Search for Long-Lived particles coupled to top-quarks with the ATLAS detector at the Large Hadron Collider at CERN

Clara Carrión Martínez
Instituto de Física Corpuscular, CSIC-UV, València
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The team

University of Washington (US)

GOLUB, Alex
JANUSIAK, Roger Thomas Ralph
OVSIANNIKOVA, Tatiana
WATTS, Gordon

IFIC - Valencia (Spain)

CARRION MARTINEZ, Clara
ESCOBAR IBÁÑEZ, Carlos
TORRÓ PASTOR, Emma

University of Mainz (Germany)

CHRISTIANSEN, Martin
FISCHER, Frederic
MASETTI, Lucia
STEIN, Annika

LPCA Clermont-Ferrand (France)

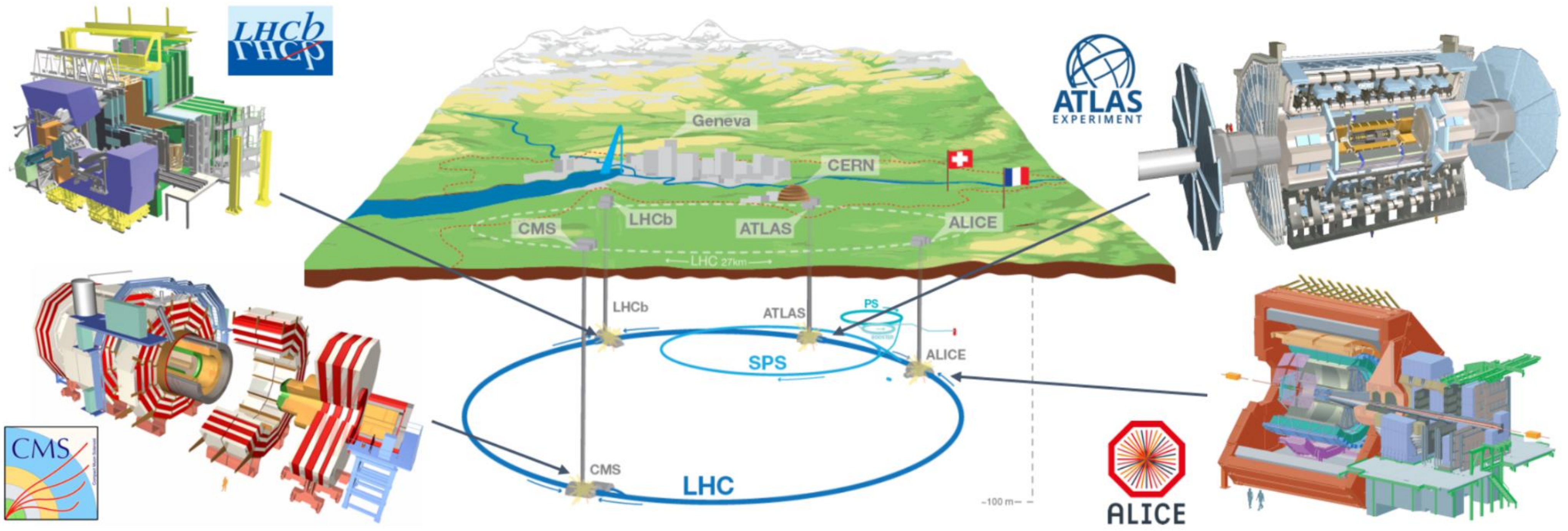
ALHADHUR, Ahlam
CORPE, Louie Dartmoor
LOUIS-CISTAC, Pierre
MISSIO, Marion

USTC (China)

LIU, Yanwen
YE, Feirui

Search for Long-Lived particles coupled to top-quarks with the ATLAS detector at **the Large Hadron Collider at CERN**

The Large Hadron Collider (LHC) at CERN



LHC: *Large Hadron Collider*

Biggest and most powerful hadron collider in the world.

CERN, Geneva, Switzerland.

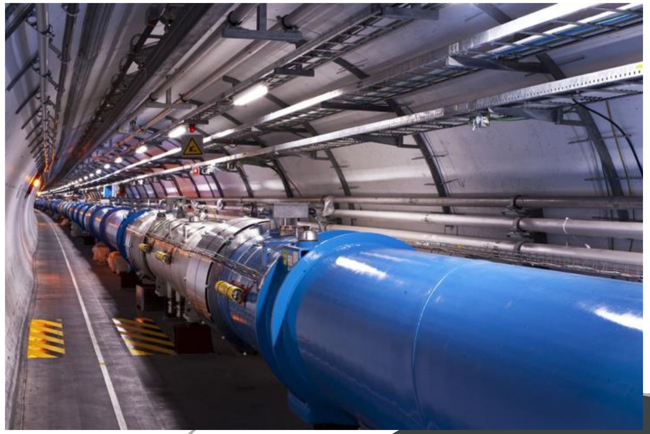
27 km of circumference.

100 m underground.

Energy of the proton/hadron beam up to **6.8 TeV each** (Run 3).

Luminosity up to $2 \cdot 10^{34}$ cm^{-2} s^{-1} (Run 3).

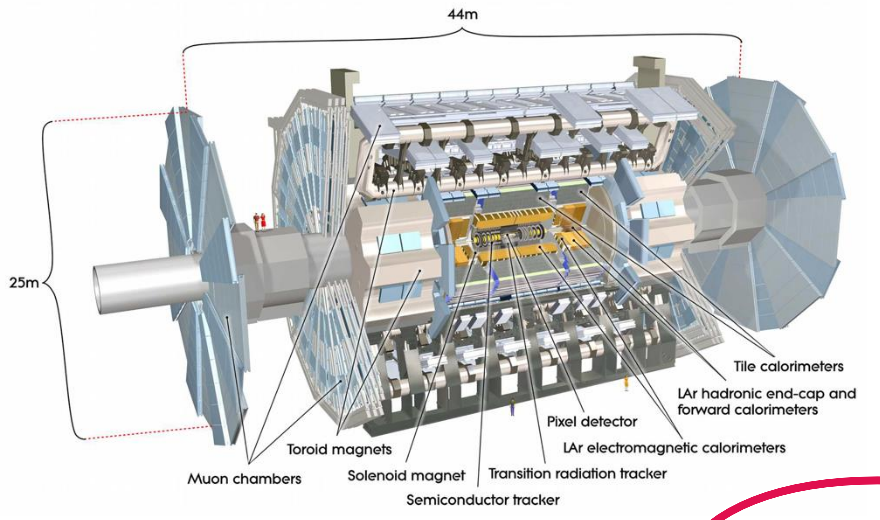
Collision rate: **40 MHz** (1 bunch crossing per 25 ns).

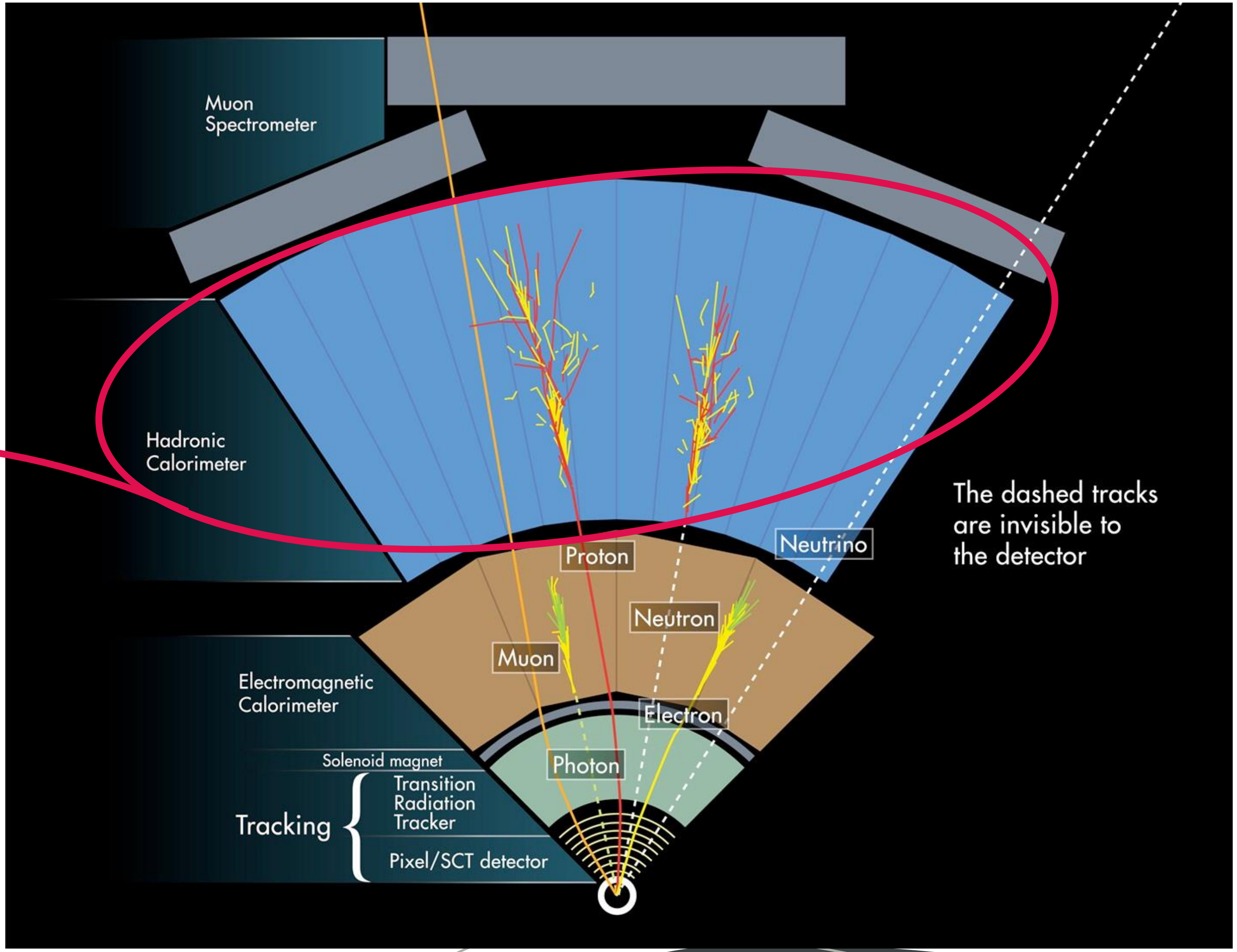


Search for Long-Lived particles coupled to top-quarks **with the ATLAS detector** at the Large Hadron Collider at CERN

The ATLAS experiment at LHC

ATLAS: *A Toroidal LHC ApparatuS*





What do the hadronic objects in the Calorimeters look like?

- **Jets:** collimated set (cluster) of energy produced by the hadronisation of a high-energy quark or gluon.
  - Charged hadrons ($\pi^{\pm}$, $K^{\pm}$, protons…).
  - Neutral hadrons (K^0, neutrons…).

Search for **Long-Lived particles coupled to top-quarks** with the ATLAS detector at the Large Hadron Collider at CERN

Long-lived particles (LLPs) at colliders

Standard Model (SM) particles exist over a wide range of mean proper lifetimes. → **Particles Beyond the Standard Model (BSM) can too!**

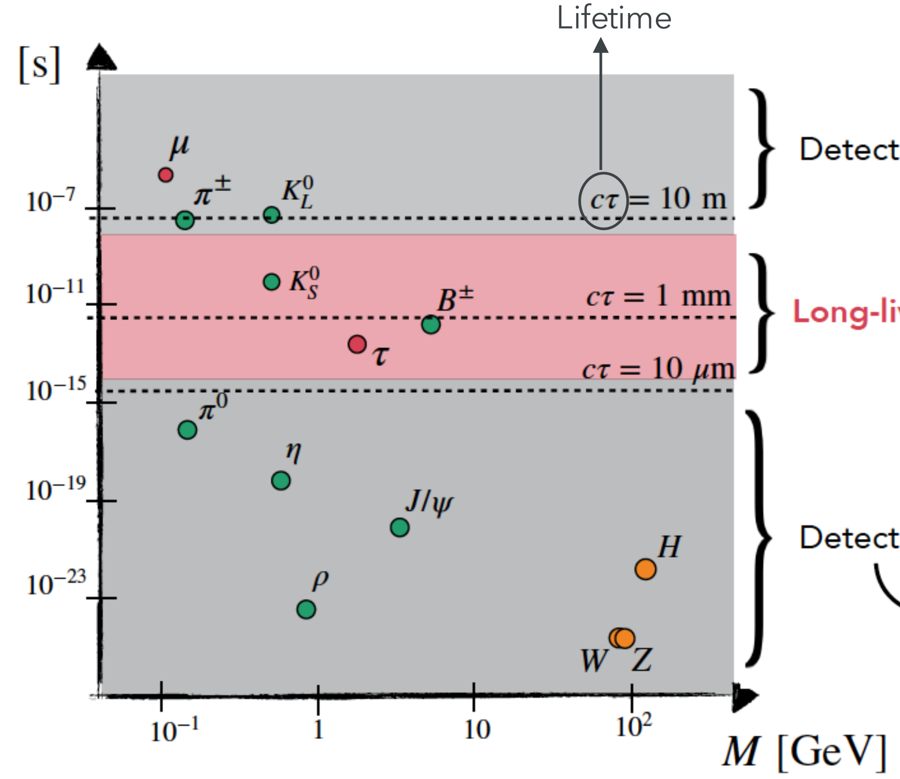


Figure adapted from arxiv:1810.12602

Small couplings

Small mass splittings

Decays via massive particles

can result in **Long-Lived particles (LLPs)**

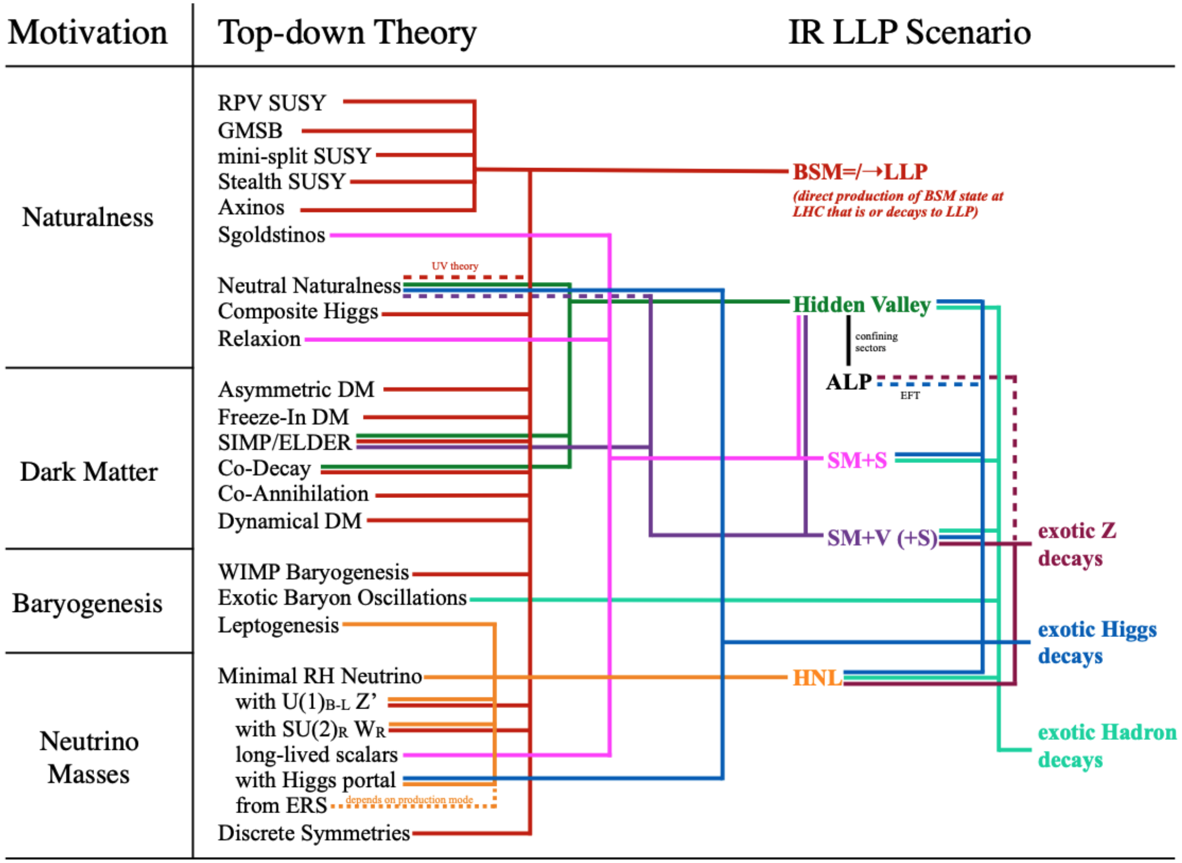
Without dedicated searches, we are missing large corners of potential BSM physics

Axion portal: Long-lived Axion-like particles

Many BSM scenarios:

- Supersymmetry (SUSY)
- Neutral Naturalness
- Dark Matter producing mechanisms
- **Portal interactions between a Hidden Sector (HS) and the SM →** feeble SM–HS interaction mediated by a single new field

$$\mathcal{L} \supset \begin{cases} (\mu S + \lambda S^2) H^\dagger H & \text{scalar} \\ \frac{a}{f}\widetilde{F}_{\mu\nu}F^{\mu\nu} & \text{pseudoscalar} \\ -\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu}F^{\mu\nu} & \text{vector} \\ y_n LHN & \text{neutrino} \end{cases}$$



Axion-like particles (ALPs)

- Pseudo-Nambu-Goldstone bosons - breaking of global U(1) symmetries
- Could couple to any SM particle
  - ALP-fermion coupling ∝ fermion mass

strong motivation to study the ALP coupling to top quarks in LHC experiments

LLPs at colliders: *unconventional detector signatures*

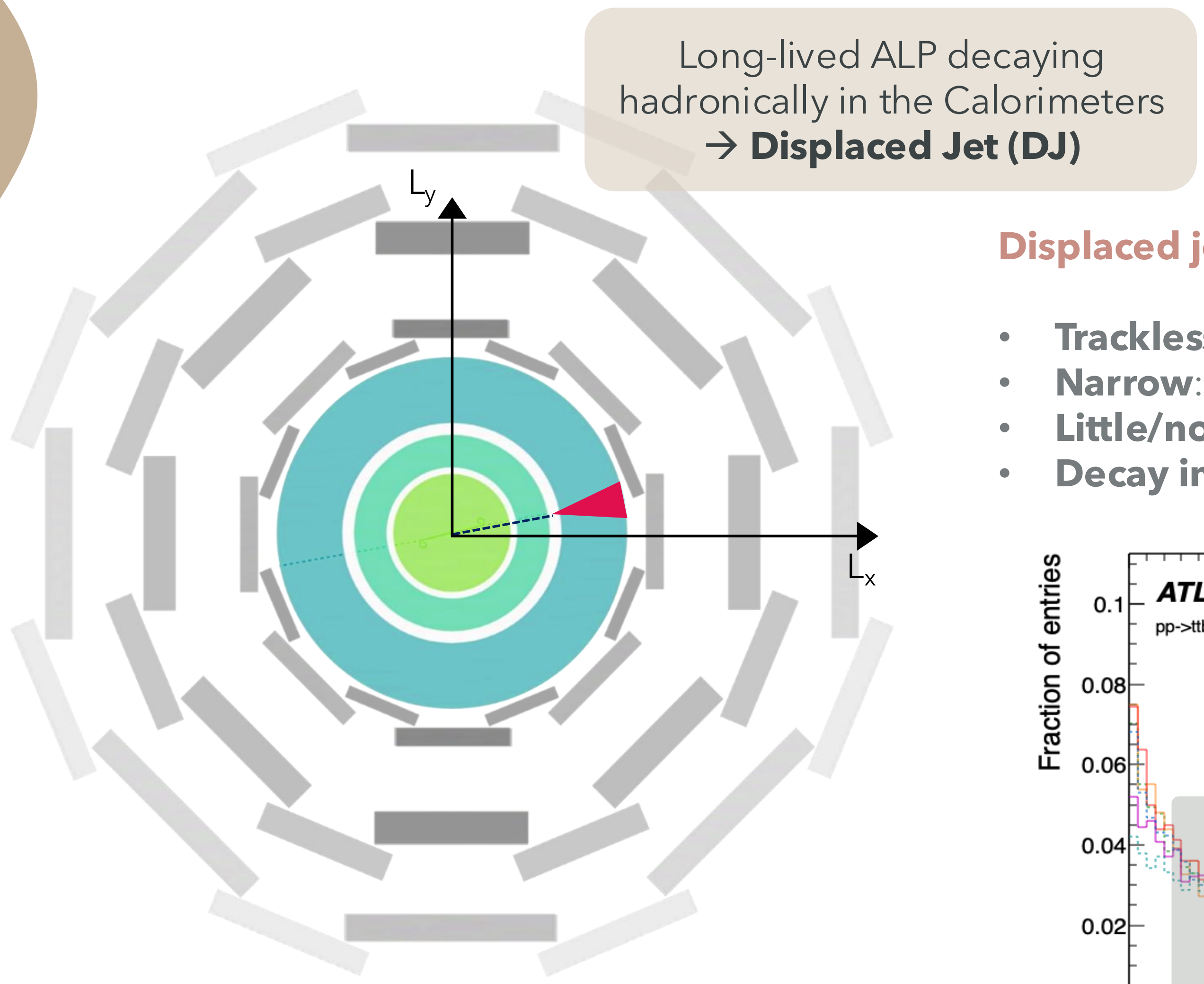
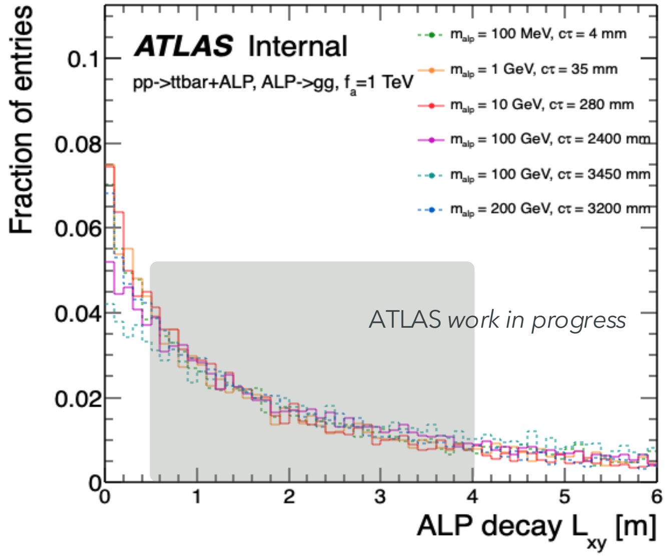
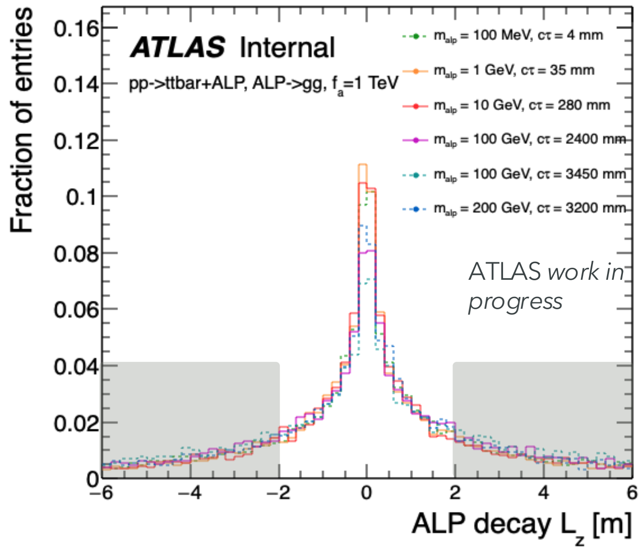


Image credit: Heather Russell

Displaced jet in the Hcal → unusual features compared to SM jets

- **Trackless**: no tracks in the Inner Detector
- **Narrow**: shower starts later, less time to become spatially separated
- **Little/no-energy in the Electromagnetic Calorimeter** (ECal)
- **Decay inside the HCal dimensions**





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Analysis workflow

- Theoretical Benchmark signatures
- Background content
- Event preselection
- Signal identification
- Background estimation

This approach aims to explore, **for the first time in ATLAS**, a specific region in the parameter space of Long-Lived ALP models, potentially leading to the discovery of New Physics

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Theoretical Benchmark signatures

Charming ALP model

[ALPs from the Top - arXiv:2202.09371]

EFT where ALPs only interact with up-type quarks at tree-level:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a}(c_{u_R})_{ij}\bar{u}_{Ri}\gamma^\mu u_{Rj}$$

$$c_{u_R} = \begin{pmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{pmatrix} = \begin{pmatrix} c_{uu} & c_{uc} & c_{ut} \\ c_{cu} & c_{cc} & c_{ct} \\ c_{tu} & c_{tc} & c_{tt} \end{pmatrix}$$

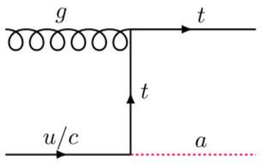
coupling matrix elements

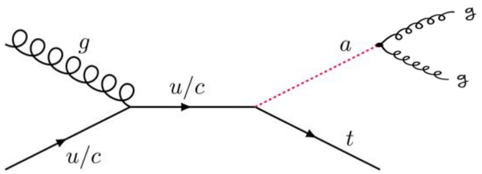
$c_{ij} = 1$ → flavour violating coupling except for

$c_{uc} = c_{cu} = 0$

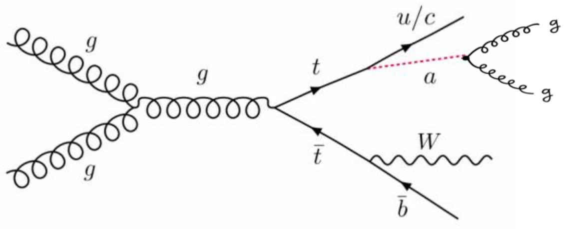
c_{ii} *free parameters for tuning lifetime*

Single top + ALP (DJ)





Top + light q + ALP (DJ)



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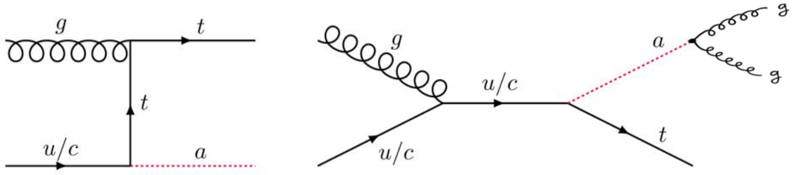

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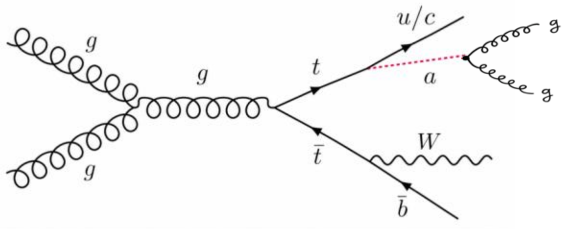


Linear ALP model

[On the coupling of axion-like particles to top quark – arXiv:2303.17634v3]

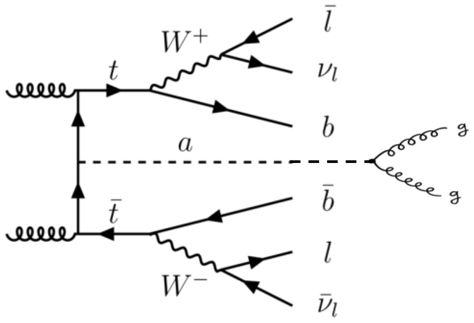
EFT describes the ALP to third-generation fermion couplings as:

$$\mathcal{L} = \frac{\partial_\mu a}{f_a}\left(c_{Q_3}\bar{Q}_L^3\gamma^\mu Q_L^3 + c_{t_R}\bar{t}_R\gamma^\mu t_R + c_{b_R}\bar{b}_R\gamma^\mu b_R\right)$$

$$\mathcal{L} = -i\, c_t \frac{m_t a}{f_a}(\bar{t}\gamma^5 t)$$

Only the ALP-top quark coupling ≠ 0

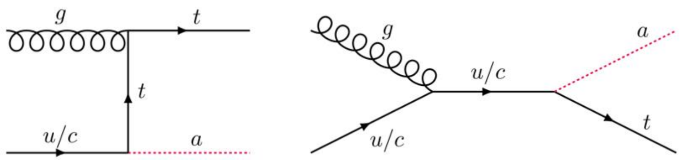
SM $t\bar{t}$ + ALP (DJ)



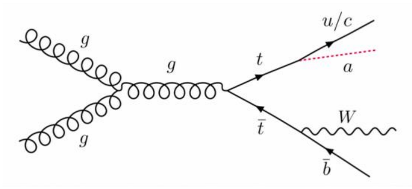
Theoretical Benchmark signatures

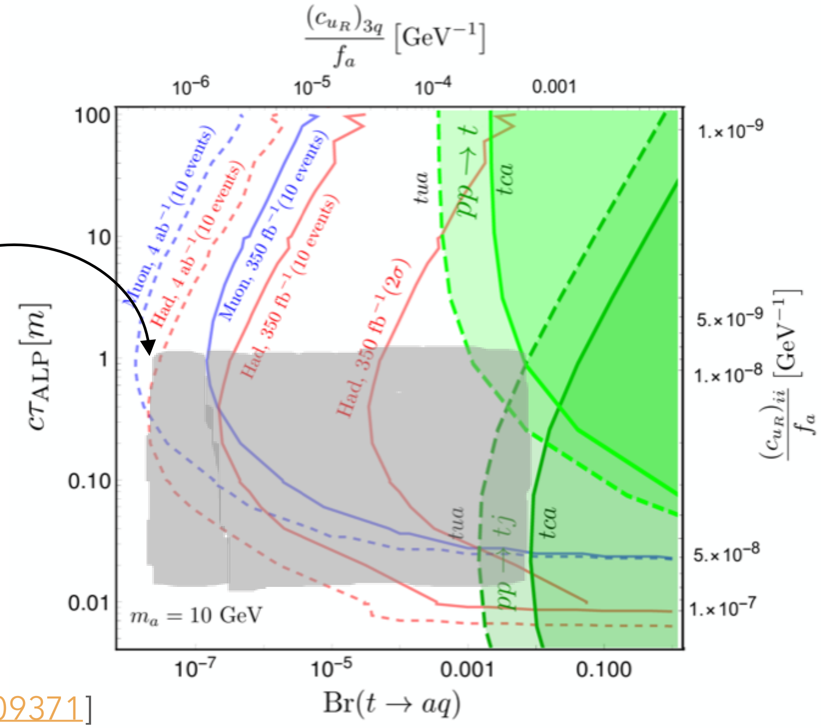
Charming ALP model

Single top + DJ



Top + qDJ



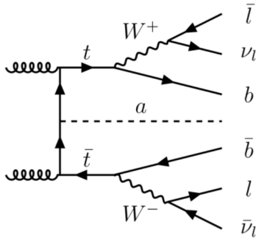


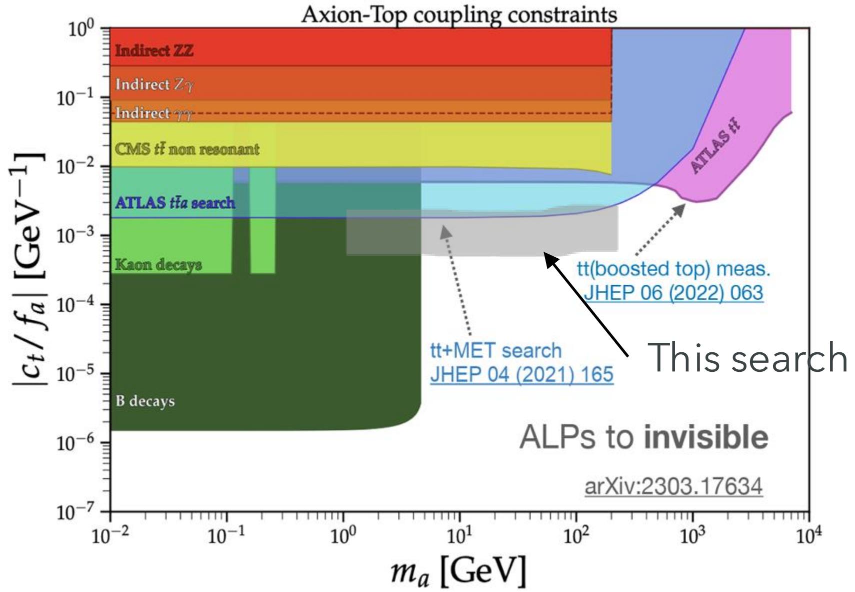
This search

Paper: [arXiv:2202.09371]

Linear ALP model

$t\bar{t}$+ DJ





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- Theoretical Benchmark signatures
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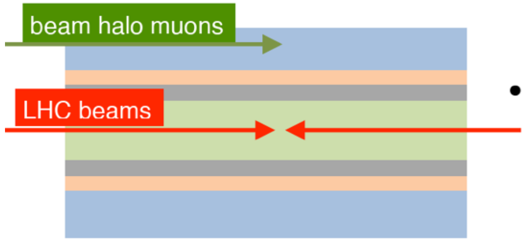
Background content

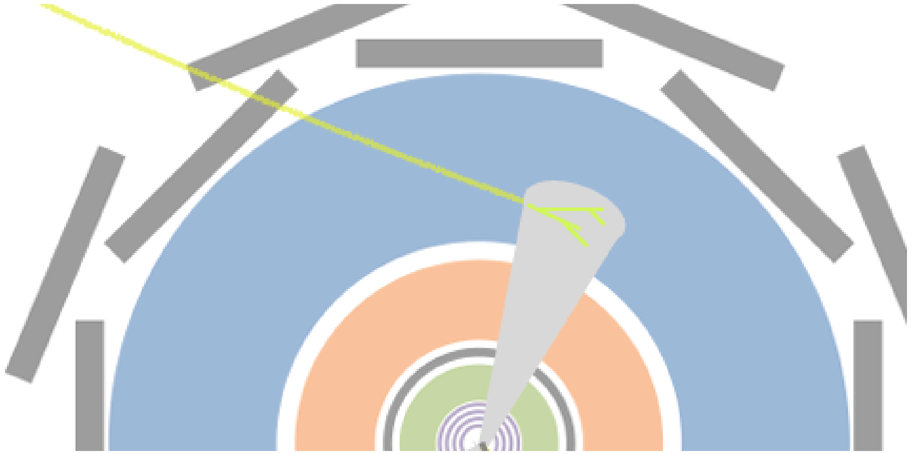
Main Backgrounds:

- **QCD multi jets (SM jets):**
  - dominant background due to high cross-section
  - low probability to mimic signal
- **Beam-induced background (BIB):** muon from bunch interacting with beam pipe undergoing bremsstrahlung in the HCAL
- **Cosmics**: lowest rate.

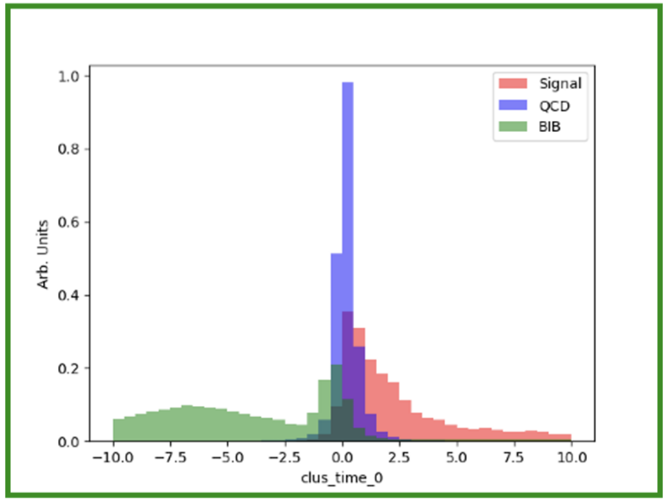
Can all look like trackless, narrow, with low/no energy in the ECal!



- QCD jets
- Beam-induced background (BIB)
- Cosmic Rays



BIB can be differenciated from signal with the timing



BIB travels parallel to the beam pipe: no travel time from IP to Calo!

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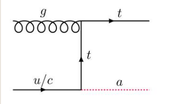
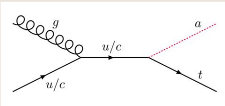
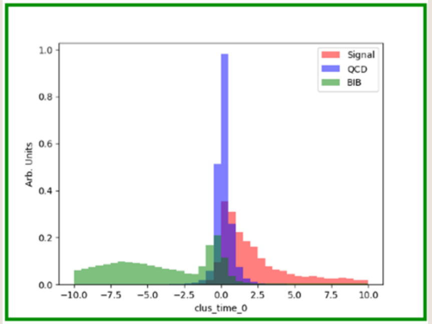
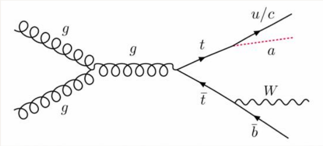
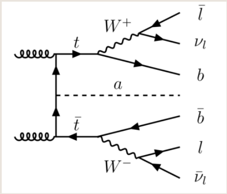
	Signal	Trigger	Event cleaning	Final selection	ALP candidate jet
Single top + DJ  	**ALP →** DJ **Top quark →** 1 b-jet + W decay products (lepton +MET or 2 hadronic jets)	Single lepton	$-3 <$ time(sig; bib) <15 ns $\log_{10}(E_H/E_M) > -1.5$ for jet^{sig}  BIB travels parallel to the beam pipe: no travel time from IP to Calo!	Cuts in top quark decay products e.g: $p_T^{lepton} > 25$ GeV(μ) > 27 GeV(e) MET > 30 GeV $m_{T,W} > 50$ GeV	ALP decay products features p_T(jet^{sig}) Trackless? Ef_{rac} per calo layer Reconstructed as 1 or 2 jet cones? $\Delta R < 0.4 \rightarrow 1$ jet $\Delta R > 0.4 \rightarrow 2$ jet Neural Net for DJ identification
top +qDJ 	**Exotic-top quark →** 1 light jet (u/c) + ALP → DJ **SM anti-top quark →** 1 b-jet + W decay products (lepton +MET or 2 hadronic jets)				
$t\bar{t}$+ DJ 	**ALP →** DJ **Top and anti-top quark** → 2 b-jets + 2 lept + MET or → 2 b-jets + 1 lept + 2 hadronic jets	Single lepton Dilepton			

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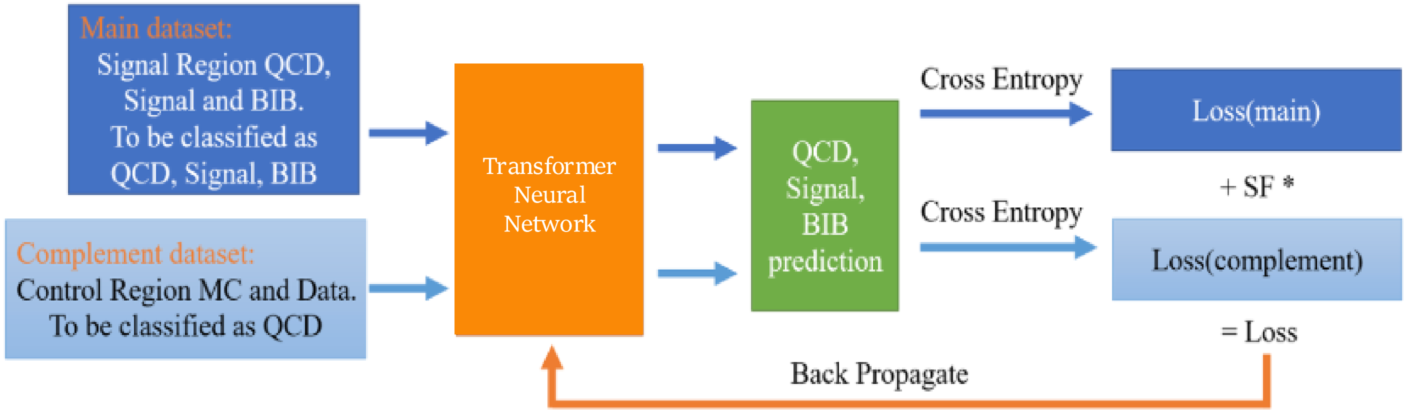
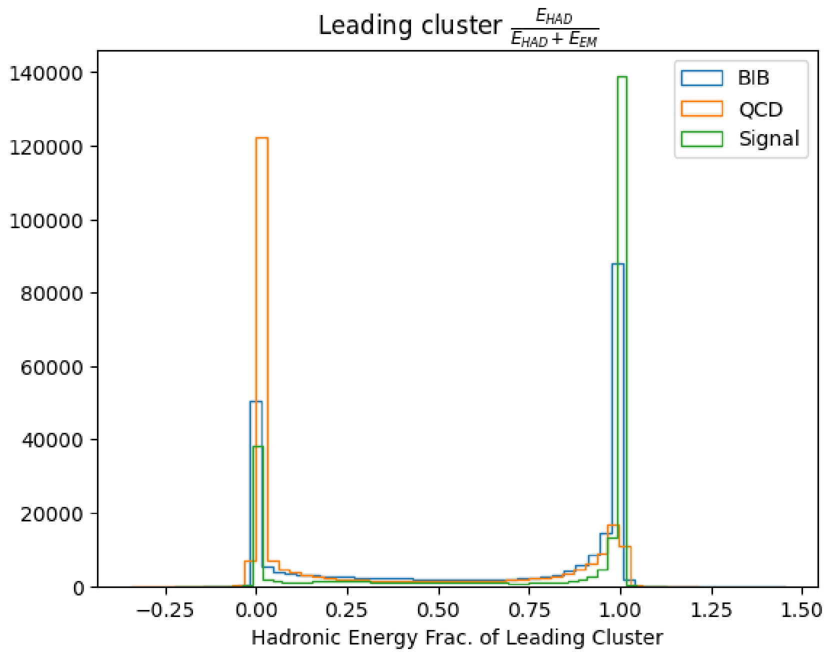
Signal identification: per-jet NN

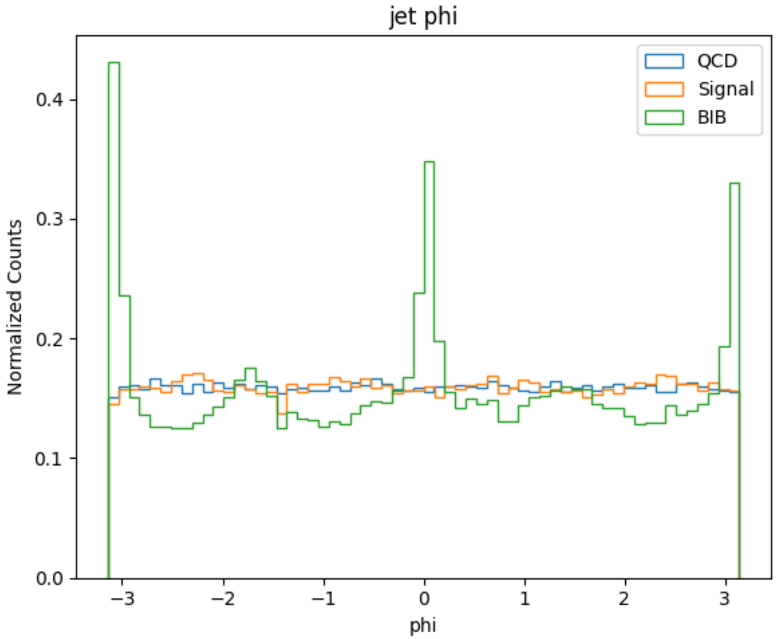
Developing a per-Jet Transformer Neural Network (NN) to classify a jet as signal, QCD-like or BIB

Inputs variables:

- Track variables (p_T, η, ϕ, d_0, z_0 …)
- Jet variables (p_T, η, ϕ)
- Muon segment variables (η and ϕ position, η and ϕ direction, t0 direction)







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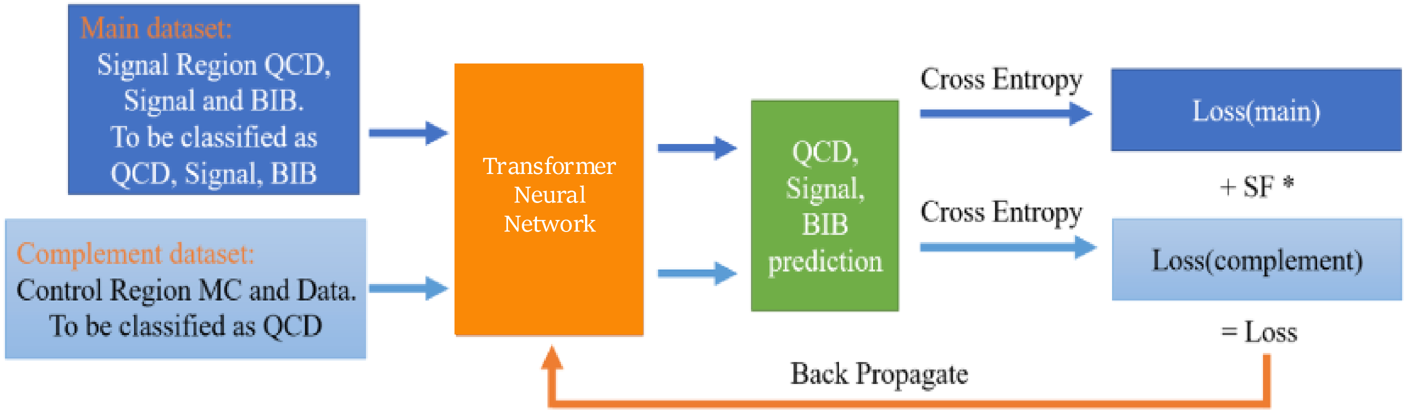

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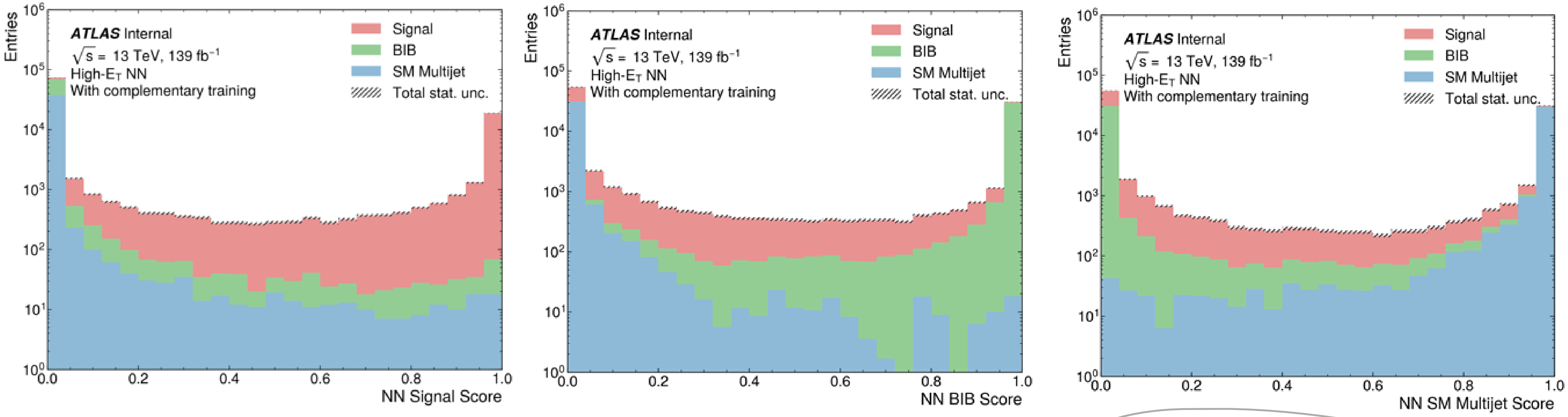
Output: 3 scores for each jet → Signal, BIB or SM-QCD



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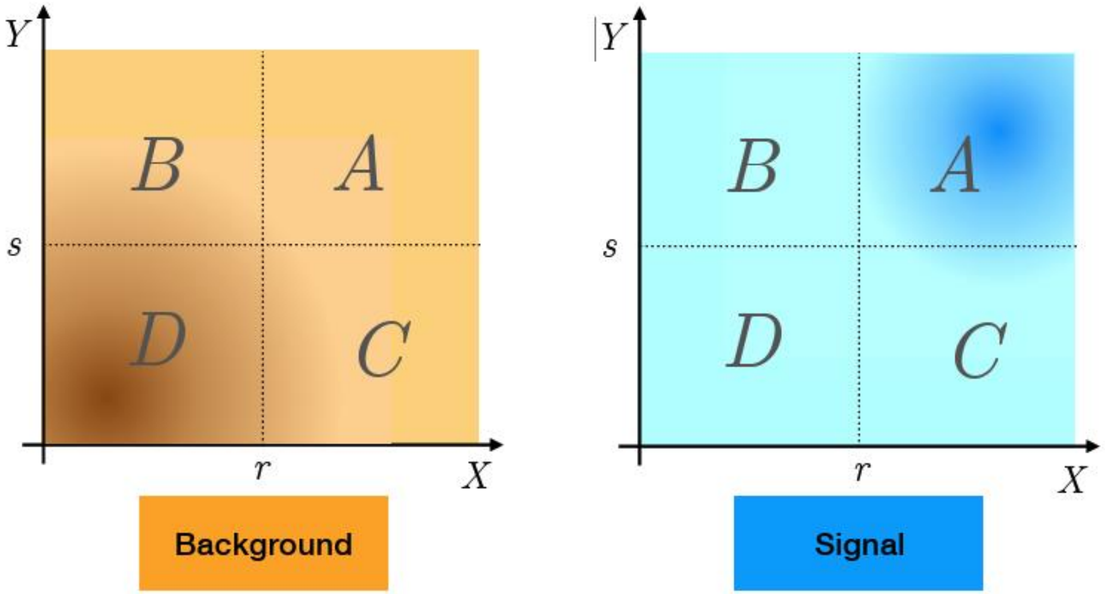
Background estimation

Using only Monte Carlo (MC) simulations leads to:
- Low statistics when removing background
- No MC for BIB

Data driven background estimation - The ABCD method
- Use two uncorrelated variables, divide a plane into 4 regions:
  A (signal region) and B, C, D (control regions)
- **Background content in A** can be estimated as

$$N_{A,\mathrm{bkg}} = \frac{N_B \cdot N_C}{N_D}$$



Summary

- **Long-lived particles** are one of the **most promising** approaches for **Beyond Standard Model theories**
- Two **benchmark model**s based on EFTs: charming ALP & Linear ALP
- A **complete analysis staretgy** is being developed from the scratch
  - Event preselections defined
  - Background content under study
  - Developing new NN for signal identification
  - Developing background estimation techniques to well identify signal from background

Expecting new data coming from HL-LHC era!!

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Thanks for your attention!

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Backup

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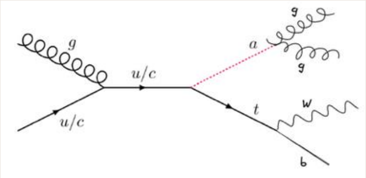
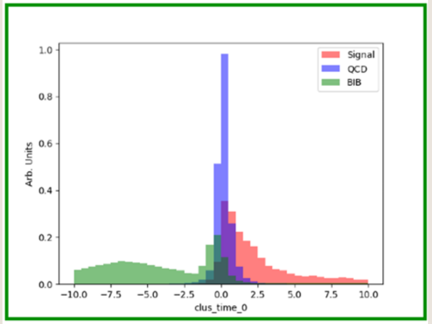
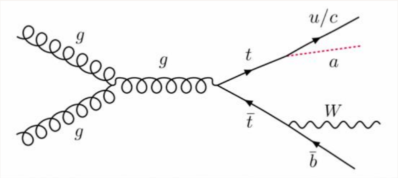
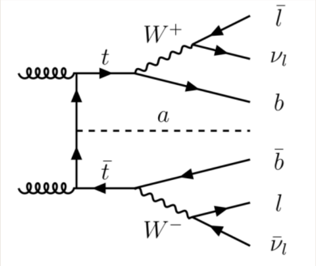
Single top + DJ		Single lepton	$-3 <$ time(sig; bib) <15 ns $\log_{10}(E_H/E_M) > -1.5$ for jet^{sig} BIB travels parallel to the beam pipe: no travel time from IP to Calo!	Cuts in top quark decay products e.g: $p_T^{lepton} > 25$ GeV(μ) > 27 GeV(e) MET > 30 GeV $m_{T,W} > 50$ GeV	ALP decay products features $p_T(jet^{sig})$ Trackless? Ef_{rac} per calo layer Reconstructed as 1 or 2 jet cones? $\Delta R < 0.4 \rightarrow$ 1 jet $\Delta R > 0.4 \rightarrow$ 2 jet Neural Net for DJ identification
top +qDJ					
$t\bar{t}$+ DJ		Single lepton Dilepton			

Long-lived particles (LLPs) at colliders

Decay rate (Γ): probability per unit time that a particle will decay.

For N identical particles, the decay rate satisfies

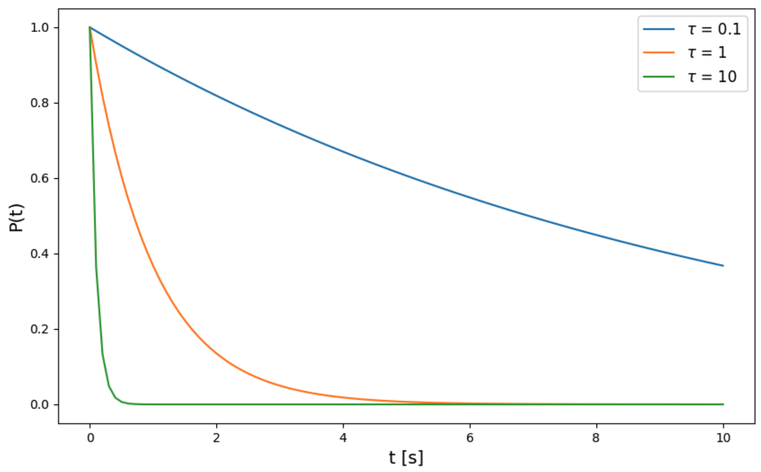
$dN = -\Gamma N dt$

The probability that a particle survives for time t before decaying is thus given by an exponential distribution with time constant $\tau = 1/\Gamma$

$P(t) = \exp(-t/\tau)$

τ is called **the mean proper lifetime** of the particle, governed by.

- The kinematically allowed decay modes of the particle
- The strength of the coupling between the particle and its decay products



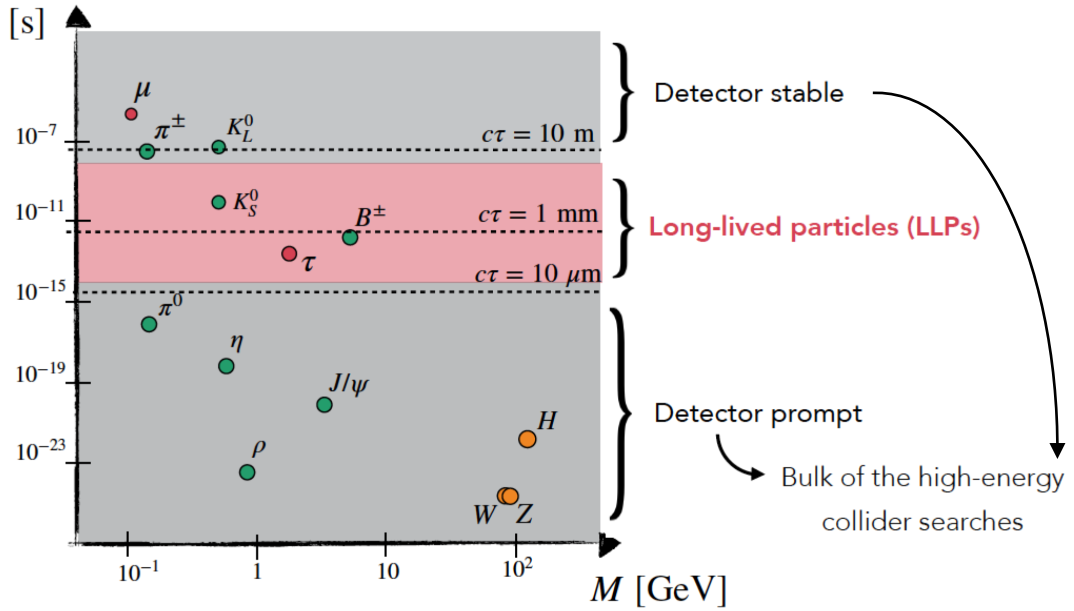


Figure adapted from arxiv:1810.12602

Standard Model (SM) particles exist over a wide range of proper lifetimes. **Particles Beyond the Standard Model (BSM) can too!**

Any model with small couplings, small mass splittings, or decays via off-shell particles can result in **Long-Lived particles (LLPs)**

Without dedicated searches, we are missing large corners of potential BSM physics

Long-lived particles at colliders

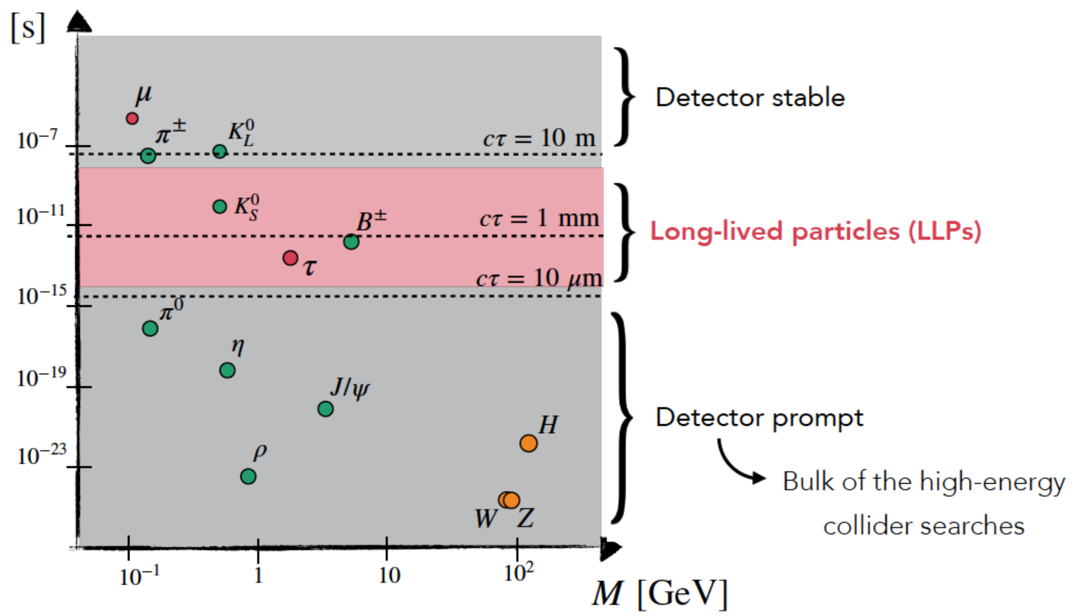


Figure adapted from arxiv:1810.12602

Standard Model particles exist over a great range of proper lifetimes, so **too can particles beyond the Standard Model!**

Any model with small couplings, small mass splittings, or decays via off-shell particles can result in LLPs

Without dedicated searches, we are missing large corners of potential BSM physics

2 Theoretical Motivation for Long-Lived Particles

The proper lifetime of a particle, τ, is given by

$$\tau^{-1} = \Gamma = \frac{1}{2m_X} \int d\Pi_f |\mathcal{M}(m_X \to \{p_f\})|^2 \tag{1}$$

where m_X is the mass of the particle, $\mathcal{M}$ is the matrix element for the particle's decay into the decay products $\{p_f\}$, and $d\Pi_f$ is the Lorentz-invariant phase space for the decay. We use $\hbar = c = 1$. For a particle to be long-lived, there must be a small matrix element and/or limited phase space for the decay. There are several mechanisms that typically lead to a small matrix element. One is an approximate symmetry which would, if exact, forbid the operator that mediates the decay. Small breaking of the symmetry results in a small coupling constant for this operator. Another mechanism arises from an effective higher dimension operator. In this case, the coupling constant is suppressed by powers of the scale $\Lambda >> m_X$ at which the decay is mediated. This, in fact, is the mechanism for long lifetimes in the case of weakly decaying particles in the SM. To summarize, for a model to predict LLPs, it must satisfy at least one of the following:

- (nearly) mass-degenerate spectra
- small couplings
- highly virtual intermediate states.

These conditions, and the LLPs that result from them, are generic features of many BSM models developed to address the big open questions of particle physics mentioned in Sec. 1.

In what follows, we categorize the discussion of LLP mechanisms into models of supersymmetry (SUSY), models of Neutral Naturalness, mechanisms of producing dark matter (DM), and portal interactions between a hidden sector and the SM. We also briefly discuss magnetic monopoles. This section is meant to provide theoretical context for the experimental searches described later in the report, and not as an exhaustive summary of theoretical models. A more detailed description of theoretical models can be found in Ref. [25]. Therefore, we give the most attention to those models in which there are existing searches, in particular models of SUSY. Note that the different mechanism categories are not mutually exclusive. For example, models of SUSY can also give rise to DM, produced via the mechanisms described in Sec. 2.3. We summarize the dominant features that gives rise to long lifetimes for the different scenarios in Table 1.

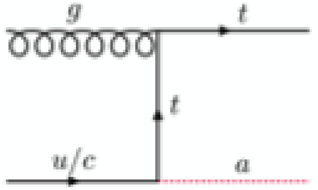
Theoretical Benchmark signatures

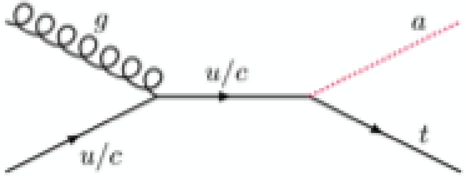
Charming ALP model

Paper: ALPs from the Top - [arXiv:2202.09371]

Single top + DJ

One neutral long-lived ALP decaying to SM fermions in the HCal **and a single SM top quark.**





Upper limit on the cross section (σ_{tj}) of New Physics contributing to pp $\rightarrow$ t + j is $\sigma_{tj} \simeq 0.29$ pb at $\sqrt{s}$ = 13 TeV [1].

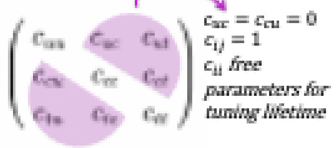
Signature in ATLAS:
ALP → DJ
top quark → 1 b-jet +W decay products (lepton+MET or 2 hadronic jets)

→ Single top quark production in the SM suppressed by the b quark PDF.
→ DJ requirement together with top quark identification can efficiently suppress SM backgrounds.

EFT scenario where ALPs only interact with up-type quarks at tree-level:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a}(c_{u_R})_{ij}\bar{u}_{Ri}\gamma^\mu u_{Rj}$$

$$c_{u_R} = \begin{pmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{pmatrix} =$$

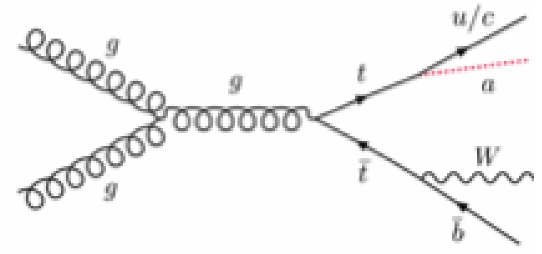


Coupling matrix elements

Flavour violating coupling of the top quark to a lighter quark and an ALP allows for **direct production of the ALP in association with a top quark** (single top + DJ signature) as well as **exotic top decays** (top+qDJ signature).

top+qDJ

A $t\bar{t}$ event with a **SM top quark decay** and an **exotic top quark decay** into long-lived ALP + light up-type quark.



Signature in ATLAS:
top-quark → 1 light-jet + ALP→ DJ
anti-top quark→ 1 b-jet +W decay products (lepton+MET or 2 hadronic jets)

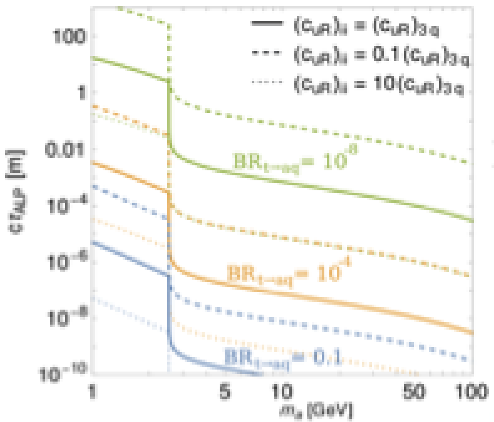
→ High $t\bar{t}$ production cross-section ($\sigma_{t\bar{t}}$) balances small Branching Ratio $\mathrm{Br}(t \rightarrow aq)$.

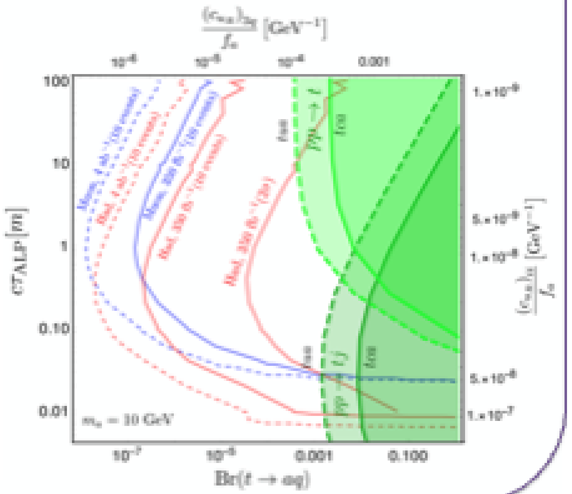
$\sigma_{\mathrm{signal}} = \sigma_{t\bar{t}} \times \mathrm{Br}(t \rightarrow Wb) \times \mathrm{Br}(t \rightarrow aq)$

$\sigma_{t\bar{t}} \sim 830$ pb [2] , $\mathrm{Br}(t \rightarrow Wb) \sim 0.96$ [3]

→ New search strategies using top quark as a **trigger object.**

Masses and scale factors (f_a) optimised to maximize decays in the HCal.

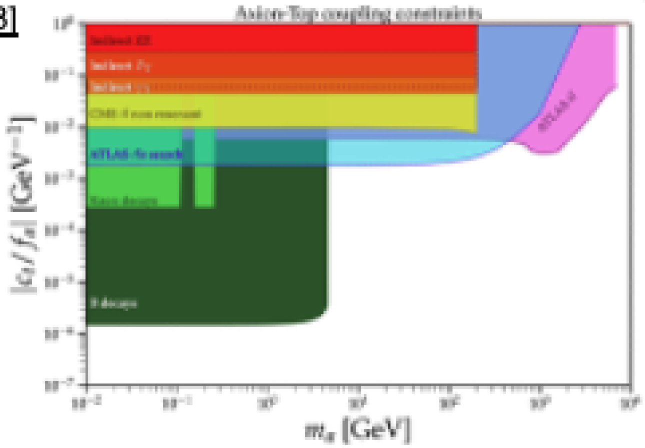




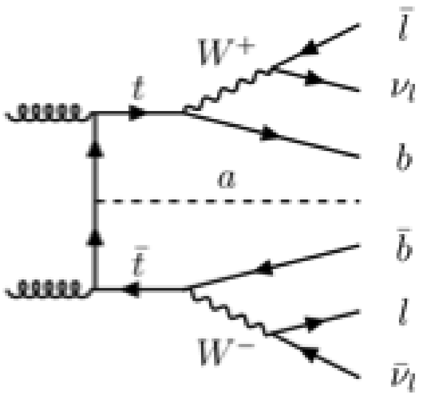
Theoretical Benchmark signatures

Linear ALP model

Paper: On the coupling of axion-like particles to the top quark - [JHEP09(2023)063]



$t\bar{t}$ + DJ → **A SM $t\bar{t}$ event + long-lived ALP.**



Signature in ATLAS:
ALP → DJ
top and anti-top quark
→ 2 b-jets + 2 lept + MET
or
→ 2 b-jets + 1 lept + 2 hadronic jets

Assuming the ALP is associated with a heavy new scale $f_a \gg$ electroweak scale.
An EFT describes the ALP to third-generation couplings as:

$$\mathcal{L} = \frac{\partial_\mu a}{f_a}\left(c_{Q_3}\bar{Q}_L^3\gamma^\mu Q_L^3 + c_{t_R}\bar{t}_R\gamma^\mu t_R + c_{b_R}\bar{b}_R\gamma^\mu b_R\right)$$

$$\mathcal{L} = -i\, c_t \frac{m_t a}{f_a}\left(\bar{t}\gamma^5 t\right)$$

Simplified scenario in which only the ALP-top quark coupling is non-zero. All other couplings ALP-SM fields set to zero at tree-level.

Background estimation & systematics

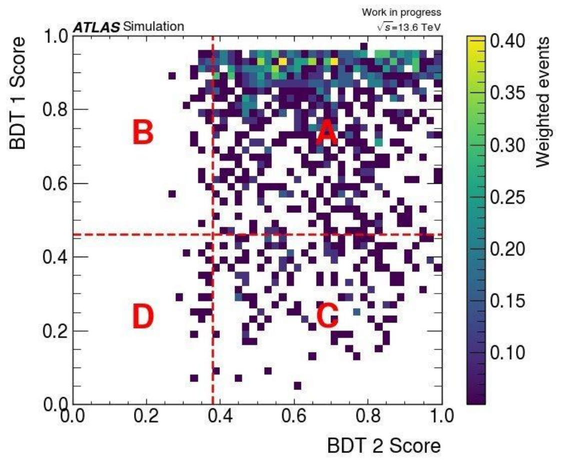
Only using MC leads to:

- Low statistics when removing background
- No MC for BIB

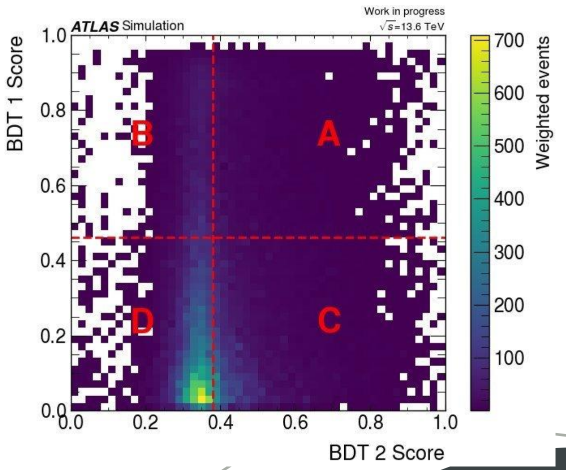
Data driven background estimation: used to predict the expected background yield in the search region given the data in the other three regions

The ABCD method: use two uncorrelated variables, divide plane into 4 regions and use $N_{A,\mathrm{bkg}} = \frac{N_B \cdot N_C}{N_D}$
Goal: estimate the background in the signal region

- Train two BDTs to separate signal from background
- Use decorrelation to keep the BDT scores independent
- Define ABCD regions in the 2D BDT score plane:
  Optimize for expected significance but maintain closure → i.e. keep ABCD prediction consistent with MC expectation



Signal MC



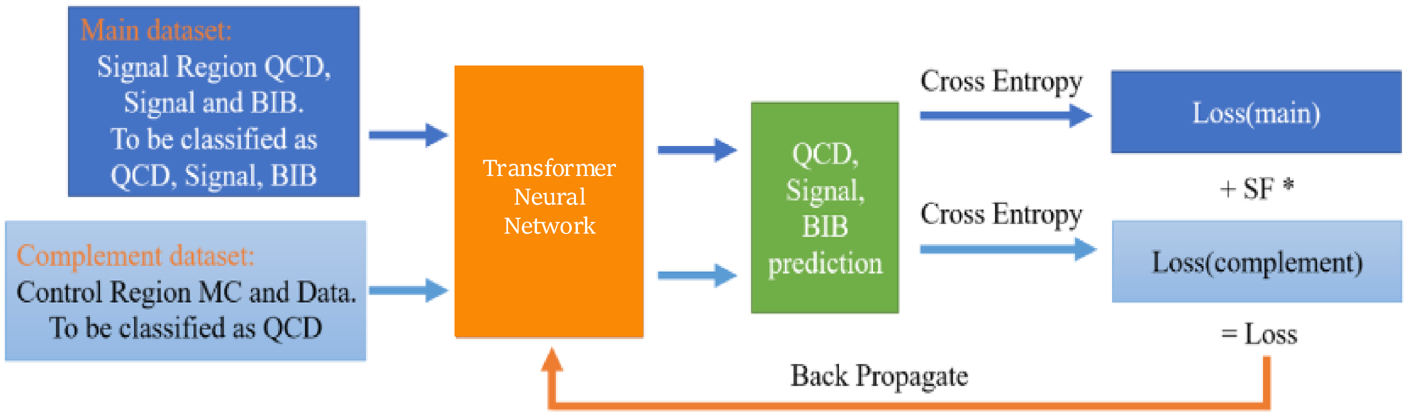
Background MC (ttbar, W+jets, single top)

→Algo de sistemáticos

Signal identification: per-jet NN

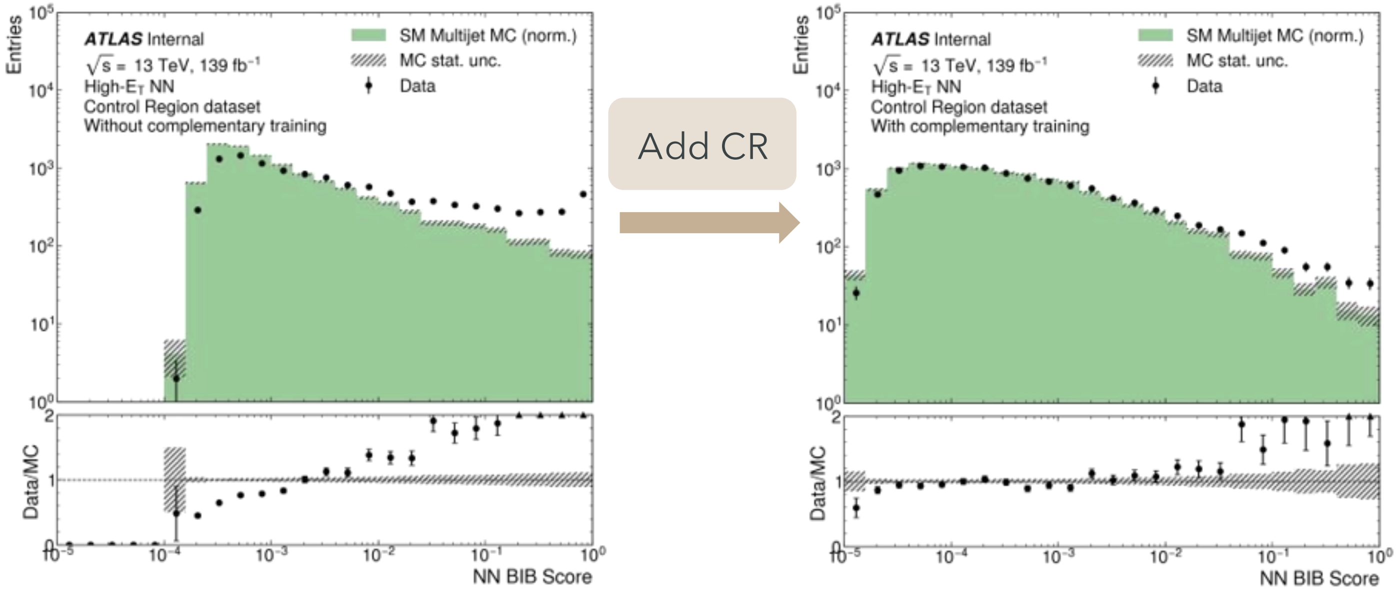
Mismodelling
- Large mismodelling in some variables can lead to data/MC discrepancies e.g: timing

Timing:
- Very useful variable for distinguidh between BIB jets and signal
- Not well modelled in simulations



Solution: Define a QCD **Control Region**

- Complementary training in the TNN comparing data and MC
- Specific preselection to have low signal/BIB contamination, distinct region from training dataset
- Goal - dataset where data/MC are identical except for mismodeled variables



Signal identification: per-jet NN

Timing is a variable that is very useful for distinguishing BIB jets from signal jets; however, it is not modelled correctly. The data timing does not correspond to the timing used in the simulation. This prevents the neural network from learning properly, which would introduce a systematic error. Therefore, timing is a variable that leads to mis-modelling.

mismodelling in some variables can lead to big differences in data/MC performance

Control Region for NN Training Data: creation of a Control Region with only MC and data background to prevent the NN model learning from data/MC mismodeling in classification

CR dataset: multijet events - data and MC

- Specific preselection to have low signal/BIB contamination, distinct region from training dataset
- Goal - dataset where data/MC are identical except for mismodeled variables