





Università degli Studi di Padova

SM and BSM Higgs searches at LHCb

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JINST 3 (2008) S08005 Int. J. Mod: Phys. A 30, 1530022 (2015)

LHCb detector

- LHCb was originally designed to study b- and c- hadron physics, but is now considered a **general purpose** forward detector
- Excellent track momentum resolution: from 0.4% at 5 GeV to 0.6% at 100 GeV
- Impact parameter (IP) resolution: $(15+29/p_{T}) \mu m$
- Excellent vertex resolution
- Muon ID efficiency 97% with 1-3% muon pions mis-identification
- LHCb allows to test a phase space region complementary to ATLAS and CMS





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Higgs at LHCb

- Main limits in studying Higgs at LHCb are: reduced acceptance with respect to ATLAS and CMS and lower luminosity due to leveling
- However LHCb presents strong points:
 - Excellent vertex reconstruction system (this is a plus for b- and c- tagging and displaced vertex searches)
 - \circ LHCb can complement ATLAS and CMS in searches (forward coverage and low p_{τ} threshold trigger)



Eur. Phys. J. C 82, 373 (2022)

Search for massive long-lived particles decaying semileptonically in 5.4 fb⁻¹ at $\sqrt{s}=13$ TeV

- Search for massive long-lived particles (LLP) decaying semileptonically into a muon and two quarks with Run II (L=5.4 fb⁻¹, 13 TeV)
- Signature: single displaced vertex and a high p_{τ} muon
- Two kinds of LLP production processes are considered:
 - Higgs-like bosons from gluon fusion (with mass $m_{\mu} \in [30,200] \text{ GeV/c}^2$) decaying into 2 LLPs with m^{LLP} from 10 GeV/c²
 - Direct production from quark interaction, with LLPs masses $m^{LLP} ∈ [10,90] \text{ GeV/c}^2$
- LLPs lifetimes considered range goes from 5 ps to 200 ps



- Fit to the reconstructed LLP mass \rightarrow no signal excess found
- 95 % CL upper limits are set on σ (LLPs) × \mathfrak{B} (LLPs $\rightarrow q\bar{q}\mu$) for both searches \rightarrow sensitivity of the order O(1 pb)



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Search for long-lived particles decaying to $e^{\pm} \mu^{\mp} v$

- Search for massive long-lived particles (LLP) flavoured leptonic decays with Run II (L=5.4 fb⁻¹, 13 TeV)
- Signature: displaced vertex containing electron and muon of opposite charges
- Three kinds of LLP production processes are considered:
 - Higgs-like bosons from gluon fusion (with mass $m_{\mu} = 125 \text{ GeV/c}^2$) decaying into 2 LLPs
 - Direct production from quark interaction
 - Charged current production (on-shell W decaying into lepton+ LLP)
- LLPs lifetimes considered range goes from 2 ps to 50 ps and LLPs masses $m^{LLP} \in [7,50] \text{ GeV/c}^2$



- Simultaneous fit to the reconstructed displaced vertex corrected mass and flight distance distributions \rightarrow no signal excess found
- 95 % CL upper limits are set on the three production mechanisms \rightarrow sensitivity of the order O(0.1 pb)

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Projected sensitivities for LLPs decaying semileptonically

- Projected sensitivities based on Run I results
- Upper limits on the branching fraction of the Higgs boson decay to a pair of neutralinos are calculated for different assumptions of neutralino masses and lifetimes



• most of the LHCb accessible neutralino phase space can be excluded for a branching fraction > 0.5%

→ Further improvements are expected in the Upgrades due to: **higher trigger efficiency** (hardware trigger removal), precise **mapping of the VELO material**, **jet reconstruction techniques** to disentangle low mass jets

Search for H to bb or cc in association with a W or Z boson

- Search for a Higgs boson (m_{H} =125 GeV) produced in association with a W or a Z using Run I data (L=2 fb⁻¹)
- Signature: pair of heavy tagged jets ($b\overline{b}$ or $c\overline{c}$) and one or two high p_{τ} leptons (electrons or muons)
- Heavy flavour tag: presence of a secondary vertex (SV) in jets
- BDTs used to separate b jets from c jets and heavy from light jets





JINST 10 P06013

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- No signals are observed, upper limits on σ ·BR at 95% C.L. are set:
 - $\circ \qquad \sigma(\text{ pp}{\rightarrow}\text{W/Z} + \text{H}) \times \textbf{B}(\text{ H} \rightarrow b\overline{b} \text{ }) < 1.6 \text{ pb}$
 - \circ σ(pp→W/Z + H) × 𝔅(H→ CC)< 9.4 pb

Upper limits on Yukawa couplings: y^b<7 y^b_{SM}, y^c<80 y^c_{SM}

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Search for high mass resonances decaying to heavy flavour di-jets

- Studies ongoing for inclusive decay of high mass resonances decaying to bb and cc di-jets
- A first study (L= 1.6 fb⁻¹, 13 TeV) in this direction has been performed to measure **bb** and **cc** differential cross section as a function of 4 differential variables (leading jet p_{τ} , leading jet η , dijet invariant mass, $\Delta y^* = \frac{1}{2} |y^0 y^1|$)



- bb and cc di-jets will be the main QCD background in searches for high mass resonances
- The technique for disentangle the bb and cc processes has been demonstrated

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 Flavour composition determined by fitting the combination of two Multivariate discriminators:

JHEP 02 (2021) 023

 $t_0 = \text{BDT}_{bc|q}(j_0) + \text{BDT}_{bc|q}(j_1),$ $t_1 = \text{BDT}_{b|c}(j_0) + \text{BDT}_{b|c}(j_1).$

Cross section ratio also computed as a function of kinematic variables



Projected sensitivities for Higgs to cc

- The upper limit on $\sigma(pp \rightarrow W/Z + H) \times \mathcal{B}(H \rightarrow cc)$ obtained in Run 1 was 6400 x σ_{sM} and $y^c < 80 y^c_{sM}$
- In the HL-LHC we expect to collect 300 fb⁻¹ at 14 TeV
- The improved VELO performance is expected to increase the c-tagging efficiency from 25% to 35%
- Going from 8 to 14 TeV the VH cross section is expected to increase by a factor 7



LHCB-PUB-2018-009 CERN-LPCC-2018-04

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Conclusions

- LHCb allows to perform interesting SM and BSM Higgs searches and in a complementary phase space region with respect ATLAS and CMS
- Studies of BSM (like Long Lived Particles) are ongoing and will improve in the future and with the next upgrades
- In the HL-LHC era, LHCb could push the limit on the Higgs-charm coupling to 2-3 times the SM expectation
- Further improvements are expected: new tagging methods, the search in the inclusive channel (without associated production)

LHCb performance Run 2



LHCb performance Run 3



CERN-LHCC-2013-021

Details on search for long-lived particles decaying to $e^{\pm} \mu^{\mp} v$

Fig. 1 Production modes of the LLP considered in this search. From left to right: direct pair production (DPP), decay of a SM-like Higgs with a mass of $125 \text{ GeV}/c^2$ produced by gluon-gluon fusion (HIG) and production by charged current (CC)



Corrected invariant mass formula:

$$\tilde{m}_{corr} = \sqrt{m(e\mu)^2 + p(e\mu)^2 \sin^2 \theta} + p(e\mu) \sin \theta$$

MSSM with R parity violation

L: lepton number, B: baryon number, S: spin of the particle

All SM particles have $R_p = +1$ and their superpartners have $R_p = -1$

$$R_p = (-1)^{L+3B+2S}$$

neutralino flavoured leptonic decays

$$W_{RPV} = \mu_i L_i H_u + \frac{1}{2} \lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \frac{1}{2} \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

neutralino semileptonic decay

 μ_i , λ_{ijk} , λ_{ijk} , λ_{ijk} are the coefficients for the RPV interactions, L is the lepton doublet, H the Higgs doublet, e the lepton singlet, Q the quark doublet, d the down quark singlet and u the up quark singlet.

In the Left-Right Symmetric Model: SM-singlet heavy neutrinos N , a heavy neutral lepton (HNL), which are introduced as the parity gauge partners of the corresponding left-handed neutrino fields, and a right-handed gauge boson W_p .

$$\begin{array}{c} \ell_{\alpha}^{\pm} \\ \ell_{\beta}^{\pm} \\ N \\ \ell_{\beta}^{\pm} \\ \ell_{\alpha}^{\pm} \end{array}$$

Eur. Phys. J. C 77, 812 (2017) Updated search for long-lived particles decaying to jet pairs

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 10^{2}

- Search for Higgs boson that decays to a pair of Hidden Valley (HV) pions π_{v} , that subsequently decay into bb pairs, full Run I dataset (\mathscr{L} ~2 fb⁻¹)
- Signature: two jets associated to a displaced SV
- Fits of the dijet invariant mass distribution for several intervals of displacement from the beam axis $\mathrm{R}_{_{_{XY}}} \rightarrow$ no signal eccess found
- 95% CL upper limits are set on $\sigma(gg \rightarrow H_0) \times \mathcal{B}(H_0 \rightarrow \pi_v \pi_v)$
- Several masses $m_{\pi v} \in [25,50]$ GeV/c² and lifetime $T_{\pi v} \in [2,500]$ ps hypothesis are tested

 10^{-3}

 10^{2}

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 10^{-}

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 $\rightarrow \pi_{v}\pi_{v}$)

 $[\sigma/\sigma^{SM}_{gg \to H^0}) \cdot \mathcal{B}(H^0$

LHCb results are compared with ATLAS/CMS

 π_V

 π_V

***************** ******************

 H^0



LHCb-CONF-2018-006

Projected sensitivities for LLPs decaying into dijet

• Projected sensitivities of the search for HV pions decaying hadronically



Eur. Phys. J. C 78, 1008 (2018) Search for lepton flavour-violating decays of Higgs-like bosons

- Search for Higgs-like boson $H^0 \rightarrow \mu^{\pm} T^{\mp}$ with mass in the range 45 to 195 GeV/c²
- Run I data, 8 TeV (L=2 fb⁻¹)
- Signature: prompt muon and displaced T decay
- T lepton is reconstructed in 4 different decay channels



- Limits on $\sigma(gg \rightarrow H \rightarrow \mu T)$ are set with different mass hypothesis
- Upper limit on σ ·**3** at 95% C.L.
 - \circ 22 pb for mass 45 GeV/c²
 - \circ 4 pb for mass 195 GeV/c²
- For Higgs boson,

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.7 \times 10^{-2}$$





• The search provides complementary results w.r.t. ATLAS and CMS