Triggering in high energy physics experiments

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What is a trigger?

trig·ger (trĭg′ər)
n.

1.

a. The lever pressed by the finger to discharge a firearm.
b. A similar device used to release or activate a mechanism.

2. An event that precipitates other events.
3. *Electronics* A pulse or circuit that initiates the action of another component.

tr.v. **trig·gered**, **trig·ger·ing**, **trig·gers**

1. To set off; initiate: *remarks that triggered bitter debates.*
2. To fire or explode (a weapon or an explosive charge).

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Colliders and triggers

Most experiments require a trigger because they need to know when to record data. I'll distinguish

Trivial triggers : triggers which select when to record data in a periodic manner or in a way which is otherwise independent of the actual properties of the event being selected

Non-trival triggers : triggers which select whether or not to record an event based on the properties of that event

What kind of trigger does your experiment need?

Colliders and triggers

Two parameters to consider

1) The frequency with which events occur

2) The complexity (size) of each event

These determine the trigger design, for example

A) If events occur more frequently than it is possible to read out the full detector, then a trigger has to reduce their rate

B) If the combined size of all events is too big to store anywhere on the planet, then a trigger has to reduce their rate

C) The more complex the events, the longer they will take to process

So what will be covered?

I will discuss non-trivial triggers using the LHCb experiment as a pedagogical example

- **The LHC environment is extremely complex : if you can trigger there, you can trigger anywhere**

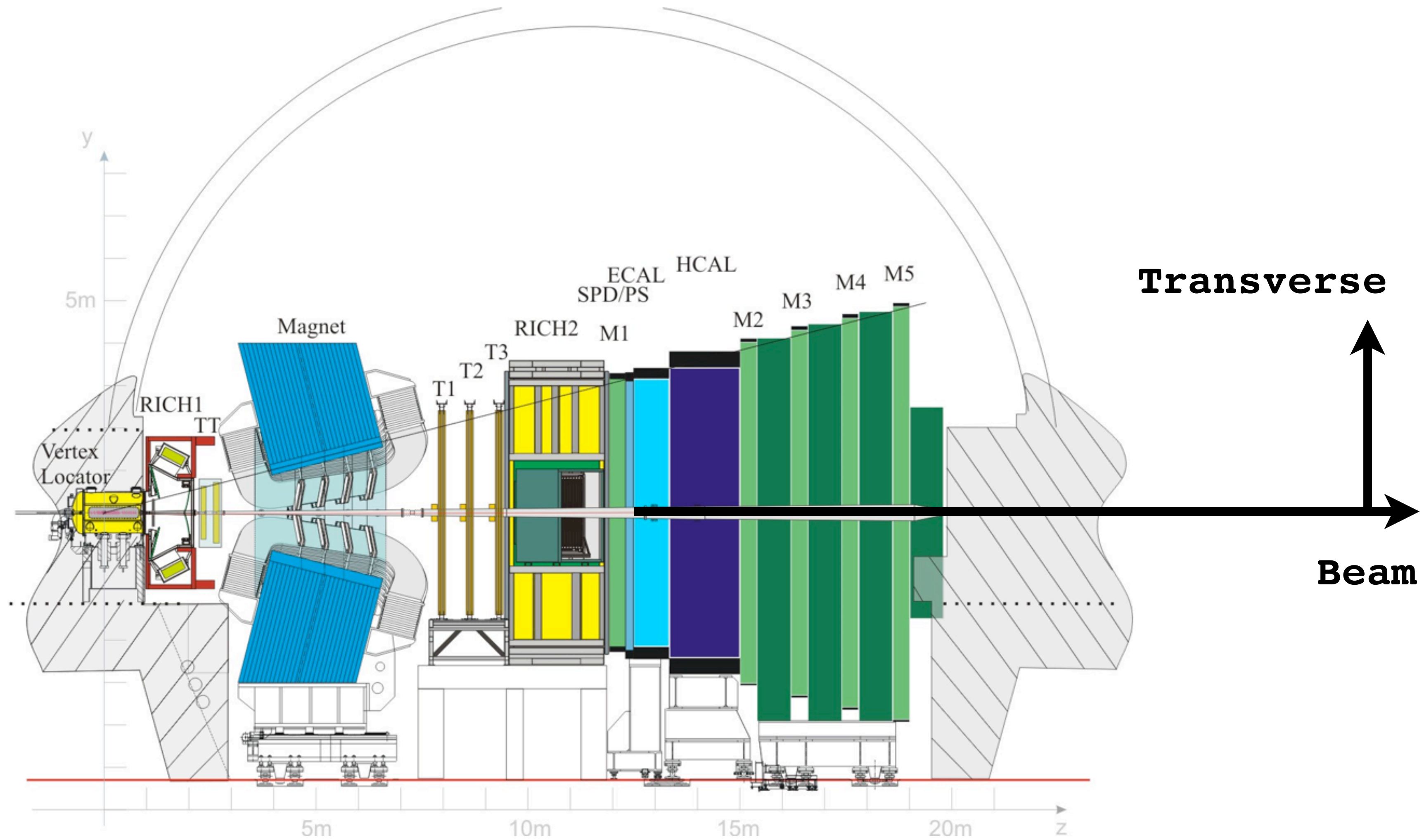
- **Trivial triggers are often an interesting engineering challenge, but they will not be covered here**

Before we begin I will describe the LHCb experiment and the LHC collision environment

At the end I'll discuss briefly other LHC experiments' triggers

The LHCb trigger

LHCb

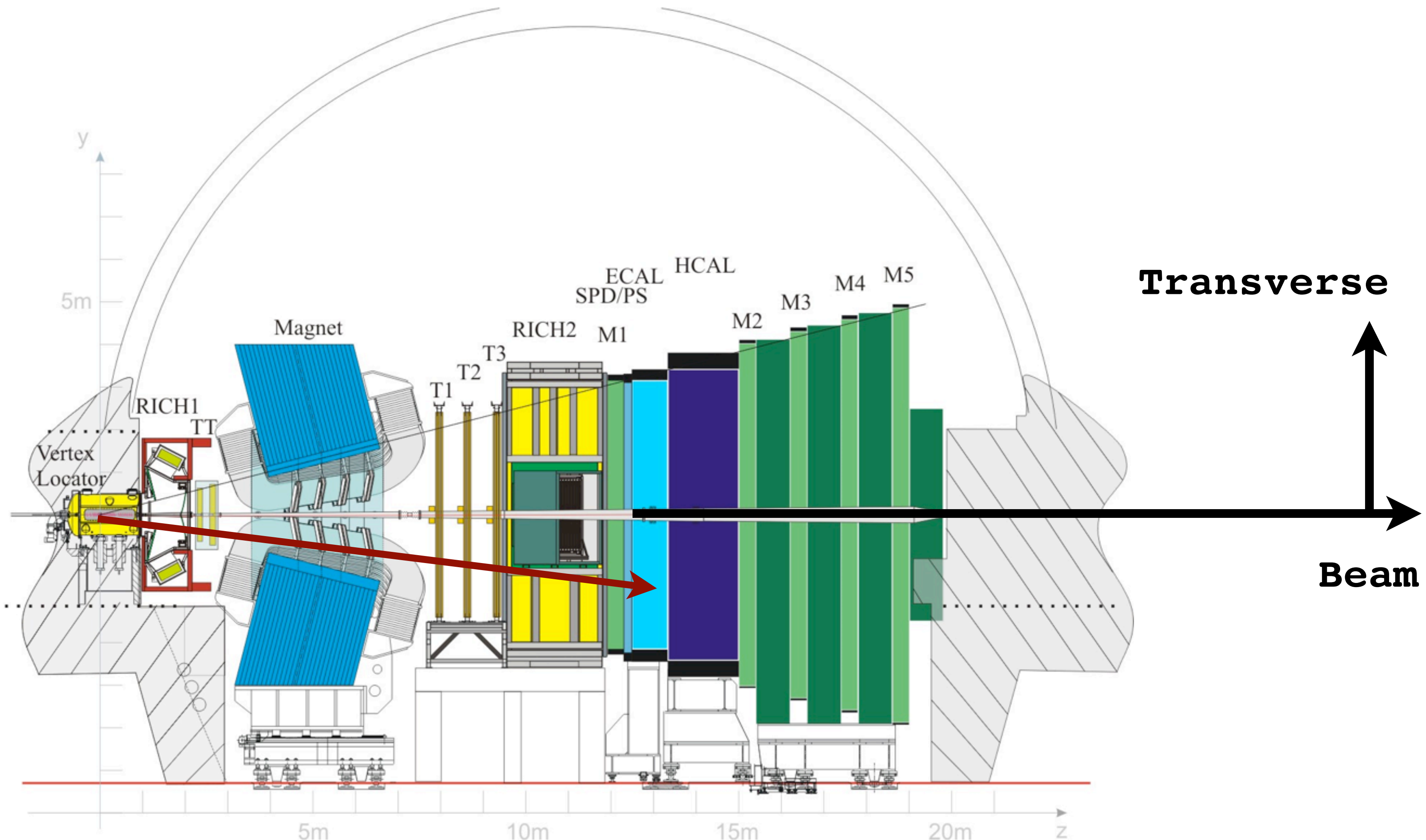


p_T = Transverse momentum

E_T = Transverse energy

LHCb

➡ **ELECTRONS**
➡ **PHOTONS**



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LHCb

- **ELECTRONS**
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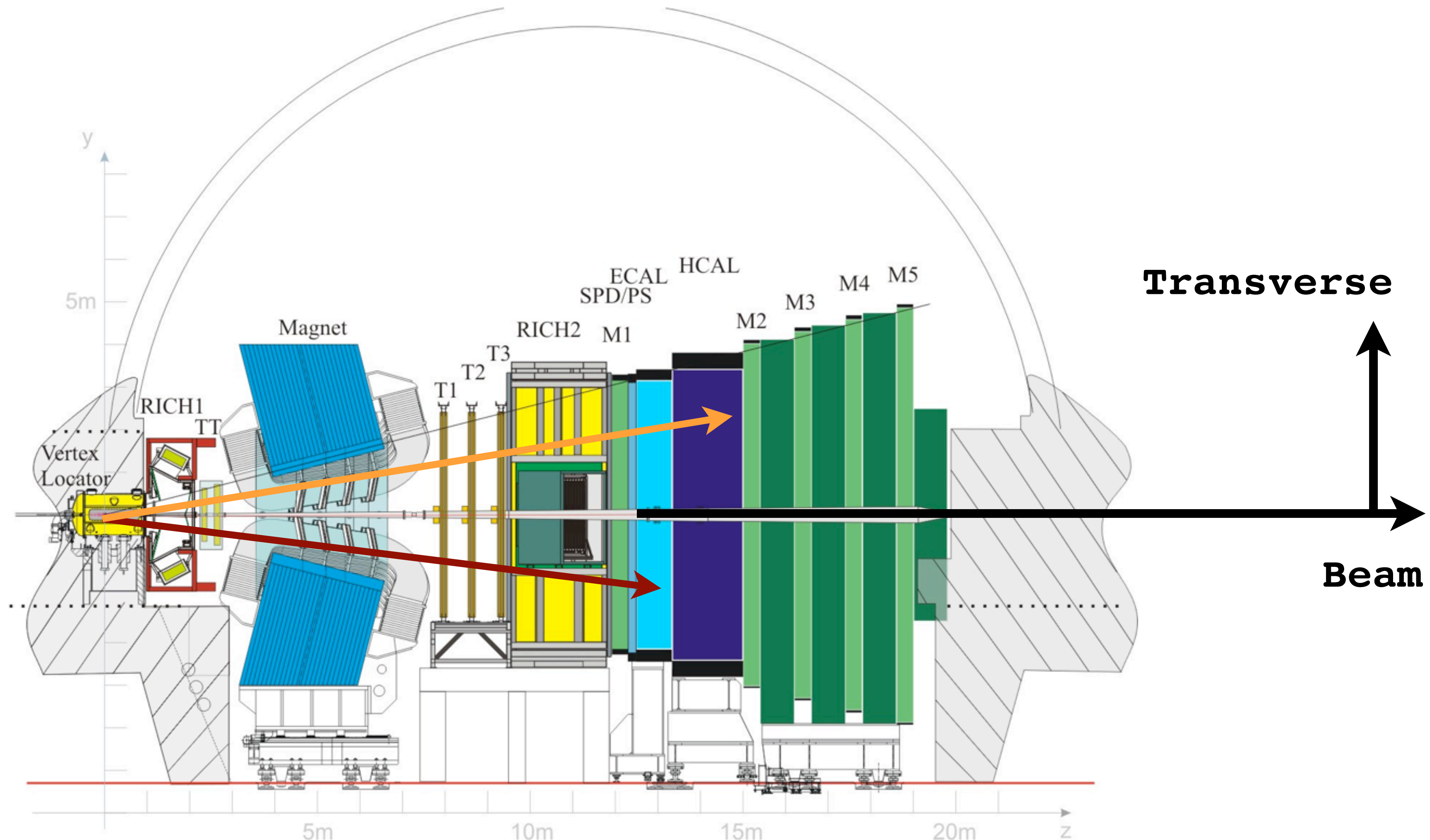
- **HADRONS**



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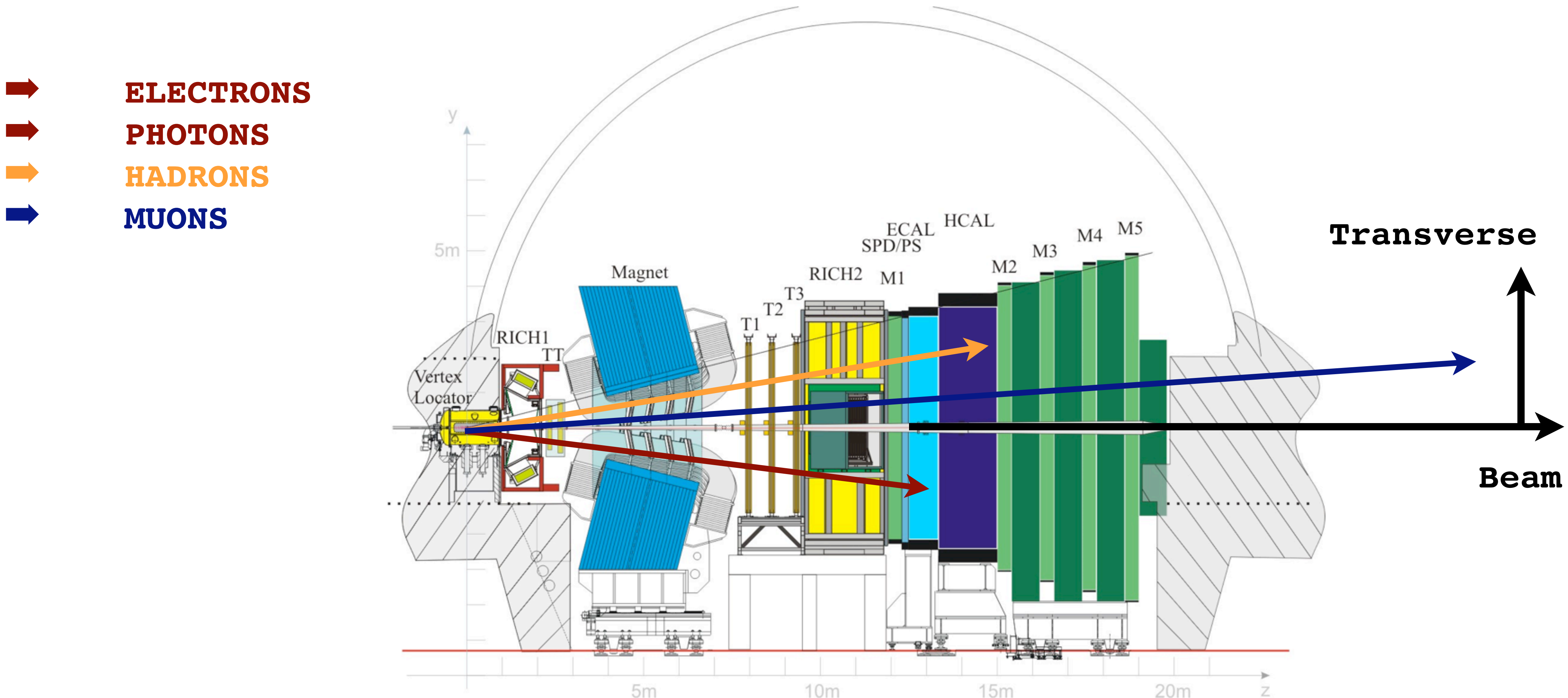

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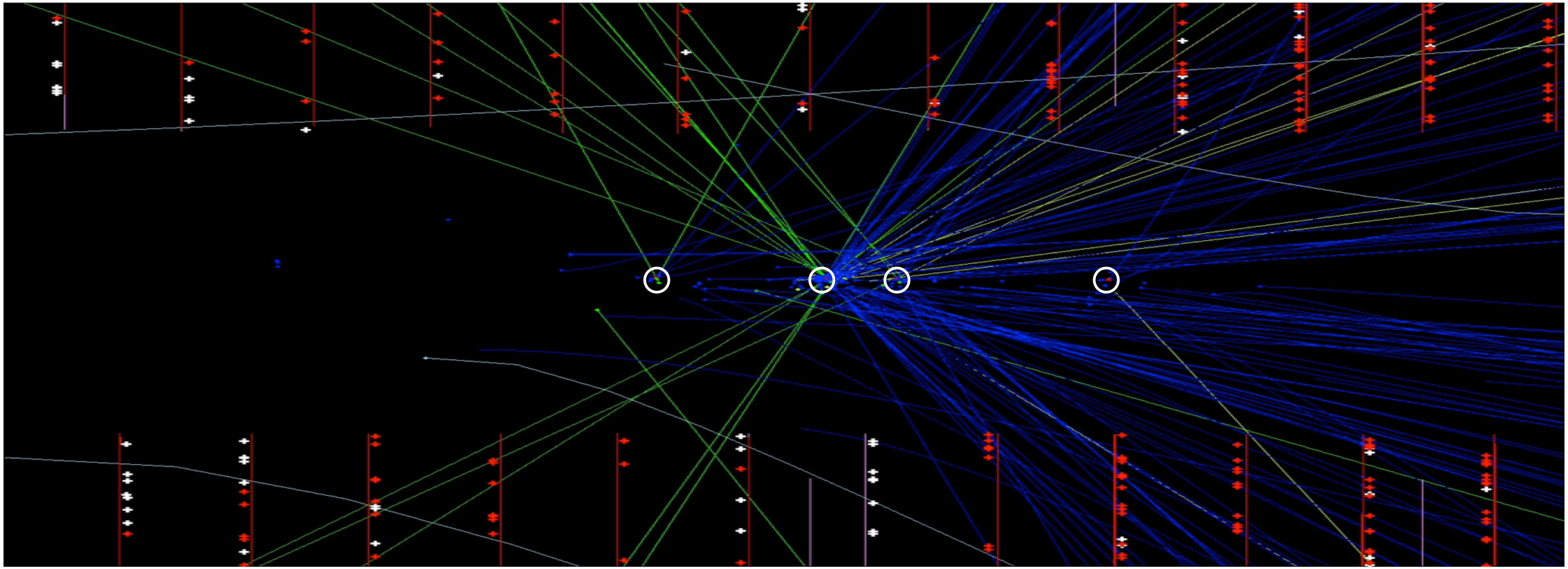
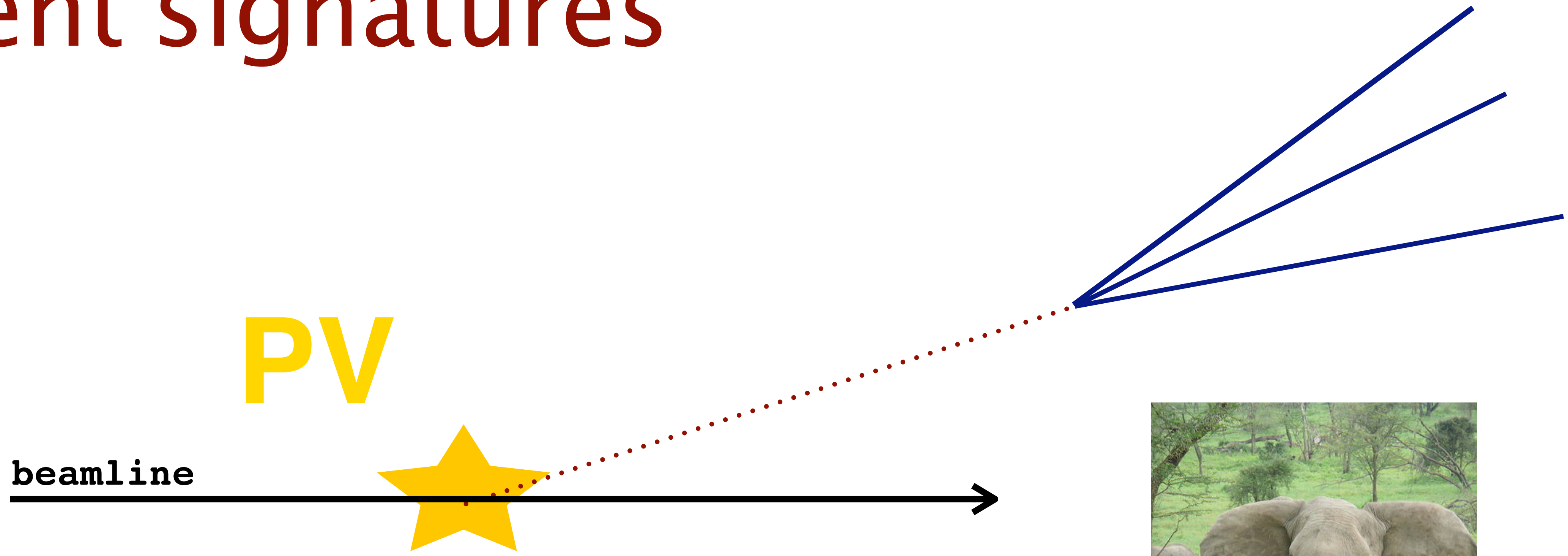
LHC environment

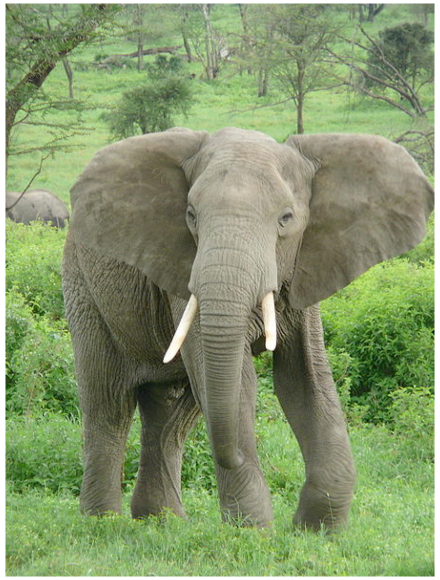
VELO rz view



20 MHz of bunch crossings with an average of 2 proton-proton interactions per bunch crossing, and about 30 particles produced per interaction

B event signatures





B meson signatures :

- **Large child transverse momentum**
- **Large child impact parameter or vertex displacement**

"A B is the elephant of the particle zoo: it is very heavy and lives a long time" -- T. Schietinger

LHCb trigger overview

The tracking and particle-ID systems of the detector can only be read out at 1MHz : must therefore start with Calorimeter/Muon based hardware trigger

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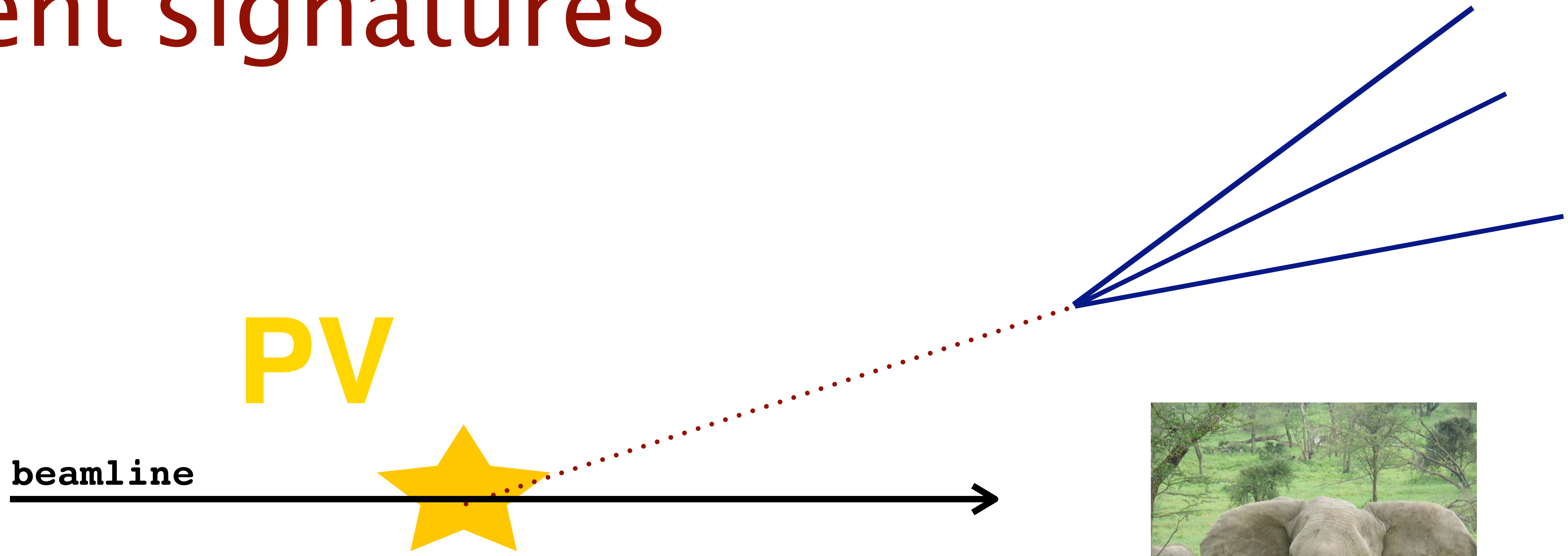

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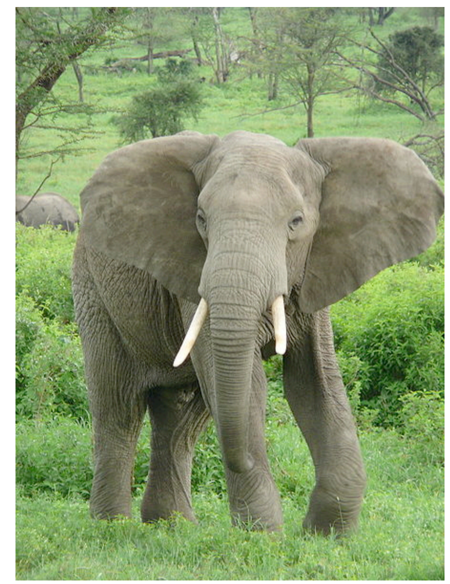

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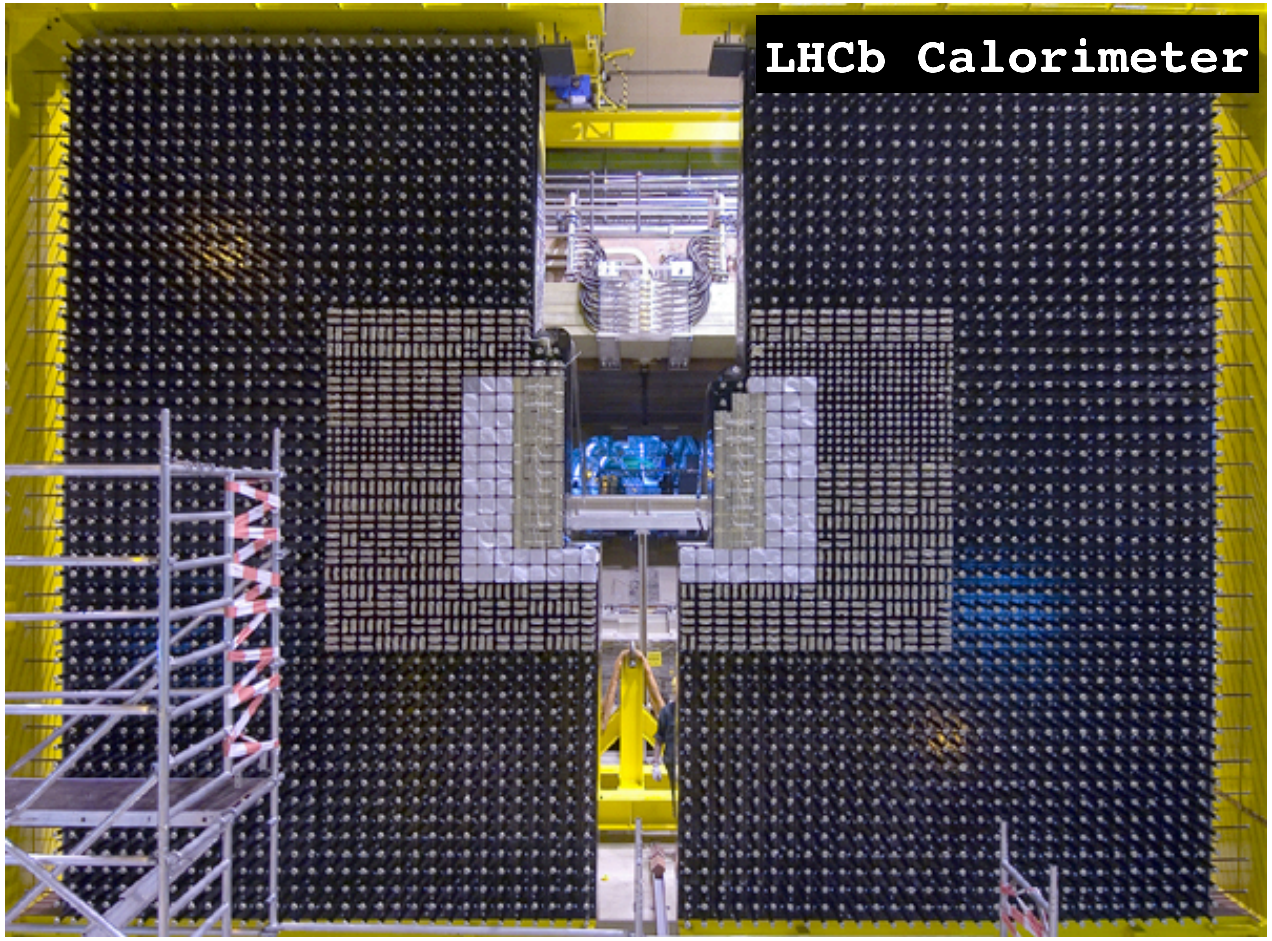

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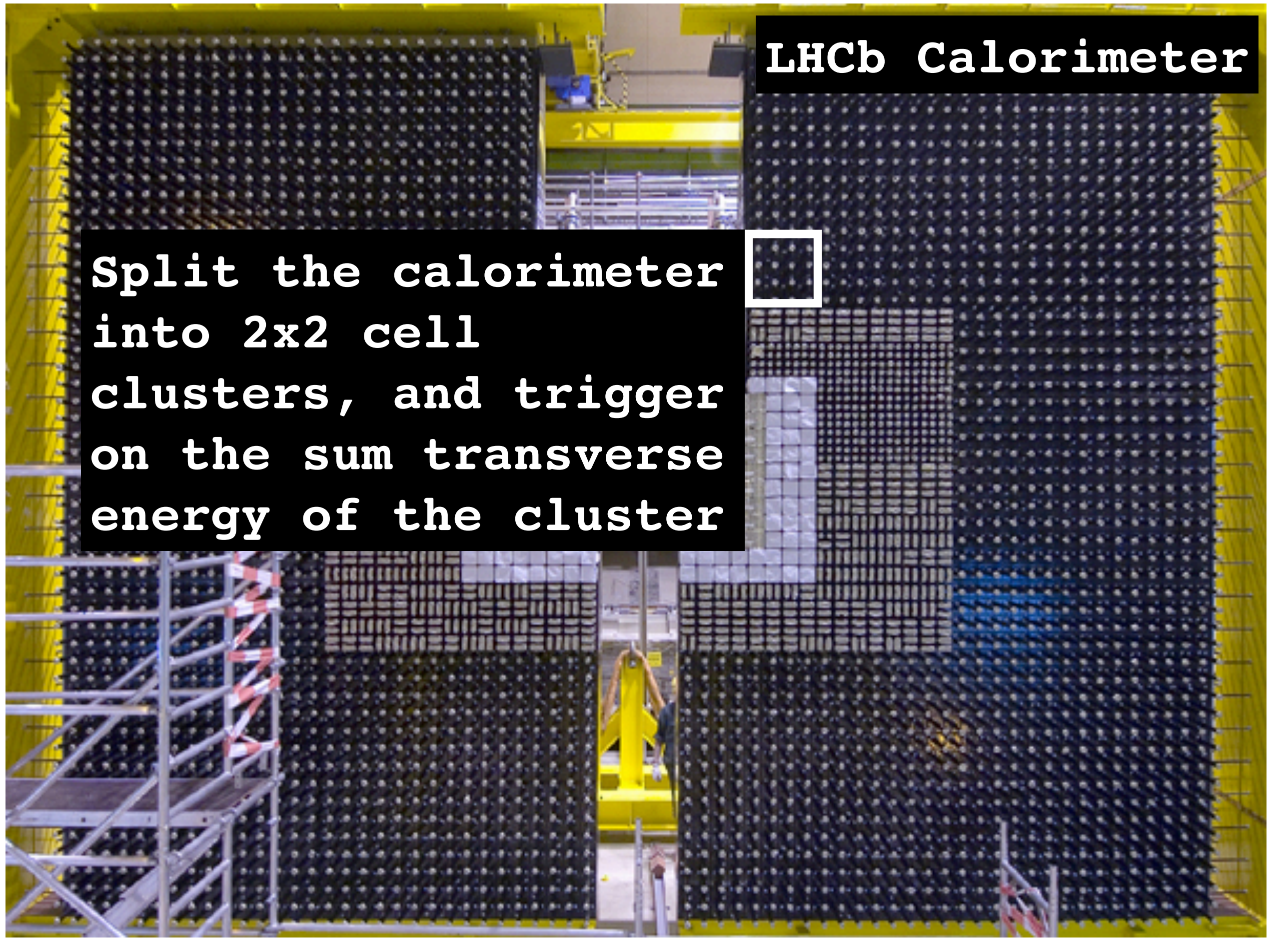

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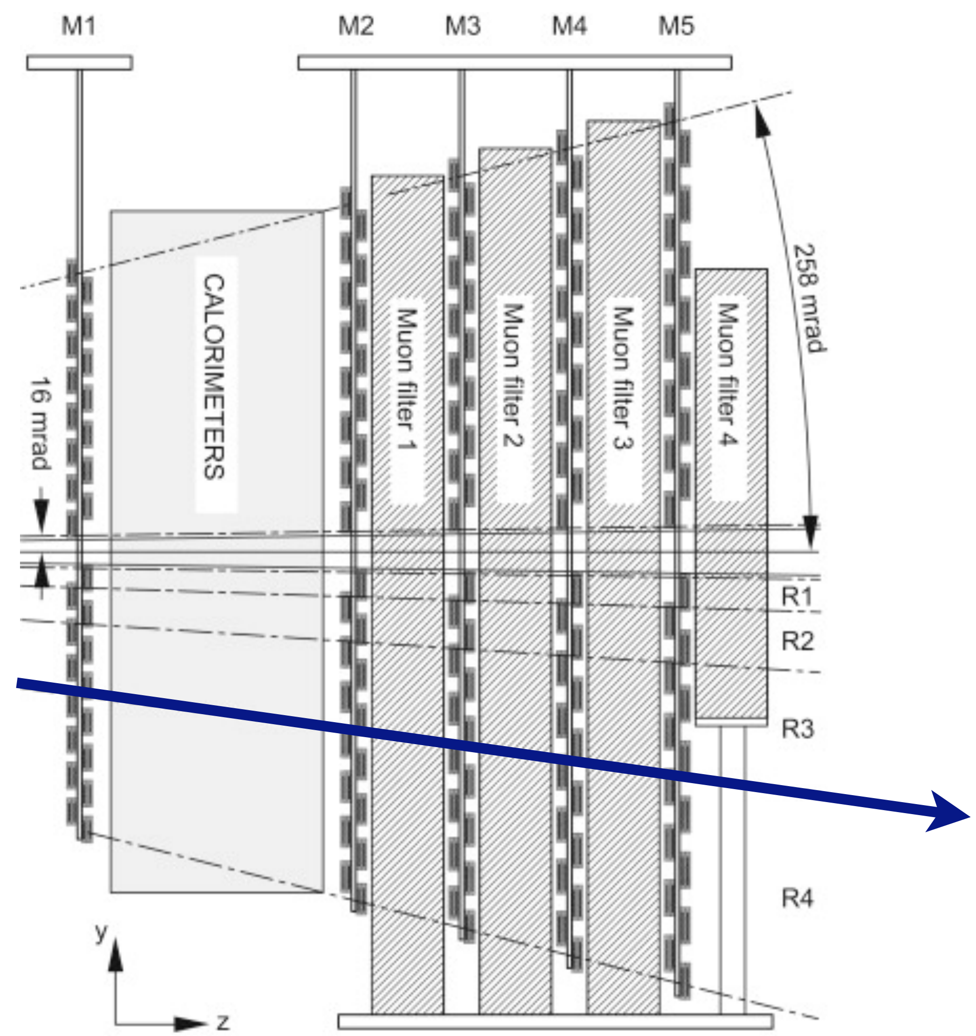
For muons search for track in all five muon system stations



LHCb trigger overview

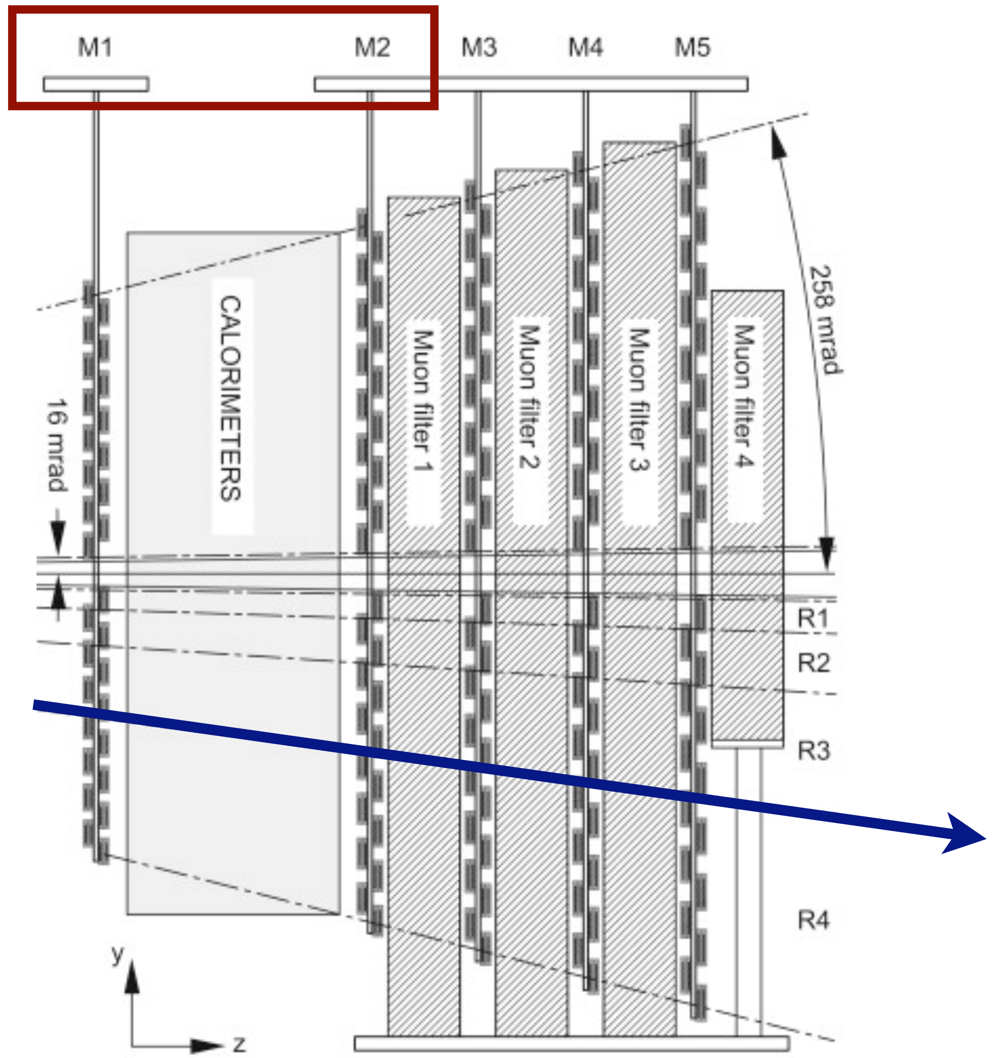
The tracking and particle-ID systems of the detector can only be read out at 1MHz : must therefore start with Calorimeter/Muon based hardware trigger

For muons search for track in all five muon system stations

Information from first two stations gives a momentum estimate to within 25%

Detector is split into four quadrants, and muons traversing quadrant boundaries cannot be reconstructed

Classic trigger limitation due to ability of front-end boards to collect and process information in time



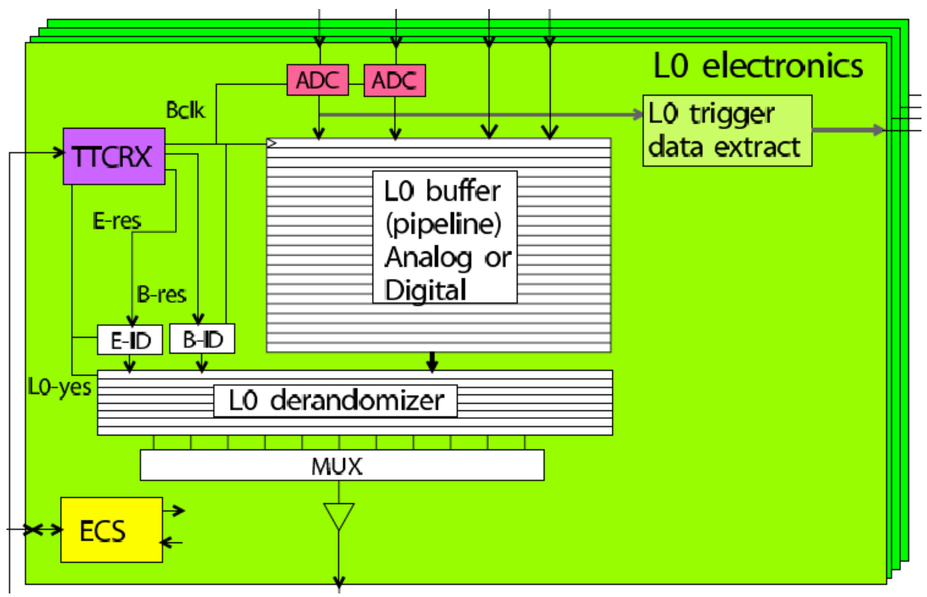
LHCb hardware trigger latency

The LHC bunch spacing is 50ns : 20 MHz of collisions

The maximum latency of the L0 trigger is 4 μs

Half of this is the time for the particles to travel to the detector and their signals to travel through the cables in the readout system, the other half is the time to make a decision

Therefore need to be able to process 80 events in parallel



LHCb hardware trigger decision unit

Collects information from the CALO/Muon Front-End boards and applies trigger conditions : independent selection chains

For example

Muon : One muon with $P_T > 2$ GeV

DiMuon : Two muons with $\prod p_T > 4$ GeV^2

Hadron : One HCAL cluster with $E_T > 4$ GeV

... and so on

This introduces two crucial concepts : independence and overlap

TIS-TOS-TOB

All triggered events can be split into three categories

TIS–TOS–TOB

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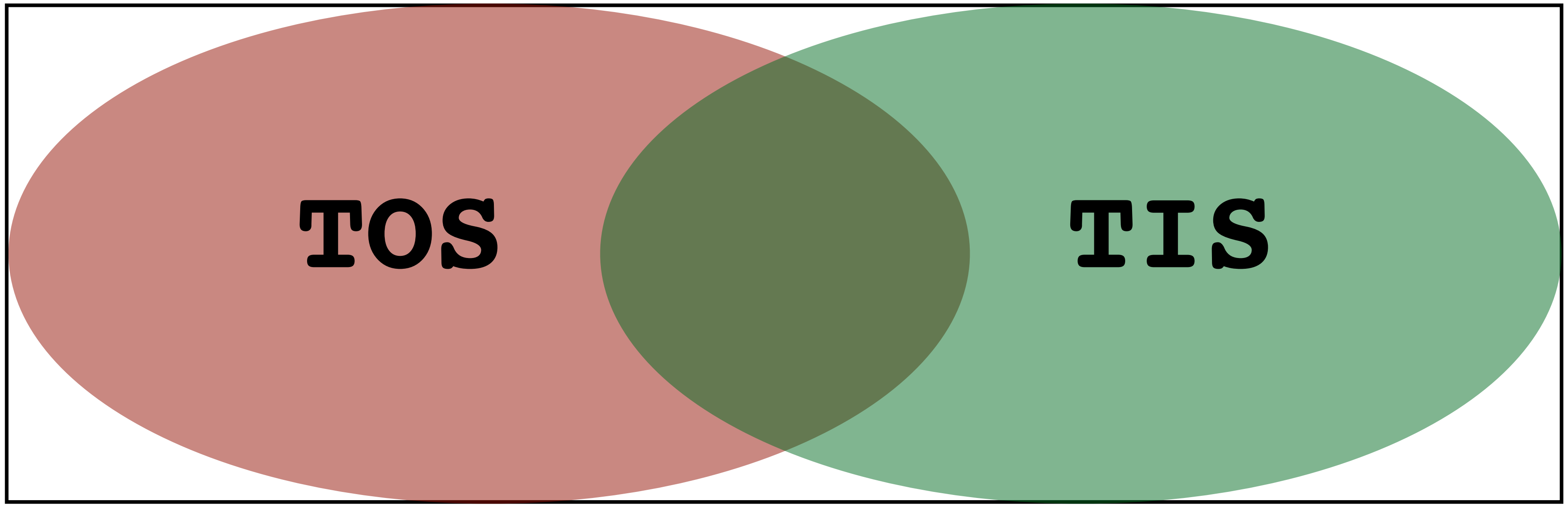
TOS : The event would have triggered if only the particles belonging to the signal candidate were present.

TIS-TOS-TOB



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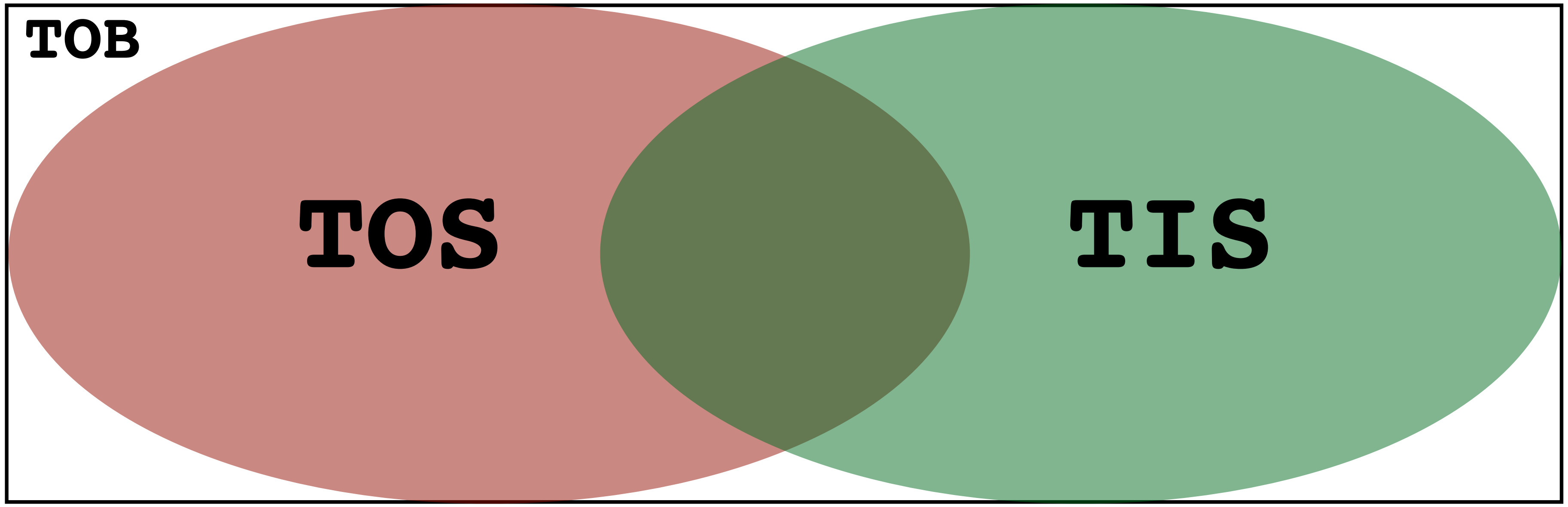
TIS-TOS-TOB



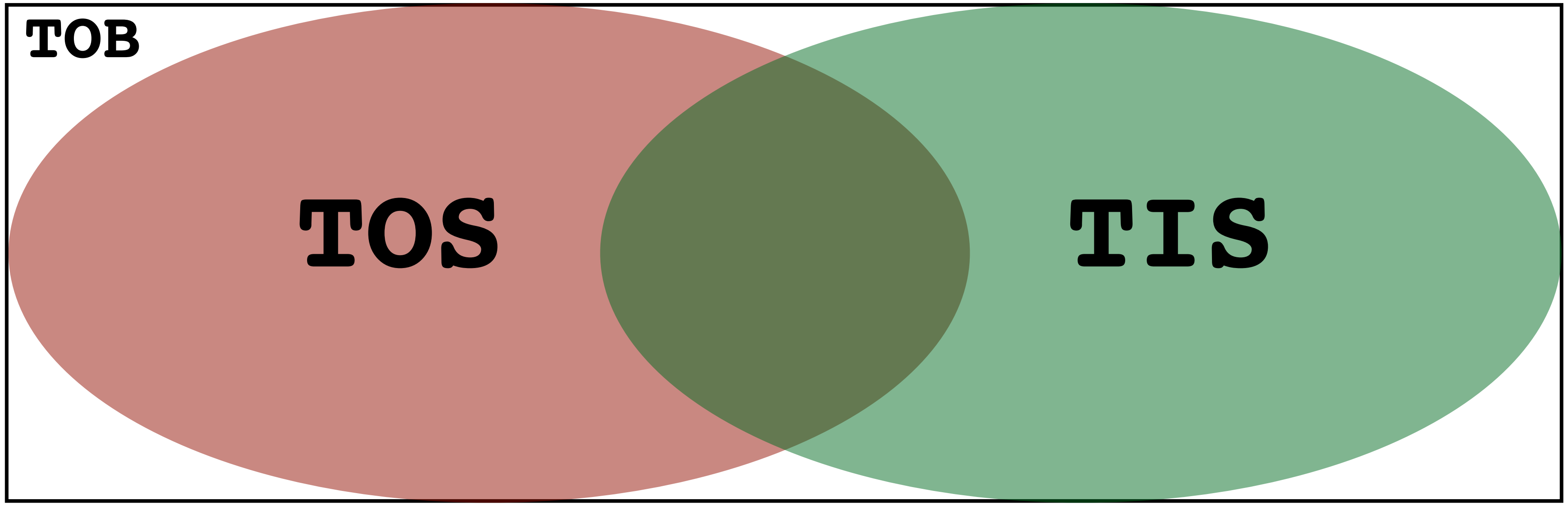
All triggered events can be split into three categories

TOS : The event would have triggered if only the particles belonging to the signal candidate were present.

TIS : The event would have triggered if the particles belonging to the signal candidate were not present.

TOB : neither TIS nor TOS

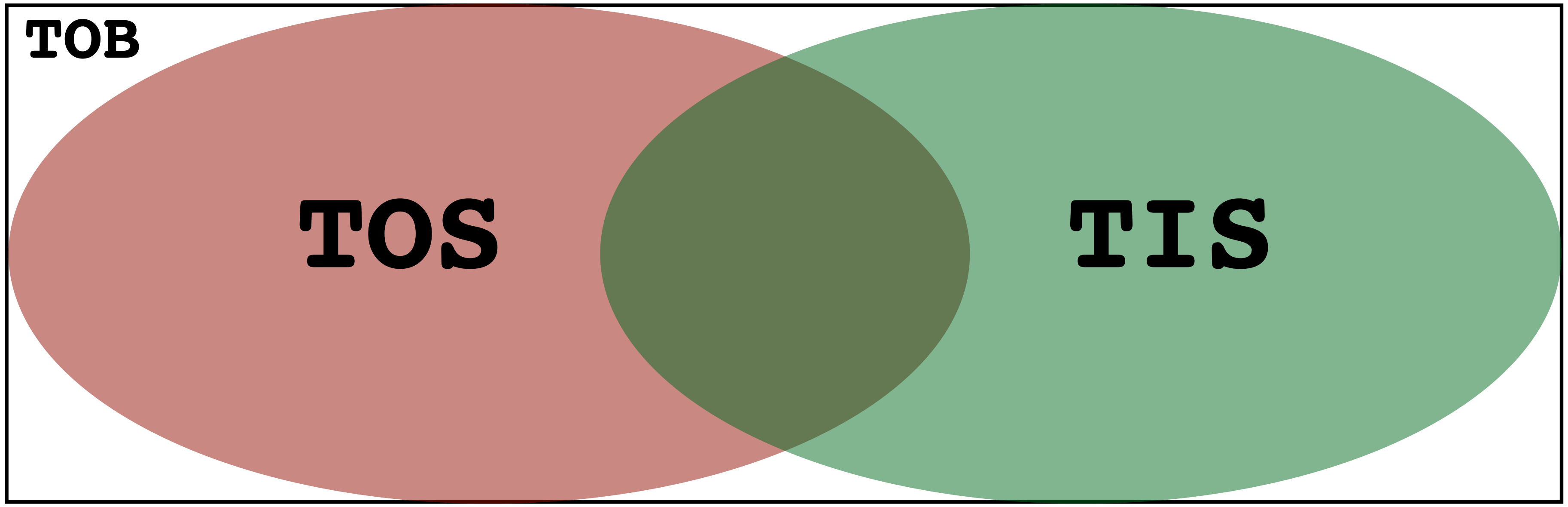
TIS-TOS-TOB



The overlap between TIS and TOS can be used to measure the trigger efficiency on data.

1) **Select your signal events offline**
2) **Measure the fraction of TIS events which are also TOS of the trigger line which you are interested in**
3) **This gives the TOS efficiency of that line relative to the offline selection. The TIS efficiency can be similarly measured (fraction of TOS which are also TIS)**

TIS-TOS-TOB

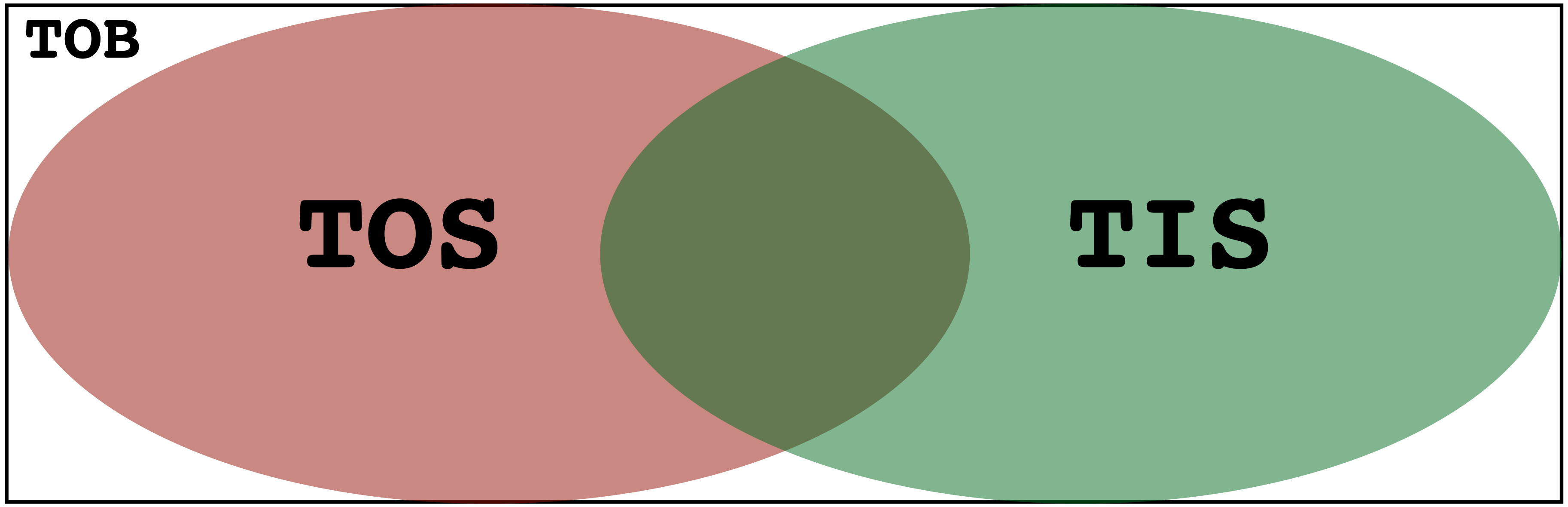


Things to watch out for

-- **Your TIS and TOS lines should share the same global event cuts, or at least the TOS line should have harder GEC cuts than the TIS line (since GEC cuts act on "the rest of the event")**

-- **TOB events can only be used if you do not care about trigger efficiencies.**

TIS-TOS-TOB



Things to watch out for

-- This whole concept relies on the fact that individual trigger decisions are independent of each other!

The High Level trigger of LHCb

15 MHz pp interactions

1 MHZ Detector readout

450 kHz	350 kHz	120 kHz	80 kHz
$h^{\pm}$	μ	e/γ	$\mu\mu$

Software trigger :

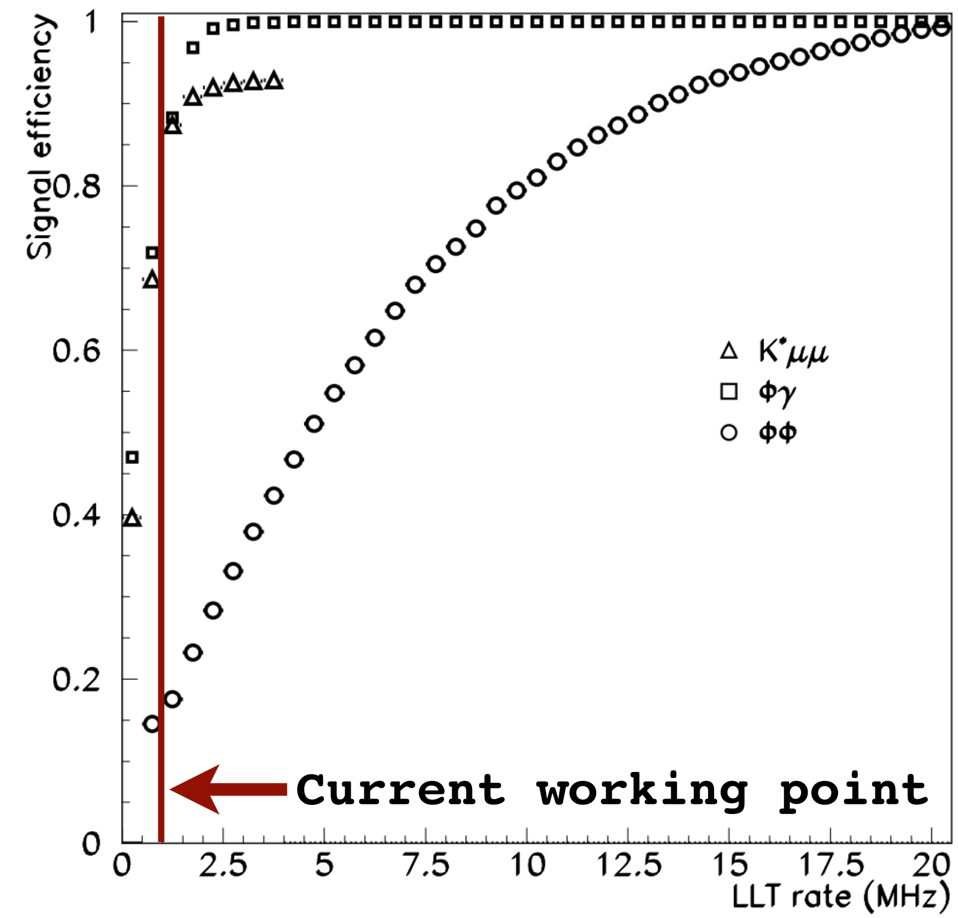
29000 Logical CPU cores

Access to the full event information

Use offline reconstruction software tuned for HLT time constraints

4 kHz data output

The hardware trigger loses efficiency if forced to reduce the rate too much : it does not have enough information to do so efficiently!



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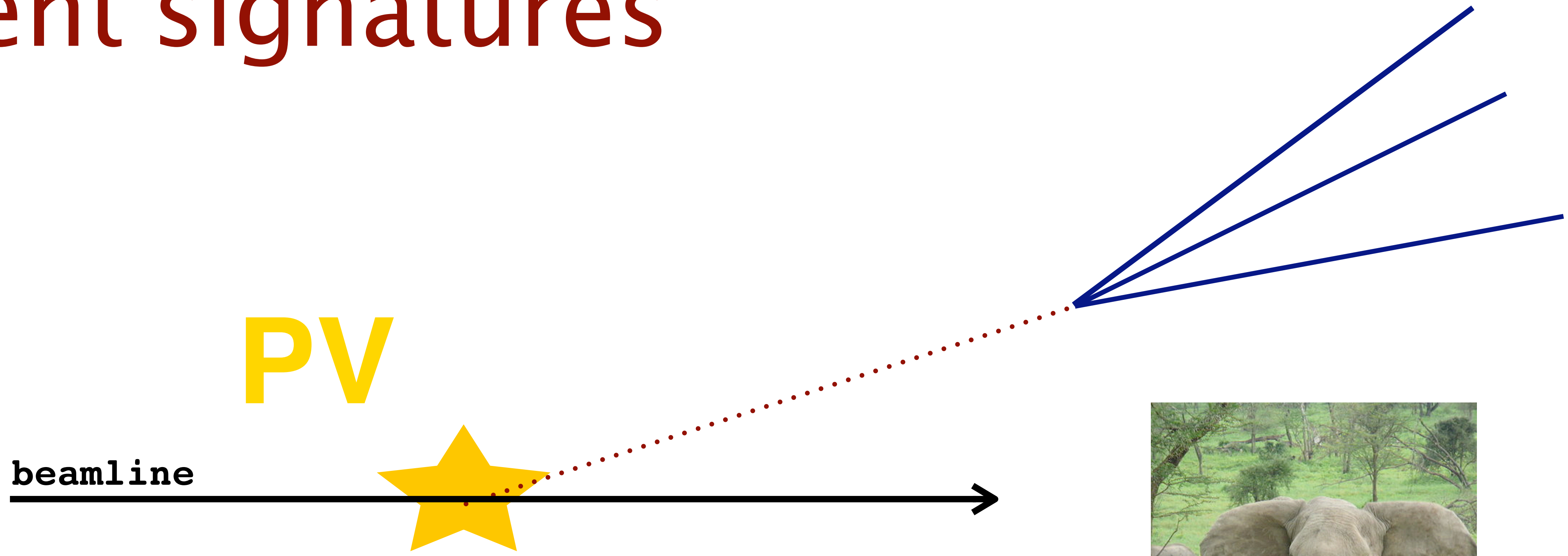

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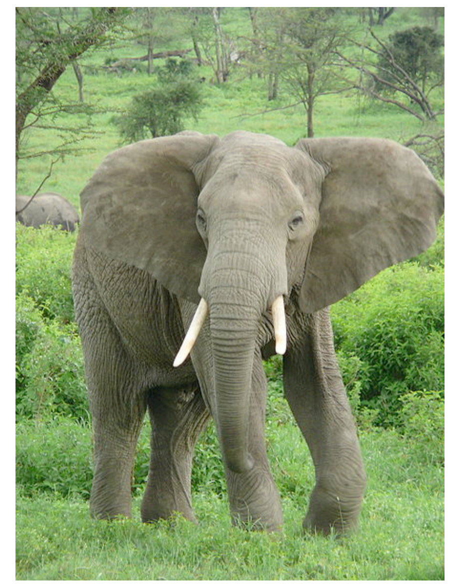

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Time constraints

The High Level Trigger has 20-30 ms to process an average event

- Driven by the size of the available CPU farm

The complete offline event reconstruction in LHCb takes 1 s

- Therefore even though the HLT has access to the full event information in principle, in practice it cannot use all of it at once

Information costs time and enables efficient background rejection

- These must be balanced. This is very different from a hardware trigger where the time and information available are fixed.

Real time event selection

1. Information gathering
("reconstruction") stage

Real time event selection

1.

Information gathering
("reconstruction") stage

⇒

Real time event selection

1. Information gathering ("reconstruction") stage ⇒ 

⇓

2. Event selection stage

Real time event selection

1. Information gathering ("reconstruction") stage ⇒ 

⇓

2. Event selection stage ⇒ Selected | Rejected

Real time event selection

1. Information gathering (“reconstruction”) stage ⇒

2. Event selection stage ⇒

Selected | Rejected

3. Next reconstruction stage ⇒

Deciding on criteria

In order to solve this problem we need to know

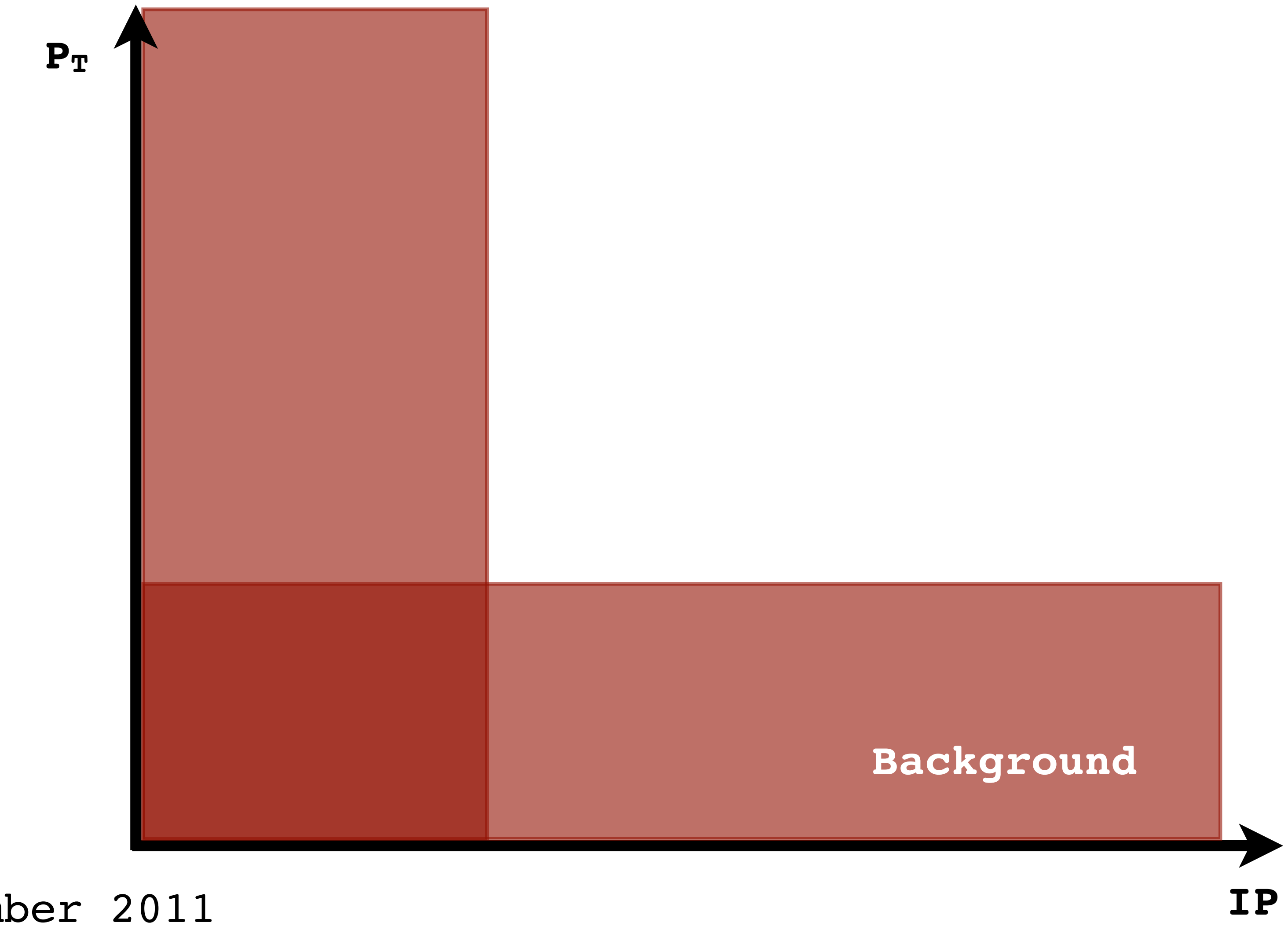
1) **The time cost of any piece of information**

2) **What is the optimal way to combine the information in order to reject background events while remaining efficient for signal**

Let us consider a simple problem with only two variables first

Multivariate selections

In a simple cut based selection, the event has to be perfect in every variable.
This can work if the background is poor in at least one variable



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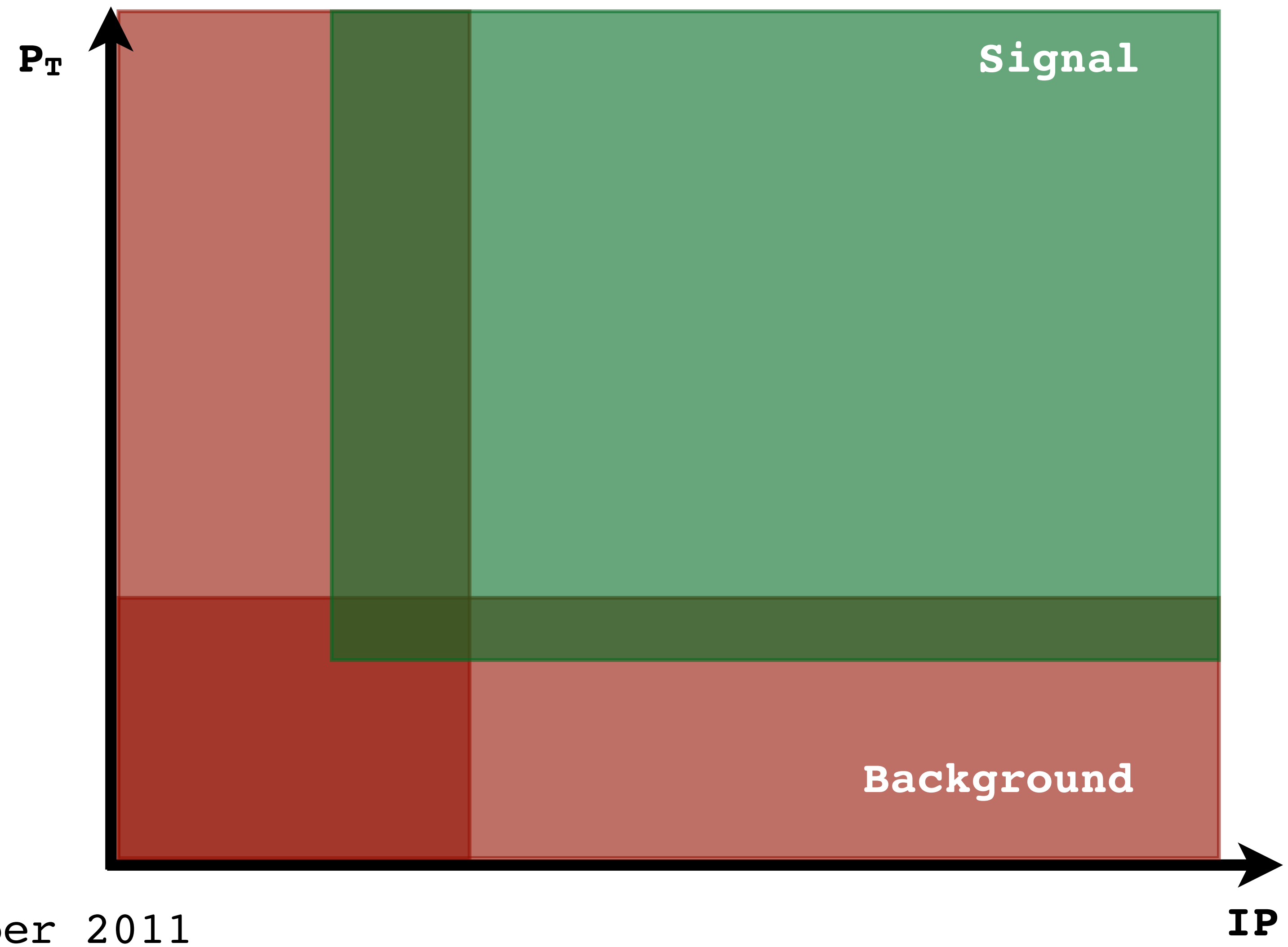

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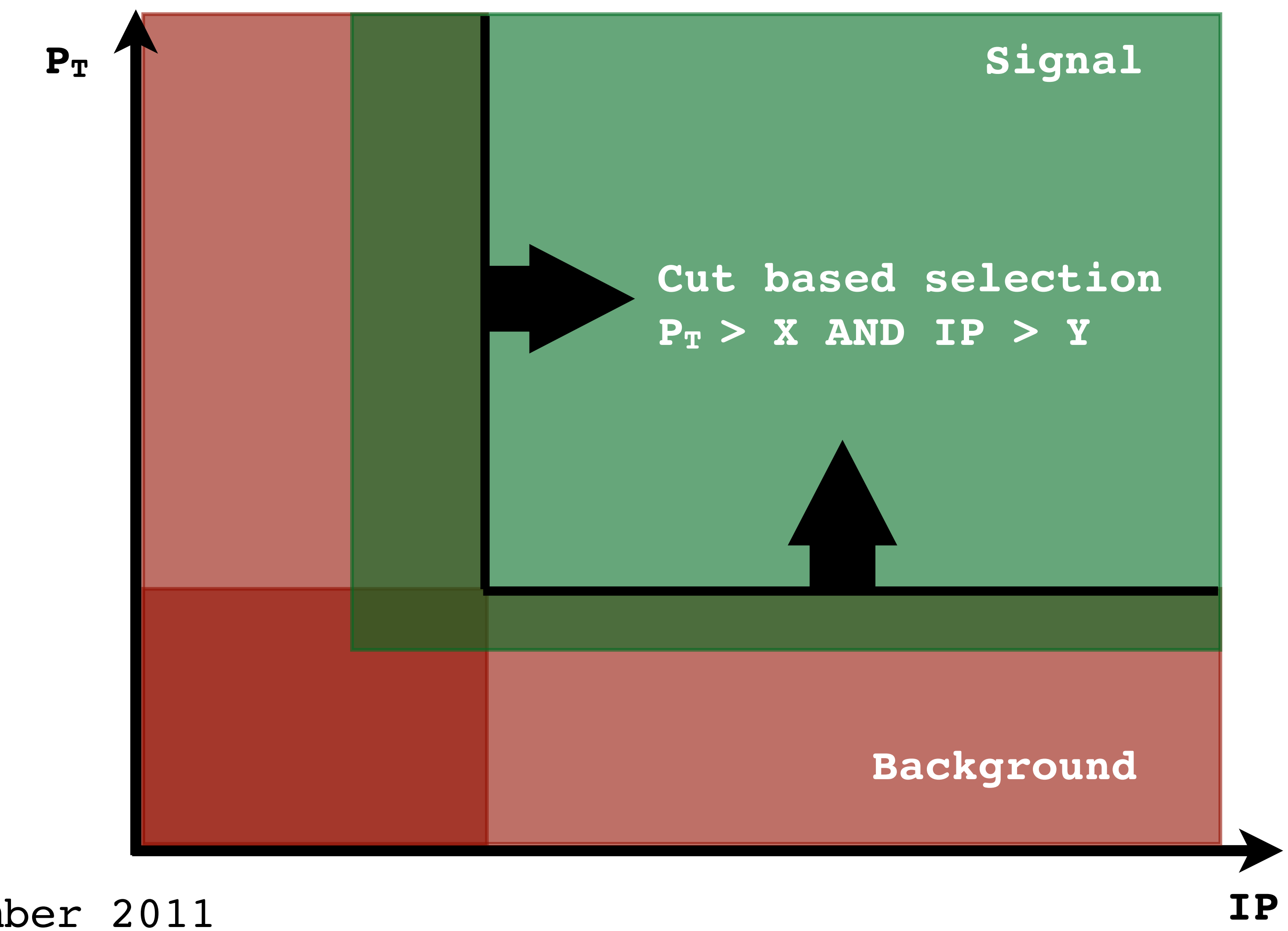
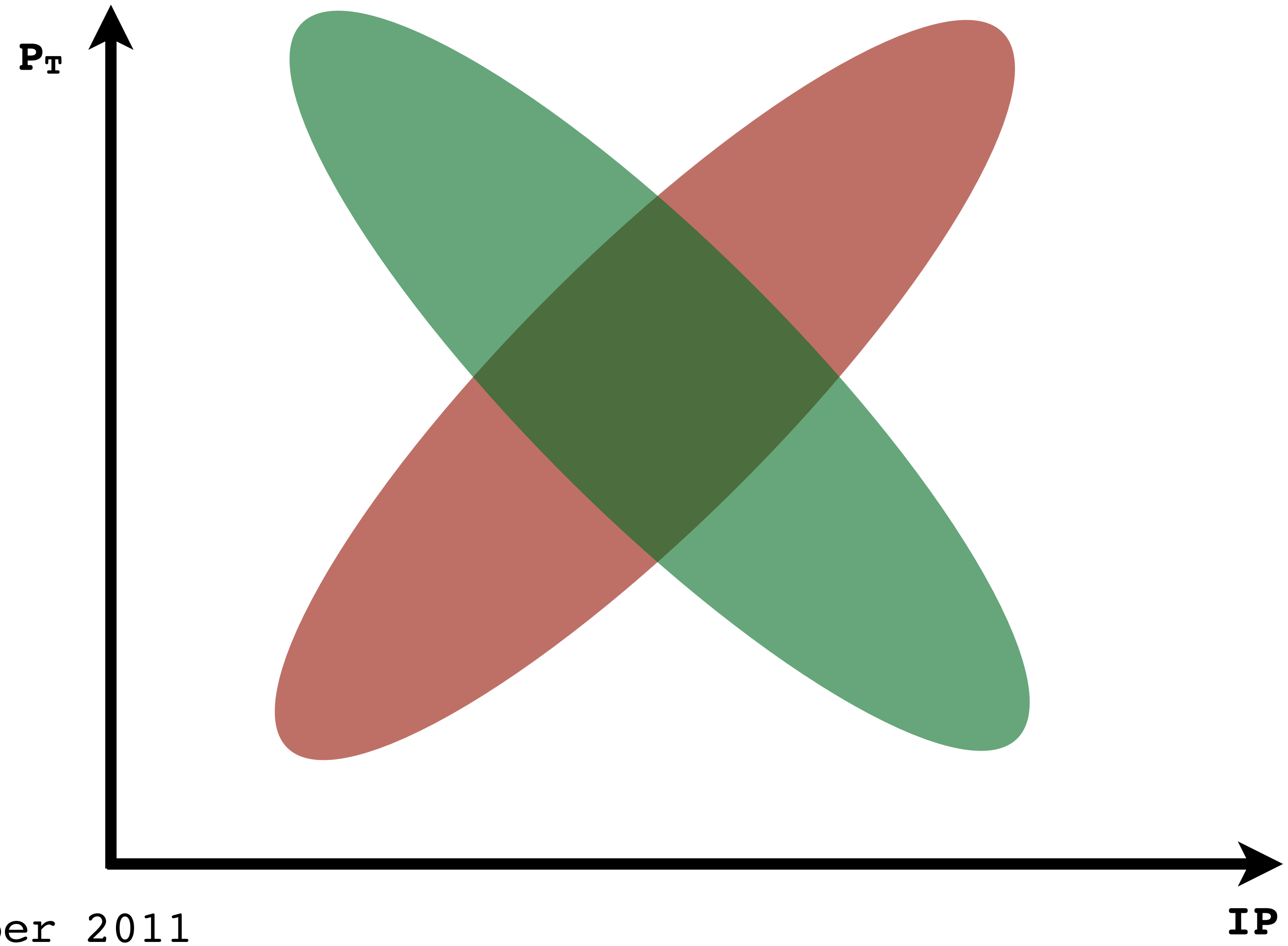


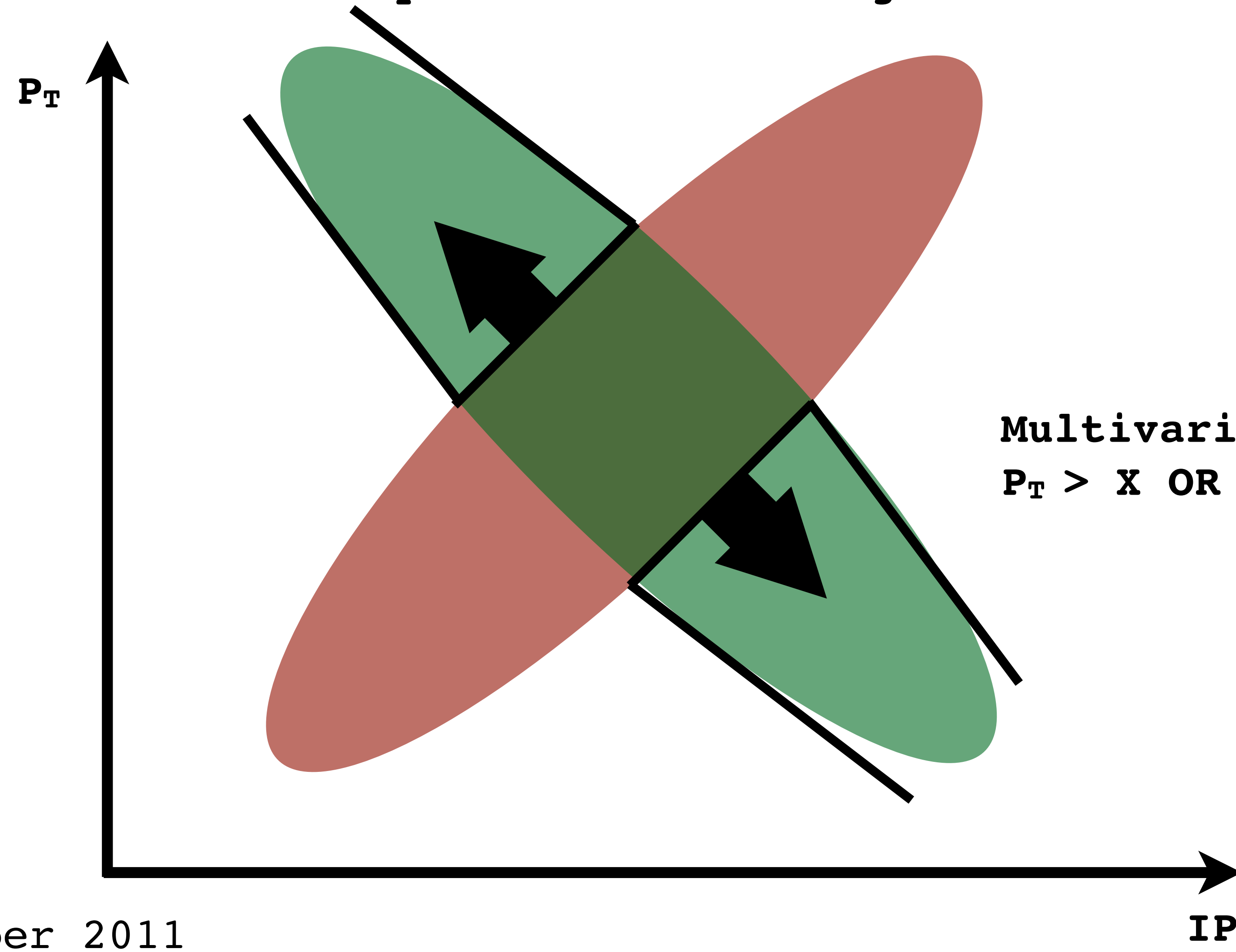
Multivariate selections

Reality tends to be more complicated than this, however



Multivariate selections

Reality tends to be more complicated than this, however
What you really want is to accept an OR of two regions...



Multivariate selection
P_T > X OR IP > Y

Deciding on criteria

In order to solve this problem we need to know

1) The time cost of any piece of information

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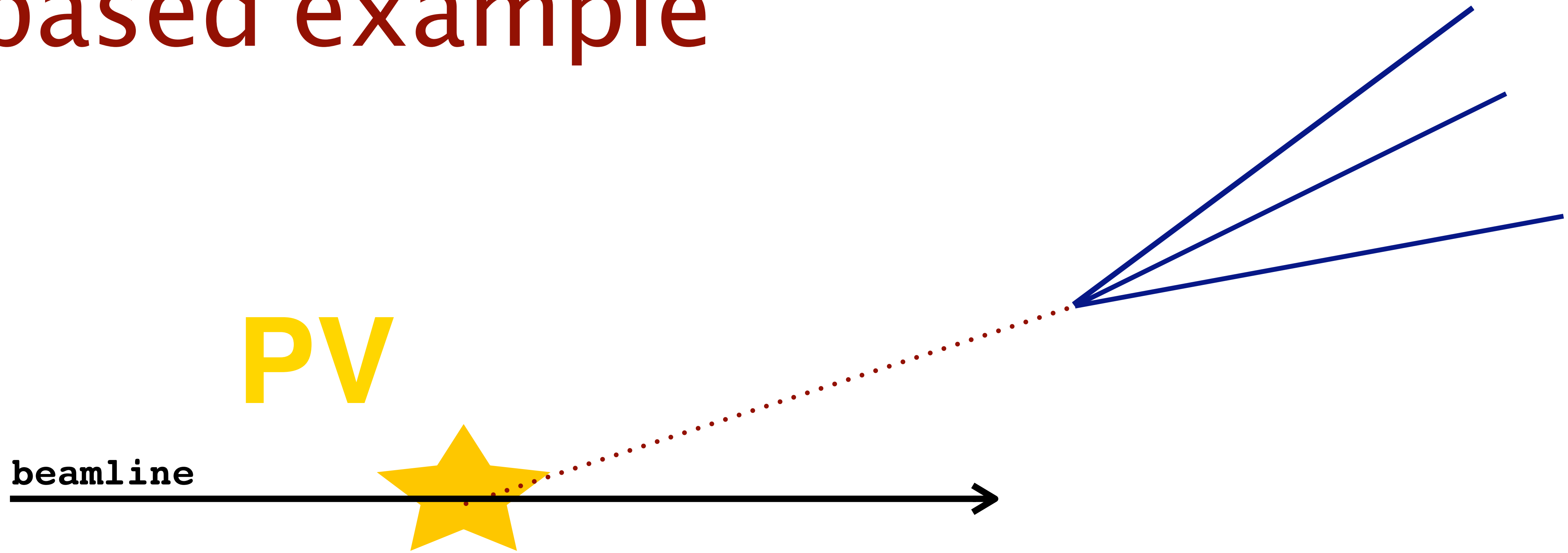
Let us consider a simple problem with only two variables first

In a cut based approach, we can obtain information in any order as the correlations between variables are ignored.

In a multivariate approach, we need all the variables at the same time, in order to use the correlations between them.

The optimal approach depends on the circumstances and the precise balance between speed and efficiency which can be achieved.

Cut based example



A cut based selection works best when the candidate is perfect in every variable. It turns out that a B always has one "perfect" child particle, with huge transverse momentum and displacement from the primary interaction.

This is a very powerful signature as it is independent of the exact number of B children and their exact nature (pions, kaons, muons, etc.)

Only 5% of background events have such a particle. Hence can go from 1 MHz to 50 kHz with such a trigger while keeping 90% of the signal events.

Multivariate example

Once the cut based selection runs, the remaining background looks a lot more like signal. Now we need a multivariate approach to extract the maximum efficiency while gaining another factor 20 in rate.

But the cut based selection bought us the time to do this :

Say the total budget for an event is 20 ms

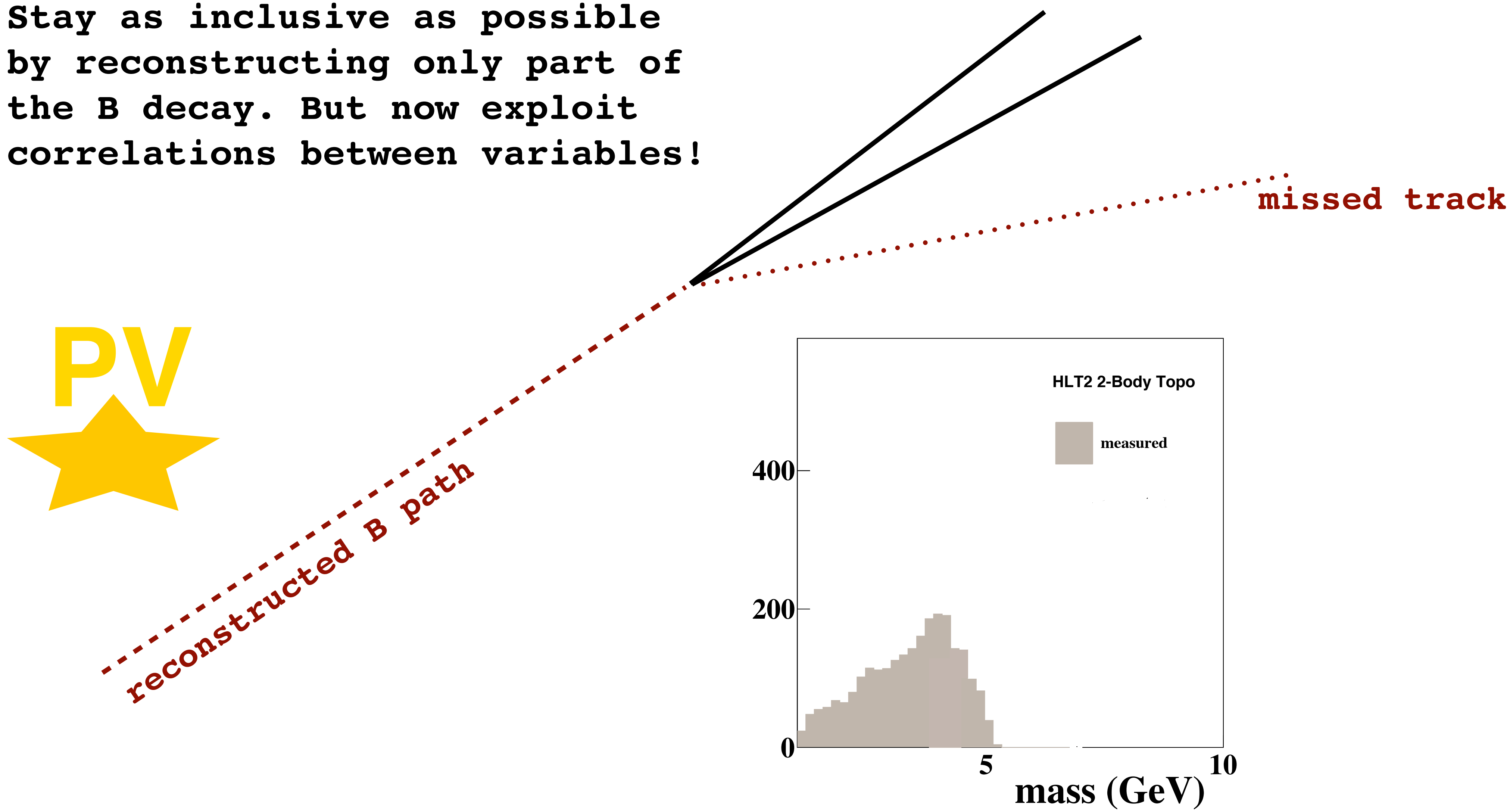
The cut based selection takes 10 ms

But the cut based selection reduces the background by 1/20

So the multivariate selection now has 200 ms to make its decision, as it only runs on 5% of all the events!

The topological trigger

Stay as inclusive as possible by reconstructing only part of the B decay. But now exploit correlations between variables!



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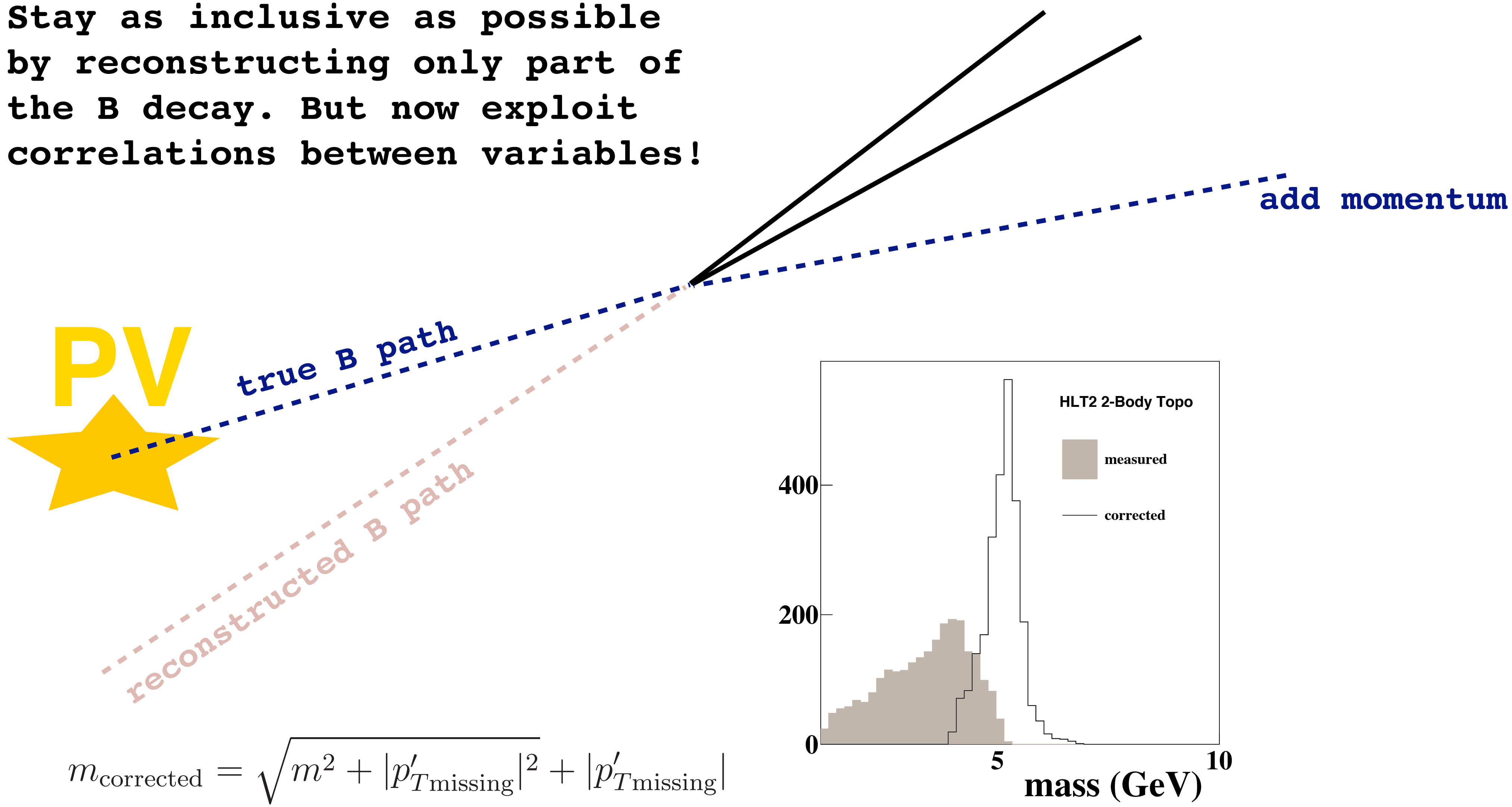
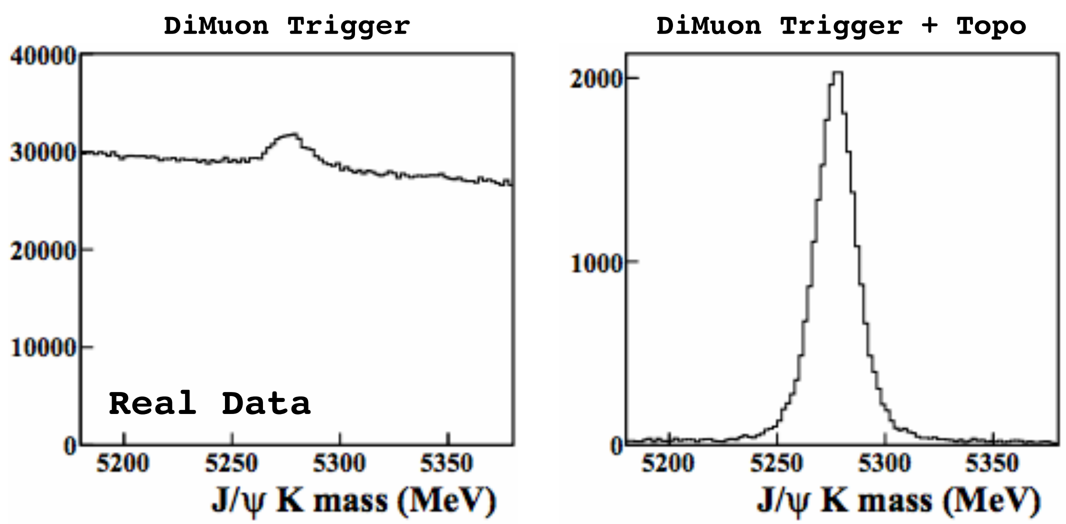


$$m_{\text{corrected}} = \sqrt{m^2 + |p'_{T\text{missing}}|^2} + |p'_{T\text{missing}}|$$

The topological trigger

The full trigger uses a total of 7 variables

Reduces rate by required factor 20 (combined factor 400 with cut based pre-selection) with >75% signal efficiency



This is probably the most complex and advanced trigger ever deployed at a High Energy Physics experiment.

The ATLAS/CMS triggers

ATLAS/CMS vs. LHCb

	Rate of bunch crossings	Mean interactions per bunch crossing	Mean event size
ATLAS/CMS	20 MHz	> 30	1500 kB
LHCb	20 MHz	2	100 kB

The data rates at ATLAS and CMS are 15 times greater than at LHCb. This drives a design in which much more work is done by hardware triggers which make their decisions based on information from only a part of the detector.

The confirmation strategy

For LHCb, the High Level Trigger ignores the hardware trigger

In ATLAS/CMS, in order to speed up execution, the high level trigger is set up to “confirm” the decision of the hardware trigger

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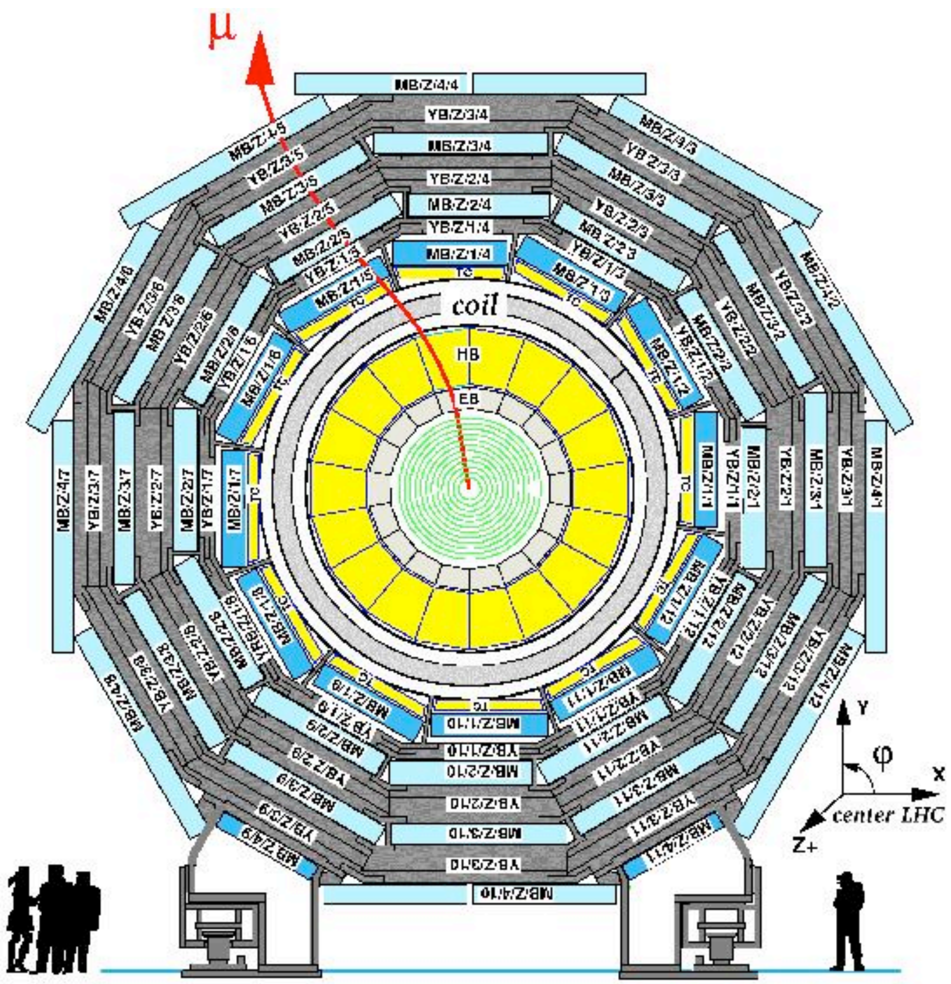

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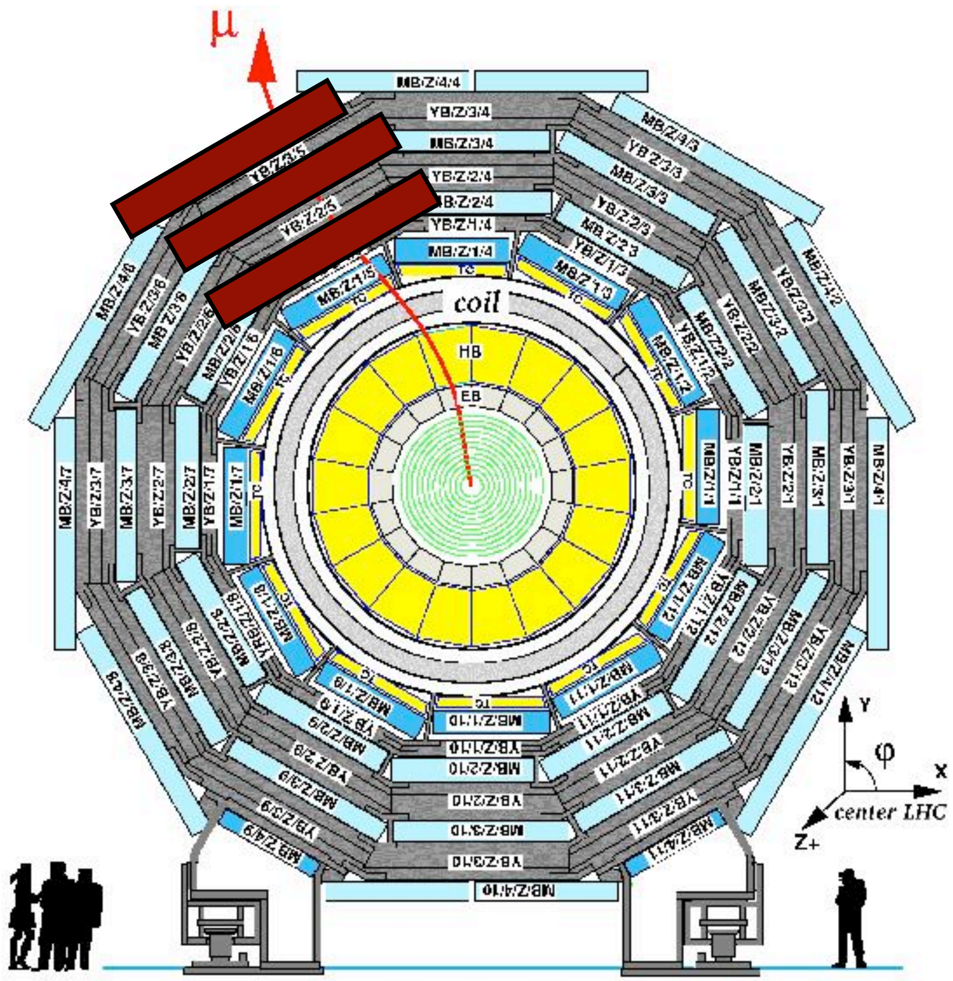

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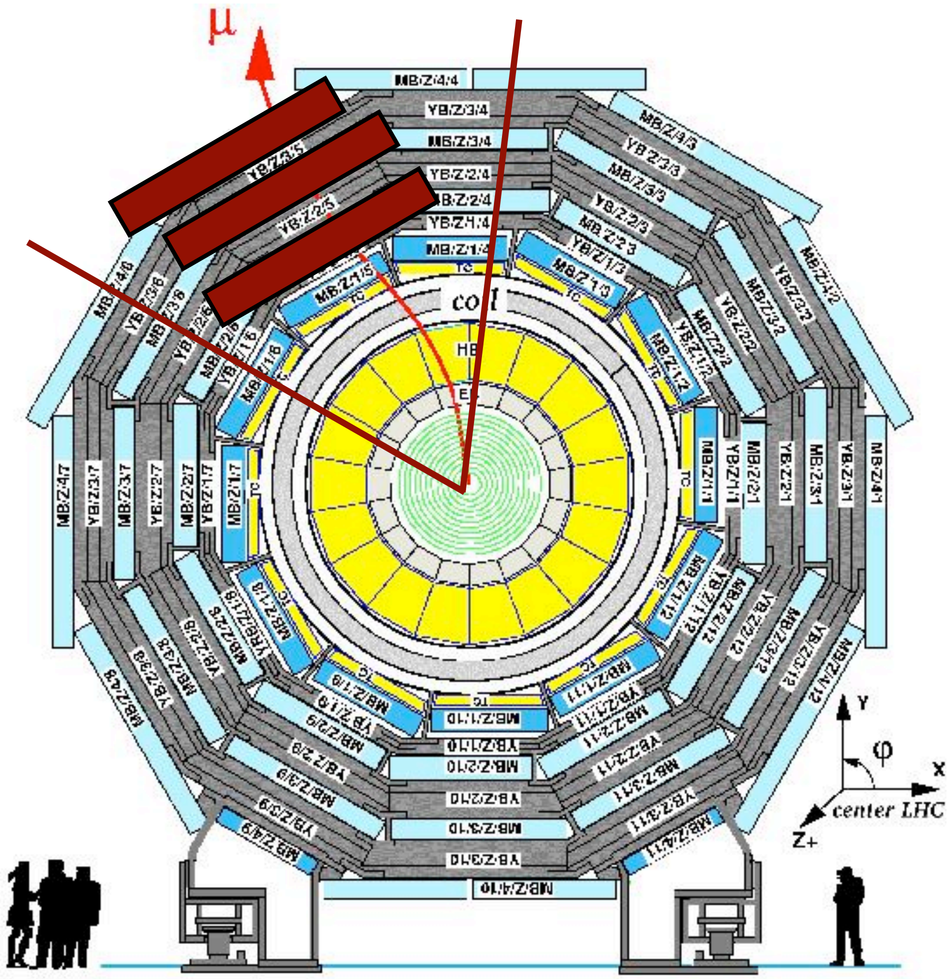

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The region of interest for this search is defined by the detector geometry and the location of the hardware trigger candidate

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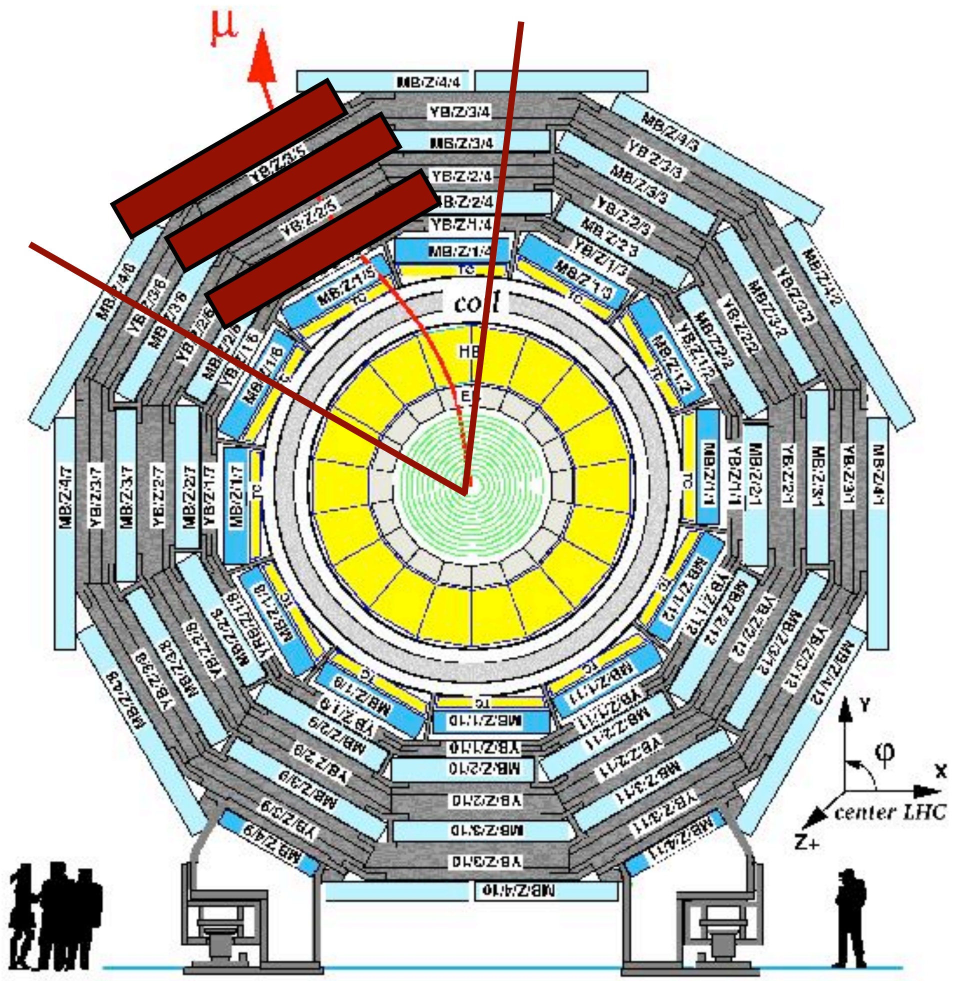

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Confirmation is a very common strategy in triggering. It works if the early triggers fire predominantly because of the presence of signal.

Summary

If you need to build a trigger…

Two parameters to consider

1) The frequency with which events occur

2) The complexity (size) of each event

Key concepts to remember from this seminar

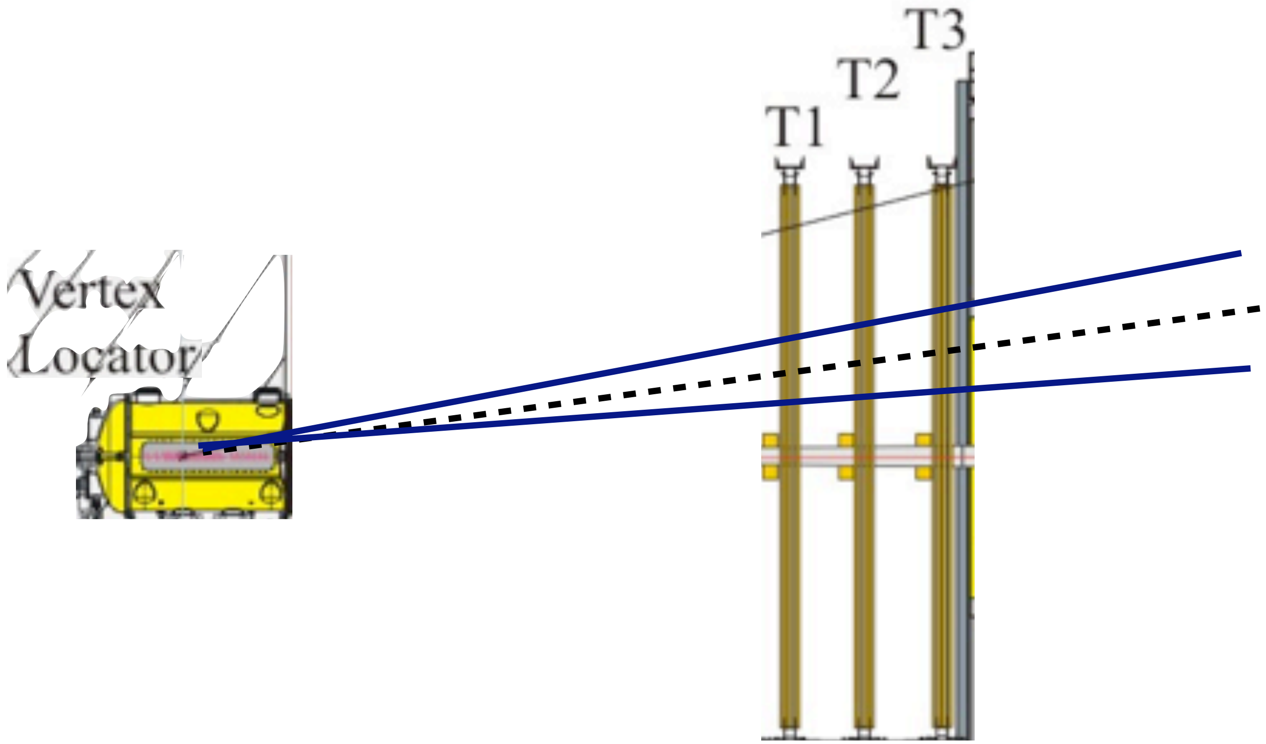
Different triggers make their selection on different criteria, but they must always be independent of each other.

A trigger has a finite time to make its selection, so you need to optimize taking into account the time cost of obtaining information

Multivariate selections are very powerful but usually need a simpler preselection to allow them the time to do their job

Backup

Merging reconstruction and selection



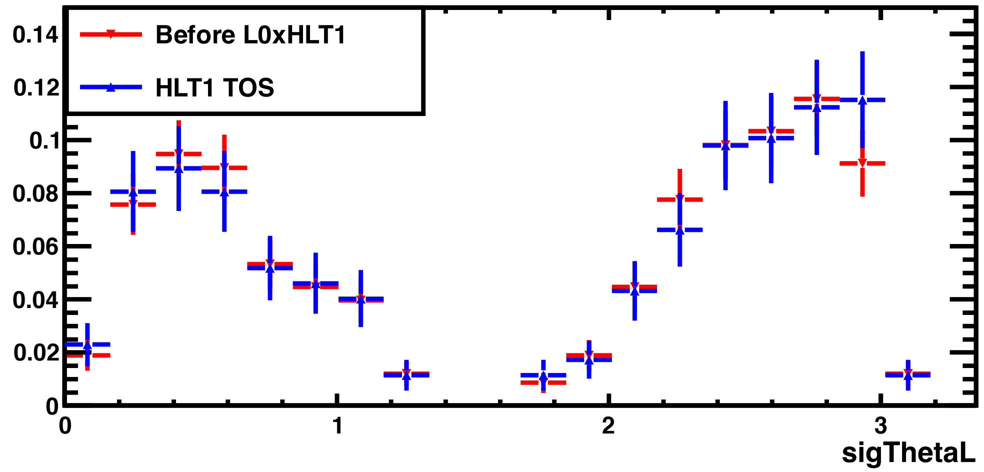
A lot of time is spent in the trigger reconstructing charged particles

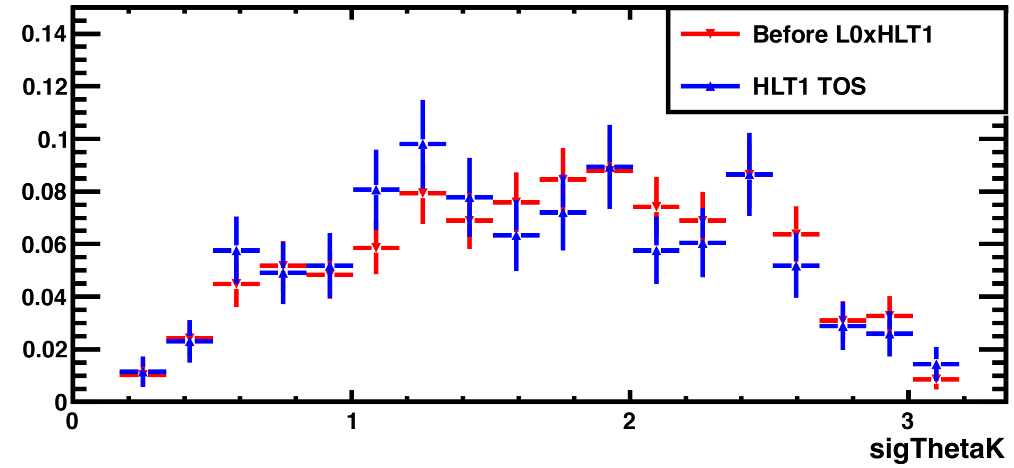
If you know that you will cut on some minimum momentum of these particles, you can build this cut into the reconstruction

- The higher the momentum the straighter the charged particle path
- Can define a narrow path depending on momentum; saves a lot of time looking for fake paths

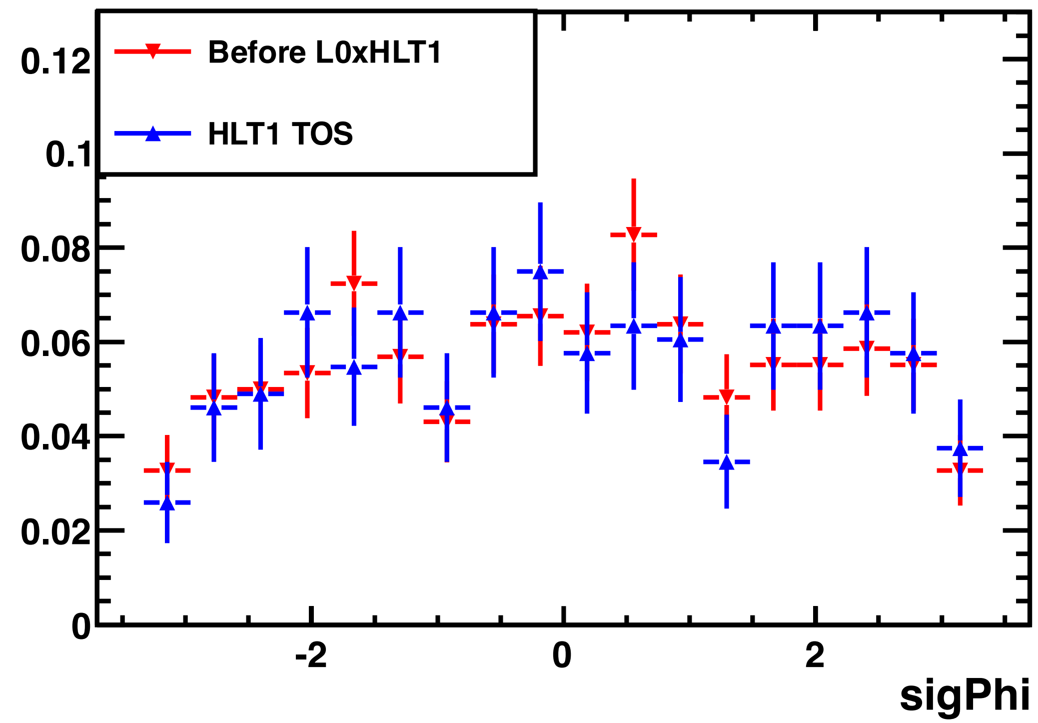
Always look for ways to build a selection into your reconstruction!

Angular biases?

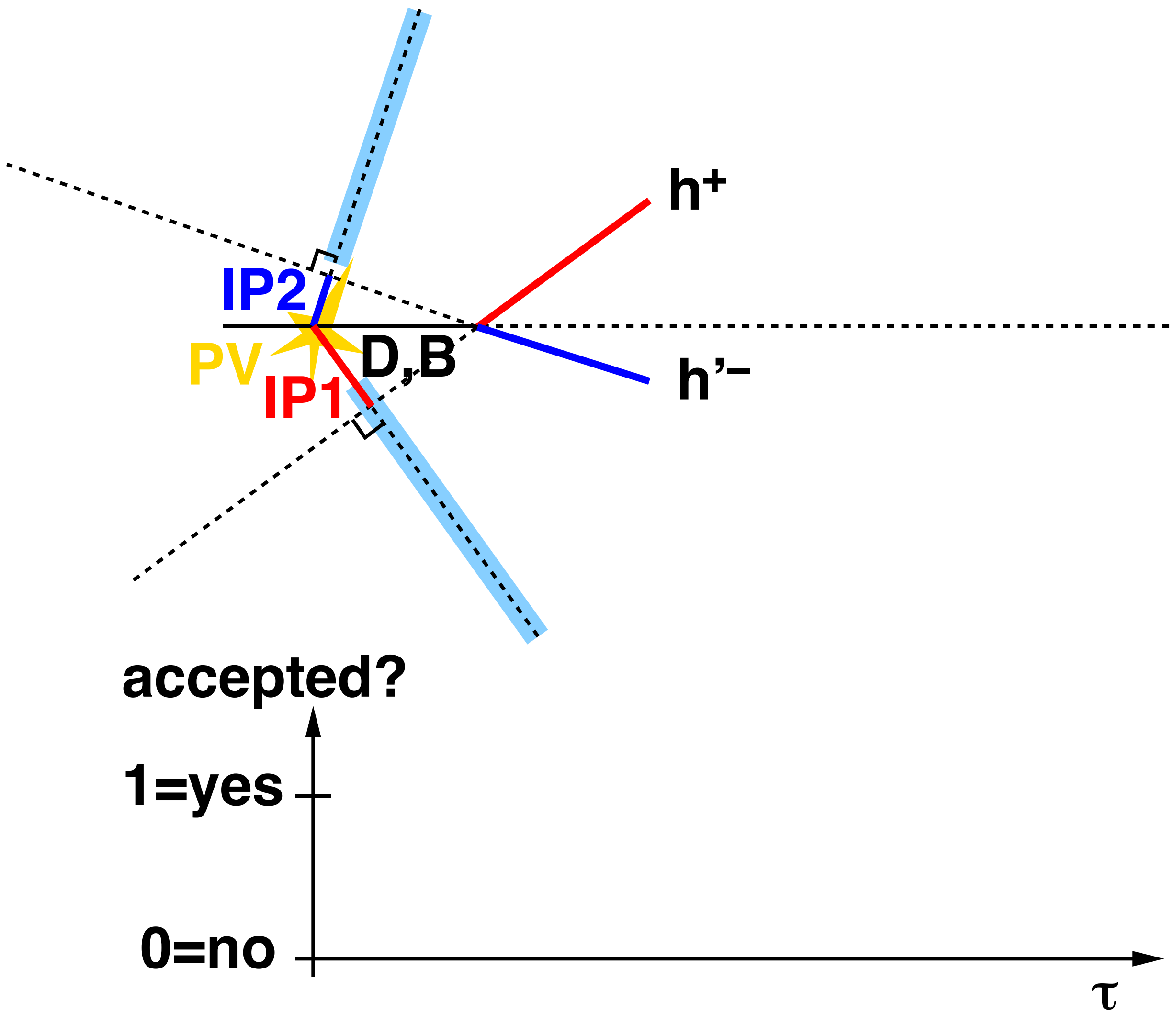




One of the key advantages of an inclusive trigger is that we minimally bias offline distributions, e.g. angular acceptances in K*μμ, or Dalitz acceptances in KKπ, are kept as flat as possible



Lifetime biases?

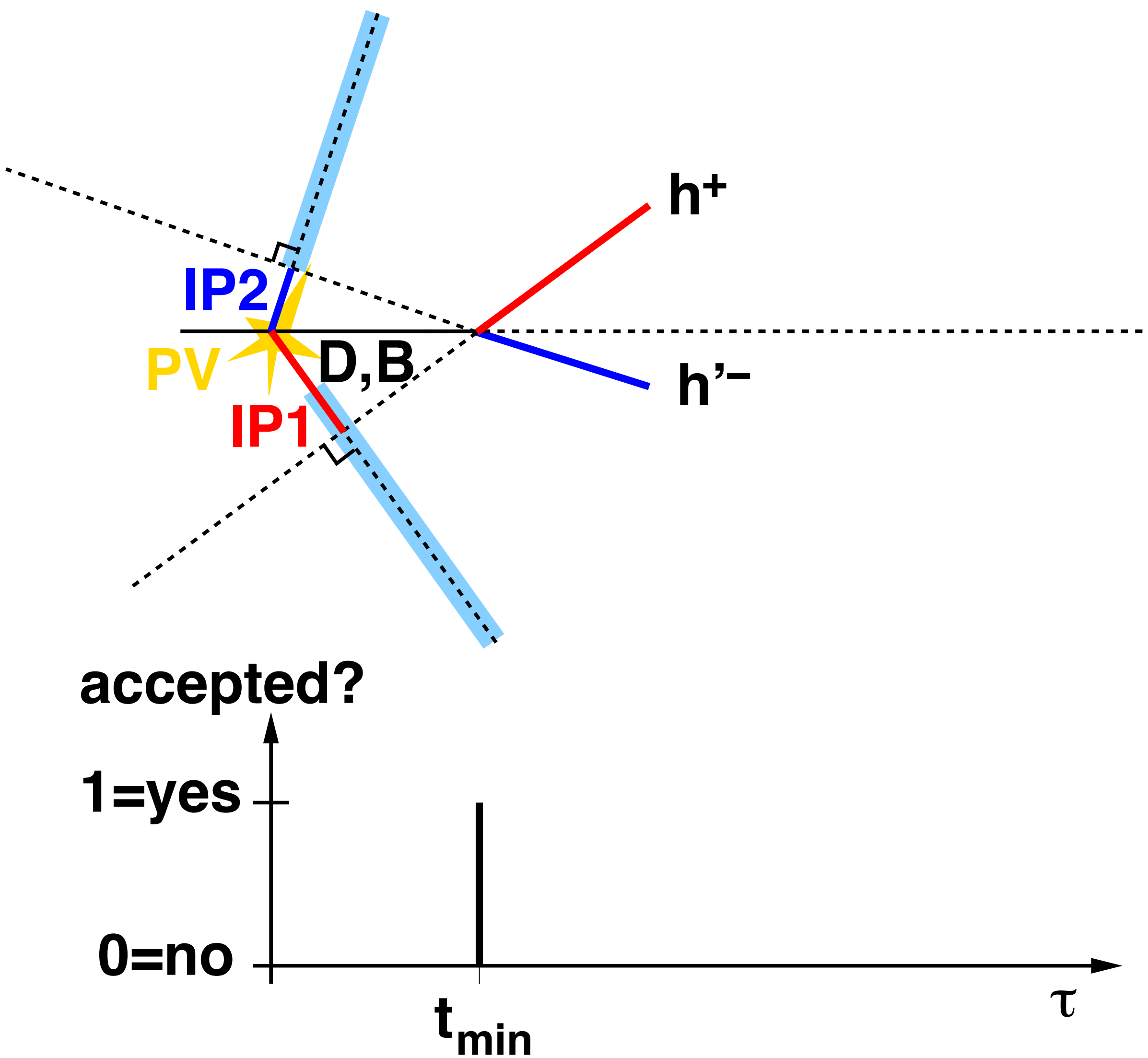


Because we can reproduce the trigger decisions offline, we can measure lifetime biases in a data driven way offline

Get an event-by-event acceptance by replaying the trigger decision for the full range of possible B/D lifetimes

No trigger emulation needed, correct alignment and detector conditions automatically taken into account.

Lifetime biases?



Because we can reproduce the trigger decisions offline, we can measure lifetime biases in a data driven way offline

Get an event-by-event acceptance by replaying the trigger decision for the full range of possible B/D lifetimes

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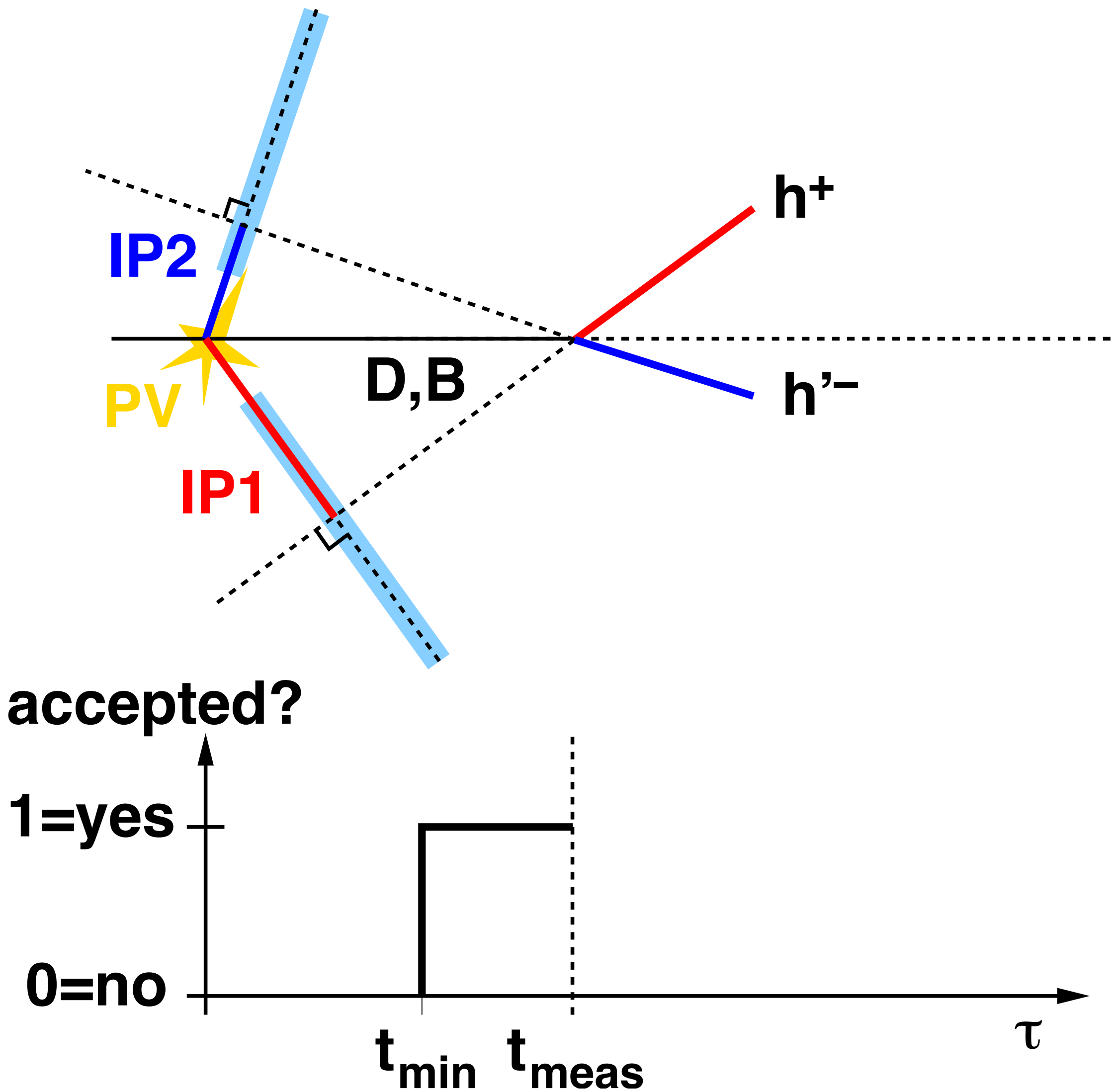

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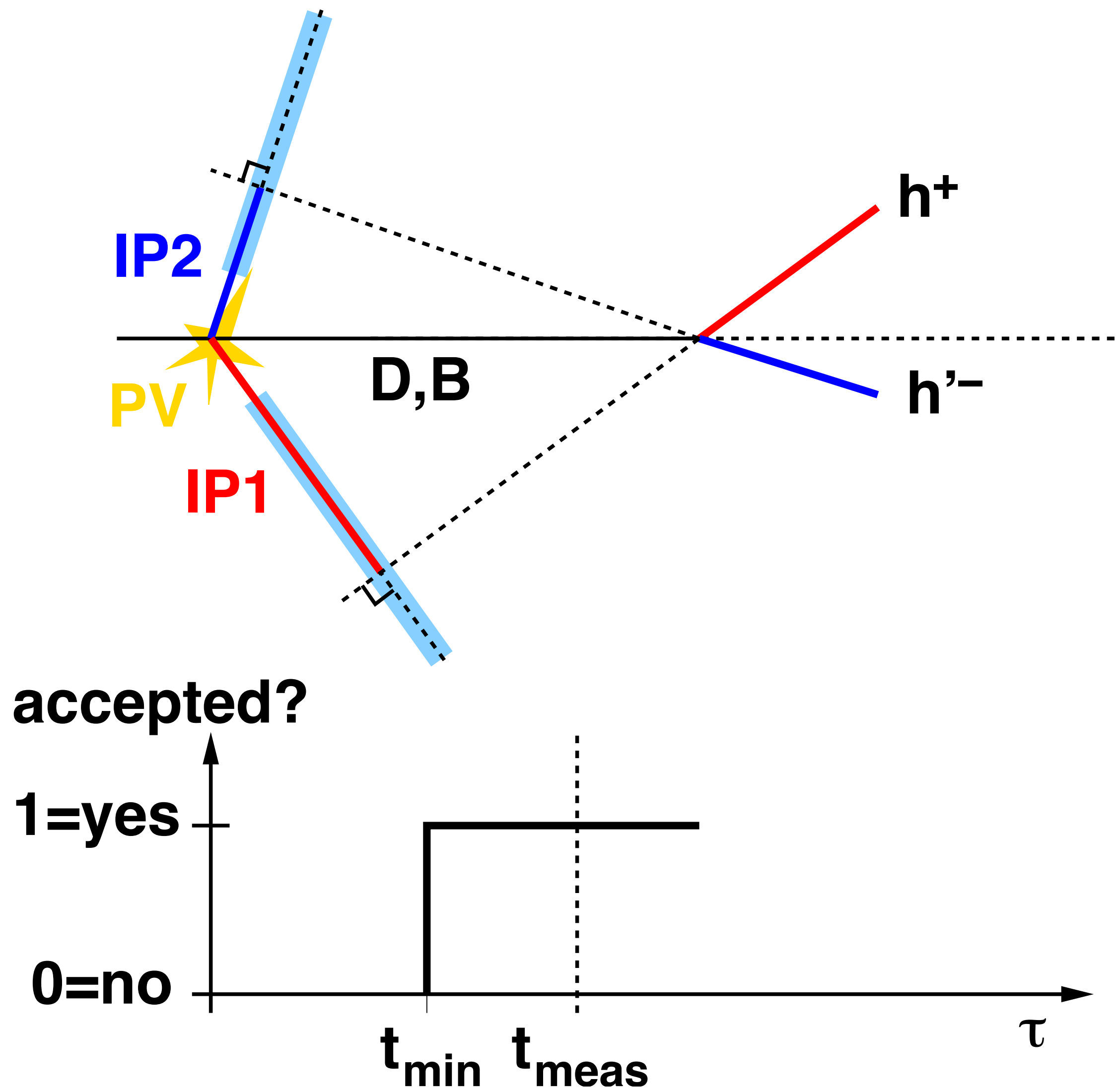

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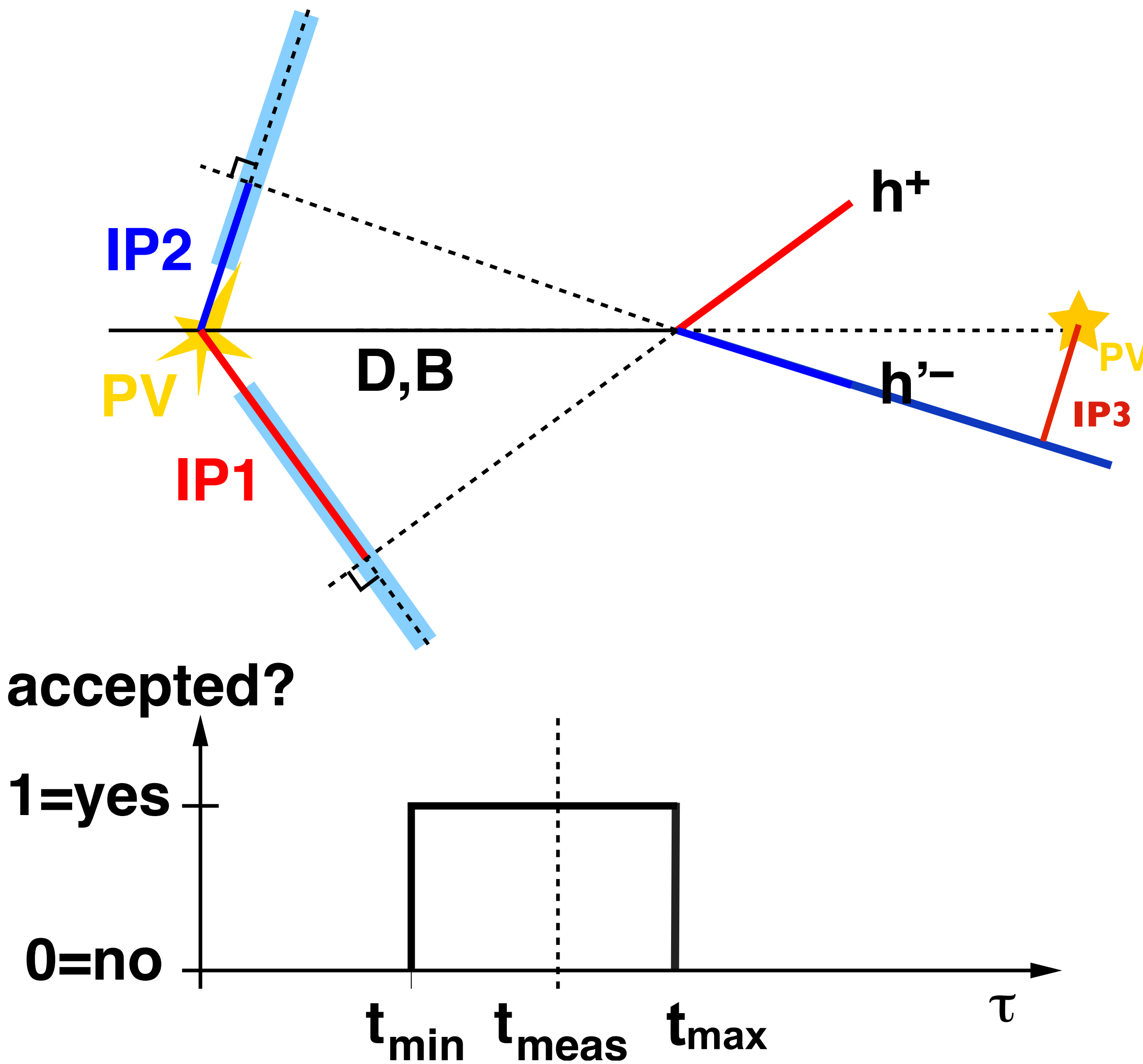

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The LHCb physics programme...

Charm Physics	CPV in B decays	Rare B decay searches	Spectroscopy and Exotica

Note : clearly not the entire physics programme, see the LHCb upgrade LOI for more details

…and its demands on the trigger

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And all this must fit into an output rate of ~4 kHz!

KEY CHALLENGE : discriminate against prompt charm (300 kHz in the LHCb acceptance) while keeping the most interesting prompt charm!

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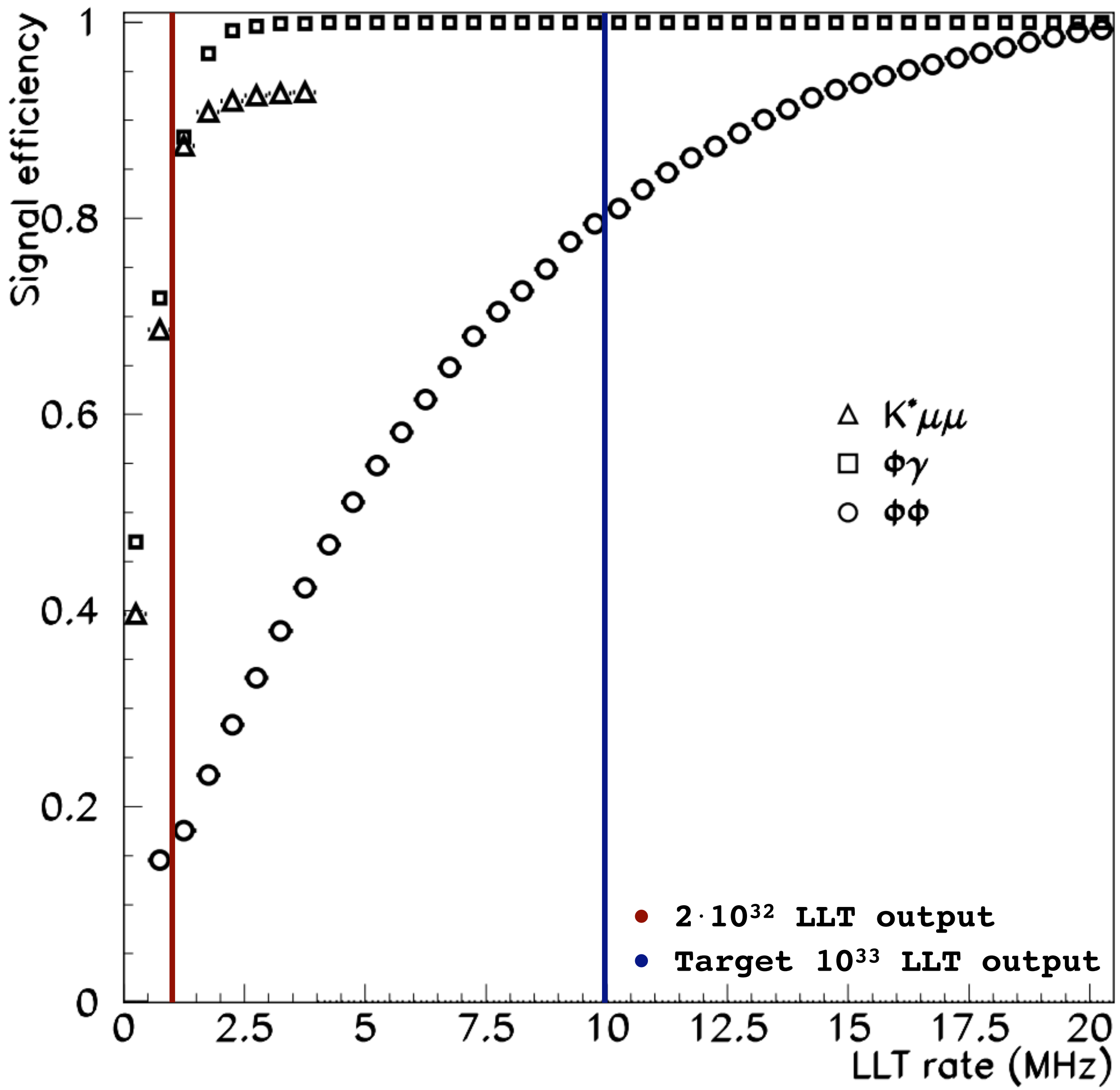
Triggers in the era of the upgraded LHC

The LHCb trigger upgrade



The 1 MHz detector readout is the bottleneck in the current DAQ chain

Particularly limiting for hadronic decay modes, and would become more limiting as the luminosity rises due to pileup

Therefore LHCb will upgrade all subdetectors to read out at 40 MHz

And then scale the actual detector readout according to the available CPU capacity in the HLT farm

Make the L0 (LLT) trigger less and less important as the upgrade progresses