The LHCb High Level Trigger

Design Issues for Post Long-Stop 1 Running

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CERN & the University of Cincinnati, on behalf of the LHCb Trigger Team

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Overview

- Progess in charm physics emerges from larger and larger samples.
  - Fully reconstructed open charm samples have increased by more than a **factor of a million** in the past 30 years.
  - To provide context, I will quickly review *part* of the history of measuring mixing and CP violation parameters in the neutral D-meson system.
  - The **LHCb experiment** has collected the largest samples of reconstructed charm, and is poised to increase its statistics by **two orders of magnitude** in the next 10 years. Doing so requires a new trigger strategy.
- The LHCb trigger for exclusive charm worked very well in Run 1.
- Moving into Run 2, the LHCb High Level Trigger (HLT) has been substantially re-engineered.
- In the upgrade era, the **hardware level trigger will be removed** and the HLT will need to do much more work.

From Fermilab Experiment E516

using a “recoil” trigger

VOLUME 52, NUMBER 6 PHYSICAL REVIEW LETTERS 6 FEBRUARY 1984

Study of the Decay $D^0 \to K^- \pi^+ \pi^0$ in High-Energy Photoproduction

D. J. Summers, V. K. Bharadwaj,[a] B. H. Denby, A. M. Eisner,[b] R. G. Kennett,[c]
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and

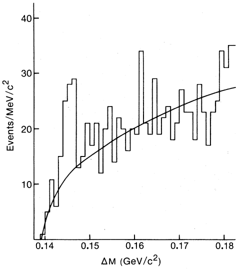

FIG. 2. $\Delta M = M_{K\pi\pi\pi} - M_{K\pi\pi}$ for events with $M_{K^-\pi^+\pi^0}$ within 50 MeV/c^2 of the D^0. The smooth curve is a fit to the background of the form described in the text.

We reported the signal above background to be **39 $\pm$ 8 events, almost 5 σ.**

Search for Mixing, From Fermilab Experiment E691

very open E_T trigger: no mixing or DCS signal, 611 RS $K\pi$ with $t_d > 0.22$ ps

VOLUME 60, NUMBER 13 PHYSICAL REVIEW LETTERS 28 MARCH 1988

Study of D^0-$\bar{D}^0$ Mixing

J. C. Anjos,[3] J. A. Appel,[5] A. Bean,[1] S. B. Bracker,[8] T. E. Browder,[1] L. M. Cremaldi,[4] J. R. Elliott,[4] C. O. Escobar,[7] P. Estabrooks,[2] M. C. Gibney,[4] G. F. Hartner,[8] P. E. Karchin,[1],[a] B. R. Kumar,[8] M. J. Losty,[6] G. J. Luste,[8] P. M. Mantsch,[5] J. F. Martin,[8] S. McHugh,[1] S. R. Nash,[5] U. Nauenberg,[4] P. Ong,[8] J. Pinfold,[2] G. Punkar,[1] M. V. S. Santoro,[3] J. S. Sidhu,[2],[c] K. Sliwa,[5] M. D. Sokoloff,[5],[d] M. H. ,[5] M. E. Streetman,[5] A. B. Stundžia,[8] and M. S. Witherell[1]

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(Received 18 December 1987)

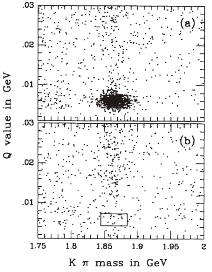

FIG. 1. (a) The scatter plot of $Q = M(K\pi\pi) - M(\pi) - M(K\pi)$ vs $M(K\pi)$ for the $(K^-\pi^+)\pi^+$ sample. There is a requirement that $t > 0.22$ ps. (b) The same plot for $(K^-\pi^+)\pi^-$ events.

mixing using events of the type $D^{*+} \to \pi^+ D^0$, with $D^0 \to K^+\pi^-$ and
time is used to separate mixing from doubly Cabibbo-suppressed decays.
ing in either mode. Combining the results from the two decay modes, we
$_M < 0.0037$ at the 90% confidence level, where r_M is the ratio of wrong-
nt-sign decays. We also present limits on doubly Cabibbo-suppressed de-
possible interference.

Search for Mixing, From Fermilab Experiment E791

open E_T trigger: no mixing or DCS signal, 5643 RS $K\pi$ & 3469 RS $K\pi\pi\pi$.

PHYSICAL REVIEW D VOLUME 57, NUMBER 1 1 JANUARY 1998

Search for D^0-$\overline{D^0}$ mixing and doubly-Cabibbo-suppressed decays of the D^0 in hadronic final states

E. M. Aitala,[9] S. Amato,[1] J. C. Anjos,[1] J. A. Appel,[5] D. Ashery,[15] S. Banerjee,[5] I. Bediaga,[1] G. Blaylock,[8] S. B. Bracker,[16] P. R. Burchat,[14] R. A. Burnstein,[6] T. Carter,[5] H. S. Carvalho,[1] N. K. Copty,[13] L. M. Cremaldi,[9] C. Darling,[19] A. Fernandez,[12] P. Gagnon,[2] C. Gobel,[1] K. Gounder,[9] A. M. Halling,[5] G. Herrera,[4] G. Hurvits,[15] C. James,[5] P. A. Kasper,[6] S. Kwan,[5] D. C. Langs,[11] J. Leslie,[2] B. Lundberg,[5] S. MayTal-Beck,[15] B. Meadows,[3] J. R. T. de Mello Neto,[1] Napier,[17] A. Nguyen,[7] A. B. d'Oliveira,[3,12] K. O'Shaughnessy,[2] K. C. Peng,[6] ı,[9] S. Radeztsky,[18] A. Rafatian,[9] N. W. Reay,[7] J. J. Reidy,[9] A. C. dos Reis,[1] S. Santoro,[1] A. J. Schwartz,[11] M. Sheaff,[18] R. A. Sidwell,[7] A. J. Slaughter,[19] on,[18] D. J. Summers,[9] S. Takach,[19] K. Thorne,[5] A. K. Tripathi,[10] S. Watanabe,[18] Witchey,[7] E. Wolin,[19] D. Yi,[9] S. Yoshida,[7] R. Zaliznyak,[14] and C. Zhang[7]

(Fermilab E791 Collaboration)

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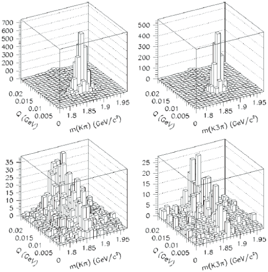

Finally, Evidence for Mixing from BaBar

very open hadronic + EM trigger: $1\,141\,500 \pm 1200$ RS & 4030 ± 90 WS $K\pi$

PRL **98,** 211802 (2007) PHYSICAL REVIEW LETTERS week ending 25 MAY 2007

Evidence for D^0-$\overline{D}^0$ Mixing

B. Aubert,[1] M. Bona,[1] D. Boutigny,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] X. Prudent,[1] V. Tisserand,[1] A. Zghiche,[1]
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O. Long ... agnari,[16]
A. Cunha, ... J. Flacco,[17]
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M. G. W ... itenko,[18]
F. C. Porte ... S. Chen,[20]
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D. D. Alter ... T. Brandt,[23]
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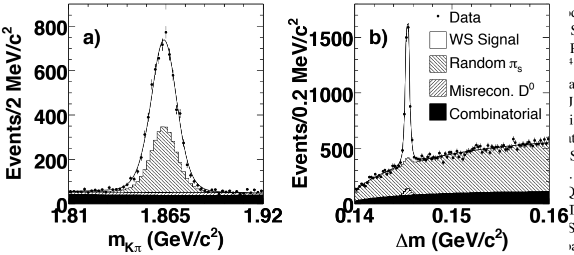
C. Bozzi,[26] R. Calabrese,[26] A. Cecchi,[26] G. Cibinetto,[26] P. Franchini,[26] E. Luppi,[26] M. Negrini,[26] A. Petrella,[26]



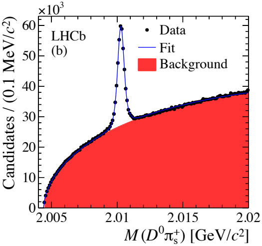
Charm Mixing and CPV from LHCb

exclusive triggers; ≈ 54 M “right-sign” and ≈ 230 K “wrong-sign”

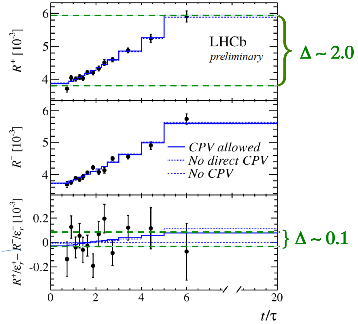
$D^0 \rightarrow K\pi$ Mixing and CPV Measurements at LHCb

$$\mathbf{R}^{\pm}(\mathbf{t}) \equiv \frac{\mathbf{WS}(\mathbf{t})}{\mathbf{RS}(\mathbf{t})} = \mathbf{R}_{\mathbf{D}}^{\pm} + \sqrt{\mathbf{R}_{\mathbf{D}}^{\pm}}\,\mathbf{y}'^{\pm}\left(\frac{\mathbf{t}}{\tau}\right) + \left(\frac{\mathbf{x}'^{\pm 2} + \mathbf{y}'^{\pm 2}}{\mathbf{4}}\right)\left(\frac{\mathbf{t}}{\tau}\right)^{\mathbf{2}}$$

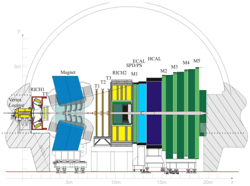
- Measure the WS/RS ratio in each of 13 decay time bins, separately for D^0 and $\overline{D}^0$.



Phys. Rev. Lett. 111, 251801 (2013)



Heavy Flavor Production: Some Characteristic Properties



- high precision tracking and vertexing
- RICH for particle ID
- high efficiency muon detection
- EM & hadronic calorimeters

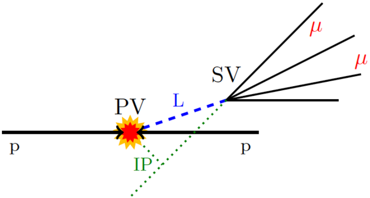
- Pair production is correlated; predominantly forward (backward).
  - $\rightarrow$ single arm forward spectrometer, $2 < \eta < 5$
- $\sigma_{b\bar{b}} = (75.3 \pm 14.1)\,\mu$b at $\sqrt{s} = 7$ TeV [Phys. Lett. **B694** (2010)]
  - **$\sim$ 0.2% of events contain b$\bar{\text{b}}$ in acceptance**
- $\sigma_{c\bar{c}} = (1419 \pm 134)\,\mu$b at $\sqrt{s} = 7$ TeV [Nucl. Phys. **B871** (2013)]
  - **$\sim$ 4% of events contain c$\bar{\text{c}}$ in acceptance**
- $\sigma_{b\bar{b}}$ and $\sigma_{c\bar{c}}$ increase linearly as $\sqrt{s}$ increases to 14 TeV. [P. Nason et al, Nucl. Phys. **B327**, 49 (1989)] and [R. Nelson et al., Phys. Rev. **C87**, 014908 (2013)]

Heavy Flavor Decay: Some Characteristic Properties

Key to the current trigger strategy

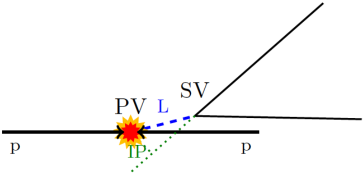
b-hadrons

- mass: $m(B^+) = 5.28$ GeV
  daughter p_T $\mathcal{O}(1\,\mathrm{GeV})$
- lifetime: $\tau(B^+) = 1.6$ ps
- common signature: detached $\mu\mu$
  e.g., $B \to J/\psi\, X$; $J/\psi \to \mu\mu$

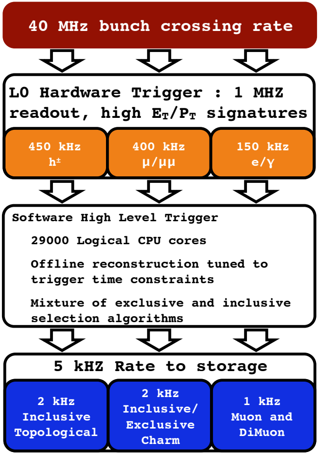


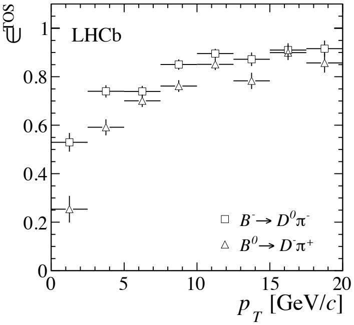
charmed hadrons

- mass: $m(D^0) = 1.86$ GeV
  daughter p_T $\mathcal{O}(0.3 - 1\,\mathrm{GeV})$
- lifetime: $\tau(D^0) = 0.4$ ps
- secondary charm from *b*-hadron decay is also common



The Run 1 Trigger, Circa 2011/2012





The efficiency of the Hlt2 topological n-body trigger for selected final states when at least one track from the decay satisfies the Hlt1 criteria. [V. V, Gligorov and M. Williams, (20130 JINST 8 P02013]

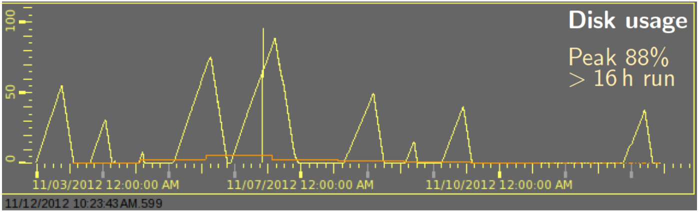
The Run 1 Trigger, 2012 Improvements

(i) extended Hlt1 tracking from $p_T > 1.7$ GeV/c to $p_T > 1.6$ GeV/c (for hadrons),

(ii) extended Hlt2 tracking from $p_T > 0.5$ GeV/c to $p_T > 0.3$ GeV/c and added Hlt2 tracking for K^0_S and Λ decays downstream of the VELO,

(iii) deployed "deferred triggering":

- added $\sim$ 1 petabyte of hard disk to the EFF;
- stored 20% of L0 rate on disk;
- processed data stored on disk through Hlt1 and Hlt2 between machine fills.



The Run 2 Trigger: "Fired Up and Ready to Go"

- Doubled the number of physical processors (CPU cores) available in the Event Filter Farm (EFF).
- Increased the disk capacity for deferred triggering from 1 PB to 4 PB.
- **Run Hlt1 and Hlt2 asynchronously** (Hlt2 start delayed by an hour)
  - Increases the effective power of the EFF $\approx 3\times$.
  - Allows Hlt2 to use calibration and alignment constants derived from the data processed by Hlt1.
- **Speeded up all elements of the reconstruction software**.
  - More complete tracking in Hlt1 and offline tracking in in Hlt2.
  - Almost full particle ID used in Hlt2 educes backgrounds, especially for exclusive SCS and DCS charm; the limited bandwidth can be used more effectively.
- Hlt1 "box cuts" for single tracks **replaced with MVA.**
- **Added a secondary vertex MVA line to Hlt1.**
- Introducing **"turbo-stream"** output to reduce size of some saved events.

Building HLT Performance Models

The moral equivalent of back-of-the-envelope calculations.

2015 Processing and Deferral Models

- The models considered here assume
  - twice the 2012 computing power (50000 processors, 2012 units) and 4 PB of disk for deferral;
  - An Hlt1 process which will run in real time and an Hlt2 process which will run after calibration constants are available, nominally an hour later.
- Four tunable knobs:

Hlt1 time/evt
18 ms in 2012

Hlt2 time/evt
200 ms in 2012

Fraction of events sent to Hlt2
8% in 2012

Size of events sent to Hlt2
(55 kB in 2012)

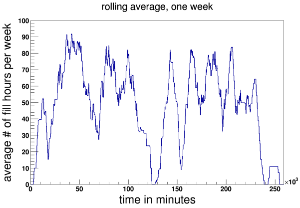
Some Models

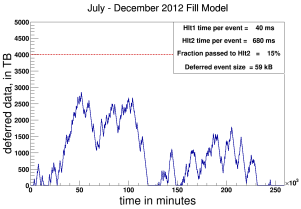
The only numbers which count are those we encounter when running with real data.

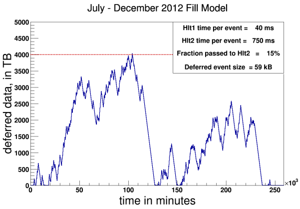
Using the July – December 2012 Fill Model

- Clock week = 168 hours;
- Machine in fill ~ 50 hours/week;
- Best week, ~ 90 hours in fill;
- Deferral allows us to use all 168 hours in a week if disk available

- Split Hlt increases effective CPU power by more than a factor of 2







Personal Thoughts and Comments

not approved by LHCb management

A useful measure of trigger efficiecny is

$$\boldsymbol{\varepsilon(\text{trigger}) = \frac{\#\ \text{events selected}}{\#\ \text{of events fully reconstructed in offline software}}}$$

In very round numbers:

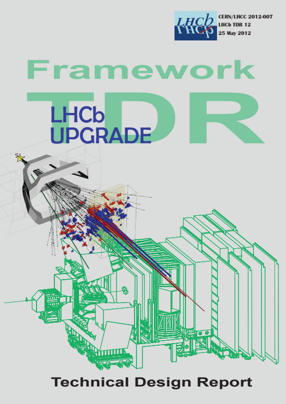
- $\varepsilon(\text{trigger})$ for charm was **less than 1% in 2012.**
- $\varepsilon(\text{trigger})$ for charm will increase to **$\mathcal{O}(2\%)$ for easy D decays in 2015.**
- $\varepsilon(\text{trigger})$ for charm is conceptually limited by the need to discriminate signal from background using separation of primary and secondary vertices. The relevant resolution is $\mathcal{O}(40)\,\text{fs}$.

We are losing most of our efficiency for charm to the L0 hardware trigger.

Despite improvements in Hlt1 (using both single track and secondary vertex MVAs), we cannot afford to pass all interesting events to Hlt2. We lose a bit more in Hlt2 because our output bandwdith is limited by offline computing resources constraints (primarily disk space).

Goals for the Upgrade Era

official policy: see also the talk by Chris Parkes on Friday afternoon

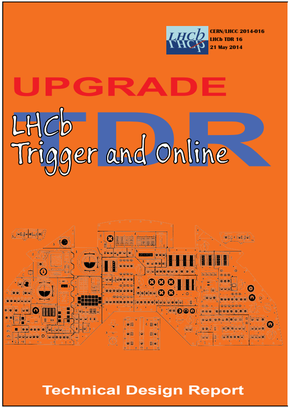


cds.cern/ch/record/1647400

- Physics reach, relative to 2011:
  - increase data rate for muonic B decay $10\times$: $\boldsymbol{\mathcal{L}_{\text{inst}}\ 5\times, \quad \sigma(b\bar{b})\ 2\times;}$
  - increase data rate for "heavy flavor decays to hadronic final states" $20\times$: $\boldsymbol{\mathcal{L}_{\text{inst}}\ 5\times, \quad \sigma(b\bar{b})\ 2\times; \quad \varepsilon(\text{trigger})\ 2\times.}$
- Implementation Strategy
  - increase $\mathcal{L}_{\text{inst}}$ from $4 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ to $20 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. (Bring the beams closer together.)
  - upgrade detector and increase readout from 1 MHz to 40 MHz;
  - **eliminate L0 hardware trigger;**

The Upgrade Era Trigger

official policy



cds.cern/ch/record/1701361

30 MHz — Inelastic collision rate

↓

Full Software Trigger — Full detector data

LLT (optional)
p_T of h, μ, e, γ — EB Farm; Fast algorithms use partial information

↓ 15 to 30 MHz

Full track reconstruction — EF Farm

↓ 1 to 2 MHz

Track fit
RICH particle ID
Inclusive and exclusive selections

↓

20 to 100 kHz

Challenges for the Upgrade Era

now, a personal perspective

Increasing reconstructed charm statistics $100\times$ will require trade-offs. Today's paradigm cannot work given the limited computing budgets.

- "We" would like to **fully reconstruct** all potentially interesting events in the HLT and write out only the equivalent of today's stripping selections.
  - This approach requires much more prep work.
  - Interesting physics will be lost through lack of foresight.
- **Moore's Law** suggests that CPU power will increase $5\times - 10\times$ by 2020.
  - Higher pile-up will require more time per event, so even being optimistic, we will have difficulty doing full reconstruction and event selection for 2 MHz of data.
- Raw-plus-reco data requires about 100 kB/event now.

$$100\,\mathrm{kHz} \times 100\,\mathrm{kB/evt} \times 4 \times 10^{6}\,\mathrm{s/year} \rightarrow 40\,\mathrm{PB/year}$$

  - Can we use **"turbo-stream"** output, perhaps removing raw data, perhaps retaining only some reconstructed objects from each event? Concept will be developed and tested in Run 2.

Concluding Remarks

- Fully reconstructed open charm samples have increased by a factor of **more than a million** in the past thirty years.
- LHCb reconstructed **hundreds of millions** of open charm decays in Run 1, in large part due to the excellent performance of the trigger.
- The High Level Trigger has been substantially improved for Run 2.
    - The EFF has 2$\times$ as many CPUs as in 2012 + 4 PB of disk. Running Hlt1 and Hlt2 asynchronously leverages these resources to provide more than 5$\times$ the processing power.
    - Extending Hlt1 tracking and introducing more sophisticated trigger lines **increases efficiencies and reduces biases**.
    - By working harder and smarter, we can run almost the complete offline reconstruction in Hlt2. This allows us to **trigger higher $\mathcal{L}$ more efficiently and more selectively**.
- Eliminating the L0 hardware trigger in Run 3 opens the possibility of **increasing open charm trigger efficiencies another 10$\times$ while examining 5$\times$ greater luminosity**. Project **more than 20 billion CF charm and 5 million tagged, WS Kπ** reconstructed decays per year.