LEPTON FLAVOUR UNIVERSALITY AT LHCb

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On behalf of the LHCb Collaboration

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Why flavour physics?

Most BSM physics models **predict additional heavy particles**:

- can enter in tree and internal loop diagrams
- can lead to sizeable modification of observables such as branching ratios

Comparison of **precise measurements** with precise predictions from SM can reveal the presence of BSM physics.

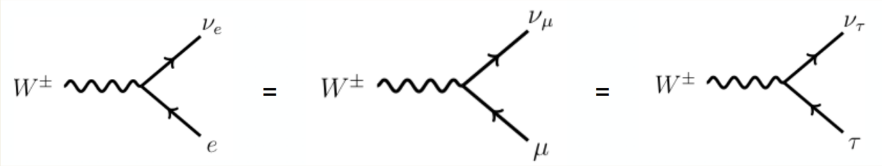
- *Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed (A. Soni)*

Indirect searches for BSM physics are sensitive to **much higher mass scales** O(10 - 100TeV) than direct searches for new particles

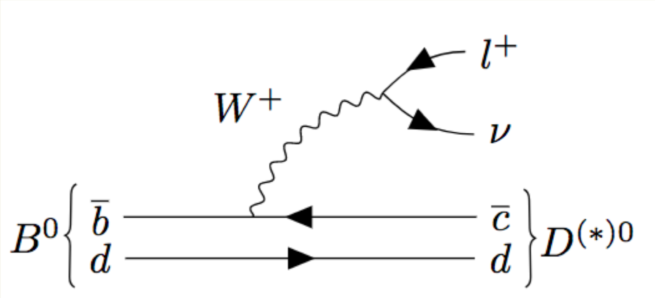
Theoretical uncertainties are under control for many observables

Never stop checking

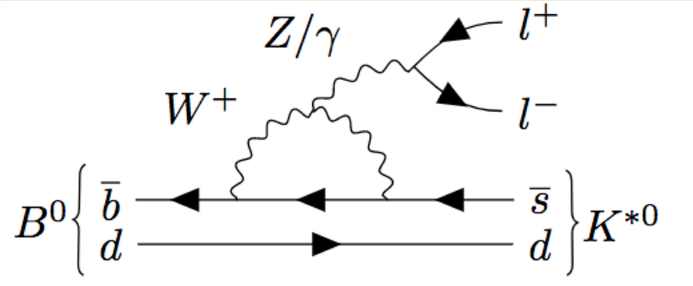
- Standard Model features **Lepton Flavour Universality**: accidental symmetry of the SM
  - Equal electroweak coupling to all charged leptons.
- Difference in dynamics driven solely by the **difference in the masses $m_e < m_\mu \ll m_\tau$**



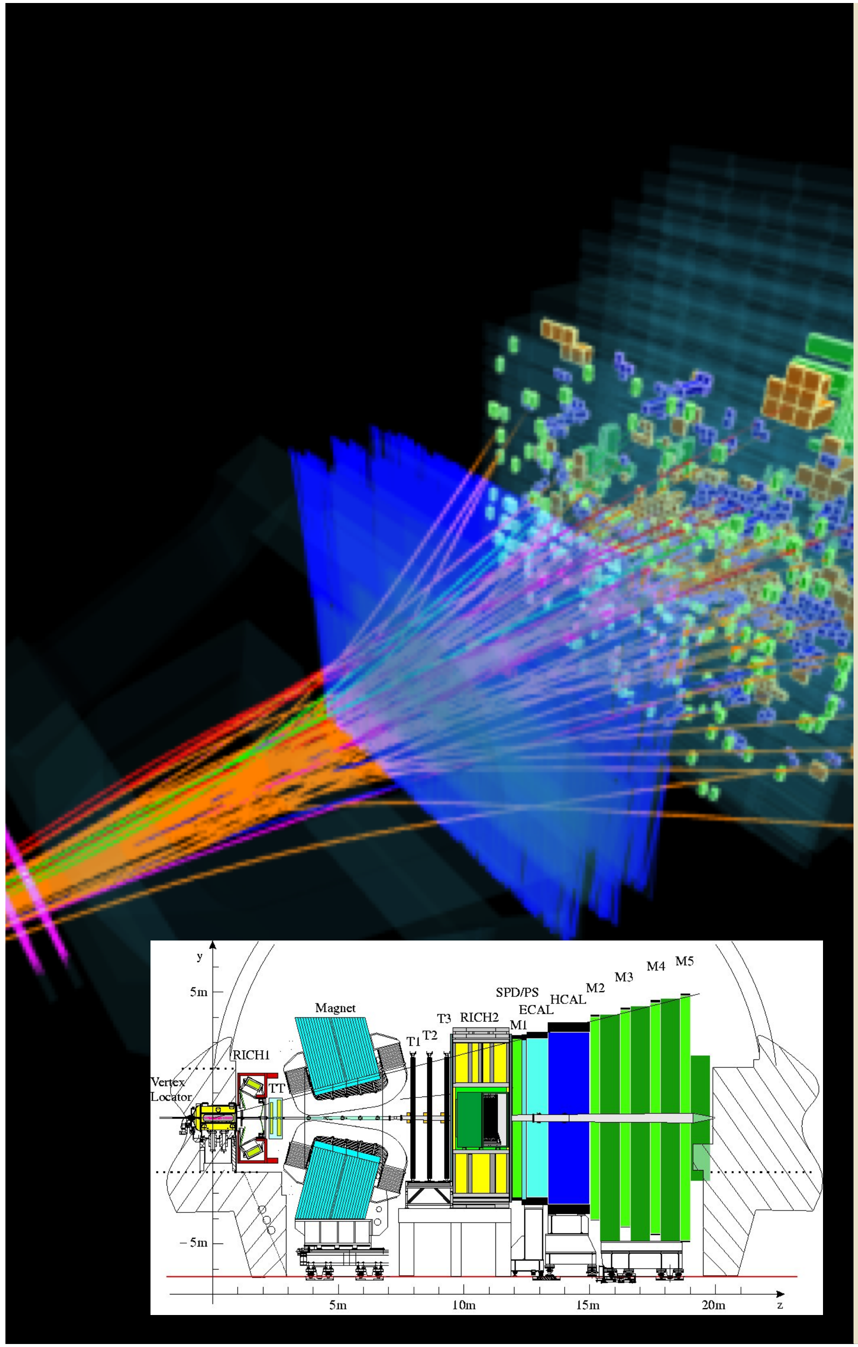
  - In this presentation: intriguing hints of anomalies in B decays observed by different experiments in



Flavour-changing CHARGED current ($b \to c\ell\bar{\nu}$)



Flavour-changing NEUTRAL current ($b \to s(d)\ell^+\ell^-$)



Flavour physics at LHCb

- Single arm spectrometer designed for high precision flavour physics measurements
- Pseudorapidity range $\eta \epsilon [2,5]$

- ◦ # of Primary Vertices ~ 2
- ◦ Decay time res: ~45 fs
- ◦ IP res: ~20 μm for high p_T
- ◦ Highly eff. PID
- ◦ Excellent primary and secondary vertex reconstruction [INT.J.MOD.PHYS A30 (2015) 1530022]

BEAUTY SIGNATURES

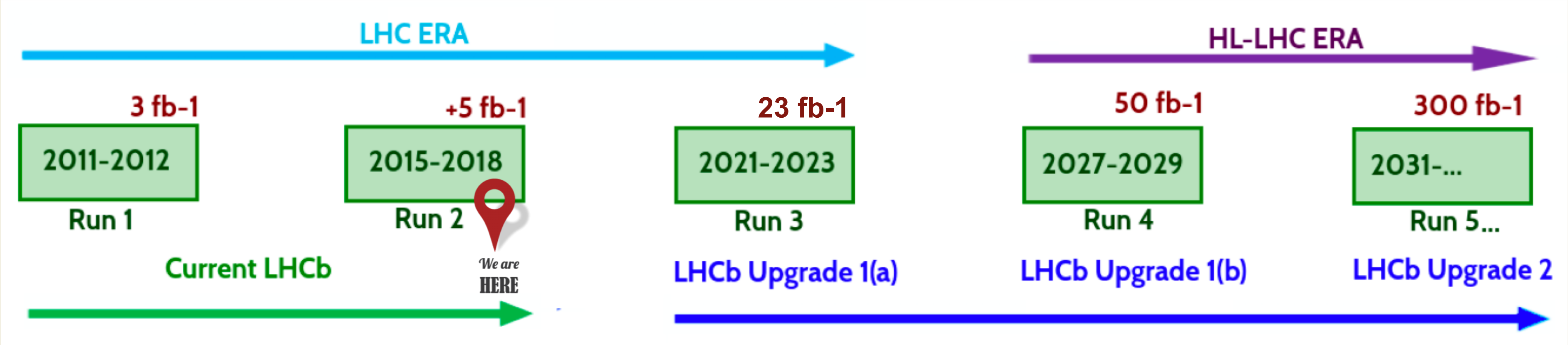
- Mass $m(B^+) = 5.28$ GeV
- Daughter p_T $\mathcal{O}(1$ GeV$)$
- Lifetime $\tau(B^+)$~1.6 ps
- Flight distance ~1 cm
- Detached secondary vertex

Large number of beauty hadrons:

- ◦ $\sigma_{b\bar{b}}$(7 TeV) = 72.0 ± 0.3 ± 6.8 μb
- ◦ $\sigma_{b\bar{b}}$(13 TeV) = 154.3 ± 1.5 ± 14.3 μb

[PRL 118 (2017) 052002]

The experimental scenario



LHCb may be the only large-scale flavour physics experiment operating in the HL-LHC era.

Pre-HL-LHC → Post-HL-LHC

- End Run 3 → End Run 5: **LHCb:** 23/fb → 300/fb
- NP scale probed by LHCb scales as $\Lambda_{NP} \propto \sqrt[4]{\int \mathcal{L}\, dt}$, factor 1.9 gain from HL-LHC [LHCb Upgrade Physics Document]

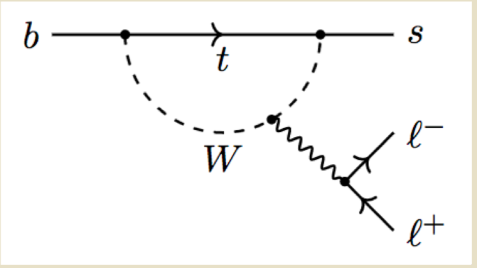
Impact of Upgrade II comparable to moving from 14 TeV to 27 TeV for on-shell production!

RARE DECAYS

Rare decays as probe for NP

- Rare FCNC decays are loop-suppressed in the SM ($\mathcal{B}\sim10^{-6}-10^{-7}$)
- New heavy particles can significantly contribute, affecting decay rates and angular distributions
- Model independent description using effective, four-fermion point interactions

Standard Model



Local operator (effective vertex)

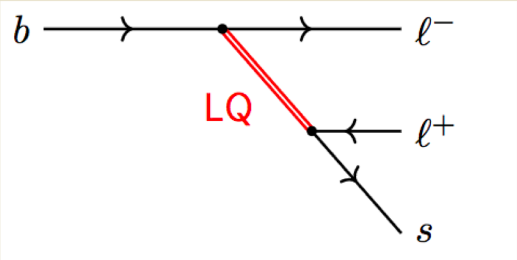
NP coupling

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^{*} \sum_i C_i \mathcal{O}_i + \frac{k}{\Lambda_{NP}^2}\mathcal{O}_{NP}$$

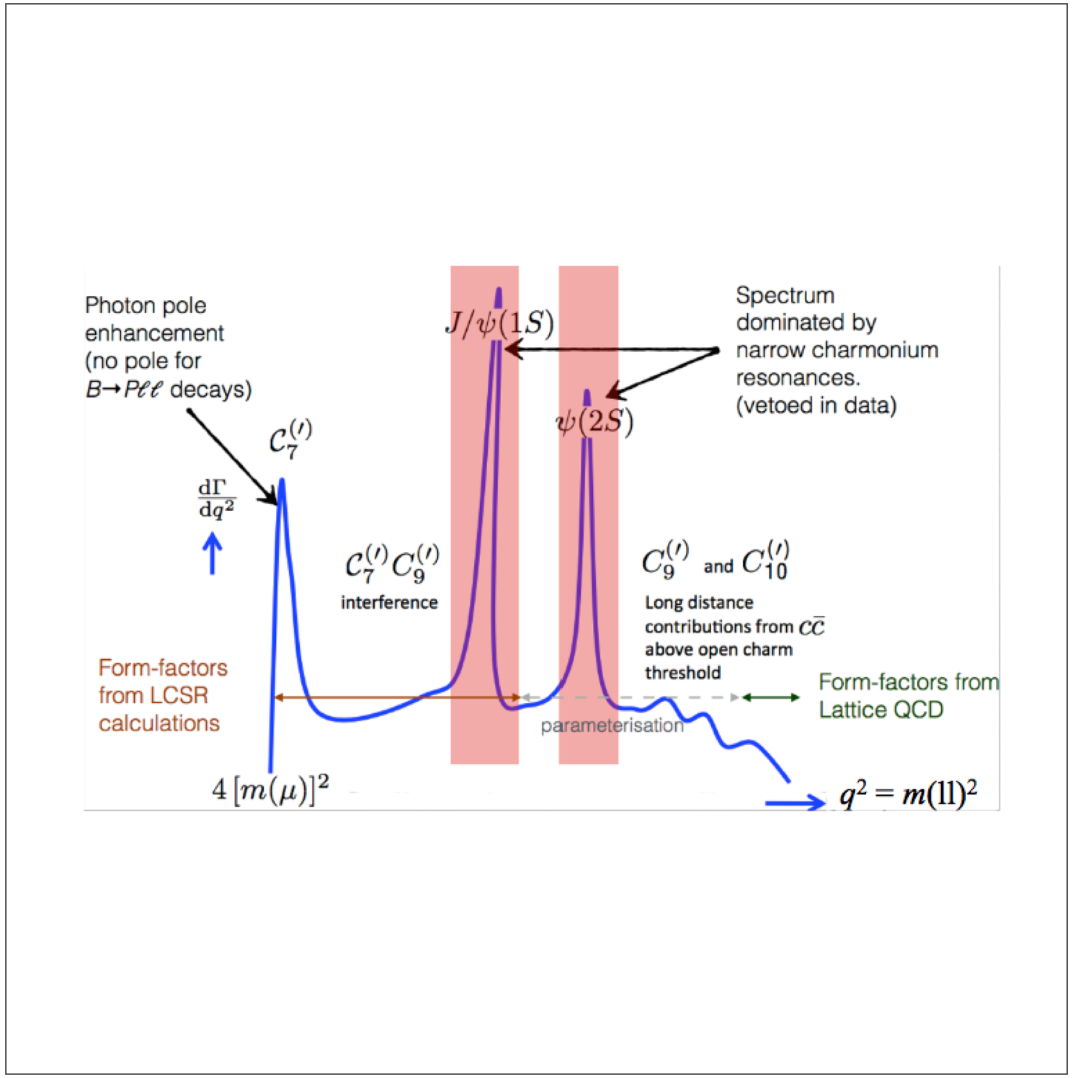
Wilson Coefficient (effective coupling)

NP scale

New Physics



i=1,2 Tree
i=3-6,8 Gluon Penguin
***i*=7 Photon penguin**
***i*=9,10 EW penguin**
i=S,P (Pseudo)scalar penguin



Experimental analysis and q² dependence

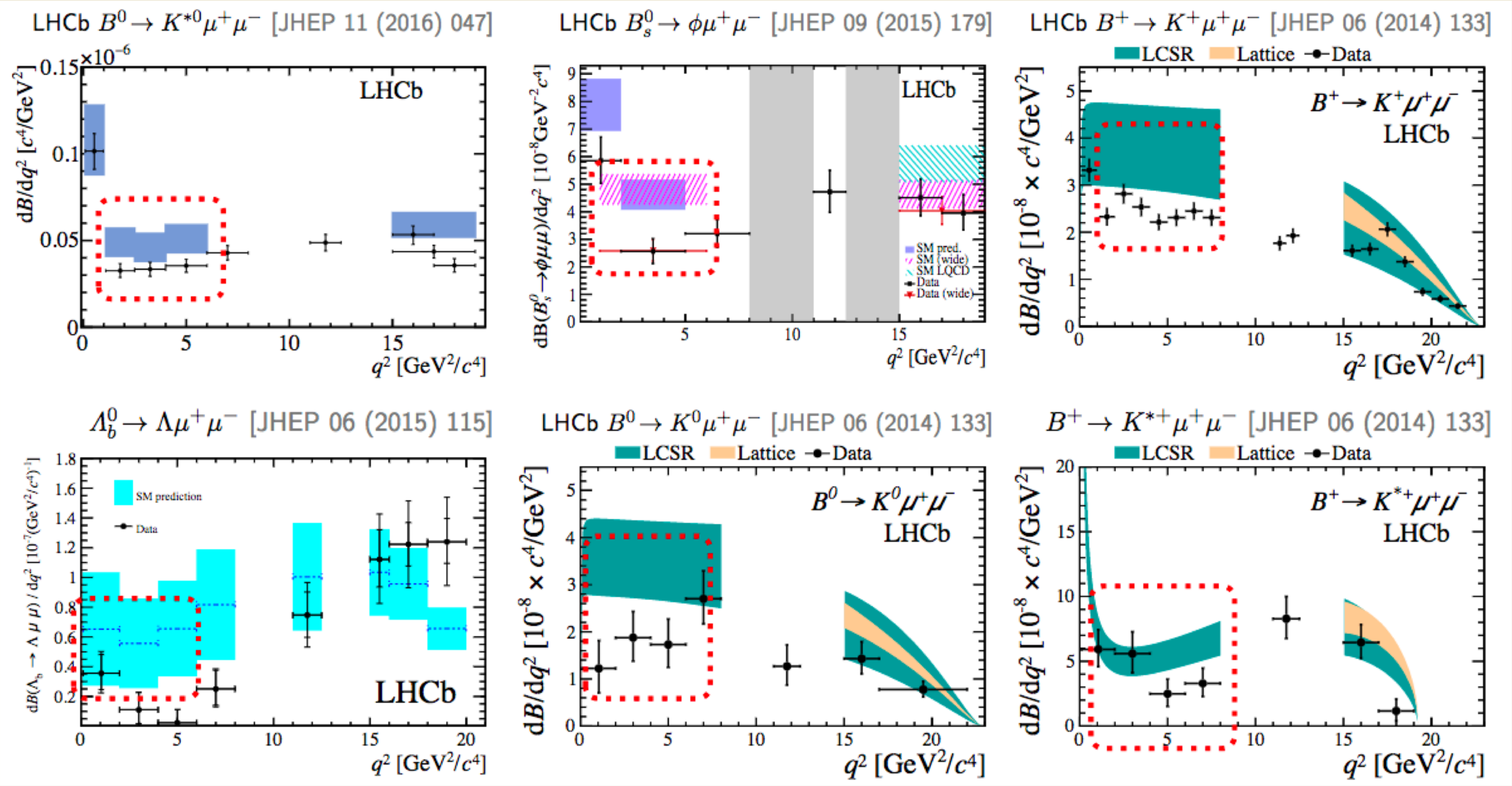
- B-hadron mass is reconstructed from final hadron decays and two energetic leptons
- Background events suppressed by requiring displaced vertices
- Study of the differential branching fraction in bins of $\boldsymbol{q^2 = m(\ell^+\ell^-)^2}$**, invariant mass of di-lepton system**
- In order to remove long distance effects (i.e. $b \to (c\bar{c} \to \ell^+\ell^-)s$) the narrow charmonium resonances are vetoed and used as control samples.

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

Anomaly

- **Low q^2 region**: Data consistently below SM predictions
- But sizeable hadronic theory uncertainties
- Tensions at 1-3 σ

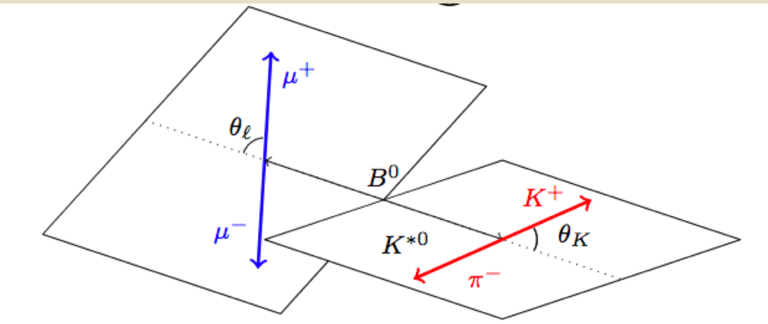
- **Future:** measurement of CP and Isospin asymmetries – percent level accuracy expected in Upgrade II



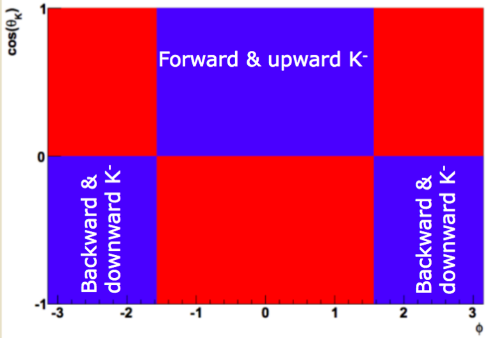
Angular analysis of $b \to s\mu^+\mu^-$ decays

Anomaly

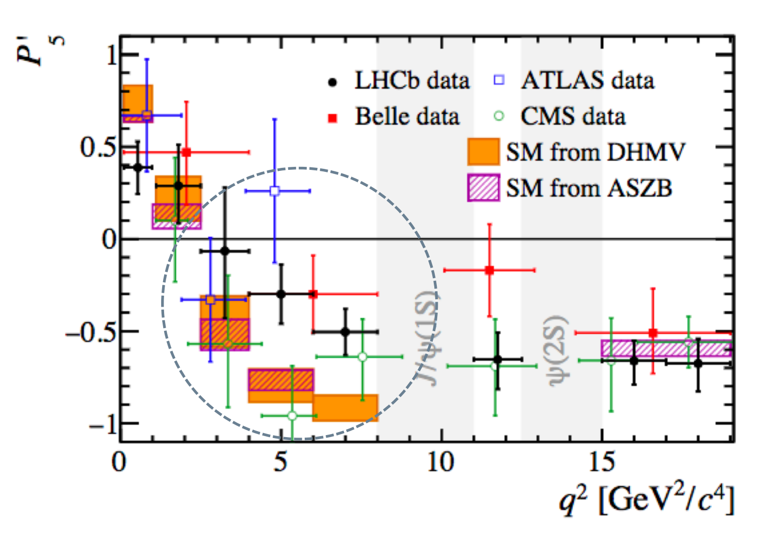
- $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ exhibits rich angular structure, e.g. the less form-factor dependent observable P_5': proportional to asymmetry of red and blue



(a) θ_K and θ_ℓ definitions for the B^0 decay



Counting S_5: blue minus red

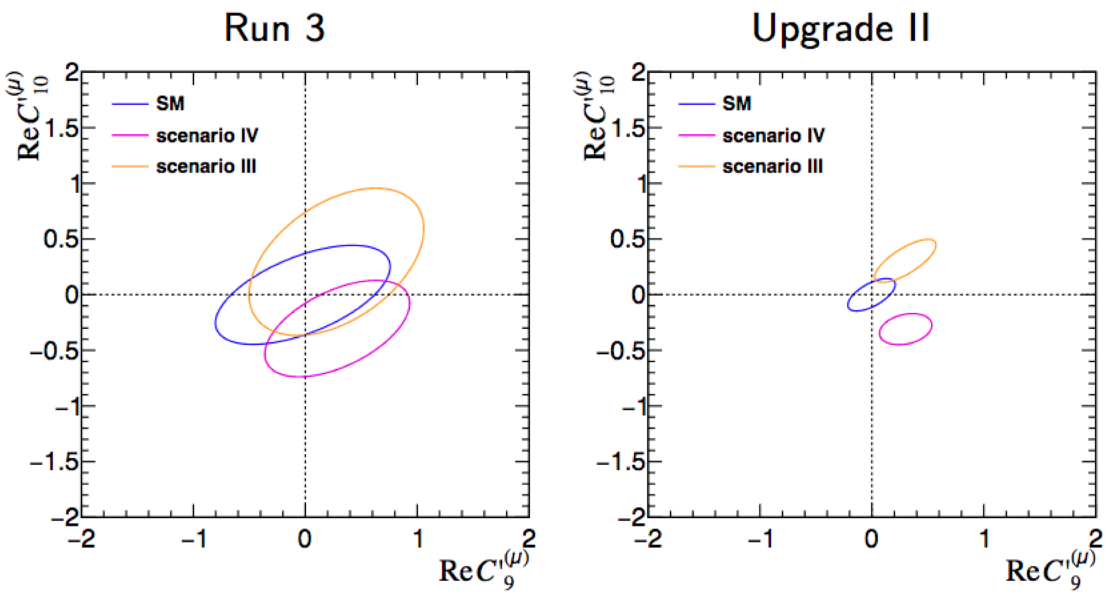


LHCb, JHEP02 (2016) 104
Belle, PRL 118 (2017) 111801
ATLAS-CONF-2017-023
CMS, PLB 81 (2018) 517

- In q^2 bins [4,6] and [6,8] 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 $3.4\,\sigma$
- Debate ongoing on SM calculations

Preliminary

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

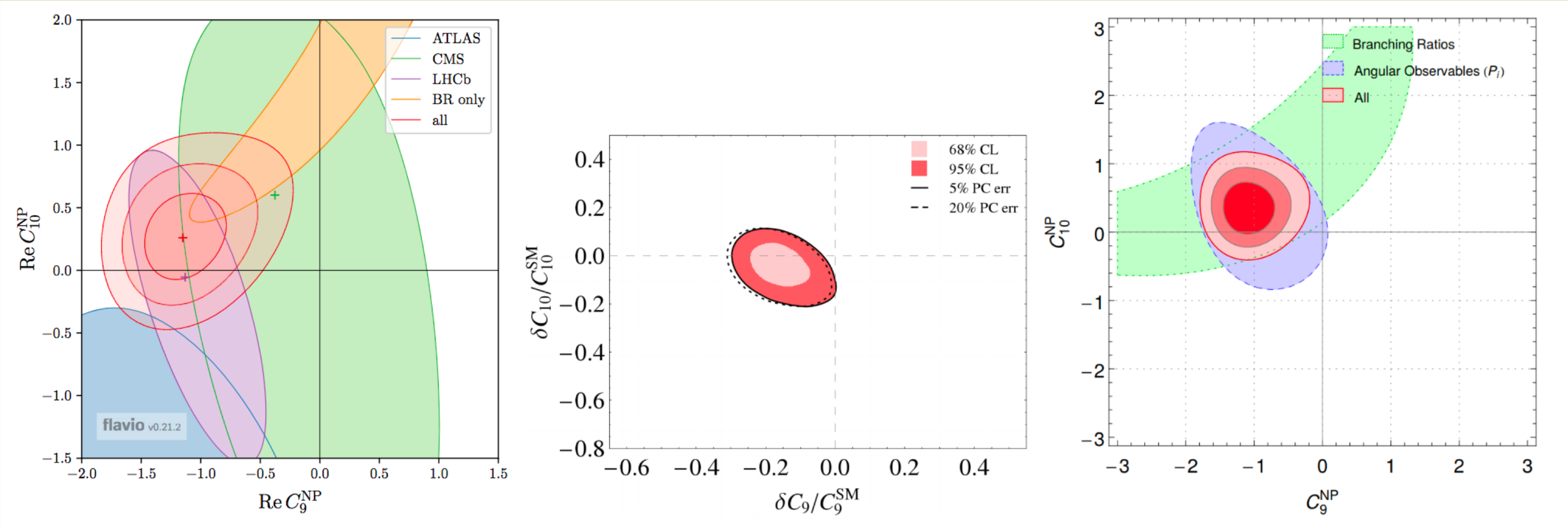


Scenario	$\mathcal{C}'_9$	$\mathcal{C}'_{10}$
SM	0	0
III	+0.3	+0.3
IV	+0.3	-0.3

[LHCb Upgrade Physics Document]
PUB-2018-009 (in preparation)

- Expect ~440 000 $B^0 \to K^{*0}\mu^+\mu^-$ candidates in Upgrade II (roughly Run 1 statistics for tree-level charmonia modes)
- Allows for determination of angular observables with unprecedented precision
- Different NP scenarios can be cleanly separated
- q^2-unbinned approaches allow to better exploit the data [JHEP 11 (2017) 176]

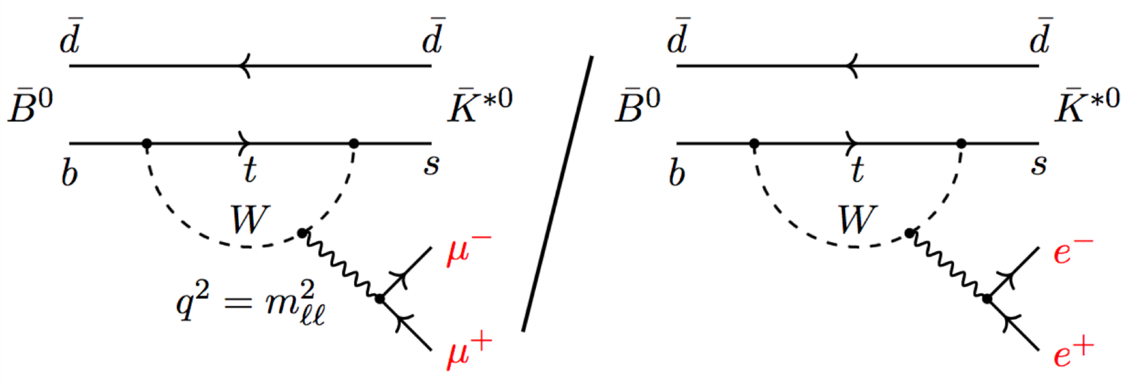
Global fit from $b \to s\mu^+\mu^-$ decays



[JHEP 06(2016)092]
[arXiv:1611.05060]
[EPJC 77 6(2017)377]

- Global fit to the real part of C_9 and C_{10}
- The best fit for several global analyses points towards a shift in C_9
- Discrepancy up to 5σ
- Discussion is ongoing about our understanding of QCD effects in branching fractions and angular observables

Lepton universality: $R(K^{(*)})$



$$R_{K^{(*)}} = \frac{\Gamma(\bar{B}\to\bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B}\to\bar{K}^{(*)}J/\psi\to\mu^+\mu^-)} \Big/ \frac{\Gamma(\bar{B}\to\bar{K}^{(*)}e^+e^-)}{\Gamma(\bar{B}\to\bar{K}^{(*)}J/\psi\to e^+e^-)}$$

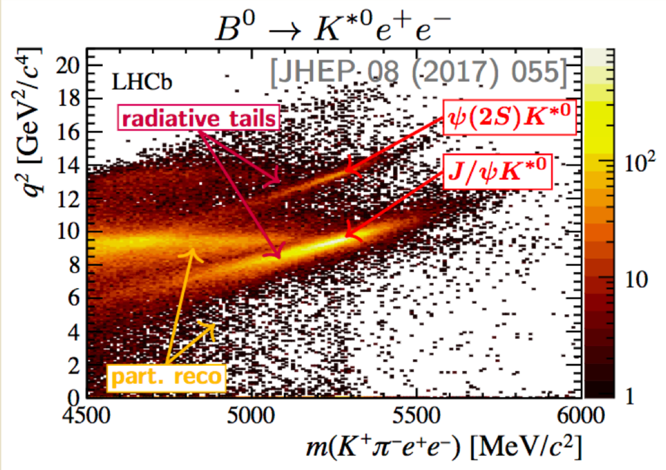
- The double ratio reduces systematic uncertainties
- $R_X^{SM} = 1 \pm \mathcal{O}(10^{-3})$ (neglecting m_ℓ), QED effects $\mathcal{O}(10^{-2})$ [EPJC 76 (2016) 8,440]
- Selection between μ and $\boldsymbol{e}$ channel as similar as possible
- Challenging due to the differences between μ and $\boldsymbol{e}$

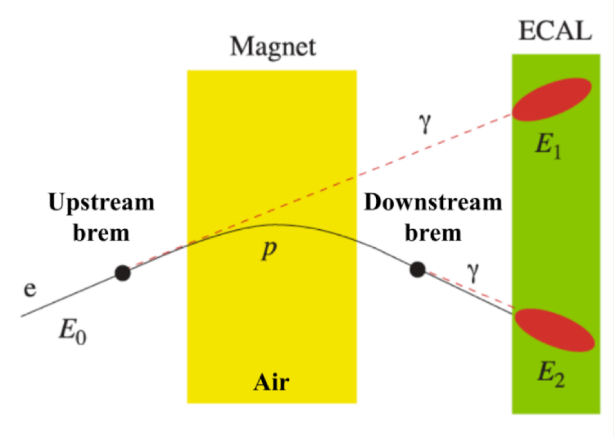
Bremsstrahlung correction to improve mass res.

- **Upstream brem**: photon emitted before the magnet, momentum underestimated

Upgrade II: higher backgrounds/combinatorics due to #pp collisions

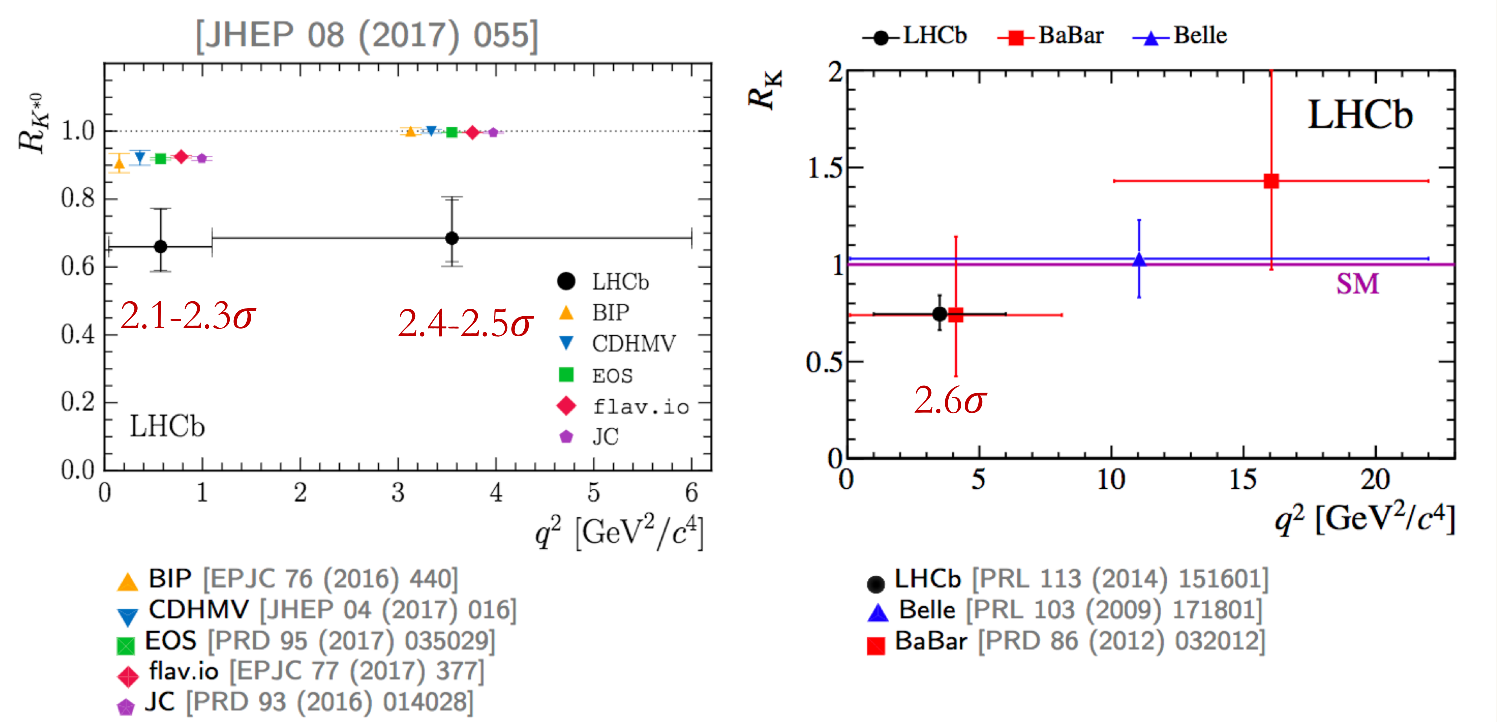
- Higher calorimeter granularity
- Timing information





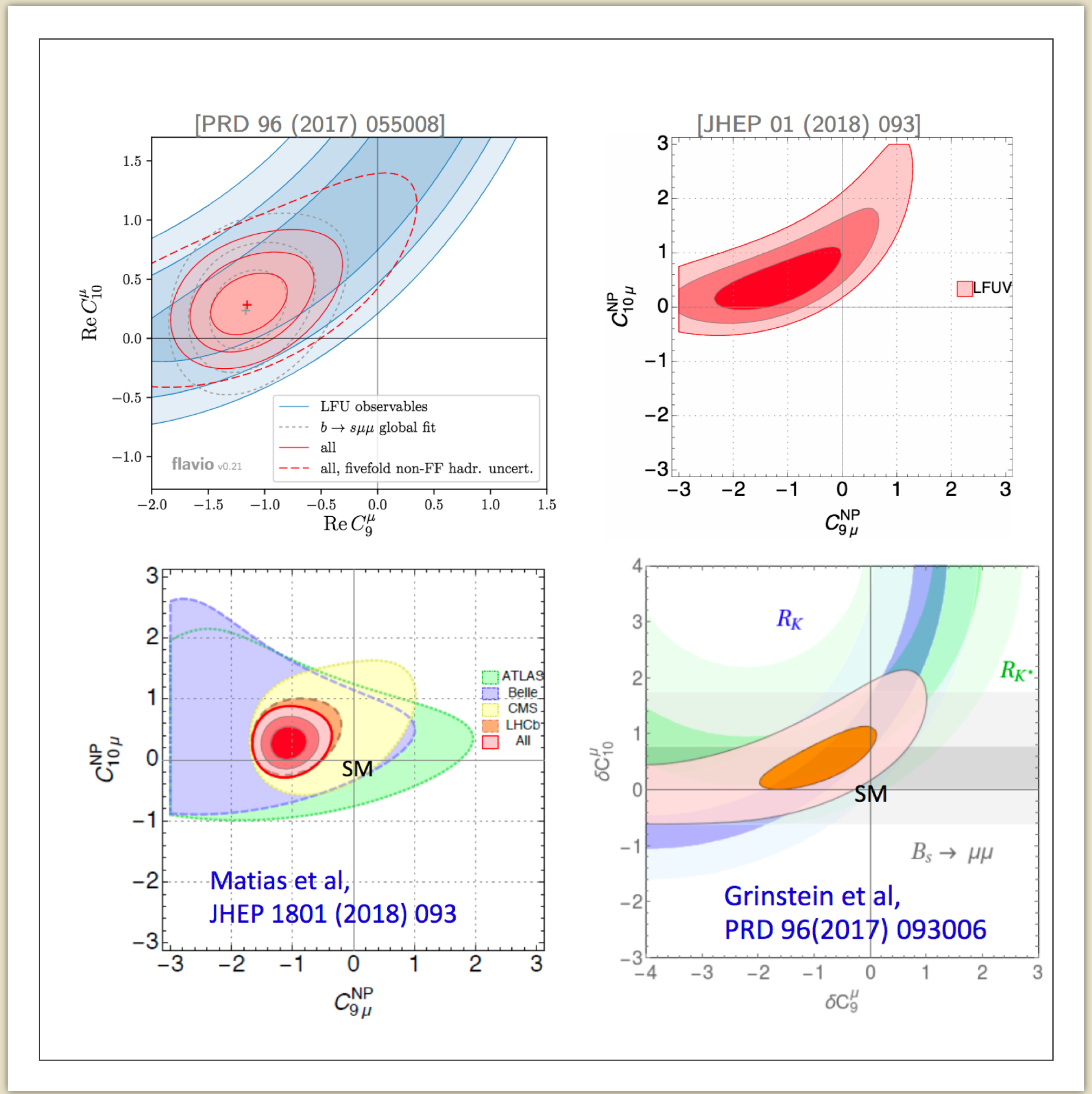
Anomaly

Current experimental status $R(K^{(*)})$



PRL 113(2014)151601
JHEP 08(2017)055

- LHCb results are consistently lower than 1
- Results from B-factories are compatible (with less precision)
- These results point to a shift in the muonic C_9 in accordance with the other anomalies detected in $b \to s\ell^+\ell^-$ decays



Combination of $b \to s\ell^+\ell^-$

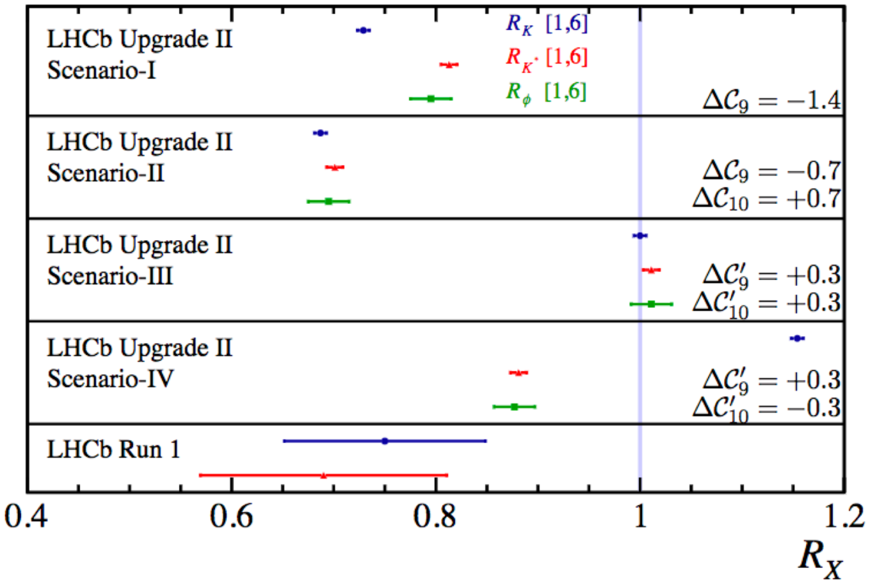
- Many different global fits incorporating different measurements (up to 100 observables)
- Combine LFU obs. in effective theory framework to determine Wilson coeff. (here: C^9 and C^{10})
- Combination of $R(K^{(*)})$ and angular analysis of $B^0 \to K^{*0}\ell^+\ell^-$ [arXiv:1612.05014] shows **tension with SM prediction at ~4σ** [PRD 96 (2017) 055008]
- **Remarkable consistency**: BF, angular, $R(K^{(*)})$, b→sγ data all point to $\Delta C_\mu^9 \sim -1$.
- Triggered models with Z', leptoquarks(LQ), and composite Higgs

Upgrade II expectations for $R(K^{(*)})$

Preliminary

Nominal NP scenario

Right-handed components



Expected yields

Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to K^+e^+e^-$	254 ± 29 [272]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0}e^+e^-$	111 ± 14 [273]	490	1 400	3 300	20 000
$B^0_s \to \phi e^+e^-$	–	80	230	530	3 300
$\Lambda^0_b \to pKe^+e^-$	–	120	360	820	5 000
$B^+ \to \pi^+e^+e^-$	–	20	70	150	900

R_X precision	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
R_K	$0.745 \pm 0.090 \pm 0.036$ [272]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [273]	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

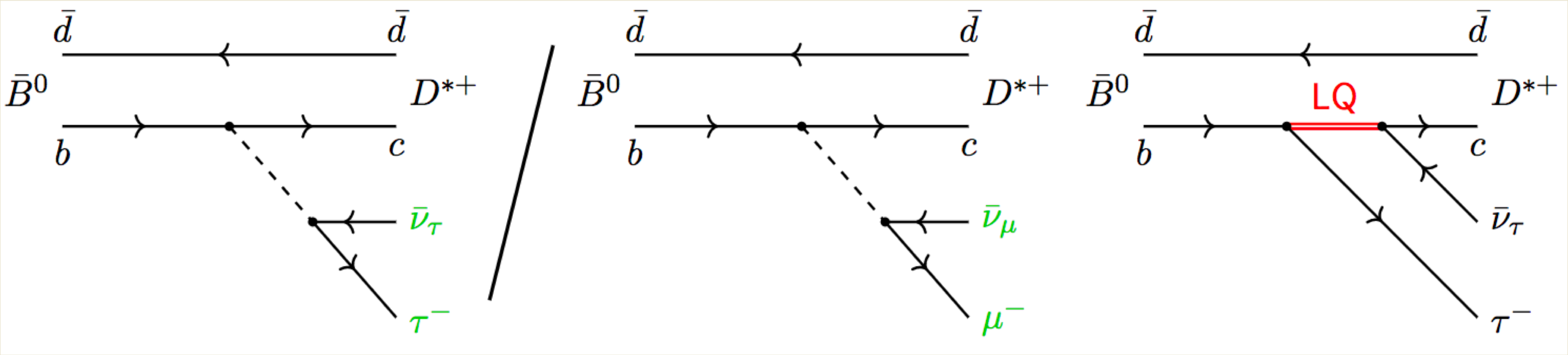
Expected R_X uncertainties

[LHCb Upgrade Physics Document]
PUB-2018-009 (in preparation)

- 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 possible!
- Projections don't include improved ECAL for Upgrade II

SEMI-LEPTONIC DECAYS

Lepton universality test in tree-level decays



Tests of LFU in semitauonic decays are obtained measuring the following ratios

$$R_X = \frac{\Gamma(B \to X_c\, \tau^+ \nu_\tau)}{\Gamma(B \to X_c\, \mu^+ \nu_\mu)} \quad \text{with } X_c = D^* \text{ or } J/\psi$$

Ratios sensitive to possible NP coupling mainly to the 3rd generation

- SM predictions:
- R(D*) = 0.258 ± 0.005 [HFLAV Summer 2018]
- R(J/ψ) ϵ [0.25, 0.28] [PLB452 (1999) 120, arXiv:0211021, PRD73 (2006) 054024, PRD74 (2006) 074008]

Anomaly

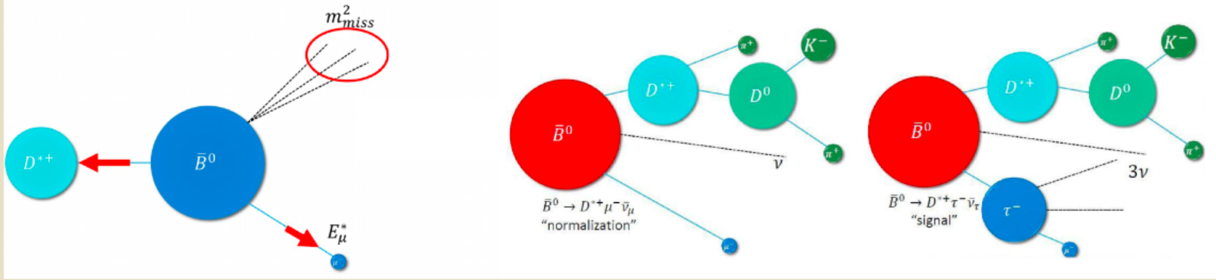
Current experimental status

LHCb has performed analysis of

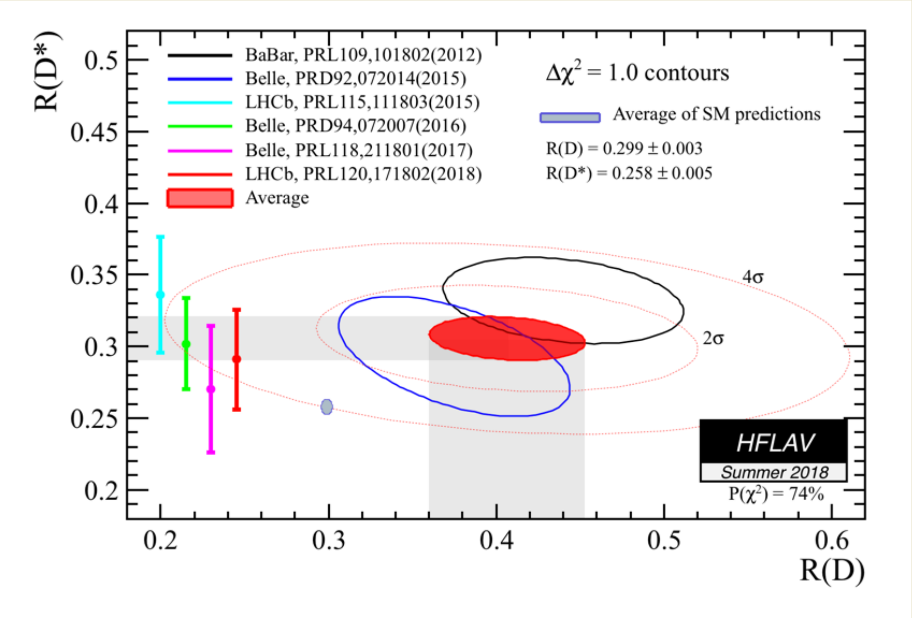
- $R_{D*} = 0.336 \pm 0.027 \pm 0.030$ with $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ compatible with the SM at 2.1 σ [PRL 115 (2015) 111803]
- $R_{D*} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$ with $\tau^- \to \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$ compatible with the SM at 1 σ [PRL 120 (2018) 171802]
- $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ 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_{miss}, q^2, E^*_ℓ relying on

- its excellent vertexing to approximate the B-momentum
- powerful particle identification and tracking to suppress backgrounds



Combination of $R_{D^{(*)}}$ measurements



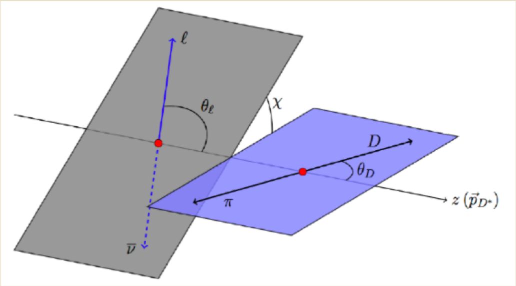
Combine LHCb $R_{D^{(*)}}$ with B-factory results.
All measurements are above SM predictions.
Deviation of $R_{D^{(*)}}$ combination **from SM ~4.1σ**
Recent theory input reduces tension [JHEP 11 (2017) 061] to 3.8 σ

Upgrade II prospects

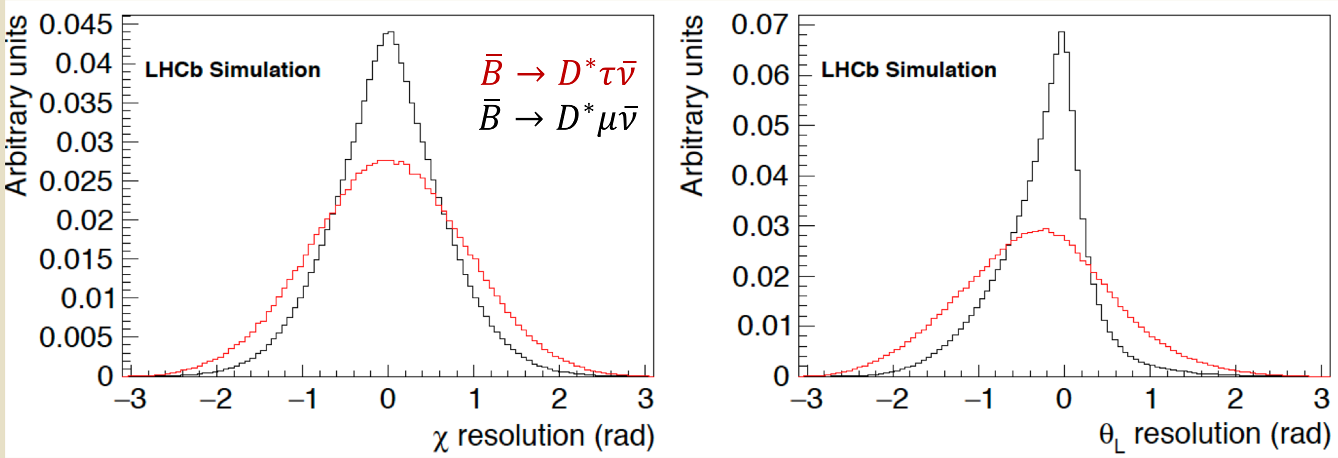
Preliminary

Upgrade II: new observables beyond the BF ratio

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



- Kinematics of $\bar{B} \to D^{(*)}\tau\bar{\nu}$ fully described by dilepton mass, and three angles, χ, θ_L and θ_d (better resolution)



Upgrade II: exploit other b-hadron species

- $\overline{B_s^0} \to D_s^{(*)+}\tau^-\bar{\nu}$: 6% (2.5%) relat. unc. after Run 3 (Upgrade II)
- Semitauonic decays of b-baryons and of B_c^+ mesons
  - $R(\Lambda_c^+)$ 4% (2.5%) relat. unc. after Run 3 (Upgrade II)

Lepton flavour violation

- LFV branching fractions enhanced to 10^{-11} in certain models of leptoquarks, Z' [Medeiros Varzielas, Hiller, JHEP 06 (2015) 072]
- LHCb was the first experiment to search for LFV τ decays in a hadron collider

Translate BR limits into limits on leptoquark mass

	$\mathcal{B}(B^0_{(s)} \to e\mu)$	$\mathcal{B}(B \to \tau\mu)$	$\mathcal{B}(\tau \to \mu\mu\mu)$
Run I @ 90 C.L.	$< 1.0\ (5.4) \times 10^{-9}$	Soon	$< 4.6 \times 10^{-8}$
HL-LHC @ 90 C.L.	$< 3\ (9) \times 10^{-10(11)}$	$< 3 \times 10^{-6}$	$< \mathcal{O}(10^{-9})$

Similar to what is expected from Belle II

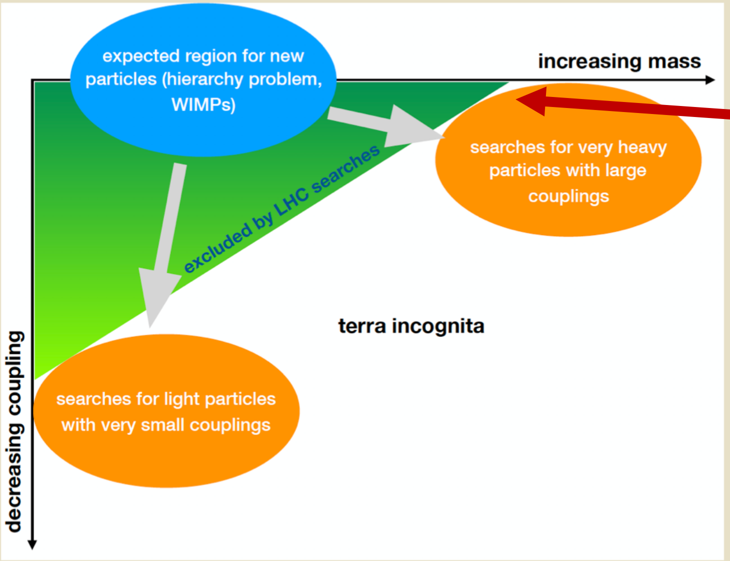
Searches for $B \to Ke\mu, B \to K^{*0}\tau(\to \pi\pi\pi\nu)\mu$, $\mathrm{B} \to K\tau(\to \pi\pi\pi\nu)\mu$ and $\Lambda^0_b \to \Lambda^0 e\mu$ are ongoing

- Using Run1 + Run2 data expects limits $\mathcal{O}(10^{-9})$ and $\mathcal{O}(10^{-6})$ for $B \to Ke\mu$ *and* $B \to K^{*0}\tau\mu$, respectively
- Complementary as charged lepton FV couplings among different families are expected to be different
- Multi-body final states: allow the measurement of more observables

Conclusions

- Intriguing hints of anomalies in B decays, powerful probes of the SM!
- Both Belle2 and LHCb experiments could individually confirm or rule out the current flavour anomaly **by ~2025** [arXiv:1709.10308]
- If true, hugely important for the future development of high-energy particle physics, providing a **clear target for future searches at energy frontier**… exactly what's missing right now!

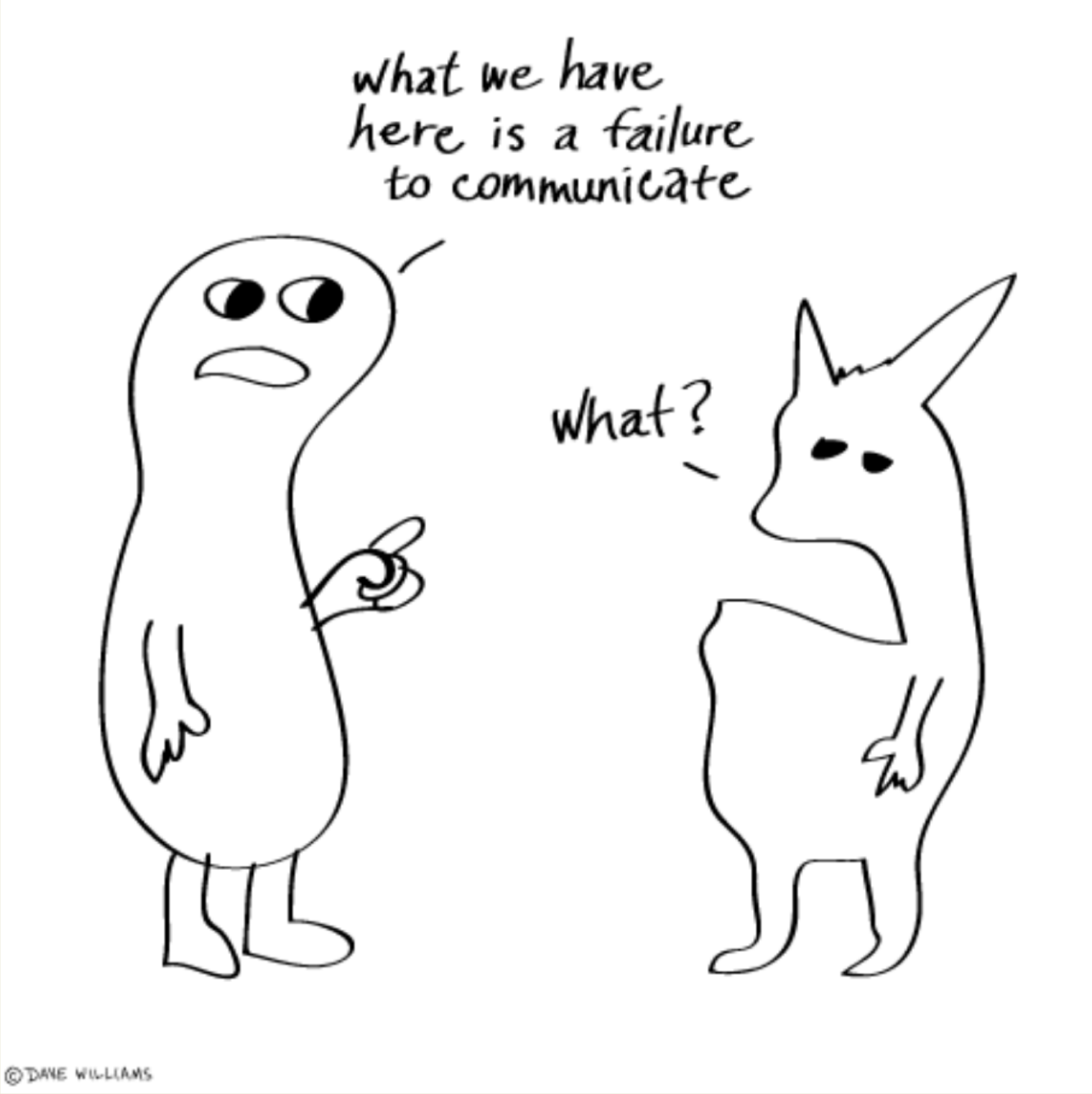
Even if not confirmed, they serve as a good example of the potential of FP at Upgrade II to probe beyond the energy frontier.



NP should be around here (driven by $\boldsymbol{R_{D^*}}$)

Neubert, Beauty 2018

Thanks for your attention!


what we have here is a failure to communicate
what?
©DAVE WILLIAMS

BACKUP

B-anomalies and neutrino interplay

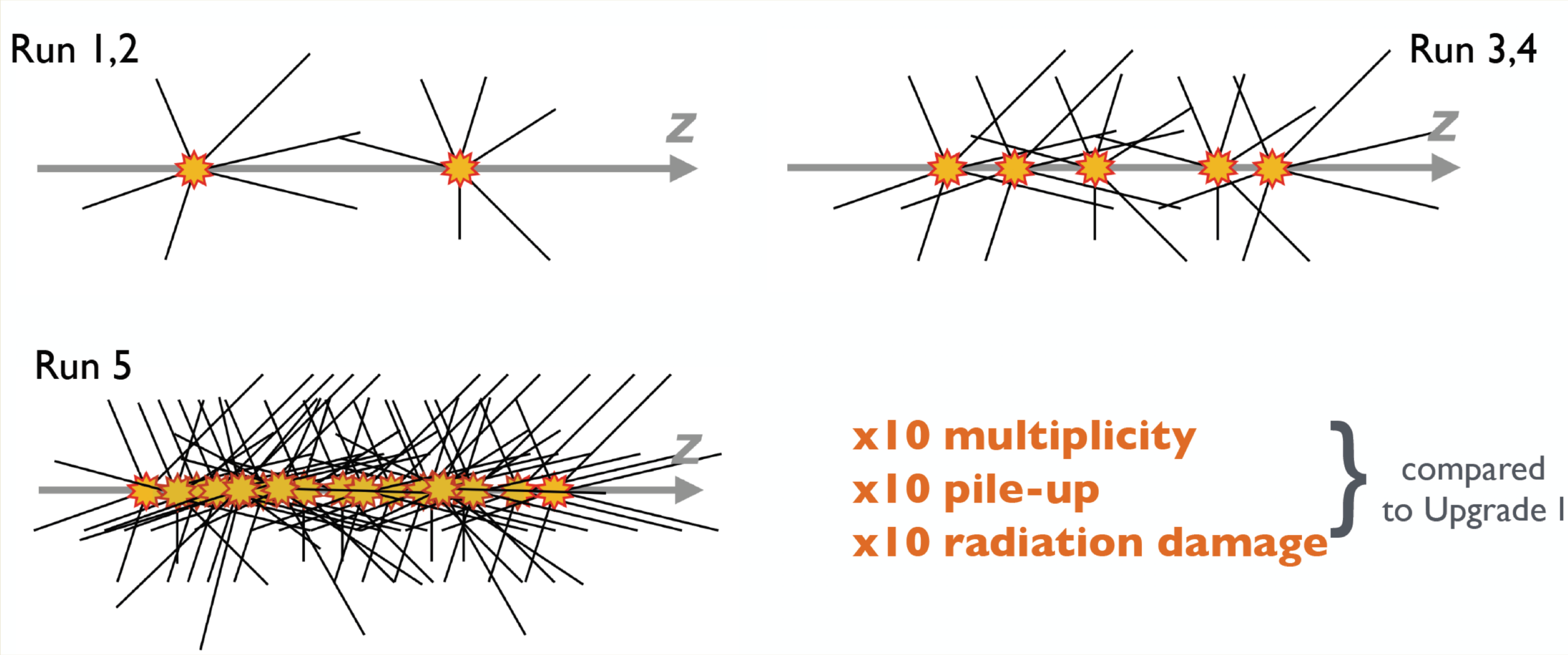
- **Impact of lepton flavour universality violation on CP violation sensitivity of long baseline neutrino oscillation experiments** [https://arxiv.org/abs/1701.00327]
- **Combined explanations of B-physics anomalies: the sterile neutrino solution** [https://arxiv.org/abs/1807.10745]
- **Anomalies in (semi)-leptonic *B* decays and possible resolution with sterile neutrino** [https://arxiv.org/abs/1702.04335]
- **Leptoquarks in Flavour Physics and the anomalous magnetic moment of the muon** [https://arxiv.org/abs/1801.03380]
- **Synergy and complementarity between neutrino physics and low-energy intensity frontiers** [https://arxiv.org/abs/1712.05947]
- **B-physics anomalies: a guide to combined explanations** [https://arxiv.org/abs/1706.07808]
- **And many more!**

Prospects for selected flavour observables

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	GPDs Phase II
EW Penguins					
R_K $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [255]	0.022	0.036	0.006	–
R_{K^*} $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [254]	0.029	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.07, 0.04, 0.11	–	0.02, 0.01, 0.03	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [123]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [152]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [569]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [32]	14 mrad	–	4 mrad	22 mrad [570]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [37]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	150 mrad [571]	60 mrad	–	17 mrad	Under study [572]
a_{sl}^s	33×10^{-4} [193]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert / \lvert V_{cb}\rvert$	6% [186]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [244]	34%	–	10%	21% [573]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [244]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	9% [199, 202]	3%	2%	1%	–
$R(J/\psi)$	25% [202]	8%	–	2%	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [574]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [222]	4.3×10^{-5}	3.5×10^{-5}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [210]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Based on extrapolations from current measurements, and take no account of detector improvements apart from an approximate **factor two increase in efficiency for hadronic modes**, coming from the full software trigger that will be deployed from Run 3 onwards.

Similar challenges



Pileup in HL-LHC: ~200 for ATLAS/CMS, ~50 for LHCb

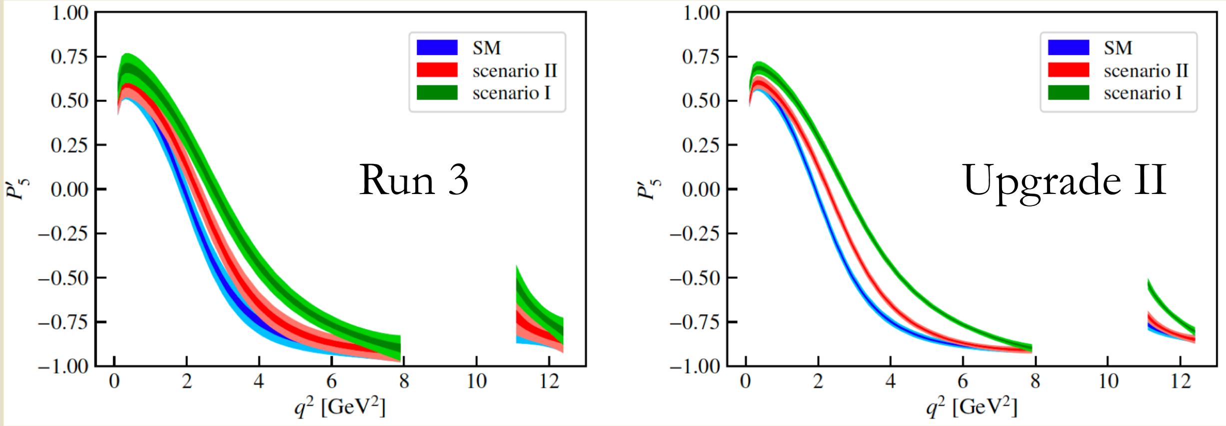
Common themes: timing, granularity and radiation hardness

G. Cowan, HL-LHC Workshop 2017

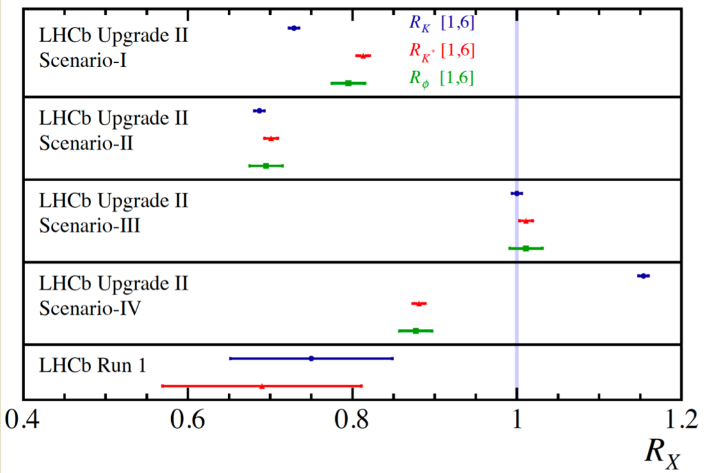
FCNC transitions

scenario	C_9^{NP}	C_{10}^{NP}	C_9'	C_{10}'
I	-1.4	0	0	0
II	-0.7	0.7	0	0
III	0	0	0.3	0.3
IV	0	0	0.3	-0.3

- LFU will play a large role in Upgrade II physics case
- Improvements: Reduce the material (e.g. RF-foil), improve ECAL granularity, better Brem recovery algorithms
- Upgrade II: 440k fully reconstructed $B^0 \to K^{*0}\mu^+\mu^-$ will allow a q^2-unbinned approach ⇒ probe the SM contributions, NP expected to have no q^2 dependence
- Compare angular distr. $B^0 \to K^{*0}e^+e^- / B^0 \to K^{*0}\mu^+\mu^-$



- Upgrade will provide thousands of $b \to d\ell^+\ell^-$ decays (e.g. 4300 $B_s^0 \to K^{*0}\mu^+\mu^-$), angular analysis possible
- 45k $B^+ \to K^+e^+e^-$ and 20k $B^0 \to K^{*0}e^+e^-$ in the Upgrade II → **Ultimate precision on $R_{K^{(*)}}$<1%**
- $R_\varphi, R_{pK}, R_\pi, \ldots$ will be possible un Upgrade II



All four NP scenarios could be distinguished at more than 5σ in Upgrade II!

Where are we?

- After Higgs discovery, no more guarantees
- Situation may resemble around 1900 "*... it seems probable that most of the grand underlying principles have been firmly established ...*" (Michelson 1894)

- LHC confirms that the SM is robust, but:
  - Hierarchy problem
  - Dark part of the Universe
  - Matter/Antimatter asymmetry
  - …

LHC at present is our most powerful accelerator to address these challenges