Constraining long-lived particles from Higgs boson decays at the LHC with displaced vertices and jets

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HEFEI UNIVERSITY OF TECHNOLOGY

Motivation

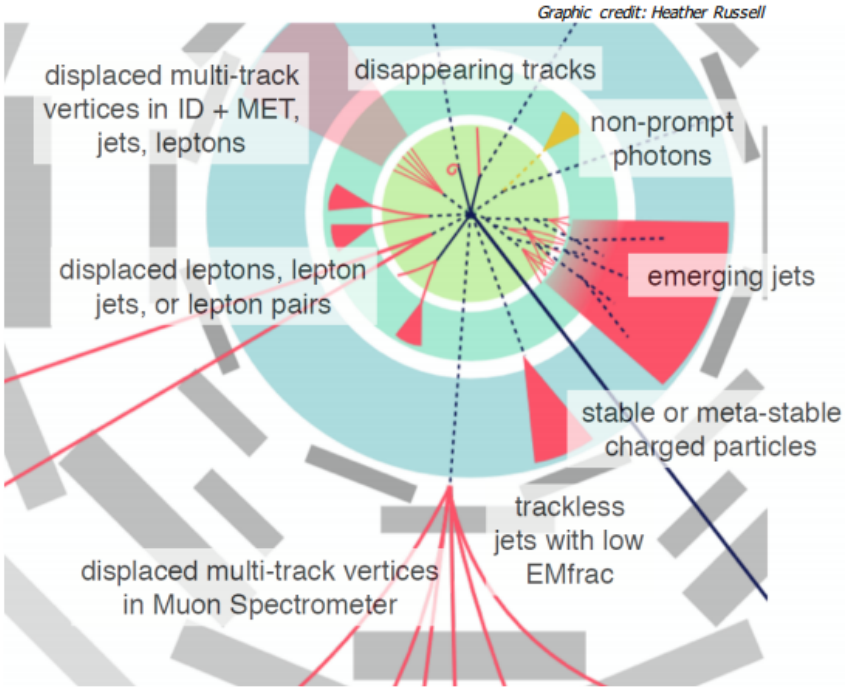
- The LHC has been focusing on searches for heavy new particles; large p_T or MET; NO discovery so far
- Increasingly more attention given to signatures related to long-lived particles (LLPs), among others
- LLP: produced, travel a macroscopic distance, and decay
- Predicted in various BSM scenarios and well motivated
  - $m_\nu \neq 0$
  - DM
  - $v \ll m_{\text{Pl.}}$
  - ...
- LLP candidates: dark scalar, heavy neutral leptons, axionlike particle, dark photon, RPV SUSY bino, inelastic DM, chargino (compressed SUSY), ...
- Dark scalar predicted in:
  - SM extended by a singlet scalar that mixes with h
  - Neutral-naturalness models that solve the little hierarchy problem
  - 2HDMs including SUSY
  - ...
- Heavy neutral leptons predicted in:
  - SM extended by 3 ν_R's that mix with $\nu_{e/\mu/\tau}$
  - $U(1)$ extensions of the SM such as $U(1)_{B-L}$

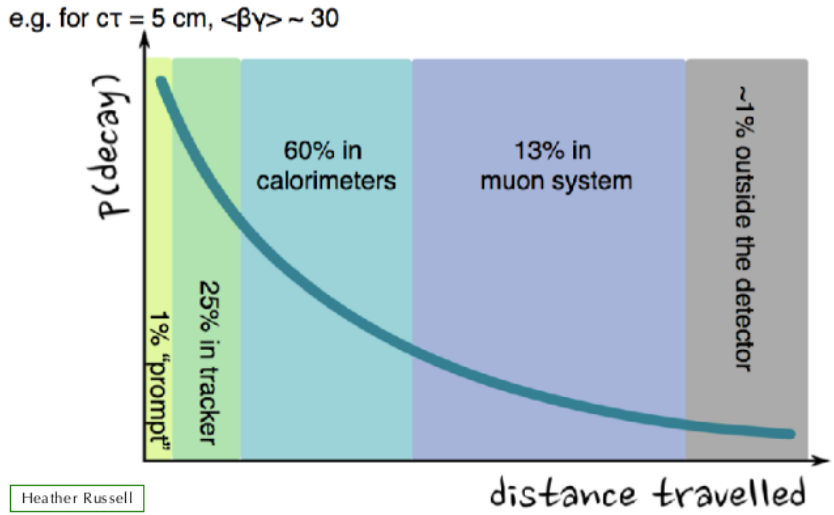
Long lifetime and LLP-search experiments

- Causes of the long lifetime:
  - **Feeble** couplings
  - **Heavy** mediators
  - **Small** phase space
  - ...
- Experiments:
  - Beam dumps: PS191, NA62, SHiP, DUNE, ...
  - Neutrino detectors: Super-Kamiokande, IceCUBE, ...
  - Colliders: LEP, BABAR, LHC, Belle II, ...
  - LHC far detectors: FASER(2), MoEDAL-MAPP1(2), MATHUSLA, CODEX-b, ...
  - ...
- Focus of the talk:

LLP searches at the LHC

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**, recast instruction from ATLAS
  recast in JHEP 07 (2024) 209 by *K. Cheung, F.-T. Chung, G. Cottin,* ***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 or exclusion limits
3. **Reinterpretation**: apply the same analysis on your favorite NP model to derive the corresponding limits

The ATLAS "DVs+jets" search

- Full Run-2 dataset of 139 fb^{-1}, $\sqrt{s} = 13$ TeV
- Signature: DVs + jets
- 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 $n_{\text{jet}}^{55} \geq 7$, $n_{\text{disp. jet}}^{70} \geq 1$ or $n_{\text{disp. jet}}^{50} \geq 2$

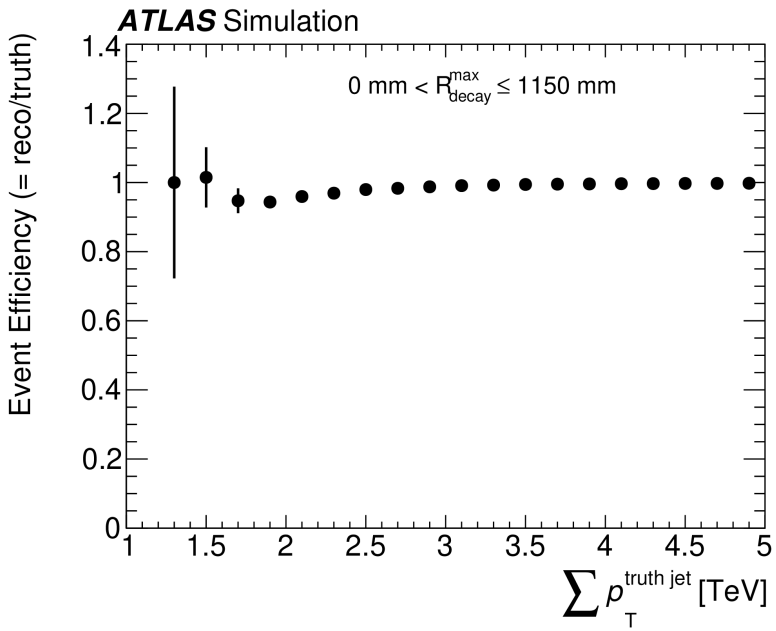
- Vertex-level acceptance:
  At least one vertex should pass a list of vertex requirements:
  1. 4 mm $< R_{xy} < 300$ mm and $|z| < 300$ mm
  2. At least one track should satisfy $d_0 > 2$ mm
  3. The displaced vertex should have at least 5 decay products of a massive particle satisfying the following 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

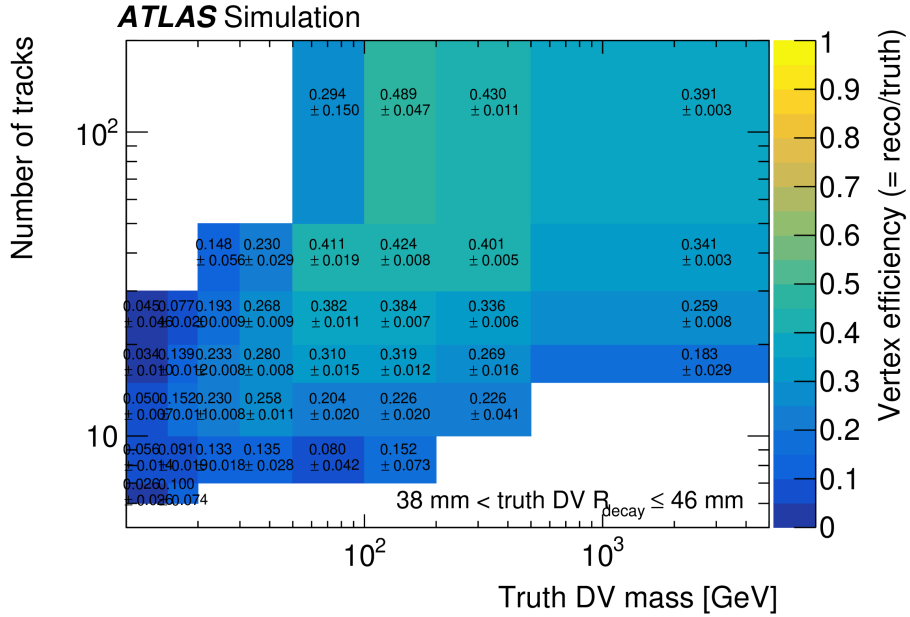
- Parameterized efficiencies provided by the ATLAS collaboration at both event- and vertex-levels that account for delicate requirements such as multi-jet trigger, jet filter, and material effects that are difficult to simulate
- Applied to **truth-level** objects!

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

Background

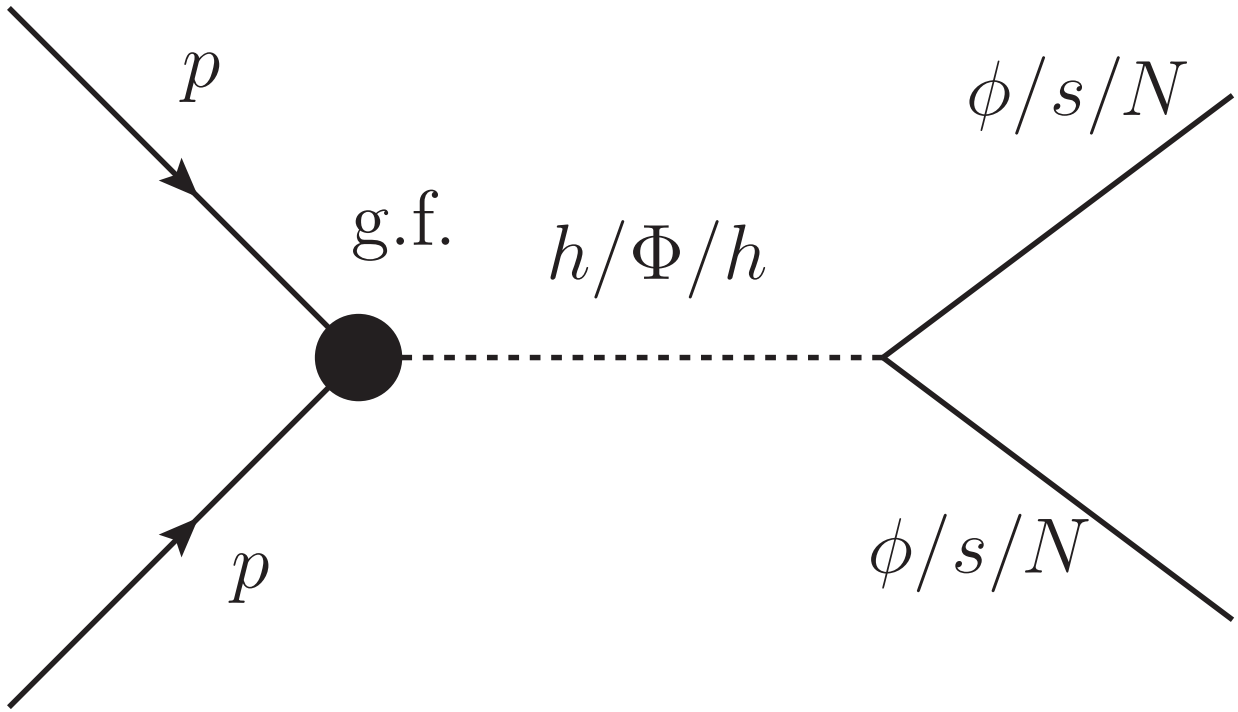
- Erroneous merge of nearby DVs of small invariant masses by vertexing algorithms resulting in a high-mass DV
- Hadronic interactions between particles and detector materials
- Accidental crossings of a track with unrelated low-mass DVs

- Background-event numbers expected to be $0.46^{+0.27}_{-0.30}$ and $0.83^{+0.51}_{-0.53}$ at the High-p_T-jet and Trackless-jet SRs, respectively

SR	Observed	Expected	S^{95}_{obs}	S^{95}_{exp}	$\langle\sigma_{\text{vis}}\rangle^{95}_{\text{obs}}$ [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

- We optimistically project the same level for the 3 ab^{-1} int. lumi.

Signal-process topology

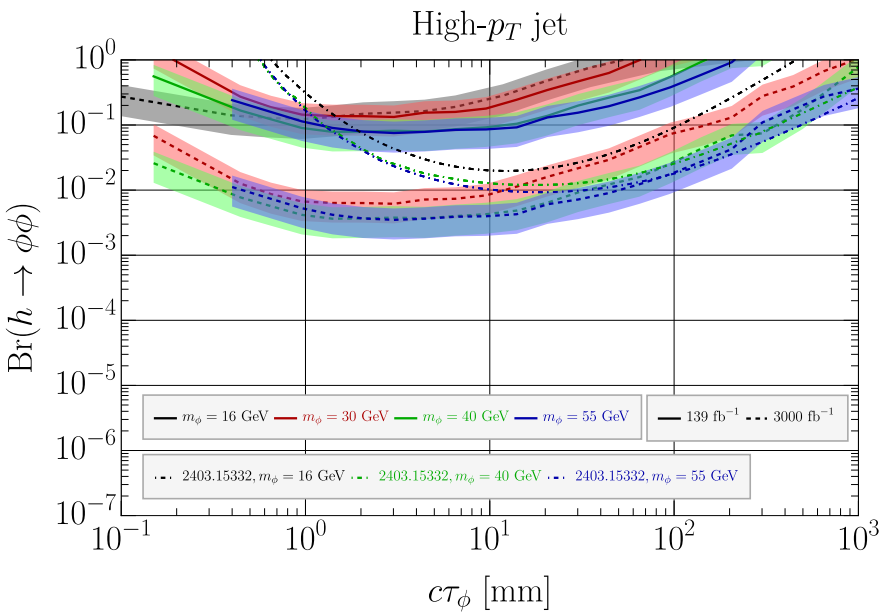


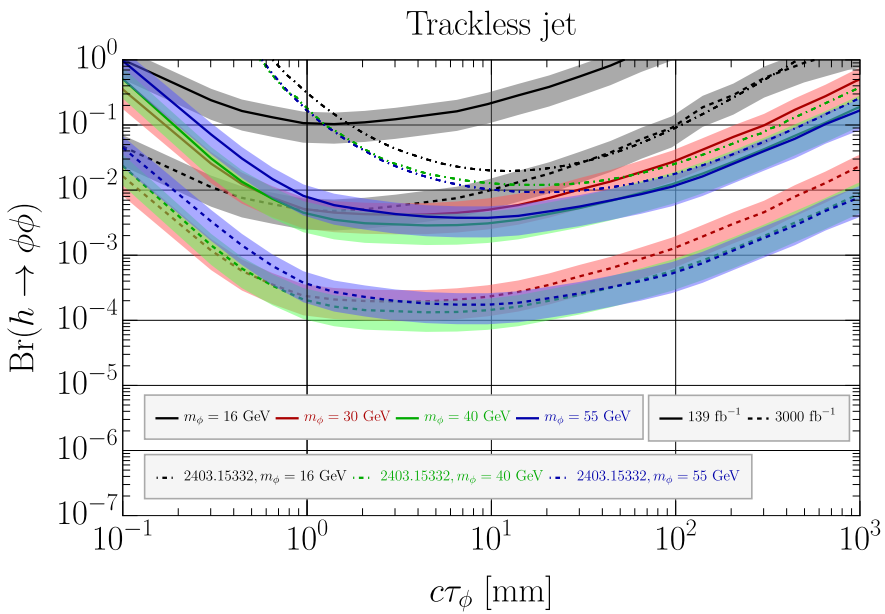
- $\phi/s/N$'s then decay into specific signal final states

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

$h \to \phi\phi$

- 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: $pp \xrightarrow{\text{g.f.}} h \to \phi\phi, (\phi \to b\bar{b}, \phi \to b\bar{b})$





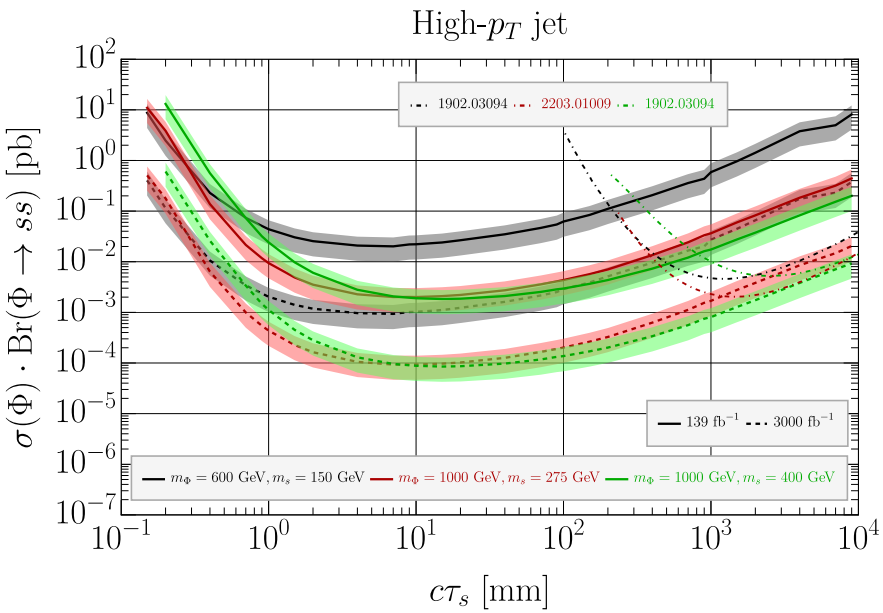
2403.15332: ATLAS search for DVs

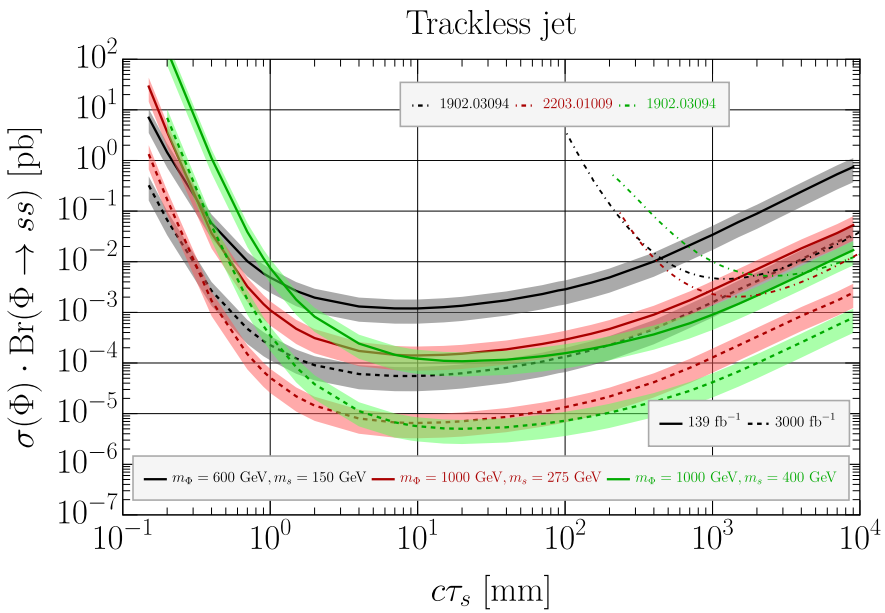
$\Phi \to ss$

- 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 $x = b, c, \tau$

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





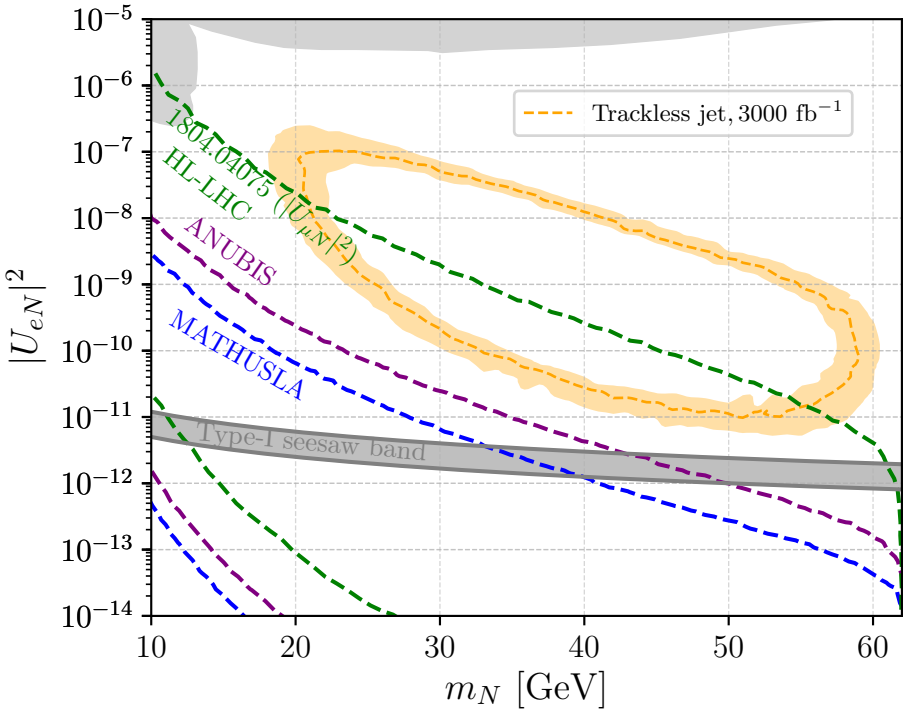
1902.03094 & 2203.01009: ATLAS searches for displaced hadronic jets

$h \to NN$

- Long-lived heavy neutral leptons (HNLs) from SM-like h decays
- $U(1)_{B-L}$ with N Majorana HNLs

Signal process: $pp \xrightarrow{\text{g.f.}} h \to NN$

- Signal final state: $N \to \nu_e/e + jj$, $j = u, d, c, s, b$
- HNL production and decay decoupled



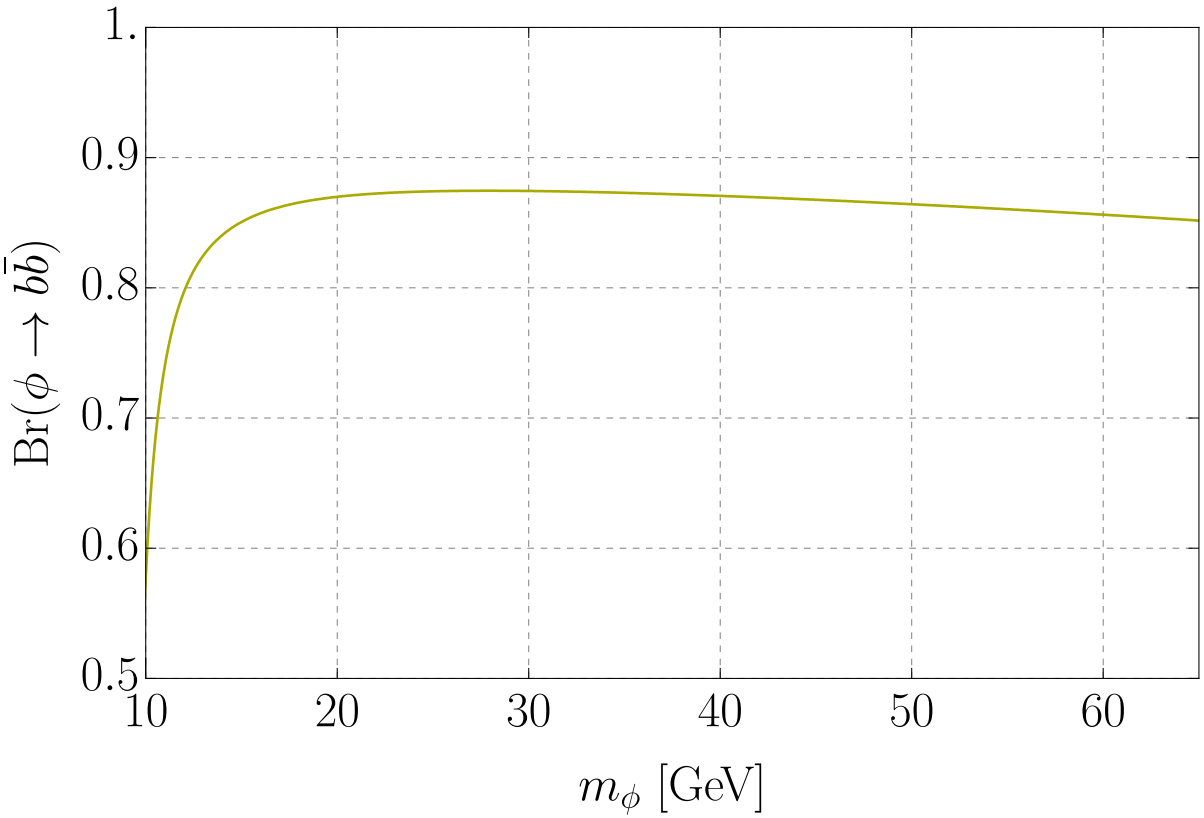
Summary

- No new heavy resonances have been found yet at the LHC
- Searching for (light) long-lived particles becomes more important
- (HL-)LHC can search for LLPs
- Higgs portal special and intriguing
- Applied a recast of an ATLAS search for DVs plus jets to scenarios of LLPs from Higgs-boson decays at the LHC
- LLPs decaying semi-leptonically or hadronically
- For the considered scenarios, trackless-jet SR more powerful than high-p_T-jet SR
- Particularly sensitive to LLPs with $c\tau$ between 1–100 mm
- Outlook: lower the jet-p_T thresholds to enhance sensitivities
  see JHEP05(2025)238 and 2510.05525

Thank You! 谢谢!

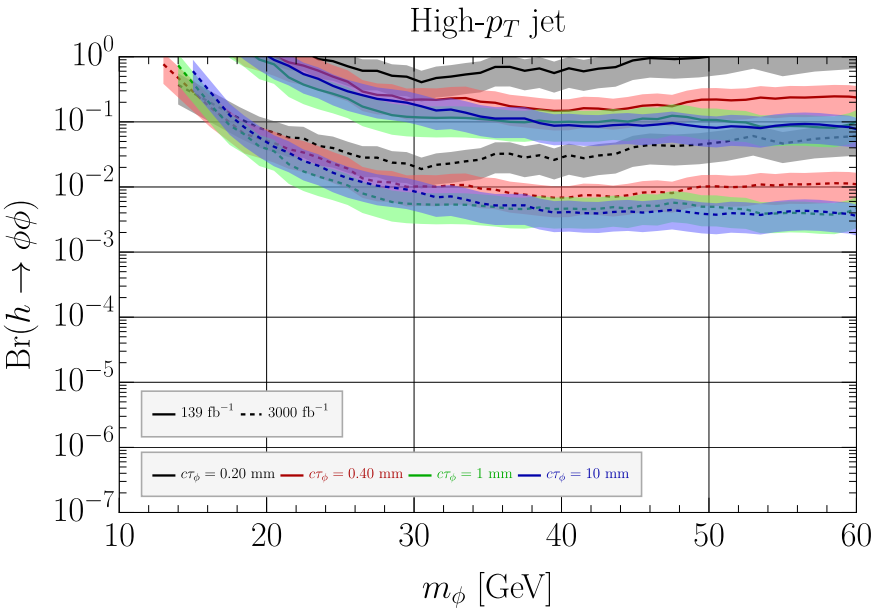
Back-up slides

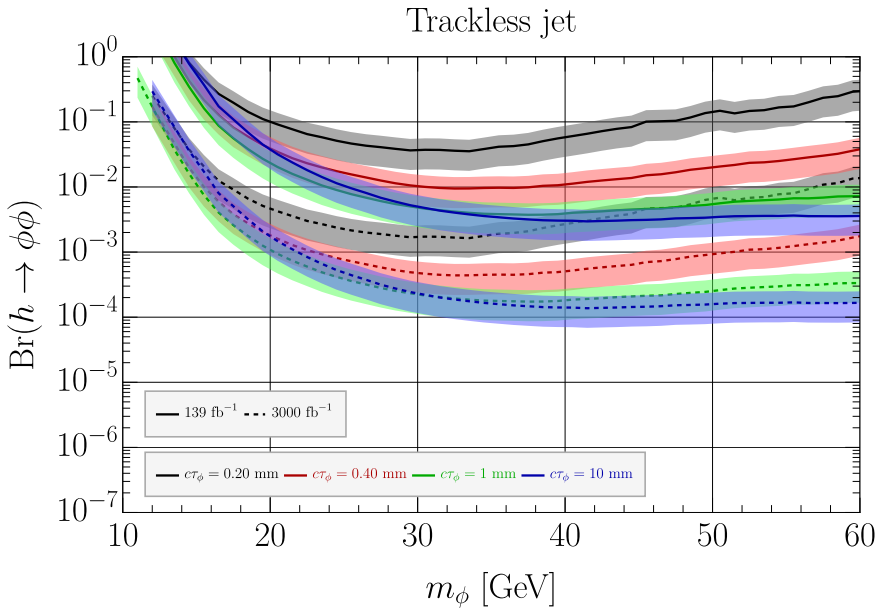
$\mathrm{Br}(\phi \to b\bar{b})$ vs. m_ϕ



- obtained with `HDECAY 3.4`

Further sensitivity plots for $h \to \phi\phi$





$h \to NN$

- 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

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

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

$h \to NN$

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
- Signal 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 $|U_{eN}|^2$