The LHCb upgrade

Technology and Instrumentation in Particle Physics 2011
Chicago 9-14 June 2011

Abraham Gallas for the LHCb Collaboration
Outline:

• Current LHCb performance
• LHCb upgrade plan & main issues
• Overview of the sub-detector modifications
• Summary & Conclusions
Current LHCb

- Current LHCb goals:
  - Indirect search for new physics via CP asymmetries and rare decays
  - Focus on flavor physics with b and c decays
- Forward spectrometer designed to exploit huge $\sigma_{b\bar{b}}$ @ LHC
  - $10^{12}$ $b\bar{b}$ pairs produced per 2 year of data taking @ $\mathcal{L} = 2\times10^{32}$ cm$^{-2}$s$^{-1}$
  - Access to all b-hadrons: $B_d$, $B_u$, $B_s$, b-baryons and $B_c$
- Big experimental challenge: $\sigma_{b\bar{b}} < 1\% \sigma_{\text{inel total}}$, $B_s$ of interest $\text{BR} < 10^{-5}$
- Current LHCb: Collect \textasciitilde5 fb$^{-1}$ before 2$^{\text{nd}}$ LHC shutdown 2017
Detector performance: vertexing & mass resolution

- **very good mass resolution**
- **very low background**
  (comparable to $e^+e^-$ machines)

**Comparison GPDs:**
- CMS: $\sigma \sim 16$ MeV
- ATLAS: $\sigma \sim 26$ MeV

**$B_u^+ \to J/\psi \, K^+$**

- $\sigma_x \approx 13.1 \, \mu$m
- $\sigma_y \approx 12.5 \, \mu$m
- $\sigma_z \approx 69.2 \, \mu$m

**$B_s^0 \to J/\psi \, \phi$**

**$X$ and $Y$ resolution - offline, exactly 1 PV**

<table>
<thead>
<tr>
<th>nTracks</th>
<th>Resolution (mm)</th>
</tr>
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<tbody>
<tr>
<td>5</td>
<td>0.05</td>
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<tr>
<td>10</td>
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<td>30</td>
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<tr>
<td>35</td>
<td>0.02</td>
</tr>
<tr>
<td>40</td>
<td>0.015</td>
</tr>
</tbody>
</table>

**$IP_x$ Resolution Vs $1/p_T$**

- $\sqrt{s} = 7$ TeV
- 2011 Data

- $\sigma_x = 13.2 + 24.7/p_T \, \mu$m
- $\sigma_y = 12.5 \, \mu$m
- $\sigma_z = 69.2 \, \mu$m

**Data Distribution**

- $X$ and $Y$ resolution - offline, exactly 1 PV
- $\sigma \sim 11$ MeV

**LHCb VELO Preliminary**

- $N_{\text{signal}} = 10049 \pm 106.7$
- $\sigma_0 = 10.7 \pm 0.6 \, \text{MeV}/c^2$

**$N_{\text{signal}} = 877 \pm 31.59$**

- $\sigma_0 = 7.28 \pm 0.24 \, \text{MeV}/c^2$
- $\sigma \sim 7$ MeV
Detector performance: hadron PID

\[ \Lambda_b \rightarrow p K \]

\[ \Lambda_b \rightarrow p \pi \]
Detector performance: Particle Identification on $B \rightarrow hh$

No particle identification $\rightarrow$ any 2 hadrons!

$B^0 \rightarrow h^+ h^-$

large width

particle identification of 2 $\pi$

$BR(B \rightarrow \pi^+ \pi^-) = 5 \times 10^{-6}$!

$B_s^0 \rightarrow K^+ K^-$

$B_d^0 \rightarrow K^0 \pi$ & $B_s^0 \rightarrow K^0 \pi$

(will get as many $K\pi$ in $<1$ fb$^{-1}$ as Belle in 1000 fb$^{-1}$)

particle identification of 1 $\pi$ and 1 $K$

$B_d^0 \rightarrow \pi^+ \pi^-$

229±23 events in 35 pb$^{-1}$

Expectations 2011:

LHCb: 6500 ev./fb$^{-1}$

(CDF: 1100 ev./fb$^{-1}$)
Detector performance: photon PID

$\pi^0$ reconstruction performance

$B^0 \rightarrow K^{*}\gamma$

$\chi_c \rightarrow J/\psi \gamma$

See talk by Frédéric Machefert
Muons: key ingredient for many LHCb physics analyses!
The LHCb Detector

Tracking environment of the upgrade already present now!

Typical event at $\mu \sim 2.5$
Future LHCb: Upgrade

- Excellent performance of current detector in hadronic environment demonstrated:
  - vertexing, mass resolution, PID
  - High selectivity and low background
  - Very efficient trigger

<table>
<thead>
<tr>
<th>Year</th>
<th>Muon trigger (J/ψ)</th>
<th>Hadron trigger (D⁰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>94.9±0.2%</td>
<td>60±4%</td>
</tr>
<tr>
<td>MC</td>
<td>93.3±0.2%</td>
<td>66%</td>
</tr>
</tbody>
</table>

- After recording ∼5 fb⁻¹ time to double stats is too slow → increase $\mathcal{L}$ → Level-0 trigger loses efficiency because the DAQ readout limited to 1MHz, $E_T$ -cut raised...

**Solution:**

40MHz DAQ readout rate
Fully software trigger

accumulate ∼1 fb⁻¹/year ↔ Storage: event size ∼50kB
Upgrade plot and strategy

- LHCb detector readout at 40MHz with a fully software based trigger:
  - Upgrade of all sub-detector Front-End electronics to 40 MHz readout
- Rebuild of all silicon detectors attached to the current 1MHz electronics
  - VELO, IT, TT, RICH photo-detectors
- Remove some detectors due to increased occupancies or no necessity at higher luminosity
  - RICH1-aerogel, M1, possibly PS&SPD
- Eventually improved PID at low momenta:
  - **Tight time schedule** → try to optimize:
    - Cost
    - Manpower
    - Time (R&D, production, installation)

- Re-use existing electronics & infrastructure as much as possible
- Develop common solutions for use by all sub-detectors
  - e.g.: use GBT @ 4.8 Gbit/s with zero suppression ~ 13,000 links with 8,300 optical fibers already installed in LHCb
Upgraded LHCb

Mission of upgrade LHCb:
- General purpose detector in the forward region with a 40 MHz Readout and a full software trigger.
- Quark flavour physics main component but expand physics program to include:
  - Lepton flavour physics
  - Electroweak physics
  - Exotic searches
- Possible due to full software trigger

LHCb Upgrade:
- Collect 50 $\text{fb}^{-1}$:
  - ~5 $\text{fb}^{-1}$/year
  - $\sqrt{s} = 14$ TeV
  - $\mathcal{L} = 10^{33}$ cm$^{-2}$s$^{-1}$
Upgraded LHCb environment: $\mathcal{L}$ & Pile-up

**LHCb operation (design):**
- $\mathcal{L} \sim 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ with 25ns BX-ings
  - $\sim 10$ MHz xings with $\geq 1$ interaction
  - $\mu^* \sim 0.42$

**Upgrade operation:**
- $\mathcal{L} \sim 1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ with 25ns BX-ings
  - $\sim 26$ MHz xings with $\geq 1$ interaction
  - $\mu \sim 2.13$

**Current operation:**
- LHC has < 2622 bunches so the $\mu \sim 2$

* $\mu = \text{number of visible pp collisions per bunch crossing} \ast
Tracking and Occupancy:
Si can be operated without spillover
Outer Tracker straws: occupancy at limit
Good PR experience now from 50 ns running
Increase area coverage of IT and use faster gas
Move to scintillating fibres
Material Budget an important issue (occupancy, momentum resolution)

Irradiation:
Integrated dose up by a factor 10
Affects mainly large $\eta$ (trackers, inner part of calorimeter)
Silicon will anyway be replaced and cooling optimised
Experience from current experiment will guide decisions
- Front-end electronics should:
  - Transmit collision data @ 40 MHz
  - Zero-suppress to minimize data bandwidth
- The L0 hardware trigger is re-used to reduce the event rate to match the installed router and CPU farm capacity (staging). Initially run at 5~10 MHz
Generic sub-detector readout & control:

- Bundle of 8 x 12 way ribbon

- Number of GBT links:

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>TFC/ECS</th>
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<tbody>
<tr>
<td>Velo</td>
<td>2496</td>
<td>52</td>
</tr>
<tr>
<td>OT</td>
<td>3456</td>
<td>72</td>
</tr>
<tr>
<td>ST</td>
<td>1200</td>
<td>~100</td>
</tr>
<tr>
<td>RICH</td>
<td>2476</td>
<td>~200</td>
</tr>
<tr>
<td>Calo</td>
<td>952</td>
<td>238</td>
</tr>
<tr>
<td>Muon</td>
<td>1248</td>
<td>104</td>
</tr>
<tr>
<td>Total</td>
<td>11684</td>
<td>766</td>
</tr>
</tbody>
</table>

- Total optical links required ~ 13000
- Current LHCb has already 8300 links installed
Common developments

**TELL40: Common Back-End readout module:**
- Modular mezzanine-based approach (diff tasks)
- Processing in FPGAs
- Format: Advanced-TCA motherboard (under investigation)
- Tests of high-speed links on proto-board: 12-way Optical I/Os (12 x > 4.8 Gb/s), GBT compatible
- 24 channels/mezzanine ➔ up to 96/BE module
- Transmission to the DAQ using 10 Gb Ethernet

**ACTEL Flash FPGA for front-end modules**
- Advantages over ASICs: re-programmable, faster development time.
- Can they survive the radiation?
- Irradiation program started on A3PE1500
  - Preliminary results: up to 30 krad ok.
Upgrade LHCb Trigger

- flexible software trigger with up to 40 MHz input rate and 20 kHz output rate
- trigger has all the event information
- runs in a stageable Event Filter Farm
- run at 5 times LHCb luminosity ($\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{s}^{-1}$)
- big gain in signal efficiency with up to factor 7 for hadronic modes

### Signal efficiencies

<table>
<thead>
<tr>
<th>LLT-rate (MHz)</th>
<th>1</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \rightarrow \phi\phi$</td>
<td>0.12</td>
<td>0.51</td>
<td>0.82</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^*\mu\mu$</td>
<td>0.36</td>
<td>0.89</td>
<td>0.97</td>
</tr>
<tr>
<td>$B_s \rightarrow \phi\gamma$</td>
<td>0.39</td>
<td>0.92</td>
<td>1.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EFF size *</th>
<th>5x2011</th>
<th>10x2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLT-rate (MHz)</td>
<td>5.1</td>
<td>10.5</td>
</tr>
<tr>
<td>HLT1-rate (kHz)</td>
<td>270</td>
<td>570</td>
</tr>
<tr>
<td>HLT2-rate (kHz)</td>
<td>16</td>
<td>26</td>
</tr>
<tr>
<td>Total signal efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_s \rightarrow \phi\phi$</td>
<td>0.29</td>
<td>0.50</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^*\mu\mu$</td>
<td>0.75</td>
<td>0.85</td>
</tr>
<tr>
<td>$B_s \rightarrow \phi\gamma$</td>
<td>0.43</td>
<td>0.53</td>
</tr>
</tbody>
</table>

* See talk by Roel Aaij

* Size of the Event Filter Farm available for the 2011 run
NEW VELO @ 40MHz Readout
• Challenges: Data rates $<\text{rate}_{\text{max}}>$ = 200MHz cm$^{-2}$
  
  $\text{Irradiations}_{\text{max}} = 5 \times 10^{15}$ 1 MeV n$_{\text{eq}}$ cm$^{-2}$
  
  Low material budget
• PIXEL Detector: VELOPIX based on TimePix
  • 55 µm x 55 µm pixel size
  • CVD Diamond substrate
• Strip detector: minimum pitch 30 µm improved geometry

R&D ongoing
• Module layout and mechanics
• Sensor options:
  • Planar Si, 3D, Diamond
• CO$_2$ cooling
• FE electronics
• RF-foil of vacuum box

* See talk by Daniel Hynds
VELO-Pixel R&D

- Test Beam TimePix Telescope
- Results:
  - 2011 JINST 6 P05002 doi: 10.1088/1748-0221/6/05/P05002
  - arXiv:1103.2739v2 [physics.ins-det]
Main Tracker stations upgrade: OT, IT, TT

- Current tracker works already with upgrade level pile-up (but not yet with spill-over)
- OT straw detector remains
  - Detector aging in hot area is still under investigation
  - Consider module replacements with 1mm Scintillating Fiber Tracker in hottest region, increase granularity. In conjunction with IT replacement.
  - Replace on-detector electronics by 40 MHz version (FPGA-TDCs):
    - re-use front-end
    - implement TDC (1ns) in ACTEL ProASIC FPGA
    - prototype already working

![Tracking efficiency vs. multiplicity](image)

![Nsig/Nbkg for B→J/ψK⁺](image)
Main Tracker stations upgrade: OT, IT, TT

- Current IT and TT Si-strip detectors must be replaced:
  - 1 MHz Readout electronics integrated

- Two technologies:
  - Silicon strips:
    - Development of a new rad-hard FE chip @ 40MHz
  - 250 µm Scintillating Fiber Tracker
    - 8 layers (same X₀ as the Si-strip option)
    - Fibers coupled to a Silicon Photo-Multiplier (SiPM)
    - Signals outside acceptance with clear fibers:
      - SiPM shielding
      - Cooling, electrical components
    - SiPM radiation tolerance under investigation
    - ASIC to read out the SiPM under investigation

IT-fiber detector layout:

- SiPM array
- SiPM cell coverage

32 channels Si PM: 0.25 x 1 mm²
128 channels SiPM available
PID upgrade: RICH detectors

- RICH-1 and RICH-2 detectors are retained, replace HPDs (1 MHz internal Readout):
  - Baseline readout: replace pixel HPDs by MaPMTs & readout with 40 MHz custom ASIC

- Baseline MaPMTs (Hamamatsu):

R7600 vs R11265 (baseline):
- 8x8 pixels, 2.0x2.0 mm², 2.3 mm pitch (2.9 mm)
- 18.1x18.1 mm² active area (23.5x23.5 mm²)
- CE (simulation): 80% (90%)
- Fractional coverage: 50% (80%)

Prototyping using 40 MHz Maroc-3 RO chip:
- Gain compensation
- Binary output

R7600 characterization:
- Channel to channel gain variation (correction in FE)
- Excellent cross-talk (below 1%)
- ~10% gain reduction in 50 gauss $B_L$-field (25 gauss max $B_L$-field in LHCb)

Digital functions in ACTEL Flash FPGA FE module. 3712 R7600/R11265 units for RICH1&2 ~238k #
PID upgrade: TORCH

- Time of Flight detector based on a 1 cm quartz plate, for the identification of p<10 GeV hadrons (replacing Aerogel) combined with DIRC technology:
  - TORCH=Time Of internally Reflected Cherencov light*
  - reconstruct photon flight time and direction in specially designed standoff box
  - Measure ToF of tracks with ~15 ps (~70 ps per photon)

K-π separation vs p in upgrade:

→ could be installed later than 2018!

* See talk by Neville Harnew
Calorimeters Upgrade

- **ECAL and HCAL remain**
  - Keep all modules & PMTs
  - Radiation tolerance of inner modules being assessed @ LHC tunnel
  - Reduce the PMTs gain by a factor 5 to keep same <current>

- **PS and SPD might be removed (under study)**
  - (e/γ/hadron separation later in HLT with the whole detector info.)

- **New FEE to compensate for lower gain and to allow 40 MHz readout:**
  - Analogue part: ASIC or Discrete* components solutions *(keeping noise ≤1 ADC cnt (ENC < 5-6 fC))*
  - Digital part: prototype board to test FPGAs (flash/antifuse) for:
    - Radiation tolerance
    - Packing of Data @ 40 MHz

* See poster by Carlos Abellán

**New digital electronics prototype**
Muon Detector Upgrade

- Muon detectors are already read out at 40 MHz in current L0 trigger
  - Front-end electronics can be kept
  - Remove detector M1 (background and upgraded L0(LLT), room for TORCH)

- Investigations:
  - MWPC aging:
    - tested at two sites up to 0.25 C/cm and 0.44 C/cm with no loss of performance
    - 1C/cm is considered as an upper limit for safe operation of MWPC chambers
  - Rate limitations of chambers and FE:
    - High-rate performance tested @ CERN-GIF no saturation effect up to 30nA/cm² (factor 2 for 10^{33})
    - No deterioration in the FE electronics up to 1MHz

### Accumulated charge (C/cm) for 50 fb^{-1}

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>0.67</td>
<td>0.42</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>M3</td>
<td>0.17</td>
<td>0.08</td>
<td>0.02</td>
<td>0.01</td>
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<tr>
<td>M4</td>
<td>0.22</td>
<td>0.06</td>
<td>0.01</td>
<td>0.004</td>
</tr>
<tr>
<td>M5</td>
<td>0.15</td>
<td>0.03</td>
<td>0.01</td>
<td>0.003</td>
</tr>
</tbody>
</table>

### Maximum rates/channel MHz @ 10^{33} cm^{-2}s^{-1}

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>0.81</td>
<td>0.55</td>
<td>0.12</td>
<td>0.10</td>
</tr>
<tr>
<td>M3</td>
<td>0.24</td>
<td>0.11</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>M4</td>
<td>0.09</td>
<td>0.07</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>M5</td>
<td>0.07</td>
<td>0.07</td>
<td>0.04</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Muon Detector Upgrade

- Performance at higher occupancy: OK
  - Studied with real data July-October 2010 \( <PV> \geq 2 \).
  - After retuning the Muon ID algorithm the \( J/\psi \):
    - Worsening S/B \( \leq 15\% \)
    - Efficiency loss \( \leq 5\% \)

\( J/\psi \rightarrow \mu^+ \mu^- \) for single PV events

\[ \sigma = 14.74 \pm 0.66 \text{ MeV/c}^2 \]
\[ N_{\text{sig}} = 251.2 \pm 9.1 \]
\[ N_{\text{bg}} = 753 \pm 32 \]
\[ m_0 = 3094.86 \pm 0.69 \text{ MeV/c}^2 \]
\[ t_{k_1} = -0.001155 \pm 0.00028 \]

\( J/\psi \rightarrow \mu^+ \mu^- \) for events with \( <PV>=2.3 \)

\[ \sigma = 14.66 \pm 0.36 \text{ MeV/c}^2 \]
\[ N_{\text{sig}} = 970 \pm 18 \]
\[ N_{\text{bg}} = 2524 \pm 60 \]
\[ m_0 = 3095.20 \pm 0.38 \text{ MeV/c}^2 \]
\[ t_{k_1} = -0.001326 \pm 0.00014 \]
A possible schedule*

2010-2012+
Ramping up to fewx$10^{33}$ @ 7TeV
Up to 5 fb$^{-1}$ delivered

LHC had a very bright startup:
2010: 250 bunches with ca. $2.6 \times 10^{13}$ ppb
2011: 1092 bunches and beyond
Luminosity > $10 \times 10^{32}$ cm$^2$

Plan to run at 7 TeV for 2011 and 2012+

18 month shutdown 2013-2014:
to repair splices $\Rightarrow$ 13-14 TeV
GPDs 1$^{\text{st}}$ phase upgrade (e.g. ATLAS b-layer)

Next shutdown ~ 2018:
Full luminosity upgrade of LHC
GPDs 2$^{\text{nd}}$ phase upgrade for “nominal” lumi
LHCb full upgrade to 40MHz R/O

Towards High Luminosity LHC

2015-2016/7
Ramping up to $10^{34}$
Up to 100 fb$^{-1}$ delivered

Injector and LHC Phase I upgrades

2018-2020/1
Ramping up to $10^{34}$
Up to 100 fb$^{-1}$ delivered per year

Long shutdown
Splice repairs,
LHC $\Rightarrow$ 13-14 TeV

Installation of Upgraded LHCb

* Different scenarios under discussion at present between CERN and Experiments
Summary

- The LHCb experiment has demonstrated very successful operation in a hadronic and high multiplicity environment in 2010 & 2011:
  - Excellent vertexing, PID and tracking performances give confidence that the upgrade will be successful

- LHCb has a firm plan to upgrade in 2018:
  - Read out entire detector at 40 MHz with a fully software-based trigger @ $L \sim 10^{33}$ cm$^{-2}$ s$^{-1}$
  - Massive statistical power
  - Independent of the LHC luminosity upgrade
  - No major detector changes needed, except for VELO, ST and RICH
  - The sub-detectors electronic developments are well underway

- Given its forward geometry, its excellent tracking and PID capabilities and the foresee flexible software-based trigger, the upgraded LHCb detector:
  - is an ideal detector for the next generation of quark flavour physics experiments
  - provides unique and complementary capabilities for New Physics studies beyond flavour physics

- Submitted upgrade LOI to LHCC beginning of March [CERN-LHCC-2011-001]
Back-up slides
LHCb Upgrade Physics program

- Quark Flavour Physics
  - CPV in b-decays:
    - in $B_s$ oscillations
    - in charmless hadronic decays
    - measurement of gamma
  - Rare b-decays
  - Charm Physics

- Lepton Flavour Physics
  - Searches for Majorana neutrinos
  - Lepton Flavour Violating tau decays

- Physics Beyond Flavour
  - Electroweak Physics
  - Exotics
  - Central Exclusive Production

Complementary Acceptance
+ Excellent vertexing and PID
+ Software-based trigger
## Quark flavour physics goals overview

<table>
<thead>
<tr>
<th>Exploration</th>
<th>Precision studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search for $B_s \rightarrow \mu^+\mu^-$ down to SM value</td>
<td>Measure unitarity triangle angle $\gamma$ to $\sim 4^\circ$ to permit meaningful CKM tests</td>
</tr>
<tr>
<td>Search for mixing induced CP violation in $B_s$ system ($2\beta_s$) down to SM value</td>
<td>Search for CPV in charm</td>
</tr>
<tr>
<td>Look for non-SM behaviour in forward-backward asymmetry of $B^0 \rightarrow K* \mu^+\mu^-$</td>
<td></td>
</tr>
<tr>
<td>Look for evidence of non-SM photon polarisation in exclusive $b \rightarrow s\gamma(\ast)$</td>
<td></td>
</tr>
</tbody>
</table>

### Current LHCb

- ~5 fb$^{-1}$

<table>
<thead>
<tr>
<th>Exploration</th>
<th>Precision studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search for $B^0 \rightarrow \mu^+\mu^-$</td>
<td>Measure $\mathcal{B}(B_s \rightarrow \mu^+\mu^-)$ to a precision of $\sim 10%$ of SM value</td>
</tr>
<tr>
<td>Study other kinematical observables in $B^0 \rightarrow K^* \mu^+\mu^-$, e.g. $A_T(2)$</td>
<td>Measure $2\beta_s$ to precision $&lt; 20%$ of SM value</td>
</tr>
<tr>
<td>CPV studies with gluonic penguins e.g. $B_s \rightarrow \phi\phi$</td>
<td>Measure $\gamma$ to $&lt; 1^\circ$ to match anticipated theory improvements</td>
</tr>
<tr>
<td>Measure CP violation in $B_s$ mixing ($A_{fs}^s$)</td>
<td>Charm CPV search below $10^{-4}$</td>
</tr>
<tr>
<td>Measure photon polarisation in exclusive $b \rightarrow s\gamma(\ast)$ to the % level</td>
<td></td>
</tr>
</tbody>
</table>

### Upgraded LHCb

- ~50 fb$^{-1}$