The LHCb Upgrade

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Outline

- Why upgrade LHCb?
- The physics case
- The LHCb detector upgrade
  - Trigger & DAQ
  - The detector components
- Summary
Reminder of LHCb

- Forward-peaked production $\rightarrow$ LHCb is a forward spectrometer (operating in LHC collider mode)
- $b\bar{b}$ cross-section $= 284 \pm 53 \, \mu b$ at $\sqrt{s} = 7$ TeV and around a factor 2 greater at 14 TeV [PLB 694 209]
  $\rightarrow$ $\sim 10^{12} b\bar{b}$ pairs produced per LHC year
Why upgrade?

- Any New Physics model with new heavy particles or flavour breaking interactions must “hide” behind the SM interactions

$$\mathcal{A}_{SM} + \mathcal{A}_{NP}$$

$$\mathcal{A}_{BSM} = \mathcal{A}_0 \left( \frac{c_{SM}}{m_W^2} + \frac{c_{NP}}{\Lambda^2} \right)$$

- We know by now NP contributions are small.
- We have clean Standard Model predictions
- We have precise measurements (high statistics, incl. control channels)
Standard Model withstands challenges

- $B_s$ mixing phase $\phi_s$
- $\text{BR}(B_s \to \mu^+ \mu^-)$

Theo. uncertainty: $\pm 0.0016 \text{ rad}$
Exp. error (best): $\pm 0.07 \text{ rad}$

Theoretical precision not reached $\rightarrow$ higher statistics required!
What can be tested?

- Predictions with small SM theory uncertainty
  - “Null tests”, no signals expected in SM
  - Precision tests of the unitarity of the CKM matrix
    - Only one CP violating phase, look for in consistency of angles
    - Measure sides via ratios of CKM matrix elements (needs theory I/P)
  - Precision measurements of BRs and angular distributions of forbidden, or nearly forbidden decays
  - Lepton universality

- Type of decays (beauty and charm)
  - Fully leptonic decays
  - Ratios in semi-leptonic decays
  - CP violation in hadronic decays
Example of a null test: $B^0_s \rightarrow \phi \phi$

- Measure CP violation in $B^0_s \rightarrow \phi \phi$
- The $B^0_s \rightarrow \phi \phi$ decay is a unique place to look for NP in loop decays
- In SM the CP violation in the decay and the loop cancel
- This is a null-test of the SM that has high predictive power with small uncertainties
**B^0_s → ϕϕ continued**

- Current status of LHCb’s B^0_s → ϕϕ measurement

  - N_{events} ~ 4000 of B^0_s → ϕ(K+K^-)φ(K+K^-)
  - A vector-vector decay; a mixture of CP even and CP odd distributions

- No significant CP violation observed

\[ \phi_s = -0.17 \pm 0.15 \text{ (stat)} \pm 0.03 \text{ (syst)} \text{ rad} \]
$B^0_s \rightarrow \phi \phi$ with the upgraded detector

- LHCb upgrade will bring precision on this down to 0.02
- To the same level as the current theoretical uncertainty
Unitarity of CKM matrix

- The SM requires that many different fits to the unitary triangle all result in the same apex
- If not, there will be additional amplitudes coming from NP
- Largest uncertainties are coming from left side ($|V_{ub}|/|V_{cb}|$) and the angle $\gamma$
Unitarity of CKM matrix

- Current measurements are dominated by loop processes.
- These are still large uncertainties from measurements coming solely from tree processes.
Determination of CP angle $\gamma$

- Best determined through interference between tree amplitudes
- $D$ or $\bar{D}$ produced followed by decay to a common final state: $K^+ \pi^-$, $K^+ \pi^- \pi^0$, $K^+ K^-$, ... etc
- Theoretical uncertainty on the method is extremely small (JHEP 01 (2014) 05)

$$V_{ub} = |V_{ub}| e^{-i\gamma}$$
Need large signal yield in the different final states (and to differentiate them cleanly)

LHCb currently measure $(67 \pm 12)\degree$ with mainly 2011 (1 fb$^{-1}$) data

Statistical reach for LHCb upgrade will be 1° (for Belle-II it is $\sim 2\degree$)

To keep systematic uncertainty below this requires to understand tracking for positive/negative particles exceptionally well
The need to resolve $|V_{ub}|$

- The measurement of $|V_{ub}|$ has an internal inconsistency between
  - Exclusive measurement: $B^0 \rightarrow \pi^- \mu^+ \nu$
  - Inclusive measurement: $B^0/B^+ \rightarrow X_u \mu^+ \nu$

\[
V_{ub}(excl) = (3.42 \pm 0.22) \times 10^{-3}
\]
\[
V_{ub}(incl) = (4.40 \pm 0.31) \times 10^{-3}
\]
\[
V_{ub} = (3.75 \pm 0.46) \times 10^{-3}
\]

\(~1.9 \sigma~ discrepancy\)

D. Derkach UTFIT@ICHEP2014
|V_{ub}| continued ...

- Is internal inconsistency a sign of NP ... maybe not, but need more measurements and theoretical improvements.

- More independent measurements required
  - $\Lambda_b \rightarrow p \mu^- \nu$ In progress with LHCb (which rely on new $\Lambda_b \rightarrow p$ form factors from the lattice)

- $B_c^+ \rightarrow D^0 \mu^+ \nu$
  - Possible at LHCb or LHCb upgrade.

- Also inclusive measurements from Belle-II

- $|V_{ub}|$ at a few percent level will be possible
In 2025 with the LHCb upgrade ...

- Left side (|V_{ub}|/|V_{cb}|) and the angle $\gamma$ will be precision measurements in the future
Nearly forbidden decays

The $B_0^s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ decays

- The two very rare decays $B_0^s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ have attracted much interest
- Predictions of SM branching fractions with good precision
  - $\text{BF}(B_0^s \rightarrow \mu^+\mu^-) \text{ SM} = 3.56 \pm 0.18 \times 10^{-9}$
  - $\text{BF}(B^0 \rightarrow \mu^+\mu^-) \text{ SM} = 0.10 \pm 0.01 \times 10^{-9}$

- Sensitive to the scalar sector of flavour couplings
Observing $B^0 \rightarrow \mu^+ \mu^-$

- LHCb and CMS combined result
  \[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9} \]
  \[ B(B^0 \rightarrow \mu^+ \mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10} \] (> 5 sigma)

- Following $B_s^0 \rightarrow \mu^+ \mu^-$ observation, challenge now is to observe for $B^0 \rightarrow \mu^+ \mu^-$
- In the SM suppressed by $|V_{ts}|^2/|V_{td}|^2 \sim 25$
- New physics may manifest itself as a higher $B^0 \rightarrow \mu^+ \mu^-$ rate
- LHCb upgrade expects to measure the ratio to a 35% accuracy
- CMS upgrade at full 3 ab$^{-1}$ expected to improve this to 21%
**$B_s$ weak mixing phase $\phi_s$ in $B_s \rightarrow J/\psi \phi$**

Measurements by ATLAS, CMS and LHCb:

- **LHCb (50 fb$^{-1}$):** $\delta \phi_s \approx \pm 0.009$ (SM $-0.036 \pm 0.003$) (current meas. $\pm 0.07$)
Due to lepton universality, the $B^+ \rightarrow K^+ \mu^+ \mu^-$ and $B^+ \rightarrow K^+ e^+ e^-$ decays should have same BF to within a factor $10^{-3}$.

The ratio

$$R_K = \frac{BF(B^+ \rightarrow K^+ \mu^+ \mu^-)}{BF(B^+ \rightarrow K^+ e^+ e^-)}$$

is sensitive to lepton flavour violating NP.

The electron mode is a challenge for LHCb.
Lepton universality test in $B^+ \rightarrow K^+ \ell^+ \ell^-$

- Current status of measurements as a function of dilepton mass:
  \[ R_K = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)} \]

- Expected precision from both LHCb upgrade (and also Belle-II) at the few % level
- Will resolve the issue with the 2.6 $\sigma$ tension currently seen
# Upgrade sensitivities 50 fb⁻¹

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb 2018</th>
<th>Upgrade (50 fb⁻¹)</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$2\beta_s \left( B_s^0 \to J/\psi \phi \right)$</td>
<td>0.10 [24]</td>
<td>0.025</td>
<td>0.008</td>
<td>~ 0.003</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s \left( B_s^0 \to J/\psi f_0(980) \right)$</td>
<td>0.17 [26]</td>
<td>0.045</td>
<td>0.014</td>
<td>~ 0.01</td>
</tr>
<tr>
<td></td>
<td>$A_{fs}(B_s^0)$</td>
<td>6.4 x 10⁻³ [41]</td>
<td>0.6 x 10⁻³</td>
<td>0.2 x 10⁻³</td>
<td>0.03 x 10⁻³</td>
</tr>
<tr>
<td>Gluonic penguin</td>
<td>$2\beta_s^\text{eff} \left( B_s^0 \to \phi\phi \right)$</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^\text{eff} \left( B_s^0 \to K^{*0} K^{*0} \right)$</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^\text{eff} \left( B^0 \to \phi K^0_s \right)$</td>
<td>0.17 [41]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed</td>
<td>$2\beta_s^\text{eff} \left( B_s^0 \to \phi\gamma \right)$</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>currents</td>
<td>$\tau^\text{eff} \left( B_s^0 \to \phi\gamma \right)/\tau_{B_s^0}$</td>
<td>–</td>
<td>5%</td>
<td>1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak penguin</td>
<td>$S_3(B^0 \to K^{*0} \mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.08 [42]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$s_0 A_{FB}(B^0 \to K^{*0} \mu^+\mu^-)$</td>
<td>25% [42]</td>
<td>6%</td>
<td>2%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>$A_1(K\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.25 [9]</td>
<td>0.08</td>
<td>0.025</td>
<td>~ 0.02</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \to \pi^+\mu^+\mu^-)/B(B^+ \to K^+\mu^+\mu^-)$</td>
<td>25% [43]</td>
<td>8%</td>
<td>2.5%</td>
<td>~ 10%</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$B(B_s^0 \to \mu^+\mu^-)$</td>
<td>1.5 x 10⁻⁹ [4]</td>
<td>0.5 x 10⁻⁹</td>
<td>0.15 x 10⁻⁹</td>
<td>0.3 x 10⁻⁹</td>
</tr>
<tr>
<td></td>
<td>$B(B^0 \to \mu^+\mu^-)/B(B_s^0 \to \mu^+\mu^-)$</td>
<td>–</td>
<td>~ 100%</td>
<td>~ 35%</td>
<td>~ 5%</td>
</tr>
<tr>
<td>Unitarity</td>
<td>$\gamma \left( B \to D^{(<em>)}K^{(</em>)} \right)$</td>
<td>~ 10–12° [28,29]</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td>triangle</td>
<td>$\gamma \left( B_s^0 \to D_s K \right)$</td>
<td>–</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td>angles</td>
<td>$\beta \left( B^0 \to J/\psi K^0_s \right)$</td>
<td>0.8° [41]</td>
<td>0.6°</td>
<td>0.2°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_\Gamma$</td>
<td>$2.3 \times 10^{-3}$ [41]</td>
<td>0.40 x 10⁻³</td>
<td>0.07 x 10⁻³</td>
<td>–</td>
</tr>
<tr>
<td>$CP$ violation</td>
<td>$\Delta A_{CP}$</td>
<td>$2.1 \times 10^{-3}$ [8]</td>
<td>0.65 x 10⁻³</td>
<td>0.12 x 10⁻³</td>
<td>–</td>
</tr>
</tbody>
</table>
Complementarity with Belle-II

LHCb

- Rare decays: $B_{d,s} \rightarrow \mu\mu$
- $B_s$ system
- $b$-baryons

- Spectroscopy
  - CKM phases ($\beta, \gamma$)
  - Gluonic penguins
  - EW penguins
  - Charm physics
  - Semileptonics: Mixing, $A_{SL}$

Belle II

- Semileptonics: $V_{xb}$
- $B \rightarrow \tau\nu, D\tau\mu,$
- $B \rightarrow K^{*}\nu\nu$
- $\tau$-physics

ATLAS & CMS

- Some only LHCb, some only Belle II

On-going
The LHCb detector upgrade

- Detector overview
- The issue with the trigger
- The major hardware changes
  - The VELO
  - The tracking detectors
  - The RICH
LHCb subsystems overview

- Tracker
- VELO
- RICHs
- Muon
- Calorimeter
Why upgrade: current LHCb limitations

- No evidence for New Physics in LHC Run I
  - Need more (x10 or more) data, aiming at experimental sensitivities comparable to theoretical uncertainties

- Need to increase levelled luminosity from $0.4 \times 10^{33}$ up to $2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ (pile-up ~8)

- However the current 1 MHz level-0 trigger output is a severe limitation!

- If we increase the luminosity
  - Need harder cuts on $P_t$ due to the 1 MHz bandwidth limit
  - The trigger yield of hadronic events saturates
  - there’s no real gain in statistics

**Need a radical change in the trigger strategy to get to 5pb$^{-1}$ per year**
The trigger

- Remove the level-0 hardware trigger
  - Readout an event every bunch crossing (40 MHz)
  - New front-end electronics (on-chip zero suppression)
  - New DAQ system

- Use an efficient fully software trigger accessing complete event information, running at the bunch crossing rate

- The high instantaneous luminosity of $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ implies higher occupancies in all subsystems $\Rightarrow$ redesign several detectors to adapt them to new conditions

- Install by LS2 (Long-shutdown 2) in 2018-2019
Upgraded VELO (vertex detector)

- Challenges
  - Very high particle rates
  - Highly non-uniform radiation damage (up to $8 \times 10^{15} \text{n}_{eq}\text{cm}^{-2}$ for 50 fb$^{-1}$)

- Technical choices
  - Silicon strips replaced by pixels. 256 x 256 pixel matrices, with 55 x 55 $\mu$m$^2$ pixels
  - Micro-channel CO$_2$ cooling
  - New FE electronics: Velopix

CO$_2$ passes through channels etched in a silicon plate
New VELO option under discussion
New VELO Performance

Predicted performance at $2 \times 10^{33}/\text{cm}^{-2}\text{s}^{-1}$ is superior in almost every aspect with respect to the current VELO operating at high luminosity.
Fiber Tracker (FT) technology

- Current tracker straw tubes will be replaced
- Upgrade will have scintillating fibre planes (5-6 fibres thick)
- 250 μm diameter scintillating fibres
- 12 detection layers in 3 stations
- Readout via 2x64 channel silicon photomultiplier (SiPM) arrays
- Electronics: dedicated 128 channels 40 MHz PACIFIC ASIC
Upgraded Tracker Performance

Efficiency for $B_s \to \phi \phi$

- FT: Improved tracking efficiency
- UT: Improved background rejection

Ghost rate (long tracks) for $B_s \to \phi \phi$
RICH Upgrade

- New readout: 64 channel multi-anode PMTs
- 40 MHz CLARO front-end ASIC
- In addition, for RICH1:
  - Remove aerogel
  - improve optics to spread out Cherenkov rings on the focal plane
Upgraded RICH performance at $2 \times 10^{33}$ close to current one
The timeline ...

ATLAS & CMS  ~100 fb⁻¹  Phase 1  ~300 fb⁻¹  Phase 2  ~3000 fb⁻¹
Upgrade       Upgrade   HL - Upgrade  2035
LHCb   >8 fb⁻¹
Upgrade   >23 fb⁻¹  >50 fb⁻¹
LHC   Run 2: 13-14 TeV  LS 2  Run 3: 14 TeV  LS 3  Run 4+5

SuperKEKB & Belle II  50 ab⁻¹

BES III
Summary

- LHCb is producing world best measurements in the beauty and charm sector and has a rich future ahead.

- The Upgraded LHCb trigger scheme allows collection of 5 fb⁻¹ of data per year.

- The upgrade will be performed in 2018-19 during LS2; data taking will start in 2020.

- All future facilities LHCb upgrade, Belle-II, CMS/ATLAS have their respective strengths and combined information will be a great handle to reveal New Physics.
Spare slides from here on
# B-Physics at the Intensity Frontier

<table>
<thead>
<tr>
<th></th>
<th>LHC era</th>
<th>High-lumi LHC era</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS &amp; CMS</td>
<td>25 fb^{-1}</td>
<td>100 fb^{-1}</td>
</tr>
<tr>
<td>LHCb</td>
<td>3 fb^{-1}</td>
<td>8 fb^{-1}</td>
</tr>
<tr>
<td>Belle II</td>
<td>0.5 ab^{-1}</td>
<td>25 ab^{-1}</td>
</tr>
</tbody>
</table>
Outlook: LHCb Upgrade

- Main limitation that prevents exploiting higher luminosity is the Level-0 (hardware) trigger.
- To keep output rate < 1 MHz requires raising thresholds → hadronic yields reach plateau.
- Proposed upgrade is to remove hardware trigger: read out detector at 40 MHz (bunch crossing rate). Trigger fully in software in CPU farm. Requires replacing all front-end electronics.
- Will allow to increase luminosity by factor ~ 10 to 1–2 × 10^{33} cm^{-2} s^{-1}.
- Framework TDR submitted to the LHCC: Physics case enthusiastically endorsed, detector R&D underway.

Upgrade of LHCb detector planned for 2019 to take at least 10× more data: 50 fb^{-1}. 
Upgrade scenario

- Data taking conditions
  - Leveled instantaneous luminosity of $2 \cdot 10^{33}/cm^2/s$
  - 30 MHz collisions
  - 20-100 kHz to disk
  - $\sim 5 \text{ fb}^{-1}$ per year

- Challenges
  - High pile-up
  - Large occupancies
    - event reconstruction is more difficult
    - more difficult PID
  - Radiation damage
LHCb requirements

- Separate secondary decay vertices from primary production vertex $\rightarrow$ 20$\mu$m impact parameter resolution for high-$p_t$ tracks

- Excellent momentum resolution: as low as 0.35% at 5 GeV/c (and still 0.55% at 100 GeV/c), which provides a mass resolution of 10 – 25 MeV/c$^2$

- Excellent particle identification capabilities, to unambiguously identify photons, electrons, muons, pions, kaons, protons in the b-meson decay chain, essential to select rare beauty and charm exclusive decays

- Efficient multi-stage trigger for leptonic and hadronic final states
The software trigger

30 MHz

\[ \downarrow \]

Full Software Trigger

LLT (optional)
\[ p_T \text{ of } h, \mu, e, \gamma \]

\[ \downarrow \]

15 to 30 MHz

Full track reconstruction

\[ \downarrow \]

1 to 2 MHz

Track fit

RICH particle ID

Inclusive and exclusive selections

\[ \downarrow \]

20 to 100 kHz

- Trigger farm: 50k logical CPU cores
- Offline-like reconstruction tuned to available time constraints
- Mixture of exclusive and inclusive selection algorithms
- LLT output rate progressively increases as trigger farms grows

![Graph](image-url)
The 40 MHz R/O architecture

Event Builder PCs (& software LLT)

Event Builder network

HLT Farm

40 MHz

40 MHz R/O architecture

individual sub-systems
Front-End electronics
underground

Front-end incl. Zero-Suppression

optical link via GBT ~300m

PC servers with PCIe40 R/O LLT and Event Building on surface

pure software trigger

[status: ECFA-Workshop 10/2013]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Event-size [kB]</th>
<th>Rate [kHz]</th>
<th>Bandwidth [Gb/s]</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE</td>
<td>20000</td>
<td>50</td>
<td>8000</td>
<td>2019</td>
</tr>
<tr>
<td>ATLAS</td>
<td>4000</td>
<td>200</td>
<td>6400</td>
<td>2022</td>
</tr>
<tr>
<td>CMS</td>
<td>4000</td>
<td>1000</td>
<td>32000</td>
<td>2022</td>
</tr>
<tr>
<td>LHCb</td>
<td>100</td>
<td>40000</td>
<td>32000</td>
<td>2019</td>
</tr>
</tbody>
</table>
- Replace current inner silicon planes
- Upgrade: 4 detection planes, stereo
- Silicon strip detector, 250 μm thick
- Segmentation and technology depends on expected dose and occupancy
- 40 MHz R/O via SALT ASIC
FT Design

- 12 detection layers in 3 stations
- Each station has XUVX layers ($U, V: \pm 5^\circ$)
- Advantages
  - Single technology easy to operate
  - High granularity (250 $\mu$m) gives excellent x-position resolution (50-75 $\mu$m)
  - Uniform material budget
  - SiPM & R/O outside acceptance
- Challenges
  - Radiation damage to fiber $\rightarrow$ tested, ok
  - SiPM rad. damage $\rightarrow$ operate @ -40°C
Calorimeter System Upgrade

Occupancy and radiation issues

- Pre-shower and SPD will be removed (no more L0 calorimeter trigger)

- ECAL expected to be fine up to 20 fb$^{-1}$, inner ECAL cells could be replaced at LS3

- HCAL OK up to 50 fb$^{-1}$

- Lower PMT gains to guarantee extended operation at HL

- New front-end electronics: ICECAL

- New back-end electronics, calculating ECAL and HCAL 2x2 cell energy for LLT
Muon system Upgrade

R/O and occupancy issues

- Muon detector front-end CARIOCA already operating at 40 MHz

- New off-detector board for efficient readout via PCIe40 common R/O boards

- Remove M1
  - no muon level-0 muon trigger
  - Very high occupancies

- Additional shielding behind HCAL to reduce rate in inner regions of M2

- Possible replacement of M2/M3 inner region detectors under study
Run2 starts in 2015, the aim is to collect 5 fb\(^{-1}\)

LS2: 18 months for full LHCb upgrade

Then: collect \(~5\) fb\(^{-1}/\)year