Search for long-lived particles decayed in calorimeter with the ATLAS detector

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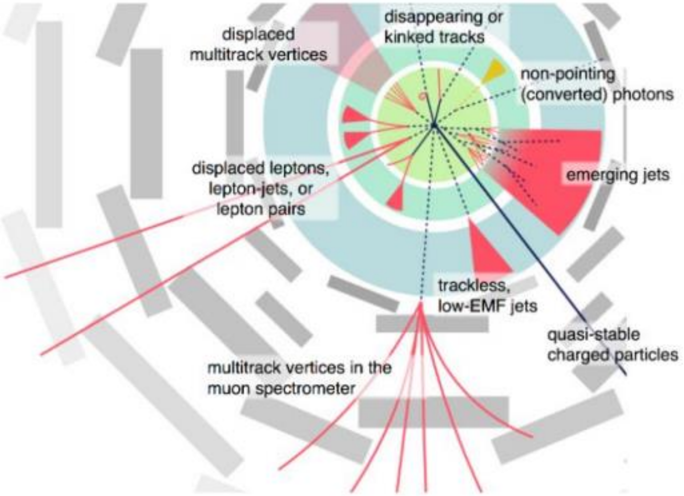
[2407.09183] Search for neutral long-lived particles that decay into displaced jets in the ATLAS calorimeter in association with leptons or jets using pp collisions at $\sqrt{s}=13$ TeV

Outline

- Introduction to long-lived particles (LLPs)
- Previous searches for LLPs at LHC
- Signal models and channels in this analysis
- Analysis strategy
- Event selection
- Main background and data-driven ABCD method
- Systematic uncertainties
- Final results
- Summary

Introduction of long-lived particles (LLP)

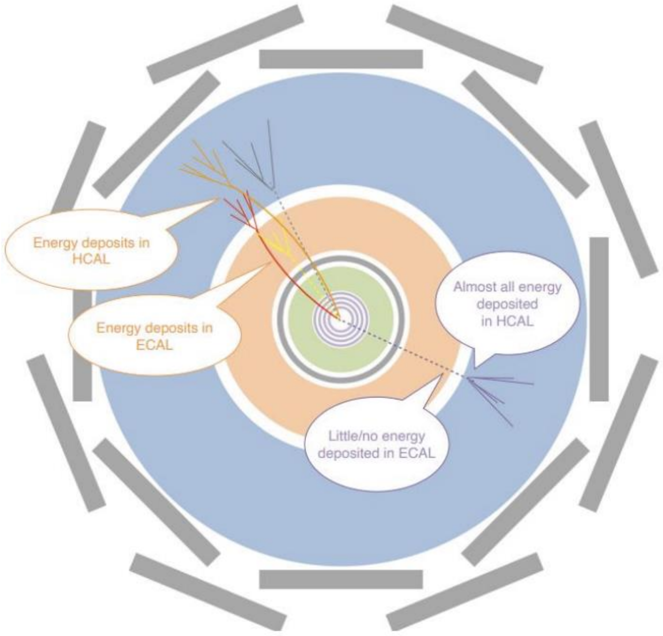
- Although the discovery of Higgs Bosons has completed the Standard model (SM), there are still some problems can’t be explained:
  - Dark matter and dark energy;
  - Matter–antimatter asymmetry;
  - Strong CP problem.
- Lots of extensions to the SM try to explain these problems, and many of them predicts new particles which acquire large lifetimes, becoming long-lived particles (LLPs).



- LLPs have unusual experimental signatures:
  - Small, localized energy deposits inside the calorimeters without associated tracks;
  - Displaced vertices in the inner detector or muon spectrometer;
  - Disappearing, appearing, and kinked tracks.

Differences between SM jets and LLP jets

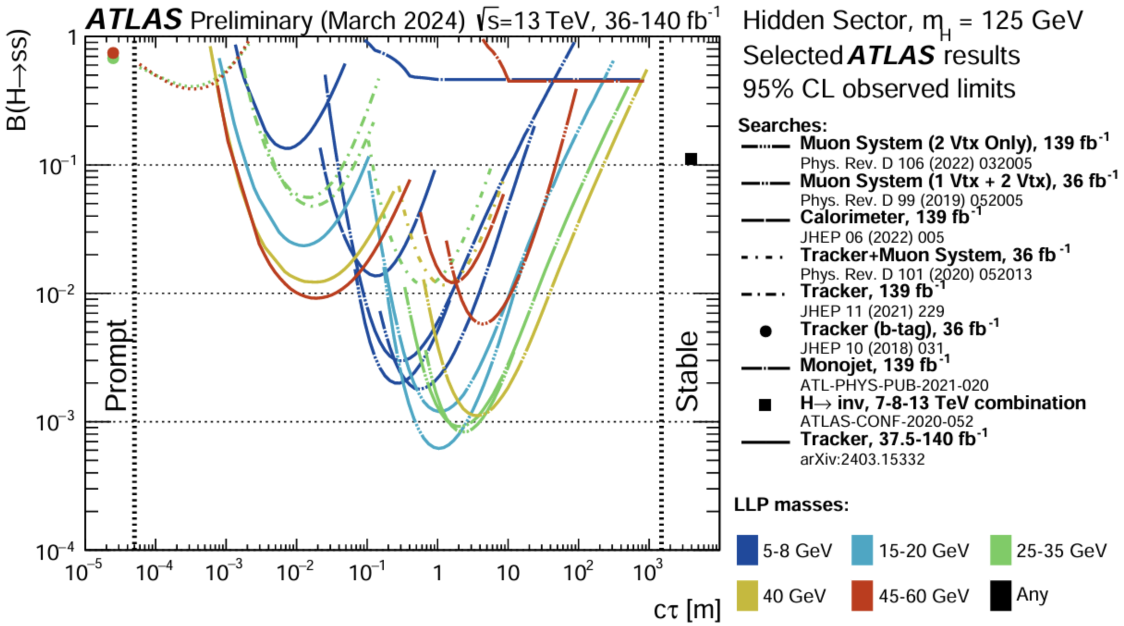
- Jets from SM decays:
  - Originate from the interaction point;
  - Associated tracks ;
  - Energy deposits in the Electromagnetic Calorimeter (**ECAL**) and the Hadronic Calorimeter (**HCAL**).
- Jets from LLPs decaying after the 1st HCAL layer:
  - Originate from a point in the HCAL;
  - Trackless;
  - High $E_{\mathrm{H}}/E_{\mathrm{EM}}$, the ratio of energy deposited in the HCAL to that deposited in the ECAL, the so called CalRatio (**CalR**).
- The standard reconstruction algorithms may reject events or objects containing LLPs precisely.
- Dedicated searches are needed to uncover LLP signals.



SM jets vs LLP jets

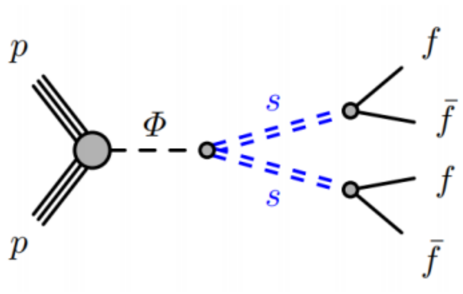
Previous searches for LLPs at LHC

- LHCb:
  - Search for LLPs decaying to jet pairs [1]
- CMS:
  - Search for LLPs using displaced jets [2]
  - Search for LLPs produced in association with a Z boson [3]
  - Search for LLPs using displaced vertices and missing transverse momentum [4]
  - Search for LLPs decaying in the CMS muon detectors [5]
- ATLAS:
  - Search for displaced vertices in the tracking system [6][7][8], hadronic calorimeter [9], and the muon spectrometer [10]
  - Search for the combination of one displaced vertex in the muon spectrometer and one in the inner tracking detector [11]
  - Search for hadronic decays of LLPs in association with a Z boson [12]

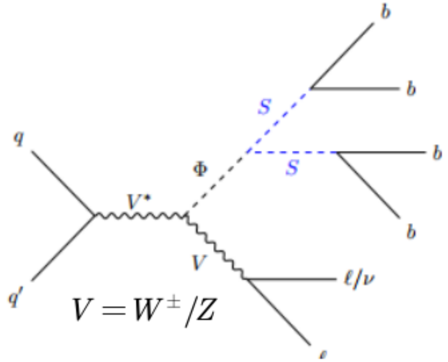


Summarized ATLAS 95% confidence level exclusion limits on the Higgs boson branching to a pair of LLPs as a function of cτ. Current as of March 2024.

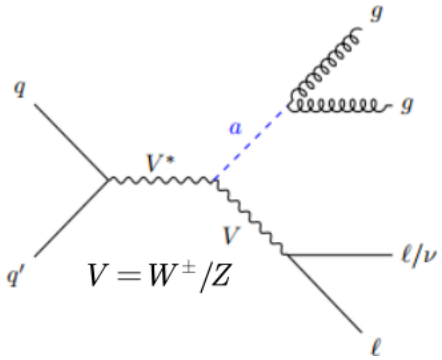
Signal models and channels in this analysis



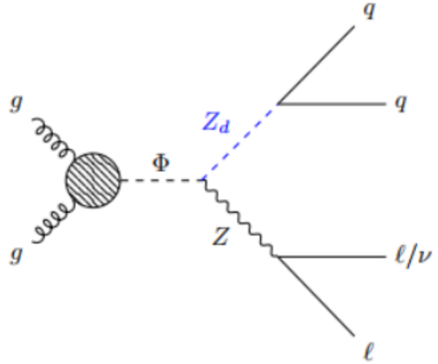
Benchmark HS model



HS model associated with a vector boson



ALP model



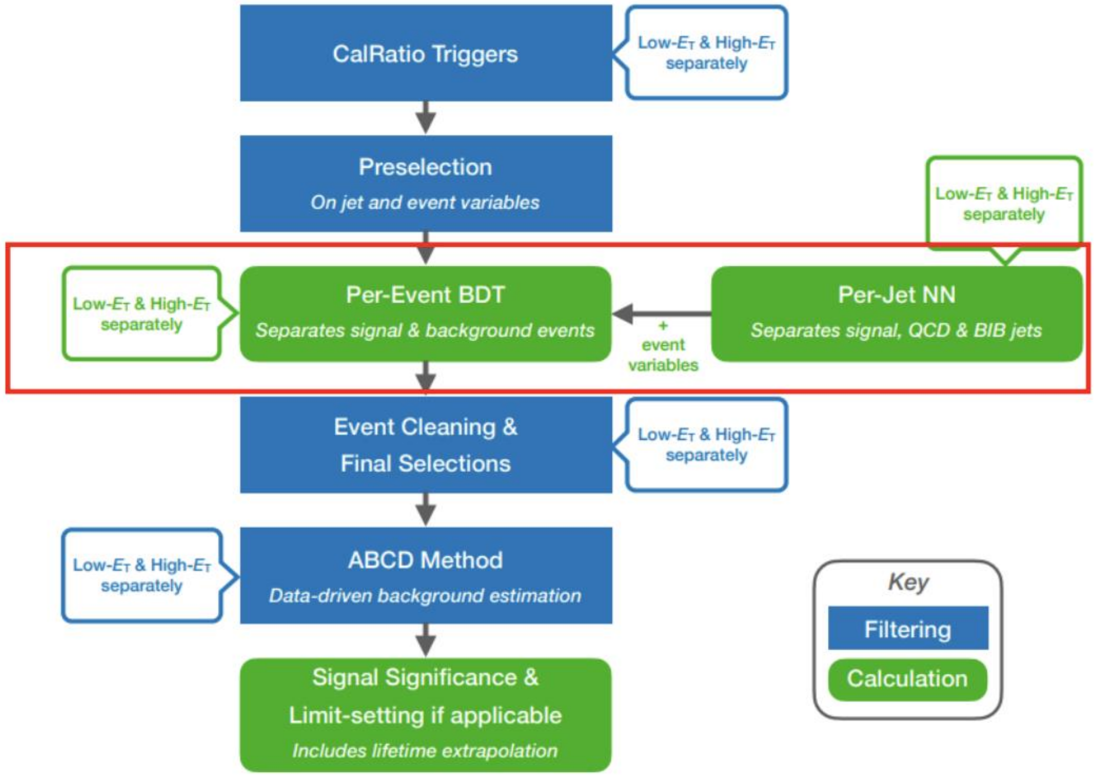
Dark photon model

- Hidden sector(**HS**) model:
  - SM and HS are connected via a heavy neutral boson Φ, which can decay into neutral long-lived scalars S.
  - Φ can be produced in association with a vector boson (W/Z) decaying to leptons. (**ZHSS**/**WHSS**)
- Axion-like particles (**ALPs**) model: (**ZALP**/**WALP**)
  - The long-lived ALP a decays into gluons, produced in association with a vector boson (W/Z).
- Dark photon (Z_d) model: (**HZZd**)
  - Z_d is produced with a Z boson from the decay of a mediator Φ.

- CalRatio + 2 jets channel (CalR+2J):
  - HS model: One LLP decays after HCAL, another decays before HCAL, leading to one CalRatio jet and two prompt jets.
- CalRatio + lepton(s) channel (CalR+W/Z):
  - ZHSS, WHSS, ZALP, WALP and HZZd: At least one LLP decays after HCAL and W/Z boson decays into leptons, leading to at least one CalRatio jet and leptons from W/Z.

Analysis strategy

- Use the ATLAS Run 2 dataset of 140 fb^{-1} of *pp* collisions at $\sqrt{s} = 13\ \mathrm{TeV}$.
- A jet-level neural network (NN) is used to identify CalRatio jets, qcd jets and beam-induced background (BIB) jets.
- For different channels and different E_T regions, use different event-level Boosted Decision Trees (BDTs) to tag events as signal or background.
- Use a modified ABCD method to do the data-driven background estimation.
- Use the Blind Analysis to avoid bias.



CalRatio Triggers

Low-E_T & High-E_T separately

Preselection

On jet and event variables

Low-E_T & High-E_T separately

Per-Event BDT

Separates signal & background events

Low-E_T & High-E_T separately

\+ event variables

Per-Jet NN

Separates signal, QCD & BIB jets

Event Cleaning & Final Selections

Low-E_T & High-E_T separately

ABCD Method

Data-driven background estimation

Low-E_T & High-E_T separately

Signal Significance & Limit-setting if applicable

Includes lifetime extrapolation

Key

Filtering

Calculation

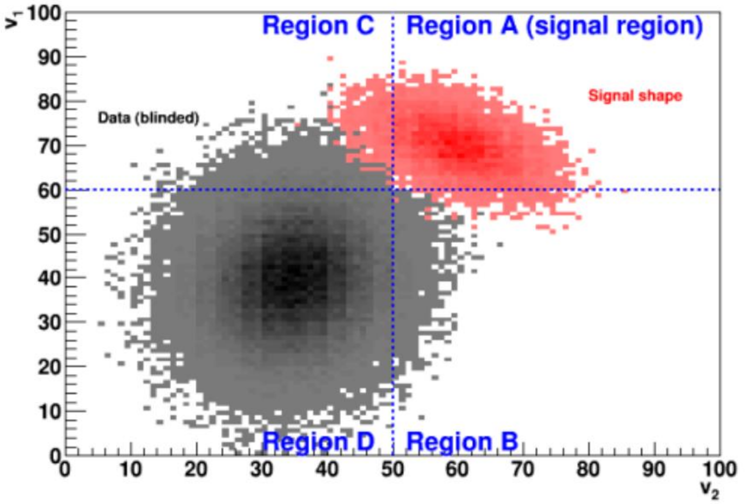
Event selection

- In CalR+2J channel, besides a series of basic preselections on events and jets, an event-level NN is trained to remove all remaining BIB events.
- In CalR+W/Z channel, after the preselection, combinations of additional cuts are optimized to maximize the $S/\sqrt{B}$ ratio in signal region. And several BDTs are trained with different input signal sample sets to discriminate the signal against the background processes.

$\mathrm{BDT}^{\mathrm{ALP}}_{\mathrm{CalR+W}}$	$\mathrm{BDT}^{\mathrm{low}-E_{\mathrm{T}}}_{\mathrm{CalR+W}}$	$\mathrm{BDT}^{\mathrm{high}-E_{\mathrm{T}}}_{\mathrm{CalR+W}}$	$\mathrm{BDT}^{\mathrm{low}-E_{\mathrm{T}}}_{\mathrm{CalR+Z}}$	$\mathrm{BDT}^{\mathrm{high}-E_{\mathrm{T}}}_{\mathrm{CalR+Z}}$
All WALP mass points	WHSS events with $m_\Phi \leq$ 200 GeV	WHSS events with $m_\Phi >$ 200 GeV	All ZALP mass points, HZZd and ZHSS events with $m_\Phi \leq$ 250 GeV	HZZd and ZHSS events with $m_\Phi >$ 200 GeV

Main background and data-driven ABCD method

- CalR+2J:
  - SM multijets events;
  - Non-collision backgrounds (NCBs):
    - Beam-induced background (BIB);
    - Cosmic rays.
- CalR+W/Z:
  - SM processes involving vector bosons produced with jets;
  - Single or pair production of top quarks.
- After event selections, the contributions from cosmic rays are found to be negligible.



- Use data-driven ABCD method to estimate the remained backgrounds.
- One axis of the plane is $\sum \Delta R_{\min}(\text{jet}, \text{tracks})$, and the other is the score of NN/BDT , which are uncorrelated.

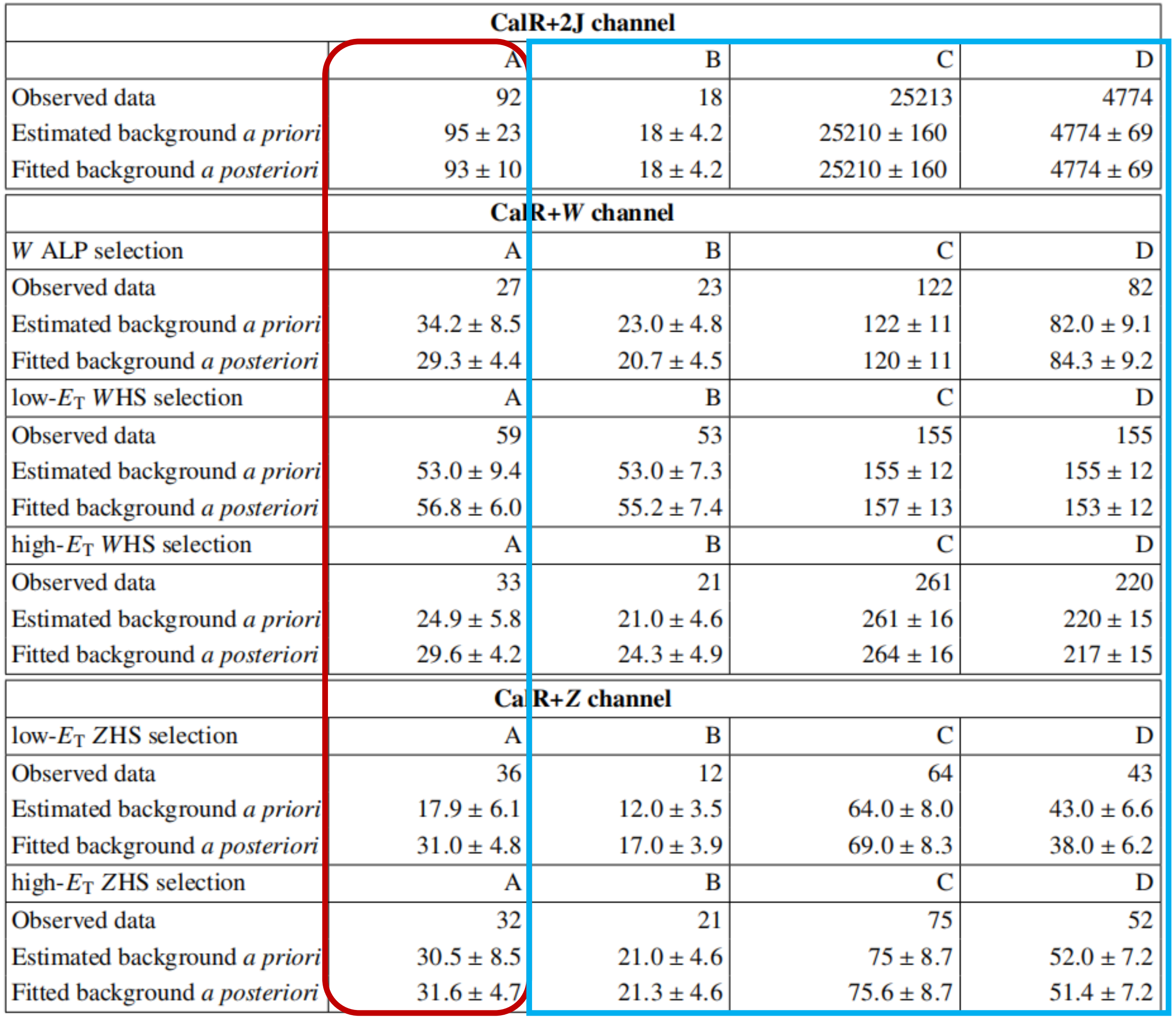
$\sum \Delta R_{\min}(\text{jet}, \text{tracks})$: Sum of the angular distance between the jet axis and the closest track over jets above a certain pT threshold.

Systematic uncertainties

- The maximum uncertainty caused by this background estimate is approximately 5%.
- All remaining sources of uncertainty affect the signal efficiency estimate.
- For CalR+2J, the largest contribution comes from jet energy scale and jet energy resolution: 0.3–16.0%.
- For CalR+W/Z, the largest contribution comes from mis-modelling in Machine Learning (ML): 0.4–9.1%.
- Lepton systematics and luminosity errors are independent of the signal model, included in the total systematic uncertainty.

Unblinding Results

- The a *priori* estimate refers to the "pre-unblinding" case:
  - Data in region A is ignored
  - Signal strength is fixed to zero.
- The a *posteriori* estimate refers to the "post-unblinding" case:
  - Observed data in region A is included in the background-only global fit.
- The post-unblinding yields in region B, C and D remain consistent with the observed yields within their statistical uncertainties.
- No significant excess is observed in signal region A.

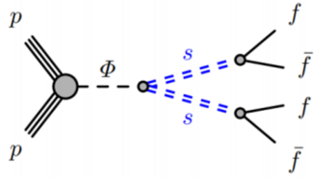


CalR+2J channel				
	A	B	C	D
Observed data	92	18	25213	4774
Estimated background *a priori*	95 ± 23	18 ± 4.2	25210 ± 160	4774 ± 69
Fitted background *a posteriori*	93 ± 10	18 ± 4.2	25210 ± 160	4774 ± 69
CalR+W channel				
W ALP selection	A	B	C	D
Observed data	27	23	122	82
Estimated background *a priori*	34.2 ± 8.5	23.0 ± 4.8	122 ± 11	82.0 ± 9.1
Fitted background *a posteriori*	29.3 ± 4.4	20.7 ± 4.5	120 ± 11	84.3 ± 9.2
low-E_T WHS selection	A	B	C	D
Observed data	59	53	155	155
Estimated background *a priori*	53.0 ± 9.4	53.0 ± 7.3	155 ± 12	155 ± 12
Fitted background *a posteriori*	56.8 ± 6.0	55.2 ± 7.4	157 ± 13	153 ± 12
high-E_T WHS selection	A	B	C	D
Observed data	33	21	261	220
Estimated background *a priori*	24.9 ± 5.8	21.0 ± 4.6	261 ± 16	220 ± 15
Fitted background *a posteriori*	29.6 ± 4.2	24.3 ± 4.9	264 ± 16	217 ± 15
CalR+Z channel				
low-E_T ZHS selection	A	B	C	D
Observed data	36	12	64	43
Estimated background *a priori*	17.9 ± 6.1	12.0 ± 3.5	64.0 ± 8.0	43.0 ± 6.6
Fitted background *a posteriori*	31.0 ± 4.8	17.0 ± 3.9	69.0 ± 8.3	38.0 ± 6.2
high-E_T ZHS selection	A	B	C	D
Observed data	32	21	75	52
Estimated background *a priori*	30.5 ± 8.5	21.0 ± 4.6	75 ± 8.7	52.0 ± 7.2
Fitted background *a posteriori*	31.6 ± 4.7	21.3 ± 4.6	75.6 ± 8.7	51.4 ± 7.2

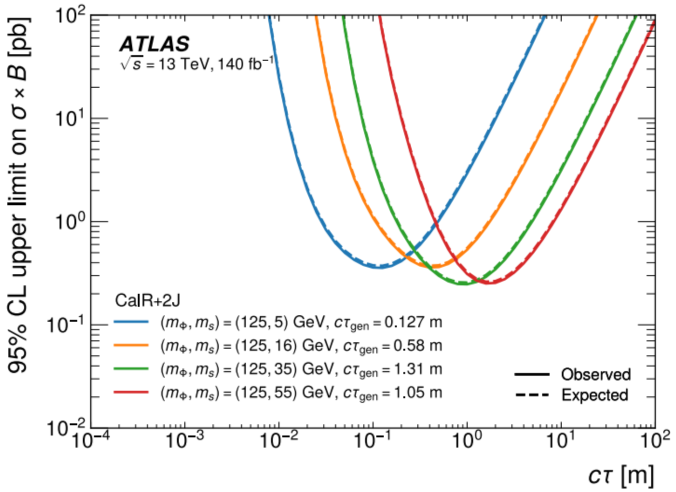
Signal region

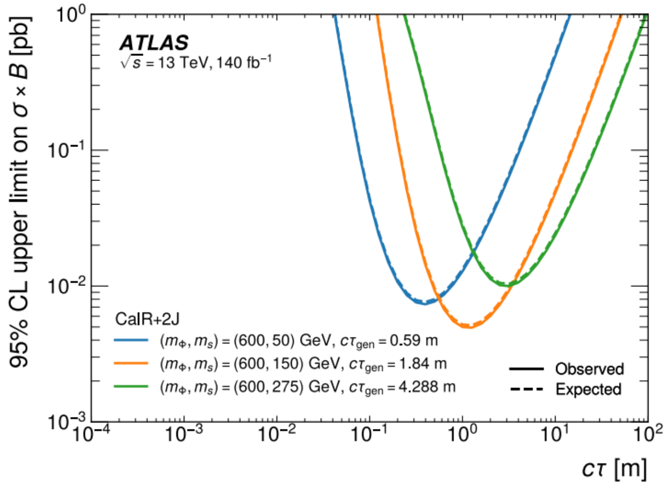
Control region

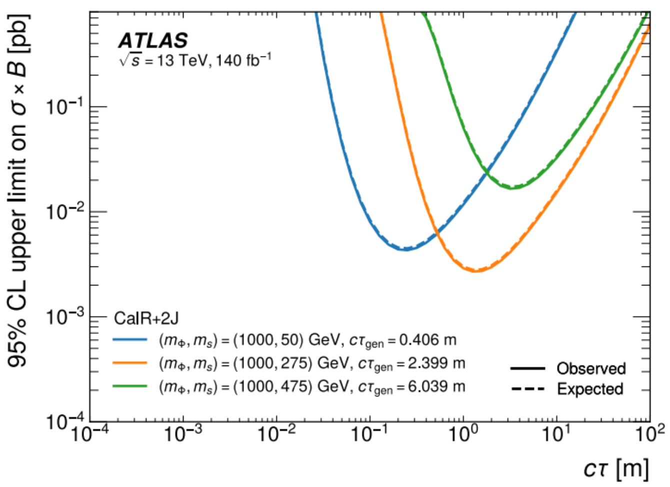
Upper limits Results for HS model



Benchmark HS model

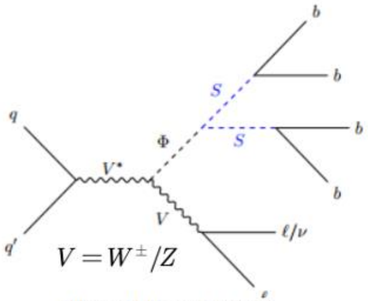




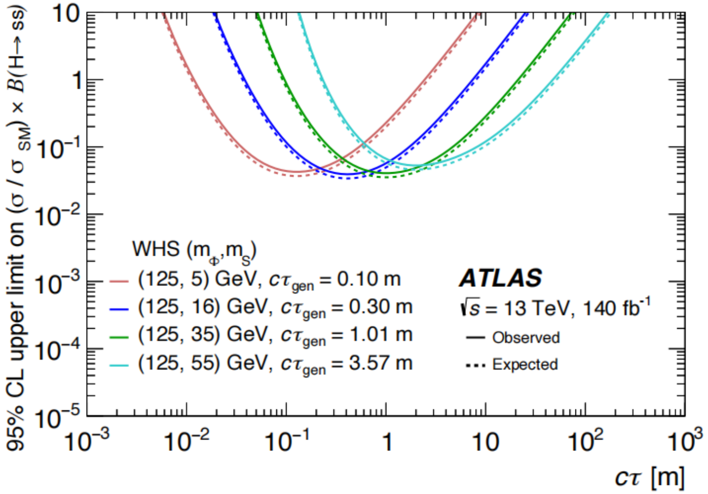


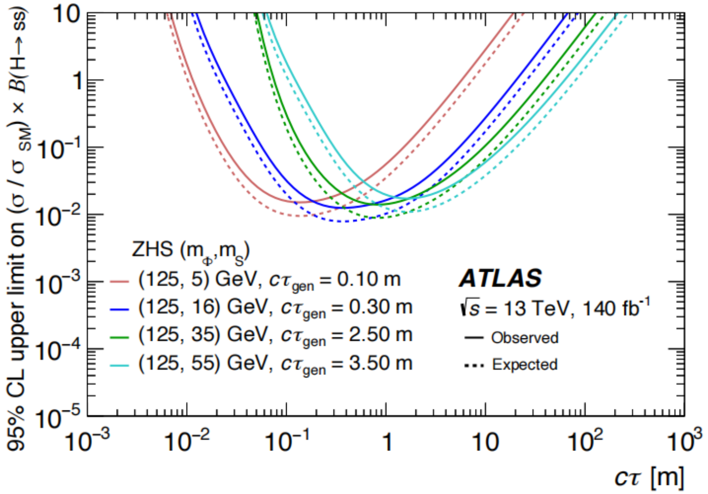
- The constraints obtained by CalR+2J shows about **a threefold improvement** relative to the previous search [9], with the branching fraction of Higgs bosons to LLPs above 1% excluded in the $c\tau$ range of 30 cm to 4.5 m.
- This improvement comes from relaxing a restriction and exploiting additional jet information, which allows a substantial background reduction while maintains signal efficiency.

Upper limits Results for HS model



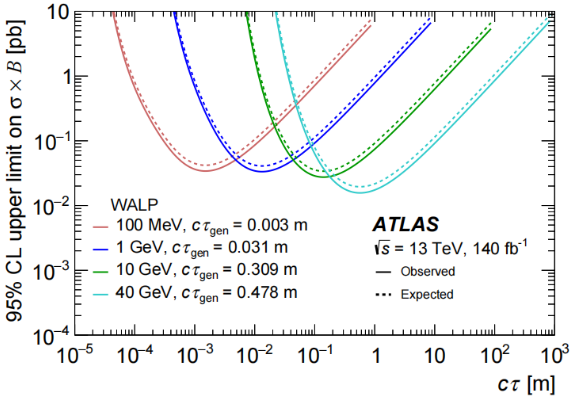
HS model association with a vector boson

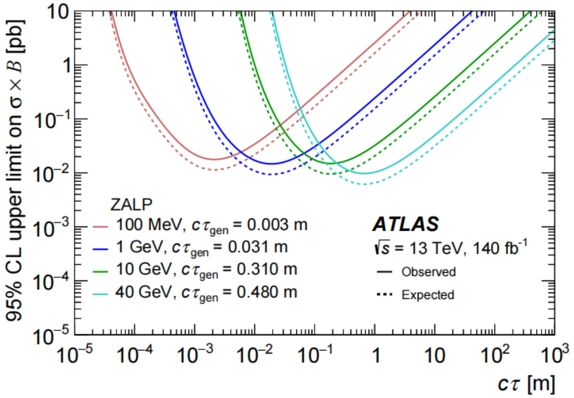


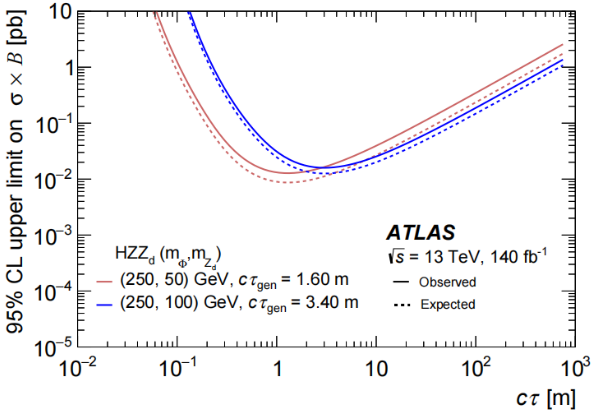


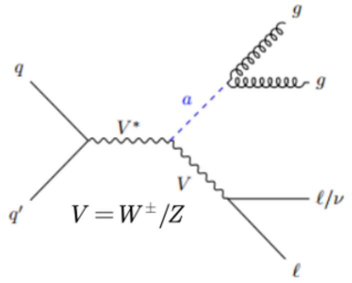
- The CalR+*W*/*Z* channels **provide the first constraints** on the process where a scalar mediator is produced with a vector boson. Higgs boson branching fractions to LLPs above 50% are excluded for cτ in the cm to m range.
- This provide a complementary constraint in a different production mode.

Upper limits Results for ALPs model and Z_d model

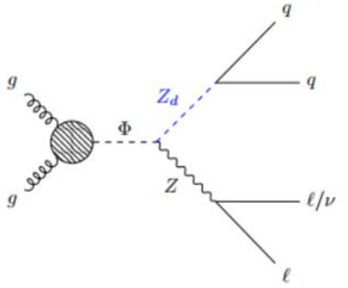








ALP model



Dark photon model

- Constraints on photophobic ALP models are set for the first time with cross-sections above 0.1 pb excluded in the 0.1 mm-10 m range.
- New constraints on the HZZd model are set, which are **more sensitive** than previous results [12] **by an order of magnitude**, with production cross-sections above 0.1 pb excluded for the 20 cm to 50 m range.
- The improvement is because displaced jet identification efficiency and background rejection are improved by using the per-jet NN. And also a four times larger dataset is used.

Summary

- This analysis uses the ATLAS Run 2 dataset of 140 fb^{-1} of pp collisions at $\sqrt{s} = 13\ \mathrm{TeV}$ to search for hadronically decaying LLPs giving rise to displaced jets in the ATLAS HCAL.
- No significant excess of events is observed.
- Constraints on the production cross-section times branching fraction at 95% confidence level are set.
- This analysis is part of a wider programme of searches for LLPs with the ATLAS experiment, and has unique sensitivity to LLP laboratory decay lengths of the order of 1 m.
- It targets signatures involving neutral hadronically decaying LLPs with prompt objects in that decay range for the first time with the aid of ML discriminants.

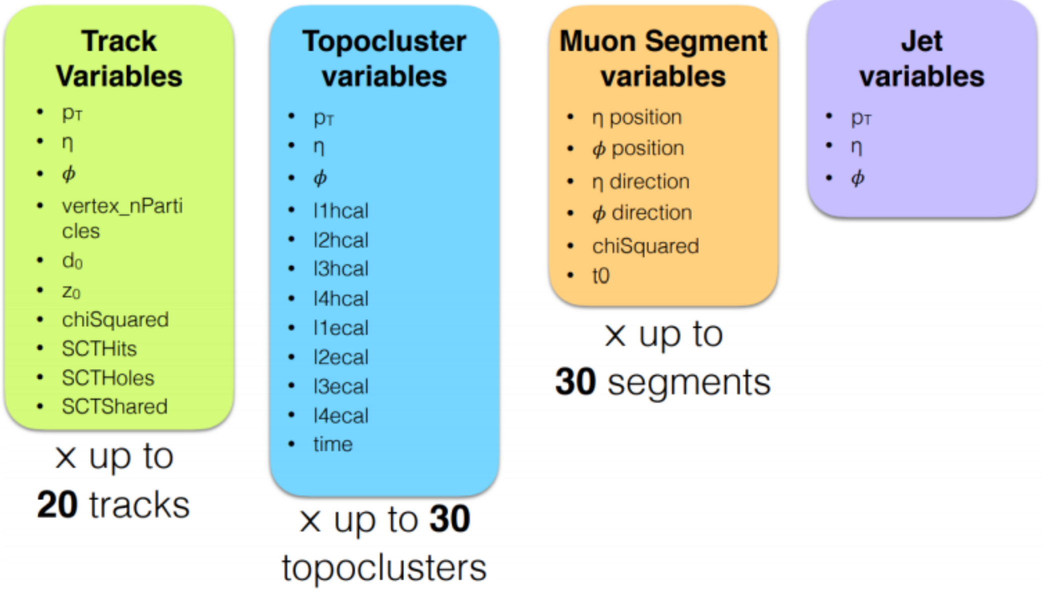
Backup

NN training sample and variables

Samples:

- Signal jet:
  - Use clean Jets
    - Jet passes LooseBadLLP trigger
    - Jet p_T > 40 GeV
    - Jet $|\eta|$ < 2.5
  - For truth particle associated with the jet
    - $|\eta| < 1.4$, $1.2\text{m} < L_{xy} < 4.0\text{m}$ (barrel)
    - $|\eta| > 1.4$, $3.0\text{m} < L_z < 6.0\text{m}$ (end-caps)
- QCD jet:
  - jets from QCD MC samples with 60 GeV < p_T < 800 GeV
- BIB jet:
  - events that pass the HLT CalRatio triggers for BIB but not pass HLT BIB removal algorithms
  - ΔR (BIB HLT jet, offline jet) < 0.4
    - find the offline jet closest to the HLT-triggering jet

Variables for each jet (total 743):



Track Variables
- p_T
- η
- ϕ
- vertex_nParticles
- d_0
- z_0
- chiSquared
- SCTHits
- SCTHoles
- SCTShared

× up to **20** tracks

Topocluster variables
- p_T
- η
- ϕ
- l1hcal
- l2hcal
- l3hcal
- l4hcal
- l1ecal
- l2ecal
- l3ecal
- l4ecal
- time

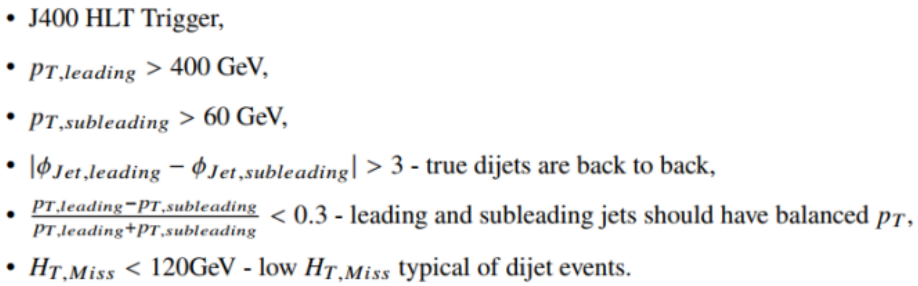
× up to **30** topoclusters

Muon Segment variables
- η position
- ϕ position
- η direction
- ϕ direction
- chiSquared
- t0

× up to **30** segments

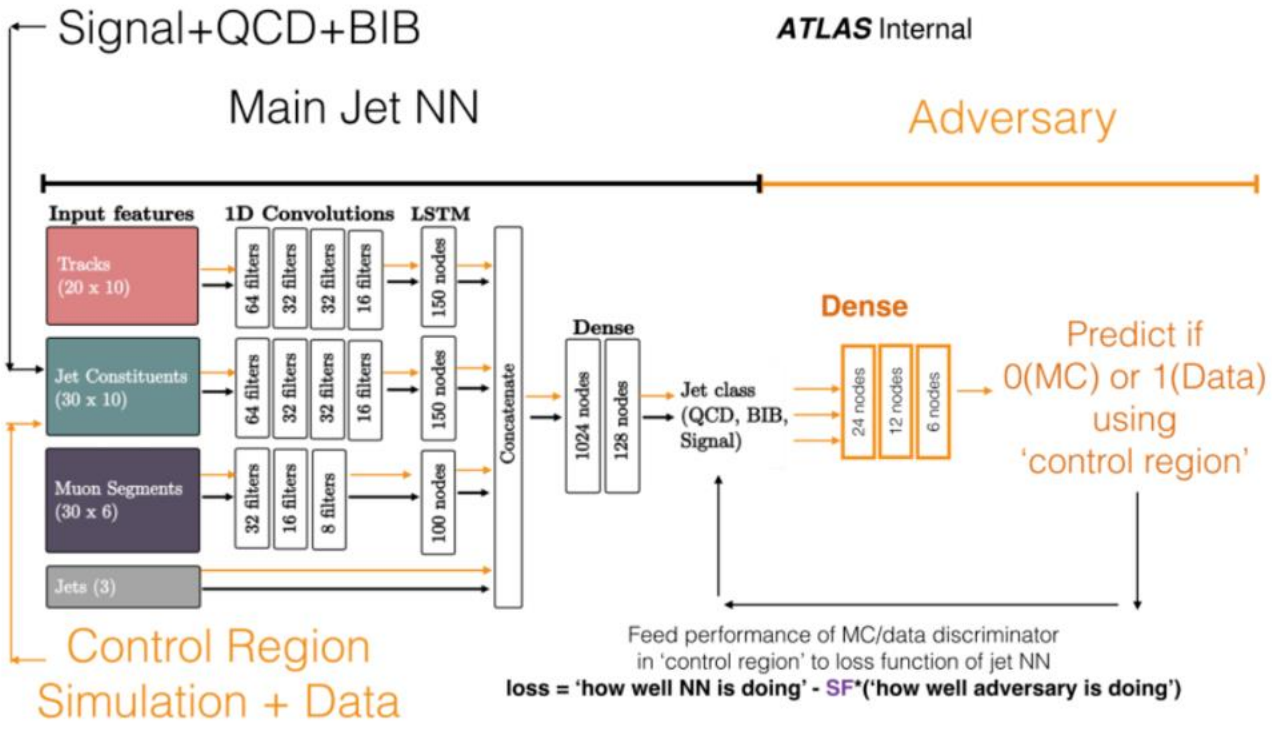
Jet variables
- p_T
- η
- ϕ

Control region for NN training:



- J400 HLT Trigger,
- $p_{T,leading} > 400$ GeV,
- $p_{T,subleading} > 60$ GeV,
- $|\phi_{Jet,leading} - \phi_{Jet,subleading}| > 3$ - true dijets are back to back,
- $\frac{p_{T,leading} - p_{T,subleading}}{p_{T,leading} + p_{T,subleading}} < 0.3$ - leading and subleading jets should have balanced p_T,
- $H_{T,Miss} < 120$GeV - low $H_{T,Miss}$ typical of dijet events.

Machine Learning Method



Signal+QCD+BIB

Main Jet NN

Adversary

Predict if 0(MC) or 1(Data) using 'control region'

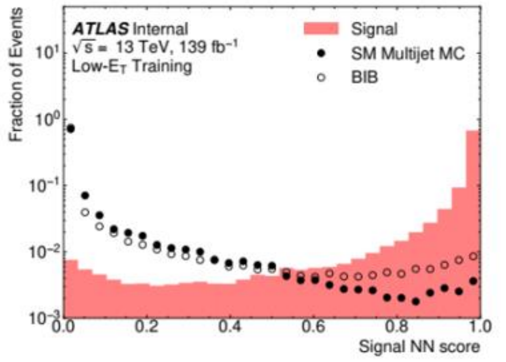
Control Region Simulation + Data

Feed performance of MC/data discriminator in 'control region' to loss function of jet NN

loss = 'how well NN is doing' - SF*('how well adversary is doing')

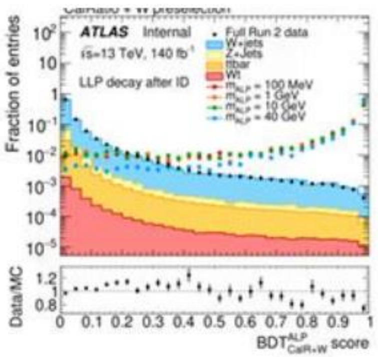
The control region contains selected QCD MC and data samples.

- The NN calculate the correlations of the input variables and use that to predict signal weight, QCD weight and BIB weight.
- An adversary network was added to the network to reduce dependence of output on MC/data mis-modelling
- The adversary network calculates MC, Data scores. Then return **negative loss** of MC, Data cross entropy and **positive loss** of Signal, QCD, BIB cross entropy.

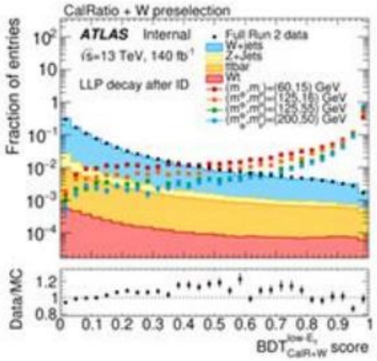


BDT of CalRatio jets + leptons channel

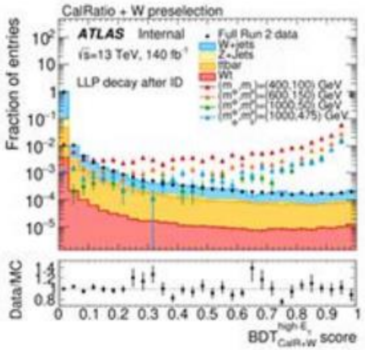
- BDTs are trained with XGBoost corresponding to three input signal sample sets → discrimination of signal and bkg
  - 5 BDTs trained: WALP, low mass WHSS, high mass WHSS, low mass ZHSS, high mass ZHSS
- BDT output as one of the ABCD plane axes



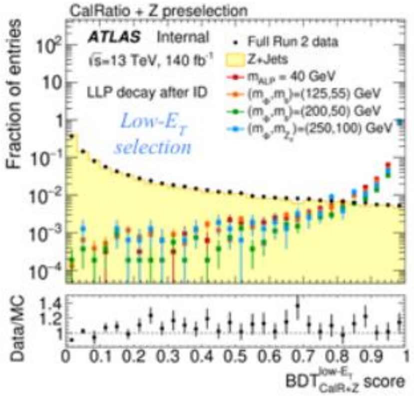
Combination of all WALP mass points

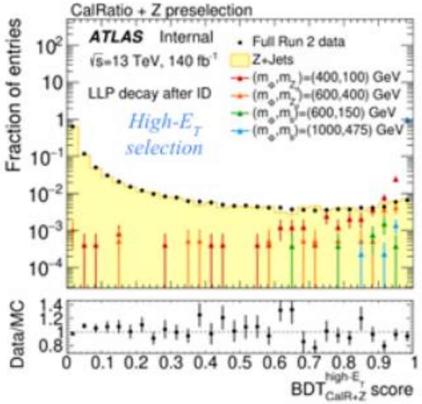


Low ($m_\Phi \leq$ 200 GeV) WHS mediator masses

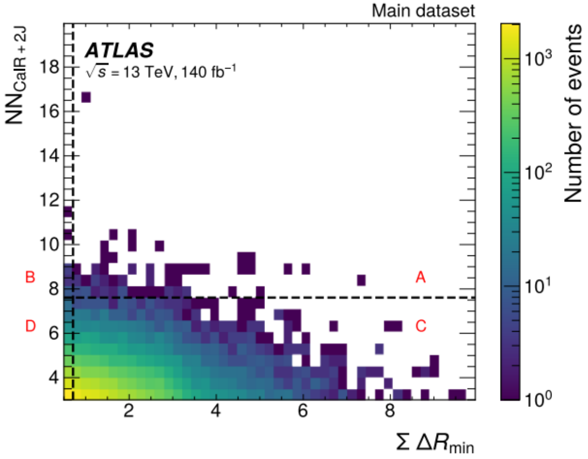


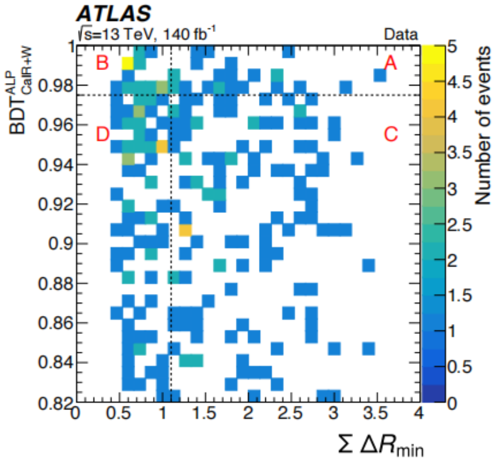
High (m_Φ > 200 GeV) WHS mediator masses

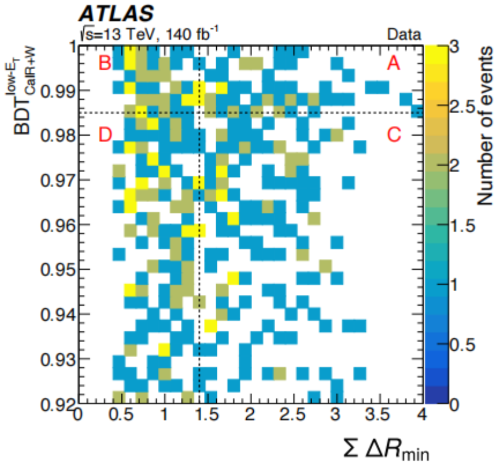


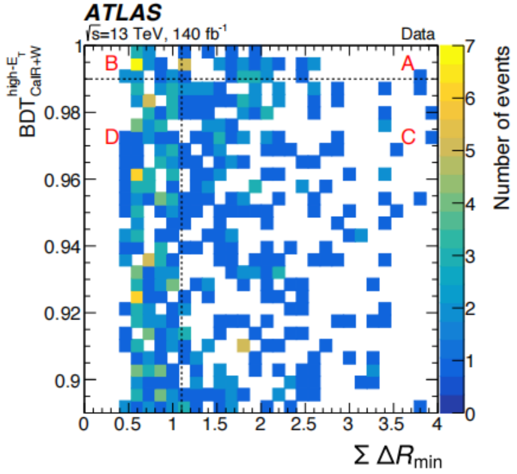


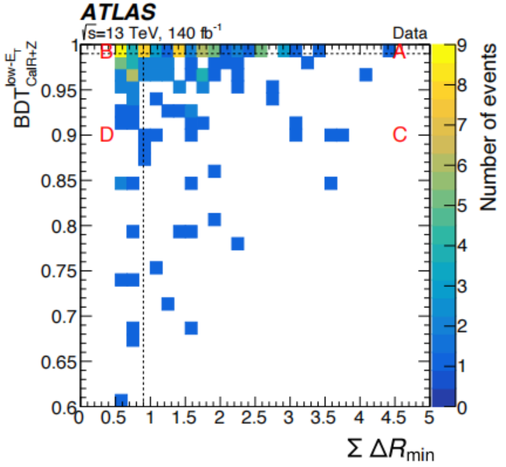
ABCD Plane: background estimation

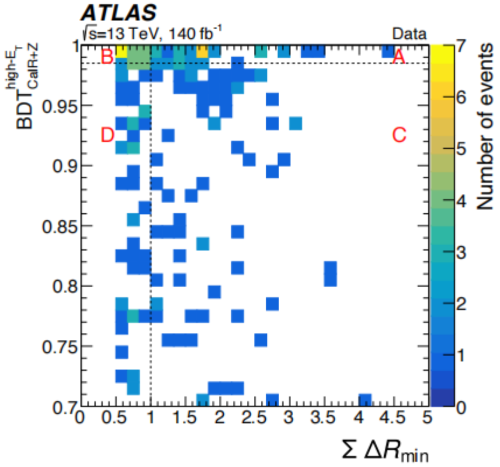






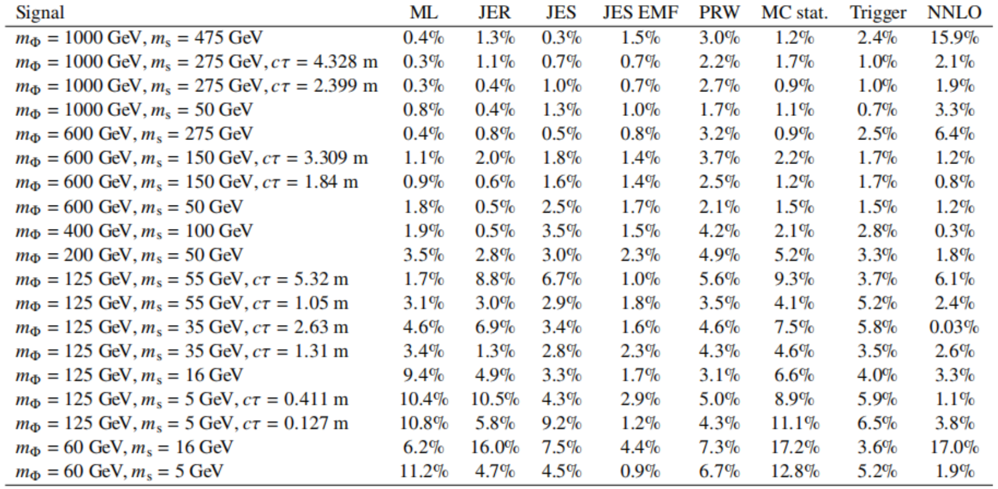






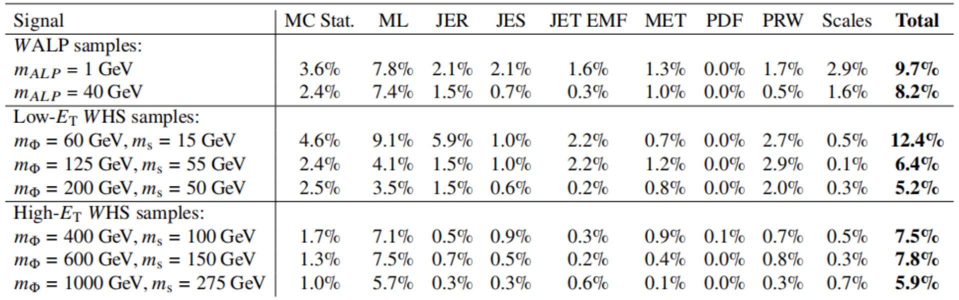
- The maximum uncertainty caused by this background estimate is approximately 5%.

Systematic uncertainties



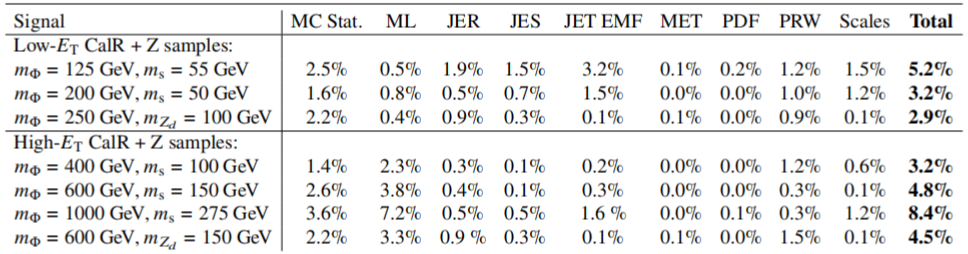
Signal	ML	JER	JES	JES EMF	PRW	MC stat.	Trigger	NNLO
m_Φ = 1000 GeV, m_s = 475 GeV	0.4%	1.3%	0.3%	1.5%	3.0%	1.2%	2.4%	15.9%
m_Φ = 1000 GeV, m_s = 275 GeV, $c\tau$ = 4.328 m	0.3%	1.1%	0.7%	0.7%	2.2%	1.7%	1.0%	2.1%
m_Φ = 1000 GeV, m_s = 275 GeV, $c\tau$ = 2.399 m	0.3%	0.4%	1.0%	0.7%	2.7%	0.9%	1.0%	1.9%
m_Φ = 1000 GeV, m_s = 50 GeV	0.8%	0.4%	1.3%	1.0%	1.7%	1.1%	0.7%	3.3%
m_Φ = 600 GeV, m_s = 275 GeV	0.4%	0.8%	0.5%	0.8%	3.2%	0.9%	2.5%	6.4%
m_Φ = 600 GeV, m_s = 150 GeV, $c\tau$ = 3.309 m	1.1%	2.0%	1.8%	1.4%	3.7%	2.2%	1.7%	1.2%
m_Φ = 600 GeV, m_s = 150 GeV, $c\tau$ = 1.84 m	0.9%	0.6%	1.6%	1.4%	2.5%	1.2%	1.7%	0.8%
m_Φ = 600 GeV, m_s = 50 GeV	1.8%	0.5%	2.5%	1.7%	2.1%	1.5%	1.5%	1.2%
m_Φ = 400 GeV, m_s = 100 GeV	1.9%	0.5%	3.5%	1.5%	4.2%	2.1%	2.8%	0.3%
m_Φ = 200 GeV, m_s = 50 GeV	3.5%	2.8%	3.0%	2.3%	4.9%	5.2%	3.3%	1.8%
m_Φ = 125 GeV, m_s = 55 GeV, $c\tau$ = 5.32 m	1.7%	8.8%	6.7%	1.0%	5.6%	9.3%	3.7%	6.1%
m_Φ = 125 GeV, m_s = 55 GeV, $c\tau$ = 1.05 m	3.1%	3.0%	2.9%	1.8%	3.5%	4.1%	5.2%	2.4%
m_Φ = 125 GeV, m_s = 35 GeV, $c\tau$ = 2.63 m	4.6%	6.9%	3.4%	1.6%	4.6%	7.5%	5.8%	0.03%
m_Φ = 125 GeV, m_s = 35 GeV, $c\tau$ = 1.31 m	3.4%	1.3%	2.8%	2.3%	4.3%	4.6%	3.5%	2.6%
m_Φ = 125 GeV, m_s = 16 GeV	9.4%	4.9%	3.3%	1.7%	3.1%	6.6%	4.0%	3.3%
m_Φ = 125 GeV, m_s = 5 GeV, $c\tau$ = 0.411 m	10.4%	10.5%	4.3%	2.9%	5.0%	8.9%	5.9%	1.1%
m_Φ = 125 GeV, m_s = 5 GeV, $c\tau$ = 0.127 m	10.8%	5.8%	9.2%	1.2%	4.3%	11.1%	6.5%	3.8%
m_Φ = 60 GeV, m_s = 16 GeV	6.2%	16.0%	7.5%	4.4%	7.3%	17.2%	3.6%	17.0%
m_Φ = 60 GeV, m_s = 5 GeV	11.2%	4.7%	4.5%	0.9%	6.7%	12.8%	5.2%	1.9%

CalR+2J



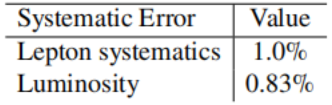
Signal	MC Stat.	ML	JER	JES	JET EMF	MET	PDF	PRW	Scales	**Total**
*W*ALP samples:										
m_{ALP} = 1 GeV	3.6%	7.8%	2.1%	2.1%	1.6%	1.3%	0.0%	1.7%	2.9%	**9.7%**
m_{ALP} = 40 GeV	2.4%	7.4%	1.5%	0.7%	0.3%	1.0%	0.0%	0.5%	1.6%	**8.2%**
Low-E_T *W*HS samples:										
m_Φ = 60 GeV, m_s = 15 GeV	4.6%	9.1%	5.9%	1.0%	2.2%	0.7%	0.0%	2.7%	0.5%	**12.4%**
m_Φ = 125 GeV, m_s = 55 GeV	2.4%	4.1%	1.5%	1.0%	2.2%	1.2%	0.0%	2.9%	0.1%	**6.4%**
m_Φ = 200 GeV, m_s = 50 GeV	2.5%	3.5%	1.5%	0.6%	0.2%	0.8%	0.0%	2.0%	0.3%	**5.2%**
High-E_T *W*HS samples:										
m_Φ = 400 GeV, m_s = 100 GeV	1.7%	7.1%	0.5%	0.9%	0.3%	0.9%	0.1%	0.7%	0.5%	**7.5%**
m_Φ = 600 GeV, m_s = 150 GeV	1.3%	7.5%	0.7%	0.5%	0.2%	0.4%	0.0%	0.8%	0.3%	**7.8%**
m_Φ = 1000 GeV, m_s = 275 GeV	1.0%	5.7%	0.3%	0.3%	0.6%	0.1%	0.0%	0.3%	0.7%	**5.9%**

CalR+*W*



Signal	MC Stat.	ML	JER	JES	JET EMF	MET	PDF	PRW	Scales	**Total**
Low-E_T CalR + Z samples:										
m_Φ = 125 GeV, m_s = 55 GeV	2.5%	0.5%	1.9%	1.5%	3.2%	0.1%	0.2%	1.2%	1.5%	**5.2%**
m_Φ = 200 GeV, m_s = 50 GeV	1.6%	0.8%	0.5%	0.7%	1.5%	0.0%	0.0%	1.0%	1.2%	**3.2%**
m_Φ = 250 GeV, m_{Z_d} = 100 GeV	2.2%	0.4%	0.9%	0.3%	0.1%	0.1%	0.0%	0.9%	0.1%	**2.9%**
High-E_T CalR + Z samples:										
m_Φ = 400 GeV, m_s = 100 GeV	1.4%	2.3%	0.3%	0.1%	0.2%	0.0%	0.0%	1.2%	0.6%	**3.2%**
m_Φ = 600 GeV, m_s = 150 GeV	2.6%	3.8%	0.4%	0.1%	0.3%	0.0%	0.0%	0.3%	0.1%	**4.8%**
m_Φ = 1000 GeV, m_s = 275 GeV	3.6%	7.2%	0.5%	0.5%	1.6 %	0.0%	0.1%	0.3%	1.2%	**8.4%**
m_Φ = 600 GeV, m_{Z_d} = 150 GeV	2.2%	3.3%	0.9 %	0.3%	0.1%	0.1%	0.0%	1.5%	0.1%	**4.5%**

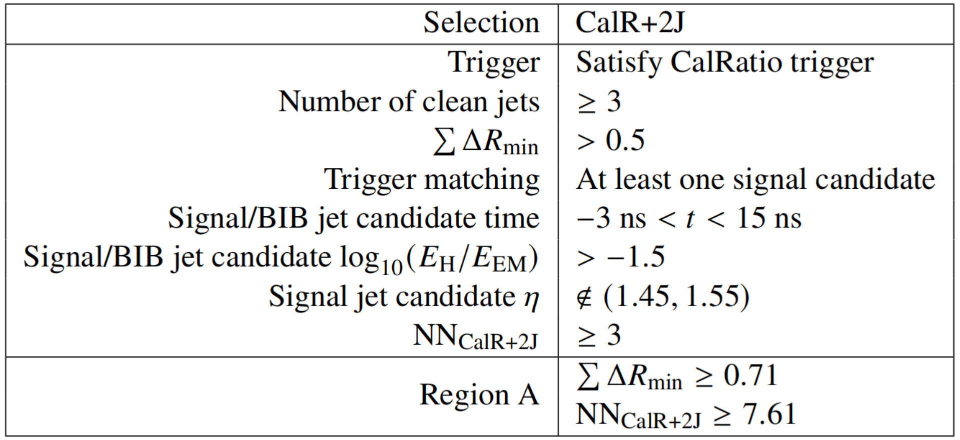
CalR+*Z*



Systematic Error	Value
Lepton systematics	1.0%
Luminosity	0.83%

- For CalR+2J, the largest contribution on signal efficiency comes from jet energy scale (JES) and jet energy resolution(JER): 0.3–16.0%.
- For CalR+*W*/*Z*, the largest contribution on signal efficiency comes from mis-modelling in Machine Learning (ML): 0.4–9.1%.
- Lepton systematics and luminosity errors are independent of the signal model, included in the total systematic uncertainty.

Event selection for CalR+2J



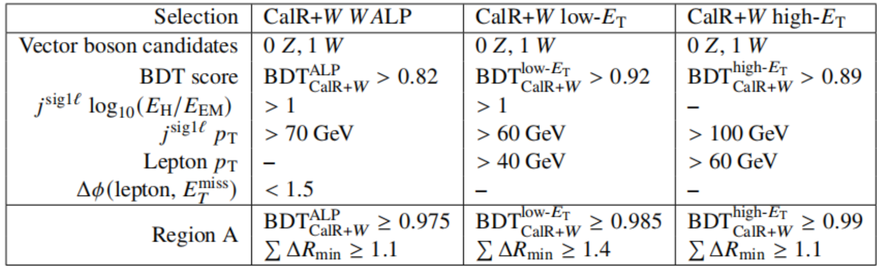
Selection	CalR+2J
Trigger	Satisfy CalRatio trigger
Number of clean jets	≥ 3
$\sum \Delta R_{\text{min}}$	> 0.5
Trigger matching	At least one signal candidate
Signal/BIB jet candidate time	-3 ns $< t <$ 15 ns
Signal/BIB jet candidate $\log_{10}(E_{\text{H}}/E_{\text{EM}})$	> -1.5
Signal jet candidate η	$\notin (1.45, 1.55)$
$\text{NN}_{\text{CalR+2J}}$	≥ 3
Region A	$\sum \Delta R_{\text{min}} \geq 0.71$ $\text{NN}_{\text{CalR+2J}} \geq 7.61$

- Clean jets: $p_{\mathrm{T}} > 40$ GeV, $|\eta| < 2.5$ and satisfy the CalRatio jet cleaning requirement.
- $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$.
- $\Delta R_{\min}$ represents the angular distance between the jet axis and the closest track with $p_{\mathrm{T}} > 2$ GeV.
- $\sum \Delta R_{\min}$: The sum of $\Delta R_{\min}$ over jets with $p_{\mathrm{T}} > 50$ GeV.
- CalRatio jet candidate: Be matched to an HLT jet that meet the criteria of one of the CalRatio triggers. $\Delta R_{\min}$(jet, track) > 0.2 and $\log_{10}(E_{\mathrm{H}}/E_{\mathrm{EM}}) > 1.2$.

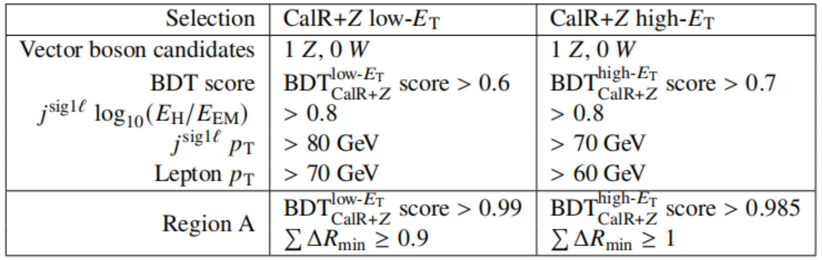
- There must be a candidate in the three jets with the highest signal scores.
- The two other jets represent the resolved additional jets from a second LLP decay.
- t: Relative to the time a particle take to travel at the speed of light directly from the interaction point to the jet's calorimeter location, aiming to reject BIB jets and noise-induced jet candidates.
- The jets with the highest signal scores should not be in the barrel-endcap transition regions.

Event selection for CalR+W/Z

- Preselection:
  - At least one trackless jet with p_{T} > 40 GeV. A trackless jet means a clean jet with $\Delta R_{\min}$ > 0.2.
  - $\sum \Delta R_{\min}$ > 0.5, where the sum runs over jets with p_{T} > 40 GeV.
  - The most signal-like jet:
    - Trackless;
    - p_{T} > 50 GeV;
    - $\log_{10}(E_{\mathrm{H}}/E_{\mathrm{EM}})$ > -1;
    - −3 ns < t < 15 ns;
    - Not be in the barrel-endcap transition regions;
    - NN signal score > 0.4



Selection	CalR+W WALP	CalR+W low-E_{T}	CalR+W high-E_{T}
Vector boson candidates	0 Z, 1 W	0 Z, 1 W	0 Z, 1 W
BDT score	$\mathrm{BDT}^{\mathrm{ALP}}_{\mathrm{CalR}+W} > 0.82$	$\mathrm{BDT}^{\text{low-}E_{\mathrm{T}}}_{\mathrm{CalR}+W} > 0.92$	$\mathrm{BDT}^{\text{high-}E_{\mathrm{T}}}_{\mathrm{CalR}+W} > 0.89$
$j^{\mathrm{sig}1\ell}$ $\log_{10}(E_{\mathrm{H}}/E_{\mathrm{EM}})$	> 1	> 1	–
$j^{\mathrm{sig}1\ell}$ p_{T}	> 70 GeV	> 60 GeV	> 100 GeV
Lepton p_{T}	–	> 40 GeV	> 60 GeV
$\Delta\phi$(lepton, E_T^{miss})	< 1.5	–	–
Region A	$\mathrm{BDT}^{\mathrm{ALP}}_{\mathrm{CalR}+W} \geq 0.975$ $\sum \Delta R_{\min} \geq 1.1$	$\mathrm{BDT}^{\text{low-}E_{\mathrm{T}}}_{\mathrm{CalR}+W} \geq 0.985$ $\sum \Delta R_{\min} \geq 1.4$	$\mathrm{BDT}^{\text{high-}E_{\mathrm{T}}}_{\mathrm{CalR}+W} \geq 0.99$ $\sum \Delta R_{\min} \geq 1.1$



Selection	CalR+Z low-E_{T}	CalR+Z high-E_{T}
Vector boson candidates	1 Z, 0 W	1 Z, 0 W
BDT score	$\mathrm{BDT}^{\text{low-}E_{\mathrm{T}}}_{\mathrm{CalR}+Z}$ score > 0.6	$\mathrm{BDT}^{\text{high-}E_{\mathrm{T}}}_{\mathrm{CalR}+Z}$ score > 0.7
$j^{\mathrm{sig}1\ell}$ $\log_{10}(E_{\mathrm{H}}/E_{\mathrm{EM}})$	> 0.8	> 0.8
$j^{\mathrm{sig}1\ell}$ p_{T}	> 80 GeV	> 70 GeV
Lepton p_{T}	> 70 GeV	> 60 GeV
Region A	$\mathrm{BDT}^{\text{low-}E_{\mathrm{T}}}_{\mathrm{CalR}+Z}$ score > 0.99 $\sum \Delta R_{\min} \geq 0.9$	$\mathrm{BDT}^{\text{high-}E_{\mathrm{T}}}_{\mathrm{CalR}+Z}$ score > 0.985 $\sum \Delta R_{\min} \geq 1$

- For CalR+W:
  - Pass at least one of the single-lepton triggers;
  - Events with more than one lepton are rejected;
  - A W boson candidate is required;
  - The most signal-like jet: $\Delta\varphi(j^{\mathrm{sig}1l}, E_{\mathrm{T}}^{\mathrm{miss}})$ > 0.5, to reject any potential fake electrons.
- For CalR+Z:
  - Pass at least one of the lowest unprescaled single- or di-lepton triggers;
  - A Z boson candidate is required;

$\mathrm{BDT}^{\mathrm{ALP}}_{\mathrm{CalR+W}}$	$\mathrm{BDT}^{\mathrm{low}-E_{\mathrm{T}}}_{\mathrm{CalR+W}}$	$\mathrm{BDT}^{\mathrm{high}-E_{\mathrm{T}}}_{\mathrm{CalR+W}}$	$\mathrm{BDT}^{\mathrm{low}-E_{\mathrm{T}}}_{\mathrm{CalR+Z}}$	$\mathrm{BDT}^{\mathrm{high}-E_{\mathrm{T}}}_{\mathrm{CalR+Z}}$
All WALP mass points	WHSS events with m_{Φ} ≤ 200 GeV	WHSS events with m_{Φ} > 200 GeV	All ZALP mass points, HZZd and ZHSS events with m_{Φ} ≤ 250 GeV	HZZd and ZHSS events with m_{Φ} > 200 GeV

BDTs and their training samples