Exotic Higgs decays into displaced jets at the LHeC

work with Kingman Cheung, Oliver Fischer, Jose Zurita

arXiv: 2008.09614

Zeren Simon Wang

Eighth workshop of the LHC LLP Community
Nov. 19, 2020

asia pacific center for theoretical physics

NTHU

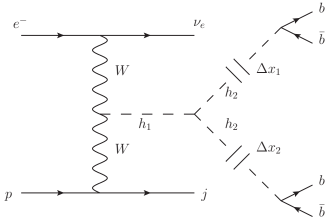
Motivation

- Surge of interest in LLPs in recent years (Why we are here!)
- *Portals* connecting the SM to a hidden sector:
  - Vector portal (dark photon)
  - Neutrino portal (heavy neutral lepton)
  - Pseudoscalar portal (axion-like particle)
  - Higgs portal (dark Higgs)
- Higgs boson: discovered in 2012, center of studying the underlying physics of Electroweak Symmetry Breaking
- Important to study the properties of the Higgs boson
- Higgs factories: CEPC, FCC-ee, ILC, LHeC, FCC-he, etc.
- A large and clean sample of the Higgs bosons at the LHeC $\sim 10^5$ allows for studying *Higgs rare decays*

The SM extended with a complex singlet scalar

$$V(H,S) = -\mu_1^2 H^\dagger H - \mu_2^2 S^\dagger S + \lambda_1 (H^\dagger H)^2 + \lambda_2 (S^\dagger S)^2 + \lambda_3 (H^\dagger H)(S^\dagger S)$$

- Mixing between h_1 and h_2
- The dominant Higgs production at *ep* colliders: *charged-current vector-boson fusion*



E_e	E_p	$\mathcal{L}$	N_h
60 GeV	7 TeV	1 ab^{-1}	1.1×10^5

Signature: $p\, e^- \to \nu_e\, j\, h_1 \to \nu_e\, j\, h_2\, h_2 \to \nu_e\, j\, (b\bar{b})_{\text{displaced}}\, (b\bar{b})_{\text{displaced}}$

Production, decay, signature

- Production:

$$\Gamma(h_1 \to h_2 h_2) \simeq \frac{1}{32\pi m_{h_1}}(\lambda_3 v)^2 \left(1 - \frac{4m_{h_2}^2}{m_{h_1}^2}\right)^{1/2} \simeq$$

$$\frac{\sin^2\alpha(m_{h_1}^2 - m_{h_2}^2)^2}{32\pi m_{h_1} x^2}\left(1 - \frac{4m_{h_2}^2}{m_{h_1}^2}\right)^{1/2}$$

- Decay: $\Gamma(h_2 \to f\bar{f}) = \frac{N_C(Y_f \sin\alpha)^2}{8\pi} m_{h_2} \left(1 - \frac{4m_f^2}{m_{h_2}^2}\right)^{3/2}$

- Total width: $\Gamma_{\rm tot} = \sum_f \Gamma(h_2 \to f\bar{f})$

- Decay length: $c\tau = \frac{c}{\Gamma_{\rm tot}} \approx 1.2 \times 10^{-5} \left(\frac{10^{-7}}{\sin^2\alpha}\right)\left(\frac{10\ \rm GeV}{m_{h_2}}\right) \quad \rm m$

- Numerically using HDECAY for $\Gamma_{\rm tot}$ and $\Gamma_{b\bar{b}}$

Simulation detail

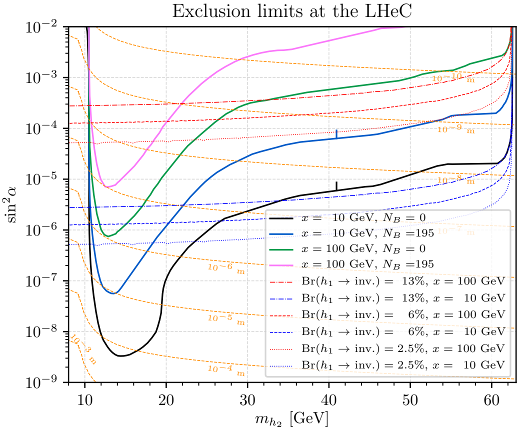
- Parton level: MadGraph 5 3.0.2 with Hidden Abelian Higgs Model:
  - 10 GeV $< m_{h_2} < m_{h1}/2$, 10^{-12} m $< c\tau <$ 100 m
  - $p_T^{b,j} > 5$ GeV, $\eta^{b/j} < 5.5$, $\Delta R(b, b/j) > 0.2$
- Showering & hadronization: Pythia 6 patched for *ep* collider studies
- Detector simulation: Delphes 3.3.2 customized with a displaced-jets module [Nemevšek, Nesti, Popara 2018]:
  - the transverse displacement of a jet $d_T(j) = \sqrt{d_x^2(j) + d_y^2(j)}$ is defined to be the minimum d_T of all the tracks associated to the jet which are required to have a transverse momentum larger than a certain threshold:
    $\Delta\mathrm{R}(\mathrm{track}, j) < 0.4$, $p_T(\mathrm{track}) > 1$ GeV
- Background processes: $p + e^- \to \nu_e + j + n_b\, b + n_\tau\, \tau + n_j\, j$ for $n_b + n_j + n_\tau \leq 4$
- In principle, the prompt jet background ($n_j > 0$) leads to no displaced objects, but a huge cross section times a tiny selection efficiency still generate a handful of events

Event selection

1. Number of reconstructed jets: $n_J \geq 5$
2. $n_{\text{disp.}J} > 0$ with disp. reconstructed jets defined to be $d_T(J) > 50\ \mu$m
3. Disp. jets J_i and J_j belong to the same group if $|d_T(J_i) - d_T(J_j)| < 50\ \mu$m, require at least 1 "heavy group": $n_{\text{hG}} \geq 1$ with $m_{hG} > 6$ GeV
4. Invariant mass of all heavy groups combined $m_{SS} \in [100, 150]$ GeV
5. Require $n_{\text{hG}} = 2$

$$N_S = N_{h_1} \cdot \text{Br}(h_1 \to h_2 h_2) \cdot \left(\text{Br}(h_2 \to b\bar{b})\right)^2 \cdot \epsilon^{\text{pr-cut-XS}} \cdot \epsilon_S^{\text{cut}},\ N_{h_1} = 1.1 \times 10^5$$

$$N_B = \sum_{i=1}^{12} \mathcal{L}_{\text{LHeC}} \cdot \sigma_{B_i} \cdot \epsilon_{B_i}^{\text{cut}} \ \ (12 \text{ bgd processes}),\ N_B = 195$$



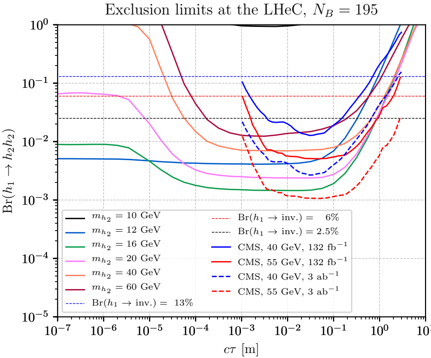
Higgs-portal model results:

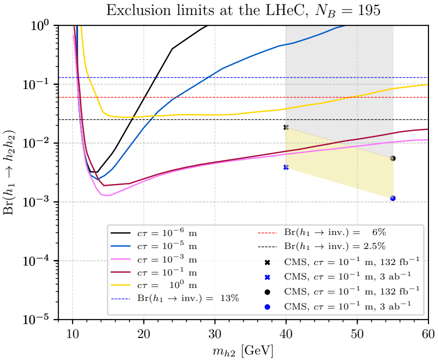
α: mixing angle

m_{h_2}: mass

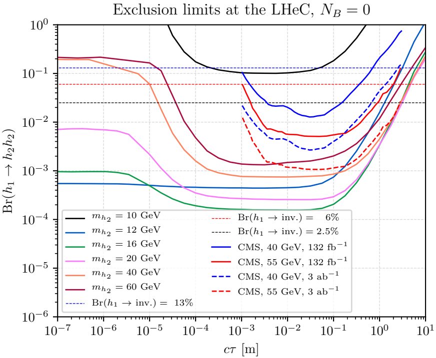
x: light scalar VEV

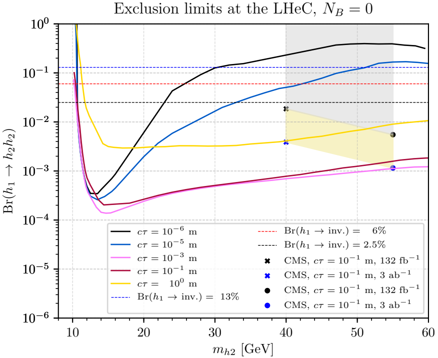
$$\left.\begin{array}{l} N_B = 195 \rightarrow N_S = 2\sqrt{B} = 28 \\ N_B = 0 \quad\ \rightarrow N_S = 3 \end{array}\right\} = 95\% \text{ exclusion limit}$$





Model-independent results for $N_B = 195$





Model-independent results for $N_B = 0$

Summary of results

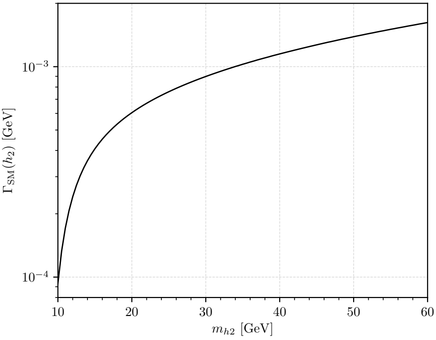
- With bgd taken into account, LHeC can probe $\mathrm{Br}(h_1 \to h_2 h_2)$ down to $\mathcal{O}(1‰)$, much better than the current LHC (HL-LHC) limits: $\mathrm{Br}(h_1 \to \text{invisible}) \simeq 13\%$ (2.5%)
- The most sensitive regime: 10^{-4} m $< c\tau < 10^{-1}$ m and 12 GeV $< m_{h_2} <$ 20 GeV
- For $c\tau < 1$ μm the h_2 decay is practically prompt. The reconstructed displacement of the final state cannot be disentangled from displaced decays of B mesons. Thus, efficiencies are much lower than those of long lifetime
- For those with $c\tau > 0.1$ m, the decay of h_2 would be outside the IT
- In the ideal case $N_B = 0$, the sensitivity can reach $\mathrm{Br}(h_1 \to h_2 h_2) \sim 10^{-4}$

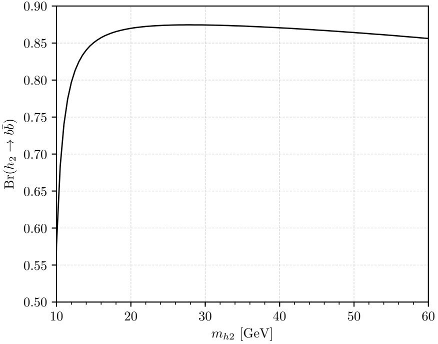
Conclusions and outlook

- The copious production of the SM Higgs at the LHeC with its clean environment allows for searching for long-lived light scalars pair-produced from h_1
- The LHeC can reach $\text{Br}(h_1 \to h_2 h_2)$ down to $\mathcal{O}(10^{-4} - 10^{-3})$
- We performed a detector-level analysis making use of fast detector simulation instead of truth-level geometric cuts, which can be extended for more LLP scenarios

Thank You!

Backup: total width of a SM-like h_2 and its BR into $b\bar{b}$





Numeric results obtained by `HDECAY`