The LHCb Level-1 Trigger

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for the

LHCb collaboration

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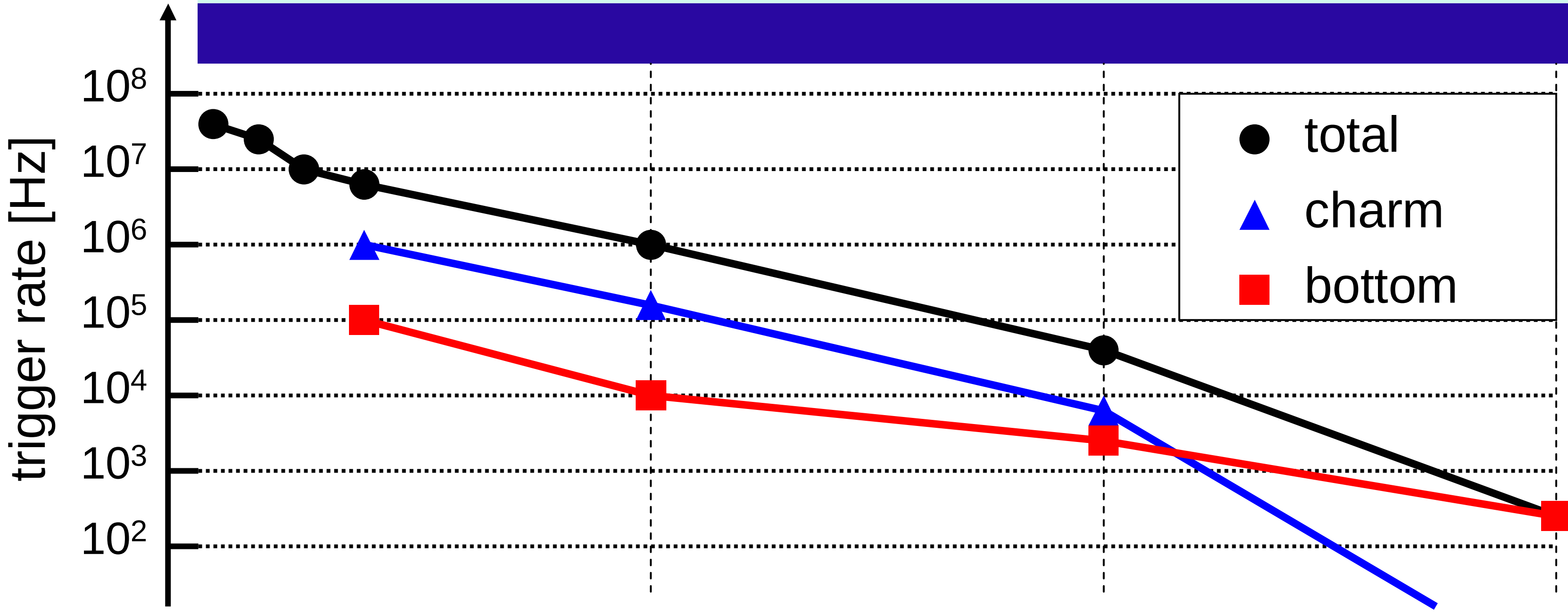
LHCb IN NUMBERS

- Design Luminosity: $L = 2 \times 10^{32}\ \text{cm}^{-2}\ \text{s}^{-1} = 200\ \mu\text{b}^{-1}/\text{s}$
- $\sigma_{total} \approx 100$ mb, $\sigma_{inel} \approx 80$ mb, **$\sigma_{vis} \approx 60$ mb**
  $\Rightarrow$ 12 MHz total (visible) interaction rate
  $\Rightarrow$ **10 MHz total (visible) event rate (pile-up)**
- Assumed **$\sigma_{bb} \approx 500\ \mu b$**
  $\Rightarrow$ **100 kHz B event rate!**
- But low branching fractions!
  Expect (offline reconstructable events):
  - $B_d \to J/\psi(\mu^- \mu^+)\ K_S(\pi^-\pi^+)$: 1 per minute
  - $B_d \to \pi^-\pi^+$: 1 in two minutes
  - $B_s \to D_s^-(K^+K^-\pi^-)\ K^+$: 1 in six minutes
  - $B_s \to \mu^- \mu^+$: 1 per week (?)

LHCb TRIGGER OVERVIEW



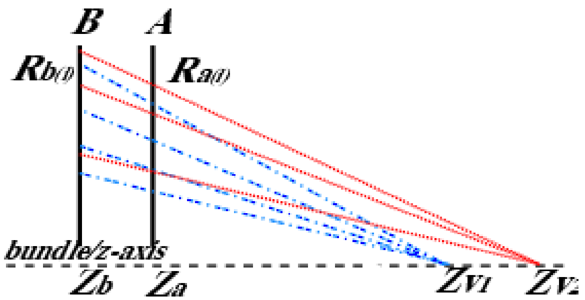
Level-0:
- hardware
- 10 MHz → 1 MHz
- Uses:
  - calorimeters
  - muon chambers
  - pile-up veto (Si)

Level-1:
- software
- 1 MHz → 40 kHz
- Uses:
  - **vertices (Si)**
  - some tracking
  - L0 objects

High-Level:
- software
- 40 kHz → 200 Hz
- Uses:
  - full event data

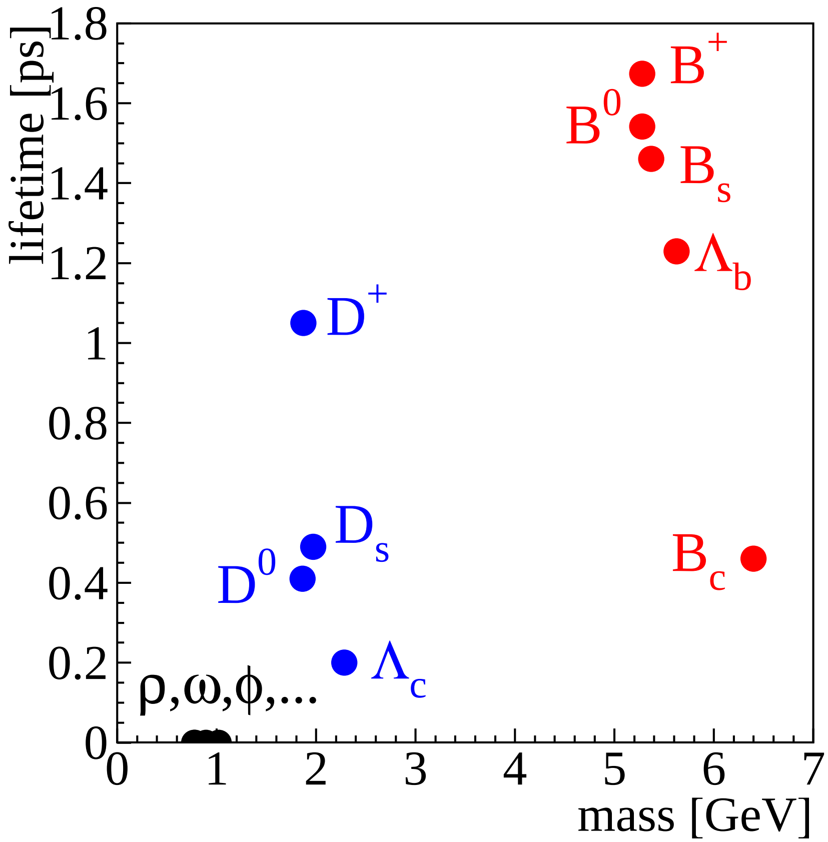
LEVEL-0 TRIGGER

- **Fully synchronous** and **pipelined hardware trigger**
- **~10 MHz** visible event rate (30 MHz bunch crossing)
- Global event variables (10 MHz $\rightarrow$ 7 MHz):
  - **pile-up detector** (two backward-looking silicon disks): reject events with multiple primary vertices
  - **multiplicity** in pile-up detector and SPDs in front of calorimeter (scintillator pad detectors for e/γ separation): reject too complicated events
  - **minimum Σ E_T** in all **HCAL** cells (avoid "empty" events)



- B signatures (7 MHz $\rightarrow$ 1 MHz):
  - **high-p_T muons:** track segments in muon chambers (MWPC)
  - **high-E_T electrons, photons, π^0:** ECAL clusters (+SPD/PS)
  - **high-E_T hadrons:** HCAL clusters

LEVEL-1 STRATEGY



B hadrons are the **elephants** of the particle zoo: they are **heavy** and **long-lived**

Approximation at trigger level: look for tracks with both

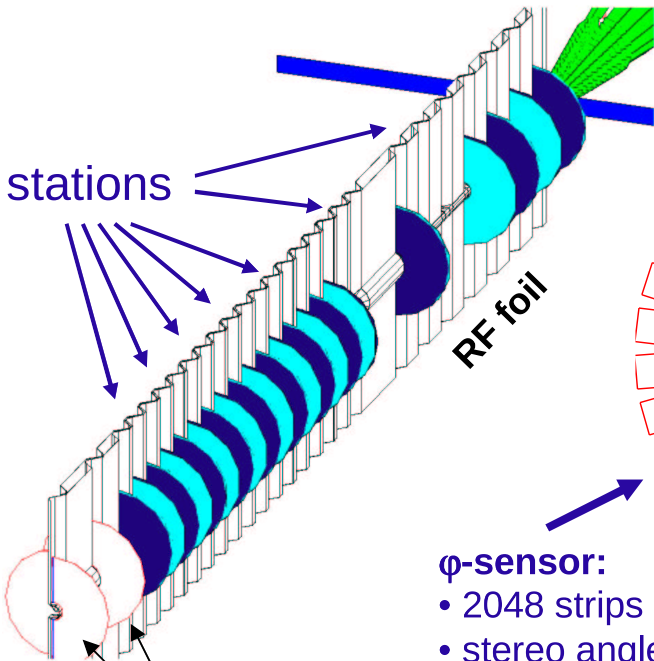
- **high transverse momentum (p_T)**
  and
- **high impact parameter** (relative to primary vertex)

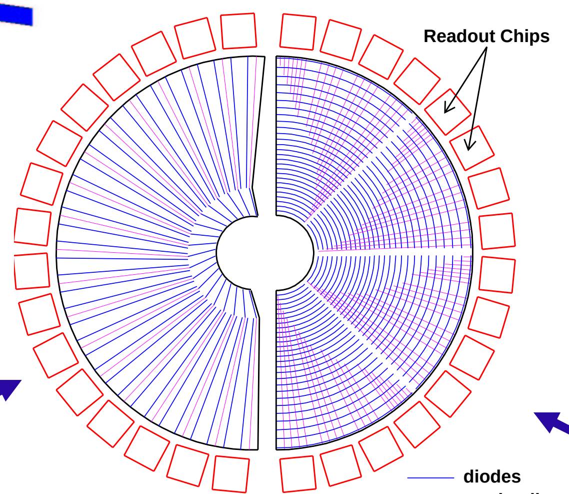
How do we measure impact parameters and p_T?

IMPACT PARAMETER (1)

measure impact parameters with the **VE**rtex **LO**cator:

- 21 stations, each with 2 r- and 2 φ-sensors
- –17.5 cm < z < 75 cm
- 220 μm Si, n-on-n
- sensitive area: 0.8 cm < r < 4.2 cm
- 170k channels
- ~1000 clusters/event to L1





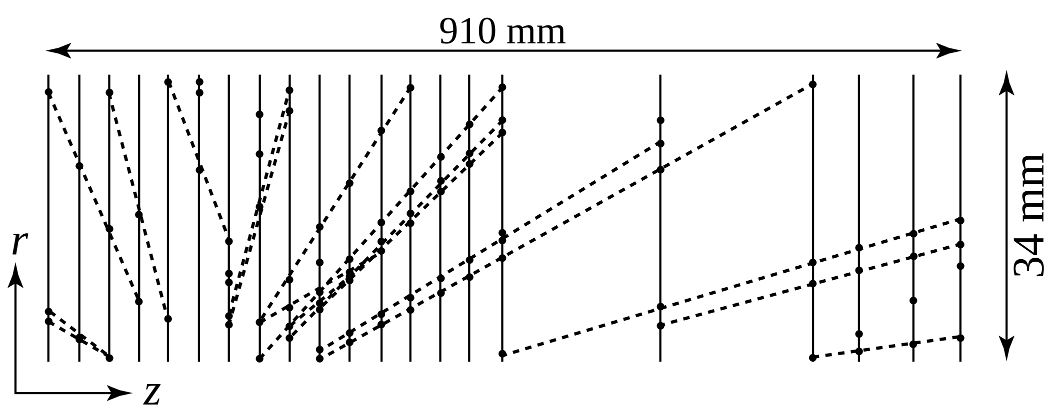
φ-sensor:
- 2048 strips
- stereo angle (+10°, –20°)
- 37–98 μm pitch

r-sensor:
- 2048 strips
- 4 sectors (45°)
- 40–103 μm pitch

IMPACT PARAMETER (2)

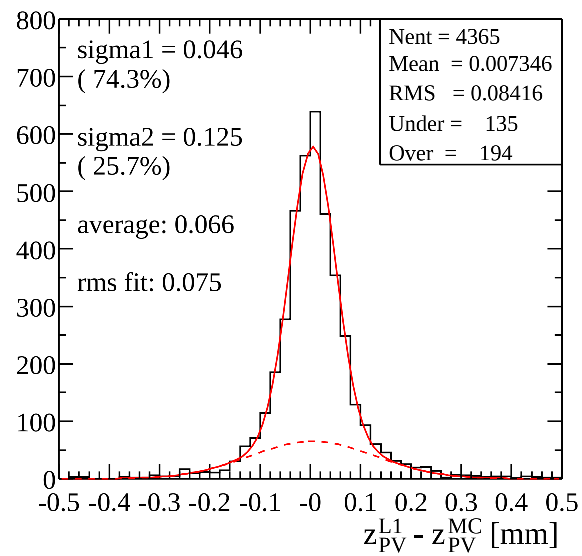
r-z projection contains most of the impact parameter information:

⇒ fast r-z tracking using only r-sensors (straight-forward thanks to rather low occupancy in 45° sectors!)



ε = 98% for B tracks

primary vertex resolution:

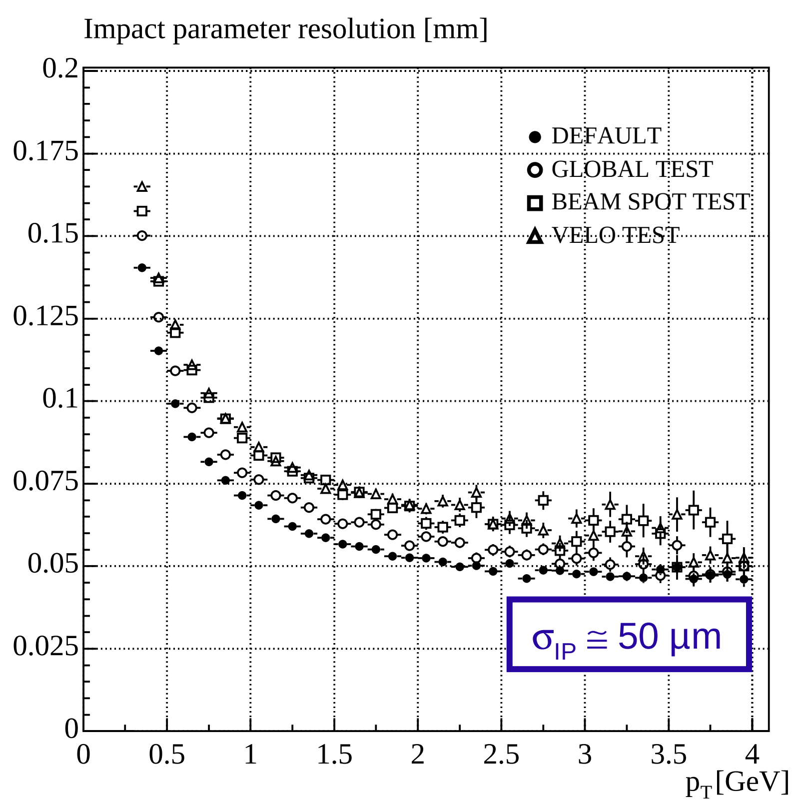


$\sigma_z \cong 75\ \mu m$

IMPACT PARAMETER (3)

impact parameter resolution:

(also for various robustness scenarios…)

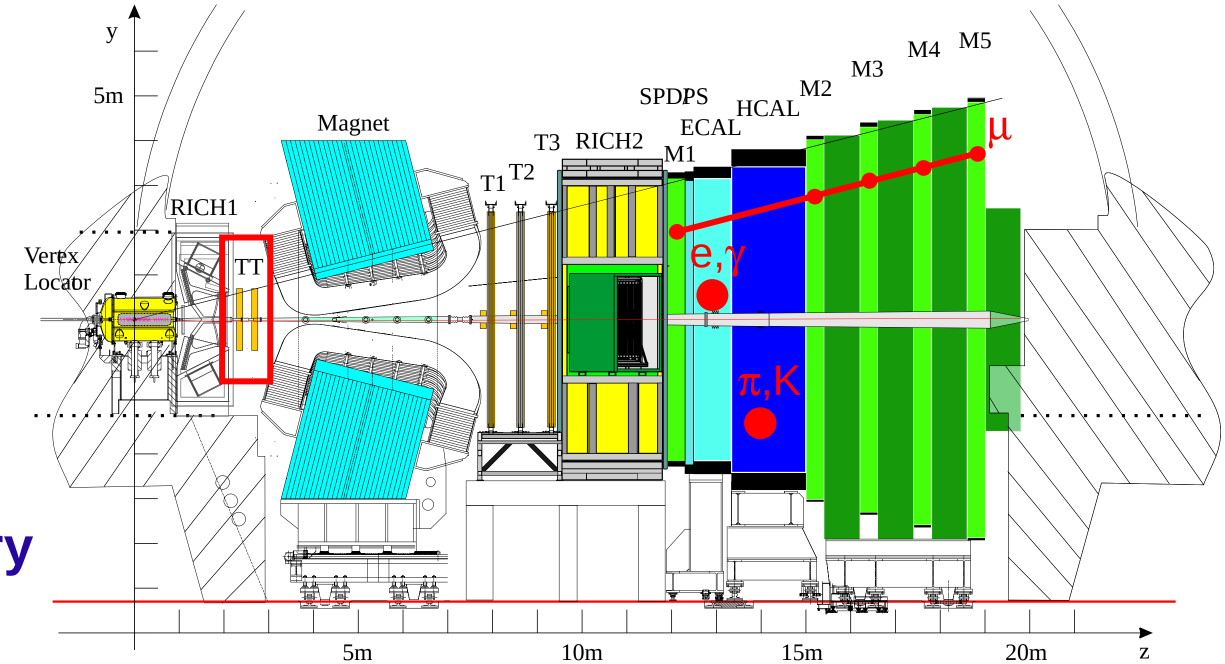


Good resolutions are obtained with (fast) 2D tracks!

But: p_T measurement via extra-polation necessitates 3D tracks!
⇒ Reconstruct in 3D (φ-sensors) **only** those tracks that have **large impact parameter!** (between 0.15 mm and 3 mm)

P_T MEASUREMENT

We must extrapolate tracks to some measurement that is influenced by the magnetic field!



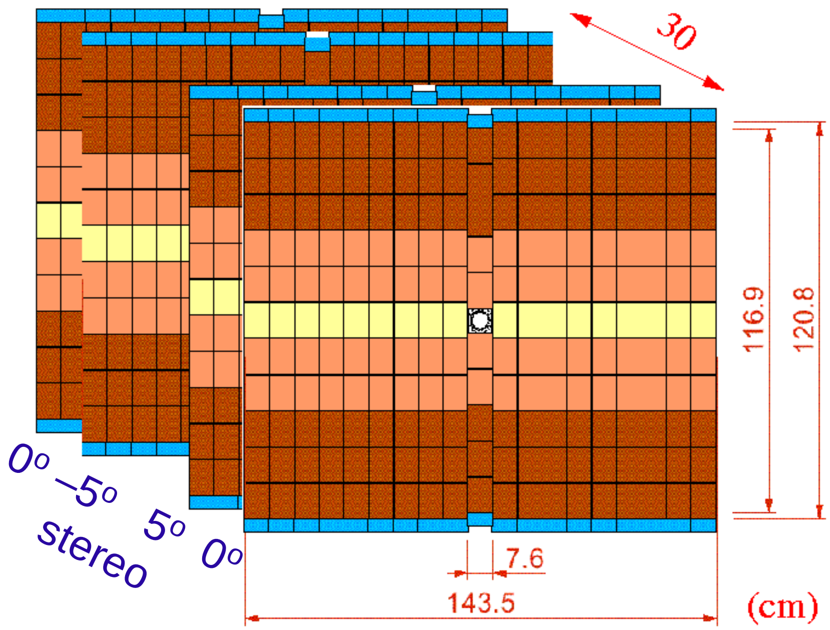
Two complementary approaches:

1) Fringe field before the magnet:
extrapolation to first tracking station, **TT** (= **Trigger Tracker**), situated between VELO and magnet
⇒ coarse momentum resolution but high efficiency

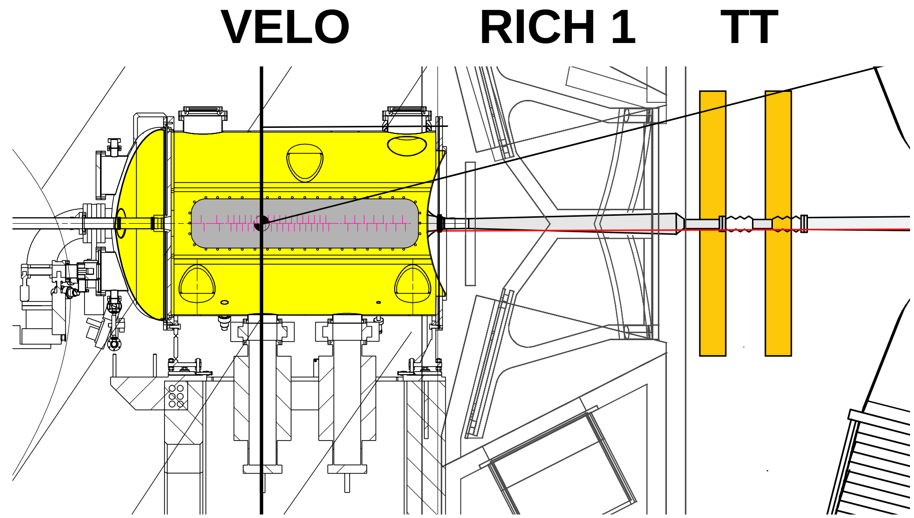
2) Full p_T kick after the magnet:
recycle calorimeter clusters and muon track segments found by **Level-0**, try to match them to VELO tracks!
⇒ better momentum resolution but low over-all efficiency and low purity

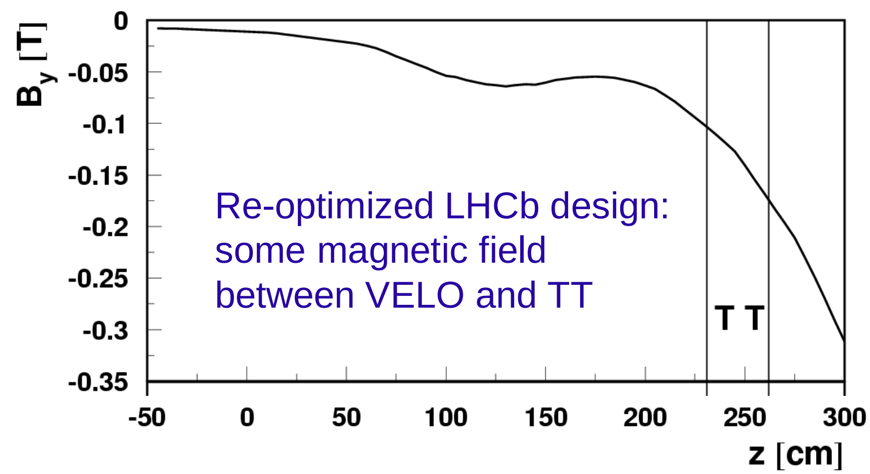
P_T MEASUREMENT: TT

The Trigger Tracker (TT):



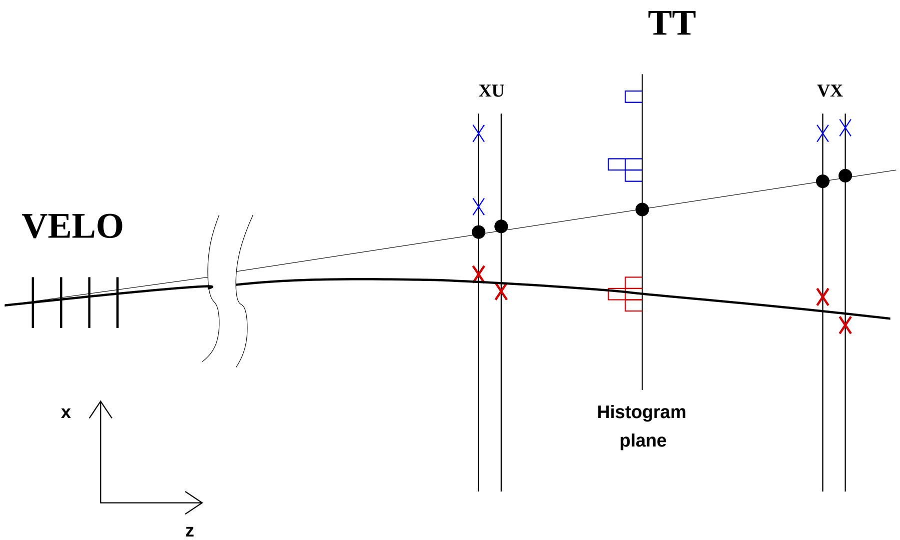
- 4 layers of Si (500 μm thick, 200 μm pitch)
- 836 sensors of 7.8 × 11 cm^2 (7 m^2 total)
- ca. 400 clusters / event for Level-1

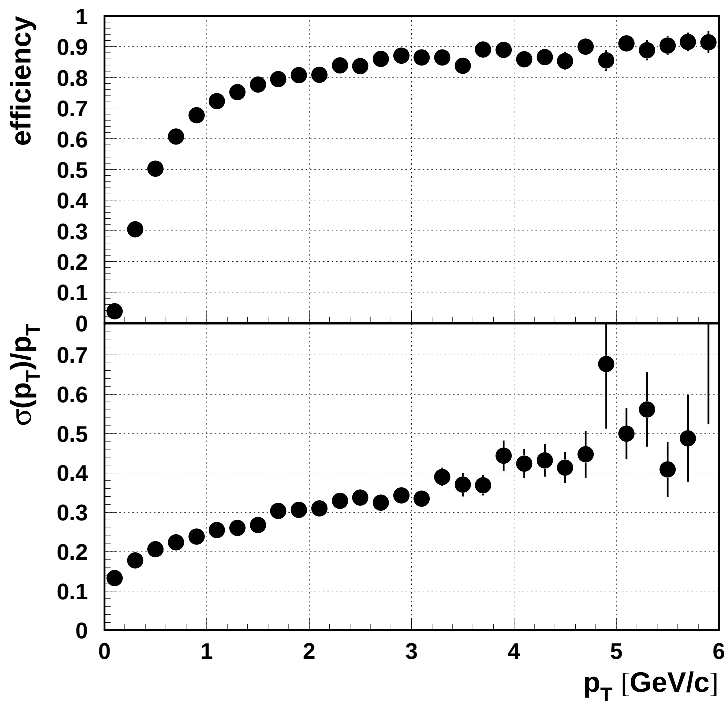




P_T MEASUREMENT: TT

integrated Bdℓ ≈ 115 kG cm
⇒ 10-GeV track is deflected by 3.4 mm at TT





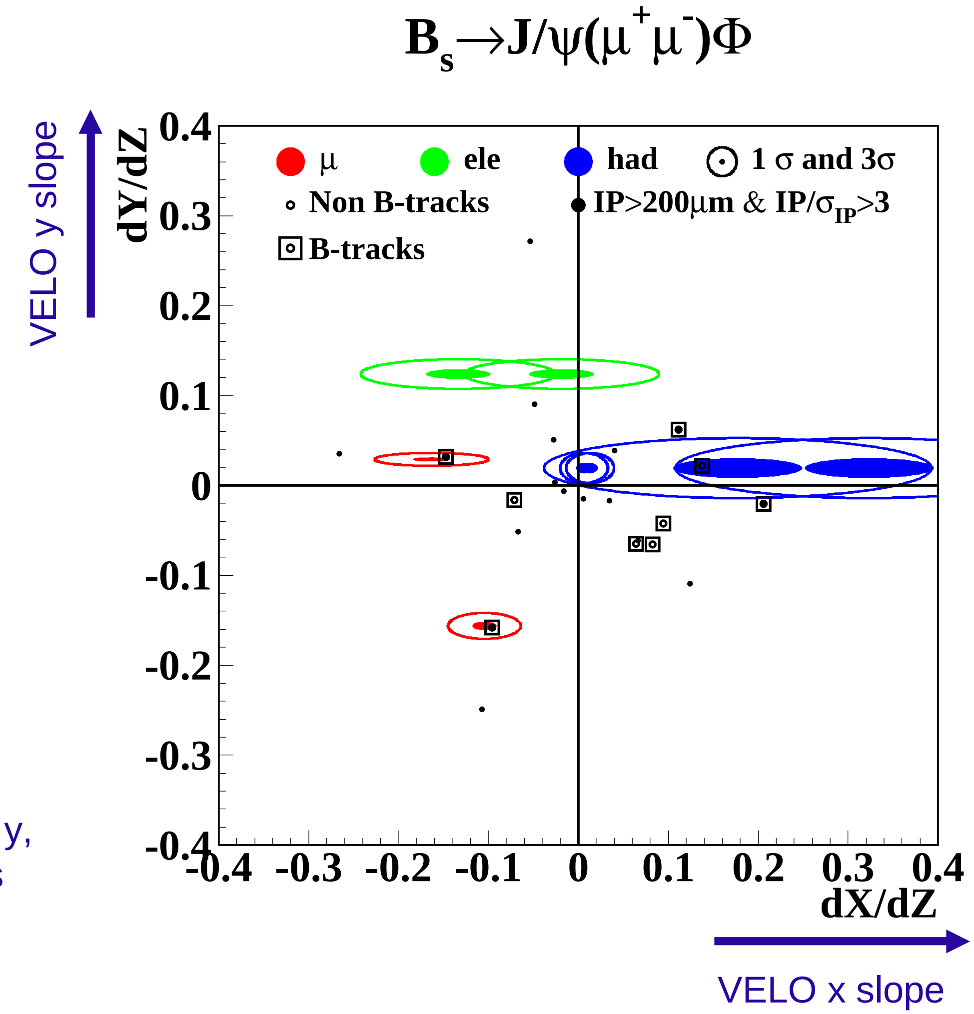
extrapolation of VELO track to TT clusters, matching with histogramming method

Momentum resolution: 20–40%

P_T MEASUREMENT: L0

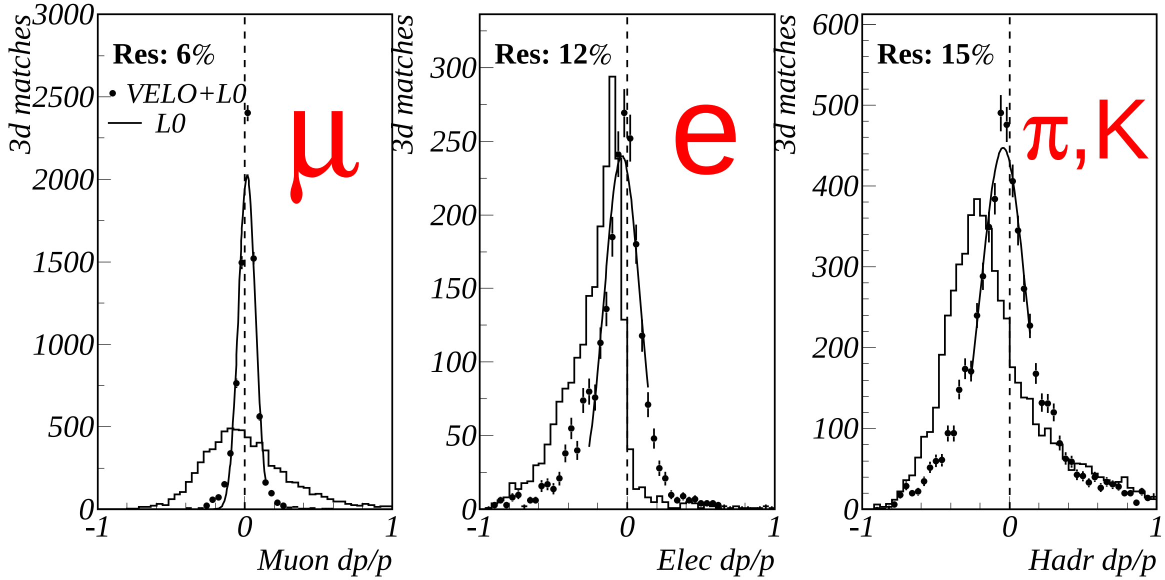
Complementary approach:

Try to match tracks found in the VELO to **high-p_T objects found by Level-0:**
- muon track segments
- calorimeter clusters (ECAL and HCAL)



Example: VELO slopes in x and y, comparison between predictions from Level-0 objects and actual VELO tracks

P_T MEASUREMENT: L0



momentum resolution:	**6%**	**12%**	**15%**
matching efficiency:	**95%**	**96%**	**93%**
purity:	**51%**	**33%**	**27%**

P_T MEASUREMENT: L0

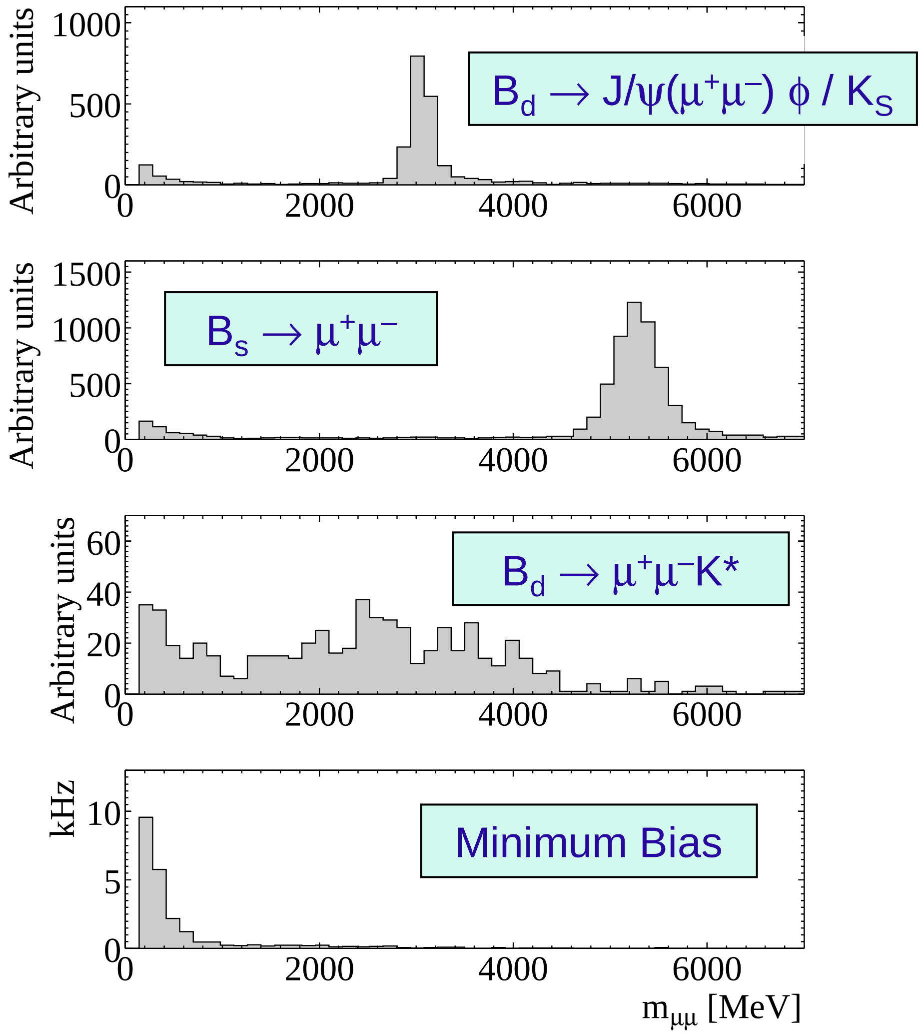
Example:

μμ **invariant mass** available at Level-1!

⇒ can boost dimuon channels at small cost in bandwidth!

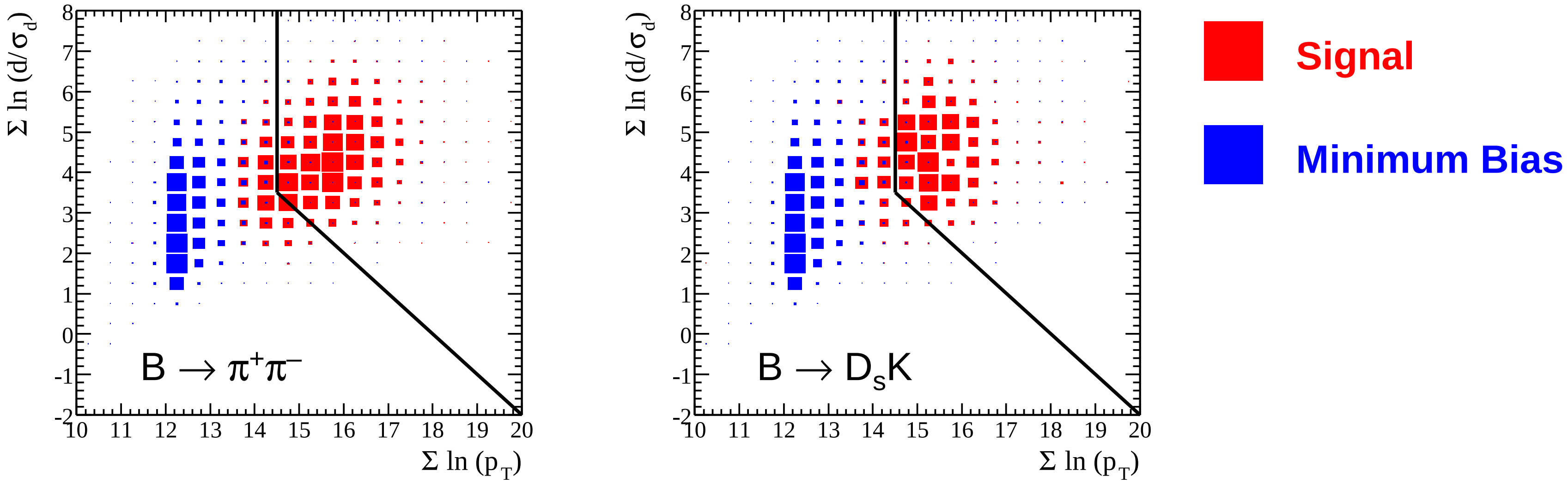
- $B \to J/\psi(\mu^+\mu^-)X$ channels
- $B \to \mu^+\mu^- K^*$
- $B \to \mu^+\mu^-$

More knobs to turn…, under study!



DECISION ALGORITHM

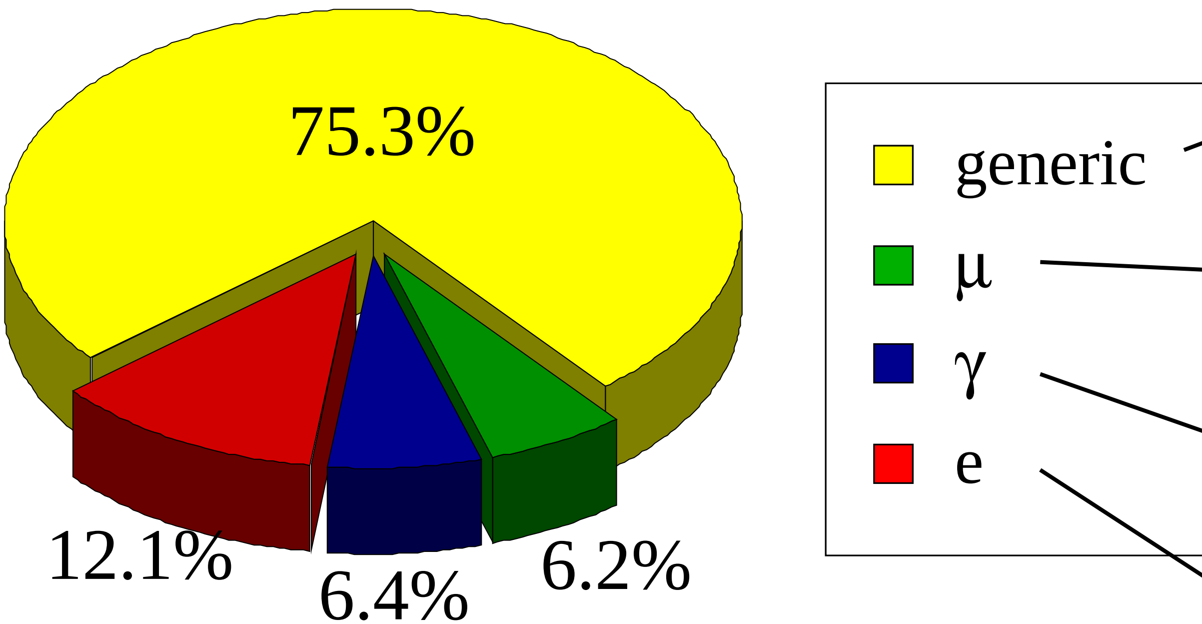
- among the tracks with high impact parameter [0.15 – 3 mm], select the **two with the highest p_T**
- using the measured p_T's estimate the **significances of the impact parameters** of the two tracks (d/σ_d)
- apply a **2D cut** in the plane $\Sigma \ln(p_T)$ vs $\Sigma \ln(d/\sigma_d)$



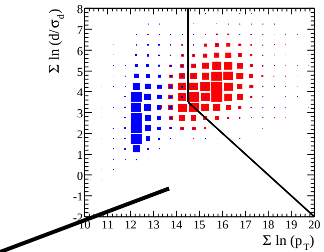
- **relax** the cut in the presence of **specific signatures:** dimuon mass, high-p_T photons and electrons from L0

BANDWIDTH DIVISION

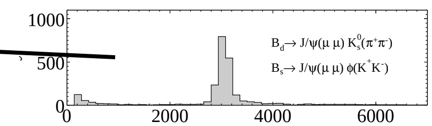
Applied for "TDR Trigger":



high-p_T (VELO-TT)



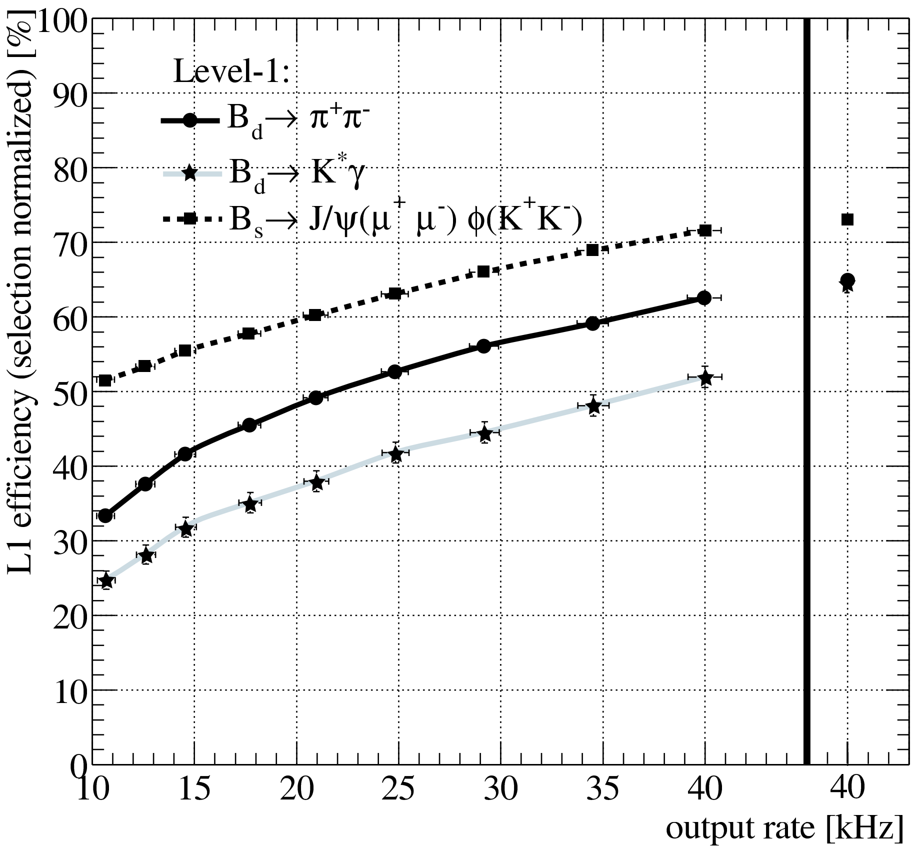
dimuons (VELO+L0)



high-E_T γ (L0)

high-E_T $e^{\pm}$ (L0)

PERFORMANCE



$B \to$	ε_{L1}	$\varepsilon_{L0\times L1}$
$\pi^+\pi^-$	62.7%	33.6%
$D_s^-K^+$	62.6%	29.5%
$J/\psi(\mu^+\mu^-)\ K_S$	67.7%	60.5%
$J/\psi(e^+e^-)\ K_S$	54.9%	26.5%
$J/\psi(\mu^+\mu^-)\ \phi$	71.4%	64.0%
$K^{*0}\gamma$	51.9%	37.8%

IMPLEMENTATION

- Level-1 is a **software trigger**
  - maximum flexibility at an early stage!

- Level-1 farm now a part of the LHCb online farm:
  - larger L1 event size (with TT data, possibly more tracking stations)
  - smaller global event size due to detector re-optimization
  - $\Rightarrow$ L1 and global event sizes not so different anymore!

- 1800 processors foreseen for the entire LHCb farm
  - flexible allocation between offline reconstruction and triggers (L1 and HLT), currently planning on 1000 processors for L1 and 400 for HLT
  - $\Rightarrow$ average processing time of **1 ms per event** (1 MHz input rate)

- Level-1 buffer holds 58k events $\Rightarrow$ **> 50 ms latency**

  (Quad Data Rate SRAM)

TIMING

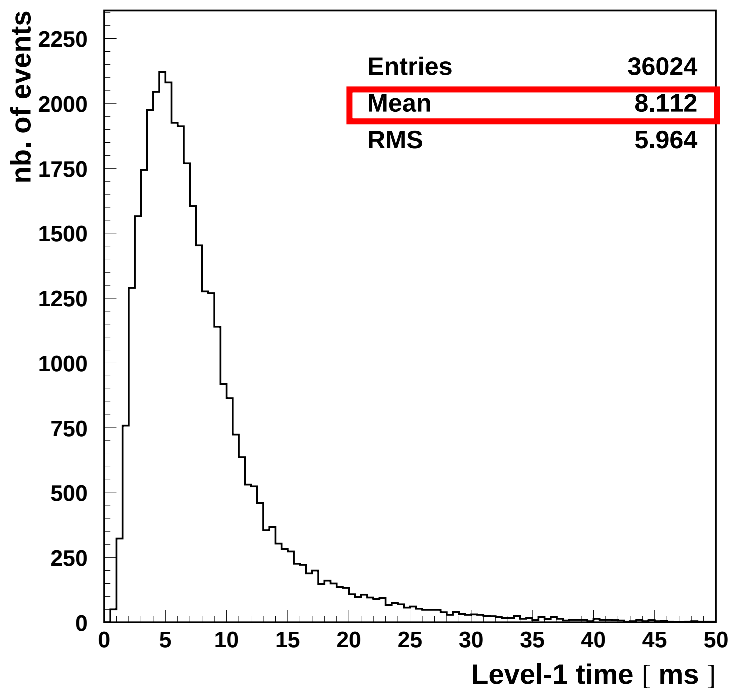
initialization	~13%
2D tracking	~45%
primary vertex	~6%
3D tracking*	~20%
p_T measurement* (match to TT+L0)	~16%

* selected tracks only

- **on average ~8 ms / event for complete L1 decision measured with 2002 CPUs**
- **expect a factor ~6 in CPU power between 2002 and 2007 (PASTA* report)**

⇒ we are already in the right ballpark! (many optimizations still to come)

(TDR studies)



* **PASTA** = The LHC Technology Tracking Team for **P**rocessors, Memory, **A**rchitectures, **ST**orage and **TA**pes

HIGH-LEVEL TRIGGER

- A second layer of **software trigger** for final decision on whether to write event to storage (~200 Hz foreseen)

- **Full detector information available** at this level (except RICH)

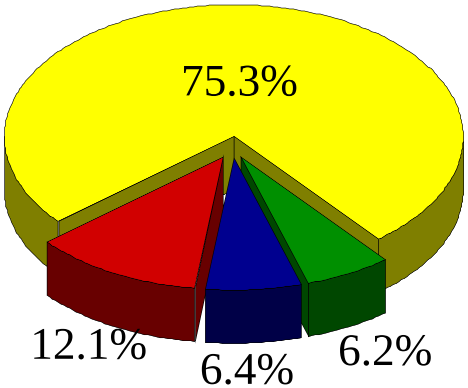
- Algorithms are **still under development**; current strategy:
  1) **Confirmation of Level-1 decision** with momentum resolution from all tracking stations (T1–T3): 40 kHz $\rightarrow$ 20 kHz
  2) **Full reconstruction** of (long) tracks.
  3) **Exclusive selection** of priority channels (simplified offline selections): 10–20 Hz per channel
  4) **Inclusive selection** of other channels (exploit common features in offline selections): fill remaining bandwidth

$\Rightarrow$ **hadron colliders force us to run the physics selection algorithms in the trigger!**

SUMMARY

- The LHCb Level-1 trigger is a **software trigger**
- Selection of events containing b hadrons by searching for **high impact parameter** and **high transverse momentum** of daughter tracks
- detector input from:
  - **VErtex LOcator** (impact parameter)
  - **Trigger Tracker**
  - **L0 decision unit**

  } (p_T)



- Extensive studies show satisfactory physics performance **within time budget**
- **Technical Design Report** for the LHCb Trigger System has just appeared! See there for more details.

TRIGGER TDR

CERN / LHCC 2003-31

9 September 2003

together with:

Reoptimized Detector
Design and Performance
TDR