Phenomenological studies on searching for long-lived particles with displaced vertices and jets at the LHC

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JHEP 07 (2024) 209: *K. Cheung, F.-T. Chung, G. Cottin,* ***ZSW***

Phys. Rev. D 110, 055033: ***ZSW***

2501.09065: *R. Beltrán, G. Cottin, J. Günther, M. Hirsch, A. Titov,* ***ZSW***

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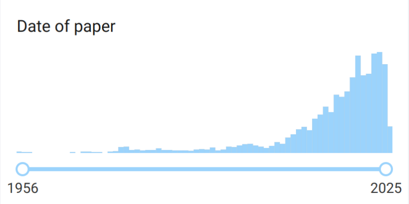
Outline

Motivation

- SM: basis of modern understanding of particle physics
- Successful predictions: W, Z, h, g, c, t, τ, ...
- Excellent performance in experimental tests (*e.g.* EW sector)
- Issues: neutrino masses, baryon asymmetry, DM, non-unification of gauge couplings, strong CP problem, charge quantization...
- Hint at GUT & NP $\Rightarrow$ the *hierarchy problem*
- NP models including SUSY predict new heavy fields
- No new fundamental particles found yet at the LHC
- More stringent limits placed on NP models, e.g. $m_{\tilde{q},\tilde{g}} \gtrsim 1$ TeV
- LHC focus: **promptly decaying** NP particles

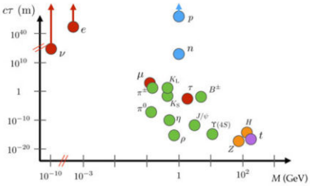
Perhaps this assumption is **wrong**
$\rightarrow$ **Long-Lived Particles!**



'long-lived particle' on INSPIRE

LLPs in the SM

- LLPs: produced, travel a macroscopic distance, and then decay
  $\rightarrow$ Displaced objects



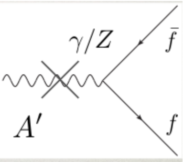
LLPs in the SM, B. Shuve's talk

- Causes of the long lifetime:
  - **Feeble** couplings
  - **Heavy** mediators
  - **Small** phase space
  - ...
- Similarly applicable to BSM particles

LLPs in the BSM theories

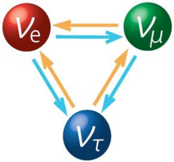
Examples:

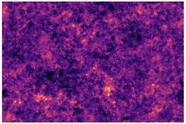
- Portal physics: ν_4, γ', s, and a
- RPV/compressed SUSY
- Mirror glueballs
- ...
- See 1903.04497 for a review



Motivation:

- Non-vanishing active-neutrino masses
- Dark matter
- ...





$\Rightarrow$ *Can we search for LLPs at colliders e.g. at the LHC?*
Yes!

Part I: Recast and reinterpret an ATLAS search for DVs and jets

Quark flavor violation and axion-like particles from top-quark decays at the LHC, JHEP 07 (2024) 209; *K. Cheung, F.-T. Chung, G. Cottin,* ***ZSW***

Constraining long-lived particles from Higgs boson decays at the LHC with displaced vertices and jets, Phys. Rev. D 110, 055033; ***ZSW***

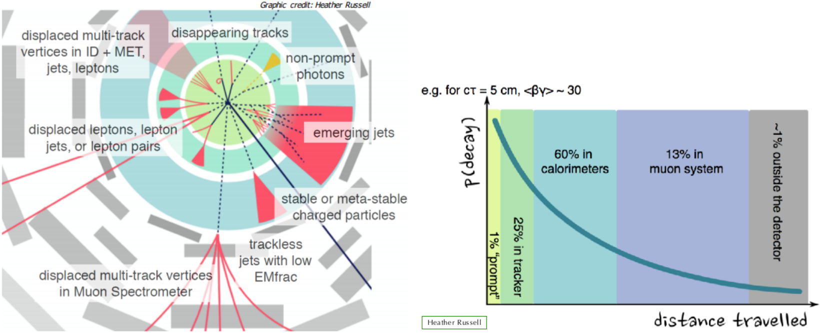
Recast & Reinterpretation

- Experimentalists have performed multiple (LLP) searches
- These reported searches constrained a limited class of models only
- How to obtain their bounds on *other* models predicting *similar/identical signatures*?

Pheno approach:

1. **Recast**: follow event selections of experimental searches step by step
2. **Validation**: reproduce the published cutflow and/or exclusion limits
3. **Reinterpretation**: apply the same analysis on your favorite NP model to derive the corresponding limits

LHC LLP searches

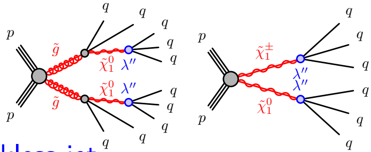


LLP signatures at colliders and the exponential decay distribution (H. Russell's talk)

- Disappearing track: 2309.16823, 2201.02472, . . .
- DVs and missing transverse momentum: 2402.15804, 1710.04901, . . .
- DV and a lepton: 2003.11956, . . .
- Displaced leptons: 2011.07812, 2110.04809, . . .
- Delayed or non-pointing photons: 2209.01029, . . .
- **DVs and jets: 2301.13866**

The ATLAS DV+jets search

- 2301.13866: 13 TeV, 139 fb^{-1}



- Signal regions: High-p_T jet and Trackless jet
- Long-lived electroweakinos with RPV $\lambda'' \bar{U}\bar{D}\bar{D}$ operators: $\tilde{\chi} \to qqq$
  - Strong channel: $pp \to \tilde{g}\tilde{g}$ with $\tilde{g} \overset{\text{prompt}}{\to} \tilde{\chi}_1^0 qq$
  - EW channel: $pp \to \tilde{\chi}\tilde{\chi}$ with $\tilde{\chi} = \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^{\pm}$
- Require large jet-p_T at the truth-level (differing between the two SRs)
- Requires at least one DV of quality
- Delicate requirements such as multi-jet trigger and material veto

SR	Observed	Expected	S_{obs}^{95}	S_{exp}^{95}	$\langle\sigma_{\text{vis}}\rangle_{\text{obs}}^{95}$ [fb]
High-p_T-jet SR	1	$0.46^{+0.27}_{-0.30}$	3.8	$3.1^{+1.0}_{-0.1}$	0.027
Trackless-jet SR	0	$0.83^{+0.51}_{-0.53}$	3.0	$3.4^{+1.3}_{-0.3}$	0.022

Recast procedure of the ATLAS DV+jets search

- Follow ATLAS recast instructions for this search; see also HEPData
- Event generation:
  - Generate signal events in `MadGraph5` with the SUSY SLHA spectrum files provided by ATLAS
  - CKKW-L jet-merging with up to 2 additional jets in the hard processes
  - Truth jets reconstructed with `FastJet`; using particles including those from the LLP decays
- Event selections:
  - Event- & Vertex-level acceptances: $\mathcal{A}_{\text{event}}$, $\mathcal{A}_{\text{vertex}}$
  - Event- & Vertex-level efficiencies: ϵ_{event}, ϵ_{vertex}
- Apply parameterized efficiencies to account for delicate requirements; Provided by ATLAS
- Final cutflow efficiency:

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

Event- and vertex-level acceptances

- $\mathcal{A}_{\text{event}}$:

SR	High-p_T jet	Trackless jet
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 $n^{50}_{\text{displaced jet}} \geq 2$

  - "displaced jet" defined by matching jets with LLP decay products

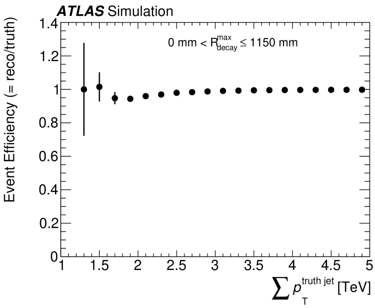
- $\mathcal{A}_{\text{vertex}}$: at least one vertex should pass a list of vertex requirements:
  1. 4 mm $< R_{xy} < 300$ mm and $|z| < 300$ mm
  2. At least one track should satisfy $d_0 > 2$ mm
  3. The displaced vertex should have at least 5 decay products of a massive particle satisfying the following requirements:
     1. It should be a track with a boosted transverse decay length > 520 mm
     2. Its p_T and charge q should obey the relation $p_T/|q| > 1$ GeV
  4. $m_{\text{DV}} > 10$ GeV; truth vertex constructed with the decay products passing the requirements above, for which the mass of each decay product is assumed to be $m_{\pi^\pm}$

Parameterized efficiencies

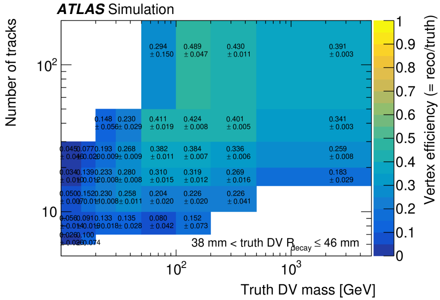
- Parameterized efficiencies provided by the ATLAS collaboration at both event- and vertex-levels that account for quality requirements such as multi-jet trigger, jet filter, and material effects that are difficult to simulate
- Applied to **truth-level** objects!

ϵ_{event}: functions of the truth-jet scalar p_T sum and R_{xy} of the furthest LLP decay

ϵ_{vertex}: for reconstructing the DVs; functions of R_{xy}, m_{DV}, and the LLP decay-product multiplicity n_{trk}



Sample ϵ_{event} function



Sample ϵ_{vertex} function

Validation results: High-p_T-jet SR acceptance and final cutflow efficiency

- Strong channel, $\tilde{\chi}_1^0$ decaying to light-flavor quarks

	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:								
$R_{xy}, \lvert z \rvert < 300$ 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 $\lvert d_0 \rvert > 2$ 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

$m(\tilde{g}), m(\tilde{\chi}_1^0), \tau(\tilde{\chi}_1^0)$	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%

Validation results:
Trackless-jet SR acceptance and final cutflow efficiency

- EW-channel, electroweakinos decaying to light-flavor quarks

$m(\tilde{\chi}_1^0)$ [GeV] / $\tau(\tilde{\chi}_1^0)$ [ns]	Acceptance [%] 500 / 0.1		500 / 1		1300 / 0.1		1300 / 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

$m(\tilde{\chi}_1^0), \tau(\tilde{\chi}_1^0)$	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%

Discussions on the validation

- Generally excellent validation results with the acceptance requirements only $\Rightarrow$ we should have selected the correct set of events from the whole event samples
- Inputs of the event-level and vertex-level efficiencies determine also the acceptance-level cutflows
- Cannot find issues within coding itself either
- Cannot explain the discrepancies, and urge for further collaboration between the theorists and experimentalists
- Uploaded our code to the public LLP Recasting Repository
- Assign an **uncertainty of 50%** in numerical studies

Reinterpretation: axion-like particles

- Axion-like particles (ALPs): pseudoscalar particles; predicted in string compactifcations, supersymmetry models, Froggat-Nielsen models of favor, ...
- Do not necessarily solve the strong CP problem in the SM as the QCD axions do
- A rich phenomenology at various terrestrial experiments

Quark flavor violation

- Consider a scenario with a Lagrangian where the ALPs couple at tree level to quarks only, both diagonally and off-diagonally

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

- g's: real and positive
- Quark-flavor off-diagonal couplings motivated in UV-complete models
- *Off-diagonal*: focus on $t-u-a$ and $t-c-a$
- *Diagonal*: all quarks
- Remain agnostic on a UV-completion origin for exactly this particular flavor structure and treat the ALP-quark couplings as independent parameters in this phenomenological work

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* channel

- jj denotes two jets including the b-quarks
- a: long-lived and decays to jj with a displacement from the IP
- Assume g_{ii} with $i = 1, 2, 3$ ('decay couplings') are non-vanishing and universal, and $g_{31} = g_{13} = g_{32} = g_{23}$ ('production couplings')

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

ALP decays via diagonal couplings

- The main channel:

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

- Applicable for $m_a \gtrsim 1$ GeV (perturbative QCD)

- Other channels:
  - $a \to gg$ via g_{ii}: Br can be up to about 40% for $m_a \lesssim 100$ GeV; leads to the same signatures and could only enhance the bounds on the production couplings mildly; ignored for simplicity
  - $a \to \gamma\gamma$: for $m_a \sim \mathcal{O}(10)$ GeV, suppressed by more than two orders of magnitude; ignored
  - $a \to q_i q_j$ at loop level: suppressed and ignored

ALP decays via off-diagonal couplings

- $g_{3i} \Rightarrow$ 3-body or 4-body ALP decays; important if $g_{3i} \gg g_{jj}$:

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

- W-boson off-shell (4-body decays) or on-shell (3-body decays), depending on m_a
- For $m_a \lesssim m_W + m_b \sim 85$ GeV, g_{3i}'s can induce ALP 4-body decays which can be the dominant decay modes if the production coupling is larger than the decay coupling by at least around 4 orders of magnitude (checked numerically with `MadGraph5`)
- Automatic calculation of the decay widths of these 4-body decay modes within `MadGraph5` too much time-consuming $\Rightarrow$ Not including them in our computation and restrict ourselves to the parameter space where such contributions are unimportant
- For $m_t \gtrsim m_a \gtrsim m_W + m_b$, the off-diagonal couplings can result in ALP 3-body decays and these modes are included in our computation

Present bounds on ALP-quark couplings

- Low-energy precision measurements: rare decays of kaons, D- and B-mesons, and J/Ψ; relevant only to the ALPs lighter than the B-mesons
- Collider searches: dominant bounds for $m_a \gtrsim 10$ GeV

- We focus on $m_a \gtrsim 10$ GeV because of $m_{\text{DV}} > 10$ GeV required
- Relevant existing bounds:

Ref.	Method	Couplings bounded	Our finding
JHEP 09 (2023) 063	Recast an ATLAS search	g_{tt}/Λ	Orders of magnitude weaker than our bounds
Phys.Rev.Lett. 133, 161803	Performed an ATLAS DV search	$g_{3,1}/\Lambda$ & $g_{3,2}/\Lambda$	1+ order of magnitude weaker than our bounds
JHEP 07 (2022) 122	Recast CMS & ATLAS searches	$g_{3,1}/\Lambda$ & $g_{3,2}/\Lambda$	We recast&reinterpret the searches

- CMS search: top + jets
- ATLAS search: top + MET
- Following JHEP 07 (2022) 122 for recasting these searches
- Not giving detail here

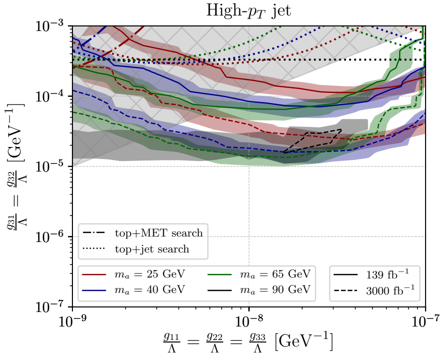
Simulation & Computation

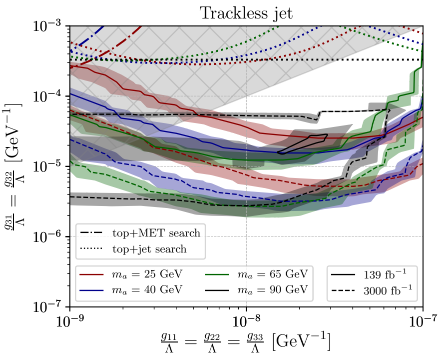
- UFO model of the ALP: `FeynRules`
- Signal-event generation: `MadGraph5`, 10^6 events simulated at each parameter point in a grid scan over prod. coup., decay coup., and m_a
- Γ_a: auto-computed within `MadGraph5`
- Showering, hadronization, and completing the truth-level decay chains of the produced particles: `Pythia8`
- Estimate of ϵ: *our recasting code*

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

- $\mathcal{L}$: integrated luminosity
- $j = u, d, s, c, b$
- $\mathcal{B}(t \to W^+ b) = 99.7\%$
- $\mathcal{B}(W^+ \to jj) = 67.41\%$
- $\sigma(pp \to t\bar{t})_{\rm SM} = 833.9$ pb computed at NNLO+NNLL with the `Top++2.0` program for $\sqrt{s} = 13$ TeV

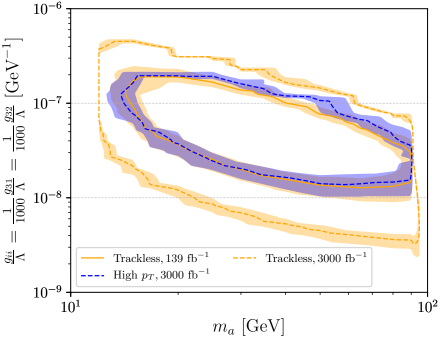
Reinterpretation results – g vs. g

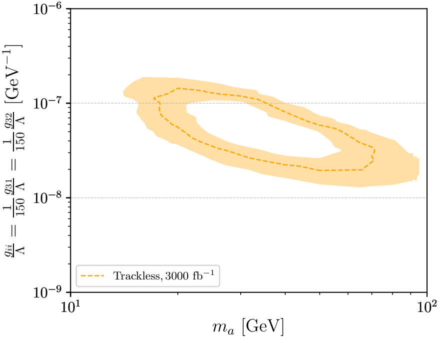




- Assume the same S^{95}_{obs} values for both 139 fb^{-1} and 3000 fb^{-1}

Reinterpretation results – g vs. m_a





Long-lived scalars from Higgs-boson decays at the LHC

- New scalars: models of singlet-scalar-extended SM, neutral-naturalness, 2HDM, SUSY, ...
- Benchmark scenarios: $h \to \phi\phi$, $\Phi \to ss$
- Simulation:
  - Monte-Carlo simulation with `Pythia8`
  - Scan over mass and lifetime of the LLPs
  - Use the module *HiggsSM:gg2H* for simulating the gluon-fusion process with $\sqrt{s} = 13$ TeV

$$N_S = \sigma(\text{LLP}) \cdot \mathcal{L} \cdot \epsilon \cdot \Big(\text{Br}(\text{sig.})\Big)^2$$

- ϵ: the final cutflow efficiencies of the ATLAS DV+jets search
- Br(sig.): signature final states
- Power of 2: *both* LLPs $\xrightarrow{\textit{decay}}$ the specified signature final states

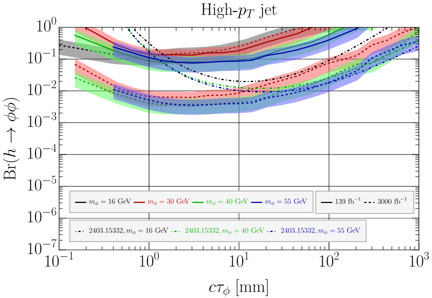
$h \to \phi\phi$

- A light singlet scalar from SM-like Higgs-boson decays
- mass range: $m_\phi \sim [10 \text{ GeV}, 62 \text{ GeV}]$
  - 10 GeV: $m_{\text{DV}} > 10$ GeV
  - 62 GeV: phase-space requirement

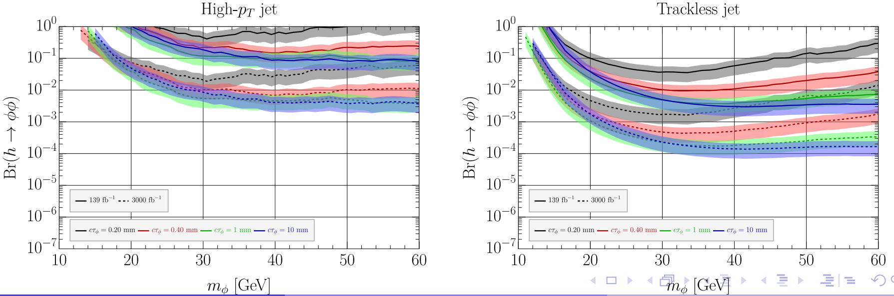
  - Signal process: $pp \xrightarrow{\text{g.f.}} h \to \phi\phi, (\phi \to b\bar{b}, \phi \to b\bar{b})$
- $\text{Br}(\phi \to b\bar{b})$ computed with `HDECAY`

  - $\sigma(pp \xrightarrow{\text{g.f.}} h) = 48.5$ pb at $\sqrt{s} = 13$ TeV

Reinterpretation results



2403.15332: ATLAS search for DVs



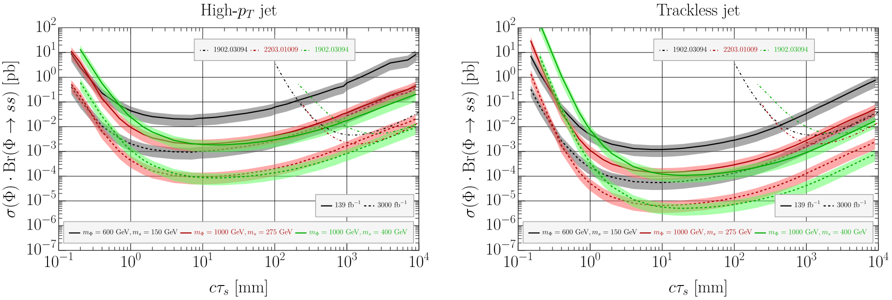
$\Phi \to ss$

- A heavy Higgs boson and a long-lived light scalar
- Benchmark scenarios following ATLAS searches:
  - 1911.12575
  - 1902.03094
  - 2203.01009
    - $(m_\Phi, m_s) = (600\ \text{GeV}, 150\ \text{GeV})$
    - $(m_\Phi, m_s) = (1000\ \text{GeV}, 275\ \text{GeV})$
    - $(m_\Phi, m_s) = (1000\ \text{GeV}, 400\ \text{GeV})$

Signal process: $pp \xrightarrow{\text{g.f.}} \Phi \to ss, (s \to x\bar{x}, s \to x\bar{x})$, with $x = b, c, \tau$

- $\text{Br}(s \to b\bar{b}) = 85\%, \text{Br}(s \to c\bar{c}) = 5\%, \text{Br}(s \to \tau\bar{\tau}) = 8\%$

Reinterpretation results



1902.03094 & 2203.01009: ATLAS searches for displaced hadronic jets

Part II: Propose an LHC search for DVs and jets

Heavy neutral leptons and top quarks in effective field theory, 2501.09065;
R. Beltrán, G. Cottin, J. Günther, M. Hirsch, A. Titov, ***ZSW***

JHEP accepted

An additional theoretical scenario

- N_RSMEFT
- Long-lived HNLs and $d = 6$ operators with top quarks
- HNLs produced from
  1. *pp* collisions in association with a single top
  2. Non-standard decays of top quarks
- Experiments and Signature:
  - ATLAS; DV+jets
  - LHC far detectors; DV
- Motivations: non-zero m_ν, dark matter, baryon asymmetry, ...

N_RSMEFT

- Minimal scenario: m_N and $|V|^2$
- UV-completions beyond the SM: Z', U$(1)_{B-L}$, leptoquarks, ...
- No new resonances at the LHC $\Rightarrow$ Effective Field Theory
- Separation of scales: $m_N \lesssim v$ and $\Lambda \gg v$; v, Higgs VEV
- N_RSMEFT: EFT that describes the SM with additional light fermionic singlets
- Multiple pheno studies using N_RSMEFT exist
- We focus on operators with top quarks
- Long-lived HNL$\Rightarrow$ displaced signals in the LHC main detectors or far detectors
- Pair-N_R and Single-N_R operators

Model scenario

- $\mathcal{L}_{\rm Yuk} = Y_\ell^\nu \overline{L_\ell} \tilde{H} N_R + \text{h.c.} \Rightarrow \nu\text{–}N$ mixing $V_{\ell N}$ after EWSB
- Assume only one N kinematically relevant
- Assume a Dirac HNL
- 1^{st}-gen leptons, 1^{st}- and 3^{rd}-gen quarks
- $V_{\ell N}$ treated as a free parameter
- Focus on LNC and BNC 4-fermion operators
- We do not use second-generation quark indices

EFT operators

	Name	Structure (+ h.c. when needed)
Pair-N_R	$\mathcal{O}_{uN}^{13}$	$\boldsymbol{(\overline{u_R}\gamma^\mu t_R)\left(\overline{N_R}\gamma_\mu N_R\right)}$
	$\mathcal{O}_{uN}^{33}$	$(\overline{t_R}\gamma^\mu t_R)\left(\overline{N_R}\gamma_\mu N_R\right)$
	$\mathcal{O}_{QN}^{13}$	$\left(\overline{Q_1}\gamma^\mu Q_3\right)\left(\overline{N_R}\gamma_\mu N_R\right) = \boldsymbol{(\overline{u_L}\gamma^\mu t_L)\left(\overline{N_R}\gamma_\mu N_R\right)} + \left(\overline{d_L}\gamma^\mu b_L\right)\left(\overline{N_R}\gamma_\mu N_R\right)$
	$\mathcal{O}_{QN}^{33}$	$\left(\overline{Q_3}\gamma^\mu Q_3\right)\left(\overline{N_R}\gamma_\mu N_R\right) = (\overline{t_L}\gamma^\mu t_L)\left(\overline{N_R}\gamma_\mu N_R\right) + \left(\overline{b_L}\gamma^\mu b_L\right)\left(\overline{N_R}\gamma_\mu N_R\right)$
Single-N_R	$\mathcal{O}_{duNe}^{13}$	$\boldsymbol{\left(\overline{d_R}\gamma^\mu t_R\right)\left(\overline{N_R}\gamma_\mu e_R\right)}$
	$\mathcal{O}_{duNe}^{33}$	$\boldsymbol{\left(\overline{b_R}\gamma^\mu t_R\right)\left(\overline{N_R}\gamma_\mu e_R\right)}$
	$\mathcal{O}_{LNQd}^{31}$	$\left(\overline{L}N_R\right)\epsilon\left(\overline{Q_3}^T d_R\right) = (\overline{\nu_L}N_R)\left(\overline{b_L}d_R\right) - \boldsymbol{(\overline{e_L}N_R)(\overline{t_L}d_R)}$
	$\mathcal{O}_{LNQd}^{33}$	$\left(\overline{L}N_R\right)\epsilon\left(\overline{Q_3}^T b_R\right) = (\overline{\nu_L}N_R)\left(\overline{b_L}b_R\right) - \boldsymbol{(\overline{e_L}N_R)(\overline{t_L}b_R)}$
	$\mathcal{O}_{LdQN}^{13}$	$\left(\overline{L}d_R\right)\epsilon\left(\overline{Q_3}^T N_R\right) = (\overline{\nu_L}d_R)\left(\overline{b_L}N_R\right) - \boldsymbol{(\overline{e_L}d_R)(\overline{t_L}N_R)}$
	$\mathcal{O}_{LdQN}^{33}$	$\left(\overline{L}b_R\right)\epsilon\left(\overline{Q_3}^T N_R\right) = (\overline{\nu_L}b_R)\left(\overline{b_L}N_R\right) - \boldsymbol{(\overline{e_L}b_R)(\overline{t_L}N_R)}$
	$\mathcal{O}_{QuNL}^{13}$	$\left(\overline{Q_1}t_R\right)\left(\overline{N_R}L\right) = \boldsymbol{(\overline{u_L}t_R)\left(\overline{N_R}\nu_L\right)} + \boldsymbol{\left(\overline{d_L}t_R\right)\left(\overline{N_R}e_L\right)}$
	$\mathcal{O}_{QuNL}^{31}$	$\left(\overline{Q_3}u_R\right)\left(\overline{N_R}L\right) = \boldsymbol{(\overline{t_L}u_R)\left(\overline{N_R}\nu_L\right)} + \left(\overline{b_L}u_R\right)\left(\overline{N_R}e_L\right)$
	$\mathcal{O}_{QuNL}^{33}$	$\left(\overline{Q_3}t_R\right)\left(\overline{N_R}L\right) = (\overline{t_L}t_R)\left(\overline{N_R}\nu_L\right) + \boldsymbol{\left(\overline{b_L}t_R\right)\left(\overline{N_R}e_L\right)}$

HNL production – pair-N_R op.

- $\mathcal{O}_{uN}^{13}$ and $\mathcal{O}_{QN}^{13}$

1. $pp \to t\bar{t}$ followed by rare top-quark decays

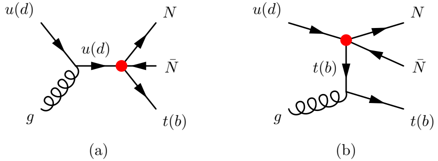
$$\Gamma(t \to uN\bar{N}) = \frac{m_t^5 g(x)}{1536\pi^3\Lambda^4}\left[\left(c_{uN}^{13}\right)^2 + \left(c_{QN}^{13}\right)^2\right]$$

where

$$g(x) = \left(1 - 14x - 2x^2 - 12x^3\right)\sqrt{1-4x} - 12x^2\left(1-x^2\right)\left[\ln\frac{1-\sqrt{1-4x}}{1+\sqrt{1-4x}} - \ln\frac{1+\sqrt{1-4x}-2x}{2x}\right]$$

and $x = m_N^2/m_t^2$

2. $pp \to N\bar{N}\,t/b$



HNL production – single-N_R op.

1. $pp \to t\bar{t}$ followed by rare top-quark decays

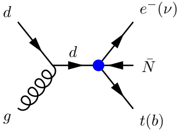
$$\Gamma(t \to d e^+ N) = \frac{m_t^5 f(x)}{6144\pi^3\Lambda^4}\Big[4\left(c^{13}_{duNe}\right)^2 + \left(c^{13}_{QuNL}\right)^2 + \left(c^{31}_{LNQd}\right)^2 + \left(c^{13}_{LdQN}\right)^2 - c^{31}_{LNQd}c^{13}_{LdQN}\Big]$$

$$\Gamma(t \to u\bar{\nu}N) = \frac{m_t^5 f(x)}{6144\pi^3\Lambda^4}\left(c^{13}_{QuNL}\right)^2$$

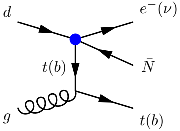
$$\Gamma(t \to u\nu\bar{N}) = \frac{m_t^5 f(x)}{6144\pi^3\Lambda^4}\left(c^{31}_{QuNL}\right)^2$$

where $f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$, with $x = m_N^2/m_t^2$

2. $pp \to \bar{N} e^- / \nu \;\; t/b$

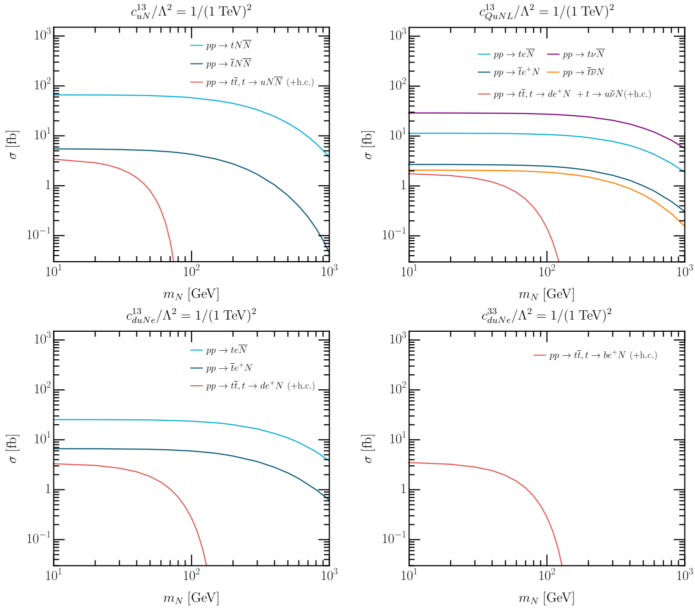


(a)



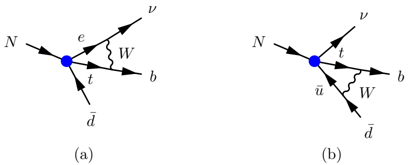
(b)

Production cross sections



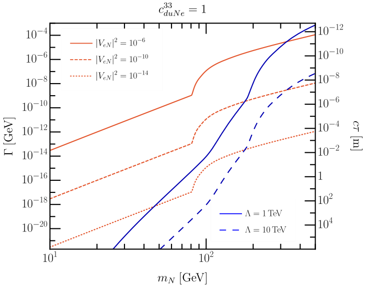
HNL decays

- Pair-N_R operators: the HNLs decay essentially only via $V_{\ell N}$
- Single-N_R operators: induce HNL decays
  1. All induce HNL 5-body decays via an off-shell t and an off-shell W-boson; can become 4-body or 3-body decays if m_N large enough
  2. Operators containing two terms, one of which does not involve the top quark, trigger 3-body decays (m_N assumed to be heavy enough to ensure on-shell b-quark): $\mathcal{O}^{31}_{LNQd}$, $\mathcal{O}^{33}_{LNQd}$, $\mathcal{O}^{13}_{LdQN}$, $\mathcal{O}^{33}_{LdQN}$, and $\mathcal{O}^{31}_{QuNL}$
  3. At the one-loop level, the operators leading to 5-body tree-level decays will also trigger 3-body decays:

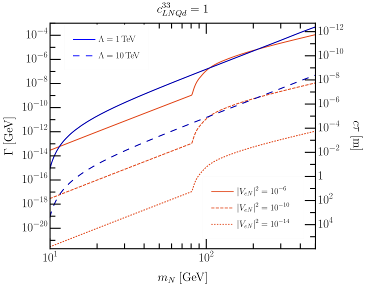


One-loop diagrams (in the unitary gauge) for the 3-body decay $N \to \nu b \bar{d}$ by the operator $\mathcal{O}^{13}_{QuNL}$

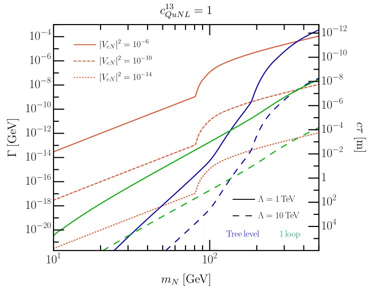
Partial decay widths of N



5-body decays



$N \to \nu b\bar{b}$



green: $N \to \nu b\bar{d}$ one-loop

blue: 5-body decays

Summary of **tree-level** HNL production and decay modes

Operator		HNL production modes		HNL decay channels	
Name	Flavor	Top decay	*pp* collision	5-body	3-body
$\mathcal{O}_{uN}$	13	$t \to uN\bar{N}$	$pp \to tN\bar{N}$	$\times$	$\times$
$\mathcal{O}_{QN}$	13	$t \to uN\bar{N}$	$pp \to tN\bar{N}/bN\bar{N}$	$\times$	$\times$
$\mathcal{O}_{QuNL}$	13	$t \to u\bar{\nu}N/de^+N$	$pp \to t\nu\bar{N}/te^-\bar{N}$	$N \to \nu\, t^*\bar{u}/e^-t^*\bar{d}$	$\times$
	31	$t \to u\nu\bar{N}$	$pp \to t\bar{\nu}N/be^+N$	$N \to \nu\, u\, \bar{t}^*$	$N \to e^-u\bar{b}$
	33	$t \to be^+N$	$\times$	$N \to e^-t^*\bar{b}/\nu t^*\bar{t}^*$	$\times$
$\mathcal{O}_{duNe}$	13	$t \to de^+N$	$pp \to te^-\bar{N}$	$N \to e^-t^*\bar{d}$	$\times$
	33	$t \to be^+N$	$\times$	$N \to e^-t^*\bar{b}$	$\times$
$\mathcal{O}_{LNQd}$	31	$t \to de^+N$	$pp \to te^-\bar{N}/b\nu\bar{N}$	$N \to e^-t^*\bar{d}$	$N \to \nu b\bar{d}$
	33	$t \to be^+N$	$\times$	$N \to e^-t^*\bar{b}$	$N \to \nu b\bar{b}$

Benchmark scenarios

Operator	Dominant production	Dominant decays
$\mathcal{O}^{13}_{uN}$	$pp \to tN\bar{N}$	$V_{\ell N}$
$\mathcal{O}^{13}_{QuNL}$	$pp \to te\bar{N}$, $pp \to t\nu\bar{N}$	one-loop 3-body and $V_{\ell N}$
$\mathcal{O}^{13}_{duNe}$	$pp \to te\bar{N}$	$V_{\ell N}$ for $m_N < m_W$ 4-body (3-body) for $m_N > m_W$ (m_t)
$\mathcal{O}^{33}_{duNe}$	top-quark decays	both op. and $V_{\ell N}$

Always turn on a single effective operator structure, together with the standard $V_{\ell N}$

ATLAS search

- Signature: a DV from the HNL decay, with jets from top-quark or HNL decays
- The ATLAS DV+jets search fails because of its too strong thresholds on jets' p_T
- Propose a new search strategy with optimal jet cuts and the optional requirement of a b-jet:
  - jet-p_T thresholds from a past 8-TeV ATLAS search for DVs
  - DV selections from the recent 13-TeV ATLAS search for DV+jets
- Event generation:
  - `FeynRules`: UFO model
  - `MadGraph5`: HNL production processes
  - Scan over $|V_{eN}|^2$ and m_N, keeping $c_{\mathcal{O}}^{ij}/\Lambda^2$ constant
  - `MadSpin`: forcing the HNLs to decay into ejj and νjj via mixing and channels with ≥ 2 jets via operators
  - `Pythia8`: showering, hadronization, and event selections
  - Implemented a toy-detector module in `Pythia` to reconstruct truth-level jets with `FastJet`
  - Detector response for jet-p_T measurements included

ATLAS event selections

1. Event-level selections:
   - $n_{\text{jet}}^{90} \geq 4$ or $n_{\text{jet}}^{65} \geq 6$ or $n_{\text{jet}}^{55} \geq 6$, following 1504.05162
   - *Optionally*: require iden. of b-jets for discovery potential
2. DV-level selections:
   - Follow 2301.13866 and its recast JHEP 07 (2024) 209
   - ≥ 1 vertex in the event satisfy the following conditions:
     - 4 mm $< R_{xy} < 300$ mm and $|z| < 300$ mm
     - At least one track should satisfy $d_0 > 2$ mm
     - The displaced vertex should have at least 5 decay products of a massive particle satisfying the following requirements:
       - It should be a track with a boosted transverse decay length > 520 mm
       - Its p_T and charge q should obey the relation $p_T/|q| > 1$ GeV
     - $m_{\text{DV}} > 10$ GeV
3. Apply parameterized vertex-level efficiencies discussed previously (but not event-level efficiencies)

Computation of N_S^{ATLAS} and projected sensitivities

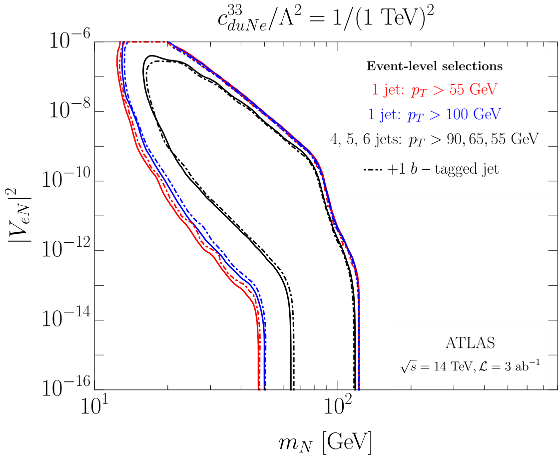
$$N_S^{\text{ATLAS}} = \sigma \cdot \mathcal{L} \cdot \left\{ \mathcal{B}_{\text{mix}} \cdot \varepsilon^{\text{mix}} + \mathcal{B}_{\text{op}} \cdot \varepsilon^{\text{op}} \right\}$$

$$\mathcal{B}_{\text{mix}} = \mathcal{B}(N \to ejj) + \mathcal{B}(N \to \nu jj)$$

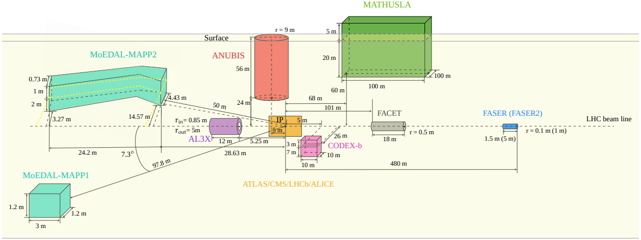
$$\mathcal{B}_{\text{op}} = \mathcal{B}(N \to \text{5-body tree}) + \mathcal{B}(N \to \text{3-body loop})$$

- $\mathcal{L} = 3$ ab^{-1}; $j: u, d, c, s, b$; $\varepsilon^{\text{mix/op}}$: final cutflow efficiencies
- The vertex-level selection criteria designed to suppress all backgrounds
- 95% C.L. exclusion limits: 3 signal events

Example of effect on sensitivity if varying jet-p_T thresholds



LHC far detectors



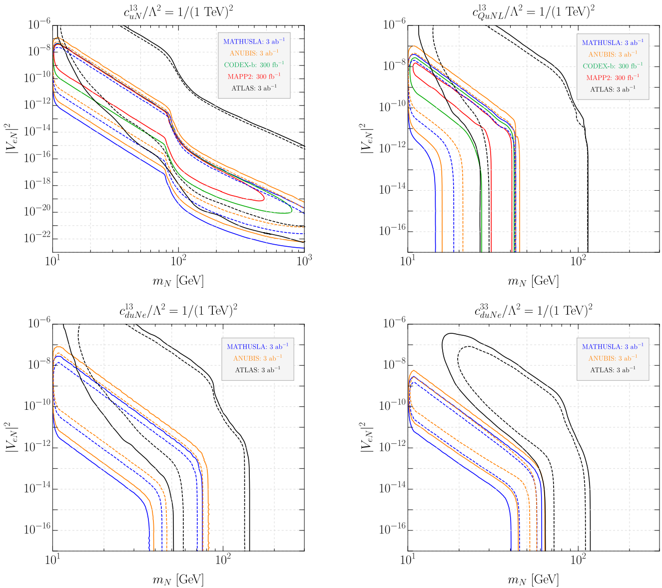
- reproduced from [2410.19561] (C.-T. Lu, X. Wang, X. Wei, Y. Wu)

- With proton-proton collisions at $\sqrt{s} = 13$–14 TeV
- ATLAS and CMS usually hard to test meson decay products; LHCb can do, but other limitations (int. lumi.)
- "Far detectors" specifically for LLP searches, macroscopic distances from various IPs allowing for shielding and veto; DV reconstruction inside fiducial volume
- ANUBIS, CODEX-b, FACET, FASER and FASER2, MoEDAL-MAPP1 and MAPP2, and MATHUSLA
- Little background, if not background-free

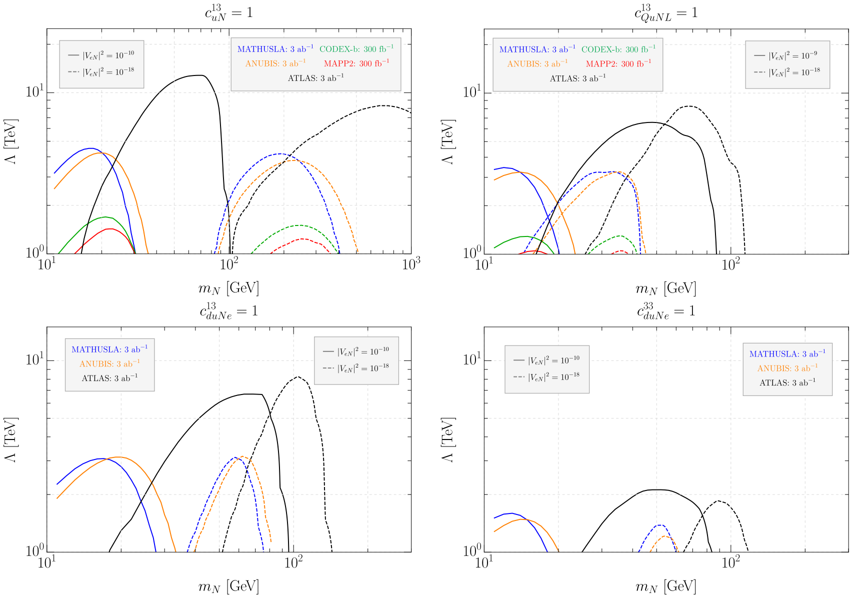
Computation of $N_S^{\rm FD}$ and projected sensitivities

- Not simulating HNL decays in this case
- $\langle P\,[N \text{ decay in f.v.}]\rangle = \frac{1}{k}\sum_{i=1}^{k} P\left[N^i \text{ decay in f.v.}\right]$
  - k: total number of the simulated HNLs for each HNL mass
  - Individual decay prob. determined by the HNL's boosted decay length and momentum angle besides the geometry and position of the far detectors
- $N_S^{\rm FD} = \sigma \cdot \mathcal{L} \cdot \langle P\,[N \text{ decay in f.v.}]\rangle \cdot \mathcal{B}(N \to \text{vis.}) \cdot \varepsilon$
  - $\mathcal{B}(N \to \text{vis.})$: BR of the HNL into visible final states (that can be induced either via mixing or the operator), for which we have only excluded the fully invisible tri-neutrino final states
  - Assume a detection efficiency of $\varepsilon = 100\%$
- Zero background: 3 signal events for exclusion limits at 95% C.L.
- Sensitivity limits for larger numbers of signal events provided; sensitivities for other acceptance or background levels

Numerical results – $|V_{eN}|^2$ vs. m_N



Numerical results – Λ vs. m_N



Conclusions

- NP might be hidden in LLPs
- (HL-)LHC can search for LLPs
- Recast a recent ATLAS search for DV plus jets and reinterpreted it in terms of ALPs with QFV and BSM particles from Higgs-boson decays
- Proposed a search for HNLs coupled to top quarks in N_RSMEFT, based on past 8-TeV and 13-TeV ATLAS searches for DV and DV+jets
- Studied also LHC far detectors for the latter case

Thank You!

谢谢!

Appendix

Pre-selections

- Truth jets are reconstructed with `FastJet`, using anti-k_t algorithm and $R = 0.4$ from all selected stable particles excluding neutrinos and muons This definition includes particles from the LLP decay
- Jet momentum smearing is applied
- Displaced jets are defined as those among the jets selected above that are matched with the LLPs' decay positions and have $|\eta| < 2.5$. By calculating ΔR between the LLP decay products and the truth jets, we determine that a truth jet stems from the LLP decay if the closest decay products of the LLP has $\Delta R < 0.3$
- For the displaced truth jets, we require that the matched LLPs should decay with a transverse distance from IP smaller than 3870 mm which corresponds to the region of the calorimeter

Conditions for safely using the parameterized efficiencies

1. The event- and vertex-level acceptances combined should exceed 10%;
2. For any parameter-space point, if the corresponding signal events have an acceptance of over 90% with the High-p_T-jet SR, the parameterized efficiencies of the Trackless-jet SR should not be used; and
3. The LLP proper decay length of less than 3 meters are recommended for models where "jets primarily originate from the decay of LLPs".

Validation results: additional High-p_T-jet SR acceptance and final cutflow efficiency

	Acceptance [%]					
$m(\tilde{\chi}_1^0)$ [GeV]	1500		1500		1500	
$\tau(\tilde{\chi}_1^0)$ [ns]	0.032		0.1		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

$m(\tilde{\chi}_1^0), \tau(\tilde{\chi}_1^0)$	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%

- EW channel, $\tilde{\chi}_1^0$ decaying to heavy-flavor quarks

Validation results: additional Trackless-jet -p_T-jet SR acceptance and final cutflow efficiency

$m(\tilde{\chi}_1^0)$ [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
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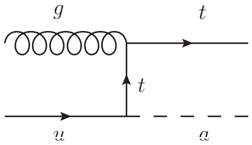
$n_{\text{selected decay products}} \geq 5$	45.7	46.9	73.3	72.3	78.4	76.5
Invariant mass > 10 GeV	45.7	46.9	73.3	72.3	78.4	76.5

$m(\tilde{\chi}_1^0), \tau(\tilde{\chi}_1^0)$	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%

- EW channel, $\tilde{\chi}_1^0$ decaying to heavy-flavor quarks

Recast&Reinterpret single top+jets/MET searches

- QFV and ALP [JHEP 07 (2024) 209]
    - $pp \to ta$:



- $a \to jj$ appears as either prompt jets, displaced jets/vertices, or MET
- CMS search for a single leptonic top + prompt jets
- ATLAS search for a single top + MET
- Upper bounds on NP contributions to the cross sections [1609.04838]: $\sigma_{tj} \sim 0.29$ pb and $\sigma_t \sim 0.10$ pb
- Generate $pp \to ta$ at $\sqrt{s} = 13$ TeV with `MadGraph5` and require:

$$\epsilon^{\text{acc.}}_{\text{prompt}} = \frac{1}{N_{\text{MC}}} \sum_{i=1}^{N_{\text{MC}}} \left(\left(1 - e^{\frac{-10^{-4}\text{ m}}{\beta_i^r \gamma_i c \tau_a}}\right) + \left(e^{\frac{-2.5\times 10^{-2}\text{ m}}{\beta_i^r \gamma_i c \tau_a}} - e^{\frac{-2\text{ m}}{\beta_i^r \gamma_i c \tau_a}}\right) \right)$$

$$\epsilon^{\text{acc.}}_{\text{MET}} = \frac{1}{N_{\text{MC}}} \sum_{i=1}^{N_{\text{MC}}} e^{\frac{-10\text{ m}}{\beta_i^r \gamma_i c \tau_a}}$$

Cutflow – high-p_T-jet SR

- 10^6 events generated
- $\frac{g_{3i}}{\Lambda} = 10^{-6}$ GeV^{-1} small $\Rightarrow$ ignore their induced decay width of a

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

Cutflow – trackless-jet SR

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

$h \to NN$

- Long-lived heavy neutral leptons (HNLs) from SM-like h decays
- $\mathrm{U}(1)_{B-L}$, new particles: N, Z', H, ...
- N: Majorana HNLs

$$\Gamma(h \to NN) = \frac{1}{2}\frac{m_N^2}{\tilde{x}^2}\sin^2\alpha\,\frac{m_h}{8\pi}\left(1-\frac{4m_N^2}{m_h^2}\right)^{3/2}$$

- α: scalar-mixing angle
- g_1': gauge coupling of $\mathrm{U}(1)_{B-L}$
- $\tilde{x} = m_{Z'}/2g_1'$: vev of the new scalar H

- Assume only one generation of N kinematically relevant and that N mixes only with ν_e

$$\mathrm{Br}(h \to NN) = \frac{\Gamma(h \to NN)}{\Gamma(h \to NN) + \cos^2\alpha\,\Gamma^h_{\mathrm{SM}}}$$

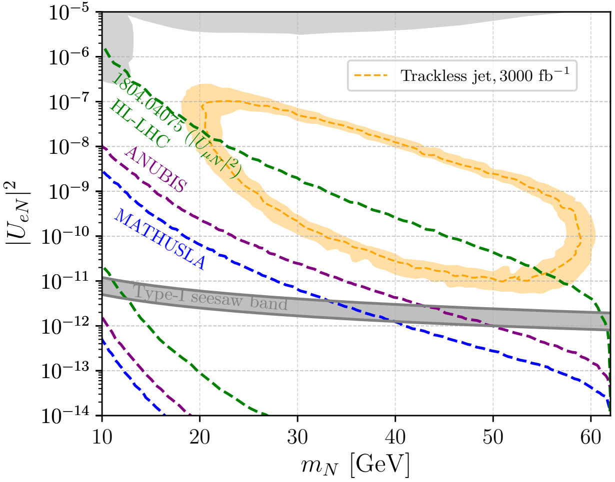
$$\begin{aligned} m_N &= 12\text{ - }62\ \mathrm{GeV}, |U_{eN}|^2 = 10^{-12}\text{ - }10^{-6}, \\ m_{Z'} &= 6\ \mathrm{TeV}, g_1' = 0.8, \tilde{x} = 3.75\ \mathrm{TeV}, \\ & m_H = 450\ \mathrm{GeV}, \sin\alpha = 0.3 \end{aligned}$$

$h \to NN$

Signal process: $\sigma(pp \xrightarrow{\text{g.f.}} h \to NN) = \cos^2\alpha \cdot \sigma_h^{\text{g.f.}} \cdot \text{Br}(h \to NN)$

- Decay width of the Majorana HNL: 2010.07305
- Signature final state: $N \to \nu_e/e + jj$, $j = u, d, c, s, b$
- HNL production mediated by α and $\tilde{x}$
- HNL decay induced separately by $|U_{eN}|^2$

Reinterpretation results



Identification of *b*-jets

- 2501.09065

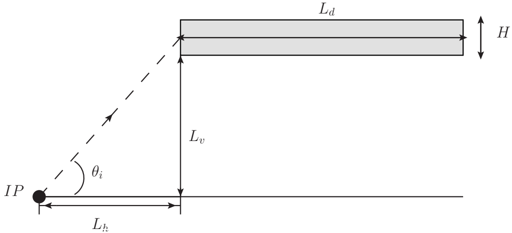
We treat a jet as a *b*-jet based on the flavor of the truth quark that initiated the jet. From all truth jets in the event with $p_T > 20$ GeV and $|\eta| < 2.5$, we tag a jet as a *b*-jet if a Monte-Carlo truth *b*-quark with $p_T > 5$ GeV is found within a cone of size $\Delta R = 0.3$ around the jet direction. We additionally force a flat *b*-jet identification efficiency of 77%

Experiments at the LHC

- Consider pp collisions at $\sqrt{s} = 14$ TeV with equal beam energies
- HL-LHC with 3 ab^{-1} integrated luminosity
- Various far detectors have different projected integrated luminosities

MATHUSLA

- MAssive Timing Hodoscope for Ultra Stable neutraL pArticles: a surface detector above the CMS IP: 100 m $\times$ 100 m $\times$25 m [2009.01693]

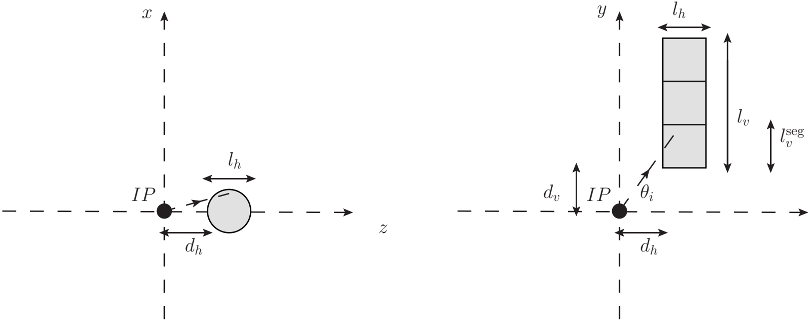


Extracted from [1810.03617]

L_d (m)	L_h (m)	L_v (m)	H (m)	$\phi/2\pi$	$\mathcal{L}$ (fb^{-1})
100	68	60	25	0.22	3000

ANUBIS

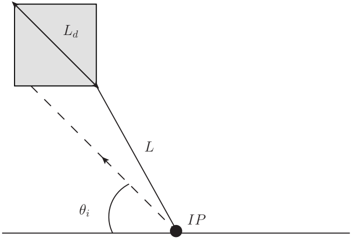
- AN Underground Belayed In-Shaft search experiment: [1909.13022]
  In one of the service shafts above the ATLAS or CMS IP



Extracted from [2001.04750]

- $d_h = 5$ m, $d_v = 24$ m, $l_h = 18$ m, $l_v = 56$ m
- $\mathcal{L} = 3000$ fb^{-1}

CODEX-b



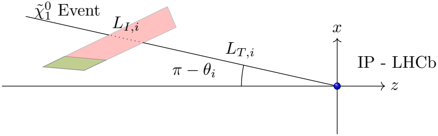
Extracted from [1810.03617]

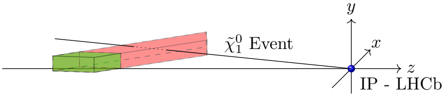
A Compact Detector for Exotics at LHCb:
10 m × 10 m × 10 m [1708.09395]

L_d (m)	L (m)	$\phi/2\pi$	η	$\mathcal{L}$ (fb^{-1})
10	25	0.06	[0.2, 0.6]	300

MoEDAL-MAPP1 & MAPP2

- MoEDAL's Apparatus for Penetrating Particles
- A sub-detector of the MoEDAL experiment [Universe 5 (2019) 2, 47] near IP8 of the LHCb
- MAPP1 (approved): 130 m^3, during LHC run 3, 30 fb^{-1}, ~ 55 m from the IP
- MAPP2: 430 m^3, HL-LHC, 300 fb^{-1}, the whole of the UGC8 gallery

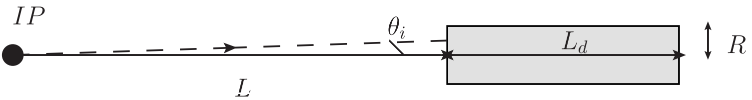




Extracted from [2008.07539]

FASER & FASER2

- ForwArd Search ExpeRiment: [1901.04468]
  a cylindrical detector in very forward direction along beam axis



Extracted from [1810.03617]

- FASER duing LHC run 3 (approved), and FASER2 during HL-LHC
- $L + L_d = 480$ m, $L_d = 1.5/5$ m, $R = 0.1/1$ m, full ϕ coverage
  $\eta : [9.17/6.86, \infty]$, $\mathcal{L} = 150/3000$ fb^{-1}