Studies of $b \to sll$ and the role of $B_s^0 \to \mu^+\mu^-\gamma$

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EPFL

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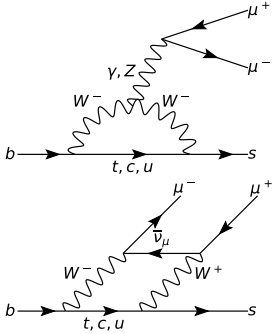
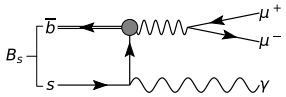
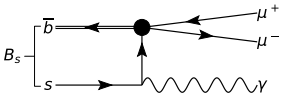
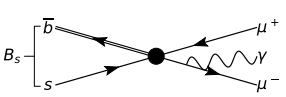
Theoretical Motivation

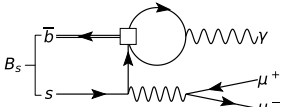
- **Flavor Changing Neutral Currents** such as $b \to s l^+ l^-$ are forbidden at tree level in the Standard Model (SM).
- Branching ratios (BRs) are suppressed $\Rightarrow$ sensitive to new physics (NP).
  - Discrepancies in decay width and angular distribution of $B^{(+,0)} \to K^{(+,*0)} \mu^+ \mu^-$ and $B^{(+,0)} \to K^{(+,*0)} e^+ e^-$ decays between observations and SM.
    - ★ Tests on lepton universality (see [10.1007/JHEP07(2025)069] and refs. therein.)
  - The channel $B_s^0 \to \mu^+ \mu^- \gamma$ adds a QED vertex, lowering the BR, but this is compensated for by the lifting of the chiral suppression.
  - Diagrams contributing to $B_s^0 \to \mu^+ \mu^- \gamma$ ($\bullet = \mathcal{O}_7^{(\prime)}$, $\blacksquare = \mathcal{O}_{9,10}^{(\prime)}$, $\square = \mathcal{O}_{1,2}$):





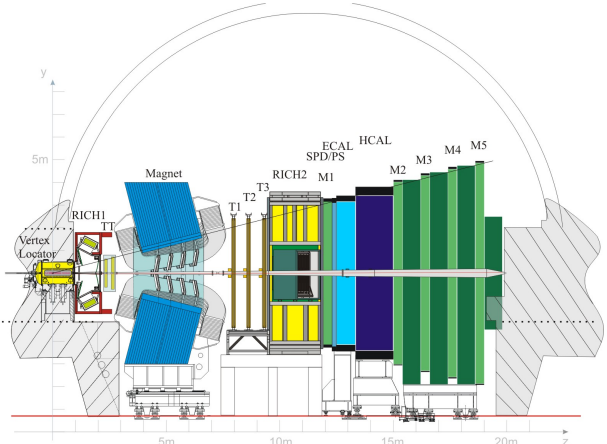


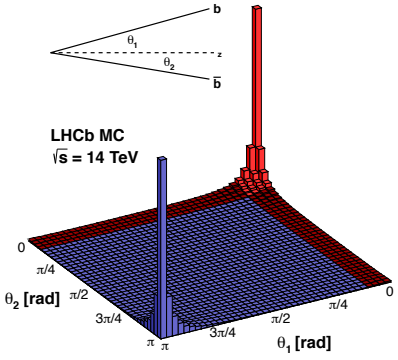




LHCb

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





LHCb during Run 1 and Run 2.
Credits: The LHCb Collaboration [JINST3(2008)S08005, Int. J. Mod. Phys. A 30 (2015) 1530022]

Angular Analysis of the decay $B_s^0 \to \phi e^+ e^-$

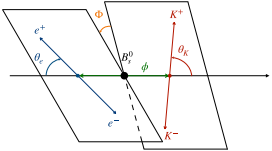
[10.1007/JHEP07(2025)069]

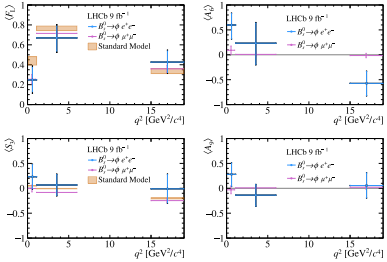
- (See also study on photon polarization [10.1007/JHEP03(2025)047] and angular analysis of $B^0 \to K^{*0} e^+ e^-$ [10.1007/JHEP06(2025)140].)
- First angular analysis of $B_s^0 \to \phi e^+ e^-$ in $q^2 \equiv m(l^+l^-)^2$ bins $[0.1, 1.1], [1.1, 6.0], [15.0, 19.0]\,\mathrm{GeV}^2/c^4$.
- Using data between 2011 and 2018, with $\sqrt{s} = 7, 8, 13\,\mathrm{TeV}$, $\mathcal{L} = 9\,\mathrm{fb}^{-1}$.
- Low statistics $\Rightarrow$ measured a subset of angular observables by integrating over decay time:

$\Rightarrow$ Consistent with SM [1810.08132] and $B_s^0 \to \phi\mu^+\mu^-$ results [10.1007/JHEP11(2021)043].

$$\frac{\mathrm{d}^3[\Gamma + \widetilde{\Gamma}]}{\mathrm{d}q^2 \mathrm{d}\cos(\theta_K)\mathrm{d}\cos(\theta_e)} \propto \frac{3}{4}(1 - \langle F_\mathrm{L}\rangle)\sin^2(\theta_K) + \langle F_\mathrm{L}\rangle \cos^2(\theta_K)(1 - \cos(2\theta_e)) + \langle A_6\rangle \sin^2(\theta_K)\cos(\theta_e)$$

$$\frac{\mathrm{d}^2[\Gamma + \widetilde{\Gamma}]}{\mathrm{d}q^2 \mathrm{d}\Phi} \propto 1 + \langle S_3\rangle \cos(2\Phi) + \langle A_9\rangle \sin(2\Phi)$$

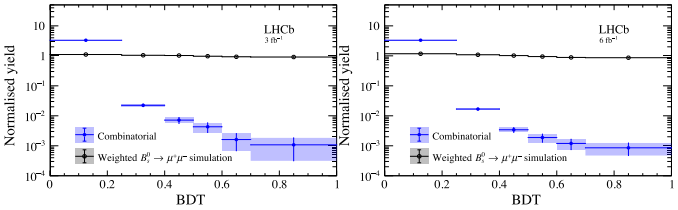




Measurement of the $B_s^0 \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ decay (I)

[10.1103/PhysRevD.105.012010]

- Data collected at $\sqrt{s} = 7, 8, 13\,\text{TeV} \Rightarrow \mathcal{L} = 1, 2, 6\,\text{fb}^{-1}$.
- Normalization channels $B^+ \to J/\psi K^+$, $B^0 \to K^+\pi^-$.
- Backgrounds:
  - Combinatorial: reduced with BDT (calibrated with control channels).
  - Hadron misidentification: $B^0_{(s)} \to h^+h^-$, $h, h' \in [K, \pi]$.
  - Partially reconstructed decays: (e.g. $B^0 \to \pi^-\mu^+\nu_\mu$).



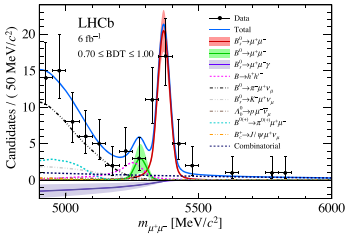
Measurement of the $B_s^0 \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ decay (II)

[10.1103/PhysRevD.105.012010]

- Simultaneous fit through all BDT bins with: Direct search of $B^0_{(s)} \to \mu^+\mu^-$ and indirect search of $B_s^0 \to \mu^+\mu^-\gamma$ through the signature $\mu^+\mu^-$.
  - Search for $B_s^0 \to \mu^+\mu^-\gamma$ limited to high q^2 region due to missing photon reconstruction.
- No signal observed, leading to 95% CL upper limits:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 2.0 \cdot 10^{-9}, \quad m_{\mu\mu} > 4.9\,\mathrm{GeV}/c^2$$

$\Rightarrow$ Consistent with SM.



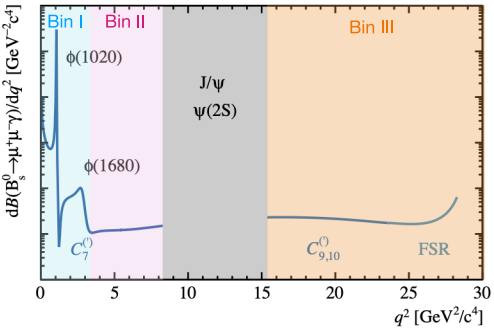
Search for the $B_s^0 \to \mu^+\mu^-\gamma$ decay (I)

[10.1007/JHEP07(2024)101]

- Run 2 data (2016-2018), $\sqrt{s} = 13\,\text{TeV}$, $\mathcal{L} = 5.4\,\text{fb}^{-1}$.
- Full q^2-range analysis $\Rightarrow$ sensitive to more Wilson coefficients.

$\Rightarrow$ Fully reconstructed final state with photons observed in ECAL.

- Analysis split in q^2 bins (veto around $m_{J/\psi}, m_{\psi(2S)}$):
  - I. $[4m_\mu^2, 2.89]\,\text{GeV}^2/c^4$
  - II. $[2.89, 8.29]\,\text{GeV}^2/c^4$
  - III. $[15.37, m_{B_s^0}^2]\,\text{GeV}^2/c^4$
  - IV. Identical to bin I, but with ϕ-veto.
- Each bin is sensitive to different physics effects.



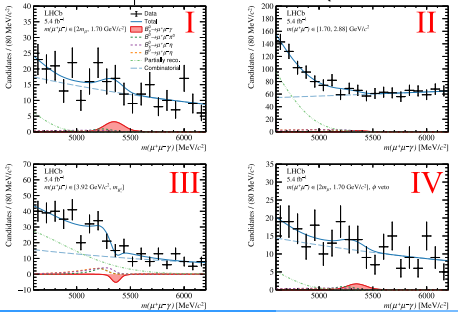
Search for the $B_s^0 \to \mu^+\mu^-\gamma$ decay (II)

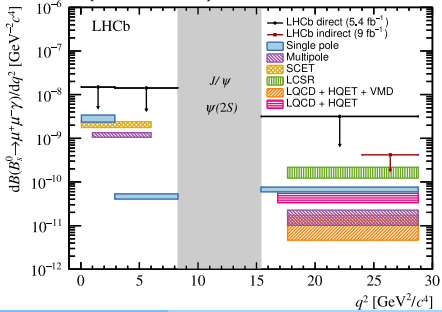
[10.1007/JHEP07(2024)101]

- No signal observed, leading to 95% CL upper limits (ULs):

⇒ Consistent with SM [10.1007/JHEP11(2017)184].

Bin	I	II	III	IV	comb
			$10^8\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)$		
95% CL UL	< 4.2	< 7.7	< 4.2	< 3.4	< 2.8
SM prediction	0.82 ± 0.15	$(2.54 \pm 0.34) \cdot 10^{-2}$	$(9.1 \pm 1.1) \cdot 10^{-2}$	–	–

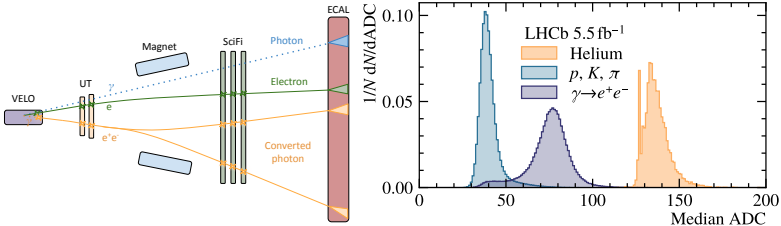




First evidence of the $B_s^0 \to K^-\pi^+\gamma$ decay (I)

[2601.03083]

- Underlying $b \to d\gamma$ process is similarly sensitive to NP as $b \to sll$.
  - Ratio of BRs of decays mediated by $b \to d\gamma$ and $b \to s\gamma$ help to measure $|V_{td}/V_{ts}|$.
  - Inclusion of photon relevant for $b \to sll$ studies.
- Only converted photons ($\gamma \to e^+e^-$) are used;
  - improves mass resolution (due to e momentum reconstruction), reduces $\overline{B}^0 \to K^-\pi^+\gamma$ background,
  - photon vertex matching, reducing combinatorial background.
- BDT trained to reduce combinatorial background using;
  - kinematic and topological properties,
  - VELO charge deposit; strong trace of converted photons.



Credit: right – [JINST19(2024)P02010]

First evidence of the $B_s^0 \to K^-\pi^+\gamma$ decay (II)

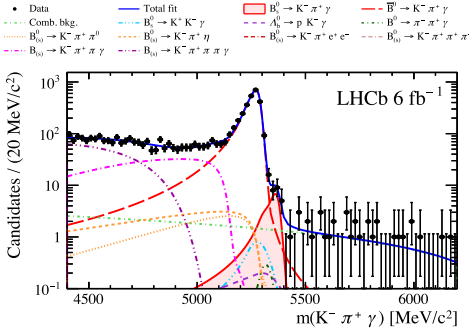
[2601.03083]

- The following data subsets give optimal sensitivity;
  - I. low $m(K^-\pi^+)$, downstream e, Run 1
  - II. low $m(K^-\pi^+)$, downstream e, Run 2
  - III. high $m(K^-\pi^+)$, downstream e, Run 2
  - IV. low $m(K^-\pi^+)$, long e, and Run 2
- Pseudoexperiments show significance of 3.5σ.

$$\mathcal{R} \equiv \frac{\mathcal{B}(B_s^0 \to K^-\pi^+\gamma)}{\mathcal{B}(\overline{B}^0 \to K^-\pi^+\gamma)} = \begin{cases} (3.7 \pm 1.2 \pm 0.4) \cdot 10^{-2} & \text{low } m(K^-\pi^+) \\ (0.2 \pm 2.7 \pm 1.3) \cdot 10^{-2} & \text{high } m(K^-\pi^+) \end{cases}$$

$\Rightarrow$ Excellent agreement with SM.

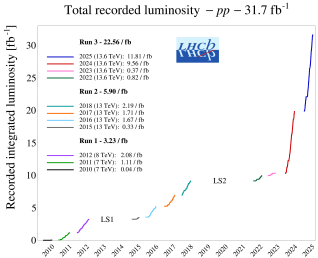
Low $m(K^-\pi^+)$	796–996 MeV/c^2
High $m(K^-\pi^+)$	996–1800 MeV/c^2
Long tracks	Hits in full tracking system
Downstream tracks	Hits only after VELO



Data subset II, which has the highest signal yield

Conclusions

- All observations and limits presented here are consistent with the SM.
  - $B_s^0 \to \phi e^+ e^-$ angular analysis
  - Indirect search for $B_s^0 \to \mu^+\mu^-\gamma$ through $\mu^+\mu^-$ signature
  - Search for $B_s^0 \to \mu^+\mu^-\gamma$ with photons observed in ECAL
  - Evidence of $B_s^0 \to K^-\pi^+\gamma$ with converted photons
- Increased Run 3 (2024–2026) LHCb luminosity and improved electron sensitivity, leading to improved sensitivity to these channels.
- Improved mass resolution inherent to studying converted photons can similarly aid in improving sensitivity.
  - Value of converted photons demonstrated in $B_s^0 \to K^-\pi^+\gamma$ study [2601.03083].



TOS efficiencies in $B^+ \to J/\psi\,(e^+e^-)\,K^+$.

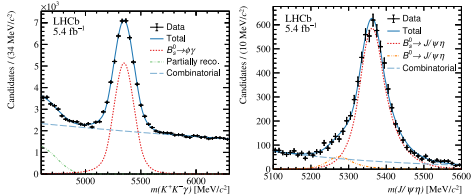
Credits: top – [LHCb Operations 2025], bottom – [LHCB-FIGURE-2024-030]

Backup

Search for the $B_s^0 \to \mu^+\mu^-\gamma$ decay

[10.1007/JHEP07(2024)101]

- Combinatorial background: Reduced with MLP classifier
  - Trained on data outside of signal mass region and simulated signal events.
  - A second MLP classifier is applied to each q^2 bin.
- Partially reconstructed backgrounds:
  - $B_s^0 \to \mu^+\mu^-(\phi \to \pi^+\pi^-\pi^0)$, $B^0 \to \mu^+\mu^-(\eta' \to \rho^0\gamma)$, $B^0 \to (D^- \to \pi^0\mu^-\overline{\nu}_\mu)\mu^+\nu_\mu$.
- Peaking backgrounds:
  - $B^0 \to \mu^+\mu^-(\pi^0 \to \gamma\gamma)$, $B^0_{(s)} \to \mu^+\mu^-(\eta \to \gamma\gamma)$.
- Control channel $B_s^0 \to (\phi \to K^+K^-)\gamma$ to correct for MC/data disagreements.
- Normalized to $B_s^0 \to (J/\psi \to \mu^+\mu^-)(\eta \to \gamma\gamma)$.



First evidence of the $B_s^0 \to K^-\pi^+\gamma$ decay

[2601.03083]

- Run 1 ($\sqrt{s} = 7, 8\,\mathrm{TeV}, \mathcal{L} = 3\,\mathrm{fb}^{-1}$) and Run 2 ($\sqrt{s} = 13\,\mathrm{TeV}, \mathcal{L} = 6\,\mathrm{fb}^{-1}$) data is used.
- Control samples: $\overline{B}^0 \to K^-\pi^+\gamma$, $B_s^0 \to K^+K^-\gamma$, $\Lambda_b^0 \to pK^-\gamma$ to correct for data-simulation differences in kinematic properties and detector effects.
  - $B_s^0 \to K^+K^-\gamma$, $\Lambda_b^0 \to pK^-\gamma$ are also used to study particle misidentification.
- Partially reconstructed backgrounds: (e.g. $B \to K^-\pi^+\pi(\pi)\gamma$)
- Misidentified backgrounds: (e.g. $B_s^0 \to K^+K^-\gamma$)
- Additional resolution improvements;
  - uncertainty off B-meson mass below $20\,\mathrm{MeV}/c^2$, photon mass below $40\,\mathrm{MeV}/c^2$,
  - electrons with Bremsstrahlung photons with $E_\mathrm{T} > 75\,\mathrm{MeV}$ are not considered.