Exclusive Displaced Hadronic Signatures in the LHC Forward Region

Searching for LLPs at the LHC: 6th workshop
Ghent (Nov 27th 2019)

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Talk fully based on arXiv:1910.05225
Exotic Higgs decays are a well studied way to produce BSM scalars ($h \rightarrow SS$)

These scalars can be weakly coupled (so long-lived) and with an arbitrary mass, hence potentially much lower than the electroweak scale

Depending on the specific scenario and flavor structure of the $S$ couplings, $S$ could decay predominantly to hadrons

How to study this case? Usual approach, **displaced jets**. However, with jets, even with jet substructure, hard to go in mass below $\sim 10$ GeV or so. Alternative, **invisible Higgs decays** (from fitting SM Higgs properties including an unknown decay fraction)

Yet other alternative, HCAL decays (e.g. ATLAS), sensitive to masses above $\sim 5$ GeV.
 Proposal: exclusive track reconstruction at LHCb

- The RICH detector can determine the identity of charged hadrons, separating for instance, kaons from pions.
- Moreover, triggering on light displaced vertices decaying to kaons is feasible at LHCb (more later)
- Other important aspects, good invariant mass and IP resolution, vertexing
- This together allows overcoming other disadvantages (worse acceptance, less integrated luminosity)
LHCb would have great sensitivity to decays of the type \( h \rightarrow S(KK)S(KK) \).

- Almost no competition from other experiments if \( m_S \sim \text{GeV} \).
- Is a dominant \( S \rightarrow KK \) decay possible?
- For \( 1 \text{ GeV} \leq m_S \leq 2 \text{ GeV} \), \( S \) dominantly decays into KK if the \( S \) coupling to quarks follows the flavor structure of Yukawa coupling!
- Build full analysis example based on this and check sensitivity
- This is an excellent example of LHCb capabilities to exclusive hadronic decays. Other hadronic decays (e.g., to protons, would work too!)
LHCb context

- LHCb currently has \(~8\) fb\(^{-1}\) of data in tape
- Run guaranteed till 2030, currently upgrading the detector
- Submitted LoI for LHCb Upgrade II, to run beyond 2030

We’re here

15 fb\(^{-1}\) accounting just for Run 3!
Run III trigger at LHCb

Run II

LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures

- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu$
- 150 kHz $e/\gamma$

Software High Level Trigger

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

Run III

LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

- Full event reconstruction, inclusive and exclusive kinematic/geometric selections
- Buffer events to disk, perform online detector calibration and alignment
- Add offline precision particle identification and track quality information to selections
- Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage
Run III trigger at LHCb

Run II

Run III

The new paradigm is particularly useful for displaced soft hadrons
- $p_T$ cuts can be relaxed, since measurement of displacement possible at every event (not the case at hardware trigger)
- Trigger upgrade mainly conceived for hadron physics (muon final states will improve less)

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage
Main background for this search QCD bb and material interactions (others checked to be subdominant). Handles against both:

- Actual analysis can benefit from existing LHCb material mapping (veto secondary vertices)
- Additional boost from Higgs production, allows large displacement even for moderate lifetimes. As a precaution, avoid detector region where most material interactions happen. Neglect material interactions in our analysis
- Kaons must form a good displaced vertex, the S candidate must point back to the PV
- Isolation of kaons (no other tracks with some displacement near by)
- Reconstruct one or both S candidates
- Veto well known resonances (e.g. $\phi \rightarrow KK$)
Different signal regions defined, providing different degree of sensitivity
Efficiency significantly better when reconstructing single S (2S suffers from acceptance)

\[\sigma_S \times \epsilon \quad m_S = 1.2 \text{ GeV} \]

\[c\tau_S = 9 \times 10^{-4} \text{ m} \]

\[1S \& 6 < SV < 10 \text{ mm} \]
\[1S \& 14 < SV < 25 \text{ mm} \]
\[2S \& 6 < SV < 10 \text{ mm} \]
\[2S \& 14 < SV < 25 \text{ mm} \]

* \(\sigma\) assumes \(\text{BR}(H \rightarrow SS) = 19\% \) and \(\text{BR}(S \rightarrow KK) = 100\%\), where 19\% is the current exclusion on Higgs \(\rightarrow\) invisible by ATLAS/CMS
Model independent limits on $\text{BR}(H \to SS)$, assuming $\text{BR}(S \to KK) = 100\%$

* LHCb limits @ 15 fb$^{-1}$
Model independent limits on BR(H→SS), assuming BR(S→KK) = 100%

* Expected exclusion on Higgs → invisible by ATLAS/ CMS @ 300 fb⁻¹ is 2.5%

Minimum Higgs $B$ excluded at 95% CL

- 0.02%
- 0.10%
- 0.50%
- 2.50%
- 7.50%
- 19.00%
Prospects at LHCb for other searches for LLPs in Higgs Exotic decays

- Model: mSUGRA neutralino decaying to a lepton and two quarks
- Model: Hidden valley V-pions decaying to jets

LHCb simulation $\int \mathcal{L} \, dt = 300 \text{ fb}^{-1}$
Hadrophilic interpretation

- Hadrophilic Higgs portal scenario, with minimal flavor violation and suppressed leptonic couplings to $S$
  - For $\text{BR}(S\rightarrow KK)$ and $\tau_S$ we take as reference Phys. Rev. D 99, 015018 (2019)
  - Given a mixing angle $\theta$ between $S$ and the Higgs boson

![Graphs showing $m_S$ and $\theta$ for different $\mathcal{B}$ values]
Similar Higgs portal scenario as before, but now $\text{BR}(S\to\mu\mu)\sim8\%$

- In this case, important constraints from LHCb in $B$ meson decays, e.g., $B^+\to K^+ S(\mu\mu)$, or neutral decay $B^0\to K^* S(\mu\mu)$
- Limit in $B$ decays dominates, but $S\to KK$ search important for on-shell Higgs searches or if $\mu$ coupling reduced

Minimum Higgs $B$ excluded at 95% CL

- 0.05%
- 0.10%
- 0.50%
- 2.50%
- 7.50%
- 19.00%
Conclusions

- Exclusive searches for LLPs decaying to hadrons can cover unique chunks of parameter space at LHCb
  - New hadronic triggers at LHCb in Run 3 provide new opportunities!

- Kaons offer an excellent example, but we recommend searching for as many hadronic final states as possible (e.g. π or p)

- Potential extension, similar searches in $B$ hadron decays, cover smaller lifetimes
STEALTH physics at LHCb

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Hybrid photon detectors (HPDs)
When reinterpreting the existing displaced muon searches at ATLAS and CMS [13, 45] from Higgs decaying into two dark photons \(2\gamma_d\) to the \(h \rightarrow SS\) process, we get a bound \(\text{BR}(h \rightarrow SS) \lesssim 10\%\) (95\% C.L.) for the \((m_S, \theta)\) of our interest. The bound excludes a small part of the sensitivity region in our 15 fb\(^{-1}\) projection. We set \(\text{BR}(\gamma_d \rightarrow \mu\mu) = 30\%\) [59] when rescaling the bound and requiring both \(S\)'s to decay into muons in the ATLAS/CMS searches. ATLAS/CMS will have 300 fb\(^{-1}\) integrated luminosity when LHCb collects 15 fb\(^{-1}\) of data. Take the CMS study [45] as an example. When rescaling the 10 background in their 36 fb\(^{-1}\) search according to the luminosity, a similar CMS search can exclude \(\text{BR}(h \rightarrow SS) \gtrsim 4\%\) in the Higgs mixing model. At that time, the LHCb \(S \rightarrow K^+K^-\) search will set a comparable (or even better) bound to the Higgs decay in this scenario.