Top Secrets: Long-lived ALPs in Top Production

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Top Secrets: Long-lived ALPs in Top Production

Phenomenology study of long-lived ALPs in top-antitop events [arXiv:2306.08686]

Outline:

Introduction
- Axion-Like Particles
- Top Scenario
- Existing ALP searches

Signal and background features
- Event selection
- Categorization

Results
- Expected sensitivity with Run 2/HL-LHC data

Summary and outlook

Top Secrets: Long-Lived ALPs in Top Production

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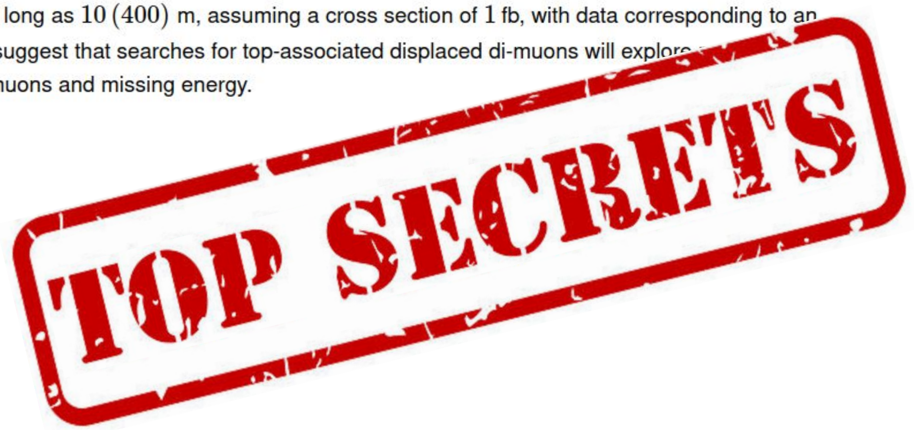
We investigate the discovery potential for long-lived particles produced in association with a top-antitop quark pair at the (High-Luminosity) LHC. Compared to inclusive searches for a displaced vertex, top-associated signals offer new trigger options and an extra handle to suppress background. We design a search strategy for a displaced di-muon vertex in the tracking detectors, in association with a reconstructed top-antitop pair. For axion-like particles with masses above the di-muon threshold, we find that the (High-Luminosity) LHC can probe effective top-quark couplings as small as $|c_{tt}|/f_a = 0.03\,(0.002)/$TeV and proper decay lengths as long as $10\,(400)$ m, assuming a cross section of 1 fb, with data corresponding to an integrated luminosity of 150 fb^{-1} (3 ab^{-1}). Our predictions suggest that searches for top-associated displaced di-muons will explore the current sensitivity gap between searches for prompt di-muons and missing energy.



Axion-Like Particles (ALPs)

Axions:

- Peccei Quinn theory solving the strong CP problem
- Low mass and low energy
- Dark matter candidate
- Axion-two photon interaction

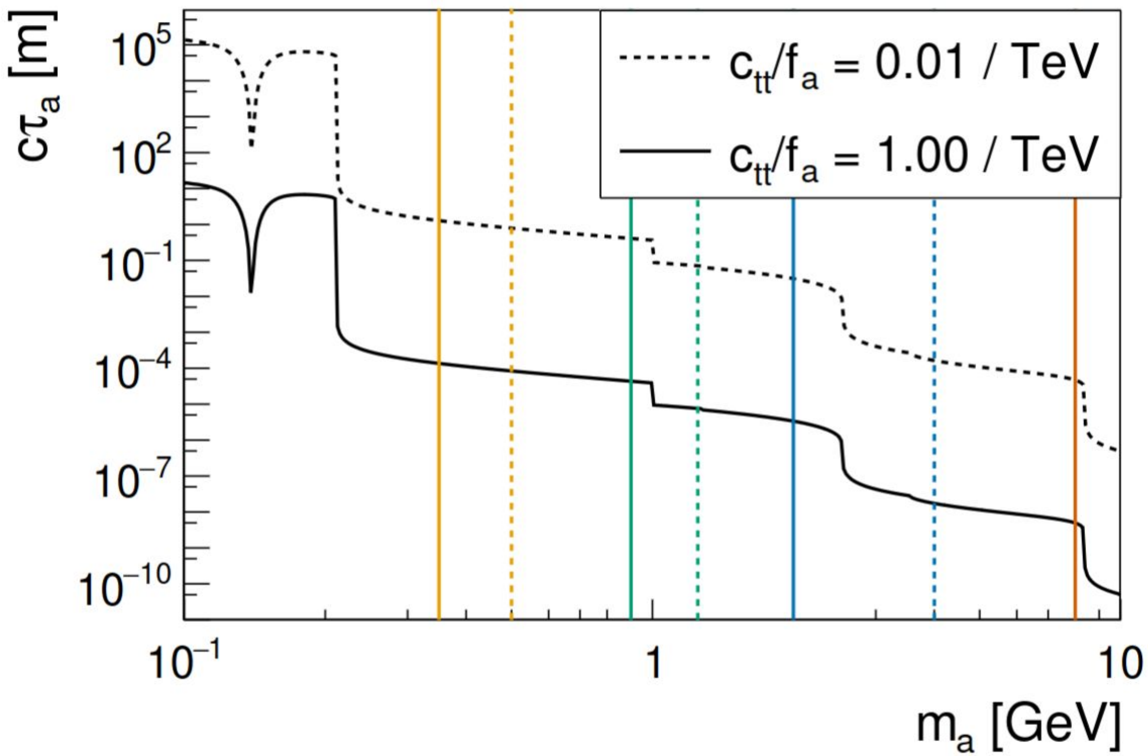
ALPs: more general class of pseudo-scalar particles

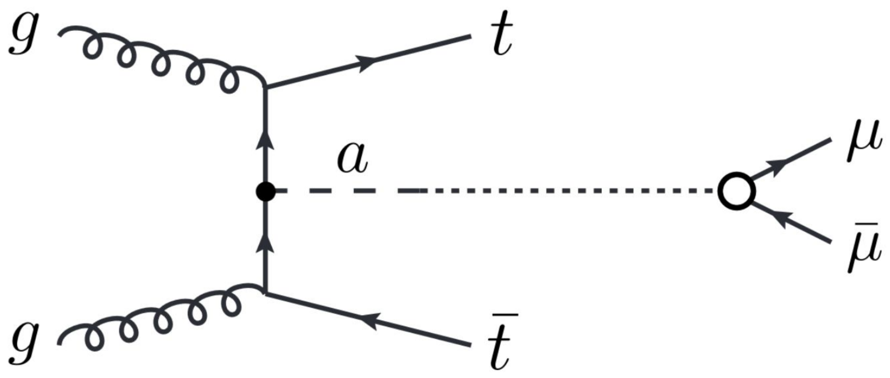
- In models with spontaneous broken global symmetry
- Mass-coupling relation is not fixed
- Occur in many extensions of the SM
- Long-lived signatures for light, weakly coupled ALPs

Axion-Like Particles (ALPs)

Top scenario:

- M.Bauer et al.,
  The low-energy effective theory of axions and ALPs,
  JHEP04(2021)063
- (Pseudo)-scalars are expected to have flavour-hierarchial couplings to quarks and leptons,
  with **the strongest coupling to top quarks**
- Assuming **top coupling only**
- 2 free parameters in the top scenario:
  - ALP mass $\mathbf{m_a}$
  - top-ALP coupling $\mathbf{c_{tt}}$
- Decays:
  - Only top loop-induced, decay width determined by c_{tt}
  - For m_a < 1 GeV ALPs decay predominantly to muons
  - **Long lifetimes** for lighter ALPs





ALPs searches at the LHC

- There exist a large variety of searches for ALPs
- Probe different regions of phase space, couplings and lifetimes
- This analysis is **complementary to existing studies**

top coupling
ℓ coupling
γ coupling
q coupling (not top)
top + missing energy
Pheno studys

Displaced

This analysis

2-10 GeV, JHEP 07(2022)122, hadronic decays

0.2-4.4 GeV, LHCb PRL 115, 161802, B decays

0.3-5 GeV, CMS JHEP04(2022)062, scouting

Prompt

15-72 GeV, ATLAS arxiv:2304.14247

0.2-3 GeV, LHCb JHEP 10(2020)156

0.3-5 GeV, LHCb PRD 95.071101, B decays

0.5 - 4 GeV ATLAS PRL 125.221802, H/Z production

5.5-15 GeV, LHCb JHEP09(2018)147

4-15 GeV, CMS PLB 2019.135087, H decays

3.6-21 GeV, CMS JHEP08(2020)139, H decays

15-30 GeV, ATLAS PRD 102.112006, H decays

16-62 GeV, ATLAS CONF-2021-009, H decays

20-62 GeV, CMS PLB 2019.06.021, H decays

6-100 GeV, ATLAS JHEP03(2021)243, UPC HI

5-90 GeV, CMS PLB 2019.134826, UPC HI

350-1600 GeV, CMS+TOTEM EXO-18-014

single-top + missing energy: 10-1000 GeV PRD 96.3 035031, 500-5000 GeV ATLAS JHEP05(2019)041, 0-1000 GeVATLAS EPJC75(2015)79

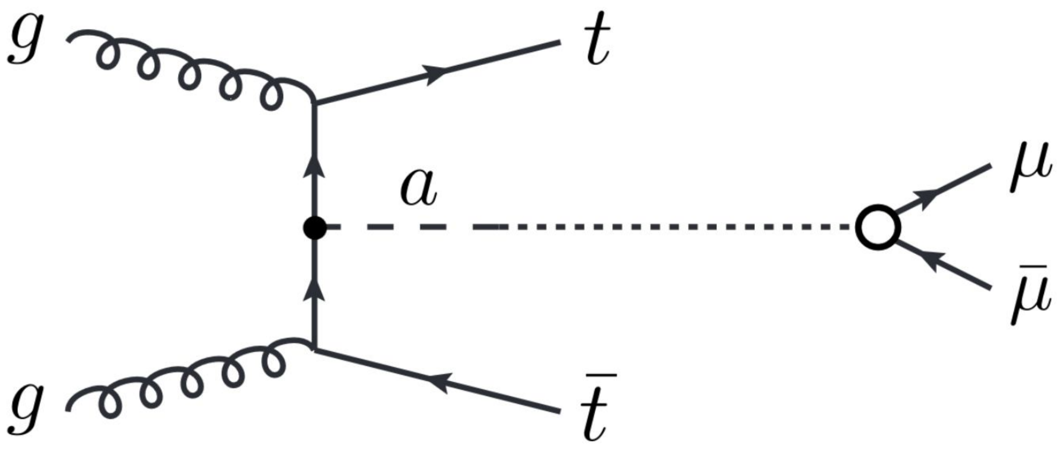
$t\bar{t}$ + missing energy: 10-500 GeV JHEP 02(2017)131, < 200 GeV arXiv:2303.17634, 10-500 GeV PRD 98.1 015012, 100 GeV CMS JHEP06(2015)121, 10-500 GeV CMS EPJC77.845, 10-500 GeV CMS JHEP03(2019)141, 10-300 GeV CMS PRL122.011803, 5-3000 GeV ATLAS EPJC 75(2015)92

m_a (not to scale)

$t\bar{t}$ + ALPs

Searching for ALPs at the LHC

- Focusing on **decays to a muon-antimuon pair**, therefore have excellent:
  - tracking
  - identification
  - secondary vertex resolution
- **top-antitop ($t\bar{t}$) events:**
  - a natural place to look for ALPs
  - triggering on tops allows accessing lower masses
  - improved sensitivity compared to inclusive displaced di-muon searches
- Assuming:
  - 100% efficient top trigger
  - 100% efficient top-tagging
- Focus on ALP masses within the range $2 \cdot m_\mu < m_a < 2 \cdot m_b$

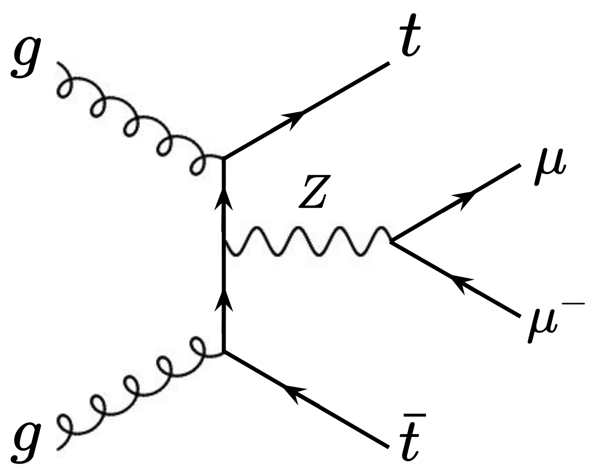


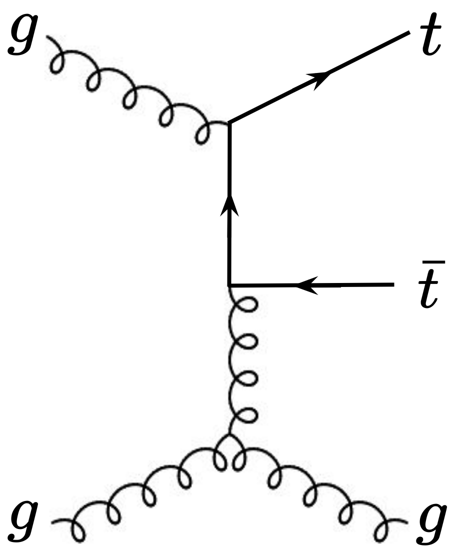
Backgrounds

We consider two background processes for our analysis:

$t\bar{t}Z^{(*)}$:

- A virtual or resonant Z boson (or photon) decays/converts into a di-muon
- (Nearly) prompt muons from the Z boson





$t\bar{t}$ + jet:

- Hadrons inside the jet decay into two opposite-sign muons
- Muons from meson decays can be displaced
- Di-muons originating from the same particle (eg. J/Ψ): “resonant”
- Di-muons from decays of two different particles (e.g. 2 different mesons): “non-resonant”

Signal and background features

Event simulation

Generated samples with MadGraph5 and Pythia 8

Event selection

We apply selection criteria in two stages:

- Pre-selection: events with a displaced di-muon
- Signal selection: suppressing background events

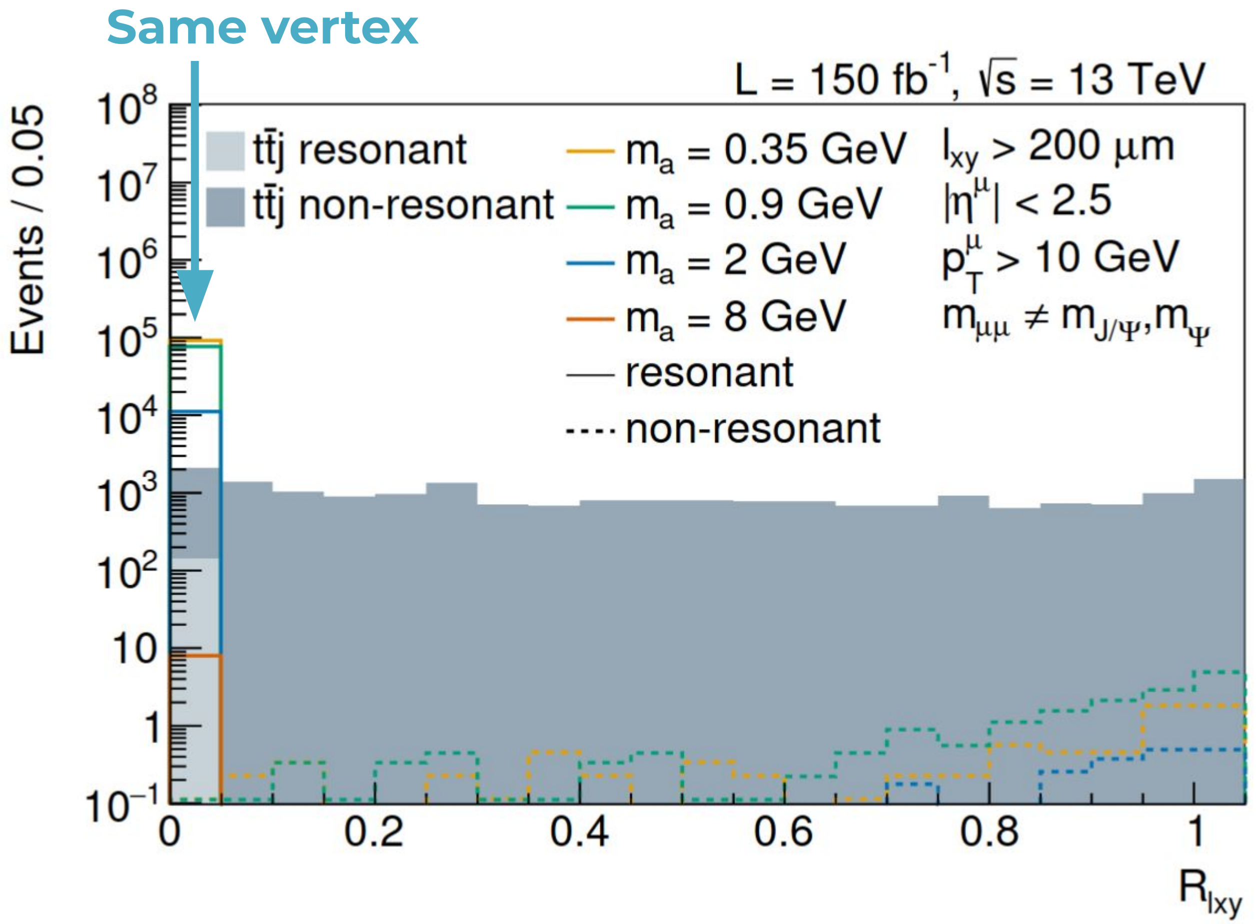
Pre-selection	
Muon kinematics	$p_T^\mu > 5$ GeV, $\|\eta^\mu\| < 2.5$
Muon displacement	$l_{xy} > 200\ \mu$m
At least one opposite-sign di-muon	
Signal selection	
Muon kinematics	$p_T^\mu > 10$ GeV
Di-muon mass	$m_{\mu\bar{\mu}} \neq m_{J/\Psi}, m_{\Psi(2S)}$
Di-muon vertex	$R_{lxy} < 0.05$

Muon R_{lxy}

- Theory study: using generation level information without reconstructed vertices
- To determine if two displaced muons originate **from the same vertex**, we define the ratio:

$$R_{lxy} = \frac{\sqrt{(x_\mu - x_{\bar{\mu}})^2 + (y_\mu - y_{\bar{\mu}})^2}}{\sqrt{(|x_\mu| + |x_{\bar{\mu}}|)^2 + (|y_\mu| + |y_{\bar{\mu}}|)^2}}$$

  - sensitive to the difference in muons' origin
  - largely independent from detector resolution



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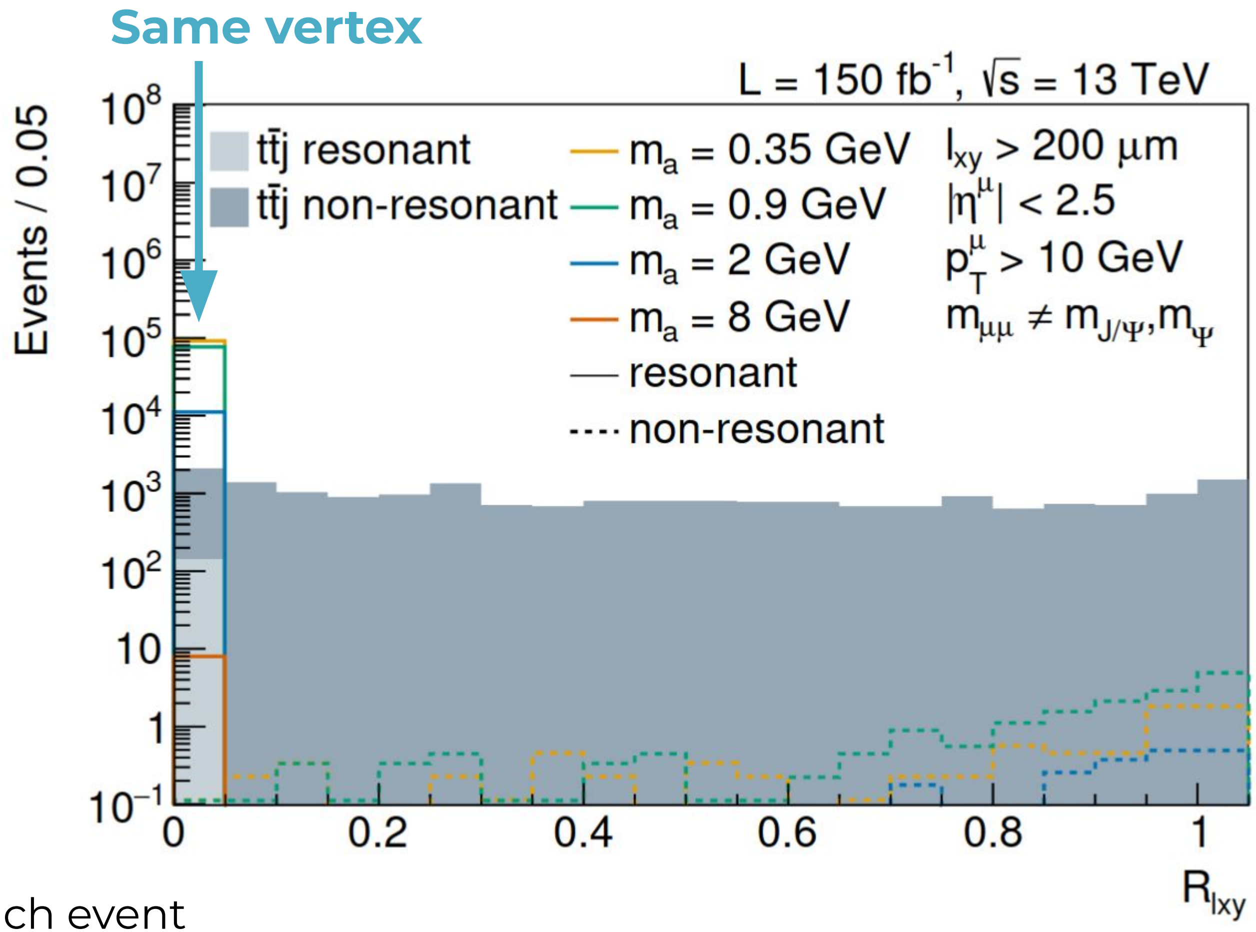
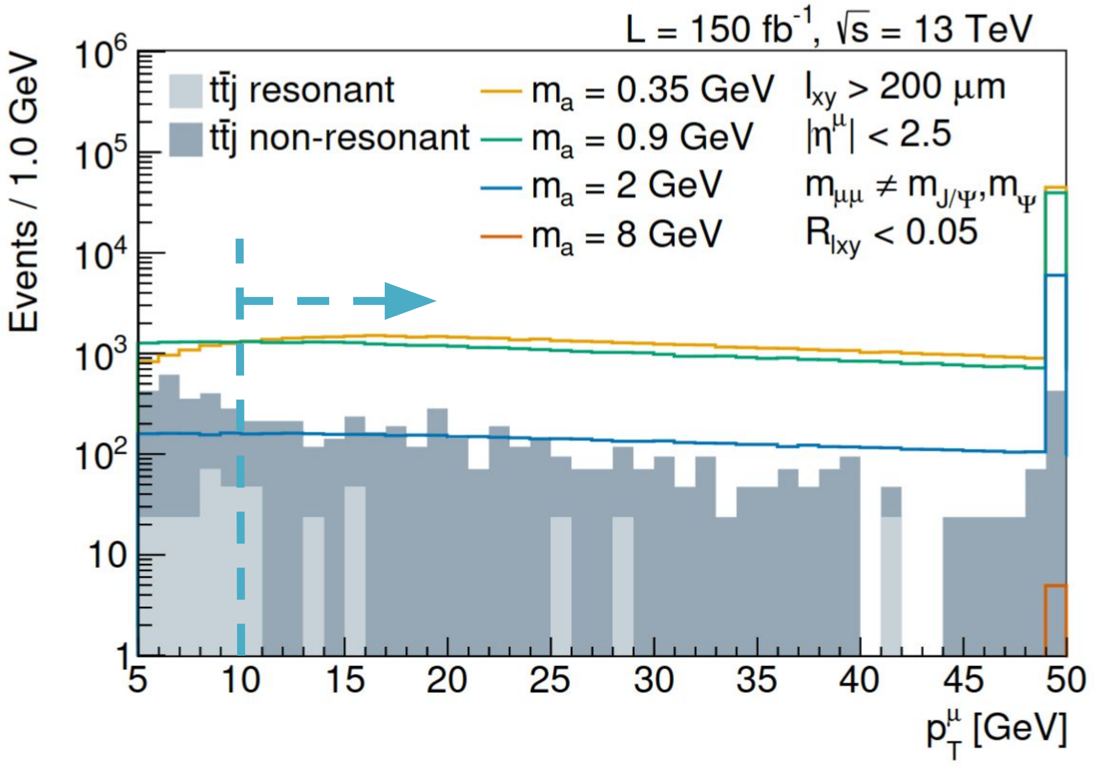


- Selection:
  - We select the di-muon with smallest R_{lxy} in each event
  - We make a conservative estimate on CMS vertex reconstruction resolution
  - Applying **R_{lxy} < 0.05** selection

Signal Selection

Muon transverse momentum

- Signal p_T tends to be harder than for the background
- Applying **p_T > 10 GeV** selection to remove low pT background



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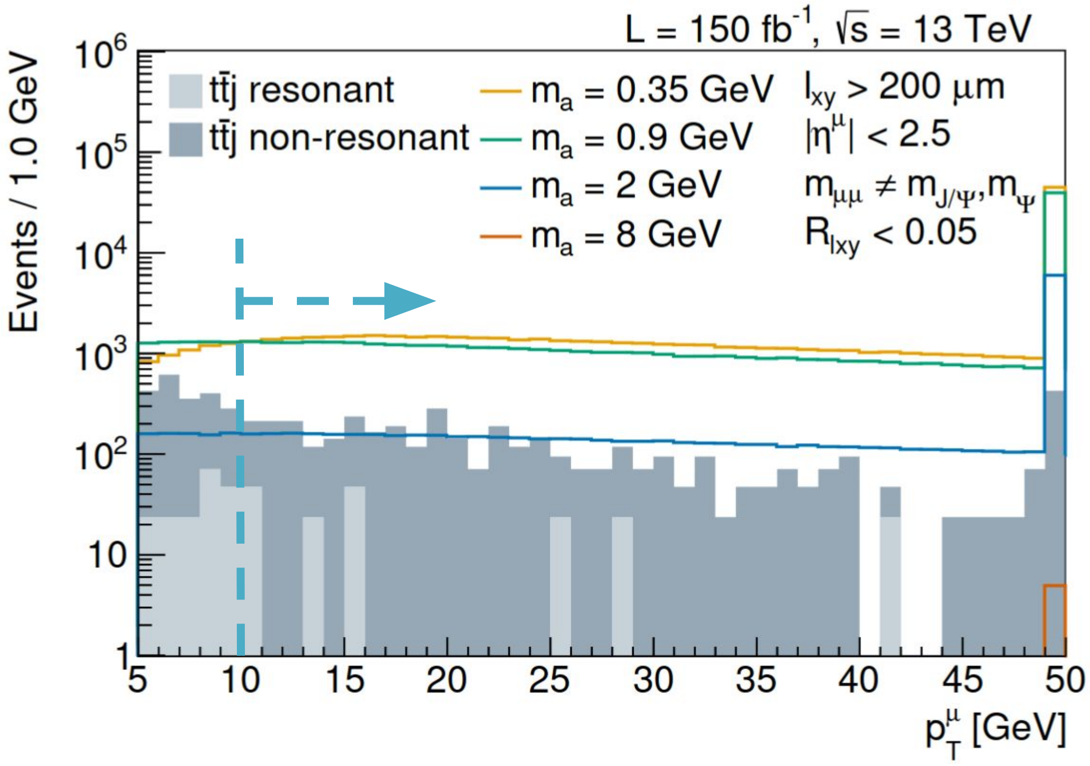
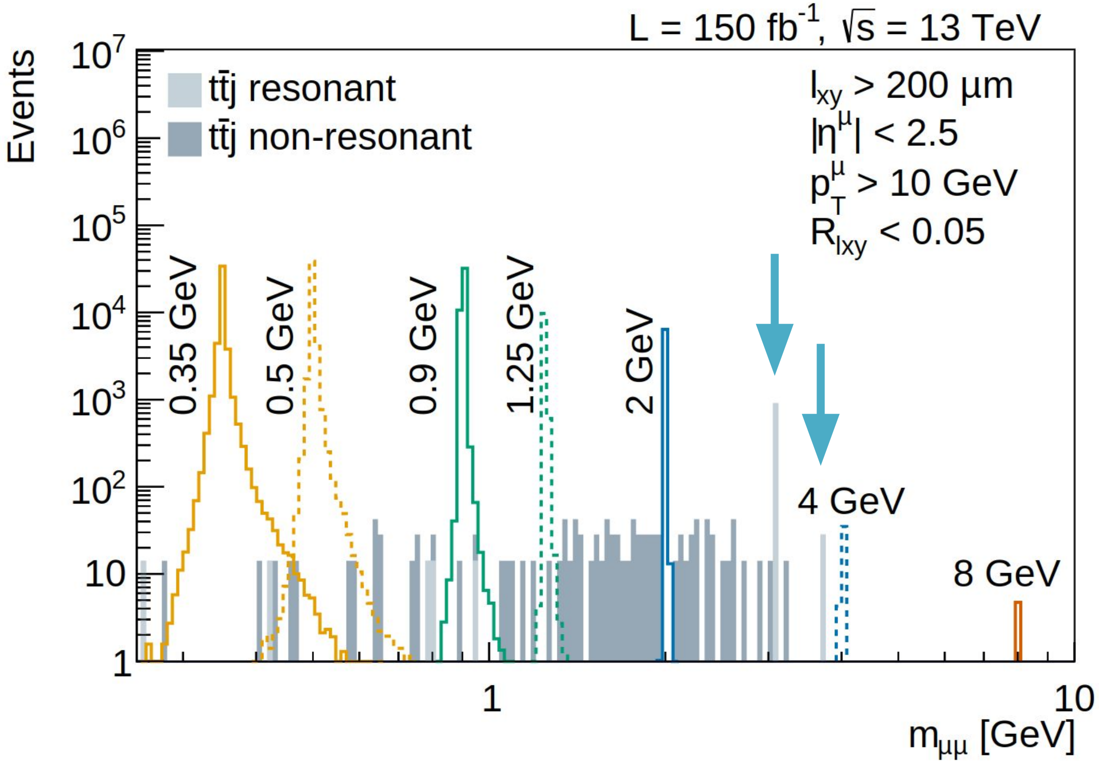




Di-muon resonances

- Suppressing know SM resonances by explicit $m_{\mu\mu}$ cuts
- Displacement cuts already reduces background resonances
- Excluding di-muon masses within 5% above and below the J/Ψ and $\Psi(2S)$ meson masses

Selection efficiency

Efficiency	$m_a = 0.35$ GeV	$m_a = 2$ GeV	$m_a = 8$ GeV	$t\bar{t}j$	$t\bar{t}Z^{(*)}$
Pre-selection	$(8.92 \pm 0.01)\times10^{-1}$	$(6.40 \pm 0.01)\times10^{-1}$	$(7.25 \pm 0.03)\times10^{-2}$	$(2.55 \pm 0.05)\times10^{-4}$	$(1.89 \pm 0.04)\times10^{-4}$
$p_T^{\mu} > 10$ GeV	$(7.99 \pm 0.01)\times10^{-1}$	$(5.58 \pm 0.01)\times10^{-1}$	$(6.87 \pm 0.03)\times10^{-2}$	$(7.4 \pm 0.2)\times10^{-5}$	$(9.4 \pm 0.3)\times10^{-5}$
$m_{\mu\bar{\mu}} \neq m_{J/\Psi}, m_{\Psi(2S)}$	$(7.99 \pm 0.01)\times10^{-1}$	$(5.58 \pm 0.01)\times10^{-1}$	$(6.86 \pm 0.03)\times10^{-2}$	$(6.8 \pm 0.2)\times10^{-5}$	$(5.8 \pm 0.2)\times10^{-5}$
$R_{lxy} < 0.05$	$(7.99 \pm 0.01)\times10^{-1}$	$(5.58 \pm 0.01)\times10^{-1}$	$(6.86 \pm 0.03)\times10^{-2}$	$(7.1 \pm 0.8)\times10^{-6}$	$(4.9 \pm 0.7)\times10^{-6}$
Events passing pre-selection	19793 ± 21	2516 ± 3	1.66 ± 0.01	15131 ± 267	0.59 ± 0.01
Events passing signal selection	17740 ± 20	2193 ± 3	1.57 ± 0.01	421 ± 45	0.015 ± 0.002

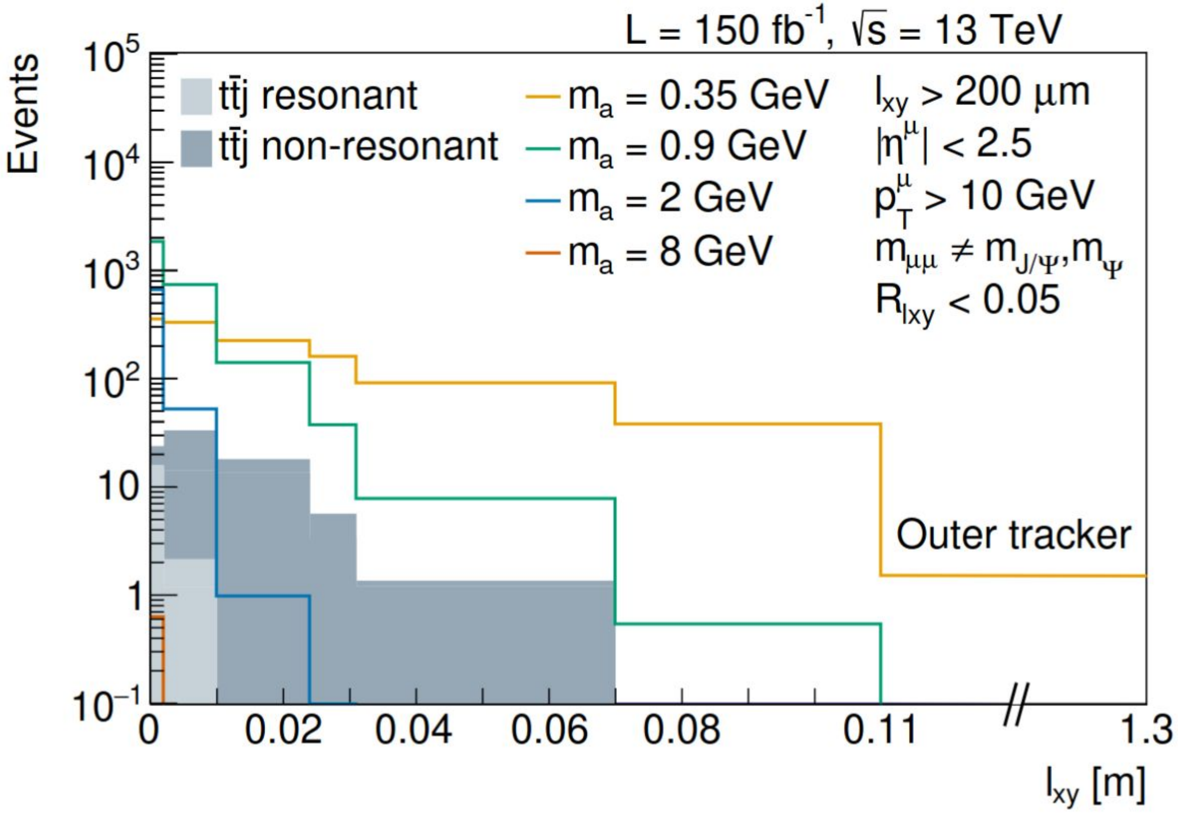
- Expected number of events for LHC Run 2 (150 fb^{-1})
- Including statistical uncertainties

- Reduces the number of background events by **> 5 orders of magnitude**
- High efficiency for signal, up to **80% for low masses** and down to **7% for high masses** (small branching ratio and more prompt)

Muon displacement

l_{xy} categorization

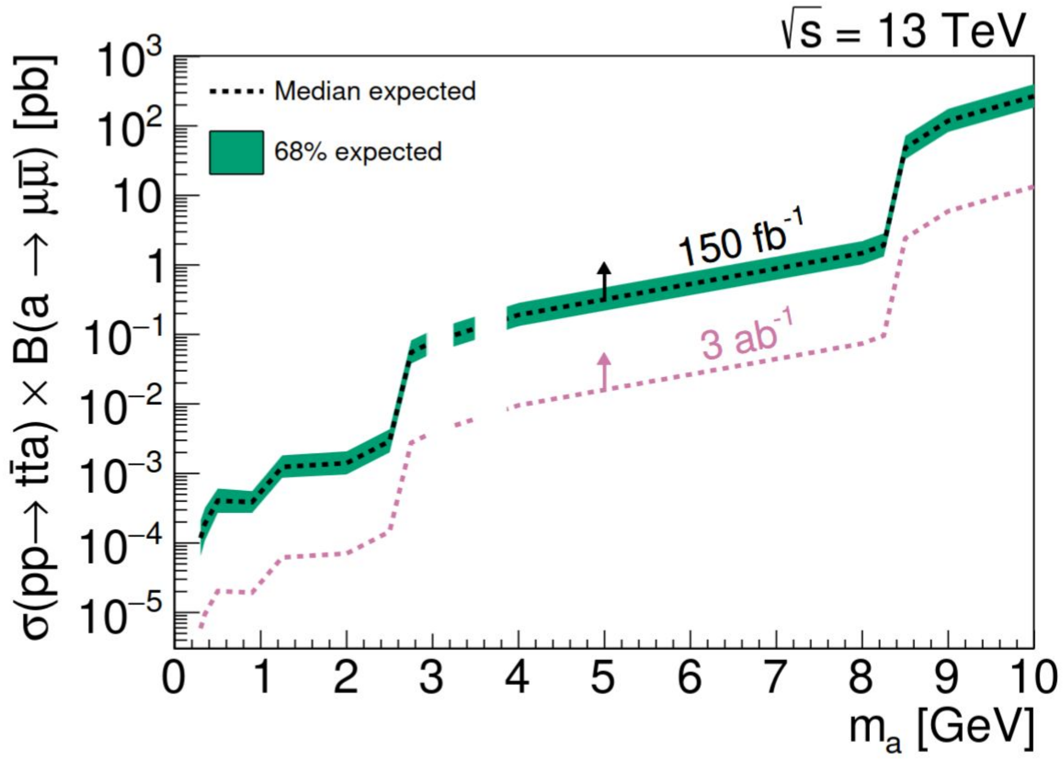
- Categorizing muon displacement in bins of l_{xy}
- Bins defined based on an existing CMS search for displaced di-muon pairs (EXO-20-014, 2112.13769), given for the beam pipe and tracker layers
- Showing l_{xy} of the least displaced muon

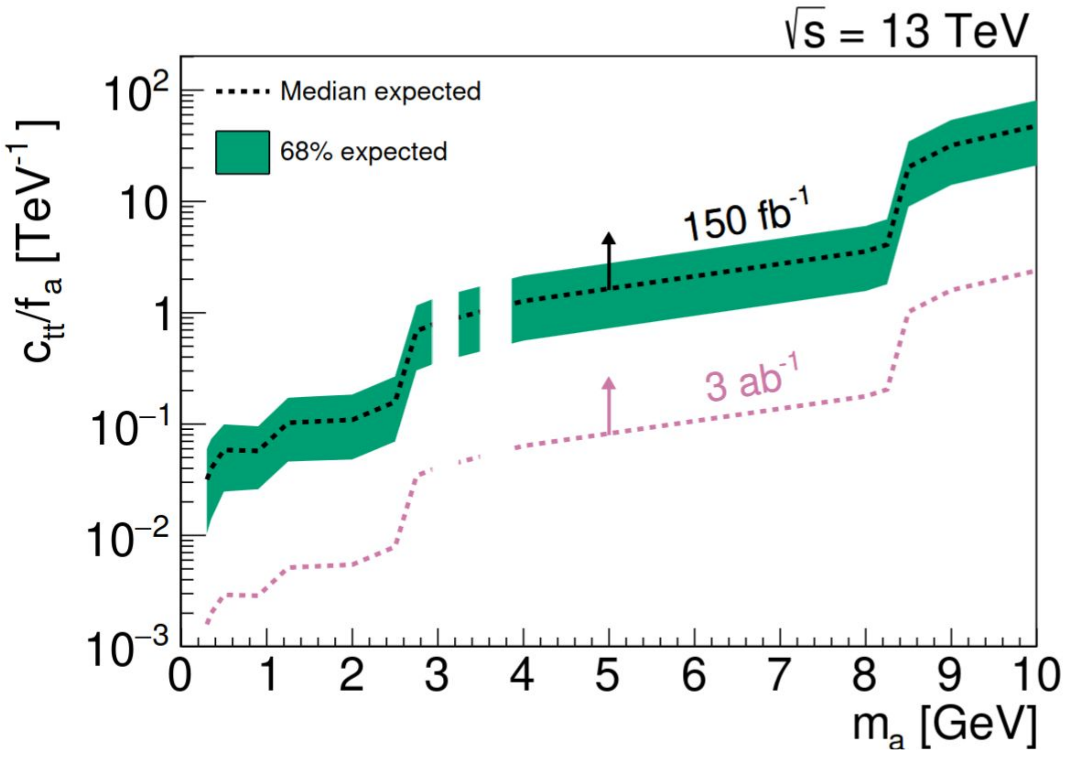


Expected sensitivity - Top scenario

- Calculating 95% CL upper limits on
  - cross section times branching ratio $\mathcal{B}(a \to \mu\mu)$ [left]
  - top-ALP coupling c_{tt}/f_a [right]

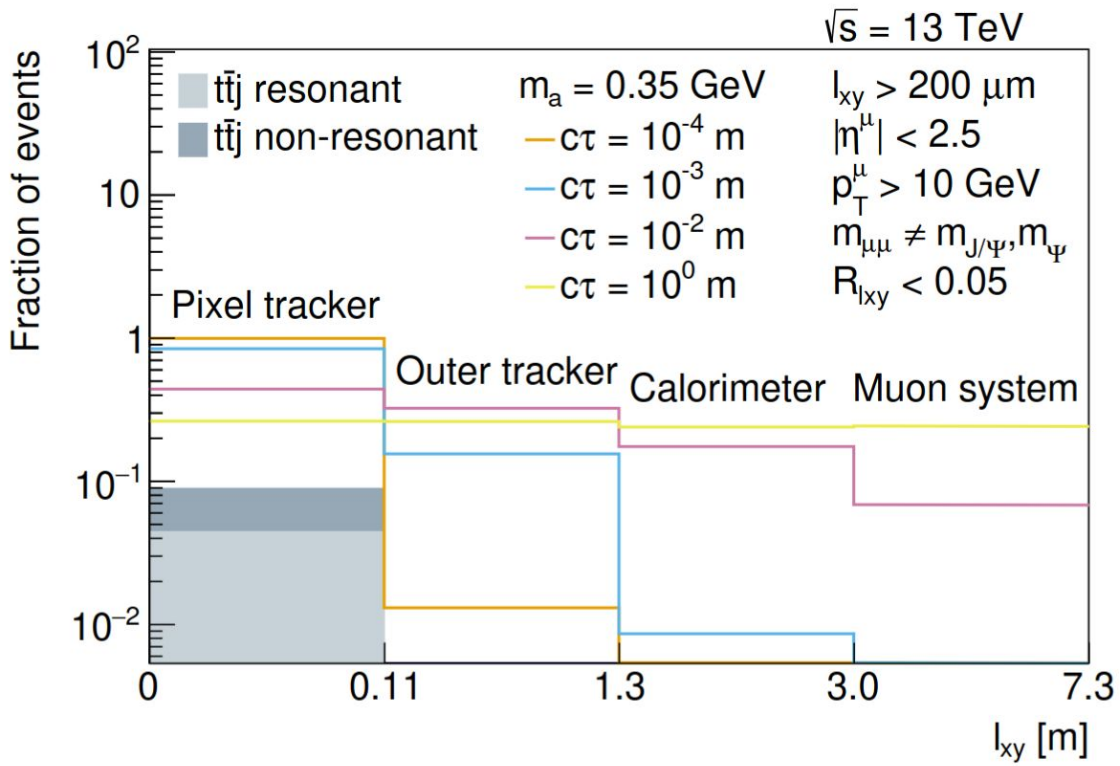
  as a function of m_a
- Excellent sensitivity with Run 2 (HL-LHC) integrated luminosity of 150 fb^{-1} (3 ab^{-1})
- Less sensitivity for higher ALP masses due to other decay channels starting to dominate (and more prompt signal)





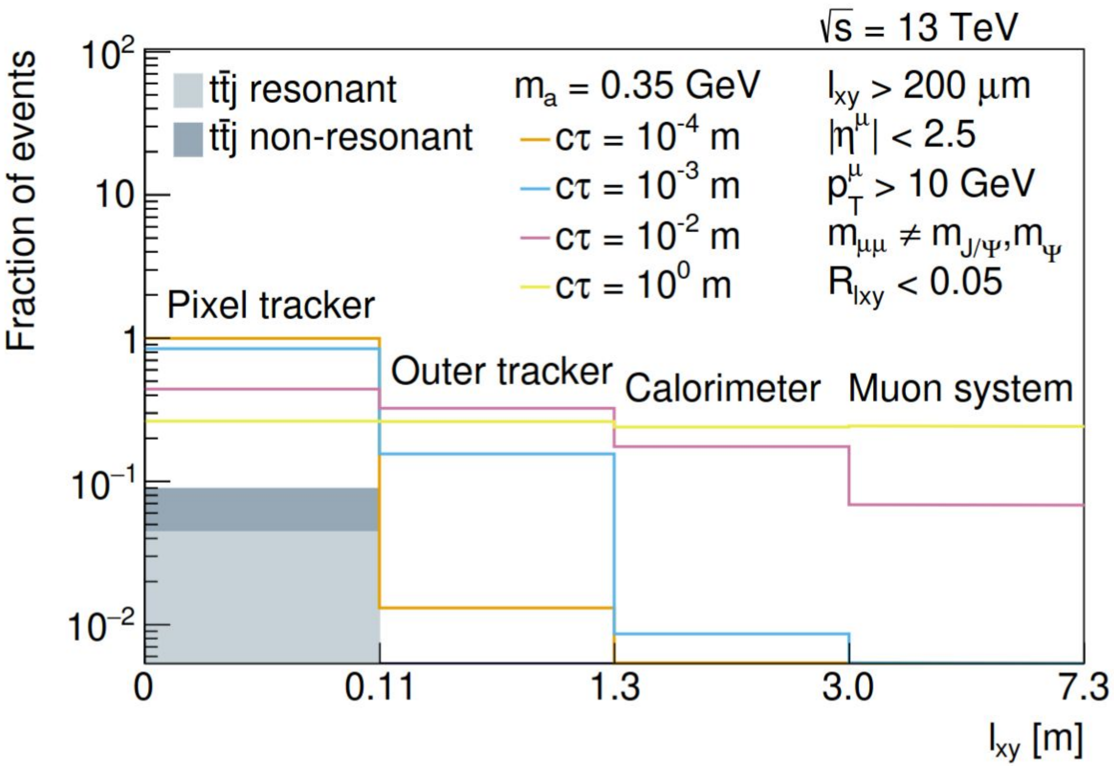
Expected sensitivity - General scenario

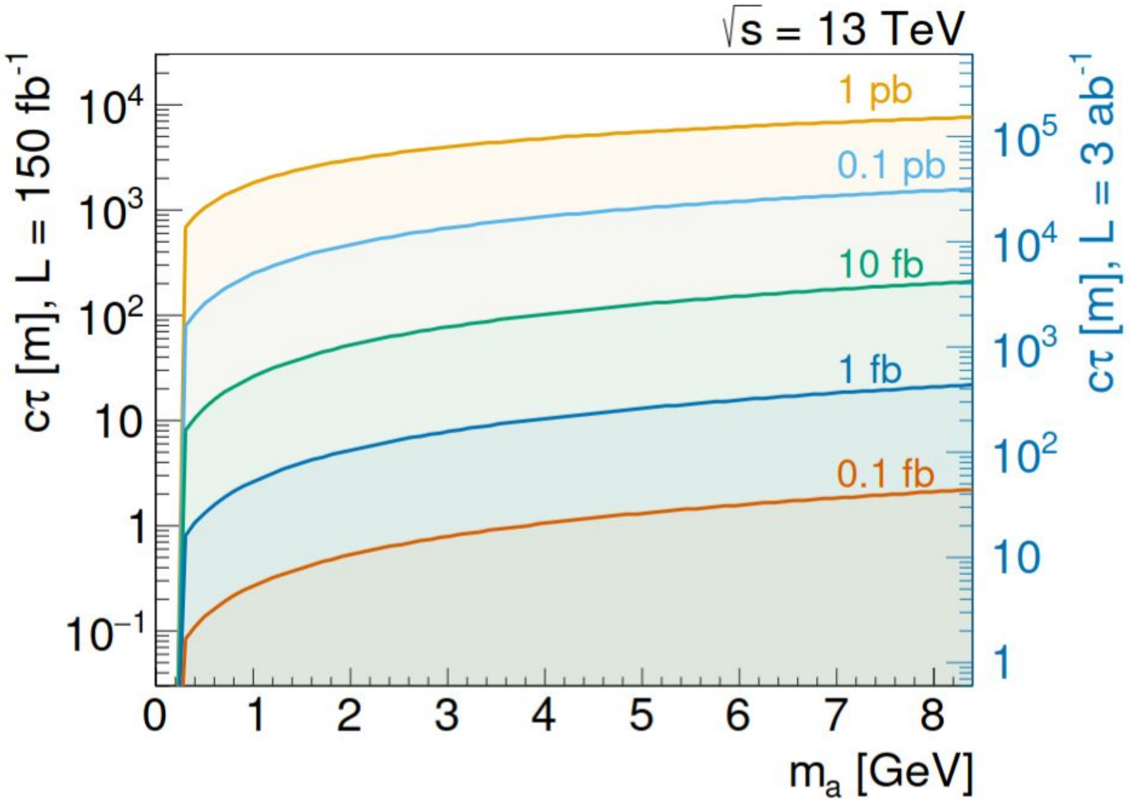
- General scenario: a new pseudo-scalar with **arbitrary lifetime** produced in $t\bar{t}$ events
- ALPs with longer lifetimes: calorimeter and muon system become more important



Expected sensitivity - General scenario

- General scenario: a new pseudo-scalar with **arbitrary lifetime** produced in $t\bar{t}$ events
- ALPs with longer lifetimes: calorimeter and muon system become more important
- Expected 95% CL upper limits on the **proper decay length cτ** as a function of m_a for different assumptions on the signal cross section times branching ratio
- for $\sigma(tt \to a) \times \mathcal{B}(a \to \mu\mu)$ = 1 fb: lifetimes up to 10 (400) m with Run 2 (HL-LHC) data

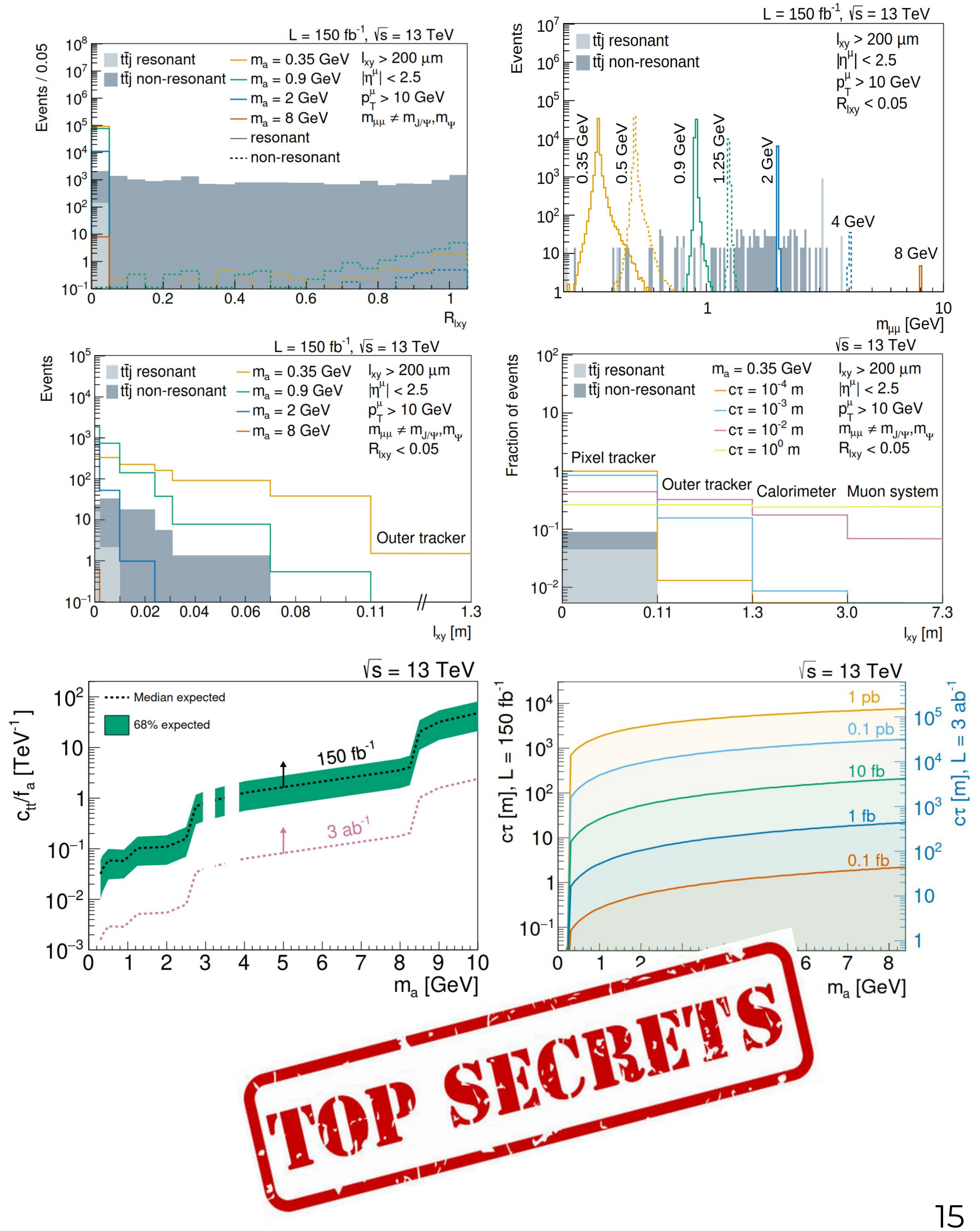




Summary and Outlook

Phenomenology study of long-lived ALPs in **$t\bar{t}$ events** with decays to displaced di-muons

- Focusing on the **top scenario** for the top-ALP coupling c_{tt}
- **Uncovered signature**, complementary to existing searches
- **Event selection** to suppress background and increase signal sensitivity
- **Expected upper limits** for the top scenario, and the general scenario with arbitrary lifetimes
- Paper on arXiv: [arXiv:2306.08686](https://arxiv.org/abs/2306.08686)
- **Next:** analysis in CMS with Run 2 and 3 data!



Backup