Flavour at LHCb

Recent results and prospects

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On behalf of the LHCb Collaboration

7^{th} Workshop on Theory, Phenomenology & Experiments in Flavour Physics
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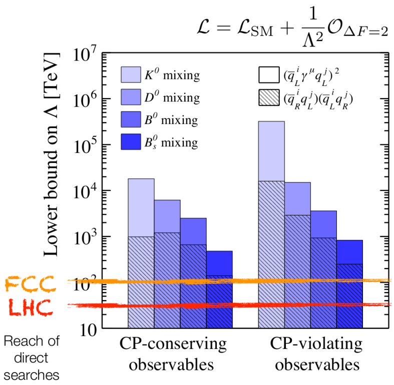
Vill Orlandi, Anacapri

Why measure properties of heavy flavour?

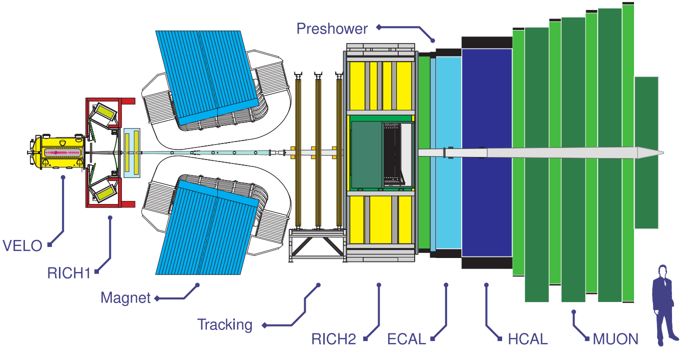
- Speaking to a biased audience here, but personal (Experimental) opinion:



- Complementarity: Probes effects of new particles at energy scales inaccessible in direct searches
- Variety: From time-dependent measurements of $\not{C}\not{P}$ observables to rare decay searches, there is a wealth of experimental challenges
- Necessity: There is much we do not know about the nature of the universe, and many places to look:
  - If new particles are observed at the (HL)LHC, we must probe their flavour structure
  - If no new particles are observed, measurements in quantum loops can tell us what to build next

LHCb: The precision flavour experiment

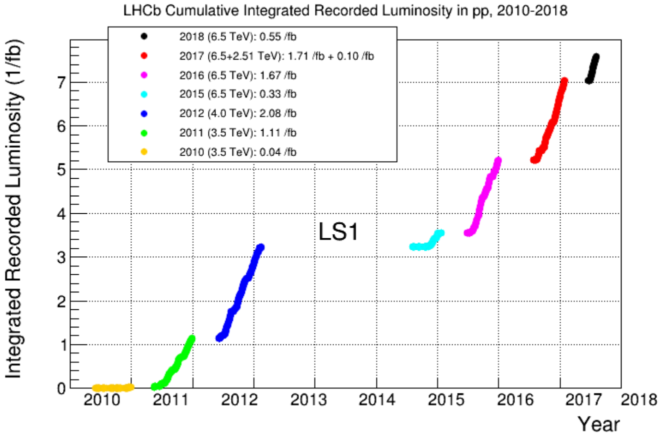
- LHCb was built to study beauty and charm at the LHC:



- Precise particle identification (RICH + MUON)
- Excellent decay time resolution: $\sim$ 45fs (VELO)
- High purity + Efficiency with flexible trigger

The LHCb dataset

- 2018 is the last year of data taking with the present LHCb detector



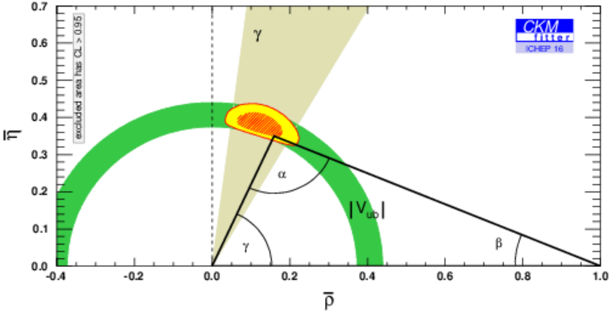
- Hoping to collect 2.5fb^{-1} this year, total Run 1 + Run 2 dataset $>$ 9fb^{-1}
- Run 2 dataset benefits from increased cross-sections and improved trigger

Recent highlights

- LHCb has a broad physics programme, covering much more than just *b*- and *c*-physics
  - Electroweak measurements
  - Spectroscopy
  - Heavy Ion & fixed-target physics
- Today I will present some recent highlights, starting with $\mathcal{CP}$ and finishing with rare and semileptonic ratios

CKM angle γ LHCb-CONF-2018-002

- γ is the least well measured angle of the UT
- Can be measured in modes dominated by tree-level contributions: Constrains the UT apex



- No current measurement has a precision better than 10°: Make multiple measurements and combine

C. Fitzpatrick

June 8, 2018

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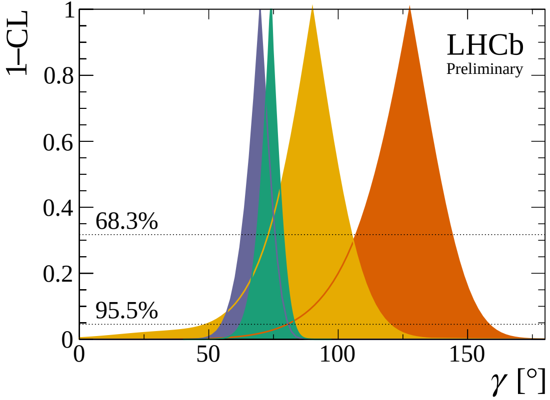
CKM angle γ LHCb-CONF-2018-002

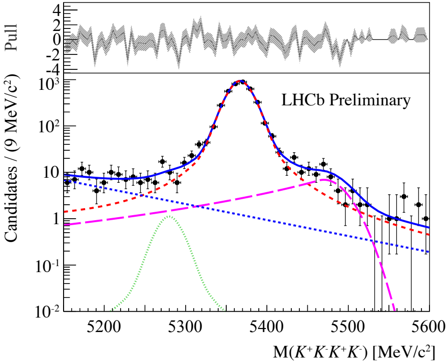
- LHCb combination with Run 1 and several Run 2 inputs:



- LHCb finds $\gamma = (74.0^{+5.0}_{-5.8})^\circ$ using a frequentist combination.
- Compare to indirect determination: $\gamma = (65.33^{+0.96}_{-2.54})^\circ$ [CKMFitter]

$\phi_s^{s\bar{s}s}$ in $B_s^0 \to \phi\phi$ LHCb-CONF-2018-001 PRELIMINARY

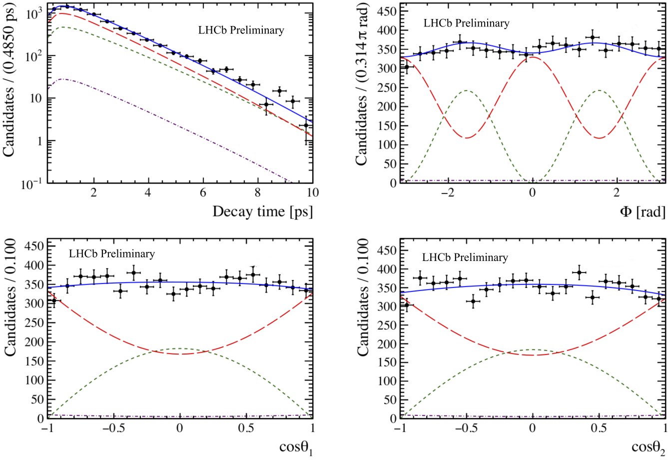
- Weak phase $\phi_s^{c\bar{c}s}$: $\mathcal{CP}$ violation in the interference between mixing and decay of B_s^0 mesons
- LHCb has made world best measurements in $B_s^0 \to J/\psi(KK, \pi\pi)$, $B_s^0 \to D_s D_s$
- $\phi_s^{s\bar{s}s}$ accessible in $B_s^0 \to \phi\phi$:
  - Signal yield of $\sim$8500 with 5fb^{-1} of Run 1 + Run 2 data



- $\Lambda_b \to \phi p K^-$ and $B^0 \to \phi\phi$ components included in the fit
- No significant B^0 component. Limit set: $\mathcal{B}(B^0 \to \phi\phi) < 2.4 \times 10^{-8}$ [90%CL]

$\phi_s^{s\bar{s}s}$ in $B_s^0 \to \phi\phi$ LHCb-CONF-2018-001 PRELIMINARY

- $\phi_s^{s\bar{s}s}$ extracted from fit to time and angular distributions of background subtracted $B_s^0 \to \phi\phi$:



- $\phi_s^{s\bar{s}s} = -0.07 \pm 0.13\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})\,\mathrm{rad}$ (preliminary)
- c.f.QCD factorisation limit: $|\phi_s^{s\bar{s}s}| < 0.02\,\mathrm{rad}$

The anomalies

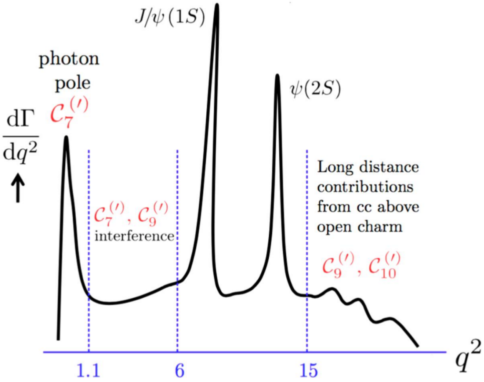
- Several interesting results recently
- We've heard already from Tobias and Marco in this session. I'll recap LHCb results and discuss prospects

$b \to s\ell\ell$: $R(K^*)$ JHEP 08 (2017) 055

- LFU test: $R(K^*) = \frac{\mathcal{B}(B^0 \to K^* \mu^- \mu^+)}{\mathcal{B}(B^0 \to K^* e^- e^+)} = 1 \pm \mathcal{O}(10^{-3})$
- Measure double ratios to minimise uncertainties:

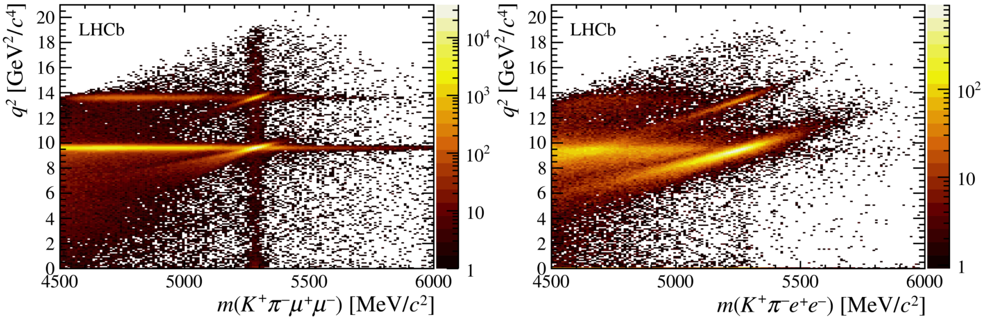
$$R(K^*) = \frac{\mathcal{B}(B^0 \to K^* \mu^- \mu^+)}{\mathcal{B}(B^0 \to K^* J/\psi(\to \mu^- \mu^+))} \Big/ \frac{\mathcal{B}(B^0 \to K^* e^- e^+)}{\mathcal{B}(B^0 \to K^* J/\psi(\to e^- e^+))}$$

- Experimentally challenging due to differences in detection and selection of μ^-, e^-
- Muons have excellent resolution and background rejection
- Measured in two q^2 regions: $[0.045, 1.1]$ (low) and $[1.1, 6]$ GeV$^2/c^4$ (central)



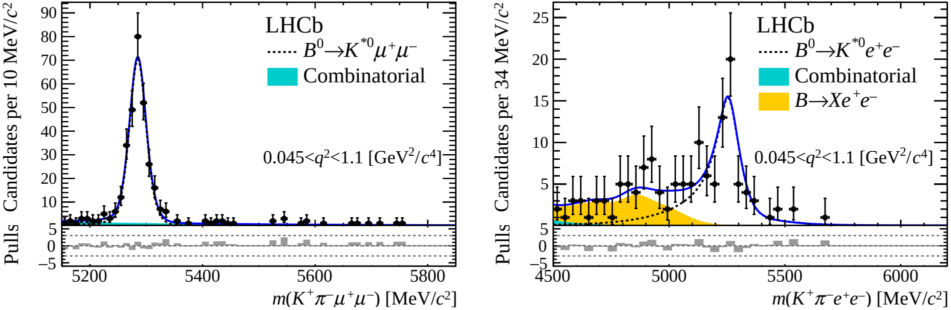
$b \to s\ell\ell$: $R(K^*)$ JHEP 08 (2017) 055

- Simultaneous fit to $B^0 \to K^* J/\psi(\to \ell\ell)$ and nonresonant channels



- Radiative J/ψ tail an important component of the central q^2 invariant mass fit

b → $s\ell\ell$: $R(K^*)$ JHEP 08 (2017) 055



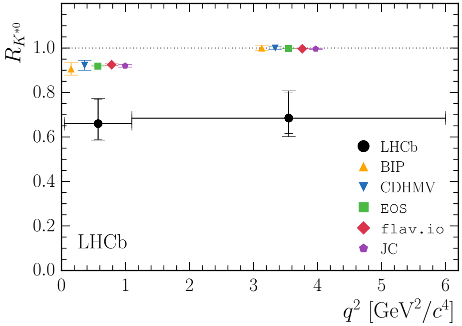
- Simultaneous fit finds:

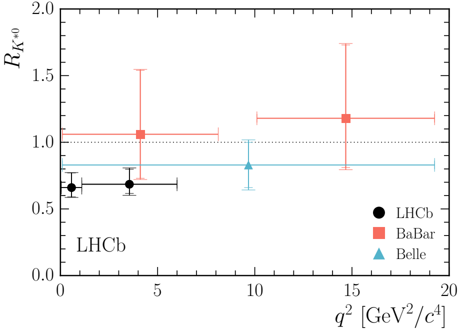
$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07}\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst}) & \text{for } 0.045 < q^2 < 1.1\,\mathrm{GeV}^2/c^4\,, \\ 0.69^{+0.11}_{-0.07}\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst}) & \text{for } 1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4\,. \end{cases}$$

- Results compatible at $\sim 2 - 2.5\sigma$ level to the SM

b → s$\ell\ell$: R(K*) JHEP 08 (2017) 055

- Comparing to predictions and past measurements:





- Results are more sensitive than, and compatible with the B-factories
- LHCb measured R(K) in 2014 and also found a 2.6σ compatibility PRL 113, 151601 (2014)

$b \to c\ell\nu$

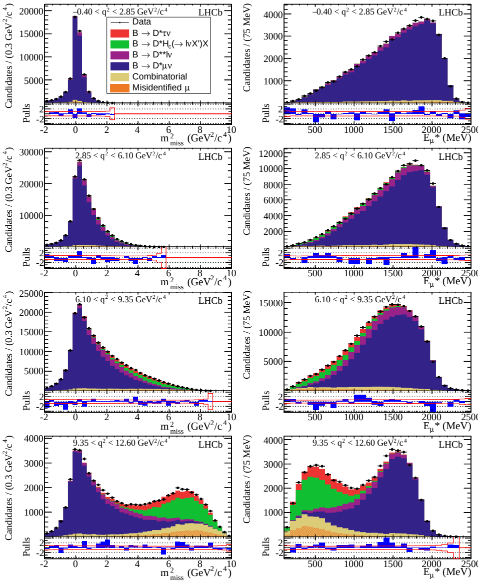
- Ratios of semileptonic decays are similarly interesting:
- $R(D^{*-}) = \mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)/\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$
- LHCb has made several measurements:
  - Using $\tau^- \to \mu^-\nu_\tau\overline{\nu}_\mu$ PRL 115, 111803 (2015)
  - Using three-prong $\tau^- \to \pi^-\pi^+\pi^-$ decays PRL 120, 171802 (2018)
  - $R(J/\psi)$ using $B_c^+ \to J/\psi\tau^+\overline{\nu}_\mu$ PRL 120, 121801 (2018)

Muonic $R(D^{*-})$ PRL 115, 111803 (2015)

- Fit in bins of q^2 to missing mass^2 and muon energy, E^*_μ
- Signal (red) more visible in higher q^2 bins
- Significant background from DD with one $D \to \mu X$

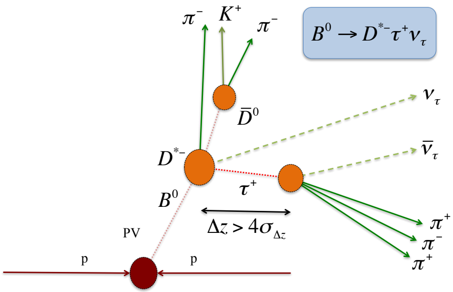
$\mathcal{R}(D^*) = 0.336 \pm 0.027(stat) \pm 0.030(syst)$
LHCb, 3fb^{-1}

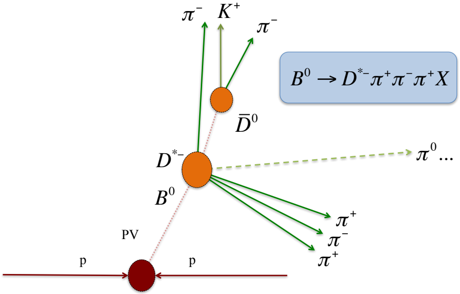
- 2.1σ above SM expectation
- Systematic uncert dominated by simulation sample size



Three-prong $R(D^{*-})$ PRL 120, 171802 (2018)

- Uses nonresonant $B^0 \to D^{*-}3\pi$ as normalisation channel:
  $$R(D^{*-}) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)} \times \frac{\mathcal{B}(B^0 \to D^{*-}3\pi)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$
- Benefits from good τ^- vertex, and no background from μ^- mode
- Main source of background is $B \to D^{*-}3\pi X$. Suppressed by B^0-τ^- vertex separation in beam axis:



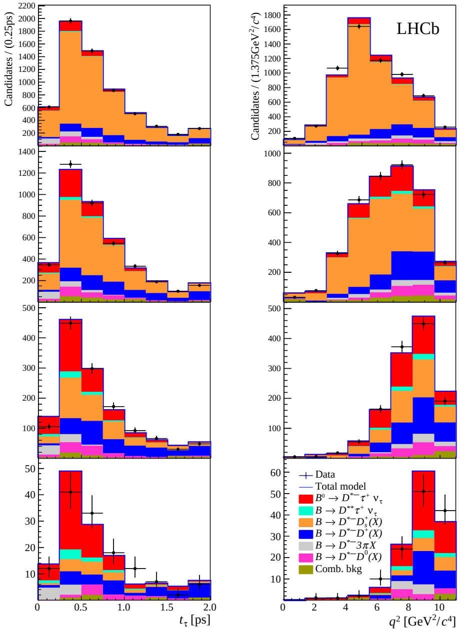


Three-prong $R(D^{*-})$ PRL 120, 171802 (2018)

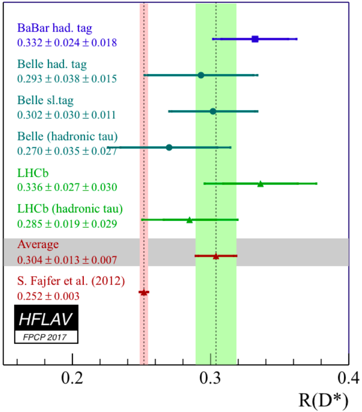
- 3D fit to bins of BDT output, τ^- decay time and q^2
- Templates determined from simulation and control channels
- Signal yield: 1300 ± 85

$\mathcal{R}(D^*) =$
$0.291 \pm 0.019(stat) \pm 0.026(syst) \pm 0.013(ext)$
LHCb, 3fb^{-1}

- Compatible with SM expectation at 1σ
- Systematic uncertainty dominated by simulation sample size



b $\rightarrow c\ell\nu$ summary

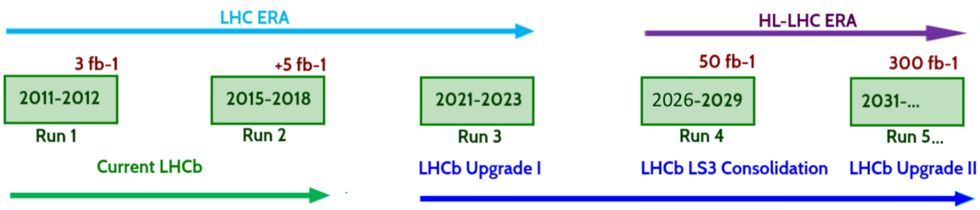


- There is a consistent tension between predictions and experimental results for $R(D^{*-})$
- LHCb results are compatible with the B factories, pattern seems to emerge
- Not shown in this talk: $R(J/\psi)$ also shows some tension at the 2σ level in the muon channel.

Prospects with current dataset

- $b \to s\ell\ell$:
  - $R(K), R(K^*)$ updates using partial Run 2 dataset underway, expect $\sim 3\times$ more $B^+ \to K^+e^-e^+$ candidates
  - Potential to include additional high q^2 bins, but challenging to fit this region:
    - Pollution from below: rare decays with higher K,K^* resonances
    - Pollution from above: $\psi(2S)$ K
  - Several additional modes under study: $R(K\pi\pi), R(pK), R(\phi)$
- For $b \to c\ell\nu$:
  - Strong potential for improved sensitivity at LHCb using Run 2 dataset: $3\times$ the signal yields
  - systematic uncertainties will decrease
  - $R(J/\psi)$ three prong analysis is also underway.

Future prospects



- Looking beyond Run 2:
  - 2019-2021: LHCb will undergo a major upgrade
  - From 2021: 5 $\times$ the instantaneous luminosity and a completely new readout/trigger
  - Aim to collect 50fb^{-1} in 2021-2029
  - A second major upgrade for the HL-LHC era to collect 300fb^{-1}
- With 50fb^{-1} LHCb will reach precisions of LHCb-PUB-2014-040:
  - $\sigma(\gamma) = 1^\circ$
  - $\sigma(\phi_s^{c\bar{c}s}) = 0.009$rad, $\sigma(\phi_s^{s\bar{s}s}) = 0.02$rad
- $b \to s\ell\ell$ analyses will need to control electron systematic uncertainties to benefit from upgrade
  - Uncertainty from background models (data driven) will scale

Conclusions

- LHCb has made many interesting measurements in heavy flavour with the Run 1 dataset
- Run 2 analyses already starting to appear
- LHCb currently dominates world averages in several beauty $\mathcal{CP}$ measurements
  - Looking forward to stiff competition from Belle II
- Some intriguing discrepancies in ratios of B decays to leptons
  - Results with more data will help clarify the situation