Rare and very rare decays at the LHCb experiment

Moriond Electroweak 2026
60th Rencontres de Moriond

H. Tilquin on behalf of the LHCb collaboration

15-22 March 2026

On the interest of (very) rare decays

- Direct searches or 'bump hunts'
  - Would lead to immediate discovery of new physics
  - **Very constrained** by energy of accelerator
- Indirect searches for (very) rare decays
  - Large change from Standard Model (SM): evidence that new physics is present (but so far, only hints)
  - **Not constrained** by energy of accelerator

On the interest of (very) rare decays

- Very rare decays: processes that should not be attainable / have not been observed (yet) given SM prediction and detector sensitivity
  - Lepton flavour violating decays
  - Lepton number violating decays
  - Low-branching fraction decays
    - For example, FCNC B-meson decays to taus (at least one missing neutrino per tau)
- Observation of a very rare decay could then hint at new physics (NP) beyond the SM, or a misunderstanding in existing calculations

See talk by C. Langenbruch for more FCNC decays at LHCb

LHCb detector in Run 2

- LHCb only covers a tiny fraction of the solid angle
  - Missing information, but excellent muon system and particle identification performance

LHCb-PHO-GEN-2012-001-4

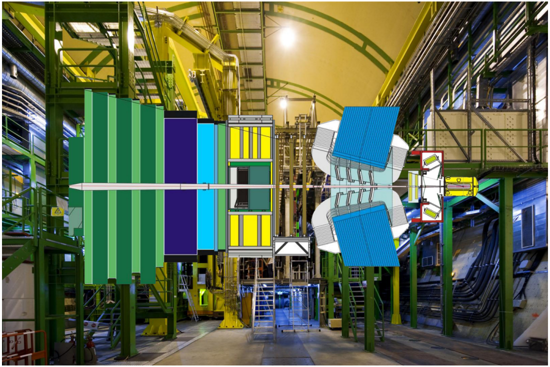


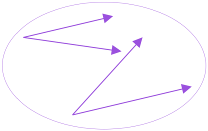
Figure: LHCb detector in Run 2, as observed from the viewing platform

During 2016–2018, LHCb collected *pp* collision data at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.4 fb^{-1}.

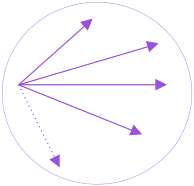
Rare decay analyses: the basics

Background types

- Focusing on decays that we cannot see in the SM ⇒ overwhelmingly dominated by background contributions
  - **Combinatorial background**: particles do not come from the same decay
    - ⋆ Represented with data: (signal-free) sideband, or wrong-sign end-state



  - **Physics background**: particles come from a non-signal decay (there could also be missing particles, such as charged tracks or neutrinos)
    - ⋆ Represented from background-enriched part of the data, or simulation



  - **Misidentified (misID) background**: some particles are misidentified

Our goal

Identify what backgrounds are present, represent them properly and reduce them as much as possible, while retaining a high sensitivity to signal.

Background removal

- Need proper way to represent / decrease misID as much as possible: topology of misID background could be the same as that of signal
  - Fortunately, LHCb has an **excellent particle identification system**
- If basic cuts not useful, using **boosted decision trees** (BDTs) or neural networks to separate signal from background

A default background removal strategy would consist of applying a series of cuts and BDTs to data.

Final fit and (for now) upper limit

- Once background is reduced as much as possible, need to understand what is left – is there any signal?
- Fitting **mass distribution** or **BDT output** to try and understand what is left
  - Templates vary between known analytic and parametric functions
- Upper limit is then obtained with the CL_s method in all cases explored here

Rare decay analyses at LHCb

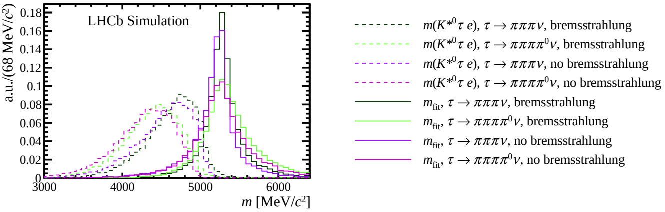
Note

All analyses reported here concern Run 2 and (when mentioned) Run 1 of the LHC, corresponding to an integrated luminosity of 5.4 fb^{-1} for the Run 2 case and 9 fb^{-1} for the Run 1 + Run 2 case. Ongoing effort to perform (very) rare decays analyses using Run 3 data!

Search for LFV (1)

JHEP 11 (2025) 172

- LFV in the SM would happen with branching fractions of $< \mathcal{O}(10^{-50})$ but could be much more prevalent if NP were present (*eg.* 10^{-10} [PRD 95 (2017) 035022])
- Search for $B^0 \to K^*(892)^0 \tau^\pm e^\mp$, using $\tau \to \pi\pi\pi(\pi^0)\nu$ decays
  - Missing information due to neutrino, which cannot be detected directly at LHCb, and from π^0, which is ignored in the reconstruction
    - ★ Three-prong tau decay allows to reconstruct the tau decay vertex
    - ★ B^0 vertex reconstructed from $K^*(892)^0$ and electron
    - ★ Tau mass is known and can be used as constraint for the tau candidate
  - Mass resolution worsened by bremsstrahlung effects ⇒ signal shape modelled differently when bremsstrahlung photons are detected



With the constraints outlined above, the reconstructed B^0 mass $m_{\rm fit}$ is much improved.

Search for LFV (1)

JHEP 11 (2025) 172

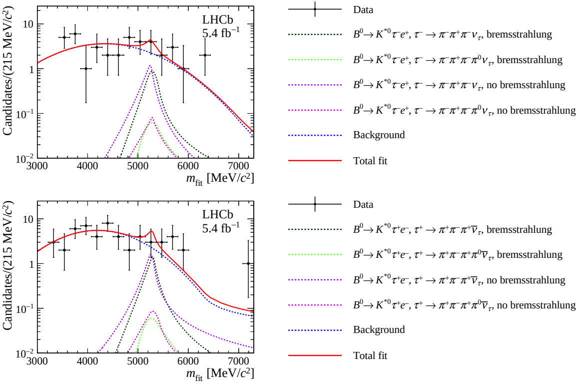
- Reducing the following backgrounds sequentially
  - Combinatorial background
  - Non-isolated candidates
  - Charm background. D-mesons have a decay time comparable to that of the tau and make up a large component of background.
  - MisID
- Dominant systematic stemming from choice of the background control region (obtained from loosening some of the selection cuts above)
- Fitting the constrained mass $m_{\rm fit}$

JHEP 11 (2025) 172

Search for LFV (1)

- Upper limits obtained separately on different charge combinations
  - Potentially different impact from NP models
  - Different sources of background

$$\mathcal{B}(B^0 \to K^{*0}\tau^- e^+) < 5.9\,(7.1) \times 10^{-6} \text{ @ } 90\% \ (95\%) \text{ CL}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^+ e^-) < 4.9\,(5.9) \times 10^{-6} \text{ @ } 90\% \ (95\%) \text{ CL} \qquad (1)$$



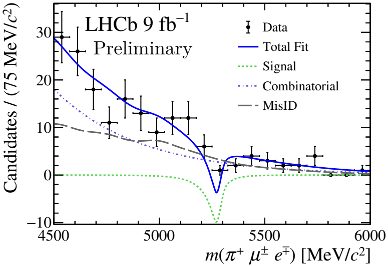
Most stringent constraint on LFV $b \to s\tau\ell$ transitions so far.

Search for LFV (2)

NEW LHCb-PAPER-2026-013 (in preparation)

- LHCb recently conducted its first search for $B^+ \to \pi^+ \mu^\pm e^\mp$
- Two BDTs:
  - BDT 1: reduces combinatorial background using upper mass sideband
  - BDT 2: reduces remaining combinatorial and physics backgrounds using lower mass sideband
- Dominant systematic stems from modelling of background component
- Most stringent limit on $B^+ \to \pi^+ \mu^\pm e^\mp$

$$\mathcal{B}(B^+ \to \pi^+ \mu^\pm e^\mp) < 1.8\,(2.2) \times 10^{-9} \text{ @ } 90\% \; (95\%) \text{ CL} \qquad (2)$$



Uses 9 fb^{-1} of LHCb data and improves on previous measurements by two order of magnitudes.

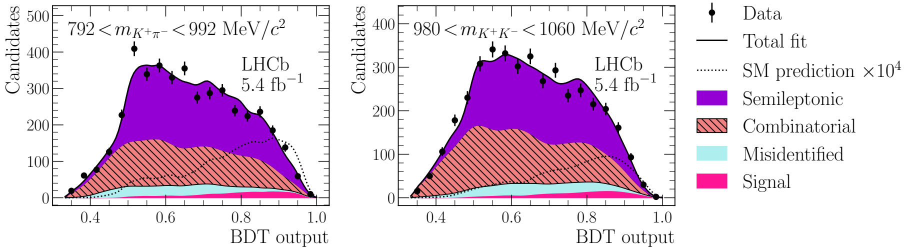
Search for $b \to s\tau\tau$

- Several new physics models predict large enhancements in $b \to s\tau\tau$ transitions – these decays have branching fractions of $\mathcal{O}(10^{-7})$ in the SM [PRL 120 (2018) 181802] but are hard to attain experimentally
- Searches for the decays $B^0 \to K^+\pi^-\tau^+\tau^-$ and $B^0_s \to K^+K^-\tau^+\tau^-$ with $\tau \to \mu\nu\nu$
  - B-meson vertex reconstructed from the two hadrons
  - Muons much 'cleaner' than other particles – easily identified and momentum well-reconstructed

Four missing neutrinos – (corrected) reconstructed mass not used in the final fits.

Search for $b \to s\tau\tau$

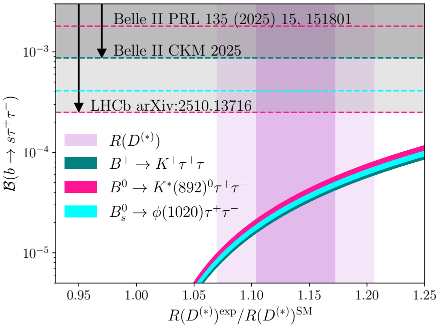
- Reducing backgrounds with a series of cuts and a BDT
  - Removing backgrounds of the type $B \to DDX$ with cuts on the reconstructed missing mass and reconstructed q^2
  - Using a multi-class BDT to separate signal from combinatorial and physics (semileptonic) background
- Not fitting (constrained) reconstructed mass as in other analyses presented here, but rather fitting the BDT output
  - Shapes are defined with a kernel density estimation



Search for $b \to s\tau\tau$

- Dominant systematic: uncertainty on background shape due to the limited size of the data-derived proxies
- Upper limits are obtained in bins of dihadron mass and recast as limits on resonances, Wilson coefficients and $\mathcal{B}(B_s^0 \to K^-\pi^+\tau^+\tau^-)$

$$\begin{aligned} \mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) &< 2.8\,(2.5) \times 10^{-4} \text{ @ } 95\%\ (90\%)\ \text{CL} \\ \mathcal{B}(B_s^0 \to \phi\tau^+\tau^-) &< 4.7\,(4.1) \times 10^{-4} \text{ @ } 95\%\ (90\%)\ \text{CL} \end{aligned} \quad (3)$$

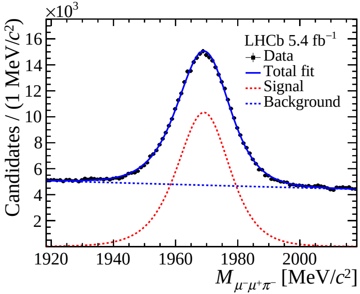


→ NP predictions from PRL 120 (2018) 181802, using latest results from HFLAV

Either new results, or world's best results.

Search for $\tau^+ \to \mu^+\mu^-\mu^+$

- $\mathcal{B}(\tau^+ \to \mu^+\mu^-\mu^-)$ very small in the SM ($\sim 10^{-55}$ [EPJC 80 (2020) 506]), but NP models predict large enhancements to $10^{-10} - 10^{-8}$ [PRD 66 (2002) 034008, PRL B547 (2002) 252]
- Reducing backgrounds with a BDT, and fitting the multimuon reconstructed mass
  - BDT 1 dedicated to removing combinatorial background
  - BDT 2 dedicated to removing background where hadrons are misidentified as muons (*eg.* hadronic $D^-_{(s)}$ decays)

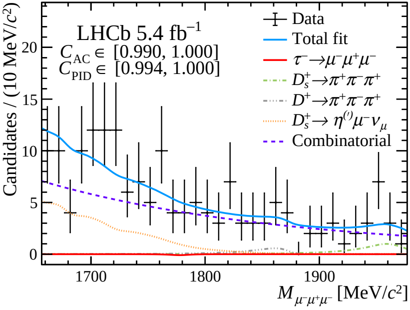


$\to$ Normalisation channel: $D_s^- \to \phi(\to \mu^-\mu^+)\pi^-$

Search for $\tau^+ \to \mu^+\mu^-\mu^+$

- Dominant systematic uncertainties due to external factors (such as knowledge of $f^{\tau}_{D_s}$)
- Resulting upper limit similar to that obtained by Belle II

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 1.9\,(2.3) \times 10^{-8} \text{ @ } 90\%\ (95\%)\ \text{CL} \quad (4)$$

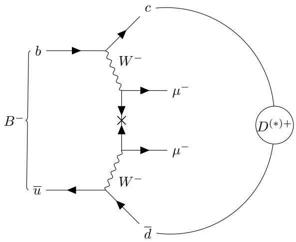


Results on par with those from Belle II – for more details see talk by D. Riccardi.

Search for lepton number violation

arXiv:2601.07657

- Decays such as $B^- \to D^{(*)+}\mu^-\mu^-$ would violate lepton number – if Majorana neutrinos existed, their branching fraction would be $\mathcal{O}(10^{-23}) - \mathcal{O}(10^{-22})$ [PRD 82 (2010) 053010]
  - Far from attainable branching fraction, but searches provide useful constraints on lepton number violating processes

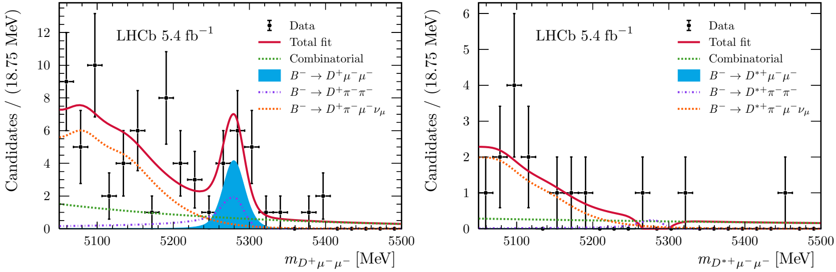


- BDT used to separate simulated signal from combinatorial background
- Pion misID to muon and pion decay in flight form a non-negligible background component

Search for lepton number violation

- Dominant systematic stemming from the decay model of the signal, assumed to be generated uniformly in phase-space

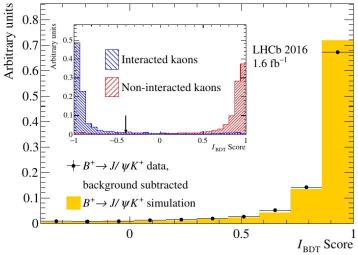
$$\mathcal{B}(B^- \to D^+\mu^-\mu^-) < 3.8\,(4.6) \times 10^{-8} \text{ @ } 90\% \ (95\%) \text{ CL}$$
$$\mathcal{B}(B^- \to D^{*+}\mu^-\mu^-) < 4.5\,(5.9) \times 10^{-8} \text{ @ } 90\% \ (95\%) \text{ CL} \quad (5)$$



Improves on previous measurements by an order of magnitude.

Loop-suppressed annihilation processes

- The process $B^0 \to \phi\phi$ is both OZI- and Cabibbo-suppressed
  - Branching fraction between 0.5×10^{-8} and 5×10^{-8} in SM (see *eg.* PDR 67 (2003) 014007, PRD 89 (2014) 014003)
- Background from $\mathcal{B}(B_s^0 \to \phi\phi)$
  - Tail dominated by kaons interacting hadronically with the tracking system or decaying to muons in flight
  - Using BDT to separate such kaons using *eg.* the track kinematics
  - Requiring no activity in muon stations associated with kaon tracks
- Dikaons required to be close to the nominal ϕ mass, reducing misID
- Combinatorial background (from D_s^- and generic) reduced with BDTs

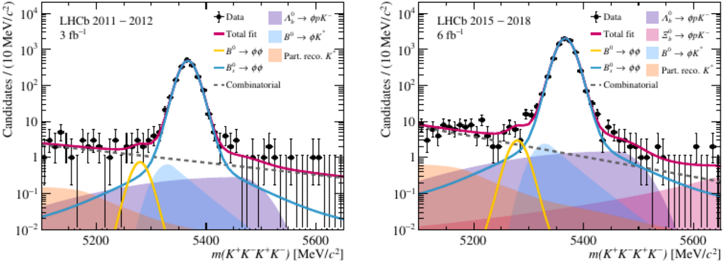


The analysis uses Run 1 *and* Run 2 data, corresponding to an integrated luminosity of 9 fb^{-1}.

Loop-suppressed annihilation processes

- Largest source of systematic uncertainty: uncertainty on (known) branching fraction of $B_s^0 \to \phi\phi$
- No signal observed and upper limit set at

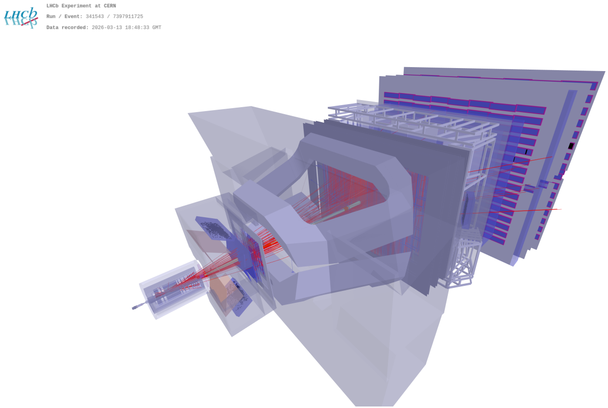
$$\mathcal{B}(B^0 \to \phi\phi) < 1.3\,(1.4) \times 10^{-8} \text{ @ } 90\% \ (95\%) \text{ CL} \tag{6}$$



Factor of 2 improvement in the upper limit.

Conclusion and future

- A series of world-leading results obtained by LHCb, but more to come with Run 3 data
  - Mainly **new** detector (with a series of sub-detectors being **added** or **upgraded**)
  - **Fully software trigger** (with a readout at 40 MHz) leading to larger efficiencies at low momenta



LHCb Event Display

Conclusion and future

- A series of world-leading results obtained by LHCb, but more to come with Run 3 data
  - (Very) rare decays $\Rightarrow$ statistics matter
  - More data being collected, as we speak!

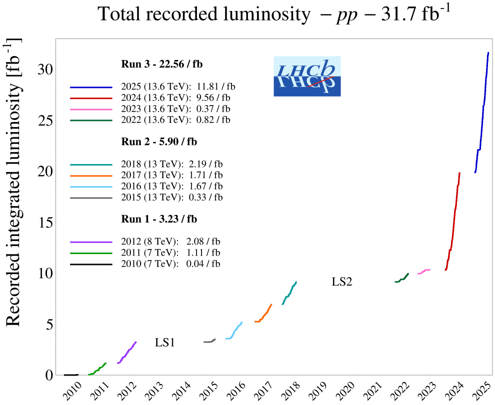


Figure: Luminosity recorded by LHCb in all Runs of the LHC [LHCb Operations Plots].

Thank you for your attention!

Backup

$B^0 \to K^*(892)^0 \tau^\pm e^\mp$: NP models

- A phase-space model is assumed for the signal decay
  - Kinematic distributions, and therefore efficiencies, could change with different NP models

Table: Limits at 90% (95%) CL with two NP models

Model	Upper limit $[10^{-6}]$	
	$B^0 \to K^{*0}\tau^- e^+$	$B^0 \to K^{*0}\tau^+ e^-$
Phase space	5.9 (7.1)	4.9 (5.9)
Left-handed ($\mathcal{C}_9^{\tau e} = -\mathcal{C}_{10}^{\tau e} \neq 0$)	6.3 (7.7)	5.4 (6.4)
Scalar ($\mathcal{C}_S^{\tau e} \neq 0$)	6.6 (8.0)	5.7 (6.8)

Limits on $b \to s(d)\tau^+\tau^-$ and Wilson coefficients

Table: Upper limits on $b \to s\tau^+\tau^-$ and $b \to d\tau^+\tau^-$ branching fractions in bins of dihadron mass at 90% and 95% CL.

CL	Upper limit on $\mathcal{B}(B^0 \to K^+\pi^-\tau^+\tau^-)$				
$m_{K^+\pi^-}$ (MeV)	[792, 992]	[992, 1330]	[1330, 1530]	[1530, 1726]	
90%	1.4×10^{-4}	2.7×10^{-5}	1.0×10^{-5}	2.7×10^{-6}	
95%	1.6×10^{-4}	3.4×10^{-5}	1.1×10^{-5}	3.3×10^{-6}	
CL	Upper limit on $\mathcal{B}(B_s^0 \to K^+K^-\tau^+\tau^-)$				
$m_{K^+K^-}$ (MeV)	[980, 1060]	[1060, 1200]	[1200, 1400]	[1400, 1600]	[1600, 1813]
90%	2.0×10^{-4}	1.3×10^{-4}	1.2×10^{-4}	6.8×10^{-5}	3.2×10^{-5}
95%	2.3×10^{-4}	1.5×10^{-4}	1.4×10^{-4}	7.6×10^{-5}	3.6×10^{-5}
CL	Upper limit on $\mathcal{B}(B_s^0 \to K^-\pi^+\tau^+\tau^-$				
$m_{K^+\pi^-}$ (MeV)	[792, 992]	[992, 1330]	[1330, 1530]	[1530, 1726]	
90%	6.5×10^{-4}	1.2×10^{-4}	5.1×10^{-5}	1.7×10^{-5}	
95%	7.3×10^{-4}	1.5×10^{-4}	6.2×10^{-5}	2.1×10^{-5}	

Table: Upper limit on Δ^2 at 90% and 95% CL, assuming $\mathcal{C}_{9(10)}^{\mathrm{NP}} = \mathcal{C}_{9(10)}^{\mathrm{SM}} \mp \Delta$ (see PRL 120 (2018) 181802).

CL	$B^0 \to K^+\pi^-\tau^+\tau^-$	$B_s^0 \to K^+K^-\tau^+\tau^-$
90%	2.5×10^4	4.5×10^4
95%	2.9×10^4	5.2×10^4

$b \to s\tau\tau$: central values

Table: Central values for $\mathcal{B}(B^0 \to K^+\pi^-\tau^+\tau^-)$, $\mathcal{B}(B_s^0 \to K^+K^-\tau^+\tau^-)$ and $\mathcal{B}(B_s^0 \to K^-\pi^+\tau^+\tau^-)$ decays. The first uncertainties are statistical, the second ones are systematic.

Central value for $\mathcal{B}(B^0 \to K^+\pi^-\tau^+\tau^-)$					
$m_{K^+\pi^-}$ (MeV)	$[792, 992]$	$[992, 1330]$	$[1330, 1530]$	$[1530, 1726]$	
	$(9.3 \pm 3.7 \pm 3.6) \times 10^{-5}$	$(-1.9^{+1.6}_{-1.5} \pm 2.4) \times 10^{-5}$	$(2.5^{+3.2}_{-3.1} \pm 4.7) \times 10^{-6}$	$(-1.2 \pm 1.1 \pm 1.9) \times 10^{-6}$	
Central value for $\mathcal{B}(B_s^0 \to K^+K^-\tau^+\tau^-)$					
$m_{K^+K^-}$ (MeV)	$[980, 1060]$	$[1060, 1200]$	$[1200, 1400]$	$[1400, 1600]$	$[1600, 1813]$
	$(1.1 \pm 0.5 \pm 0.8) \times 10^{-4}$	$(-3.4^{+5.4}_{-5.3} \pm 8.5) \times 10^{-5}$	$(5.3^{+3.3}_{-3.2} \pm 5.7) \times 10^{-5}$	$(4.6 \pm 1.3 \pm 1.9) \times 10^{-5}$	$(2.4 \pm 0.5 \pm 0.9) \times 10^{-5}$
Central value for $\mathcal{B}(B_s^0 \to K^-\pi^+\tau^+\tau^-)$					
$m_{K^+\pi^-}$ (MeV)	$[792, 992]$	$[992, 1330]$	$[1330, 1530]$	$[1530, 1726]$	
	$(4.2^{+1.6}_{-1.5} \pm 1.6) \times 10^{-4}$	$(-7.5^{+6.6}_{-6.4} \pm 9.8) \times 10^{-5}$	$(1.3 \pm 1.7 \pm 2.6) \times 10^{-5}$	$(-6.2 \pm^{7.0}_{6.8} \pm 11.6) \times 10^{-6}$	

JHEP 12 (2025) 026

$B^0 \to \phi\phi$: theoretical predictions

- Given the current upper limit on $\mathcal{B}(B^0 \to \phi\phi)$, lower values of the branching fraction predictions are favoured