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Displaced ALPs from top decays @ the LHC

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Based on collaborative work with Kingman Cheung, Fei-Tung Chung and Zeren Simon Wang, 2404.06126

Axion-Like Particles (ALPs) as a possibility for feebly coupled, long-lived new physics

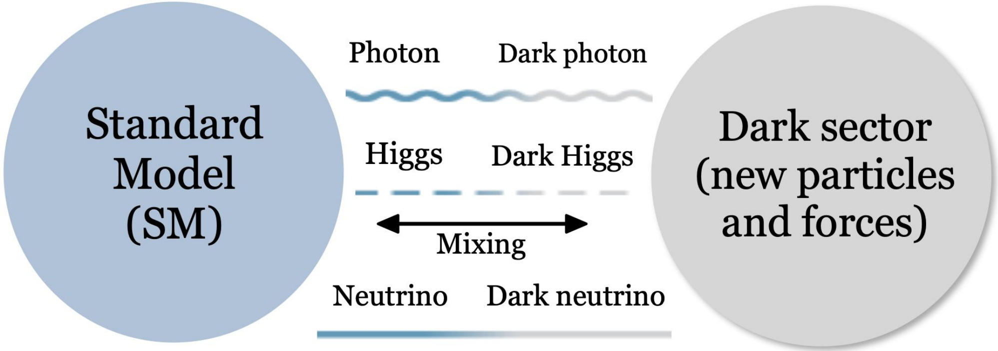


Image reproduced from Science article

- ALPs are pseudoscalar particles predicted in many new physics scenarios
- They do not necessarily solve the strong CP problem in the SM as the QCD axions
- The ALP mass and the global symmetry breaking scale are decoupled, allowing for a rich phenomenology
- A promising approach to study the phenomenology is to systematically parameterise the ALP couplings to SM particles using effective lagrangians

Low-energy EFT of ALPs
H. Georgi, et al, Phys.Lett.B 169 (1986)
K. Choi, et al, Phys.Lett.B 181 (1986)

We study Axion-like particles (ALPs) with a particular flavour structure

- ALPs couple to quarks only. They can be produced through flavour off-diagonal coupling to top quarks, and decay with flavour diagonal couplings to jets
- ALPs can be searched for in anomalous top-quark decays @ LHC
- Light (~10 GeV) and feebly coupled ALPs can be long-lived!

Existing studies on quark flavour violating ALPs

M. Bauer, et al, JHEP 09 (2022) 056
A.Carmona, et al, JHEP 08 (2021) 121
J. Martin Camalich, et al,Phys.Rev. D 102 (2020)
A.Carmona, et al, JHEP 07 (2022) 122
T. Li, et al, 2402.14232
S. Blasi, et al, 2311.16048
A.V.Phan and S. Westhoff, JHEP 05 (2024) 075
F. Esser, et al, JHEP 09 (2023) 063
L. Rygaard, et al, JHEP 10 (2023) 138

K.Cheung, Fei-Tung Chung, G. Cottin, Z. S. Wang, 2404.06126

$$\mathcal{L}_{a,\,\text{eff}} = \frac{\partial^\mu a}{2\Lambda}\Big(\sum_{i=1,2,3} g_{ii}\;\bar{q}_i\gamma_\mu\gamma_5 q_i + \sum_{i,j=1,2,3}^{i\neq j} g_{ij}\;\bar{u}_i\gamma_\mu\gamma_5 u_j\Big) + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2\,a^2,$$

- We include off-diagonal couplings to up-type quarks only
- Couplings are real and symmetric
- a is the ALP
- Λ is the effective cut-off scale

ALP production: Top quark decays to ALP via off-diagonal coupling

$$\Gamma(t \to a u_i) = \frac{N_c}{384\pi} \frac{g_{3i}^2}{\Lambda^2} \frac{m_a^2}{m_t} \left(\frac{(m_t^2 - m_{u_i}^2)^2}{m_a^2} - (m_t^2 + m_{u_i}^2) \right) \times \sqrt{\left(1 - \frac{(m_a + m_{u_i})^2}{m_t^2}\right)\left(1 - \frac{(m_a - m_{u_i})^2}{m_t^2}\right)}$$

ALP decay: ALP decay to same flavour quarks via diagonal coupling

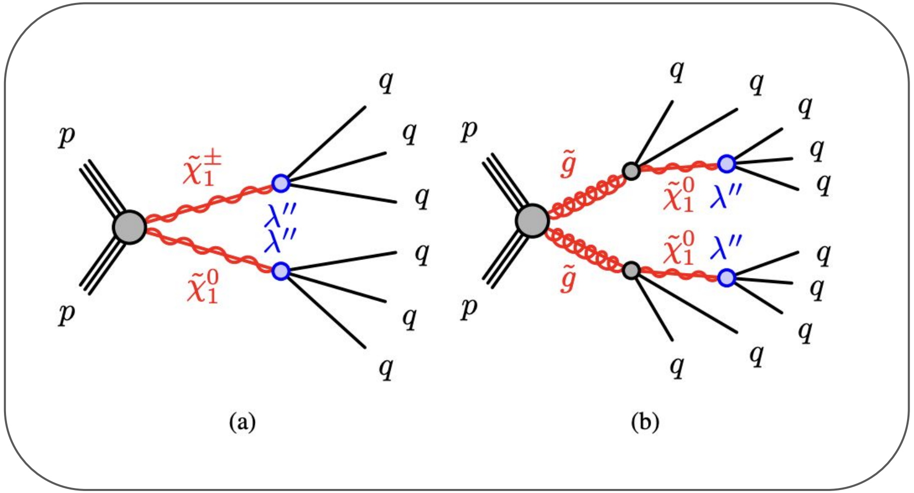
$$\Gamma(a \to q_i \bar{q}_i) = \frac{N_c m_a m_{q_i}^2}{8\pi} \frac{g_{ii}^2}{\Lambda^2} \sqrt{1 - 4m_{q_i}^2/m_a^2}$$

ALP signature: Long-lived ALP produced in rare top decays decaying to two jets with macroscopic displacement (DV) from the IP

$$pp \xrightarrow{\text{SM}} t\bar{t},\ (t \to W^+ b, W^+ \to jj),\ (\bar{t} \to \bar{u}_i\, a, a \xrightarrow{\text{disp.}} jj),\ \text{with } i = 1, 2,$$

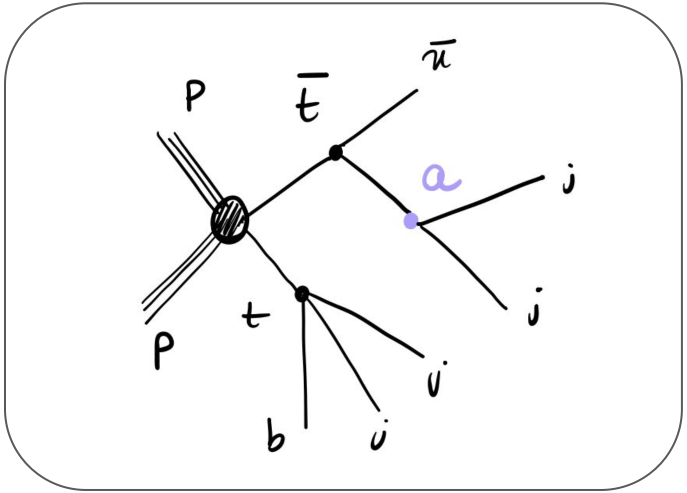
LLP collider phenomenology: We recast the ATLAS DV+jets search (arXiv:2301.13866, JHEP 06 (2023) 200) which searches for displaced vertices and multiple jets (both prompt and displaced)

ATLAS

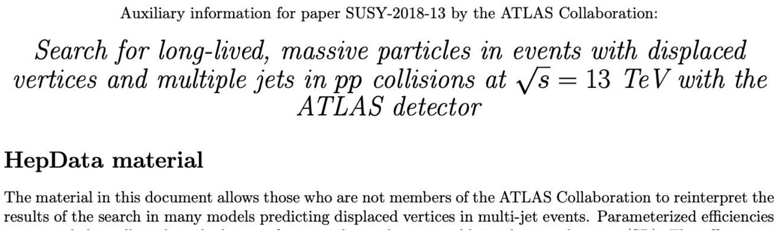


Two orthogonal signal regions (Strong or "high-pT" and EW or "Trackless")

US



We follow their reinterpretation prescription from HEPData here



Auxiliary information for paper SUSY-2018-13 by the ATLAS Collaboration:

Search for long-lived, massive particles in events with displaced vertices and multiple jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

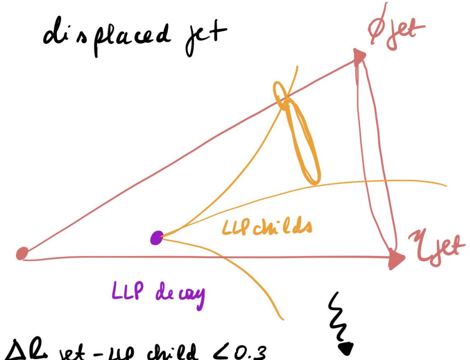
HepData material

The material in this document allows those who are not members of the ATLAS Collaboration to reinterpret the results of the search in many models predicting displaced vertices in multi-jet events. Parameterized efficiencies

Jet definitions

- Two types of jets are defined: truth jets and displaced truth jets. Displaced truth jets are truth jets that have been matched with the decay position of an LLP. Matching in DeltaR plane to LLP childs
- Displaced jets that originate from LLPs decaying outside the calorimeter are discarded

Both SRs require at least one DV passing the full selection



ΔR jet-LLP child < 0.3
in η/ϕ space

Find smallest
distance to
know which is
the truth-matched jet

Event-level selections

Signal Region	High-p_T jet SR	Trackless jet SR
Truth jet selection	$n^{250}_{\text{jet}} \geq 4$ or $n^{195}_{\text{jet}} \geq 5$ or $n^{116}_{\text{jet}} \geq 6$ or $n^{90}_{\text{jet}} \geq 7$	$n^{137}_{\text{jet}} \geq 4$ or $n^{101}_{\text{jet}} \geq 5$ or $n^{83}_{\text{jet}} \geq 6$ or $n^{55}_{\text{jet}} \geq 7$, $n^{70}_{\text{displaced jet}} \geq 1$ or $n^{50}_{\text{displaced jet}} \geq 2$

Vertex-level selections

Event has ≥ 1 DV passing:

$R_{xy}, |z| < 300$ mm

$R_{xy} > 4$ mm

≥ 1 track with $|d_0| > 2$ mm

$n_{\text{selected decay products}} \geq 5$

Invariant mass > 10 GeV

Parametrized efficiencies

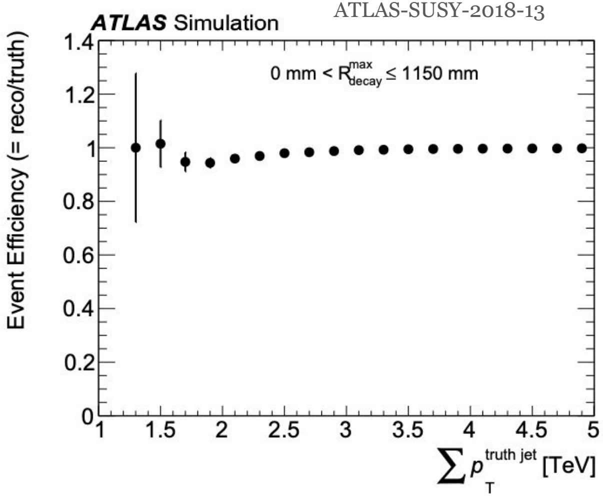
- For events that have passed the event and vertex acceptance requirements, we make use of parameterized efficiencies provided by ATLAS

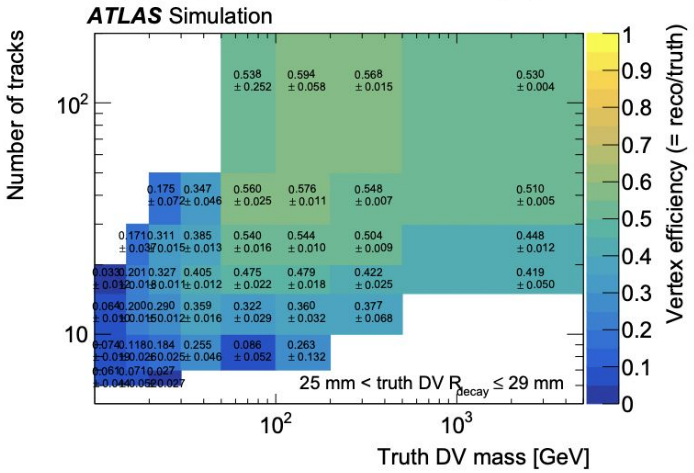
- We can then calculate our final cutflow efficiency as

$$\epsilon = \mathcal{A}_{\text{event}} \cdot \epsilon_{\text{event}} \cdot \left(1 - \prod_{\text{vertex}} (1 - \mathcal{A}_{\text{vertex}} \cdot \epsilon_{\text{vertex}})\right)$$

Following closely the ATLAS prescription in HEPData

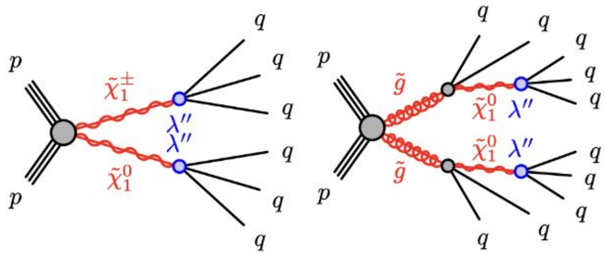
ATLAS-SUSY-2018-13





(c) Region 2: Before the IBL

We validated the ATLAS DV+jets search

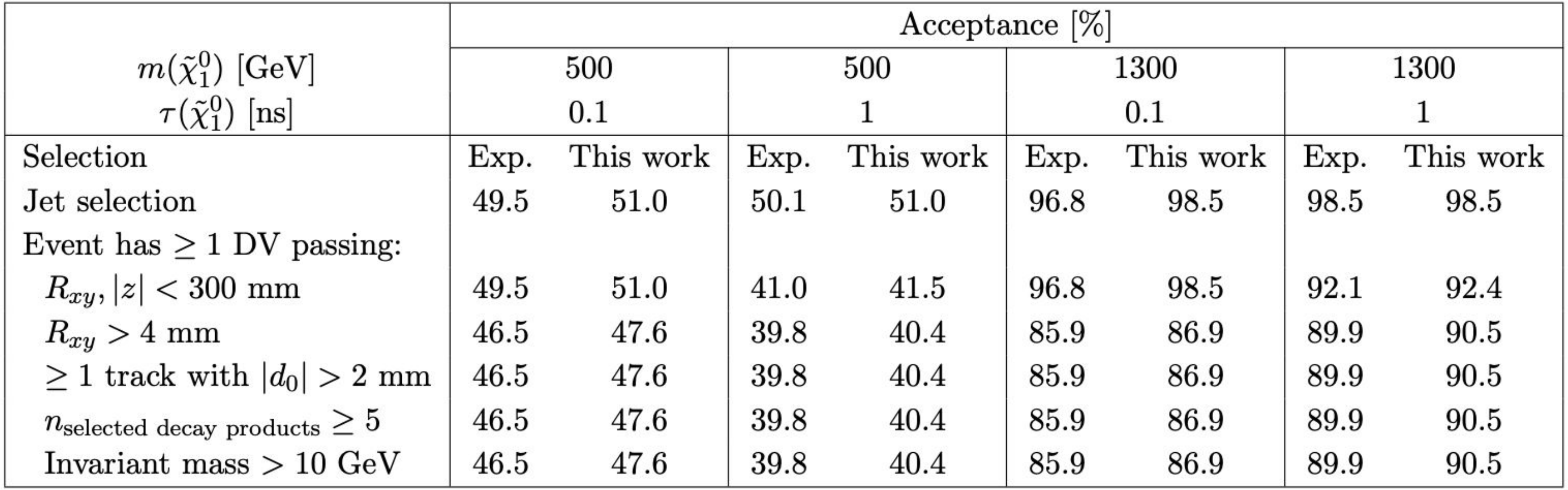


- About 14 benchmarks for different masses of the gluino or electroweakinos, as well as the lifetime

- We achieve excellent agreement at the acceptance level O(1)%

Cutflow example in the Trackless-jet SR

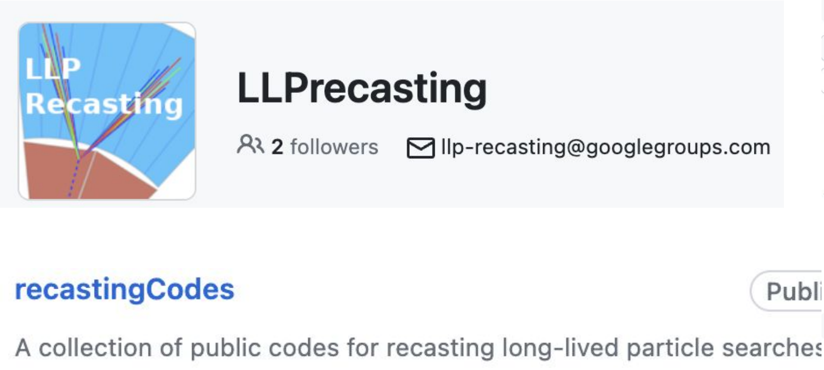
K.Cheung, Fei-Tung Chung, G. Cottin, Z. S. Wang, 2404.06126



	Acceptance [%]							
$m(\tilde{\chi}_1^0)$ [GeV]	500		500		1300		1300	
$\tau(\tilde{\chi}_1^0)$ [ns]	0.1		1		0.1		1	
Selection	Exp.	This work	Exp.	This work	Exp.	This work	Exp.	This work
Jet selection	49.5	51.0	50.1	51.0	96.8	98.5	98.5	98.5
Event has ≥ 1 DV passing:								
$R_{xy}, \lvert z \rvert < 300$ mm	49.5	51.0	41.0	41.5	96.8	98.5	92.1	92.4
$R_{xy} > 4$ mm	46.5	47.6	39.8	40.4	85.9	86.9	89.9	90.5
≥ 1 track with $\lvert d_0 \rvert > 2$ mm	46.5	47.6	39.8	40.4	85.9	86.9	89.9	90.5
$n_{\text{selected decay products}} \geq 5$	46.5	47.6	39.8	40.4	85.9	86.9	89.9	90.5
Invariant mass > 10 GeV	46.5	47.6	39.8	40.4	85.9	86.9	89.9	90.5

We validated the ATLAS DV+jets search

- But, once the parameterized efficiencies are included, deviations as large as O(10)% are observed
- We argue that we should have selected the correct set of events from the whole event samples
- Our recast code is public on the [github LLP Recasting Repository]

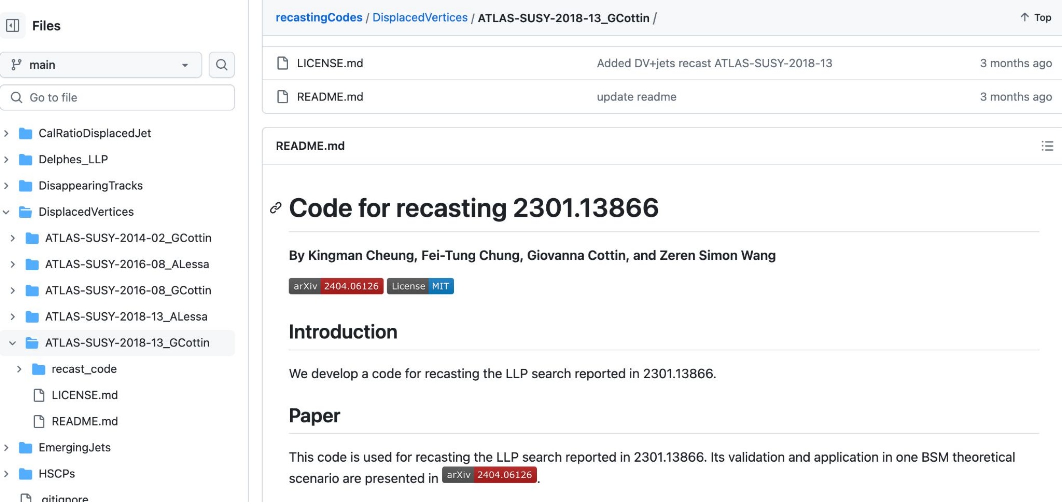


LLPrecasting

2 followers · llp-recasting@googlegroups.com

recastingCodes

A collection of public codes for recasting long-lived particle searches



recastingCodes / DisplacedVertices / ATLAS-SUSY-2018-13_GCottin /

LICENSE.md	Added DV+jets recast ATLAS-SUSY-2018-13	3 months ago
README.md	update readme	3 months ago

README.md

Code for recasting 2301.13866

By Kingman Cheung, Fei-Tung Chung, Giovanna Cottin, and Zeren Simon Wang

arXiv 2404.06126 License MIT

Introduction

We develop a code for recasting the LLP search reported in 2301.13866.

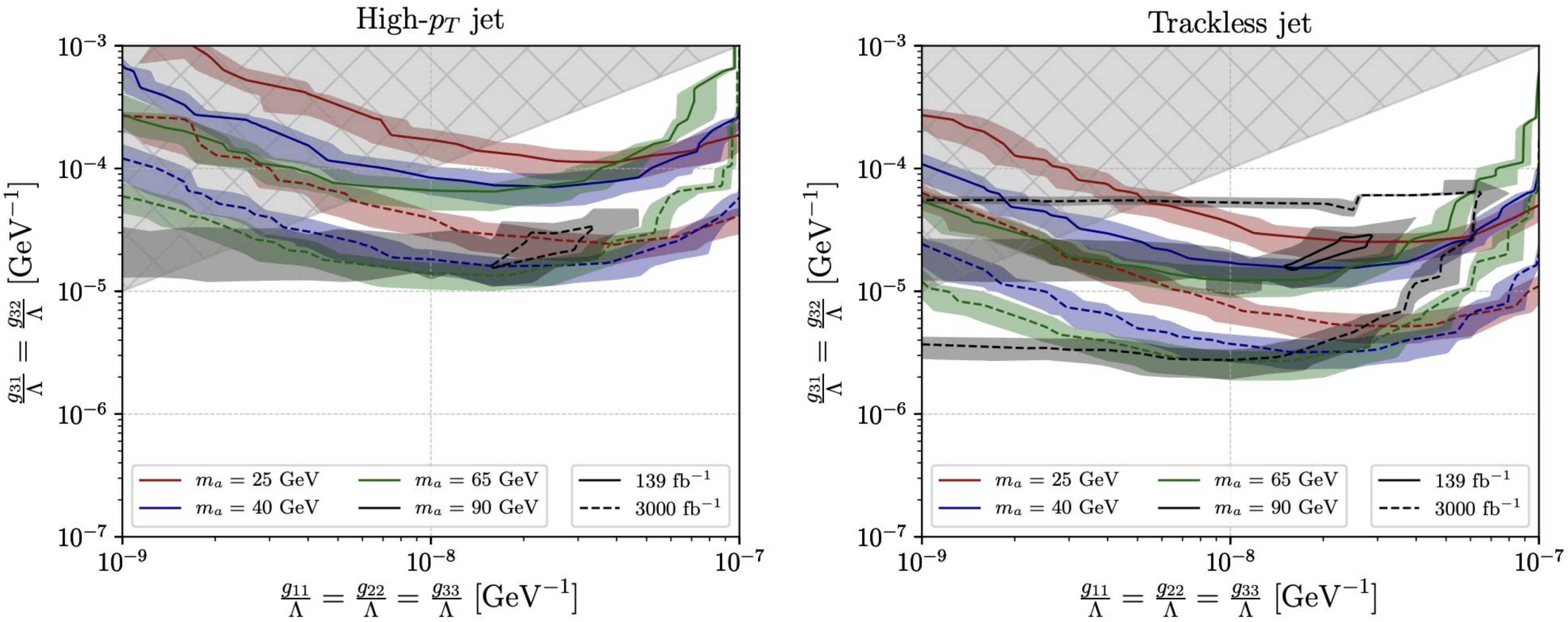
Paper

This code is used for recasting the LLP search reported in 2301.13866. Its validation and application in one BSM theoretical scenario are presented in arXiv 2404.06126.

Results: g vs. g

$$N_S = 2 \cdot \mathcal{L} \cdot \sigma(pp \to t\bar{t})_{\rm SM} \cdot \mathcal{B}(t \to W^+ b) \cdot \mathcal{B}(W^+ \to jj) \cdot \mathcal{B}(\bar{t} \to ja) \cdot \mathcal{B}(a \to jj) \cdot \epsilon$$

- We apply a 50% uncertainty band. Curves for signal-event numbers of $S^{95}_{\rm obs} = 3.8(3.0)$



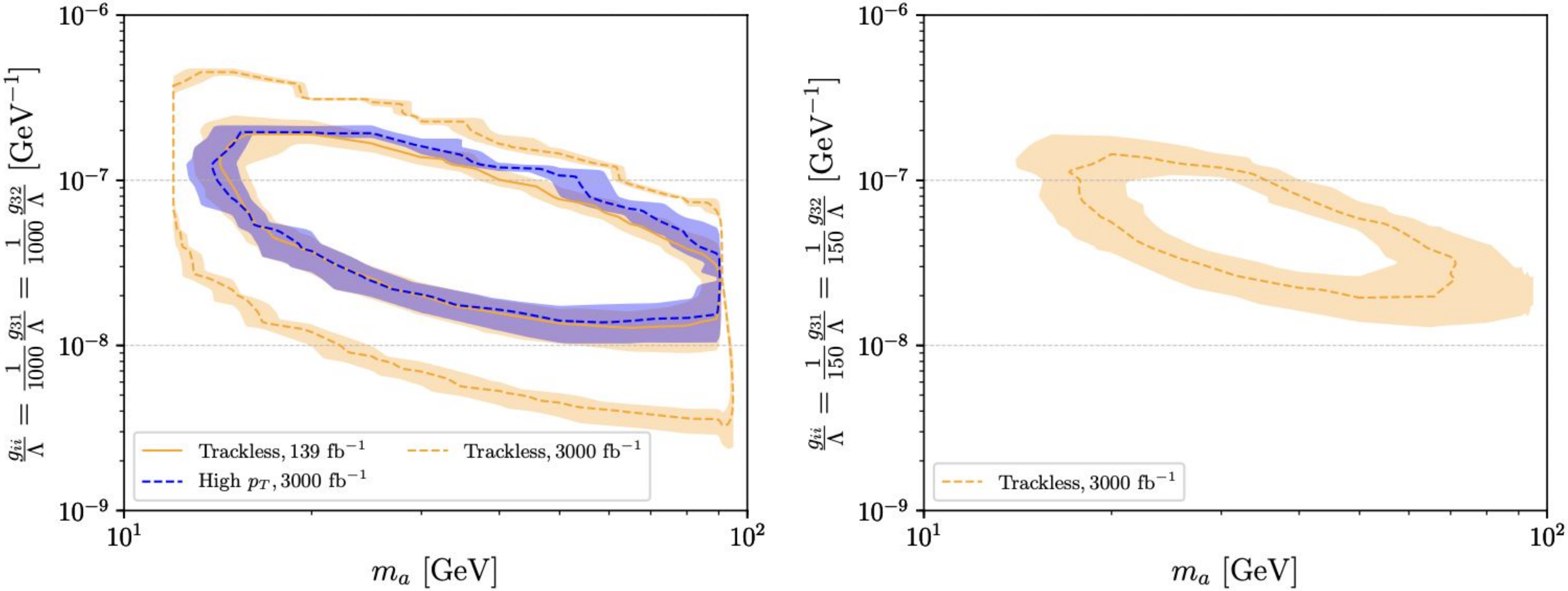
- Gray region is where 4-body ALP decays (induced by the non-diagonal couplings) are important (we do not include them)
- For ALP masses above the W-boson threshold, the non-diagonal couplings can result in 3-body decays of the ALP (ALP is too prompt)
- The two signal regions are sensitive to similar decay coupling-ranges and hence similar lifetimes of the ALP
- For the sensitivity reach in the production couplings, the trackless-jet SR performs much better (by a factor of 5)

Results: g vs. mass

$$N_S = 2 \cdot \mathcal{L} \cdot \sigma(pp \to t\bar{t})_{\mathrm{SM}} \cdot \mathcal{B}(t \to W^+ b) \cdot \mathcal{B}(W^+ \to jj) \cdot \mathcal{B}(\bar{t} \to ja) \cdot \mathcal{B}(a \to jj) \cdot \epsilon$$

- We fix the production couplings to be 1000 or 150 times the decay couplings. Smaller production couplings implies smaller rates, leading to restrictive sensitivities

- General shapes determined by the effect on the ALP mass on the total decay width (bounded by ALP decays inside the fiducial region)



Summary and outlook

- We study axion-like particles (ALPs) with a particular flavour structure, complementing recent works
- The ALPs can be produced in rare top decays at the LHC and decay to displaced vertices plus multiple jets
- We recast the ATLAS DV+jets search. We find excellent agreement at the acceptance level, although larger discrepancies for some benchmarks when including parametrized efficiencies
- Our code is public hoping it would be useful to the community
- The ATLAS DV+jets search can probe unique parts of the parameter space of the quark-flavour violating ALP scenario considered !

Backup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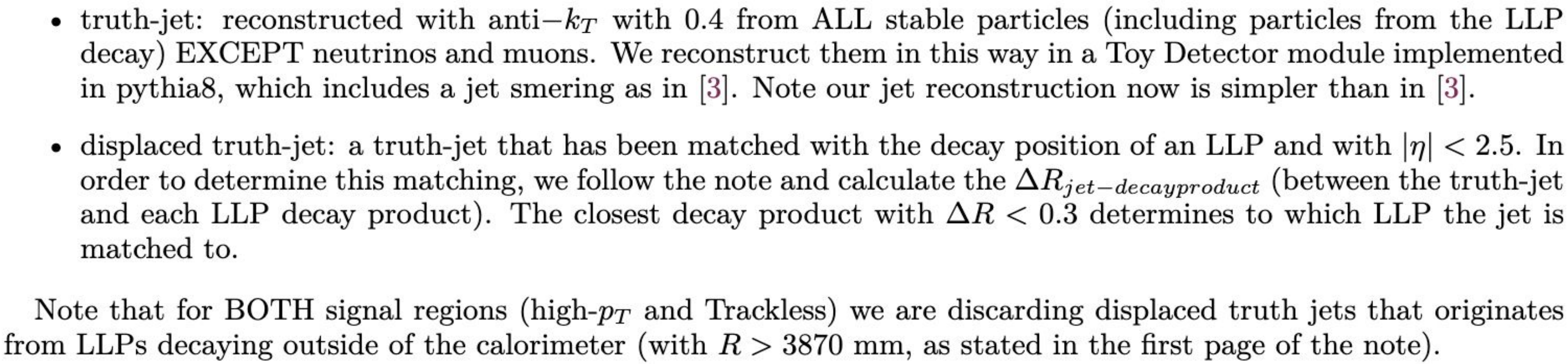
1-5 JULY 2024
UNIVERSITY OF TOKYO

Jet definitions in more detail

Following closely the ATLAS prescription in HEPData

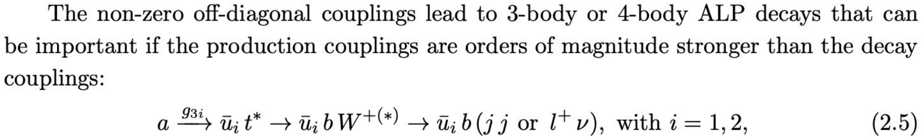


- truth-jet: reconstructed with anti$-k_T$ with 0.4 from ALL stable particles (including particles from the LLP decay) EXCEPT neutrinos and muons. We reconstruct them in this way in a Toy Detector module implemented in pythia8, which includes a jet smering as in [3]. Note our jet reconstruction now is simpler than in [3].
- displaced truth-jet: a truth-jet that has been matched with the decay position of an LLP and with $|\eta| < 2.5$. In order to determine this matching, we follow the note and calculate the $\Delta R_{jet-decayproduct}$ (between the truth-jet and each LLP decay product). The closest decay product with $\Delta R < 0.3$ determines to which LLP the jet is matched to.

Note that for BOTH signal regions (high-p_T and Trackless) we are discarding displaced truth jets that originates from LLPs decaying outside of the calorimeter (with $R > 3870$ mm, as stated in the first page of the note).

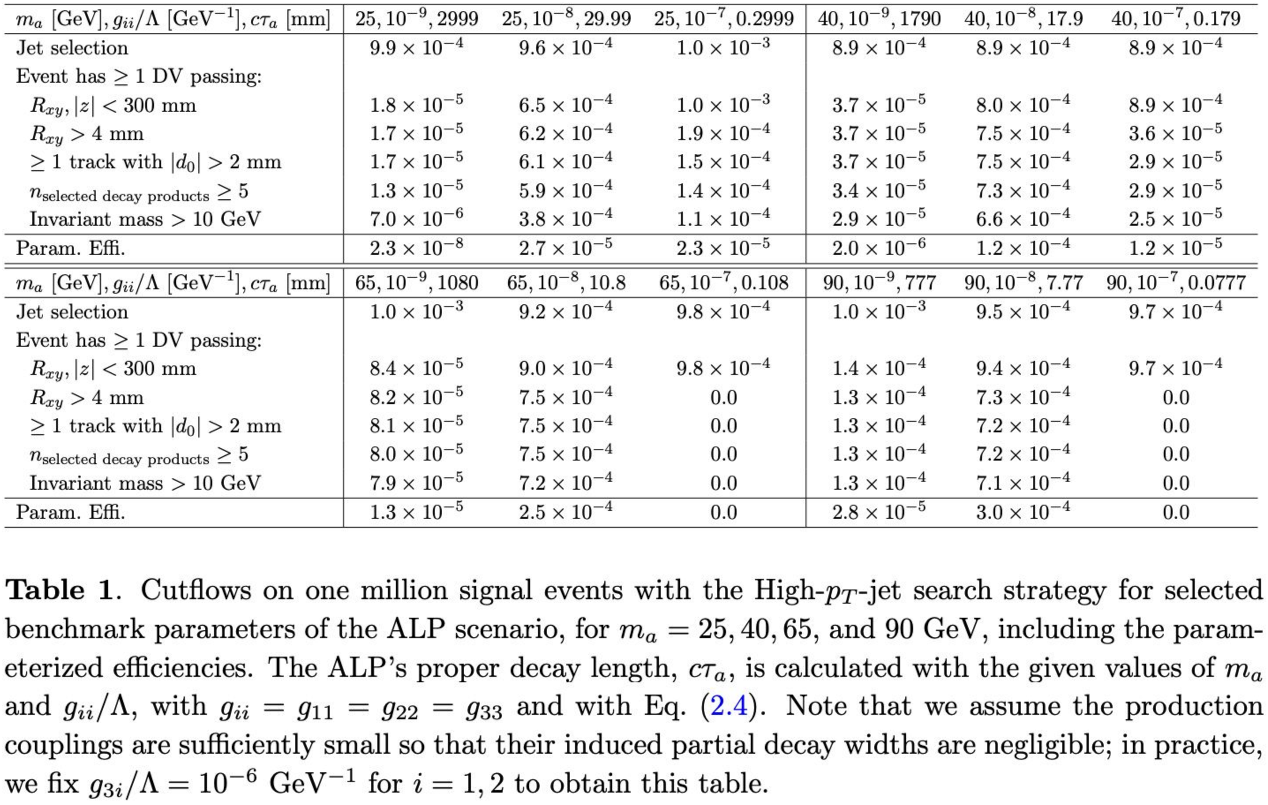
Signal cutflows

K.Cheung, Fei-Tung Chung, G. Cottin, Z. S. Wang, 2404.06126



The non-zero off-diagonal couplings lead to 3-body or 4-body ALP decays that can be important if the production couplings are orders of magnitude stronger than the decay couplings:

$$a \xrightarrow{g_{3i}} \bar{u}_i\, t^* \to \bar{u}_i\, b\, W^{+(*)} \to \bar{u}_i\, b\,(j\, j \text{ or } l^+\, \nu), \text{ with } i = 1, 2, \tag{2.5}$$



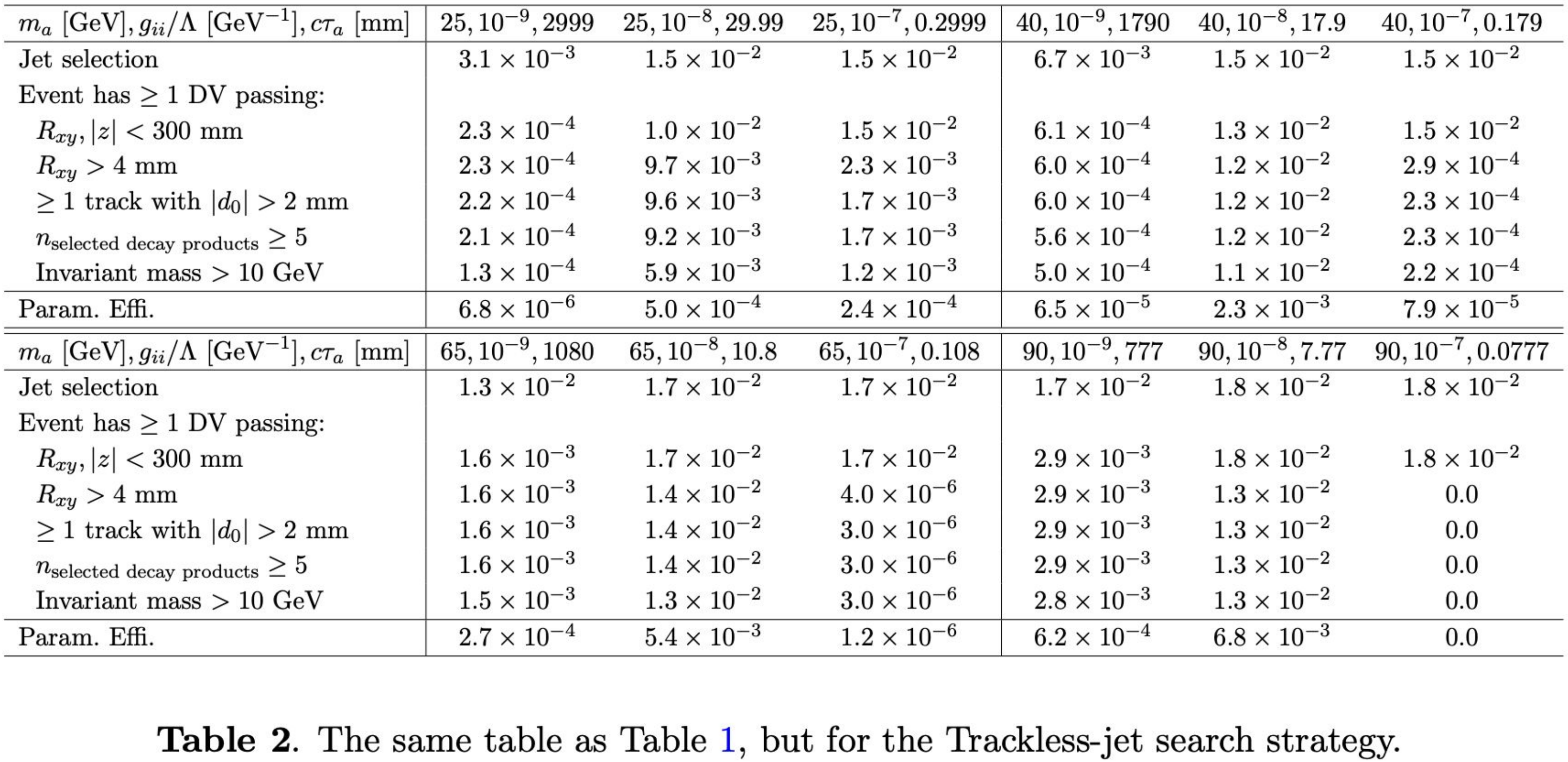
m_a [GeV], g_{ii}/Λ [GeV^{-1}], $c\tau_a$ [mm]	$25, 10^{-9}, 2999$	$25, 10^{-8}, 29.99$	$25, 10^{-7}, 0.2999$	$40, 10^{-9}, 1790$	$40, 10^{-8}, 17.9$	$40, 10^{-7}, 0.179$
Jet selection	9.9×10^{-4}	9.6×10^{-4}	1.0×10^{-3}	8.9×10^{-4}	8.9×10^{-4}	8.9×10^{-4}
Event has ≥ 1 DV passing:						
$R_{xy}, \lvert z\rvert < 300$ mm	1.8×10^{-5}	6.5×10^{-4}	1.0×10^{-3}	3.7×10^{-5}	8.0×10^{-4}	8.9×10^{-4}
$R_{xy} > 4$ mm	1.7×10^{-5}	6.2×10^{-4}	1.9×10^{-4}	3.7×10^{-5}	7.5×10^{-4}	3.6×10^{-5}
≥ 1 track with $\lvert d_0\rvert > 2$ mm	1.7×10^{-5}	6.1×10^{-4}	1.5×10^{-4}	3.7×10^{-5}	7.5×10^{-4}	2.9×10^{-5}
$n_{\text{selected decay products}} \geq 5$	1.3×10^{-5}	5.9×10^{-4}	1.4×10^{-4}	3.4×10^{-5}	7.3×10^{-4}	2.9×10^{-5}
Invariant mass > 10 GeV	7.0×10^{-6}	3.8×10^{-4}	1.1×10^{-4}	2.9×10^{-5}	6.6×10^{-4}	2.5×10^{-5}
Param. Effi.	2.3×10^{-8}	2.7×10^{-5}	2.3×10^{-5}	2.0×10^{-6}	1.2×10^{-4}	1.2×10^{-5}

m_a [GeV], g_{ii}/Λ [GeV^{-1}], $c\tau_a$ [mm]	$65, 10^{-9}, 1080$	$65, 10^{-8}, 10.8$	$65, 10^{-7}, 0.108$	$90, 10^{-9}, 777$	$90, 10^{-8}, 7.77$	$90, 10^{-7}, 0.0777$
Jet selection	1.0×10^{-3}	9.2×10^{-4}	9.8×10^{-4}	1.0×10^{-3}	9.5×10^{-4}	9.7×10^{-4}
Event has ≥ 1 DV passing:						
$R_{xy}, \lvert z\rvert < 300$ mm	8.4×10^{-5}	9.0×10^{-4}	9.8×10^{-4}	1.4×10^{-4}	9.4×10^{-4}	9.7×10^{-4}
$R_{xy} > 4$ mm	8.2×10^{-5}	7.5×10^{-4}	0.0	1.3×10^{-4}	7.3×10^{-4}	0.0
≥ 1 track with $\lvert d_0\rvert > 2$ mm	8.1×10^{-5}	7.5×10^{-4}	0.0	1.3×10^{-4}	7.2×10^{-4}	0.0
$n_{\text{selected decay products}} \geq 5$	8.0×10^{-5}	7.5×10^{-4}	0.0	1.3×10^{-4}	7.2×10^{-4}	0.0
Invariant mass > 10 GeV	7.9×10^{-5}	7.2×10^{-4}	0.0	1.3×10^{-4}	7.1×10^{-4}	0.0
Param. Effi.	1.3×10^{-5}	2.5×10^{-4}	0.0	2.8×10^{-5}	3.0×10^{-4}	0.0

Table 1. Cutflows on one million signal events with the High-p_T-jet search strategy for selected benchmark parameters of the ALP scenario, for $m_a = 25, 40, 65$, and 90 GeV, including the parameterized efficiencies. The ALP's proper decay length, $c\tau_a$, is calculated with the given values of m_a and g_{ii}/Λ, with $g_{ii} = g_{11} = g_{22} = g_{33}$ and with Eq. (2.4). Note that we assume the production couplings are sufficiently small so that their induced partial decay widths are negligible; in practice, we fix $g_{3i}/\Lambda = 10^{-6}$ GeV^{-1} for $i = 1, 2$ to obtain this table.

Signal cutflows

K.Cheung, Fei-Tung Chung, G. Cottin, Z. S. Wang, 2404.06126



m_a [GeV], g_{ii}/Λ [GeV^{-1}], $c\tau_a$ [mm]	$25, 10^{-9}, 2999$	$25, 10^{-8}, 29.99$	$25, 10^{-7}, 0.2999$	$40, 10^{-9}, 1790$	$40, 10^{-8}, 17.9$	$40, 10^{-7}, 0.179$
Jet selection	3.1×10^{-3}	1.5×10^{-2}	1.5×10^{-2}	6.7×10^{-3}	1.5×10^{-2}	1.5×10^{-2}
Event has ≥ 1 DV passing:						
$R_{xy}, \lvert z\rvert < 300$ mm	2.3×10^{-4}	1.0×10^{-2}	1.5×10^{-2}	6.1×10^{-4}	1.3×10^{-2}	1.5×10^{-2}
$R_{xy} > 4$ mm	2.3×10^{-4}	9.7×10^{-3}	2.3×10^{-3}	6.0×10^{-4}	1.2×10^{-2}	2.9×10^{-4}
≥ 1 track with $\lvert d_0\rvert > 2$ mm	2.2×10^{-4}	9.6×10^{-3}	1.7×10^{-3}	6.0×10^{-4}	1.2×10^{-2}	2.3×10^{-4}
$n_{\text{selected decay products}} \geq 5$	2.1×10^{-4}	9.2×10^{-3}	1.7×10^{-3}	5.6×10^{-4}	1.2×10^{-2}	2.3×10^{-4}
Invariant mass > 10 GeV	1.3×10^{-4}	5.9×10^{-3}	1.2×10^{-3}	5.0×10^{-4}	1.1×10^{-2}	2.2×10^{-4}
Param. Effi.	6.8×10^{-6}	5.0×10^{-4}	2.4×10^{-4}	6.5×10^{-5}	2.3×10^{-3}	7.9×10^{-5}

m_a [GeV], g_{ii}/Λ [GeV^{-1}], $c\tau_a$ [mm]	$65, 10^{-9}, 1080$	$65, 10^{-8}, 10.8$	$65, 10^{-7}, 0.108$	$90, 10^{-9}, 777$	$90, 10^{-8}, 7.77$	$90, 10^{-7}, 0.0777$
Jet selection	1.3×10^{-2}	1.7×10^{-2}	1.7×10^{-2}	1.7×10^{-2}	1.8×10^{-2}	1.8×10^{-2}
Event has ≥ 1 DV passing:						
$R_{xy}, \lvert z\rvert < 300$ mm	1.6×10^{-3}	1.7×10^{-2}	1.7×10^{-2}	2.9×10^{-3}	1.8×10^{-2}	1.8×10^{-2}
$R_{xy} > 4$ mm	1.6×10^{-3}	1.4×10^{-2}	4.0×10^{-6}	2.9×10^{-3}	1.3×10^{-2}	0.0
≥ 1 track with $\lvert d_0\rvert > 2$ mm	1.6×10^{-3}	1.4×10^{-2}	3.0×10^{-6}	2.9×10^{-3}	1.3×10^{-2}	0.0
$n_{\text{selected decay products}} \geq 5$	1.6×10^{-3}	1.4×10^{-2}	3.0×10^{-6}	2.9×10^{-3}	1.3×10^{-2}	0.0
Invariant mass > 10 GeV	1.5×10^{-3}	1.3×10^{-2}	3.0×10^{-6}	2.8×10^{-3}	1.3×10^{-2}	0.0
Param. Effi.	2.7×10^{-4}	5.4×10^{-3}	1.2×10^{-6}	6.2×10^{-4}	6.8×10^{-3}	0.0

Table 2. The same table as Table 1, but for the Trackless-jet search strategy.