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New observables in RD in the LHCb Upgrade II

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TUPFP Durham
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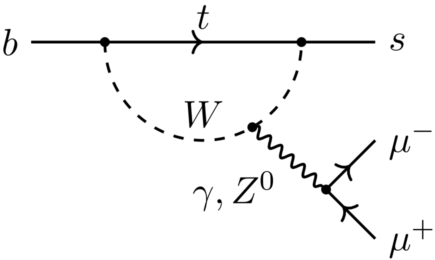
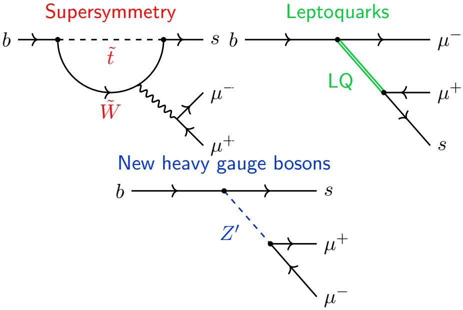
Rare decays as sensitive probes for New Physics

Rare decays in the SM



Possible contributions from NP



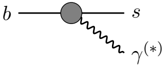
- Rare decays are so called Flavour Changing Neutral Currents
- In the SM: Only allowed via quantum fluctuations (loop suppressed)
- New heavy particles can significantly contribute and change rates and angular distributions

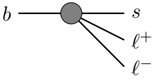
NP contributions and relevant effective couplings

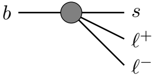
- Model independent description in effective field theory

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^{*} \frac{e^2}{16\pi^2} \sum_i \underbrace{\boxed{\mathcal{C}_i}}_{\text{Wilson coefficient (“effective coupling”)}} \overbrace{\boxed{\mathcal{O}_i}}^{\text{Local operator}} \qquad \Delta\mathcal{H}_{\text{NP}} = \frac{\overbrace{\boxed{\kappa}}^{\text{Flavour-violating coupling}}}{\underbrace{\boxed{\Lambda_{\text{NP}}^2}}_{\text{NP scale}}} \mathcal{O}_i$$

- NP can contribute to different operators $\mathcal{O}_i$ depending on its type. Relevant effective couplings for rare decays:







	Coupling	Operator
Photon penguin	$\mathcal{C}_7^{(\prime)}$	$\frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$
EW penguin	$\mathcal{C}_9^{(\prime)}$	$(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\mu}\gamma^\mu\mu)$
	$\mathcal{C}_{10}^{(\prime)}$	$(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\mu}\gamma^\mu\gamma_5\mu)$
Scalar penguin	$\mathcal{C}_S^{(\prime)}$	$\frac{m_b}{m_B}(\bar{s}P_{R(L)}b)(\bar{\mu}\mu)$
	$\mathcal{C}_P^{(\prime)}$	$\frac{m_b}{m_B}(\bar{s}P_{R(L)}b)(\bar{\mu}\gamma_5\mu)$

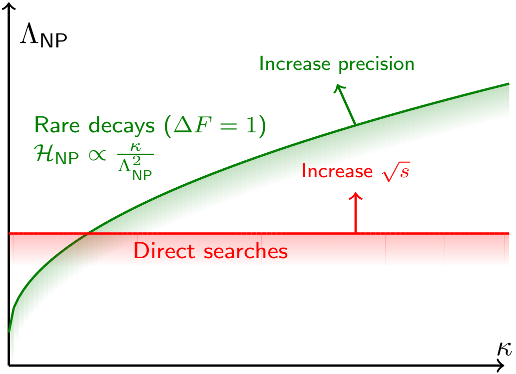
$b \to s\gamma$

$b \to s\ell\ell$

$B_s^0 \to \mu^+\mu^-$

The complementarity of NP searches with rare decays

Exclusion limits for NP searches

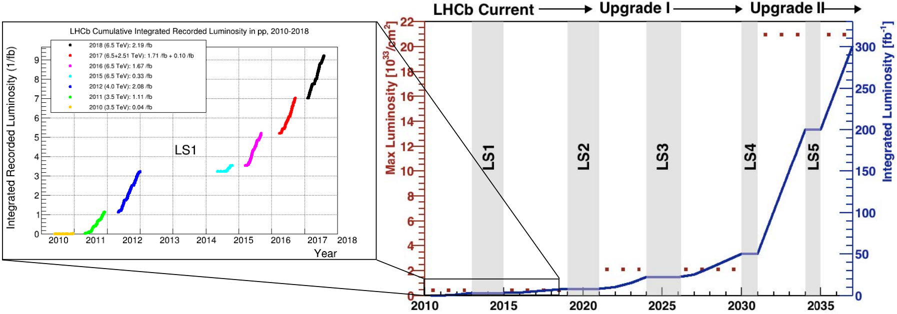


scenario	κ
Tree generic	1
Tree MFV	$V_{\text{tb}}V_{\text{ts}}$
Loop generic	$\frac{1}{16\pi^2}$
Loop MFV	$\frac{V_{\text{tb}}V_{\text{ts}}}{16\pi^2}$

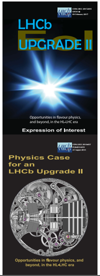
CKM-like flavour violation ⟷ generic flavour violation

- Direct searches limited by beam energy, $\Lambda_{\text{NP}} < \sqrt{s}$
- Reach with rare decays scales with $\sqrt{\kappa/\sigma(\mathcal{C}_i)}$
- Typically $\Lambda_{\text{NP}} \propto \sqrt{\kappa/\sigma(\mathcal{C}_i)} \propto \sqrt{\kappa} \times \sqrt[4]{\int \mathcal{L}\text{d}t}$

LHCb Upgrade schedule

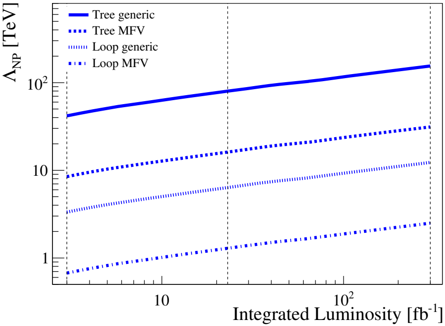


- Current status: $9\,\text{fb}^{-1}$ in Run 1+2
- Upgade I a+b: $50\,\text{fb}^{-1}$ (Run 3+4 at $\mathcal{L} = 2 \times 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$)
- Upgrade II: $300\,\text{fb}^{-1}$ (Run 5 at $\mathcal{L} = 2 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$)
- LHCb Upgrade II summarised in EoI [CERN-LHCC-2017-003] and Physics case [CERN-LHCC-2018-027]
- Physics of the HL-LHC, WG 4 Flavour [arxiv:1812.07638]



Typical NP reach of Rare Decays

$\Lambda_{\rm NP}$ reach with LFU tests $R_{K^{(*)}}$



[Upgrade II Physics case] [Physics of the HL-LHC WG 4]

$\int \mathcal{L}{\rm d}t$	$3\,{\rm fb}^{-1}$	$23\,{\rm fb}^{-1}$	$300\,{\rm fb}^{-1}$
R_K and R_{K^*} measurements			
$\sigma(\mathcal{C}_9)$	0.44	0.12	0.03
$\Lambda_{\rm NP}^{\rm tree\,generic}$ [TeV]	40	80	155
$\Lambda_{\rm NP}^{\rm tree\,MFV}$ [TeV]	8	16	31
$\Lambda_{\rm NP}^{\rm loop\,generic}$ [TeV]	3	6	12
$\Lambda_{\rm NP}^{\rm loop\,MFV}$ [TeV]	0.7	1.3	2.5
$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis			
$\sigma^{\rm stat}(S_i)$	0.034–0.058	0.009–0.016	0.003–0.004
$\sigma(\mathcal{C}'_{10})$	0.31	0.15	0.06
$\Lambda_{\rm NP}^{\rm tree\,generic}$ [TeV]	50	75	115
$\Lambda_{\rm NP}^{\rm tree\,MFV}$ [TeV]	10	15	23
$\Lambda_{\rm NP}^{\rm loop\,generic}$ [TeV]	4	6	9
$\Lambda_{\rm NP}^{\rm loop\,MFV}$ [TeV]	0.8	1.2	1.9

- Reachable NP scales $\Lambda_{\rm NP} \propto \sqrt{1/\sigma(\mathcal{C}_{\rm NP})} \propto \sqrt[4]{\int \mathcal{L}{\rm d}t}$[1]
- Precision flavour observables probe scales far beyond $\sqrt{s} = 14\,{\rm TeV}$
- Upgrade II can reach a factor 1.9 higher than Upgrade Ia

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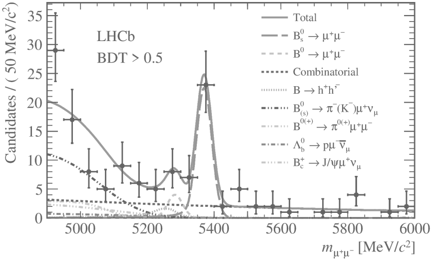
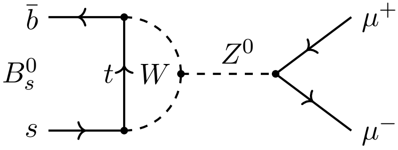
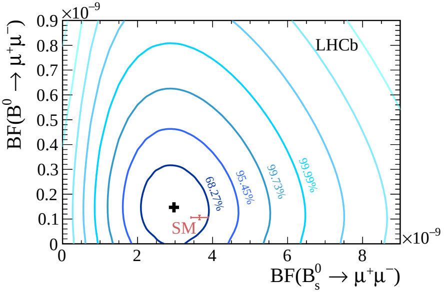
[1] Naive scaling: Assumes identical scaling of systematics

Very Rare Leptonic Decays



The very rare decay $B_s^0 \to \mu^+\mu^-$





- Loop- and helicity suppressed with purely leptonic final state: Experimentally and theoretically clean probe of new (pseudo)scalars
- Precise SM prediction [C. Bobeth *et al.*, PRL 112, 101801 (2014)]:

$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$ $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

- $B_s^0 \to \mu^+\mu^-$ sets strong constraint on MSSM $\mathcal{B} \propto \tan^6\beta/m_A^4$
- First observation of $B_s^0 \to \mu^+\mu^-$ ($7.8\,\sigma$) by single experiment [PRL 118 (2017) 191801]:

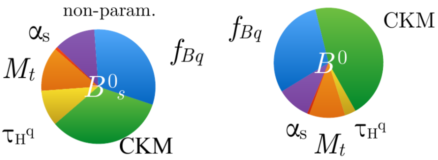
$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$ $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5^{+1.2}_{-1.0}\,^{+0.2}_{-0.1}) \times 10^{-10}$

- $B_{(s)}^0 \to \mu^+\mu^-$ in agreement with SM (and MFV) but stat. limited

$B^0_{(s)} \to \mu^+\mu^-$ in the Upgrade II

Current Experimental Systematics	
Source	size
Hadronisation fraction f_s/f_d	5.8%
Normalisation modes	3%
Particle identification	2%
Track reconstruction	2%

Current Theory Systematics



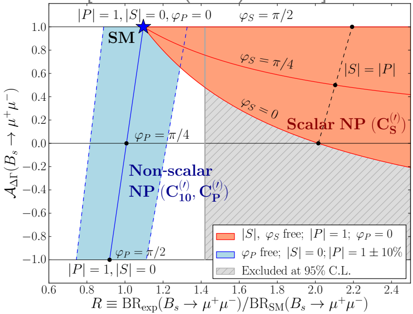
- $\mathcal{B}(B^0 \to \mu^+\mu^-)$ will remain stat. dominated with Upgrade II sample
- Projected statistical uncertainty for $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ is 1.8%
- Total exp. systematic uncertainty expected to reduce to $\sim 4\%$
- Expected total experimental uncertainties

	now	23 fb^{-1}	300 fb^{-1}
absolute uncertainty $B^0_s \to \mu^+\mu^-$ $[10^{-9}]$	0.67	0.30	0.16
rel. uncertainty $B^0 \to \mu^+\mu^- / B^0_s \to \mu^+\mu^-$ [%]	90%	34%	10%

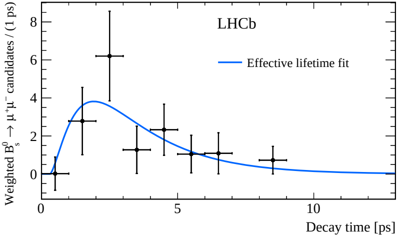
- Dominant theory uncertainties (B^0_s decay constant, CKM elements) also expected to reduce

$B_s^0 \to \mu^+\mu^-$ lifetime

[PRL 109 (2012) 041801]



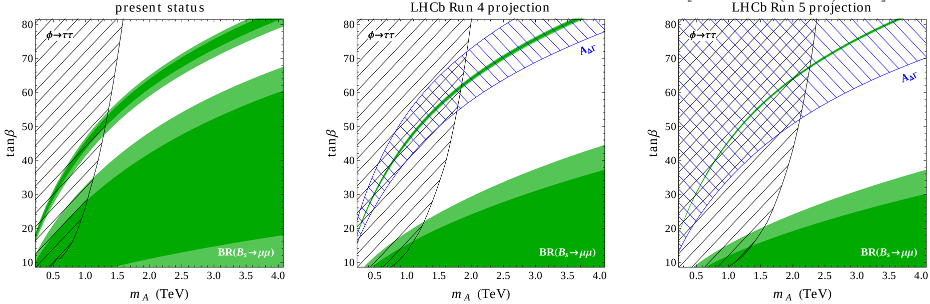
[PRL 118 (2017) 191801]



- $\Gamma(B_s^0(t)\to\mu^+\mu^-) \propto \left[\cosh\left(\frac{y_s t}{\tau_{B_s}}\right) + S_{\mu\mu}\sin(\Delta m_s t) + A_{\Delta\Gamma}\sinh\left(\frac{y_s t}{\tau_{B_s}}\right)\right] e^{-t/\tau_{B_s}}$
- Effective Lifetime probe for NP complementary to $\mathcal{B}$
  $\tau_{\mu\mu} = \frac{\tau_{B_s}}{1-y_s^2}\frac{1+2y_s A_{\Delta\Gamma}+y_s^2}{1+y_s A_{\Delta\Gamma}}$ with $y_s = \tau_{B_s}\frac{\Delta\Gamma_s}{2} = 0.062\pm0.006$
- In the SM: $A_{\Delta\Gamma}^{\mathrm{SM}} = 1$, NP models allow $A_{\Delta\Gamma}^{\mathrm{NP}} \in [-1,1]$
- $\tau(B_s^0\to\tau^+\tau^-) = 2.04\pm0.44\pm0.05\,\mathrm{ps}$ [PRL 118 (2017) 191801]
  Compatible with $A_{\Delta\Gamma}=+1\ (-1)$ at $1.0\,\sigma\ (1.4\,\sigma)$

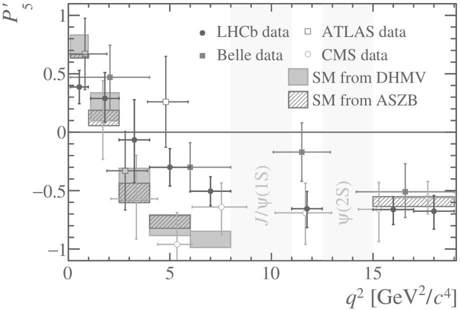
$B_s^0 \to \mu^+\mu^-$ lifetime

[JHEP05 (2017) 076]



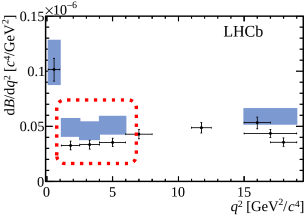
- Upgrade II: 2% uncertainty on effective lifetime $\tau_{\mu\mu}$
- Breaks degeneracy between possible contributions from $\mathcal{C}_S^{(\prime)}$ and $\mathcal{C}_P^{(\prime)}$
- Will allow to exclude second solution in $\tan\beta/m_A$ plane
- With tagging power 3.7% measure time-dep. CP-violation $\sigma(S_{\mu\mu}) \sim 0.2$

Electroweak $b \to s\mu^+\mu^-$ Penguins

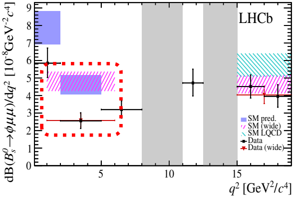


Branching fractions of rare $b \to s\mu^+\mu^-$ decays

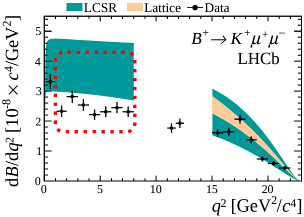
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



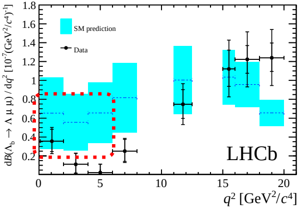
LHCb $B^0_s \to \phi\mu^+\mu^-$ [JHEP 09 (2015) 179]



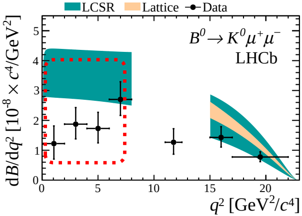
LHCb $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



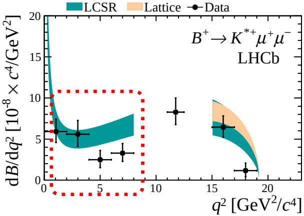
$\Lambda^0_b \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



LHCb $B^0 \to K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]



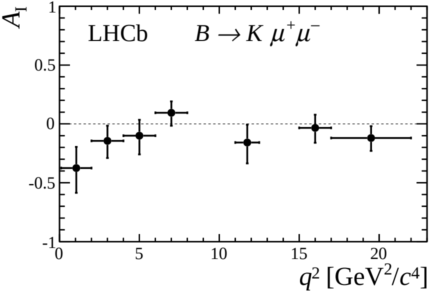
$B^+ \to K^{*+}\mu^+\mu^-$ [JHEP 06 (2014) 133]



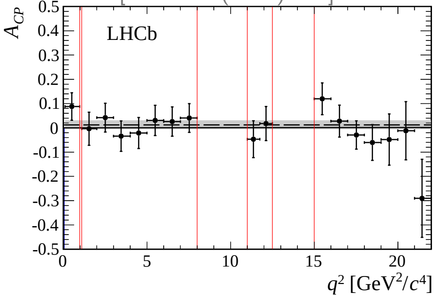
- Pattern: Data consistently below SM predictions
- But sizeable hadronic theory uncertainties
- Tensions at $1 - 3\,\sigma$ level

Future $b \to s\mu^+\mu^-$ branching fraction measurements

[JHEP 06 (2014) 133]



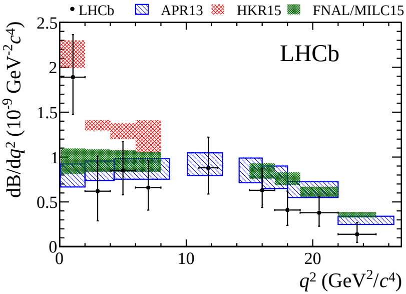
[JHEP 09 (2014) 177]



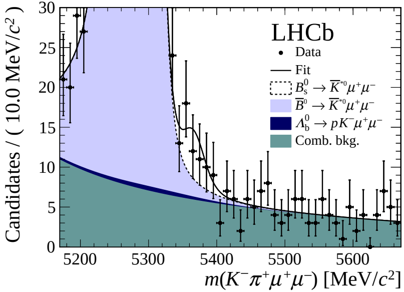
- Experimentally, $\mathcal{B}(b \to s\mu^+\mu^-)$ will be limited by normalisation modes
  More precise measurements of these possible by Belle II
- Asymmetries (experimentally and theoretically) more precise!
  - CP-Asymmetries $A_{\text{CP}} = \frac{\Gamma(\bar{B}\to\bar{K}^{(*)}\mu^+\mu^-)-\Gamma(B\to K^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B}\to\bar{K}^{(*)}\mu^+\mu^-)+\Gamma(B\to K^{(*)}\mu^+\mu^-)}$
  - Isospin-Asymmetries $A_I = \frac{\Gamma(B^0\to K^{(*)0}\mu^+\mu^-)-\Gamma(B^+\to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0\to K^{(*)0}\mu^+\mu^-)+\Gamma(B^+\to K^{(*)+}\mu^+\mu^-}$
- Expect percent-level accuracy for these quantities with Upgrade II

$b \to d\mu^+\mu^-$ processes

$B^+ \to \pi^+\mu^+\mu^-$ [JHEP 10 (2015) 034]

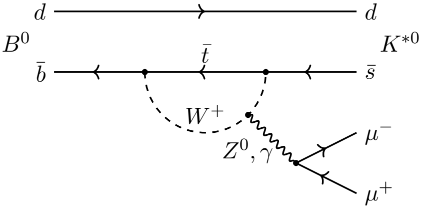


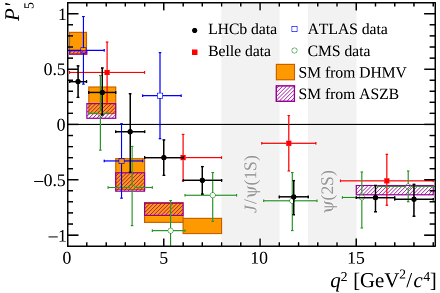
$B^0_s \to \overline{K}^{*0}\mu^+\mu^-$ [JHEP 07 (2018) 020]



- $b \to d\mu^+\mu^-$ processes are suppressed wrt. $b \to s\mu^+\mu^-$ by $|V_{\rm td}/V_{\rm ts}|^2$ in the SM (and MFV NP models)
- $N_{\pi\mu\mu} \sim 90$ (Run 1) and $N_{\overline{K}^{*0}\mu\mu} \sim 40$ (Run 1+2016)
- Upgrade II will provide $N_{\pi\mu\mu} \sim 17\,000$ and $N_{\overline{K}^{*0}\mu\mu} \sim 4\,300$
- Allows 2% level precision on $|V_{\rm td}/V_{\rm ts}|$ from rare decays
- Allows for angular analysis of $B^0_s \to \overline{K}^{*0}\mu^+\mu^-$ with better precision than Run 1 $B^0 \to K^{*0}\mu^+\mu^-$ result

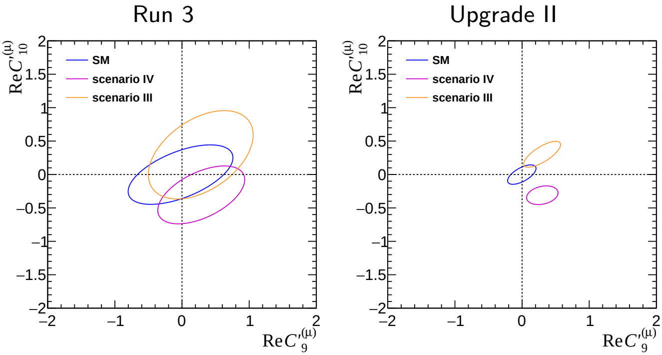
Angular analyses of $b \to s\mu^+\mu^-$ decays: P_5' and friends





- $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ exhibits rich angular structure, one example the less form-factor dependent observable P_5'
- In q^2 bins $[4.0, 6.0]$ and $[6.0, 8.0]\,\mathrm{GeV}^2/c^4$ local deviations of $2.8\,\sigma$ and $3.0\,\sigma$
- LHCb only global $B^0 \to K^{*0}\mu^+\mu^-$ analysis corresponds to $3.4\,\sigma$
- [LHCb, JHEP 02 (2016) 104] consistent with [Belle, PRL 118 (2017) 111801] [CMS-PAS-BPH-15-008] [ATLAS, arXiv:1805.04000]

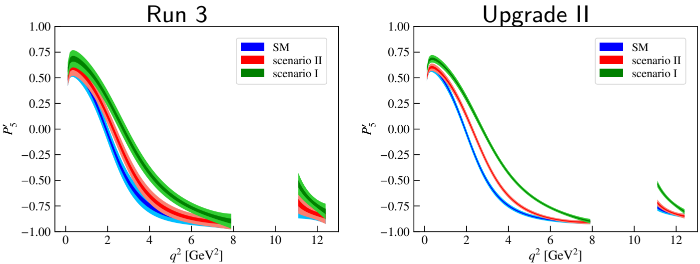
Upgrade II sensitivity with $B^0 \to K^{*0}\mu^+\mu^-$



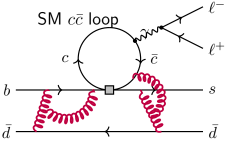
Scenario	$\mathcal{C}_9'$	$\mathcal{C}_{10}'$
SM	0	0
III	+0.3	+0.3
IV	+0.3	-0.3

- Expect $\sim 440\,000$ $B^0 \to K^{*0}\mu^+\mu^-$ candidates in Upgrade II
(Roughly corresponds to Run 1 stats for tree-level charmonia modes)
- Allows for determination of angular observables with unprecedented precision
- Different NP scenarios can be cleanly separated

New experimental approaches: q^2-unbinned

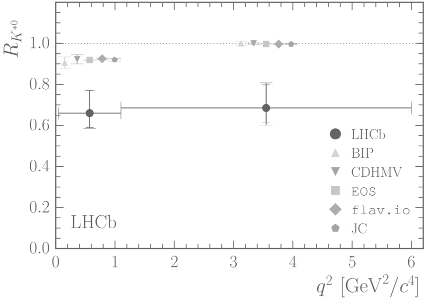


Scenario	$\Delta\mathcal{C}_9$	$\Delta\mathcal{C}_{10}$
SM	0	0
I	-1.4	0
II	-0.7	+0.7

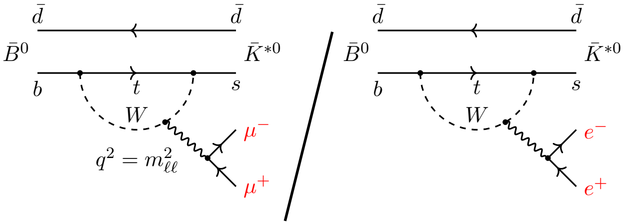


- q^2-unbinned approaches allow to better exploit the data [JHEP 11 (2017) 176]
- Will allow to separate different SM extensions with extremely high precision
- Major challenge to disentangle NP from charm-loop contribution in $\mathcal{C}_9$
- Different parameterisations of the charm-loop contributions on the market
  - Parameterisation using Breit-Wigners [EPJC 78 (2018) 453]
  - Parameterisation from analyticity [arXiv:1805.06378] [PRD 99 (2019) 013007]

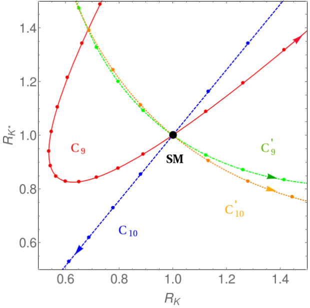
Lepton Universality Tests in Rare Decays



Lepton universality tests in rare decays: R_K, R_{K^*}



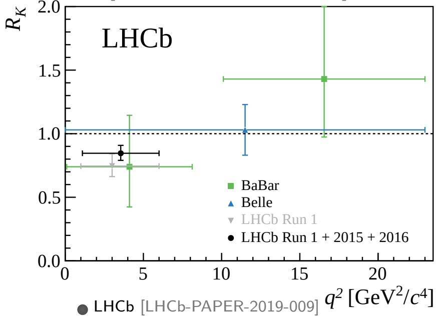
[PRD 96 (2017) 093006]



- R_X ratios extremely clean tests of the SM
  $R_X = \int \frac{\mathrm{d}\Gamma(B\to X\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2 / \int \frac{\mathrm{d}\Gamma(B\to Xe^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2$
- $R_X^{\mathrm{SM}} = 1 \pm \mathcal{O}(10^{-3})$ (neglecting m_ℓ), QED effects $\mathcal{O}(10^{-2})$ [EPJC 76 (2016) 8,440]
- Hadronic uncertainties (form factors etc.) cancel in the ratio
- Different modes probe different operator combinations

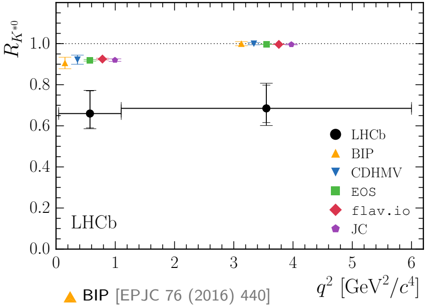
Current Experimental Status

[LHCb-PAPER-2019-009]



- ● LHCb [LHCb-PAPER-2019-009]
- ● LHCb Run 1 [PRL 113 (2014) 151601]
- ▲ Belle [PRL 103 (2009) 171801]
- 🟩 BaBar [PRD 86 (2012) 032012]

[JHEP 08 (2017) 055]



- ▲ BIP [EPJC 76 (2016) 440]
- ▼ CDHMV [JHEP 04 (2017) 016]
- 🟩 EOS [PRD 95 (2017) 035029]
- ◆ flav.io [EPJC 77 (2017) 377]
- ⬟ JC [PRD 93 (2016) 014028]

- Numerical result and compatibility with SM prediction(s):

$$R_K(1 < q^2 < 6.0\,\mathrm{GeV}^2) = 0.846^{+0.060}_{-0.054}{}^{+0.016}_{-0.014}$$

at central q^2: $2.5\,\sigma$

$$R_{K^*}(0.045 < q^2 < 1.1\,\mathrm{GeV}^2) = 0.66^{+0.11}_{-0.07} \pm 0.03$$

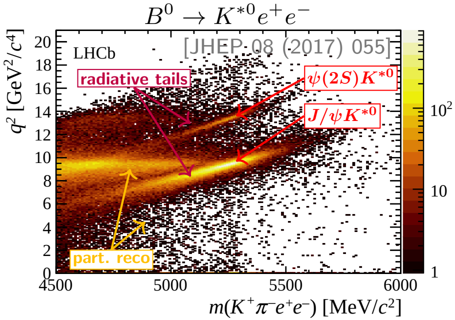
at low q^2: 2.1-$2.3\,\sigma$

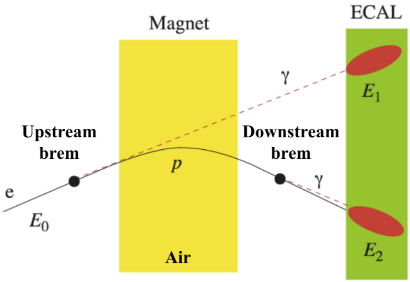
$$R_{K^*}(1.1 < q^2 < 6.0\,\mathrm{GeV}^2) = 0.69^{+0.11}_{-0.07} \pm 0.05$$

at central q^2: 2.4-$2.5\,\sigma$

- Many further modes in preparation: R_ϕ, R_{pK}, $R_{K\pi\pi}$, . . .

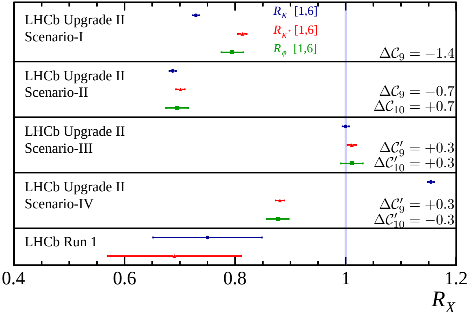
Experimental aspects: Bremsstrahlung and Trigger





- Perform Bremsstrahlung reconstruction to improve mass resolution
- Upgrade II: higher backgrounds/combinatorics due to # pp collisions
  - Higher calorimeter granularity
  - Timing information
- Improvement in trigger efficiency due to L0 removal (Upgrade I)
  Not taken into account for numbers in this presentation, conservative

Upgrade II expectations for R_X ratios

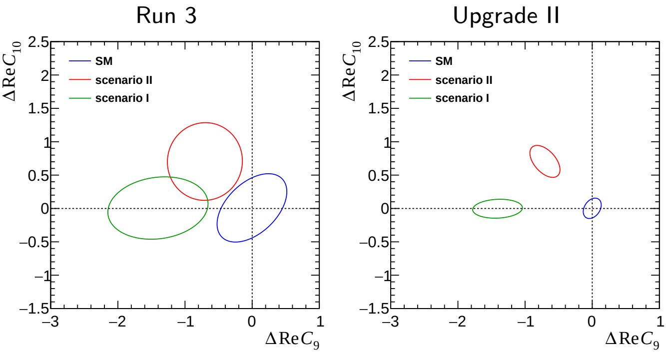


[Upgrade II Physics case] [Physics of the HL-LHC WG 4]

Yield	Run 1 result	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$B^+ \to K^+e^+e^-$	254 ± 29	1120	3300	46000
$B^0 \to K^{*0}e^+e^-$	111 ± 14	490	1400	20000
$B^0_s \to \phi e^+e^-$	–	80	230	3300
$\Lambda^0_b \to pKe^+e^-$	–	120	360	5000
$B^+ \to \pi^+e^+e^-$	–	20	70	900
R_X precision	Run 1 result	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
R_K	$0.745 \pm 0.090 \pm 0.036$	0.043	0.025	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$	0.052	0.031	0.008
R_ϕ	–	0.130	0.076	0.020
R_{pK}	–	0.105	0.061	0.016
R_π	–	0.302	0.176	0.047

- Huge samples of rare electron modes available in Upgrade II $N_{K^+e^+e^-} \sim 46\,000$, $N_{K^{*0}e^+e^-} \sim 20\,000$
- Ultimate precision on R_{K,K^*} will be better than 1%
- Different R_X allow to probe different combinations of Wilson coefficients, separation of NP scenarios with high significance

Angular analyses with electrons



[Upgrade II Physics case]

Scenario	$\Delta\mathcal{C}_9^{\mu\mu}$	$\Delta\mathcal{C}_{10}^{\mu\mu}$
SM	0	0
I	-1.4	0
II	-0.7	$+0.7$

- Differences between angular observables in electrons and muons theoretically clean, simultaneous fit useful
- Sensitivity to additional combinations of Wilson coefficients compared to R_X measurements
- Excellent NP sensitivity unaffected by hadronic contributions

Conclusions

- Rare decays are powerful probes for NP
- Reach of precision flavour measurements goes far beyond $\sqrt{s}$
- LHCb Upgrade II can extend the probed NP scales by a factor 1.9
- Expected Upgrade II performance for key RD measurements:
  - $\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$ at 10%
  - Precision measurements with $440\,000$ $B^0 \to K^{*0}\mu^+\mu^-$ candidates
  - R_{K,K^*} at sub-1% level
- LHCb Upgrade II will allow access many new observables and analysis techniques
- LHCb Upgrade II will be able to probe many types of Physics beyond the SM and discriminate between them

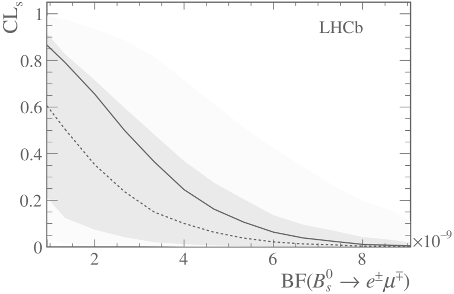
Backup

Prospects summary

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

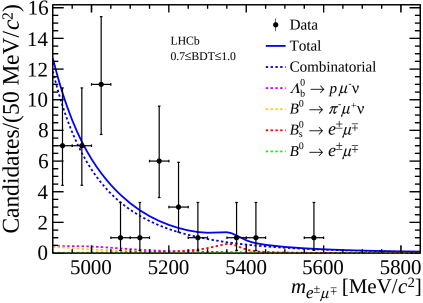
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_\mathrm{S}^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_sl^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_\mathrm{S}^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Searches for Lepton Flavour Violation

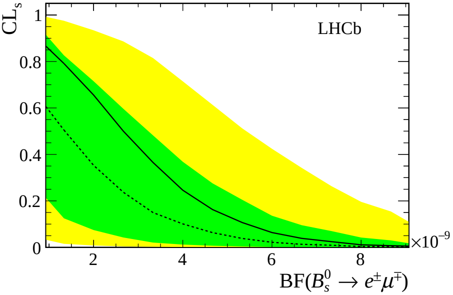


Lepton flavour violating B-decays

$B^0_{(s)} \to e^\pm\mu^\mp$ [JHEP 03 (2018) 078]



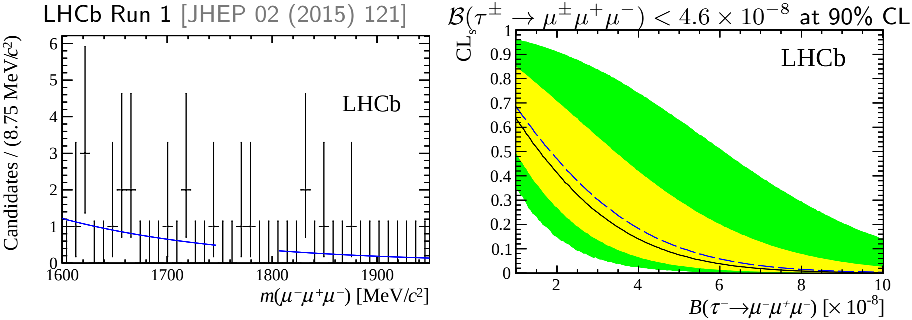
$\mathcal{B}(B^0_s \to e^\pm\mu^\mp) < 5.4 \times 10^{-9}$ at 90% CL



- Lepton non-universality generally implies lepton flavour violation [PRL 114 (2015) 091801]
- Many NP models predict sizeable $\mathcal{B}$ for LFV B decays
- Upgrade II will allow to probe down to $\mathcal{B}(B^0_s \to e^\pm\mu^\mp) < 3 \times 10^{-10}$ and $\mathcal{B}(B^0_s \to \tau^\pm\mu^\mp) < 3 \times 10^{-6}$
- Searches for $B \to K^{(*)}e\mu$ and $B \to K^{(*)}\tau\mu$ will set strong constraints

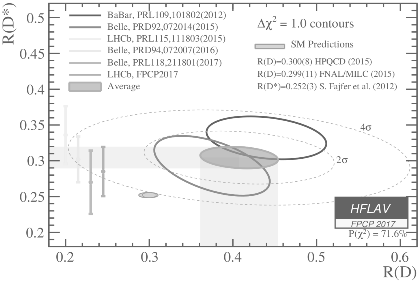
Lepton flavour violating τ-decays

LHCb Run 1 [JHEP 02 (2015) 121] $\mathcal{B}(\tau^\pm \to \mu^\pm\mu^+\mu^-) < 4.6 \times 10^{-8}$ at 90% CL

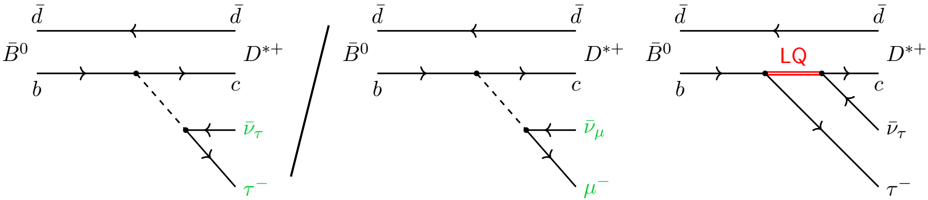


- In the SM the LFV decay $\tau^\pm \to \mu^\pm\mu^+\mu^-$ is forbidden
- Many BSM theories predict $\mathcal{O}(10^{-9} - 10^{-8})$, just below limit of $\mathcal{B}(\tau^\pm \to \mu^\pm\mu^+\mu^-) < 2.1 \times 10^{-8}$ at 90% CL [Belle, PLB 687 (2010) 139]
- Belle II will probe this interesting region with $50\,\mathrm{ab}^{-1}$
- LHCb Upgrade II expected to probe down to $\mathcal{O}(10^{-9})$
- LHCb calorimetry improvements to suppress backgrounds, *e.g.* $D_s^+ \to \eta(\to \mu^+\mu^-\gamma)\mu^+\nu_\mu$

Lepton Universality Tests in Tree-level Decays

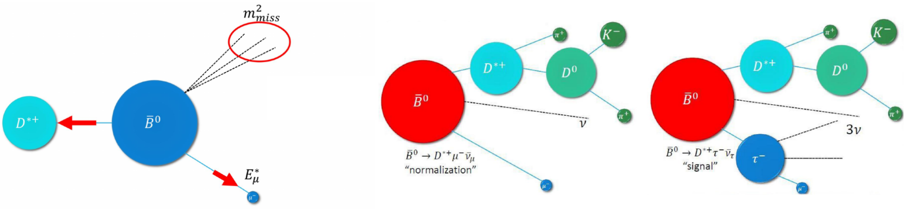


Lepton universality test in tree-level decays



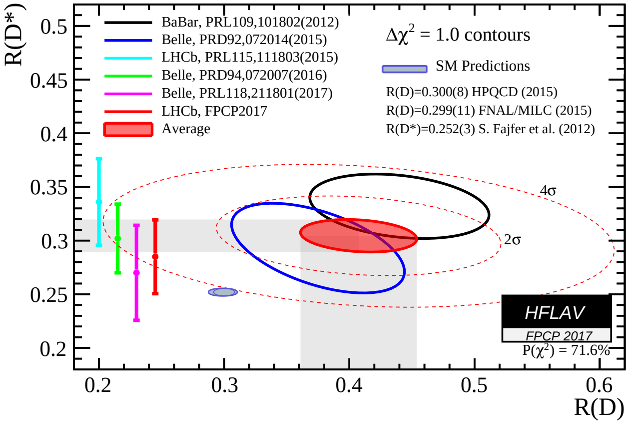
- Lepton universality can also be tested in $b \to c\ell\nu$ tree-level decays
- Modified coupling in particular possible to third generation τ
- Theoretically clean tests possible in B decays: $R_{D^*} = \frac{\mathcal{B}(B\to D^{(*)}\tau\nu)}{\mathcal{B}(B\to D^{(*)}\mu\nu)}$
- Nb. LHCb also allows for other modes using other b-hadron species: B_s^0, B_c^+, Λ_b^0, ...

Current experimental status



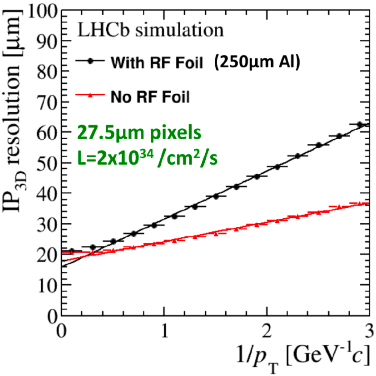
- LHCb has performed analyses of
  - $R_{D^*} = 0.336 \pm 0.027 \pm 0.030$ with $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$ compatible with the SM at $2.1\,\sigma$ [PRL 115 (2015) 111803]
  - $R_{D^*} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$ with $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ compatible with the SM at $1\,\sigma$ [PRL 120 (2018) 171802]
  - $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ using B_c^+ decays compatible with the SM at $\sim 2\,\sigma$ [PRL 120 (2018) 121801]
- LHCb performs template fits to *e.g.* $m^2_{\rm miss}$, q^2, E^*_ℓ relying on
  - its excellent vertexing to approximate the B-momentum
  - powerful particle identification and tracking to suppress backgrounds

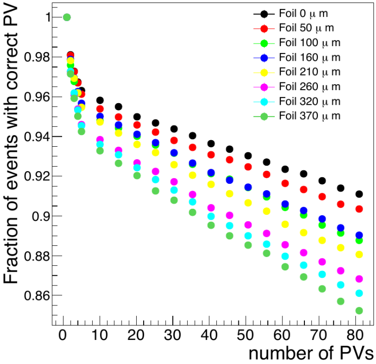
$R_{D^{(*)}}$ combination



- Combine LHCb R_{D^*} measurements with B-factory results
- All measurements are above SM predictions
- Deviation of R_D/R_{D^*} combination corresponding to $\sim 4.1\,\sigma$
- Recent theory input reduces tension [JHEP 11 (2017) 061]

Experimental improvements in Upgrade II





- RF foil removal will drastically improve vertexing performance
  - IP resolution at low p_{T} nearly doubles, better bkg. suppression
  - Fraction of wrong PV association reduced by 30%
  - More precise determination of m^2_{miss}, q^2, E^*_ℓ
- Expected trigger efficiency improvement of ~ 1.5

Upgrade II prospects for R_{D^*}

- Expect $\mathcal{O}(10\,\mathrm{M})$ $B \to D^*\tau\nu$ candidates in Upgrade II
- Sensitivity with Upgrade II: $\sigma(R_{D^*})/R_{D^*} \sim 1\%$
- Angular analysis would allow to determine spin structure of potential NP contribution