47 ± 0.28	0.8 ± 0.5	0.24 ± 0.15
$j\gamma$ events	0.088 ± 0.014	0.27 ± 0.04	0.00 ± 0.6
jj events	< 0.01	0.07 ± 0.05	$0.22^{+0.24}_{-0.22}$
ttH events	0.41 ± 0.04	0.297 ± 0.025	0.27 ± 0.06
Higgs (other)	0.40 ± 0.08	1.22 ± 0.26	0.064 ± 0.011
$\langle \epsilon\sigma \rangle^{95}_{\mathrm{obs}}$ [fb]	0.03	0.04	0.03
S^{95}_{obs}	4.8	5.5	4.8
S^{95}_{exp}	$5.4^{+2.2}_{-1.5}$	$6.7^{+2.6}_{-1.8}$	$4.6^{+1.6}_{-0.8}$
$p(s=0)$	0.50	0.50	0.43

Squarks/gluinos Decaying Via Sleptons/W

ATLAS-CONF-2023-017



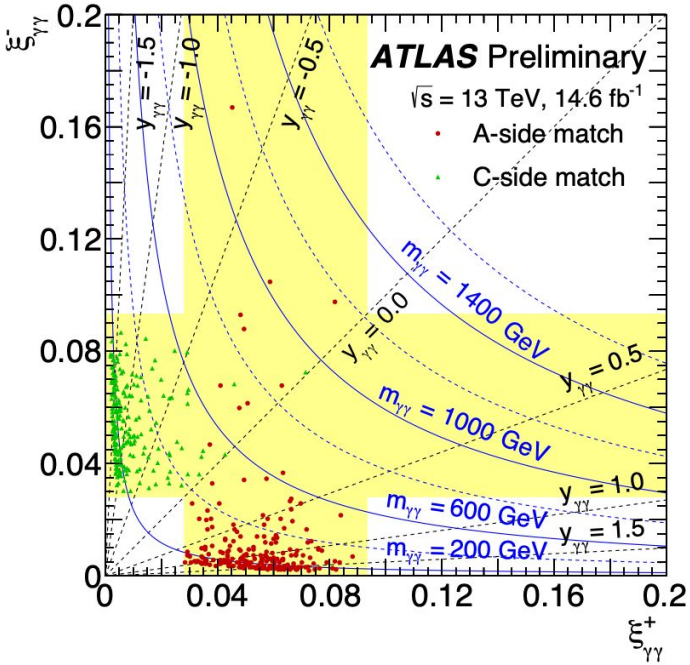
ALPs with AFP - Efficiency x Acceptance



(a) (b)

Figure 2: Signal selection efficiency times acceptance as a function of ALP mass m_X for the (a) exclusive and (b) single-dissociative process. The ratio of the number of the generated MC events and the selected events is given (black points) and is parameterised by an analytical function (red solid line). The linear (black dashed line) and cubic (blue chain line) interpolations of the black points are used to derive the envelopes (cyan filled region) which are regarded as systematic uncertainties.

ALPs with AFP - Proton Fractional Energy Loss



$$\xi = 1 - E_{\text{scattered}}/E_{\text{beam}}$$

Figure 5: $(\xi^+_{\gamma\gamma}, \xi^-_{\gamma\gamma})$ distribution of the selected data candidates after the full event selection in $m_{\gamma\gamma} \in [150, 1600]$ GeV with $m_{\gamma\gamma}$ contours (blue) and $y_{\gamma\gamma}$ contours (black). The range of $\xi_{\gamma\gamma}$ in which forward proton matching is possible, $[0.035 - \xi_{\text{th}}, 0.08 + \xi_{\text{th}}]$, is indicated by the yellow rectangle for each side. Events passing the matching selection on the A(C)-side are represented by the red dots (green triangles). No event passed the matching selection for both A and C-sides.

Dark Photons via ZH - Signal Selection and Event yield

Table 3: Optimised kinematic selections defining the signal region for $\ell^+\ell^- + \gamma + E_T^{miss}$.

Two same flavour, opposite sign, medium ID and loose isolated leptons, with leading $p_T > 27$ GeV, sub-leading $p_T > 20$ GeV
Veto events with additional lepton(s) with loose ID and $p_T > 10$ GeV
76 GeV $< m_{\ell\ell} <$ 116 GeV
Only one tight ID, tight isolation photon with $E_T^{\gamma} > 25$ GeV
$E_T^{miss} > 60$ GeV with $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{\ell\ell\gamma}) > 2.4$ rad
$m_{\ell\ell\gamma} > 100$ GeV
$N_{jet} \leq 2$, with $p_T^{jet} > 30$ GeV, $\lvert\eta\rvert < 4.5$
Veto events with b-jet(s)

BDT bin	SR 0 - 0.50	SR 0.50 - 0.64	SR 0.64 - 0.77	SR 0.77 - 0.88	SR 0.88 - 0.96	SR 0.96 - 1	$VV\gamma$ CR
Observed	910	84	59	72	42	6	32
Post-fit SM background	910 ± 29	85.5 ± 8.7	59.9 ± 7.3	69.7 ± 7.8	41.6 ± 6.1	7.3 ± 2.0	31.4 ± 5.4
Fake E_T^{miss}	800 ± 34	72.1 ± 8.3	45.7 ± 6.5	53.2 ± 7.1	27.9 ± 6.1	2.0 ± 1.9	$2.1^{+3.5}_{-2.1}$
$e \rightsquigarrow \gamma$	21.5 ± 2.0	3.33 ± 0.62	3.75 ± 0.74	6.4 ± 1.1	5.7 ± 1.4	1.47 ± 0.25	1.24 ± 0.07
$VV\gamma$	44 ± 12	5.3 ± 1.6	5.8 ± 1.7	6.4 ± 1.8	5.7 ± 1.9	3.30 ± 0.97	27.3 ± 6.4
$t\bar{t}$, $t\bar{t}\gamma$, single t	42 ± 15	4.3 ± 1.5	3.4 ± 1.2	3.6 ± 1.2	2.13 ± 0.80	0.50 ± 0.18	0.63 ± 0.22
$W\gamma$	3.3 ± 1.5	0.39 ± 0.18	1.18 ± 0.55	–	0.04 ± 0.02	–	–
$t\bar{t}H$, VH	0.15 ± 0.02	0.03 ± 0.01	0.04 ± 0.01	0.06 ± 0.01	0.09 ± 0.03	0.02 ± 0.01	$0.17^{+0.18}_{-0.17}$
Pre-fit SM background	900 ± 120	90 ± 35	65 ± 27	53 ± 24	35 ± 22	7.8 ± 4.4	24 ± 4.7
Signal ($ZH \rightarrow \gamma\gamma_d$)	5.1 ± 1.3	1.98 ± 0.51	3.2 ± 1.0	5.5 ± 1.6	11.1 ± 3.1	14.9 ± 1.9	–

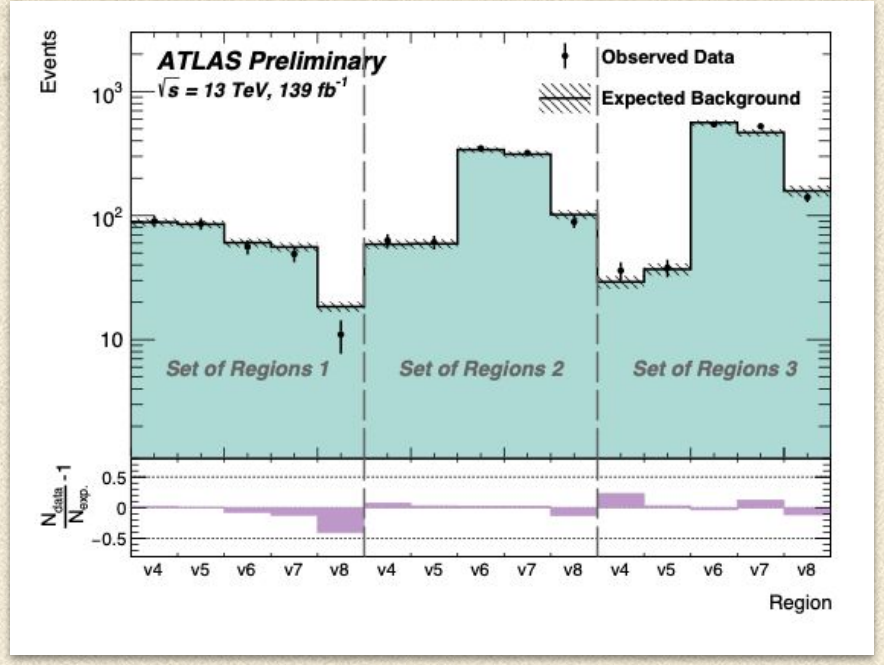
Dark Photons via ZH - Uncertainties

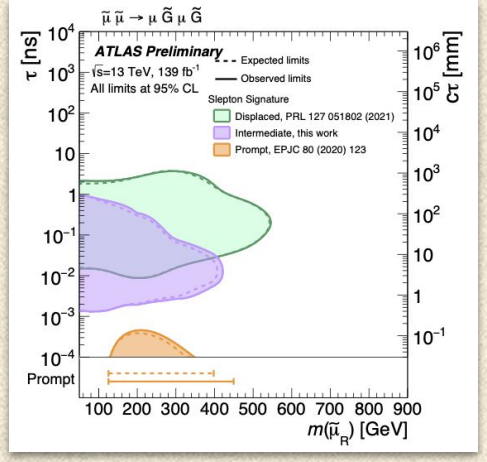
BDT bin	0 - 0.50	0.50 - 0.64	0.64 - 0.77	0.77- 0.88	0.88 - 0.96	0.96 - 1
	[%]	[%]	[%]	[%]	[%]	[%]
Total (statistical+systematic) uncertainty	3.1	10	12	11	15	28
Statistical uncertainty	3.1	9.9	12	11	14	16
Fake $E_{\mathrm{T}}^{\mathrm{miss}}$ shape	0.17	0.97	0.40	0.55	2.8	18
Jet E scale and resolution	0.02	3.3	2.1	0.47	2.1	13
Electron, photon E scale and resolution	0.04	0.45	0.75	0.46	1.7	5.6
Muon E scale and resolution	0.08	0.17	0.15	0.91	1.2	4.1
Fake $E_{\mathrm{T}}^{\mathrm{miss}}$ data-driven	0.50	0.28	0.18	0.04	0.40	3.5
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale and resolution	0.26	0.16	0.59	0.49	0.20	2.8
Electron trigger/ID/iso/reco eff.	0.01	0.10	0.10	0.01	0.17	1.0
Muon trigger/ID/iso/reco eff.	0.01	0.07	0.08	0.06	0.03	0.84
Flavour tagging eff.	< 0.01	0.08	0.10	0.04	0.02	0.82
Electrons faking photons data-driven	0.02	0.08	0.06	0.06	0.07	0.73
Photon ID/iso/reco eff.	0.01	0.07	0.08	0.04	0.09	0.61
Reweighting of $\langle\mu\rangle$ in MC simulation	0.08	0.10	0.32	0.46	0.09	0.48
Top normalization	0.08	0.06	0.06	0.02	0.09	0.13
Theoretical $VV\gamma$	0.04	0.02	0.16	0.04	0.13	0.49
Theoretical fake $E_{\mathrm{T}}^{\mathrm{miss}}$	0.05	0.11	0.12	0.22	0.29	0.45
Theoretical top	0.09	0.05	0.17	0.10	0.04	0.28
Theoretical $W\gamma$	0.04	0.10	0.18	0.05	0.13	0.24
Theoretical Higgs	0.01	0.05	0.04	0.02	0.08	0.05

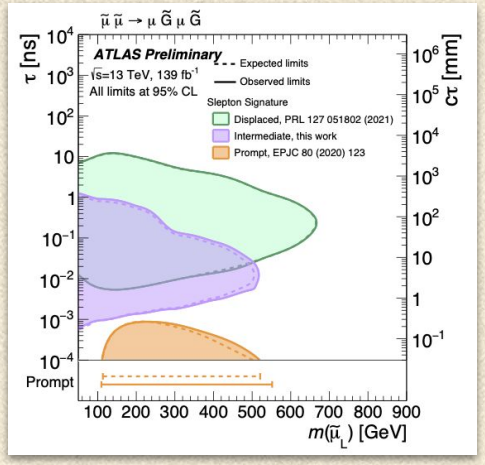
Micro-Displaced Muons

NEW

SUSY-2020-09 (to be updated when public)



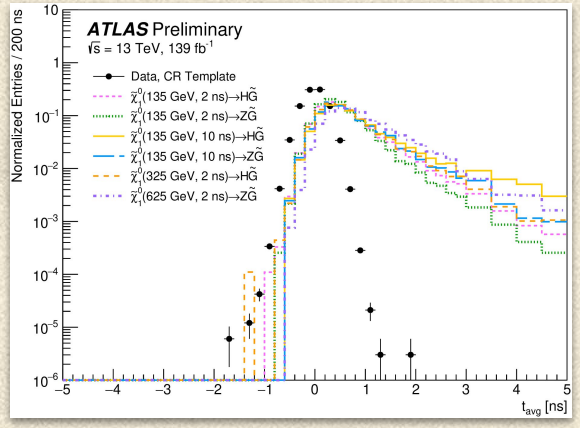


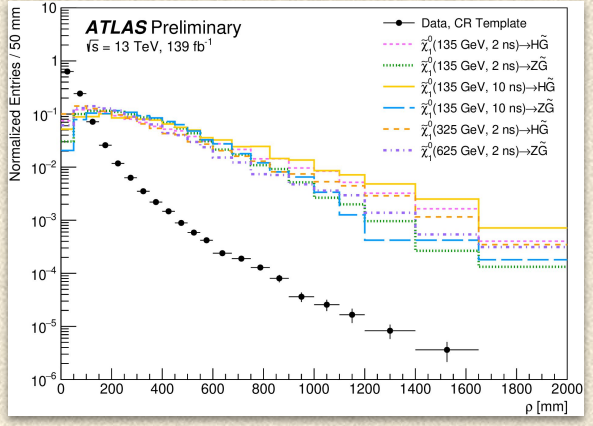


Displaced Photons

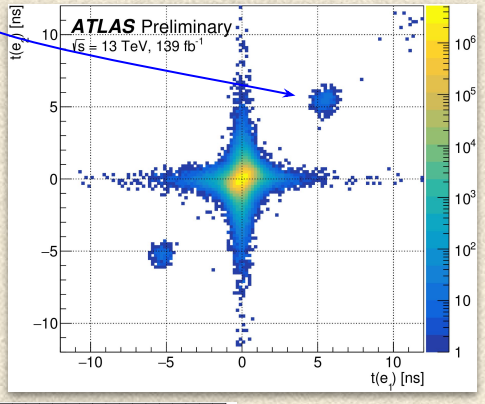
ATLAS-CONF-2022-051

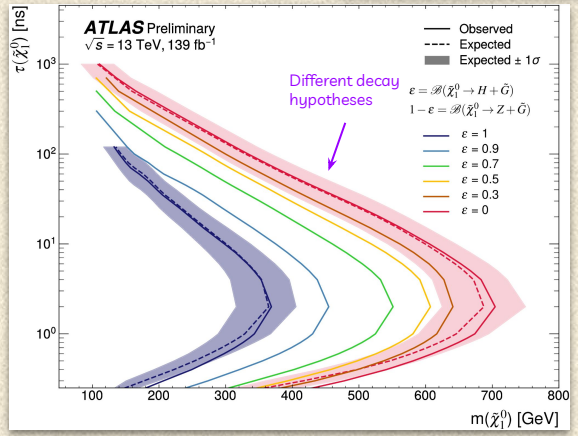
Search for displaced production of H/Z from a neutral LLP





Source of early photons through satellite bunches → background source but also helpful to tune reconstruction





Delayed Photons

SUSY-2019-14

Search for delayed and nonpointing photons from LLPs