Search for Long-Lived Axion-Like Particles in Top Production

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Search for Long-lived ALPs in Top Production

Outline:

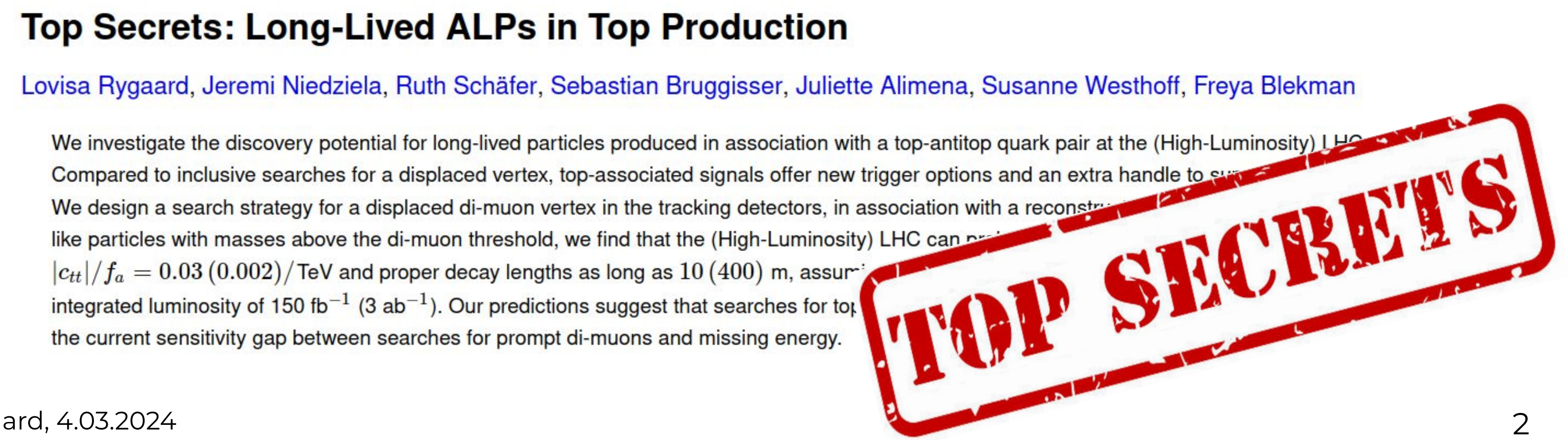
Introduction
- Axion-Like Particles

Top Secrets: Long-lived ALPs in Top Production

Phenomenology study of long-lived ALPs in top-antitop events at the LHC *J. High Energ. Phys.* **2023**, 138 (2023)
- Top Scenario
- Signal and background features
- Expected sensitivity with Run 2/HL-LHC data

CMS search: Search for long-lived ALPs in top-antitop events with CMS
- Displaced dimuons
- Signal and control regions

Summary and outlook



Top Secrets: Long-Lived ALPs in Top Production

Lovisa Rygaard, Jeremi Niedziela, Ruth Schäfer, Sebastian Bruggisser, Juliette Alimena, Susanne Westhoff, Freya Blekman

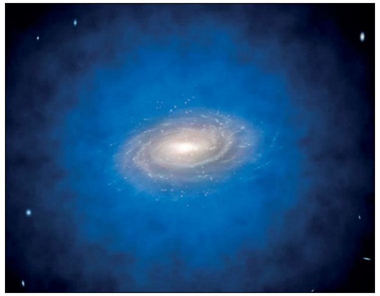
We investigate the discovery potential for long-lived particles produced in association with a top-antitop quark pair at the (High-Luminosity)
Compared to inclusive searches for a displaced vertex, top-associated signals offer new trigger options and an extra handle to
We design a search strategy for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

Axions

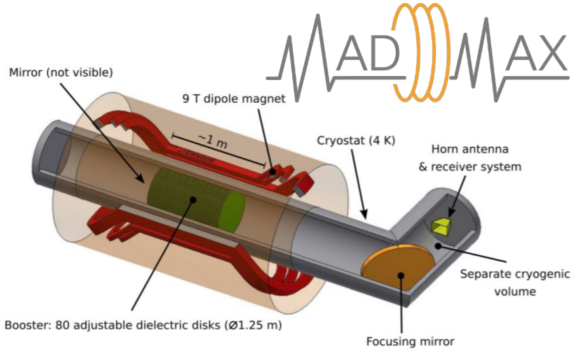
Particles introduced in the Peccei Quinn theory to solve the strong CP problem

- Low mass and low energy
- Excellent Dark Matter candidate

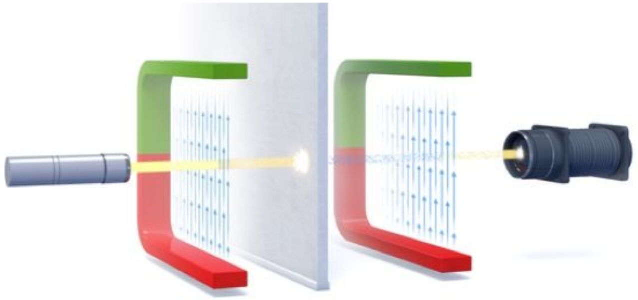
There are a large variety of experimental searches for axions, such as



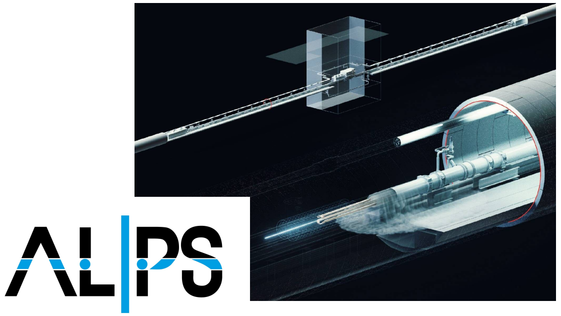
- **Haloscopes:**
  axions from the Dark Matter halo



- **Helioscopes:**
  axions from the sun



- **Light-shining through wall:**
  axion-photon coupling

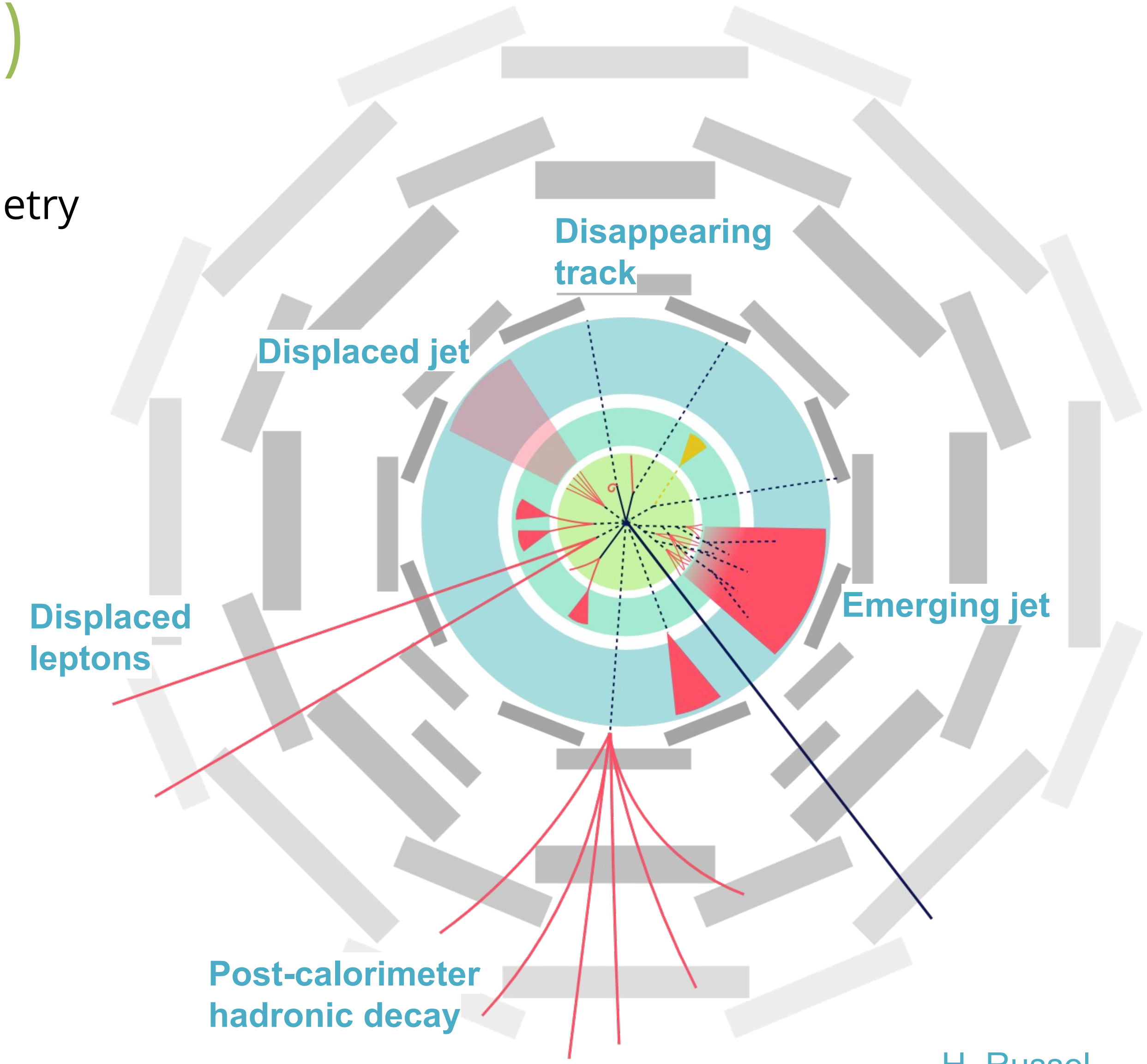


Axion-Like Particles (ALPs)

ALPs: more general class of pseudo-scalar particles
- In models with spontaneous broken global symmetry
- Mass-coupling relation not fixed
- Occur in many extensions of the SM

Experimental searches include
- haloscopes
- heliscopes
- light-shining through wall
- the **Large Hadron Collider**

Long-lived signatures for light, weakly coupled ALPs



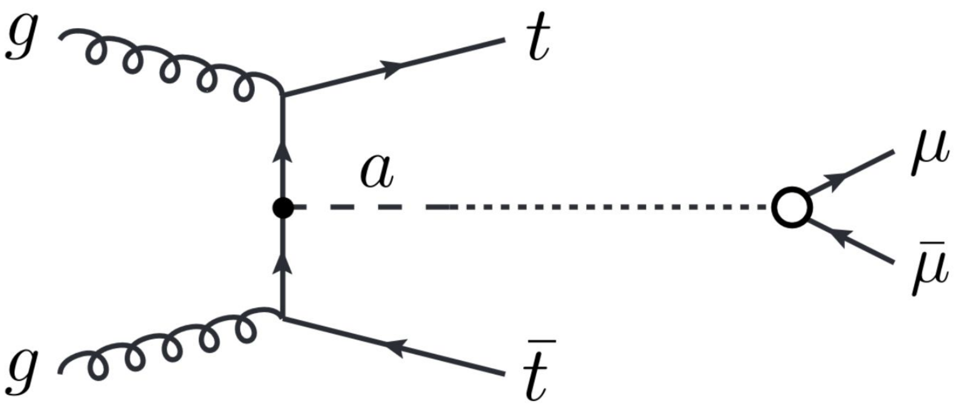
H. Russel

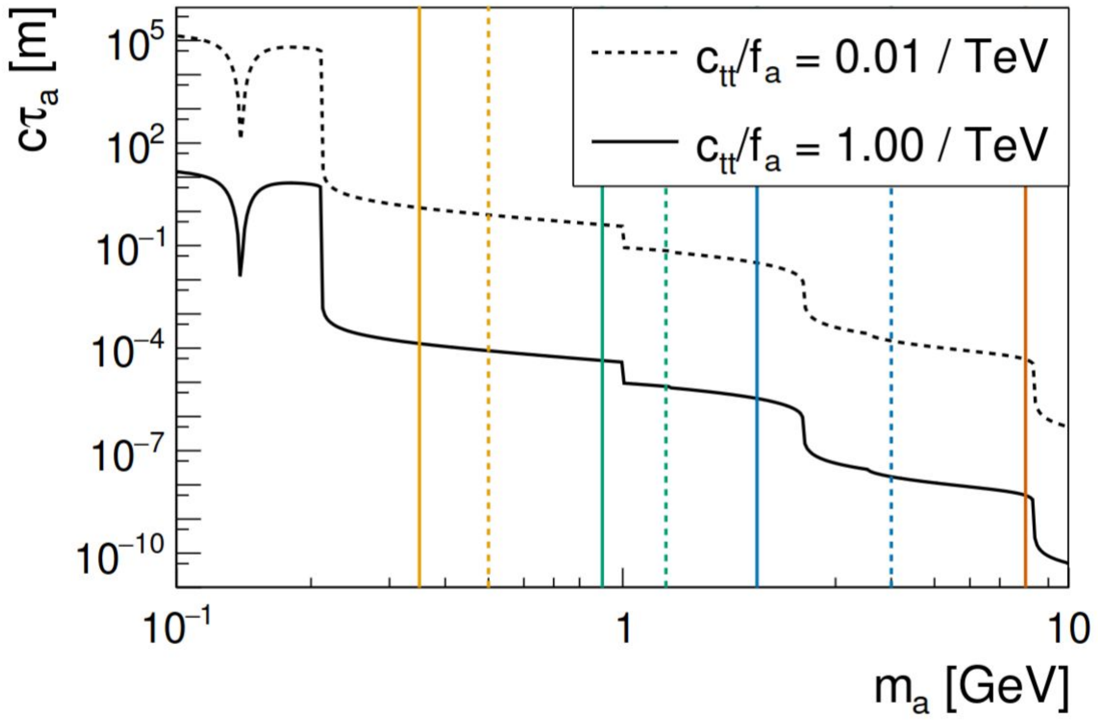
Axion-Like Particles (ALPs)

Top scenario:
The low-energy effective theory of axions and ALPs,
M.Bauer et al., JHEP04(2021)063

(Pseudo)-scalars are expected to have flavour-hierarchical 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





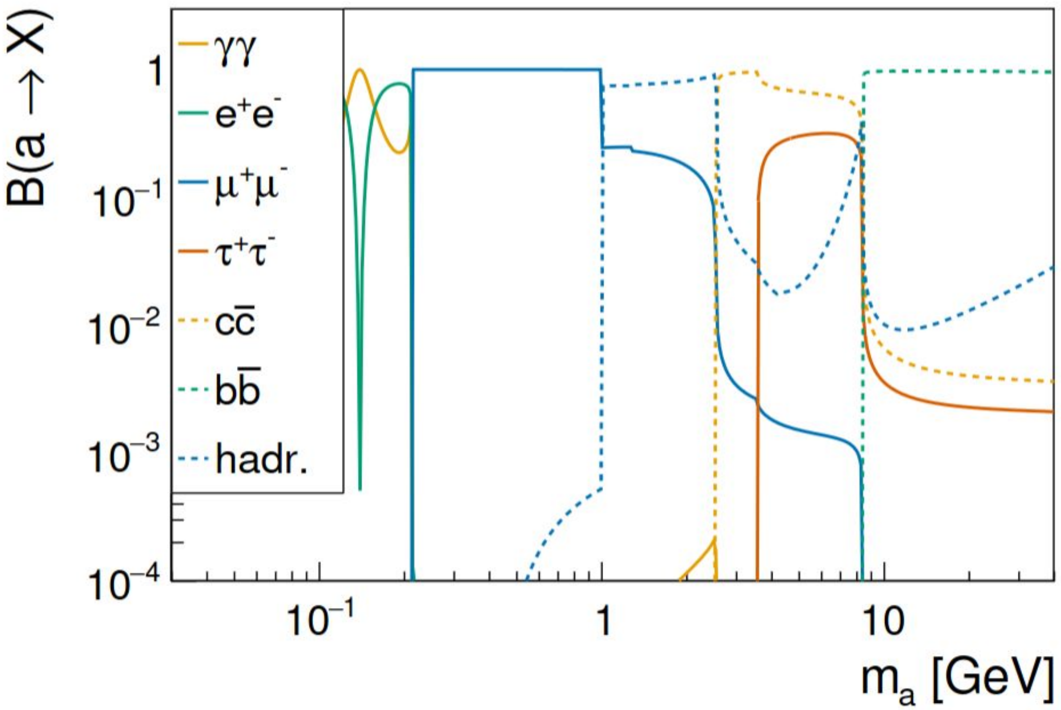
$t\bar{t}$ + ALPs

Searching for ALPs at the LHC

Focusing on **decays to a muon-antimuon pair**, therefore have excellent:

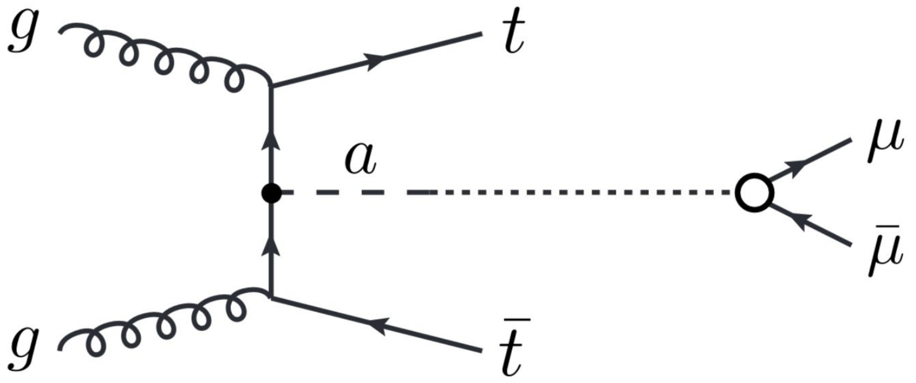
- tracking
- identification
- secondary vertex resolution

Focus on ALP masses within the range $2 \cdot m_\mu < m_a < 2 \cdot m_b$



In **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
- including all top decays
- assuming
  - 100% efficient top selection
  - 100% certainty of which muons come from the tops

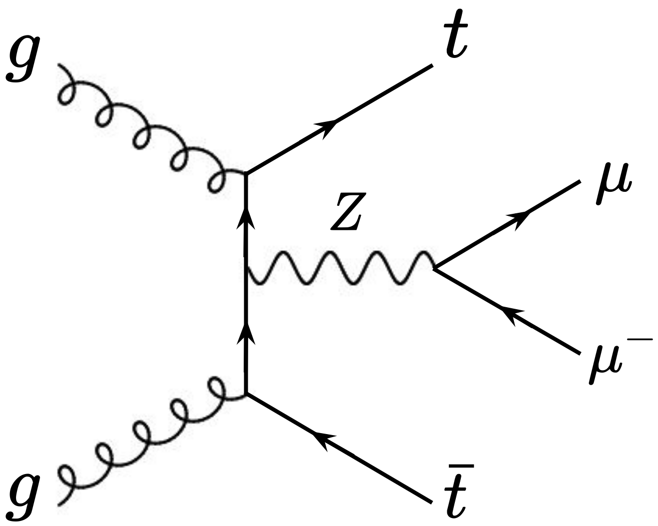


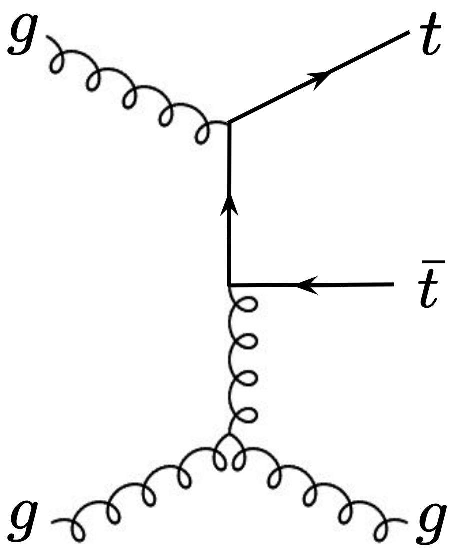
Backgrounds

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

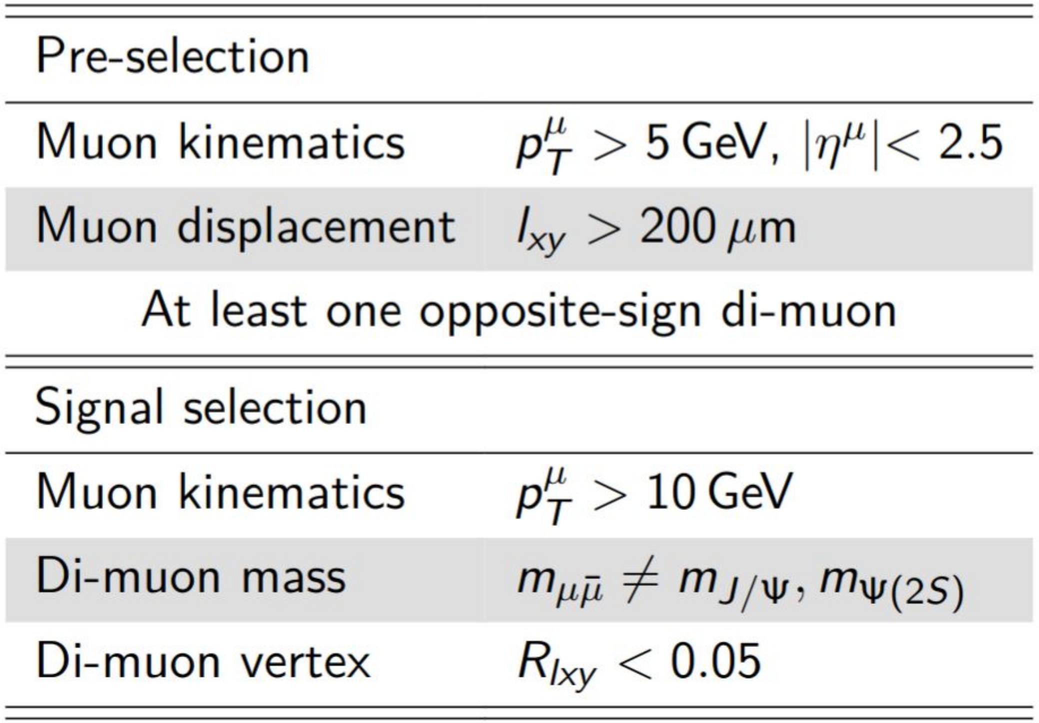
Generated samples with MadGraph5 and Pythia 8

at leading order in QCD for hard scattering processes

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

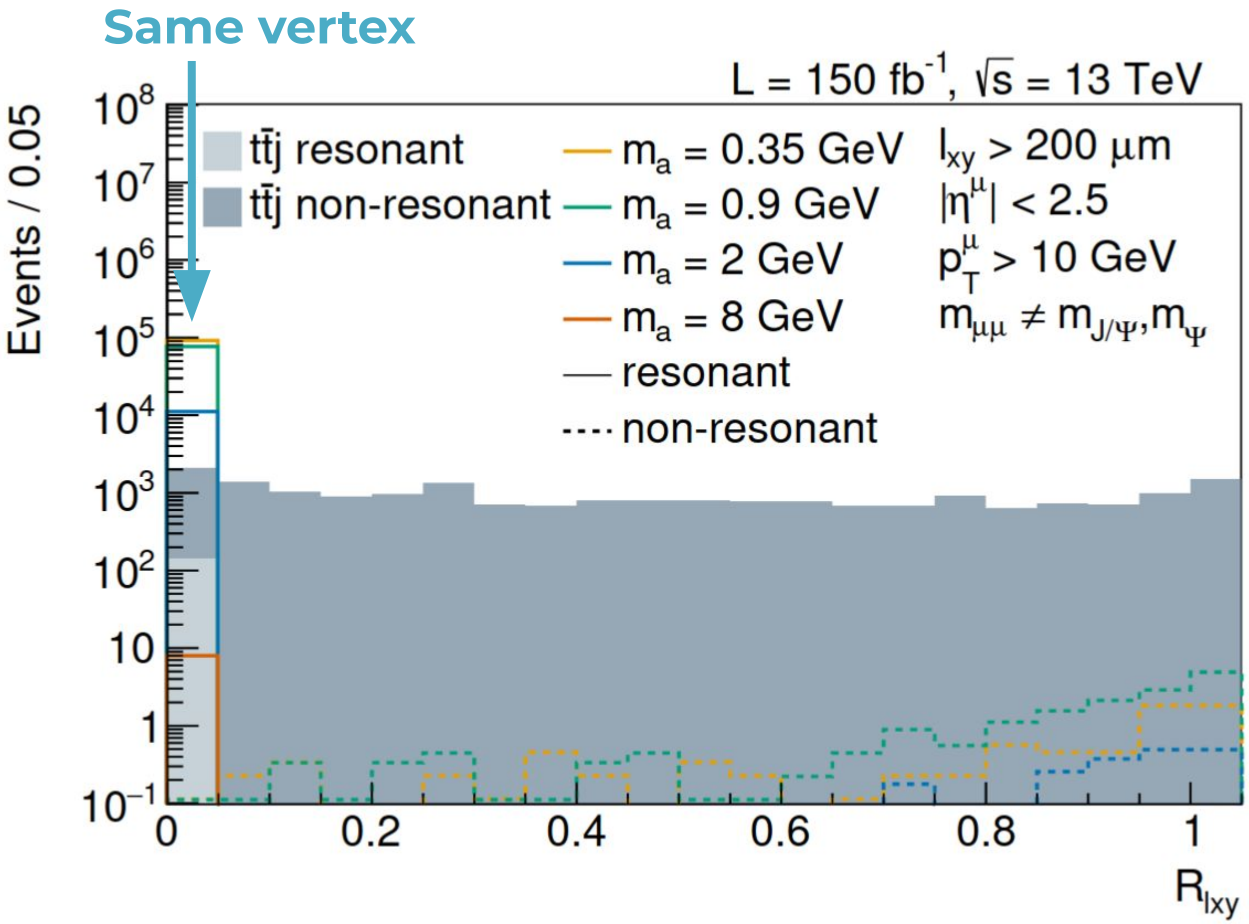
Muon R_{lxy}

Theory study: using generation level information without reconstructed vertices

To determine if two displaced muons originate **from the same vertex**, we define the ratio:

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

- x and y are muon vertex coordinates
- sensitive to the difference in muons' origin
- largely independent from detector resolution



Muon R_{lxy}

Theory study: using generation level information without reconstructed vertices

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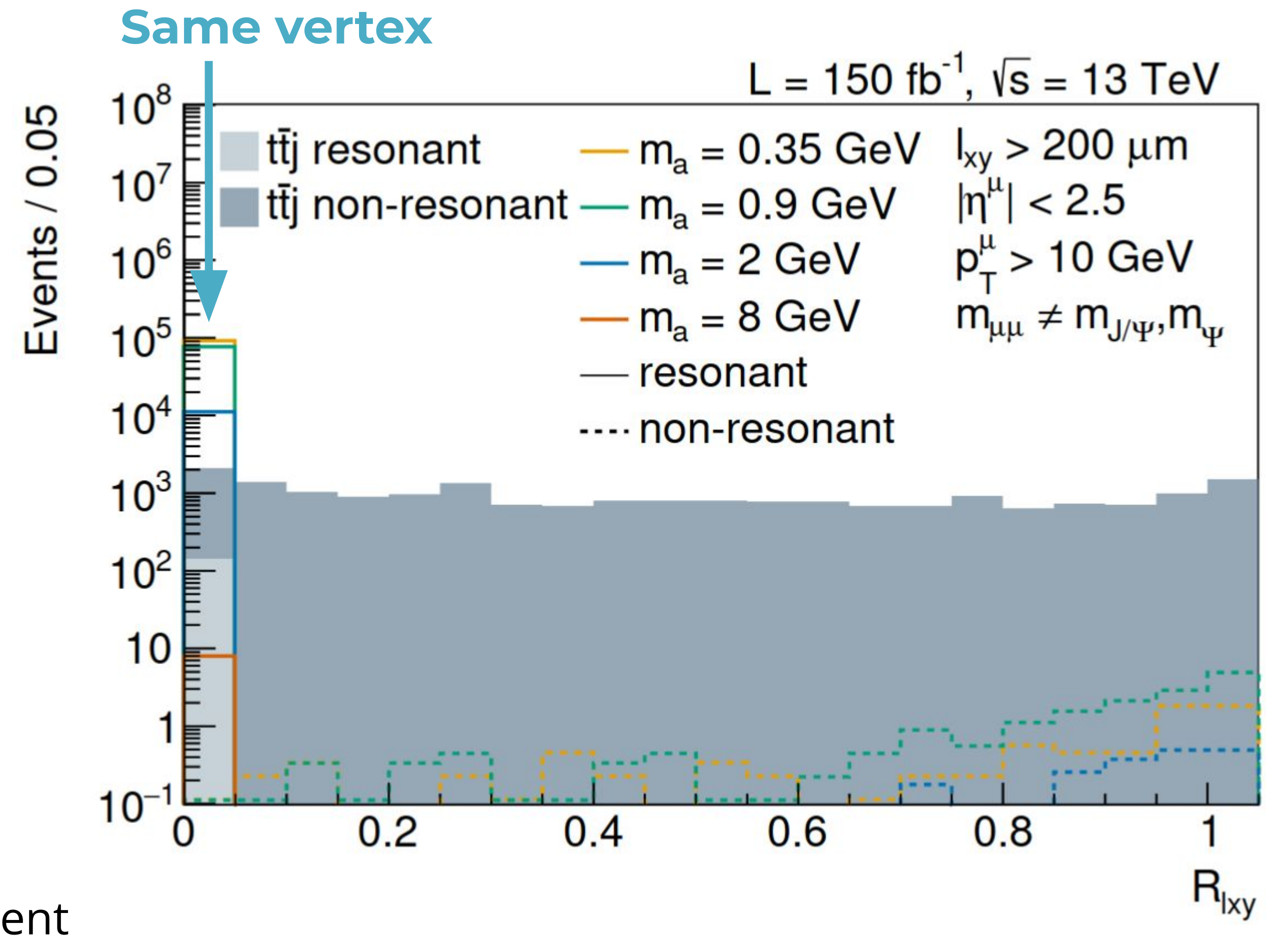
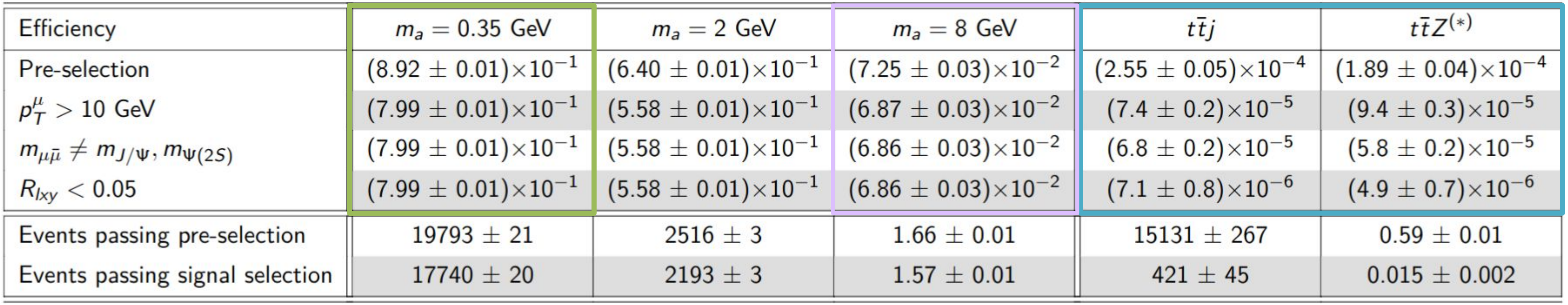


Selection:

- 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

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	$(8.92 \pm 0.01)\times 10^{-1}$	$(6.40 \pm 0.01)\times 10^{-1}$	$(7.25 \pm 0.03)\times 10^{-2}$	$(2.55 \pm 0.05)\times 10^{-4}$	$(1.89 \pm 0.04)\times 10^{-4}$
$p_T^{\mu} > 10$ GeV	$(7.99 \pm 0.01)\times 10^{-1}$	$(5.58 \pm 0.01)\times 10^{-1}$	$(6.87 \pm 0.03)\times 10^{-2}$	$(7.4 \pm 0.2)\times 10^{-5}$	$(9.4 \pm 0.3)\times 10^{-5}$
$m_{\mu\bar{\mu}} \neq m_{J/\Psi}, m_{\Psi(2S)}$	$(7.99 \pm 0.01)\times 10^{-1}$	$(5.58 \pm 0.01)\times 10^{-1}$	$(6.86 \pm 0.03)\times 10^{-2}$	$(6.8 \pm 0.2)\times 10^{-5}$	$(5.8 \pm 0.2)\times 10^{-5}$
$R_{lxy} < 0.05$	$(7.99 \pm 0.01)\times 10^{-1}$	$(5.58 \pm 0.01)\times 10^{-1}$	$(6.86 \pm 0.03)\times 10^{-2}$	$(7.1 \pm 0.8)\times 10^{-6}$	$(4.9 \pm 0.7)\times 10^{-6}$
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)

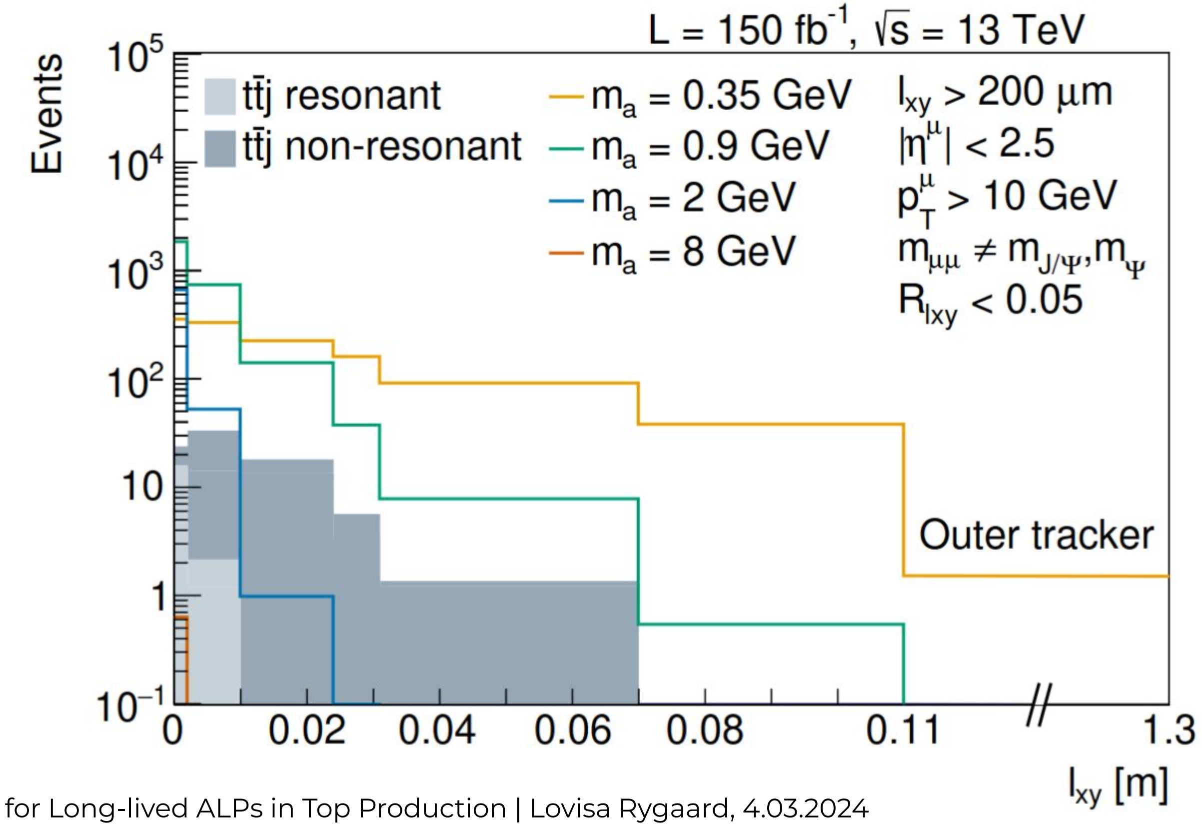
Muon displacement

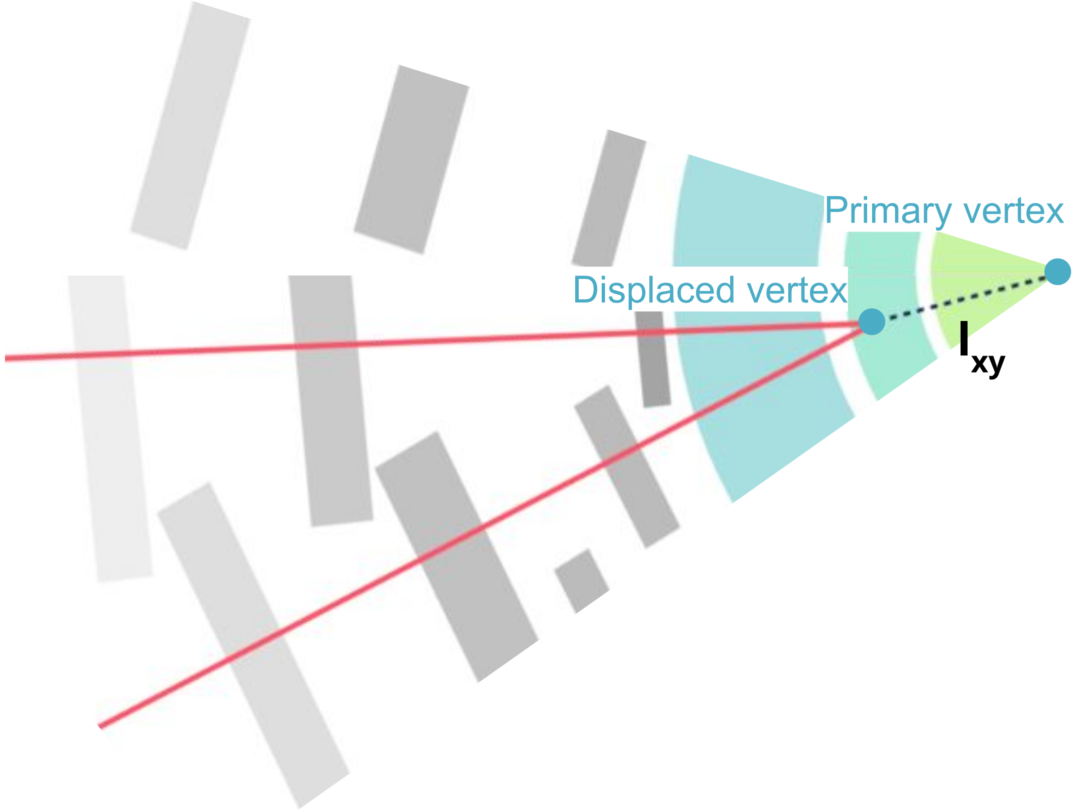
l_{xy} categorization

Categorizing muon displacement in bins of $\mathbf{l_{xy}}$

- 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





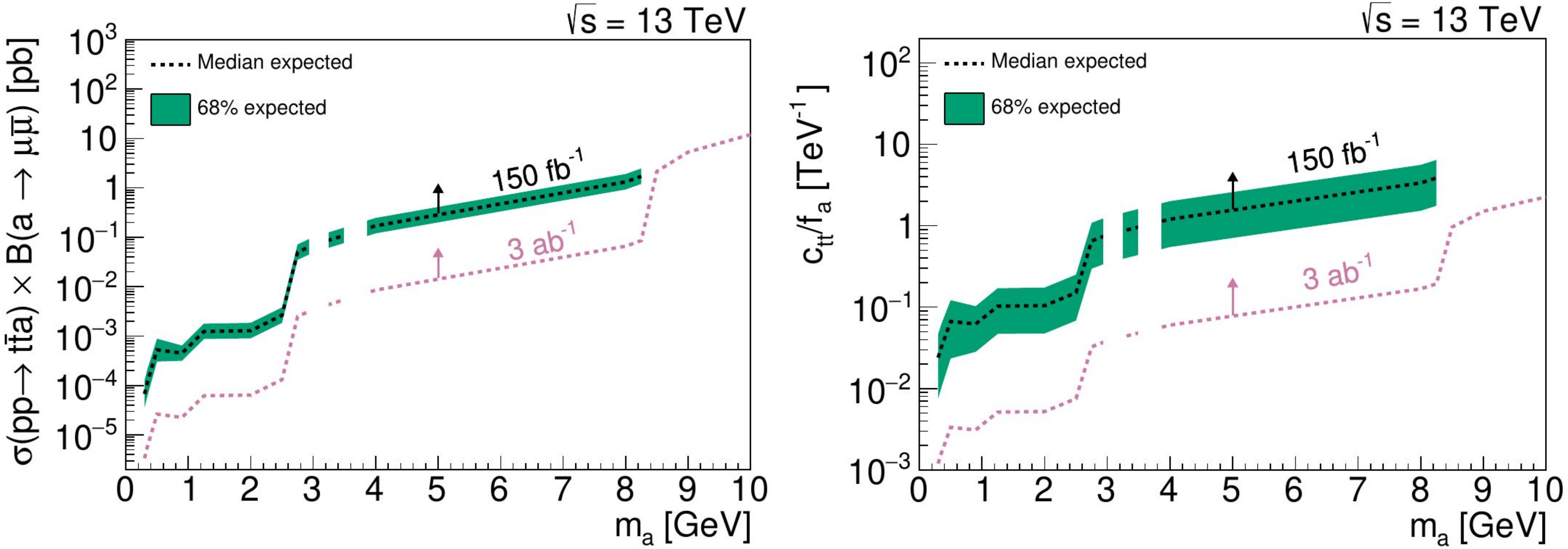
Expected sensitivity - Top scenario

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

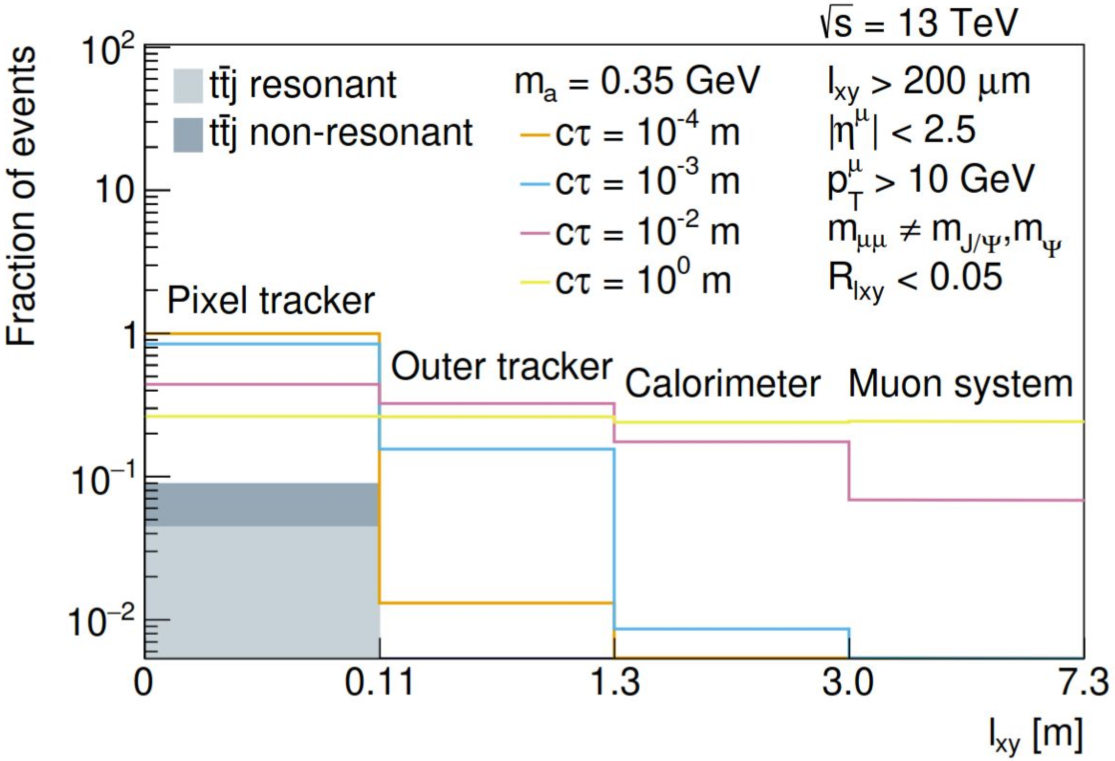
- Excellent sensitivity with Run 2 (HL-LHC) integrated luminosity of 150 fb^{-1} (3 ab^{-1})
- Less sensitivity for higher ALP masses as other decay channels starting to dominate (and more prompt signal)

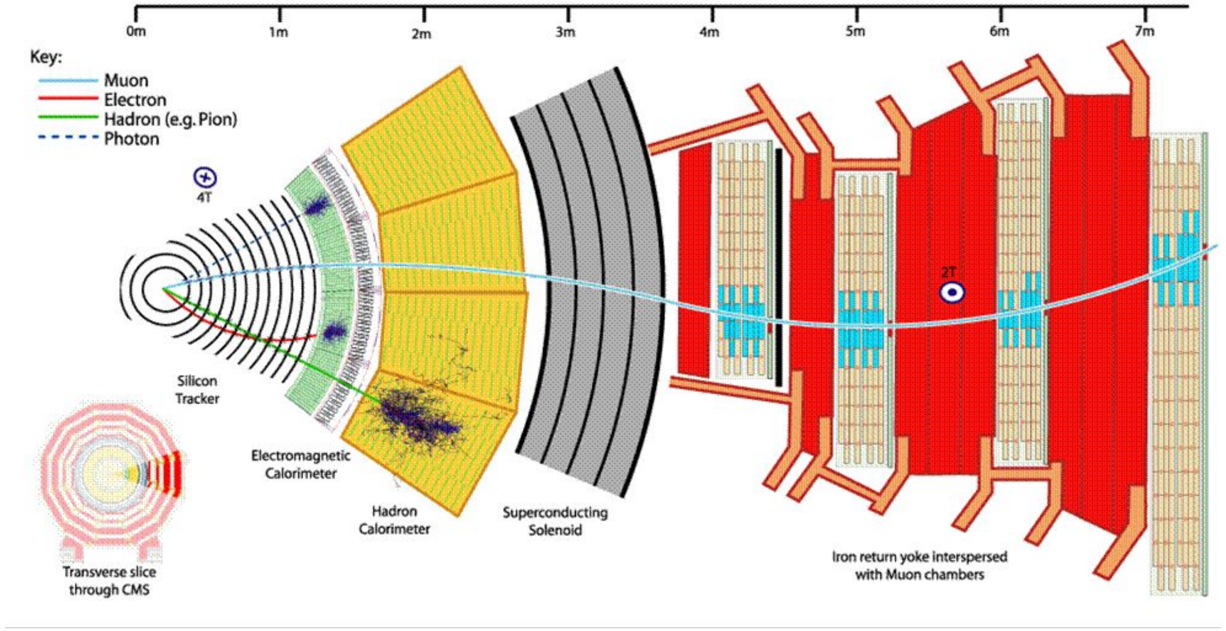


Expected sensitivity - General scenario

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





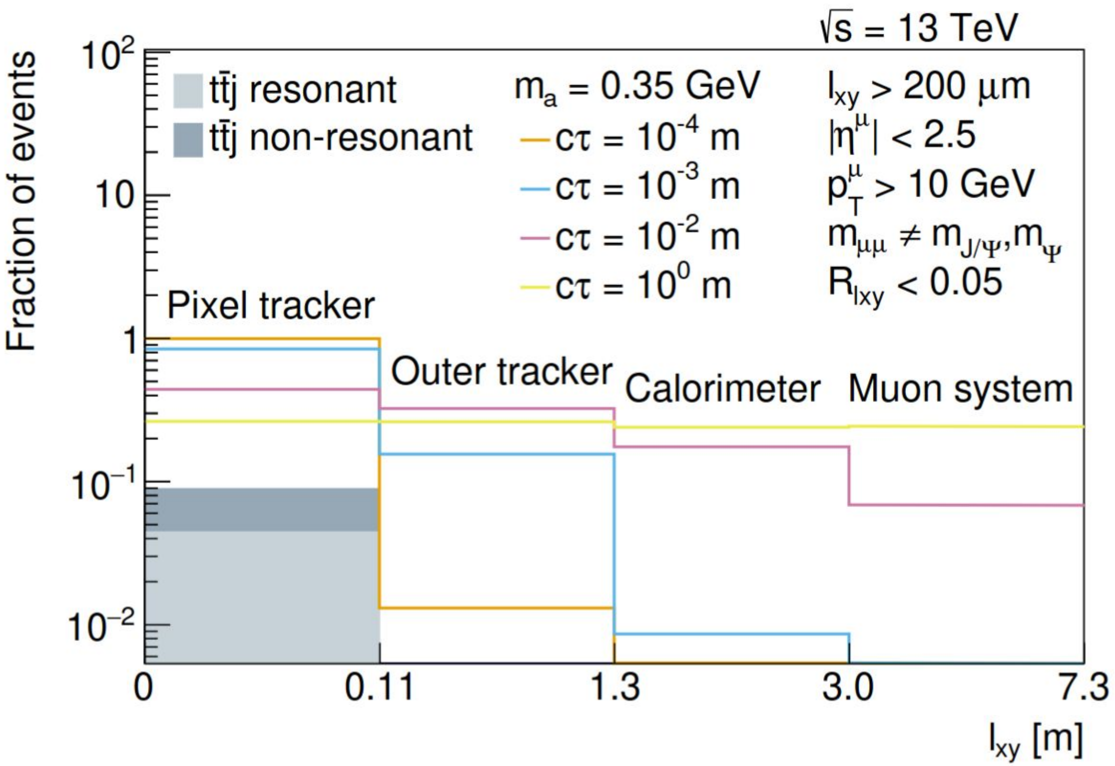
Expected sensitivity - General scenario

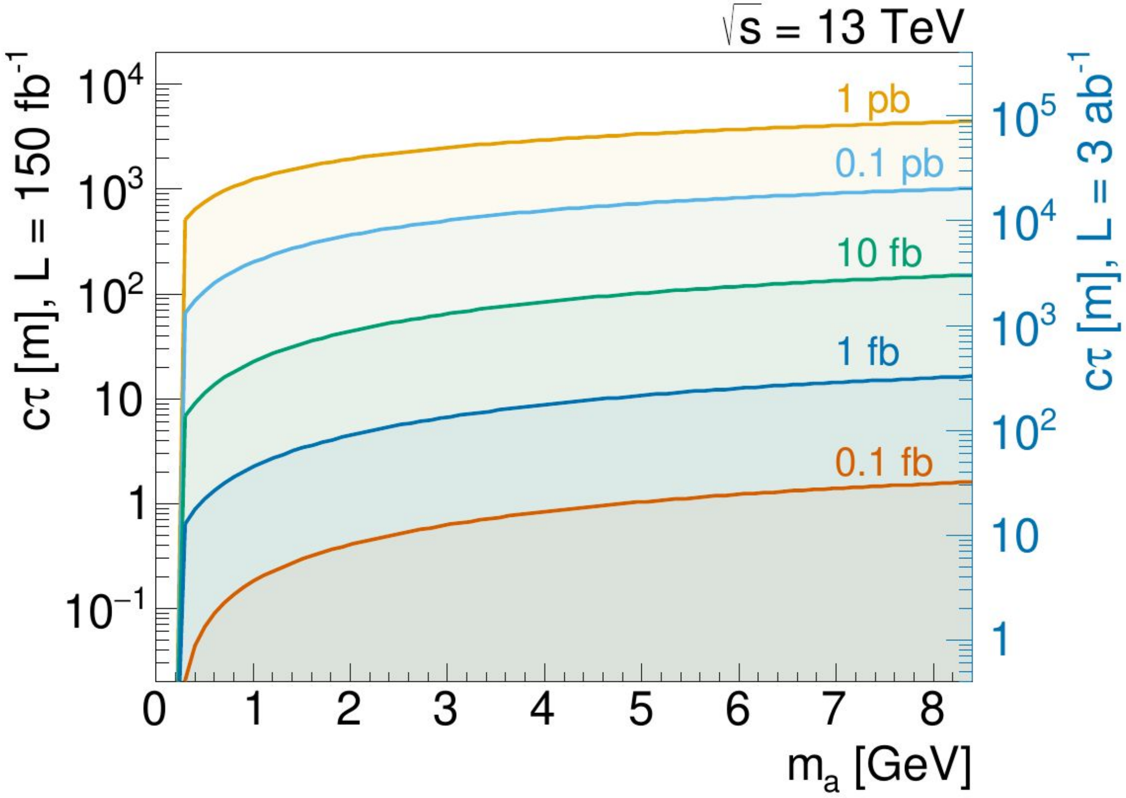
General scenario: a new pseudo-scalar with **arbitrary lifetime** produced in tt̄ events

- ALPs with longer lifetimes: calorimeter and muon system become more important

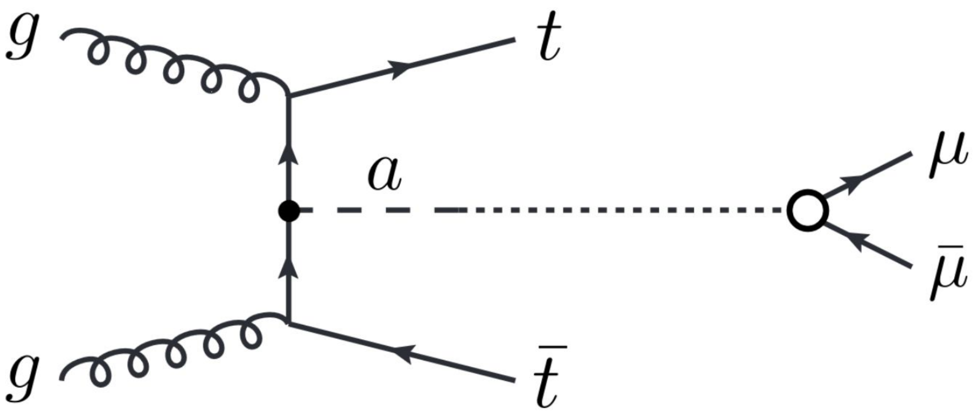
Expected **95% CL upper limits** on the **proper decay length cτ** as a function of m_a for different assumptions on the signal cross section times branching ratio

- for σ(tt̄→a)×$\mathcal{B}$(a→μμ) = 1 fb: lifetimes up to **20** (**300**) m with **Run 2** (**HL-LHC**) data





CMS Search: Overview



Search for long-lived ALPs in tt̄ events with CMS:

Starting with ALP decays to a **displaced di-muon**

- plan to include other decay channels in the future
- such as displaced electrons

Semi-leptonic tt̄ decay:

- triggering on muons/electrons from top decay allows accessing lower masses while still maintaining low background

Using full Run 2 and (2022-2023) Run 3 data

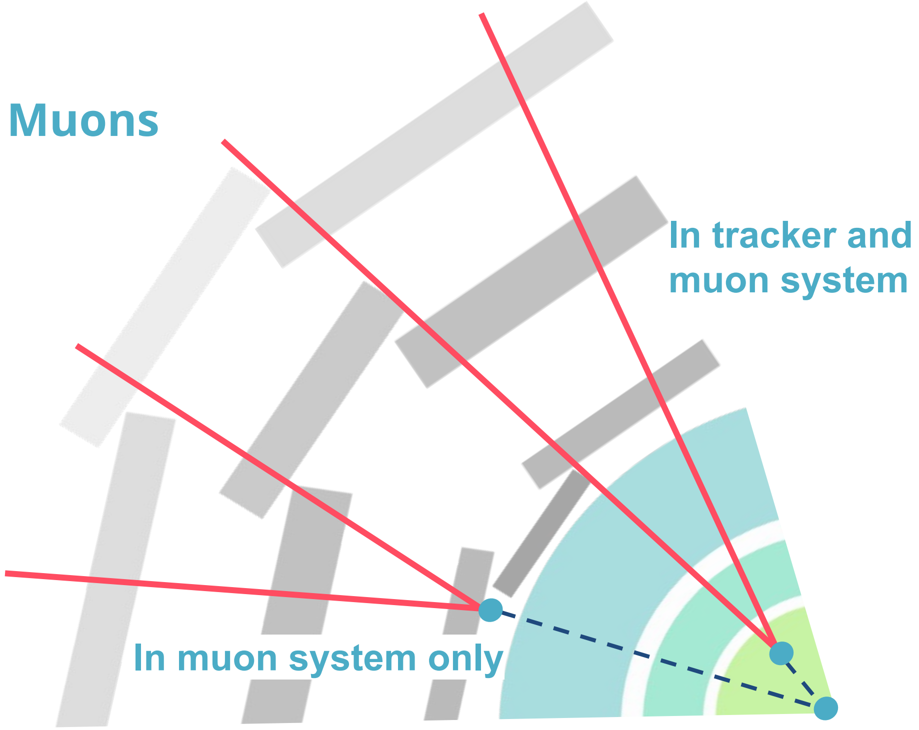
Status: CMS search started, including some of the main on-going items:

- Search strategy for displaced dimuons
- Generating samples with custom event format
- First signal-background comparisons
- Good agreement in tt̄ control region

CMS Search: Displaced Muons

Search strategy includes different CMS muon collections

- muons in both tracker and muon system
- displaced muons in the muon system only = **displaced standalone Muons**



Matching is performed between muon collections to remove overlap

- studies of **matching efficiency** for common methods used in CMS
  - using angular distance between muons
  - using spatial positions between muon hits

Displaced standalone muons not included in event format used by most CMS analyses:

→ creating dedicated event format for this analysis and other long-lived CMS analyses

- first version for displaced muons, muon matching, displaced muon vertex fits
- to be available for more long-lived analyses in future versions

CMS Search: Preliminary Selections

Starting with $t\bar{t}$ decays to muon+jets:

Pre-selection:

- $p_T^{miss} > 50$ GeV
- 1 muon
- 0 electrons
- ≥4 jets, ≥2 b-tags

Triggers

- events with at least 1 isolated muon with $p_T > 24$ GeV

Defining **signal region**

- $t\bar{t}$ (muon + jets) + displaced di-muon:

  Selection:

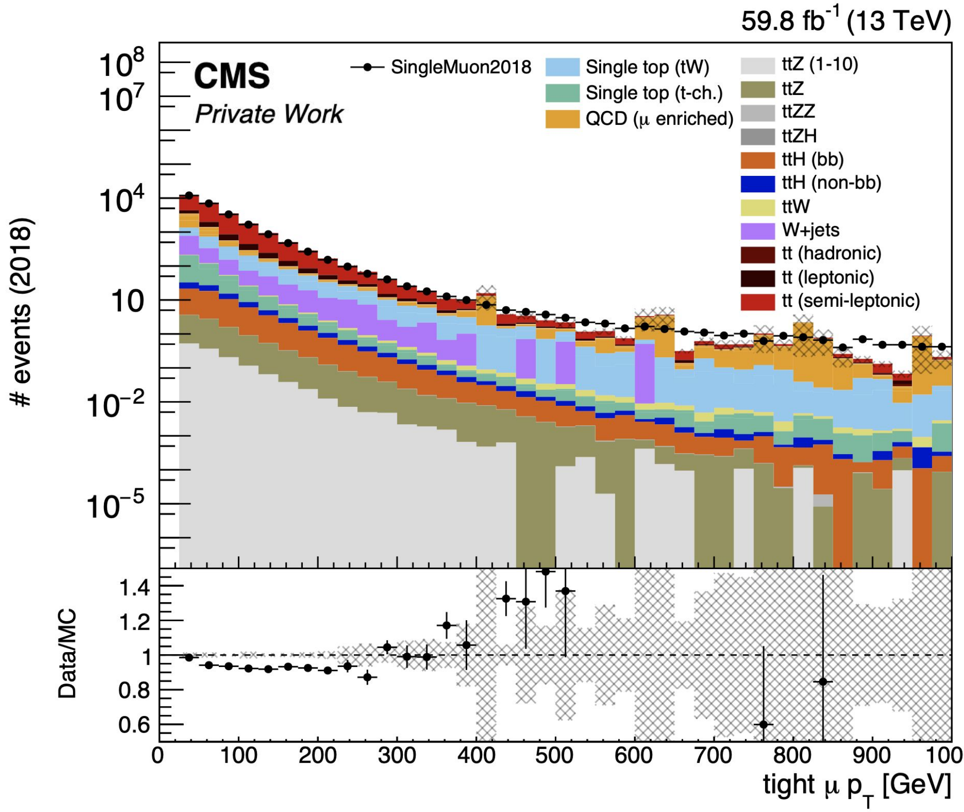
  - 2 additional muons
- $t\bar{t}$ (electron + jets) + displaced di-muon

Defining **control regions**

- **$t\bar{t}$ control region** (muon+jets):

  Selection:

  - 0 additional muons
- $t\bar{t}$ + jet, $t\bar{t}$ + prompt dimuon, $t\bar{t}$ + Z to dimuon



- Muon, jet and b-tagging scale factors applied
- Pileup-reweighting applied

Optimization of selections, triggers, SF still on-going

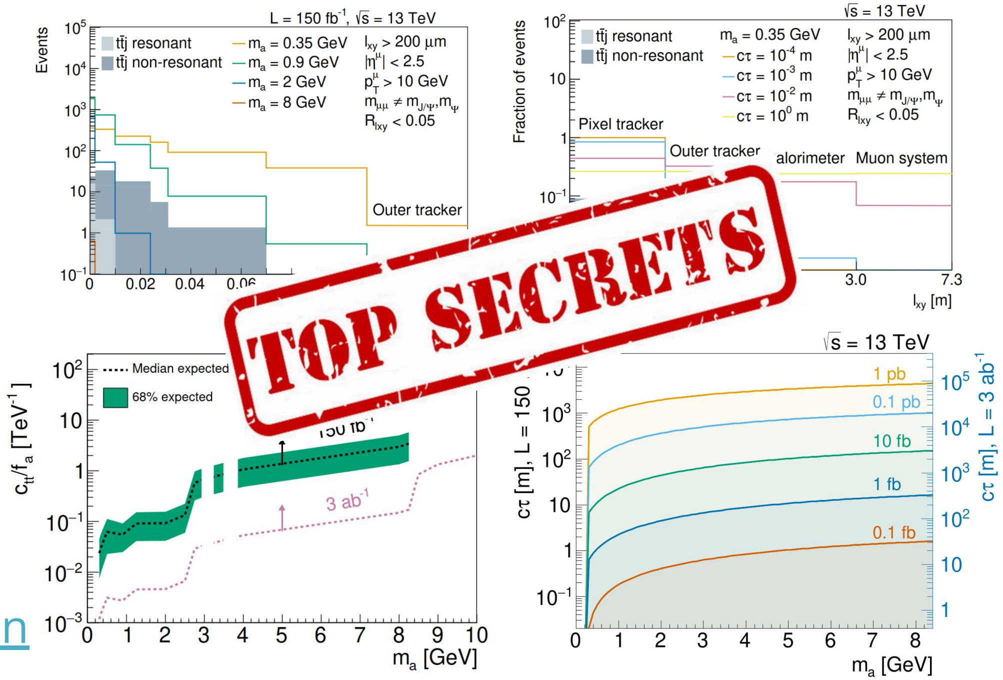
Summary and Outlook

Top Secrets: Long-lived ALPs in Top Production:

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

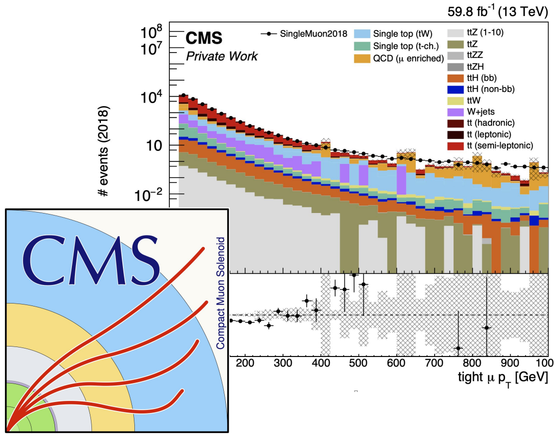
- Focusing on the **top scenario** for the top-ALP coupling c_{tt}
- **Event selections** are efficiently suppressing background and increase signal sensitivity
- **Expected upper limits** show good discovery potential for low-mass ALPs

Paper published in JHEP: [Top Secrets: long-lived ALPs in top production]()



CMS Analysis started - searching for the same signature

- Search strategy with displaced di-muons
- Defining signal and control regions
- Using full Run 2 and partial Run 3 data
- New approach to increase the discovery potential of ALPs in CMS



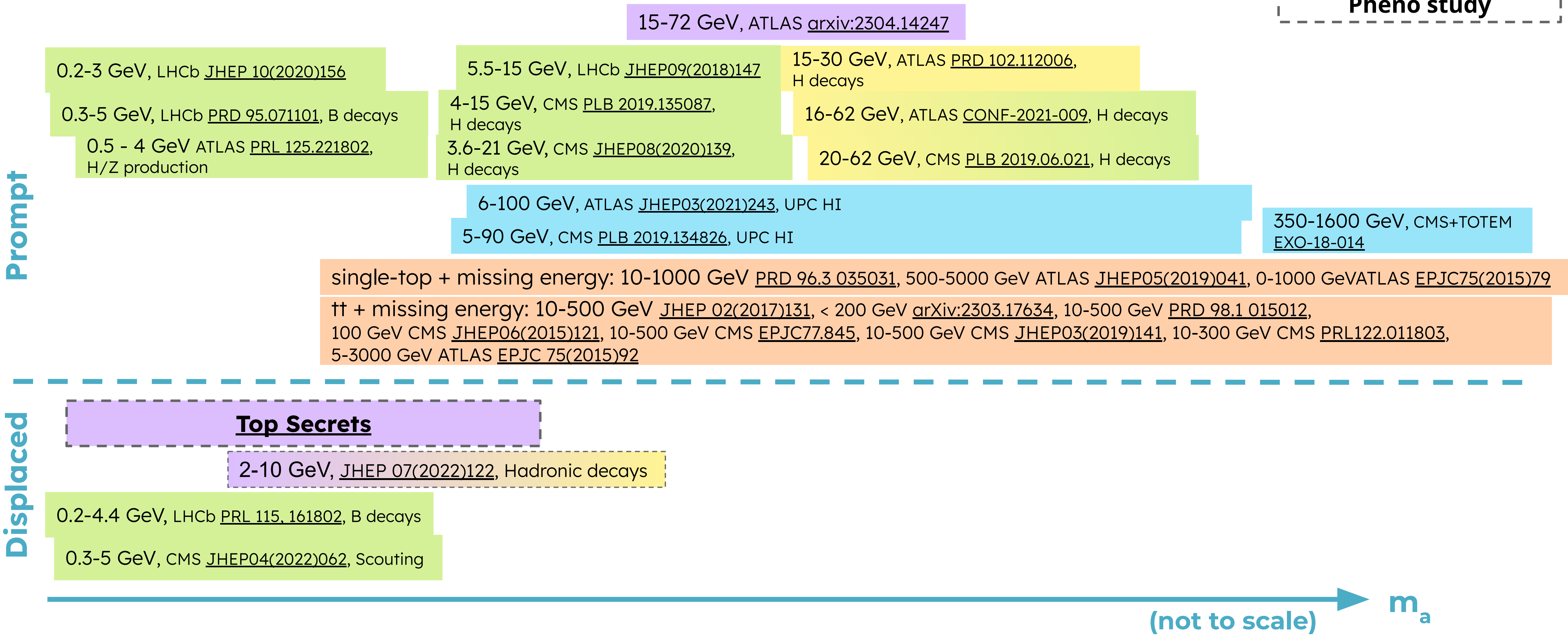
Backup

ALPs searches at the LHC

There exist a large variety of searches for ALPs which 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 study



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

tt + 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

Displaced

Top Secrets

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

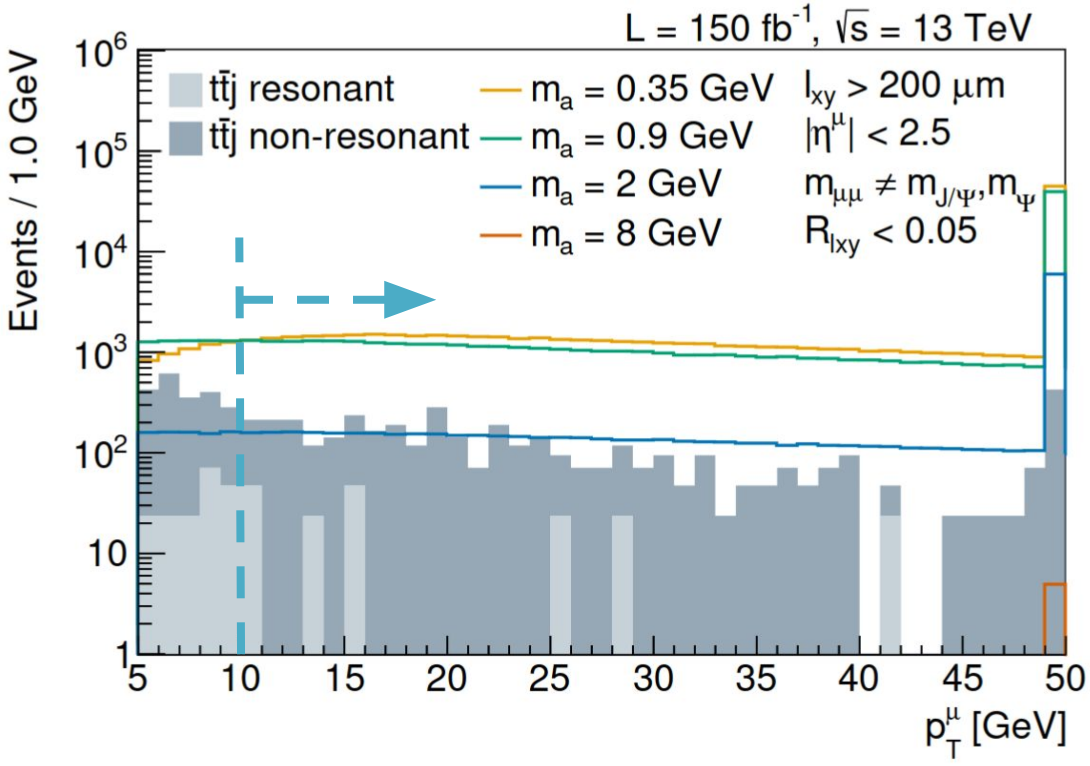
0.2-4.4 GeV, LHCb PRL 115, 161802, B decays

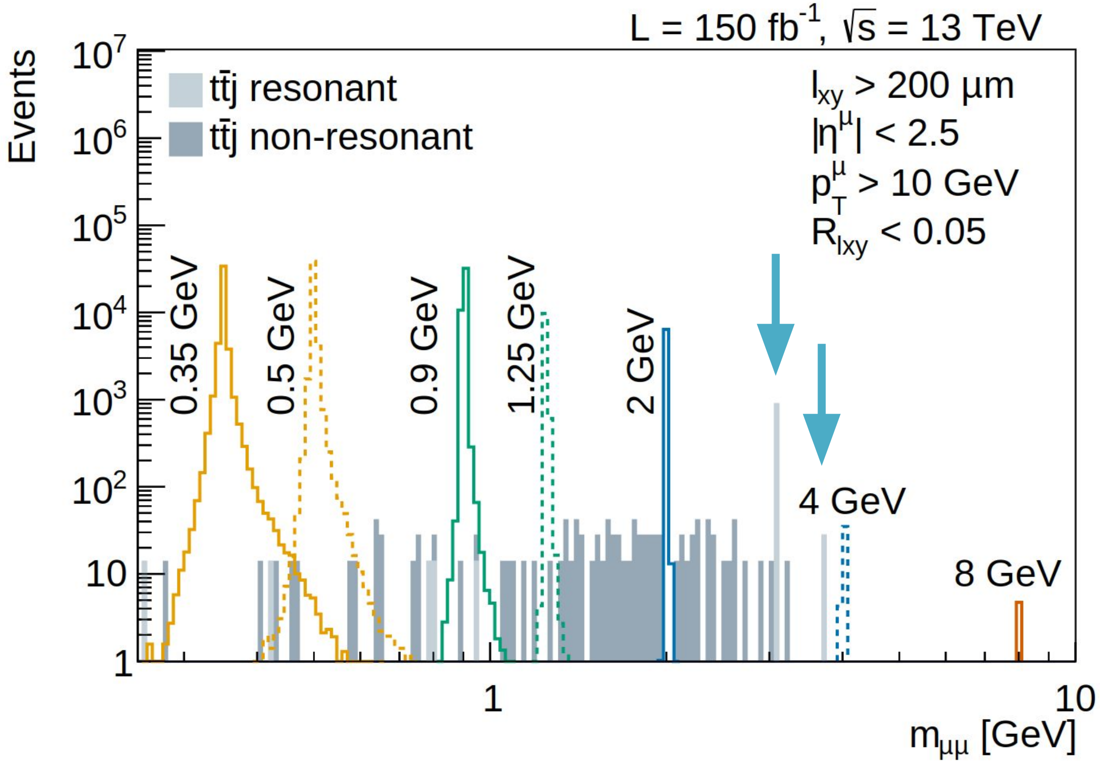
0.3-5 GeV, CMS JHEP04(2022)062, Scouting

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 p_T background





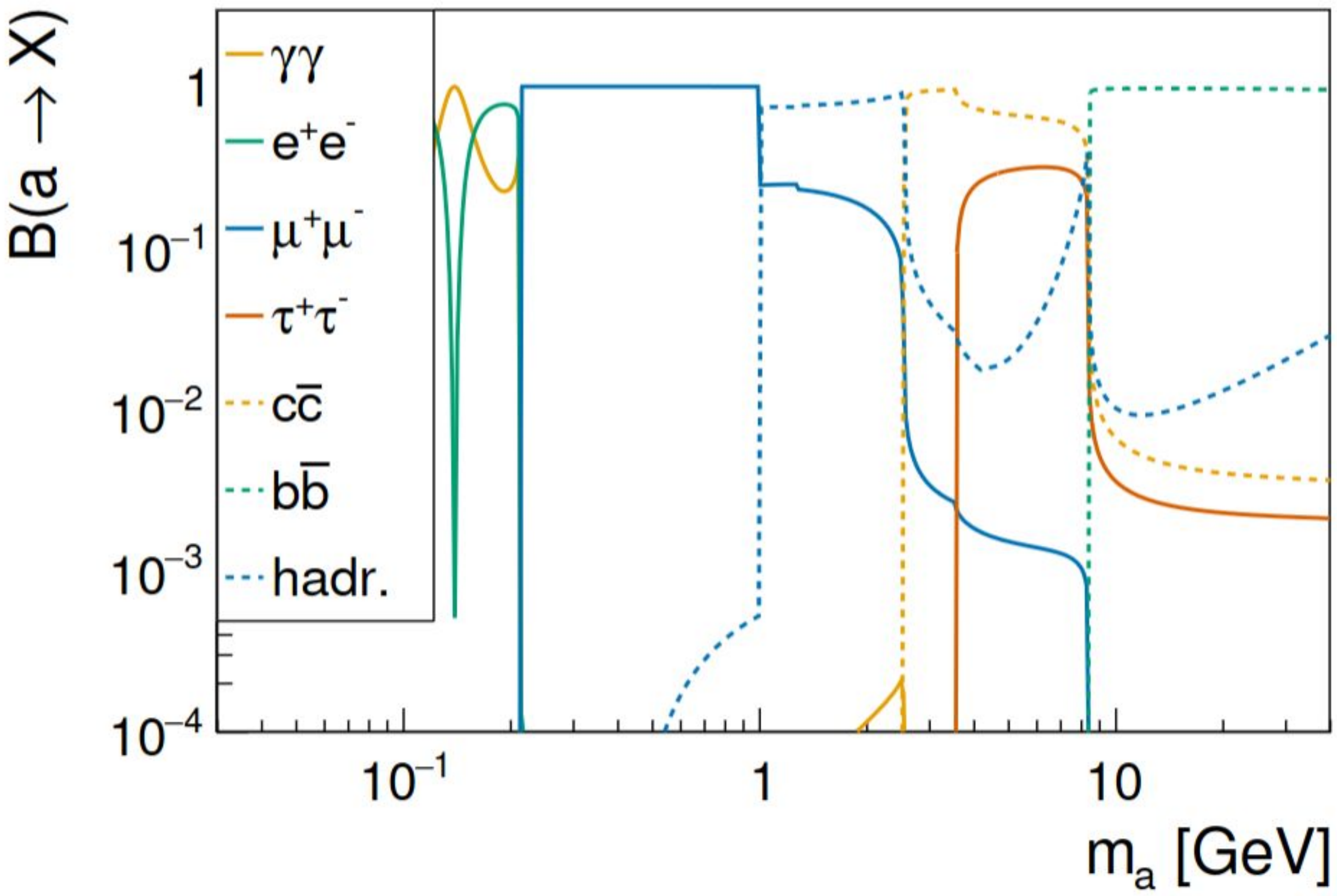
Di-muon resonances

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 Ψ(2S) meson masses

ALP branching ratios

Branching ratios of ALPs as a function of m_a

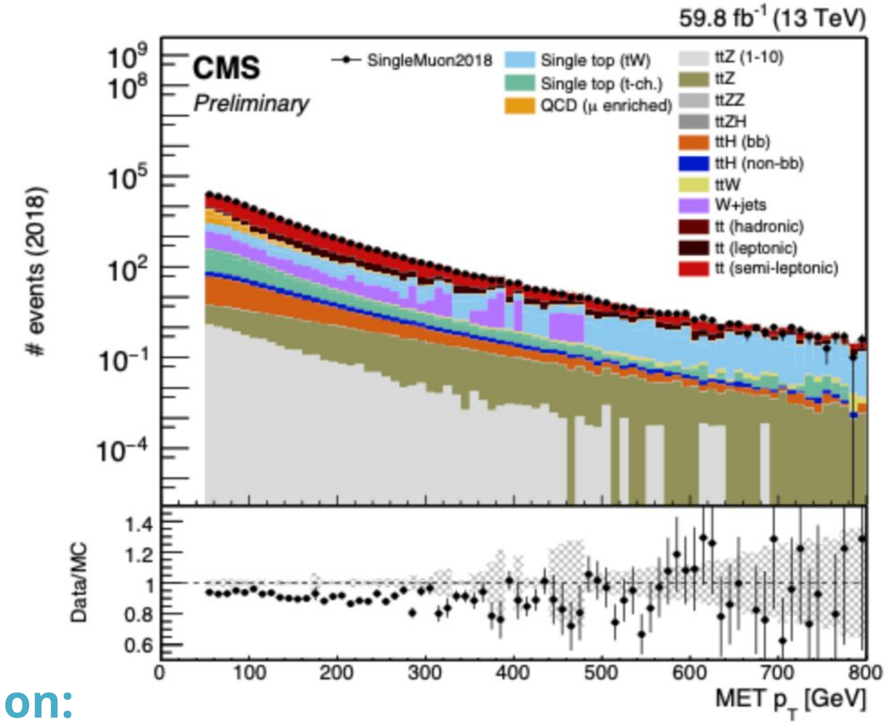


CMS Search: Object Descriptions

$t\bar{t}$ (muon+jet) control region:

Event Selection:

- $p_T^{miss} > 50$ GeV
- Exactly 1 tight muon
- 0 additional loose muons,
- 0 loose electrons
- ≥4 good jets, ≥2 good b-tags



$t\bar{t}$ (muon+jet) + dimuon signal region:

Event Selection:

- $p_T^{miss} > 50$ GeV
- Exactly 1 tight muon
- 2 additional loose muons or loose DSA muons
- 0 loose electrons
- ≥4 good jets, ≥2 good b-tags

loose DSA muons are considered if not matched to loose muons

Tight Muon

- tightId
- ≥PFIsoTight
- pT > 30 GeV, |η| < 2.4

Loose Muon

- looseId
- PFIsoVeryLoose
- pT > 15 (5) GeV for CR (SR)
- |η| < 2.5

Loose DSA Muon

- displacedID
- pT > 5 GeV, |η| < 2.5

Loose Electron

- mvaFall17V2Iso_WPL
- pT > 15 GeV, |η| < 2.5

Good (b-)Jets

- tightLepVeto
- btagDeepFlavB > 0.2783
- pT > 30 GeV, |η| < 2.4

CMS Search: LLPnanoAOD v.1

LLPnanoAOD v.1 content with displaced muons

Dedicated CMS data format for long-lived analyses

LLPnanoAOD v.1 collection	Description
DSAMuon	*displacedStandAloneMuons from MiniAOD/AOD* • *Including default values for RECO::track* • *Including custom variables for displacement* • *Including custom variables for DSAMuon ID* • *Including Segment/Hit matching to Muon collection* • *Including indexing logic for matching and MuonVertex*
Muon	*Extension of existing Muon collection* • *Including custom variables for displacement* • *Including Segment/Hit matching to Muon collection* • *Including indexing logic for matching and MuonVertex*
MuonVertex	*Fitted muon vertices in 3 combinations:* • *Muon-Muon* • *Muon-DSAMuon* • *DSAMuon-DSAMuon* *Including displaced Tracker Isolation for each di-muon combination*
BeamSpot	*Including the default NanoAOD vertex variables*
GenPart	*Extension of existing GenPart collection* • *Including vx, vy, vz variables*