LFV, lepton universality, and rare decay searches at the LHC

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On behalf of LHCb, with results from ATLAS and CMS

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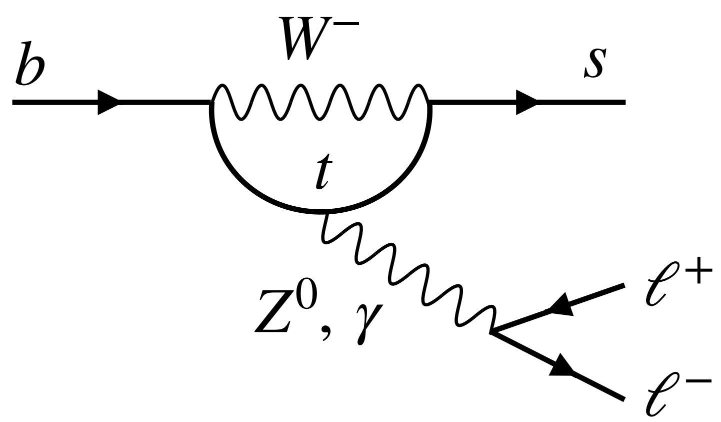
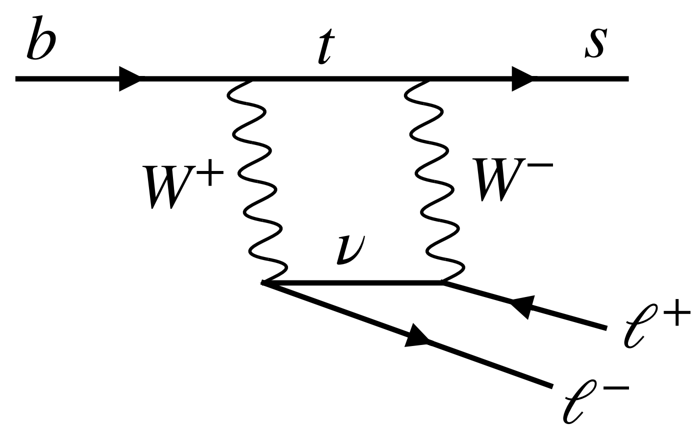
LHCb

FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

- Rare decays of b-hadrons are flavour changing neutral current (FCNC) decays that take place only at loop level

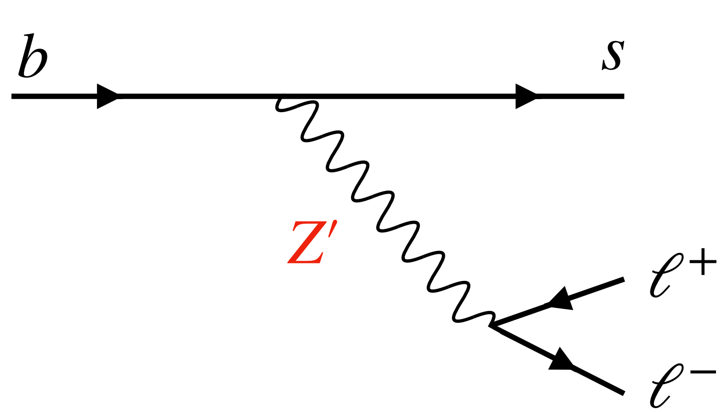
SM

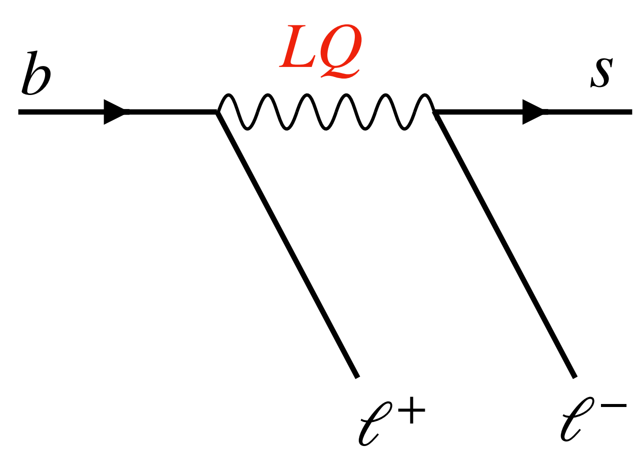




- Sensitive to theories beyond the Standard Model (SM)

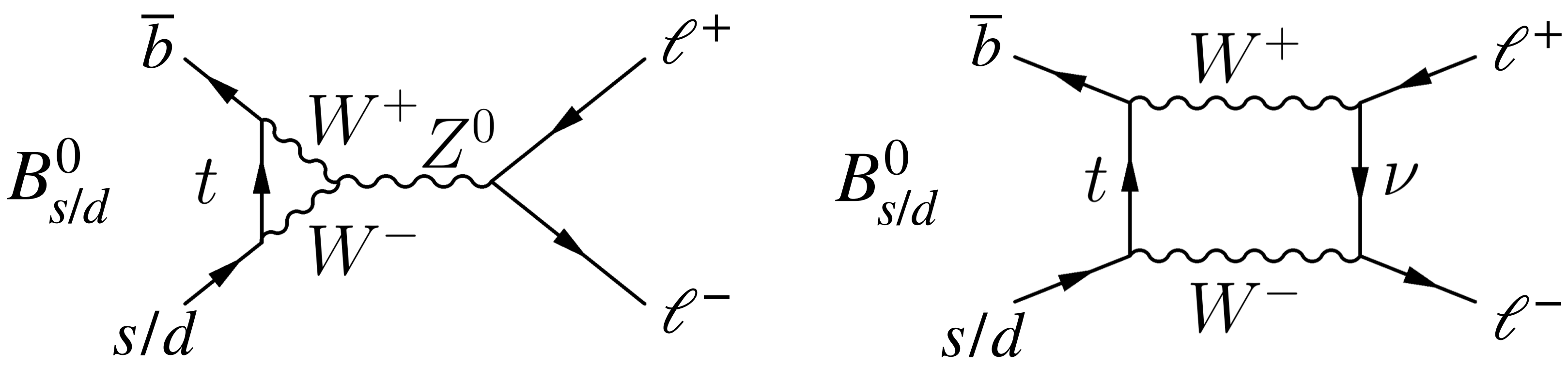
Non-SM





- Observable measurements => indirect search for non-SM effects
- Several recent results have hinted at departure from SM expectations => active area of investigation

- $B^0_{(s)} \to \ell^+\ell^-, \ell = e, \mu, \tau$ decays are helicity suppressed FCNC decays



B^0 mode more suppressed than B^0_s as $|V_{td}| < |V_{ts}|$

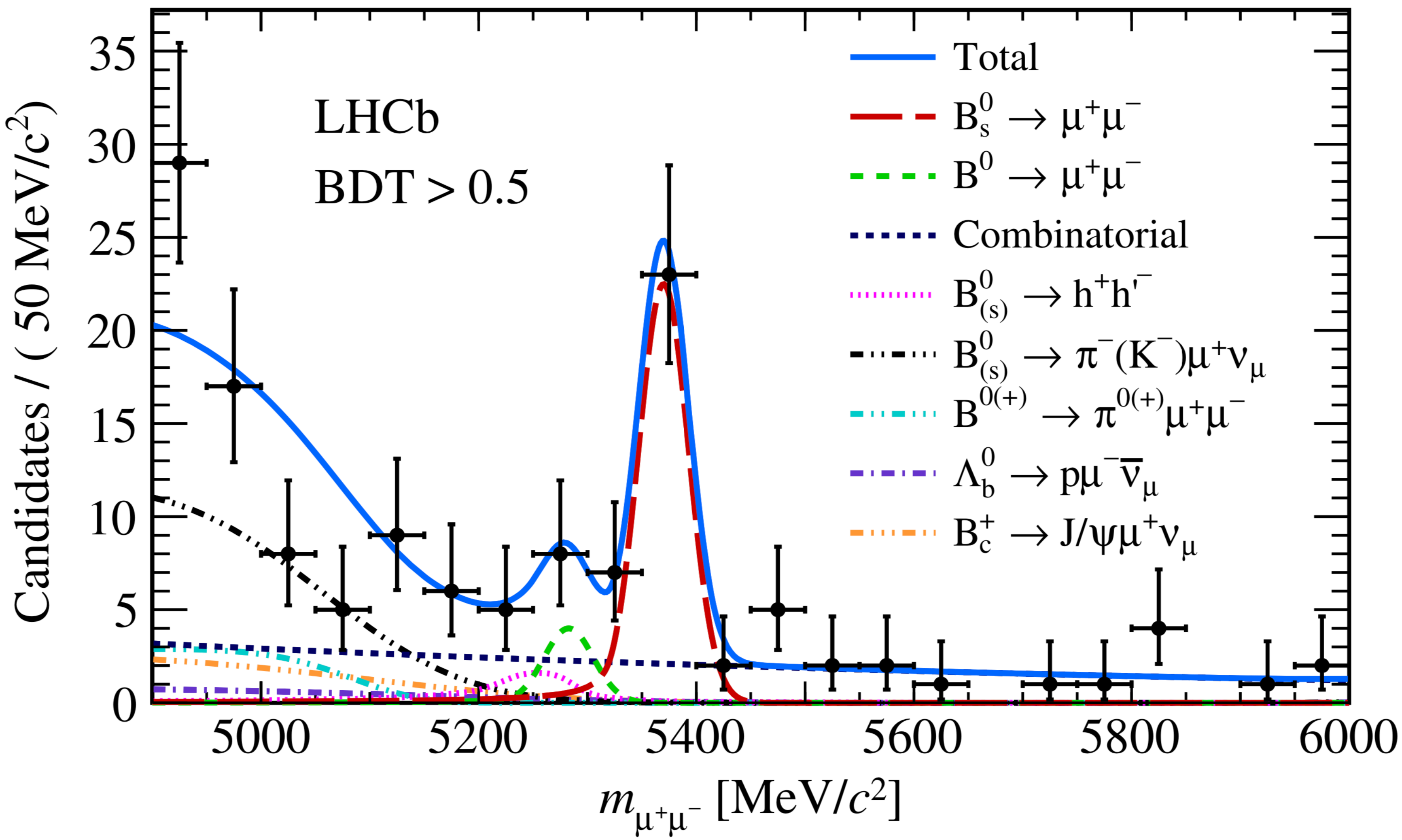
Greater helicity suppression for e than τ as $m_e < m_\tau$

- Purely leptonic final state => precise SM predictions of branching fractions (BFs):
  - $\mathscr{B}(B^0_s \to e^+e^-)/\mathscr{B}(B^0 \to e^+e^-) = (8.54 \pm 0.55) \times 10^{-14}/(2.48 \pm 0.21) \times 10^{-15}$
  - $\mathscr{B}(B^0_s \to \mu^+\mu^-)/\mathscr{B}(B^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}/(1.06 \pm 0.09) \times 10^{-10}$
  - $\mathscr{B}(B^0_s \to \tau^+\tau^-)/\mathscr{B}(B^0 \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}/(2.22 \pm 0.19) \times 10^{-8}$

  [PRL 112 (2014) 101801]

- Muon mode measurements/searches made by ATLAS, CMS and LHCb
  - $B^0_s \to \mu^+\mu^-$ seen [Nature (2015) 14474]
  - $B^0 \to \mu^+\mu^-$ no observation yet
- Tau mode searched for by LHCb — no evidence yet [PRL 118 (2017) 251802]
- Electron mode measurement at LHCb currently in progress

- Data collected in 2011-2012 (Run 1, 3 fb^{-1}), and 2015-2016 (Run 2, 1.4 fb^{-1})

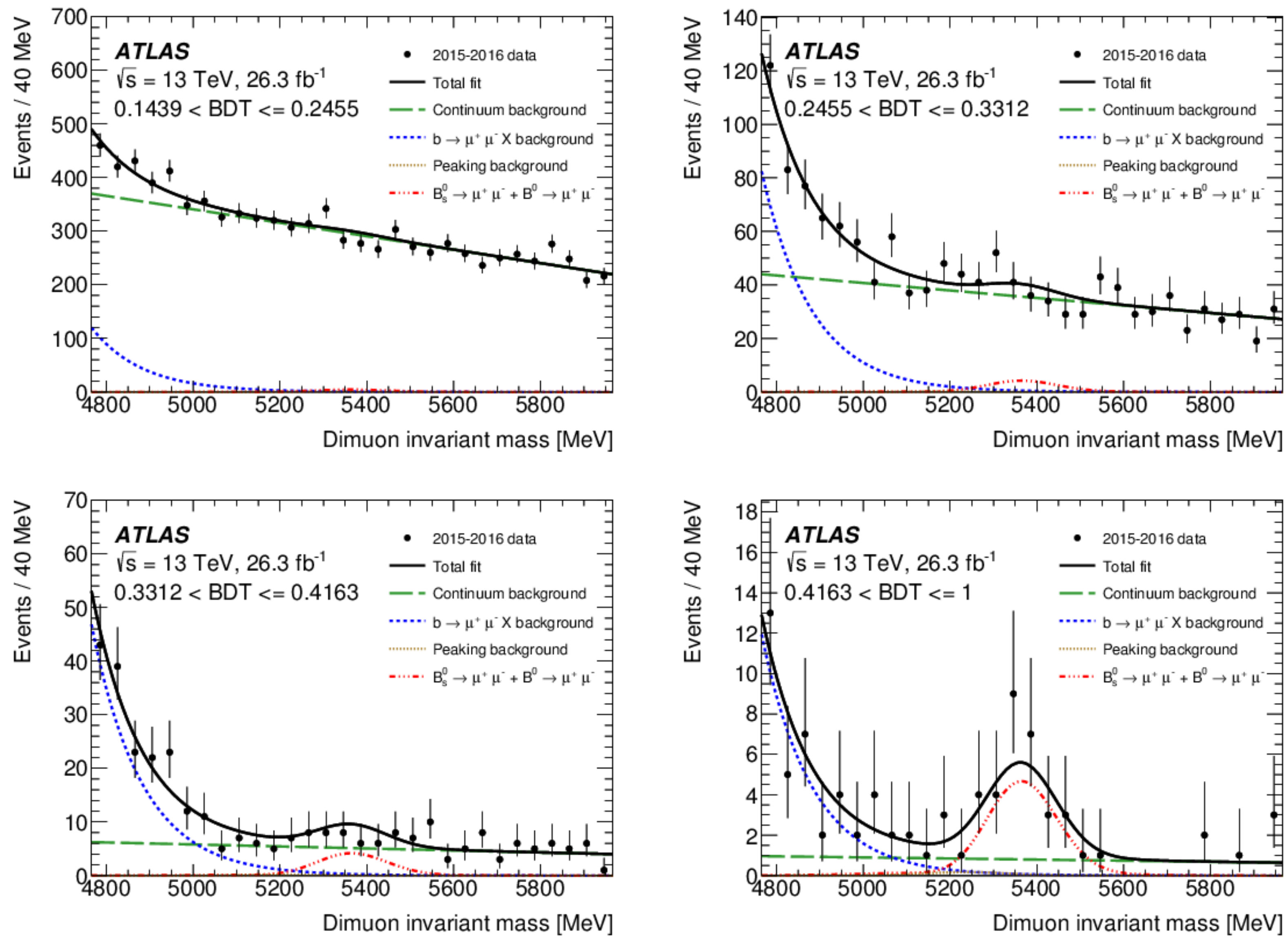


- Normalisation channels: $B^+ \to J/\psi K^+$ (similar trigger), and $B^0_{(s)} \to K^+\pi^-$ (similar topology)
- Extract BF through simultaneous unbinned maximum likelihood (UML) fit to the dimuon invariant mass distributions in five boosted decision tree (BDT) score bins for Run 1 and 2
- Measured $\mathscr{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2} \times 10^{-9})$ — first single experiment observation (7.8 σ)
- Previous evidence for B^0 mode not confirmed (1.6 σ): $\mathscr{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ at 95% C.L.

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

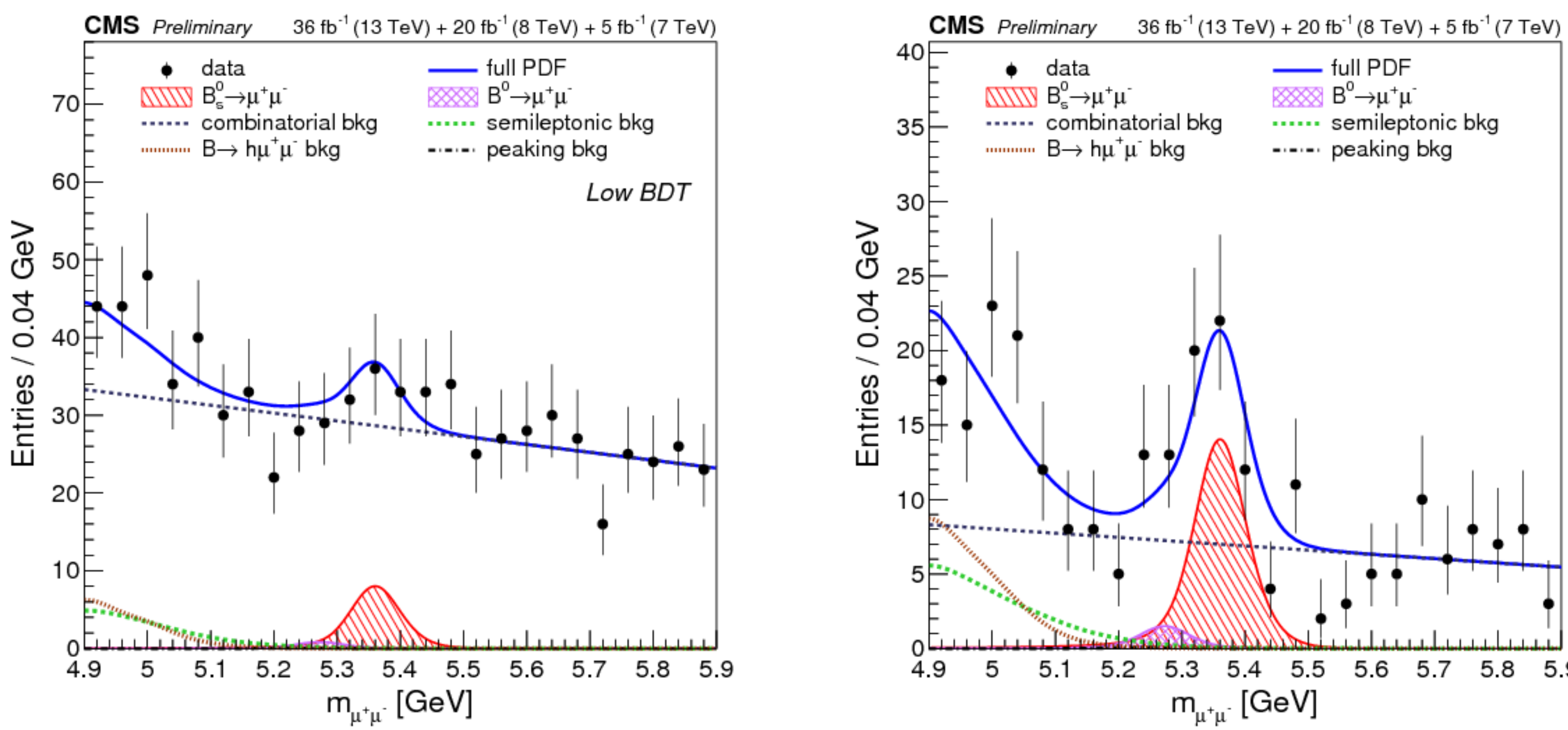
JHEP 04 (2019) 098

- Data collected in 2015-2016 (Run 2, 26.3 fb^{-1})
- Single signal component for both B^0 and B^0_s contributions due to limited resolution
- Extracted BF via simultaneous UML fit to four BDT score bins



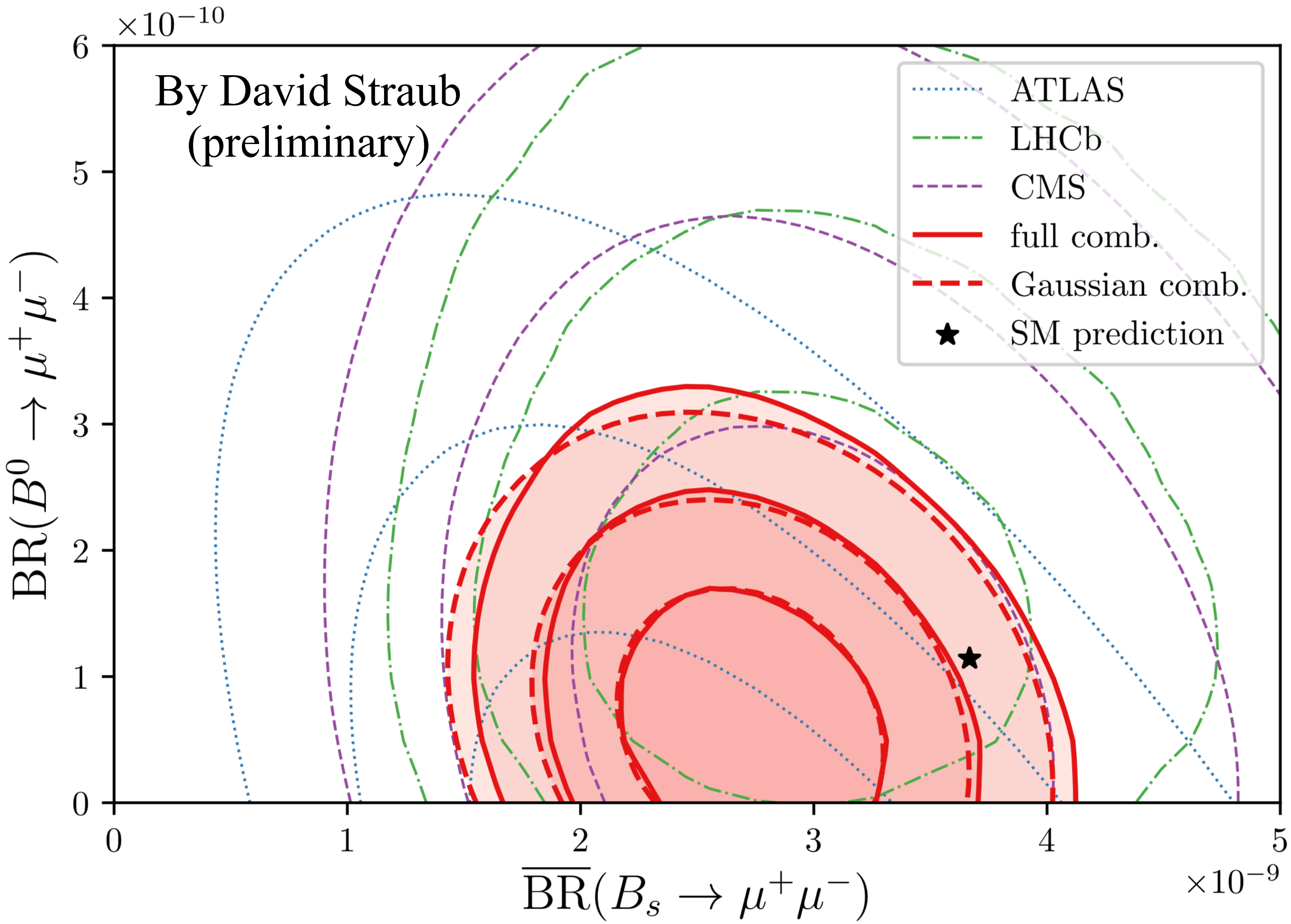
- Measured (combined with Run 1) $\mathscr{B}(B^0_s \to \mu^+\mu^-) = 3.2^{+1.1}_{-1.0} \times 10^{-9}$ $(2.8^{+0.8}_{-0.7} \times 10^{-9})$
- Determined (combined with Run 1) $\mathscr{B}(B^0 \to \mu^+\mu^-) < 4.3 \times 10^{-10}$ (2.1×10^{-10}) at 95% C.L.
- $B^0_s \to \mu^+\mu^-$ Run 1+2 significance: $4.6\,\sigma$

- Preliminary results only
- Data collected in 2011, 2012 and 2016 (61 fb^{-1})
- Extracted BF via simultaneous UML fit to 14 subsamples (four data collection eras × two bins in pseudorapidity, each sample is split further, where possible, into two regions based on BDT score)
- UML fit to $m_{\mu\mu}$, relative mass resolution ($\sigma(m_{\mu^+\mu^-})/m_{\mu^+\mu^-}$), and a binary distribution with 1 (-1) for muon tracks bending towards (away from) each other



- Measured $\mathscr{B}(B^0_s \to \mu^+\mu^-) = (2.9^{+0.7}_{-0.6}(\text{exp}) \pm 0.2(\text{frag})) \times 10^{-9}$ with 5.6 σ significance
- No significant excess observed for B^0 decay, $\mathscr{B}(B^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10}$ at 95% C.L.

- Likelihood contours (and combination) of the most recent ATLAS, LHCb and CMS (preliminary) results:



- Good agreement with SM in general, but starting to become interesting…

- Measurement of $B_s^0 \to \mu^+\mu^-$ lifetime provides a complementary test of SM
- The effective lifetime (without distinguishing $B_s^0/\overline{B}_s^0$) can be expressed as:

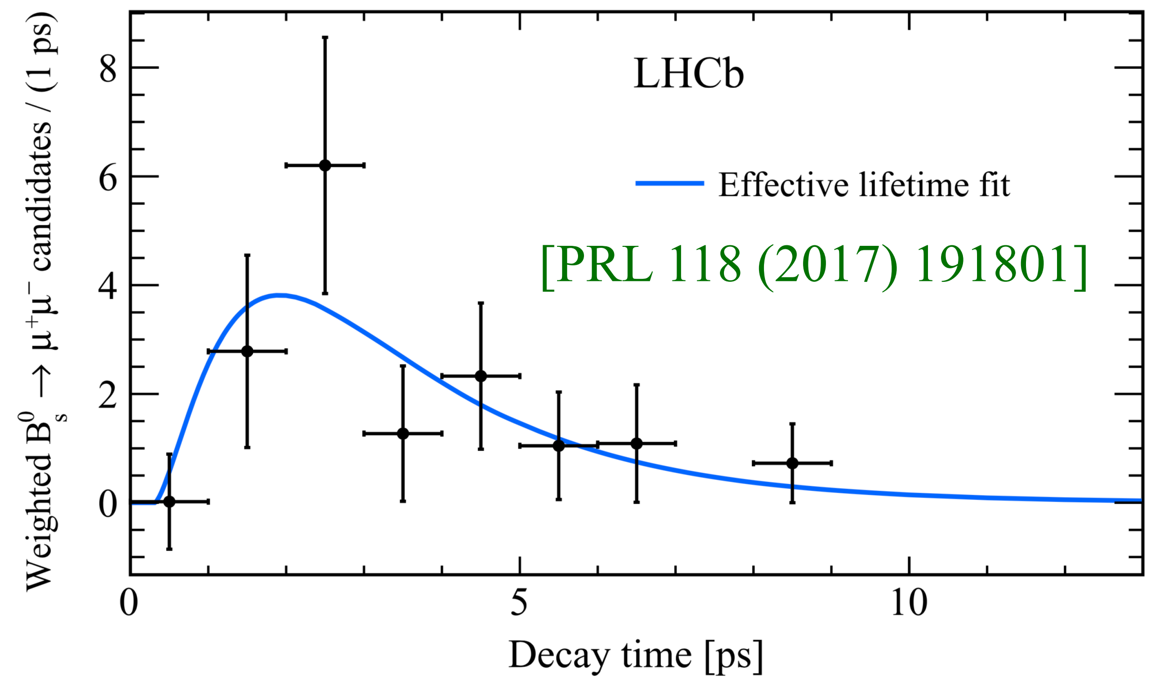
$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1-y_s^2}\left(\frac{1+2A_{\Delta\Gamma}^{\mu^+\mu^-}y_s+y_s^2}{1+A_{\Delta\Gamma}^{\mu^+\mu^-}y_s}\right)$$

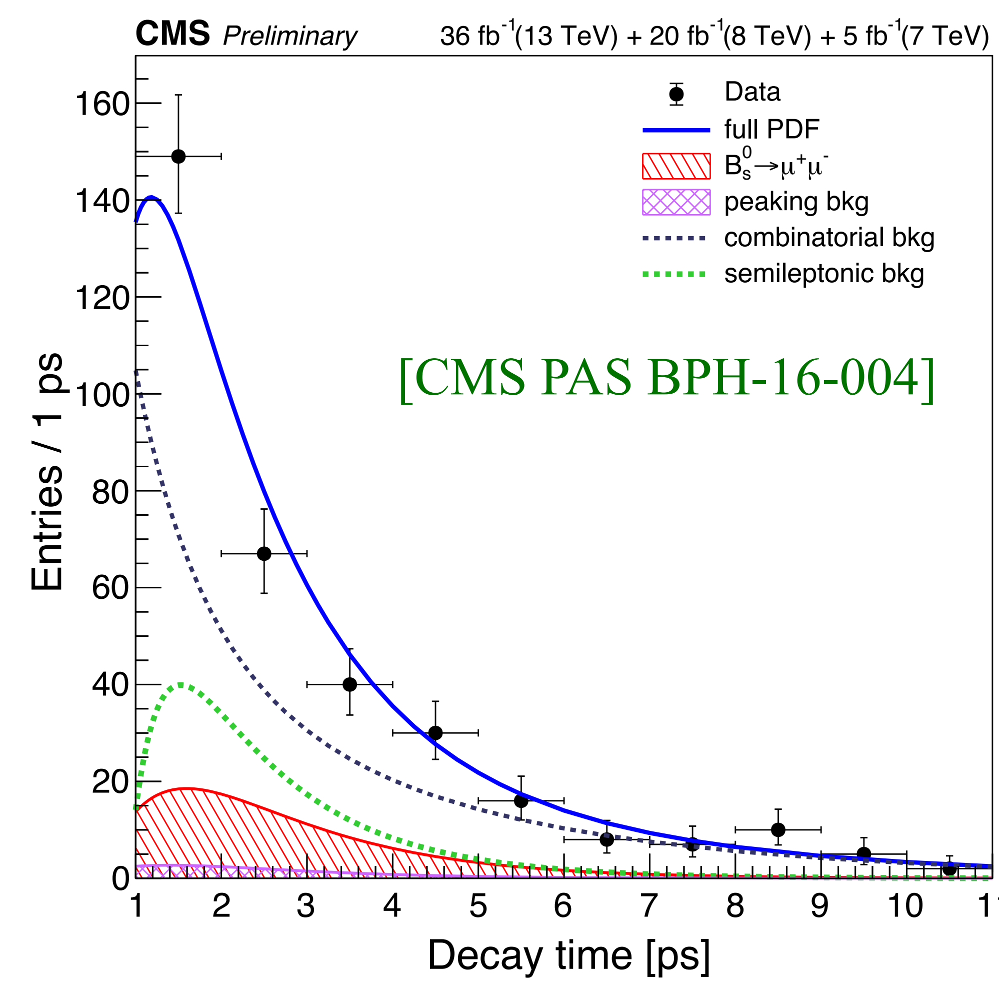
$$\tau_{B_s^0} = 1.510 \pm 0.005\ \mathrm{ps}$$

$$y_s \equiv \tau_{B_s^0}\Delta\Gamma/2 = 0.062 \pm 0.006$$

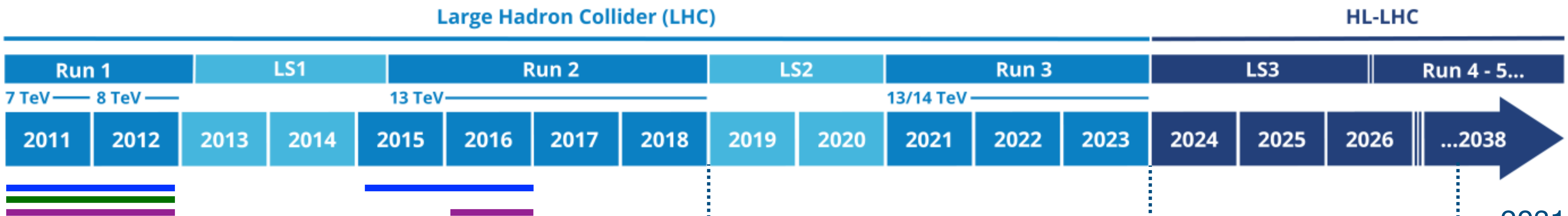
$$A_{\Delta\Gamma}^{\mu^+\mu^-} \equiv \frac{\Gamma(B_s^H \to \mu^+\mu^-) - \Gamma(B_s^L \to \mu^+\mu^-)}{\Gamma(B_s^H \to \mu^+\mu^-) + \Gamma(B_s^L \to \mu^+\mu^-)}$$

- In the SM, $A_{\Delta\Gamma}^{\mu^+\mu^-} = 1$, but in beyond SM theories it may be anywhere in the range of [-1, 1]
- Both LHCb and CMS measured $\tau_{\mu^+\mu^-}$, yielding:
  - $2.04 \pm 0.44\ (\mathrm{stat}) \pm 0.05\ (\mathrm{syst})$ ps (LHCb)
  - $1.70^{+0.61}_{-0.44}$ ps (CMS preliminary)
- Results are in agreement with SM





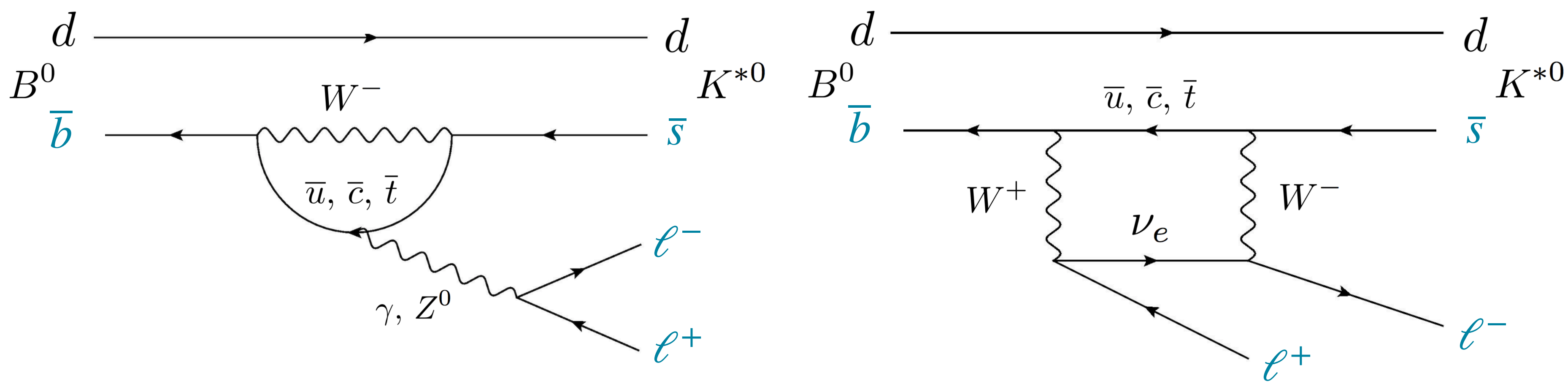
- LHCb, ATLAS and CMS produced estimations of total uncertainties/BF limits for future runs/upgrades: [LHCB-PUB-2018-009] [ATL-PHYS-PUB-2018-005] [CMS PAS FTR-14-013/-015]



	Current			
LHCb		$8\ \text{fb}^{-1}$	$23\ \text{fb}^{-1}$	$300\ \text{fb}^{-1}$
$\mathcal{B}(B^0_s \to \mu^+\mu^-)$:	$\pm 0.6^{+0.3}_{-0.2} \times 10^{-9}$		$\pm 0.30 \times 10^{-9}$	$\pm 0.16 \times 10^{-9}$
$\mathcal{B}(B^0_s \to \tau^+\tau^-)$:	$< 6.8 \times 10^{-3}$		$< 1.3 \times 10^{-3}$	$< 5 \times 10^{-4}$
$\tau_{\mu^+\mu^-}$ (ps) :	$\pm 0.44 \pm 0.05$		$\sim \pm 0.16$	$\sim \pm 0.04$
ATLAS		$150\ \text{fb}^{-1}$	$300\ \text{fb}^{-1}$	$3000\ \text{fb}^{-1}$
$\mathcal{B}(B^0_s \to \mu^+\mu^-)$:	${}^{+0.8}_{-0.7} \times 10^{-9}$	$\pm 0.83 \times 10^{-9}$		$\pm(0.46 - 0.55) \times 10^{-9}$
$\mathcal{B}(B^0 \to \mu^+\mu^-)$:	$< 2.1 \times 10^{-10}$	$\pm 1.43 \times 10^{-10}$		$\pm(0.28 - 0.54) \times 10^{-10}$
CMS				
$\mathcal{B}(B^0_s \to \mu^+\mu^-)$:	${}^{+0.7}_{-0.6} \pm 0.2 \times 10^{-9}$		$\sim \pm (0.43 - 0.46) \times 10^{-9}$	$\sim \pm 0.39 \times 10^{-9}$
$\mathcal{B}(B^0 \to \mu^+\mu^-)$:	$< 3.6 \times 10^{-10}$		$\sim \pm (0.44 - 0.51) \times 10^{-10}$	$\sim \pm 0.19 \times 10^{-10}$
$\tau_{\mu^+\mu^-}$ (ps) :	${}^{+0.61}_{-0.44}$		± 0.15	± 0.05

Rare decays: $b \to s\ell^+\ell^-$ processes

- Another group of rare b-hadron FCNC decays feature the underlying $b \to s\ell^+\ell^-$ transition



- Measurements of observables of these decays have shown some interesting (albeit inconclusive) tensions with the SM
- Of particular interest are 'clean' observables with precise SM predictions, in particular ratios of branching fractions ($R_{K^{(*)}}$),

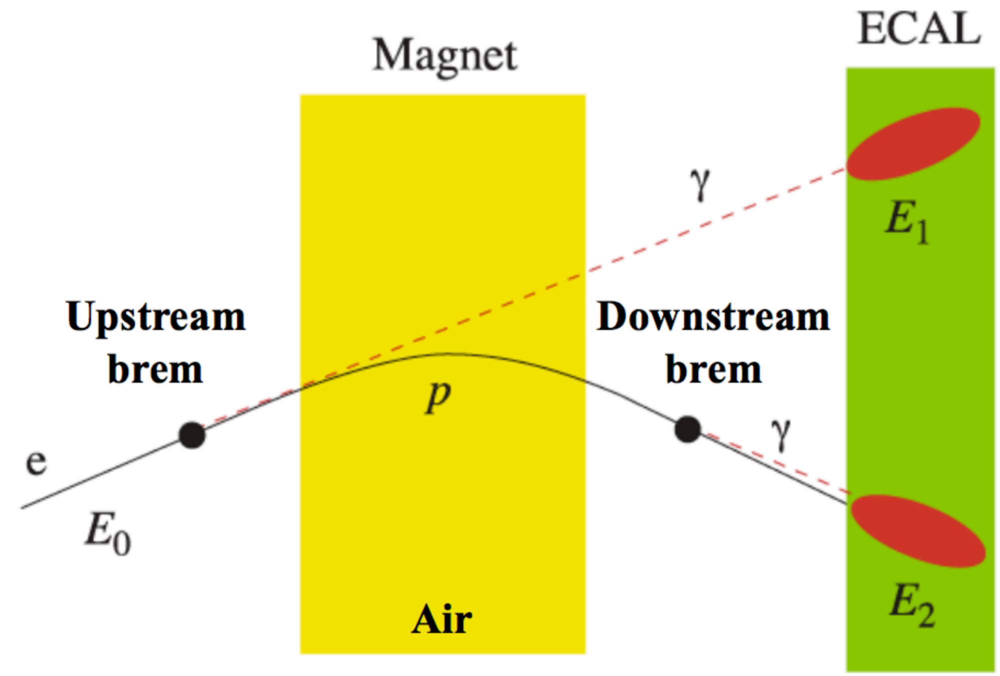
$$R_{K^{(*)}} = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B \to K^{(*)}\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B \to K^{(*)}e^+e^-)}{dq^2} dq^2}$$

[PRD 69 (2003) 074020]

Lepton flavour universality (LFU): electroweak couplings are identical for all lepton flavours, and differences between decay modes are due only to their mass differences

- Most recent (and precise) update to R_K uses data collected in 2011, 2012, and 2015, 2016

- $R_K = 1 \pm \mathcal{O}(10^{-2})$, $1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$ (SM) [EPJC 10 (2016) 1140]
- Experimentally, electron and muon reconstruction are very different
- Muons are relatively easy to trigger on and reconstruct
  => higher efficiency
- Electrons undergo significant bremsstrahlung emission
  => reduced trigger/reconstruction efficiency and resolution



- To mitigate experiment-related electron-muon differences, the R_K measurement is made using a double ratio, which makes use of the normalisation mode $B^0 \to KJ/\psi$:

$$R(K) = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to KJ/\psi(\to \mu^+\mu^-))} \times \frac{\mathcal{B}(B \to KJ/\psi(\to e^+e^-))}{\mathcal{B}(B \to Ke^+e^-)},$$

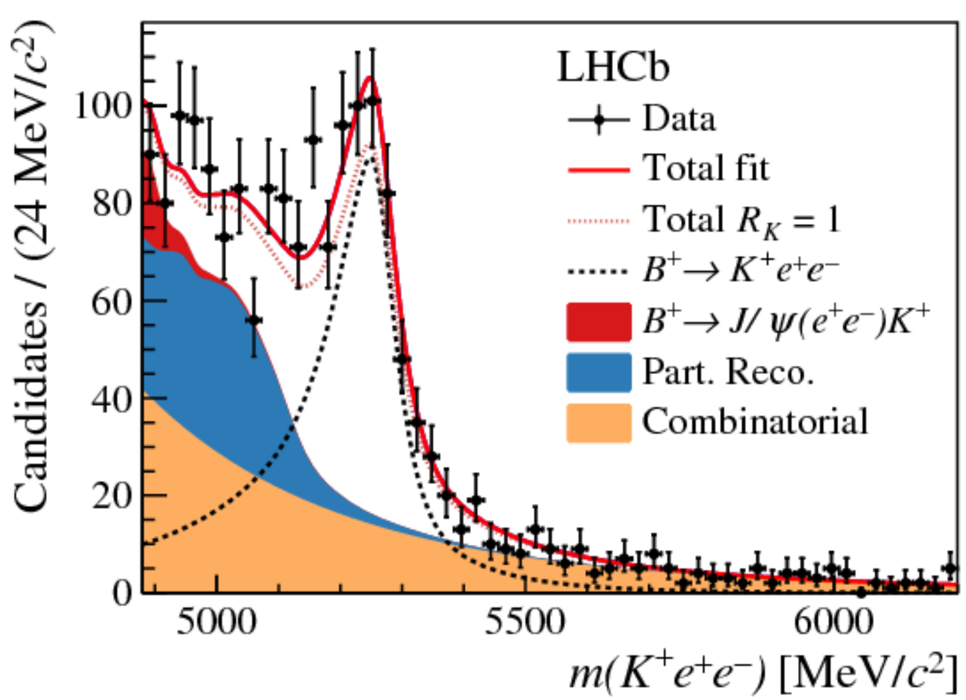
$$= \frac{N_{B^+\to K^+\mu\mu}}{\epsilon_{B^+\to K^+\mu\mu}} \times \frac{N_{B^+\to K^+ee}}{\epsilon_{B^+\to K^+ee}} \times \frac{\epsilon_{B^+\to K^+J/\psi(\mu\mu)}}{N_{B^+\to K^+J/\psi(\mu\mu)}} \times \frac{\epsilon_{B^+\to K^+J/\psi(ee)}}{N_{B^+\to K^+J/\psi(ee)}}$$

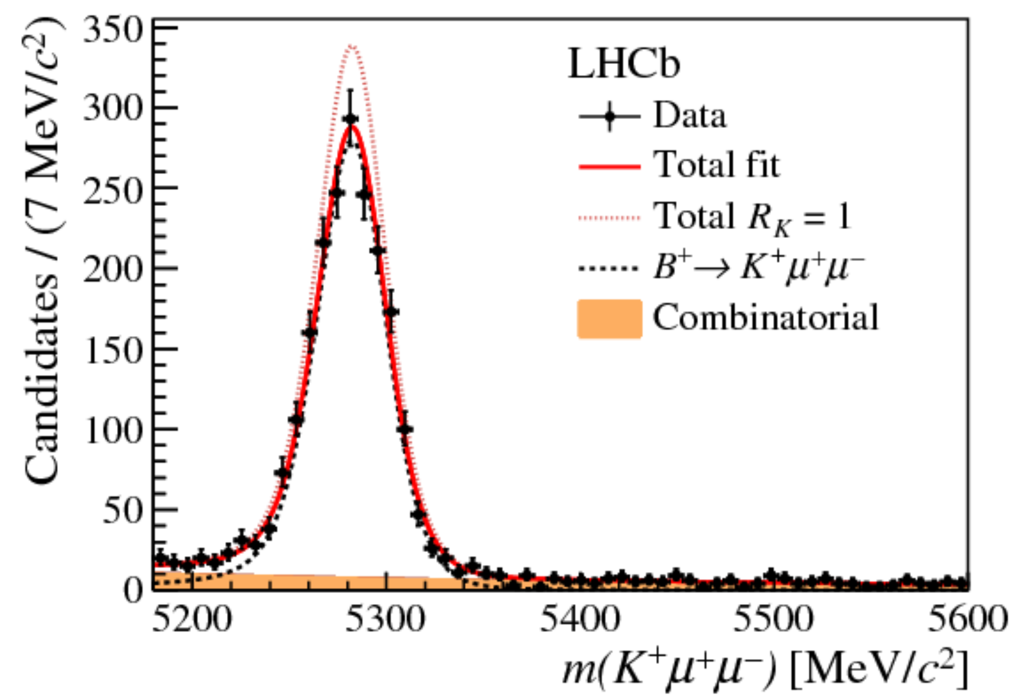
- Several cross-checks to validate the analysis strategy:
  - Measured $r_{J/\psi}$ single ratio:

$$r_{J/\psi} = \frac{\mathscr{B}(B^+ \to K^+ J/\psi(\to \mu^+\mu^-))}{\mathscr{B}B^+ \to K^+ J/\psi(\to e^+e^-))} = 1.014 \pm 0.035$$

  - Measured $R_K^{\psi(2S)}$ double ratio:

$$R_{\psi(2S)} = \frac{\mathscr{B}(B^+ \to \psi(2S)(\to \mu^+\mu^-)K^+)}{\mathscr{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathscr{B}(B^+ \to \psi(2S)(\to e^+e^-)K^+)}{\mathscr{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = 0.986 \pm 0.013$$





- The most recent R_K result is consistent with the previous measurement, and show slight tension at $\sim 2.5\sigma$ with SM:

$$R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

- LFU-test involving another group of decays — processes featuring the underlying tree-level b-hadron decays ($b \to c\ell\nu$), show notable tension with SM
- Most recent measurement of this set (R_{D^*}) performed by LHCb using data from 2011-2012 (Run 1, 3 fb^{-1}):

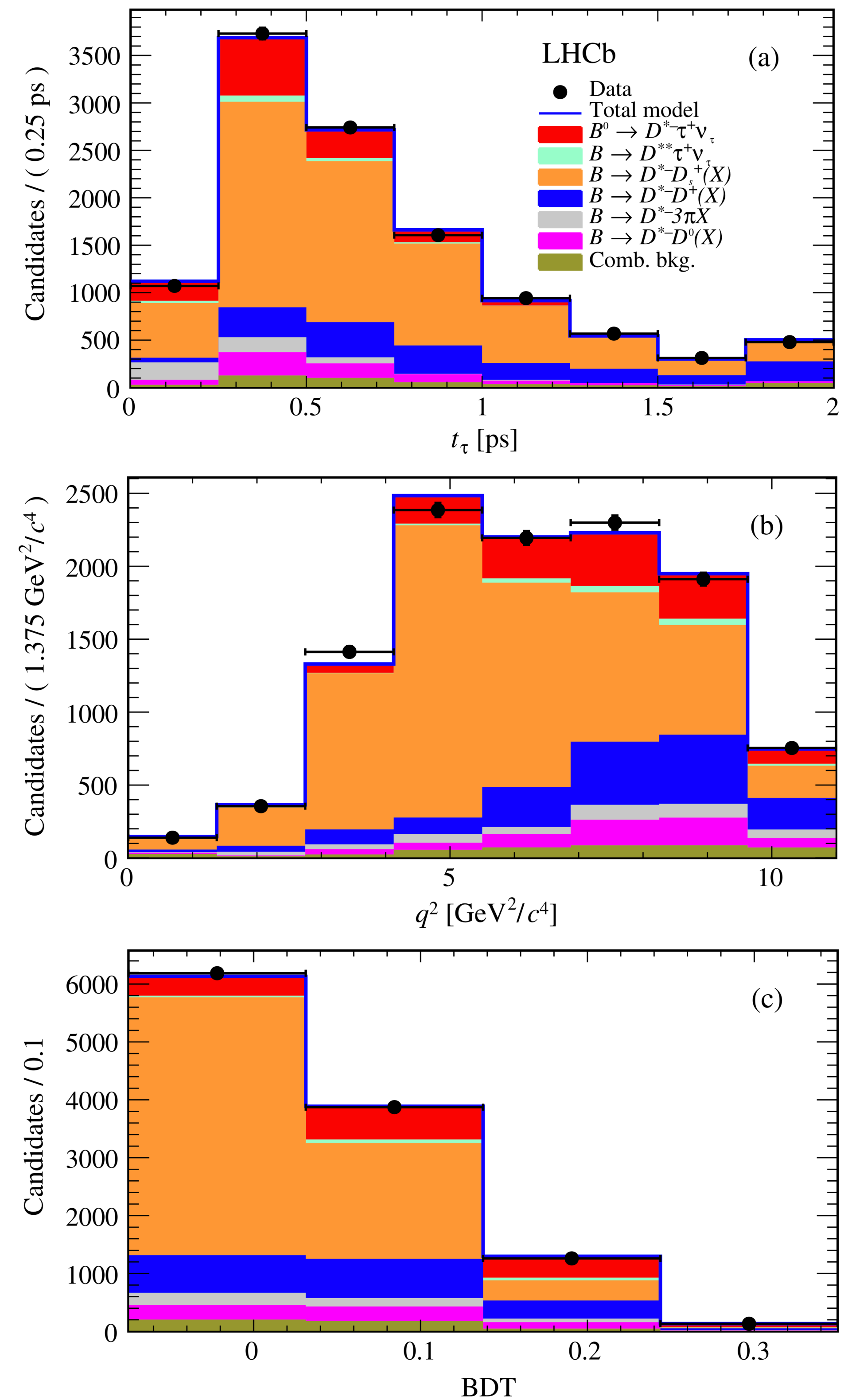
$$R_{D^{*-}} \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)} \quad \left\} \begin{array}{c} D^{*-} \to \bar{D}^0(\to K^+\pi^-)\pi^- \\ \tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau \end{array} \right.$$

- Strategy: measure $B^0 \to D^{*-}\tau^+\nu_\tau$ normalised to $B^0 \to D^{*-}3\pi$:

$$K_{D^{*-}} \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)} \qquad R_{D^{*-}} \equiv K_{D^{*-}} \times \frac{\mathcal{B}(B^0 \to D^{*-}3\pi)_{ext}}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)_{\text{ext.}}}$$

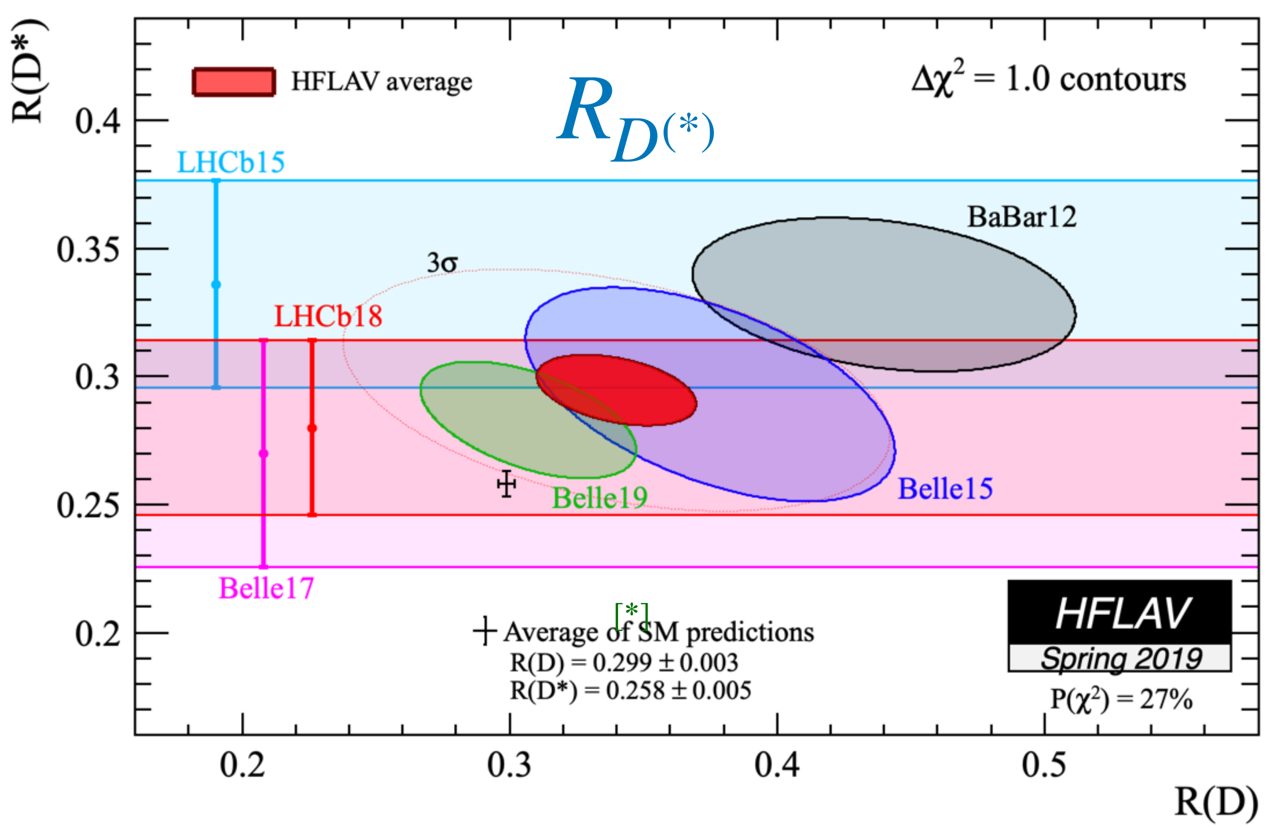
- Suppress backgrounds from $B \to D^*3\pi X$ by imposing that the 3π vertex is downstream of, and significantly detached from, the B^0 vertex
- Background from double-charm (e.g. $B^0 \to D^{*-}D^+(X)$) decays suppressed using BDT
- Extract signal yield via 3d binned maximum likelihood fit to τ decay time, q^2 and BDT output distributions
- Final result is compatible with SM (within 1σ):

$R_{D^*} = 0.291 \pm 0.019\,(\text{stat}) \pm 0.026\,(\text{syst}) \pm 0.013\,(\text{ext})$

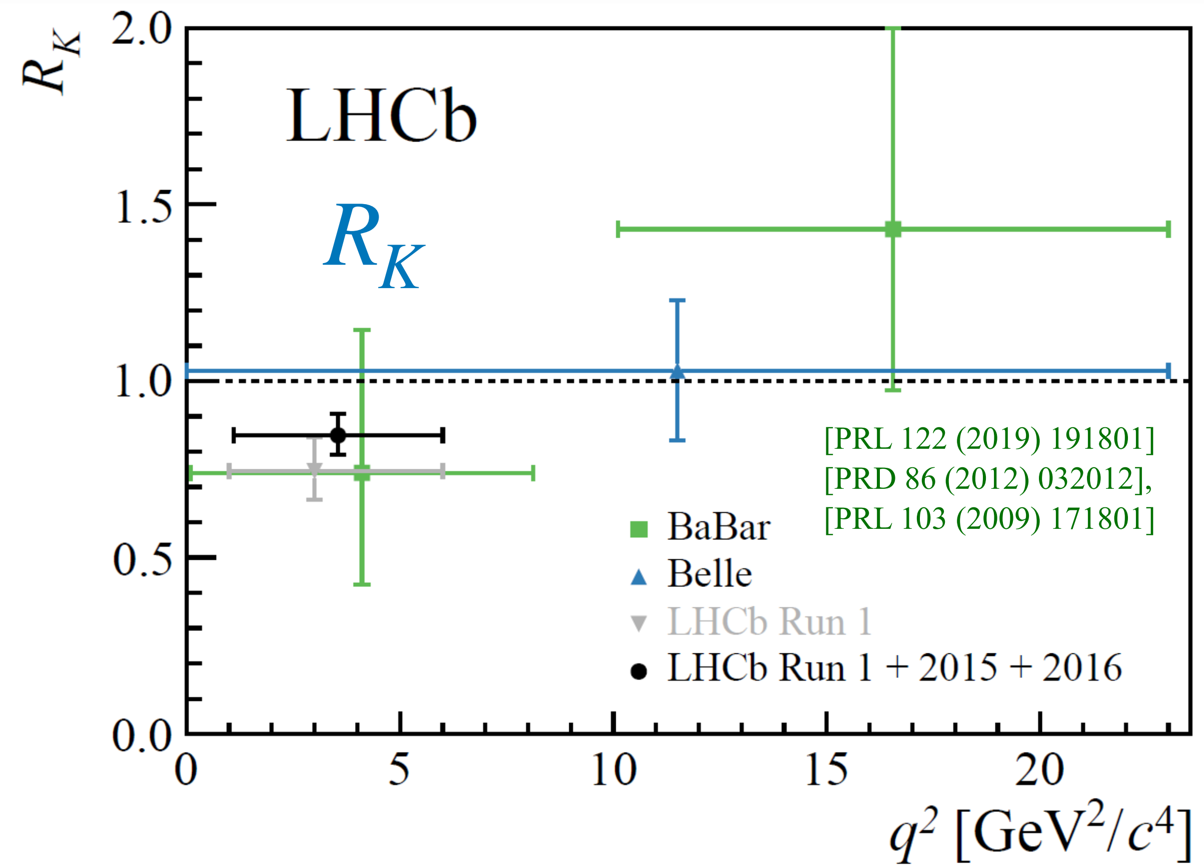


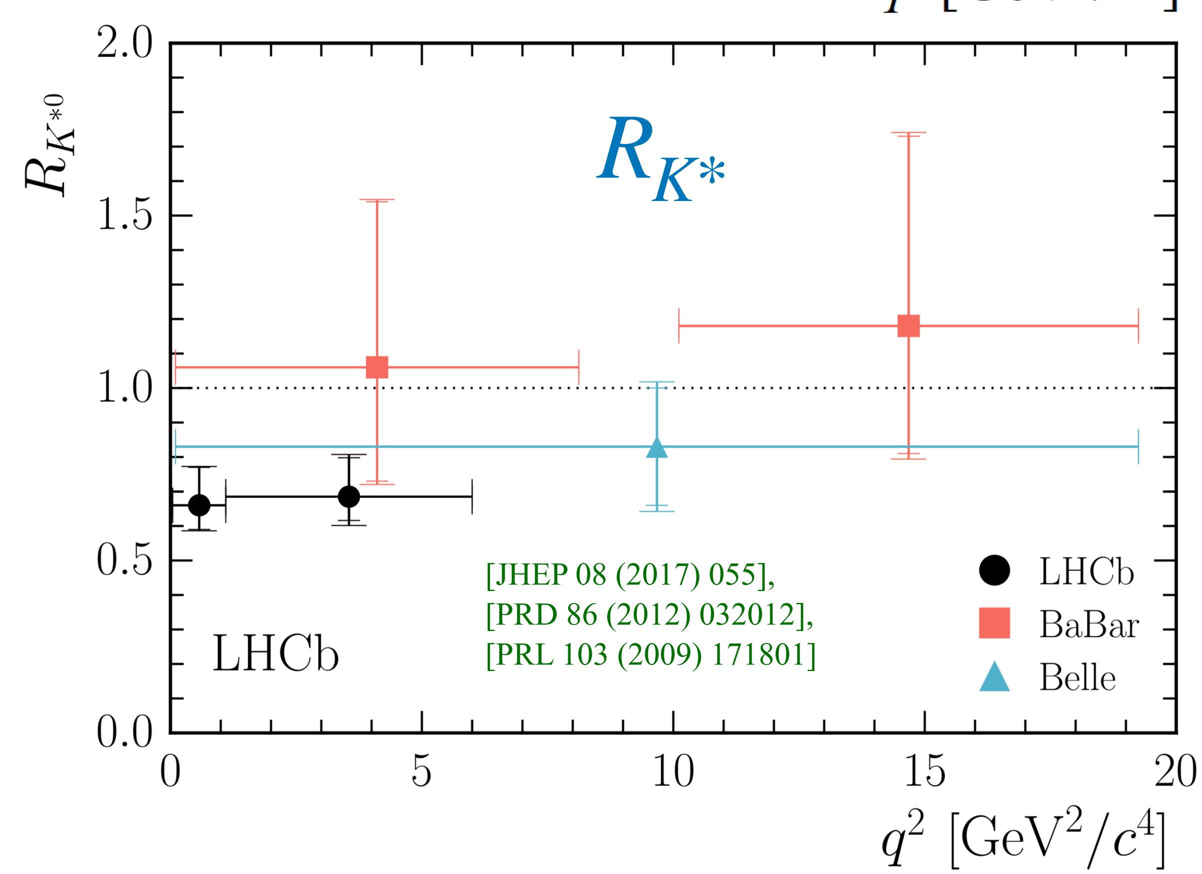
Lepton flavour universality tests: current status

- Current LFU-tests at the LHCb involving $b \to s\ell^+\ell^-$ ($R_{K^{(*)}}$) and $b \to c\ell\nu$ ($R_{D^{(*)}}$, $R_{J/\psi}$) decays show tensions with SM predictions [see also Backup slide A]
- More statistics and additional measurements from LHCb and other collaborations (e.g. Belle-II) will help to clarify the picture



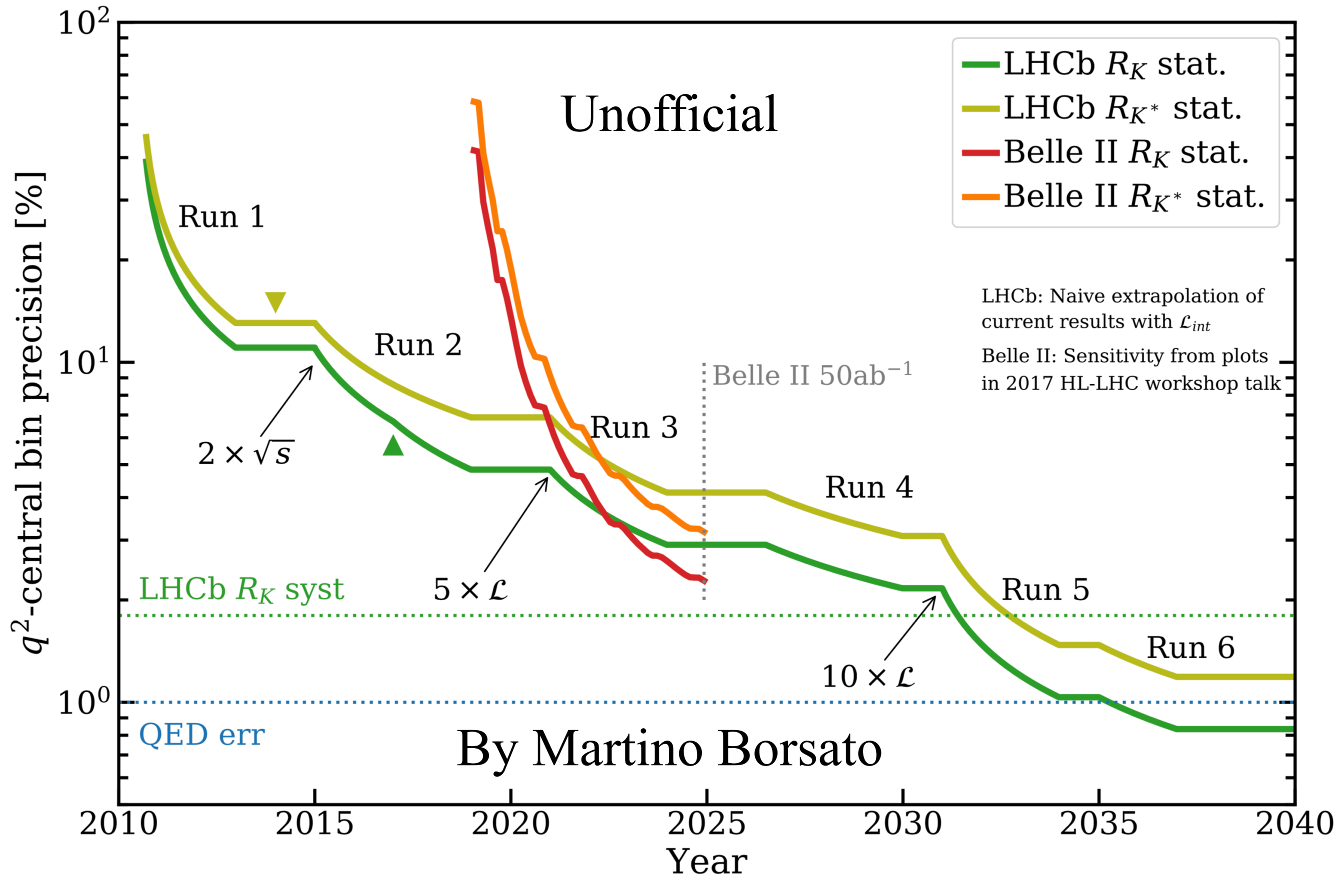
*By HFLAV, using: [PRL 115 (2015) 111803], [PRD 97 (2018) 072013], [PRL 120 (2018) 171802], [arXiv:1904.08794], [PRL 109 (2012) 101802], [PRD 88 (2013) 072012], [PRD 92 (2015) 072014], [PRL 118 (2017) 211801], [PRD 97 (2018) 012004]

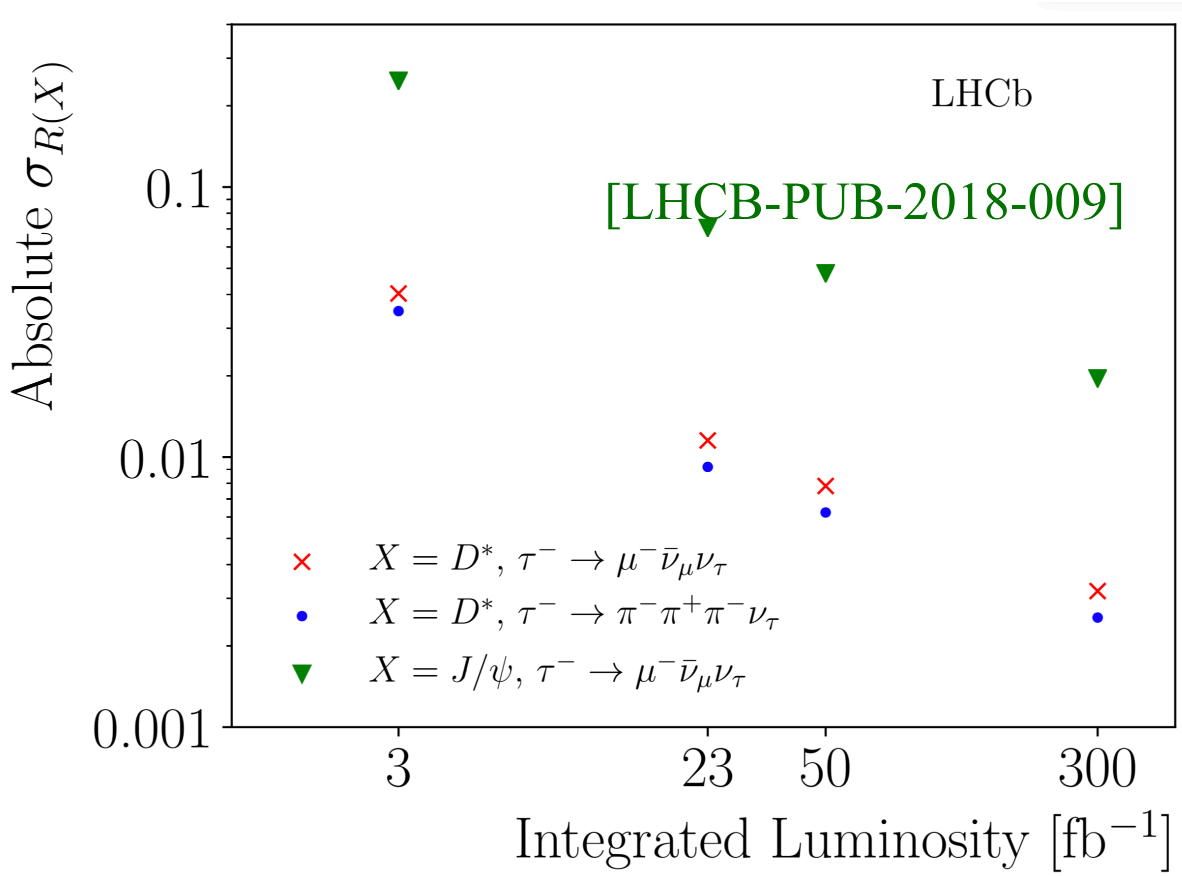




Lepton flavour universality tests: the future

- A number of rare b-hadron decay R_X analyses are currently in progress, including updates to $R_{K^{(*)}}$ using full Run 2 (up to 2018) statistics, R_ϕ, R_{pK} and R_π
- R_X measurements involving tree-level b-hadron decays are also ongoing, with interesting prospects





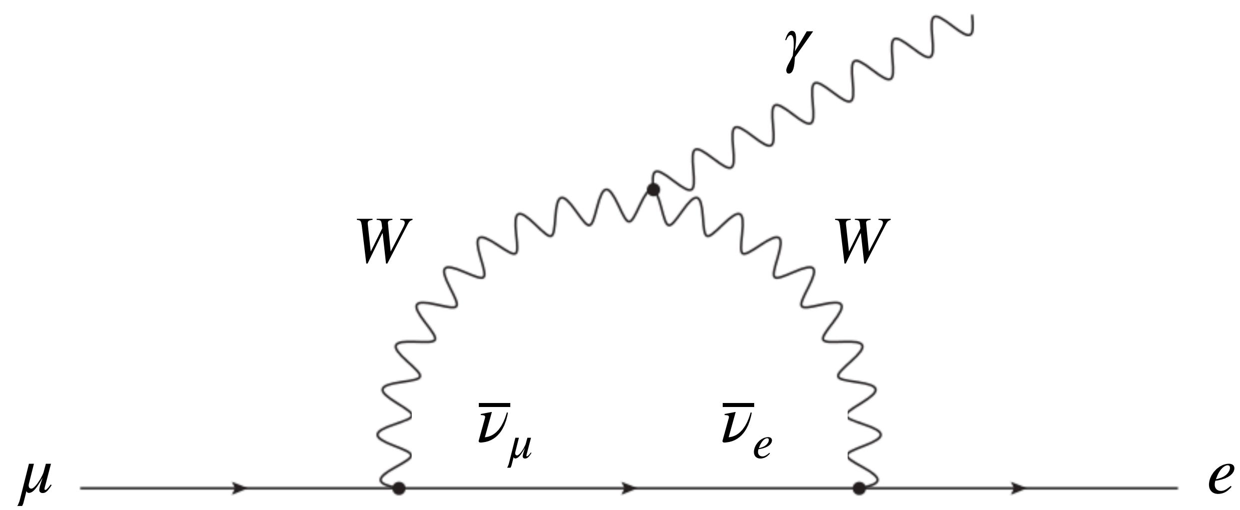
R_X precision	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
R_K	$0.745 \pm 0.090 \pm 0.036$	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

[LHCB-PUB-2018-009]

- CMS started to gather data (B-parking) for LFU tests, including the potential measurement of $R_{K^{(*)}}$

Lepton flavour violation

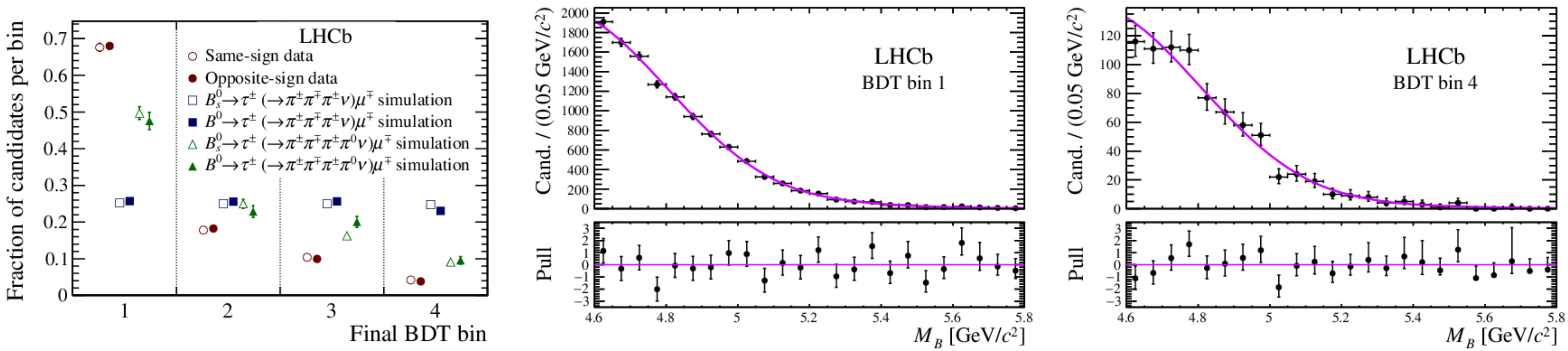
- Lepton flavour violation (LFV), e.g. $\mu \to e\gamma$, is forbidden in the SM
- Observations of neutrino oscillations suggest LFV occurs for neutral leptons
- However, no evidence for LFV involving charged leptons has ever been found



$$\mathcal{B}(\mu \to e\gamma)_{SM} < 10^{-50}$$

- Recent hints of LFU violation motivate the search for LFV in the decays of b-hadrons, as beyond-SM models capable of accommodating for LFU generally predict charged LFV with measurable BFs
- LHCb is the main experiment involved in the searches for LFV decays of b-hadrons
- Recent developments in this area include searches (at LHCb) for:
  - $B^0_{(s)} \to \tau^\pm \mu^\mp$
  - $B^+ \to K^+ \mu^\pm e^\mp$

- Analysis performed by LHCb using data collected in 2011-2012 (Run 1, 3 fb^{-1})
- Reconstruct τ from the decay chain $\tau^- \to a_1^-(1260)\nu_\tau$, $a_1^-(1260) \to \rho^0(770)(\to \pi^+\pi^-)\pi^-$
- Normalisation mode: $B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+$
- Reduce backgrounds with cut based selection, e.g. τ decay time and masses of pion combinations
- Use two BDTs to further reduce backgrounds

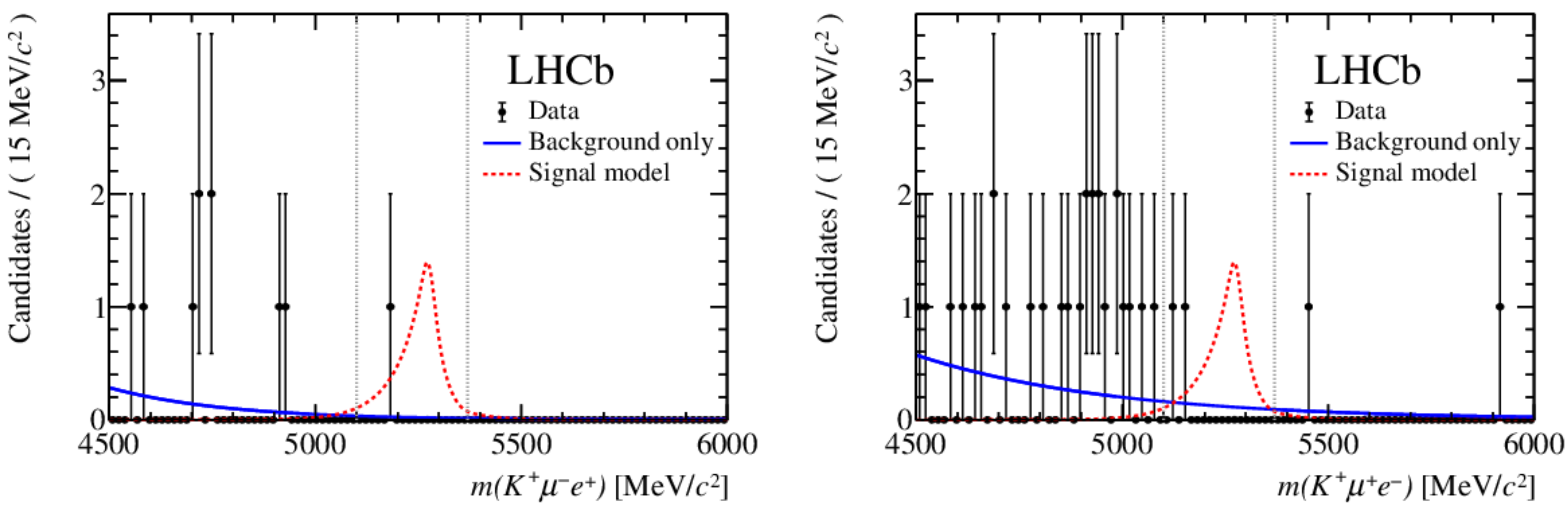


- Use a final classifier to split sample into four bins to further enhance signal-background separation
- Extract BF by performing UML fit to $m_{\tau\mu}$ (from analytical reconstruction) in the four bins, taking the expected signal fraction per bin into account
- Obtained BF limits at 95% CL of
  - $\mathcal{B}(B_s^0 \to \tau^\pm\mu^\mp) < 4.2 \times 10^{-5}$
  - $\mathcal{B}(B^0 \to \tau^\pm\mu^\mp) < 1.4 \times 10^{-5}$

BF can be as large as $\mathcal{O}(10^{-5})$ in some models with Z'/leptoquarks
e.g. [JHEP 11 (2016) 035]

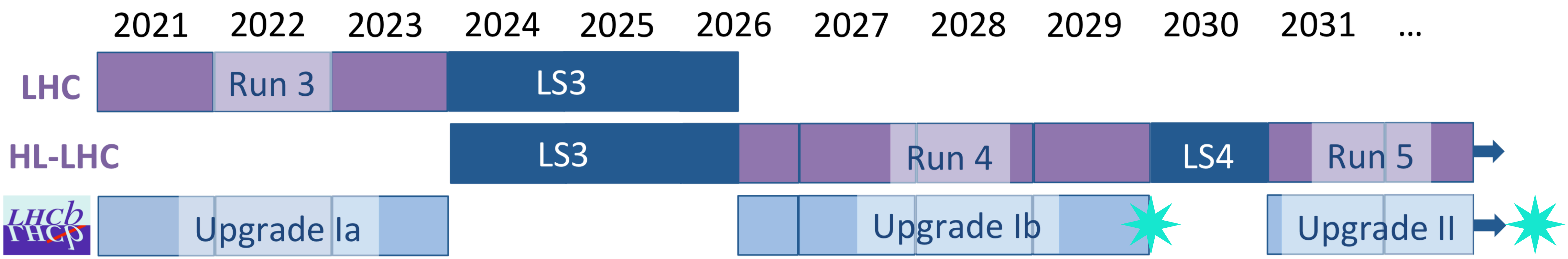
- Search performed by LHCb using data taken in 2011-2012 (Run 1, 3 fb^{-1})
- Different lepton charge combinations studied separately
- One multivariate classifier to reduce combinatorial background, another to reduce background from partially reconstructed b-hadron decays
- Classifier output cuts optimised for best expected BF upper limit
- Found 1 (2) candidates in signal region
- Upper limits at 95% CL determined to be:
  - $\mathcal{B}(B^+ \to K^+\mu^- e^+) < 9.5 \times 10^{-9}$
  - $\mathcal{B}(B^+ \to K^+\mu^+ e^-) < 8.8 \times 10^{-9}$

BF up to $\mathcal{O}(10^{-8})$ in some leptoquark models
e.g. [JHEP 06 (2015) 072]



Lepton flavour violation search - the future

- LHCb has produced some limit estimations for the future:



	Run 1 (Current)	Upgrade I	Upgrade II
$B^0 \to e^\pm\mu^\mp$	$< 1.3 \times 10^{-9}$	$< 2 \times 10^{-10}$	$< 9 \times 10^{-11}$
$B_s^0 \to e^\pm\mu^\mp$	$< 6.3 \times 10^{-9}$	$< 8 \times 10^{-10}$	$< 3 \times 10^{-10}$
$B^0 \to \tau^\pm\mu^\mp$	$< 1.4 \times 10^{-5}$	–	$< 3 \times 10^{-6}$

[LHCB-PUB-2018-009]

- Searches for other LFV decays of b-hadrons at LHCb, such as $B^0 \to K^{*0}\tau^\pm\mu^\mp$, $B^+ \to K^+\tau^\pm\mu^\mp$ and $\Lambda_b^0 \to \Lambda e^\pm\mu^\mp$ are in progress
- Limits for $B^+ \to K^+\tau^\pm\mu^\mp$ and $B^0 \to K^{*0}\tau^\pm\mu^\mp$ using Upgrade II data are expected to provide strong constraints on beyond-SM models

Summary

- Observables of rare b-hadron FCNC decays are ideal for the indirect search for beyond-SM effects
- Leptonic B decay searches/BF measurements carried out for the muon (and tau modes), producing results consistent with SM predictions
- Multiple LFU tests involving b-hadron decays, such as $R_{K^{(*)}}$ (rare $b \to s\ell^+\ell^-$ processes) and $R_{D^{(*)}}$ (tree-level $b \to c\ell\nu$), show slight tension with SM
- LFV searches produced limits that are starting to encroach upon beyond-SM theory predictions in some cases
- Upcoming LFU tests with full Run 2 statistics and beyond will help clarify the current situation
- Significant improvements to more challenging rare decays/LFV searches require larger statistics from Run 3 (end of 2023) onwards

Backup

Other lepton flavour universality tests

- Other tests of LFU at the LHCb include:

$b \to s\ell\ell$

$$R_{K^*} = \frac{\mathcal{B}(B \to K^*\mu\mu)}{\mathcal{B}(B \to K^*ee)} = 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) \text{ for } 1.1 < q^2 < 6.0\,\text{GeV}^2/\text{c}^4$$

Compatibility with SM ($1 \pm \mathcal{O}(10^{-2})$): $2.4 - 2.5\sigma$ [JHEP 08 (2017) 055]

$b \to c\ell\nu$

- Tree level decays with large BF (few precent), and precise SM predictions

$$R_{D^{(*)}} \equiv \frac{\mathcal{B}(B^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$

$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$: $0.336 \pm 0.027\,(\text{stat}) \pm 0.030\,(\text{syst})$

Compatibility with SM (0.252 ± 0.003): $\sim 2.1\sigma$ [PRD 85 (2012) 094025]

$\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$: $0.291 \pm 0.019\,(\text{stat}) \pm 0.026\,(\text{syst}) \pm 0.013\,(\text{ext})$ Compatibility with SM: 1σ

[PRL 115 (2015) 111803] [PRD 97 (2018) 072013]

$$R_{J/\psi} \equiv \frac{\mathcal{B}(B_c \to J/\psi\tau\bar{\nu}_\tau)}{\mathcal{B}(B_c \to J/\psi\mu\bar{\nu}_\mu)} = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$$

[PRL 120 (2018) 121801]

Compatibility with SM (0.25-0.28)*: $\sim 2\sigma$

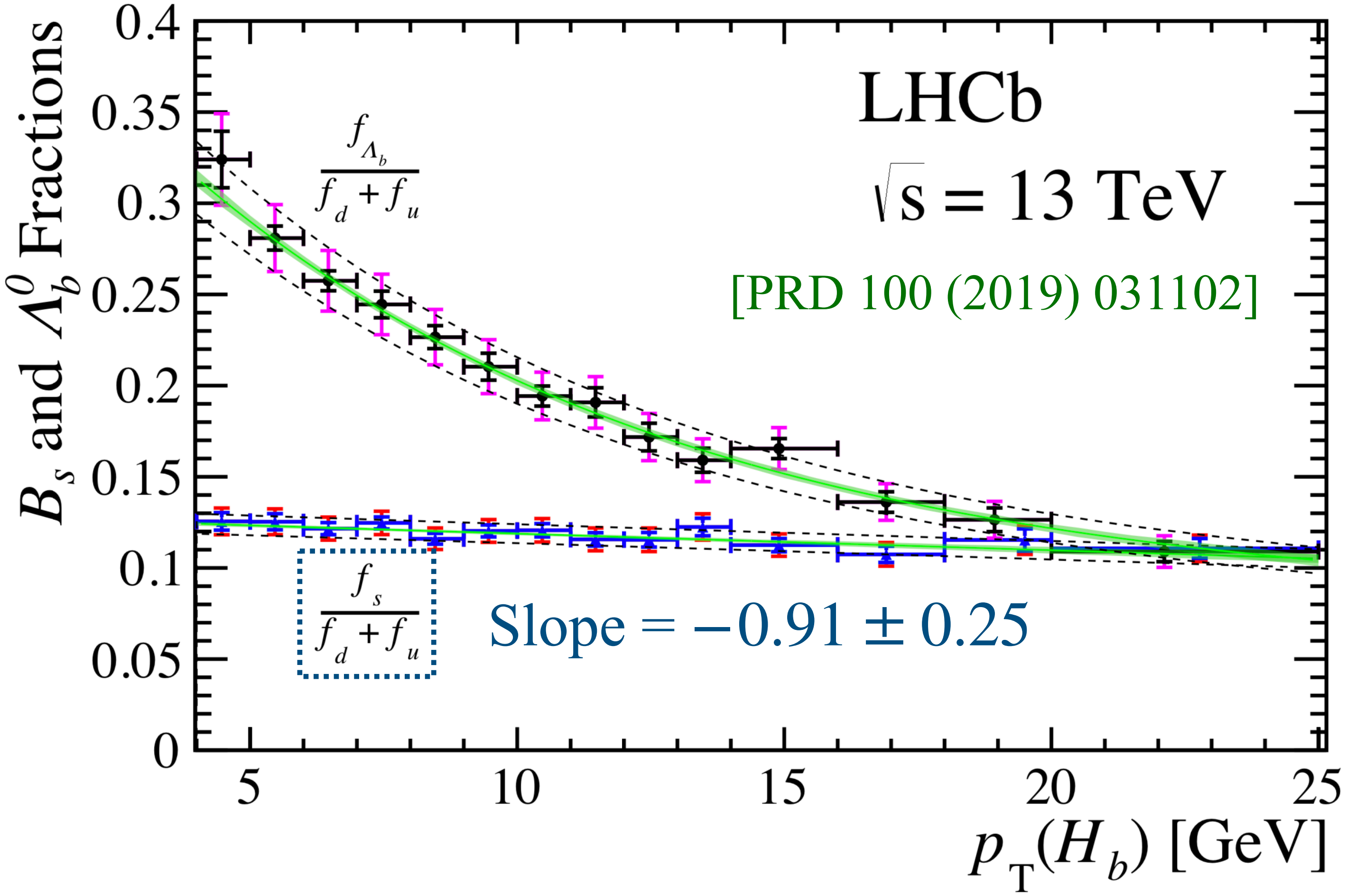
*[PLB 452 (1999) 129136] [PRD 74 (2006) 074008] [hep-ph/0211021] [PRD 73 (2006) 054024]

$B^0_{(s)} \to \mu^+\mu^-$: normalisation

- In the determination of $B^0_{(s)} \to \mu^+\mu^-$ BF, LHCb, ATLAS and CMS all* use the normalisation mode of $B^+ \to (J/\psi \to \mu^+\mu^-)K^+$ involving a $B^\pm$ [bu]:

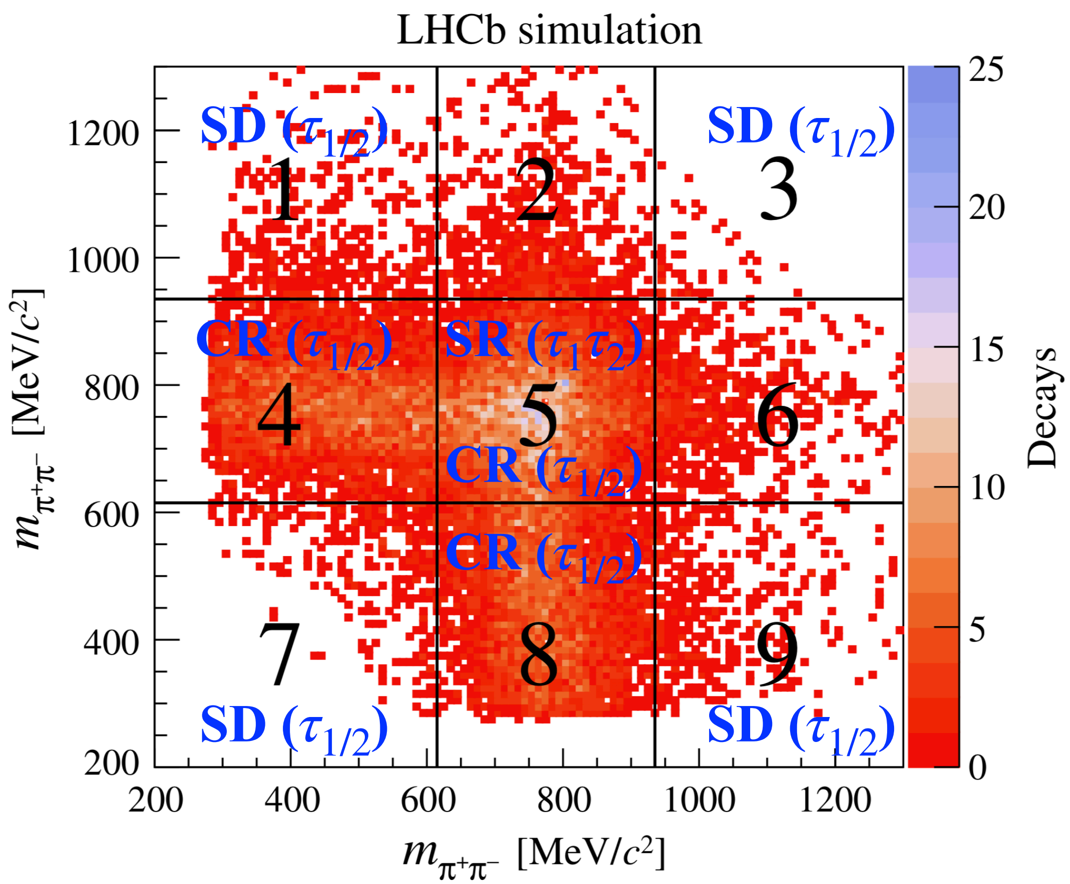
$$\mathscr{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{\mathscr{B}_{norm}\epsilon_{norm}}{N_{norm}\epsilon_{sig}} \frac{f_{norm}}{f_{d(s)}} N_{B^0_{(s)}\to\mu^+\mu^-} \equiv \alpha^{norm}_{B^0_{(s)}\to\mu^+\mu^-} N_{B^0_{(s)}\to\mu^+\mu^-}$$

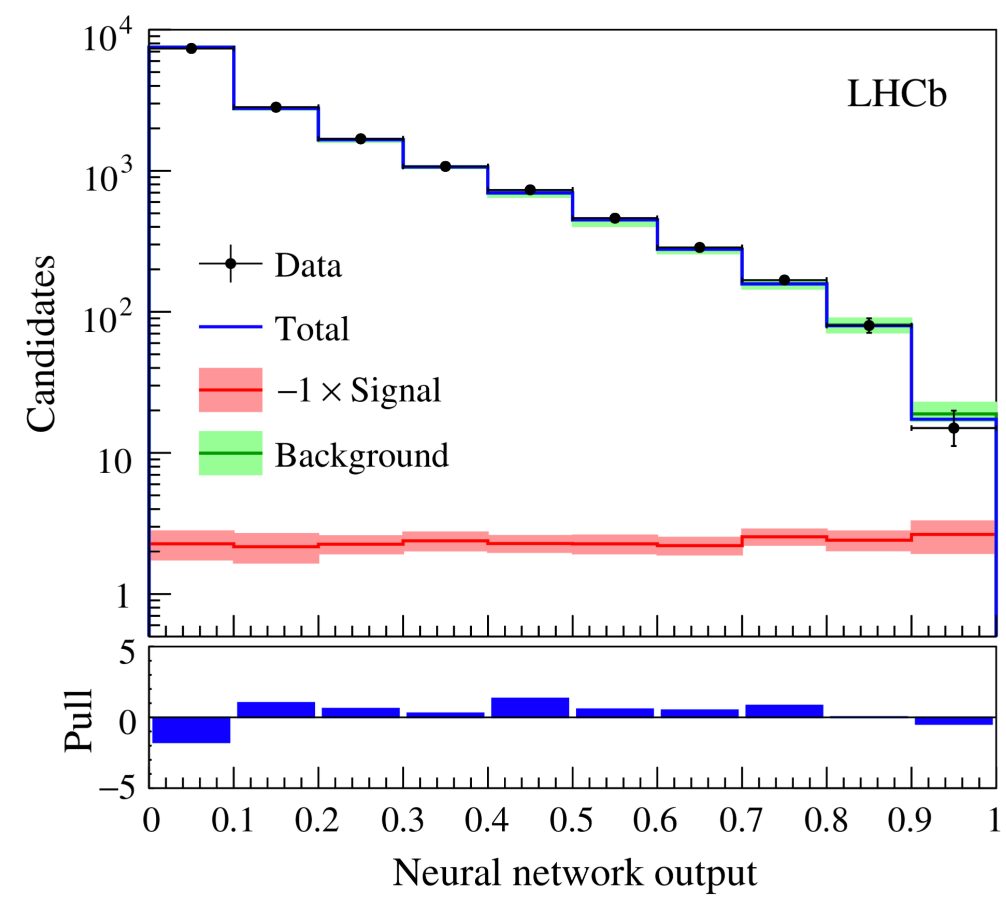
- This necessitates the value for f_s/f_d, which has the (latest) LHC-average of 0.252 ± 0.012 (assuming $f_u/f_d = 1$) [PDG]
- However f_s/f_d will vary depending on e.g. centre-of-mass energy and PT
- Some evidence of variation with PT has been seen by LHCb
- CMS added extra uncertainty for most recent measurement (± 0.015)
- CMS is considering other options, e.g. $B_s \to J/\psi\phi$ (need to be careful about BF uncertainty)



*LHCb uses $B^0_{(s)} \to K^+\pi^-$ in addition, but contribution to average ($\alpha^{norm}_{B^0_{(s)}\to\mu^+\mu^-}$) dominated by B^+ mode with more events

- Data collected in 2011 and 2012 (3 fb^{-1})
- Reconstruct τ from the decay chain $\tau^- \to a_1^-(1260)\nu_\tau$, $a_1^-(1260) \to \rho^0(770)(\to \pi^+\pi^-)\pi^-$
- Normalisation channel: $B^0 \to D^-(\to K^+\pi^-\pi^-)D_s^+(\to K^-K^+\pi^+)$
- Larger BF (less helicity suppressed), but analysis complicated by undetected neutrinos: $m_{\tau\tau}$ allows for only weak signal-background separation, B^0/B_s^0 not resolved => optimise for B_s^0
- Use two neural networks (NN) following cut-based selection
- Perform 1d histogram fit to second NN output distribution

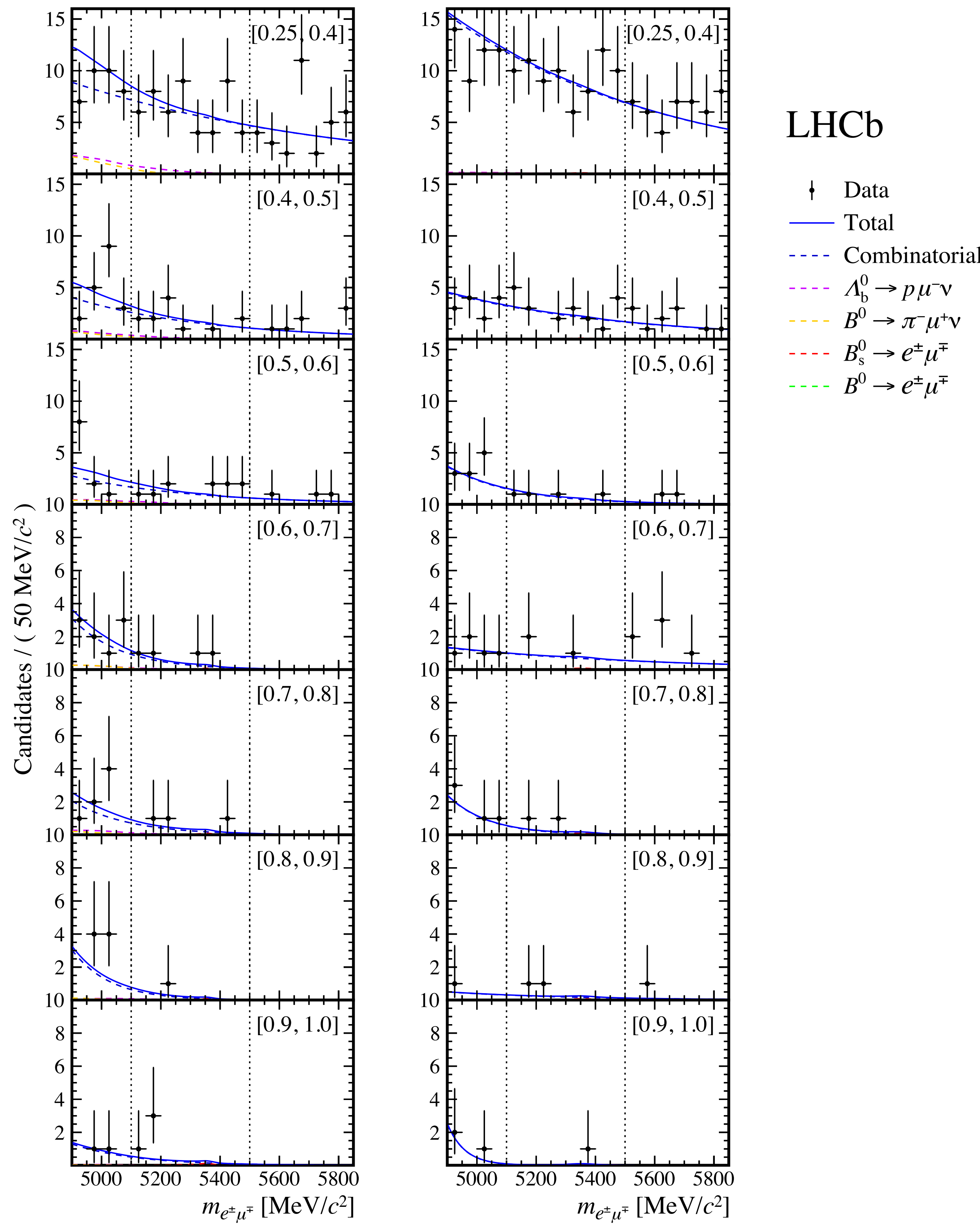




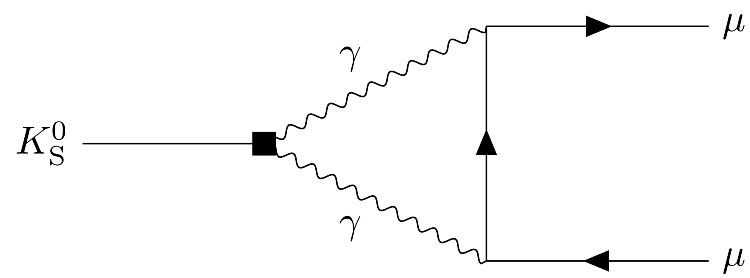
- No evidence (yet), BR limits at 95% CL:
  - $\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3}$
  - $\mathcal{B}(B^0 \to \tau^+\tau^+) < 2.1 \times 10^{-3}$ (assuming no B_s^0 contribution)

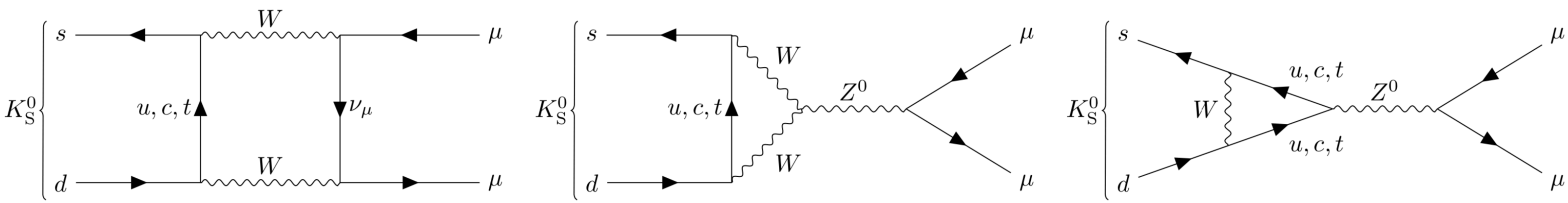
JHEP 03 (2018) 078

- Analysis performed by LHCb using data collected in 2011-2012 (Run 1, 3fb-1)
- Combinatorial BDT trained using simulated $B^0_{(s)} \to e^+\mu^-$ (signal) and same sign $B^0_{(s)} \to e^\pm\mu^\mp$ data (background)
- Extract BF via simultaneous UML fit to seven BDT output bins and two bremsstrahlung categories
- No excesses observed, upper limits at 95% CL are found to be:
  - $\mathcal{B}(B^0_s \to e^\pm\mu^\mp) < 6.3(7.2) \times 10^{-9}$ for heavy (light) mass eigenstate
  - $\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 1.3 \times 10^{-9}$



- $K_S^0 \to \mu^+\mu^-$ is a rare, as-of-yet unobserved FCNC decay that is highly suppressed in the SM, with $\mathscr{B}(K_s^0 \to \mu^+\mu^-)_{SM} = (5.18 \pm 1.5_{\mathrm{LD}} \pm 0.02_{\mathrm{SD}}) \times 10^{-12}$
- Feynman diagrams showing long distance (LD) and short distance (SD) SM contributions:

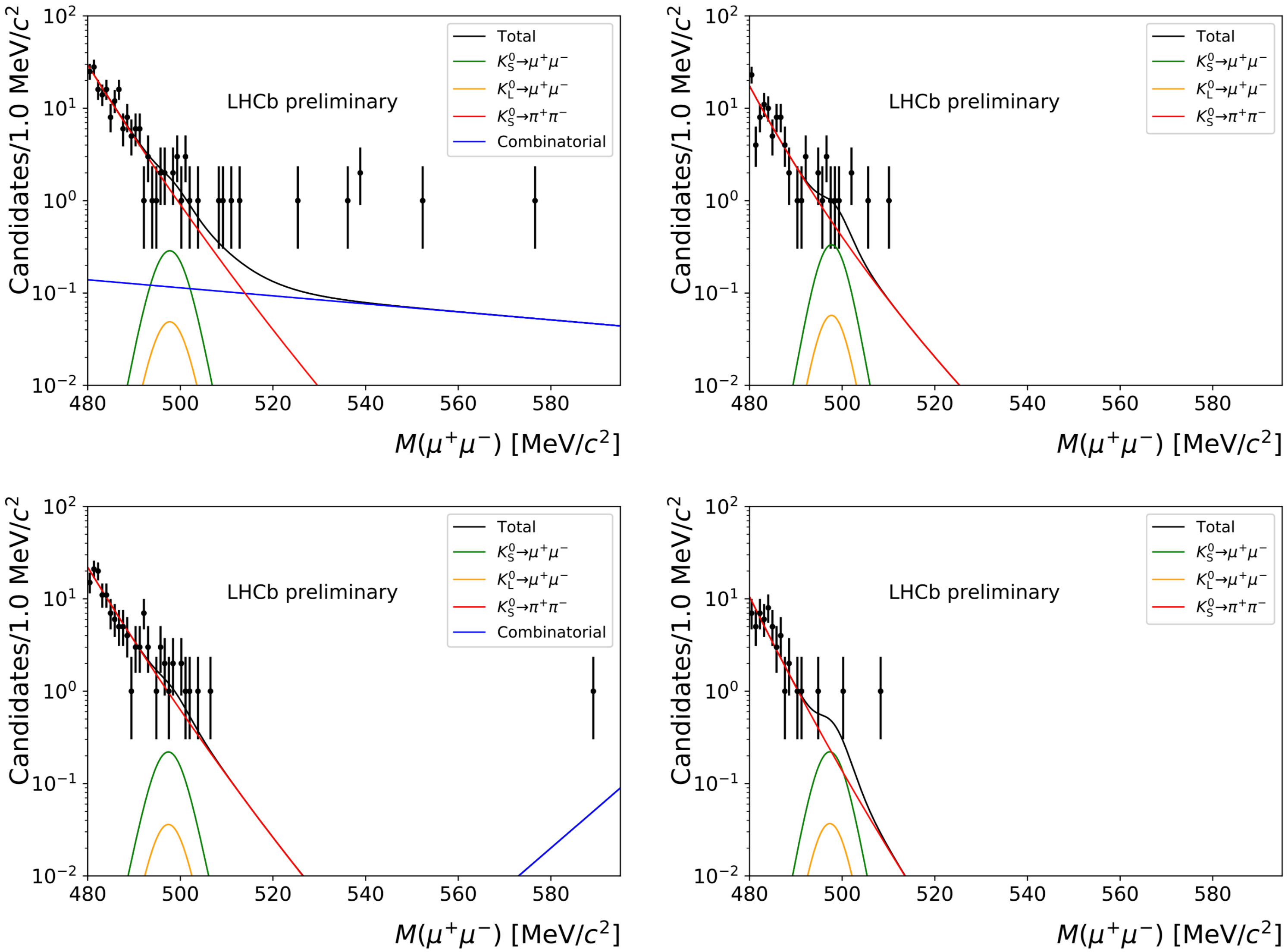




- Beyond-SM theories, including some leptoquark models, predict deviations in $\mathscr{B}(K_s^0 \to \mu^+\mu^-)$
- Recently LHCb reported the (preliminary) result of a search that uses data collected in 2016, 2017 and 2018 (Run 2, 5.6 fb^{-1})

Search for $K_S^0 \to \mu^+\mu^-$

- Normalisation mode (similar topology): $K_s^0 \to \pi^+\pi^-$
- Simultaneous UML fit to $m_{\mu^+\mu^-}$ of twenty subsamples (two trigger categories × ten combinatorial BDT bins)
- $K_s^0 \to \pi^+\pi^-$ background suppressed via dedicated muon identification BDT, $K_L^0 \to \mu^+\mu^-$ constrained using well-known BF and K_S^0/K_L^0 efficiency ratio from corrected simulation



TIS

TOS-exclusive

- Determined (combined with Run 1) $\mathcal{B}(K_s^0 \to \mu^+\mu^-) < 2.4 \times 10^{-10}$ (2.3×10^{-10}) at 95% C.L.
- $B_s^0 \to \mu^+\mu^-$ Run 1(+2) significance: 1.5(1.4)σ