LHCb Upgrade II challenges

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Drawing heavily on (& with many thanks to everyone who contributed to)

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Figure 2.1: Luminosity projections for the original LHCb, Upgrade I, and Upgrade II experiments as a function of time. The red points and the left scale indicate the anticipated instantaneous luminosity during each period, with the blue line and right scale indicating the integrated luminosity accumulated.

Figure 2.2: Schematic side-view of the Upgrade II detector.

The data sample collected by the end of the HL-LHC period will be more than a factor thirteen higher than that collected in the pre-HL-LHC period, and at least a factor six higher than that at the end of Run 4. This will lead to remarkable improvements in precision in the LHCb upgrade II plans and timescales.
1. Key observables which can tell us something about the scale of New Physics won’t be theory limited

2. Current LHCb measurements do not generally indicate any fundamental experimental systematics either

3. Unique combination of large integrated luminosity, large cross-section, and relatively short timescale.
For one thing, an overabundance of signal. I discussed this at length at the previous TUPIFP & will only touch on here.
So what’s so challenging about LHCb upgrade II?

Also, processing complexity goes quadratically with lumi, so must suppress pileup “for free” (timing?) to have a chance
So what’s so challenging about LHCb upgrade II?

And there’s the simulation paradox: more precision needs more simulation but this simulation must get “faster”…
And of course, keeping the measurements systematics free will itself be highly challenging!
LHCb Upgrade II

- CKM metrology
- Rare beauty processes
- Charm & Kaon physics
- (Exotic) Spectroscopy
- Semileptonic processes
Overconstrain the CKM triangle at <1% level
## Objective of CKM metrology with LHCb Upgrade II

LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. See subsequent Table 1:

### Summary of prospects for future measurements of selected flavour observables for LHCb. The projected CKM tests

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current LHCb</th>
<th>LHCb 2025</th>
<th>Upgrade II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CKM tests</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma$, with $B_s^0 \to D_s^+ K^-$</td>
<td>$(+17)\degree$ [7]</td>
<td>$4\degree$</td>
<td>$1\degree$</td>
</tr>
<tr>
<td>$\gamma$, all modes</td>
<td>$(+5.0)\degree$ [8]</td>
<td>$1.5\degree$</td>
<td>$0.35\degree$</td>
</tr>
<tr>
<td>$\sin 2\beta$, with $B^0 \to J/\psi K_s^0$</td>
<td>0.04 [9]</td>
<td>0.011</td>
<td>0.003</td>
</tr>
<tr>
<td>$\phi_s$, with $B_s^0 \to J/\psi \phi$</td>
<td>49 mrad [10]</td>
<td>14 mrad</td>
<td>4 mrad</td>
</tr>
<tr>
<td>$\phi_s$, with $B_s^0 \to D_s^+ D_s^-$</td>
<td>170 mrad [11]</td>
<td>35 mrad</td>
<td>9 mrad</td>
</tr>
<tr>
<td>$\phi_s^{ss}$, with $B_s^0 \to \phi \phi$</td>
<td>154 mrad [12]</td>
<td>39 mrad</td>
<td>11 mrad</td>
</tr>
<tr>
<td>$a_s^\ell$</td>
<td>$33 \times 10^{-4}$ [13]</td>
<td>$10 \times 10^{-4}$</td>
<td>$3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
</tr>
</tbody>
</table>

Overconstrain the CKM triangle at $<1\%$ level
CKM angle $\gamma$ in Upgrade II

Fig. 11: Comparison between the current LHCb 3-body GGSZ and 2-body GLW/ADS measurements alongside their future projections with 300 fb$^{-1}$ in the plane of $r_{DK}^B$ vs. $\gamma$. The scan is produced using a pseudo-experiment, centred at $\gamma = 70^\circ$, $r_{DK}^B = 0$, with $B \rightarrow DK^\pm$ decays only. Which is expected to reach $1.5$ with a data sample of $50 \text{ ab}$. This is comparable to the sensitivity that the LHCb combination will achieve with a data sample corresponding to approximately $23 \text{ fb}^{-1}$. Subsequently input from Belle II will still contribute towards the world average by the end of Run 4 but LHCb will dominate measurements with Upgrade II ($300 \text{ fb}^{-1}$) contributing entirely towards a world average precision of $\sim 0.35$. It should be emphasised that this projection includes only the currently used strategies, and does not include improvements from other approaches. A comparison between the projected uncertainties for LHCb and the world average as a function of integrated luminosity is shown in Fig. 10.

2.5.6 Determinations of $m_s$, $m_d$, and interplay with $b$-hadron lifetimes

The world-leading measurements of both $m_d$ and $m_s$ are from LHCb [116, 117], and can be improved further assuming that good flavour tagging performance can be maintained. This will not only reduce systematic uncertainties in $CP$-violation measurements but also provide a strong constraint on the length of one side of the unitarity triangle, although progress here is mainly dependent on improvements in lattice QCD calculations. The decay-time-dependent angular analysis of $B_0 \rightarrow J/\psi K_S$ allows measurement of $\delta$ simultaneously with $CP$-violation parameters. Therefore, improved knowledge of $\delta$ will be obtained together with measurements of $c\bar{s}$. Precision at the LHC is expected not to be systematically limited. The LHCb Upgrade II will allow to exploit measurements in various channels. ATLAS and CMS projections in the $B_s \rightarrow J/\psi K_S$ decay mode can be found in 2.5.8.1. For theory predictions of $\delta$ see Ref. [118].

Width differences between different types of $b$-hadrons, such as $s$, $d$, are also of interest. They test the heavy-quark expansion, used to make theoretical predictions. In addition, their precise knowledge is important to control systematic uncertainties in measurements where a decay mode of one type of $b$-hadron is used as a control channel in studies of a decay of another. Detailed understanding of acceptances is necessary for such measurements, which can be achieved using topologically similar final states (see, e.g., Ref. [119]). These measurements are therefore expected to be significantly improved with LHCb Upgrade II.

2.5.7 Semileptonic asymmetries and prospects for $D_s$/$D_s$

Semileptonic decays, being flavour specific, provide a unique probe of $B_0 q$, where $q = s, d$, meson mixing phenomena. In particular, $CP$-violation in $B_0 q$ meson mixing can be expressed through the semileptonic...
phenomena. In particular, semileptonic decays, being flavour specific, provide a unique probe of CP violation in B mesons. ATLAS and CMS projections in the type of studies show small, but clean signals. As long as the fully and partially reconstructed data sets are kept systematically limited. The LHCb Upgrade II will allow to exploit measurements in various channels of the Dalitz space.

They test the heavy-quark expansion, used to make theoretical predictions. In addition, their precise measurements in lattice QCD calculations. The decay-time-dependent angular analysis of B decays has recently been proposed for feed down and large asymmetries in the ADS/GLW-like region of the Dalitz space. The most developed multi-mode analysis is that of B_s mesons, where the CP asymmetry is found in an ADS/GLW-like body. However, these are tractable problems, and studies have already been done to understand them. However these are tractable problems, and studies have already been done to understand them.

Analogously to the neutral modes, a variety of high-multiplicity modes can be exploited [44] contributing entirely towards a world body. In particular, the charged mode B^+ \to DK^+ provides a unique probe of CP violation in B mesons. ATLAS and CMS projections in the type of studies show small, but clean signals. As long as the fully and partially reconstructed data sets are kept systematically limited. The LHCb Upgrade II will allow to exploit measurements in various channels of the Dalitz space.

External inputs will be crucial for ultimate GGSZ precision. It should be emphasised that this projection includes only the currently available data and does not take into account potential future improvements to the LHCb detector. However, these are tractable problems, and studies have already been done to understand them.
1. For $D_sK$, $\Gamma_s$ and $\Delta\Gamma_s$ must also remain systematics free to not limit the hyperbolic observables. Will require exceptional understanding of the vertex detector and momentum scale calibration. The prize is a single-mode $1^\circ$ measurement of $\gamma$!

2. A more granular calorimeter with precise timing may allow LHCb to go even beyond $0.35^\circ$ precision by allowing full exploitation of modes with neutrals.

3. Similarly important to maintain low-$p_T$ tracking in a high pileup environment, to fully exploit multi-body final states.
Flavour tagging in Upgrade II

Huge challenge, timing to associate tracks to pp collisions & low-momentum PID crucial to maintain current performance

Figure 3.1: Effective tagging efficiency of (left) different HEP experiments and (right) LHCb flavour tagging algorithms [40]. The white lines indicate contours of constant tagging power.

Figure 3.2: Effective tagging efficiency of OS and SS kaon taggers, and their combination, (left) in bins of pile-up vertices and (right) in bins of track multiplicity. These results are obtained from Upgrade I simulation of $B_0 \to D_s^{(*)} \pi$ decays. The OS performances correspond to those obtained from combination of the individual OS taggers.

If 50–100 ps time resolution can be obtained in the VELO, the PV misassociation rate can be kept down to $\sim 5\%$, and comparable FT performance to that achieved with the current detector can be expected. Further improvement in FT performance may be achieved by using more sophisticated multivariate techniques, from better understanding of the hadronisation processes, and from additional information from new instrumentation in the Upgrade II detector.

In particular, particle identification for low momentum tracks from the TORCH detector, and additional acceptance for tracks through magnet side stations should both help. Therefore, it is assumed in the remainder of this section that the FT performance from existing LHCb results can be maintained for Upgrade II, although detailed simulation studies will be necessary for a precise quantification.

3.3 Measurements of $s$ and $d$ in theoretically clean modes

3.3.1 $s$ from $B_0 \to J/\psi \phi$ and related modes

Measurements of decay-time-dependent CP asymmetries in the $B_0$ system using $b \to c \bar{s}$ transitions are sensitive to the CKM phase $s\phi$. If penguin loop transitions are small, the CP asymmetry is given by:

$$\frac{\text{CP asymmetry}}{\text{Expected CP asymmetry}} = \frac{V_{ts}^* V_{tb}}{V_{cs}^* V_{cb}}.$$
Ideas for low-momentum PID

TORCH: a massive quartz-based time-of-flight detector for low-momentum PID in LHCb. Many thanks to TORCH team for the performance plots!
Have to balance timing, granularity, and radiation hardness in the vertex detector. Can timing in tracker/PID help?
Granularity and resolution important but timing is key to reduce backgrounds. Low momentum tracking also crucial for e-\(\gamma\) separation but very time consuming, big challenge!
Mass and width differences in Upgrade II

1. No inherent reason why $\Delta m_s$ and $\Delta m_d$ should be systematics limited, but will require precise control of detector length and momentum scales and tagging performance.

2. $\Delta \Gamma_s$ should continue to scale but LHCb Upgrade II has a chance to see evidence for a non-zero $\Delta \Gamma_d$! Control of detector acceptances between the $J/\psi K^{*0}$ and $J/\psi K_S$ topologies will be critical for this to succeed.

$\Delta \Gamma_d/\Gamma_d$ theory $\sim 0.004$; Upgrade II sensitivity $\sim 0.001$
Visually resolve both the $B_d$ and $B_s$ time-dependent CPV!

**$\phi_s$ and $\text{Sin}2\beta$ in Upgrade II**

*Figure 3.3 (right):* The data points are obtained from simulation with the expected sample size at 300 fb$^{-1}$.

*Figure 3.4:* Here, $\left(\frac{N_{B_s}^0 - N_{B_s}^s}{N_{B_s}^0 + N_{B_s}^s}\right)$ is the number of (left) $s$ decays from a simulated data set corresponding or (right) $s$ decays with $\Delta m_s < 0.3 \text{ mrad}$ predicted in the mixture of $B^0$ and $B^0$ or $B^0$ and $B^0$. The values used in the simulation.

*Signal yield asymmetry:* The expected precision on $\phi_s$ and $\text{Sin}2\beta$ can be measured to be significantly non-zero in several channels. The data points are obtained from simulation with the expected sample size at 300 fb$^{-1}$.

Systematic uncertainties are mainly based on the sizes of control samples, and are therefore expected to remain subdominant.
Among other channels, competitive precision can be obtained with 
which have been found to be dominated by the 
The LHCb detector has excellent time resolution ( 
information can be obtained from 
the Run 1 analysis [44], but this strategy will become the default in 
mimic the signature of beyond-the-SM physics (see Sect. 3.3.3).

$\Delta f_{\text{CP}}$ angular momentum between the two vector resonances. In addition, there is a small (interfering 
background ratio of about 50 in the signal region of 
used in LHCb to suppress backgrounds e 
to a high trigger e 
has a relatively high branching fraction and the presence of two muons in the final state leads 

Having multiple independent precision measurements is important since it allows not simply 

The current result has statistical and systematic uncertainties of comparable size, but both 

Penguin pollution control vital for interpretation, but wide 
range of channels accessible @ Upgrade II greatly helps!
Mixing related constraints on NP

Belle II and LHCb Upgrade II combination powerfully constrains the available parameter space for NP in FCNCs.
LHCb Upgrade II

CKM metrology

Charm & Kaon physics

Rare beauty processes

(Exotic) Spectroscopy

Semileptonic processes
Unique selling point is access to all b-hadron species, with complementary experimental and theoretical systematics.

Standalone measurements of $|V_{ub}|$ and $|V_{cb}|$ possible with decays such as $B_c \rightarrow D \mu \nu$ and $B^\pm \rightarrow \mu \mu \mu \nu$ becoming statistically accessible in Upgrade II.

$|V_{ub}|/|V_{cb}| < 1\%$ reducing material budget is important for both the statistical sensitivity and systematics control!
Other benefits of removing RF foil

Performance at low-$\eta$ (which are the most costly tracks to reconstruct!) is particularly improved.
Control K-π detection asymmetries using a combination of high stats MC and tag-and-probe at the 10^{-4} level
Unique selling point is again the access to all b-hadron species, with complementary experimental and theoretical systematics

With Upgrade II measurements from $B_c \to J/\psi \tau$ will reach the precision regime

**RD* and other lepton-(non)-universal friends**

Fast & accurate simulations critical for ultimate precision
Many different approaches to fast simulation on the market

ReDecay: simulate many signal decays reusing the underlying event

Simulate only parts of the detector, most commonly tracker

Use GANs and other ML/AI methods to “learn” particularly costly steps like the calorimeter simulation…

In general these approaches gain speed compared to the “full” simulation by assuming that some part of the analysis can be factorized, i.e. some correlations can be ignored. Unclear to me how well this will interplay with increasing use of ML methods for signal discrimination, which draw their power precisely from correlations.

Often hear argument that “data doesn’t look like MC anyway” but as we learned to our cost with the 13 TeV beauty cross-section paper, smaller disagreements lead to smaller systematics. Standard candles & data control modes will be more important than ever.
New observables in RD* with Upgrade II

Angular observables are resolvable, but Upgrade II statistics needed for precision because of limited resolution
Charm & Kaon physics

CKM metrology

Rare processes

Semileptonic processes

(Exotic) Spectroscopy

LHCb Upgrade II
A truly unique reach for all kinds of exotic hadron species. The main challenge here will be fully processing the data!

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>LHCb</th>
<th>Belle II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow X(3872)(\rightarrow J/\psi \pi^+\pi^-)K^+$</td>
<td>14k</td>
<td>30k</td>
</tr>
<tr>
<td>$B^+ \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^+$</td>
<td>500</td>
<td>1k</td>
</tr>
<tr>
<td>$B^0 \rightarrow \psi(2S)K^-\pi^+$</td>
<td>340k</td>
<td>700k</td>
</tr>
<tr>
<td>$B^- \rightarrow D_+^+D^0\bar{D}^0$</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow J/\psi pK^- $</td>
<td>340k</td>
<td>700k</td>
</tr>
<tr>
<td>$\Xi_b^- \rightarrow J/\psi \Lambda K^- $</td>
<td>4k</td>
<td>10k</td>
</tr>
<tr>
<td>$\Xi_{bc}^{++} \rightarrow \Lambda_c^+ K^-\pi^+\pi^+$</td>
<td>7k</td>
<td>15k</td>
</tr>
<tr>
<td>$\Xi_{bc}^+ \rightarrow J/\psi \Xi_c^+$</td>
<td>50</td>
<td>100</td>
</tr>
</tbody>
</table>

 Upgrade II will be an exotica factory!
Improvements to the LHCb calorimeter will be critical for accessing the full range of final states and decay modes.
PID is equally critical for spectroscopy, both for ruling out structures caused by reflections and for improving S/B for amplitude analyses. Timing information will be mandatory to achieve an acceptable timing performance with Upgrade II.
LHCb Upgrade II

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- Rare beauty processes
- Charm & Kaon physics
- (Exotic) Spectroscopy
- Semileptonic processes
an analysis of lepton specific measurements and corresponding global fits; and Wilson coefficients have to be determined; smoking guns that allow one to establish a possible deviation from the SM. At the same time, global fits to the LHCb measurements of $B(B_s^0 \rightarrow \mu^+ \mu^-)$, depending on the theoretical assumptions. 

Extrapolations of global fits to the LHC data after the HL phase, in the $B(B_s^0 \rightarrow \mu^+ \mu^-)$ channel, can be included, where for LFUV NP a simultaneous amplitude analysis can be performed the first measurement of the $\mu\mu$-decay to $t\bar{t}$. The observables included are the branching fraction $B(B_s^0 \rightarrow \mu^+ \mu^-)$, as discussed in Ref. [10].

The signal lifetime distribution for each pseudo-experiment is obtained using the sPlot technique [820]. In the SM, it can take any value between $0-5\,\mu\mu$ transitions, then $B(B_s^0 \rightarrow \mu^+ \mu^-)$ is more powerful than separate analyses [120].

For the LHCb dataset, on the other hand, is too low to allow a meaningful constraint to be set on $B(B_s^0 \rightarrow \mu^+ \mu^-)$; this is due to the fact that there is no experimental correlation between any possible contribution from new scalar and pseudoscalar mediators. A NP shift is expected to decrease to approximately $10^{-3}$, if combined, are already in tension with the SM and lepton-flavor violation anomalies, but they allow one to simultaneously determine $C_{9,10}$ and $C_{R,1}$. Singling out $C_{9}$, if combined, is expected to be characterized by a not well understood hadronic effect. Second, changes in neutral currents, as discussed in Ref. [9].

The outcome of such a pseudo-experiment is obtained using the sPlot technique [820], which convolves with a Gaussian function that describes the expected decay time resolution, and multiplies by an efficiency function that accounts for reconstruction effects. The software package [820] might still hide in observables that are optimized for $B(B_s^0 \rightarrow \mu^+ \mu^-)$, or by a not well understood hadronic effect. Second, changing neutral currents, as discussed in Ref. [9].

The observables included are the branching fraction $B(B_s^0 \rightarrow \mu^+ \mu^-)$, as discussed in Ref. [10].

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Even $\text{b} \rightarrow \text{d} \mathcal{U}$ transitions will be abundant with Upgrade II.
1. No reason to expect limiting systematics. In particular for e.g. P5’ notice that LHCb’s Upgrade II yields for $K^*\mu\mu$ will be similar to today’s yields for $J/\psi K^*$ and $J/\psi \phi$. And we have already demonstrated we can control those.

2. Reducing the vertex detector and tracker material budget will benefit electron modes by decreasing brems.

3. As with semileptonics, the challenge will be to fully exploit LHCb’s reach across the full range of b-hadron species and decay modes. A timing calorimeter is again crucial here.

4. Many of the most interesting lepton flavour violating modes for Upgrade II involve $\tau$ leptons, and all the improvements which will benefit semileptonic decays will also improve the reach for these.
LHCb Upgrade II

- Charm & Kaon physics
- CKM metrology
- Rare beauty processes
- (Exotic) Spectroscopy
- Semileptonic processes
The biggest collider charm factory ever

Upgrade II will “see” $10^{15}$ charm hadrons
The challenge is the data

Particularly to maintain full breadth of current programme, i.e. not only $D^0$ but charged CPV, baryons, spectroscopy...
We lose ~40% of charm because tracks too soft — can magnet side stations gain it back and make it usable?
1. As with many other areas, full exploitation of the charm physics programme would benefit from a timing calorimeter. But the neutrals from charm are particularly soft...

2. Requirements for timing, granularity, and energy resolution are to some extent contradictory. A lot of work to balance these in the coming years.
And what about Kaons?

Excellent prospects in both rare decays and LFV
1. Having low momentum tracking in the first stages of the trigger will be very hard indeed. This is not a “technological” challenge but a resource challenge, because those tracks always cost much more to reconstruct.

2. If you had a dream of a fully timing tracker and calorimeter, could probably associate tracks to a PV even without a VELO component and gain factors in reach for Kaon physics.
Conclusion — opportunities

The Upgrade II reach makes it a dream worth chasing
Conclusion — challenges

LHCb 2032

>1000
Eb/year

ATLAS+CMS 2027

260 Eb/year

Square Kilometre Array (2030s)

~30000 Eb/year

Sequence genome of all humans on Earth

8000 Eb

Global internet dataflow 2021

2800 Eb/year

But a detector to handle these data rates won’t be easy...
BACKUP