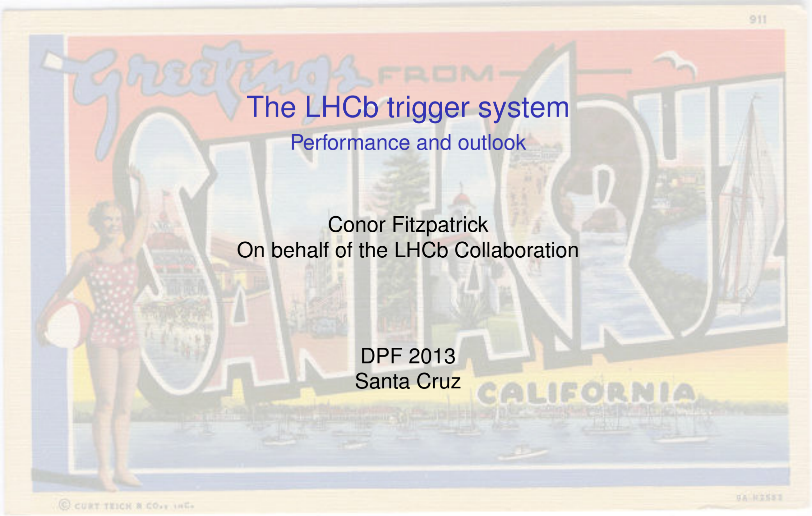


The LHCb trigger system

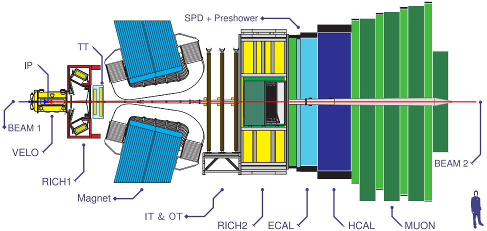
Performance and outlook

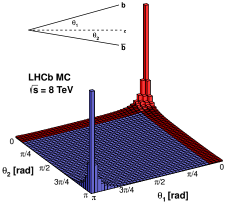
Conor Fitzpatrick
On behalf of the LHCb Collaboration

DPF 2013
Santa Cruz

The LHCb Experiment

- LHCb is a single-arm ($2 < \eta < 5$) spectrometer at the LHC
  - Precision beauty and charm physics: $\mathcal{CP}$ violation measurements, rare decays, heavy flavor production
  - Exploits the correlated production of $b\bar{b}$ pairs in the LHC environment

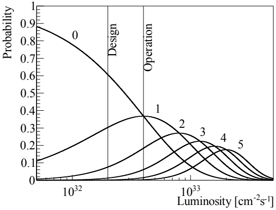




- Time-dependent analyses require good time resolution: ~ 40 fs (VELO)
- Flavor tagging, final state discrimination needs excellent particle ID: (RICH)
- Rare decays and extremely small asymmetries require pure data samples with high signal efficiency: (Trigger)

The LHC environment

- The LHC is a great place to study precision beauty and charm physics, but it isn't easy:

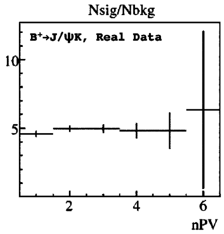


- 40 MHz bunch crossing frequency
- Luminosity
  $\mathcal{L} = 4 \times 10^{32}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
  (2 × design)
- 15 MHz visible pp interaction rate

N_{PV}	1	2	3	>4
$P(\%)$	55	30	11	4

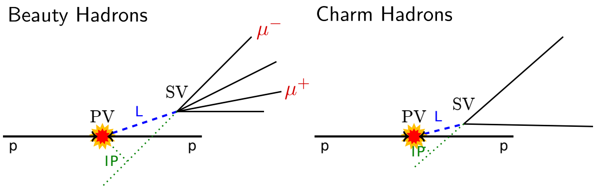
- $\mu \sim 1.6$ interactions per bunch crossing

- $\sigma_{\mathrm{b\bar{b}}} = 75.3 \pm 14.1$ µb [Phys. Lett. B694(2010)]
- $\sigma_{\mathrm{c\bar{c}}} = 1419 \pm 134$ µb [Nucl. Phys. B871 (2013)]
- Corresponds to 30 kHz $\mathrm{b\bar{b}}$ pairs, 600 kHz $\mathrm{c\bar{c}}$ pairs in acceptance.
- Signal purity is independent of pileup:



Typical Signatures

- Beauty and charm hadron typical decay topologies:



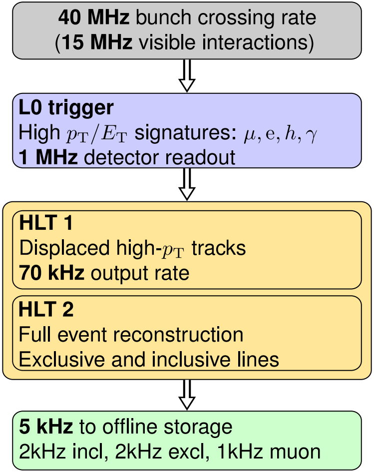
- $\mathrm{B}^{\pm}$ mass $\sim$5.28 GeV, daughter p_{T} $\mathcal{O}(1$ GeV$)$
- $\tau \sim$ 1.6 ps, Flight distance $\sim$ 1 cm
- Important signature: Detached muons from $\mathrm{B} \to \mathrm{J}/\psi X$, $\mathrm{J}/\psi \to \mu\mu$

- D^0 mass $\sim$1.86 GeV, appreciable daughter p_{T}
- $\tau \sim$ 0.4 ps, Flight distance $\sim$ 4 mm
- Also produced as 'secondary' charm from B decays.

Underlying trigger strategy:

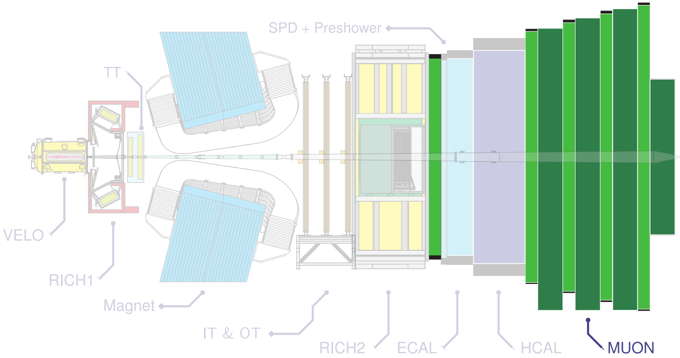
- Inclusive triggering on displaced vertices with high-p_{T} tracks
- Exclusive triggering for anything else

2011-2012 trigger architecture



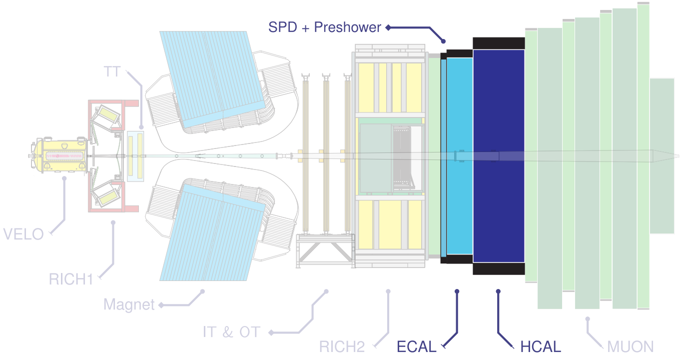
- Trigger consists of three stages:
- Level 0 (L0) near-detector hardware, readout decision in 4 µs
- Higher Level Trigger (HLT) 1&2: flexible software triggers running on dedicated Event Filter Farm (EFF), 29,000 cores
- Documented in [JINST 8 (2013) P04022]

L0 muon trigger



- Momentum resolution $\Delta p/p \sim 20\%$
- Single- and Di-muon triggers: $p_{\rm T} > 1.5$ GeV, $p_{{\rm T}1} \times p_{{\rm T}2} > 1.3$ GeV^2
- 90% efficient for most dimuon channels
- L0 muon rate: 400 kHz

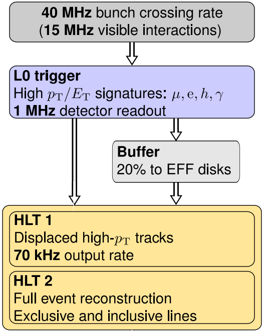
L0 calo trigger



- Selects High E_{T} hadrons, $\mathrm{e}^{\pm}$, γ
- Threshold $E_{\mathrm{T}} > 2.5 - 3.5$ GeV
- Preshower and SPD discriminate between $\mathrm{e}^{\pm}$, γ

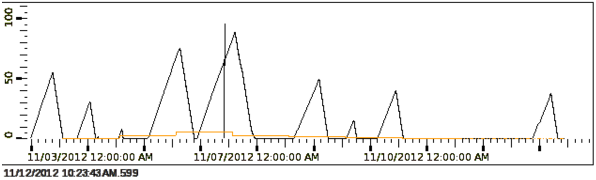
- Hadronic B-decay efficiency 50%
- 80% efficient for radiative $\mathrm{B} \rightarrow \mathrm{X}\gamma$ decays
- L0 $\mathrm{e}^{\pm}/\gamma$ rate: $\sim$150 kHz
- L0 hadron rate: $\sim$450 kHz

Interlude: Deferred trigger



- L0-accepted events are sent to the Event Filter Farm to be processed by the HLT
- Farm nodes idle between fills, large disks (1PB total) not used by HLT software
- Instead: Buffer 20% of L0 events on EFF disks, process in inter-fill time
- Effective 20% Extra CPU allows us to lower tracking thresholds from $p_T = 500 \to 300$ MeV
- Increases efficiency for charm signatures
- Peak disk usage, 88% after $>$ 16h fill

Disk usage as a function of time



- Possible thanks to the ingenuity of the LHCb online team!

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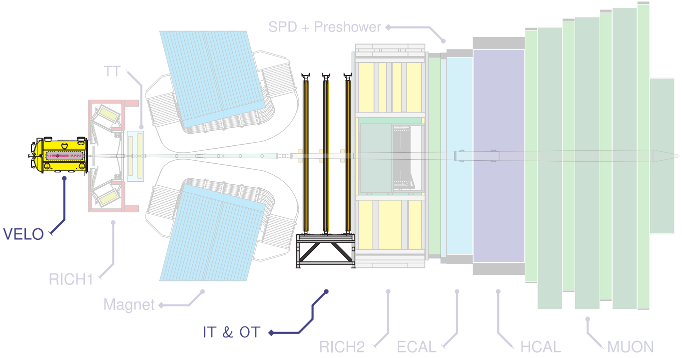
HLT1



- HLT1 Adds tracking and PV information:
- VErtex LOcator (VELO) tracking + PV reconstruction
- Tracks matched to L0muon hits or with large IP are selected for forward tracking into the Inner & Outer trackers (IT&OT)

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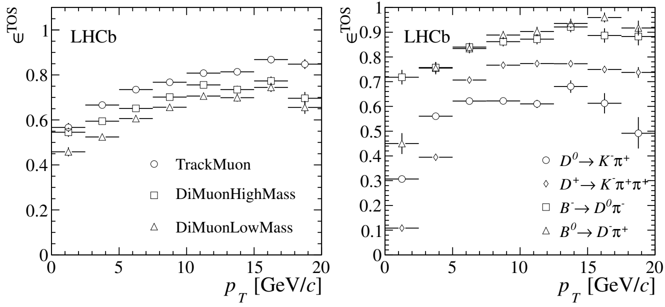
HLT1 forward tracking

- Forward tracking looks for corresponding hits in IT & OT
- p_{T} dependent search windows for single muon, dimuon and high-p_{T} track categories:

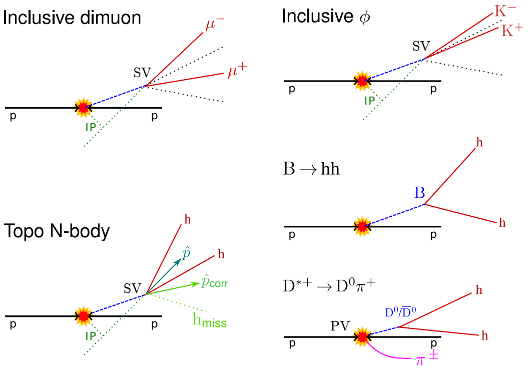
track	μ	$\mu\ \mu$	other
min. p_{T} [GeV]	1.0	0.5	1.6



- HLT1 efficiencies vs. p_{T} [JINST 8 (2013) P04022]
  - left: $\mathrm{B}^+ \to \mathrm{J}/\psi \mathrm{K}^+$ candidates with HLT1 muon triggers
  - right: Hadronic modes

HLT2 Full reconstruction

- HLT2 fully reconstructs the event
- Allows for a range of selection criteria of varying complexity
- Close to offline reconstruction performance
- Combination of Inclusive and Exclusive lines, eg:



- Extremely flexible, powerful software environment: Supports MVA-based selections
- Composition of trigger lines and individual prescales can be adjusted to suit running conditions

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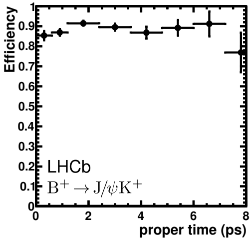
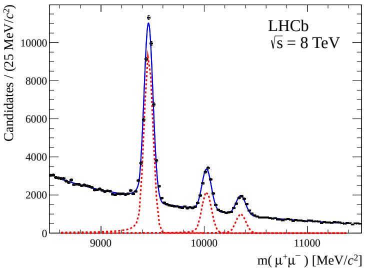
HLT2 inclusive dimuon

- Many important analyses at LHCb have two muons in the final state:
  - Rarest B decay $B_s^0 \to \mu\mu$: [LHCb-PAPER-2013-046]
  - $\not{CP}$ "golden mode" $B_s^0 \to J/\psi\phi$: [PRD87 112010 (2013)]
  - $B^0 \to K^*\mu\mu$: [LHCb-PAPER-2013-037] (in preparation)



- Make use of the same muon ID strategy as offline: [LHCb-DP-2013-001]
- "Prompt and Detached" strategy:
  - Prompt lines avoid lifetime-biasing cuts but are prescaled (unless high p_T)
  - Detached lines use IP cuts to increase purity
- 92% efficient on $B^+ \to J/\psi K^+$ [LHCb-PUB-2011-017]

- Υ spectrum with $\sim 51\text{pb}^{-1}$
- $\sigma(\Upsilon(1S)) \sim 43$ MeV [JHEP 06 (2013) 064]



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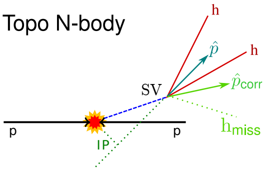
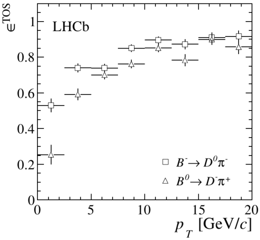
Topological $N-$body lines

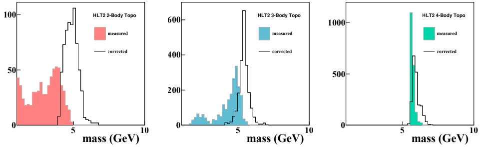




- Inclusive trigger on 2,3,4-body detached vertices [LHCb-PUB-2011-016]
- Primary trigger for B decays to charged tracks
- Uses modified BDT algorithm [JINST 8 (2013) P02013]
- BDT inputs: p_T, $IP\chi^2$, Flight distance $IP\chi^2$, mass and m_{corr}, corrected mass:

$$m_{corr} = \sqrt{m^2 + |p_{\mathrm{T}miss}|^2} + |p_{\mathrm{T}miss}|$$

- $p_{\mathrm{T}miss}$: missing momentum transverse to flight direction



- Very efficient on fully hadronic B decays

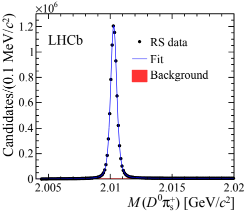
Trigger performance

- Trigger efficiencies for selected channels:

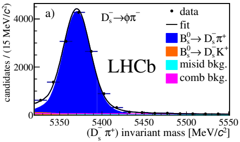
	Hadronic		Dimuon	Radiative
Mode	$D \to hhh$	$B \to hh$	$B^+ \to J/\psi K^+$	$B^0 \to K^*\gamma$
ϵ(L0) [%]	27	62	93	85
ϵ(HLT | L0) [%]	42	85	92	67
ϵ(HLT $\times$ L0) [%]	11	52	84	57

- Extremely pure samples after offline selection:

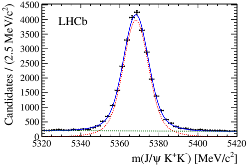
$D^* \to D^0\pi$ [1211.1230]



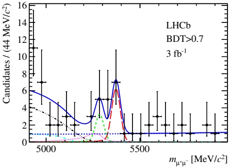
$B_s^0 \to D_s\pi$ [1304.4741]



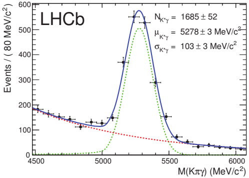
$B_s^0 \to J/\psi\,\phi$ [1304.2600v3]

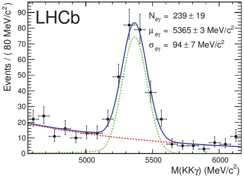


$B_s^0 \to \mu\mu$ [1211.2674]



$B_d^0 \to K^*\gamma$, $B_s^0 \to \phi\gamma$ [1202.6267]





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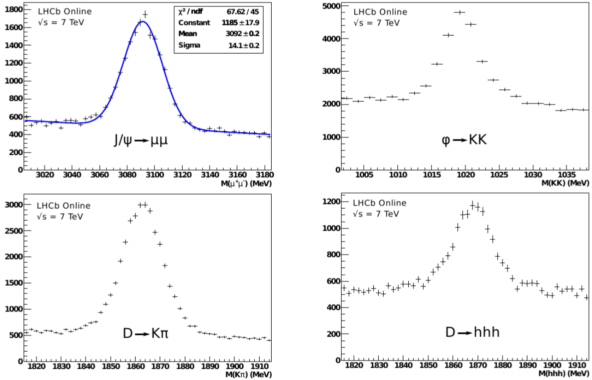
Online Monitoring

- It isn't just offline selected data that is clean:



- Online monitoring plots as seen in the control room, straight from HLT2

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Post-LS1 trigger

- Work is ongoing to improve trigger performance for LHC run 2:

40 MHz bunch crossing rate

⇓

L0 trigger
High $p_{\mathrm{T}}/E_{\mathrm{T}}$ signatures: $\mu, \mathrm{e}, h, \gamma$
1 MHz detector readout

⇓

HLT 1
Displaced high-p_{T} tracks

⇓

Buffer
Detector alignment & calibration

⇓

HLT 2
Full event reconstruction

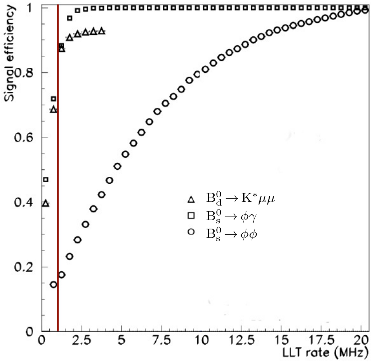
⇓

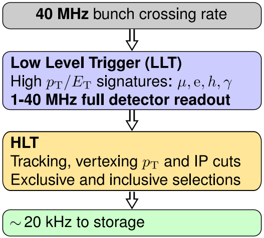
$\sim$12.5 kHz to storage

- Goal: make trigger more compatible with offline analysis environment
- Requires HLT to perform detector alignment and calibration
  - Move buffering to after HLT1
  - Buffer to disk while alignment is performed
  - Run HLT2 after alignment
- Allows us to use selection-level cuts in the trigger
- eg: full RICH PID [EPJC 73 2431], currently used in a limited capacity
- Major advantage: Allows prescaling of Cabbibo-favored charm decays while keeping 100% of DCS.

Upgrade trigger

- Post LHC-upgrade: $\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, L0 trigger becomes the Low-Level Trigger (LLT)
- 1 MHz detector readout becomes a bottleneck, particularly for fully hadronic modes
- Upgrade LHCb will be able to read out full detector at 40 MHz
- Increasing the LLT accept rate greatly improves efficiency
- For more on the LHCb upgrade see `Federico's talk` tomorrow



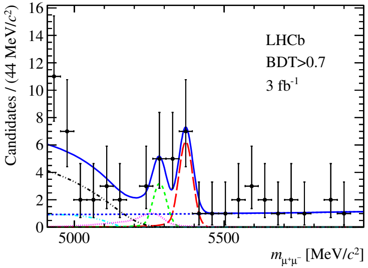


- Initially use LLT to reduce input rate to HLT
- HLT will consist of exclusive/inclusive line strategy similar to present design
- As farm size increases, LLT progressively loosened

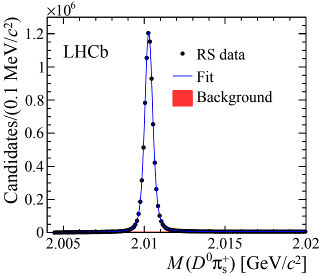
Conclusions

- The LHCb trigger is a powerful and flexible design that covers an extremely wide range

- From the rarest B decay at high efficiency:



- to the largest charm samples at high purity:



- Combination of exclusive and inclusive lines for maximum coverage
- Deferral of trigger makes optimal use of resources
- Exciting prospects for the post-upgrade trigger

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L0 efficiencies

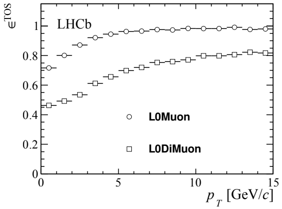

Figure 3. Efficiency $\varepsilon^{\rm TOS}$ of $B^+ \to J/\psi(\ ^+\ ^-)K^+$ as a function of p_T (J/ψ) for `L0Muon` and `L0DiMuon` lines.

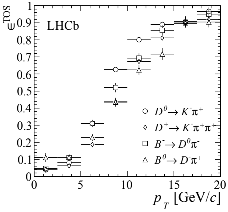

Figure 4. The efficiency $\varepsilon^{\rm TOS}$ of `L0Hadron` is shown for $B^0 \to D^-\pi^+$, $B^- \to D^0\pi^-$, $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ as a function of p_T of the signal B and D mesons.

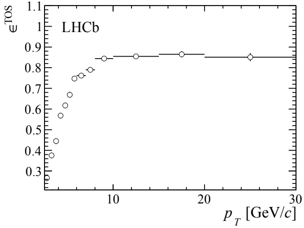

Figure 5. The efficiency $\varepsilon^{\rm TOS}$ of `L0Electron` is shown for $B^0 \to J/\psi(e^+e^-)K^{*0}$ as a function of p_T (J/ψ).

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HLT1 efficiencies

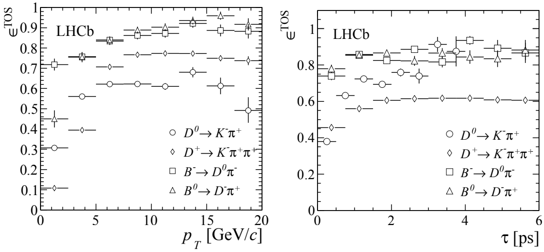

Figure 7. Efficiency ε^{TOS} of `Hlt1TrackAllL0` is shown for $B^- \to D^0\pi^-$, $B^0 \to D^-\pi^+$, $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ as a function of p_T and τ of the B-meson and prompt D-meson respectively.

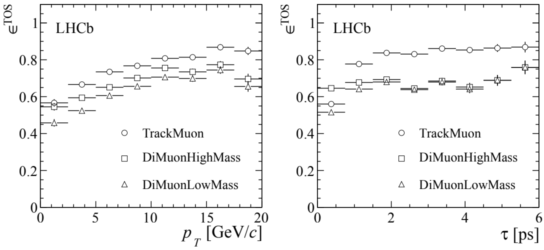

Figure 6. Efficiency ε^{TOS} of `Hlt1TrackMuon`, `Hlt1DiMuonHighMass` and `Hlt1DiMuonLowMass` for $B^+ \to J/\psi(\ ^+\ ^-)K^+$ as a function of the p_T and lifetime of the B^+.

HLT2 μ, charm efficiencies

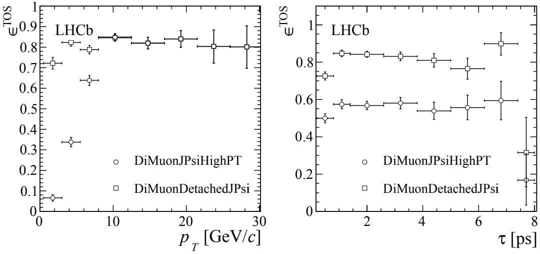

Figure 8. Efficiencies ε^{TOS} of `Hlt2DiMuonJPsiHighPT` and `Hlt2DiMuonDetachedJPsi` for $B^+ \to J/\psi K^+$ as a function of p_T and τ of the B^+.

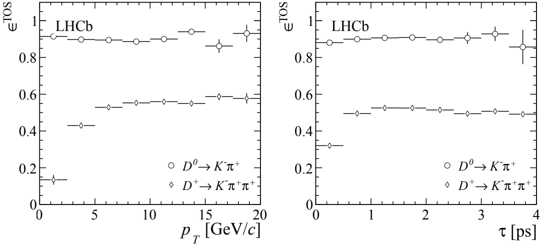

Figure 11. Efficiency ε^{TOS} of the lines `Hlt2CharmHadD2HHH` and `Hlt2CharmHadD02HH_D02KPi` for $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$ respectively as a function of p_T and τ of the D-meson. The efficiency is measured relative to events that are TOS in `Hlt1TrackAllL0`.

HLT2 Topo efficiencies

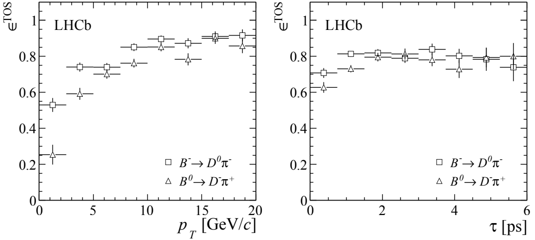

Figure 9. Efficiency $\varepsilon^{\mathrm{TOS}}$ if at least one of the lines `Hlt2TopoNBody`, with $n = 2$‹3, selected the event for $B^- \to D^0\pi^-$ and one of the lines with $n = 2$‹3‹4 for $B^0 \to D^-\pi^+$ as a function of p_T and τ of the B-meson. The efficiency is measured relative to events that are TOS in `Hlt1TrackAllL0`.

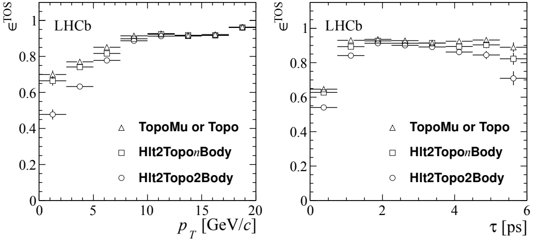

Figure 10. Efficiency $\varepsilon^{\mathrm{TOS}}$ if at least one of the lines `Hlt2TopoNBody` or `Hlt2TopoMuNBody`, with $n = 2$‹3, selected events for $B^+ \to J/\psi K^+$, as a function of p_T and τ of the B-meson. Also shown is $\varepsilon^{\mathrm{TOS}}$ if the line `Hlt2TopoNBody`, with $n = 2$‹3, selected the events. `Hlt2Topo2Body` shows the inclusive performance of the topological lines. The efficiency is measured relative to events that are TOS in either `Hlt1TrackAllL0` or `Hlt1TrackMuon`.

The LHCb dataset