Quark flavor violation and axion-like particles from top quark decays at the LHC

Kingman Cheung Fei-Tung Chung Giovanna Cottin
Zeren Simon Wang

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The ALP model with quark flavor violation

Low-energy effective Lagrangian with ALP axial couplings to the quarks:

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

- $g_{ij} = g_{ji}$ for $i \neq j$, i.e. g_{ij} are symmetrical.
- $\sum_{i,j=1,2,3}^{i\neq j} g_{ij}\ \bar{d}_i\gamma_\mu\gamma_5 d_j = 0$, i.e. no off-diagonal couplings for the down-type quarks.
- a: ALP.
- Λ: effective cutoff scale.

The ALP model with quark flavor violation

Signal process:

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

and its charge-conjugated mode.

The ALP here is long-lived and decays to two jets with a macroscopic displacement from the IP.

The ATLAS DV+jets search

The ATLAS search [arXiv:2301.13866] focuses on the final-state signature of a displaced vertex (DV) plus multiple jets.

The search employs two signal regions (SRs):

- High-p_T jet
- Trackless jet

Event-level acceptance

Both SRs start with a certain but different set of selections on the numbers of jets with various p_T thresholds. This step accounts for the event-level acceptance.

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

Table: Truth-jet selection requirements. $n_{\text{jet}}^{250} \geq 4$ means at least 4 jets should have a p_T larger than or equal to 250 GeV, and similarly for the other notations.

Vertex-level acceptance

The two SRs then require that in the event there should be at least one vertex passing a list of vertex-level selections:

1. $R_{xy}, |z| < 300$ mm, where R_{xy} and $|z|$ are the transverse distance and the absolute longitudinal distance of the vertex from the IP, respectively.
2. $R_{xy} > 4$ mm.
3. At least one track should have a transverse impact parameter satisfying $d_0 > 2$ mm.
4. The displaced vertex should have at least 5 selected decay products satisfying:
   (a) It should be a track with a boosted transverse decay length larger than 520 mm.
   (b) Its p_T and charge q should obey the relation $p_T/|q| > 1$ GeV.
5. The truth vertex should have an invariant mass larger than 10 GeV, which is constructed with the above selected decay products whose masses are assumed to be $m_{\text{charged pion}}$.

Parameterized efficiencies

For events that have passed the above event and vertex acceptance requirements, we make use of parameterized efficiencies provided by the ATLAS collaboration at both event and vertex levels that account for quality requirements such as multi-jet trigger and material veto that are difficult to simulate.

Event-level efficiencies

The event-level efficiencies ϵ_{event} are functions of the truth-jet scalar p_T sum and the transverse distance of the furthest LLP decay.

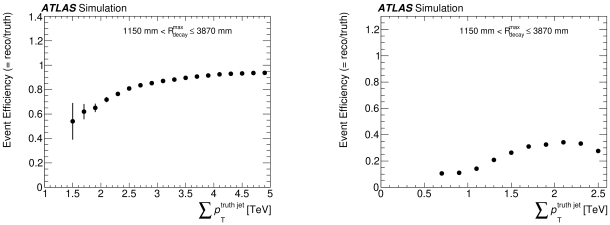

Figure: Event-level efficiencies for "High-p_T jet" (left) and "Trackless jet" (right) SRs, with the transverse distance of the furthest LLP decay satisfying 1150 mm $< R_{\text{decay}}^{\text{max}} \leq$ 3870 mm.

Vertex-level efficiencies

The vertex-level efficiencies ϵ_{vertex} are for reconstructing the DVs, and are functions of the DV's transverse distance to the IP, its invariant mass, as well as the LLP decay product multiplicity.

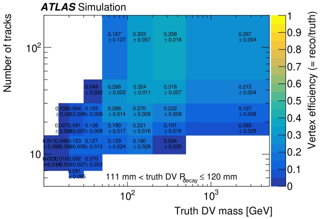

Figure: Vertex-level efficiencies, with the DV's transverse distance to the IP satisfying 111 mm $<$ truth DV $R_{\text{decay}} \leq 120$ mm.

Cutflow efficiency

Formula of computing the final cutflow efficiency:

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

where $\mathcal{A}_{\text{event}}$ and $\mathcal{A}_{\text{vertex}}$ label the portion of events satisfying the event-level and vertex-level acceptance requirements, respectively.

Simulation and computation

We generate one million signal events of the ALPs at the LHC at multiple parameter points in a grid scan covering the production couplings, decay couplings, as well as the ALP mass.

With our recasting code, we obtain the cutflow efficiencies ϵ for all the parameter points scanned.

Numerical results

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: 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 $g_{ii} = g_{11} = g_{22} = g_{33}$. 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.

Numerical results

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:						
$R_{xy}, \|z\| < 300$ 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 $\|d_0\| > 2$ 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:						
$R_{xy}, \|z\| < 300$ 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 $\|d_0\| > 2$ 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: The same table as the previous one, but for the Trackless-jet search strategy.

Numerical results: g vs. g

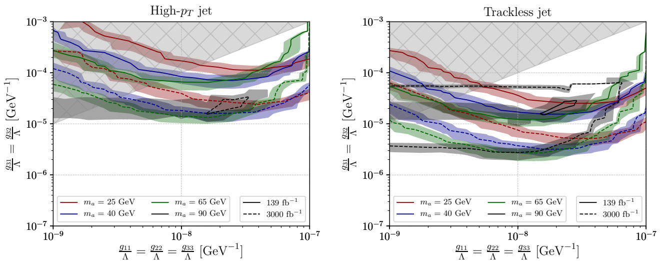

Figure: ATLAS sensitivity reach at 95% C.L. with 139 fb^{-1} (solid) and 3 ab^{-1} (dashed) integrated luminosities, in the plane $\frac{g_{31}}{\Lambda} = \frac{g_{32}}{\Lambda}$ vs. $\frac{g_{11}}{\Lambda} = \frac{g_{22}}{\Lambda} = \frac{g_{33}}{\Lambda}$, for various ALP mass choices, with the "High-p_T jet" (left) and "Trackless jet" (right) search strategies. An error band at 50% level is displayed together. The gray hatched region is where our results do not apply because we do not include the 4-body decay modes of the ALP induced by the production couplings for ALP masses below roughly 85 GeV.

Numerical results: g vs. mass

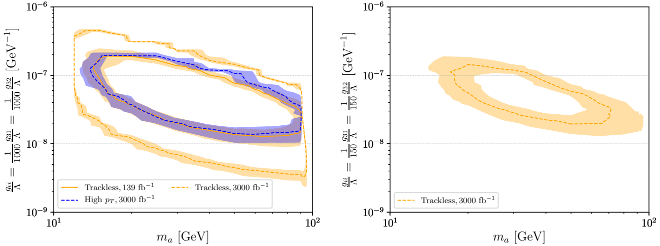

Figure: ATLAS sensitivity reach at 95% C.L. with 139 fb^{-1} and 3 ab^{-1} integrated luminosities, respectively, in the plane $\frac{g_{ii}}{\Lambda} = \frac{1}{x}\frac{g_{31}}{\Lambda} = \frac{1}{x}\frac{g_{32}}{\Lambda}$ vs. m_a for $x = 1000$ (left panel) and $x = 150$ (right panel), with the two search strategies. g_{ii} labels the universal quark-flavor-diagonal couplings with $g_{ii} = g_{11} = g_{22} = g_{33}$. Error bands at the level of 50% are shown.

Recast of the DV+jets search

	Acceptance [%]							
$m(\tilde{g})$ [GeV]	2000		2000		2400		2000	
$m(\tilde{\chi}_1^0)$ [GeV]	850		50		200		1250	
$\tau(\tilde{\chi}_1^0)$ [ns]	0.01		0.1		1		10	
Selection	Exp.	This work	Exp.	This work	Exp.	This work	Exp.	This work
Jet selection	99.9	99.8	96.6	96.9	97.2	98.2	96.1	99.9
Event has ≥ 1 DV passing:								
$R_{xy}, \|z\| < 300$ mm	99.9	99.8	78.7	79.7	44.7	45.5	31.7	31.2
$R_{xy} > 4$ mm	29.6	29.7	77.0	78.3	43.8	44.7	30.9	30.5
≥ 1 track with $\|d_0\| > 2$ mm	29.6	29.7	75.6	77.6	43.7	44.7	30.9	30.5
$n_{\text{selected decay products}} \geq 5$	29.6	29.7	75.5	77.3	43.7	44.7	30.9	30.5
Invariant mass > 10 GeV	29.6	29.7	74.7	75.8	43.7	44.7	30.9	30.5

Table: High-p_T-jet SR acceptance with full cutflow, strong channel, light flavor.

Recast of the DV+jets search

$m(\tilde{g}), m(\tilde{\chi}_1^0), \tau(\tilde{\chi}_1^0)$	Full Sim.	Param. Exp.	Param. Ours	Non-closure
2000 GeV, 850 GeV, 0.01 ns	27.8%	26.0%	26.6%	-4.3%
2000 GeV, 50 GeV, 0.1 ns	14.4%	13.8%	21.6%	50.0%
2400 GeV, 200 GeV, 1 ns	11.5%	11.5%	14.4%	25.2%
2000 GeV, 1250 GeV, 10 ns	9.2%	8.6%	8.4%	-8.7%

Table: High-p_T-jet SR ϵ including the parameterized efficiencies' effect, strong channel, light flavor.

Recast of the DV+jets search

$m(\tilde{\chi}_1^0)$ [GeV]	Acceptance [%]							
	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:								
$R_{xy}, \|z\| < 300$ 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 $\|d_0\| > 2$ 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

Table: Trackless-jet SR acceptance with full cutflow, EW channel, light flavor.

Recast of the DV+jets search

$m(\tilde{\chi}_1^0), \tau(\tilde{\chi}_1^0)$	Full Sim.	Param. Exp.	Param. Ours	Non-closure
500 GeV, 0.1 ns	31.1%	28.1%	34.6%	11.3%
500 GeV, 1 ns	14.3%	14.3%	24.9%	74.1%
1300 GeV, 0.1 ns	12.2%	11.7%	11.1%	-9.0%
1300 GeV, 1 ns	8.3%	7.9%	11.7%	41.0%

Table: Trackless-jet SR ϵ including the parameterized efficiencies' effect, EW channel, light flavor.

Recast of the DV+jets search

$m(\tilde{\chi}_1^0)$ [GeV] / $\tau(\tilde{\chi}_1^0)$ [ns]	Acceptance [%]					
	1500 / 0.032		1500 / 0.1		1500 / 1	
Selection	Exp.	This work	Exp.	This work	Exp.	This work
Jet selection	84.7	82.5	84.7	82.4	84.7	82.4
Event has ≥ 1 DV passing:						
$R_{xy}, \lvert z \rvert < 300$ mm	84.7	82.5	84.7	82.4	80.1	78.0
$R_{xy} > 4$ mm	45.7	46.9	73.3	72.3	78.4	76.5
≥ 1 track with $\lvert d_0 \rvert > 2$ mm	45.7	46.9	73.3	72.3	78.4	76.5
$n_{\text{selected decay products}} \geq 5$	45.7	46.9	73.3	72.3	78.4	76.5
Invariant mass > 10 GeV	45.7	46.9	73.3	72.3	78.4	76.5

Table: High-p_T-jet SR acceptance with full cutflow, EW channel, heavy flavor. Note that for this scenario, the EW production channel, instead of the strong channel, is considered.

Recast of the DV+jets search

$m(\tilde{\chi}_1^0), \tau(\tilde{\chi}_1^0)$	Full Sim.	Param. Exp.	Param. Ours	Non-closure
1500 GeV, 0.032 ns	39.6%	42.7%	45.6%	15.2%
1500 GeV, 0.1 ns	57.7%	62.7%	68.9%	19.4%
1500 GeV, 1 ns	36.7%	43.0%	65.0%	77.1%

Table: High-p_T-jet SR ϵ including the parameterized efficiencies' effect, EW channel, heavy flavor.

Recast of the DV+jets search

$m(\tilde{\chi}_1^0)$ [GeV]	Acceptance [%] 700		700		700	
$\tau(\tilde{\chi}_1^0)$ [ns]	0.032		0.1		1	
Selection	Exp.	This work	Exp.	This work	Exp.	This work
Jet selection	69.8	72.2	74.1	72.2	74.7	71.9
Event has ≥ 1 DV passing:						
$R_{xy}, \lvert z\rvert < 300$ mm	69.8	72.2	74.1	72.2	64.8	62.4
$R_{xy} > 4$ mm	48.4	48.5	68.1	66.3	62.9	60.9
≥ 1 track with $\lvert d_0\rvert > 2$ mm	48.4	48.5	68.1	66.3	62.9	60.9
$n_{\text{selected decay products}} \geq 5$	48.4	48.5	68.1	66.3	62.9	60.9
Invariant mass > 10 GeV	48.4	48.5	68.1	66.3	62.9	60.9

Table: Trackless-jet SR acceptance with full cutflow, EW channel, heavy flavor.

Recast of the DV+jets search

$m(\tilde{\chi}_1^0), \tau(\tilde{\chi}_1^0)$	Full Sim.	Param. Exp.	Param. Ours	Non-closure
700 GeV, 0.032 ns	26.6%	28.2%	30.0%	12.8%
700 GeV, 0.1 ns	37.5%	36.7%	42.5%	13.3%
700 GeV, 1 ns	20.0%	21.1%	34.9%	74.5%

Table: Trackless-jet SR ϵ including the parameterized efficiencies' effect, EW channel, heavy flavor.

Summary and outlook

We have recast the search [arXiv:2301.13866] and validated our code by comparing cutflow efficiencies.

We achieve excellent agreement in the acceptance level.

However, once the parameterized efficiencies are included, we find good agreement only in some benchmarks while in other benchmarks our results can be off from the experimental full simulation by up to about 70%.

We then apply our recasting code to our ALP model, and find the search can be sensitive to the decay couplings $\frac{g_{ii}}{\Lambda}$ of order $\mathcal{O}(10^{-9} - 10^{-6})$ GeV^{-1}, for the ALP mass roughly between 12 GeV and 95 GeV.