Rare decays (excluding $b \to s l^+ l^-$)

19th International Conference on B-physics at Frontier Machines (Beauty 2020)
Tokyo (virtual), 21st September – 24th September 2020

Ifan Williams (iwilliam@cern.ch)
on behalf of the LHCb collaboration

LHCb

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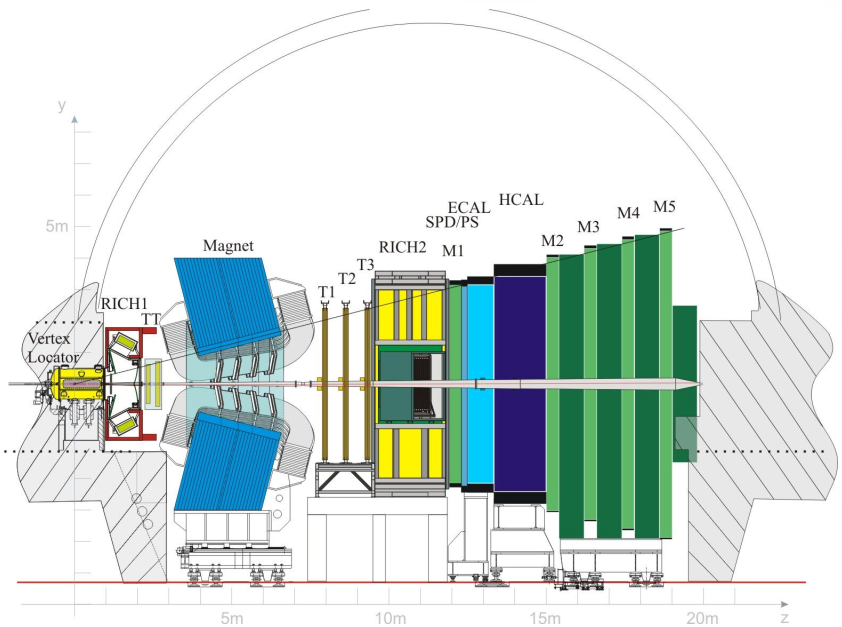
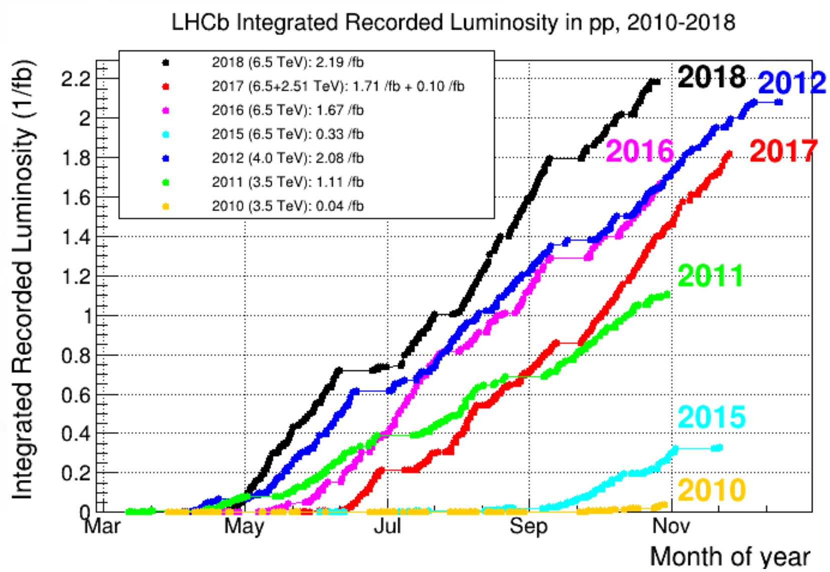
- Why rare decays?
- Selection of recent analyses:
  - $B^0_{(s)} \to \mu^+\mu^-$ combination (ATLAS + CMS + LHCb) [CERN-LHCb-CONF-2020-002]
  - Search for the rare decays $B^0_s \to e^+e^-$ and $B^0 \to e^+e^-$ [Phys. Rev. Lett. 124 (2020) 211802]
  - Search for the lepton flavour violating decay $B^+ \to K^+\mu^-\tau^+$ using B^{*0}_{s2} decays [JHEP 06 (2020) 129]
  - Measurement of CP-violating and mixing-induced observables in $B^0_s \to \phi\gamma$ decays [Phys. Rev. Lett. 123 (2019) 081802]
  - First observation of the radiative decay $\Lambda^0_b \to \Lambda\gamma$ [Phys. Rev. Lett. 123 (2019) 031801]
  - Searches for 25 rare and forbidden decays of D^+ and D^+_s mesons [LHCb-PAPER-2020-007 (in preparation) – see ICHEP20 Talk]
- Summary

(Very Rare Decays: first three analyses; Radiative Decays: fourth and fifth; Charm Physics: sixth)

LHCb experiment

- Single-arm forward spectrometer at the LHC designed for the study of heavy flavour physics
- Pseudorapidity coverage $2 < \eta < 5$ and collisions occur at reduced instantaneous luminosity compared to ATLAS/CMS
- Boosted heavy flavour hadrons travel $\sim$ cm at small angles relative to beam axis, leading to decay vertices displaced from production vertices – experiment exploits this topology



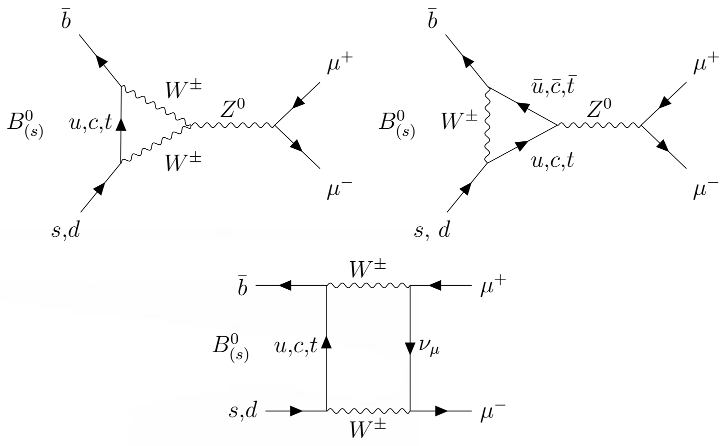


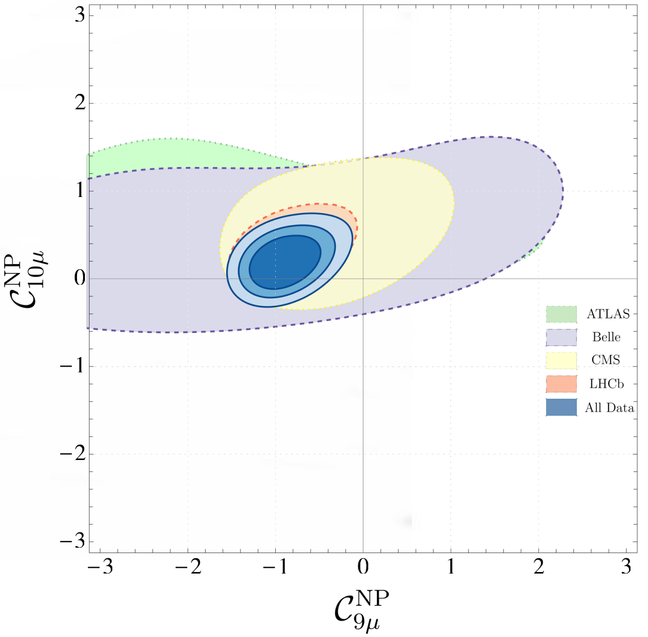
$\sim 10\text{fb}^{-1}$ delivered, $\sim 9\text{fb}^{-1}$ recorded

Why rare decays?

- Flavour changing neutral currents forbidden at tree level in SM – rare decays often Cabibbo/helicity suppressed
- Off shell NP contributions can significantly alter rates and angular observables compared to SM predictions
- Search for decays forbidden in the SM - allowed in some NP models
- Effective field theory formalism used to parametrise short distance effects - combine measurements and perform global fits to observables (tension in several $b \rightarrow sl^+l^-$ measurements – see talk by Da Yu Tou)

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi} \sum_i \mathcal{C}_i \mathcal{O}_i$$



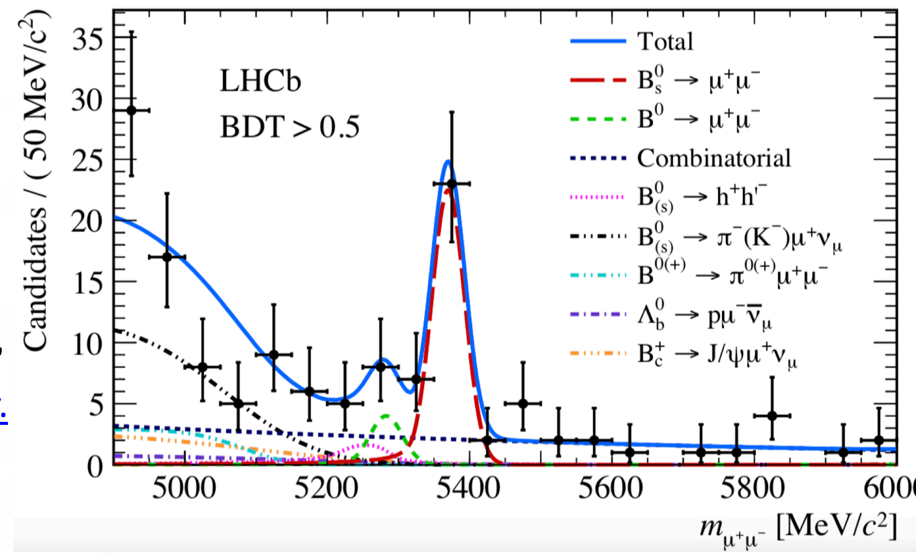


[Eur. Phys. J. C, 80 6 (2020) 511]

$B^0_{(s)} \to \mu^+\mu^-$ combination (ATLAS + CMS + LHCb)

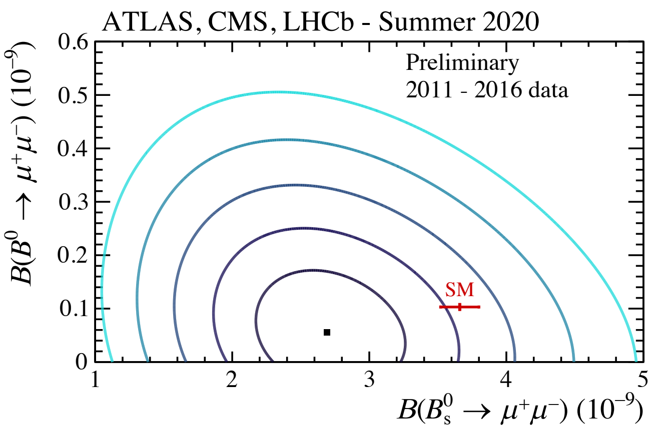
Normalisation channels:
$B^+ \to J/\psi(\to \mu^+\mu^+)K^+$
and $B^0 \to K^+\pi^-$ (LHCb only)

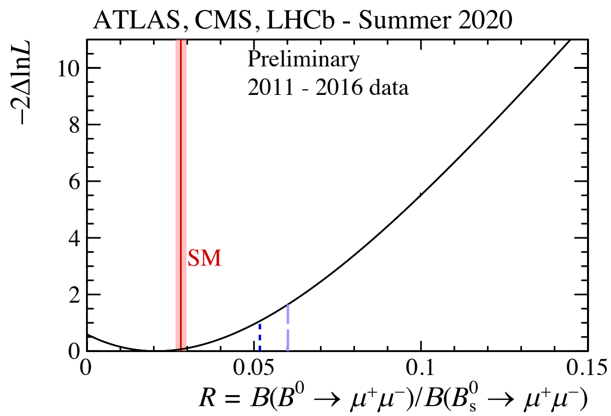
- $B^0_{(s)} \to \mu^+\mu^-$ decays highly suppressed in the SM (loop + helicity) – excellent NP probe
- Measured observables:
  - Branching fractions of $B^0_{(s)} \to \mu^+\mu^-$ decays
  - Ratio of branching fractions ($\mathcal{R}$)
  - Effective lifetime of $B^0_s \to \mu^+\mu^-$ decays $(\tau_{\mu\mu})$
- ATLAS [JHEP 04 (2019) 098] (excluding $\tau_{\mu\mu}$) , CMS [JHEP 04 (2020) 188] and LHCb [Phys. Rev. Lett. 118, 191801 (2017)] all published results with $B^0_{(s)} \to \mu^+\mu^-$ decays – measurements combined using (profile) likelihoods

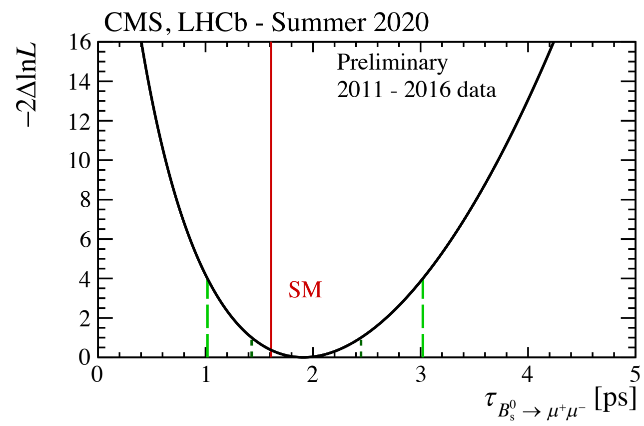


Experiment	Data-taking years (CoM energy (TeV), Int luminosity (fb^{-1}))
ATLAS	11(7, 4.9), 12(8, 20), 15-16(13, 26.3)
CMS	11(7, 5), 12(8, 20), 16(13, 36)
LHCb	11(7, 1), 12(8, 2), 15-16(13, 1.4)

$B^0_{(s)} \to \mu^+\mu^-$ combination (ATLAS + CMS + LHCb)







$$\mathcal{B}(B^0_s \to \mu^+\mu^+) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^+) < 1.6\ (1.9) \times 10^{-10}$$
at 90% (95%)CL

$$\mathcal{R} < 0.052\ (0.060)$$
at 90% (95%) CL

$$\tau_{\mu\mu} = 1.91^{+0.37}_{-0.35}\ \text{ps}$$

- $B^0_s \to \mu^+\mu^-$ BF result is compatible at 2.4σ with SM
- $B^0 \to \mu^+\mu^-$ BF limit is compatible at 0.64σ with SM
- 2-D compatibility at 2.1σ with SM

$$\mathcal{B}(B^0_s \to \mu^+\mu^-)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{SM} = (1.03 \pm 0.05) \times 10^{-10}$$
$$(\tau_{\mu\mu})_{SM} = 1.609 \pm 0.010\ \text{ps}$$

[JHEP 10 (2019) 232]

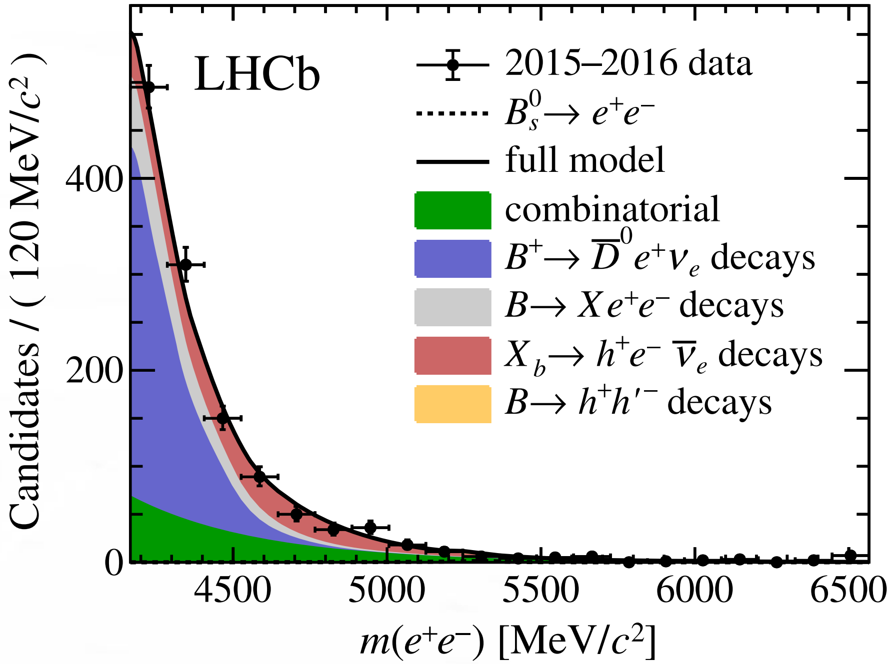
- Most precise measurement to date!

Search for the rare decays $B_s^0 \rightarrow e^+e^-$ and $B^0 \rightarrow e^+e^-$

Normalisation channel :
$B^+ \rightarrow J/\psi(\rightarrow e^+e^-)K^+$

- Helicity suppressed by $\mathcal{O}(10^{-4})$ relative to $B^0_{(s)} \rightarrow \mu^+\mu^-$ - NP effects could increase BFs by $\mathcal{O}(10^6)$ - SM null test
- Simultaneous fit to data split by run and bremsstrahlung category
- Selection BDT incorporates MVA-based isolation tools developed for $B^0_{(s)} \rightarrow \mu^+\mu^-$ analysis to improve performance
- Yield of physical background (partially reconstructed and misidentified) components constrained in the fit to expected values

Data-taking years
11, 12, 15 - 16

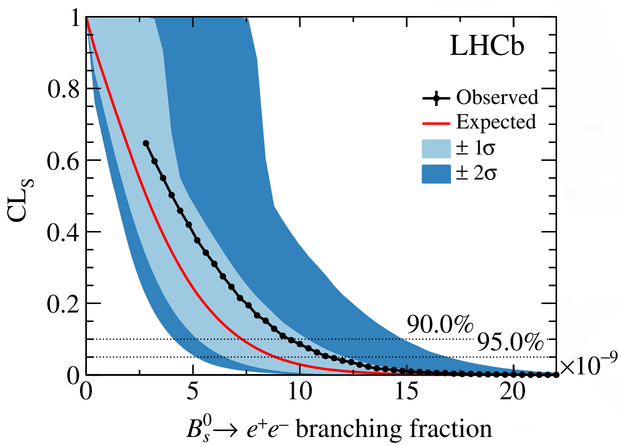


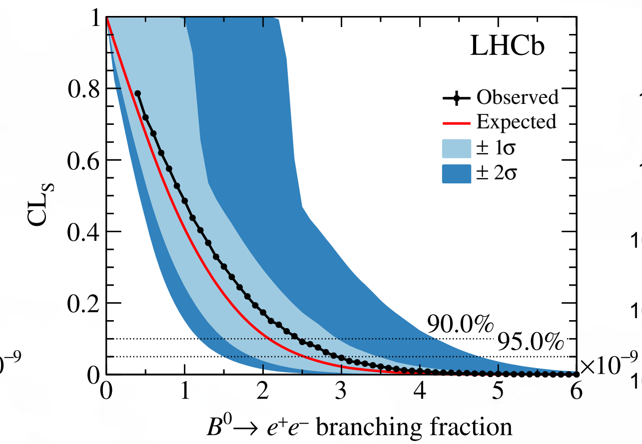
$$\mathcal{B}(B_s^0 \rightarrow e^+e^-)_{SM} = (8.35 \pm 0.39) \times 10^{-14}$$
$$\mathcal{B}(B^0 \rightarrow e^+e^-)_{SM} = (2.39 \pm 0.14) \times 10^{-15}$$

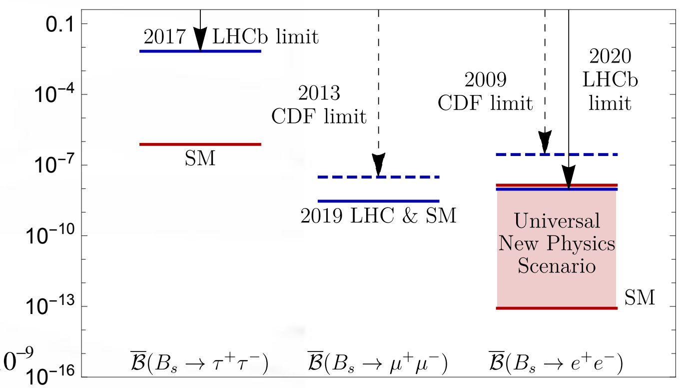
[JHEP 05 (2017) 156]

Search for the rare decays $B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$

- No excess of events are observed over the background – limits set (while neglecting the contribution from the other decay) using the CL_s method







$\mathcal{B}(B_s^0 \to e^+e^-) < 9.4\ (11.2) \times 10^{-9}$

$\mathcal{B}(B^0 \to e^+e^-) < 2.5\ (3.0) \times 10^{-9}$

at 90% (95%) CL

Previous results from the CDF collaboration

$\mathcal{B}(B_s^0 \to e^+e^-)_{\mathrm{CDF}} < 2.8 \times 10^{-7}$

$\mathcal{B}(B^0 \to e^+e^-)_{\mathrm{CDF}} < 8.3 \times 10^{-8}$

at 90% CL [Phys. Rev. Lett. 102 (2009) 201801]

- World leading limit!

[JHEP 06 (2020) 129]

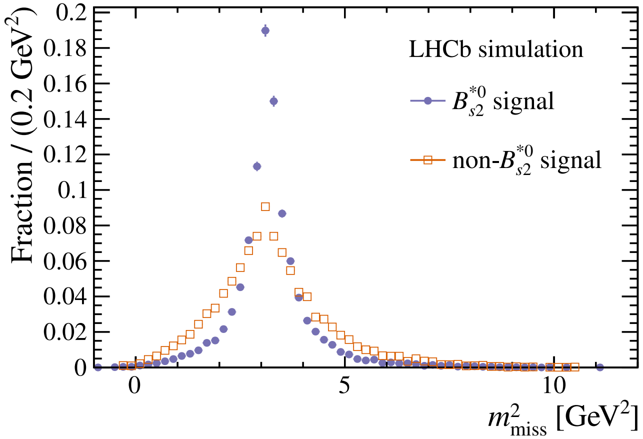
Search for the lepton flavour violating decay $B^+ \to K^+\mu^-\tau^+$ using B_{s2}^{*0} decays

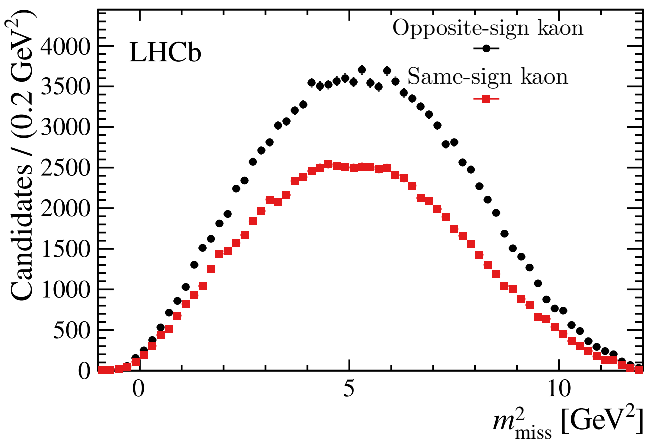
- Decay is forbidden in the SM but predicted in several LFV models
  - PS[3] model predicts $\mathcal{B}(B^+ \to K^+\mu^-\tau^+) \sim 10^{-5}$ [JHEP 10 (2018) 148]
- τ four-momentum fully reconstructed using $B_{s2}^{*0} \to B^+K^-$ decays (~1% of B^+production)
  - Kinematic constraints used to reconstruct missing mass m_τ - search for peak in m_τ^2 distribution
- Select τ inclusively offline by requiring additional charged track near $K^+\mu^-$ pair

Previous result from the BaBar collaboration
$\mathcal{B}(B^+ \to K^+\mu^-\tau^+)_{\text{BaBar}} < 2.8 \times 10^{-5}$
at 90% CL [Phys. Rev. D 86, 012004 (2012)]

Data-taking years
11, 12, 15, 16, 17, 18

Normalisation channel :
$B^+ \to J/\psi(\to \mu^+\mu^-)K^+$

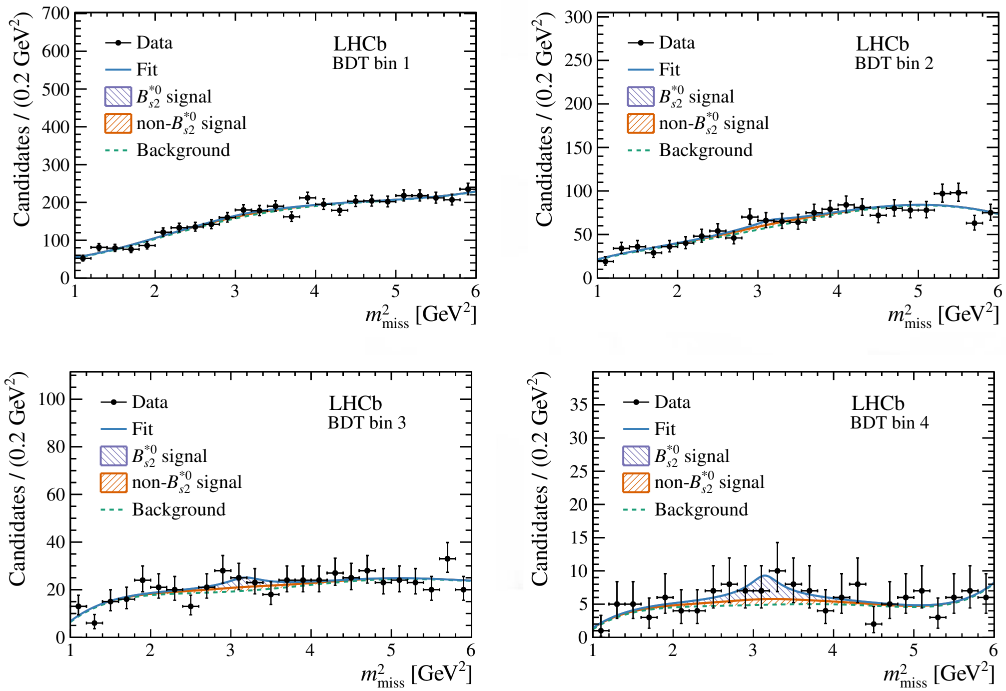


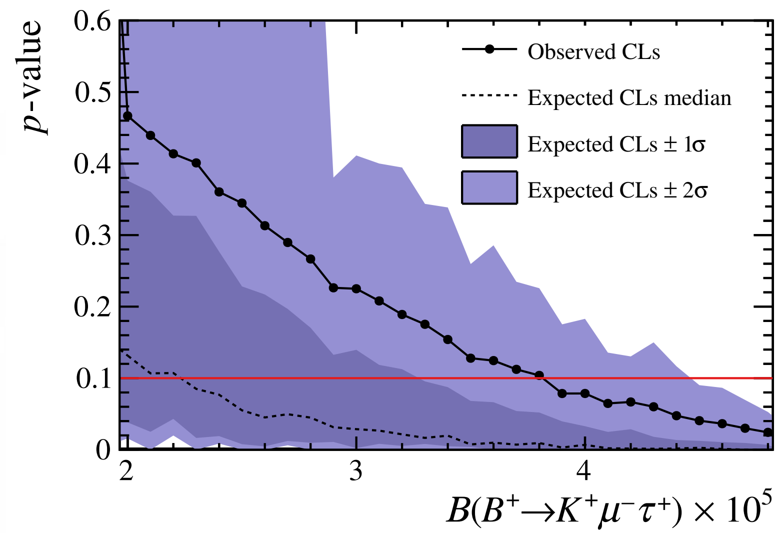


[JHEP 06 (2020) 129]

Search for the lepton flavour violating decay $B^+ \to K^+\mu^-\tau^+$ using B_{s2}^{*0} decays

- Simultaneous fit to data in four bins of BDT output - polynomial background parameterisation determined from same-sign kaon sample
- No excess of events observed over the background – limits set using the CL_s method





$\mathcal{B}(B^+ \to K^+\mu^-\tau^+) < 3.9\ (4.5) \times 10^{-5}$
at 90% (95%) CL

Measurement of CP-violating and mixing-induced observables in $B_s^0 \to \phi\gamma$ decays

- In SM (loop) $b \to s\,\gamma$ decays, photon mainly produced with LH helicity due to parity violation – small RH component
  - Several NP models predict an enhanced RH component – effects particular observables
- Measure time-dependent $B_s^0 \to \phi(\to K^+K^-)\gamma$ decay rate to extract mixing induced/CP-violating coefficients $\{\mathcal{A}^\Delta, S, C\}$
- Flavour-tagging algorithm used ($\epsilon_{eff} \sim 5\%$)

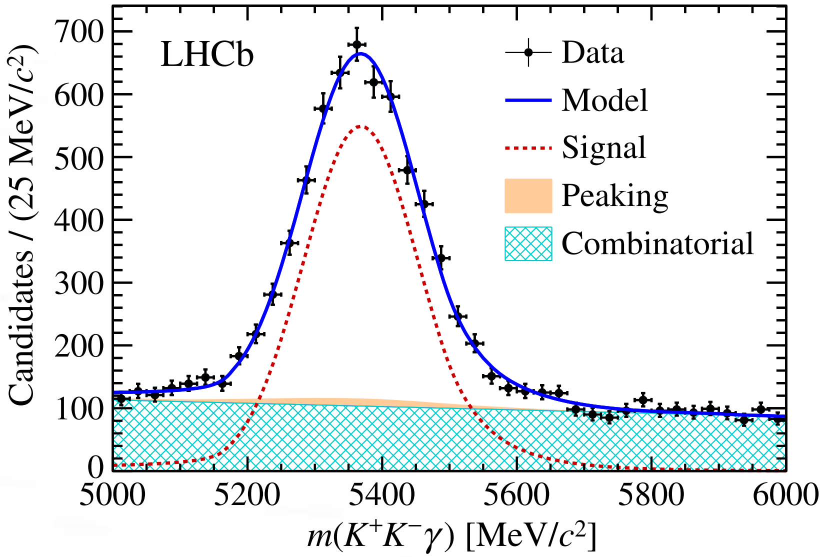
Untagged

$$\mathcal{P}(t) \propto e^{-\Gamma_s t}\{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^\Delta \sinh(\Delta\Gamma_s t/2) + \zeta C\cos(\Delta m_s t) - \zeta S \sin(\Delta m_s t)\},$$

Dependent on B_s^0 or $\bar{B}_s^0$

Data-taking years
11, 12

Calibration channel:
$B^0 \to K^*(\to K^+\pi^-)\gamma$
(Used to control decay time efficiency)

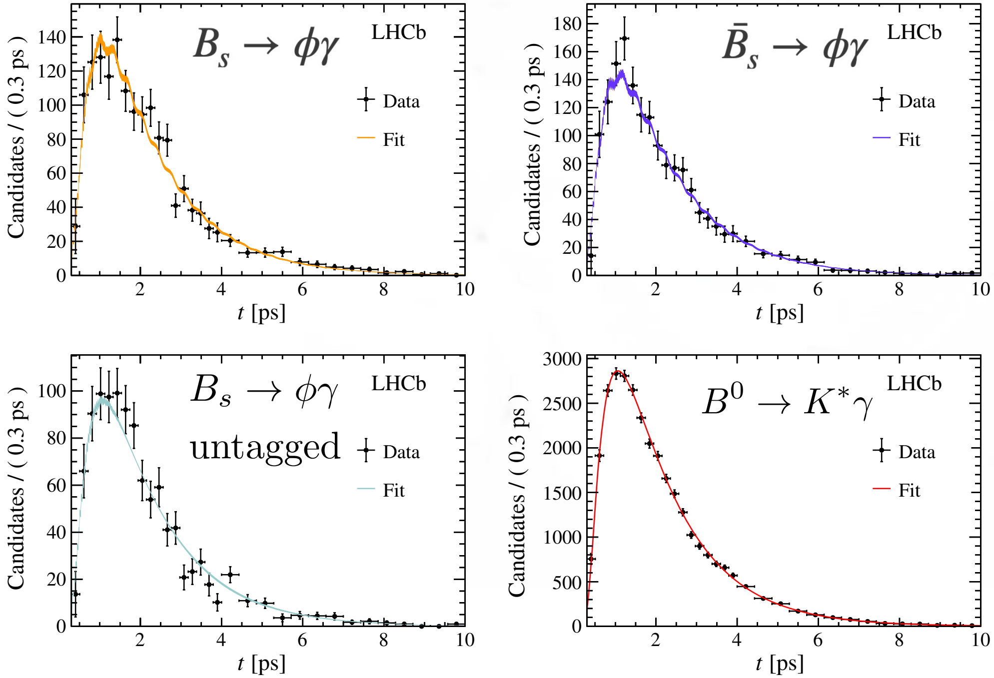


- Fit signal peak in order to perform background subtraction

[Phys. Rev. Lett. 123 (2019) 081802]

Measurement of CP-violating and mixing-induced observables in $B_s^0 \to \phi\gamma$ decays

- Simultaneous decay time fit to background subtracted $B_s^0 \to \phi\gamma$ and $B^0 \to K^*\gamma$ data to extract coefficients
- Decay time resolution $\mathcal{R}(t)$ from per-candidate uncertainties/simulation and decay time efficiency $\epsilon(t)$ from fit to data (driven by $B^0 \to K^*\gamma$)



$$\text{PDF}_t = \epsilon(t)\,(\mathcal{R}(t) \circledast \mathcal{P}(t))$$

$$\mathcal{A}^{\Delta} = -0.67^{+0.37}_{-0.41} \pm 0.17$$
$$S = 0.43 \pm 0.30 \pm 0.11$$
$$C = 0.11 \pm 0.29 \pm 0.11$$

$$\mathcal{A}^{\Delta}_{\rm SM} = 0.047 \pm 0.025 \pm 0.015$$
$$S_{\rm SM} = 0 \pm 0.002$$
$$C_{\rm SM} = 0.005(5)$$

[Phys. Lett. B 664 (2008) 174]

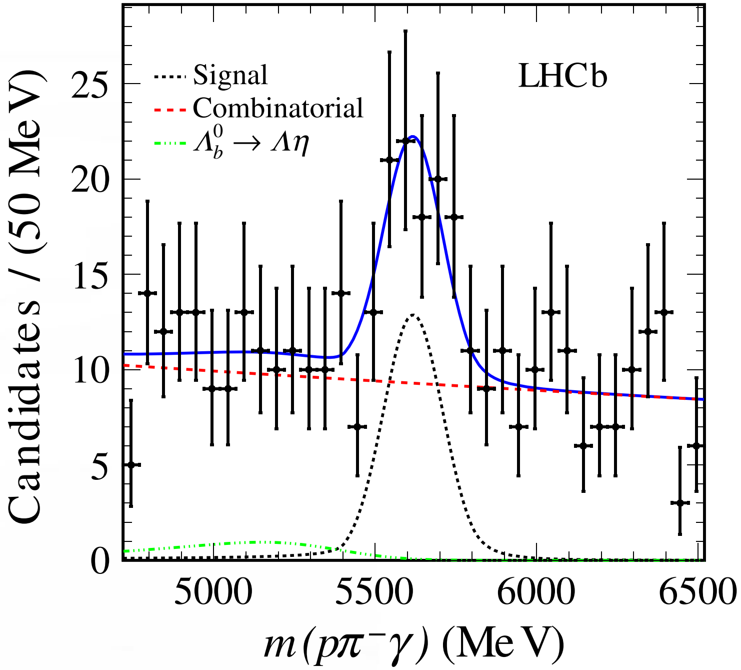
- $\mathcal{A}^{\Delta}$ compatible with SM at 1.7σ
- S compatible with SM at 1.3σ
- C compatible with SM at 0.3σ
- <u>Still statistically limited!</u>

[Phys. Rev. Lett. 123 (2019) 031801]

First observation of the radiative decay $\Lambda_b^0 \to \Lambda\gamma$

- Like $B_s^0 \to \phi\gamma$, sensitive to NP enhanced RH components via photon polarisation λ_γ- prior to angular analysis need observation!
- Difficult to reconstruct due to long Λ lifetime and unknown γ direction i.e. no decay vertex – decay reconstructed as $\Lambda_b^0 \to \Lambda(\to p\pi^-)\gamma$
- Custom 'distance of closest approach' variable between Λ_b^0 and Λ trajectories used to discriminate between signal and background (dominated by combinatorial)
- 5.6σ excess observed – first observation of a radiative baryonic decay!

Normalisation channel: $B^0 \to K^*\gamma$



$$\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$$

Data-taking years
16

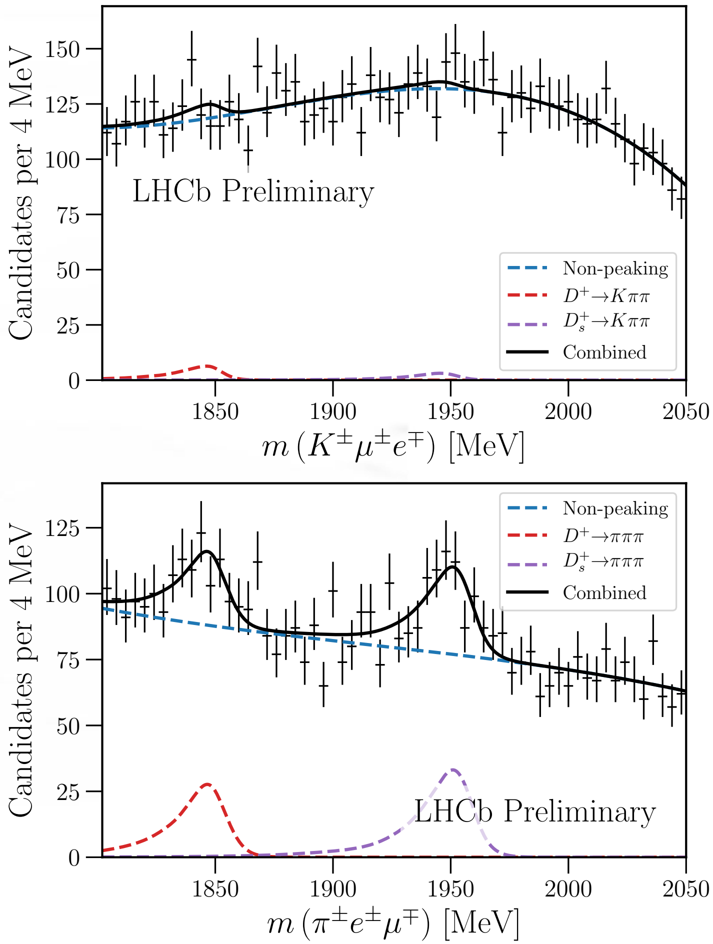
Previous result from the CDF collaboration $\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma)_{\rm CDF} < 1.3 \times 10^{-3}$ at 90% CL [Phys. Rev. D 66 (2002) 112002]

$$\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma)_{\rm SM} = (6 - 500) \times 10^{-7}$$

Searches for 25 rare and forbidden decays of D^+ and D_s^+ mesons

- Rare charm decays have additional GIM suppression compared to rare B decays
- Broad search for 25 rare and forbidden (topologically similar) decays of the form $D^+_{(s)} \to h^{\pm} l^{+} l^{\mp}$ ($h = \{K, \pi\}, l = \{e, \mu\}$)
- Resonances vetoed when fitting signal in three-body invariant mass distribution
- Different background sources for different final states – physical backgrounds modelled using fast simulated samples

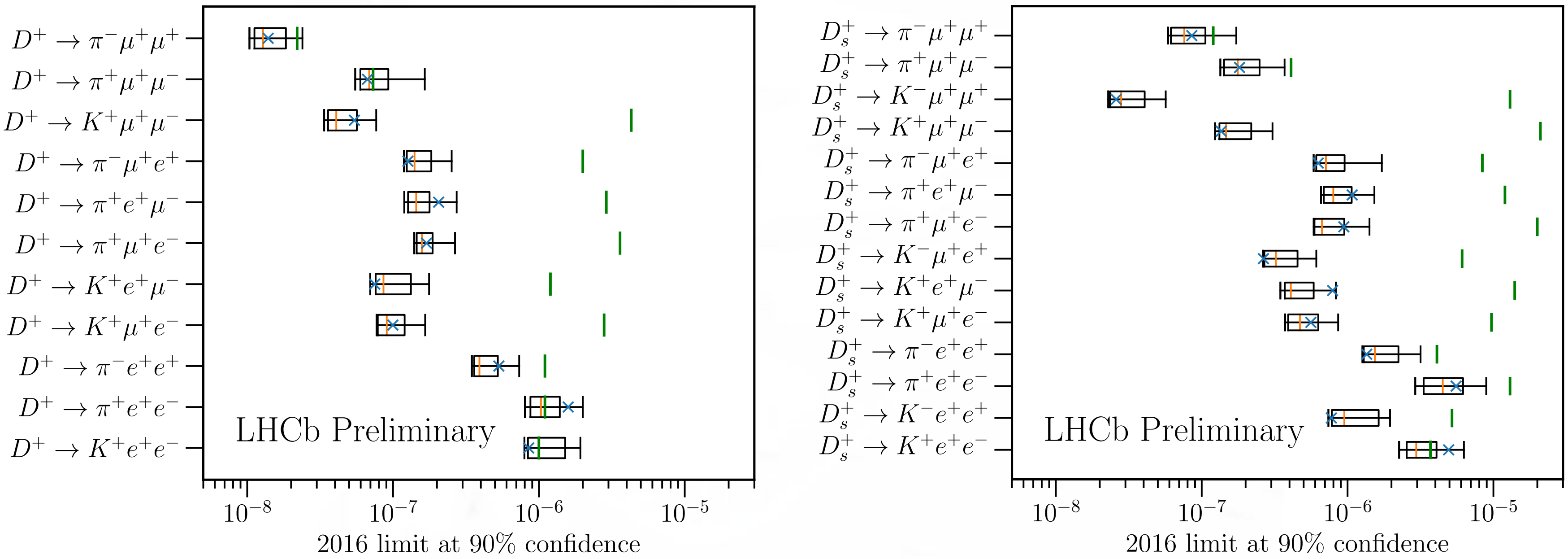
Normalisation channel : $D^+_{(s)} \to \phi(\to l^+ l^-)\pi^+$



Data-taking years
16

Searches for 25 rare and forbidden decays of D^+ and D_s^+ mesons

- (Preliminary) results all consistent with background-only hypothesis



| - expected median   X - observed limit | - previous world's best limit (BaBar, CLEO, LHCb)

- Limits improve on the previous world best results by up to a factor of 500!

Summary

- Rare decays are very sensitive probes for new physics contributions and shall remain an active research topic in the years to come
- Many exciting LHCb rare decays analyses published/currently ongoing
- LHCb is setting world's best measurements and limits on observables within flavour physics (and beyond)
- Non $b \to sl^+l^-$ measurements still provide important tests of LFV and new physics may manifest in measurements
- The LHCb upgrades will offer significantly higher luminosities and improved detector performance – should provide exciting new discoveries and allow SM rare decays to be tested to even greater precision

- LHC upgrade II will allow precision tests of observables such as the $B^0_{(s)} \to \mu^+\mu^-$ BF ratio ($\mathcal{R}$) (~10%)
- Decisive measurements of observables such as the B^0_s effective lifetime $(\tau_{\mu\mu})$ (~2%) and per cent measurements of observables such as the photon polarisation (λ_γ) (~4%) [LHCB-PUB-2018-009]
- If tensions in $b \to sl^+l^-$ are confirmed, upgrade will allow to discriminate between potential NP models, and allow complementary, rarer measurements to be studied such as $b \to dl^+l^-$ decays

Thanks for listening!

Backup

Search strategy

- Many presented analyses measure branching fractions relative to a known normalization channel, as this allows large systematic uncertainties in $\sigma_{pp\to b\bar{b}}$ and $\mathcal{L}_{\text{Int}}$, as well as other systematic uncertainties related to reconstruction and selection to cancel in the ratio

$$\mathcal{B}(\text{Signal}) = \frac{N_{\text{Signal}}}{2 \times \mathcal{L}_{\text{Int}} \times \sigma_{pp\to b\bar{b}} \times f \times \epsilon_{\text{Signal}}}$$

Large uncertainties ($\mathcal{L}_{\text{Int}}$, $\sigma_{pp\to b\bar{b}}$)

N_{Signal} = Signal yield
$\mathcal{L}_{\text{Int}}$ = Integrated luminosity
$\sigma_{pp\to b\bar{b}}$ = $b\bar{b}$ cross section
f = Hadronisation fraction
ϵ = Total efficiency

- Instead measure:

$$\mathcal{B}(\text{Signal}) = \frac{\mathcal{B}(\text{Norm})}{N_{\text{Norm}}} \times \frac{\epsilon_{\text{Norm}}}{\epsilon_{\text{Signal}}} \times \frac{f_{\text{Norm}}}{f_{\text{Signal}}} \times N_{\text{Signal}}$$

$B^0_{(s)} \to \mu^+\mu^-$ combination (ATLAS + CMS + LHCb)

Effective lifetime definition

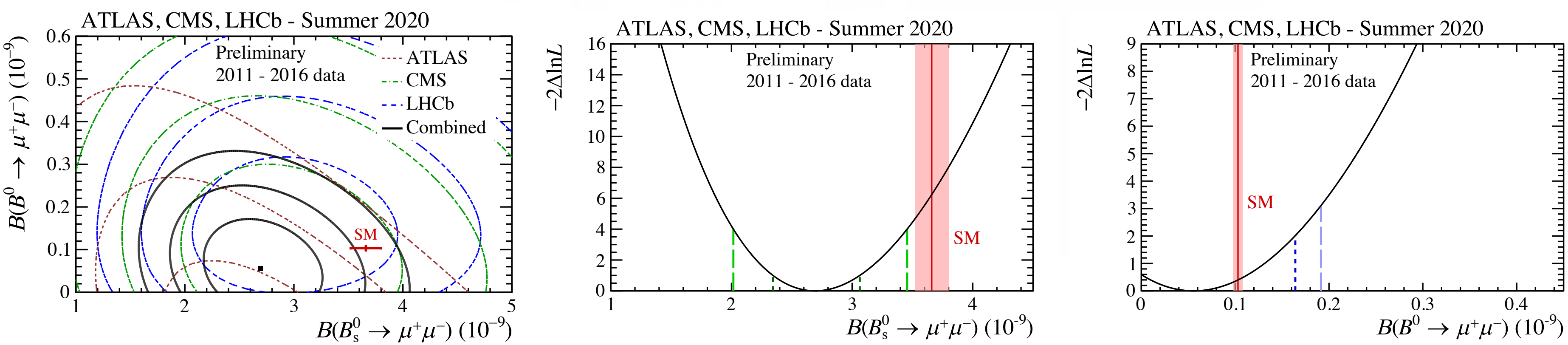
(mean decay time of an untagged sample of decays)

$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t \,\langle \Gamma\left(B_s^0 \to \mu^+\mu^-\right)\rangle \,\mathrm{d}t}{\int_0^\infty \langle \Gamma\left(B_s^0 \to \mu^+\mu^-\right)\rangle \,\mathrm{d}t} = \frac{\tau_{B_s^0}}{1-y_s^2}\left[\frac{1+2\mathcal{A}_{\Delta\Gamma}y_s+y_s^2}{1+\mathcal{A}_{\Delta\Gamma}y_s}\right]$$

$$y_s \equiv \frac{\Delta\Gamma_s}{2\Gamma_s},$$

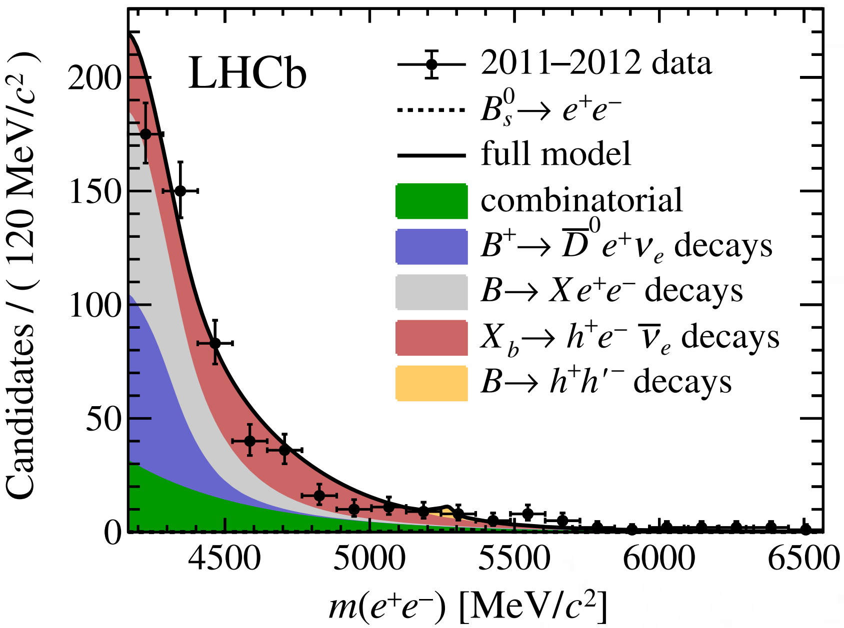
$$\mathcal{A}_{\Delta\Gamma} \equiv \frac{R_H^{\mu^+\mu^-} - R_L^{\mu^+\mu^-}}{R_H^{\mu^+\mu^-} + R_L^{\mu^+\mu^-}}$$

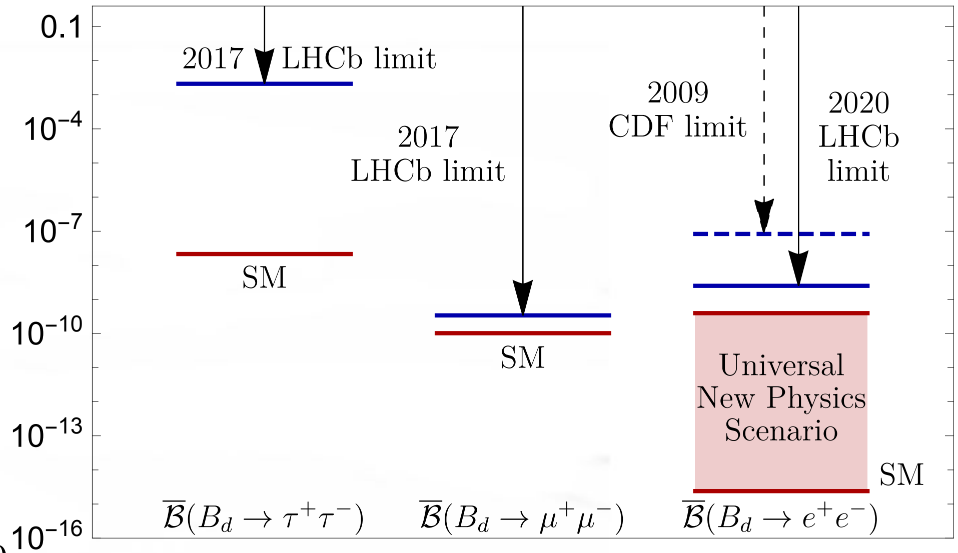
1D likelihood projections



Search for the rare decays $B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$

- Bremsstrahlung losses corrected by adding momentum of all photons consistent with being emitted upstream of magnet





- Several primary physical backgrounds:

$$B \to X e^+ e^-$$
$$B^+ \to \bar{D}^0(\to Y^+ e^- \bar{\nu}_e) e^+ \nu_e$$
$$B^0 \to \pi^- e^+ \nu_e$$
$$B \to h^+ h^{-'}$$

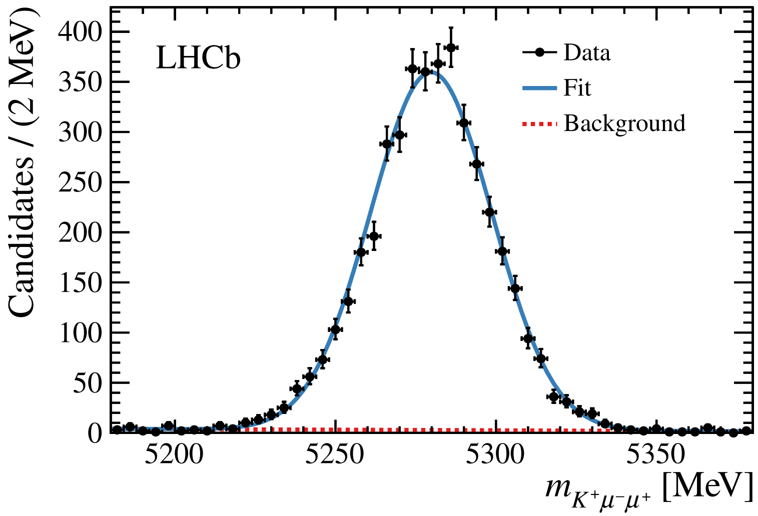
- There are different relative proportions of physical background contributions between Run 1 and Run 2 due to different performances of the particle identification and BDT algorithms

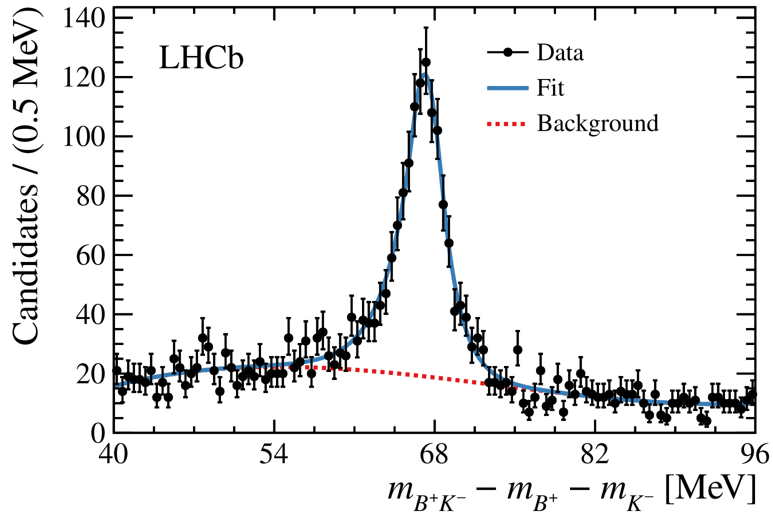
[JHEP 06 (2020) 129]

Search for the lepton flavour violating decay $B^+ \to K^+\mu^-\tau^+$ using B_{s2}^{*0} decays

Fits to normalisation mode mass and B^+- K^- mass difference

- Fits to determine yields and to quantify contributions from B_{s2}^{*0} decays and non-B_{s2}^{*0} candidates with nearby kaons





How missing mass is reconstructed

$$E_B = \frac{(m_{BK}^2 - m_B^2 - m_K^2)^2}{2E_K)^2}\frac{1}{1-(p_K/E_K)^2\cos^2\theta}\left(1 \pm \sqrt{d}\right)$$

$$d = \frac{p_K^2}{E_K^2}cos^2\theta - \frac{4m_B^2 p_K^2 cos^2\theta}{(m_{BK}^2 - m_B^2 - m_K^2)^4}\left(1 - \frac{p_K^2}{E_K^2}cos^2\theta\right)$$

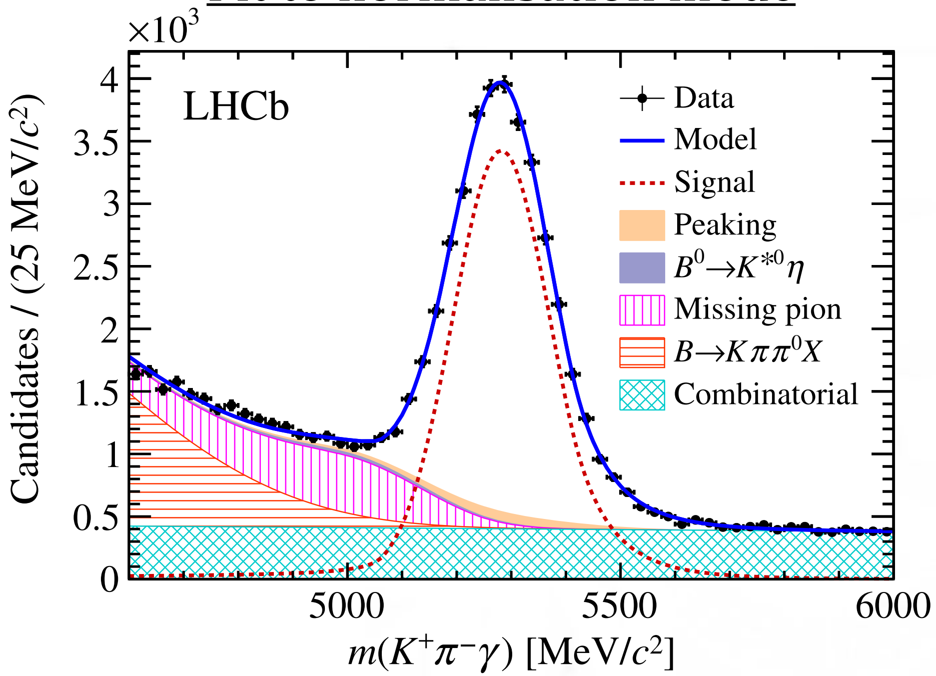
$$P_{\text{miss}} = P_B - P_{K^+\mu^-}$$

- Missing mass squared – lowest energy, real solution for which the missing energy is greater than energy of reconstructed third track under π mass hypothesis

[Phys. Rev. Lett. 123 (2019) 081802]

Measurement of CP-violating and mixing-induced observables in $B_s^0 \to \phi\gamma$ decays

Fit to normalisation mode



- Several additional partially reconstructed backgrounds: $B \to K\pi\pi\gamma$

$$B \to K\pi\pi^0 X$$

$$B^0 \to K^*\eta(\to \gamma\gamma)$$

- Decay time resolution modelled by sum of two Gaussians
- Decay time efficiency modelled as

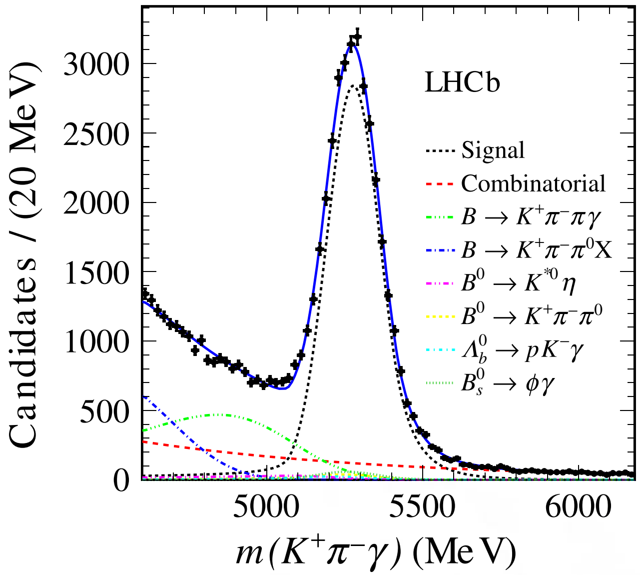
$$\epsilon(t) \propto \frac{t^{a/t}}{\cosh(bt)}$$

Flavour tagging algorithms

- Same-side (SS) – identifies flavour of signal candidate by identifying charge of kaon produced alongside B_s^0 meson – neural network implementation
- Opposite-side (OS) – rely on pair production of b hadrons – examine decay products of other b hadron in the event

First observation of the radiative decay $\Lambda_b^0 \to \Lambda\gamma$

Fit to normalisation mode



- Several additional physical backgrounds:

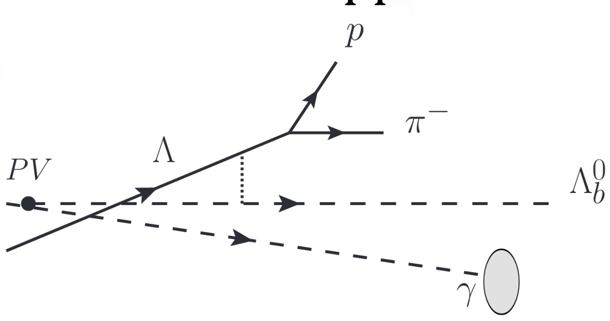
$$B \to K^+\pi^-\pi\gamma$$
$$B^0 \to K^*\eta$$
$$B_s^0 \to \phi\gamma$$
$$\Lambda_b^0 \to pK^-\gamma$$
$$B^0 \to K^+\pi^-\pi^0$$

Primary systematic uncertainties

Source	Uncertainty (%)
Data/simulation agreement	7.7
Λ_b^0 fit model	3.0
$B^0 \to K^{*0}\gamma$ backgrounds	2.7
Size of simulated samples	1.7
Efficiency ratio	1.4
Sum in quadrature	9.0
$f_{\Lambda_b^0}/f_{B^0}$	8.7
Input branching fractions	3.0
Sum in quadrature	9.2

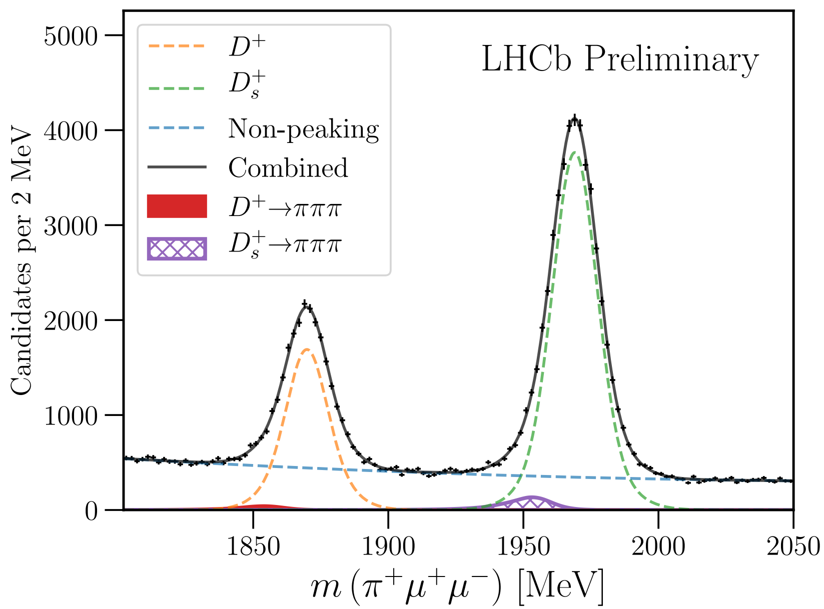
- Largest systematic from $f_{\Lambda_b^0}/f_{B^0}$

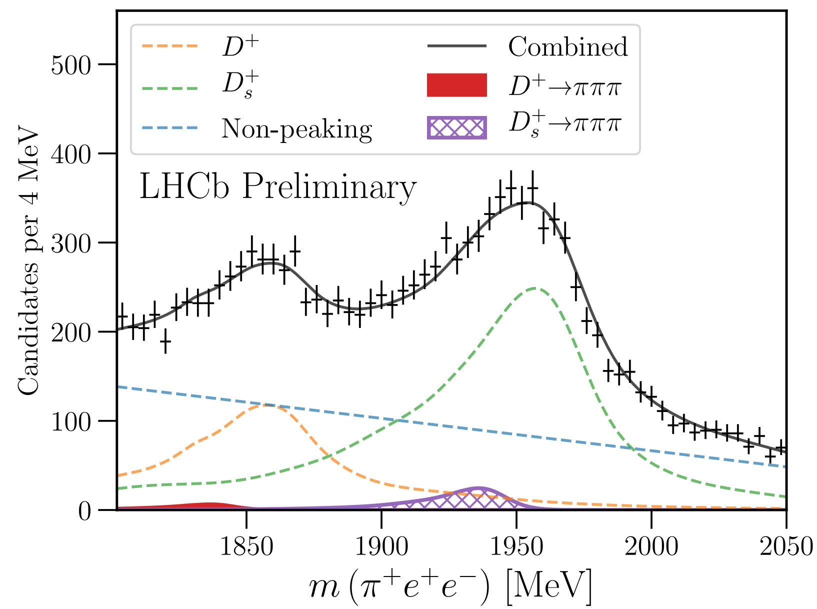
Distance of closest approach variable



Searches for 25 rare and forbidden decays of D^+ and D_s^+ mesons

Fits to two normalisation modes





- Primary physical backgrounds (same as for signal):

$$D^+ \to hhh$$

$$D_s^+ \to hhh$$