Lepton Flavor Universality tests in $b \to s\ell^+\ell^-$ decays at LHCb

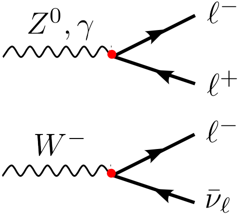
Biplab Dey

on behalf of the LHCb collaboration

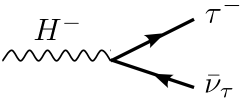
ICHEP 2018, Seoul

Lepton flavor universality (LFU)

EW bosons in SM:



Charged Higgs in NP:

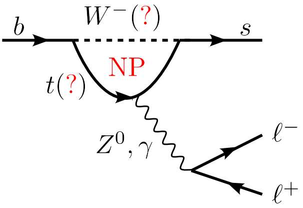


- Fundamental feature of EW theory in the SM: gauge couplings universal between $\ell \in \{e, \mu, \tau\}$
- Difference in dynamics driven solely by the difference in the masses ($m_e < m_\mu \ll m_\tau$).
- Even if NP occurs, *minimal flavor violation*: SM-like hierarchy in couplings
- Eg., H^+ couples to the 3^{rd} generation heavy τ
  [see LFU with τ's by O. Leroy at 3:20pm today]

- LFU violations between e and μ *really* unexpected and require non-SM-like NP couplings.

$b \to s\ell^+\ell^-$ as a sensitive LFU probe at LHCb

- Electroweak penguins: sensitive to very high mass particles propagating inside the loop

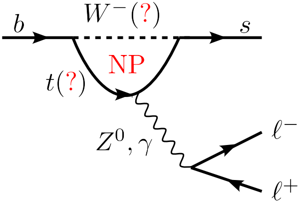


$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^-\mu^+)}{\mathcal{B}(B \to K^{(*)}e^-e^+)}$$

- $R_X = 1 \pm \mathcal{O}(10^{-3})$ in SM up to small e-μ mass difference. $\mathcal{O}(10^{-2})$ QED corrections. [EPJC 76 (2016) 8, 440]
- Unlike τ's, no new form-factor. Hadronic uncertainties cancel in ratio. *Very* clean from QCD perspective. But...

$b \to s\ell^+\ell^-$ as a sensitive LFU probe at LHCb

- Electroweak penguins: sensitive to very high mass particles propagating inside the loop



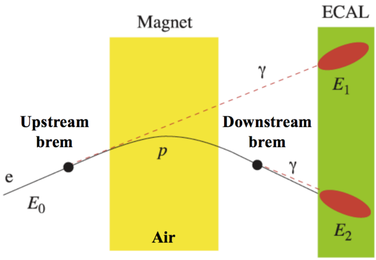
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^-\mu^+)}{\mathcal{B}(B \to K^{(*)}e^-e^+)}$$

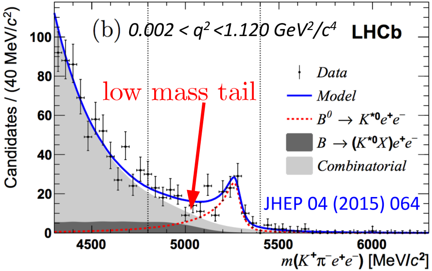
- $R_{K^{(*)}} = 1 \pm \mathcal{O}(10^{-3})$ in SM upto small e-μ mass difference. $\mathcal{O}(10^{-2})$ QED corrections. [EPJC 76 (2016) 8, 440]
- Unlike τ's, no new form-factor. Hadronic uncertainties cancel in ratio. *Very* clean from QCD perspective. But...

- Electrons are hard at LHCb. Trigger, bremsstrahlung recovery...

Lepton reconstruction at LHCb: electrons

- Large "shashlik" based ECAL: L0 trigger, γ/π^0 separation, electron reconstruction, radiative B-decays [see $b \to s\gamma$ by F. Ramikov earlier today]
- Energy resolution: $\frac{\sigma_E}{E} \sim 1\% \otimes \frac{10\%}{\sqrt{E}}$
- Large bremsstrahlung losses from material interaction. Not 100% recoverable. Low mass tail for the signal B; poorer resolution.



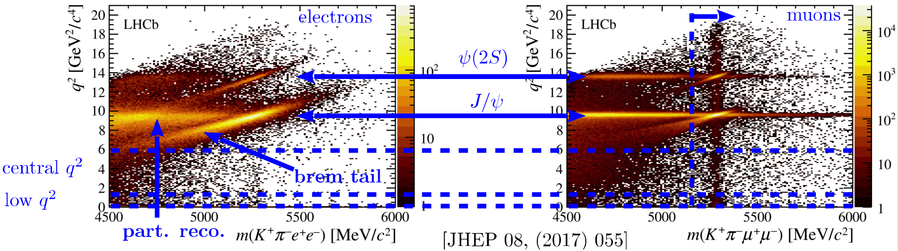


Electron modes: trigger categories

- Triggering on $B \to K^{(*)}e^+e^-$ more complicated than $B \to K^{(*)}\mu^+\mu^-$
- L0 triggers: higher E_T thresholds in the ECAL due to higher occupancies, than for muons (much softer p_T requirements).
  - L0E: any of the electrons with $E_T > 2.5$ GeV
  - L0H: any of π/K with $E_T > 3.5$ GeV
  - L0I: fired by other tracks in the pp collision event, independent of signal
- Studies performed on each exclusive trigger categories (different resolutions and purities)

$B^0 \to K^*\ell^+\ell^-$: PART-RECO BACKGROUNDS

- Analysis in two $q^2 \equiv m(\ell^+\ell^-)^2$ bins:
  - low q^2: $[0.045, 1.1]$ GeV^2, close to the photon pole and $C_{7\gamma}$
  - central q^2: [1.1,6] GeV^2, feed-down from J/ψ radiative tail



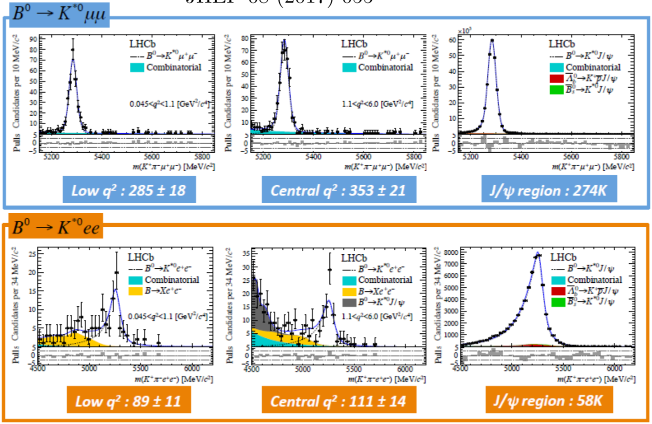
- $m(K^+\pi^-\mu^+\mu^-) > 5150$ MeV: selection for muons remove partially reconstructed backgrounds from $B \to K^* X \ell^+\ell^-$

Double ratios and yields: R_{K^*}

- Measure double ratios using $J/\psi \to \ell^+\ell^-$ as the control modes:

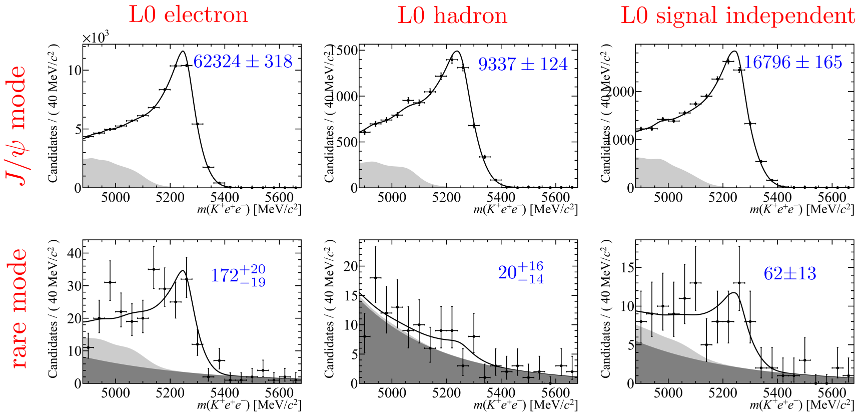
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^-\mu^+)/\mathcal{B}(B \to K^{(*)}J/\psi)}{\mathcal{B}(B \to K^{(*)}e^-e^+)/\mathcal{B}(B \to K^{(*)}J/\psi)}$$

JHEP 08 (2017) 055



Yields for R_K

- Yields for $B^+ \to K^+e^+e^-$ broken down in to the three trigger categories, $q^2 \in [1, 6]$ GeV^2:

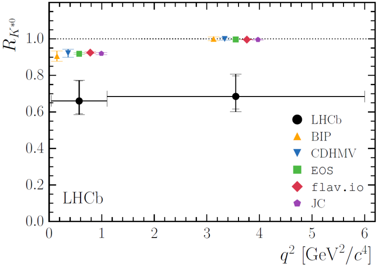


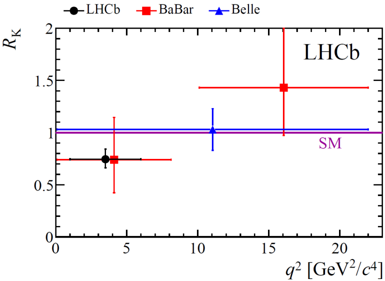
[PRL 113, 151601, (2014)]

- Yield for $B^+ \to K^+\mu^+\mu^- = 1226 \pm 40$

LHCb Run 1 status for R_{K^*} and R_K

[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]

- LHCb [PRL 113 (2014) 151601]
- Belle [PRL 103 (2009) 171801]
- BaBar [PRD 86 (2012) 032012]

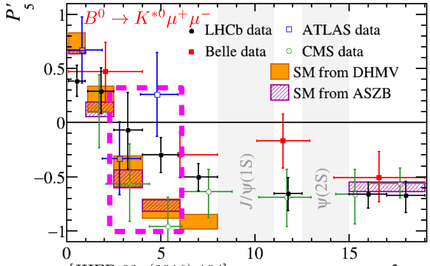
- Tension with SM, depending on theory model:
  - $R_{K^*}(0.045 < q^2 < 1.1\ \mathrm{GeV}^2) = 0.66^{+0.11}_{-0.07} \pm 0.03$: $2.1 - 2.3\sigma$
  - $R_{K^*}(1.1 < q^2 < 6.0\ \mathrm{GeV}^2) = 0.69^{+0.11}_{-0.07} \pm 0.05$: $2.4 - 2.5\sigma$
  - $R_K\ (1 < q^2 < 6.0\ \mathrm{GeV}^2) = 0.745^{+0.090}_{-0.074} \pm 0.036$: 2.6σ

Other Run 1 tensions in $b \to s\ell^+\ell^-$

- Several other tensions in the muonic sector ($b \to s\mu^+\mu^-$)

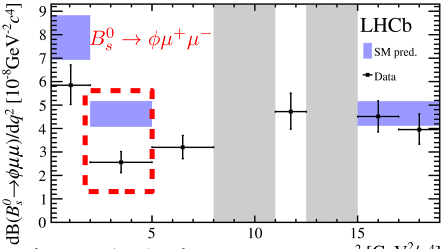
  [see talk by T. Blake at 2pm today]

Angular analysis:



[JHEP 02, (2016) 104]

Branching fractions:



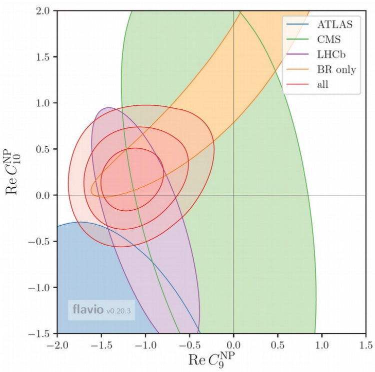
[JHEP 09, (2015) 179]

- 2.8 σ and 3.0 σ local deviations in P'_5
- BF's in several $b \to s\mu^+\mu^-$ modes 1-3σ lower than SM.
- Note: lower BF's in muonic modes is what drives the R_X tensions.

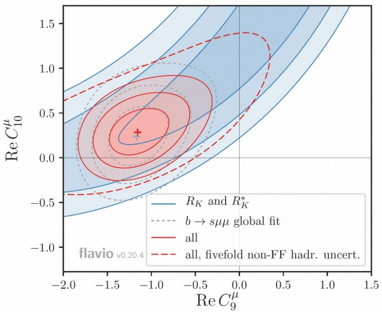
Global fits for Wilson coefficients

- Many different global fits incorporating different $b \to s\ell^+\ell^-$, $b \to s\gamma$ measurements.

BF's + angular:



Include LFU violation:

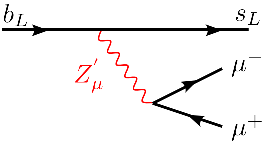


Altmannshofer *et al.* 1703.09189
Altmannshofer *et al.* 1704.05435

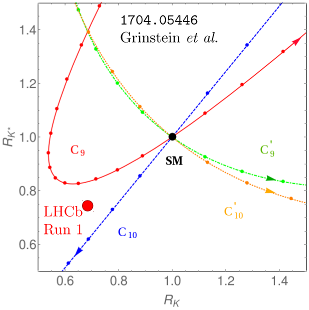
- Remarkable consistency: BF, angular, $R_{K^{(*)}}$ all point to $\Delta C_9^{\mu} \sim -1$.

More on global fits...

- $\Delta C_{9\mu} = C_{9\mu}^{NP} < 0$ from a tree-level Z'_μ would explain the anomalies
  [Altmannshofer'14, Crivellin'15,...]



- However, $c\bar{c}$ charm-loops can mimic $\Delta C_{9\mu}$.



- LFU tests do not suffer from charm-loops.
- Complementarity between R_K and R_{K^*}
- (Un)natural parity difference between K^+ and K^* gives different sensitivities to C_{9A} and C_{10V}.

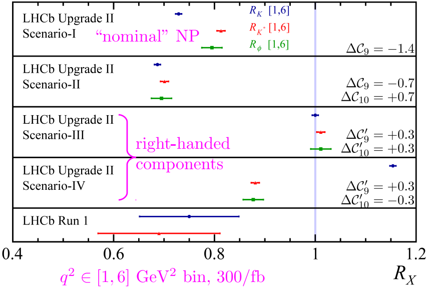
Run II and upgrade scenarios for R_X

- Run II $R_{K^{(*)}}$ updates, new R_ϕ, $R_{K\pi\pi}$ and R_{pK} in the pipeline.

- Sub-percent $R_{K^{(*)}}$ precision after Upgrade II in HL-LHC era.

		Run 2	Run 3	Upgrade II
Yield	Run 1 result	8 fb^{-1}	23 fb^{-1}	300 fb^{-1}
$B^+ \to K^+e^+e^-$	254 ± 29	970	3300	46000
$B^0 \to K^{*0}e^+e^-$	111 ± 14	430	1400	20000
$B^0_s \to \phi e^+e^-$	–	80	260	3700
$\Lambda^0_b \to pKe^+e^-$	–	210	700	9800
$B^+ \to \pi^+e^+e^-$	–	20	75	1000
R_X precision	Run 1 result	8 fb^{-1}	23 fb^{-1}	300 fb^{-1}
R_K	$0.745 \pm 0.090 \pm 0.036$	0.046	0.025	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$	0.070	0.038	0.010
R_ϕ	–	0.163	0.089	0.024
R_{pK}	–	0.100	0.054	0.014
R_π	–	0.304	0.165	0.044

- Allows to distinguish between different NP models.



- Projections don't include improved ECAL for Upgrade II: higher granularity, fast-timing to reduce combinatorics.
- L0 hardware trigger replaced by flexible software trigger from Run III

Outlook

The Case for Future Hadron Colliders From $B \to K^{(*)}\mu^+\mu^-$ Decays

B.C. Allanach,[a] **Ben Gripaios,**[b] **Tevong You**[1a,b]

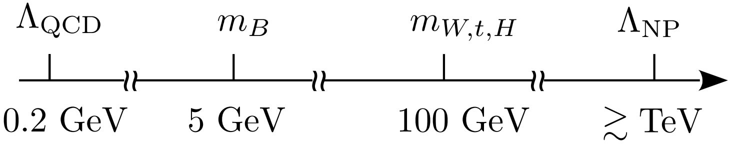
[a] *DAMTP, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, United Kingdom*
[b] *Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge, CB3 0HE, United Kingdom*

- *If* these flavor anomalies survive LHCb Run III and Belle II, strong motivation for a 100 TeV FCC-hh.

Backup slides

NP hunting strategy in b-physics

- Multi-scale problem: QCD, hadronic form-factors, Electroweak, NP.



- Effective Field Theory: separate long and short distance scales. SM + a basis of dim-6 local operators, $\mathcal{O}_i$ and Wilson coefficients C_i

Wilson coefficients encode short-distance physics after integrating over high mass SM particles

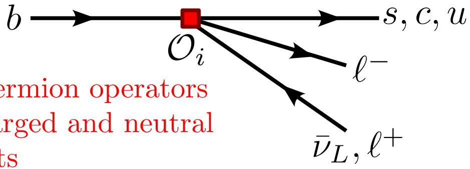
$$\mathcal{H}^{SM}_{\mathrm{eff}(6)} = -\frac{4G_F V}{\sqrt{2}} \sum_i C_i^{SM} \mathcal{O}_i$$

generic non-SM flavor content

$$\mathcal{H}^{NP}_{\mathrm{eff}(6)} = \sum_i \frac{C_i^{NP}}{\Lambda^2_{\mathrm{NP}}} \mathcal{O}_i, \ \Delta F = 1$$

- Sensitive to $\Lambda_{\mathrm{NP}} \gtrsim$ TeV scale thru' C_i. Need precision measurements.

Operators for $b \to s\ell^+\ell^-$



Four-fermion operators for charged and neutral currents

- Coupling is $V \sim \frac{\alpha}{4\pi} V_{ts}^* V_{tb}$; $\Lambda_{\mathrm{NP}} \sim$ 10-100 TeV

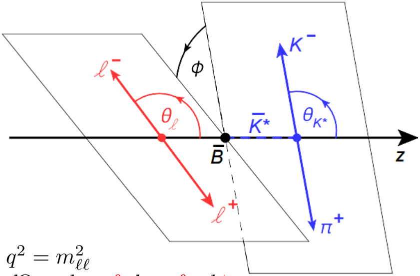
- Main operators for $b \to s\ell^+\ell^-$ are $\mathcal{O}^{(\prime)}_{7,9,10}$
- Right-handed (primed) ones suppressed by factors of m_s/m_b in the SM.

$$\mathcal{O}^{(\prime)}_{7\gamma} = \frac{m_b}{e}(\bar{s}\sigma^{\mu\nu}P_{R(L)}b)F_{\mu\nu}$$

$$\mathcal{O}^{(\prime)}_{9V} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell)$$

$$\mathcal{O}^{(\prime)}_{10A} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

$B^0 \to K^*\ell^+\ell^-$ ANGULAR ANALYSIS



$q^2 = m^2_{\ell\ell}$
$d\Omega \equiv d\cos\theta_l d\cos\theta_K d\phi$

$$\frac{d\Gamma}{dq^2 d\Omega} = \frac{9}{32\pi}\sum_{i=1}^{17} J_i(q^2) f_i(\theta_l, \theta_K, \phi)$$

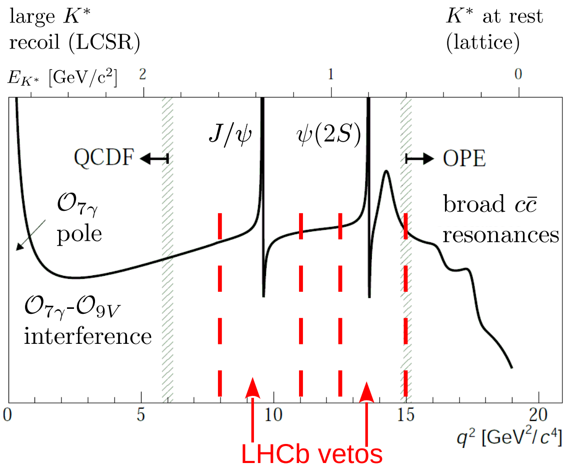
- J_i are bilinears of the transversity amplitudes $A_0^{L,R}$, $A_\perp^{L,R}$, $A_\parallel^{L,R}$, $A_S^{L,R}$

- Both short- and long-distance parts enter the amplitudes:

$$A_\perp^{L(R)} \sim \left\{ [(C_9^{\text{eff}} + C_9^{\prime\text{eff}}) \mp (C_{10}^{\text{eff}} + C_{10}^{\prime\text{eff}})] \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\text{eff}} + C_7^{\prime\text{eff}}) T_1(q^2) \right\}$$

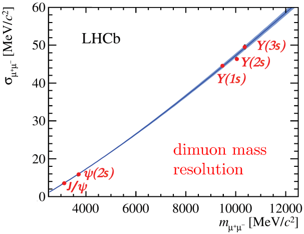
- Reduced FF uncertainties at LO: $P_5' = \frac{J_5}{\sqrt{J_{1c}(1 - J_{1c})}}$, [1303.5794]

q^2 DEPENDENCE



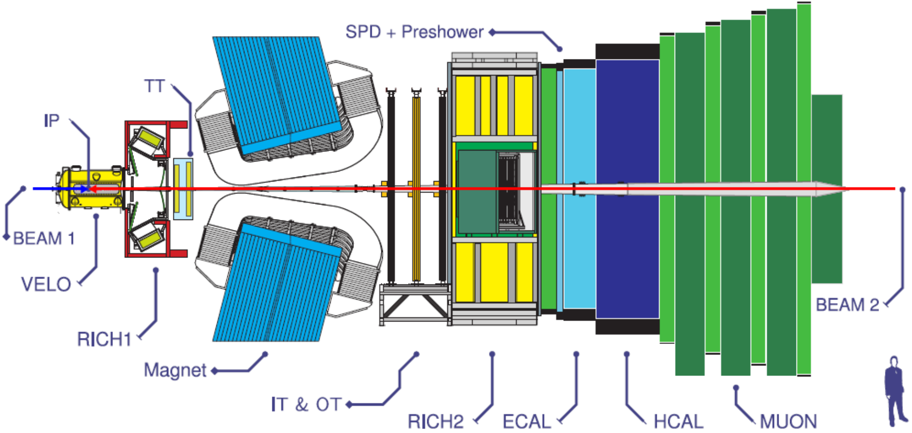
Lepton reconstruction at LHCb: muons

- Reminder: the LFU interest is only very recent: 2012 (BaBar $R(D^{(*)})$ and 2014 (LHCb $R(K)$).
- Design of LHCb primarily for muons and not electrons.

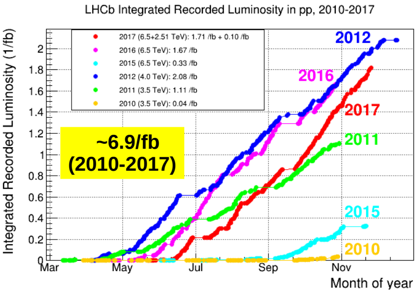


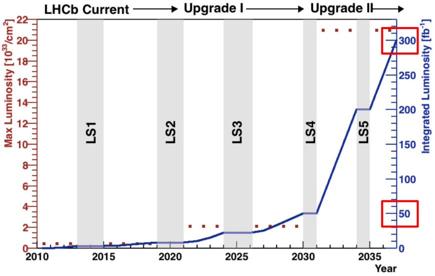
- Dedicated muon system for L0 hardware trigger. $\varepsilon_{\rm L0+HLT} \sim$ 90%, 1.3% $\pi \leftrightarrow \mu$ mis-Id.
- Low material interaction for muon tracks.
- Pair of di-muons among the best reconstructed tracks in LHCb. Excellent resolution.

The LHCb Detector components



The path ahead for LHCb...





- Aim to collect $> 2/\text{fb}$ in 2018.
- Many more R_X, asymmetry measurements. TD-CPV in $B_s \to \phi\mu^+\mu^-$, $B^0 \to K^0_s\rho^0\gamma$, ...
- Major upgrade in LS2. Consolidation in LS3.
- 50/fb by 2030. Phase II upgrade for HL-LHC, aiming for 300/fb.

More on Upgrade II reach