LHCb Trigger System

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on behalf of the LHCb collaboration

Outline

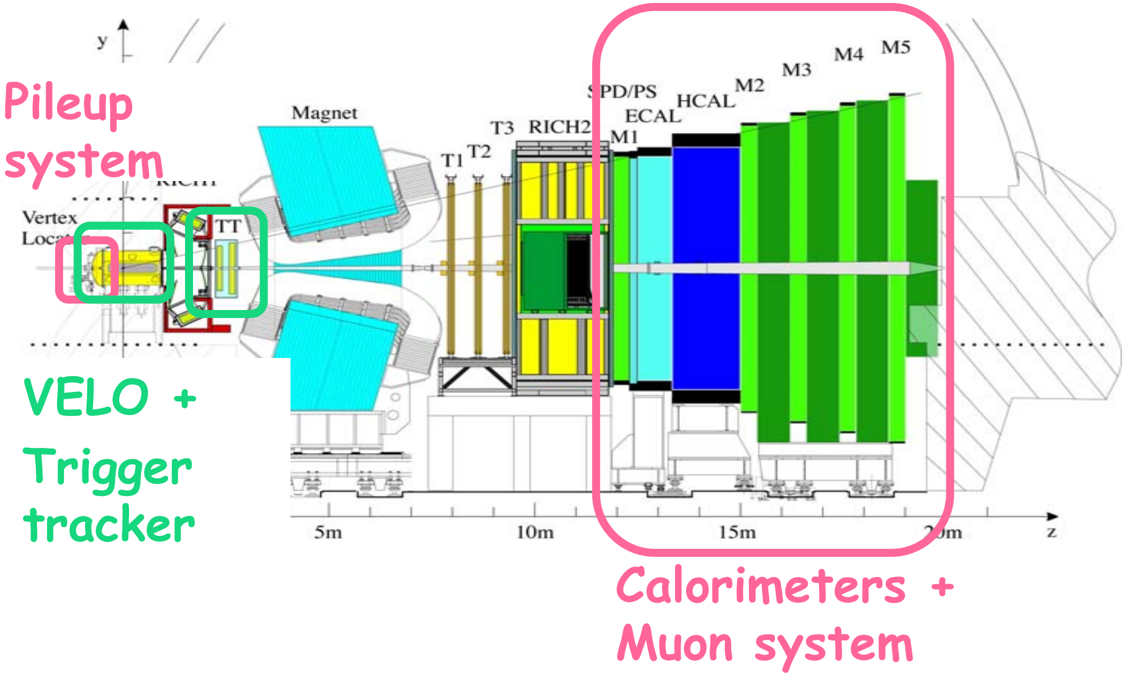
- **Overview**
- **First Level Trigger: L0**
  - L0 Subsystems
  - L0 Decision and Performance
- **Second Level Trigger: L1**
  - L1 Event Reconstruction
  - L1 Decision and Performance
- **High Level Trigger: HLT**
  - Generic HLT
  - Inclusive HLT and Output Rate
  - Exclusive HLT
- **Outlook**

Trigger overview

- 40 MHz crossing rate
- 30 MHz with bunches from both directions

- Luminosity: $2 \cdot 10^{32}$ cm^{-2} s^{-1}
  - 10 to 50 times lower than @ ATLAS, CMS

- LHC rates:
  (for visible events ≡ at least 2 tracks in acceptance)
  - Total rate (minimum bias): 10 MHz
  - bb: ~100KHz
    - Whole decay of one B in acceptance: 15KHz
  - cc: ~600KHz



10 MHz

L0: hight p_T + not too busy
- Fully synchr. (40 MHz), 4μs latency
- On custom boards

1 MHz

L1: IP + high p_T
- Ave. latency: 1 ms (max 50 ms)
- Buffer: 58254 events

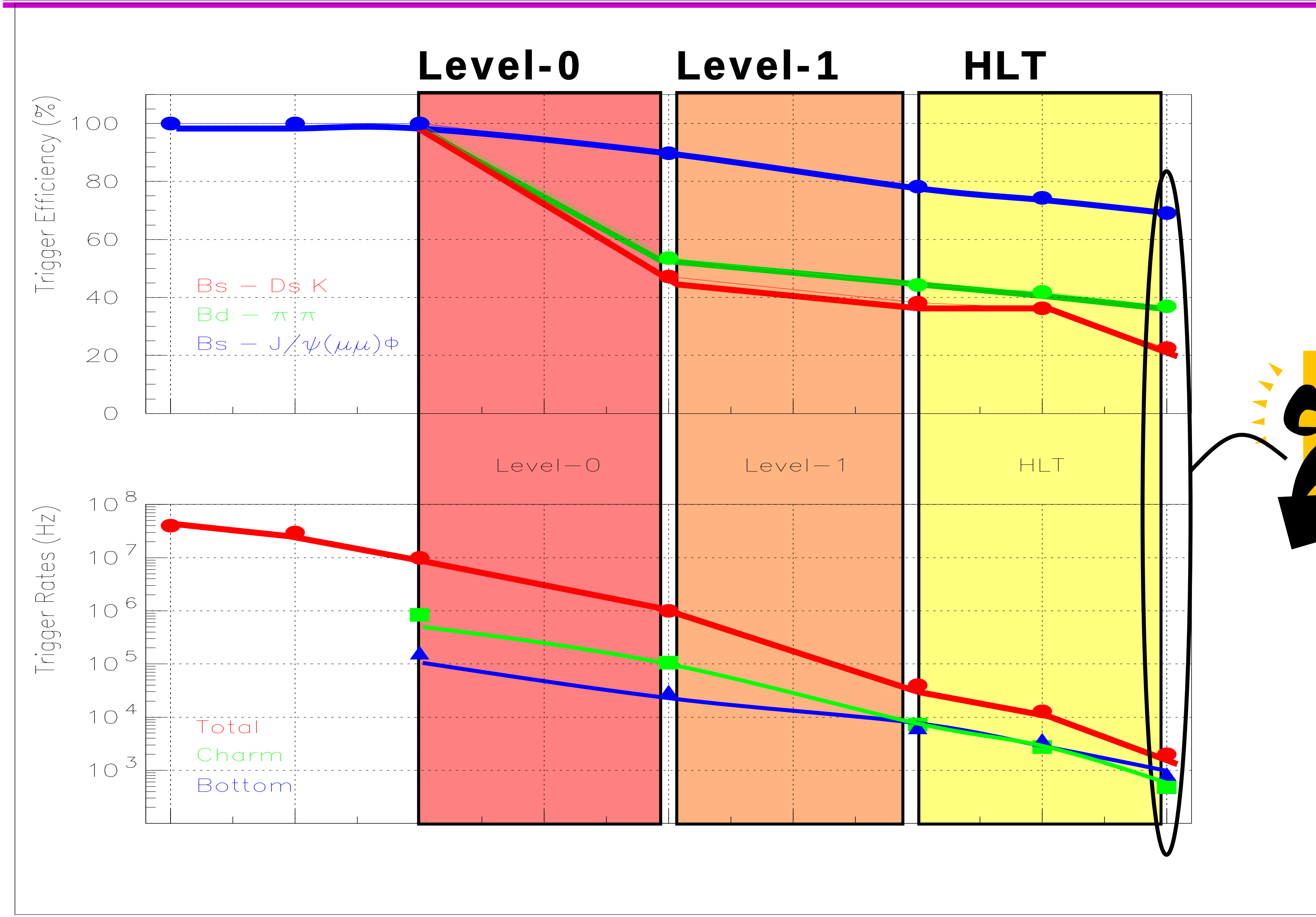
40 KHz

HLT + reconstruction
- Full detector: ~ 40 kb / evt

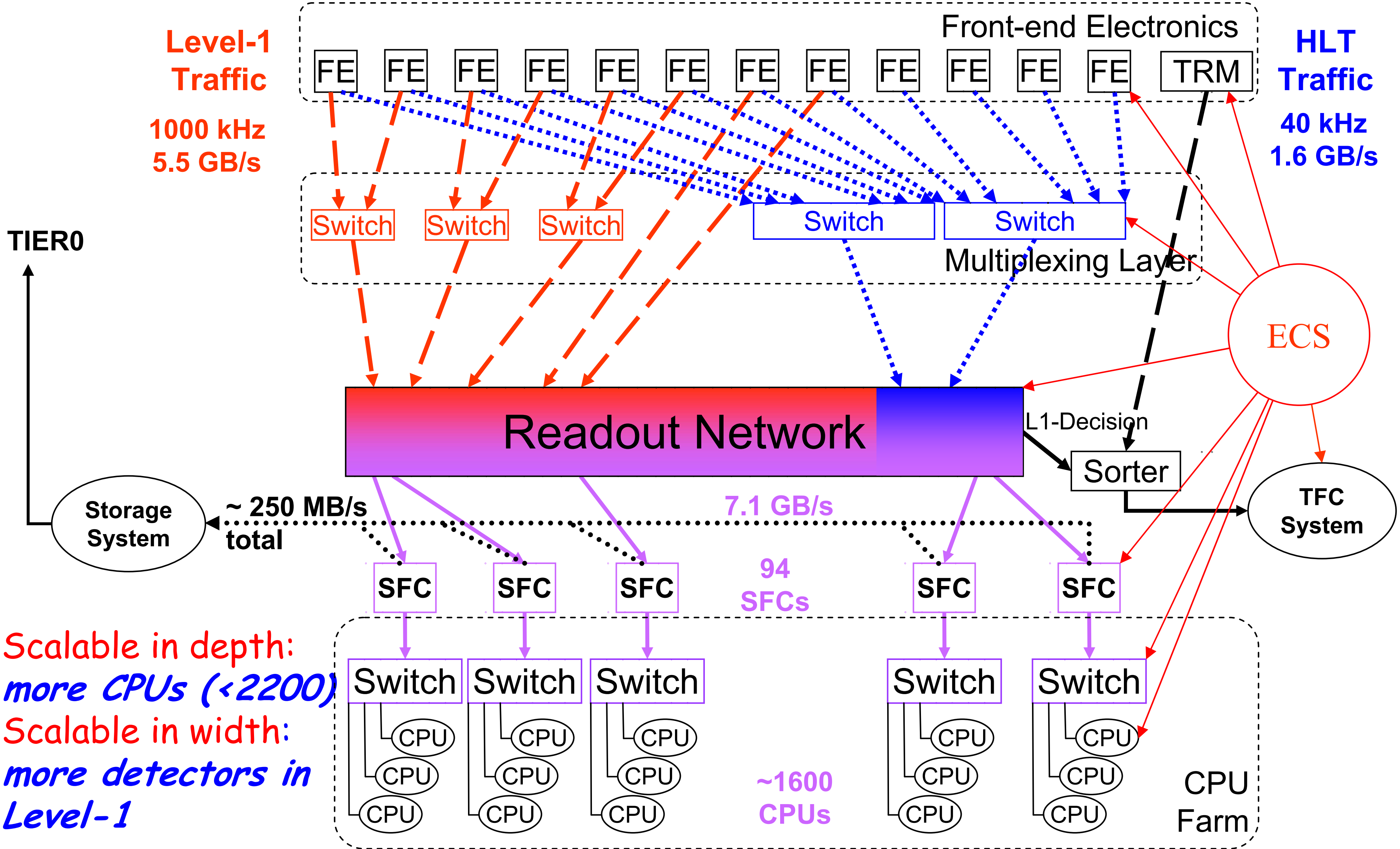
≤ 2 KHz

Single PC farm
~1600 CPUs

Trigger Overview



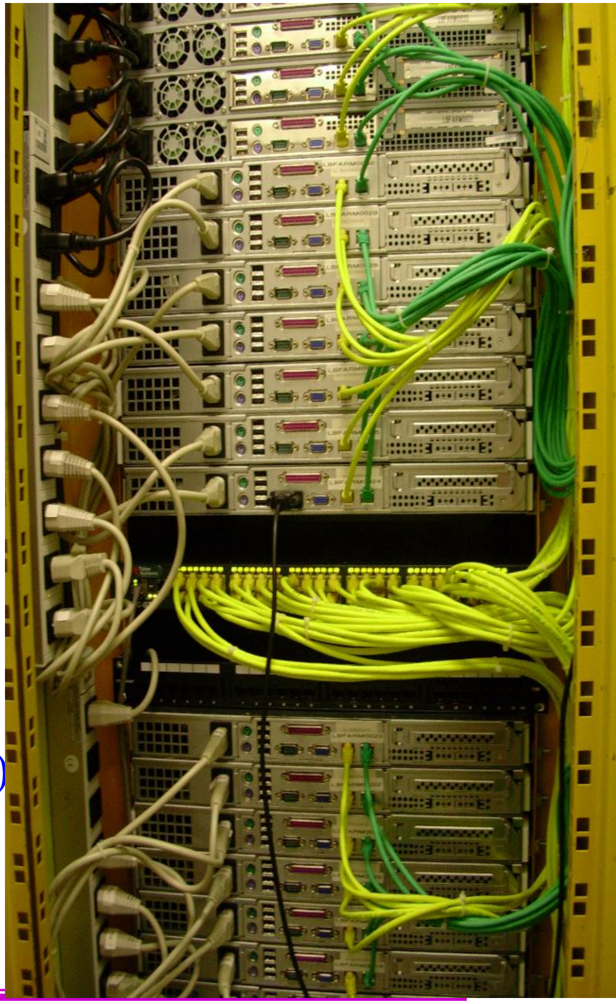
DAQ Architecture



Scalable in depth:
more CPUs (<2200)
Scalable in width:
more detectors in Level-1

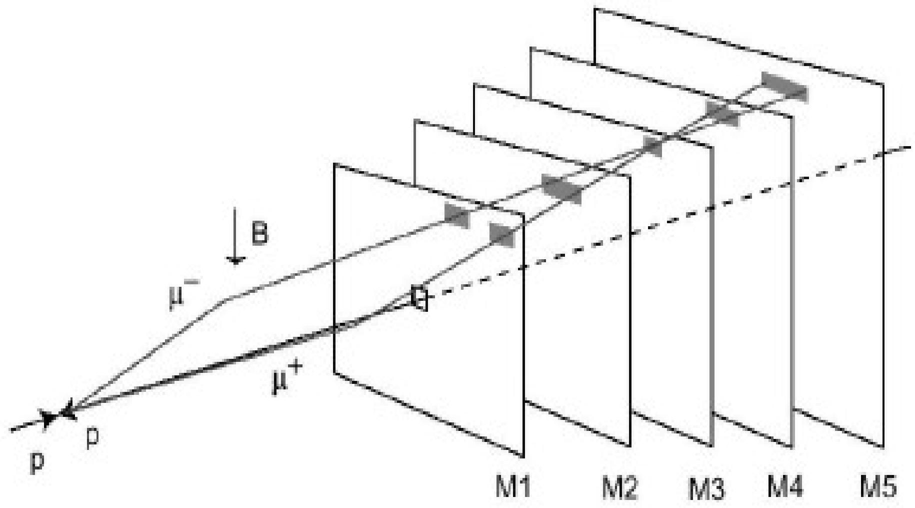
Real Time Trigger Challenge

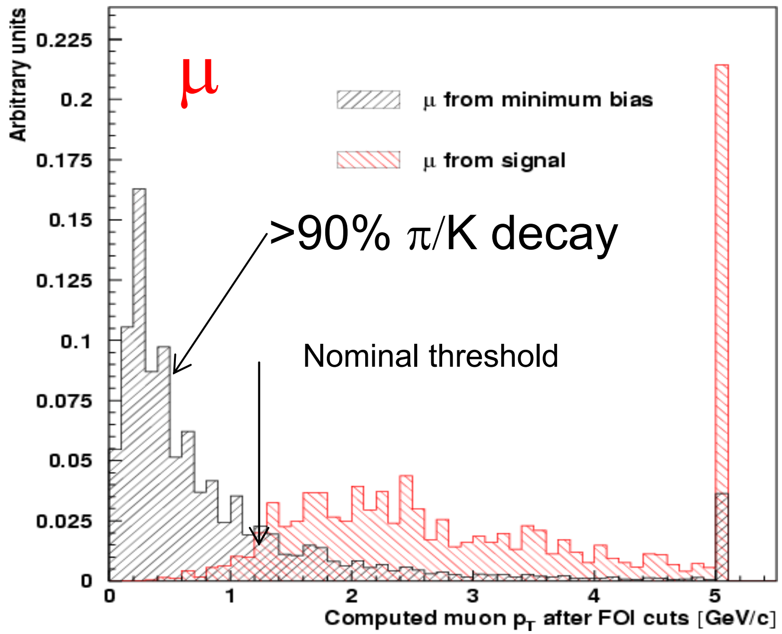
- **Aim**
  - **Operate one (few) subfarms of the DAQ under realistic conditions**
    - Full-speed Data Input/Output including data to storage
    - Long-term operation (hours)
    - Exercise realistic Level-1/HLT code
    - Exercise/evaluate realistic overheads
  - **Somehow assert performance progress of CPUs**
    - 'modern' CPUs compared to (today's) standard CERN
  - **Exercise controls part, such as Monitoring, Farm Control, etc.**
- **Infrastructure**
  - **One (two) racks of 44 dual-CPUs**
  - **2-4 Sub-Farm Controlers**
  - **One disk server to hold events**
    - 10^7 Level-0 YES, 400k Level-1 YES events
    - Event fragments organized in MEP (Multi-Event Packets)
  - **One disk server for data recording**
    - 20k HLT yes
- **Timescale: June 2005**



Level-0: Muon Trigger

- The LHCb muon system:
  - **5 stations**
  - **Variable segmentation**
  - **Projective geometry**
- Trigger strategy:
  - **Straight line search in M2-M5**
  - **Look for compatible hits in M1**
    - Momentum measurement ($\Delta p/p \sim 20\%$ for b-decays)





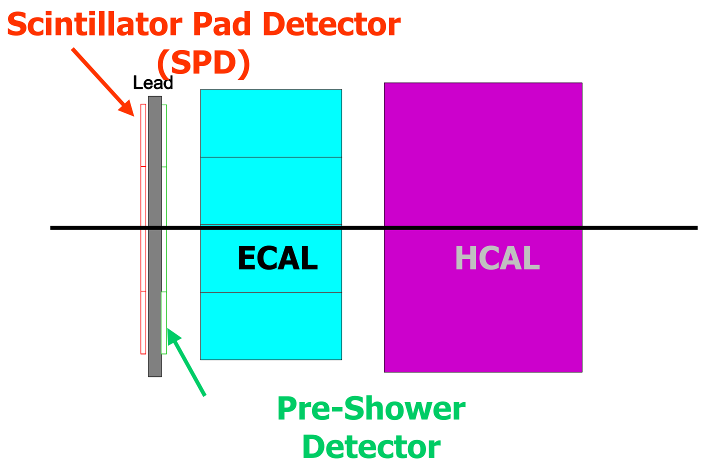
- Sent to L0 decision unit: **2 highest p_T candidates per quadrant**
- Typical Performance:
  ~88% efficiency on B->J/ψ($\mu\mu$)X.
  Algorithm latency ~1 μs.

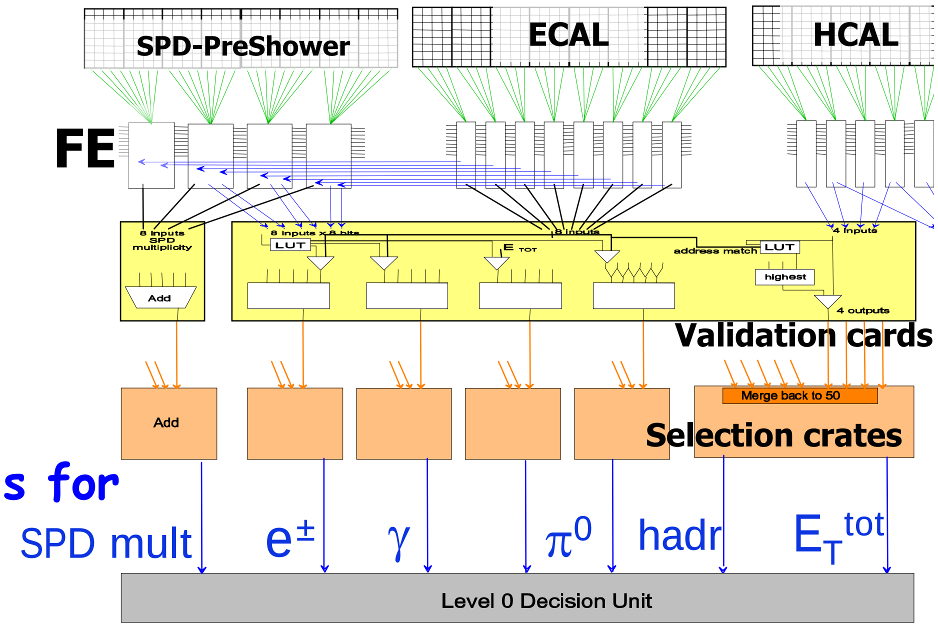
Level-0: Calorimeter Trigger

- The LHCb calorimeter:
  - ECAL: ~6000 cells, 4x4 to 12x12 cm²
  - HCAL: ~1500 cells, 13x13 to 26x26 cm²
- Trigger strategy: look for high E_T candidates,
  - In regions of 2x2 cells
  - Particle identification from
    - ECAL / HCAL energy
    - PS and SPD information
  - E_T threshold ~ 3 GeV
- Sent to L0 decision unit:
  - Highest E_T candidate of each type
  - Global variables:
    - Total calorimeter energy
    - SPD multiplicity
- Typical Performance:

30-50% efficiency on hadronic channels for about 700 kHz bandwidth .

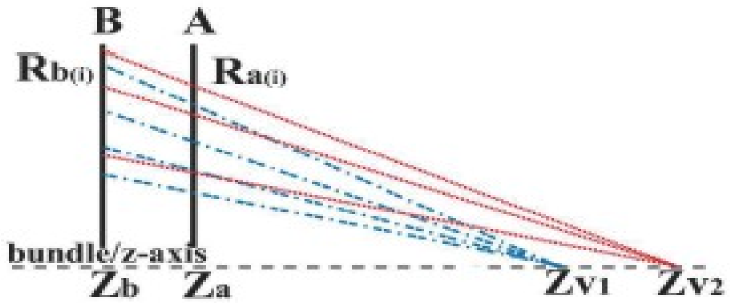
Algorithm latency ~1 μs.





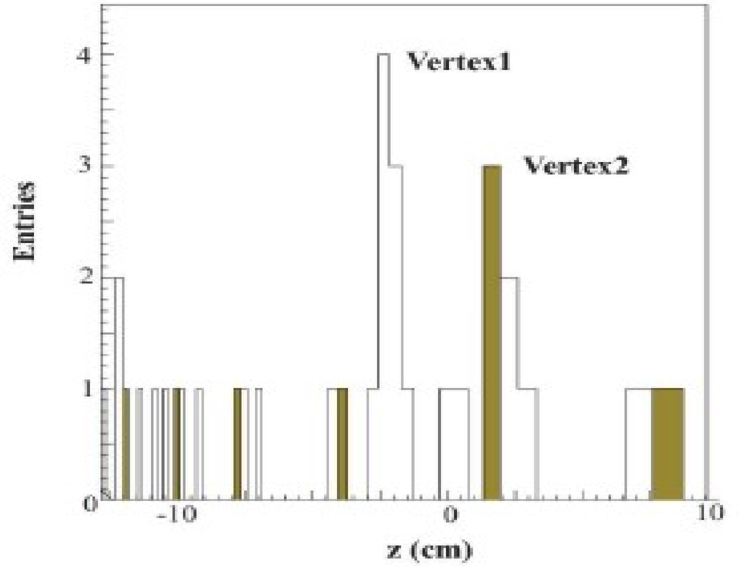
Level-0: Pileup System

- Trigger strategy: identify multi-PV evts
  - From hits on two planes → produce a histogram of z on beam axis
  - Identify largest peak and remove all hits contributing → masking scheme.
  - Look for second peak above threshold.



$$z_v = \frac{k \times z_a - z_b}{k-1} \text{ where } k = \frac{r_b(i)}{r_a(i)}$$

- Pileup system:
  - 2 silicon planes upstream
  - Measure R coordinate (-4.2<η<-2.9)
  - Algorithm fits in 4 large FPGAs
- Sent to L0 Decision Unit: # of tracks in the second peak + hits multiplicity.



- Typical performance: 60% efficiency identifying double interactions with 95% purity.

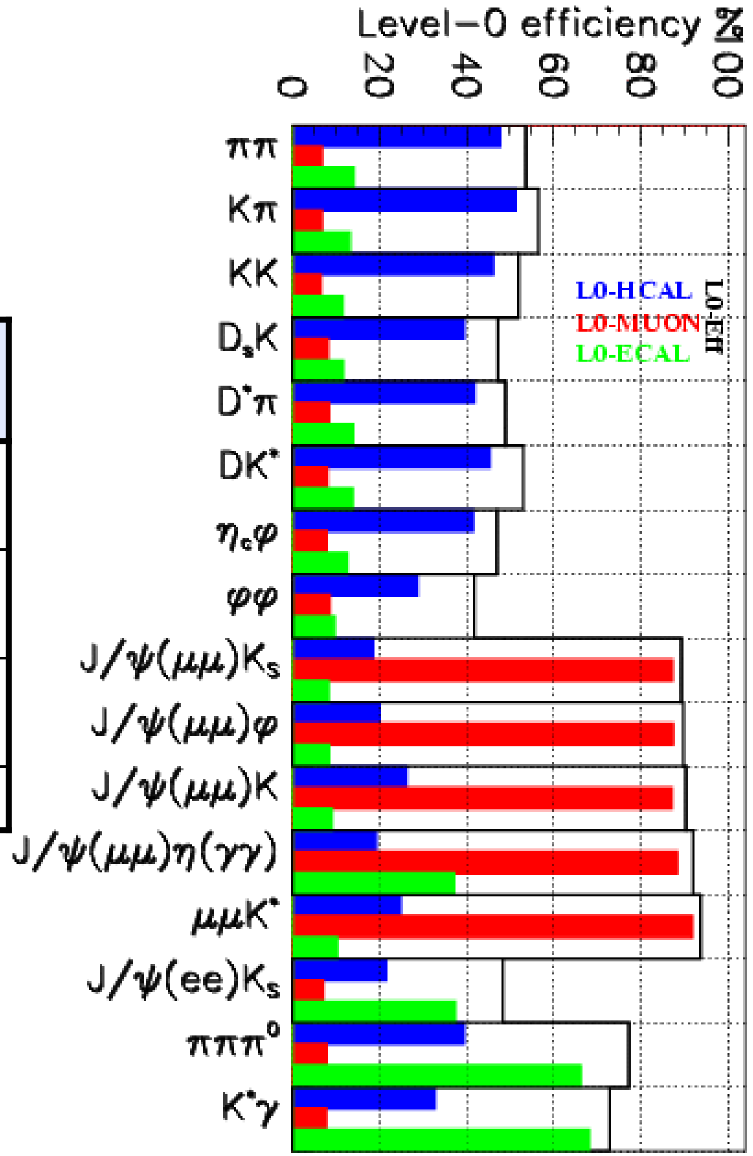
Algorithm latency ~1 μs.

Level-0: Decision and Bandwidth

- L0 decision unit:
  - OR of high E_T candidates
  - Applies cuts on global properties

Type	Thresh (GeV)	Rate (kHz)
Hadron	3.6	705
Electron	2.8	103
Photon	2.6	126
π^0 local	4.5	110
π^0 global	4.0	145
Muon	1.1	110
Di-muon Σp_T^μ	1.3	145

Global Variable	Cut
Tracks in 2nd vertex	3
Pile-Up multiplicity	112 hits
SPD multiplicity	280 hits
Total E_T	5 GeV

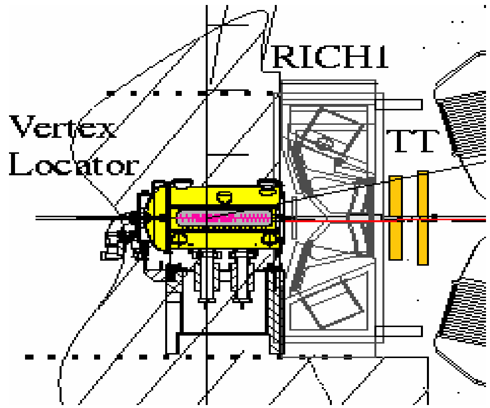


- Composition:

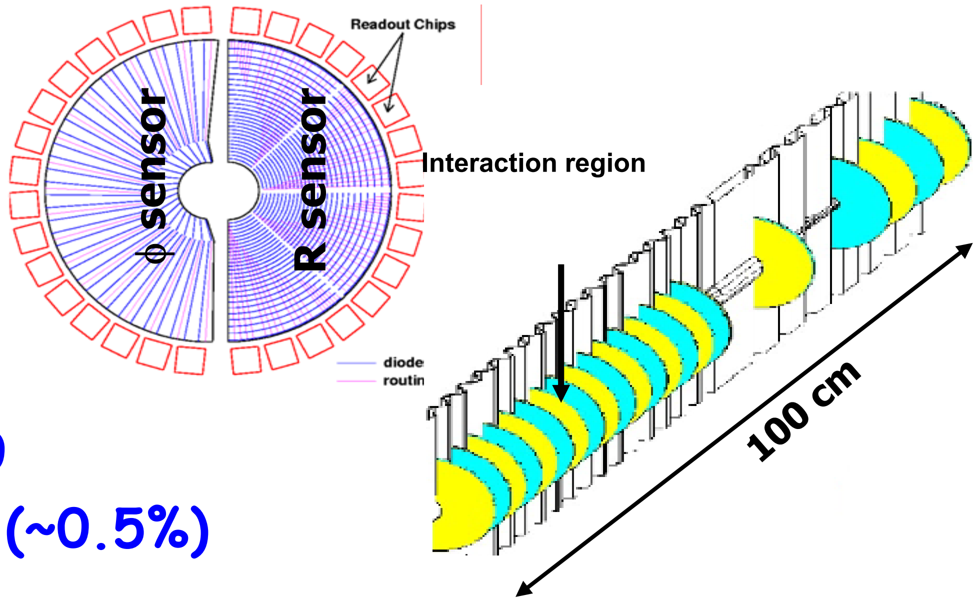
	bb (kHz)	cc (kHz)
After L0	30	106

Level-1 Overview

- Trigger strategy:
  - find high IP tracks (tracking in VELO)
  - Confirm track / Estimate p_T from TT
  - Link VELO tracks to L0-objects.



- The LHCb VELO:
  - 21 stations (~ 100 cm)
  - Alternated R-ϕ sensors
  - 40 μm to 100 μm pitch



- Environment:
  - ~ 70 tracks/event after L0
  - but low occupancy in VELO (~0.5%)

Level-1: Event Reconstruction

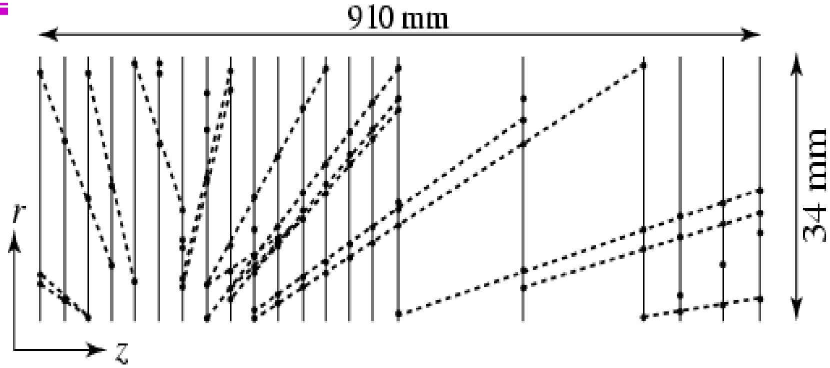
- Fast-tracking strategy:
  - **First in R-Z view (only R sensors)**
  - **Primary vertex $\sigma_z \sim 60\ \mu m$, $\sigma_{x,y} \sim 20\ \mu m$**
  - **Select 2D tracks with IP in (0.15, 3) mm**
    - about 8.5 / event
  - **3D tracking for selected tracks**

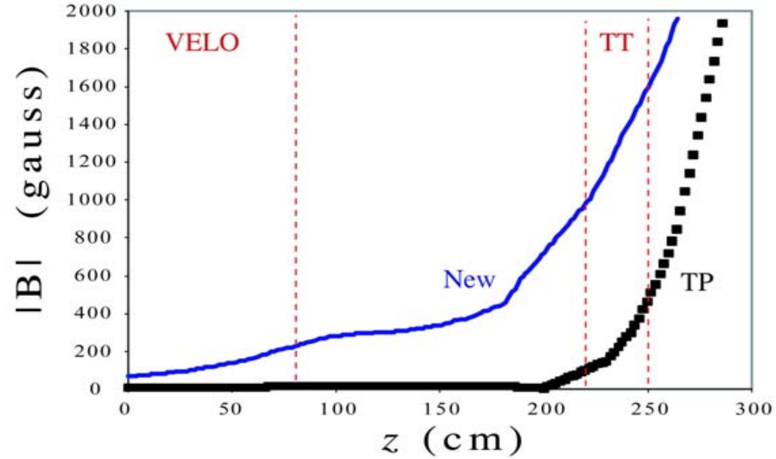
- p_T measurement using TT
  - **Silicon, 2 layers, 200 μm pitch**
  - **Only 0.15 T.m between VELO and TT**

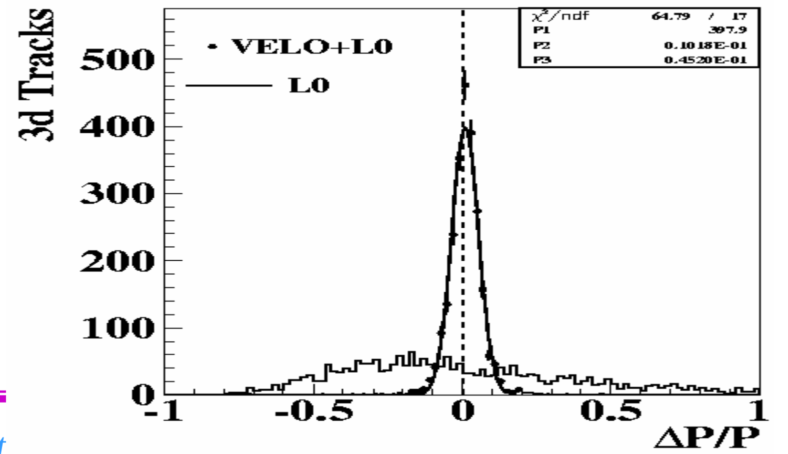
    $\Delta p_T / p_T \sim 20\text{-}40\%$
  - **Rejects most low momentum tracks, which can fake high IP**

- p_T and ID measurements using L0-objects
  - **matched L0-μ have**

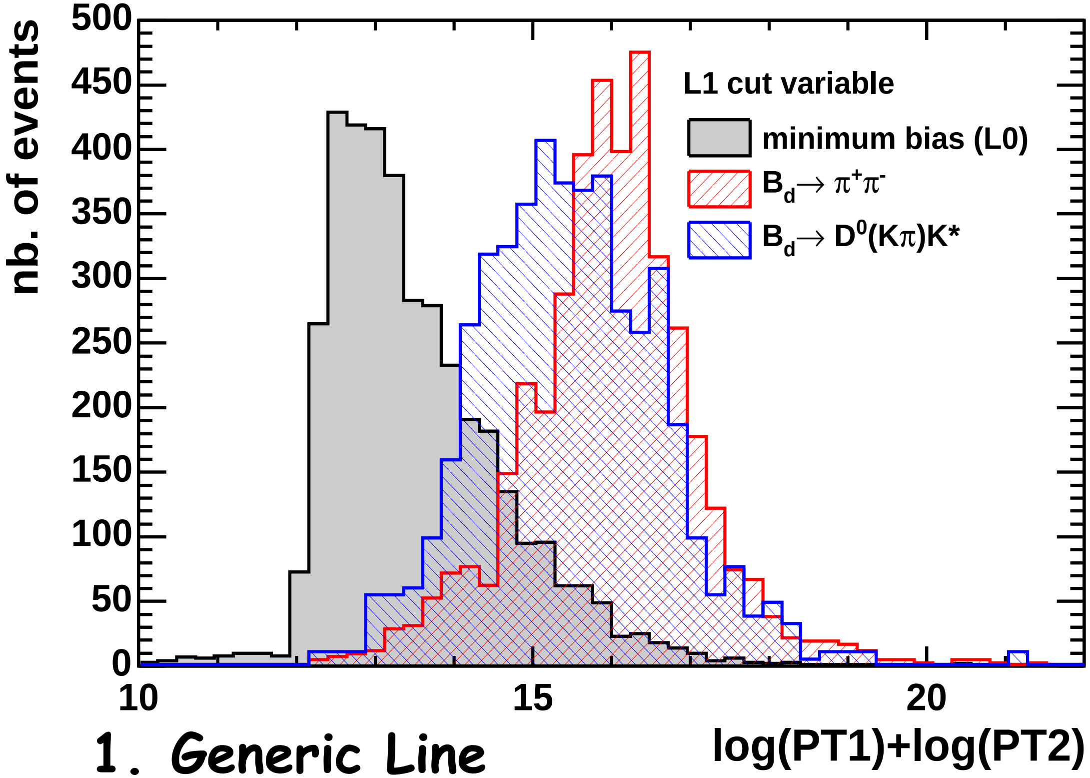
    $\Delta p_T / p_T \sim 5\%$

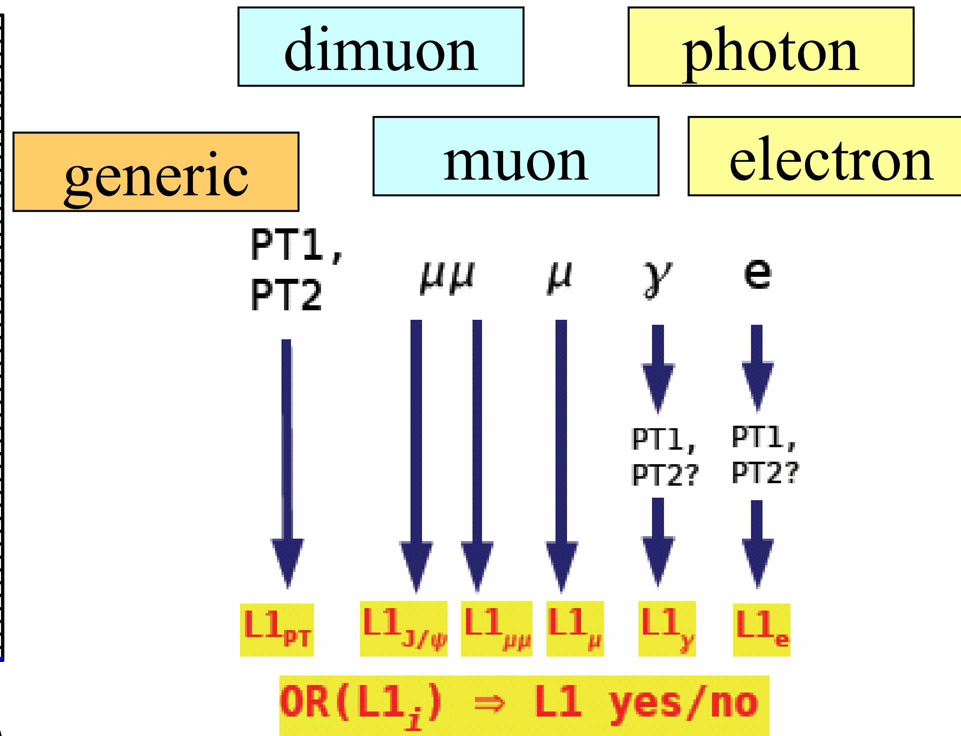






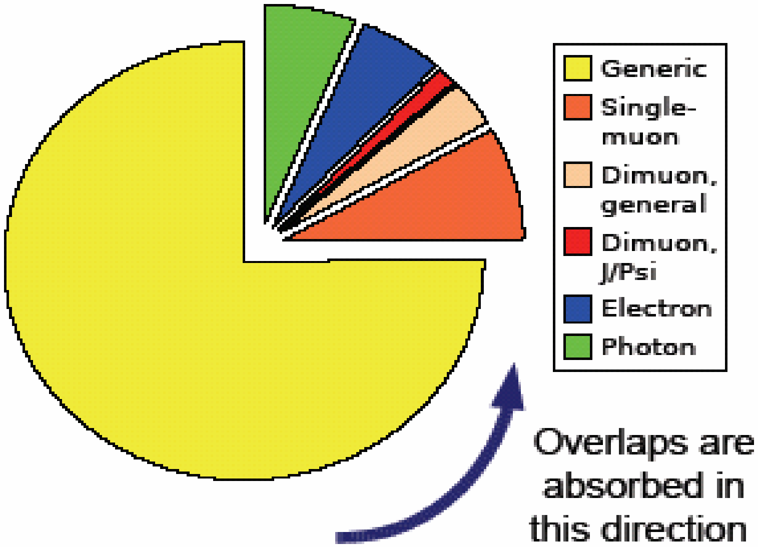
Level-1 Decision





1. Generic Line
   - L1-Variable: log(pt1)+log(pt2)
2. Muon lines:
   - Single muon: PT>2.4 GeV, IP >0.15 mm
   - Dimuons: $m_{\mu\mu}$>2.5 GeV OR ($m_{\mu\mu}$>500 MeV and IP>0.05mm)
3. Photon, electron lines:
   - L1-Variable (relaxed) + Ecal>3.1 GeV

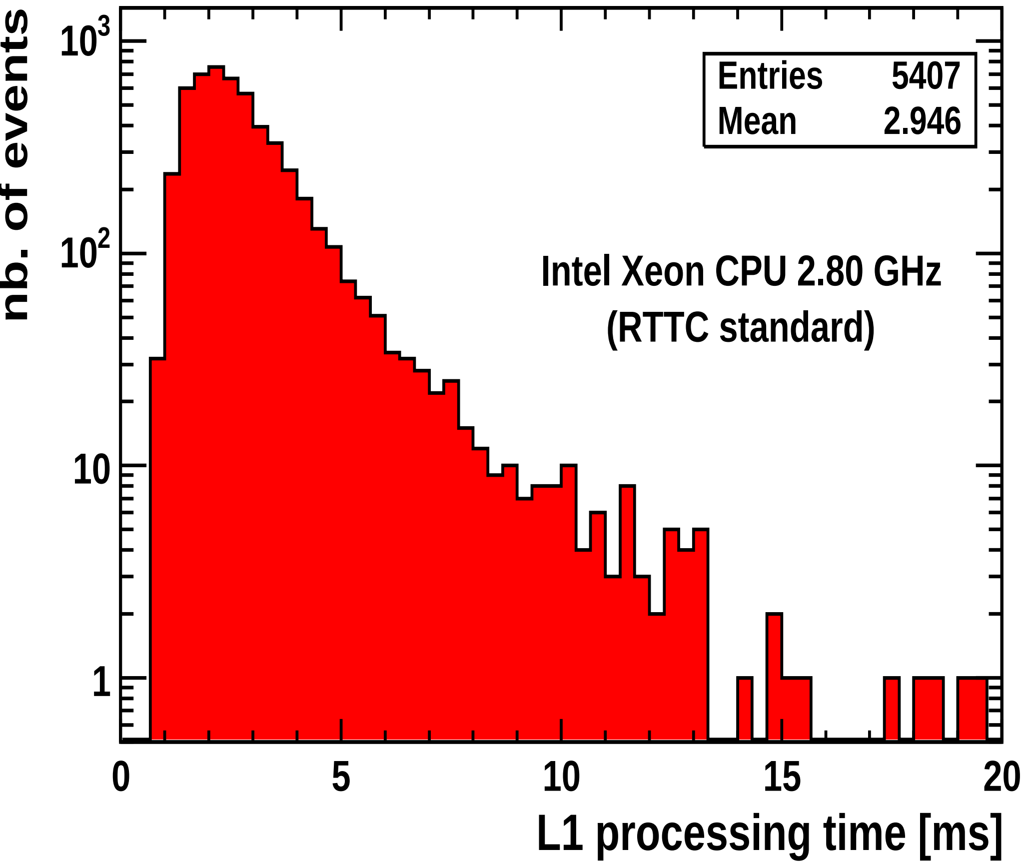
Level-1 Performance

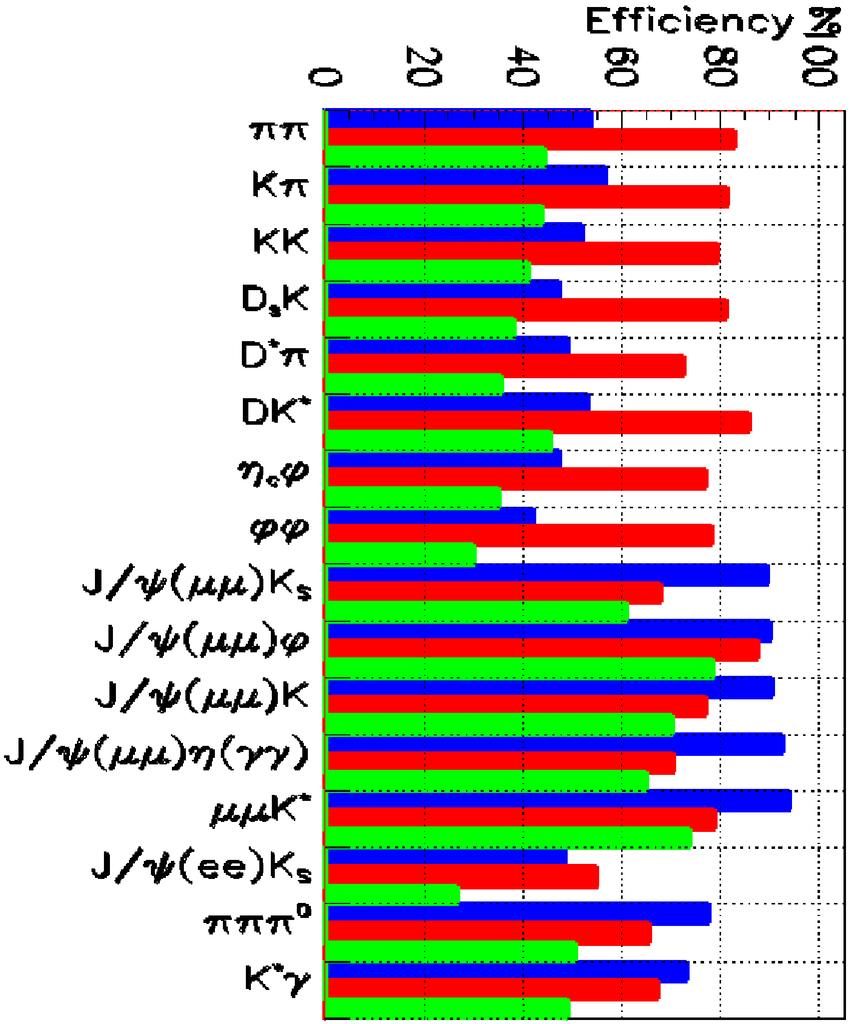


	Bandwidth (kHz)	Adjusted for overlap
Generic	29.2 (75.0%)	29.2 (75.0%)
Single-muon	6.5 (16.8%)	3.2 (8.2%)
Dimuon, general	1.7 (4.5%)	1.4 (3.6%)
Dimuon, J/Psi	1.5 (3.9%)	0.6 (1.5%)
Electron	3.9 (9.9%)	2.3 (5.8%)
Photon	3.7 (9.5%)	2.3 (6.0%)

channel	generic	single μ	dimuon	J/ψ	electron	photon	total	TDR
$B_d^0 \to \pi^+\pi^-$	81.80%	1.55%	0.15%	0.13%	4.27%	2.73%	82.63%	62.7%
$B_s^0 \to D_s^- K^+$	79.78%	4.04%	0.74%	0.79%	4.42%	2.88%	80.89%	62.6%
$B_d^0 \to \overline{D}^0(K^+\pi^-)K^*$	83.51%	2.01%	0.42%	0.08%	5.02%	3.26%	85.36%	66.7%
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi$	74.33%	42.79%	24.99%	45.45%	1.90%	1.73%	87.24%	71.4%
$B_d^0 \to K^*\gamma$	54.94%	2.35%	0.39%	0.34%	17.25%	30.94%	67.20%	51.9%
minimum bias	2.94%	0.68%	0.15%	0.18%	0.37%	0.43%	4.00%	4.00%

Level-1 Performance

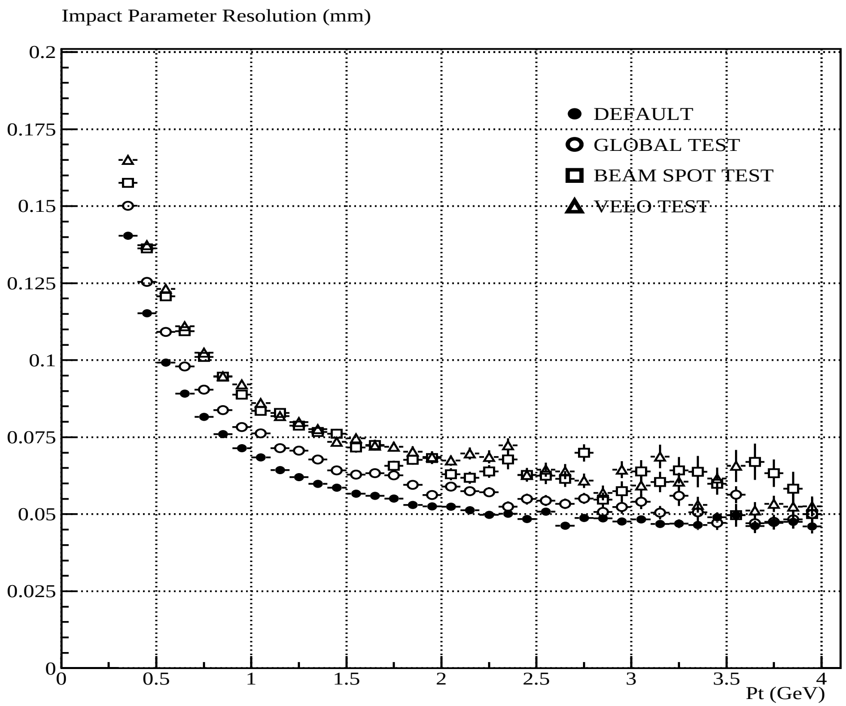


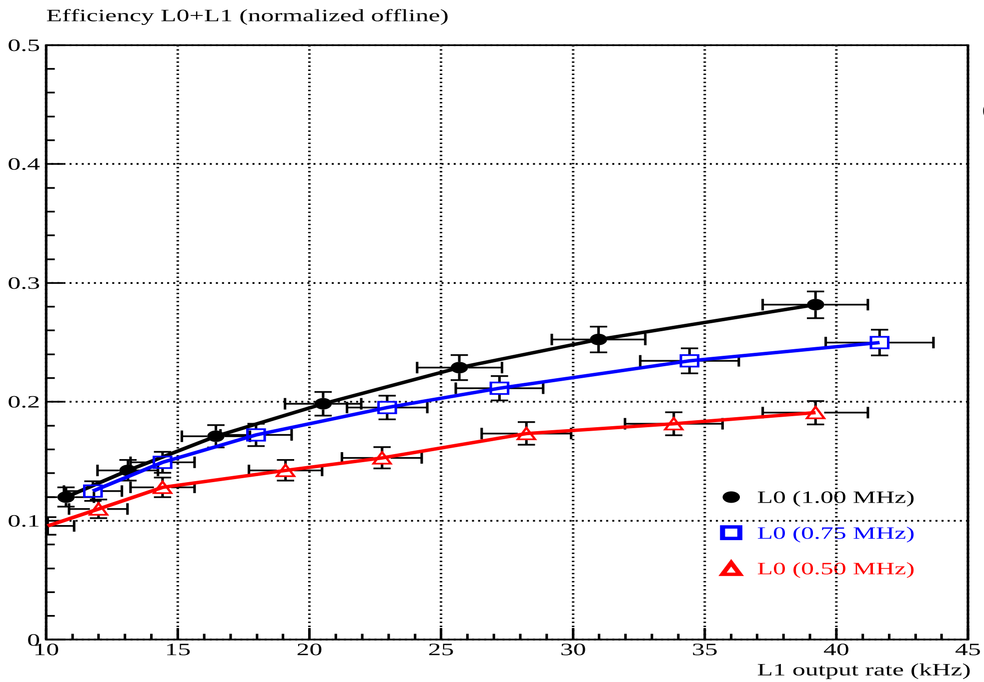


	bb (kHz)	cc (kHz)
After L0	30	106
After L1	6.4	7.2

Trigger Robustness

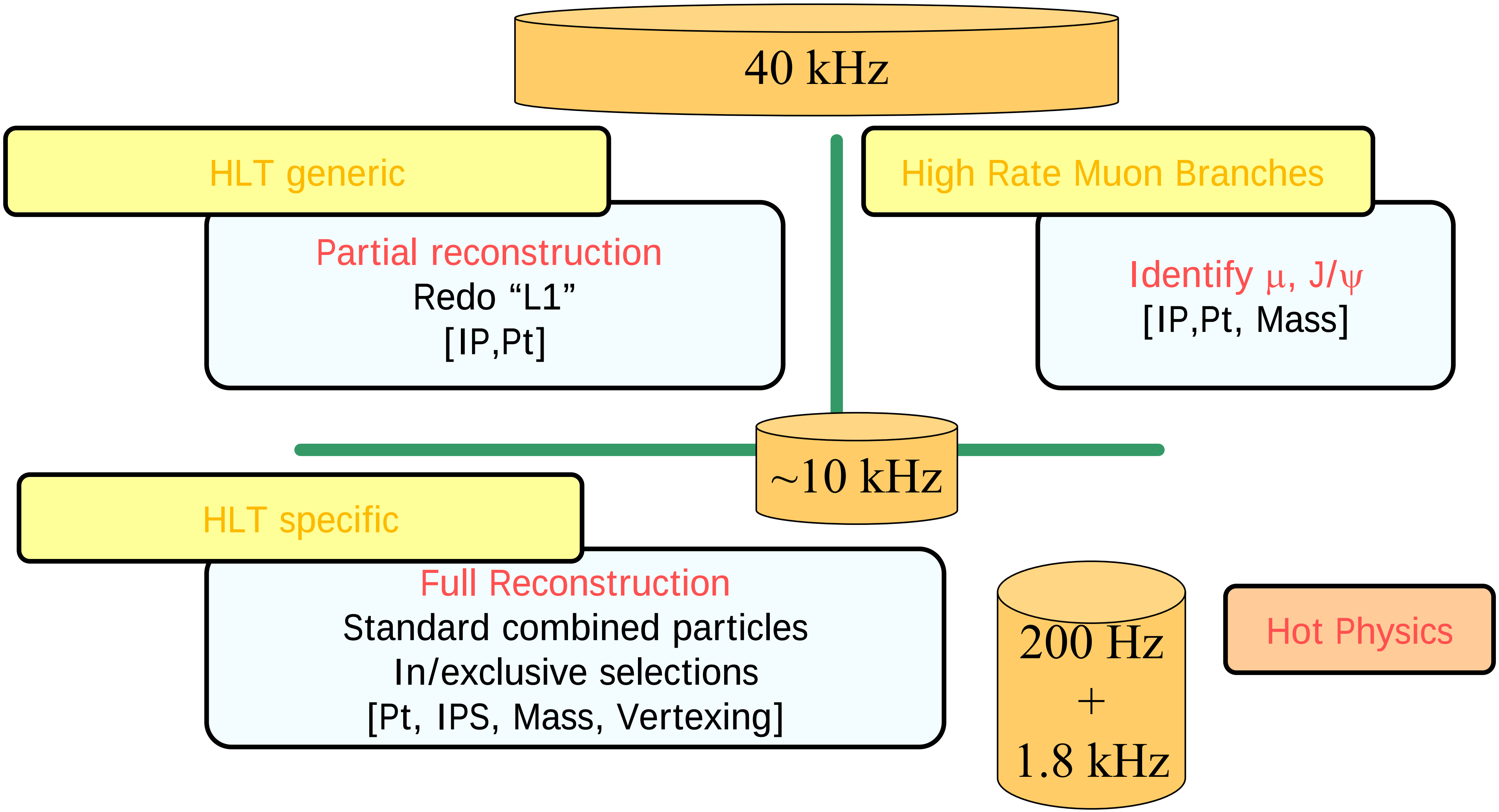
- Several scenarios considered:
  - Event multiplicity
  - Noise, Missalignment,Resolution
  - Increased material
  - LHC beam position
  - LHC background
  - Size of the CPU farm





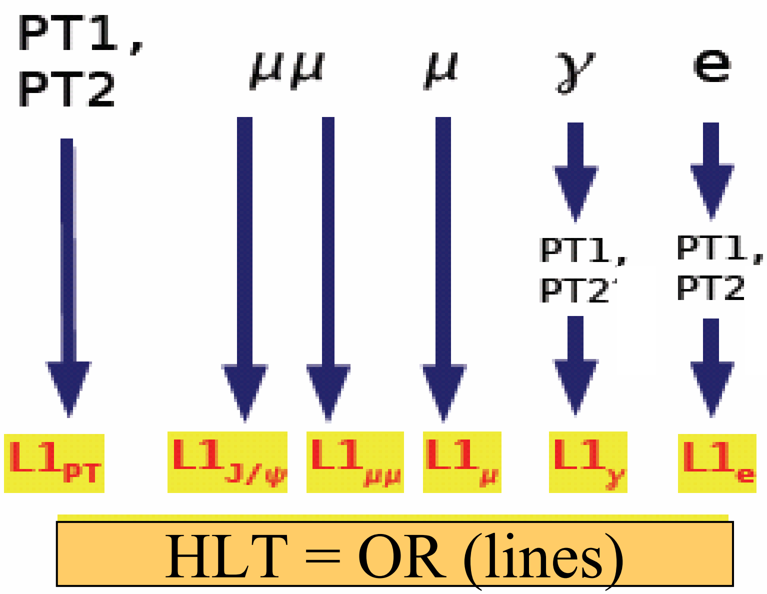
- The performance of L0 is stable within 10% while L1 is within 20%.
- The execution time and L1 event size is within 30%.
- The dependence with the size of the CPU farm is reasonable.

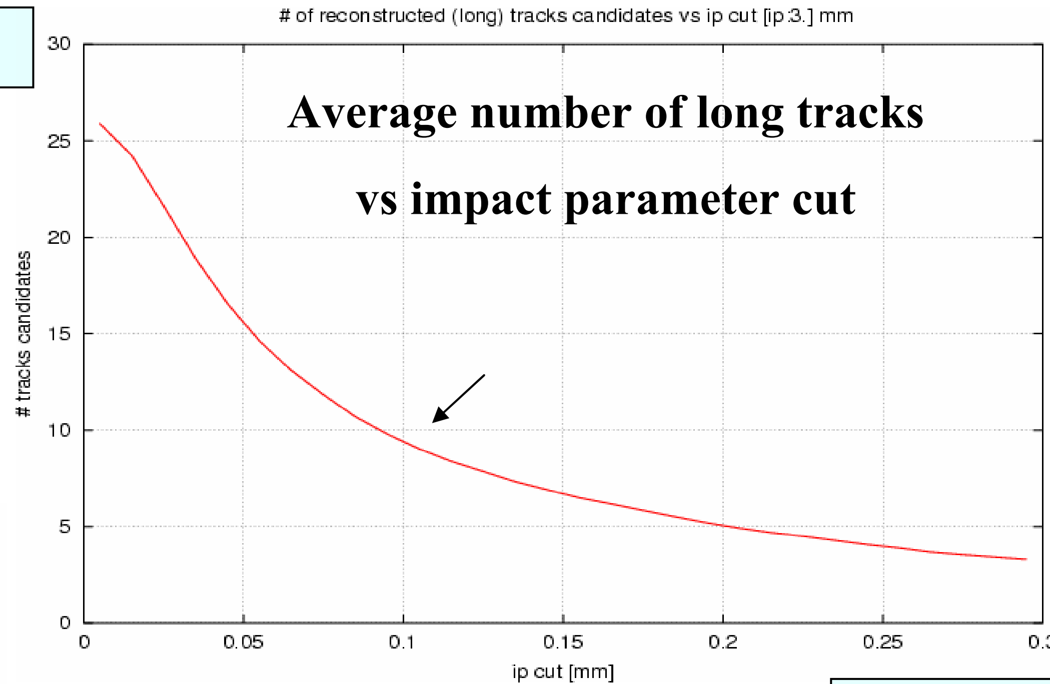
HLT Overview



HLT: Generic Algorithm

- **HLT generic:**
- Redo "L1" (L1-confirmation)
  - Same branches with improved:
    - **momentum resolution**
    - **muon matching**

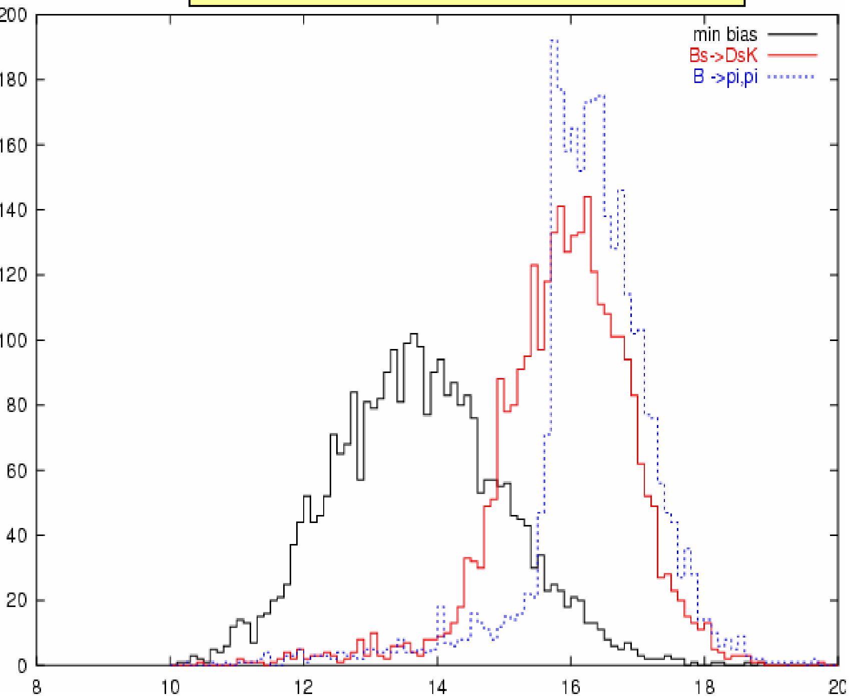




- **Time performance:**
  - HLT generic takes ~ 4 ms
  - ~1/3 event is reconstructed by the generic algorithm.
  - Time remaining for the rest of HLT-algorithms:
    - @12 kHz after the HLT generic,
    - t ~ 20 ms for specific HLT selections

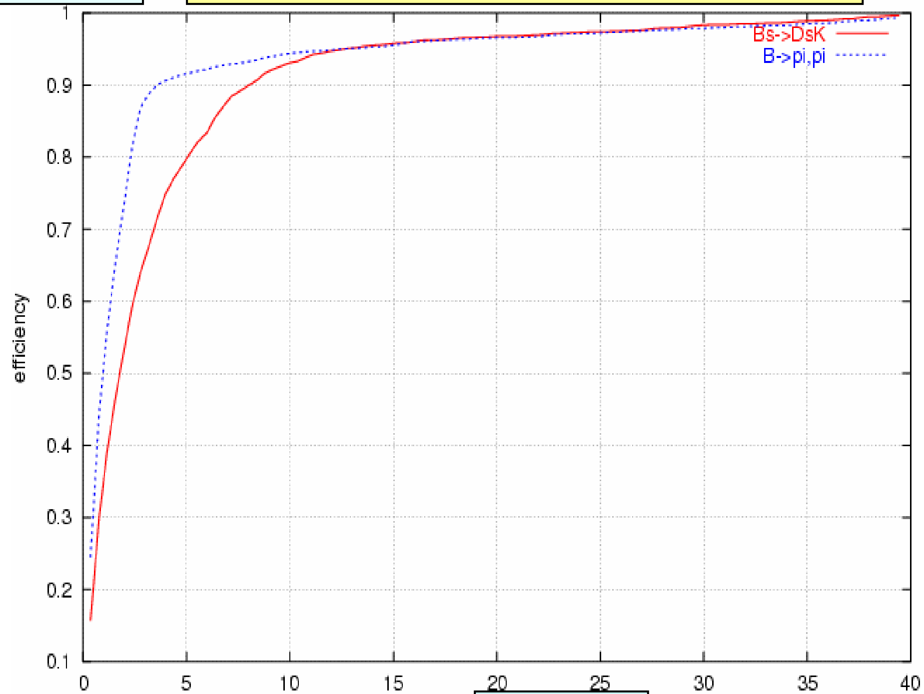
HLT: Generic Algorithm

Log(pt1)+log(pt2)



efficiency

Efficiency vs retention



kHz

	bb (kHz)	cc (kHz)
L0 (1 MHz)	30	106
L1 (40 kHz)	6.4	7.2
HLT (13 kHz)	3.8	2.7

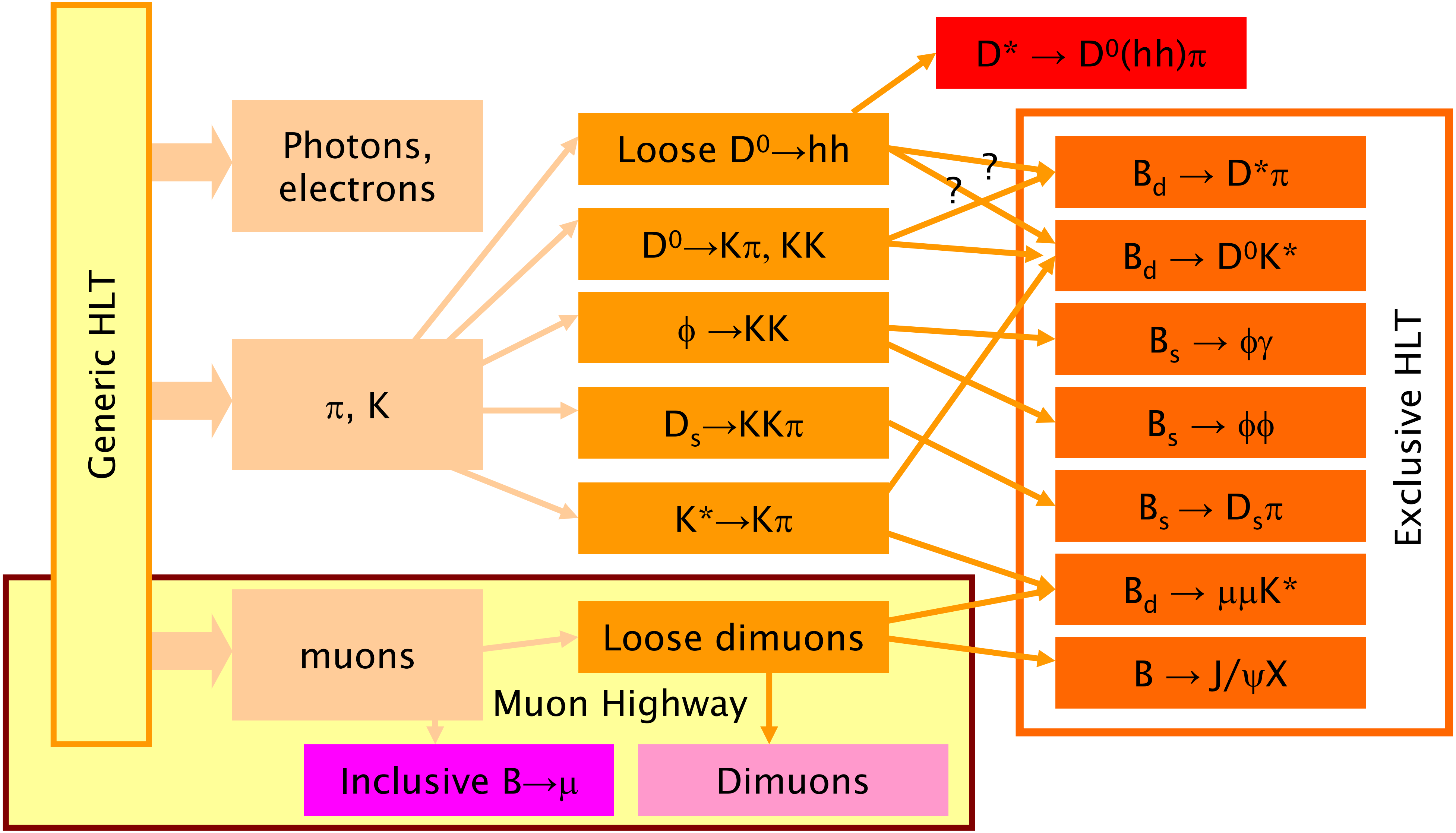
Inclusive samples and calibrations

- **Inclusive dimuon sample (~600 Hz):**
  - Clean J/ψ(1S), ψ(2S), Υ(4S), … Z (?) mass peaks for alignment, momentum (B field) calibration, etc …
  - Proper time resolution of prompt J/ψ events
  - High statistics may allow study as a function of kinematics

- **Inclusive b$\rightarrow\mu$ (~900 Hz):**
  - Extract tagging performance ?
    - Trigger On Signal: reconstruct very large sample of B $\rightarrow$D$\mu\nu$
    - Trigger Independent of Signal: reconstruct many exclusive modes “opposite” to muon

- **Inclusive D* sample (~300 Hz):**
  - Very high statistics and clean signal of $D^{*+}\rightarrow D^0\pi^+$, $D^0\rightarrow K^-\pi^+$
  - Measure PID performance as a function of momentum

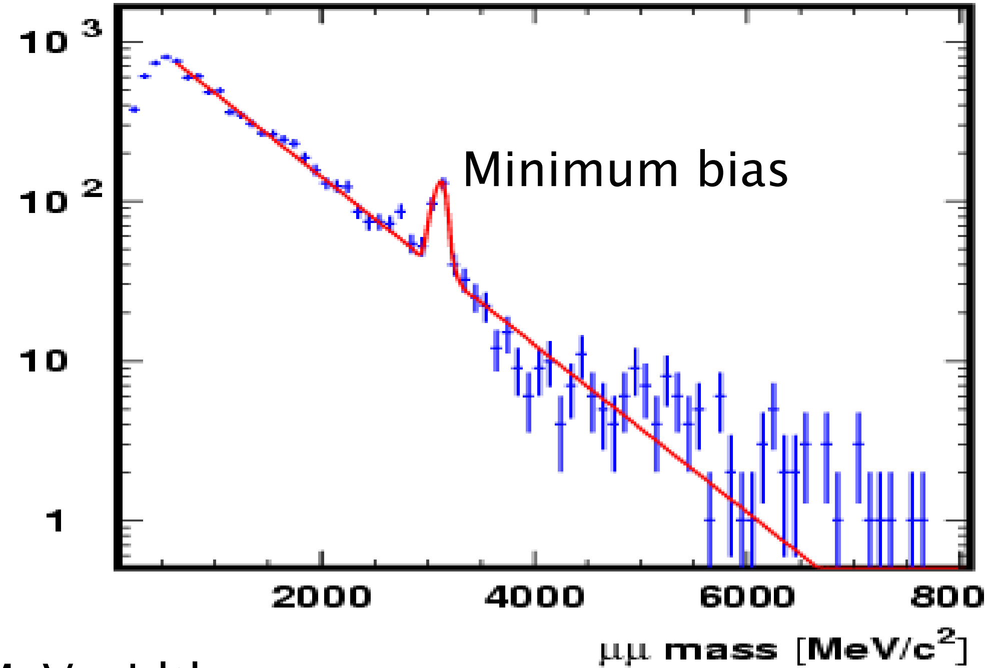
HLT: Data Flow

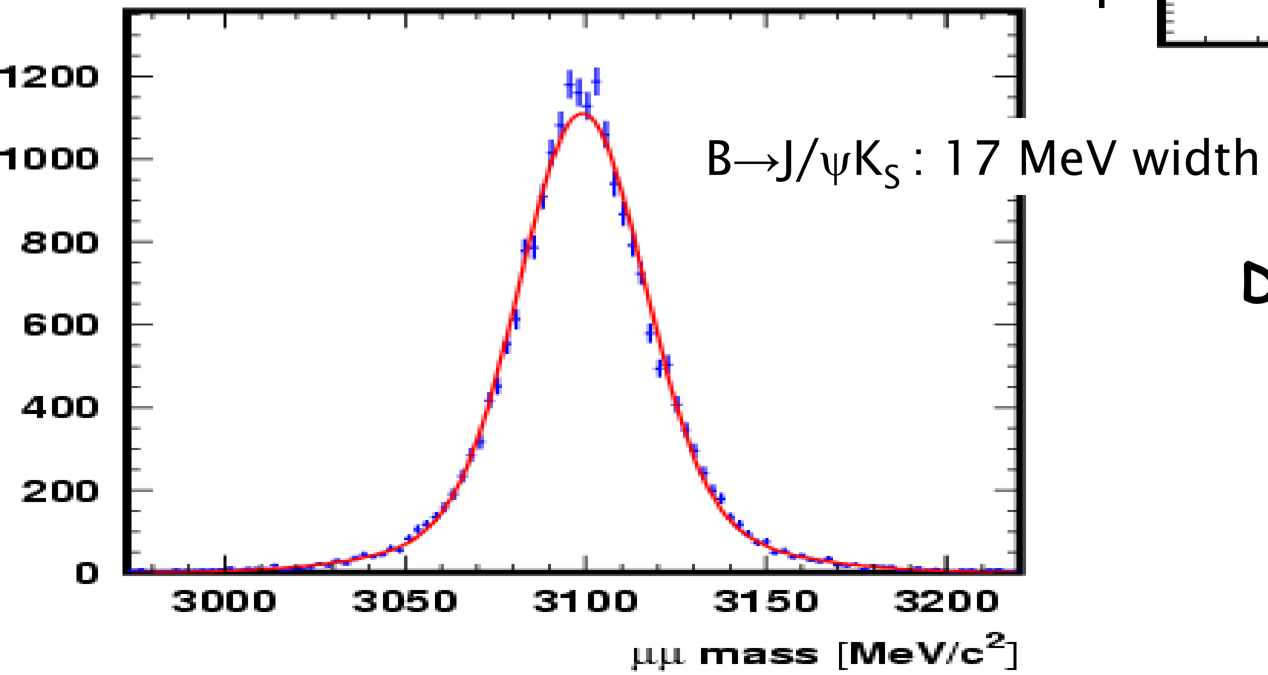


HLT: Inclusive Stream

Part of Generic HLT

- **Inclusive B stream:**
  - One muon
  - With P_T>3 GeV
  - And IP >3σ



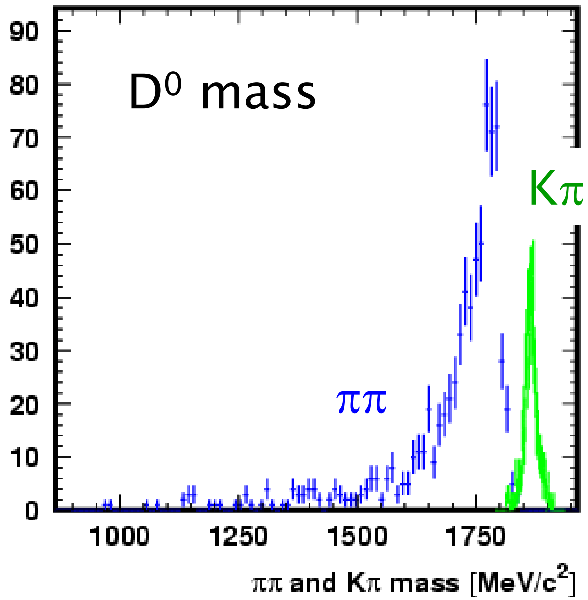


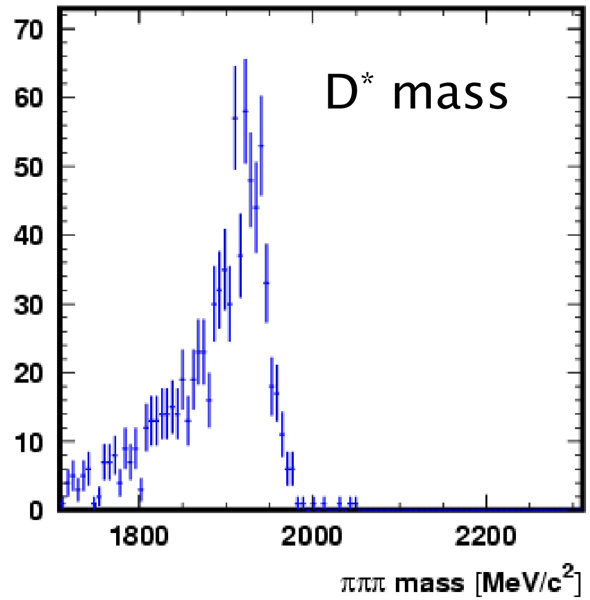
Dimuon stream:

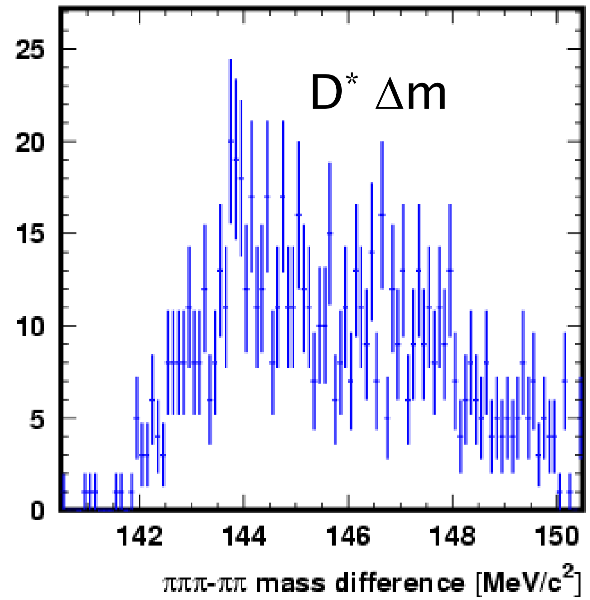
- Two tracks identified as muon
- m > 2.5 GeV
- χ^2<20

HLT: D* stream

- $D^0 \to \pi\pi$ with no mass cut
  - $\chi 2 < 50$
  - $P_T > 2$ GeV
  - Flight significance > 5
- $D^* \to D^0\pi$
  - $\chi 2 < 60$
  - $\Delta m < 10$ MeV
  - $P_T > 2$ GeV

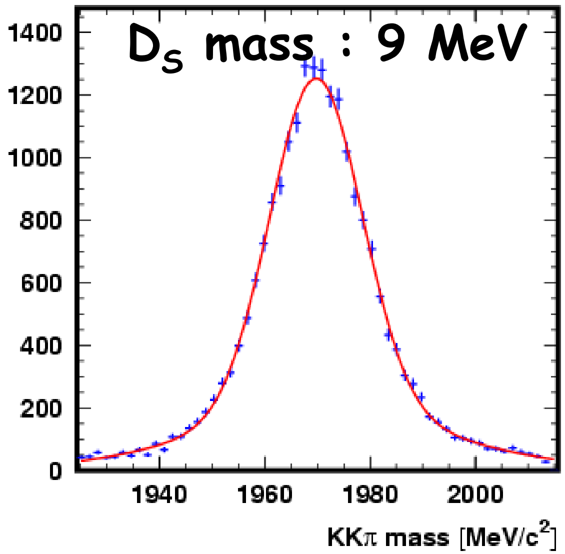


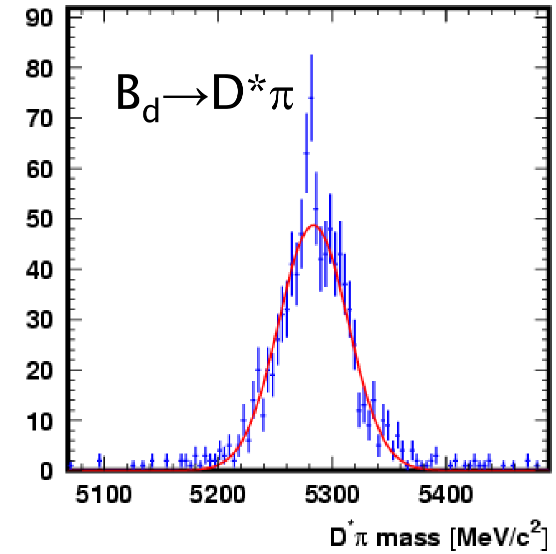


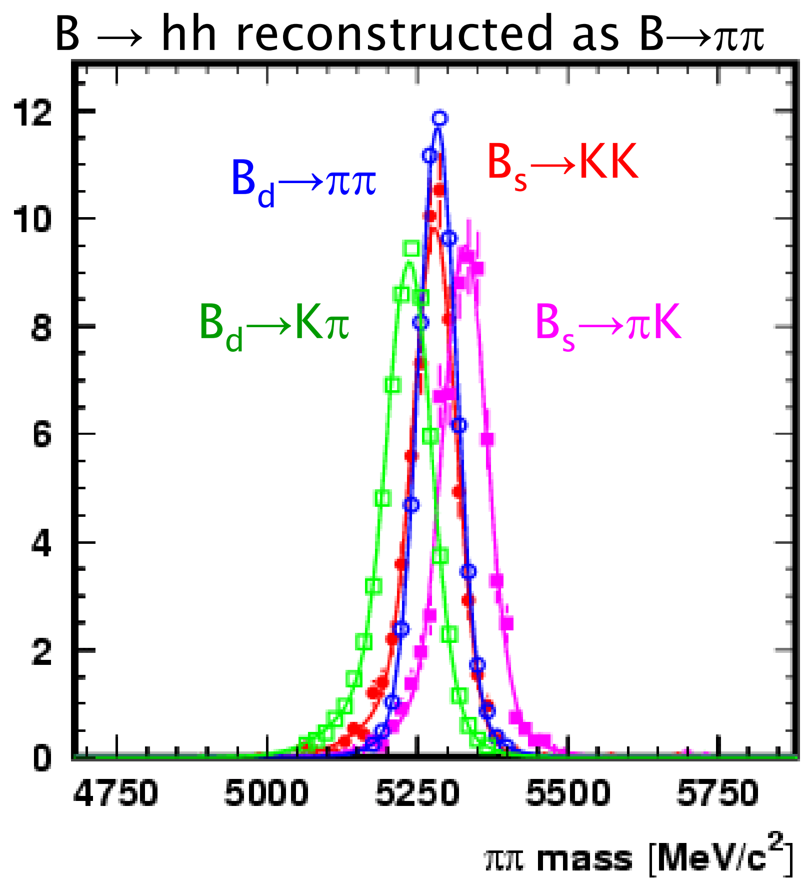


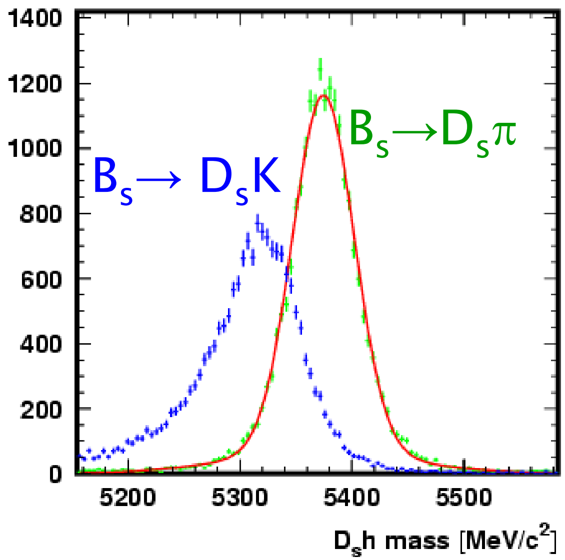
All plots from $B \to D^*\pi$ events, with $D^0 \to K\pi$

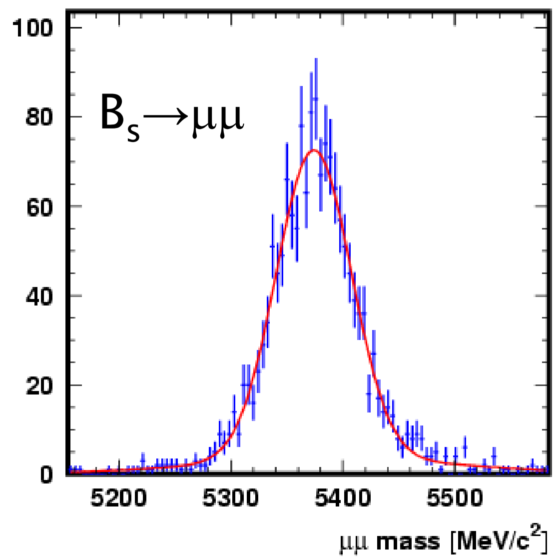
HLT: Exclusive Stream











All B mass resolutions ~ 30 MeV

Mass window: ±500 MeV, at least

HLT: Performance

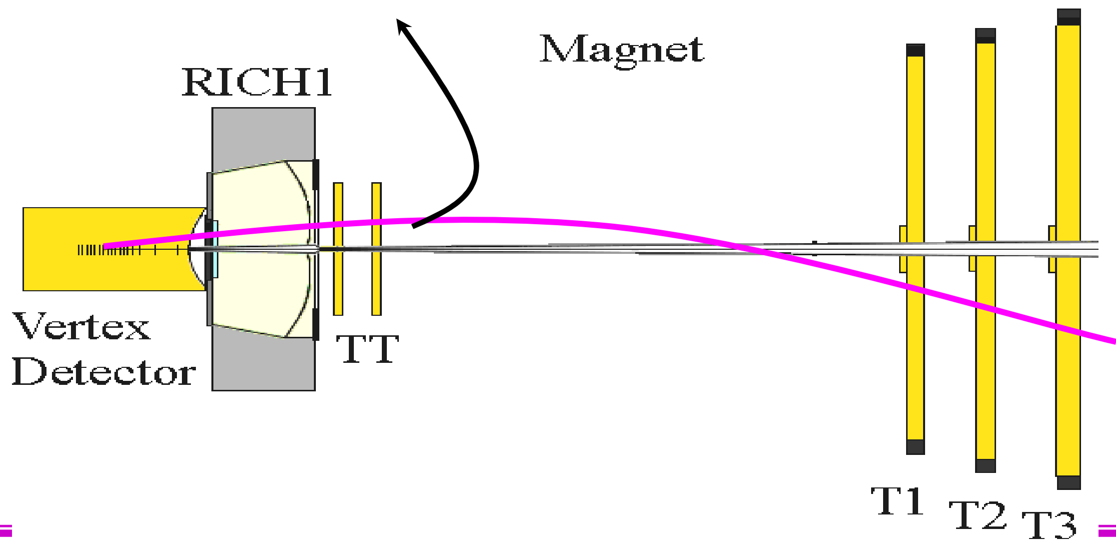
	Nominal	Rate	b-events	c-events	Correlations
Input	40 kHz	40 kHz	6.4 kHz	7.2 kHz	
Generic HLT	**10 kHz**	13 kHz	3.8 kHz	2.7 kHz	
Exclusive B	200 Hz	260 Hz	81 Hz	**68 Hz**	9% in D*
D*	300 Hz	250 Hz	**90 Hz**	**57 Hz**	
Dimuon	600 Hz	660 Hz	**119 Hz**	**211 Hz**	10% in Incl. B
Inclusive B	900 Hz	850 Hz	603 Hz	**162 Hz**	8% in $\mu\mu$
Total HLT	2.0 kHz	1.9 kHz	0.8 kHz	0.5 kHz	

	1 GHz Pentium III	
	No RICH	With RICH
VeLo Tracking	7 ms	7 ms
Generic HLT	19 ms	19 ms
Rest of Forward Tracking	5 ms	5 ms
PID (mainly RICH)	4 ms	12 ms
Shared Resonances	4 ms	3 ms
D* stream	<1 ms	< 1 ms
Exclusive stream	5 ms	3 ms
Total	**44 ms**	**50 ms**

Rates are within specifications and timing is well in 60 ms budget

HLT: Performance

Channel	Efficiencies w.r.t. Offline and L0xL1 selected signal						
	Generic	Tracking	Total Efficiencies				
			Excl. B	$\mu\mu$	Incl. B	D*	Total
$B_s \to \mu^+\mu^-$	99%	93%	91%	90%	94%	Order of 1%	98%
$B_d \to K^*\mu^+\mu^-$	98%	82%	73%	62%	58%		91%
$B_{d,s} \to h^+h^-$	94%	95%	88%	Order of 0.5%	Order of 2%		88%
$B_s \to \phi\gamma$	71%	93%	61%				62%
$B_s \to D_s h$	93%	82%	60%				62%



HLT: Work in progress

- **Strategies to overcome current limitations:**
  - **Improve tracking.**
    - Allow less hits in TT, for VELO-TT-T tracks
    - Improve speed of VELO-T tracks “a la offline”.
  - **Reduce the number of tracks to consider.**
    - Select only VELO tracks compatible:
      - with secondary vertices in the generic.
      - under some specific hypothesis using RICH info (Bs -> DsK)
  - **Inclusive Triggers: do not depend on having all tracks found.**
    - Improve generic to achieve lower output rate
    - 3 track vertex for 4 prong.
    - 4-5 track vertex for 6 prong (DD, $\eta_c\phi$)
    - 3 prong with K identified by RICH
    - ...

Outlook

- The design of the L0 trigger is finalized and production started. Its performance is very good for leptonic and photonic channels and adequate for hadronic channels.
- The software triggers L1/HLT work within the time budget: 1/10 ms.
- The design of the software triggers continues to evolve as our understanding of the LHCb physics potential evolves. An example of this is the change of the output rate from 200 Hz to 2 kHz.