Rare & Strange with the LHCb trigger

Conor Fitzpatrick on behalf of the LHCb HLT group

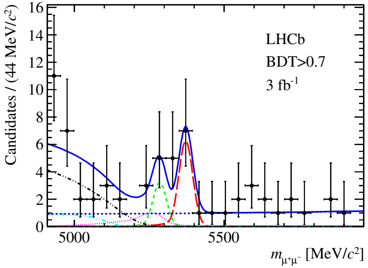
Rare'n'Strange Workshop, CERN

The LHCb Trigger

- The LHCb trigger is a flexible 3-stage system covering the extremely broad LHCb core physics program:

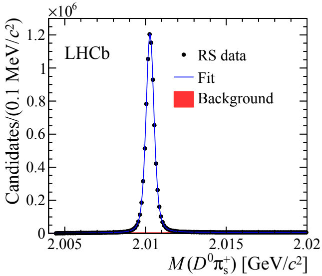
- The rarest B decays at high efficiency:

$B_s^0 \to \mu\mu$: [PRL 111, 101805 (2013)]



- The largest charm samples at high purity:

$D^* \to D^0\pi$: [PRL 110, 101802 (2013)]



- This talk will describe the present LHCb trigger, plans for the future and prospects for K_S^0 decays

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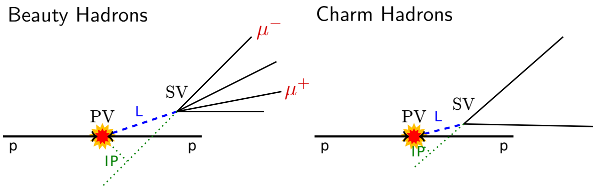
Typical Signatures

- The LHCb trigger is optimised for beauty and charm hadron topologies:



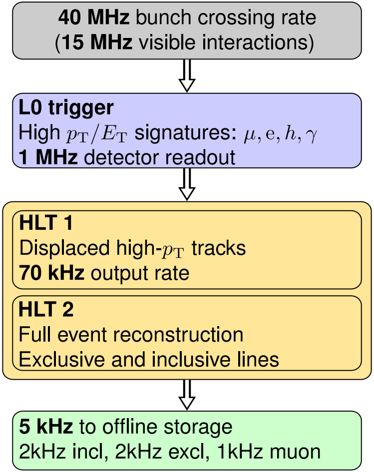
- $\mathrm{B}^{\pm}$ mass ~ 5.28 GeV, daughter p_{T} $\mathcal{O}(1$ GeV$)$
- $\tau \sim 1.6$ ps, Flight distance ~ 1 cm
- Important signature: Detached muons from $\mathrm{B} \to \mathrm{J}/\psi X$, $\mathrm{J}/\psi \to \mu\mu$

- D^0 mass ~ 1.86 GeV, appreciable daughter p_{T}
- $\tau \sim 0.4$ ps, Flight distance ~ 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]

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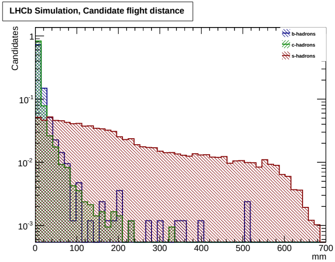
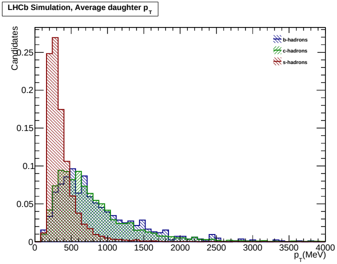
How do strange decays fit in?

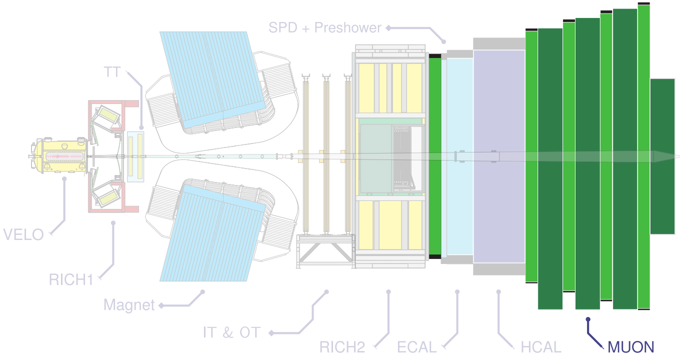
- As background! On average, one in every three events at $\sqrt{s} = 7$ TeV contained a reconstructible $K_S^0 \to \pi\pi$ decay in LHCb
- This is far beyond our resources to keep with high efficiency
- Compared to beauty and charm signals, strange decays have very different signatures:
  - Much longer flight distances
  - Much lower daughter p_T





- p_T thresholds in the trigger are essential to keep rates down, not just for backgrounds, but for signal too.
- Over the next few slides I will describe the trigger lines relevant to $K_S^0 \to \mu\mu$ and their limitations
- Efficiency estimates are from CERN-STUDENTS-Note-2013-151

L0 muon trigger



- Momentum resolution $\Delta p/p \sim 20\%$
- Single- and Di-muon triggers: $p_{\mathrm{T}} > 1.5$ GeV, $p_{\mathrm{T}1} \times p_{\mathrm{T}2} > 1.3$ GeV^2
- Typically 90% efficient for dimuons from B, J/ψ, Υ
- 16% efficient with respect to offline selected $\mathrm{K^0_S} \to \mu\mu$
- L0 muon rate: 400 kHz

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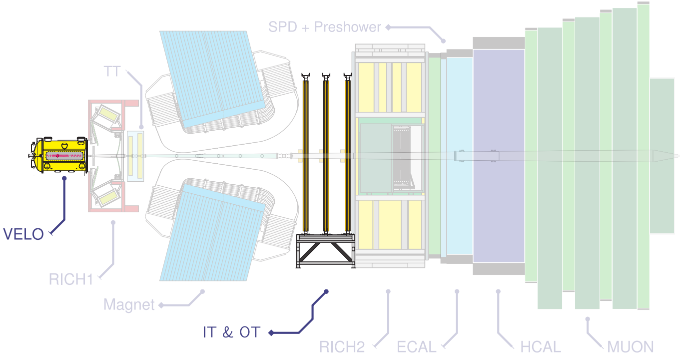
HLT1

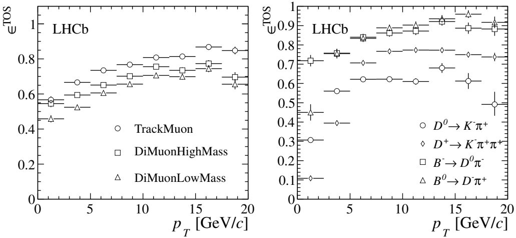


- HLT1 Adds tracking and PV information:
- VErtex LOcator (VELO) tracking + PV reconstruction
- Tracks matched to L0muon hits or with large IP are selected for forward tracking into the Inner & Outer trackers (IT&OT)

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
- For $\mathrm{K}^0_{\mathrm{S}} \to \mu\mu$ the efficiency with respect to L0 accepted candidates is $\sim$21%
- Reducing the p_{T} threshold on the dimuon line to 350 MeV would greatly improve $\mathrm{K}^0_{\mathrm{S}}$ efficiency but leads to 10% increase in timing.
- This was not possible in 2012, and not planned for post-LS1 startup

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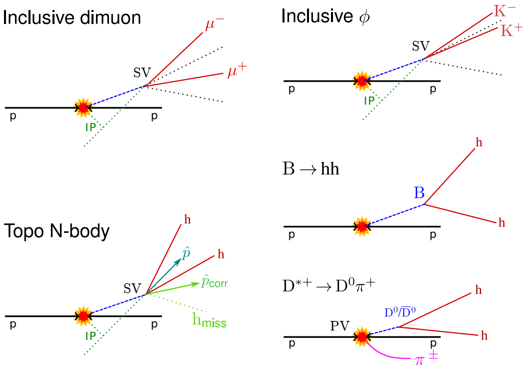
HLT2 Full reconstruction

- 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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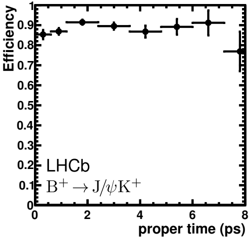
HLT2 muon lines

- Several HLT2 lines trigger on muons, but output rates are critical at HLT2



- Makes 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]

- For the $K^0_S \to \mu\mu$ paper HLT2 was the major efficiency loss:
  - HLT2 dimuon lines had explicit mass requirements incompatible with K^0_S for 2011 data.
  - Single muon 73% efficient on HLT1 accepted $K^0_S \to \mu\mu$ but prescaled by 50%
- From 2012 data taking onwards a low mass dimuon line compatible with K^0_S has been included.
- This results in a factor of 3 increase in trigger efficiency for $K^0_S \to \mu\mu$

Total trigger efficiencies

- For the $\mathrm{K^0_S} \to \mu\mu$ 1fb^{-1}paper the total trigger efficiency was $\sim$0.8% with respect to offline selection
- The addition of a low mass HLT2 dimuon trigger improves this to $\sim$2.4%
  - This doesn't sound great, but bear in mind: $\mathrm{K^0_S}$ are produced in vast amounts at LHCb
  - The 1fb^{-1}paper set an impressive limit! $< 11 \times 10^{-9}$ @ 95% C. L. JHEP 01 (2013) 090
- A low trigger efficiency can be enhanced by events that your signal didn't trigger on. The $\mathrm{K^0_S} \to \mu\mu$ analysis used two trigger combinations:
  - Trigger On Signal (TOS): Events that were explicitly triggered by signal candidates
  - Trigger Independent of Signal (TIS): Events that were triggered by something else in the event
- For $\mathrm{K^0_S} \to \mu\mu$ the TIS sample alone set a limit 10 times lower than the previous best.
- Channels that suffer from very low TOS efficiencies can still have excellent sensitivity through TIS.

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
  - Buffer to disk after HLT1 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
- For rare strange decays this increased flexibility may be an advantage
- Output rate is also going to increase

- Additional studies are underway to investigate an exclusive dimuon trigger at HLT1

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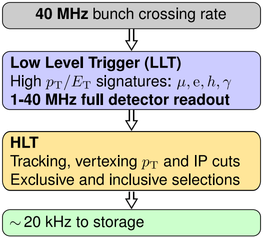
Upgrade trigger

- Post LHC-upgrade: $\mathcal{L} = 2 \times 10^{33}$ cm^{-2} 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

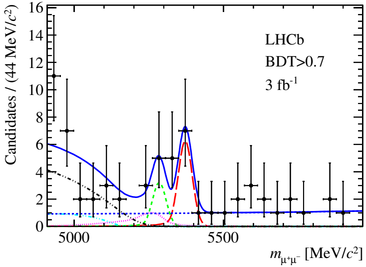


- Initially use LLT to reduce input rate to HLT
- HLT will consist of exclusive/inclusive line strategy similar to present design
- As farm size increases, LLT progressively loosened
- $>$ 1 fully reconstructible $\mathrm{K^0_S} \to \pi\pi$ in our acceptance per event
- The absence of a hardware L0 trigger will be a big boost for $\mathrm{K^0_S}$ efficiencies...
- More work can be done in software to trigger these intelligently

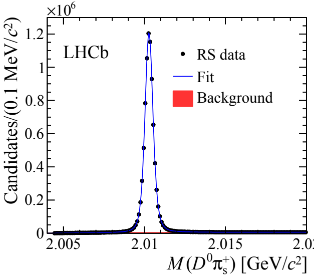
Conclusions

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

- From the rarest B decay at high efficiency:

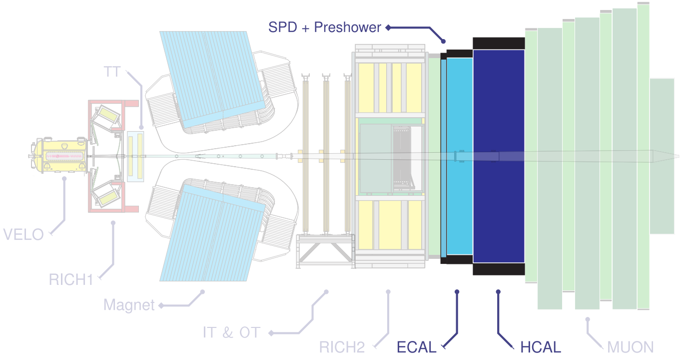


- to the largest charm samples at high purity:



- K_S^0 decays are a challenge to trigger on efficiently within our rate requirements, but:
  - Major improvements have been made since the first fb^{-1} from the HLT2 dimuon line
  - Trigger rates to disk will increase for both run 2 and the upgrade $\rightarrow$ TIS-based selections

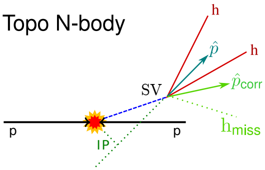
L0 calo trigger



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

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

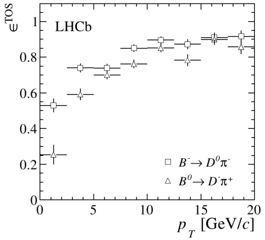
HLT2 Topological N−body lines

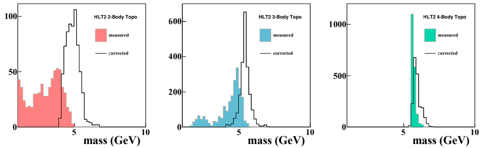


- Inclusive trigger on 2,3,4-body detached vertices [LHCb−PUB−2011−016]
- Primary trigger for B decays to charged tracks
- Uses modified BDT algorithm [JINST 8 (2013) P02013]
- BDT inputs: p_{T}, $IP\chi^2$, Flight distance χ^2, mass and m_{corr}, corrected mass:

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

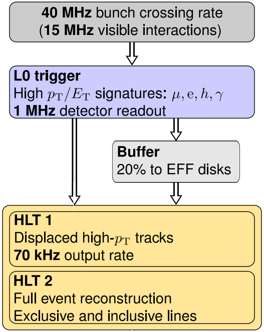
- $p_{\mathrm{T}\,\text{miss}}$: missing momentum transverse to flight direction





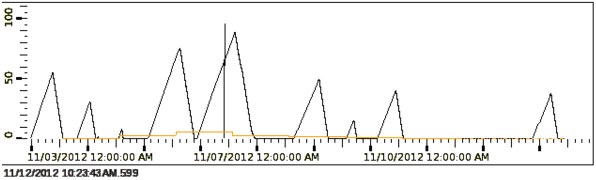
- Very efficient on fully hadronic B decays

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 $p_{\mathrm{T}} = 500 \rightarrow 300$ 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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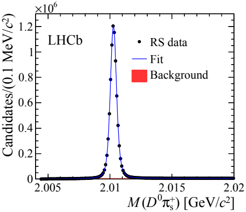
Trigger performance

- Trigger efficiencies for selected channels:

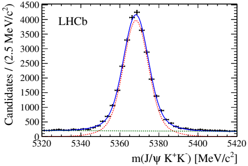
	Hadronic		Dimuon	Radiative
Mode	$D \to hhh$	$B \to hh$	$B^+ \to J/\psi K^+$	$B^0 \to K^*\gamma$
ϵ(L0) [%]	27	62	93	85
ϵ(HLT | L0) [%]	42	85	92	67
ϵ(HLT $\times$ L0) [%]	11	52	84	57

- Extremely pure samples after offline selection:

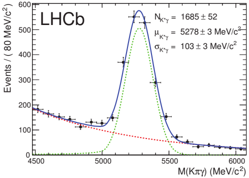
$D^* \to D^0\pi$ [1211.1230]



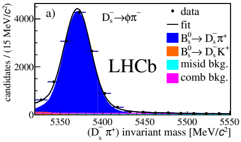
$B_s^0 \to J/\psi\,\phi$ [1304.2600v3]



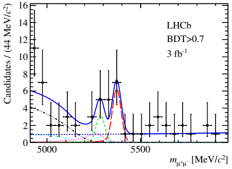
$B_d^0 \to K^*\gamma$, $B_s^0 \to \phi\gamma$ [1202.6267]

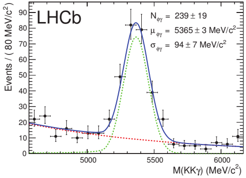


$B_s^0 \to D_s\pi$ [1304.4741]



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





L0 efficiencies

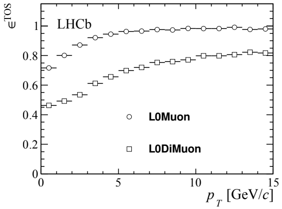


Figure 3. Efficiency ε^{TOS} of $B^+ \to J/\psi(\ ^+\ ^-)K^+$ as a function of p_T (J/ψ) for `L0Muon` and `L0DiMuon` lines.

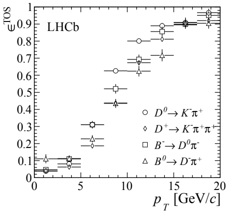


Figure 4. The efficiency ε^{TOS} of `L0Hadron` is shown for $B^0 \to D^-\pi^+$, $B^- \to D^0\pi^-$, $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ as a function of p_T of the signal B and D mesons.

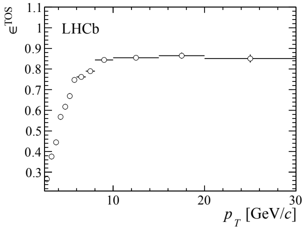


Figure 5. The efficiency ε^{TOS} of `L0Electron` is shown for $B^0 \to J/\psi(e^+e^-)K^{*0}$ as a function of p_T (J/ψ).

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HLT1 efficiencies

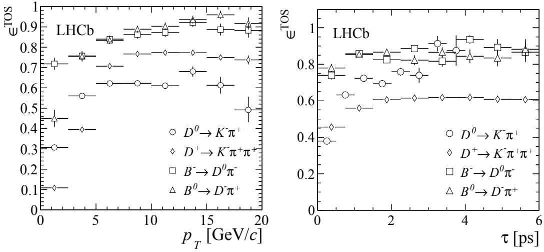

Figure 7. Efficiency $\varepsilon^{\mathrm{TOS}}$ of `Hlt1TrackAllL0` is shown for $B^- \to D^0\pi^-$, $B^0 \to D^-\pi^+$, $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ as a function of p_T and τ of the B-meson and prompt D-meson respectively.

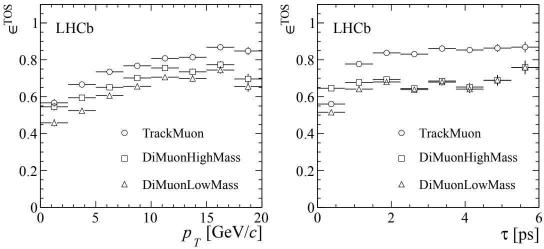

Figure 6. Efficiency $\varepsilon^{\mathrm{TOS}}$ of `Hlt1TrackMuon`, `Hlt1DiMuonHighMass` and `Hlt1DiMuonLowMass` for $B^+ \to J/\psi(\ ^+\ ^-)K^+$ as a function of the p_T and lifetime of the B^+.

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HLT2 μ, charm efficiencies

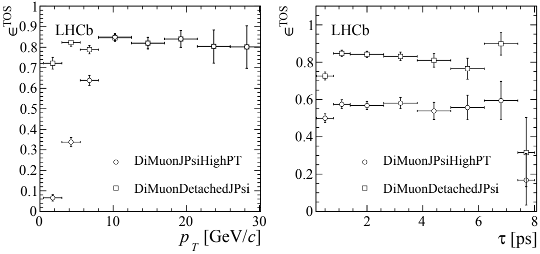


Figure 8. Efficiencies ε^{TOS} of `Hlt2DiMuonJPsiHighPT` and `Hlt2DiMuonDetachedJPsi` for $B^+ \to J/\psi K^+$ as a function of p_T and τ of the B^+.

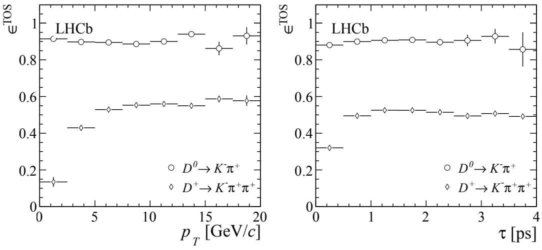


Figure 11. Efficiency ε^{TOS} of the lines `Hlt2CharmHadD2HHH` and `Hlt2CharmHadD02HH_D02KPi` for $D^+ \to K^- \pi^+ \pi^+$ and $D^0 \to K^- \pi^+$ respectively as a function of p_T and τ of the D-meson. The efficiency is measured relative to events that are TOS in `Hlt1TrackAllL0`.

HLT2 Topo efficiencies

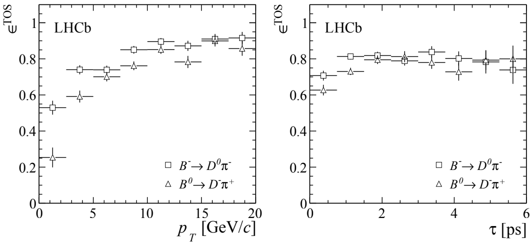


Figure 9. Efficiency ε^{TOS} if at least one of the lines `Hlt2TopoNBody`, with $n = 2‹3$, selected the event for $B^- \to D^0\pi^-$ and one of the lines with $n = 2‹3‹4$ for $B^0 \to D^-\pi^+$ as a function of p_T and τ of the B-meson. The efficiency is measured relative to events that are TOS in `Hlt1TrackAllL0`.

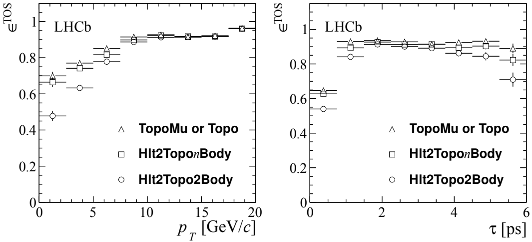
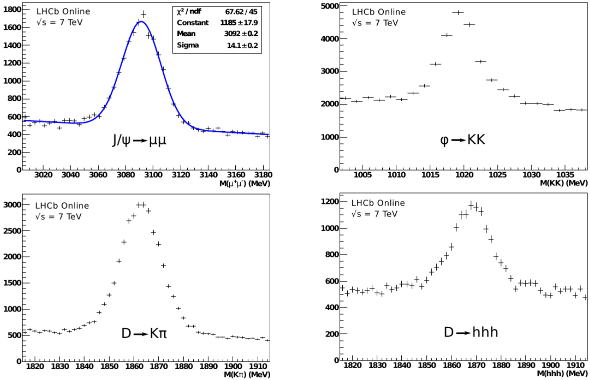


Figure 10. Efficiency ε^{TOS} if at least one of the lines `Hlt2TopoNBody` or `Hlt2TopoMuNBody`, with $n = 2‹3$, selected events for $B^+ \to J/\psi K^+$, as a function of p_T and τ of the B-meson. Also shown is ε^{TOS} if the line `Hlt2TopoNBody`, with $n = 2‹3$, selected the events. `Hlt2Topo2Body`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

Online Monitoring

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



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