LHCb Higgs: bottom, charm and BSM

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on behalf of the LHCb collaboration

Higgs days at Santander 2018
Wednesday, September 12th 2018
Outline

✦ Introduction

✦ LHCb Higgs in Run 1
  ➞ SM Higgs decays
  ➞ BSM Higgs

✦ A look ahead: Prospects and LHCb upgrade(s)

✦ Discussion
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Introduction
Introduction

Collision region!
Introduction

Collision region!

- JINST3(2008)S08005

Magnet

RICH-1

VELO

TT

Tracker

RICH-2

Calorimeters

ECal

HCal

Muon System

OT

IT

M1

SPD

PS
LHCb vs ATLAS/CMS

- Obvious disadvantage: LHCb collects less data than ATLAS/CMS (factor ~10) and has a limited acceptance for several searches
- But softer triggers (for instance, can trigger detached di-muons with $p_T \sim 1$ GeV/c), also good vertexing, PID, $p$ resolution...
- In practice that means we can look into complementary phase space regions
- For theory colleagues, we need to motivate the collaboration towards other physics → big inertia to do flavour physics
Jet reconstruction at LHCb

**Particle Flow** approach, with neutral recovery

- Jets reconstructed using anti-$k_T$
- $R = 0.5$
- Calibration in data, using $Z \rightarrow \mu\mu + \text{jets}$
- Efficiency above 90% for jets with $p_T$ above 20 GeV/c
- Jets reconstructed both online and offline!

*JHEP01 (2014) 033*
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,...) and jet properties combined in two BDTs.
- $\text{BDT}_{bc|udsg}$ optimised for heavy flavour versus light discrimination.
- $\text{BDT}_{b|c}$ optimised for $b$ versus $c$ discrimination.
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Motivations to study the (SM) Higgs at LHCb

✧ Only experiment currently existing beyond ATLAS and CMS that could observe the SM Higgs (so yet another cross check)
  ➡ Additional interest from the different geometrical region

✧ H→cc: only third-generation decays observed so far
  ➡ LHCb vertex detector good to distinguish c from b jets
  ➡ Still factor of 30 suppression with respect to H→bb

✧ Main sensitivity will come in the future (prospects later) but studies with data already happening!
Studying Higgs backgrounds

- Measurement using 2012 dataset
  - Events with high $p_T$ isolated lepton (electron or muon) and two heavy flavour tagged jets (> 12.5 GeV/c)

- Strategy → Simultaneous 4D fit to $\mu^+, \mu^-, e^+, e^-$ samples. Variables:
  - Di-jet mass
  - BDT(b|c) for both jets
  - MVA (uGB) to separate $W+bb$ from $tt$: Use topology and kinematic variables and sub-combination masses

- In the fit:
  - $W+bb, W+cc$ and $tt$ floated. Background fixed to theory
  - Nuisance parameters included in fit
Studying Higgs backgrounds

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- In the fit:
  - $W^{+}bb,W^{+}cc$ and $tt$ floated. Background fixed to theory
  - Nuisance parameters included in fit
Higgs searched for in association to W or Z at 8 TeV

- Same samples as W+bb, tighter $p_T$ cuts on jets (20 GeV/c)
- Fix backgrounds to theory predictions
- Independent uGBs to separate WH or ZH from tt and W+bb/cc, respectively
Higgs searched for in association to W or Z at 8 TeV

- Use CL$_s$ method to extract limits
- For $H \rightarrow bb$, best limit at LHCb on a Higgs search.
- For $H \rightarrow cc$, exploratory study (first direct limit ever from experiment). Same strategy as for $bb$ + **use of BDT$(b|c)$ to separate from $H \rightarrow bb$**.
- Limits on Yukawa couplings
  
  \[
  \gamma_b < 7 \times \gamma_b^{(SM)} \\
  \gamma_c < 80 \times \gamma_c^{(SM)}
  \]
First observation of forward $Z \rightarrow bb$

- Measurement of the cross section, benchmark for the inclusive $H \rightarrow bb$ search
- Key point: balancing jet (jet3) that makes $p_T (Z+jet3)$ minimum to separate $Z \rightarrow bb$ from QCD
- Discrimination achieved using again uGB
- Good agreement with aMC@NLO prediction

$$\sigma \times \mathcal{B} = 332 \pm 46(stat) \pm 59(sys)$$
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Search performed with Run 1 LHCb dataset, motivated by previously existing excess in $H \to \mu\tau$
- Extended to large mass range (45-195 GeV/c^2)

τ reconstructed in both leptonic and hadronic decay channels: 4 channels considered
- $\mu T_\mu$, $\mu T_e$, $\mu T h_3$, $\mu T h_1$
- Different selections depending on the mass of the H searched for (e.g. different $p_T$ cuts). Isolation applied on leptons

Main backgrounds are $Z \to ll$, QCD and $V + \text{jet}$. First estimated from theory, second from same-sign data
Results

- Fit data to obtain $N_{\text{sig}}$ and determine efficiencies from simulation, corrected with data
- Main systematics, efficiency determination and PDFs
- No signal found, so set upper limits set with the CL$_S$ method. For each mass, use selection providing better expected upper limit
- Combine different channels into single measurement
- For the SM Higgs, $\text{BR}(H \rightarrow \tau \mu) < 26\%$
  0.25% and 1.85% for CMS and ATLAS

- Worse than ATLAS/CMS for high masses, but first search in low masses! Could be extended to even lower masses
Weakly coupled Dark Sectors help to address SM problems

Dark sector portals:
- Higgs portal (H)
- Vector portal (A’)
- Neutrino portal (N)
- Axion portal (a)

Very different properties (mass & lifetime) of the dark sector particles allowed
- Main challenge is triggering
- This is where the role of LHCb can be more important
**Signature:** single displaced vertex with several tracks and a high $p_T$ muon. Use Run-1 dataset

- Model: mSUGRA neutralino decaying to a lepton and two quarks
- LLP $m=[20-80]$ GeV/$c^2$, $\tau=[5-100]$ ps
- Background dominated by $bb$
  - tight selection + MVA classifier
  - Number of candidates from fit to LLP mass
Result: no excess found: result interpreted in various models

- In particular, SM Higgs decay

Rejecting BR(H→χχ)>10% down to m_X = 40 GeV/c^2, cτ_X = 1.5 mm

Eur. Phys. J. C 77 224
**Signature**: single displaced vertex with two (b-) jets

**Model**: Hidden valley V-pions from SM Higgs decay

**Use Run 1 dataset, trigger on displaced vertex.**

**Selection**:
- Find two associated jets, quality requirement on jets, di-jet pointing
- Material veto + selection optimised as a function of $R_{xy}$

**Main remaining background**: QCD

**Signal** from di-jet mass fit in 6 bins of $R_{xy}$

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![Figure](image.png)

**EUR. PHYS. J. C77 (2017) 812**

- $0.4 < R_{xy} < 1.0 \text{ mm}$
- $\sqrt{s} = 7 \text{ TeV}$

- $5.0 \text{ mm} < R_{xy}$
- $\sqrt{s} = 7 \text{ TeV}$
Again, no excess found

Tested the region: \(m_n = [25-50] \text{ GeV}, \tau = [2-500] \text{ ps}\)

Compatible search in Eur. Phys. J. C (2016) 76664 (look for both LLPs in the same event)
- Model independent search with LHCb Run 1 dataset
- Inclusive **scalar boson search** with $m \sim 10$ GeV/c$^2$ difficult with $\gamma\gamma$ or $\tau\tau$ searches
  - For $\mu\mu$ invariant mass resolution is the key ($\Upsilon$ resonances present)
  - For this, it is crucial to keep the selection efficiency mass-independent [uBoost: JINST 8 (2013) P12013] and to model precisely [NIM A, 764, 150 (2014)] the $\Upsilon(nS)$ tails to extend the mass range search

- Use of different kinematic bins to maximize the efficiency!
No excess: results can be interpreted in different models

- World best very near to $\Upsilon$ (8.7-11.5 GeV/c$^2$), competitive with CMS elsewhere

Upper limits on the direct production of a spin-0 boson decaying to $\mu\mu$ [following PRD93 (2016) 055047]

Also interpreted as a search for a scalar produced through the SM Higgs decay!
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Some planning

- LHCb Higgs related analysis so far, data taken <2013 (3 fb⁻¹)
- We’ll have O(6 fb⁻¹) more in tape at the end of this year!
- Submitted LoI for LHCb Upgrade II, to run beyond 2030
The additional boost given by the increase of energy favors the LHCb acceptance.

Accounting for larger acceptance and larger cross section, \( \sigma(gg \rightarrow H \rightarrow bb)_{13\text{TeV}} / \sigma(gg \rightarrow H \rightarrow bb)_{8\text{TeV}} \approx 4 \). Similar or better for VH.

\[ \varepsilon_{\text{geo}} \approx 1.5\% \]

\[ \varepsilon_{\text{geo}} \approx 3\% \]

\( gg \rightarrow H \rightarrow bb \) with Pythia at different energies.
Prospects

✧ We are currently trying to establish LHCb’s physics case for Upgrade II.

➡ Since our interest in Higgs is ~recent, that means we actually have more prospects for Upgrade 2 than for Upgrade 1!

➡ For BSM Higgs, more analysis will follow with Run 2 and Run 3 data. Inclusive $H \to bb$ possible too.

➡ The next VH(bb/cc) analysis most likely won’t happen till (at least) Run 3

arxiv:1808.08865
Simple luminosity scaling would give us $y_c \approx 7 \times y_c^{(SM)}$

But improvements in the c jet tagging possible! (we’ll need to deal with pile-up)

- The improved VELO performance in LHCb Upgrade I will already help. If the di-c-jet tagging strategy is altered to have (at least) one tagged c-jet → di-c-jet tagging efficiency dramatically increased to ~30% (from current ~2%), with minimal impact on the background composition. Using this jet-tagging strategy improves the predicted sensitivity to ~ 4 x $y_c^{(SM)}$

- If the LHCb electron reconstruction performance is improved in the upgrade such to be close to muons, the expected sensitivity is ~ 3 x $y_c^{(SM)}$.

- Finally, if separation between b and c jets can be further improved, such that only backgrounds consisting of c-jets are important, ultimate sensitivity $\sim 2 \times y_c^{(SM)}$. This could be achieved, e.g. by using deep-learning algorithms.
Run I search presented above
- Scale to the upgrade(s) luminosities, conservative assumptions
- Reconstruction of displaced vertices and their associated tracks is crucial, also keep under control the dominant background contributions and pile-up effects.
- Material interactions kept under control by the use of a very detailed veto map. Removal of VELO RF foil would further enhance the sensitivity!

**H → LLP projected exclusions**

- Hopefully we’ll cover the low mass region too: Jet substructure! Nothing more quantitative for the moment
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Take home messages

✦ LHCb: general purpose detector in the forward region! Run I results presented
  ➪ We have potential in SM Higgs physics
  ➪ Already producing BSM Higgs interesting results. Complementarity to ATLAS and CMS

✦ Much more to come in Run II and beyond
  ➪ Will have \(~9\) fb\(^{-1}\) in a couple of months (3 fb\(^{-1}\) in Run I)
  ➪ Increased cross sections and better acceptance for most of the Higgs physics presented at 13 TeV
  ➪ After LS2: **LHCb upgrade**. 50 fb\(^{-1}\) of data expected with purely software trigger! 300 fb\(^{-1}\) possible?
Other ideas for discussion (I)

- More Higgs at LHCb?
  - Higgs BSM production, favoring the forward region
  - Strange tagging, to look for $H \rightarrow ss$
  - Low $p_T$ Higgs through $H \rightarrow VV$

P. Ilten

- assume electron efficiency similar to muon
- $H[Z[\ell\ell]Z[\ell\ell]]$ with $p_T > 1$ GeV, $2.0 < \eta < 5.0$, and $115 < m < 135$ GeV
  - $\approx 1 \times 10^{-1}$ fb (signal)
  - $\approx 3 \times 10^{-1}$ fb (background from $ZZ$)
- $H[W[\mu\nu]W[\nu\nu]]$ with $p_T > 1$ gev and $2.0 < \eta < 5.0$
  - $\approx 10$ fb (signal)
  - $\approx 160$ fb (background from $WW$)
Other ideas for discussion (II)

✦ More Higgs at LHCb?

$\rightarrow H \rightarrow \tau\tau$

- used $\mu\mu$, $\mu e$, $\mu h$, and $e h$ final states
- 7 TeV expectation
  - $\approx 3 \times 10^{-1}$ fb (signal)
  - $\approx 1000$ fb (background)
- 14 TeV expectation
  - $\approx 3$ fb (signal)
  - $\approx 1600$ fb (background)
  - assume background scales proportionally to $Z$ cross-section

- what about $3\pi$ final state with secondary vertex?
  - $\approx 1$ fb without efficiencies
  - backgrounds (charm)?
Thank you!
Backup
LHCb datasets

- Main pp datasets (LHC Run I and Run II)
  - 1 fb$^{-1}$ at $\sqrt{s}=7$ TeV (2011)
  - 2 fb$^{-1}$ at $\sqrt{s}=8$ TeV (2012)
  - 0.3 fb$^{-1}$ at $\sqrt{s}=13$ TeV (2015)
  - 1.7 fb$^{-1}$ at $\sqrt{s}=13$ TeV (2016)
  - 1.8 fb$^{-1}$ at $\sqrt{s}=13$ TeV (2017)
Integrated luminosity determination

- Most precise at the LHC in Run 1! (~1%)

- Bunch intensity ($N_1N_2$) measured by LHC instrumentation (uncertainties: ~0.3%).

- Overlap integral depends on beams properties (e.g. beam width, position, angle, shape)

- Determined with 2 independent methods:
  - Classic “van der Meer scan” (VDM) used by all 4 LHC experiments
  - Beam-gas imaging (BGI): new method exclusive to LHCb

$L = f \cdot N_1N_2 \cdot \text{Overlap}$

2014 JINST 9 P12005
Results: cross sections and theoretical predictions in LHCb fiducial region

- NLO theory prediction: MCFM with PDF set CT10 interleaved with Pythia8
- Uncertainties dominated by statistics!

LHCb, $\sqrt{s} = 8$ TeV

<table>
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<th>Sample</th>
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<td>$tt$</td>
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<td>$W^+ + b\bar{b}$</td>
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<td>$W^- + c\bar{c}$</td>
<td>2.5$\sigma$</td>
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Strategy → Simultaneous 4D fit to $\mu^+, \mu^-, e^+, e^-$ samples. Variables:

- Di-jet mass
- BDT$_{b|c}$ for both jets
- MVA to separate W+bb from tt: Use topology and kinematic variables and sub-combination masses

- In order to reduce correlation with mass, use uniform Gradient Boosting BDT ($u$GB)

**JINST 10 (2015) T03002**

- Simplifies fit, considering 4 dimensions uncorrelated
Sensitivity to long lived particles (LLPs)

- reconstructable decay-lengths are:
  - within VELO: ideally \(\sim 50\) cm (standard more like \(\sim 20\) cm)
  - up to TT: \(\sim 200\) cm
  - minimum detachment sensitivity \(\sim\) around \(\tau\) lifetime

Figure 27: Distribution of the invariant mass of \(K_S^0\) candidates with a decay vertex at a significant distance to the PV, for long tracks (left) and downstream tracks (right). A mass resolution of 3.5 MeV/c\(^2\) is achieved for the candidates reconstructed from long tracks and 7 MeV/c\(^2\) for those using downstream tracks.
Recasting result

✧ This result has just been recast to look for sterile neutrinos!

- arxiv just came out this morning!
- 95% confidence level exclusion plot
- world best limit for masses in the 5-10 GeV/c^2 range. Excellent prospects!
Di-muon with current trigger

Plot from 2016 data

LHCb preliminary

Prompt Trigger Output
- $p_T(\mu) > 1$ GeV
- $\chi^2_{IP}(\mu) < 6$
- $\chi^2_{V}(\mu\mu) < 9$
- $\mu$-ID neural network $> 0.95$

Prompt trigger output, no offline reconstruction!
Prospects for dark photon search

Inclusive $A' \rightarrow \mu\mu$

$\sigma_{\omega}$

$m_{A'}$ [GeV]

$\pi^0$, $\eta$

Current limits

300 fb$^{-1}$ $D^*$

50 fb$^{-1}$ $\mu\mu$

50 fb$^{-1}$ $D^*$

300 fb$^{-1}$ $\mu\mu$

Inclusive $A' \rightarrow \mu\mu$

arxiv:1603.08926

Radiative Charm Decays

arxiv:1509.06765
The LHC(b) schedule

Approved LHCb upgrade!
- Major upgrade of subdetectors (ongoing)
- Run till ~2030 guaranteed
- Expect to collect $\sim 50 \text{ fb}^{-1}$
- (23 fb$^{-1}$ at the end of Run 3)
**The LHC(b) schedule**

- **Nivel de texto 1**

LHC roadmap: according to MTP 2016-2020 V1

- LS2 starting in 2019 => 24 months + 3 months BC
- LS3 LHC: starting in 2024 => 30 months + 3 months BC
- Injectors: in 2025 => 13 months + 3 months BC

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**PHASE 1**

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**PHASE 2**

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Change in trigger paradigm

- Readout the detector at 30 MHz!
- Full software trigger
LHCb VELO material

- Mapped through secondary interactions of hadrons produced in beam-gas collisions
  - Material interactions occur along the entire length of the VELO in beam-gas events, rather than just near the pp-interaction region
  - Include RF Foil and VELO stations
  - Provide interaction probability

arxiv:1803.07466
Why one single tight tag?

Given that $\sigma(Wcc)$ and $\sigma(Wcj)$ are of the same order of magnitude when the di-jet mass is Higgs-like, the use of a much looser $c$-tag on one jet will not have a large impact on the total background yield. Furthermore, since $\sigma(Wbc)$ is small compared to $\sigma(Wcc)$ and $\sigma(Wbb)$, it is only necessary to discriminate $b$ from $c$ for one jet.
New sub-detector just proposed for the HL-LHC

- During LHCb upgrade, we will remove a lot of trigger CPUs from the LHCb cavern
- Use the space available to search for LLPs, by building a new detector
- Very preliminary studies done for now... ... but could outperform similar proposals next to ATLAS/CMS for a much reduced budget