HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Searches for Long Lived ALPs in $t\bar{t}$ events

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Outline

Introduction

- axions & axion-like particles
- ALP model — top scenario
- existing ALP searches at LHC

Analysis details

- MC samples
- background suppression
- categorization and signal extraction

Results

- expected sensitivity with Run 2 (HL-LHC) data

Summary & outlook

AXION-LIKE PARTICLES

Axions

- **original axions**: Peccei-Quinn theory solving the strong CP problem,
- characteristic two-photon vertex:
  - light shining through the wall experiments.

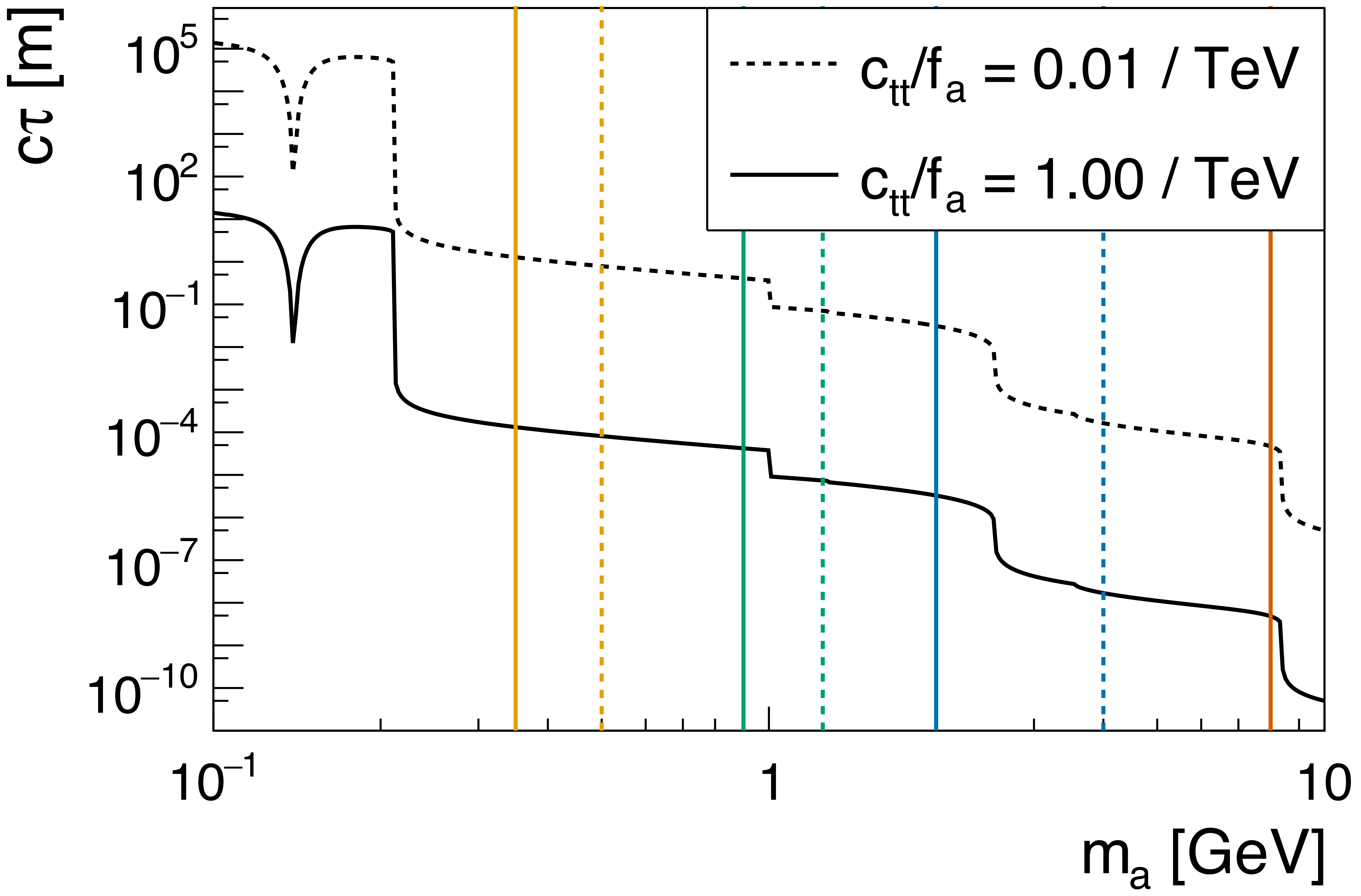
Axion-Like Particles (ALPs)

- more general class of **elementary pseudo-scalar** particles,
- **mass-coupling** relation is **not fixed**,
- occur in many **extensions of SM**,
- **extensive searches at DESY**: ALPS II, (Baby)IAXIO, LUXE, MADMAX…
- many other **collider and non-collider searches.**

ALPs model — Top scenario

The top scenario of the ALP model

- a new (pseudo-)scalar is expected to have **Yukawa-like couplings** to SM fermions,
- if that is the case, it would couple **predominantly to the top quark** (light quark coupling suppressed by small masses),
- for simplicity, we assume **only top couplings**.



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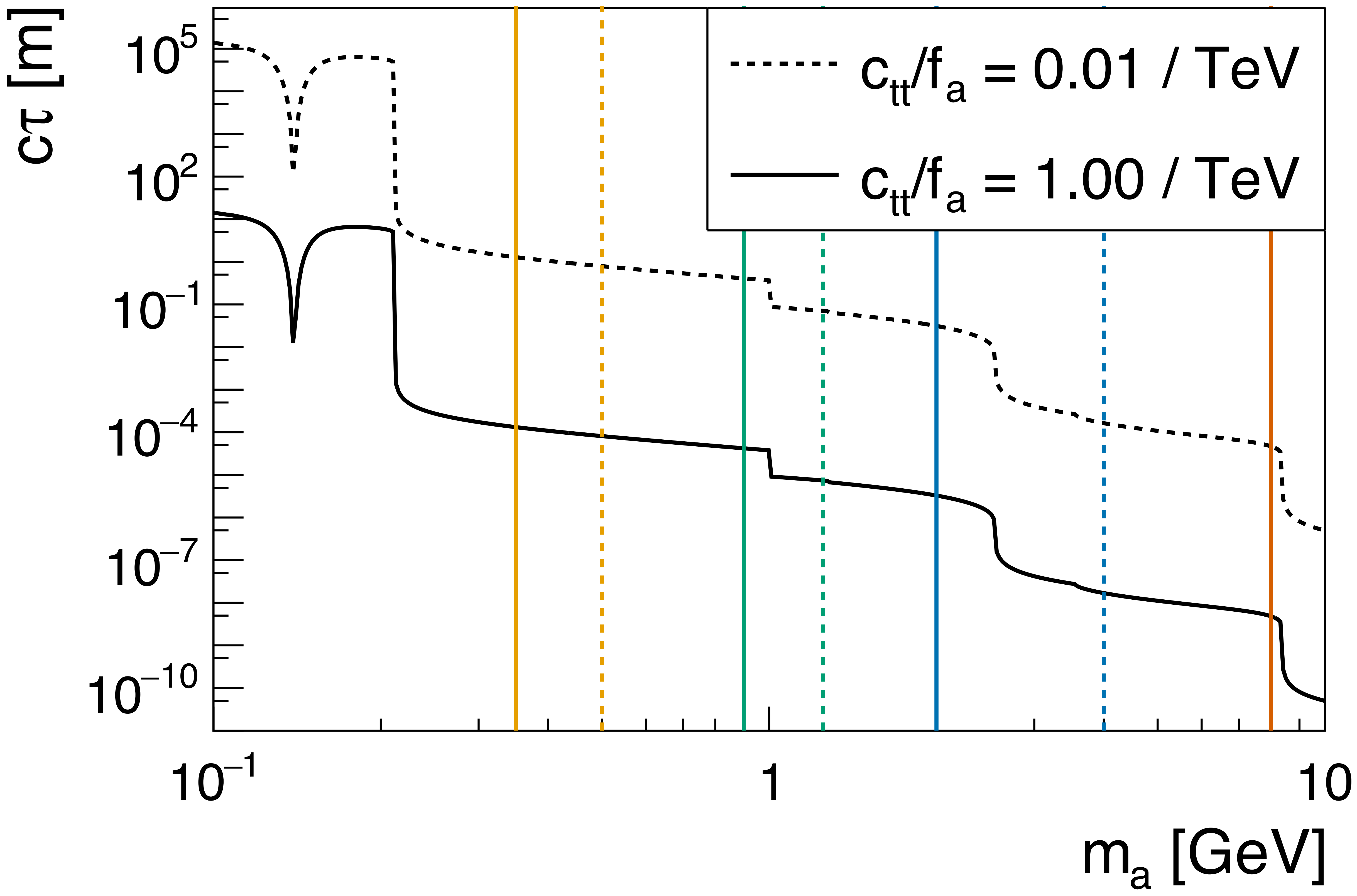
Model parameters

Overall, just **2 free parameters** in the model:

- m_a - ALP **mass**,
- c_{tt} - top-ALP **coupling**.



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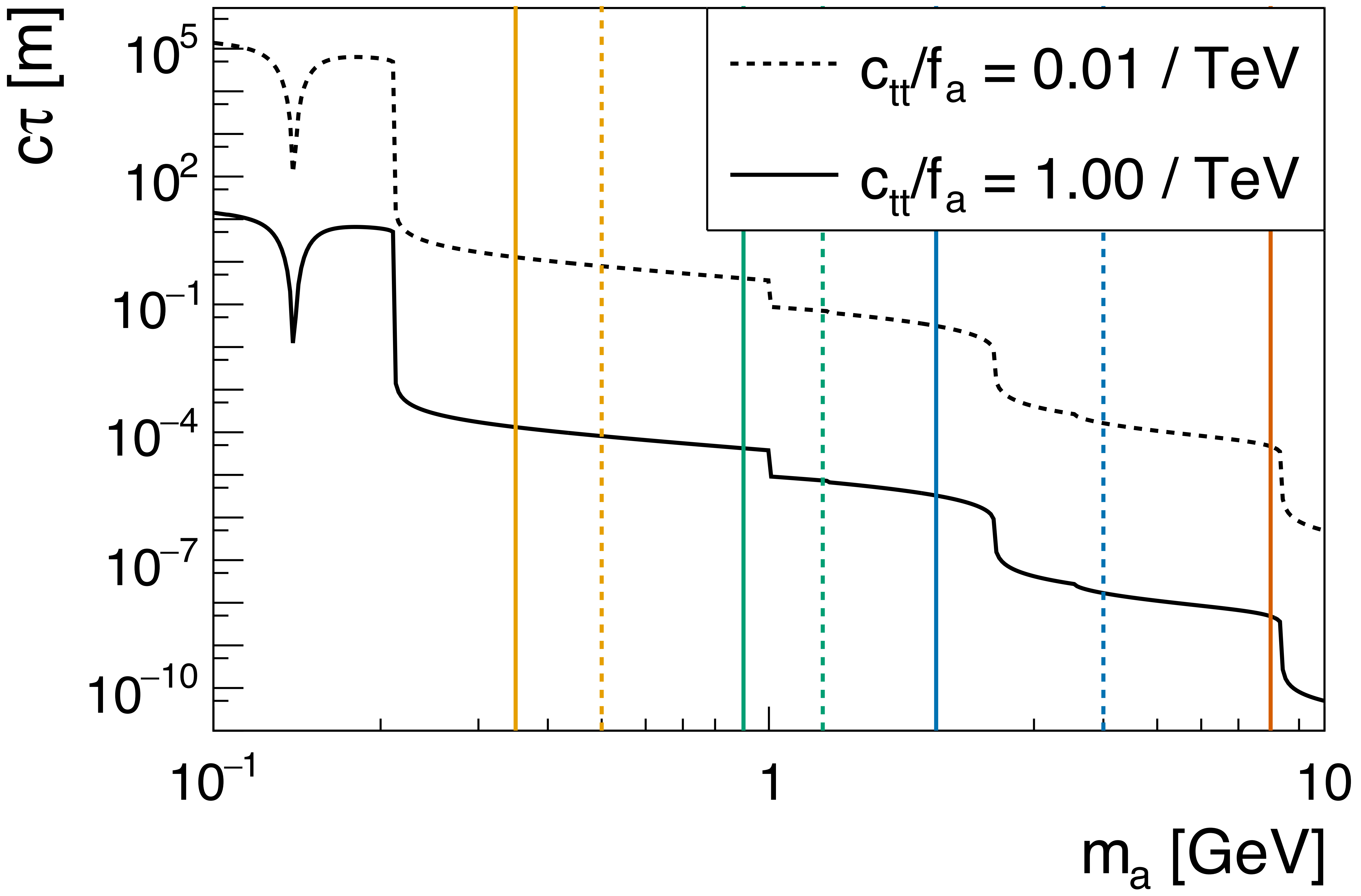
ALP decays

- **loop induced** (decay width determined by c_{tt}),
- ALPs likely to be **long-lived**,
- for $m_a < 1$ GeV predominantly to **muons**,
- above that **other channels** open (like $c\bar{c}$, $\tau\tau$, $b\bar{b}$, etc.).

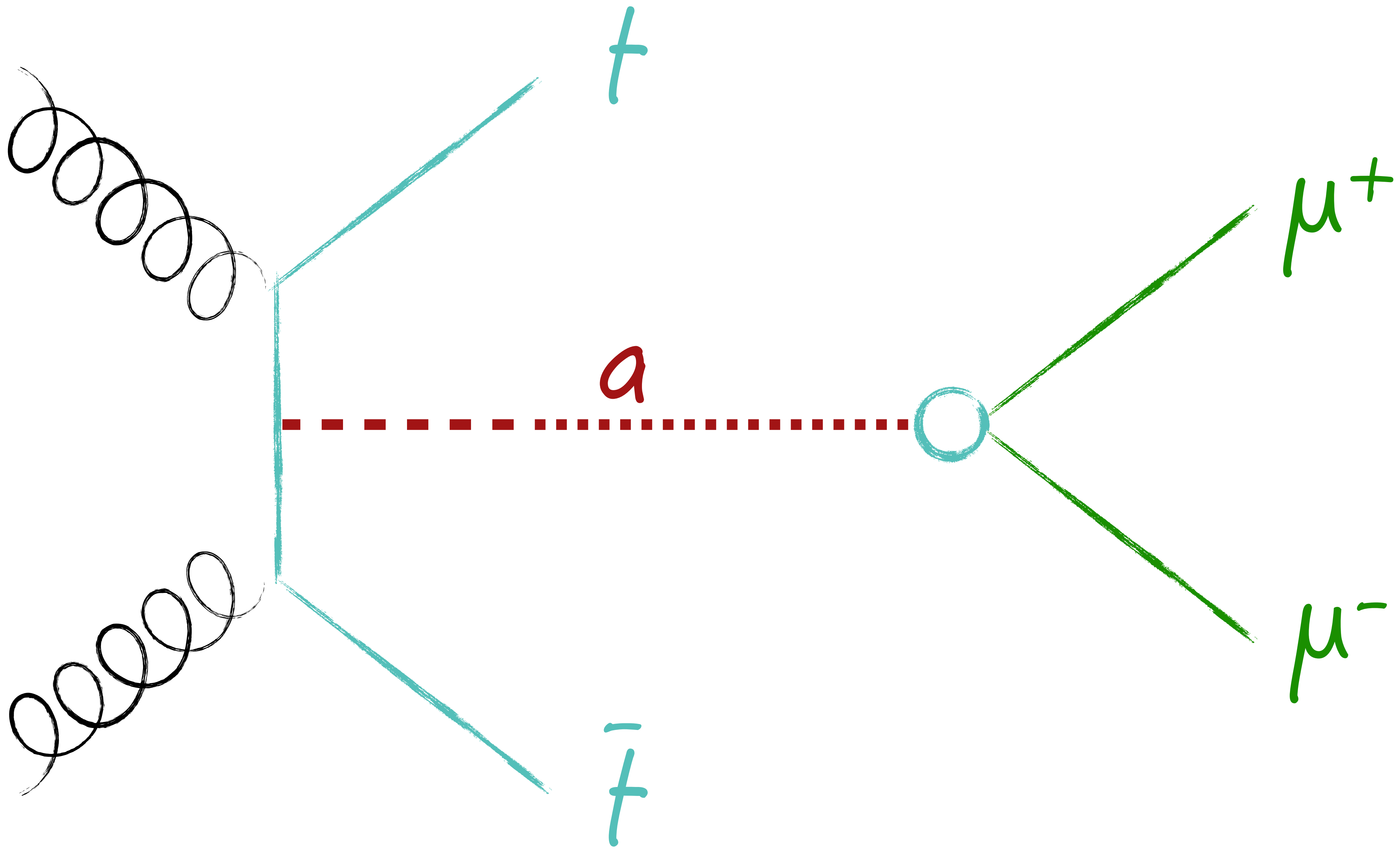


$t\bar{t}$+ALPs at the LHC

Searching for ALPs at LHC

Using $t\bar{t}$ events:

- a **natural place** to look for such ALPs,
- **triggering on tops** & requiring $t\bar{t}$ pair → improved sensitivity,
  - assuming 100% efficient **trigger**,
  - assuming 100% efficient **top-tagging** (recognizing muons coming from top decays).



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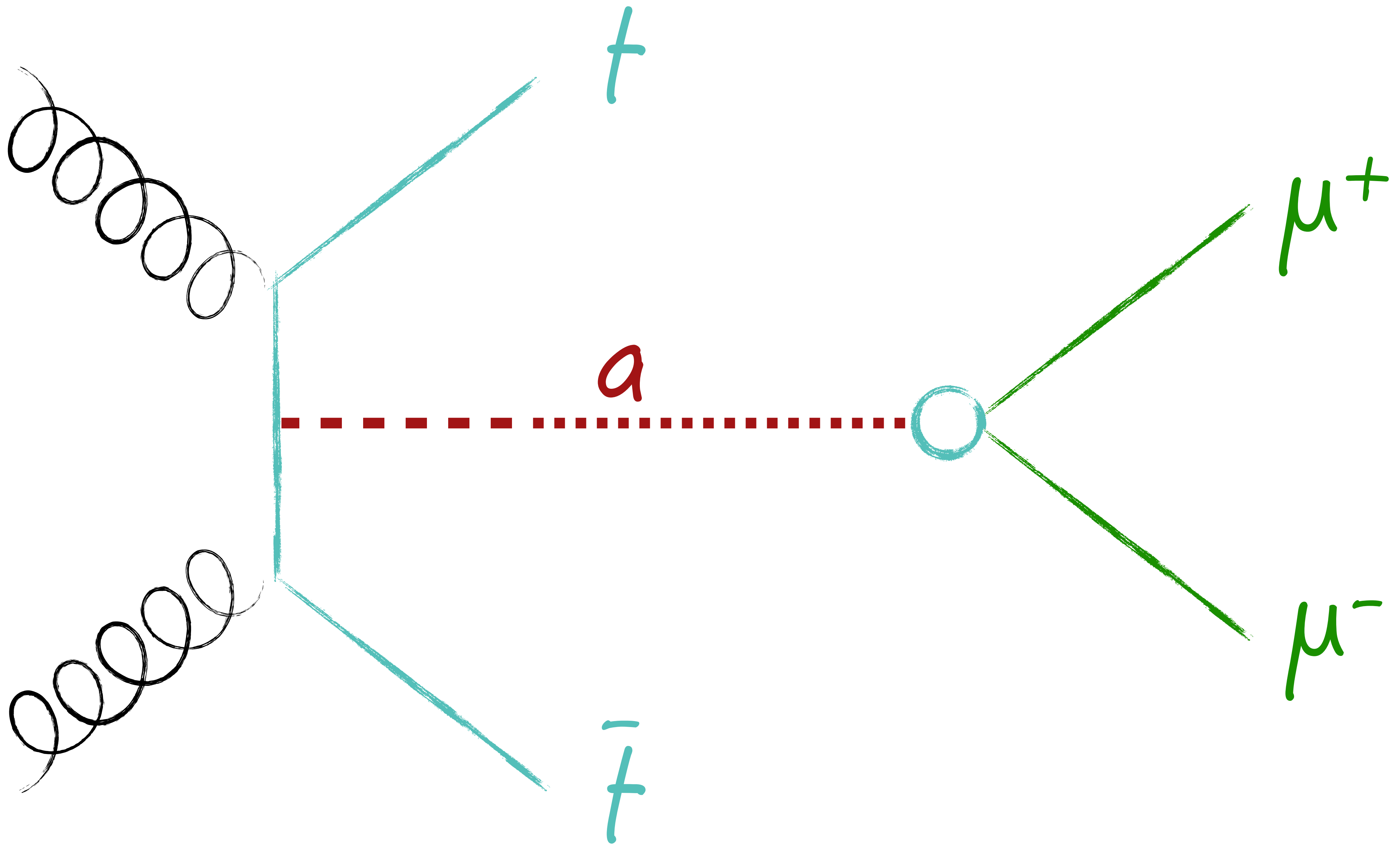
Long lifetime:

- **displaced decay** vertex
- easier background rejection.



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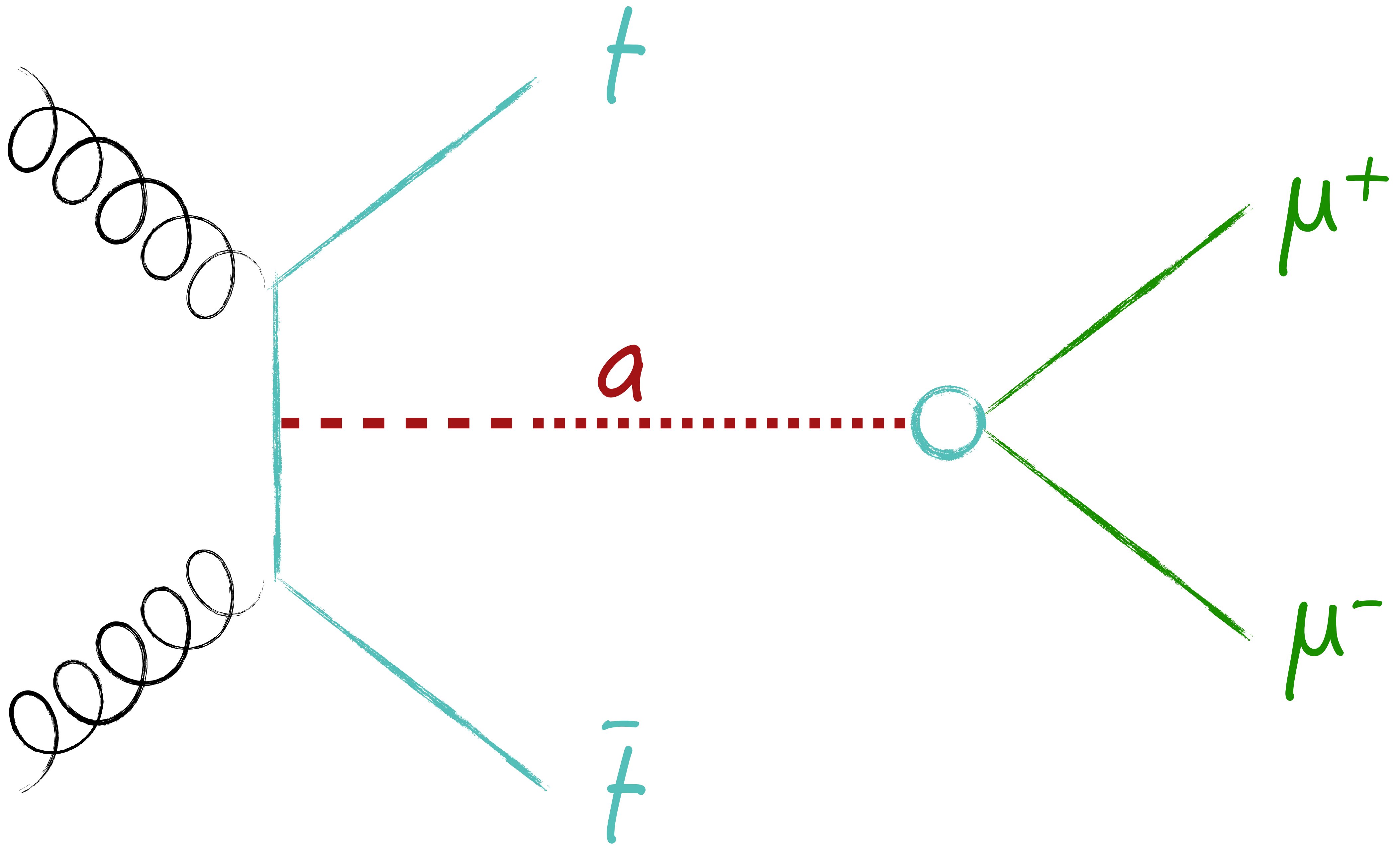
Focus on **decays to muons**:

- excellent tracking,
- easy identification,
- good secondary vertex resolution.



ALPs at the LHC

ALPs have been extensively searched for **at the LHC**:

- huge **mass range**: 0.2 to 1600 GeV,
- various final states and production mechanisms, probing **various ALP couplings**,
- only one (very recent) paper covering **top-ALP coupling**.

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➡ **this analysis**:

- directly probing **top-ALP coupling** → well **theoretically motivated**,
- improved sensitivity thanks to **$t\bar{t}$ requirement**,
- interesting, **uncovered signature** ($t\bar{t}$ + displaced dimuon),
- accessing **lower mass range**.

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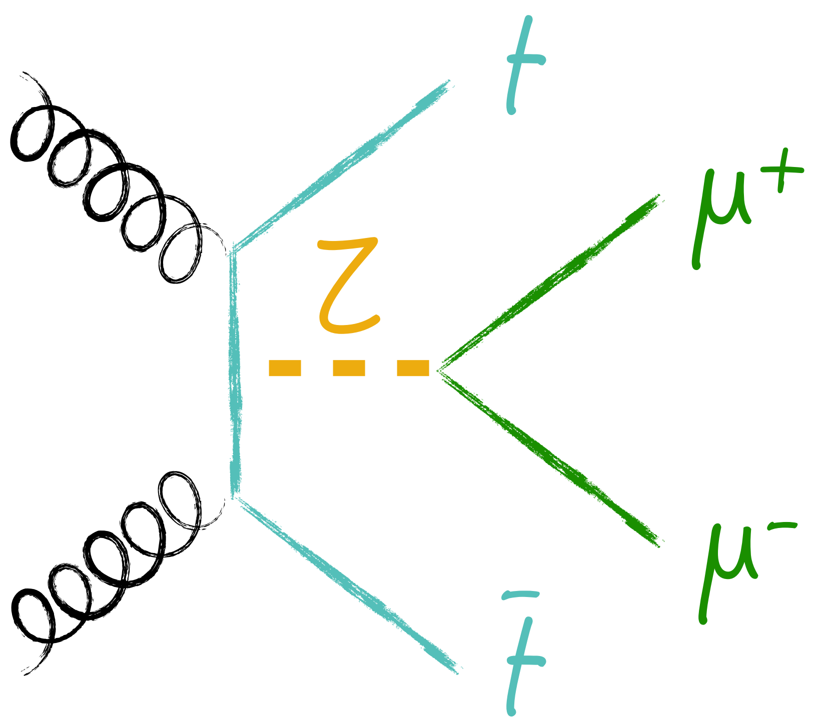
SIGNAL & BACKGROUND SAMPLES

Considering **two sources of backgrounds**

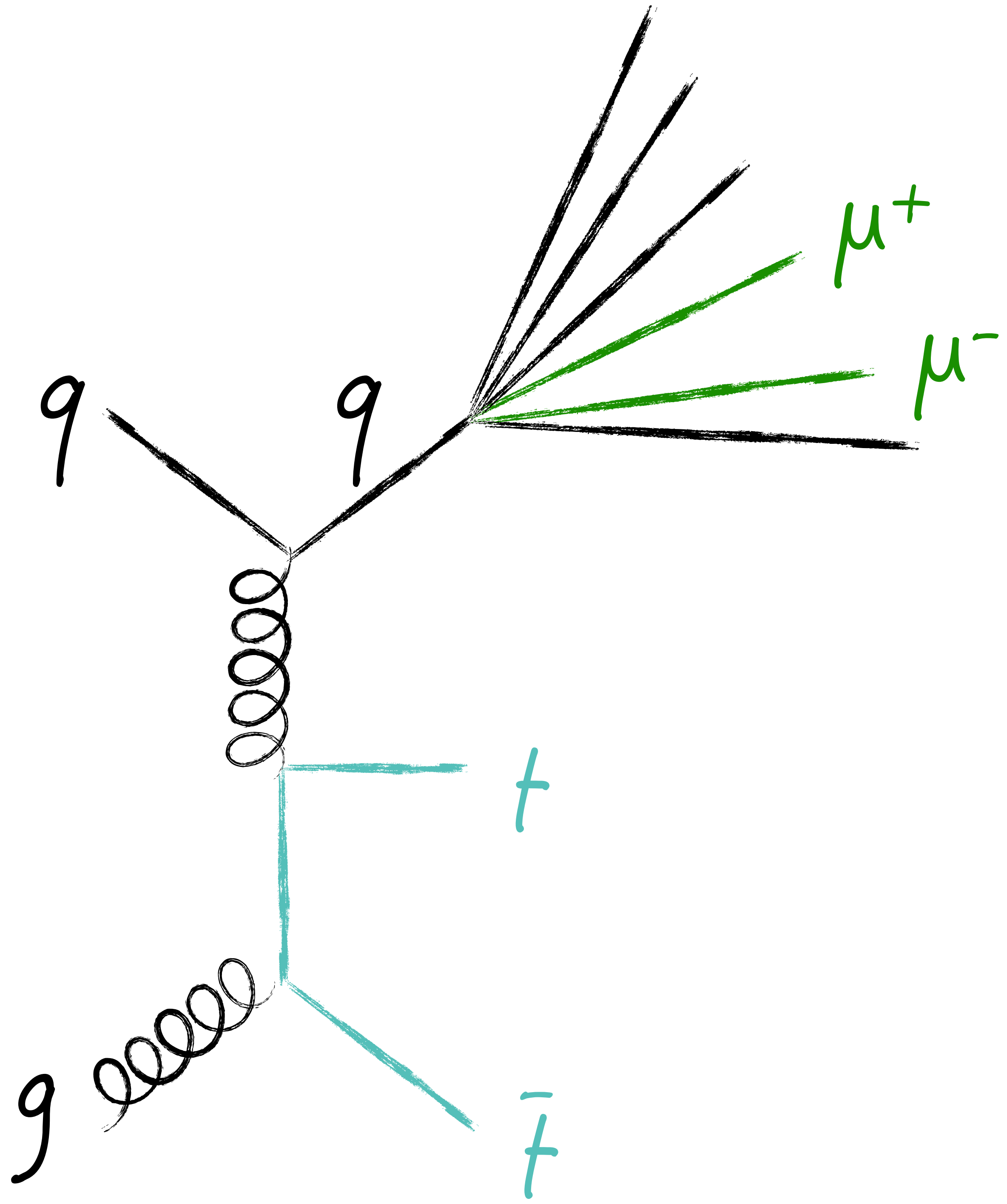
$t\bar{t}Z^*$

Z boson (photon) produced in association with $t\bar{t}$ pair and **decaying to $\mu^+\mu^-$**



$t\bar{t}$+jet

particles in the jet **decay to muon(s)**



MC generation details

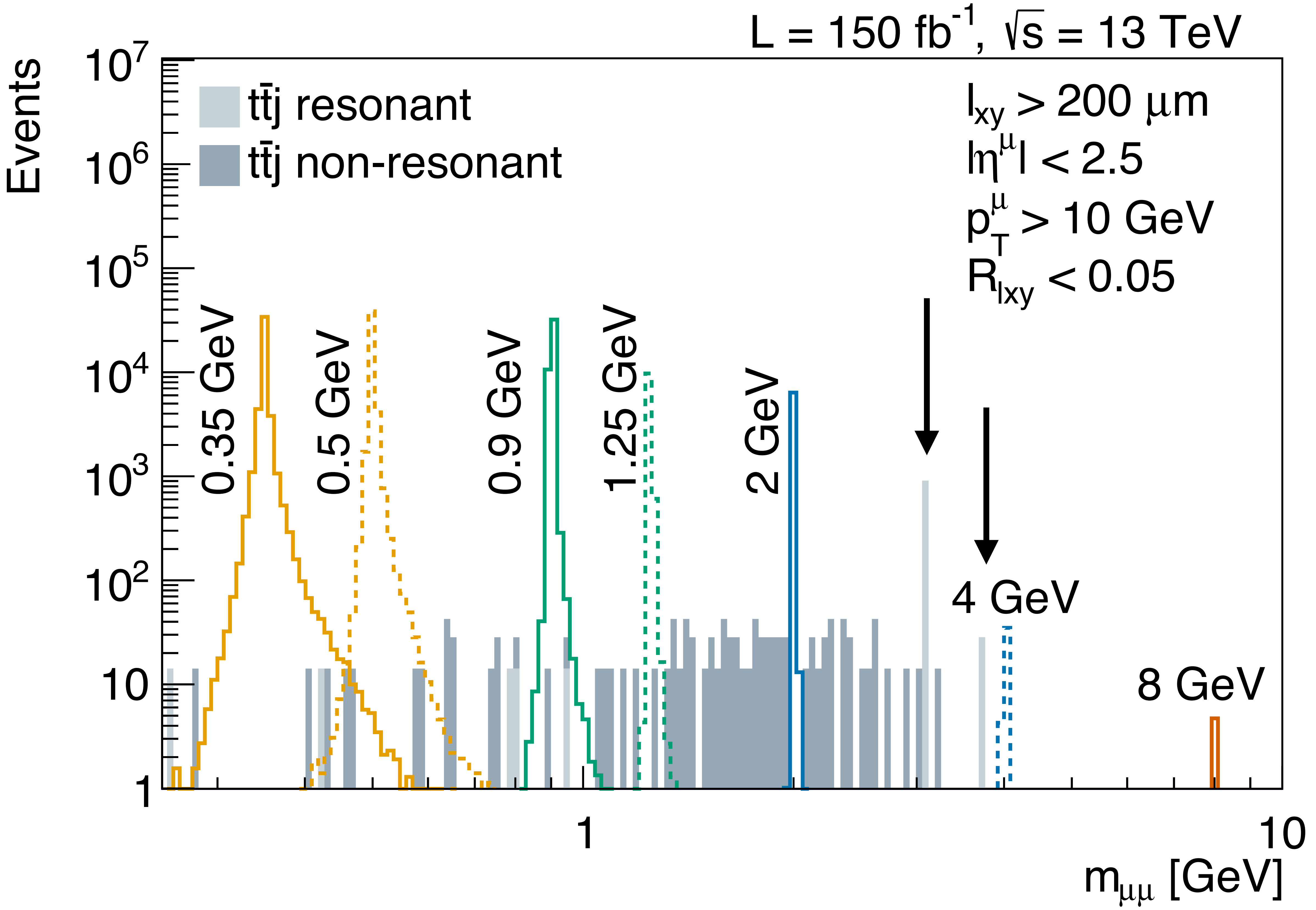
- all processes generated with **MadGraph 5**,
- hadronization and ALP decays performed with **Pythia 8**,
- **setting c_{tt}/f_a = 1.0/TeV** for ALP signal samples,
- setting luminosity to **150 fb^{-1}** (3 ab^{-1}) for Run 2 (HL-LHC).

BACKGROUND SUPPRESSION

Suppressing known resonances

Muons coming from decays of known resonances suppressed by **explicit $m_{\mu\mu}$ cuts**:

- considering J/Ψ and Ψ(2S) mesons,
- cutting at $m_R \pm 5\% \cdot m_R$.



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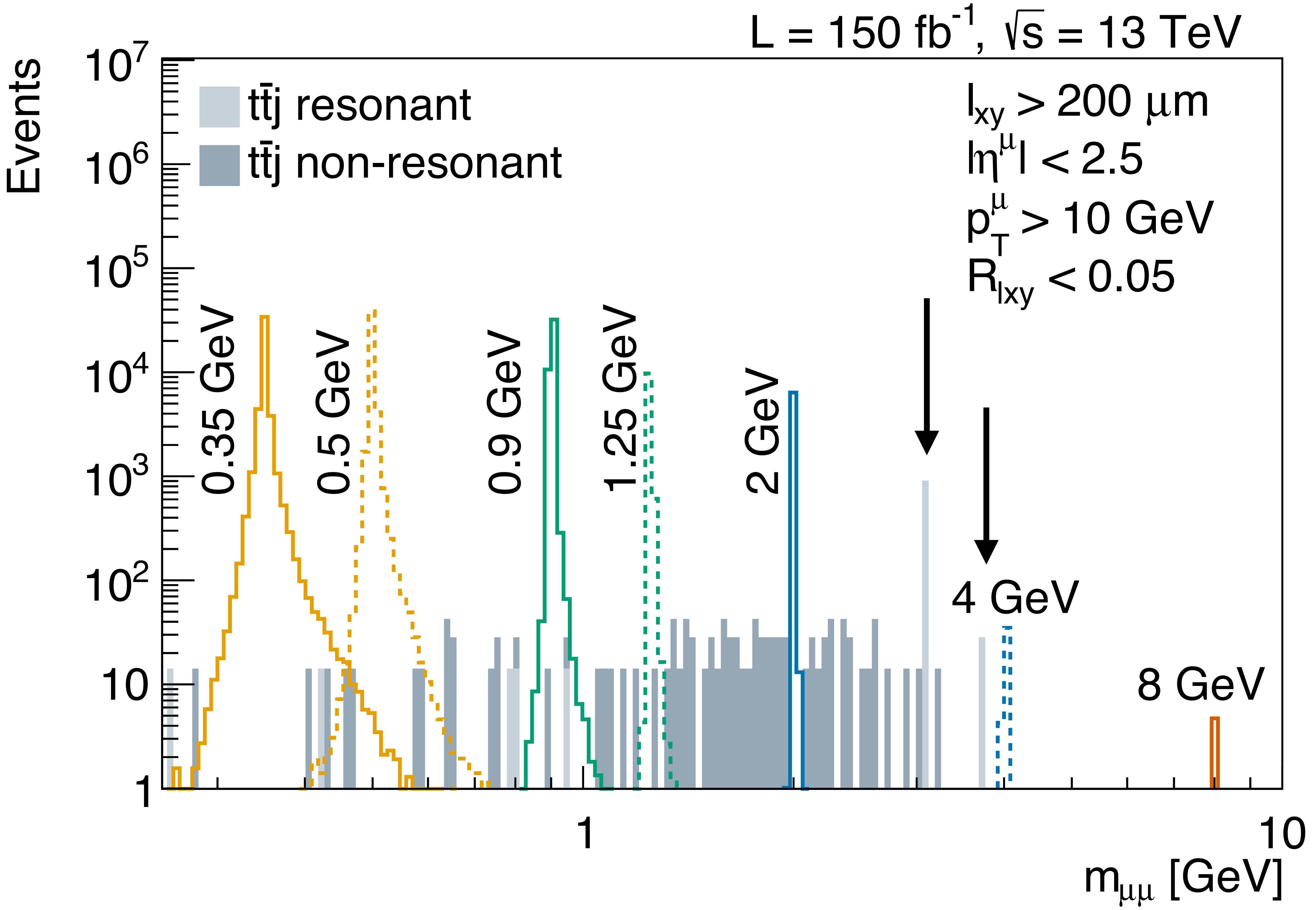
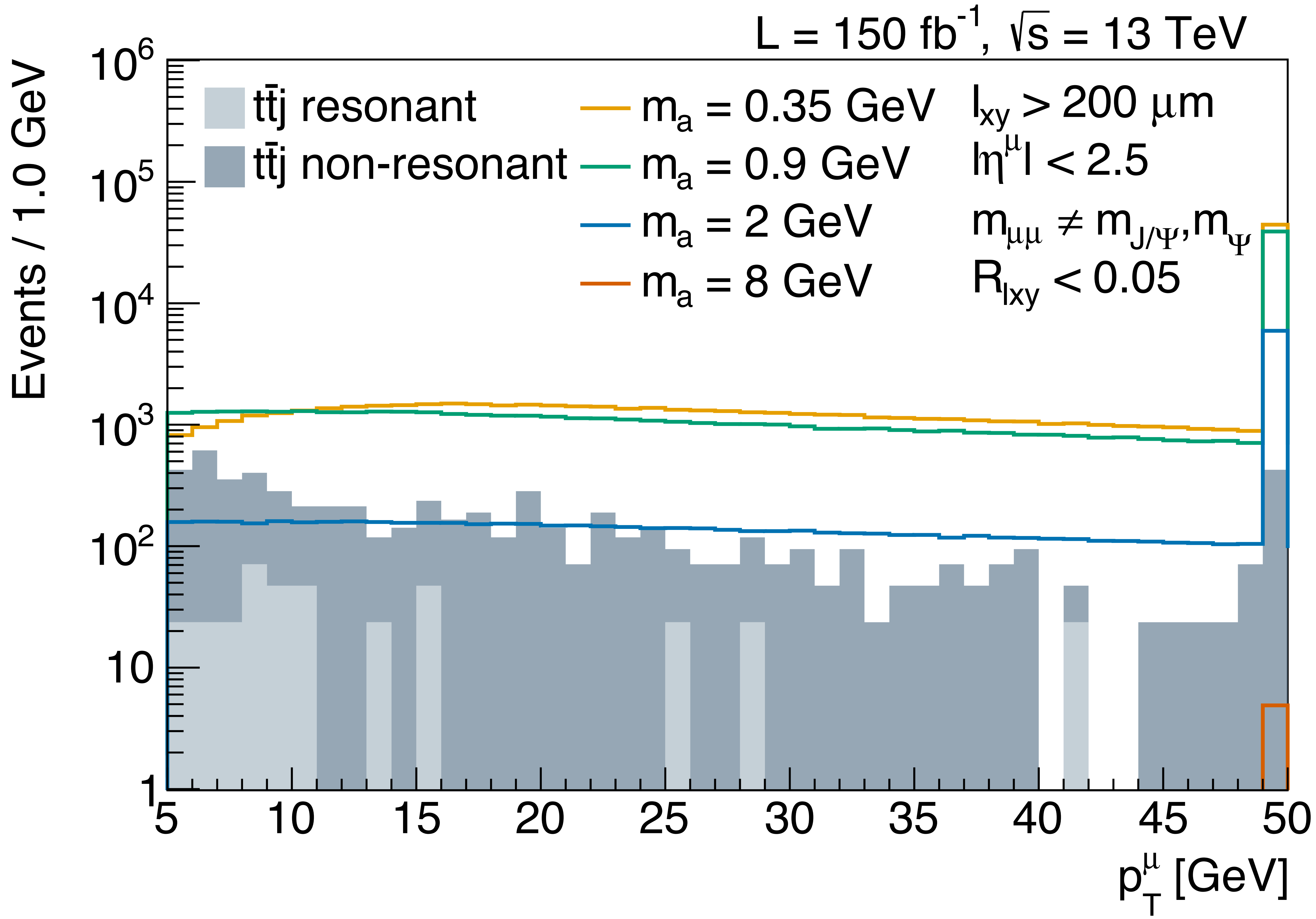




Exploiting p_T spectrum

Signal muon transverse momentum (p_T) tends to be **harder** than for the backgrounds

→ applying **p_T^μ** > 10 GeV selection.

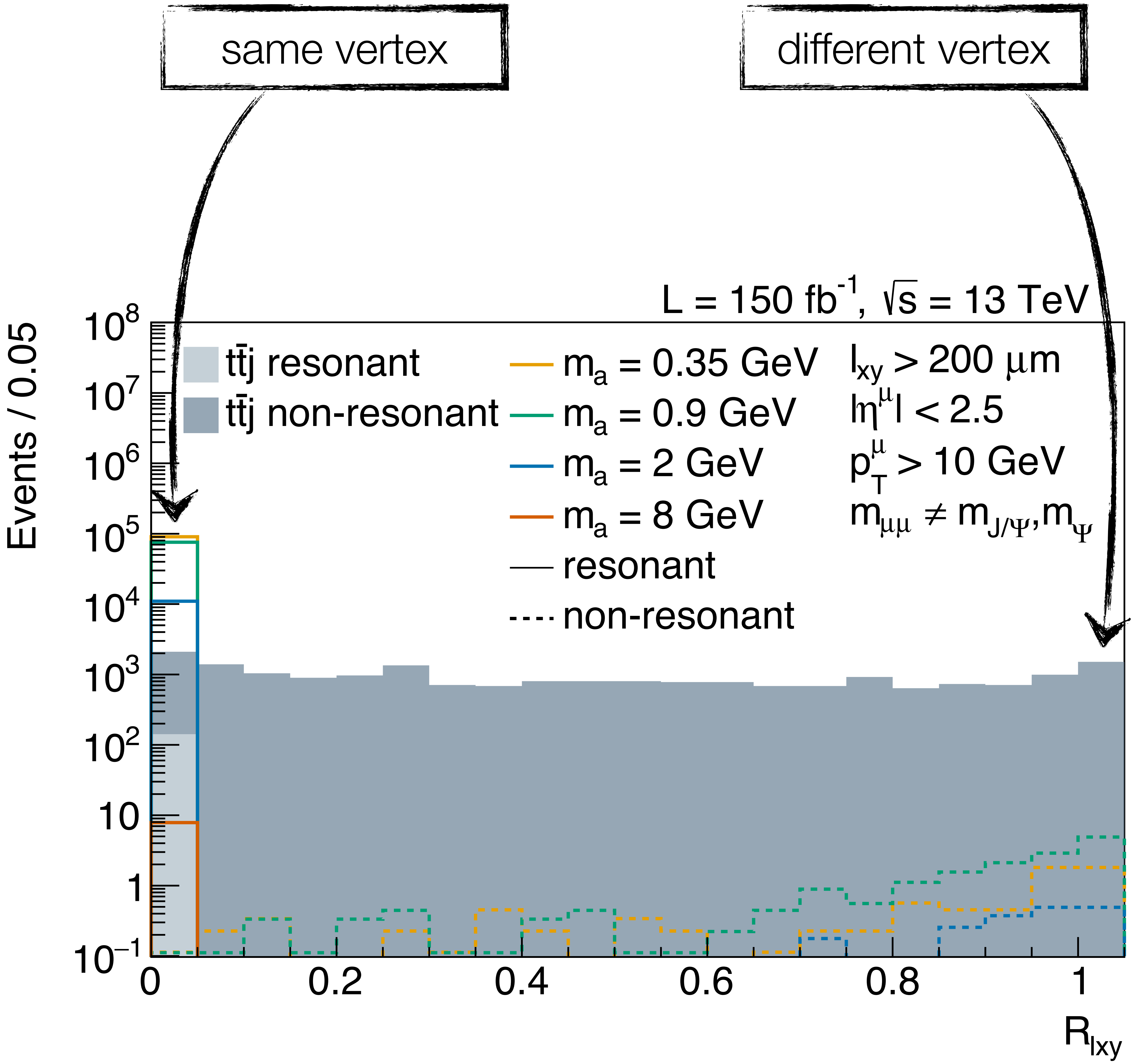
DIMUONS SELECTION

Custom-made variable — R_{lxy}

- want to **select pairs of muons** originating from the **same vertex**,
- don't want to be too dependent on **detector resolution** (this study doesn't include detector simulation),
- proposing the following variable:

$$R_{l_{xy}} = \sqrt{\frac{(x^{\mu} - x^{\bar{\mu}})^2 + (y^{\mu} - y^{\bar{\mu}})^2}{(|x^{\mu}| + |x^{\bar{\mu}}|)^2 + (|y^{\mu}| + |y^{\bar{\mu}}|)^2}}$$

  - x and y are **muon vertex coordinates**,
  - sensitive to the **difference in muons' origin**,
  - largely independent from **detector resolution**,
- selection:
  - the pair with the **smallest** R_{lxy} is picked,
  - events with R_{lxy} **< 0.05** are kept (conservative estimate based on CMS vertex reconstruction resolution → in reality we should be able to do better than that).



SELECTIONS SUMMARY

Pre-selection

- p_T^μ > 5 GeV,
- $|\eta_\mu|$ < 2.5,
- l_{xy} > 200 μm,
- **veto** muons coming **from top decays**,
- at least one pair of **opposite-sign** muons in the event.

Signal selection

- **known resonances**: explicit mass cuts,
- exploit **p_T spectrum**: p_T^μ > 10 GeV,
- muons coming from the same **vertex**: R_{lxy} < 0.05.

Expected number of events for 150 fb^{-1}

Signal efficiency	$m_a = 0.35$ GeV	$m_a = 0.9$ GeV	$m_a = 2$ GeV	$m_a = 8$ GeV
Pre-selection	$(8.92 \pm 0.01)\times10^{-1}$	$(7.94 \pm 0.01)\times10^{-1}$	$(6.40 \pm 0.01)\times10^{-1}$	$(7.25 \pm 0.03)\times10^{-2}$
$p_T^\mu > 10$ GeV	$(7.99 \pm 0.01)\times10^{-1}$	$(6.79 \pm 0.01)\times10^{-1}$	$(5.58 \pm 0.01)\times10^{-1}$	$(6.87 \pm 0.03)\times10^{-2}$
$m_{\mu\bar{\mu}} \neq m_{J/\Psi}, m_{\Psi(2S)}$	$(7.99 \pm 0.01)\times10^{-1}$	$(6.79 \pm 0.01)\times10^{-1}$	$(5.58 \pm 0.01)\times10^{-1}$	$(6.86 \pm 0.03)\times10^{-2}$
$R_{lxy} < 0.05$	$(7.99 \pm 0.01)\times10^{-1}$	$(6.79 \pm 0.01)\times10^{-1}$	$(5.58 \pm 0.01)\times10^{-1}$	$(6.86 \pm 0.03)\times10^{-2}$
Events passing pre-selection	19793 ± 21	17697 ± 20	2516 ± 3	1.66 ± 0.01
Events passing signal selection	17740 ± 20	15116 ± 18	2193 ± 3	1.57 ± 0.01

Background efficiency	$t\bar{t}j$	$t\bar{t}Z^{(*)}$
Pre-selection	$(2.55 \pm 0.05)\times10^{-4}$	$(1.89 \pm 0.04)\times10^{-4}$
$p_T^\mu > 10$ GeV	$(7.4 \pm 0.2)\times10^{-5}$	$(9.4 \pm 0.3)\times10^{-5}$
$m_{\mu\bar{\mu}} \neq m_{J/\Psi}, m_{\Psi(2S)}$	$(6.8 \pm 0.2)\times10^{-5}$	$(5.8 \pm 0.2)\times10^{-5}$
$R_{lxy} < 0.05$	$(7.1 \pm 0.8)\times10^{-6}$	$(4.9 \pm 0.7)\times10^{-6}$
Events passing pre-selection	15131 ± 267	0.59 ± 0.01
Events passing signal selection	421 ± 45	0.015 ± 0.002

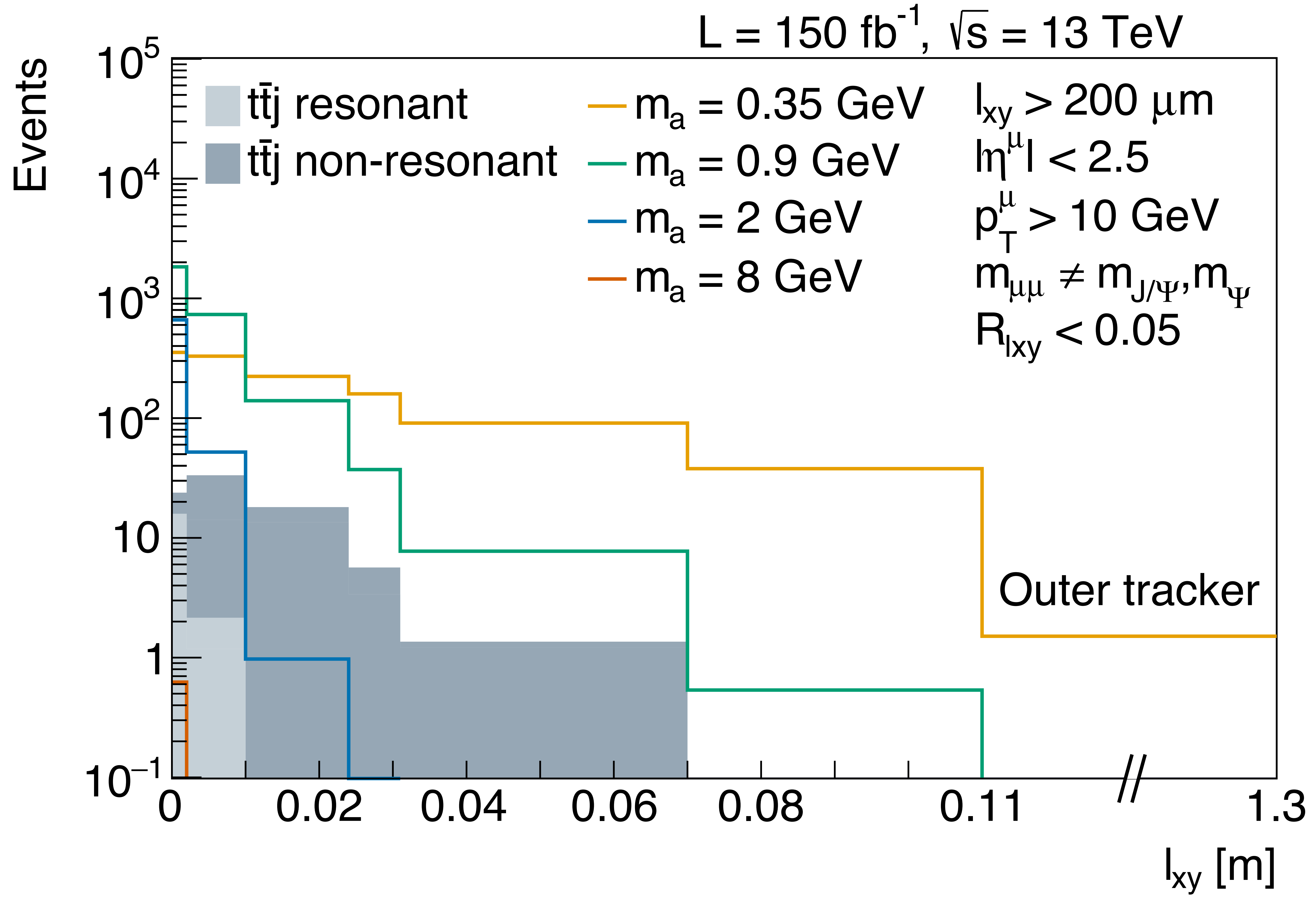
Summary

- **signal efficiency** close to 80% for low masses and decreasing to ≈7% for higher masses (other decay channel important and more prompt),
- **p_T, $m_{\mu\mu}$, and R_{lxy}** cuts suppress backgrounds by >5 orders of magnitude.

CATEGORIZATION — TOP SCENARIO

Bins in l_{xy}

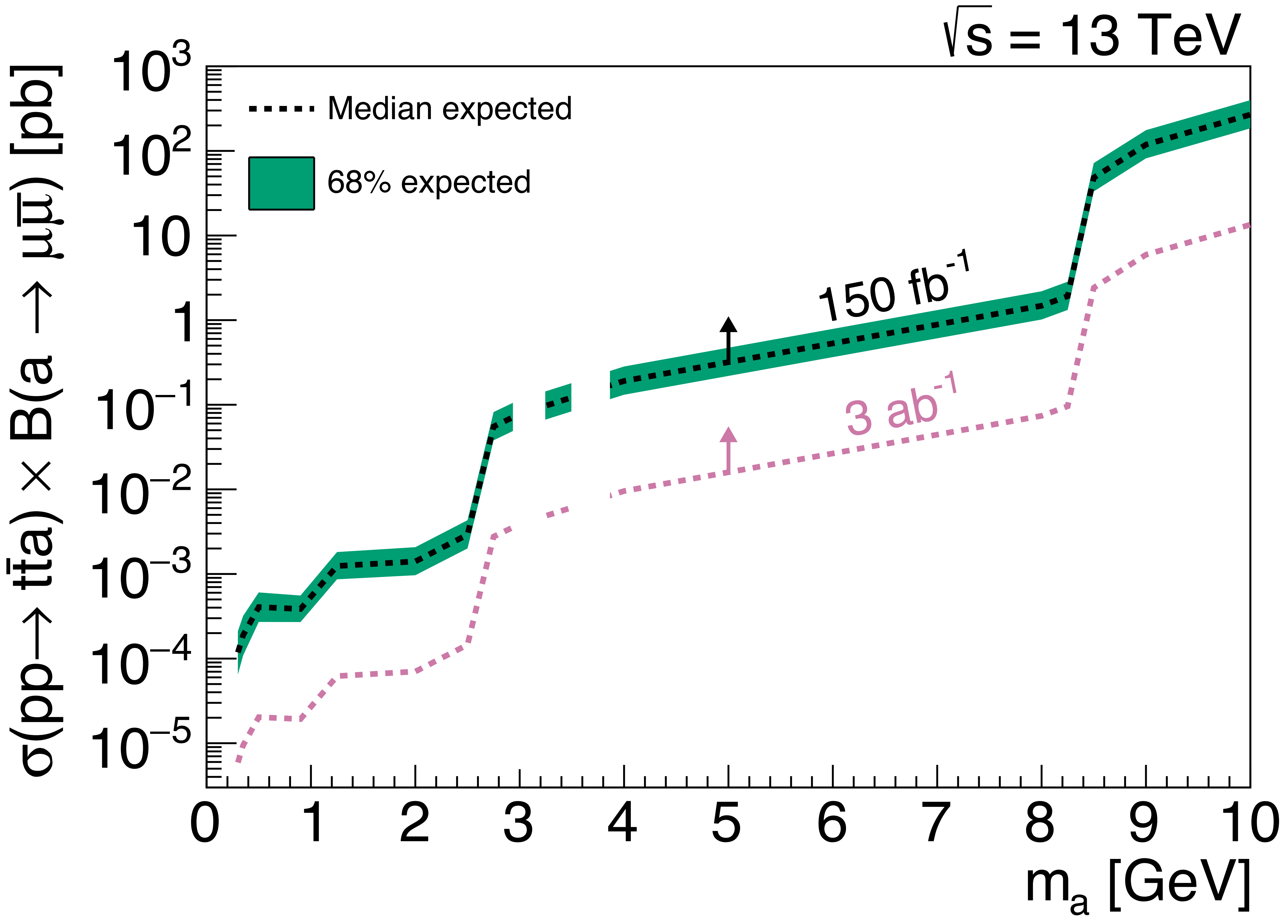
- in order to **further increase sensitivity** to displaced signatures, we bin surviving events in **secondary vertex displacement** l_{xy},
- bins based on an **existing CMS analysis** (EXO-20-014, 2112.13769), driven by beam pipe and tracker layers location.



Expected Sensitivity — Top scenario

Limits — Top scenario

- we derive 95% CL upper limits on cross section times B(a→μμ) as a function of m_a,
- **excellent sensitivity** with Run 2 (HL-LHC) luminosity of 150 fb^{-1} (3 ab^{-1}),
- **best** limits for **low masses** <1 GeV,
- >1 GeV limits deteriorate mainly due to **other decay channels** starting to dominate (but also signal becoming **more prompt**).



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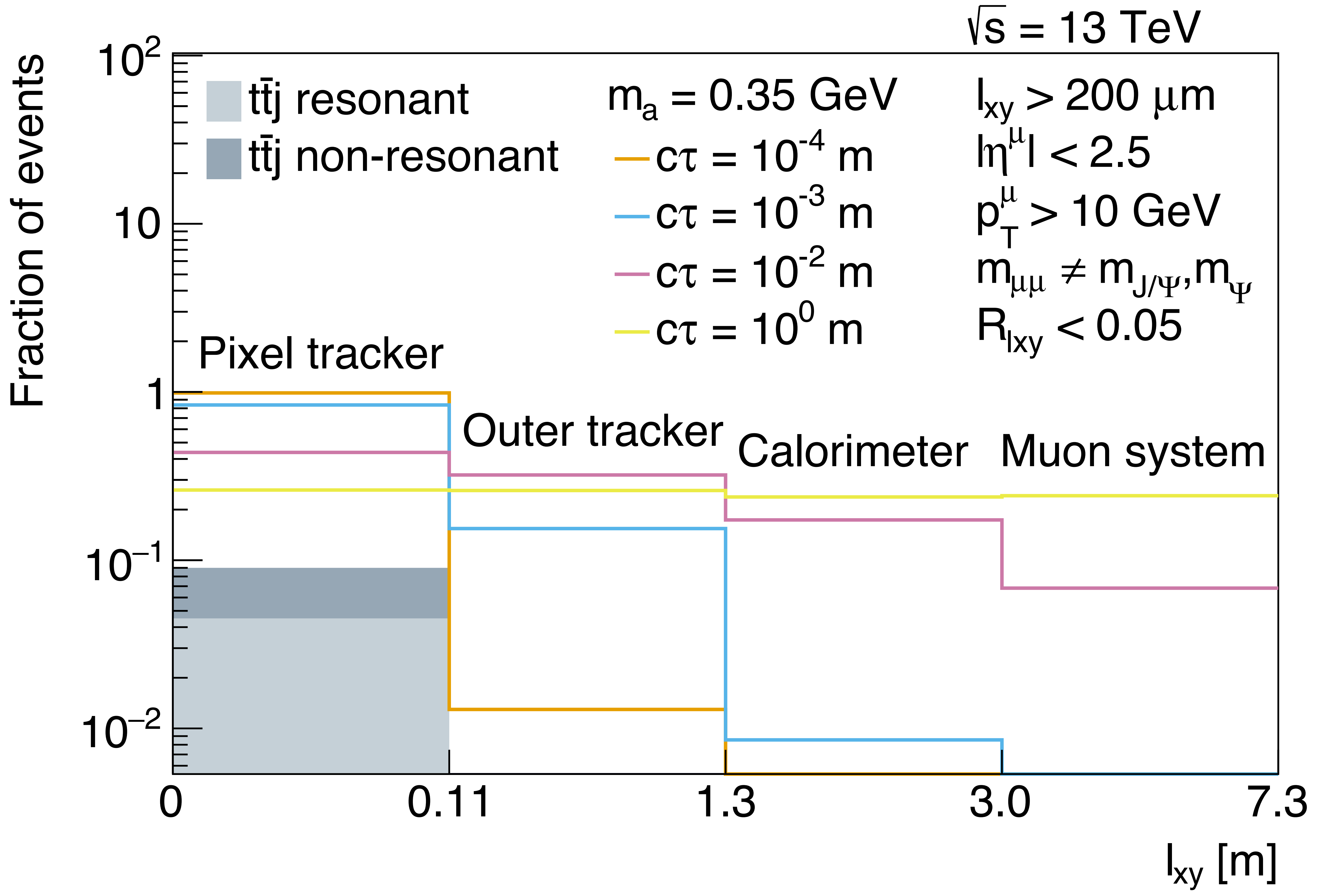
Expected Sensitivity — General scenario

Limits — General scenario

- more general scenario: a new pseudo-scalar with **arbitrary lifetime** produced in $t\bar{t}$ events,
- **cτ ≥1 mm**: decays in **calorimeters and the muon system** become important,
- e.g. for signal **σ x BR(a→μμ) = 1 fb**, one can probe lifetimes as high as **1-10 m (20-400 m)** with Run 2 (HL-LHC) data.



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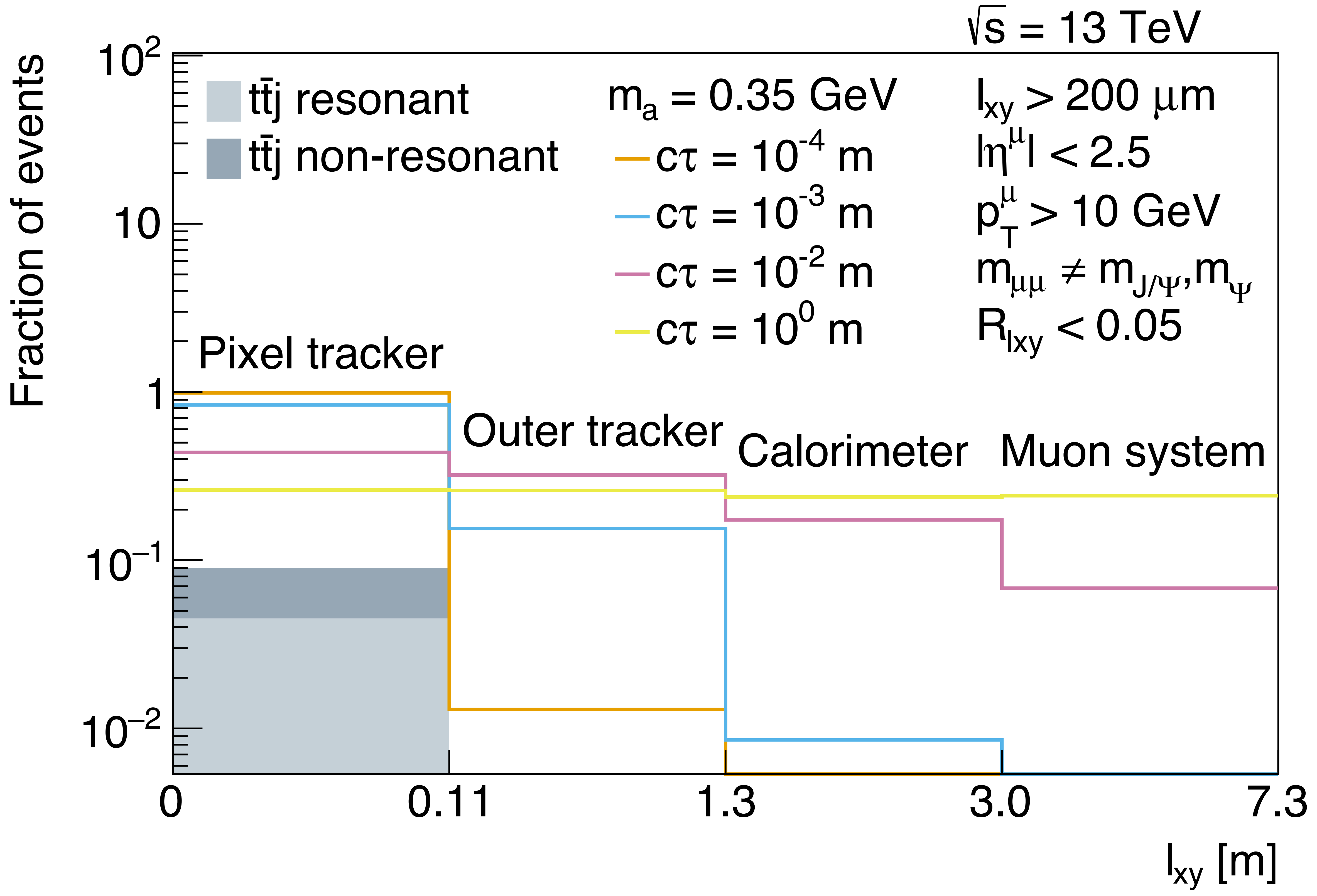

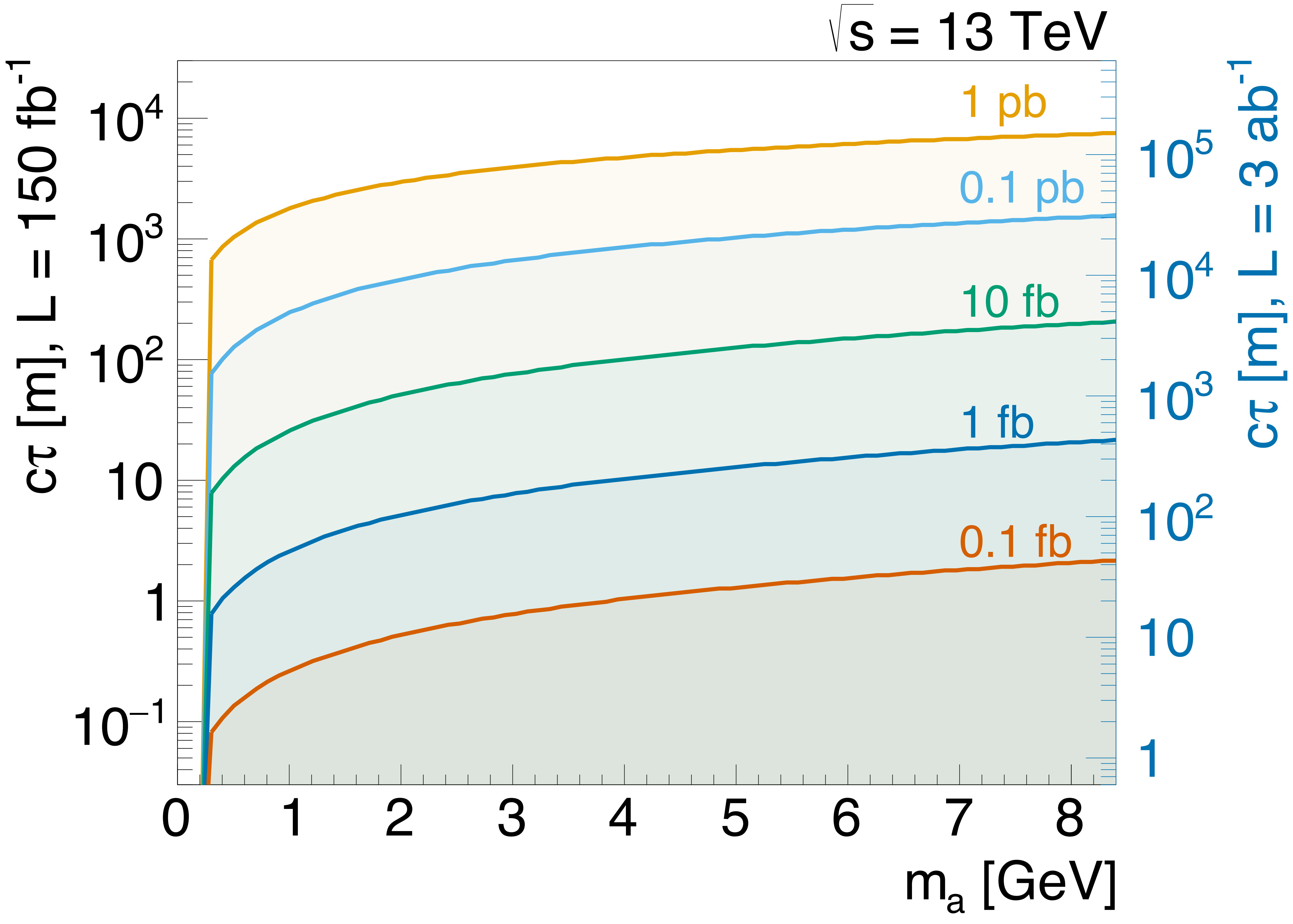

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SUMMARY & OUTLOOK

Current status

- focus on a well-motivated **top scenario ALPs model**,
- **$t\bar{t}$ events**: a natural place to search for ALPs
  - improved sensitivity,
  - **uncovered signature** with $t\bar{t}$ pairs and displaced dimuons,
- **established selections** allowing to suppress backgrounds and keep signal-like events,
- **derived expected limits** for the top scenario and for more general pseudo-scalars with arbitrary lifetime.

Next

- **submission to a journal**,

➡ implementing **analysis in CMS** and looking at the Run 2/3 data!

Backup

Expected Sensitivity — Top scenario