The Future of Charm Physics at LHCb

LHC Run II & the LHCb Upgrade

Chris Parkes
on behalf of the LHCb Collaboration
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LHCb Timeline

- **LHC Run-I** (2010-2012)
  - Many results shown this week, more to come
- **LHC Run-II** (2015-2018)
  - Trigger computing increased, strategy evolved
- **LHC Run-III** (2020-2023)
  - LHCb Upgrade
- **LHC Run-IV** (2025-)
  - LHCb Upgrade (+ additions ?)
LHC Schedule & LHCb

- Schedule till 2020 reasonably firm
- HL-LHC upgrade in LS3
- GPD main upgrades (phase II) scheduled for LS3

Chris Parkes, Delta City, May 2015
LHC Run II

First 13TeV Collisions
20th May 2015

Expectation ~ 5fb⁻¹
Trigger Evolution – Run II

Run I

15 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures

- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu^\pm$
- 150 kHz $e/\gamma$

Software High Level Trigger

- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

- 2 kHz Inclusive Topological
- 2 kHz Inclusive/Exclusive Charm
- 1 kHz Muon and DiMuon

Run II

30 MHz inelastic event rate

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures

- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu^\pm$
- 150 kHz $e/\gamma$

Software High Level Trigger

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz Rate to storage

(assuming current event size)
Online: Automatic Alignment & Calibration

- Minimise Online / Offline differences
  - Improve effective trigger performance
- Automatic evaluation at regular intervals
  - Vertex Locator (VELO) alignment as example
  - $O(1 \text{ min})$ CPU, update immediately

Half misalignment per fill in 2010

Max deviation $\sim 10\mu m$

- **Tracking**: spatial & time alignment
- **RICH**: mirror alignment, photon detector image corrections

Reference: G. Dujany, CHEP '15
Turbo Stream

Raw data: electronic signals recorded from detector
Analysis level: information of signal candidate tracks

• Analyse directly on trigger output?
  – Online calibration
    a critical first step

• Maximise number of events for user analysis
  – Output rate is a limit

• Testing mode
  – Raw events will be kept
But **NOT** Limited by LHC

- Upgrade to extend Physics reach
  - Exploit advances in detector technology
    - Displaced Vertex Trigger, **40MHz readout**
    - Better utilise LHC capabilities

- Collect >50 fb\(^{-1}\) data
- Modest cost compared with existing accelerator infrastructure

Independent of LHC upgrade
- HL-LHC not needed
- But compatible with HL-LHC phase
LHCb Upgrade Approved

- Letter Of Intent 2011
- Subsystem TDRs 2014

- Funding largely in place from end 2014

CERN-RRB-2014-105
Trigger Evolution - Upgrade

Run II

LHCb 2015 Trigger Diagram

30 MHz inelastic event rate

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures

- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu\mu$
- 150 kHz $e/\gamma$

Software High Level Trigger

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz Rate to storage

Upgrade

LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate and full event rate building

- LLT: 15-30 MHz output rate, select high $E_T/P_T$ ($h^\pm/\mu/e/\gamma$)

Software High Level Trigger

- Full event reconstruction, inclusive and exclusive kinematic/geometric selections
- Run-by-run detector calibration

Add offline precision particle identification and track quality information to selections

2-10 GB/s rate to storage

Chris Parkes, Delta City, May 2015
LHCb Trigger: the key to higher Lumi

- **Aim:** Increase integrated luminosity from $2 \text{ fb}^{-1}$ to $5 \text{ fb}^{-1}$ per year
  Increase instantaneous luminosity to $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

- **Current First Trigger Level:**
  Hardware Muon/ECAL/HCAL
  1.1 MHz readout

- **Performance:**
  Muon channels scale
  Hadronic channels saturate bandwidth
  Hardware trigger particularly poorly suited to lower momentum of charm

- No gain in hadronic channels with current trigger
Solution: Upgrade to 40MHz readout

- Read out full detector at 40MHz
  - Major detector changes
  - Front-end electronics must change
- Use fully software trigger
- Increased flexibility
- Maintain (improve) current detector performance
  - At increased multiple Interactions
    - Occupancies
    - Radiation Damage
LHCb Upgrade to 40 MHz

- VELO Pixel Detector
- Upgrade Tracker Silicon strips
- Outer Tracker Scintillating Fibres
- Muon MWPC (almost compatible)
- RICH Photon Detectors & (partial) mechanics
- Calo PMTs (reduce PMT gain, replace R/O)
LHCb Vertex Locator Upgrade

- Pixel Detector
  - 55x55µm
- In vacuum
- 5mm from LHC beam
  - $10^{16}$ $n_{eq}/cm^2$
  - Retracted for filling
- Silicon with Micro-channel
  - Bi-phase CO$_2$ cooling
LHCb Scintillating Fibre Tracker

- Mat made from
  - 250µm diameter fibres
  - SiPM readout
- Radiation hardness challenge
- Fibres & SiPMs
- Defects (bumps) in fibres
- 10,000 km fibre!
Sources of Charm

Prompt charm

Run I  $D \to K\pi$: 100M
Offline selected $D^*$ tagged (x5 untagged)

Semileptonic B-hadron decays

Run I  $D \to K\pi$: 20M
Offline selected muon tagged

Hadronic B decays
Not only useful to measure CKM $\gamma$
Also revealed first spin-3 charm state

→ LHCb collaboration, Phys. Rev. Lett. 113 (2014) 162001
Physics Coverage / Limitations

- Inclusive charm trigger selections are not feasible
  - Upgrade will produce 800 kHz of analysable charm-hadron events
  - 80 GB/s with current data format
    - can keep 2-10 GB/s for ALL LHCb physics
- Have to decide in advance what to keep
  - Cabibbo favoured modes prescaled?
  - Purely exclusive selection – trigger is offline selection
- Limits of physics programme not yet reached
  - Use of neutrals
  - Understanding production/detection asymmetries

\[ D^0 \to \pi^+\pi^-\pi^0: \text{1yr LHCb Run 1} = 80 \text{ yrs B factory v1} \]

Statistics

- See backup slides for assumptions
Statistics – Cross-section Adjusted

- 13 TeV cross-section

- See backup slides for assumptions
• 13 TeV cross-section
• Trigger efficiency adjusted for hadronic modes
  • See backup slides for assumptions
Statistics: $D^0 \rightarrow K\pi$ Events

- Millions
- D to $K\pi$ tagged

- 2014: 0
- 2019: 100M
- 2024: Billion
- 2029: 5000

Chris Parkes, Delta City, May 2015
Future Charm Measurements – key channels

- $A_\Gamma$, WS $K\pi$, $\Delta A_{CP}$
  - Inherently robust against systematics due to cancellations
  - Not all at the same level, but no limiting uncertainty known

- $y_{CP} \equiv \tau_{K\pi}/\tau_{KK} - 1 \approx y$
  - Comparison of two different final states
  - Less robust, key is controlling lifetime bias

- $K_S\pi\pi$
  - Leading systematics are either model uncertainties or measurements of CP content at threshold
  - Benefits from BESIII

- Rare Decays
  - Systematics unlikely to limit, no bandwidth issues

- Spectroscopy
  - Bandwidth limitations for Cabibbo favoured modes?
Future Sensitivities: $D^0 \rightarrow \mu \mu$

• Scaling sensitivities with $\sqrt{N}$ from current LHCb results
  • Assumes scaling of systematic uncertainties
  • Ignores potential improvements in selections and analyses
• Shows data set collection date
Future Sensitivities: $\Delta A_{CP}$

- Scaling sensitivities with $\sqrt{N}$ from current LHCb results ($D^*$ tagged only)
  - Assumes scaling of systematic uncertainties
  - Ignores potential improvements in selections and analyses
  - Shows data set collection date

~$10^{-4}$ level
Future Sensitivities: CPV & Mixing

- See backup slides for assumptions
- Current World Average + LHCb projections (D* tagged only)
- Central values of current world averages used
Conclusions

• LHCb Charm programme has exceeded expectations for LHC Run 1
• LHC Run II has begun
  • Novel trigger strategies are required to keep pace
• LHCb Upgrade
  • Approved, ~ financed
  • Significant technological challenges, fast timescale
  • Bandwidth key to charm prospects

Probe SM level CPV at LHCb Upgrade

V1

Upgrade ?
Backup Slides
Physics Performance Assumptions

Based on LHCb-PUB-2014-040

• Run-2
  • Cross-section increases linearly with $\sqrt{s}$
  • Non-muon trigger efficiency suffers from tighter thresholds and have a factor 2 lower efficiency
    • Does not assume Turbo Stream
  • $2fb^{-1}$ per year, $5fb^{-1}$ in total for run II

• Upgrade
  • Removal of hardware trigger brings factor 2 efficiency boost for non-muon triggered events
    • Charm factor may well be significantly higher
  • $\sim5fb^{-1}$ per year
Sensitivity Prediction Assumptions

Based on M. Gersabeck, LHCb-Talk-2015-039, for IHEP 100 TeV workshop

- **Mixing and CPV** – $A_\Gamma$, $y_{cp}$, WS $K\pi$, $K_{S\pi\pi}$
- **Uses current WA central values from fit**

  - $A_\Gamma$: projection of LHCb 1fb$^{-1}$ D$^*$ tagged
  - WS $K\pi$: projection of LHCb 3fb$^{-1}$
  - $y_{cp}$: projection of LHCb 0.03fb$^{-1}$
  - $K_{S\pi\pi}$: assume same sensitivity per event as Belle

- **$\Delta A_{CP}$**: projection of LHCb 1fb$^{-1}$ prelim. result D$^*$ tagged only

- **D$^0\rightarrow\mu\mu$**: projection of LHCb 1fb$^{-1}$, leptonic trigger – different scaling

In all CPV, mixing D$^*$ tagged only is used in extrapolations
Use of semileptonic B decays, muon tagged, will improve results, and is complementary in systematics
Extrapolations

M. Gersabeck, LHCb-Talk-2015-039, for IHEP workshop

<table>
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<tr>
<th>Run</th>
<th>$\sqrt{s}$ in TeV</th>
<th>$L$ in fb$^{-1}$</th>
<th>$\varepsilon_{\text{trig}}$</th>
<th>$L_{eq}$</th>
<th>$\sum L_{eq}$</th>
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<td>100</td>
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</tr>
</tbody>
</table>

- $L_{eq}$ - Calculate equivalent luminosities to 7 TeV
- Extrapolate signal yields accordingly
- Based on existing Run-I measurements where available
Future Sensitivities

M. Gersabeck, LHCb-Talk-2015-039, for IHEP workshop

• Scaling sensitivities with $\sqrt{N}$
  • Assumes scaling of systematic uncertainties
  • Ignores potential improvements in selections and analyses

| Run | $x \times 10^{-3}$ | $y \times 10^{-3}$ | $|q/p| \times 10^{-3}$ | $\phi$ [mrad] |
|-----|-------------------|-------------------|-----------------------|--------------|
| 1   | 1.22              | 0.53              | 59                    | 89           |
| 2   | 0.92              | 0.37              | 44                    | 70           |
| 3   | 0.42              | 0.15              | 20                    | 33           |
| 4   | 0.25              | 0.09              | 12                    | 20           |