Higgs searches at LHCb

Higgs 2022 (Pisa; November 7 – 11, 2022)

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on behalf of the LHCb collaboration

European Organization for Nuclear Research (CERN)

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LHCb is a 20×5 m GPD in the forward region. Single-arm *forward* spectrometer (2 < η < 5) along the beamline (z).

**Tracking and vertexing systems**

**Particle identification systems**

Excellent *vertexing resolution* (fast mixing).
Excellent *mass resolution* (low masses).

HCAL and M1 provided readout to L0 trigger.
Excellent jet reconstruction and tagging capabilities.
Higgs searches at LHCb

LHCb is a General Purpose Detector:

- Originally designed for heavy flavour physics → forward acceptance, reduced luminosity.
- Capable of competitive high $p_T$ physics (e.g. Z, W): [PLB 776 (2017) 430-439] [JHEP 01 (2022) 036]
LHCb as a Higgs hunter: [IJMP A30 (2015) 1530022]

- **VELO**: excellent $\sigma$(IP) $\sim$ 20 $\mu$m and SV reconstruction $\rightarrow$ crucial for jet flavor tagging.
- **Tracking**: excellent spatial and momentum resolution $\rightarrow$ crucial for $H^0 \rightarrow$ LLP studies.
- **Trigger**: soft, full software trigger (GPUs) in Run 3 $\rightarrow$ expensive ML algorithms in HLT1.

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**Graphs:**

1. Plot of $m_{\mu^+\mu^-}$ versus $p_T$ with $s = 8$ TeV, $3 < p_T < 4$ GeV/c, and $3.0 < y < 3.5$.
2. Plot of candidates versus decay time with red and blue markers for tagged and fit cases, respectively.
Outline of this talk

**Heavy flavor Higgs decays:**
- Jet reconstruction and tagging at LHCb,
- Search for Higgs associated production into $b\bar{b}$ and $c\bar{c}$ [2016],
- Inclusive search for $b\bar{b}$ and $c\bar{c}$ resonances [2021],
- Prospects for $H^0 \rightarrow c\bar{c}$ searches.

**Exotic Higgs decays:**
- LFV decays of a Higgs-like boson [2018],
- Neutralino pair production decaying (semi-)leptonically [2021, 2022],
- Dark pion pair production decaying hadronically [2017],
- Hidden-sector bosons from B-meson decays [2017].

**Searches for light Higgses:**
- Search for dimuon resonances in the $\Upsilon$ region (Run 1) [2018],
- Searches for low-mass dimuon resonances (Run 2) [2020].
Heavy flavor
Jet reconstruction and identification at LHCb

- **Jet reconstruction:** [JHEP (2014) 01 033]
  - Particle flow algorithm (including neutral recovery) → jet input.
  - Anti-$k_T$ algorithm for clustering ($R = 0.5$) → efficiency $> 95\%$ for $p_T > 20$ GeV.
  - Jet energy scale calibrated on data (using $Z \rightarrow \mu\mu +$ jets),
  - Energy resolution from 10 to 15\% for a $p_T$ range between 10 and 100 GeV.

- **Secondary Vertex (SV) identification and jet tagging:** [JINST 10 (2015) P06013]
  - Reconstruct SV from displaced tracks → kinematic and quality requirements on both,
  - Train two Boosted Decision Trees (BDTs) for a two-step jet flavour tagging:
    - SV displacement from PV, kinematics, charge and multiplicity;
    - SV corrected mass, defined as $M_{\text{corr}}(SV) = \sqrt{M^2 + p^2\sin^2\theta + p\sin\theta}$.
  - BDT(bc|udsg) to separate light and heavy flavour jets, BDT(b|c) to separate b-jets from c-jets.
  - Tagging efficiency of b(c)-jets of 65\% (25\%) with 0.3\% contamination from light jets.
Search for $W/Z + H^0 \rightarrow b\bar{b}/c\bar{c}$  

- Search for Higgs associated production using 2012 data (2 fb$^{-1}$ at 8 TeV).
- Trigger on the high $p_T$ $\mu$, $e$ from $W/Z +$ exploit jet tagging capabilities.
- uGB to distinguish signal from backgrounds ($W/Z +$ di-jet and $t\bar{t}$).
- CLs using $m_{jj} + 2 \times uGB \rightarrow$ compatible with background (no events) for $b\bar{b}$ ($c\bar{c}$).
- Upper limits on $H^0 \rightarrow b\bar{b}$ (69×SM) and first limits on $H^0 \rightarrow c\bar{c}$ (7900×SM).
Inclusive search for $c\bar{c}$ and $b\bar{b}$ resonances [JHEP 02 (2021) 023]

- Use 2016 data ($1.6 \text{ fb}^{-1}$ at 13 TeV) to test NLO pQCD predictions, test proton PDFs (access low Bjorken-$x$ values), and search for resonances in $m_{jj}$ (access low masses).
- Measure differential $c\bar{c}$- and $b\bar{b}$-dijet $x$-sections in the forward region and their ratio as a function of $m_{jj}$, $\eta(j_0)$, $p_T(j_0)$ and absolute difference in jet rapidities.
- Exploit jet tagging capabilities → fit to a linear combination ($t_0$, $t_1$) of tag observables.
Inclusive search for $c\bar{c}$ and $b\bar{b}$ resonances [JHEP 02 (2021) 023]

- Results compatible with SM expectations → first inclusive, direct measurement of differential $c\bar{c}$-dijet differential $x$-section at a hadron collider.
- Understand backgrounds for future searches: search for $H^0 \rightarrow c\bar{c}$ and $H^0 \rightarrow b\bar{b}$.

![Graph 1](image1)

- Scale existing limits to 300 fb$^{-1}$ and assume detector improvements affecting c-jet tagging (e.g. better IP resolution for SV separation): [CERN-LPCC-2018-04]
- No potential ML improvements considered. Best LHC sensitivity on Yukawa coupling for c quark ($2-3 \times y_{SM}^c$).

![Graph 2](image2)

![Graph 3](image3)
Exotic Higgs decays
Search for LFV decays of $H^0$-like bosons [EPJC (2018) 78 1008]

- Search for a $H^0$-like boson (45 to 195 GeV/c^2) into $\mu\tau$ in 2012 data (2 fb^{-1} at 8 TeV).
- High $p_T$ muon + reconstruct leptonic and hadronic final states of the $\tau$ lepton.
- Selections optimised depending on the mass range (around $m_H$, below, and above).
- CLs limits at 95% C.L. with CLs, ranging from 22 pb at 45 GeV to 4 pb at 195 GeV.
- For Higgs, exclusion limit on the Yukawa coupling of $\sqrt{|Y_{\tau\mu}|^2 - |Y_{\mu\tau}|^2 < 1.7 \times 10^{-2}}$. 

![Graphs showing observed and expected cross-sections for various decay modes](chart.png)
Pair produced $\tilde{\chi}_1^0 \rightarrow \mu qq'$ in Higgs decay [EPJC 82 (2022) 4 373]

- Search for RPV neutralino in 5.4 fb$^{-1}$ of LHCb Run 1 and 2 data.
- Look for a **single displaced vertex** with several tracks + high $p_T$ muon.
- Results interpreted in $H^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ benchmark model:

- Excluded production cross-section down to $\mathcal{O}(0.1)$ pb.
- Exclude $\mathcal{B}(H^0 \rightarrow \chi \chi)$ down to 0.1% by the end of Run 3 [LHCb-CONF-2018-006]
Pair produced $\tilde{\chi}_1^0 \rightarrow e^+ \mu^- \nu$ in Higgs decay [EPJC (2021) 81 261]

- Explore masses between and 7 and 50 GeV and lifetimes between 2 and 50 ps.
- Simultaneous ML fit to mass and LLP flight distance.
- UL at 95% C.L. on $\sigma B$ at 0.1 pb for $\tau < 10$ ps and $m > 10$ GeV – no excess found.
Pair produced dark pions in Higgs decay [EPJC (2017) 77 812]

- Search with full LHCb Run 1 (3 fb$^{-1}$) dataset published.
- **HV $\pi_\nu$ decaying to $b\bar{b}$ – especially with SM-like $H^0 \rightarrow \pi_\nu\pi_\nu$ production.**
- Experimental signature is a single displaced vertex with two associated jets.
- Limits at 95% C.L. as a function of $\pi_\nu$ lifetime for several $\pi_\nu$ masses:

- Plan to analyse final state including kaons and pions (lower $\pi_\nu$ masses).
- Improved simulation models including dark showers (multiple dark hadrons).
Confining Hidden Valley and dark showers: a proposal

- LHCb Run 1 search for $H^0 \rightarrow SS$, where $S \rightarrow b\bar{b}$ jets [EPJC (2017) 77 812]
- Improve simulation including dark QCD (multiple $S$) and intermediate resonances.
- Proposed search where $S \rightarrow K^+K^-$ (lower masses): [JHEP (2020) 115]

**Figure 3.** Range of $S$ lifetime and mass for which a 95% CL exclusion of the branching fraction of the decay $h \rightarrow SS$ is possible at LHCb with an integrated luminosity of 15 fb$^{-1}$ for different values of this branching fraction. We assume $\text{BR}(S \rightarrow K^+K^-) = 100\%$ in these plots. Left plot shows the limits when searching for just one $S$ at the event, while right plot when searching for both of them.
- $B^0 \rightarrow K^{*0}\chi$ [PRL 115 (2015) 161802] / $B^+ \rightarrow K^+\chi$ [PRD 95 (2017) 071101 (R)]
- Search for hidden-sector bosons $\chi \rightarrow \mu^+\mu^-$ in $b \to s$ penguin decays:
  - Axial-vector portal ($\chi$ as axion) [LNP 741 (2008) 3]
  - Scalar (Higgs) portal ($\chi$ as inflaton) [JHEP 05 (2010) 10]
Hidden-sector bosons in $B \rightarrow K^{(*)}\chi(\mu^+\mu^-)$

- Full LHCb Run I dataset (3 fb$^{-1}$) used for both searches.
- Allow for prompt and detached di-muon candidates.
- BR normalised to $\mathcal{B}(B^+ \rightarrow K^+ J/\psi)$ ($\sim 10^{-4}$) or $\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+\mu^-)$ ($\sim 10^{-7}$).
- Constraints on $\tau(\chi)$ between 0.1 and 1000 ps (left), [PRD 95 (2017) 071101 (R)]
- Constraints on mixing angle $\theta^2$ between the Higgs and $\chi$ in the inflaton model (right):

- No evidence for signal observed.
- Large fraction of allowed inflaton parameter space ruled out.
Light Higgses
Search for $\mu\mu$ resonances in the $\Upsilon$ region [JHEP 09 (2018) 147]

- Light spin-0 particles copiously produced in gluon-gluon fusion:
  - Many models: NMSSM, 2HDM+S, etc.
  - Review on LHC searches: [arXiv:1802.02156]

- Search using LHCb Run 1 (3 fb$^{-1}$) published in JHEP.

- Look for a di-muon resonance from 5.5 to 15 GeV/c$^2$ (also between $\Upsilon$ peaks):
  - Mass-interpolated efficiencies in bins of $p_T, \eta$ (model independent results also given).
  - Production x-section (8 TeV) limits for a scalar (vector) boson on the left (right).
  - First scalar limits between 8.7 and 11.5 GeV/c$^2$ and competitive with CMS elsewhere.

![Graphs showing LHCb search results for $\sigma(gg \rightarrow \phi) \times B(\phi \rightarrow \mu\mu)$ and $\sigma(q\bar{q} \rightarrow A') \times B(A' \rightarrow \mu\mu)$ in the $\Upsilon$ region.](image)
Search for dark photons decaying into a pair of muons:

- Kinetic mixing of the dark photon ($A'$) with off-shell photon ($\gamma^*$) by a factor $\varepsilon$:
  1. $A'$ inherits the production mode mechanisms from $\gamma^*$.
  2. $A' \rightarrow \mu^+ \mu^-$ can be normalised to $\gamma^* \rightarrow \mu^+ \mu^-$.
- Separate $\gamma^*$ signal from background and measure its fraction.
- **Prompt-like** search (up to 70 GeV/c\(^2\)) $\rightarrow$ **displaced** search (214 – 350 MeV/c\(^2\)):
  - $A'$ is long-lived only if the mixing factor is really small.
- Used 5.5 fb\(^{-1}\) of Run 2 LHCb data (13 TeV).
- Great sensitivity (especially in the prompt region above 10 GeV and below 0.5 GeV).
Search for di-muon low-mass resonances [JHEP 10 (2020) 156]

+ no isolation requirement
+ non-zero width considered

Inclusive Prompt

Displaced pointing

Prompt + b-jet

Displaced non-pointing

2HDM Higgs $\theta_H \rightarrow$ world-best limits:

$\rightarrow$ LHCb R1 [JHEP 09 (2018) 147]
$\rightarrow$ CMS R1 [PRL 109 (2012) 121801]
$\rightarrow$ CMS R2 [PRL 124, 131802 (2020)]
$\rightarrow$ Belle $Y \rightarrow X\gamma$ [PRD 87 (2013) 031102]

• Other scenarios covered too (i.e. HV).

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Conclusions
Conclusions

- LHCb proved to be **very competitive** for high $p_T$ searches:
  - Excellent vertexing, tracking and soft trigger.
  - Especially competitive for jet tagging separation.
  - Rich variety of BSM models and signatures can be approached (see backup).

- **Bright prospects** for the future:
  - Interesting prospects for the $H^0 \rightarrow c\bar{c}$ mode.
  - Better vertex resolution and tracking capabilities.
  - New techniques under development for ideas on new signatures.
  - Extended reach with a new compact detector for LLPs $\rightarrow$ CODEX-b (see backup).

Thanks for your attention!
Questions?
Backup
The LHCb trigger

- L0 trigger removed for Run 3 → benefit for low-mass searches (no $p_T$ bottleneck).
- Full event reconstruction from 30 MHz readout, able to select down to $p_T(\mu) \sim 80$ MeV/c.
- GPU-based HLT1 (Allen project) from Run 3 [Comp Soft Big Sci (2020) 4 7]
Long tracks:

- Tracks with hits in the tracking stations and in the VELO.
- Excellent spatial and momentum resolution $\rightarrow 0.4\% \ (0.6\%)$ at 5 (100) GeV.
- Presence of a VELO envelope (RF-foil) at $\sim 5$ mm from beam:
  - Background dominated by heavy flavour below 5 mm.
  - Background dominated by material interactions above 5 mm.
- Having a precise model of material interactions is crucial.
- A detailed VELO material veto map is used [JINST 13 (2018) P06008]
The LHCb reconstruction

- **Downstream tracks:**
  - Reconstruction of particles decaying beyond VELO.
  - Tracks with worse vertex and momentum resolution.
  - Trigger on downstream tracks → better for LLP ($\leq 2$ m) signatures.
  - Optimisation studies on-going [LHCb-PUB-2017-005]

- **Upstream tracks:**
  - Reconstruction of soft charged particles bending out of the acceptance.
  - New tracker (UT) – high granularity, closer to beam pipe.
  - Proposal to add magnet stations (MS) inside the magnet → improve low $p$ resolution.
The future of LHCb

Physics case for an LHCb Upgrade II: Opportunities in flavour physics, and beyond, in the HL-LHC era [CERN-LHCC-2018-027]

- Total dataset of 9 fb$^{-1}$ collected during Run 1 and 2.
- Changes in Run 3: SciFi, UT, removal of M1, no L0 trigger, upgrade of subsystems.
- Expect to collect 300 fb$^{-1}$ by the end of Upgrade 2.
- **Challenging conditions** – higher rate, pile-up, occupancy and fluence.
- Detector sub-systems have to be able to cope with such conditions.
- In particular – **trigger** and **tracking systems** are crucial for exotic searches.
The upgraded LHCb VELO

- **Upgrade II VERTex LOcator**: [CERN-LHCC-2017-003]
  - Probably based on Upgrade Ia VELO (silicon pixels).
  - Access to shorter lifetimes, better PV and IP resolution, and real-time alignment.
  - But – 10x multiplicity, pile-up and radiation damage w.r.t. Upgrade Ia(b).
  - **Possibility of removing RF-foil** for Upgrade II:
    → better IP resolution + no material interactions.
Background dominated by material interactions for displaced searches at LHCb.

Mandatory to **keep control** of material interactions – veto them in an efficient way:

- Background mainly due to $\gamma$ conversions (left plot).
- A new VELO material map has been developed:
  - Model in **great detail** both sensors & envelope.
  - Assign a **p-value** to material interaction hypothesis.
  - Sensitivity improvement by $\mathcal{O}(10)$ to $\mathcal{O}(100)$.
  - Based on data from **beam-gas collisions** (plot below).
Dark Photons – combined prospects

- Minimal scenario (LHCb) + Higgs portal (ATLAS/CMS):
Search for dark photons decaying into a pair of muons:

- Kinetic mixing of the dark photon ($A'$) with off-shell photon ($\gamma^*$) by a factor $\varepsilon$:
  1. $A'$ inherits the production mode mechanisms from $\gamma^*$.
  2. $A' \rightarrow \mu^+ \mu^-$ can be normalised to $\gamma^* \rightarrow \mu^+ \mu^-$. 

- Separate $\gamma^*$ signal from background and measure its fraction.

- **Prompt-like** search (up to 70 GeV/c$^2$) → **displaced** search (214 – 350 MeV/c$^2$):
  - $A'$ is long-lived only if the mixing factor is really small.

- Used 5.5 fb$^{-1}$ of Run 2 LHCb data (13 TeV).

- Great sensitivity (especially in the prompt region above 10 GeV and below 0.5 GeV).

\[ n_{exc}^{A'} [m(A'), \varepsilon^2] = \varepsilon^2 \left[ \frac{n_{ob}^{\gamma*} [m(A')]}{2\Delta m} \right] F[m(A')] \varepsilon^{\gamma*} [m(A'), \tau(A')] \]
Using templates for $\text{min}[\chi^2_{	ext{IP}}]$ (small mass dep)

- $\mu^+\mu^- \rightarrow$ from data at $m(J/\psi)$ and $m(Z)$
- $\mu_Q\mu_Q \rightarrow$ from simulation (validated)
- $h\bar{h} + h\mu_Q \rightarrow$ from same-sign dimuons (corrected)

($\mu_Q$ is a muon from a heavy-flavour decay)
Dark Photons [PRL (2020) 124 041801]

LHCb prompt-like $A'$ search

90% CL upper limit on
$n_{\text{ob}}[m(A'), \varepsilon^2] / n_{\text{ex}}[m(A'), \varepsilon^2]$

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Dark Photons – non-minimal searches [JHEP 10 (2020) 156]

+ no isolation requirement
+ non-zero width considered

Inclusive Prompt

+ non-zero width considered

Prompt + b-jet

Displaced pointing

Displaced non-pointing
Dark Photons – non-minimal searches [JHEP 10 (2020) 156]

- UL @ 90% C.L. on $\sigma(X \rightarrow \mu\mu)$ (top: inclusive, bottom: b-associated):

- 2HDM Higgs $\theta_H \rightarrow$ world-best limits:
  - $\rightarrow$ LHCb R1 [JHEP 09 (2018) 147]
  - $\rightarrow$ CMS R1 [PRL 109 (2012) 121801]
  - $\rightarrow$ CMS R2 [PRL 124, 131802 (2020)]
  - $\rightarrow$ Belle $Y \rightarrow X \gamma$ [PRD 87 (2013) 031102]

- Other scenarios covered too (i.e. HV).

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Dark Photons – the future

- Cover $ee$ in $D^{*0} \rightarrow D^0 A'(ee)$ decays (high statistics, no L0), and with inclusive $ee$ triggers.
- Prospected reach for Run III and beyond: [arXiv:1812.07831]
Projections from [arXiv:2203.07048]:

**FIG. 1:** Adapted from Ref. [14]: constraints on visible $A'$ decays from (blue regions) LHCb [2] and (gray regions) all other experiments. The solid blue line is the union of Run 3 projections for LHCb from Refs. [9, 10], updated to include inclusive $A' \rightarrow e^+e^-$ projections enabled by recent advances in the LHCb trigger. The dashed blue line projects further into the future to the end of Run 6.
**Simulation:**

- Signal (DPP and HIG) using MSSM RPV model – LLP as $\tilde{\chi}^1_0$ light neutralino,
- Signal (CC) using LRSM model – LLP as a HNL from on-shell $W$ boson decay,
- Several **signal samples** per model for different LLP mass and lifetimes.
- **Background sample** simulated for QCD $b\bar{b}$ events.

**Selection:**

- Require good quality DVs with minimum displacement and kinematic requirements.
- Leptons isolated to suppress QCD background – isolation optimised with same-sign data.
- After full selection $\rightarrow 60k \ b\bar{b} \rightarrow e\mu X$ events (consistent with observed yield).
**Corrected mass approach:**

- LHCb is a non-hermetic spectrometer → we **can not do invisibles**.
- However, we can compute a proxy to \( X + \text{invisible} \) invariant mass → **corrected mass**.
- **Required** to have only one **massless** invisible in the final state (\( \nu \)).
- **Required** to know the **direction of flight** of the parent particle.

1. Assume LLP origin vertex approximately be the same as the \( pp \) collision.
2. Obtain a (pseudo) decay vertex using the di-lepton systems.
3. Project the di-lepton system momenta to the LLP direction of flight.

\[
m_{\text{corr}} = \sqrt{m(e\mu)^2 + p(e\mu)^2 \sin^2 \theta + p(e\mu) \sin \theta}
\]

**Corrected mass as a good proxy to real mass → discriminating variable.**
Hidden-sector bosons in $B \rightarrow K^{(*)} \chi(\mu^+\mu^-)$

- Full LHCb Run I dataset (3 fb$^{-1}$) used for both searches.
- Allow for prompt and **detached** di-muon candidates – up to 1000 ps ($\sim 30$ cm).
- Look for a narrow di-muon peak (mass resolution between 2 and 9 MeV/$c^2$).
- Exclude narrow QCD resonances - mass distribution: [PRL 115 (2015) 161802]

![Graph showing the distribution of candidates for $B \rightarrow K^* \mu\mu$](image)

- MVA selection almost independent of $\chi$ mass and decay time (uBoost).
Axion-like particle in the context of Composite Higgs models: [EPJC (2022) 82 3]

- Low-mass pseudoscalar decaying into pairs of leptons, quarks or photons.
- Reinterpretation of existing $\gamma\gamma$ (QCD axion projections) and $\mu\mu$ (experimental) boundaries.
- Studies for final states consisting of $\tau\tau$ and $c\bar{c}$ into D mesons.
Major report on STEALTH physics at LHCb published in Reports on Progress in Physics [ROPP (2022) 85 024201] [arXiv:2105.12668]

More than 20 proposed searches on different models are described:

- **B-mesogenesis:** baryonic DM from $B$-hadron decays [EPJC (2021) 81 964]
- **Confining HV:** dark hadrons decaying into SM light hadrons [JHEP (2020) 115]
- **Composite ALP:** light pseudoscalar in Composite Higgs models [EPJC (2022) 82 3]
Extended reach for LLPs (CODEX-b + LHCb)

- Compact detector for exotics: [PRD 97 (2018) 015023]
  - Box of tracking layers to search for decays-in-flight of LLPs generated at IP8.
  - Interface with LHCb for identification and partial reconstruction of possible LLP events.

- Prospects for several benchmark models studied:
  - Prospects (various detectors) for $B \rightarrow X_s \varphi$ ($\varphi$ as a light scalar) shown below (original paper).
  - Updated limits including other models in the Snowmass white paper [arXiv:2203.07316]