LHCb and its upgrades

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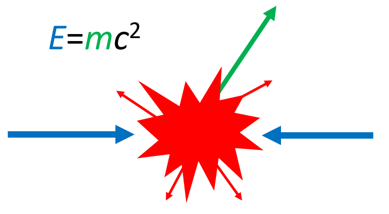
University of Birmingham Particle Physics Seminar

23rd January 2019

How to find New Physics at the LHC?

High energy frontier

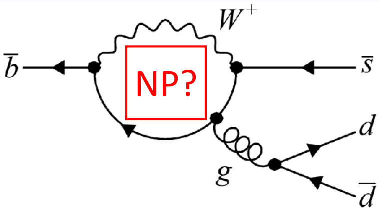
Direct observation



Require $E > mc^2$ for direct production

Precision frontier

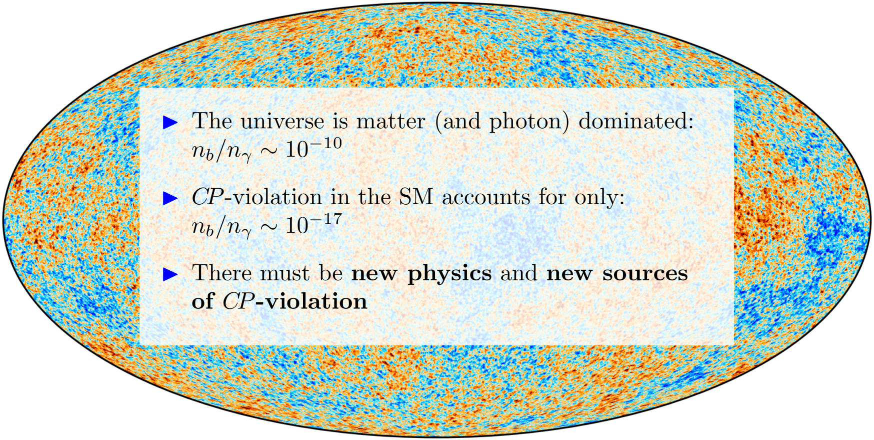
Indirect effects



New particles effect loop processes

- Most HEP direct discoveries have been preceeded by **indirect evidence first!**
  - Think charm, bottom and top quarks, even the Higgs
- If we don't see New Physics directly at the LHC, indirect evidence can guide us where to look (or what to build) next

Why is the universe matter dominated?



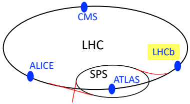
- The universe is matter (and photon) dominated: $n_b/n_\gamma \sim 10^{-10}$
- CP-violation in the SM accounts for only: $n_b/n_\gamma \sim 10^{-17}$
- There must be **new physics** and **new sources of CP-violation**

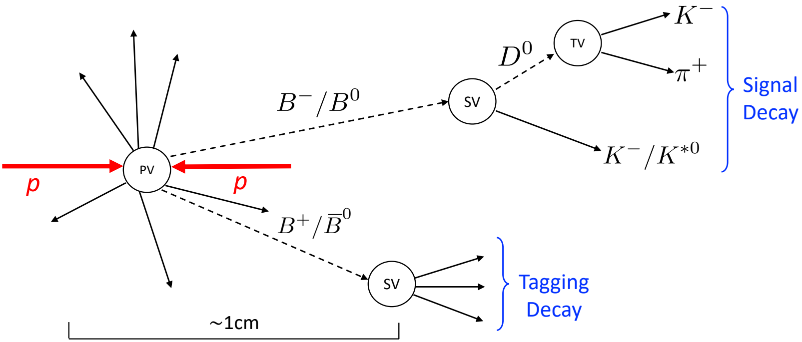
- CP-violation in the SM is generated by **quark flavour transitions**
- These contain the **only** source of CP-violation in the SM ($\theta_{\rm QCD} = m_\nu = 0$)

Overview

The goal is to **expose BSM physics** through precision studies of **quark flavour violating processes** whilst capitalising on the **unique physics opportunities** gained from a very **forward acceptance**, exploiting the **enormous heavy flavour production of the LHC**

- Copius production of B^+, B^0, B_s^0, Λ_b^0 (100K $b\bar{b}/s$)
- **LHCb detector is specifically designed to study them**





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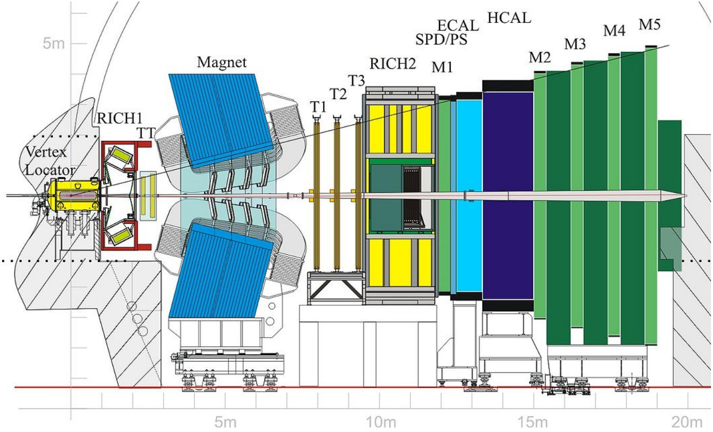
Detector performance - [Int. J. Mod. Phys. **A30** (2015) 1530022]



LHCb

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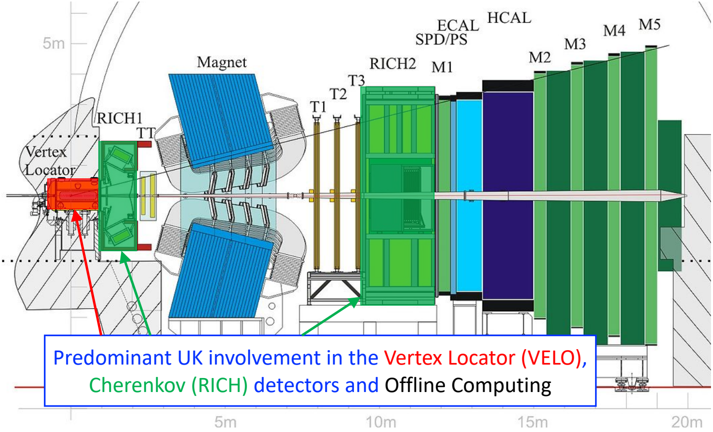

Predominant UK involvement in the Vertex Locator (VELO), Cherenkov (RICH) detectors and Offline Computing

The goal is to **expose BSM physics** through precision studies of **quark flavour violating processes** whilst capitalising on the **unique physics opportunities** gained from a very **forward acceptance**, exploiting the **enormous heavy flavour production of the LHC**

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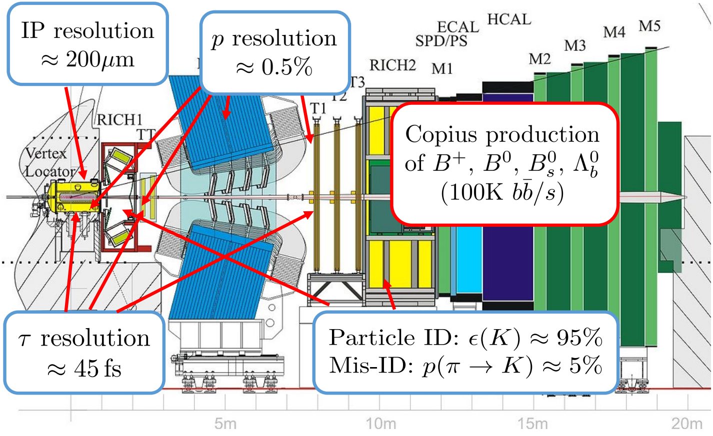
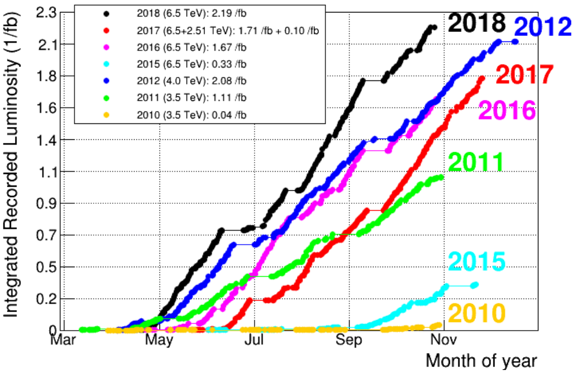


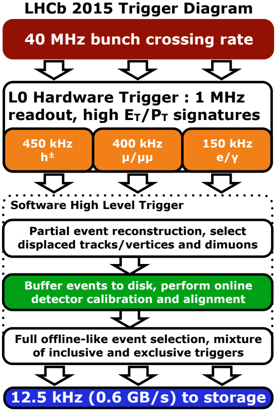
Overview

1. Current LHCb Detector
2. Highlights of recent results
   - *CP*-violation and CKM constraints
   - Flavour anomalies
3. Medium to Long Term Plans
   - Upgrade 1a
   - Upgrade 1b-II
4. Future Physics Reach

1. Highlights of recent results

- Collected $3\,\text{fb}^{-1}$ in **Run 1** and an additional $6\,\text{fb}^{-1}$ in **Run 2**
- Run 2 has seen commissioning of real-time alignment and calibration in the trigger





- Will show a selection of a few recent results, with an emphasis on the overall picture rather than any specifics

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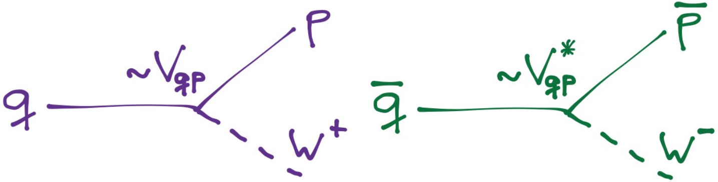
- In the SM quarks can change flavour by emission of a $W^{\pm}$ boson
  - So must also change charge (i.e. from up-type to down-type or vice-versa)



- The probability for such a transition is governed by the elements of the 3×3 **unitary** CKM matrix

CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

flavour eigenstates — mass eigenstates

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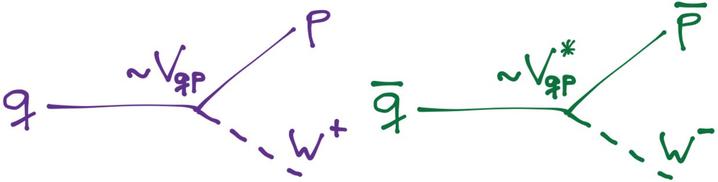

- The probability for such a transition is governed by the elements of the 3×3 **unitary** CKM matrix
  - It exhibits a **clear hierarchy** (which sets strong constraints on NP)

CKM hierarchy

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

experimentally determined values

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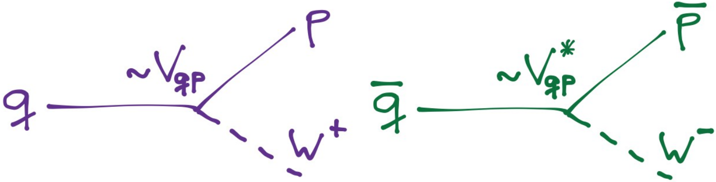

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  - Contains the only source of *CP*-violation in the SM (if $\theta_{\mathrm{QCD}} = m_\nu = 0$)

Wolfenstein parametrisation

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

4 $\mathcal{O}(1)$ real parameters (A, λ, ρ, η)

- Unitarity imposes several conditions ($V^\dagger V = \mathbb{1}$)
  - Gives rise to "unitarity" triangles
  - Internal area dictates the **total amount of CPV** in the quark sector

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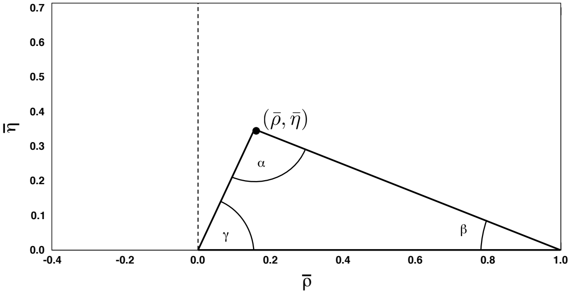

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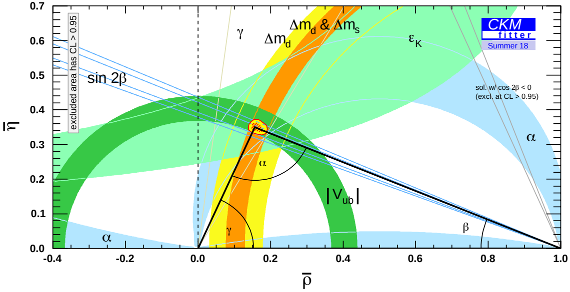
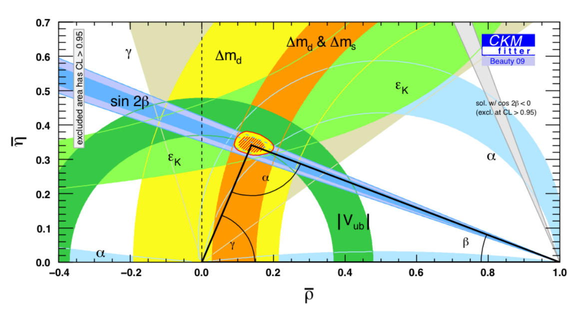
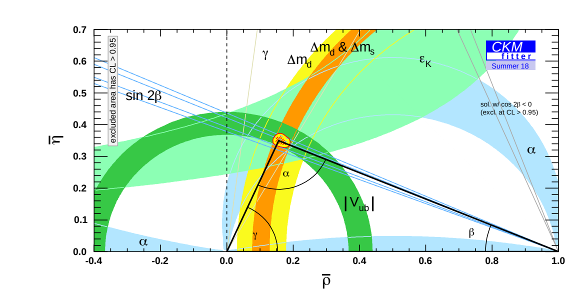


CKM unitarity and CP-violation

Unitarity Triangle 2009 - Before LHCb



Unitarity Triangle 2018



Tree-level constraints

- Uncertainty on γ now $\sim 5^\circ$
  [LHCb-CONF-2018-002]
- Measurement of V_{ub} with Λ_b^0 baryons
  [Nat. Phys. **10** (2015) 1038]

Loop-level constraints

- $\sin 2\beta_{\rm eff}$ competitive with B factories
  [JHEP **11** (2017) 170]
- World best for $\Delta m_d / \Delta m_s$
  [EPJ **C76** (2016) 412]

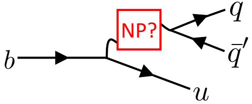
New Physics effects in the flavour sector

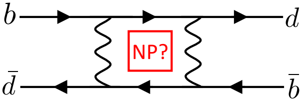
- Discrepancy between "tree" and "loop" constraints ⇒ clear sign of New Physics
- Sensitive to NP effects at extremely high energy scales $\sim \mathcal{O}(10^2 - 10^3)$ TeV

Direct: $\gamma = (72.1^{+5.4}_{-5.7})^\circ$

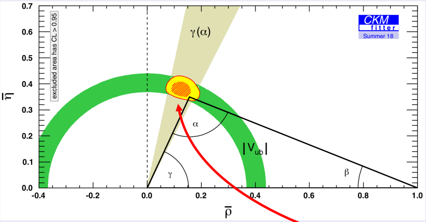
Indirect: $\gamma = (65.6^{+1.0}_{-3.4})^\circ$

} Currently a $\sim 2\sigma$ tension

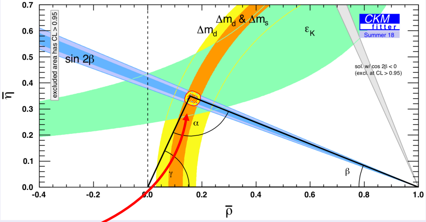




Tree-level constraints



Loop-level constraints



NP?

CP-violation in the SM

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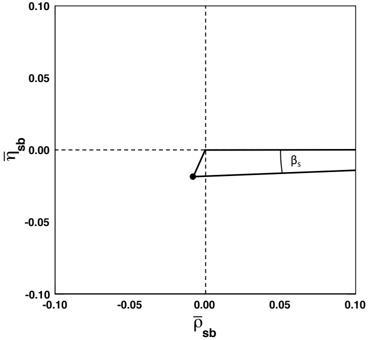

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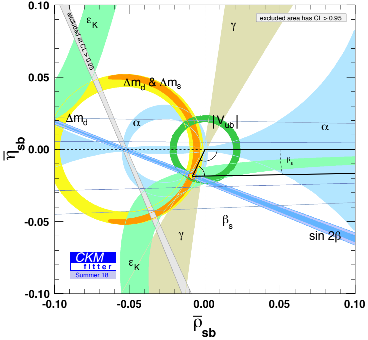
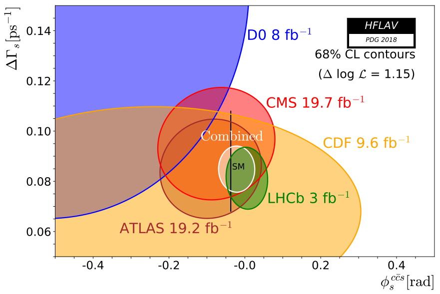


HFLAV for PDG 2018



Loop-level measurements

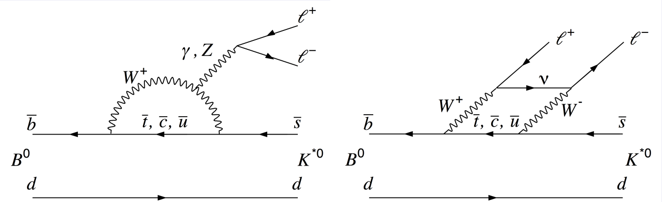
- Precision measurement of ϕ_s in golden $b \to c\bar{c}s$ modes
  - [PRL **114** (2015) 041801]
- Also in BSM sensitive loop-dominated $b \to s\bar{s}s$ and $b \to d\bar{d}s$ modes (unique to LHCb)
  - [LHCb-CONF-2018-001], [JHEP **03** (2018) 140]

Overview

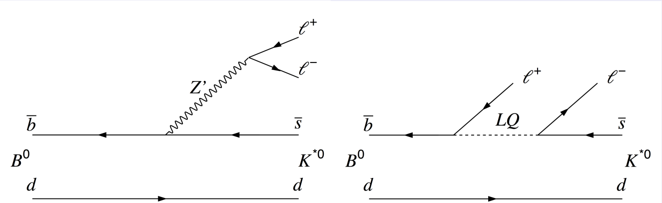
Intriguing signs of deviations from the SM in $b \to s\ell^+\ell^-$ transitions

- Angular observables in $B^0 \to K^{*0}\mu^+\mu^-$
- e/μ ratios in $B^+ \to K^+\ell^+\ell^- / B^0 \to K^{*0}\ell^+\ell^-$
- Constrained by SM-like behaviour in $B_s^0 \to \mu^+\mu^-$

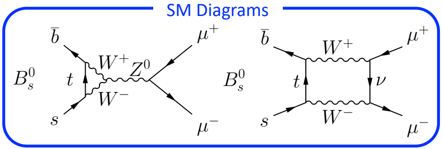
SM $B^0 \to K^{*0}\ell\ell$

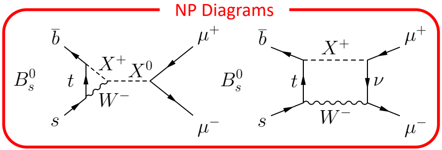


NP $B^0 \to K^{*0}\ell\ell$



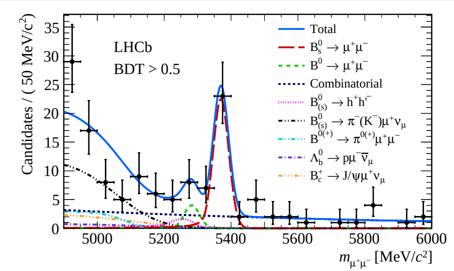
$B^0_{(s)} \to \mu^+\mu^-$

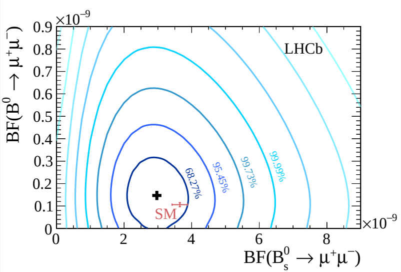




Results are consistent with the SM predictions

[PRL **118** (2017) 191801]
[Nature **522** (2015) 68-72]





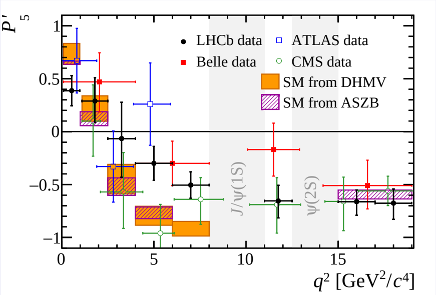
▸ **Provides strong constraints on NP from other anomalies**

Angular observables in $B^0 \to K^{*0}\mu^+\mu^-$

- Deviations of $\sim 3.5\sigma$ from the SM prediction (in LHCb alone)
- Is this hints of NP of just some unaccounted for hadronic effect?

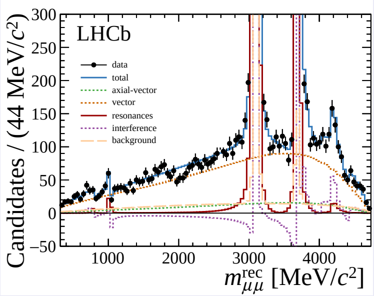
Deviation in P_5' for $B^0 \to K^{*0}\mu^+\mu^-$

[JHEP 02 (2016) 104]



Resonant structure in $B^\pm \to K^\pm\mu^+\mu^-$

[EPJ C77 (2017) 161]

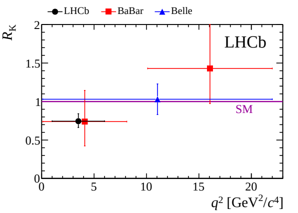


Tests of lepton flavour universality

- Further discrepancies seen in ratios $R(K)$ and $R(K^{*0})$ (a host of others under study)

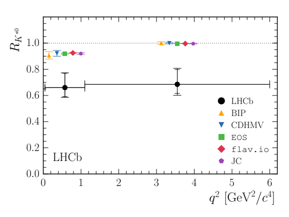
LFU in $B^{\pm} \to K^{\pm}\ell^{+}\ell^{-}$ $(R(K))$

[PRL **113** (2014) 151601]



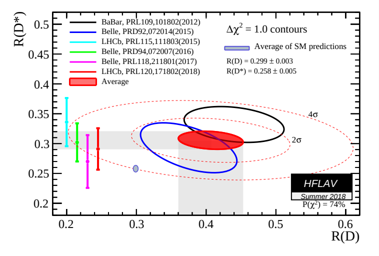
LFU in $B^{0} \to K^{*0}\ell^{+}\ell^{-}$ $(R_{K^{*0}})$

[JHEP **08** (2017) 055]



Also see discrepancies in $B \to D^{(*)}\ell\nu$ $(R_D$ and $R_{D^*})$

[PRL **120** (2018) 171802]
[PRL **115** (2015) 111803]



Flavour anomaly interpretation

- Can interpret the flavour anomalies in terms of Effective Theories
- **Deeper understanding is a key aim for Run 2 analysis**

$$\langle f|H_{\text{eff}}|i\rangle = \sum_k \frac{1}{\Lambda^k} \sum_i \mathcal{C}_{k,i} \langle f|\mathcal{O}_k|i\rangle \Big|_\Lambda$$

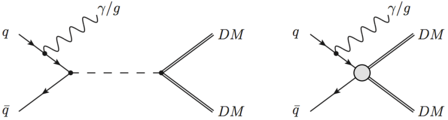
"Wilson" coefficients Independent of Λ

Short distance contribution (physics >Λ)

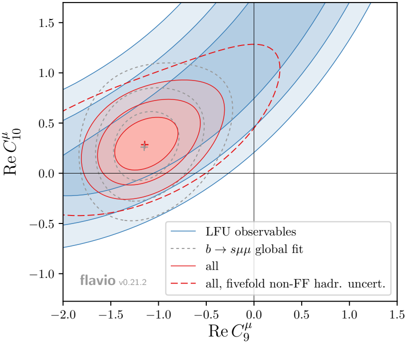
"Local operators" Long-distance contribution (physics <Λ)

Full theory

Effective theory



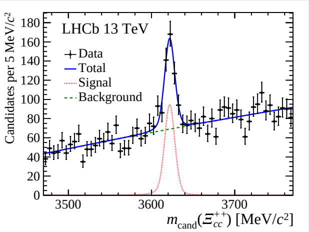
[PRD **96** (2017) 055008]



Other recent (UK) highlights

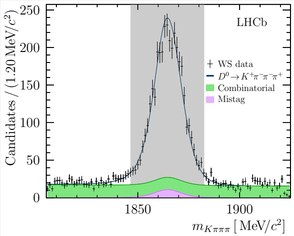
Observation (and lifetime) of Ξ_{cc}^{+}

[PRL 121 (2018) 052002]
[PRL 119 (2018) 112001]



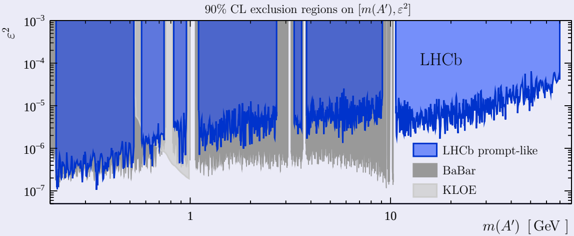
Doubly Cabibbo suppressed study in $D \to K3\pi$

[EPJ C78 (2018) 443]

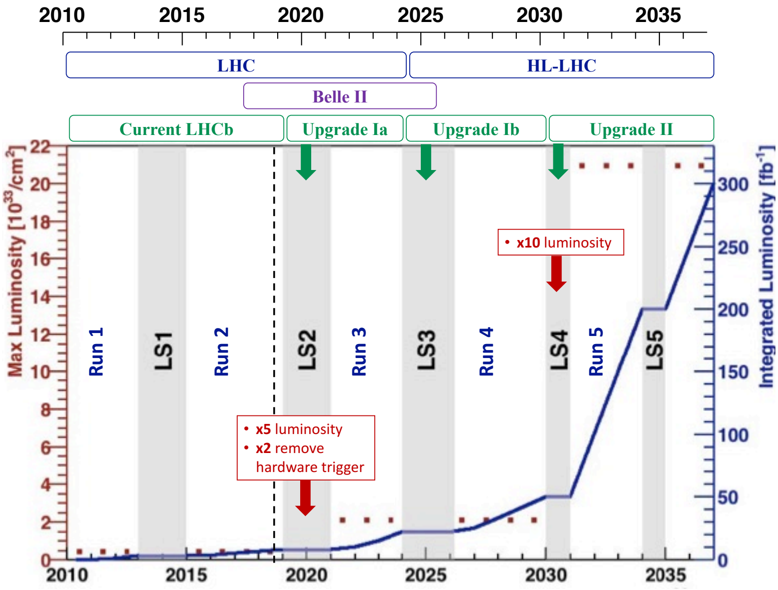


Dark photon search

[PRL 120 (2018) 061801]



2. Medium to Long Term Plans



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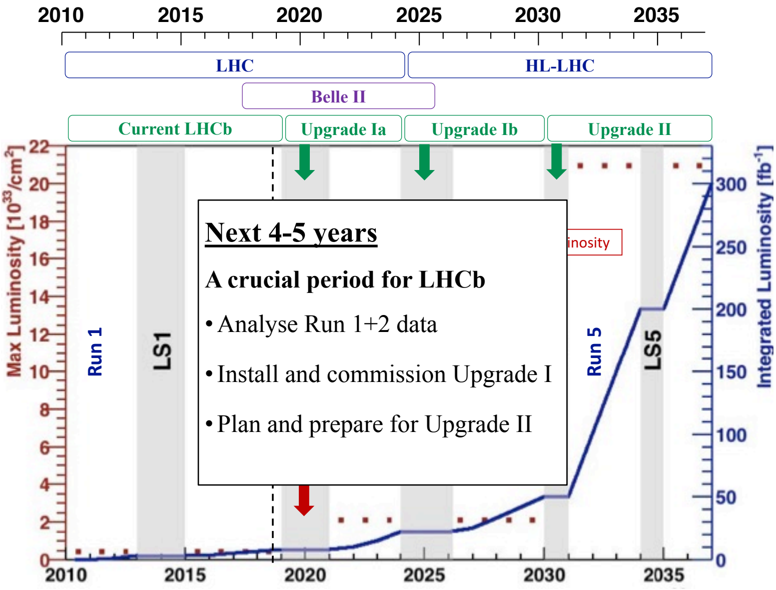


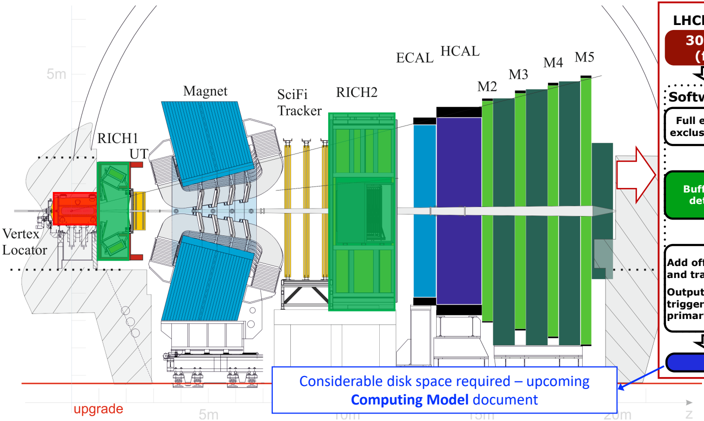
Next 4-5 years

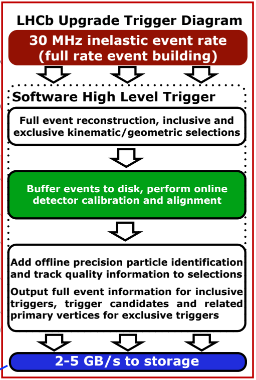
A crucial period for LHCb

- Analyse Run 1+2 data
- Install and commission Upgrade I
- Plan and prepare for Upgrade II

Overview

- The largest throughput DAQ system ever built
- **A major construction project making good progress and largely on schedule**
- Predominant UK involvement in **VELO**, **RICH** and **Offline Computing**





Considerable disk space required – upcoming **Computing Model** document

Upgrade Ia

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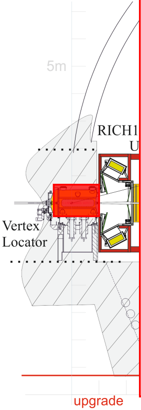
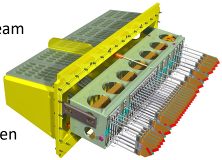
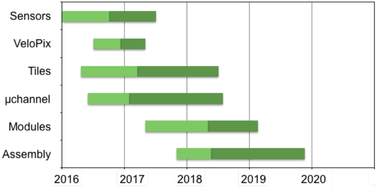
- **A major construction project making good progress**
- Predominant UK involvement in **VELO**, **RICH** and **Offline Computing**

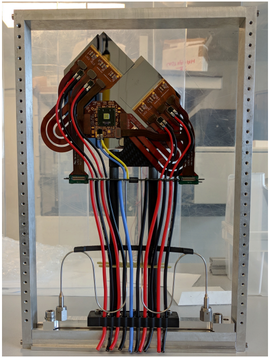


VELO

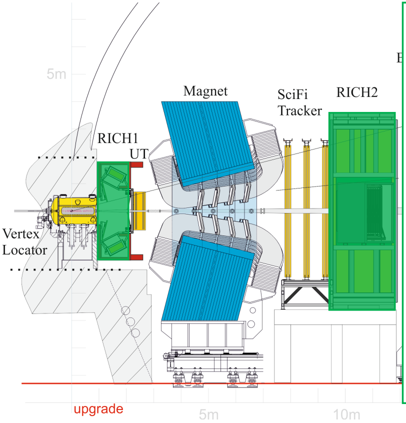
- Silicon pixels up to 5mm from beam line
- 52 modules in L-shaped config
- Some delays but **on track for production**
- No major technical issues foreseen
- **Assembly underway**





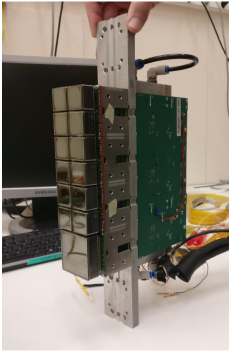


- The largest throughput DAQ system ever built
- **A major construction project making good progress and largely on schedule**
- Predominant UK involvement in **VELO**, **RICH** and **Offline Computing**



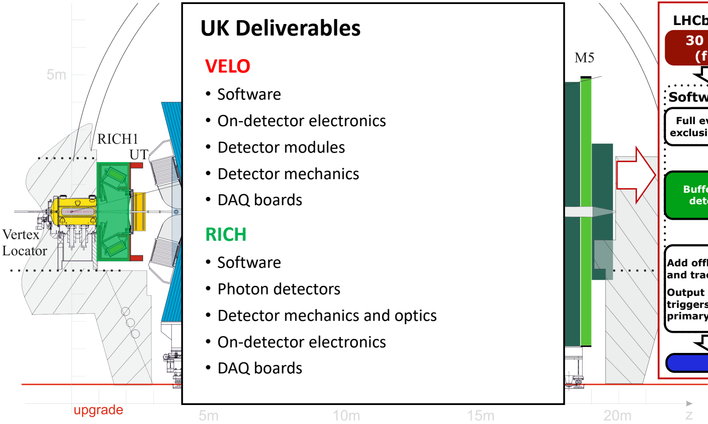
RICH

- New photon detectors
- New readout and services
- New optics and gas enclosure (RICH1)
- Test module **already installed and running**
  - Collecting light behind current system
- **All PRRs passed**
  - **No show stoppers**
- Beginning production, installation and commissioning phase



Upgrade Ia

- The largest throughput DAQ system ever built
- **A major construction project making good progress and largely on schedule**
- Predominant UK involvement in **VELO**, **RICH** and **Offline Computing**



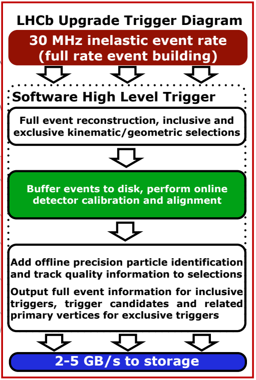
UK Deliverables

VELO

- Software
- On-detector electronics
- Detector modules
- Detector mechanics
- DAQ boards

RICH

- Software
- Photon detectors
- Detector mechanics and optics
- On-detector electronics
- DAQ boards

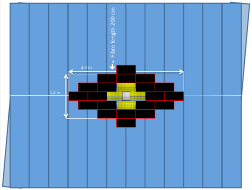


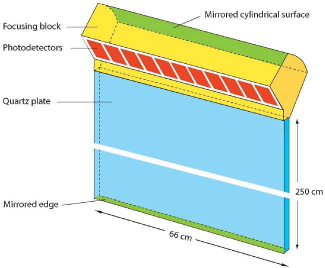
Overview

Upgrade Ib - II

Exciting ideas for consolidation of Upgrade I and preparation of Upgrade II

- **Mighty (CMOS) Tracker**
  - Downstream tracking near the beam pipe
  - Complement Upgrade I SciFi detector
- **TORCH**
  - Time-of-flight using Cherenkov light
  - PID for low momentum objects
- **Magnet side stations**
- **ECAL**
- **Timing VELO**
- **Timing RICH**

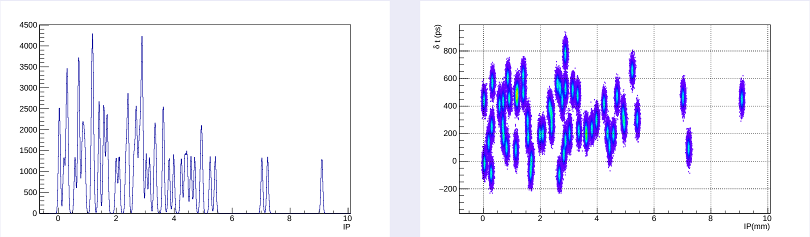




- UK has an R&D grant for TORCH
- Worldwide R&D ongoing for fast-timing and calorimetry in Upgrade Ib-II
- **Upgrade Ib TDRs aiming for LHCC in Sep 2020**
- Upgrade Ib-II Physics Case Document released [CERN-LHCC-2018-027]

- **Machine requirements** can be met to deliver $50\,\text{fb}^{-1}$/year to LHCb
  - "a range of potential solutions for operating the LHCb Upgrade II ... permitting the collection of $300\,\text{fb}^{-1}$ or more at IP8" - [CERN-ACC-NOTE-2018-003]
- **Detector requirements** in high pileup and high occupancy environment
  - Maintaining performance of the tracking, flavour tagging and particle identification requires **precise timing**
- **Large increase in physics reach**

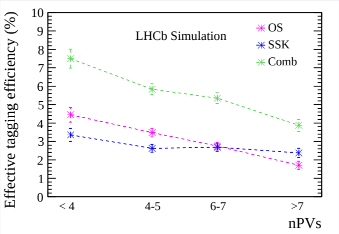
Example of timing to help associate correct primary vertex (in VELO)



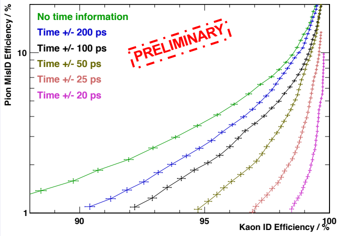
Upgrade II

- **Machine requirements** can be met to deliver 50 fb^{-1}/year to LHCb
  - "a range of potential solution for operating the LHCb Upgrade II ... permitting the collection of 300 fb^{-1} or more at IP8" - [CERN-ACC-NOTE-2018-003]
- **Detector requirements** in high pileup and high occupancy environment
  - Maintaining performance of the tracking, flavour tagging and particle identification requires **precise timing**
- **Large increase in physics reach**

Flavour tagging efficiency (with current detector)



PID efficiency (with current detector)

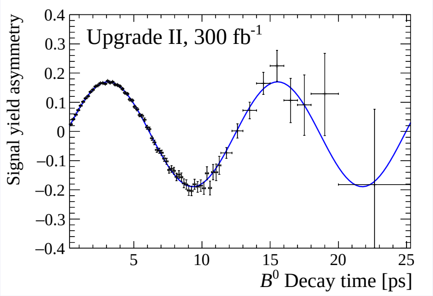


Overview

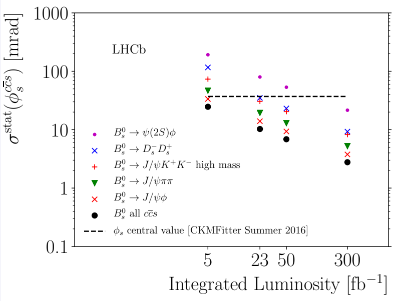
Time-dependent CPV in Upgrade II

- Vital to maintain **decay-time resolution** and **flavour-tagging** perfomance
  - Requires timing detectors
- Uncertainty on ϕ_s goes below the SM prediction for **several different modes**
- World best measurement of $\sin(2\beta)$

TD asymmetry in $B^0 \to J/\psi K^0_S$



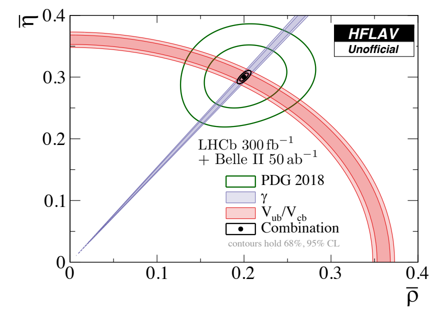
Uncertainty on ϕ_s



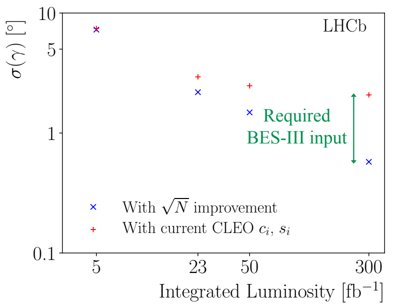
Time-integrated CPV in Upgrade II

- Unprecedented precision ($\sim 0.3^\circ$) in **theoretically clean** extraction of γ
  - Close collaboration with BES-III required (see Sneha Malde's talk)

Tree-level CKM constraints with 300 fb^{-1}



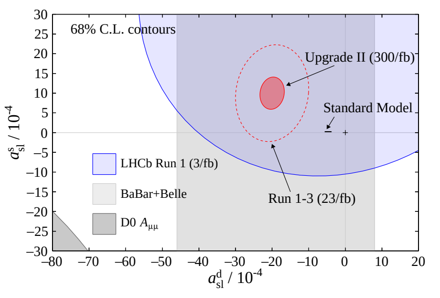
γ sensitivity with $B^\pm \to [D^0 \to K^0_S hh]K^\pm$



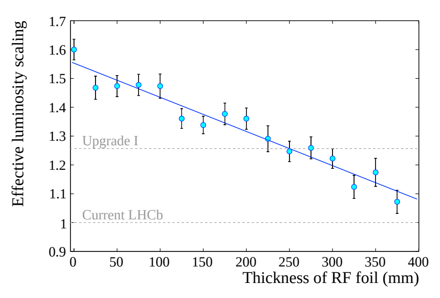
Semileptonic CPV with Upgrade II

- Particular gain for semileptonics with reduction of RF foil thickness
  - Use of TORCH for V_{ub} with $B_s^0 \to K\mu\nu$

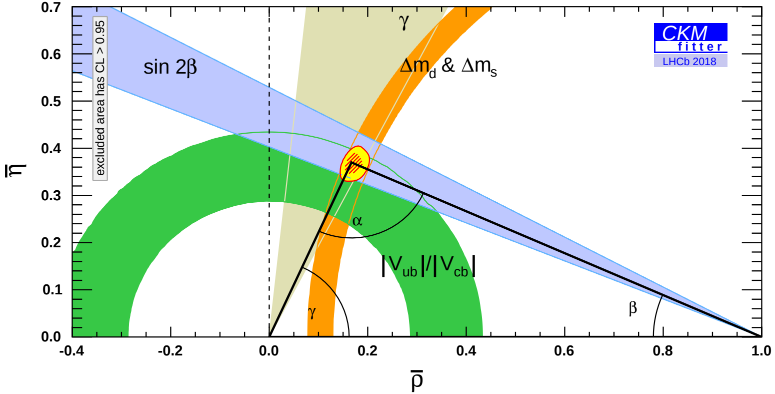
Semileptonic Asymmetries with 300 fb^{-1}



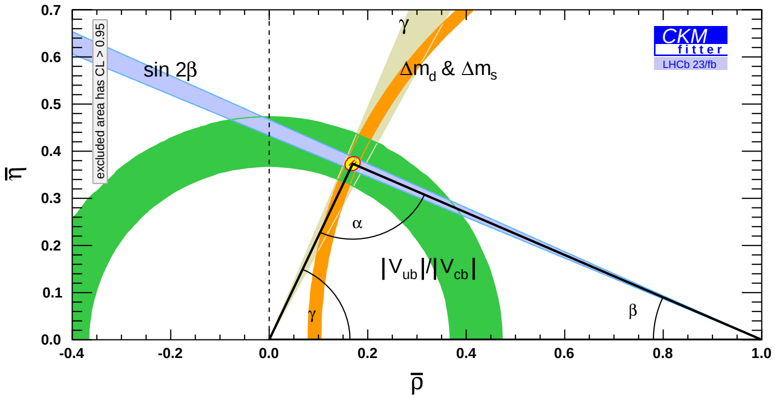
Effect of reduced RF foil



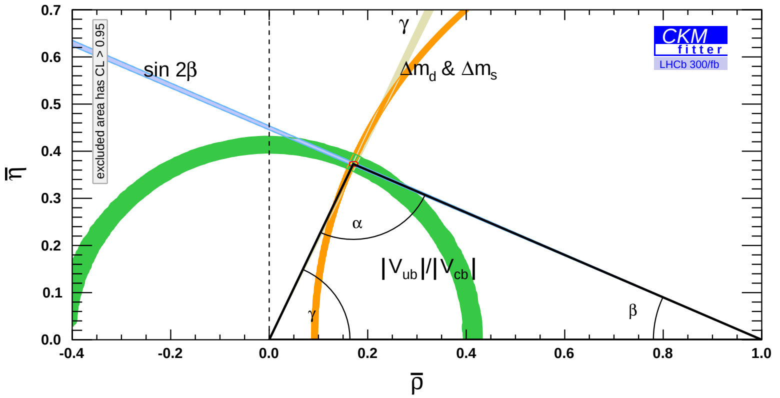
CKM constraints from LHCb **Now**



CKM constraints from LHCb **Upgrade I**

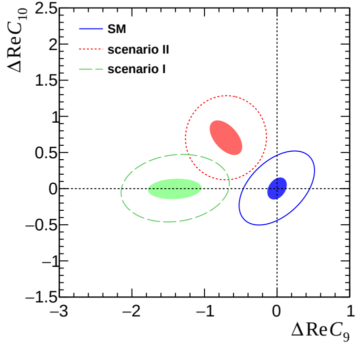


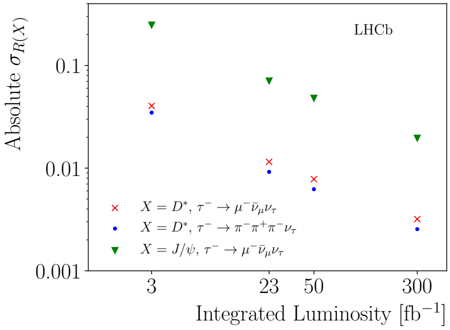
CKM constraints from LHCb **Upgrade II**



Flavour anomalies with Upgrade II

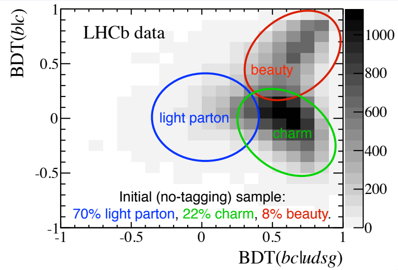
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [274]	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [275]	0.031	0.032	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05
$\boldsymbol{B^0_s, B^0 \to \mu^+\mu^-}$				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	90% [264]	34%	–	10%
$\tau_{B^0_s \to \mu^+\mu^-}$	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





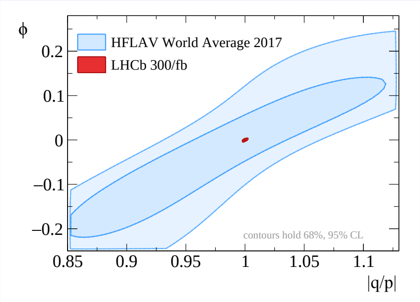
- Many, many other physics opportunites in Charm, Rare Decays, SM measurements and BSM searches

$H \to c\bar{c}$



- With $300\,\mathrm{fb}^{-1}$ can set upper limit on charm Yukawa coupling of $\approx 7y^{c}_{\mathrm{SM}}$

Charm Mixing at $300\,\mathrm{fb}^{-1}$



Summary I/II

1. The LHCb experiment is performing exceptionally well

- Delivering an incredibly broad physics programme
- Some exciting and unexpected results across a diverse range of topics
- Detector operation and data exploitation funded through CG and external grants (e.g. fellowships, ERC, etc.)

2. The first Upgrade (Ia) is on good track to deliver physics in Run 3 (2021)

- Design and prototype stages are largely complete
- Moving onto production, installation and commissioning
- Funding is in place until 2020
  - R&D and construction covered by PPRP grant plus CG effort
  - Need extensions for key posts for installation and commissioning - requested through the CG
- R&D, proto-typing & construction all covered by **a single grant**
  - This adds significant challenges (timescale + risk)
  - Although on track to have UK deliverables on time and in budget
  - **For future upgrades we would hope to have a funded R&D phase followed by a proto-type and construction phase**

Summary II/II

3. A clear vision to exploit the precision flavour physics potential of the HL-LHC

- R&D ongoing at a small level for future upgrades
  - Through small grants or unfunded effort
  - Modest effort has been requested in the CG to continue this
- **EoI** [CERN-LHCC-2017-003] and **Physics Case** [CERN-LHCC-2018-027] for Upgrade II
- Anticipate submitting an SoI to STFC later this year for UK involvement in Upgrades Ib and II
- Collect at least 300 fb^{-1} and extend physics reach to unprecedented levels

4. LHCb Upgrades Ia, Ib and II are an essential part of the UK and European particle physics programmes in the medium and long term future

- UK input to the European Strategy process must reflect this

The full exploitation of LHC + HL-LHC data should remain a top priority for the UK. This includes the extensive flavour physics program of LHCb and its upgrades

BACK UP

UK prominence within the collaboration

- LHCb consists of 61 member institutes (of which are 11 are UK) across 15 countries
- UK contributes $\sim$ 157/811 authors

Senior management roles

Collaboration Board Chair	Val Gibson
Deputy Spokesperson	Chris Parkes
Operations Coordinator	Silvia Borghi

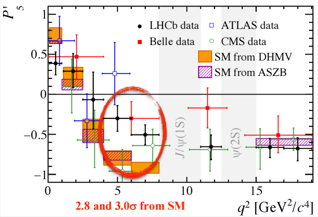
- **10/28 Physics planning group** convenors at UK institutes
  - An additional 4 were PhDs at UK institutes
  - New **Physics coordinator** was also a UK PhD
- **7/24 Operation planning group** coordinators at UK institutes
- **4/17 Upgrade planning group** coordinators at UK institutes

Whilst the LHCb collaboration continues to grow the UK component has not.
The UK maintains strong leadership positions across all areas of the experiment.

- **Deeper understanding is a key aim for Run 2 analysis**

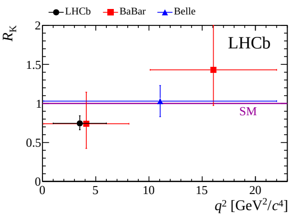
$B \to K^* \mu\mu$ angular observables

[JHEP **02** (2016) 104]



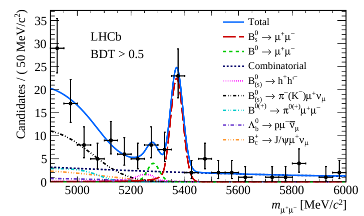
LFU in $B \to K^{(*)}\ell\ell$ (R_K and R_{K^*})

[PRL **113** (2014) 151601]
[JHEP **08** (2017) 055]



Interplay with $B^0_s \to \mu\mu$

[PRL **118** (2017) 191801]



LFU in $B \to D^{(*)}\ell\nu$ (R_D and R_{D^*})

[PRL **120** (2018) 171802]
[PRL **115** (2015) 111803]