Searches for Exotic Higgs-like boson decays at LHCb

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• Naturalness does not seem to be a **guiding principle** of Nature

• There are some **anomalies in flavour physics** which (if true) seem again to point out that our theory prejudice was wrong

• We should therefore not forget that **we have a 2D problem** (Mass VS Coupling)

• Low coupling $\rightarrow$ Long Lived

• Thanks to X. Cid, C. Vazquez, and L. Sestini

**Energy scale**

**Explored**

**Unexplored**

**Intensity frontier:**

Flavour physics, lepton flavour violation, electric dipole moment, **dark sector**
Landscape today / 1

- The Intensity frontier is a **broad and diverse**, yet **connected**, set of science opportunities: heavy quarks, charged leptons, hidden sectors, neutrinos, nucleons and atoms, proton decay, etc...
- In this talk, I will concentrate on **dark sector** and **exotic Higgs-like boson**.
- **Landscape**: LHC results in brief:
  - Direct searches for **NP** by **ATLAS** and **CMS** have not been successful so far
  - Parameter space for popular **BSM** models is **decreasing rapidly**, but only < 5% of the complete HL-LHC data set has been delivered so far
  - NP discovery **still may happen**!
  - **LHCb** reported intriguing hints for the violation of lepton flavour universality
    - In $b \rightarrow c \mu \nu$ / $b \rightarrow c \tau \nu$, and in $b \rightarrow se+e- / b \rightarrow s\mu+\mu-$ decays (see Julián’s 5 Jun 2019, 15:30 and Cedric’s 5 Jun 2019, 17:16 talks)
    - Possible evidence of **BSM** physics **if substantiated** with further studies (e.g. **BELLE II**)
In the dark sector: $L = L_{SM} + L_{mediator} + L_{HS}$
- Hidden Sector decay rates into SM final states is suppressed
- Branching ratios of $O(10^{-10})$
- Long-lived objects
- Interact very weakly with matter

Experimental challenge is **background suppression**

**Full reconstruction**, low pT triggering, and PID are essential to minimise model dependence

- **Two** strategies of searching for mediators at accelerators:
  - **Not decaying in the detector**
    - Missing energy technique
    - Scattering technique: electron or nuclei scattered by DM...
  - **Decaying in the detector**
    - Reconstruction of decay vertex
LHCb detector / 1

- **LHCb** is a dedicated flavour experiment in the **forward region** at the LHC \( (1.9 < \eta < 4.9) \) \((-1^\circ-15^\circ)\).

- **Precise vertex reconstruction** < 10 \( \mu m \) vertex resolution in transverse plane.

- Lifetime resolution of \(~ 0.2 \) ps for \( \tau = 100 \) ps.

- **Muons** clearly identified and triggered: \(~ 90\% \mu^\pm\) efficiency.

- Great **mass resolution**: e.g. 40 MeV for J/psi.

- **Low p_T trigger** means low masses accessible. Ex: \( p_T^{\mu} > 1.5 \) GeV.
Getting close to 4

Olli Lupton (CERN)

LHCb precision EW physics

October 2017

13 / 19

LHCb detector / 1 bis

- Only muons, only \( p_T \)
- Aim to go straight to the full Run 1 + 2 dataset
- \( \Delta \) simultaneously analyse
- \( 7, 8, 13 \) TeV
- LHCb's luminosity levelling means these data are rather homogeneous. The largest dataset (13 TeV) has the lowest pile-up
- Limited "LHCb visible" recoil information?
LHCb detector / 2

- Lower luminosity (and low pile-up)
  - ~1/8 of ATLAS/CMS in Run 1
  - ~1/20 of ATLAS/CMS in Run 2
- Hardware L0 trigger to be removed
- Full real-time reconstruction for all particles available to select events (since 2015)
  - Real-time reconstruction for all charged particles with $p_T > 0.5$ GeV
  - We go from 1 TB/s (post zero suppression) to 0.7 GB/s (mix of full + partial events)
- LHCb will move to a trigger-less readout system for LHC Run 3 (2021-2023), and process 5 TB/s in real time on the CPU farm
LHCb detector / 3

- Precise knowledge of the location of the material in the LHCb VELO is essential to reduce the background in searches for long-lived exotic particles.
- LHCb data calibration process can align active sensor elements, an alternative approach is required to fully map the VELO material.
- **Real-time calibration** in Run 2.
- Hardware trigger is still there, and only ~10% efficient at low pT.
Jet physics at LHCb

- Efficiency above 90% for jets with $p_T$ above 20 GeV/c
- Jets reconstructed both online and offline!
- **b and c jet tagging**
- Require jets with a secondary vertex reconstructed close enough
- **Light jet** mistag rate < 1%, $\varepsilon_b \sim 65\%$, $\varepsilon_c \sim 25\%$
- SV properties (displacement, kinematics, multiplicity, etc) and jet properties combined in two BDTs
  - $BDT_{bc|udsg}$ optimised for heavy flavour versus light discrimination
  - $BDT_{b|c}$ optimised for b versus c discrimination
Higgs$\rightarrow$LLP$\rightarrow$µ+jets / 1

- Massive LLP decaying $\rightarrow$ µ+qq ($\rightarrow$ jets)
- **Single displaced vertex** with several tracks and a high $p_T$ muon; based on Run-1 dataset
- Production of LLP could come e.g. from Higgs like particle decaying into pair of LLPs
- $m_{LLP}=[20; 80]$ GeV and $\tau_{LLP}=[5; 100]$ ps
- Background dominated by $bb$
- No excess found: result interpreted in various models
Higgs $\rightarrow$ LLP $\rightarrow$ $\mu$+jets / 2
Higgs → LLP → μ+jets / 3

Bf(Higgs → LLP+LLP) < 2 %

Bf(Higgs → LLP+LLP) < 0.5 %
Higgs→LLP→jet pairs / 1

• Massive LLP decaying →bb+bb with bb → jets
• **Single displaced vertex** with two associated tracks; based on Run-1 dataset
• Production of LLP could come e.g. from Higgs like particle decaying into pair of LLPs (e.g. πV)
• \( m_{\pi V} = [25; 50] \text{ GeV} \) and \( \tau_{\pi V} = [2; 500] \text{ ps} \)
• Background dominated by QCD
• No excess found: result interpreted in various models

\[ H^0 \rightarrow \pi V \rightarrow bb \]

Regions where \( B(H^0 \rightarrow \pi V \pi V) > 50\% \) is excluded at 95% CL

- ATLAS 20.3 fb\(^{-1}\) at 8 TeV
- LHCb 2.0 fb\(^{-1}\) at 7-8 TeV
- CMS 18.5 fb\(^{-1}\) at 8 TeV
Higgs $\rightarrow$ LLP $\rightarrow$ jets pairs / 2

Minimum $\mathcal{B}$ excluded at 95% CL

- 75%
- 50%
- 30%
- 20%
- 5%
- 2%
- 1%

LHCb results
$\int \mathcal{L} \, dt = 2 \text{ fb}^{-1}$

LHCb simulation
$\int \mathcal{L} \, dt = 23 \text{ fb}^{-1}$

LHCb simulation
$\int \mathcal{L} \, dt = 50 \text{ fb}^{-1}$

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

ATLAS and CMS dominated
Higgs$\rightarrow$LLP$\rightarrow$jets pairs / 3

$\textbf{Bf}(\text{Higgs} \rightarrow \pi \nu + \pi \nu) < 20 \%$

$\textbf{Bf}(\text{Higgs} \rightarrow \pi \nu + \pi \nu) < 2 \%$
$H \rightarrow \mu \tau$ decays / 1

- Higgs-like boson decaying $\rightarrow \mu \tau$
- Analysis is separated into **four channels**
- $m_H = [45; 195] \text{ GeV}$ and **minimal flight distance** (impact parameter) of the reconstructed candidate is imposed
- Three different selections based on $m_H \text{ w.r.t. } m_Z$
- Background dominated by QCD, $Z \rightarrow \tau \tau$, Vj
- No excess found

![Diagram of Higgs decay](image)
Searching in the Y mass region / 1

- Other light spin-0 particles in which LHCb can do well are light bosons from pp; **only Run 1**
- Spin-0 boson, $\phi$, using Run 1 prompt $\phi \rightarrow \mu^+\mu^-$ decays, have been searched for
- Use **dimuon** final states:
  - Access to different mass window w.r.t $\gamma\gamma$ or $\tau\tau$ searches in 4$\pi$ experiments
- Done in **bins of kinematics** ($[p_T, \eta]$) to maximise sensitivity
- Precise modelling of Y(nS) tails to extend search range as much as possible
- **Mass independent** efficiency (uBDT)
• Search for dimuon resonance in $m_{\mu\mu}$ from 5.5 to 15 GeV (also between $\Upsilon$(nS) peaks)
• No signal: limits on $\sigma$•BR set on (pseudo)scalars as proposed by Haisch & Kamenik [1601.05110]
• First limits in 8.7-11.5 GeV region - elsewhere competitive with CMS
• Interpreted as a search for a scalar produced through the SM Higgs decay

In summary, a search is presented for a hypothetical light dimuon resonance, produced in pp collisions recorded by the LHCb detector at centre-of-mass energies of 7 and 8 TeV. A sample of dimuon candidates with invariant mass between 5.5 and 15 GeV corresponding...
Conclusions

- LHCb has an **extensive program** of searches even beyond flavour physics
  - Searches for **on-shell** and **off-shell** new physics from heavy flavour decays
  - Searches for **long-lived** particles with low mass and short lifetime
  - Searches for **dimuon resonances** in very broad parameter space
- Bright future ahead:
  - 3 fb\(^{-1}\) in Run 1, 7 fb\(^{-1}\) in Run 2 (with larger cross-sections); LHCb Upgrade II: 300 fb\(^{-1}\)
  - A lot of potential in the upgraded trigger (also 5x luminosity)
The days of “guaranteed” discoveries or of no-lose theorems in particle physics are over, at least for the time being ....

.... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, .... )

This simply implies that, more than for the past 30 years, future HEP’s progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias
LHCb track types

**Upstream track**

**Long track**

**Downstream track**

**T track**

**VELO track**

**VELO**

**TT**

**T1**  **T2**  **T3**
Mass resolution

Figure 1: Efficiency-corrected dimuon mass distributions for (left) $\sqrt{s} = 7\,\text{TeV}$ and (right) $\sqrt{s} = 8\,\text{TeV}$ samples in the region $3 < p_T < 4\,\text{GeV}/c$, $3.0 < y < 3.5$. The thick dark yellow solid curves show the result of the fits, as described in the text. The three peaks, shown with thin magenta solid lines, correspond to the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ signals (left to right). The background component is indicated with a blue dashed line. To show the signal peaks clearly, the range of the dimuon mass shown is narrower than that used in the fit.
Searching for Dark Photons / 1

- Suppressing misidentified (non-muon) backgrounds and reducing the event size enough to record the prompt-dimuon sample
- Accomplished these by moving to real-time calibration in Run 2
- Hardware trigger is still there, and only ~10% efficient at low pT

Searching for Dark Photons / 2

- Background dominated by **material interactions** for displaced searches at LHCb
- Precise knowledge of the location of the material in the LHCb VELO is essential to reduce the background in searches for long-lived exotic particles
- LHCb data calibration process can align active sensor elements, an **alternative approach** is required to fully map the VELO material

![Image of LHCb VELO detector](Image)

![Graph showing dark photon search](Graph)
Search for Dark Photons / Results

- The 2016 dimuon results are consistent with (better than) predictions for prompt (long-lived) dark photons as discussed in [1603.08926]. We implemented huge improvements in the 2017 triggers for low masses, so plan quick turn around on 2017 dimuon search - then onto electrons.

90% CL exclusion regions on $[m(A'), \varepsilon^2]$
H→μτ decays / 1bis

from top to bottom: μτe, μτh1, μτh3, μτμ

from L to R: μτμ, μτe, μτh1, μτh3,