LHCb Status Report

Blake D. Leverington,
on behalf of the LHCb Collaboration

138th LHCC Open Session, CERN
June 5th, 2019
Outline

Upgrade and Operations

Physics Analysis and Publications
Disassembly & Installation at LHCb

- Velo, RICH 1, TT, IT, OT, M1, Calorimeter Lead, PS/SPD are out
  - all obsolete services are removed
- dismantling is well on schedule, and done safely
- installation of upgrade services:
  - Modules 1-4 of 6 for Event Filter farm in place
  - Long distance fibres being installed with very good progress
  - Installation of new cooling plants advancing well
  - First new copper cables in place
  - Sub-systems will start to enter the experimental cavern in June

- Watch our weekly videos!
  https://www.youtube.com/watch?v=CKLu1xewv7I
LHCb Upgrade

- 50 fb⁻¹, $2 \times 10^{33}$ cm⁻² s⁻¹
- All front-end electronics read out at 40 MHz
- 30 MHz avg. input to a full software trigger

New PIXEL vertex detector (VELO)

New silicon upstream tracker (UT)

New RICH1 optics and photodetectors

New scintillating fibre tracker (SciFi)

New RICH2 photodetectors

New electronics for muon and calorimeter systems

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VELO

- New hybrid pixel detector for LHCb! Evaporative CO$_2$ cooling in silicon microchannels.
- Project progressing very well, although the schedule is tight given the complexity.
- VeloPix ASIC bump bonding to silicon pixel sensors is complete.
- Module construction:
  - Several pre-production modules available;
  - Production site readiness review next week.
- RF boxes:
  - First installation pair complete; machined to 250 um thin, leak tight.
  - Second pair almost complete (in final weeks of machining).
- High speed copper links 50% manufactured.
- Other components (vacuum feedthrough boards, electronics...) on schedule.
- Large scale mechanics (base, hood, isolation vacuum volumes, piping and valve assembly) progressing well. First half currently being prepared.
• Dismantling of RICH 1 complete, HPD removal from RICH 2 to begin soon
• Upgrade RICH 1 installation about to begin, mechanics under way
• Spherical mirrors almost completed, flat mirror tender completed
• MA-PMT columns for RICH 1 & 2: 22+24 = 46 columns (+spares)
  • all 3500 MaPMTs tested, CLARO asic: all received (100k) 100% pass rate
  • Digital readout board (PDMDB): production of PCBs completed, first complete boards being received
  • received most BaseBoard, FEBs and BackBoard batches, all undergoing QA
• Commissioning Lab (ComLab@CERN) ready to integrate columns
• SALT v3asic received and tested, v3.5 sent for prod.
  • Issues seen in the previous version largely fixed
  • Test beam at Fermilab in March. Good results.

• Slice test setup in progress at Point 8
  • Instrumented stave with realistic power, cooling and proto mechanics.

• Now to finalize the hybrid and start production
  • Hybrid production June 2019, QA and tools ready

• Sensors:
  • Received all A-type, pre-series of B,C,D, prod. in Oct. 2019.

• Readout electronics: production started
  • Flex cables pre-series available, under test

• Bare staves: production finished

• Integration infrastructure at progressing full speed
SciFi Tracker

• Excellent progress! First scintillating fibre detector for LHCb.
• C-Frame 1 (of 12) nearly complete
  • already equipped with modules. Electronics in Wk 25
• All 5500 SiPM arrays delivered and tested
• Electronics:
  • 40% of PACIFIC boards prod. and tested (100% of ASICS)
  • 60% of Cluster boards prod. and tested
  • Master Boards
    • 50 boards in pre-series delivered and tested
    • 500 boards to be delivered in batches soon
• SiPM Cold-box to Fibre Module assembly on schedule
  • All QA test results look good
• Readout and control of the prototype C-Frame (4 ROB) with PCIe40/WinCC (LHCb Upgrade read-out)
• Schedule is tight but experience will help us optimize the commissioning.
Calorimeter and Muon

- To be produced: electronics boards + shielding plugs
  - All electronics in production and testing
    - MUON: nSYNCs (prod. & tested), nODE (pre-prod.): 40MHz readout, each nODE equipped with 4 nSYNCs. nSB, nPDM (pre-prod.): system configuration and pulsing, nBP (pre-prod.): custom Back Plane for nPDM/nSB crates
  - Full production finished in November
- New shielding plug, (3 parts, design finalized)
  - order placed last December, parts expected in the coming month
- Upgrade activities are proceeding well

Details of the new Muon shielding plugs

278  CALO FEB needed
+21 Control Boards
+144 HV/Calib/Moni

Muon nODE
148 needed
+8 nPDM

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Online

- Containers for Event Filter Farm and Event Builder:
  - First 4 modules installed, 2 more in Nov. 2019
  - 40% of the long-dist. optical fibres from detector to the EFF installed

- Event Builder:
  - simulation of traffic is now working for 500 nodes and gives confidence in scalability of system.
  - Review of Upgrade Event Builder on June 6

- Vertical Slice Test will allow checking simulation results at a scale of 20% of the final system.

- PCIe40 (LHCb readout) production in full swing.
  - First production batch of ~40 just delivered

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Real-time Analysis

- Quality reconstruction in the final trigger stage (HLT2), it is no longer necessary to run another reconstruction offline
  - LHCb-TDR-018
  - *JINST* 14 (2019) P04006

- Turbo model = exclusive selections, no additional objects

- Complete persistence = Turbo model for inclusive triggers,

- Selective persistence
  - explicit specification.
  - Event size reduction without sacrificing information needed offline
  - key for the migration to RTA model for Run3

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Run2: JINST 14 P04013
Real-time Analysis

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- Complete persistence = Turbo model for inclusive triggers,
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Run 3
(5x inst. lumi.)

Run2: JINST 14 P04013

Persistence method | Average event size (kB)
--- | ---
Turbo | few
Selective persistence | tens
Complete persistence | 200–250
Raw event | 200–250

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Simulation

- Increasing use of fast MC techniques
  - only the few participating particles in the signal decay under study are of interest
  - Re-decay the signal N times but reuse the rest of the event from previously simulated events = an order of magnitude increase in speed
- Be careful: the resulting events are not statistically independent anymore
• LHCb has a unique fixed target physics programme at LHC [LHCb-PUB-2018-015]
  • Heavy ions
  • Cosmic ray physics
  • Useful for early measurements such as p/He cross-section

• New SMOG will increase by up to two orders of magnitude the effective target areal density [CERN-LHCC-2019-005 ; LHCB-TDR-020]

• significant increase of the luminosity for fixed-target collisions.

• Multiple gas capabilities being studied
  • Impact on accelerator

Technical drawing of the gas storage cell to be installed inside the VELO
The case for the upgrade was very well received at the ESPP meeting in Granada.

Physics Case:
- Collect 250 fb\(^{-1}\) more \((2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1})\)
- Order of magnitude increase in precision over current results
- Rare Decays, CP violation, Heavy Ions

Detector Ideas Summary:
- Timing needed in the VELO, and PID (TORCH)
- More granular rad-hard calorimeter with timing
- Chimera tracking detector from silicon/DMAPS (inner) and scifi (outer) aka the Mighty Tracker
- Non-cpu options for tracking
Physics Analyses and Publications

(since the last LHCC)
Publications

- 482 total publications
- 25 papers submitted to journals in 2019
  - 16 since last LHCC
- 9 being processed in the Editorial Board
- About 20 more in preparation
<table>
<thead>
<tr>
<th>Paper ID</th>
<th>Title</th>
</tr>
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<tbody>
<tr>
<td>PAPER-2019-004</td>
<td>Amplitude analysis of the $B_{s}^{0} \rightarrow K^{*0} \bar{K}^{*0}$ decay and measurement of its branching fraction relative to the $B_{s}^{0} \rightarrow K^{+0} \bar{K}^{*0}$ decay</td>
</tr>
<tr>
<td>PAPER-2019-016</td>
<td>Search for the lepton-flavour-violating decays $B_{s}^{0} \rightarrow \tau^{\pm} \mu^{\mp}$ and $B^{0} \rightarrow \tau^{\pm} \mu^{\mp}$</td>
</tr>
<tr>
<td>PAPER-2019-015</td>
<td>Measurement of the mixing-induced and $CP$-violating observables of $B_{s}^{0} \rightarrow \phi \gamma$ decays</td>
</tr>
<tr>
<td>PAPER-2019-011</td>
<td>A search for $S_{cc}^{+} \rightarrow D^{+}pK^{-}\pi^{+}$ decays</td>
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<tr>
<td>PAPER-2019-012</td>
<td>Measurement of charged hadron production in $Z$-tagged jets in proton-proton collisions at $\sqrt{s} = 8$ TeV</td>
</tr>
<tr>
<td>PAPER-2019-010</td>
<td>First observation of the radiative decay $\Lambda_{b}^{0} \rightarrow \Lambda \gamma$</td>
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<tr>
<td>PAPER-2019-014</td>
<td>Observation of a narrow pentaquark state, $P_{c}^{+}(4312)$, and of two-peak structure of the $P_{c}^{+}(4450)$</td>
</tr>
<tr>
<td>PAPER-2019-007</td>
<td>Observation of an excited $B_{s}^{0}$ state</td>
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<td>PAPER-2019-009</td>
<td>Search for lepton-universality violation in $B^{+} \rightarrow K^{+}\ell^{+}\ell^{-}$ decays</td>
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<td>PAPER-2019-006</td>
<td>Observation of $CP$-violation in charm decays</td>
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<tr>
<td>PAPER-2019-005</td>
<td>Near-threshold $D\bar{D}$ spectroscopy and observation of a new charmonium state</td>
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<tr>
<td>PAPER-2018-044</td>
<td>Measurements of $CP$ asymmetries in charmless four-body $\Lambda_{b}^{0}$ and $\Xi_{b}^{0}$ decays</td>
</tr>
<tr>
<td>PAPER-2019-003</td>
<td>Measurement of the $CP$-violating phase $\phi_{s}$ from $B_{s}^{0} \rightarrow J/\psi \pi^{+}\pi^{-}$ decays in $13$ TeV pp collisions</td>
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<tr>
<td>PAPER-2019-001</td>
<td>Measurement of the mass difference between neutral charm-meson eigenstates</td>
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<tr>
<td>PAPER-2019-002</td>
<td>Search for $CP$ violation in $D_{s}^{+} \rightarrow K_{s}^{0}\pi^{+}, D_{s}^{+} \rightarrow K_{s}^{0}\pi^{+}$ and $D_{s}^{+} \rightarrow \phi \pi^{+}$ decays</td>
</tr>
<tr>
<td>PAPER-2018-051</td>
<td>Amplitude analysis of $B^{\pm} \rightarrow \pi^{\pm}K^{+}K^{-}$ decays</td>
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Preliminary

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<tr>
<td>PAPER-2019-013</td>
<td>Updated measurement of time-dependent $CP$-violating observables in $B_{s}^{0} \rightarrow J/\psi K^{+}K^{-}$ decays</td>
</tr>
<tr>
<td>PAPER-2019-020</td>
<td>Observation of the of the fragmentation-fraction ratio $f_{s}/f_{u}$ variation with $B$-meson kinematics</td>
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<tr>
<td>PAPER-2019-021</td>
<td>Measurement of $CP$ observables in the process $B^{0} \rightarrow DK^{*0}$ with two- and four-body $D$ decays</td>
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<td>PAPER-2019-019</td>
<td>Measurement of $CP$-violation in the $B_{s}^{0} \rightarrow \phi \phi$ decay and search for the $B^{0} \rightarrow \phi \phi$ decay</td>
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<tr>
<td>PAPER-2019-008</td>
<td>Precision measurement of the $\Lambda_{c}^{+}, \Xi_{c}^{0}$, and $\Xi_{c}^{+}$ baryon lifetimes</td>
</tr>
<tr>
<td>PAPER-2019-017</td>
<td>Amplitude analysis of the $B^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ decay</td>
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<td>PAPER-2019-018</td>
<td>Observation of several sources of $CP$-violation in $B^{+} \rightarrow \pi^{+}\pi^{+}\pi^{-}$ decays</td>
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<td>PAPER-2019-022</td>
<td>Search for the lepton-flavour violating decays $B^{+} \rightarrow K^{+}\mu^{\pm}\ell^{\mp}$</td>
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<td>CONF-2019-001</td>
<td>Search for time-dependent $CP$ violation in $D^{0} \rightarrow K^{+}K^{-}$ and $D^{0} \rightarrow \pi^{+}\pi^{-}$ decays</td>
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</table>
Lepton flavour violating decay $B^0_{(s)} \rightarrow \tau^\pm \mu^\mp$

- Search for lepton-flavour violating decays $B^0_{(s)} \rightarrow \tau^\pm \mu^\mp$
- BR in SM very small: $\sim 10^{-54}$
- Can be strongly enhanced in NP models: up to $O(10^{-9} - 10^{-5})$
- Look for three prong $\tau$ decays

<table>
<thead>
<tr>
<th>Mode</th>
<th>Limit</th>
<th>90% CL</th>
<th>95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_{(s)} \rightarrow \tau^\pm \mu^\mp$</td>
<td>Observed</td>
<td>$3.4 \times 10^{-5}$</td>
<td>$4.2 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>Expected</td>
<td>$3.9 \times 10^{-5}$</td>
<td>$4.7 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \tau^\pm \mu^\mp$</td>
<td>Observed</td>
<td>$1.2 \times 10^{-5}$</td>
<td>$1.4 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>Expected</td>
<td>$1.6 \times 10^{-5}$</td>
<td>$1.9 \times 10^{-5}$</td>
</tr>
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</table>

First limits
World Best limits (Factor of 2)
Lepton universality

\[ R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} \left/ \frac{\mathcal{B}(B^+ \to K^+J/\psi(\mu\mu))}{\mathcal{B}(B^+ \to K^+J/\psi(ee))} \right. \]

= 1 (cancels e/µ efficiency differences )
1.014 ± 0.035 (stat. + syst.)

- consistent with the SM expectation at the level of 2.5 \( \sigma \)
- the most precise measurement to date
  - Using integrated luminosity of 5 fb\(^{-1}\)
  - Still 4 fb\(^{-1}\) in 2017+2018 to analyse
  - Will benefit from the Upgrade data
  - Other observables to investigate still (higher \( q^2 \), other \( B \to s\ell\ell \), etc.)

Global fit to 2011 - 2016 data

\[ R_K = 0.846 \pm 0.016^+ \pm 0.016^- \]
Observation of new pentaquarks

- A narrow peak from $\Lambda_b^0 \to J/\psi pK^-$ decays is observed near 4312 MeV with a width comparable to the mass resolution
  - Analysis uses full Run 1 and 2 data
  - Statistical significance of 7.3$\sigma$
- The structure at 4450 MeV is now resolved into two narrow peaks, at 4440 and 4457 MeV
  - Statistical significance of this two-peak interpretation is 5.4$\sigma$
- Indication of a bound state
- Full amplitude analysis required to better determine the nature of the states

[arXiv: 1904.03947]
$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+)$

$\Delta A_{CP} \approx \Delta a_{CP}^{dir} \left( 1 + \frac{t}{\tau(D^0)} y_{CP} \right) + \frac{\Delta(t)}{\tau(D^0)} \Delta a_{\Gamma}$

- $\Delta A_{CP}$ is primarily sensitive to direct CP-violation
  - largely insensitive to systematic uncertainties.
- differs from zero by $5.3\sigma$
  - SM expectations $10^{-4} - 10^{-3}$
- the first observation of CP violation in charm particle decays
- Reconstruction performed online (Turbo stream)

Run 1 and 2 combined result

$\Delta A_{CP} = (-1.54 \pm 0.29) \cdot 10^{-3}$

$\Delta a_{CP}^{dir} = (-1.56 \pm 0.29) \cdot 10^{-3}$
Measurement of CP violation in $B_s^0 \rightarrow J/\psi h^+h^-$

- New results using 1.9 fb$^{-1}$ from 2015 and 2016
  - LHC Seminar by F. Dordei
- 33,500 $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ signal decays
  - 5D fit: time, 3 angles, $m_{\pi\pi}$
  - $\phi_s = -57 \pm 60 \pm 11$ mrad
- 117,000 $B_s^0 \rightarrow J/\psi K^+K^-$ signal decays
  - Time-dependent angular analysis
  - Most precise single measurement to date
  - $\phi_s = -83 \pm 41 \pm 6$ mrad

- LHCb average from combined 2011-2016 data analyses
  - $\phi_s = -41 \pm 25 \pm 6$ mrad
  - $\Delta \Gamma_s = 0.0816 \pm 0.0048 \, ps^{-1}$

- HFLAV [preliminary] average including ATLAS-CONF-2019-009
  - $\phi_s = -55 \pm 21$ mrad
  - $\Delta \Gamma_s = 0.0764^{+0.0034}_{-0.0033} \, ps^{-1}$

\[
\phi_s^{SM} \approx -2 \arg \left( \frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} \right)
\]
Measurement of CP violation in $B_s \to \phi \phi$

- Decay dominated by a penguin loop: enhanced sensitivity to New Physics
- Measure the CP-violating phase $\phi^s_{s\bar{s}s}$ analogous to $\phi_s$.
- Perform time dependent angular analysis

LHCb preliminary

$$\phi^s_{s\bar{s}s} = -0.073 \pm 0.115 \pm 0.027 \text{ [rad]}$$

$$|\lambda| = -0.99 \pm 0.05 \pm 0.01$$

- Consistent with SM predictions of CP-conservation in $b \to s\bar{s}s$ transitions: $\phi^s_{s\bar{s}s} < 20 \text{ mrad}$
- Most stringent limit on the branching fraction

$$B(B^0 \to \phi \phi) < 2.7 \times 10^{-8} \text{ (90 % CL)}$$
new measurement of $\Lambda_c^+, \Xi_c^+, \Xi_c^0$ lifetimes

- Baryons selected from semileptonic $b$-baryon decays
- Measured relative to the $D^+$ lifetime
- Very large data sets

<table>
<thead>
<tr>
<th>$H_c$</th>
<th>Yield ($10^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+$</td>
<td>809.4 ± 1.3</td>
</tr>
<tr>
<td>$\Lambda_c^+$</td>
<td>303.5 ± 0.7</td>
</tr>
<tr>
<td>$\Xi_c^+$</td>
<td>55.8 ± 0.5</td>
</tr>
<tr>
<td>$\Xi_c^0$</td>
<td>21.6 ± 0.2</td>
</tr>
</tbody>
</table>

LHCb preliminary

- Better precision by 3-4 times wrt world averages, but consistent.
- Lifetime of $\Xi_c^0$ 3.3 sigma larger than WA of $112^{+13}_{-10}$ fs.

$LHCb$ preliminary

\[
\begin{align*}
\tau_{\Lambda_c^+} &= 203.5 \pm 1.0 \pm 1.3 \pm 1.4 \text{ fs} \\
\tau_{\Xi_c^+} &= 456.8 \pm 3.5 \pm 2.9 \pm 3.1 \text{ fs} \\
\tau_{\Xi_c^0} &= 154.5 \pm 1.7 \pm 1.6 \pm 1.0 \text{ fs}
\end{align*}
\]

Stat.  Syst.  D+ lifetime uncertainty

[\text{LHCb-PAPER-2019-008, Run1 3.0 fb}^{-1}]
Conclusion

• Run 1 & 2 data analyses progressing well with many World’s Best measurements being published
  • Many more publications in the pipeline

• Upgrade 1 well under way
  • Old detector disassembly complete, with new installations started already
  • Detector production, construction and assembly under way for all detectors
  • Schedule is tight but still manageable

• Upgrade 2 on the horizon
Backups
Strategy – Prompt tag

\[
A_{\text{raw}}(f) = \frac{N(D^0 \to f) - N(D^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)}
\]

Valid up to \(\sigma(10^{-6})\)

\[A_{\text{raw}}(f) \approx A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})\]

Physical CP asymmetry

\(D^0\) detection asymmetry

\(\Rightarrow\) equal to 0, since \(K^-K^+\) and \(\pi^-\pi^+\) are symmetric final states

\[\pi_s\] detection asymmetry

\(D^*\) production asymmetry

\(\Rightarrow\) independent on the final state

If the **kinematics** of the \(D^{*+}\) and \(\pi_s\) for the two decay modes are equal

\[A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = A_{\text{raw}}(K^-K^+) - A_{\text{raw}}(\pi^-\pi^+)\]
Measuring $\phi_s$

Definition of time-dependent CP asymmetry: $A_{CP}(t) = \frac{\Gamma(B_s^0 \rightarrow f) - \Gamma(B_s^0 \rightarrow \bar{f})}{\Gamma(B_s^0 \rightarrow f) + \Gamma(B_s^0 \rightarrow \bar{f})} = \eta_f \sin \phi_s \sin(\Delta m_s t)$

Experimentally it becomes: $A_{CP}(t) = \eta_f \cdot e^{-\frac{1}{2} \Delta m_s^2 \sigma^2_t} \cdot (1 - 2\omega) \cdot \sin \phi_s \cdot \sin(\Delta m_s t)$

Critical requirements:
- CP eigenvalue of the final state $\eta_f \rightarrow$ angular analysis
- Excellent decay-time resolution $\sigma_t \sim 45$ fs
- Tagging of meson flavour @ production: probability of getting the wrong tag $\omega$
  - in the fit need to model decay-time efficiency $\epsilon(t)$ (due to selection and reconstruction) and angular efficiency $\epsilon(\Omega)$