Search for $B_s \to \mu^+\mu^-\gamma$ with Photon Conversions at LHCb

Raphael van Laak, Lesya Shchutska, Yunxuan Song

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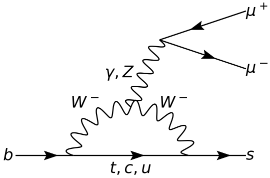
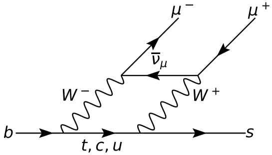
Theoretical Motivation

- Flavor Changing Neutral Currents (FCNC) such as $b \to s\mu^+\mu^-$ are forbidden at tree level in the Standard Model (SM).
- Experimental data of the Branching Ratios (BR) of these decays show deviation from SM predictions. (See e.g. [2212.10497].)
- Measurements of these decays can lead to insights of beyond the SM physics.
- The channel $B_s \to \mu^+\mu^-\gamma$ adds a QED vertex, lowering the BR, but this is compensated for by the lifting of the chiral suppression.
- SM predictions of BR in ranges of $q^2 \equiv m(\mu^+\mu^-)^2$ [1708.02649]:
  - $\mathrm{BR}(B_s \to \mu^+\mu^-\gamma) = (8.3 \pm 1.3) \cdot 10^{-9}$, $q^2 \in [0.04, 8.64]\,\mathrm{GeV}^2/c^4$
  - $\mathrm{BR}(B_s \to \mu^+\mu^-\gamma) = (8.9 \pm 1.0) \cdot 10^{-10}$, $q^2 \in [15.84, 28.27]\,\mathrm{GeV}^2/c^4$

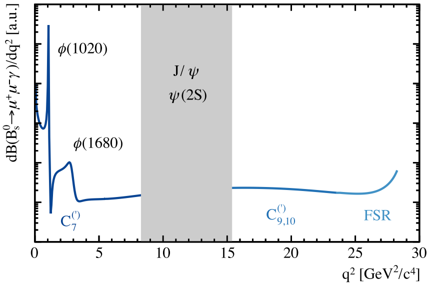




Previous Study

- A study dedicated to $B_s \to \mu^+\mu^-\gamma$ with the full final state being reconstructed has been performed at LHCb [2404.03375].
  - Run 2 data (2016–2018); $\mathcal{L} = 5.4\,\mathrm{fb}^{-1}$, at $\sqrt{s} = 13\,\mathrm{TeV}$.
  - Full range of $q^2 \in [4m_\mu^2, m_{B_s}^2]$.
  - Photons observed directly in calorimeter.
- No statistically significant signal was found, leading to limits at 95% C.L.

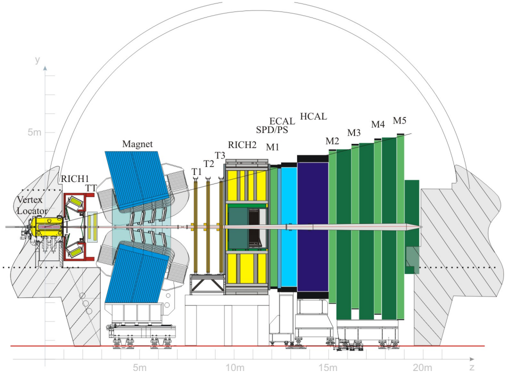
$$\boxed{\mathrm{BR}(B_s \to \mu^+\mu^-\gamma) < 2.8 \cdot 10^{-8}} \qquad (1)$$



Credit: [2404.03375]

LHCb

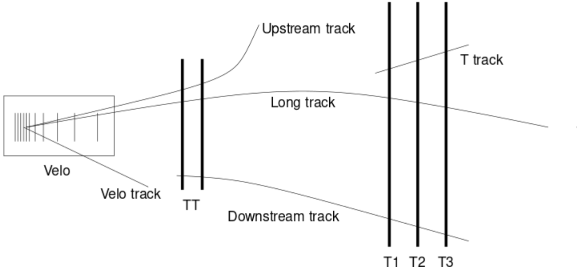
- LHCb is designed as a single arm forward spectrometer ($2 < \eta < 5$), to focus on D and B mesons.



LHCb during Run 1 and Run 2. Credit: The LHCb Collaboration [10.1088/1748-0221/3/08/S08005]

This Study: $B_s \to \mu^+\mu^-(\gamma \to e^+e^-)$

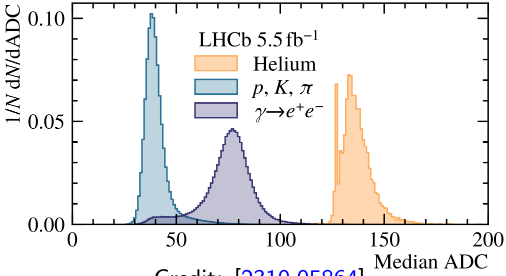
- Instead of looking for photons directly in the calorimeter, we can also look for the channel through converted photons $\gamma \to e^+e^-$ in VELO.
  - This provides us with a direction of photon momentum (and thus vertex reconstruction) at the cost of lower yield.
- We use the same Run 2 (2016–2018) dataset with $\mathcal{L} = 5.4\,\mathrm{fb}^{-1}$, with long track electrons.



Sketch for Run 1 and Run 2. Credit: [LHCb]

Photon Conversion in VELO

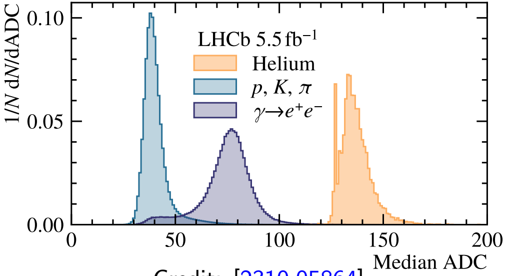
- There is no magnetic field in VELO.
- After photon conversion, electrons move in the same direction, but leave double energy deposit (encoded in VeloCharge).
- Using a single electron only is possible due to this unique signature.
- This unique signature also limits probability of misidentification of electrons.
- Therefore, we study the $B_s \to \mu^+\mu^-\gamma$ channel by looking for the signature $\mu^+\mu^-e^\pm$.



Credit: [2310.05864]

Selection

- Standard B-physics trigger selections for leptonic final states.
- Selecting $\mu^+\mu^- e^\pm$ candidates in reconstruction.
- Selection based on [2404.03375]:
  - μ: $p_\mathrm{T} > 250\,\mathrm{MeV}/c$, $m(\mu\mu) \notin [2880, 3920]\,\mathrm{MeV}/c^2$, good track quality
  - B_s: $p_\mathrm{T} > 500\,\mathrm{MeV}/c$, $\Delta m \equiv |M(\mu\mu e) - m_{B_s}| < 1500\,\mathrm{MeV}/c^2$, good track quality.
- Remaining selection:
  - Muon ID probability > 0.2, $p_\mathrm{T}(e) > 500\,\mathrm{MeV}/c$, $\mathrm{VeloCharge}(e) > 1.5$.



Credit: [2310.05864]

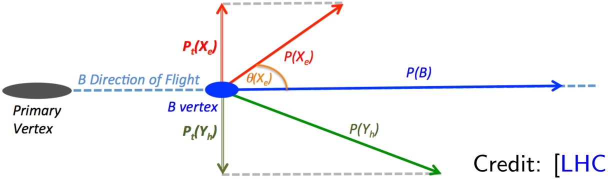
Conceptually:
Median ADC $= 40 \Leftrightarrow$ VeloCharge $= 1$
Median ADC $= 60 \Leftrightarrow$ VeloCharge $= 1.5$

Mass Correction: HOP Parameter

- Because we only reconstruct one electron, we are missing part of the momentum. The HOP parameter can correct for that.
- Take the decay $B \to Y_h X_e$, with X_e all the electrons, and Y_h the remaining particles:
  - Transverse component of the final state is zero $P_\mathrm{t} = 0$, $\mathrm{t} \equiv$ transverse to $\mathrm{DoF}(B)$.
  - When electrons are not observed, $\mathbf{P}(X_e)$ becomes smaller.
  - Therefore

$$\alpha_\mathrm{HOP} \equiv \frac{P_\mathrm{t}(Y_h)}{P_\mathrm{t}(X_e)} \neq 1. \qquad (2)$$

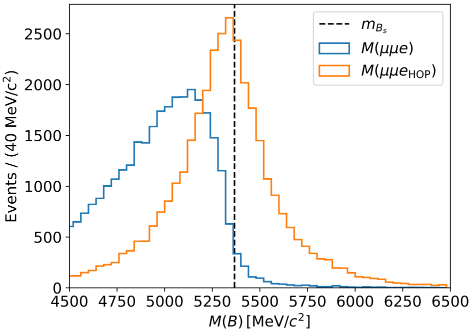
  - We can then correct for the missing electron energy $\mathbf{P}(X_e) \to \alpha_\mathrm{HOP}\mathbf{P}(X_e)$

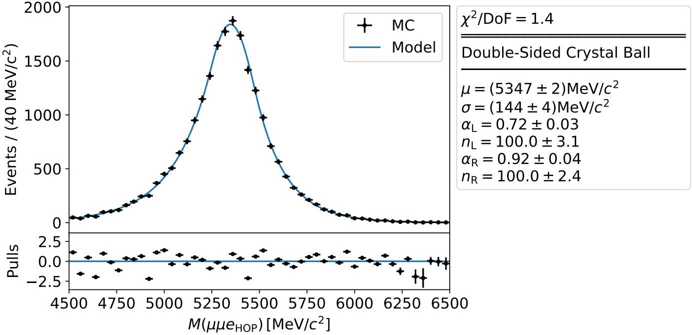


Credit: [LHCb-INT-2015-037]

HOP Parameter: Distribution

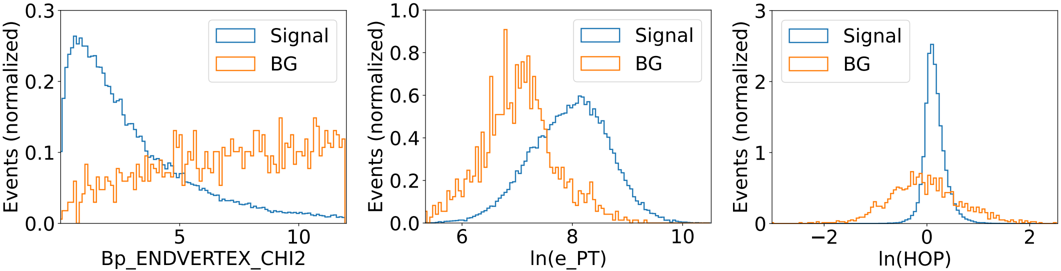
- The HOP parameter increases the resolution of $M(\mu\mu e)$ in Monte Carlo (MC), and brings the average closer to $m_{B_s} = 5367\,\mathrm{MeV}/c^2$.
- The distribution can be fitted with a Double-Sided Crystal Ball, which has a resolution of $\sigma \approx 150\,\mathrm{MeV}/c^2$.



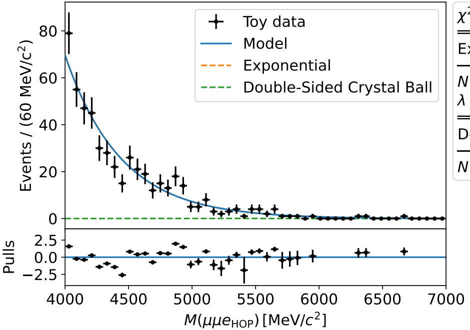


Classification BDT

- Classification BDT can be used to reduce combinatorial background (BG)
- Signal proxy: truth matched MC of the decay $B_s \to \mu^+\mu^-\gamma$ (full q^2 range).
- Background proxy: data with $M(\mu\mu e) > 5500\,\mathrm{MeV}/c^2$ (cf. $m_{B_s} = 5366.77\,\mathrm{MeV}/c^2$).
    - Bp_ENDVERTEX_CHI2: B_s vertex goodness of fit.



- A branching ratio upper limit can be found by fitting toy data with an Exponential + signal shape of a Double-Sided Crystal Ball.



χ^2/DoF = 1.1
Exponential
$N = 510 \pm 21$ $\lambda = (-2.3\times10^{-3} \pm 1.3\times10^{-4})/(\mathrm{MeV}/c^2)$
Double-Sided Crystal Ball
$N = 0 \pm 8$

Branching Ratio Upper Limit: Result

- This gives us a number of expected events N_{exp} for a 95% C.L., from which we can find the expected BR upper limit.
- Total number of expected observed events

$$N_{\mathrm{exp}}(B_s \to \mu^+\mu^-\gamma) = \mathcal{L}\sigma(pp \to B^\pm)\frac{f_s}{f_u}\mathrm{BR}(B_s \to \mu^+\mu^-\gamma)\epsilon, \tag{3}$$

  with $\sigma(pp \to B^\pm) = 86.6\,\mu\mathrm{b}$ [1710.04921] and $f_s/f_u = 0.244$ [2103.06810] and ϵ the efficiency.
- We can find an upper limit for the BR expected sensitivity

$$\boxed{\mathrm{BR}(B_s \to \mu^+\mu^-\gamma) < 1.15 \cdot 10^{-7}} \tag{4}$$

Conclusions

- Our sensitivity of $\mathcal{O}(10^{-7})$ is an order of magnitude worse than the results found by [2404.03375] ($\mathcal{O}(10^{-8})$).
  - Efficiency with which MC models photon conversion still needs to be validated so this number is still preliminary.
  - Including also upstream electrons could improve efficiency further.
- However, using the HOP correction appears to be a promising technique to study this channel and similar rare decays with just a single reconstructed electron.

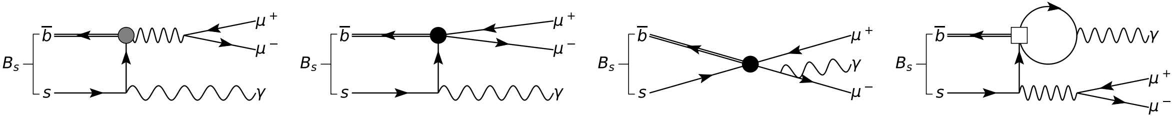
Backup slides

Theoretical Motivation [Backup]

- The operators $\mathcal{O}_i$ that describe the dynamics of the $B_s \to \mu^+\mu^-\gamma$ decay appear in the effective Hamiltonian

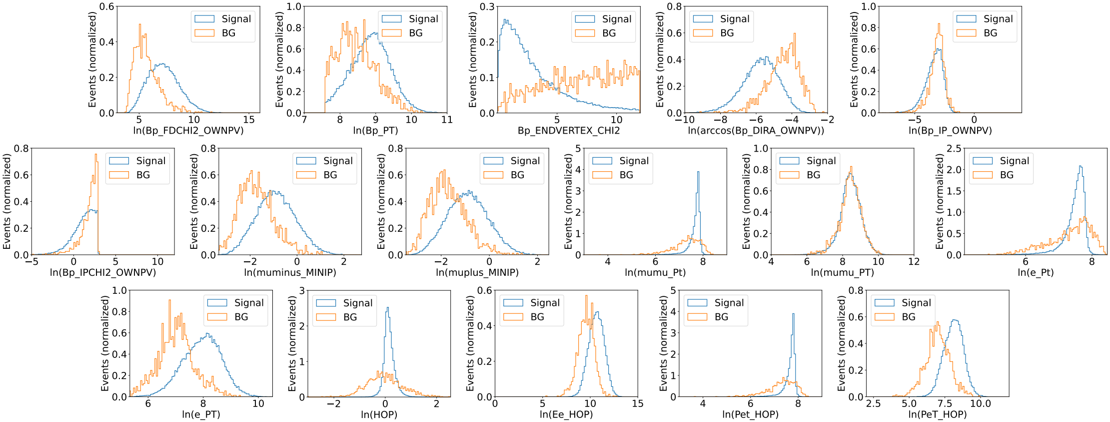
$$\mathcal{H}_{\rm eff} = \frac{4G_{\rm F}}{\sqrt{2}} \left(\sum_{i=1}^{2} (\lambda_u C - i\mathcal{O}_i^u + \lambda_c C - i\mathcal{O}_i^c) - \lambda - t \sum_{i=3}^{6} C_i\mathcal{O}_i - \lambda - t \sum_{i=7}^{10} (C_i\mathcal{O}_i + C_i'\mathcal{O}_i') \right) \tag{5}$$

  with $\lambda_i = V_{is}^* V_{ib}$ and C_i the Wilson coefficients giving the coupling strength of each operator.
- Diagrams contributing to $B_s \to \mu^+\mu^-\gamma$ (● $= \mathcal{O}_7^{(\prime)}$, ● $= \mathcal{O}_{9,10}^{(\prime)}$, □ $= \mathcal{O}_{1,2}$):



Classification BDT: Features [Backup]

- Signal proxy: truth matched MC of the decay $B_s \to \mu^+\mu^-\gamma$ (full q^2 range).
- Background proxy: data with $M(\mu\mu e) > 5500\,\mathrm{MeV}/c^2$ (cf. $m_{B_s} = 5366.77\,\mathrm{MeV}/c^2$).

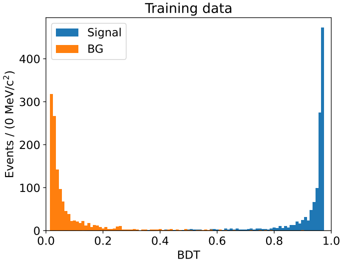


Classification BDT: Performance [Backup]

- Selecting only data where $\mathrm{BDT} > 0.95$, which maximizes the Punzi figure of merit

$$\mathrm{FoM}(\mathrm{BDT}_{\mathrm{cut}}) = \frac{\epsilon_{\mathrm{sig}}}{3/2 + \sqrt{N_{\mathrm{data}}\epsilon_{\mathrm{BG}}}} \tag{6}$$

with $\epsilon_{\mathrm{sig}}(\epsilon_{\mathrm{BG}})$ the efficiency of signal (background) for the cut $\mathrm{BDT} > \mathrm{BDT}_{\mathrm{cut}}$ and N_{data} the number of events in data within the signal region.



Branching Ratio Upper Limit [Backup]

- Fix also the double-sided CB yield and evaluate the likelihood L of the fit.
- Then we find the yield N_{sig}, where

$$\int_0^{N_{\mathrm{sig}}} \mathrm{L}\,\mathrm{d(yield)} \Big/ \int_0^{\infty} \mathrm{L}\,\mathrm{d(yield)} = 0.95. \tag{7}$$