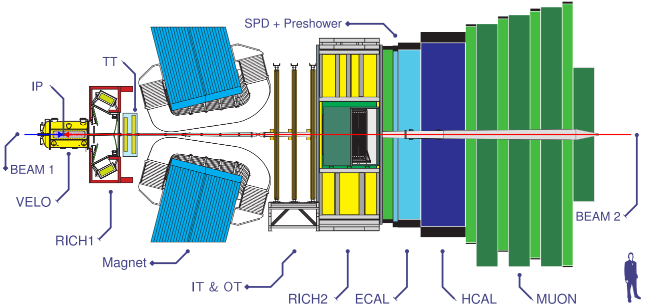
The LHCb trigger in Run 1 and prospects for Run 2

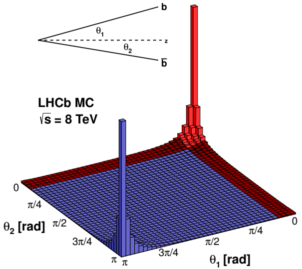
Conor Fitzpatrick
On behalf of the UZH & EPFL LHCb groups

CHIPP plenary, Châtêau de Bossey

The LHCb Experiment

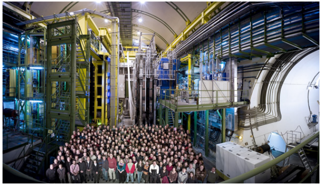
- LHCb is a single-arm ($2 < \eta < 5$) spectrometer at the LHC
  - Precision beauty and charm physics: $\mathcal{CP}$ violation measurements, rare decays, heavy flavor production, spectroscopy, etc.
  - Indirect searches: Complementary physics programme to general purpose experiments
  - Exploits the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

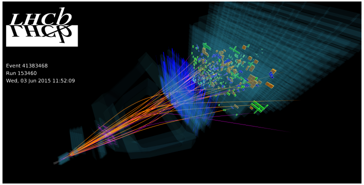


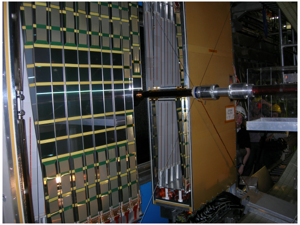


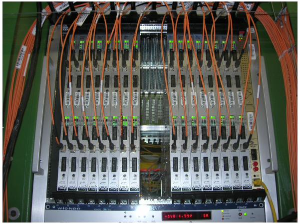
- Decay time-dependent analyses require good time resolution: $\sim$40 fs
- Flavor tagging, final state discrimination needs excellent particle ID
- Rare decays and extremely small asymmetries require pure data samples with high signal efficiency

The CHIPP contribution to LHCb







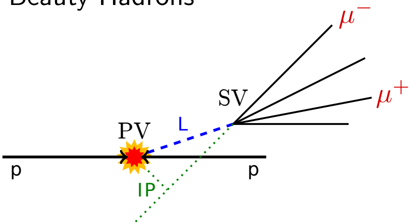


- CHIPP is well represented in LHCb by the UZH and EPFL groups. Run I and II Detector activities include:
  - Silicon tracker: 99.8% hit efficiency with 50 μm resolution
  - Data acquisition electronics: TELL1 high performance readout
  - Flavor tagging to determine B_s^0,B_d^0 flavor at production
  - Higher level trigger development, online calibration & alignment
- See Tim's talk (next) for the CHIPP involvement in the LHCb Upgrade

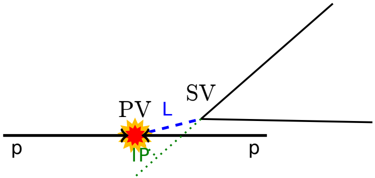
Typical Signatures

- LHCb studies beauty and charm decays. Typical topologies:

Beauty Hadrons



Charm Hadrons



- $B^\pm$ 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 $B \to J/\psi X$, $J/\psi \to \mu\mu$

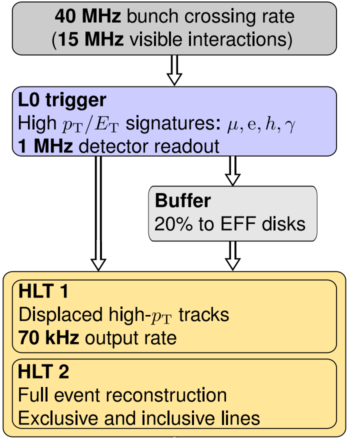
- D^0 mass $\sim$1.86 GeV, appreciable daughter p_T
- $\tau \sim$0.4 ps, Flight distance $\sim$4 mm
- Also produced in B decays.

Underlying trigger strategy:

- Inclusive triggering on displaced vertices with high-p_T tracks
- Exclusive triggering for anything else

C. Fitzpatrick

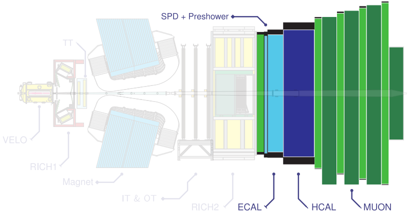
2011-2012 trigger architecture

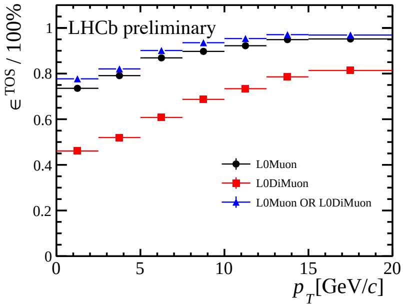


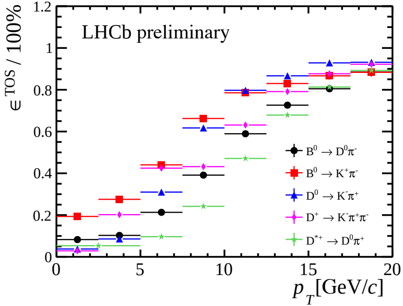
- The Run 1 Trigger consisted of three stages:
- Level 0 (L0) near-detector hardware, readout decision in 4 μs
- In 2012: Disk buffer added: 20% of events from L0 processed in inter-fill time.
- Higher Level Trigger (HLT) 1&2: flexible software triggers running on dedicated Event Filter Farm (EFF), 29,000 cores
- Documented in [JINST 8 (2013) P04022] and [arXiv:1310.8544]

L0 trigger

- L0 hardware trigger in Run I: high p_T and E_T signatures:
- L0 muon:
  - $\Delta p/p \sim 20\%$
  - Single- and Di-muon p_T thresholds
  - 90% efficient for most dimuon channels
- L0 calo: High E_T hadrons, $e^{\pm}$, γ
  - 50% efficient on hadronic B decays
  - 80% efficient for radiative $B \to X\gamma$ decays

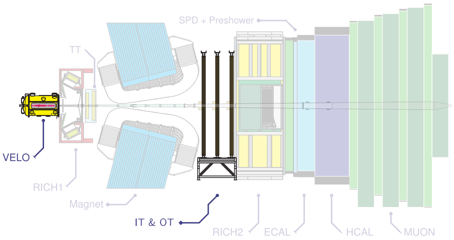




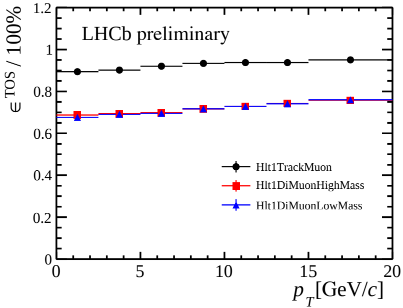


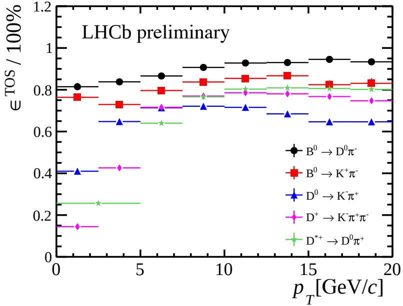
C. Fitzpatrick
June 30, 2015
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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)





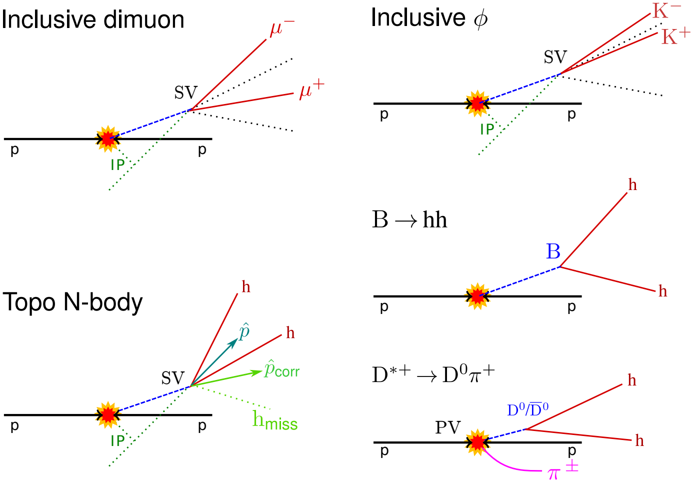
C. Fitzpatrick

June 30, 2015

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

HLT2 Full reconstruction

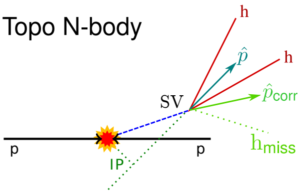
- HLT2 fully reconstructs the event
- Allows for a range of selection criteria of varying complexity
- Close to offline reconstruction performance
- Combination of Inclusive and Exclusive lines, eg:



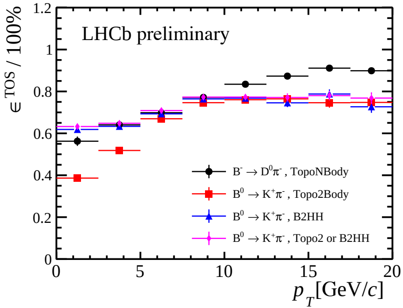
- Extremely flexible, powerful software environment: Supports MVA-based selections

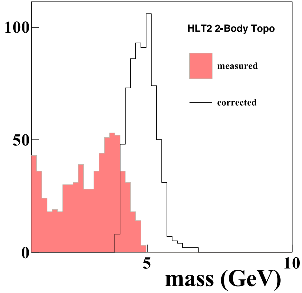
Topological $N-$body lines

Topo N-body



- Inclusive trigger on 2,3,4-body detached vertices [LHCb-PUB-2011-016





- 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:

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

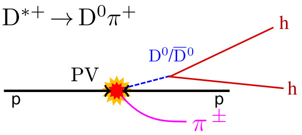
- $p_{T\,miss}$: missing momentum transverse to flight direction
- Primary trigger for B decays to charged tracks

C. Fitzpatrick

June 30, 2015

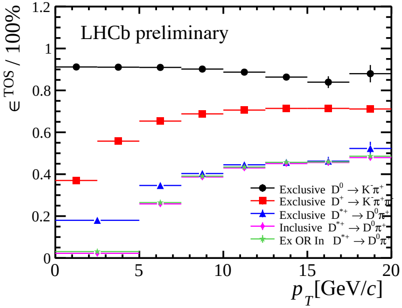
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Inclusive Charm



- Charm is an important part of the LHCb physics programme:
  - Observation of D^0-$\overline{D}^0$ oscillations: [PRL 110 (2013) 101802]
  - Measurement of D^0-$\overline{D}^0$ mixing parameters: [PRL 111 (2013) 251801]

- 600 kHz of $c\bar{c}$ in 2012: Easy to swamp the output bandwidth unless exclusive selections are used
  - Exception: $D^* \to D^0\pi$ inclusive trigger uses $M(D^*) - M(D^0)$ to reduce the rate
  - D^0 inclusively reconstructed in K K, π π, K π, π K final states, any in mass window are kept
- Cabbibo favored $D^0 \to K^-\pi^+$ is ~ 300 times more abundant than Doubly cabbibo suppressed $D^0 \to K^+\pi^-$



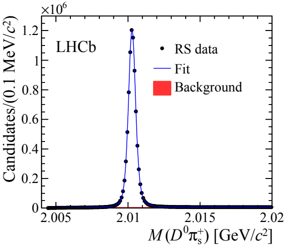
Run I Trigger performance

- Trigger efficiencies for selected channels:

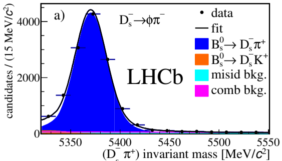
	Hadronic		Dimuon	Radiative
Mode	$D \to hhh$	$B \to hh$	$B^+ \to J/\psi K^+$	$B^0 \to K^*\gamma$
ϵ(HLT $\times$ L0) [%]	11	52	84	57

- Extremely pure samples after offline selection:

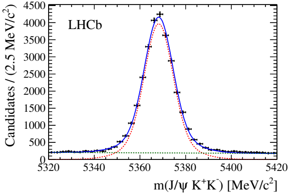
$D^* \to D^0\pi$ [1211.1230]



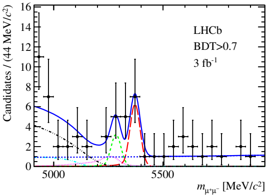
$B^0_s \to D_s\pi$ [1304.4741]



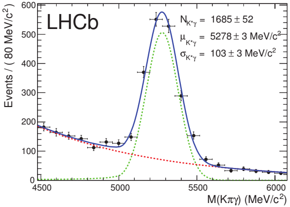
$B^0_s \to J/\psi\phi$ [1304.2600v3]

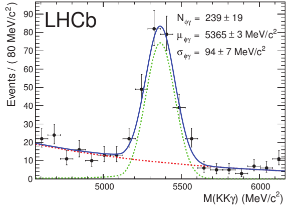


$B^0_s \to \mu\mu$ [1211.2674]



$B^0_d \to K^*\gamma$, $B^0_s \to \phi\gamma$ [1202.6267]





C. Fitzpatrick

June 30, 2015

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

What did CHIPP members do with Run 1 data?

- Too many contributions to show all: I present here some recent highlights
  - Triple product asymmetries in $D^0 \to KK\pi\pi$
  - Observation of $B_s^0 \to \eta'\eta'$
  - The P_5' anomaly in $B^0 \to K^*\mu\mu$
  - Rare decays $B_d^0, B_s^0 \to \mu\mu$
  - EW measurements in proton-proton and proton-lead collisions

C. Fitzpatrick

June 30, 2015

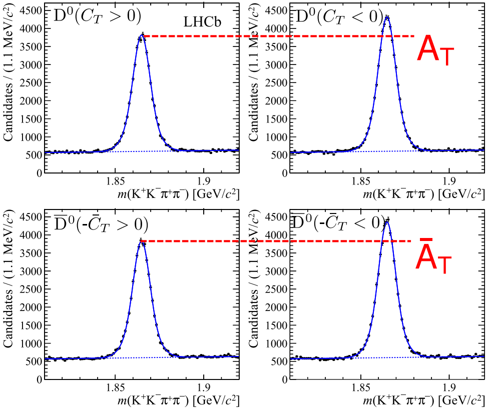
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

$D^0 \to K^+K^-\pi^+\pi^-$

- T-odd correlation asymmetry: Complementary measurement to direct CPV
- 4-body final state needed to define basis for triple-product asymmetries:

$$C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}), \qquad \bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$$

- LHCb measurement JHEP 10(2014) 005: $D^0/\overline{D}^0$ tagged using muon from semileptonic $B \to D^0\mu X$ decays



- A_T, $\bar{A}_T$ asymmetries not so clean due to FSI
- CPV asymmetry: $a_{CP}^{T-odd} = (A_T - \bar{A}_T)/2$ very clean due to cancellation
- $a_{CP}^{T-odd}(D^0) = [1.8 \pm 2.9(\text{stat}) \pm 0.4(\text{syst})] \times 10^{-3}$
- consistent with 0 CPV

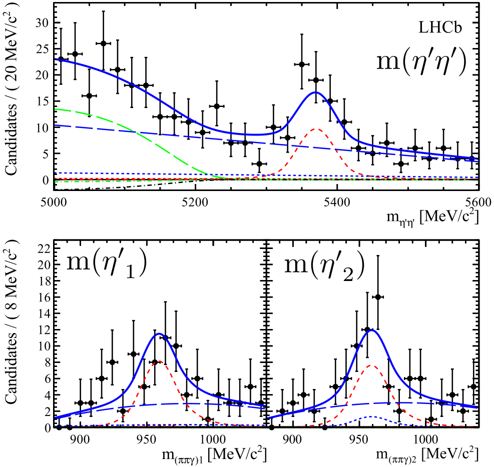
C. Fitzpatrick

June 30, 2015

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

$B_s^0 \to \eta'\eta'$

- Never-before seen, pure CP eigenstate sensitive to CP violation in interference between mixing and decay
- arXiv:1503.07483: First observation and BF using $B^\pm \to \eta' K^\pm$ control channel

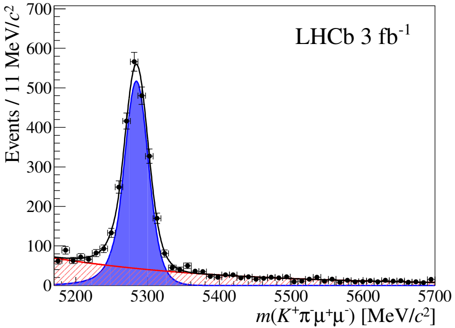


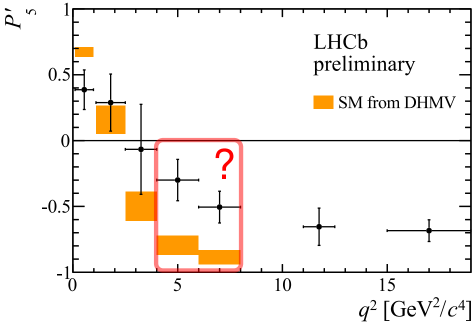
- $\eta' \to \pi^+\pi^-\gamma$ final state
- 3D fit to B_s^0, 2x η' mass distributions
- 6.4σ observation with ~ 36 signal candidates
- Charge asymmetry measurements of $B^\pm \to \eta' K^\pm$, $B^\pm \to \phi K^\pm$ control channels consistent with SM predictions
- Excellent prospects for a future CPV measurement

$\mathcal{B}(B_s^0 \to \eta'\eta') = [3.31 \pm 0.64(\text{stat}) \pm 0.28(\text{syst}) \pm 0.12(\text{BF})] \times 10^{-5}$ Accepted to PRL

$B^0 \to K^* \mu\mu$

- $B^0 \to K^* \mu\mu$ is sensitive to NP in $b \to s\ell^+\ell^-$ FCNC processes
- Rates, asymmetries and angular distributions sensitive to NP
- Experimentally clean channel with high efficiency at LHCb

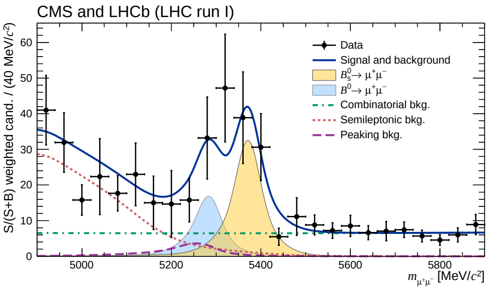


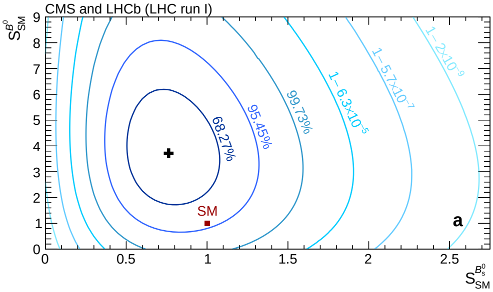


- Full angular analysis LHCb-CONF-2015-002, using 2398 ± 57 signal candidates.
- P_5': Sensitive to NP in V or A couplings.
- Theoretically cleanest observable due to form factor cancellation.
- 3.7σ local tension between measurement and SM prediction

$B \to \mu\mu$

- $B_s^0 \to \mu\mu$ is highly suppressed in the SM, BR precisely predicted: $(3.66 \pm 0.23) \times 10^{-9}$
- New physics processes could substantialy enhance the BR: Deviation from the SM BR is a smoking gun for NP!
- Combination of CMS & LHCb analyses, nature 522 (2015) 68:

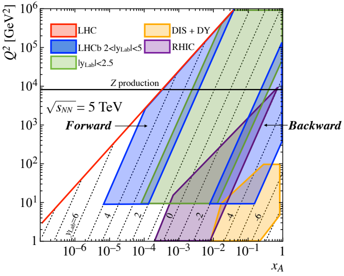


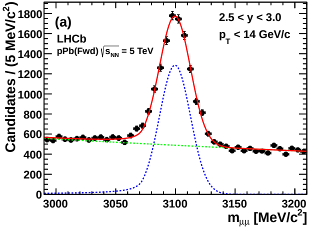


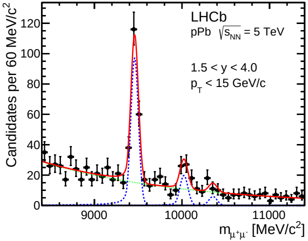
- Observation of the rarest B_s^0 decay, $B_s^0 \to \mu\mu$ (6.2σ), with evidence of $B_d^0 \to \mu\mu$ (3.2σ)
- Consistent with SM at 2σ: Plenty of room for improvement in Run II

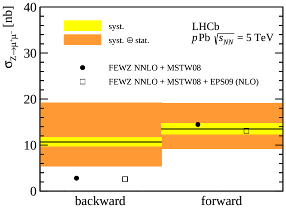
Proton-ion measurements

- LHCb isn't just about beauty and charm! LHCb covers a unique region of pA phase space
- Very successful 5 TeV proton-lead and lead-proton data taking period in run 1 with 1nb^{-1} forward and 0.5nb^{-1} backward data





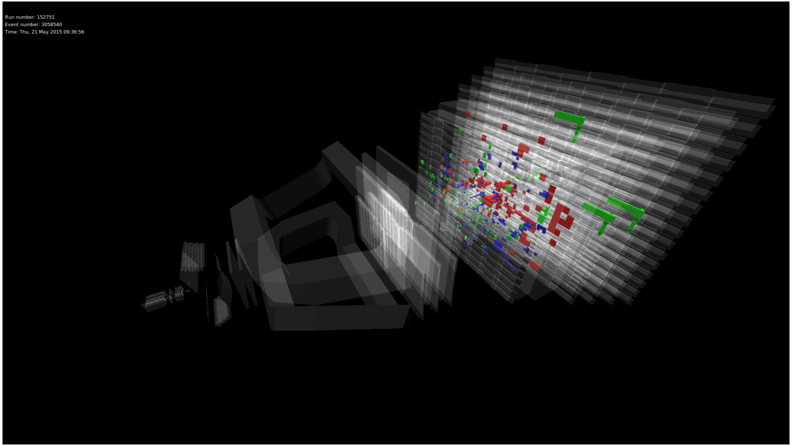




- J/ψ JHEP 02(2014) 072 and Υ JHEP 07(2014) 094 production studies, Z production JHEP 09 (2014) 030
- Plans to take lead-lead as well as proton-lead measurements in Run 2.

Run II

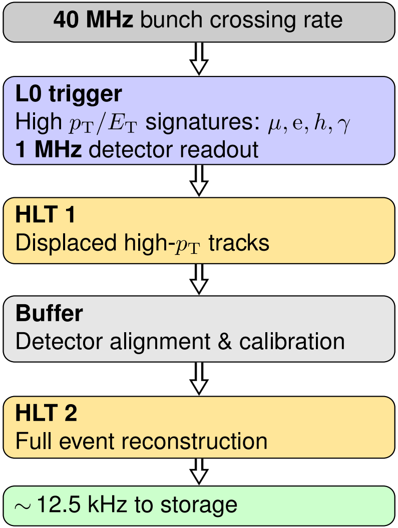
- LHCb is ready for Run II!



- No significant changes to the detector, but the trigger architecture has been improved

Run II trigger

- $8 \rightarrow 13$ TeV: Higher b, c cross sections and a larger physics programme



- Goal: make trigger more compatible with offline analysis environment
- Requires HLT to perform detector alignment and calibration
  - Move buffering to after HLT1: Buffer at kHz instead of MHz
  - Buffer to disk while alignment is performed
  - Run HLT2 after alignment
- Allows us to use selections similar to offline:
- 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.

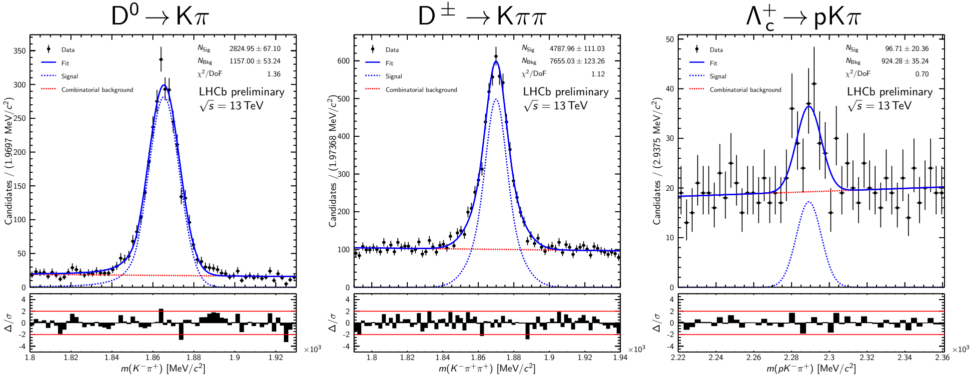
The turbo stream

- Offline-quality distributions straight from the trigger means no need to reprocess
- Turbo stream: Remove raw event, use candidates built by trigger for analysis
- Our limitation is bandwidth, not event rate, so smaller events means more events:

- LHCb full stream event size is $\sim$70kB. Trigger candidates + Primary Vertices are only $\sim$5kB
- In Run II a large fraction of the charm physics program will be covered by the turbo stream.

First data from Run II

- The Turbo stream is already producing signals with the first collisions at 13 TeV!
- Low-intensity run taken on 05/06/2015:

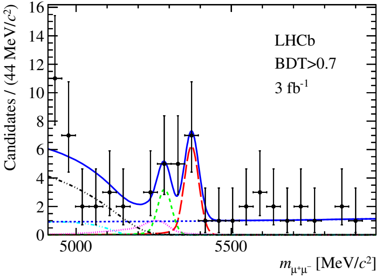


- Early Run II measurements are already underway. Expect results at EPS

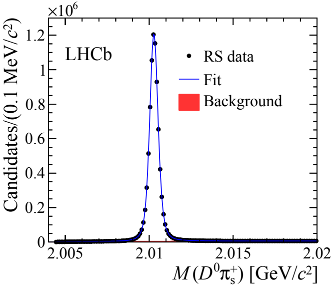
Conclusions

- The LHCb Run I trigger covered an extremely wide range in a challenging environment:

- From the rarest B decay at high efficiency:



- to the largest charm samples at high purity:

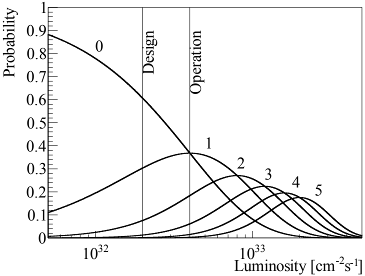


- Run II builds on the successes of Run I, introducing several new features:
  - Disk buffering for calibration and alignment
  - Turbo stream for high rate analyses

Thank you for listening!

The Run I LHC environment

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

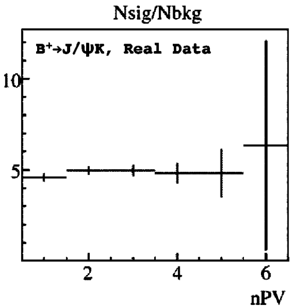


- 40 MHz bunch crossing frequency
- Luminosity $\mathcal{L} = 4 \times 10^{32}\text{cm}^{-2}\,\text{s}^{-1}$ (2 × design)
- 15 MHz visible pp interaction rate

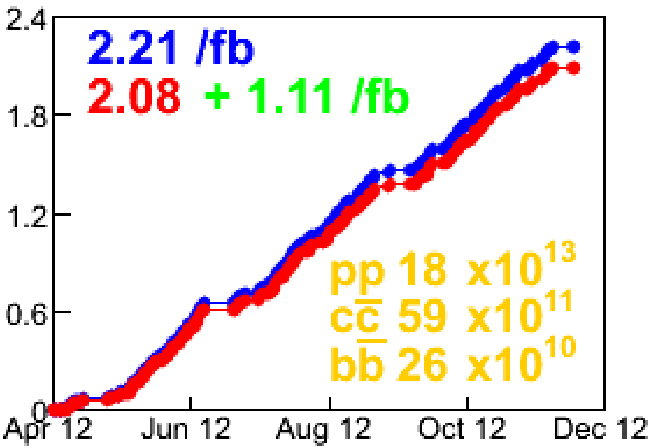
N_{PV}	1	2	3	> 4
$P(\%)$	55	30	11	4

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

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

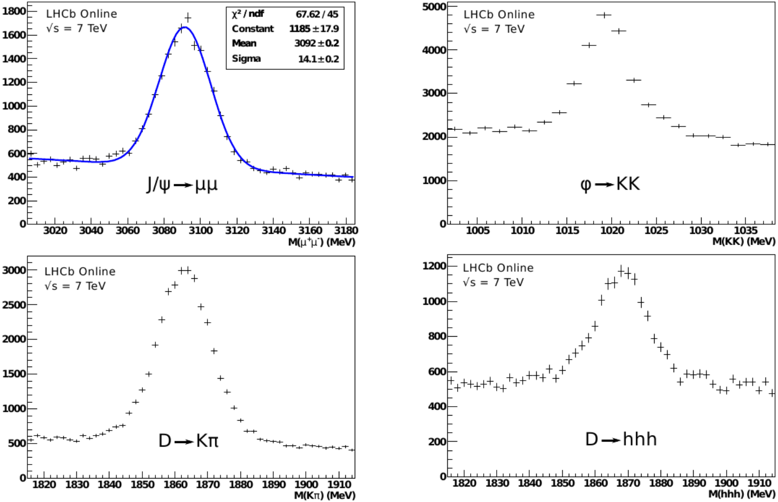


The LHCb Run I dataset



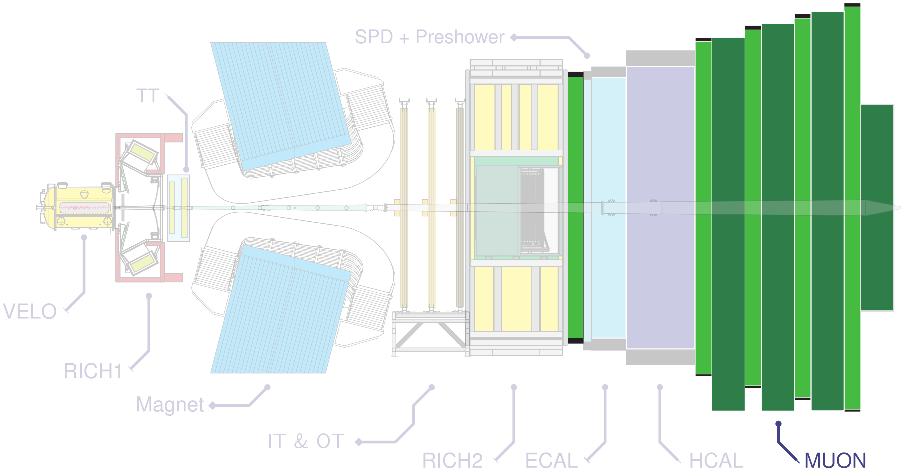
Run I Online Monitoring

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



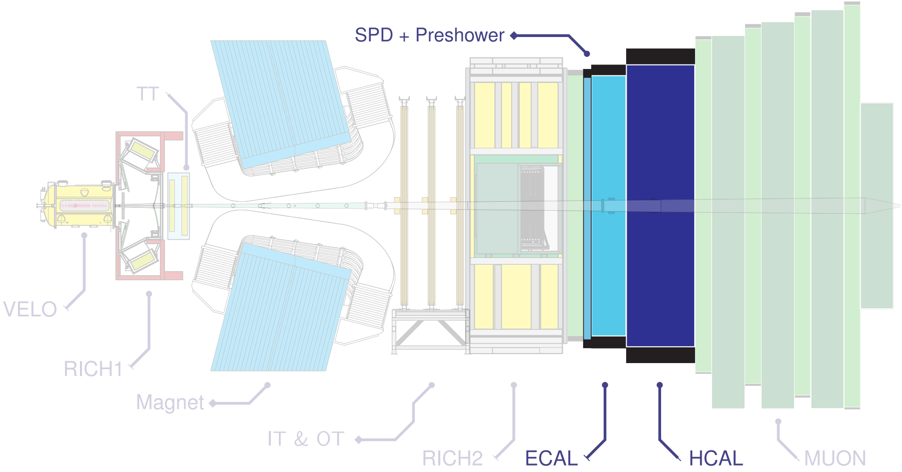
- Online monitoring plots as seen in the control room, straight from HLT2

L0 muon trigger



- Momentum resolution $\Delta p/p \sim 20\%$
- Single- and Di-muon triggers: $\mathrm{p_T} > 1.5$ GeV, $\mathrm{p_{T1}} \times \mathrm{p_{T2}} > 1.3$ GeV^2
- 90% efficient for most dimuon channels
- L0 muon rate: 400 kHz

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

Run I L0 efficiencies

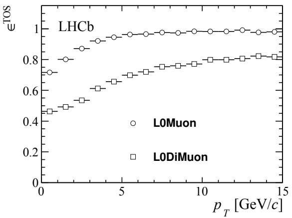


Figure 3. Efficiency ε^{TOS} of $B^+ \to J/\psi(\ ^+\ ^-)K^+$ as a function of p_T (J/ψ) for `L0Muon` and `L0DiMuon` lines.

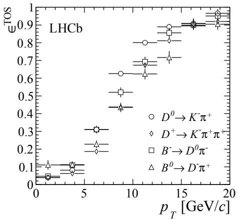


Figure 4. The efficiency ε^{TOS} of `L0Hadron` is shown for $B^0 \to D^-\pi^+$, $B^- \to D^0\pi^-$, $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ as a function of p_T of the signal B and D mesons.

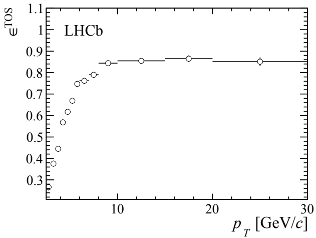


Figure 5. The efficiency ε^{TOS} of `L0Electron` is shown for $B^0 \to J/\psi(e^+e^-)K^{*0}$ as a function of p_T (J/ψ).

Run I HLT1 efficiencies

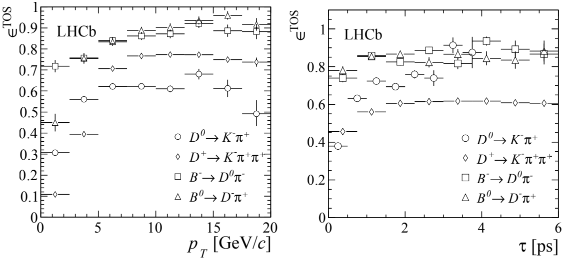


Figure 7. Efficiency ε^{TOS} of `Hlt1TrackAllL0` is shown for $B^- \to D^0\pi^-$, $B^0 \to D^-\pi^+$, $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ as a function of p_T and τ of the B-meson and prompt D-meson respectively.

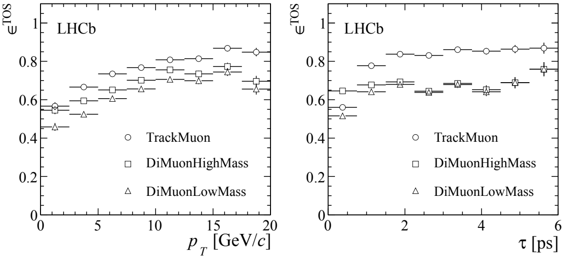
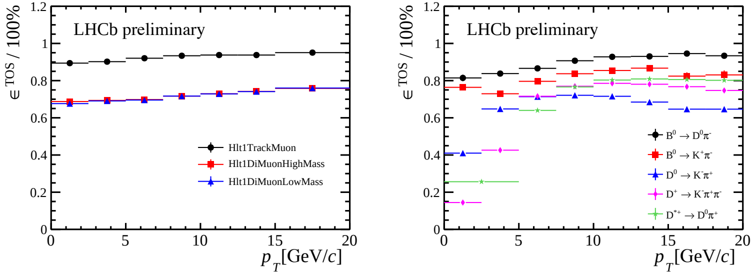


Figure 6. Efficiency ε^{TOS} of `Hlt1TrackMuon`, `Hlt1DiMuonHighMass` and `Hlt1DiMuonLowMass` for $B^+ \to J/\psi(\ ^+\ ^-)K^+$ as a function of the p_T and lifetime of the B^+.

Run I HLT1 forward tracking

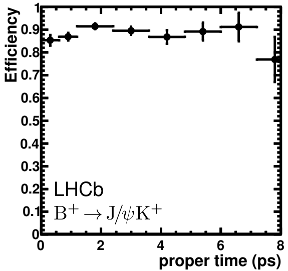
- Forward tracking looks for corresponding hits in IT & OT
- p_T dependent search windows for single muon, dimuon and high-p_T track categories:

track	μ	$\mu\,\mu$	other
min. p_T [GeV]	1.0	0.5	1.6



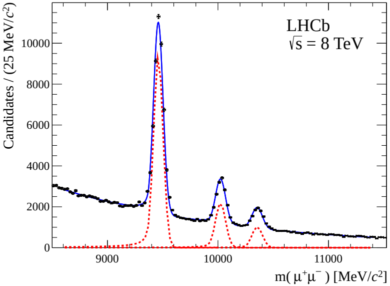
- HLT1 efficiencies vs. p_T [JINST 8 (2013) P04022]
  - left: $B^+ \to J/\psi K^+$ candidates with HLT1 muon triggers
  - right: Hadronic modes

Run I HLT2 inclusive dimuon



- Makes use of 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 $\sim 51 \text{pb}^{-1}$
- Offline $\sigma(\Upsilon(1S)) \sim 43$ MeV [JHEP 06 (2013) 064]



Run I HLT2 μ, charm efficiencies

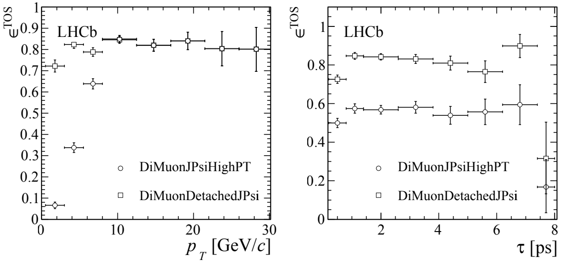


Figure 8. Efficiencies ε^{TOS} of `Hlt2DiMuonJPsiHighPT` and `Hlt2DiMuonDetachedJPsi` for $B^+ \to J/\psi K^+$ as a function of p_T and τ of the B^+.

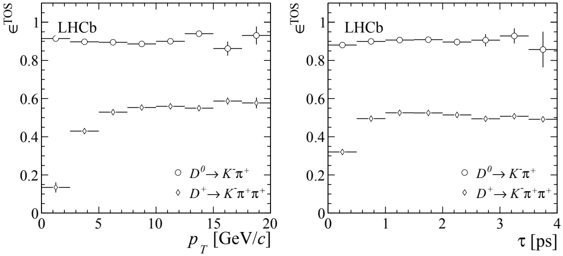


Figure 11. Efficiency ε^{TOS} of the lines `Hlt2CharmHadD2HHH` and `Hlt2CharmHadD02HH_D02KPi` for $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$ respectively as a function of p_T and τ of the D-meson. The efficiency is measured relative to events that are TOS in `Hlt1TrackAllL0`.

Run I HLT2 Topo efficiencies

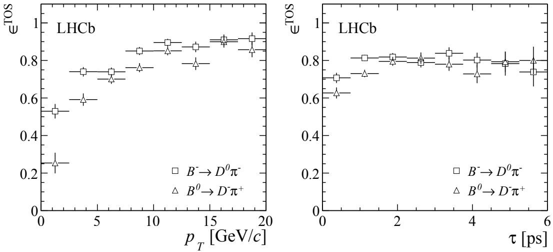


Figure 9. Efficiency ε^{TOS} if at least one of the lines `Hlt2Topo`*n*`Body`, with $n = 2,3$, selected the event for $B^- \to D^0\pi^-$ and one of the lines with $n = 2,3,4$ for $B^0 \to D^-\pi^+$ as a function of p_T and τ of the B-meson. The efficiency is measured relative to events that are TOS in `Hlt1TrackAllL0`.

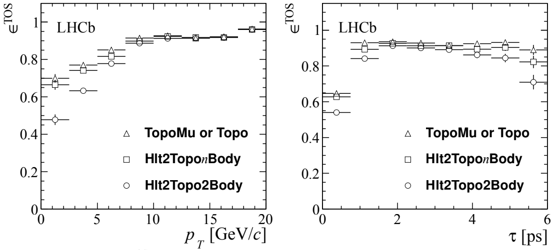
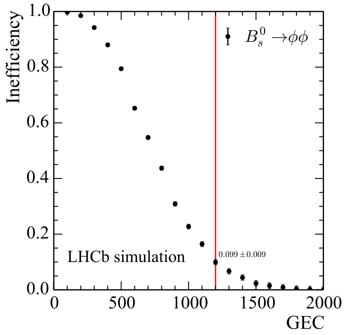
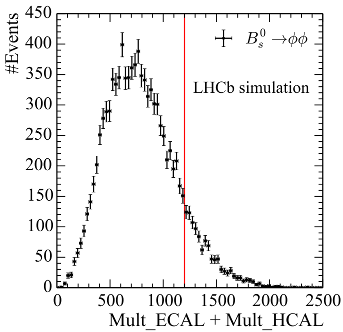


Figure 10. Efficiency ε^{TOS} if at least one of the lines `Hlt2Topo`*n*`Body` or `Hlt2TopoMu`*n*`Body`, with $n = 2,3$, selected events for $B^+ \to J/\psi K^+$, as a function of p_T and τ of the B-meson. Also shown is ε^{TOS} if the line `Hlt2Topo`*n*`Body`, with $n = 2,3$, selected the events. `Hlt2Topo2Body` shows the inclusive performance of the topological lines. The efficiency is measured relative to events that are TOS in either `Hlt1TrackAllL0` or `Hlt1TrackMuon`.

Global Event Cuts

- Very high multiplicity events take disproportionate time to reconstruct
- Global Event Cuts (GECs) are used to remove these events, freeing processing power for low. mult. events
- GEC requires Sum of HCAL + ECAL multiplicities < 1200:





- 10% inefficiency on $B_s^0 \to \phi\phi$ but
- Reduces track reconstruction time by 20% and more than halves the timing of multibody selections
- Reduced timing means looser selection requirements: Higher overall efficiency