From collisions to analysis

Vladimir V. Gligorov CNRS/LPNHE

CERN-FNAL Summer School 09-2017

What will you learn in these lectures?

How is data collected&processed prior to analysis?

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What types of processings exist, how do we choose between them and how do they affect later analysis?

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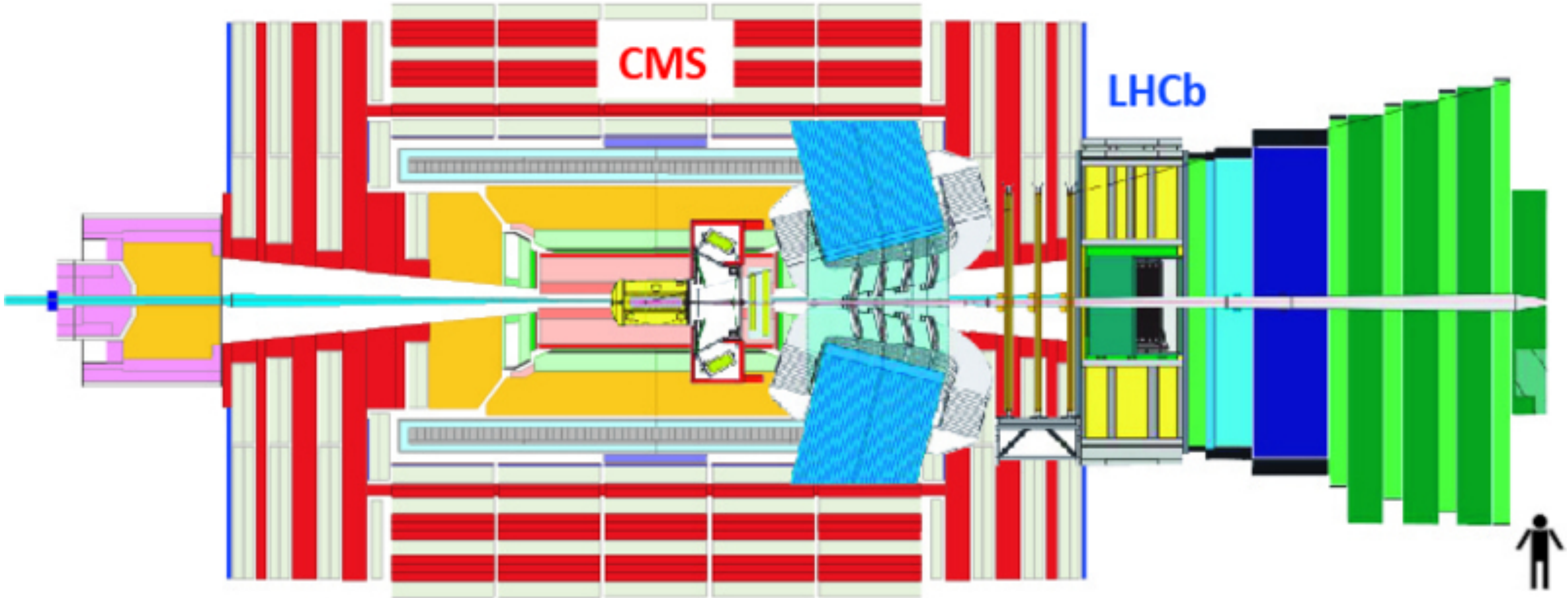
How do we calibrate&understand this processing?

In short : what I wish I'd been taught starting out!

Why do we need to process data (in real-time)?

How much data do our detectors record?



Scale : CMS is O(100M) electronics channels, LHCb is O(1M)

How much data does LHCb process?

Input data rate of the LHCb experiment today ~ 1 TB/second

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This means about 4000 PB of data every year

Which is quite some “real world” data

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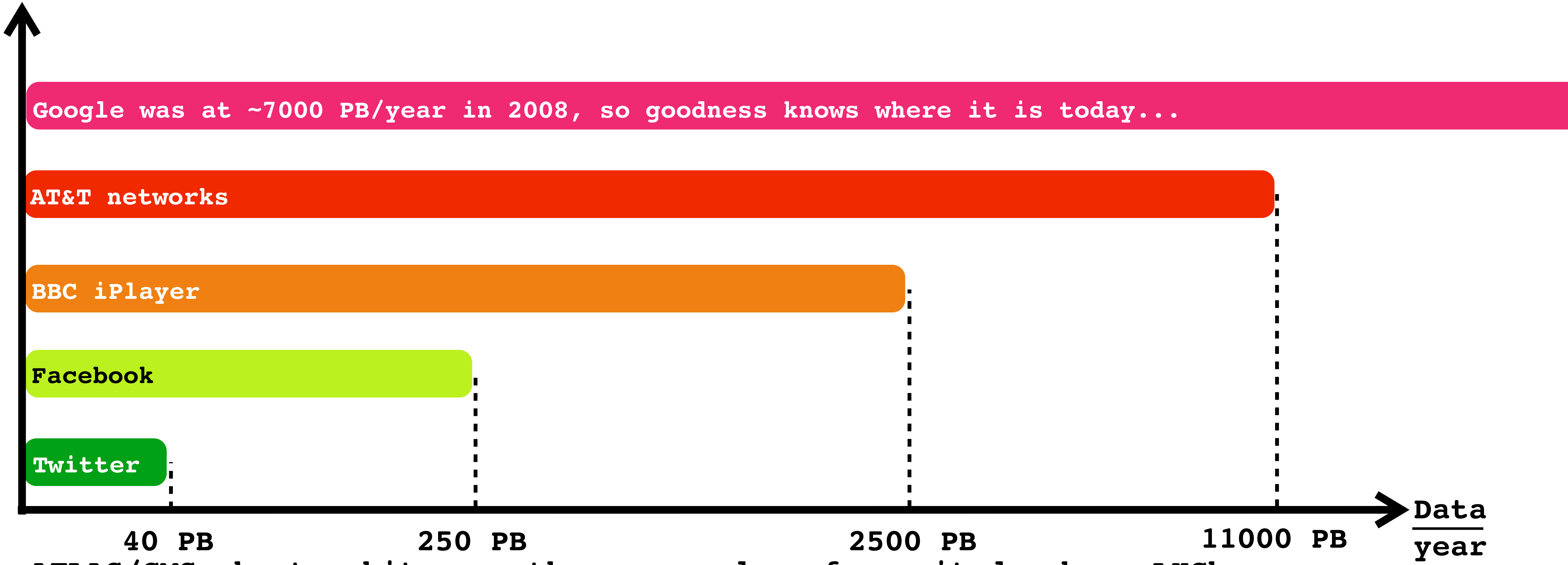
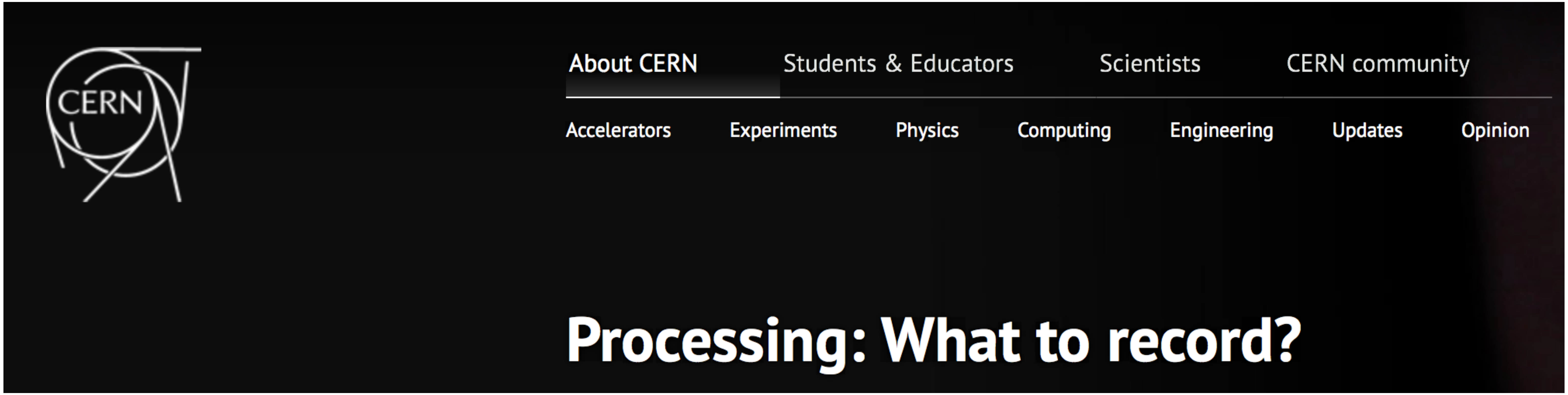


NB : ATLAS/CMS about a bit more than one order of magnitude above LHCb

This is a lot more than we usually quote



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Processing: What to record?

The volume of data produced at the Large Hadron Collider (LHC) presents a considerable processing challenge.

Particles collide at high energies inside CERN's detectors, creating new particles that decay in complex ways as they move through layers of subdetectors. The subdetectors register each particle's passage and microprocessors convert the particles' paths and energies into electrical signals, combining the information to create a digital summary of the "collision event". The raw data per event is around one million bytes (1 Mb), produced at a rate of about 600 million events per second.

The data flow from all four experiments for Run 2 is anticipated to be about 25 GB/s (gigabyte per second)

- ALICE: 4 GB/s (Pb-Pb running)
- ATLAS: 800 MB/s – 1 GB/s
- CMS: 600 MB/s
- LHCb: 750 MB/s

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- ALICE: 4 GB/s (Pb-Pb running)
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- LHCb: 750 MB/s

That's because the data has already been processed in real-time!

Basic real-time processing

A zero-suppression algorithm for the readout electronics of the SciFi Tracker for the LHCb detector upgrade

H. Chanal

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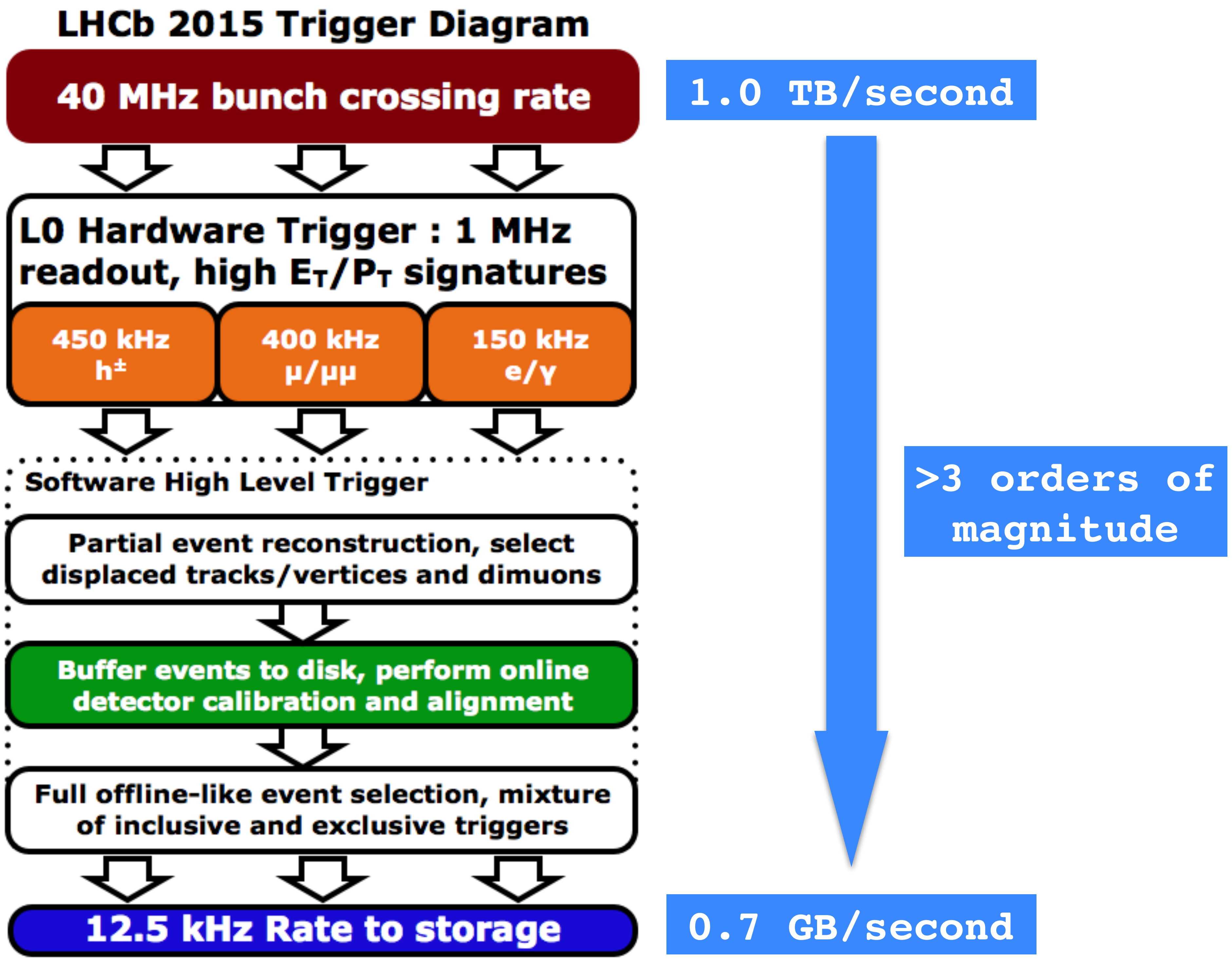
Journal of Instrumentation, Volume 11, February 2016
Topical Workshop on Electronics for Particle Physics

Abstract

A new detector made of scintillating fibres read out by arrays of silicon photomultipliers (SiPM) is planned for the LHCb detector upgrade, foreseen in 2018/19. The development of dedicated readout electronics in the harsh LHC environment leads to challenges. Each SiPM array generates 10.24 Gb/s of data after the digitization leading to a data rate of 47.2 Tb/s for the full detector. Such a large amount of data can not be reasonably processed by a computing farm. In this paper, we describe the readout scheme and the zero suppression algorithm used to reduce the data flow below 8 Tb/s.

Most basic real-time processing is zero-suppression. Gain x5-10 in the size of the data, lossless from POV of physics information

Less basic real-time processing



Real-time data selection (“trigger”) reduces more but lossy

Conceptual pause

Data processing is either lossless or lossy for the physics you are trying to measure.

If the processing is lossy you have to account for its impact on your measurement.

Different types of processing can be lossy for some physics analyses and lossless for others.

But let’s come back to our detector

Imagine you really needed to use all the detector raw data for your analysis. Could you physically do it?

Could you read all the data out?

With thanks to
Wesley Smith

ATLAS & CMS Triggered vs. Triggerless Ph. 2 Architectures

HIGH LUMINOSITY LHC

1 MHz (Triggered) - planned:

- **Network:**
  - 1 MHz with ~5 MB: aggregate ~40 Tbps
  - Links: Event Builder-cDAQ: ~ 500 links of 100 Gbps
  - Switch: almost possible today, for 2022 no problem
- **HLT computing:**
  - General purpose computing: 10(rate)x3(PU)x1.5(energy)x200kHS6 (CMS)
    - **Factor ~50 wrt today maybe for ~same costs**
  - Specialized computing (GPU or else): Possible

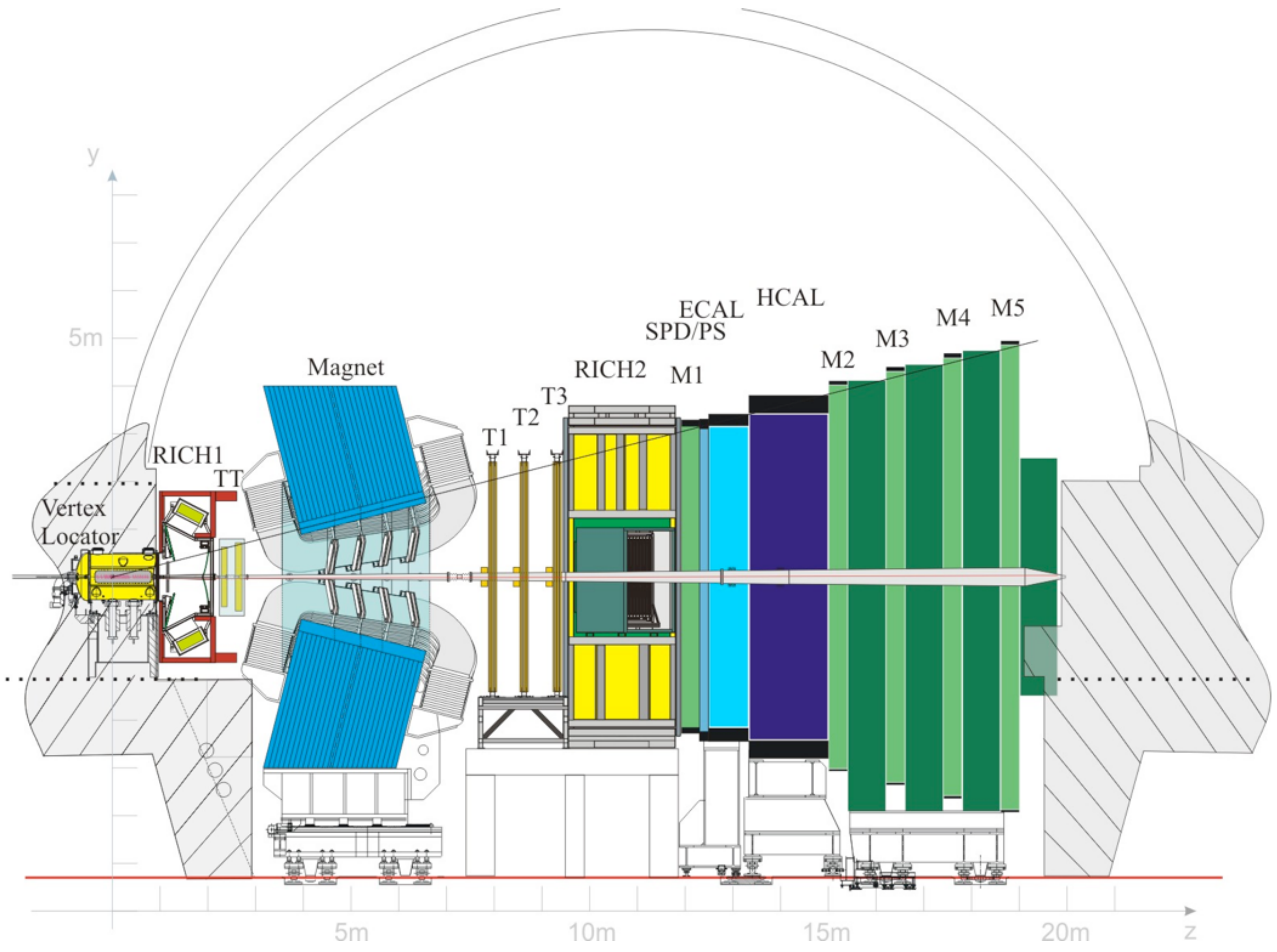
40 MHz (Triggerless) – not planned:

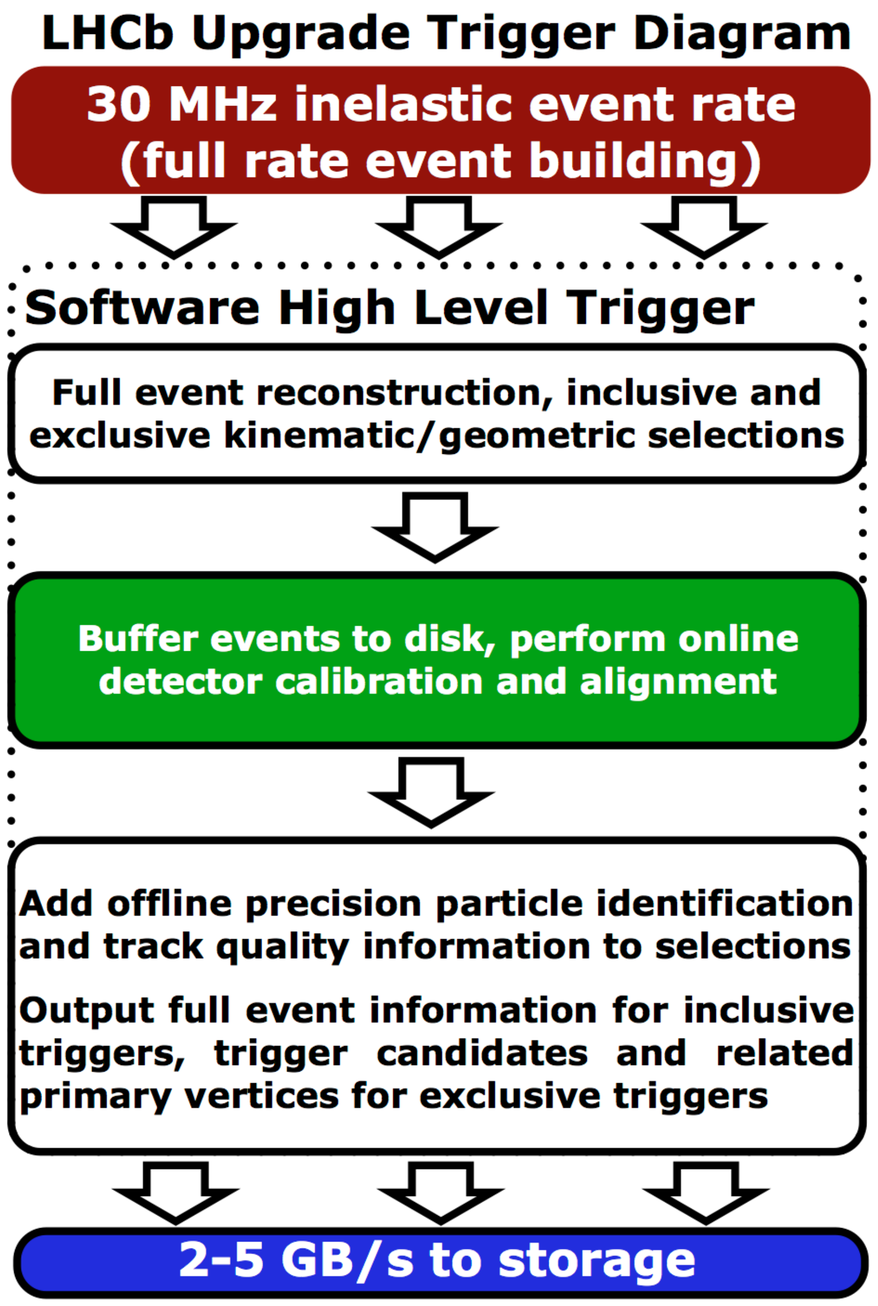
- **Network:**
  - 40 MHz with ~5 MB: aggregate ~2000 Tbps
  - Event Builder Links: ~2,500 links of 400 Gbps
  - Switch: has to grow by factor ~25 in < 10 years, difficult
- **Front End Electronics**
  - Readout Cables: Copper Tracker! – Show Stopper
- **HLT computing:**
  - General purpose computing: 400(rate) x3(PU)x1.5(energy)x200kHS6 (CMS)
    - **Factor ~2000 wrt today, but too pessimistic since events easier to reject w/o L1**
    - **This factor looks impossible with realistic budget**
  - Specialized computing (GPU or …)
    - **Could possibly provide this …**

NO

Not a high-luminosity hermetic detector, but otherwise…

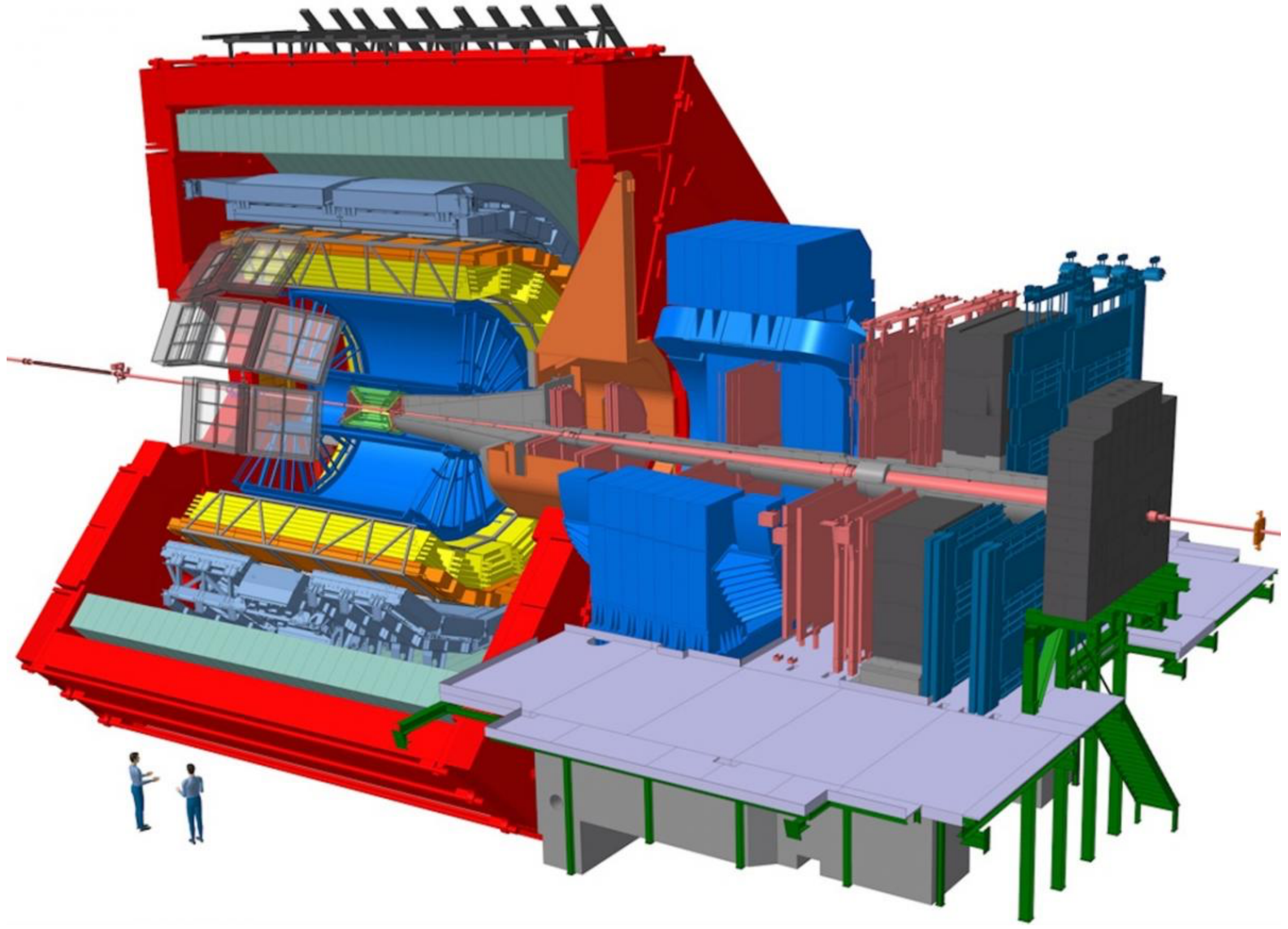
It depends on your detector geometry





…you can actually read the full zero-suppressed detector out without making the material budget of your detector infinite

And it depends on your data rate



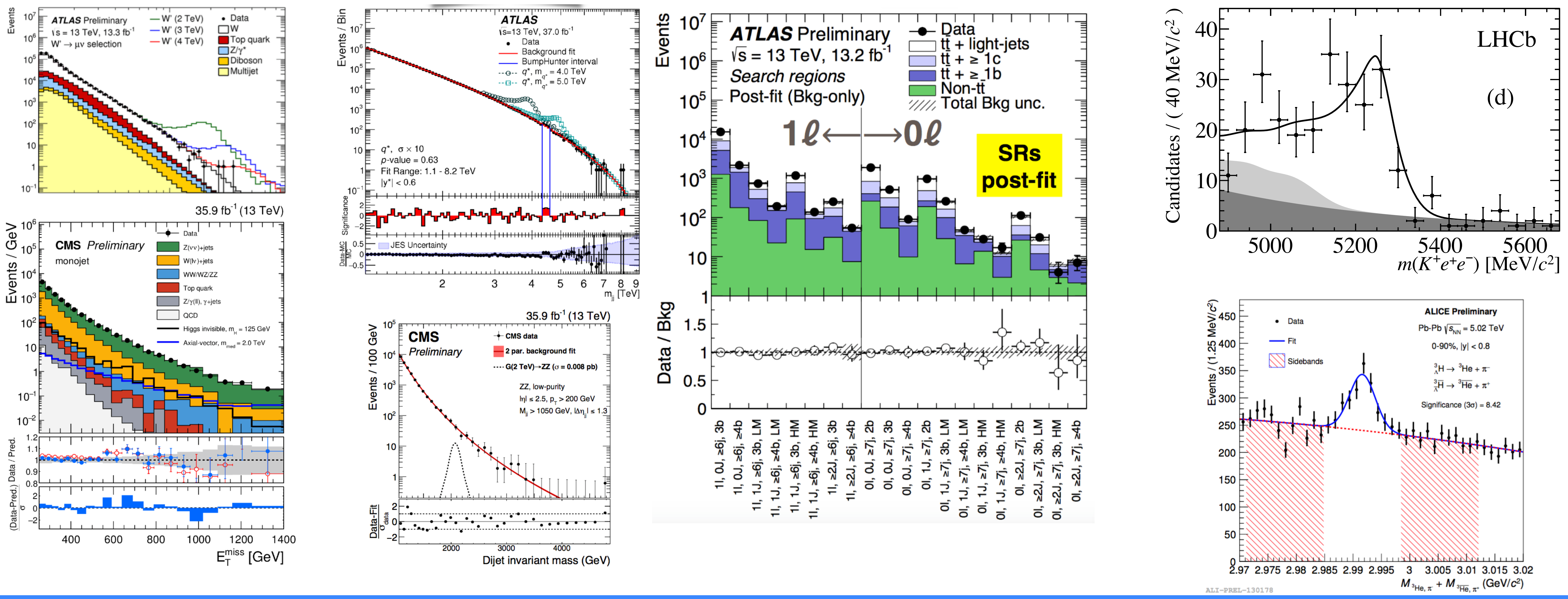
Detector	Input to Online System (GByte/s)	Peak Output to Local Data Storage (GByte/s)
TPC	1000	50.0
TRD	81.5	10.0
ITS	40	10.0
Others	25	12.5
Total	**1146.5**	**82.5**

The same is true if you have a hermetic detector but you have a lower data rate (or can compress it), for example in ALICE

Data processing also a physics choice…

Analysis aims to observe particles & force-carriers produced in LHC collisions, measure their production rates, and measure the rate at which they decay into other particles & force-carriers

…connected to what analysis measures



Most "interesting" particles&force-carriers decay before leaving a signal in the detector, so we have to measure their properties by reconstructing and studying their decay products. These products are typically known SM particles and can be thought of as common building blocks for all analyses.

What is this common reconstruction?

Raw data from detector

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Common processing

Charged particle trajectories | Neutral clusters | Jets | Composite objects

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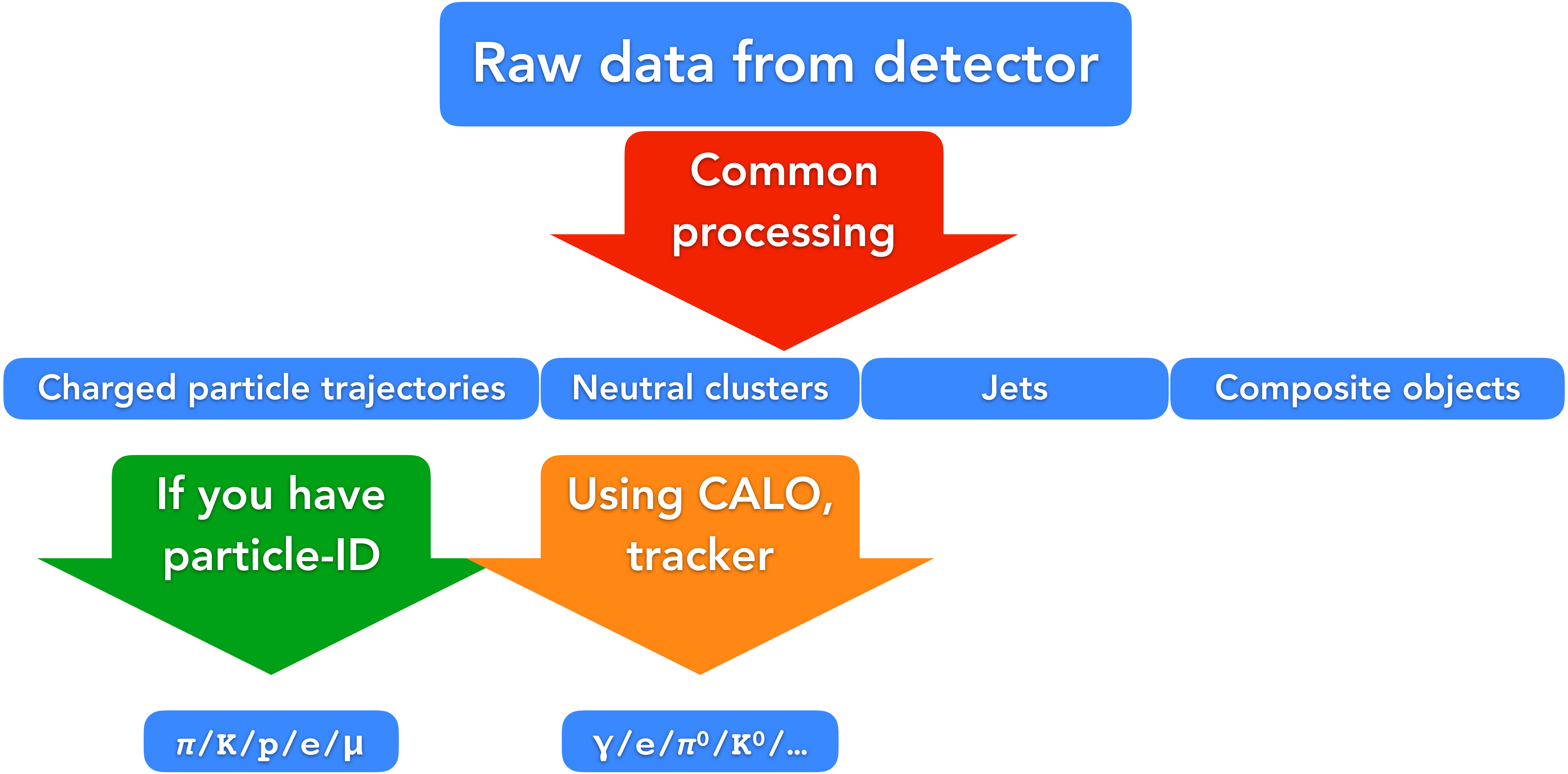
Charged particle trajectories | Neutral clusters | Jets | Composite objects

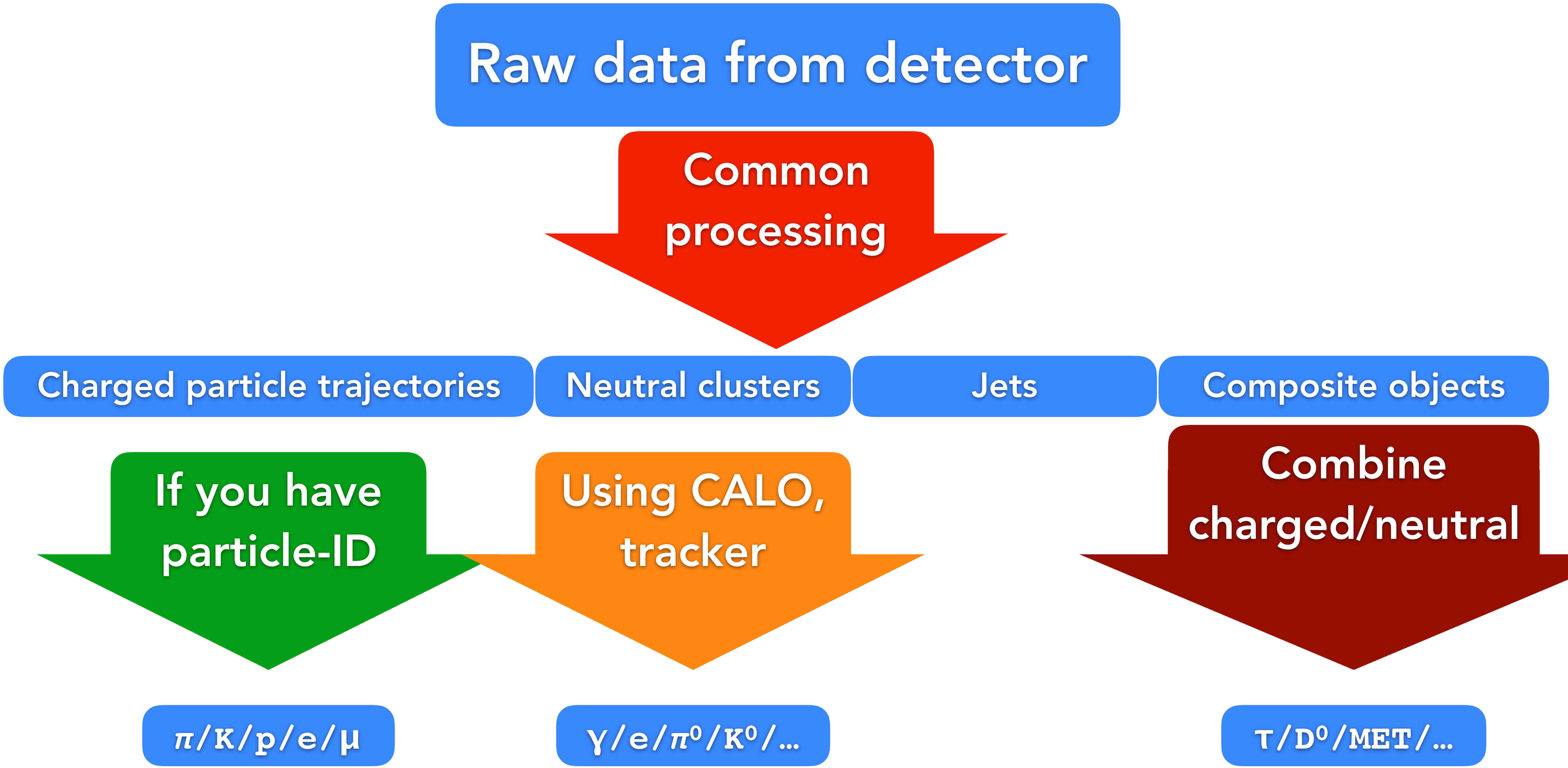
If you have particle-ID

$\pi/K/p/e/\mu$

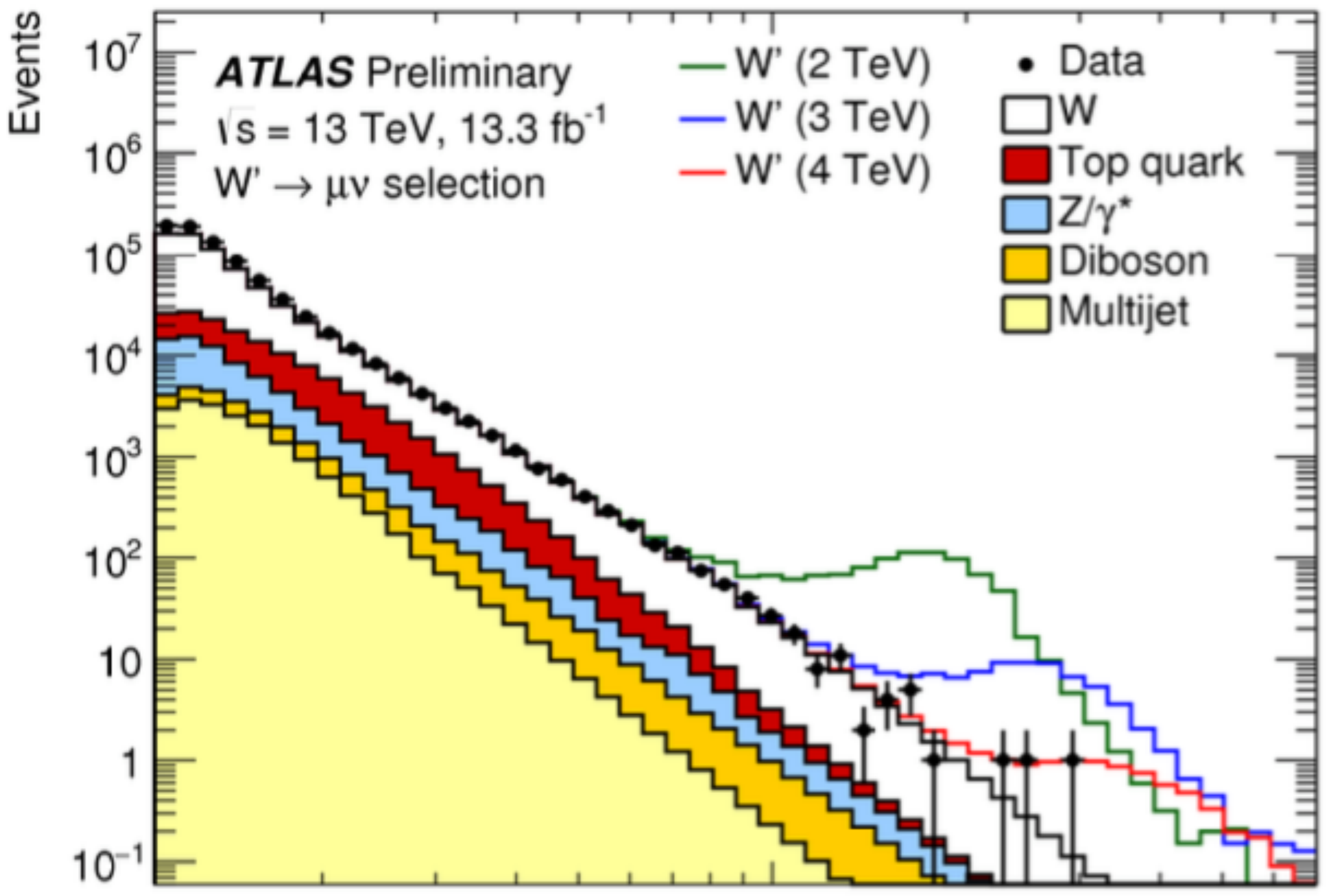
What is this common reconstruction?

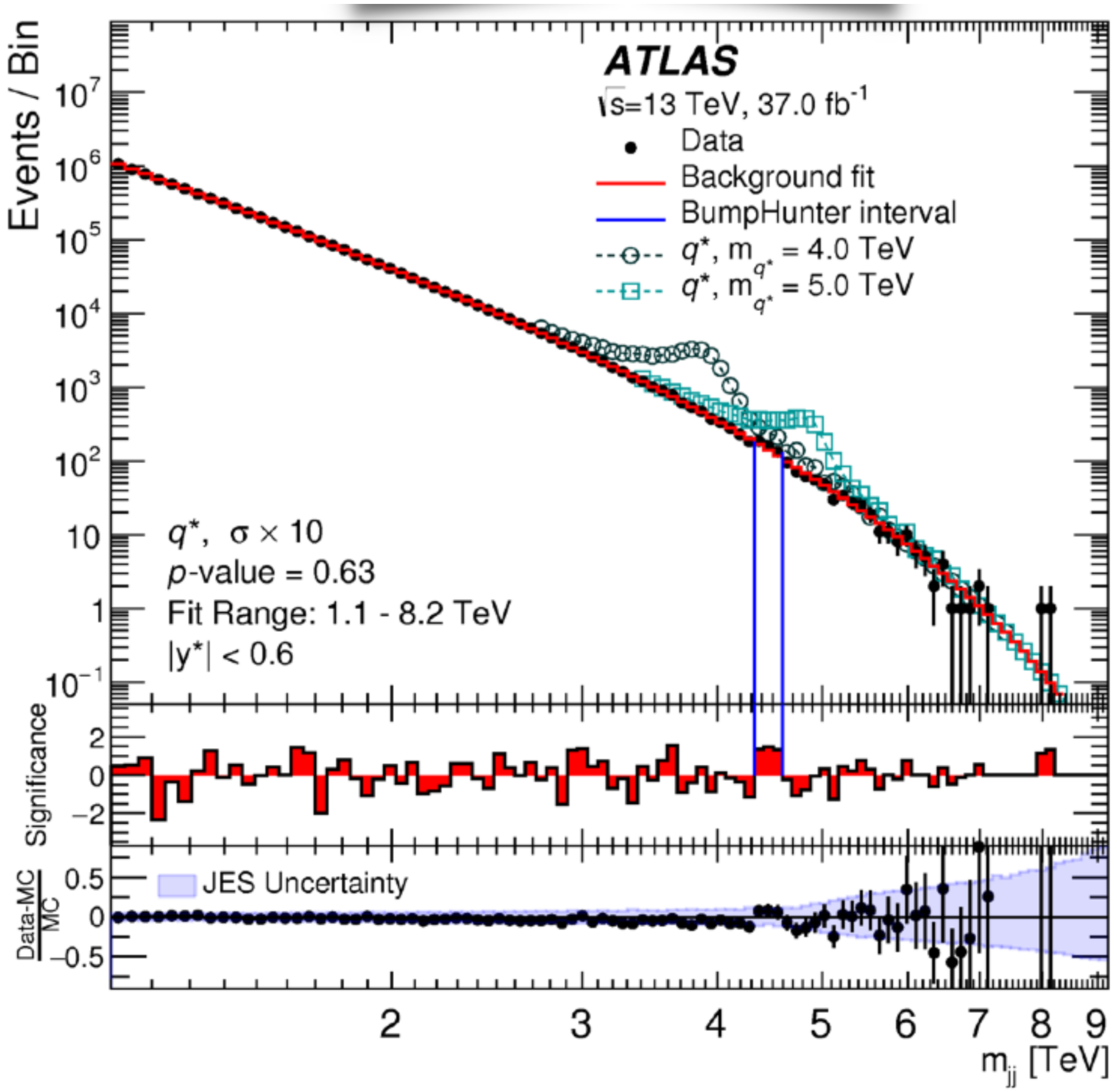


What is this common reconstruction?



Imagine if each analysis did all of this

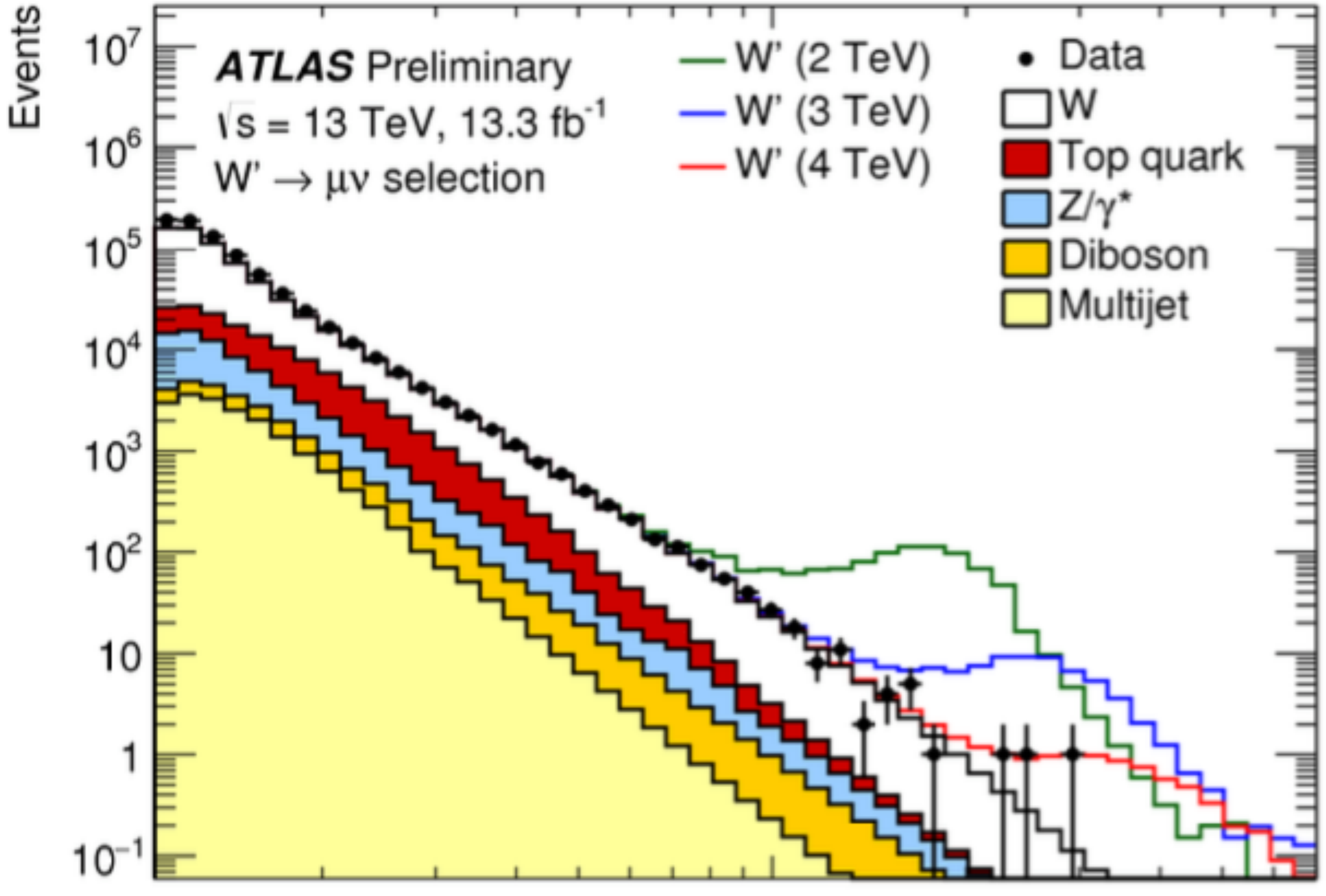


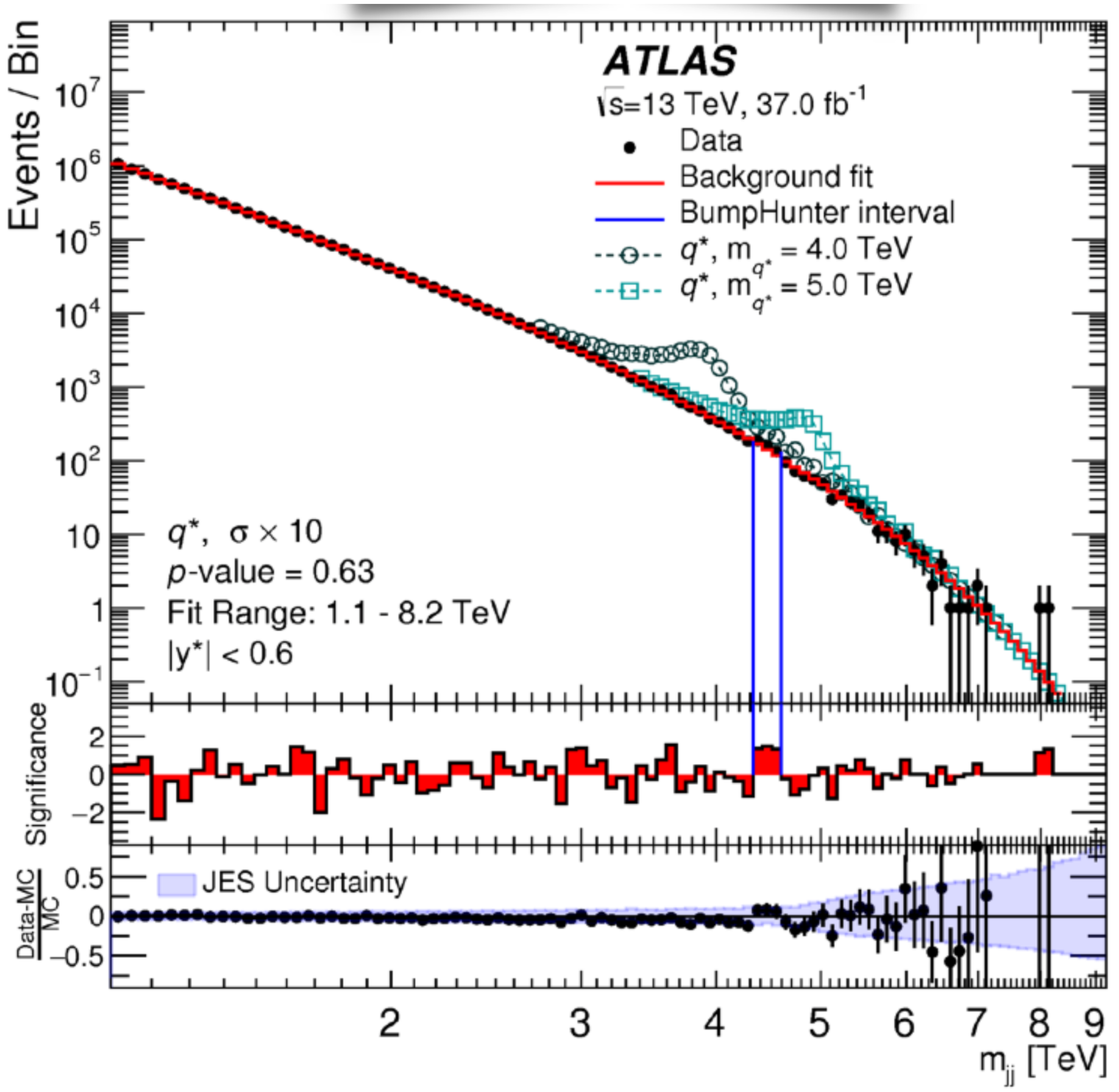


Almost every analysis has two basic components :

1. Combine&select building blocks to observe a signal above background
2. Understand the efficiency of step (1) to measure signal properties

Imagine if each analysis did all of this





If each group of analysts made their own "common" objects, how would you do this? How would you combine the results of the different analyses? How would you determine correlations between their systematics?

Nota bene, this is not purely hypothetical

Digging Deeper for New Physics in the LHC Data

Pouya Asadi, Matthew R. Buckley, Anthony DiFranzo,
Angelo Monteux and David Shih

NHETC, Dept. of Physics and Astronomy
Rutgers, The State University of NJ
Piscataway, NJ 08854 USA

arXiv:1707.05783v1

In this paper, we describe a novel, model-independent technique of "rectangular aggregations" for mining the LHC data for hints of new physics. A typical (CMS) search now has hundreds of signal regions, which can obscure potentially interesting anomalies. Applying our technique to the two CMS jets+MET SUSY searches, we identify a set of previously overlooked $\sim 3\sigma$ excesses. Among these, four excesses survive tests of inter- and intra-search compatibility, and two are especially interesting: they are largely overlapping between the jets+MET searches and are characterized by low jet multiplicity, zero b-jets, and low MET and H_T. We find that resonant color-triplet production decaying to a quark plus an invisible particle provides an excellent fit to these two excesses and all other data – including the ATLAS jets+MET search, which actually sees a correlated excess. We discuss the additional constraints coming from dijet resonance searches, monojet searches and pair production. Based on these results, we believe the wide-spread view that the LHC data contains no interesting excesses is greatly exaggerated.

Increasing focus on looking for beyond SM effects by combining the results of different individually inconclusive searches. A well calibrated common processing of the data is crucial for this.

Recap : we have to process data because

Raw data recorded by detectors too big to store

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Most analyses use same SM building blocks, allows analysts to not reinvent all wheels for every analysis

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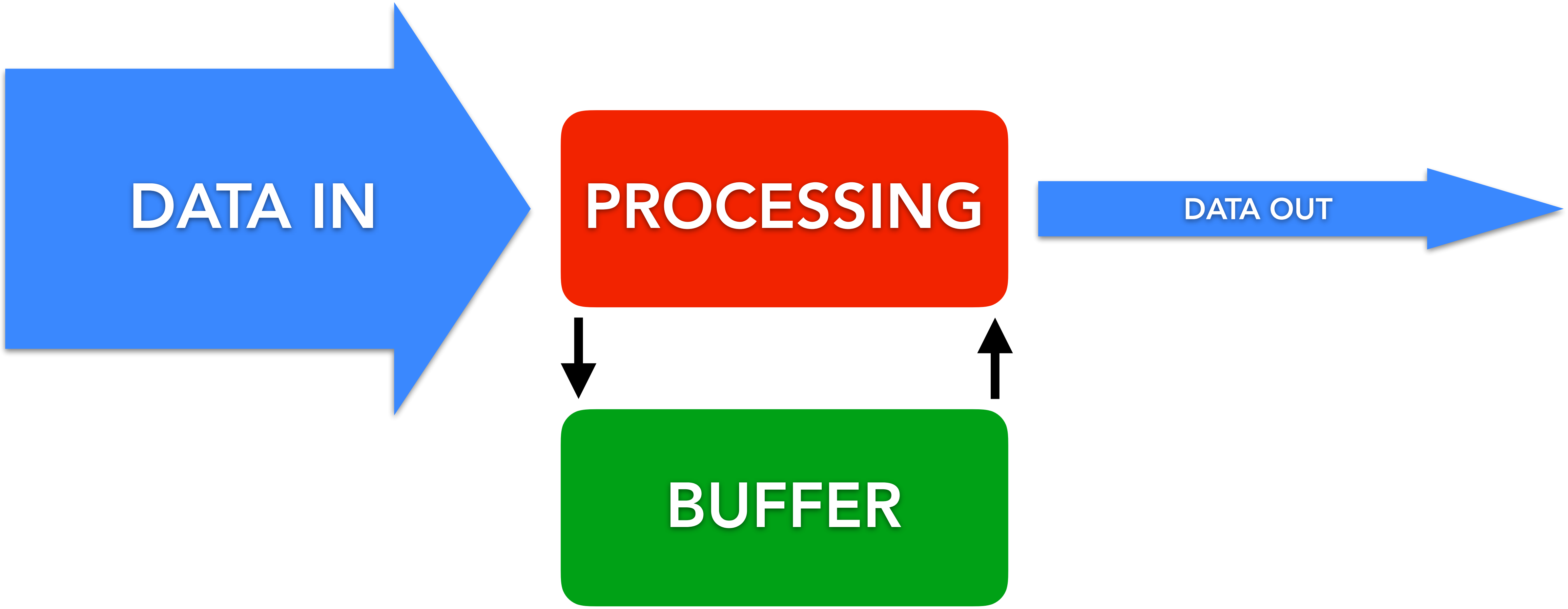
Now let's see how quick this processing should be

How real is time? Fixed latency vs. cascades of disk buffers

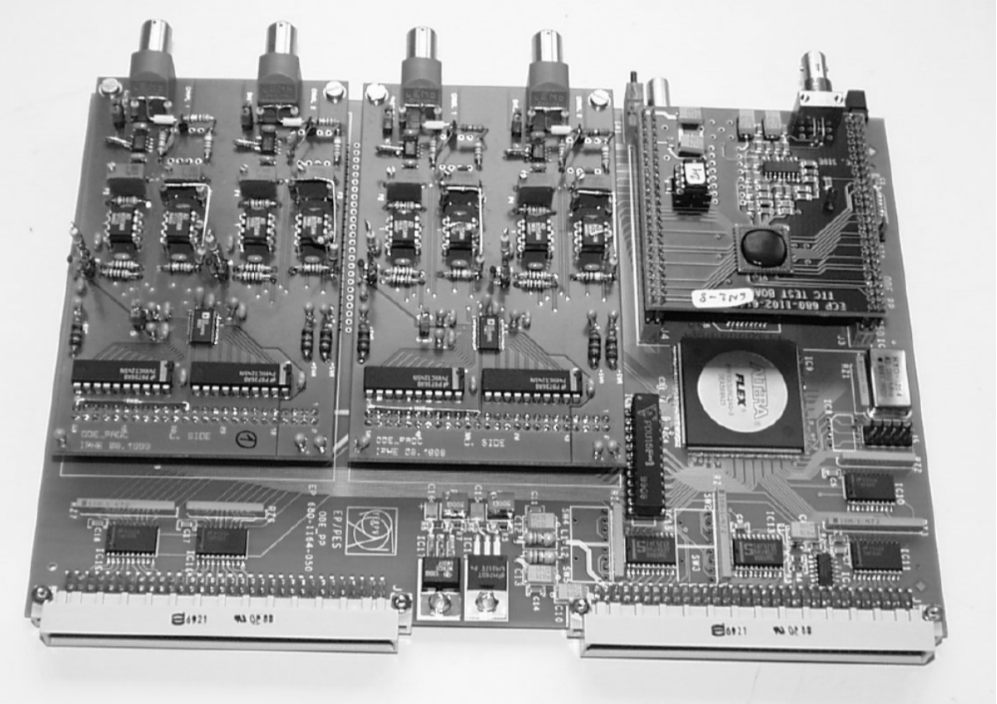
What determines the processing time?



Every data processing step has to buffer the data which is being processed, before sending a (reduced) data volume to the next processing step. Data rate and buffer size determine the speed.

Types of buffers which are available

In detector electronics



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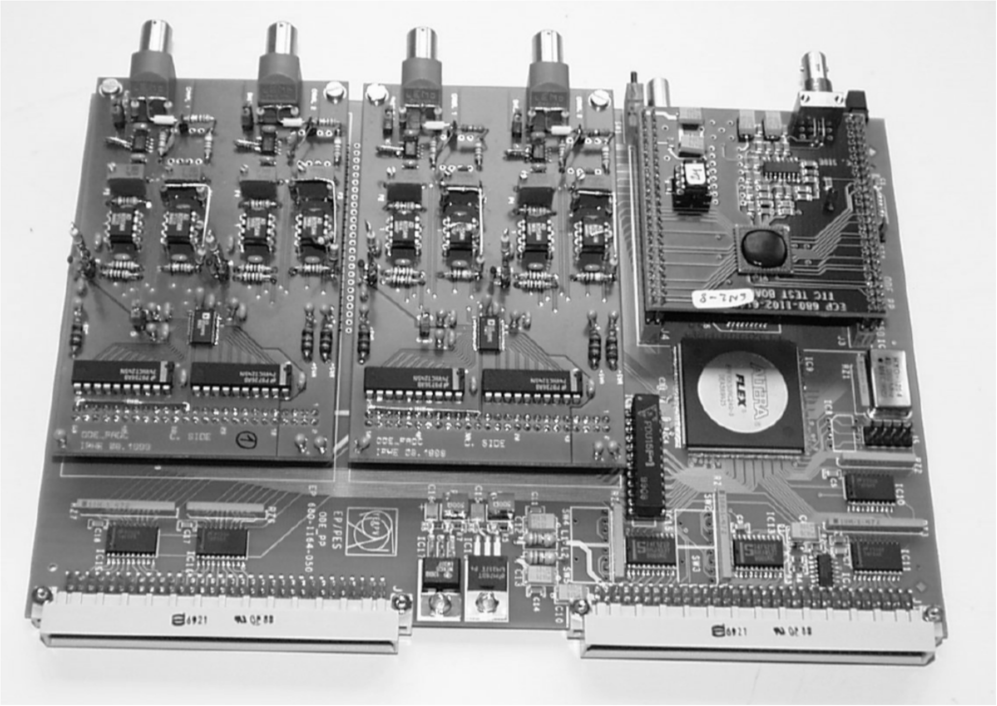

In server farm near the detector ("software trigger")

Types of buffers which are available

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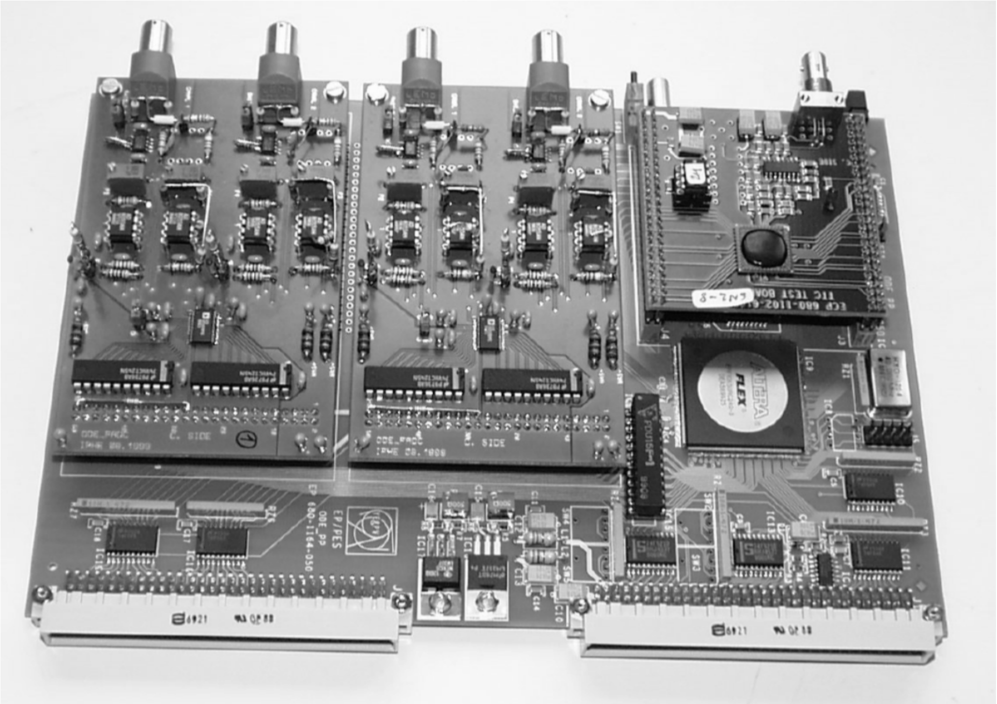
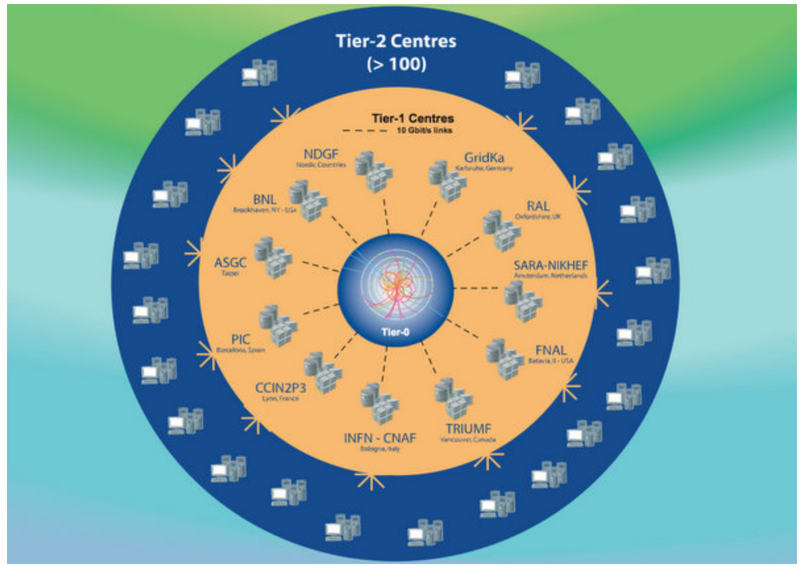


In server farm near the detector ("software trigger")

In server farm far from the detector ("GRID")



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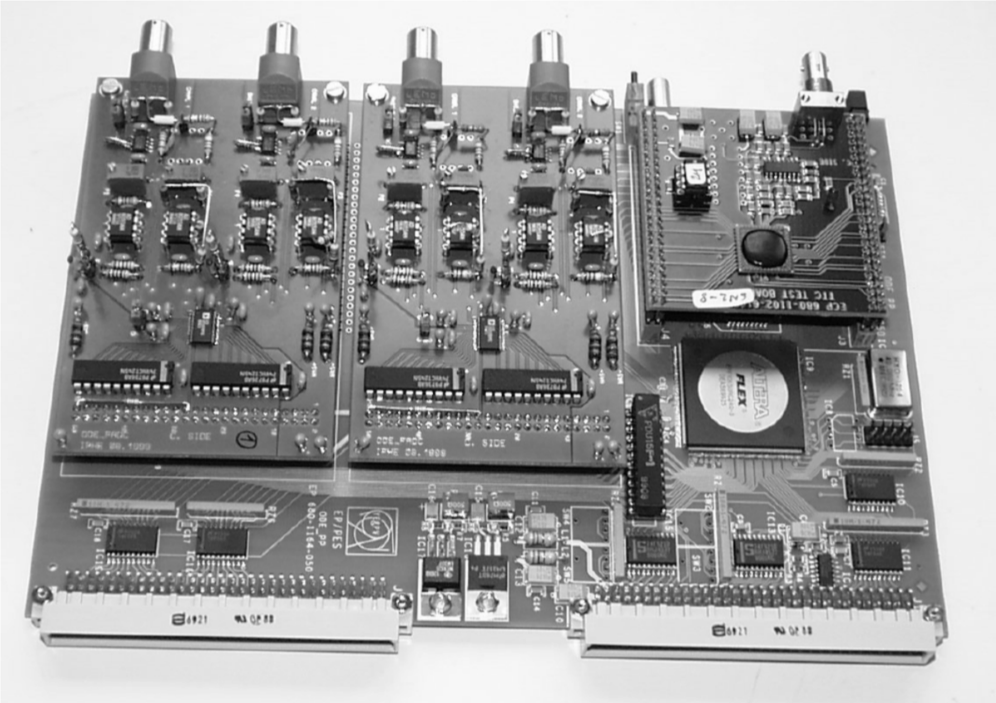

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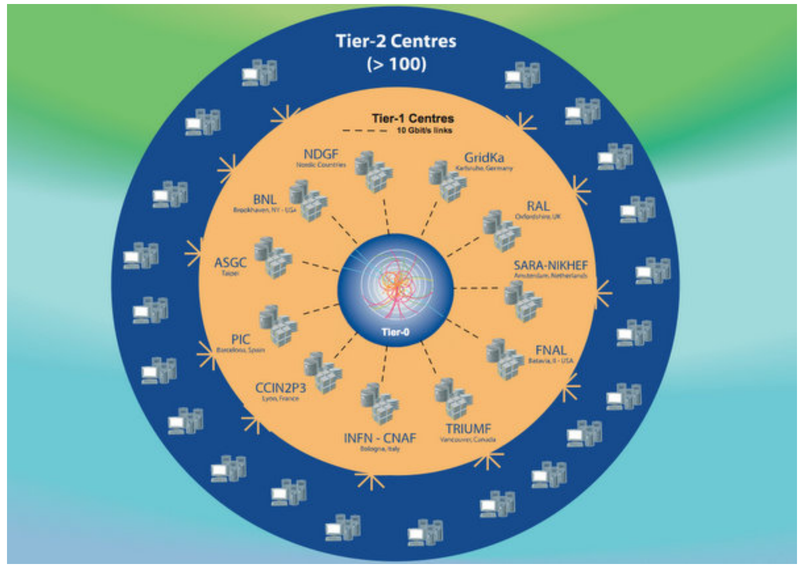


From a conceptual point of view, there is no difference: you buffer the data, process it somehow, and send it on. But each type of buffer imposes its own constraints on the processing.

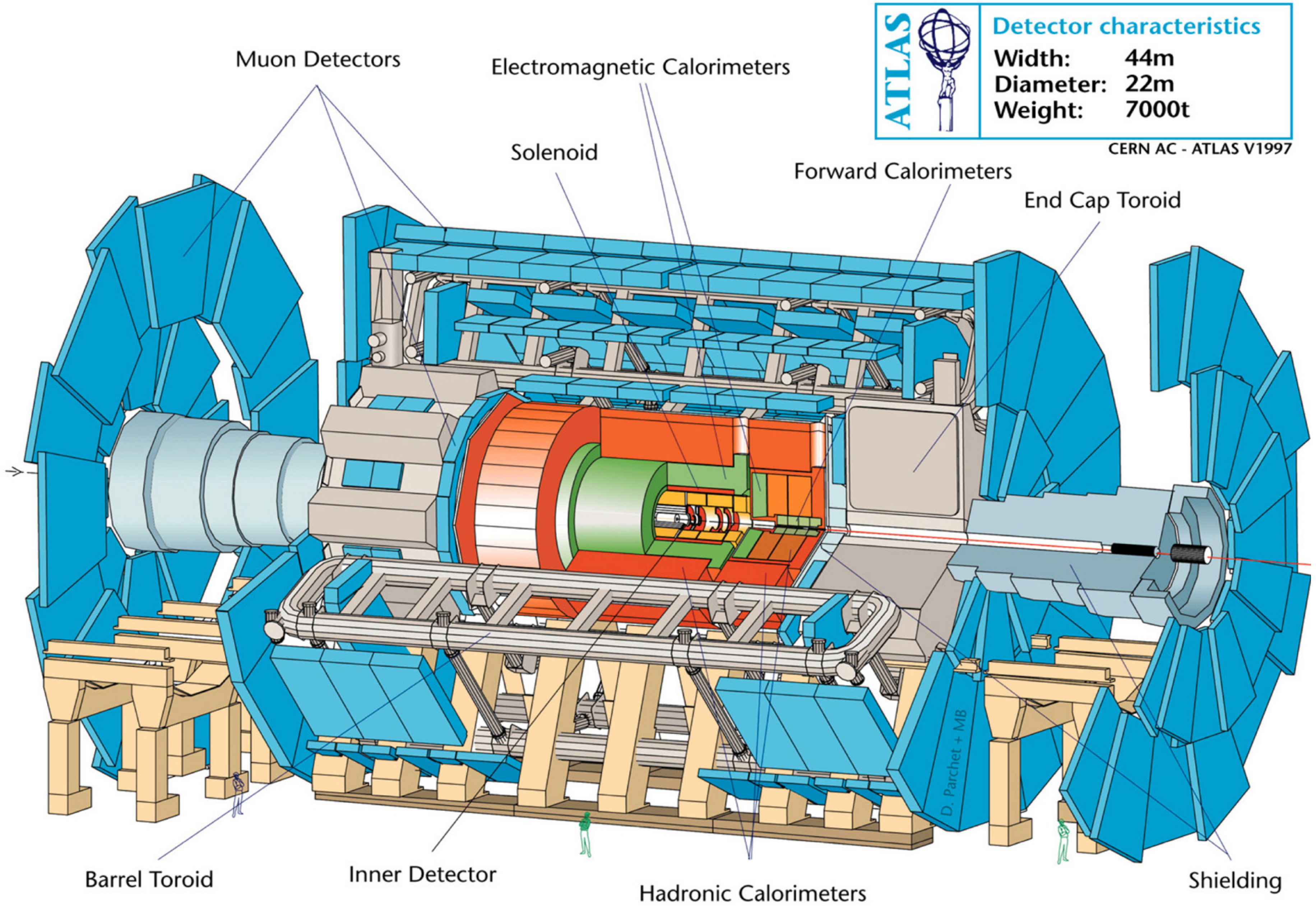
A pause for jargon

Data processing inside detector electronics (e.g. FPGAs) has a "fixed latency" => every bunch crossing has to be processed in the same amount of time to stay in sync.

Data processing in server farms does not have a fixed latency because data from all subdetectors has been aggregated ("event building"): the maximum average processing time is fixed, but busier events can take longer and emptier events less long.

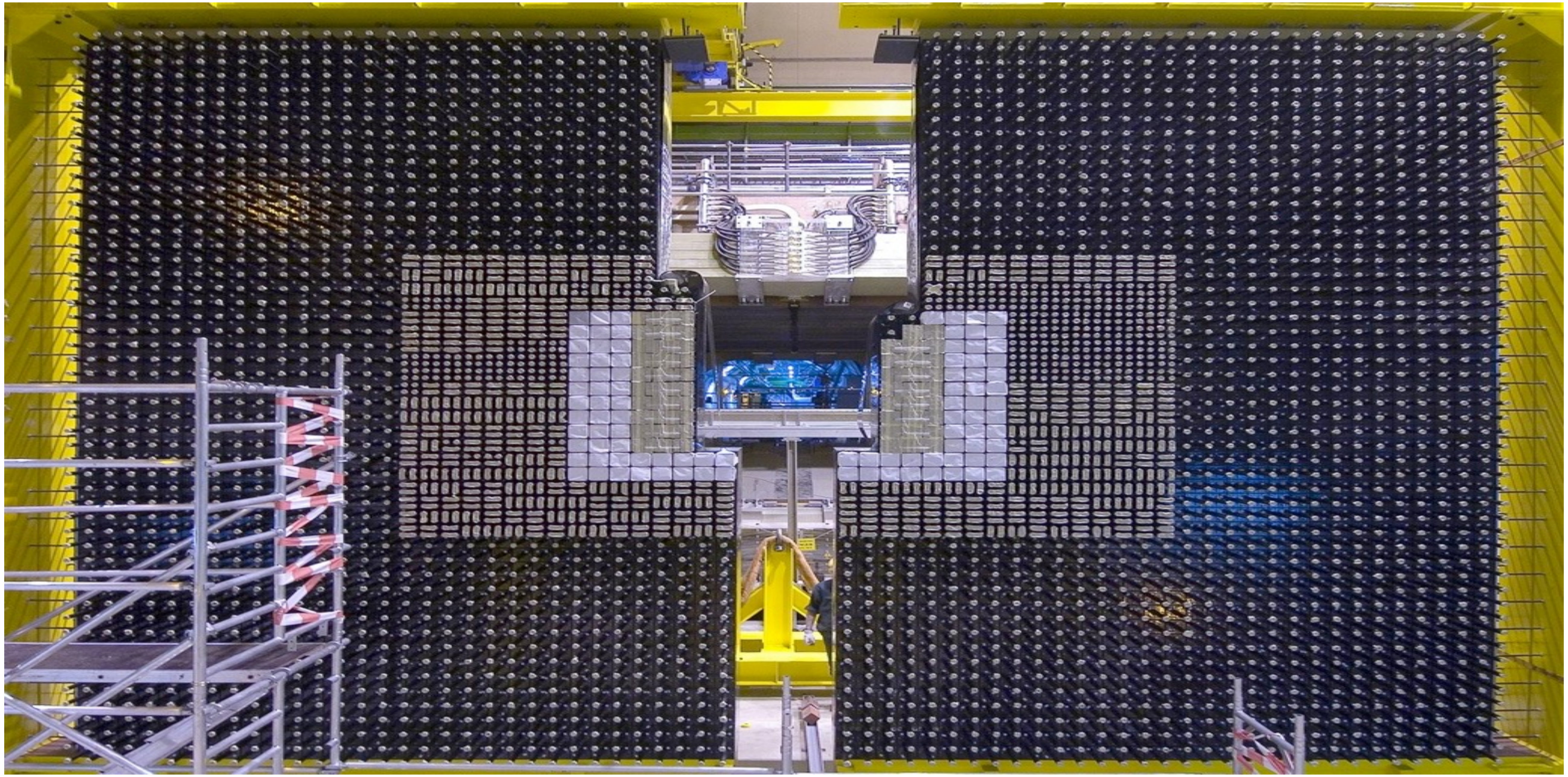
Server farm does NOT mean CPUs. Could be a farm of CPUs, GPUs, FPGAs, CPU-GPU-FPGA hybrids…

When do you need fixed latency?



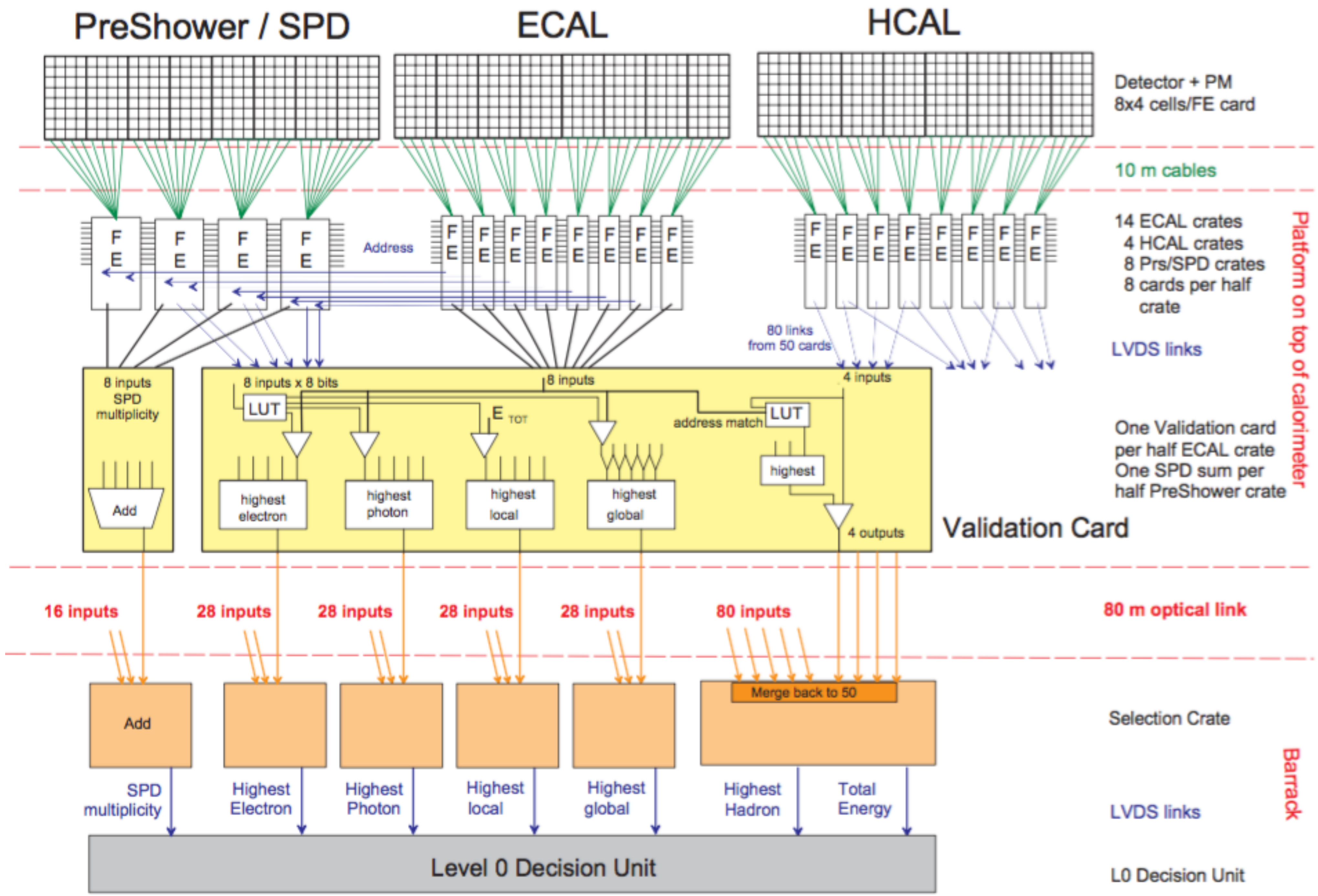
Whenever you cannot afford to read out all the information from all the subdetectors and build the "event" before processing it.

LHCb fixed latency calorimeter trigger



The problem naturally parallelizes: split CALO into regions, look for large clusters in each one. Keep event if one or more clusters passes a threshold.

LHCb fixed latency calorimeter trigger



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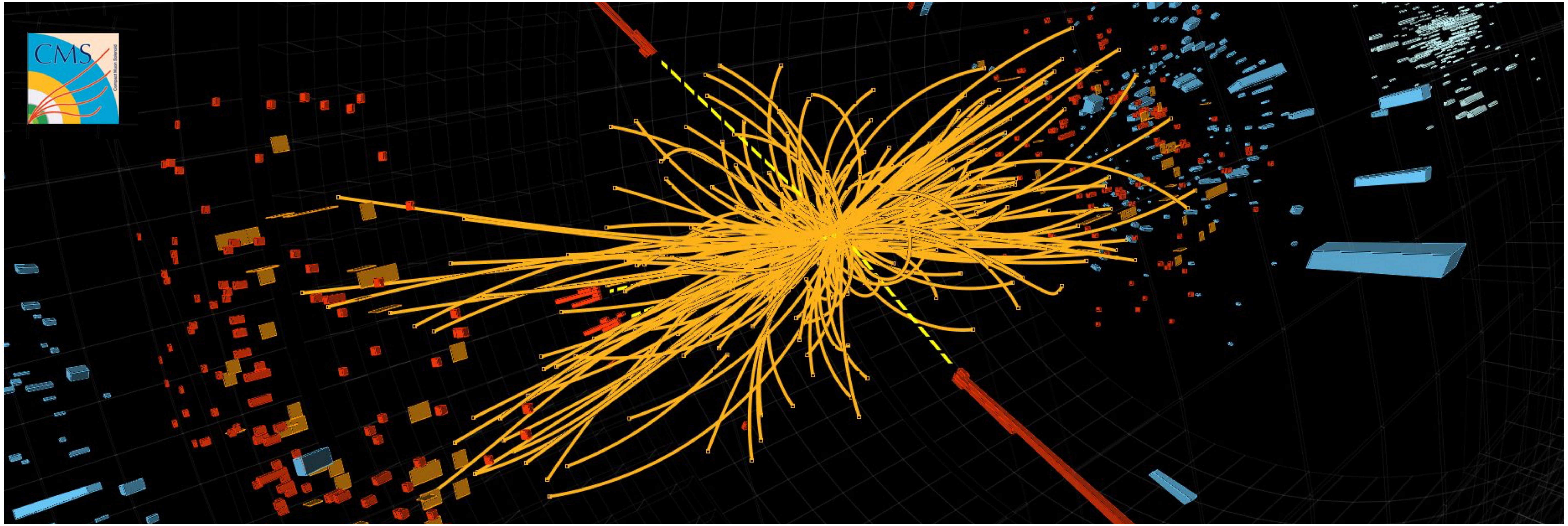
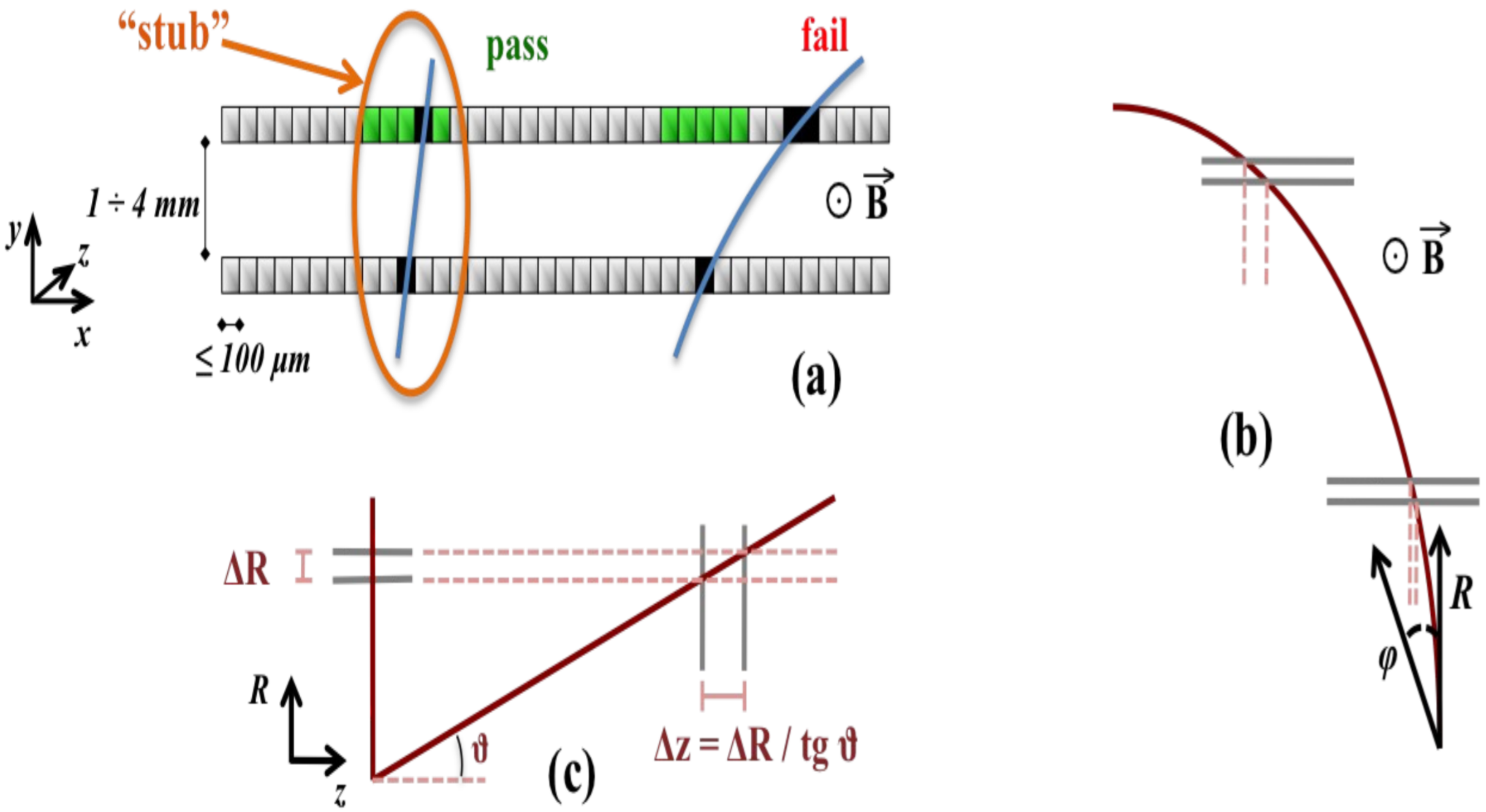
CMS HL–LHC track trigger



A cuter example : in HL-LHC CMS aim to reconstruct all charged particles with p_T>2 GeV/c at 40 MHz. But tracks are not localized, can overlap…

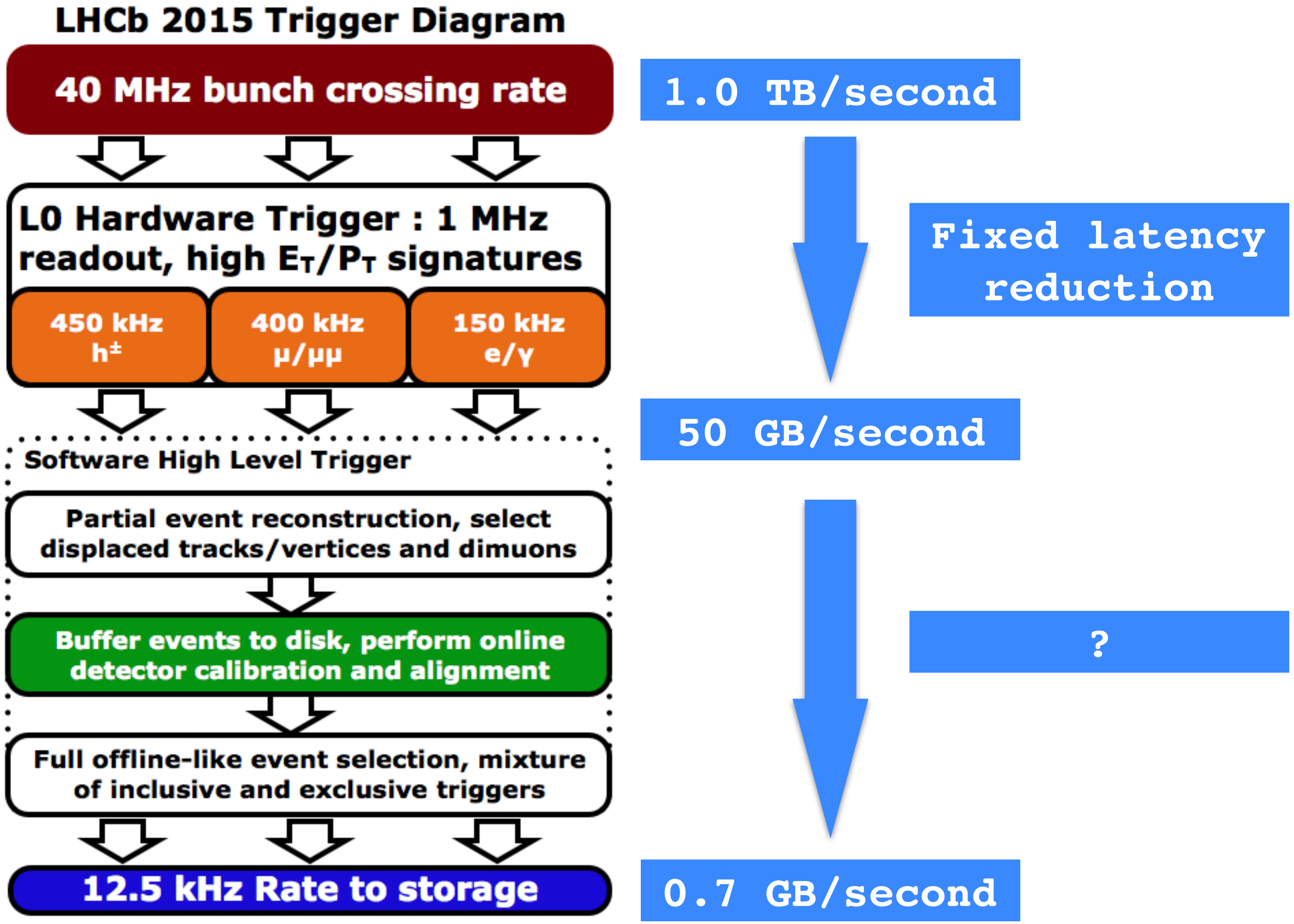
CMS HL-LHC track trigger

With thanks to
Anders Ryd



However if you build your tracker with the right module spacing, pairs of nearby hits can allow you to locally select high-p_T seeds! So designing fixed latency triggers is often closely linked to designing the detectors they use.

What about once the events are built?

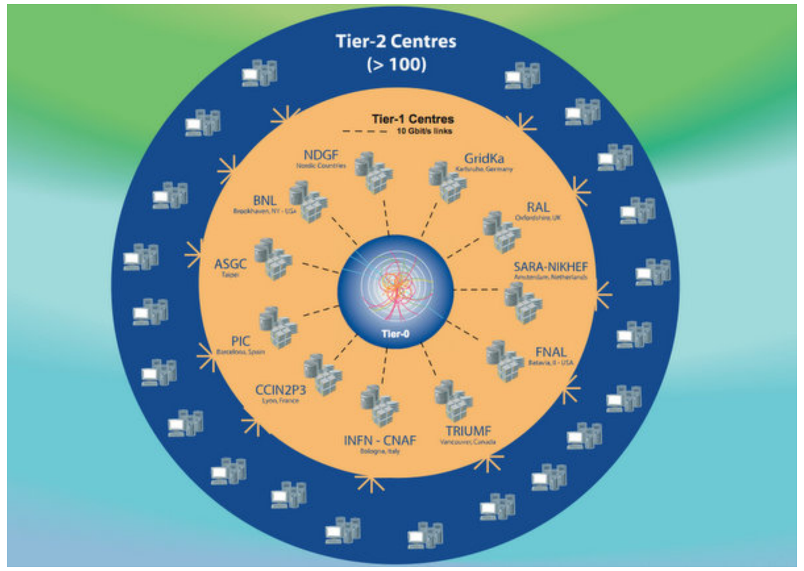


Having read out the detector and assembled information from its different parts (subdetectors) into events, you still typically have too much data

Where can you process your data then?

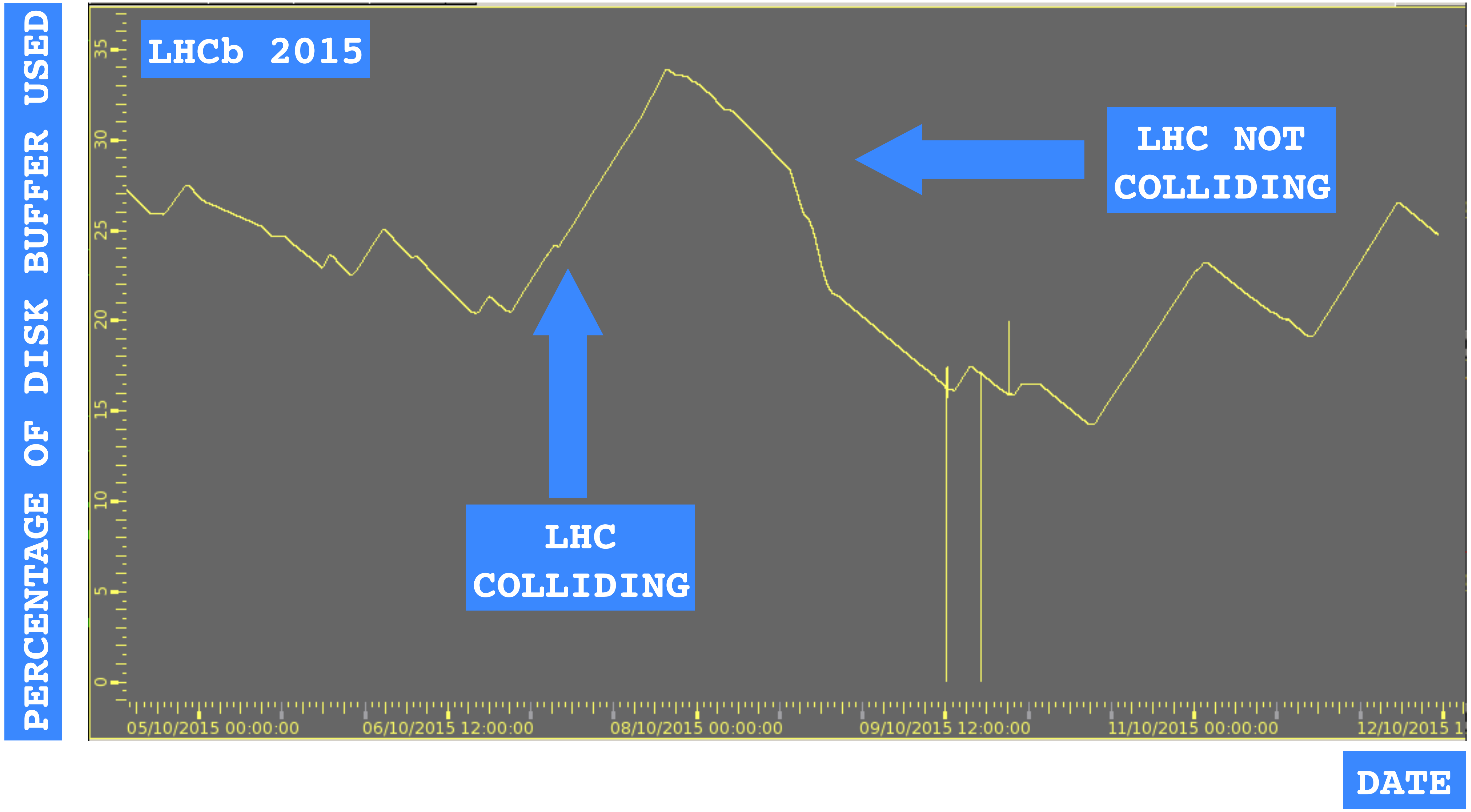
In server farm near the detector ("software trigger")

In server farm far from the detector ("GRID")



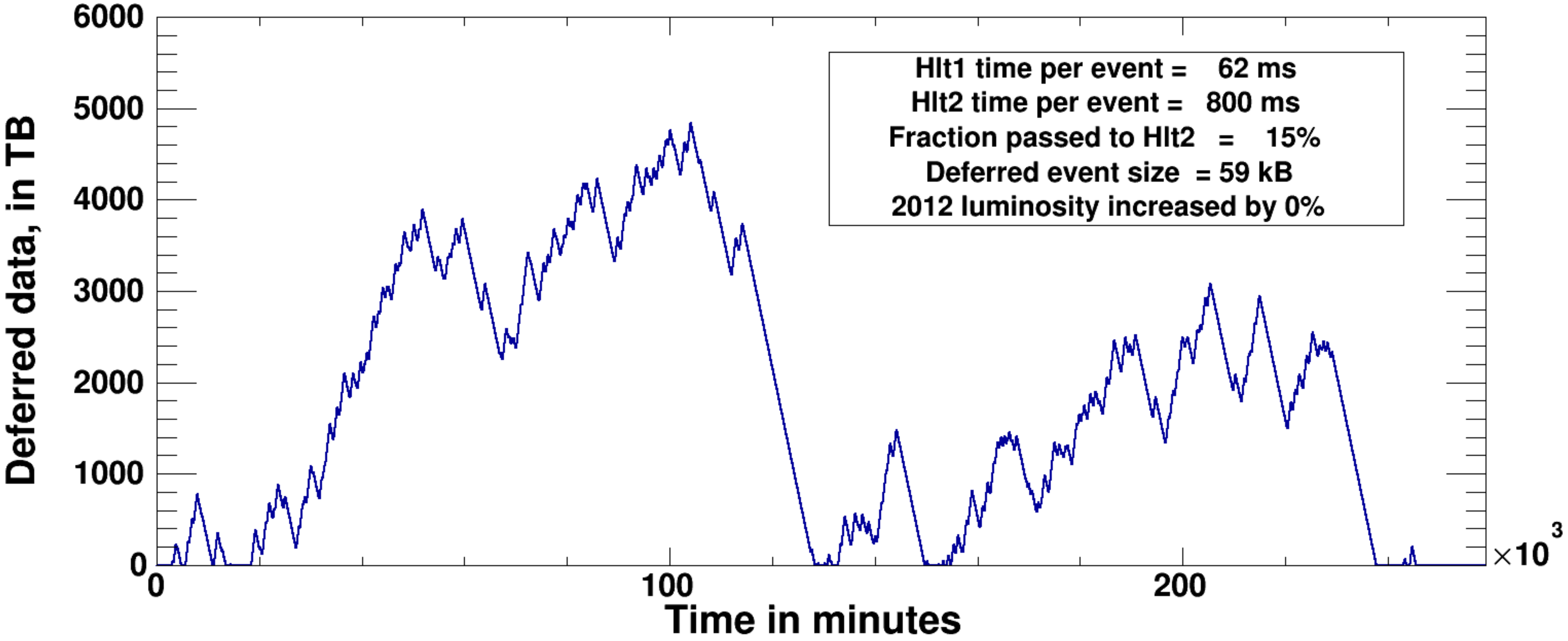
At this point the choice is where to process it further. Because of network cable costs, it is typically most cost-effective to build a custom server farm near the detector, but in the future minimizing power consumption may be more important and mandate large aggregated farms further away.

Using a server farm all year round



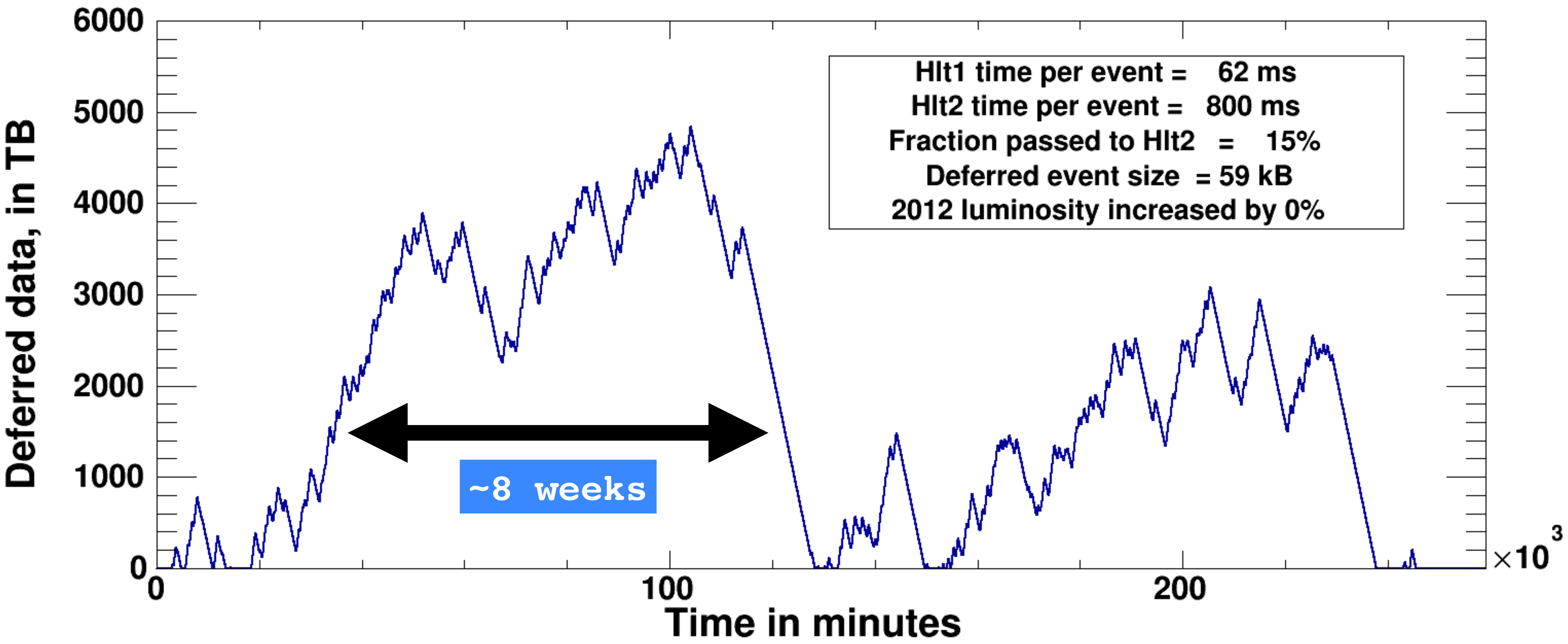
One thing which a server farm allows you to do is use the time between LHC fills to process data, so you can run a more complex data processing.

Of course you want to optimize that



The LHC actually has a broadly predicable behaviour, so use one year's fill lengths to optimize the processing time in and out of fill for your farm.

Of course you want to optimize that

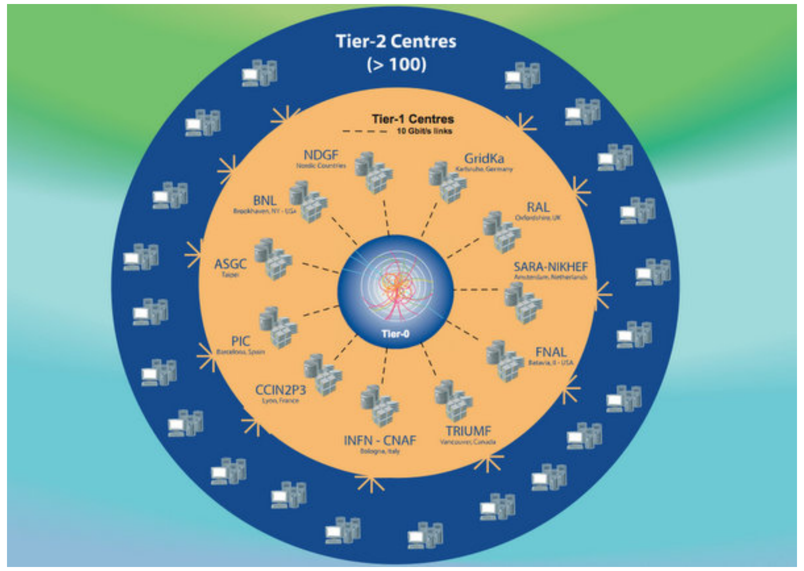


Notice that in this case individual events can hang around for weeks before finally being processed by the system. A very stretched kind of real-time.

And you can also use the GRID

In server farm near the detector ("software trigger")

In server farm far from the detector ("GRID")



You could in principle offload some of the work from your "near to the detector" server farm to some other server farm, on the GRID or even to a commercial cloud. You could also park the data (which ATLAS/CMS do in some cases) for some time and process it later when you have spare cycles. The only real question is having enough output bandwidth to send the rates required, and is it cost effective or not?

Recap : how real is time?

Fixed latency when data is too big to read out

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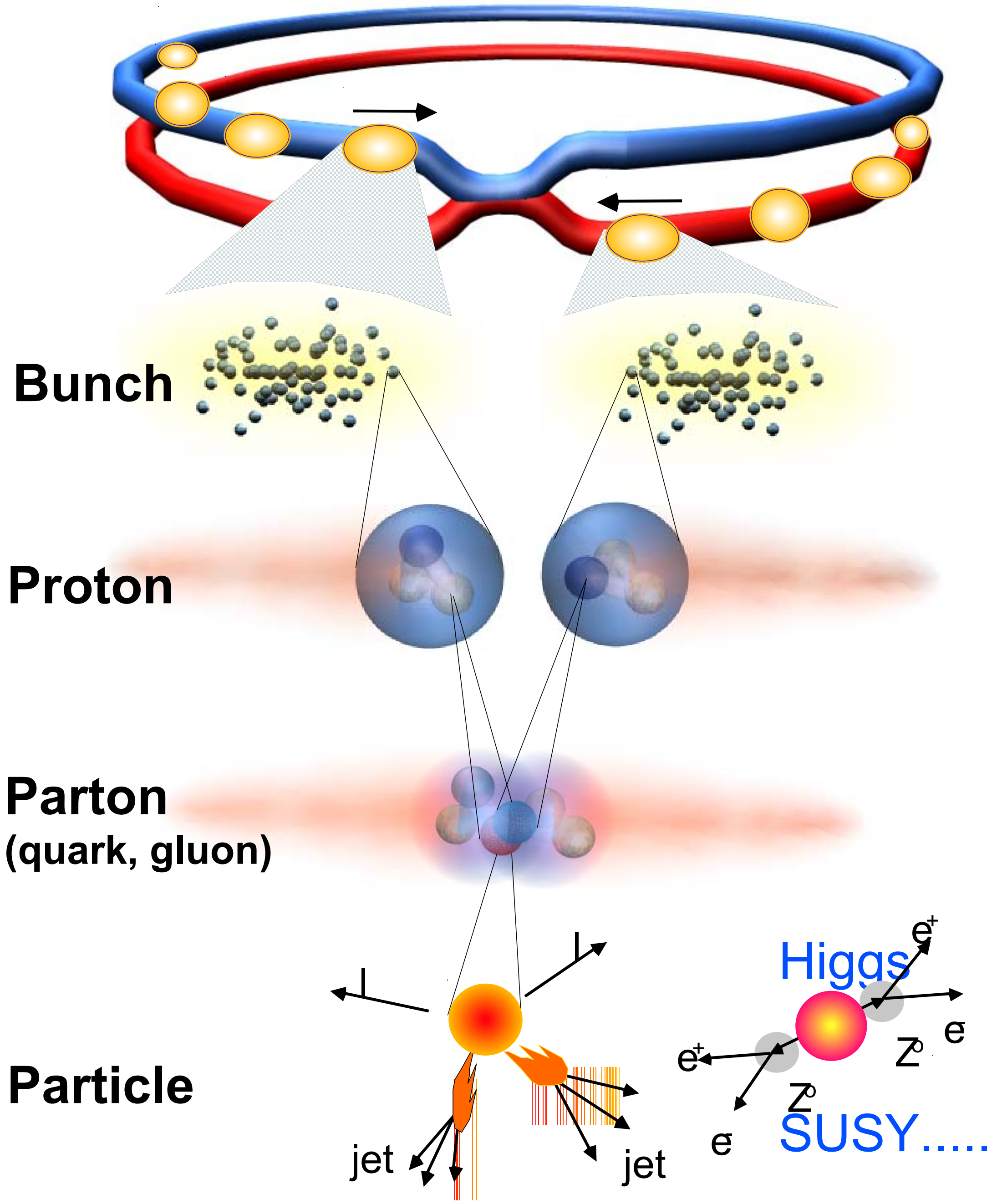
Once data can be read out, use farms of processors without fixed latency, including out of collision time.

But what kind of processing do we want to do?

Selection vs. compression in real-time data processing

Traditional view of real-time processing

Collisions at the LHC: summary



Proton - Proton	2804 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	$10^{34} cm^{-2} s^{-1}$

Bunch crossing rate : 30 MHz

Between 1-200 proton-proton collisions per crossing (depends on experiment).

New physics rate ≈ .00001 Hz

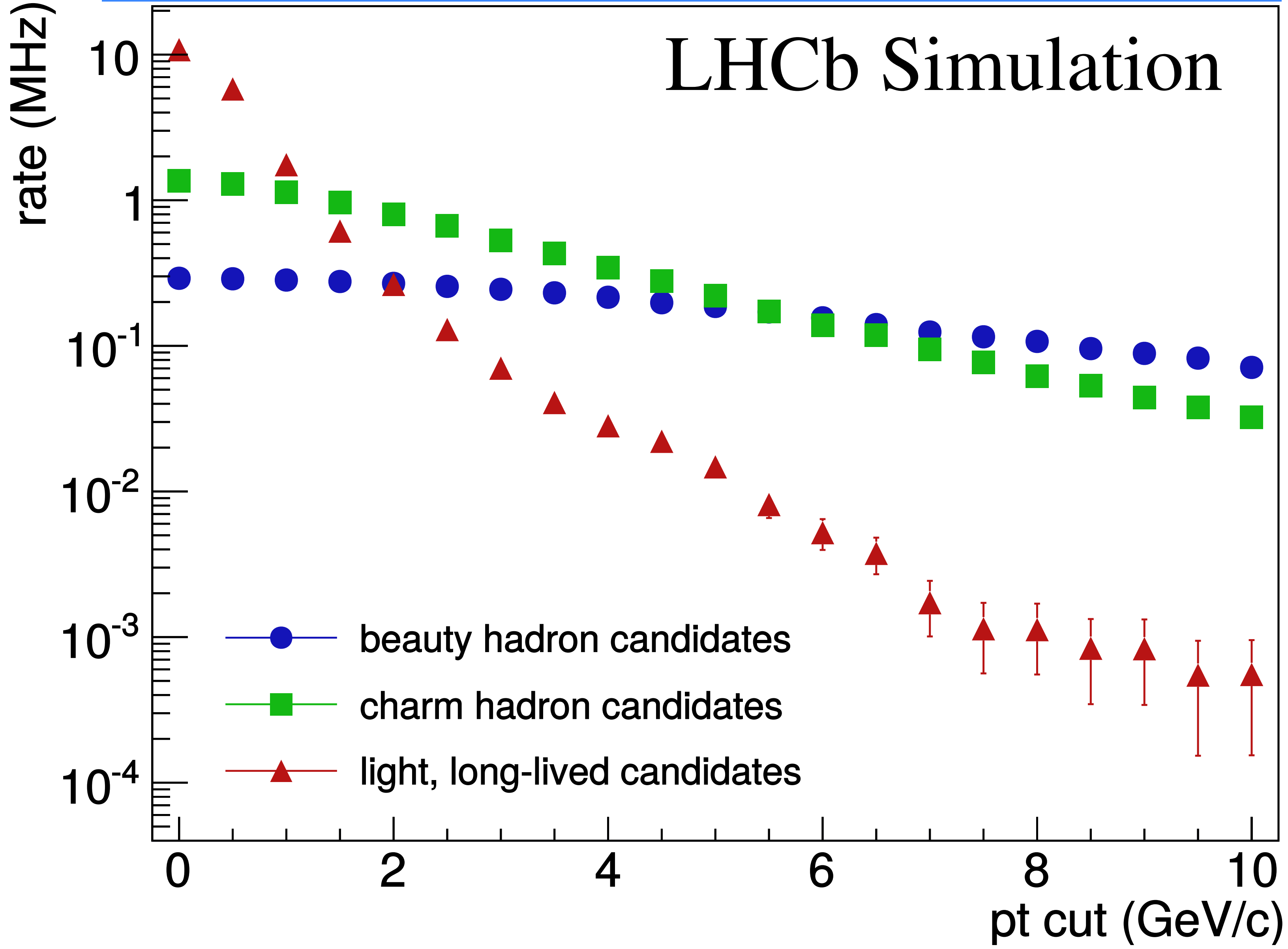
Event selection:
1 in 10,000,000,000,000

Triggers yesterday

But what if every collision is interesting?

Fitzpatrick&Gligorov
LHCb-PUB-2014-027

Remember LHC collision rate is ~30 MHz

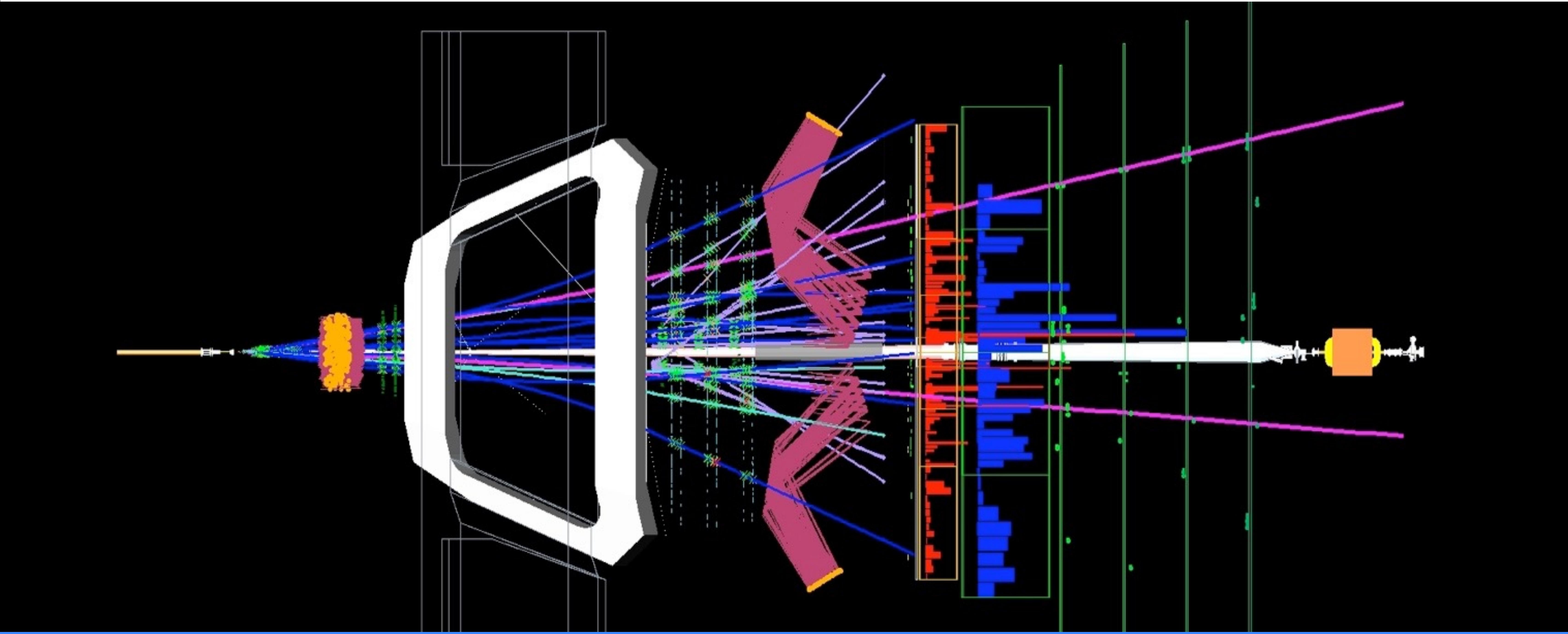


~10% of LHC collisions produce a charm-hadron pair, so events with multiple collisions are nearly all interesting if you want to study charm.

Triggers yesterday

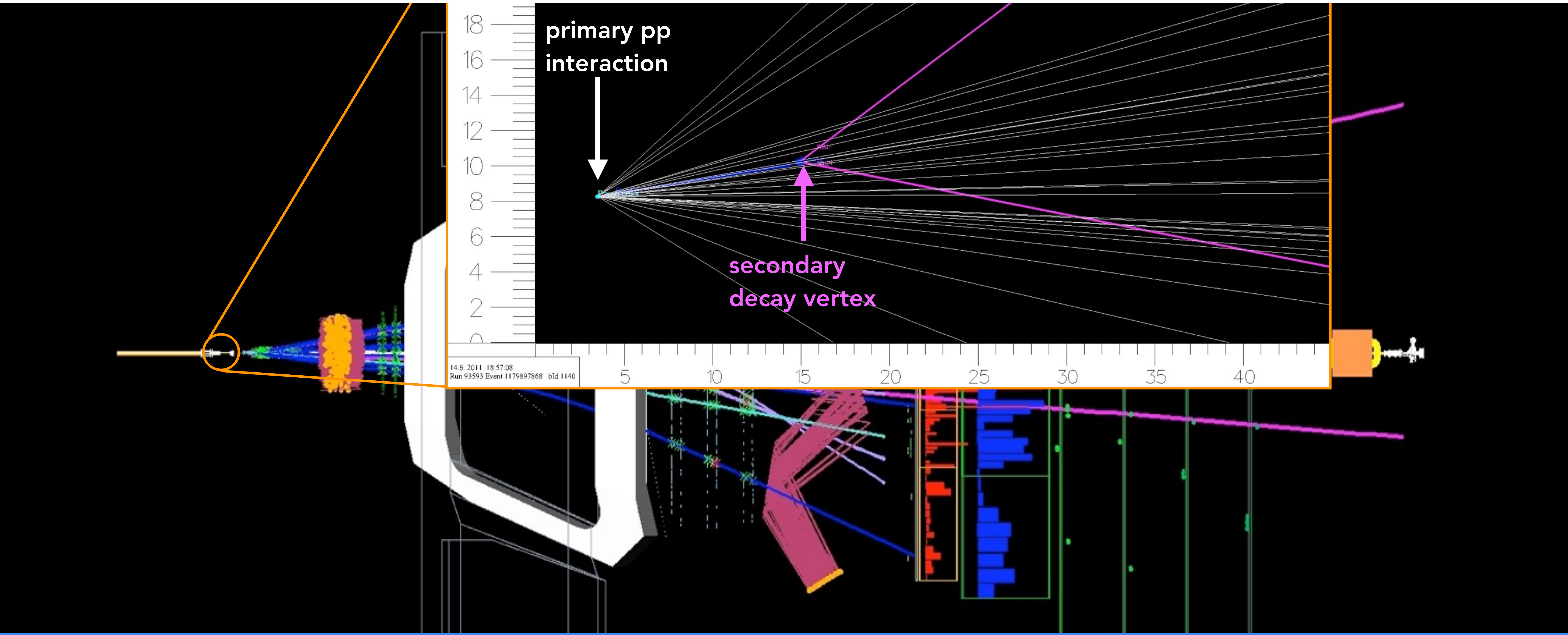
Real-time data analysis today

Is every part of the collision interesting?



An event recorded by the LHCb detector. Even in the case that every event is interesting, do you need all of this event for your analysis?

Not necessarily



Imagine your signal candidate are the two magenta tracks. You could save a lot of disk space & write more events if you only saved the magenta part!

Event selection vs. compression

Event selection

Is this event considered interesting by at least one algorithm ("trigger line")?

Write entire output of detector to permanent storage

Event selection vs. compression

Event selection

Is this event considered interesting by at least one algorithm ("trigger line")?

Write entire output of detector to permanent storage

Event compression

Is this event considered interesting by at least one algorithm ("trigger line")?

Write signal candidate identified by trigger line to permanent storage

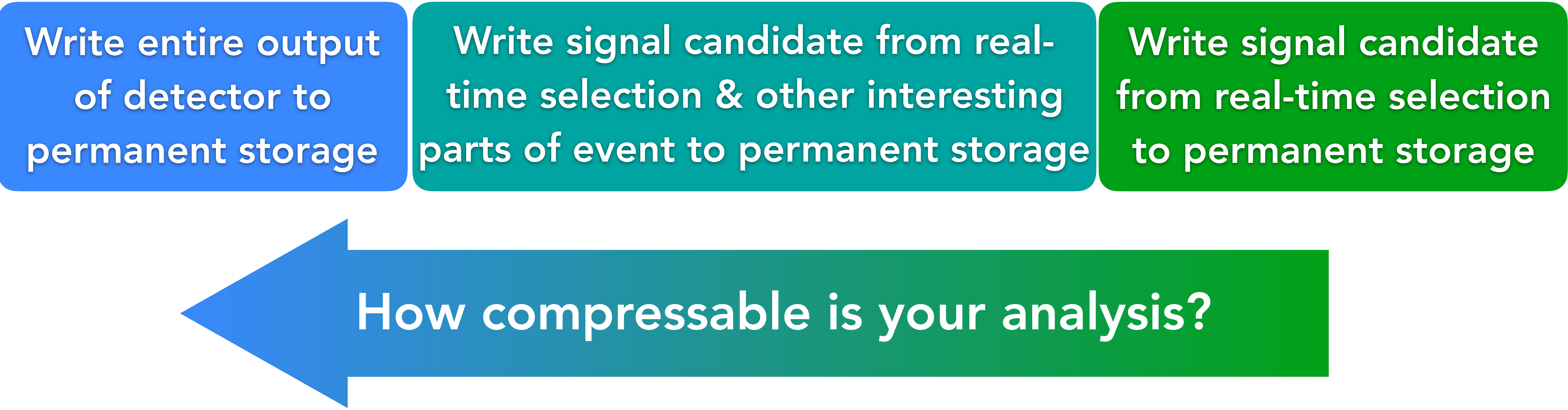
Why should this be a binary choice?

Write entire output of detector to permanent storage

Write signal candidate from real-time selection to permanent storage

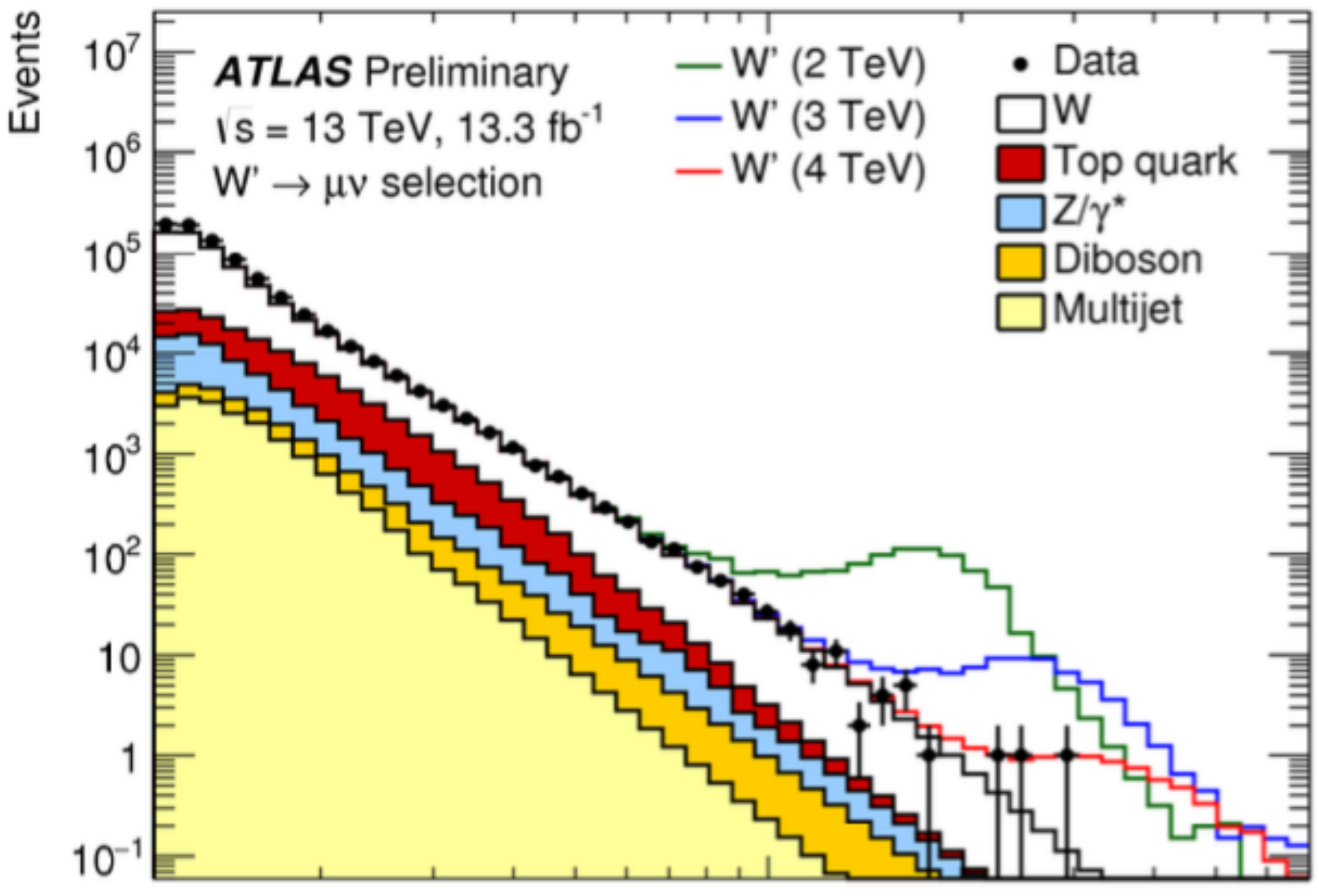
In fact, what I presented as "selection" is just a special case of compression

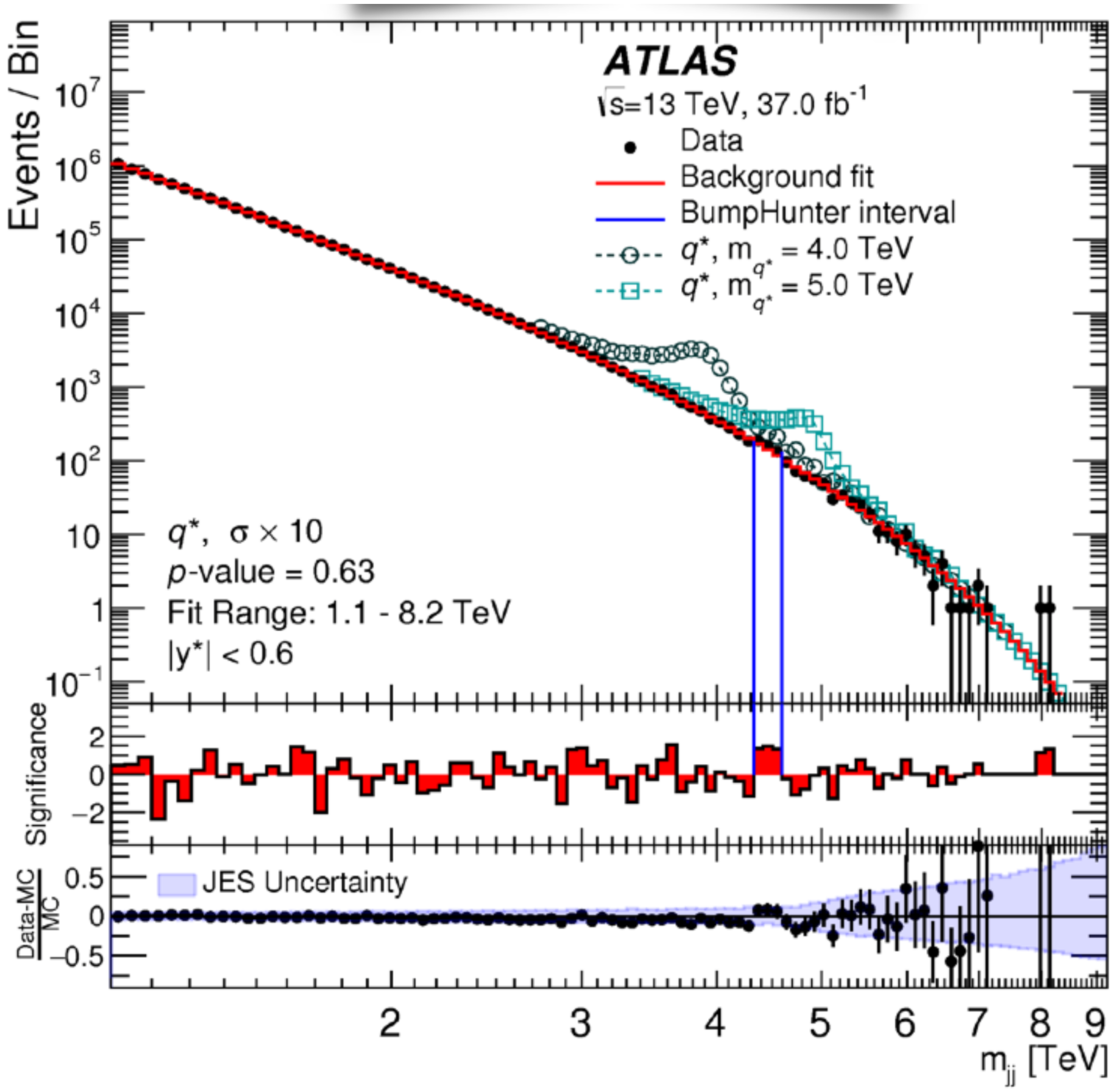
It isn’t a binary choice



A special case where “other interesting parts” is the entire event. Modern data processing (real-time or not) is a mixture of selection&compression.

Let's go back to what an analysis does

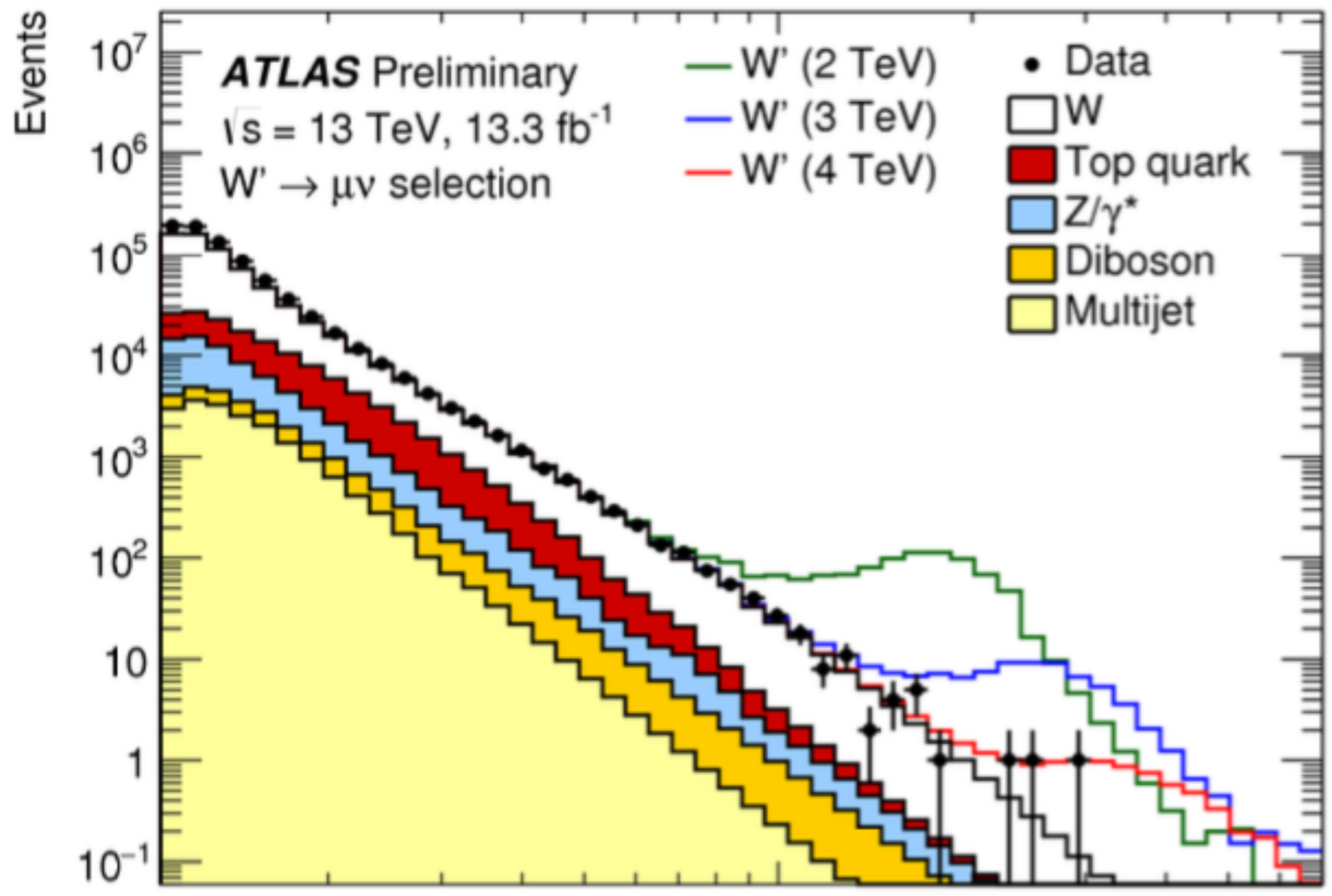


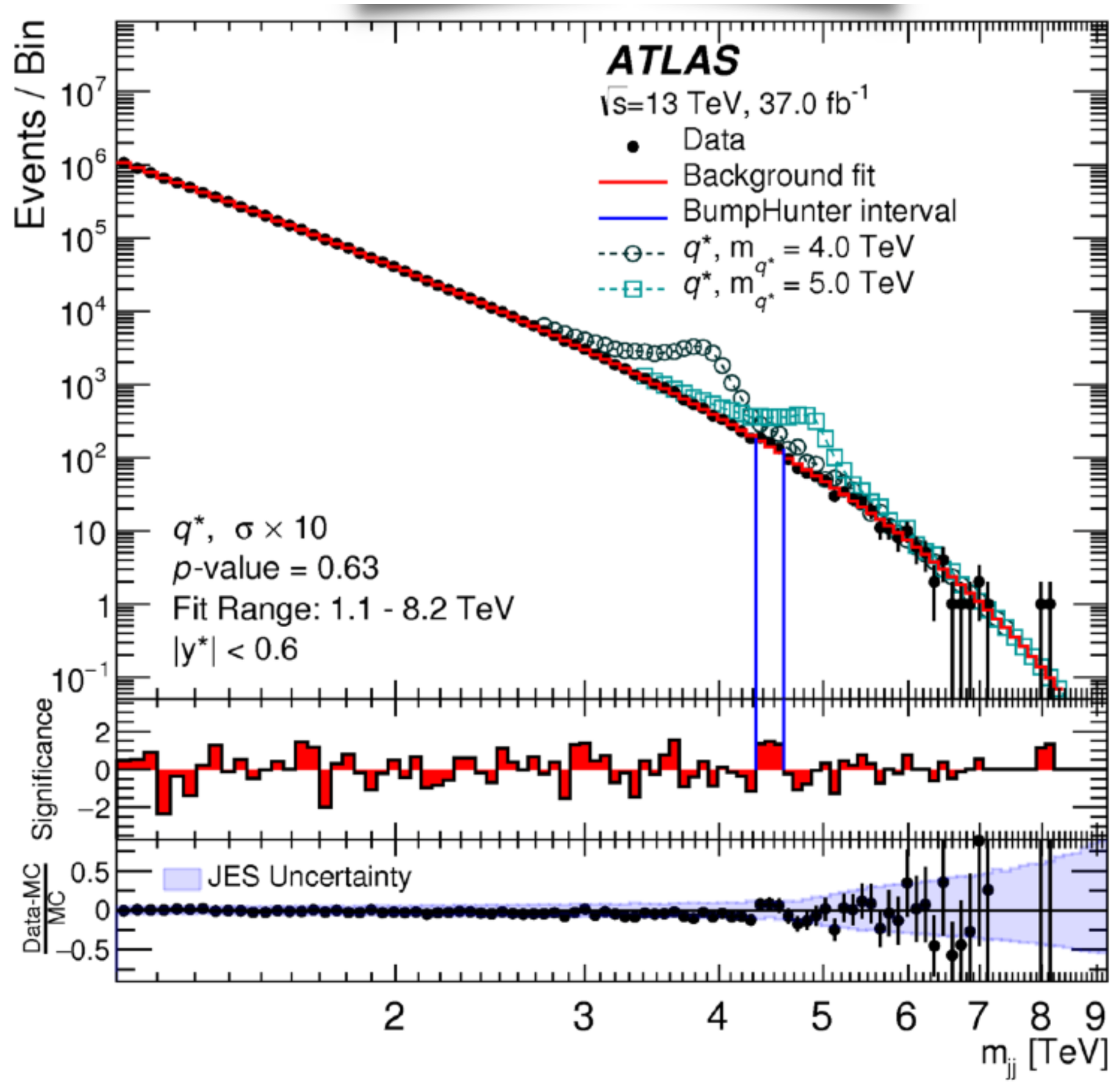


Almost every analysis has two basic components :

1. Combine&select building blocks to observe a signal above background
2. Understand the efficiency of step (1) to measure signal properties

How do we understand the efficiencies?





Almost every analysis has two basic components :

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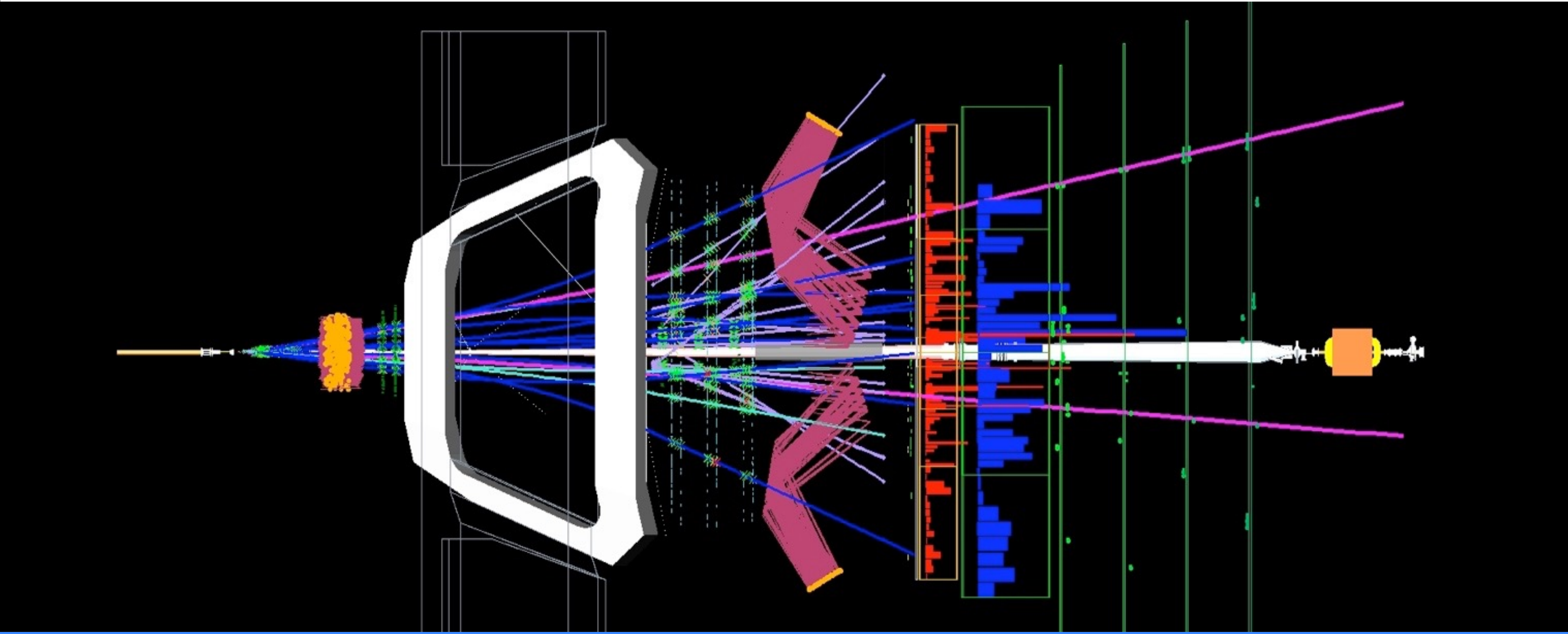
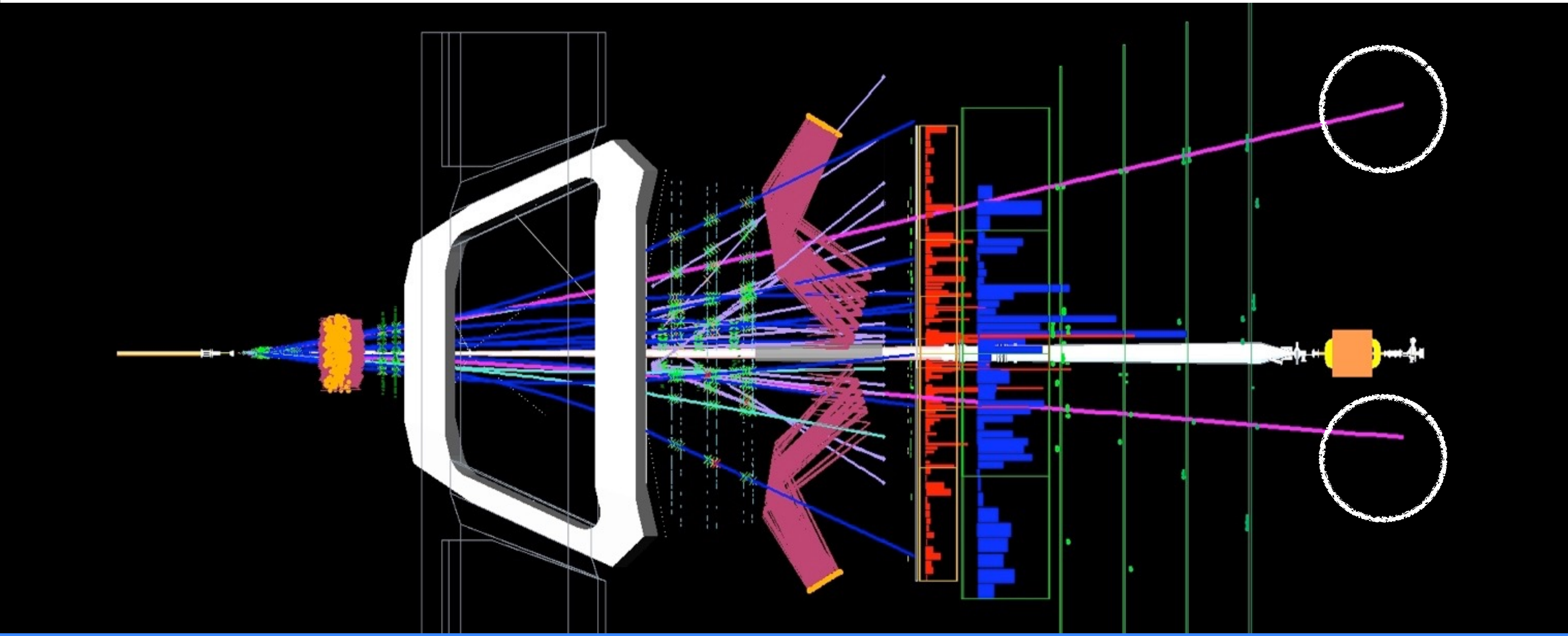
How does selection relate to efficiency?



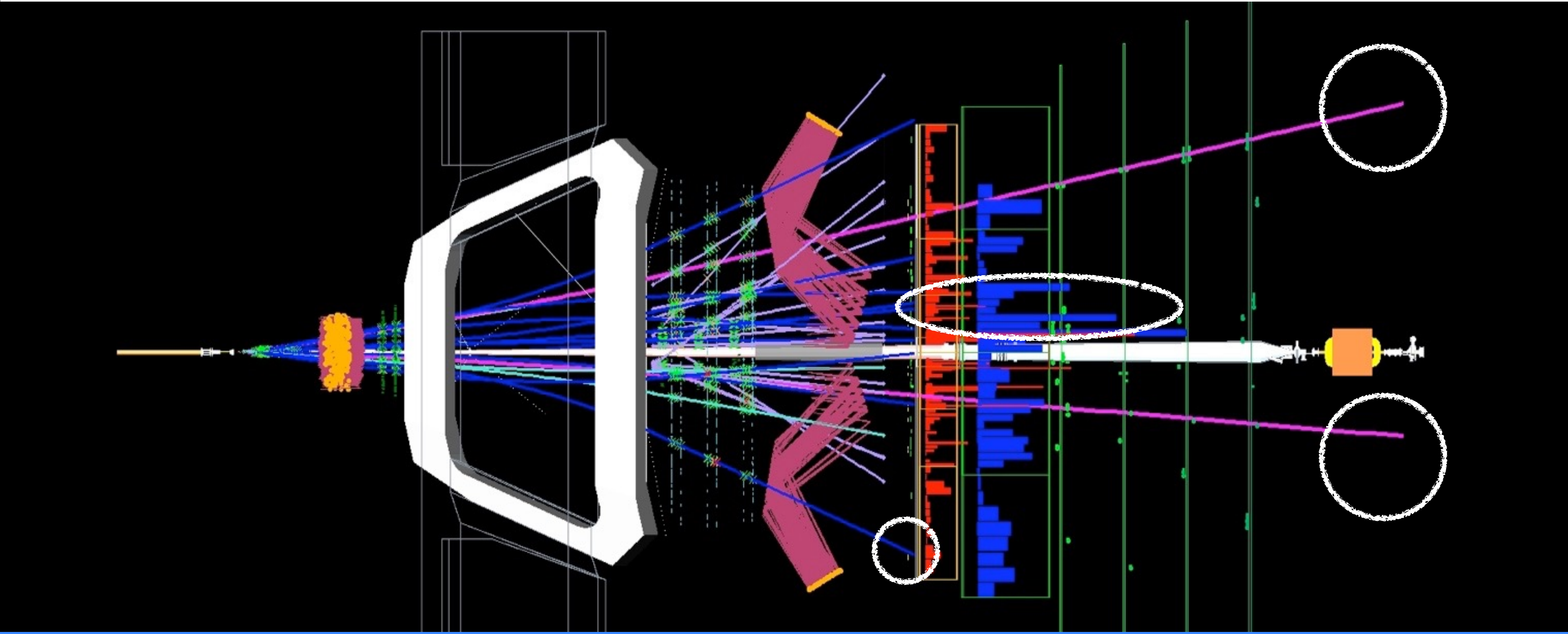
Whenever you make a decision to keep/reject an object in your analysis, you must measure the efficiency of this decision for the object in question.

It can be efficiency for selecting signal



If keep or reject the whole event for future study based on the properties of the “signal” magenta tracks, you must only know the efficiency for them

Or efficiency for selecting other objects



But if you keep only the magenta tracks plus some additional “interesting” objects, you must know the efficiency for every “interesting” object!

So there is a kind of binary aspect to this

Write entire output of detector to permanent storage

Write signal candidate from real-time selection & other interesting parts of event to permanent storage

Write signal candidate from real-time selection to permanent storage

Either end : understand only signal

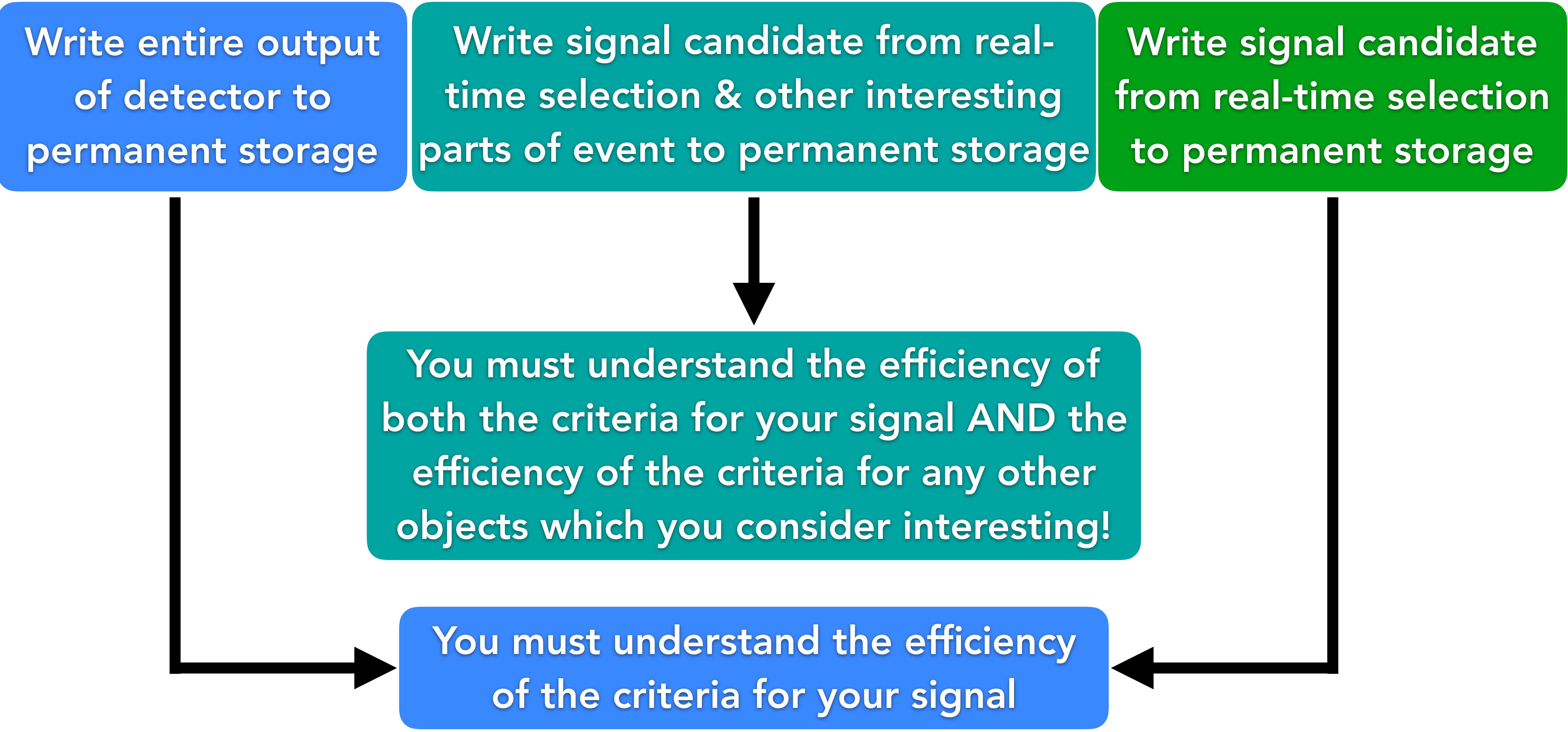
Write entire output of detector to permanent storage

Write signal candidate from real-time selection & other interesting parts of event to permanent storage

Write signal candidate from real-time selection to permanent storage

You must understand the efficiency of the criteria for your signal

But in the middle, understand more



Recap : types of data processing

The goal of the data processing is to reduce the data volume to a level which is manageable for analysis

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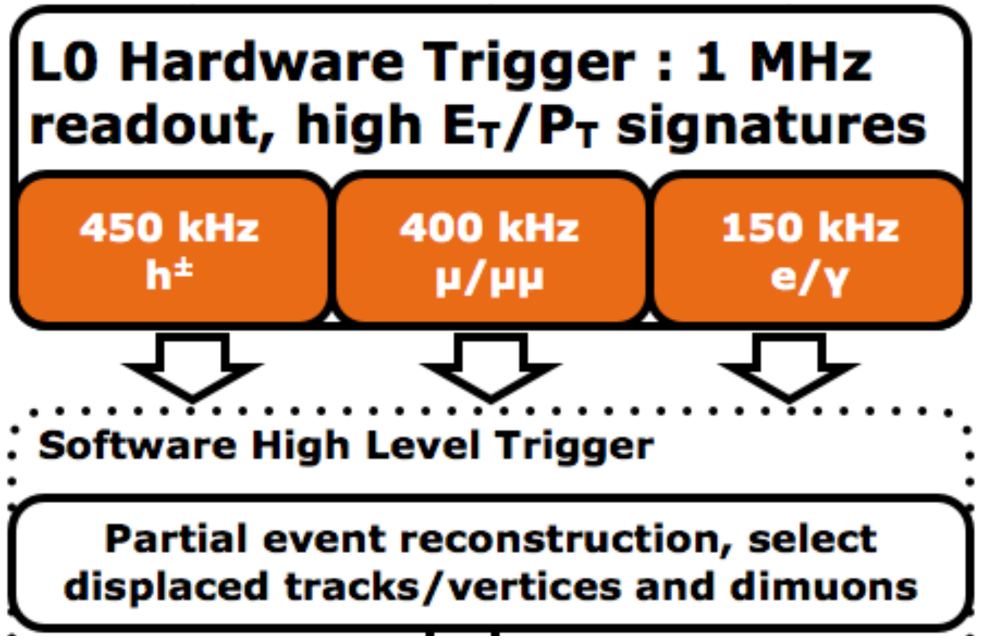
How do we optimize our finite processing budget?

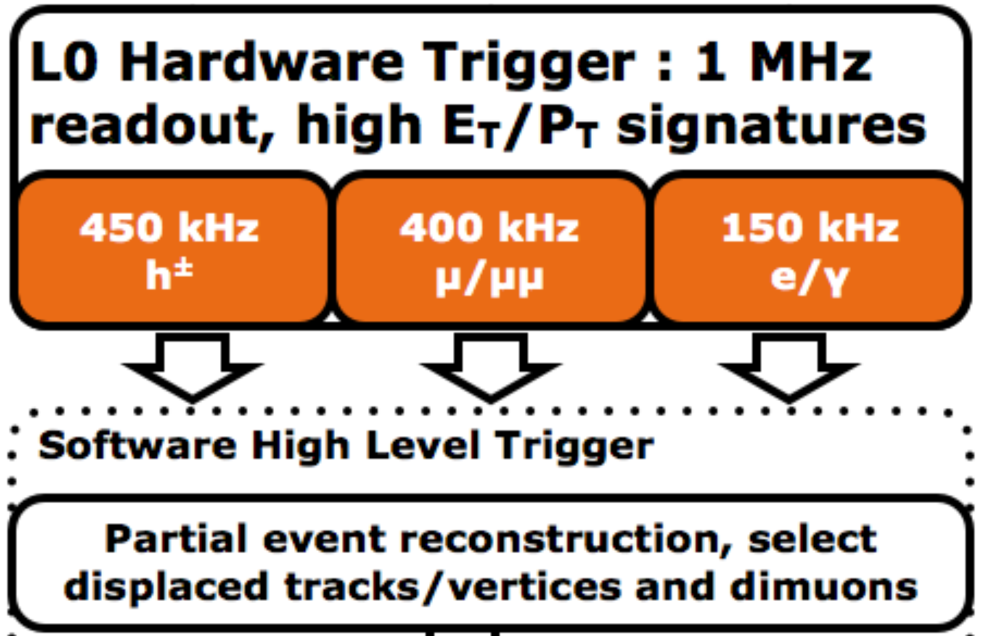
Balancing the constraints on real-time reconstruction

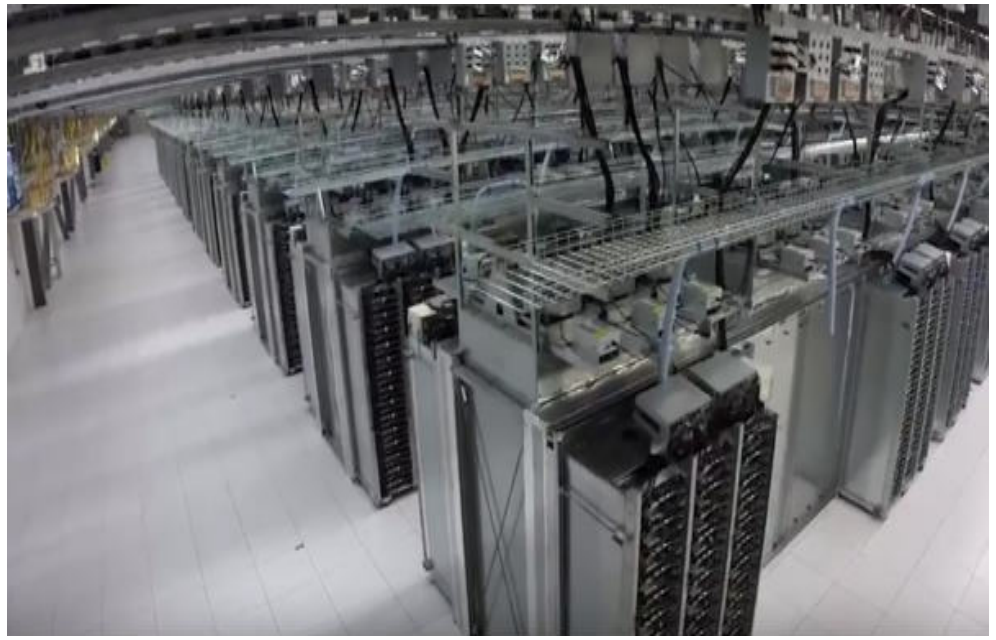
What kinds of constraints?



Take LHCb reconstruction as an example, remember that ATLAS&CMS have much more complicated events. Need to reconstruct 1 million events/s.

Limited size of processing server farm

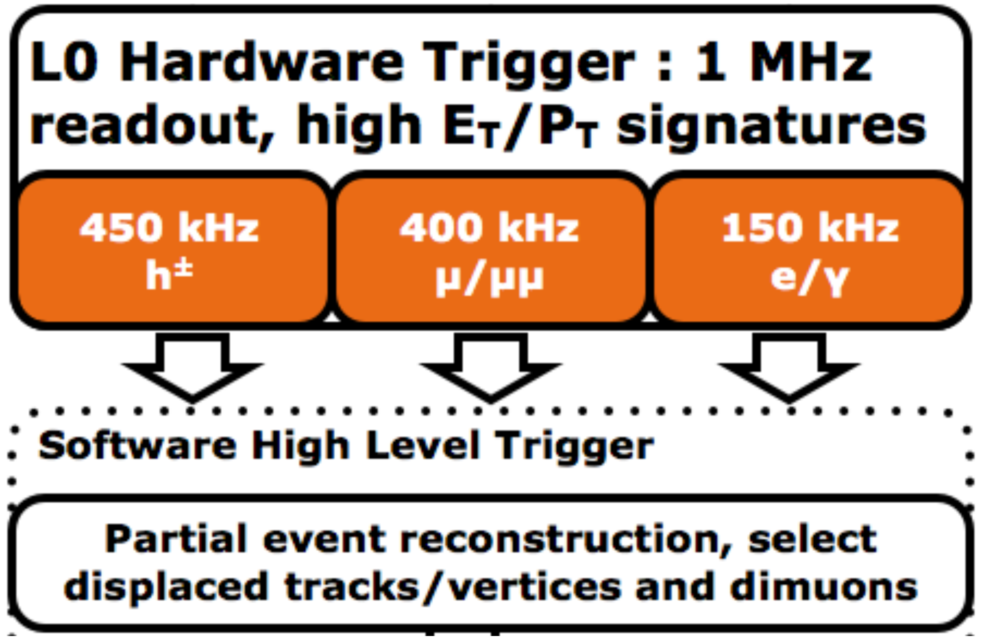


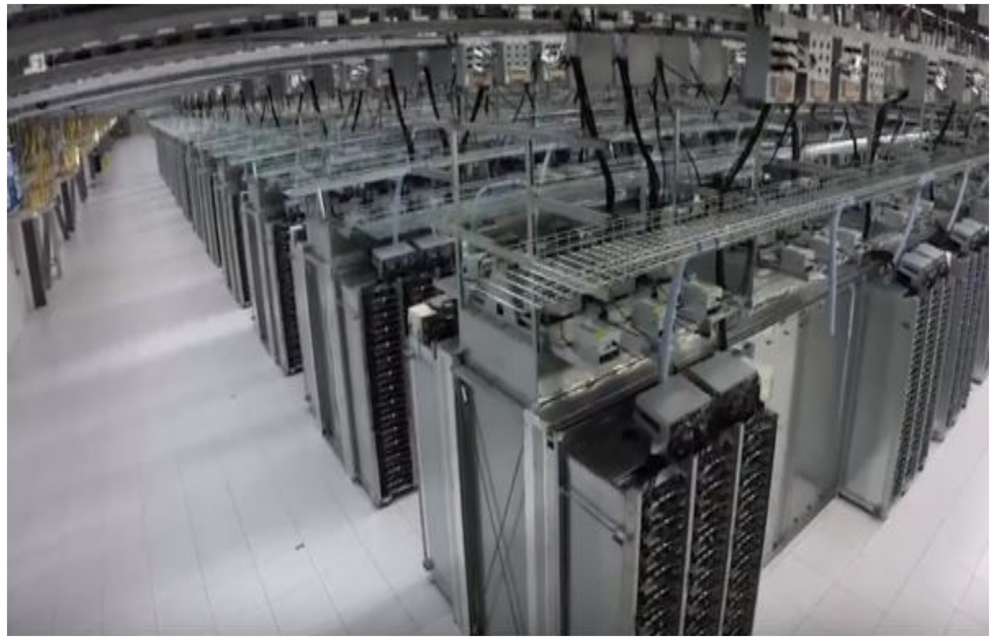


~50000 CPUs in parallel
~50 msec/event available

Take LHCb reconstruction as an example, remember that ATLAS&CMS have much more complicated events. Need to reconstruct 1 million events/s.

So the reconstruction must make choices





~50000 CPUs in parallel
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Algorithm	Time
Track finding	~ 200 ms
Full track fit	~ 100 ms
RICH reconstruction	~ 180 ms
Calo reconstruction	~ 50 ms
Muon ID	~ 2 ms
TOTAL	~ 650 ms

Take LHCb reconstruction as an example, remember that ATLAS&CMS have much more complicated events. Impossible to fully reconstruct in real-time.

So how do you optimize these choices?

Could be a lecture course in itself! Different analyses use different reconstructed objects, balance depends strongly on the physics programme of the experiment.

Will illustrate three concepts here

1. Selecting events can create time
2. Reconstructing more "expensive" event features can reduce the time cost of later reconstruction
3. Saving time by applying selection in reconstruction

How does a selection create time?

1 MHz of events

Fast/simple reconstruction

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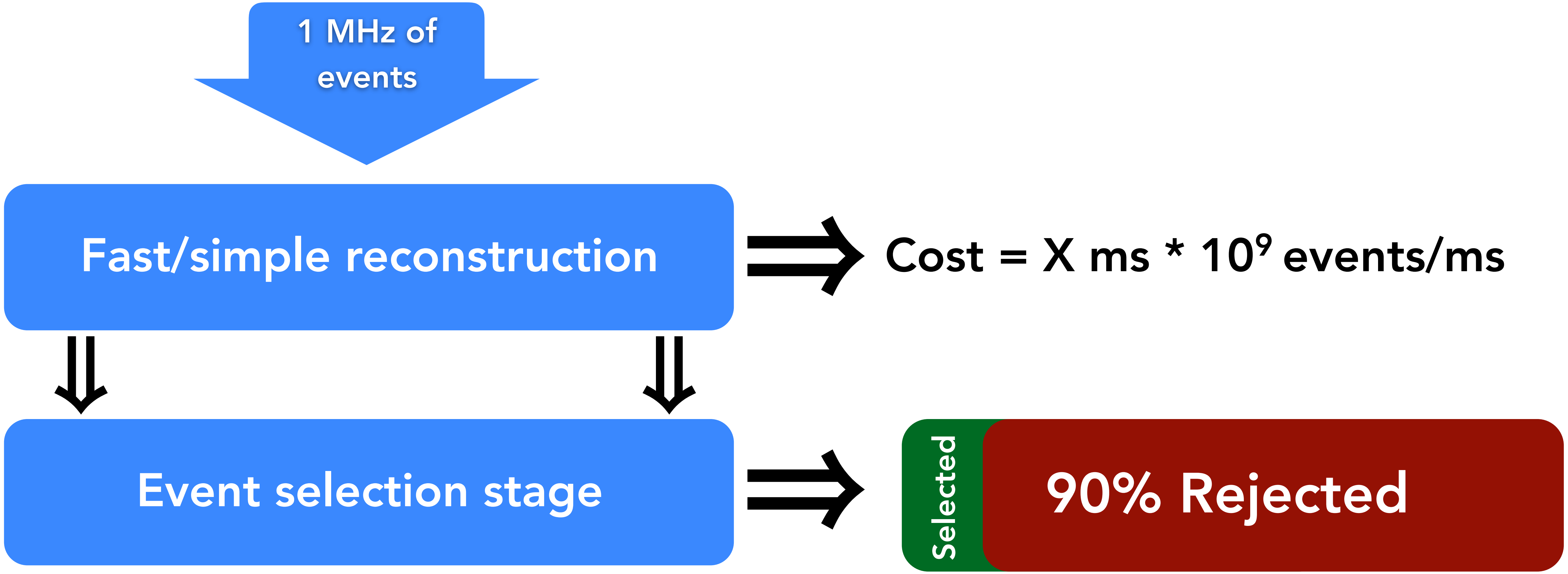
Fast/simple reconstruction $\Rightarrow$ Cost = X ms * 10^9 events/ms

How does a selection create time?



How does a selection create time?

1 MHz of events

Fast/simple reconstruction ⇒ Cost = X ms * 10^9 events/ms

⇓ ⇓

Event selection stage ⇒ Selected | 90% Rejected

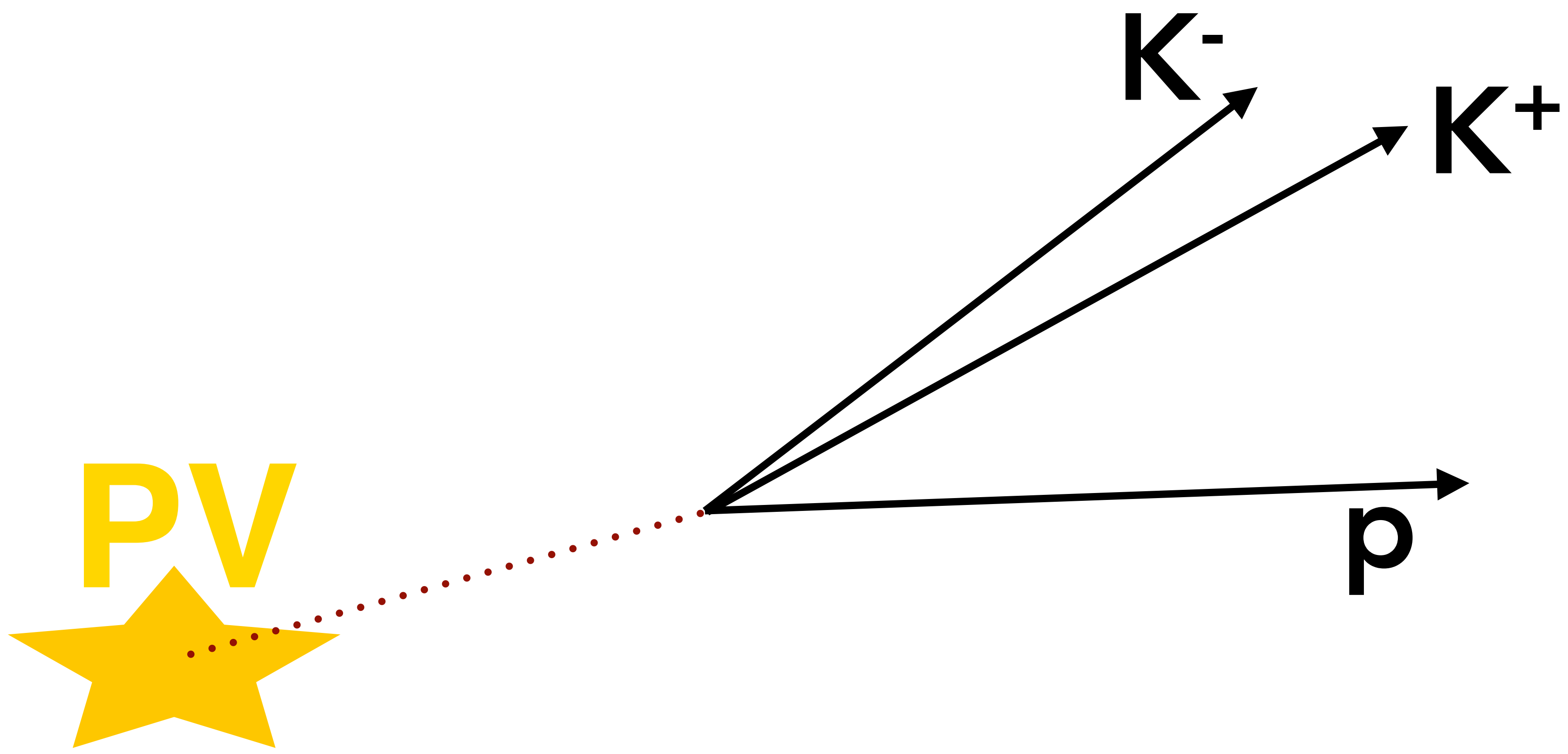
⇓ ⇓

More complex/comprehensive reconstruction stage ⇒ Cost = 10X ms * 10^8 events/ms

⇓ ⇓

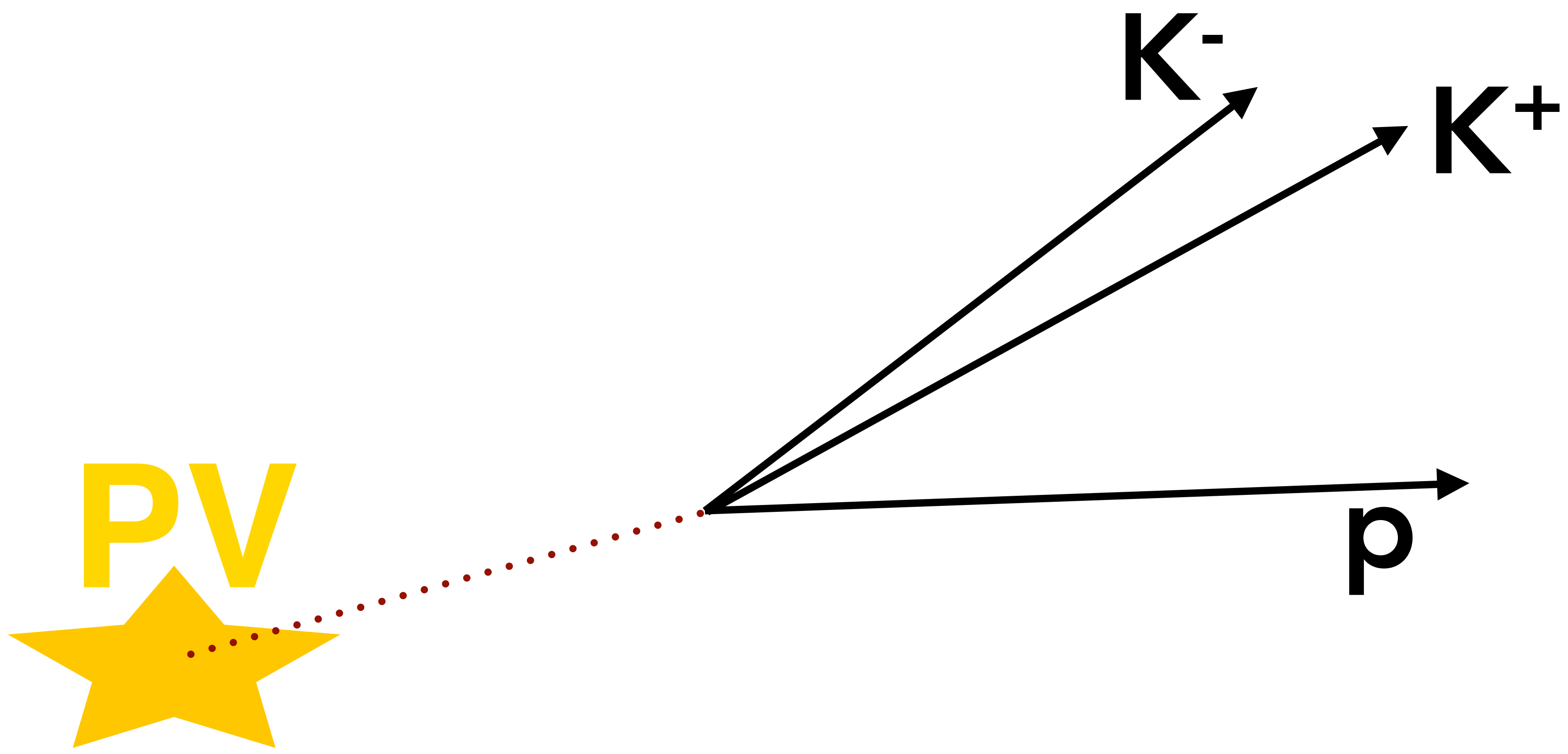
Most real-time reconstructions are in fact reconstruction-selection cascades

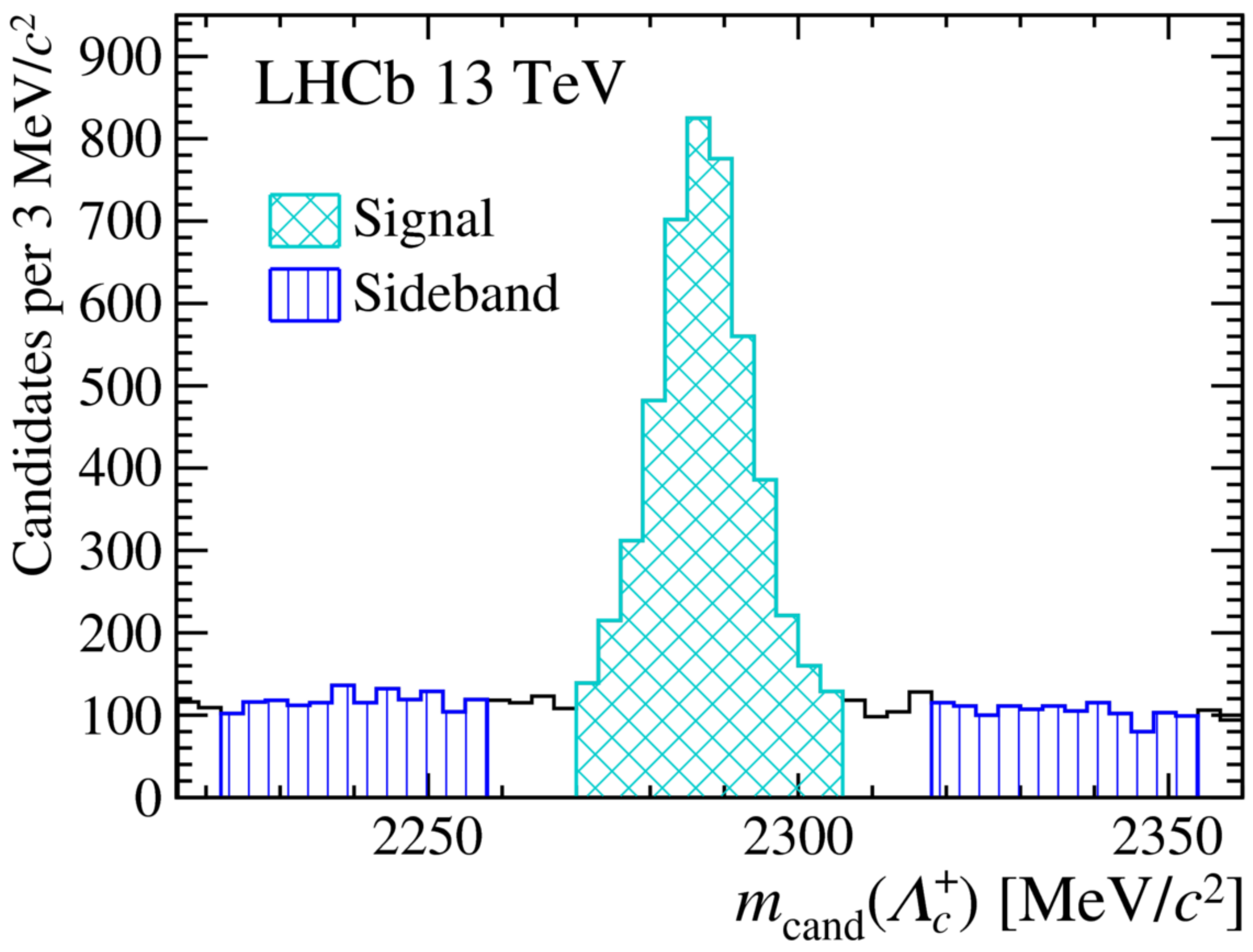
Can expensive reconstruction save time?



Let's say you want to reconstruct a $\Lambda_c \rightarrow pKK$ decay in your detector.

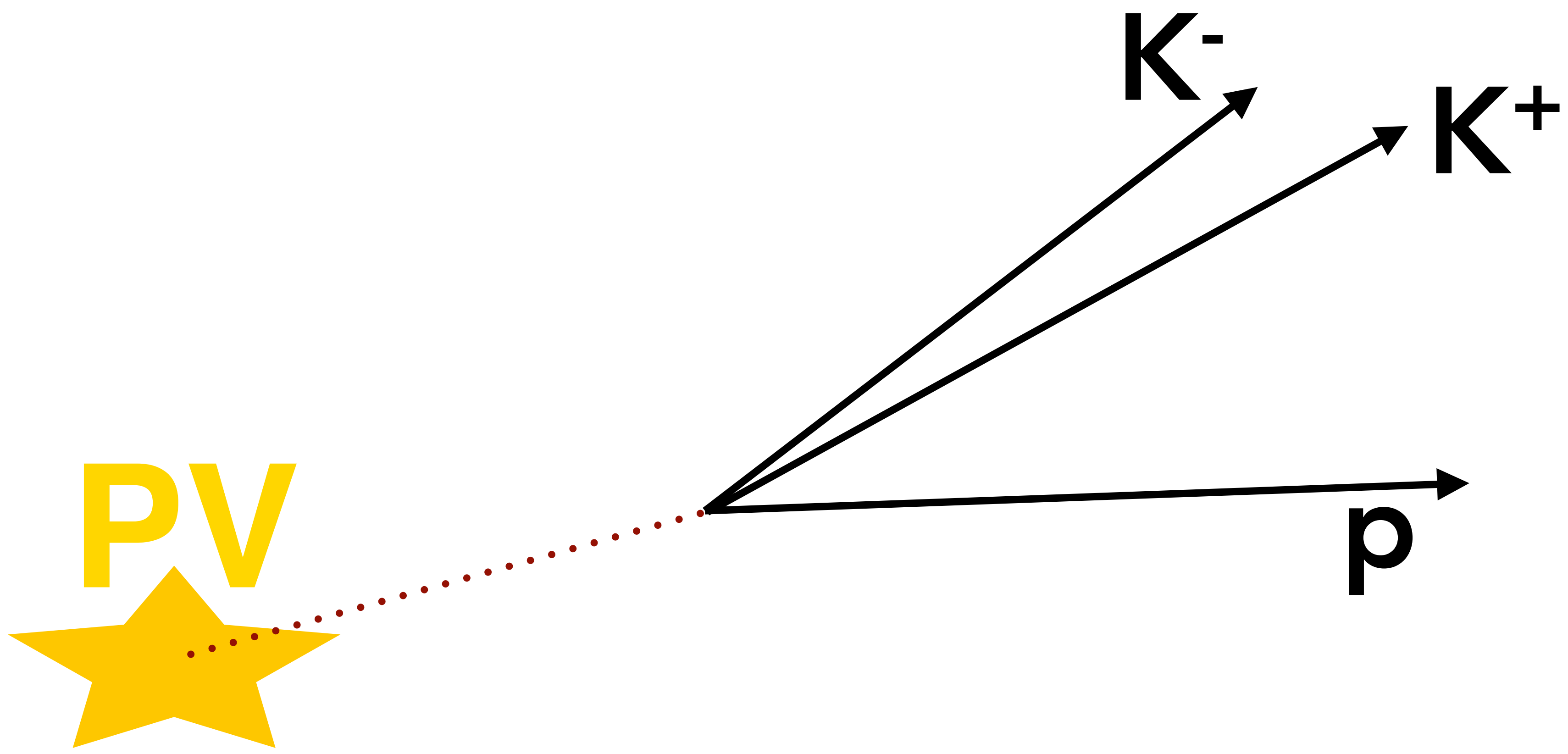
Can expensive reconstruction save time?

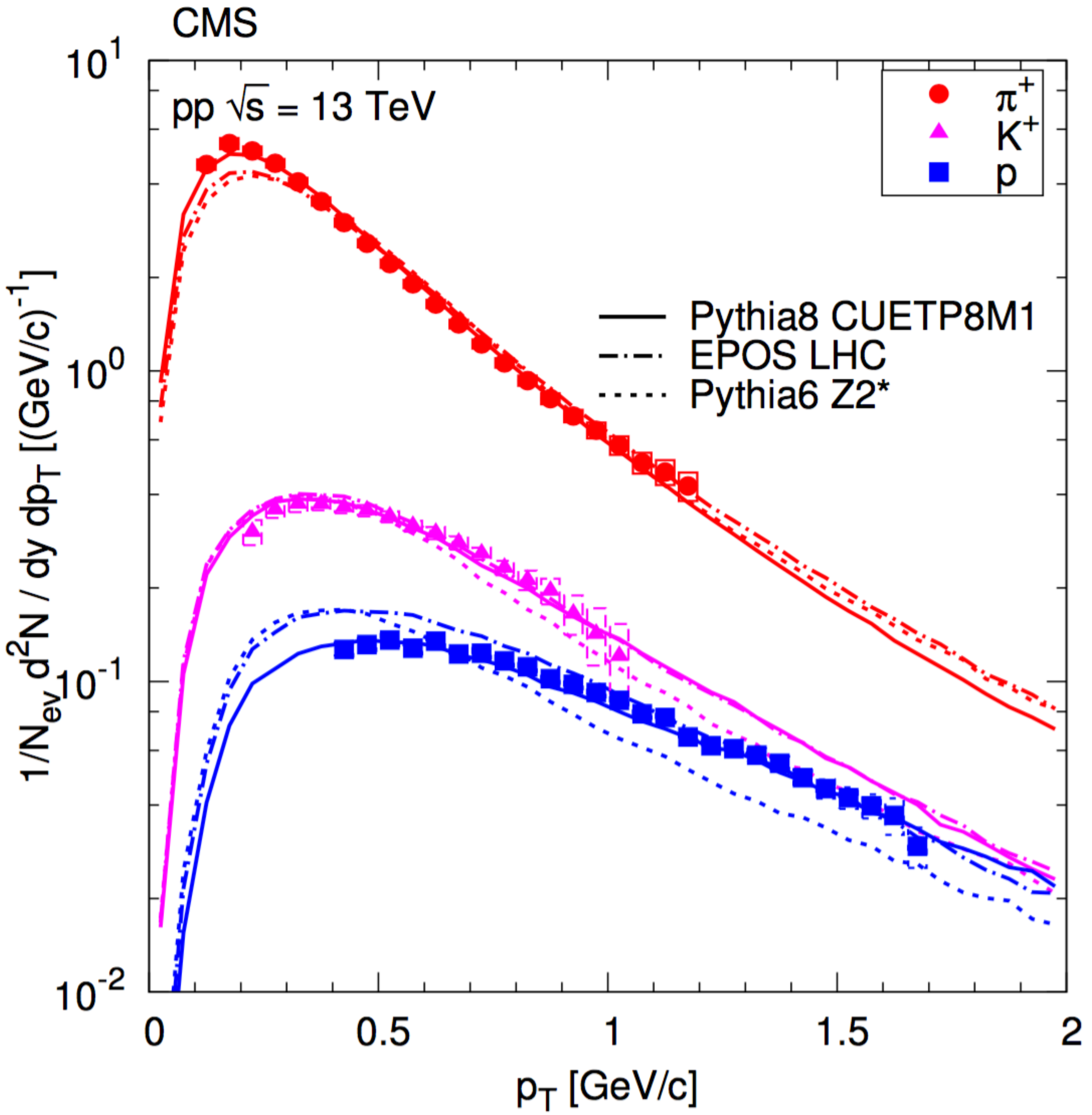




The signal are three charged particles displaced from the pp collision which vertex at the right mass. A typical LHC collision produces ~30 charged particles so ~25000 vertex combinations to fit (which takes time).

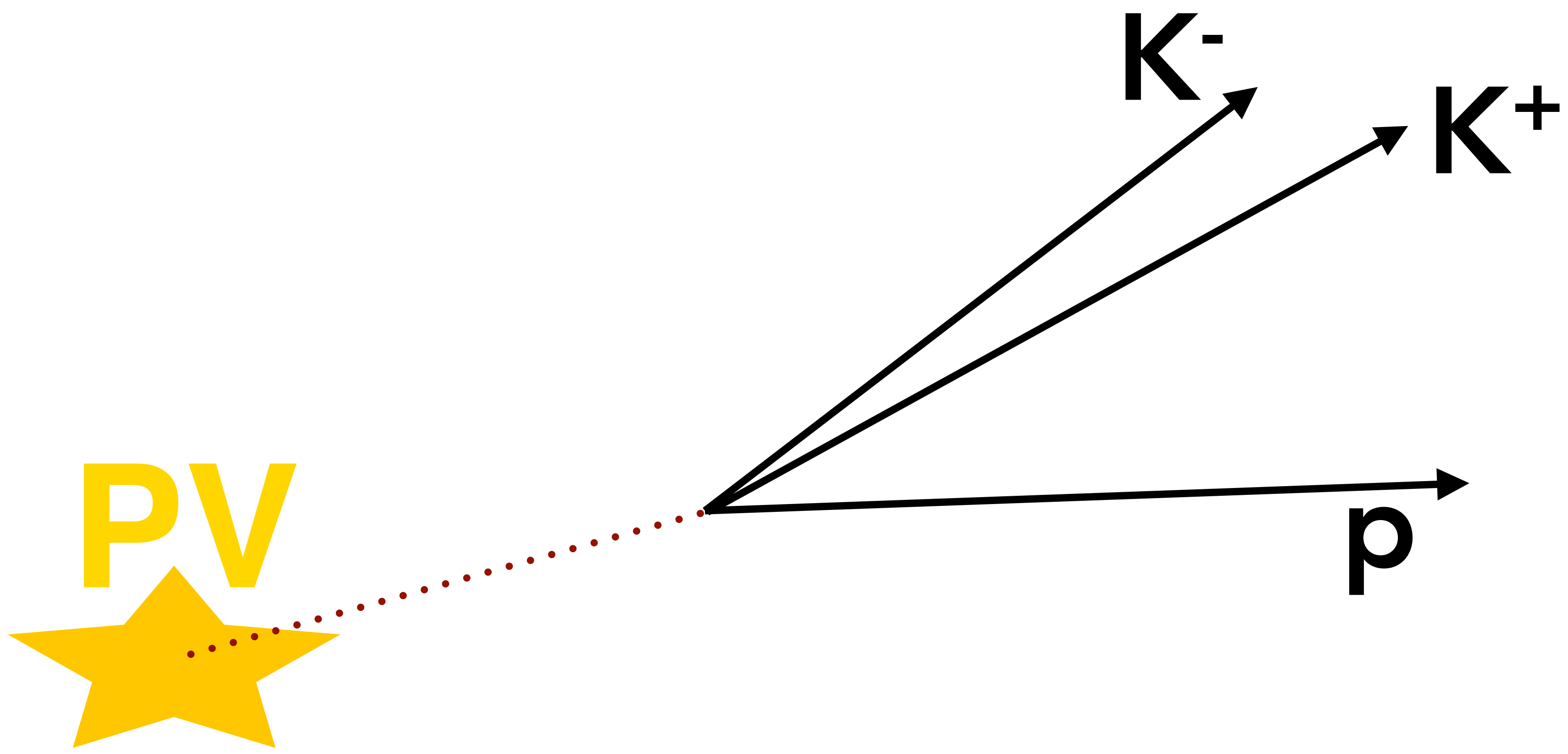
Can expensive reconstruction save time?





But most of the particles produced are pions, which we are not interested in! If we can select protons and kaons before vertexing, we can save time.

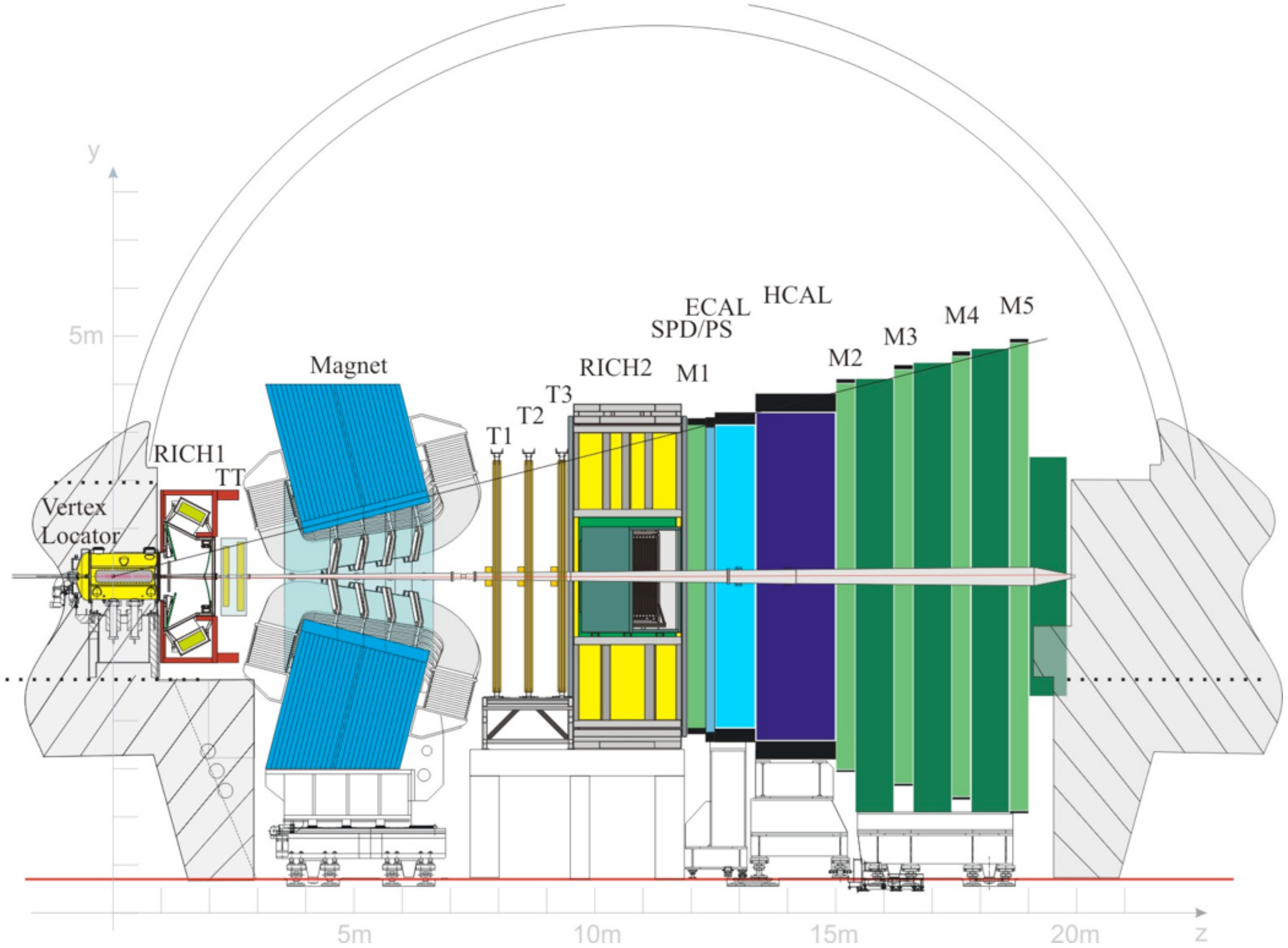
Can expensive reconstruction save time?



Algorithm	Time
Track finding	~ 200 ms
Full track fit	~ 100 ms
RICH reconstruction	~ 180 ms
Calo reconstruction	~ 50 ms
Muon ID	~ 2 ms
VERTEXING	~120 ms
TOTAL	~ 650 ms

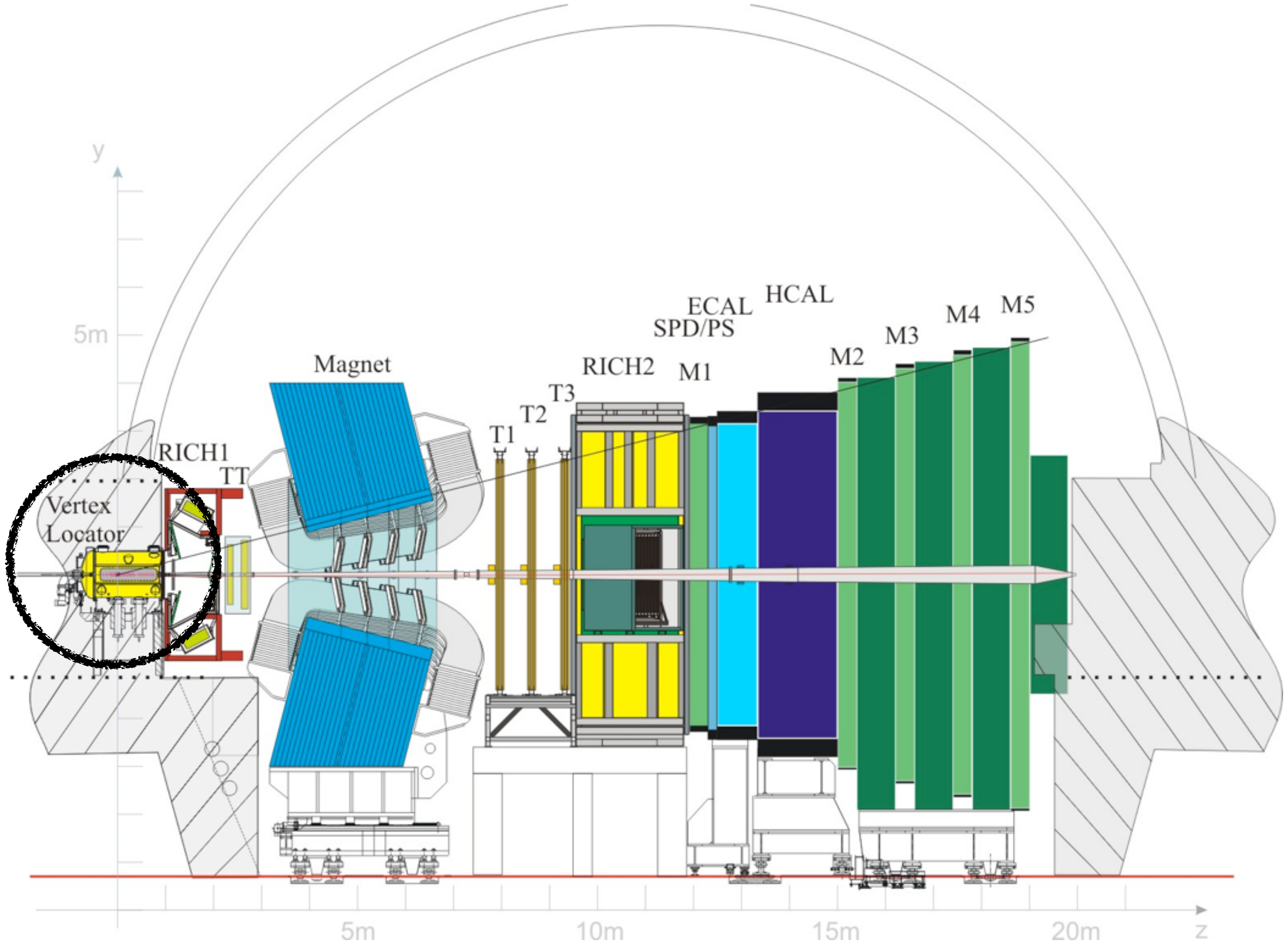
Particle identification is not cheap, but neither is vertexing many combinations. The balance will depend on the analysis&detector of course.

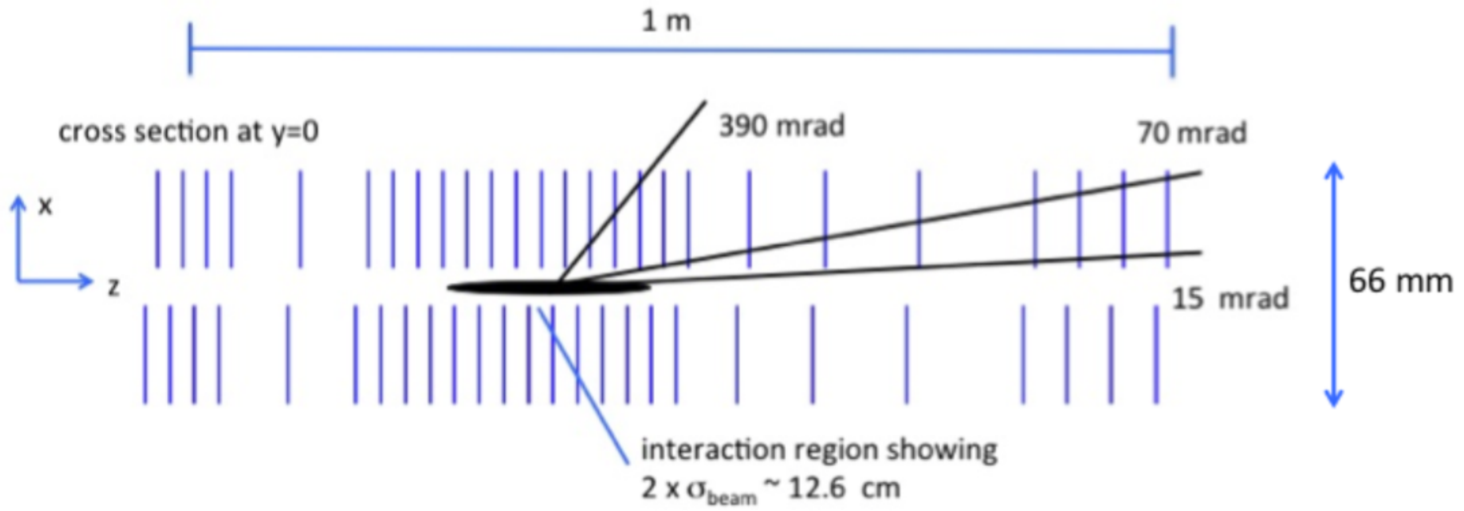
Applying selections in the reconstruction



Let's consider the LHCb detector and imagine that your signal always produces a charged particle with at least 1 GeV of p_T.

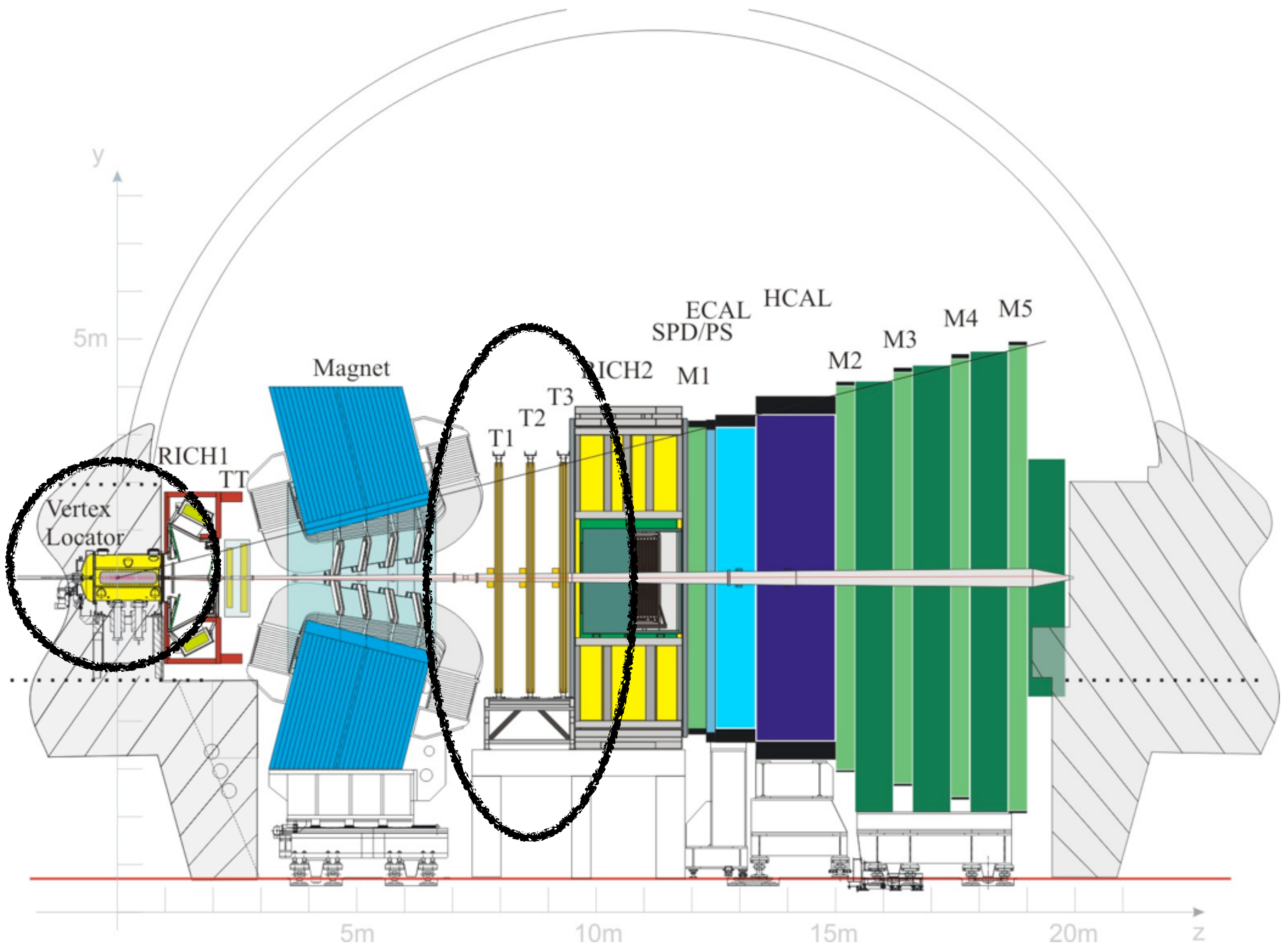
Applying selections in the reconstruction

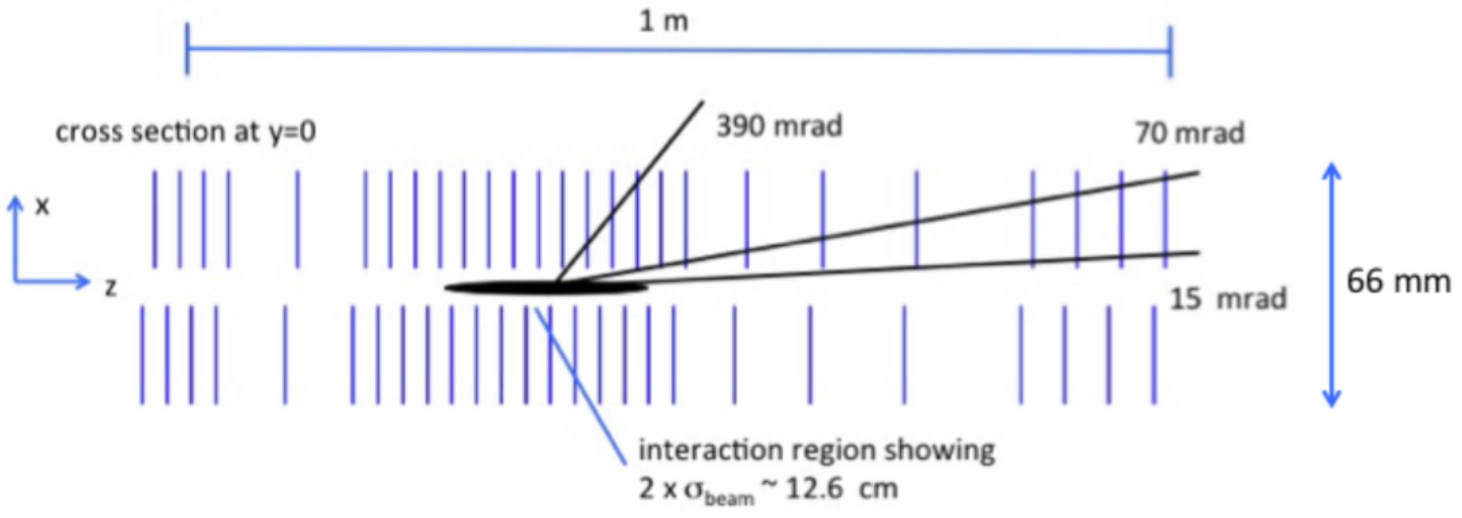


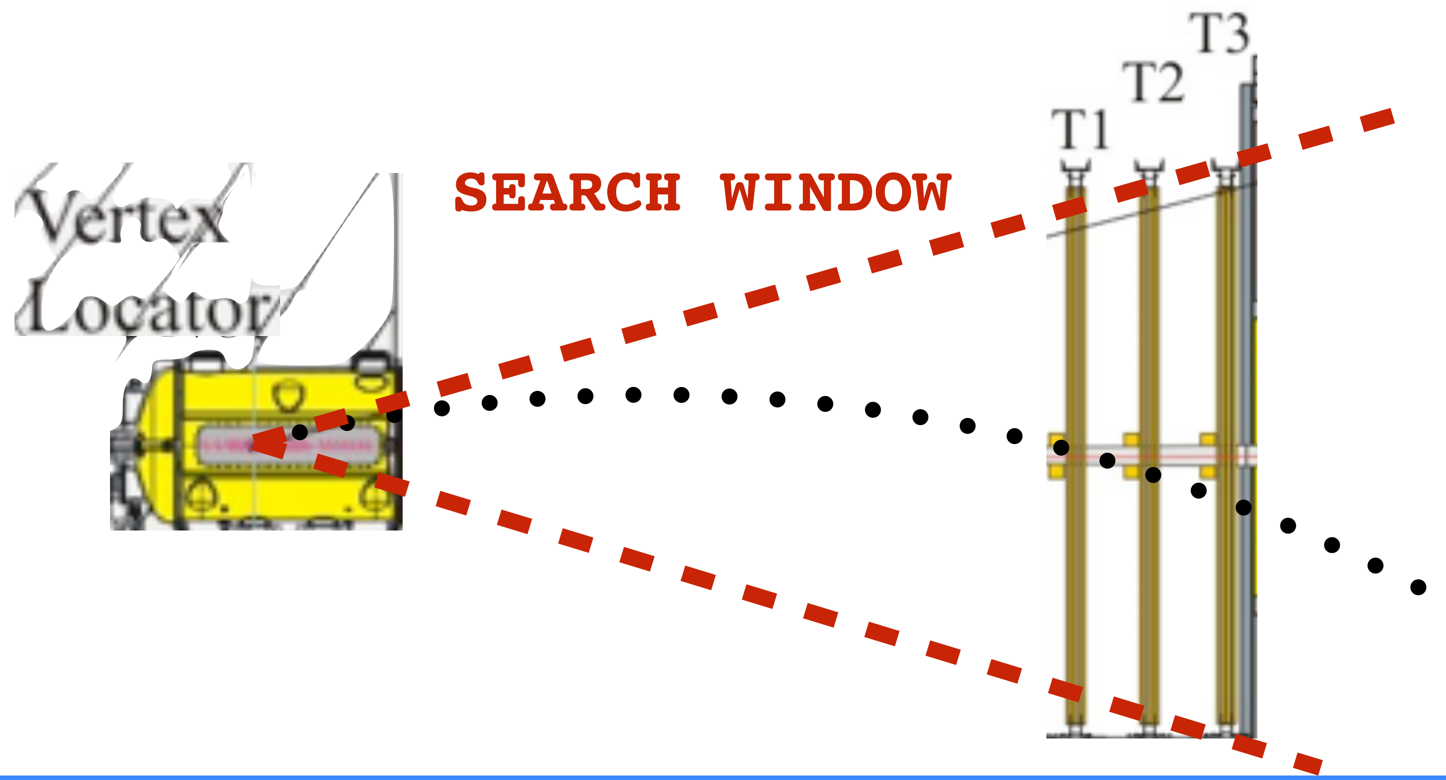


First you reconstruct particles in the vertex detector where there is no magnetic field, so this part is fast. But it does not give you the momentum.

Applying selections in the reconstruction

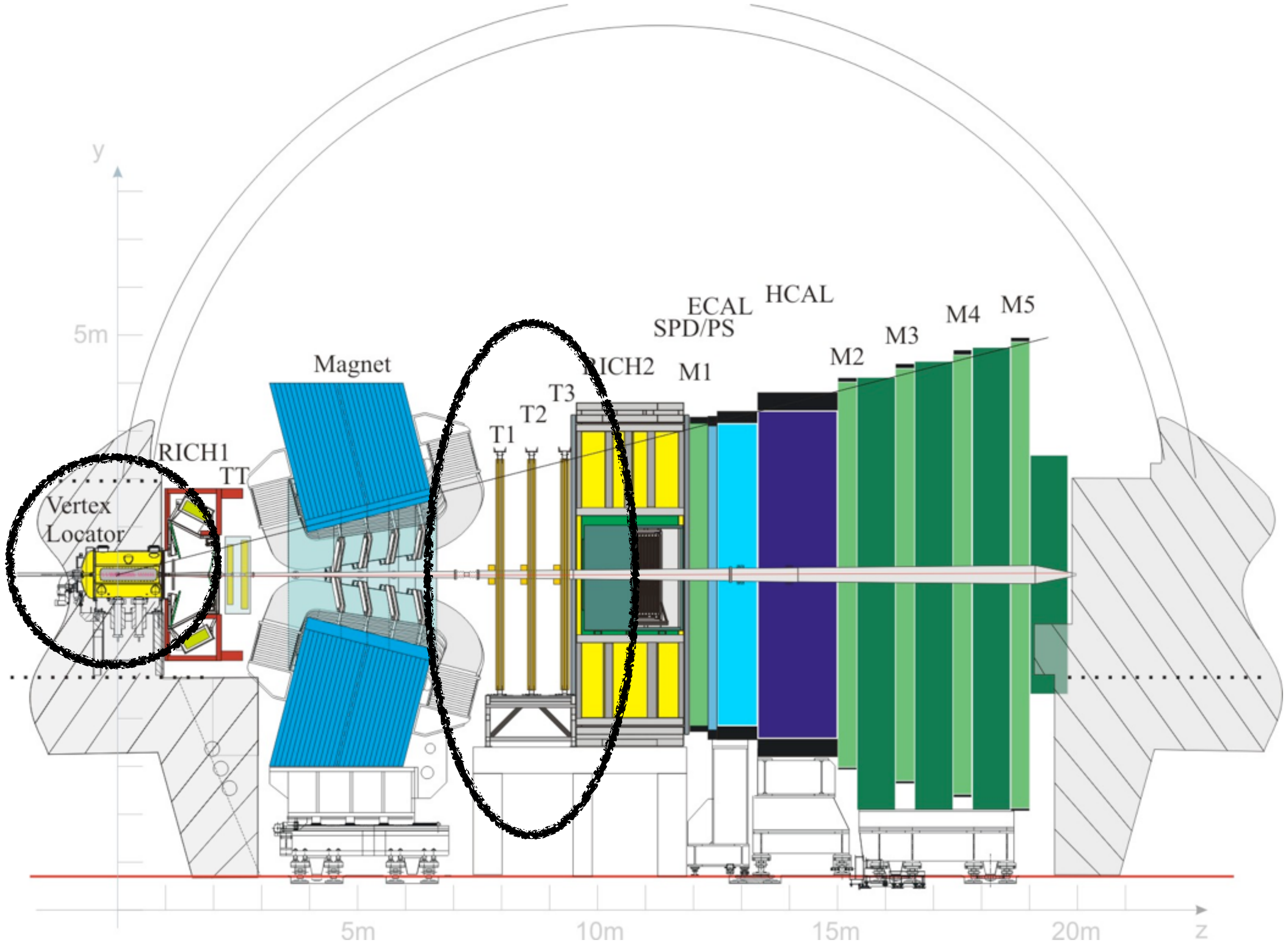


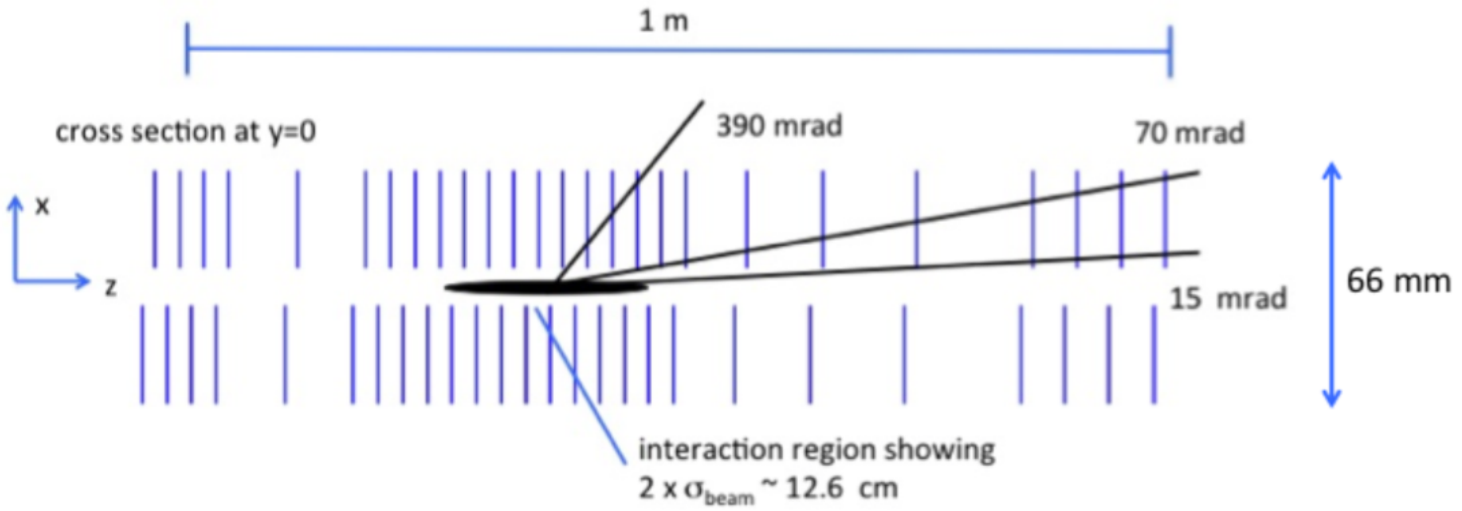


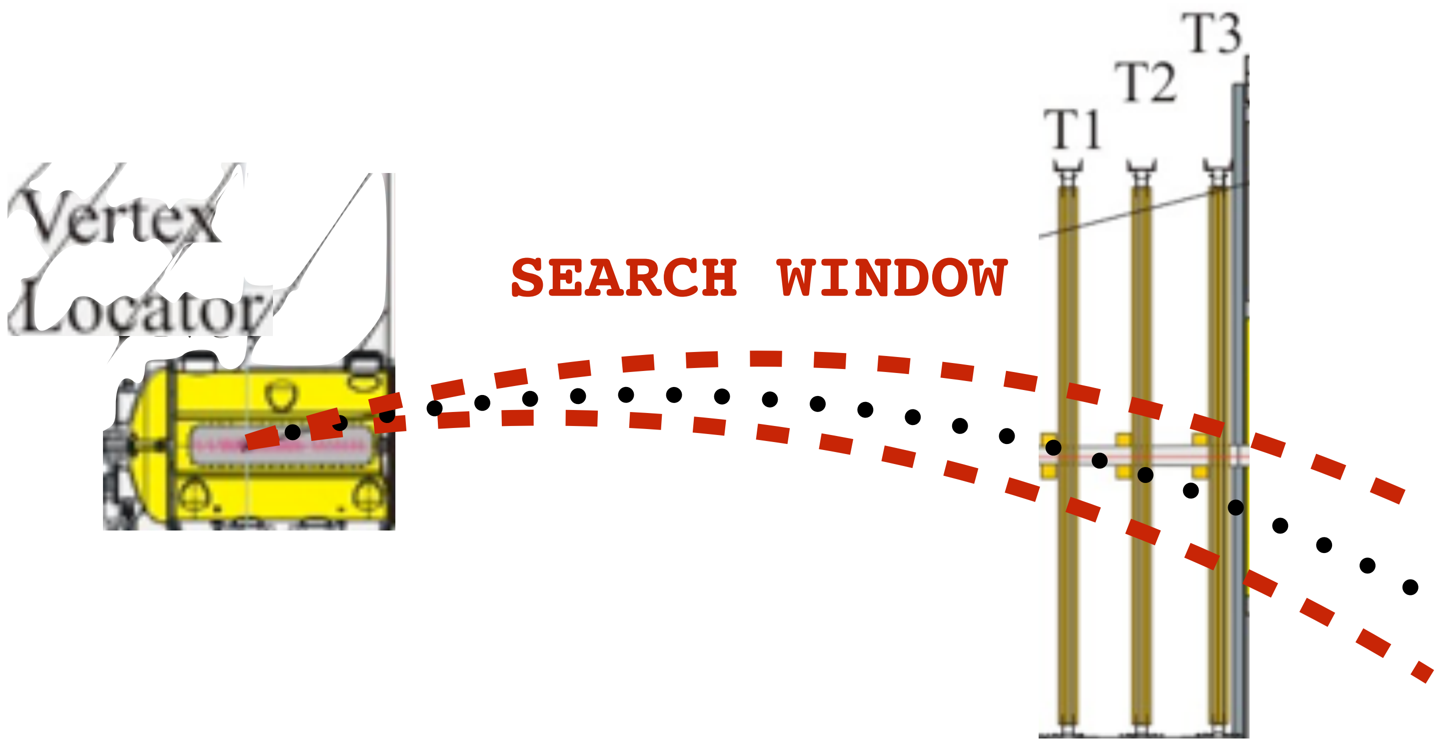


Now you need to extend this particle through the tracking system, but this can be very slow because you don't know how much the magnet bent it.

Applying selections in the reconstruction







But you know the smallest p_T which it must have to pass your selection. This allows you to narrow the search window and gain a lot of time!

Recap : optimizing the reconstruction

Detector reconstruction is limited by the processing power and usually cannot run at full the collision rate

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How is this information used to keep/reject events?

Inclusive vs. exclusive selections in real-time analysis

What do I mean by inclusive/exclusive?

signal $S = \{object_1, object_2, object_3, \ldots, object_n\}$

Any signal can be described as collection of reconstructed objects.

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inclusive — $(\exists s \subsetneq S : \text{condition})$

Any signal can be described as collection of reconstructed objects. An inclusive selection identifies the signal based on the properties of a subset of these objects, allowing that some may not have been reconstructed.

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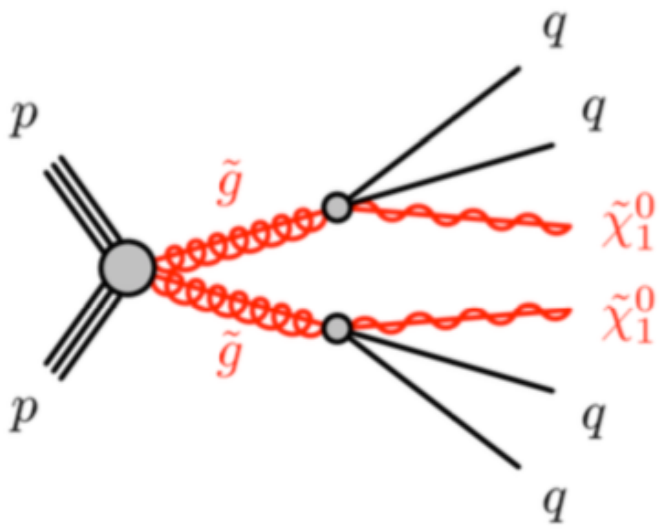
inclusive — $(\exists s \subsetneq S : \text{condition})$

exclusive — $(\exists S : \text{condition})$

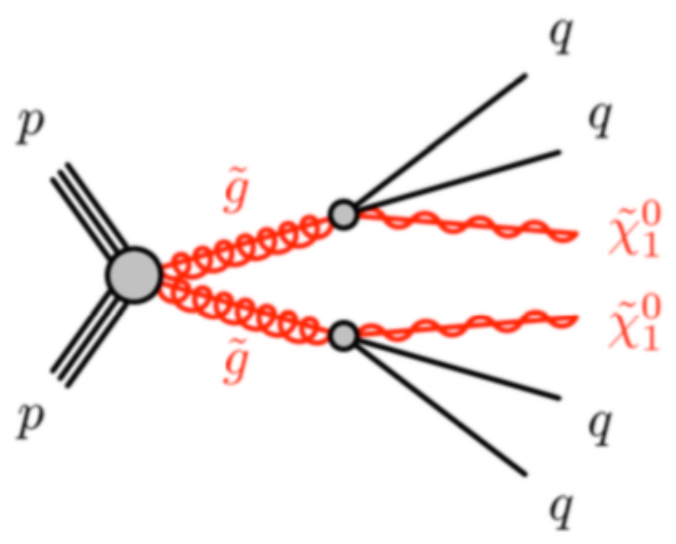
Any signal can be described as collection of reconstructed objects. An inclusive selection identifies the signal based on the properties of a subset of these objects, allowing that some may not have been reconstructed. An exclusive selection requires all the objects in order to identify the signal.

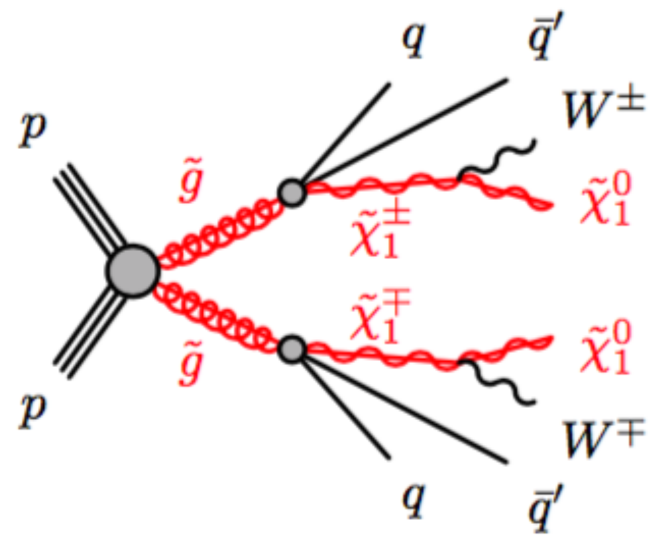
The benefit of an inclusive selection



Inclusive selections help if you don't fully know what you are looking for

The benefit of an inclusive selection





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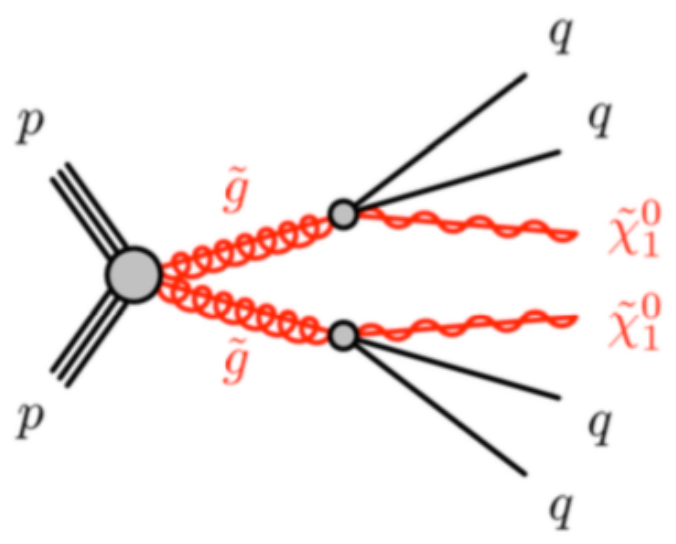

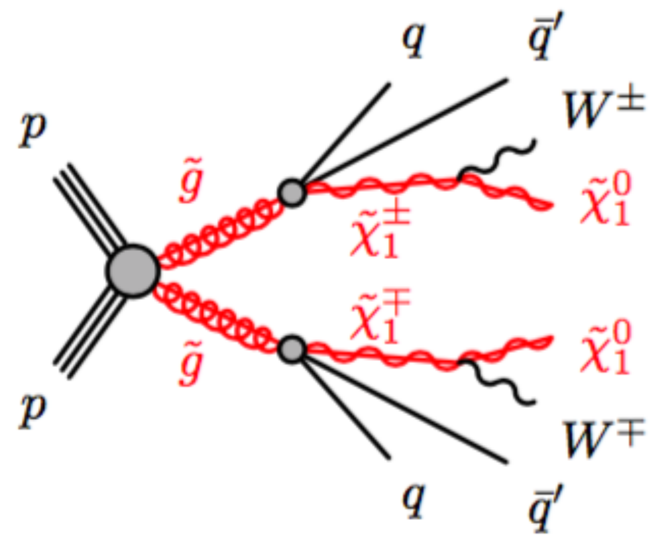

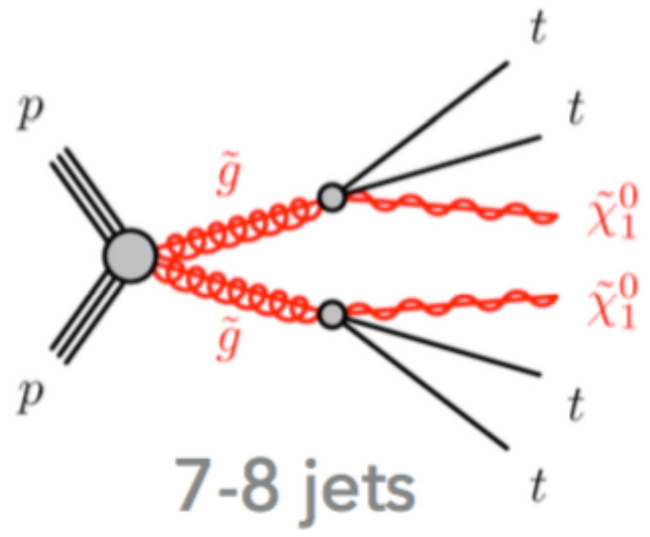

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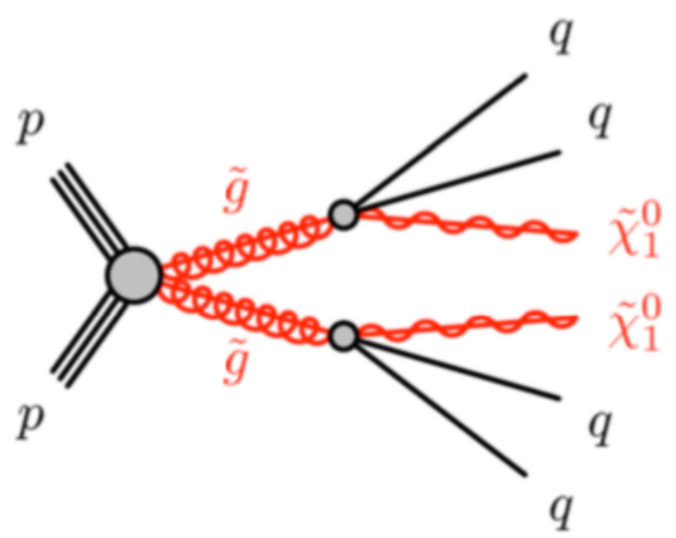
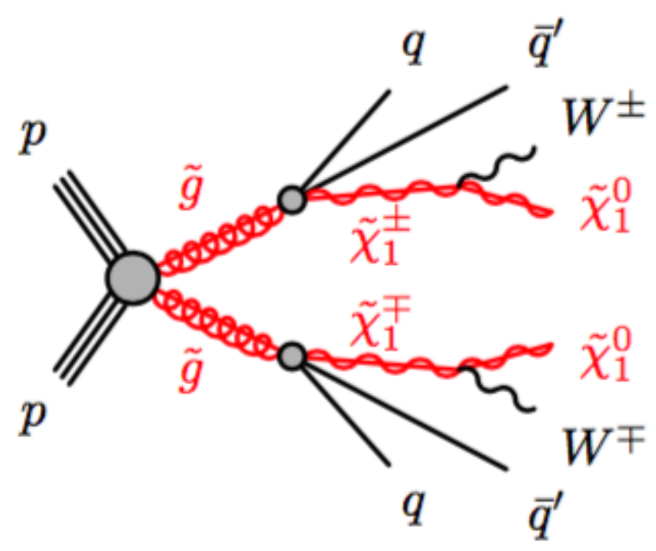
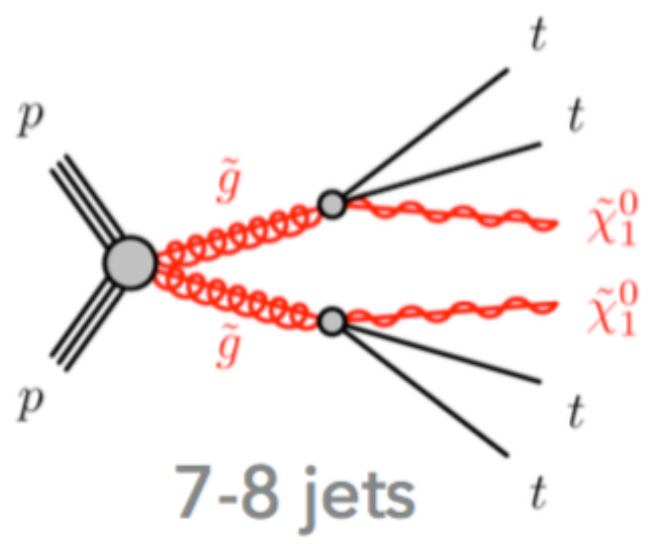
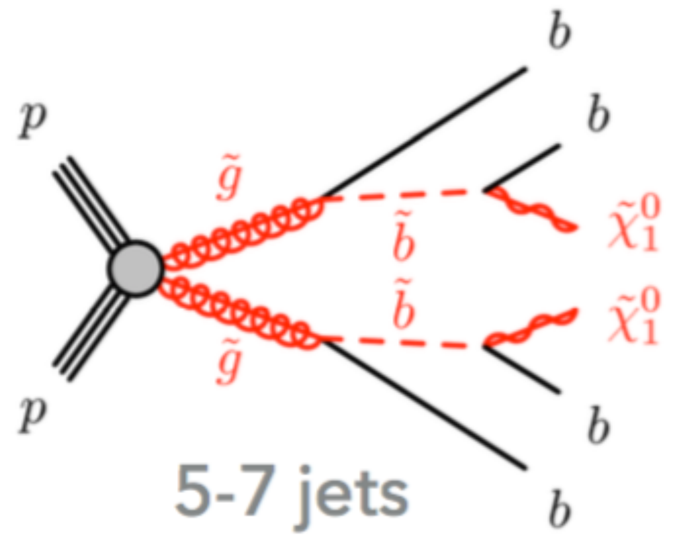


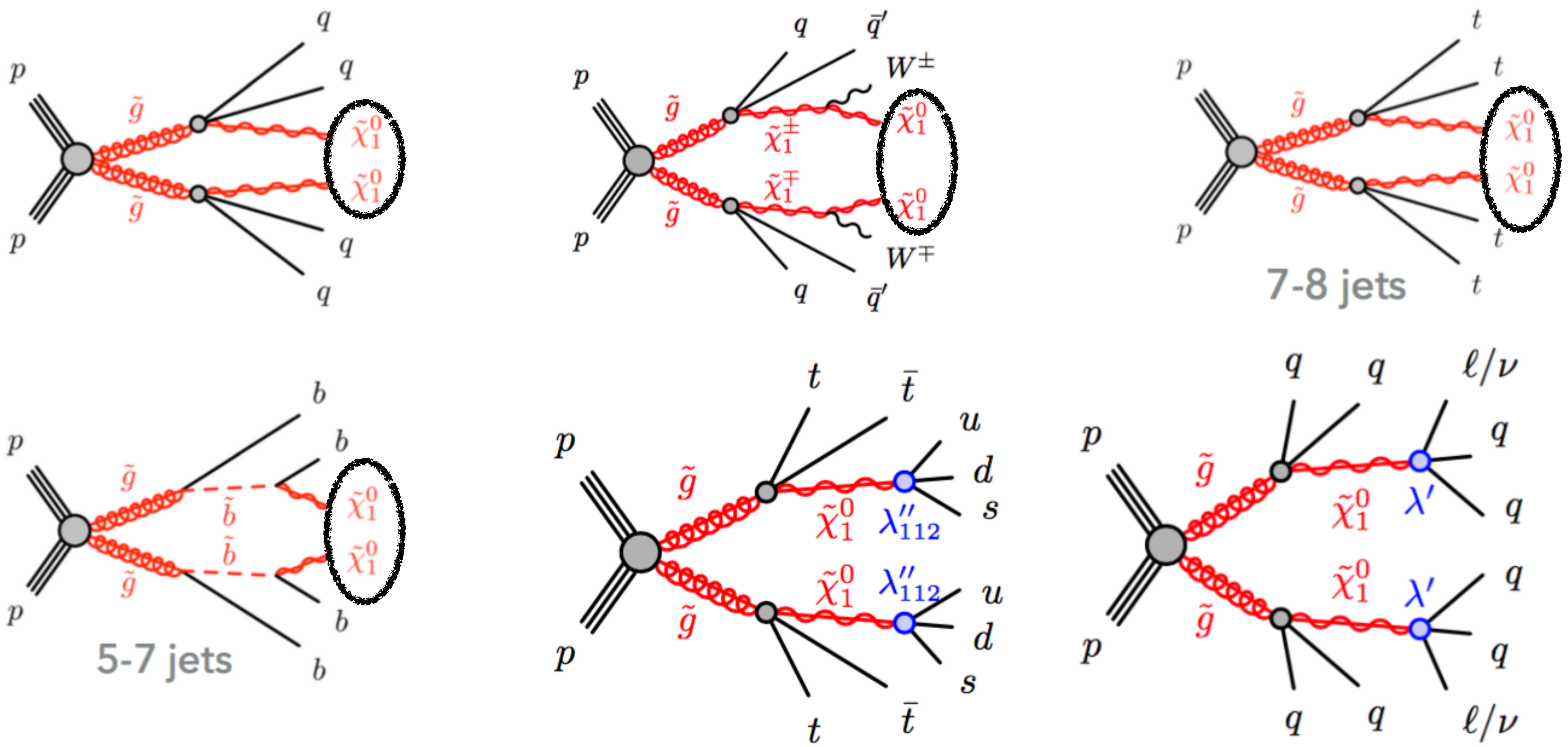






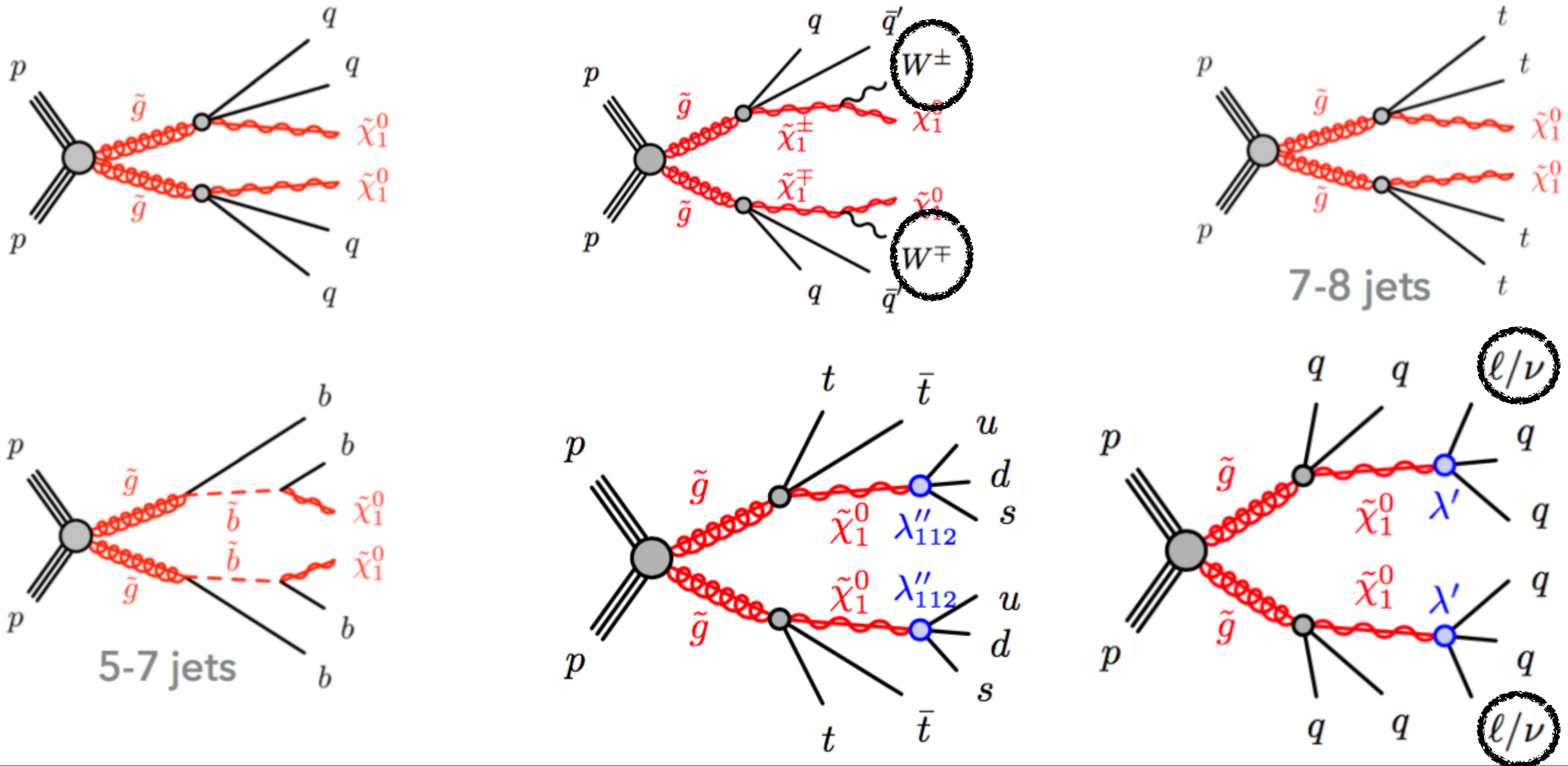
Inclusive selections help if you don't fully know what you are looking for

It helps you look for a class of signals



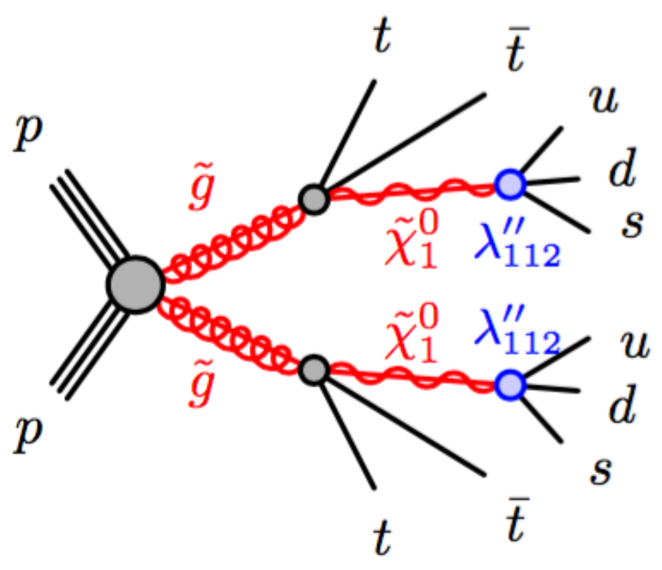
Many new proposed particles leave missing energy in the detector for example.

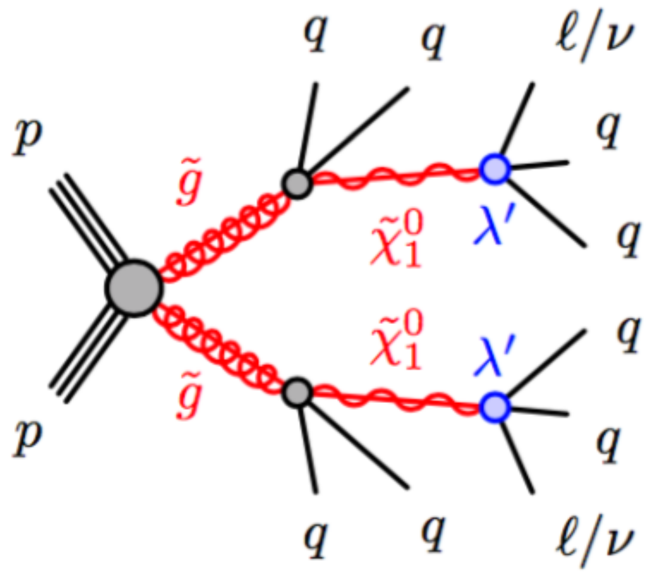
It helps you look for a class of signals



Many new proposed particles leave missing energy in the detector for example. Many others involve isolated high-energy leptons.

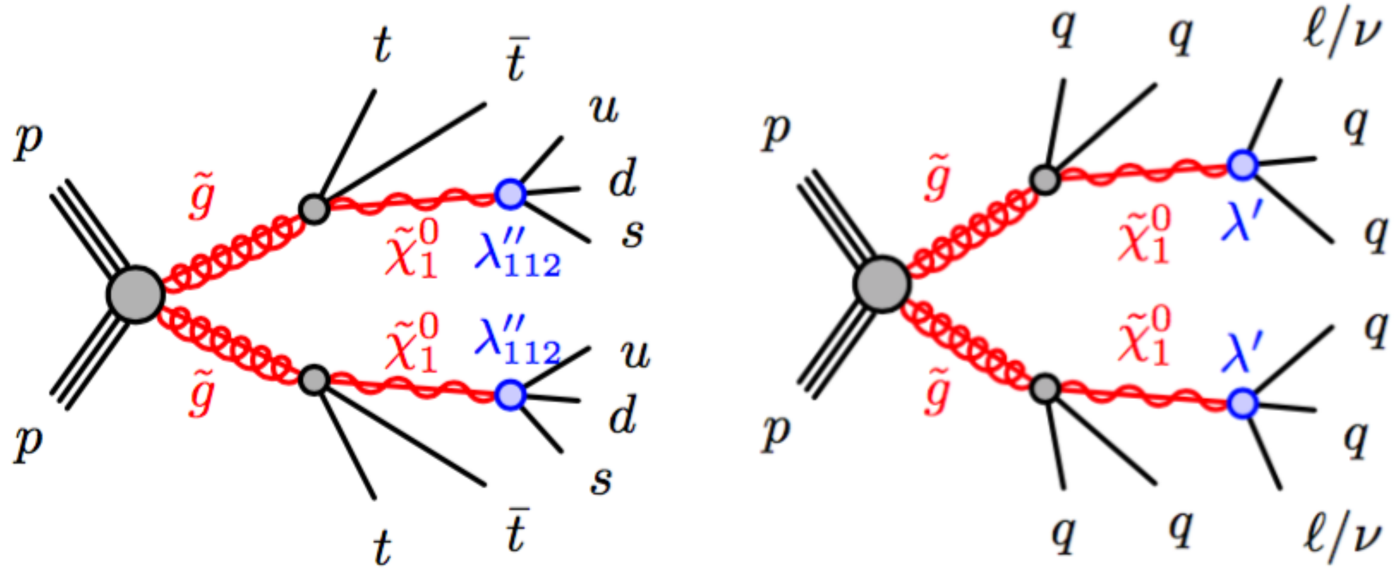
Another benefit of being inclusive

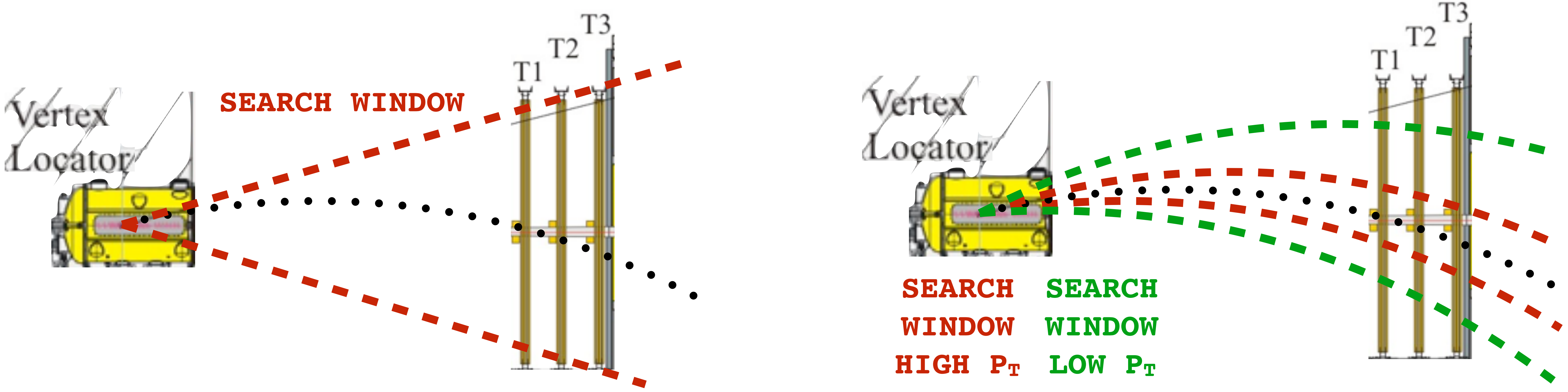




The signal might be too complicated to fully reconstruct in real-time. Remember the trick with applying a pT cut in the reconstruction?

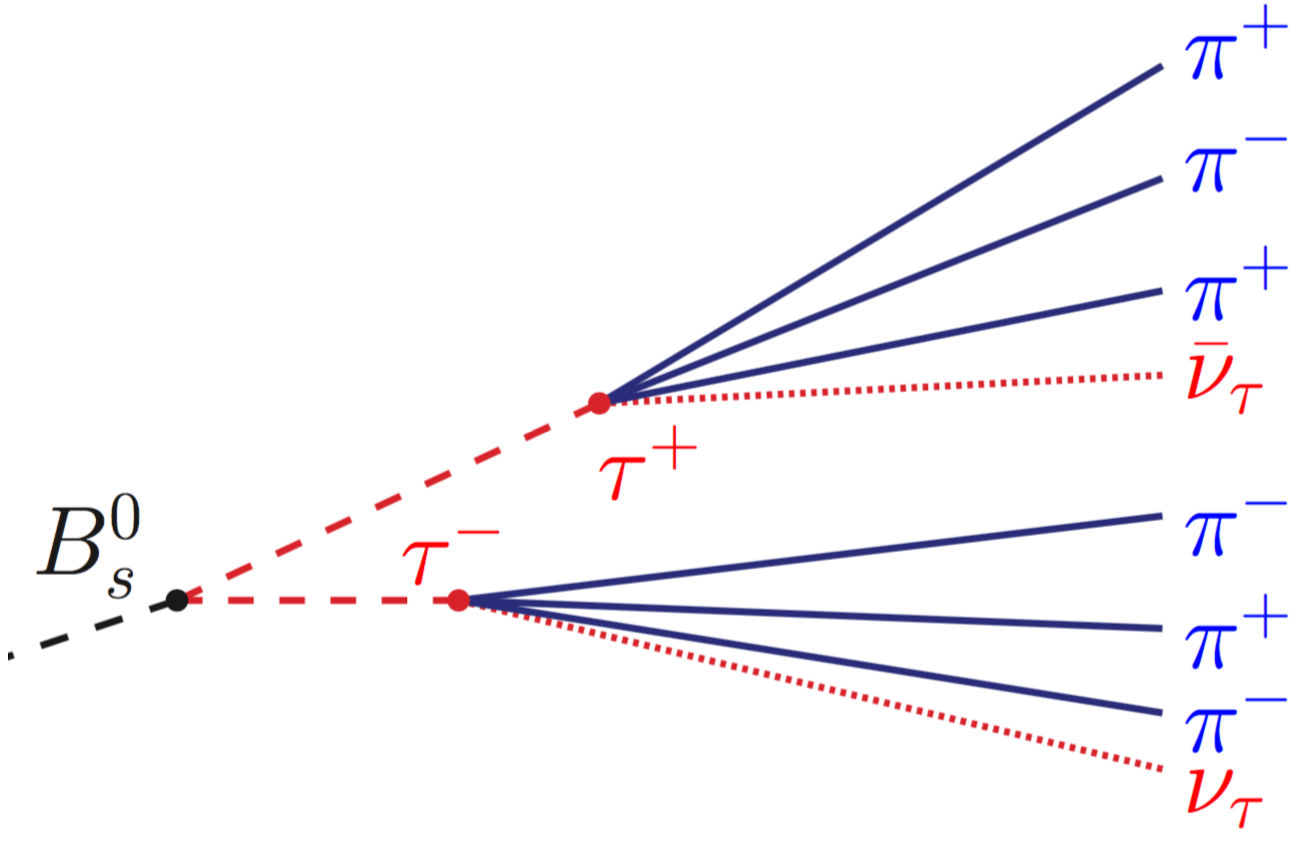
is you don't have to find all its children

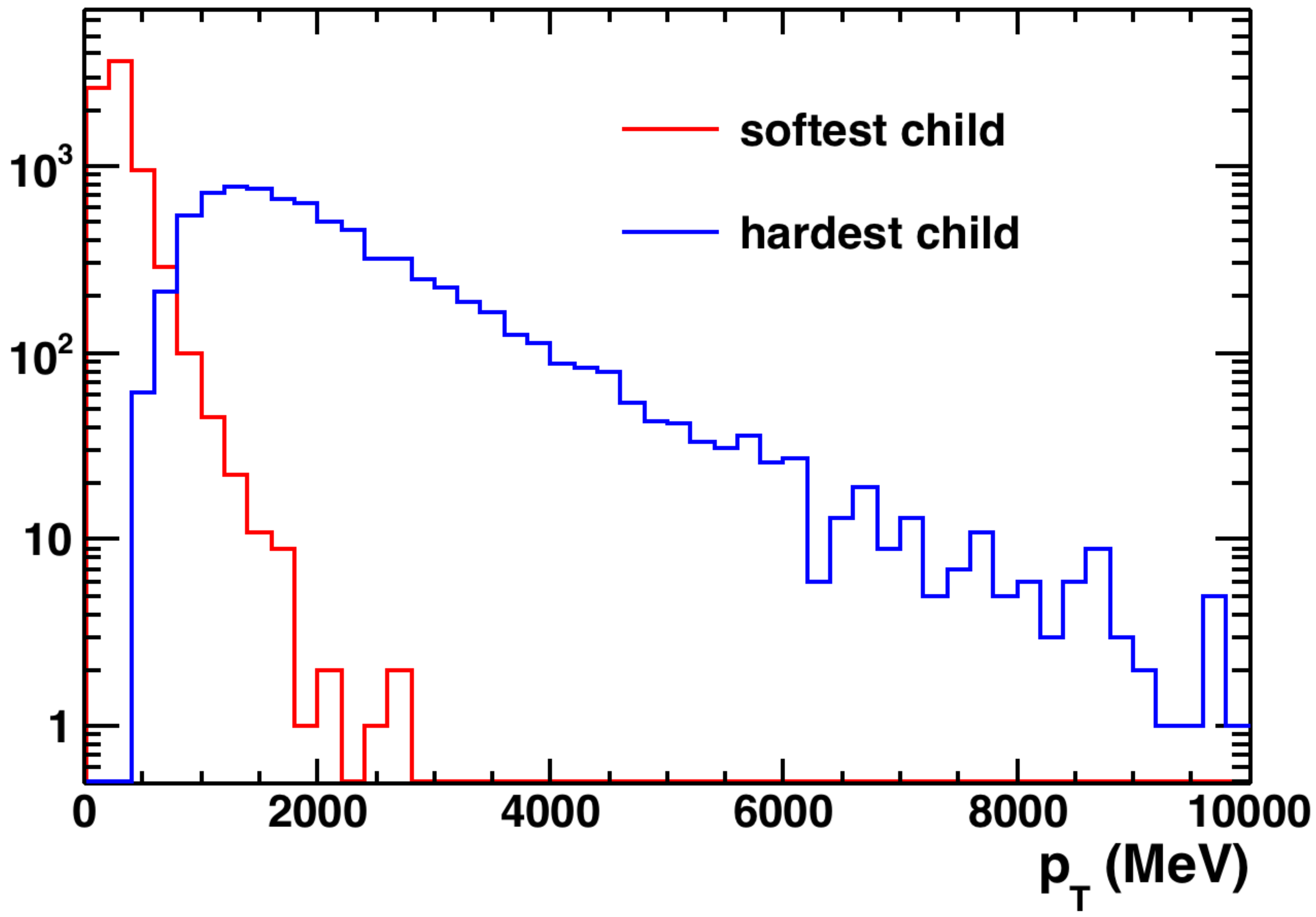




The smaller the p_T you want to search for, the less time this trick gains you.
That is a general rule, lower p_T objects take longer to reconstruct.

You select the signal on its hardest child



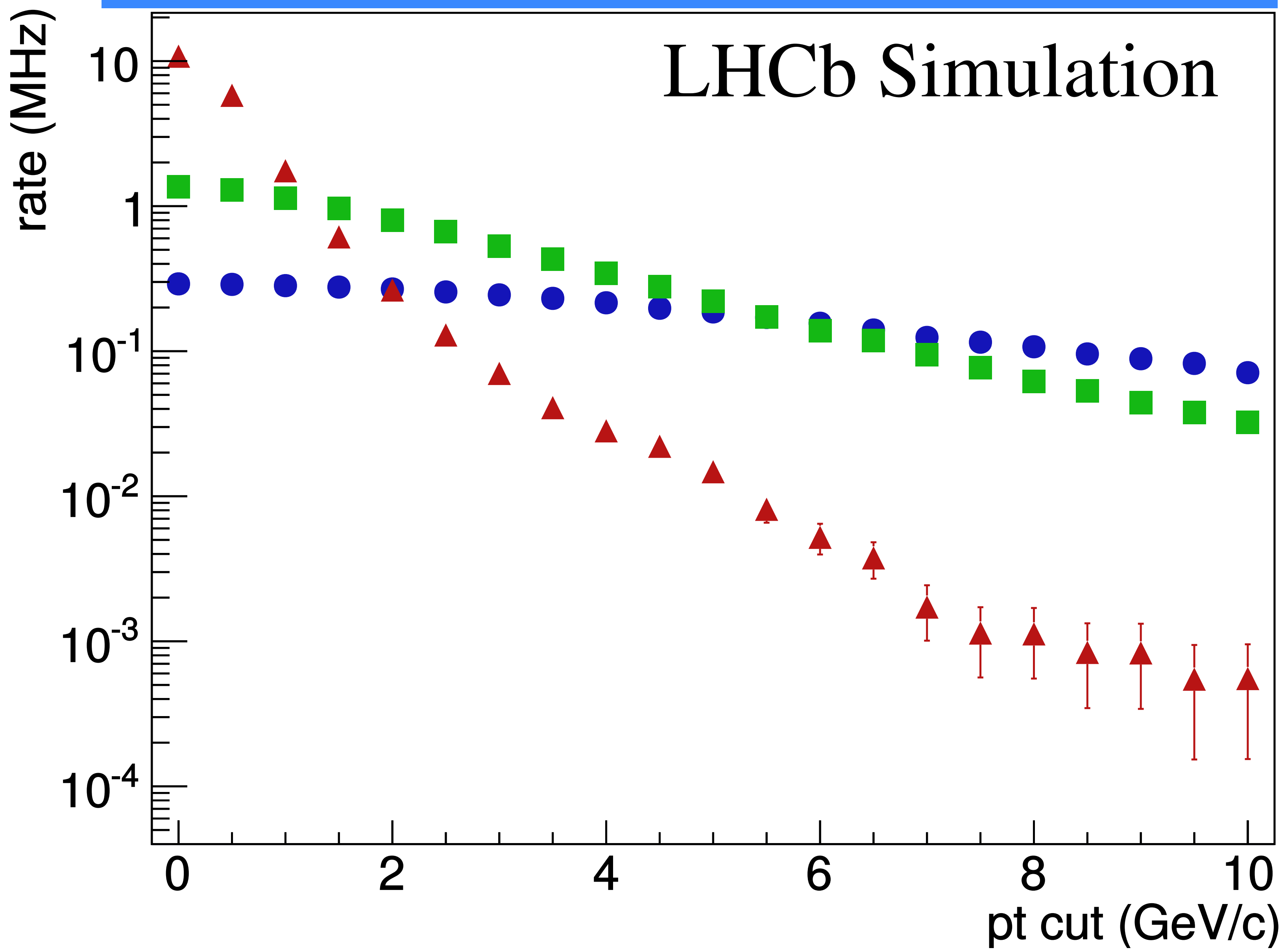


If your signal decays into multiple objects, on average one of those objects will have quite low p_T, and the bigger the number of objects the more this is true. Being able to select the signal using only its hardest product helps

So why not use an inclusive selection?

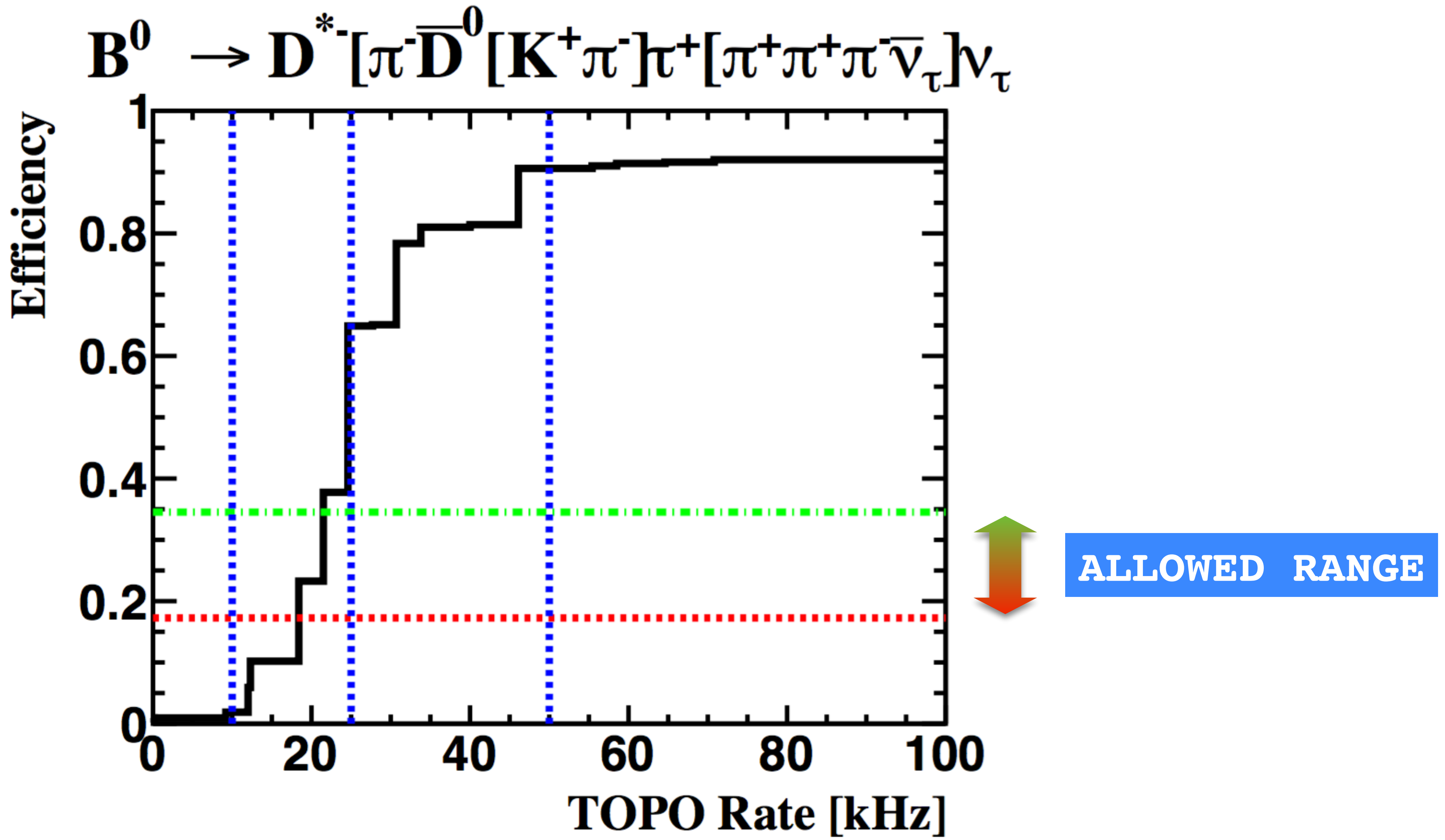
Fitzpatrick&Gligorov
LHCb-PUB-2014-027

Remember LHC collision rate is ~30 MHz



If you can use it, an inclusive selection is always a great idea. But if you have too much signal, it becomes impossible to select it efficiently

Example from LHCb upgrade simulation



Efficiency of Run-I inclusive bbar selection retuned for the LHCb upgrade. The fall-off is not because of background, but because of real b-hadrons which *by definition* cannot be *inclusively* separated from a specific signal.

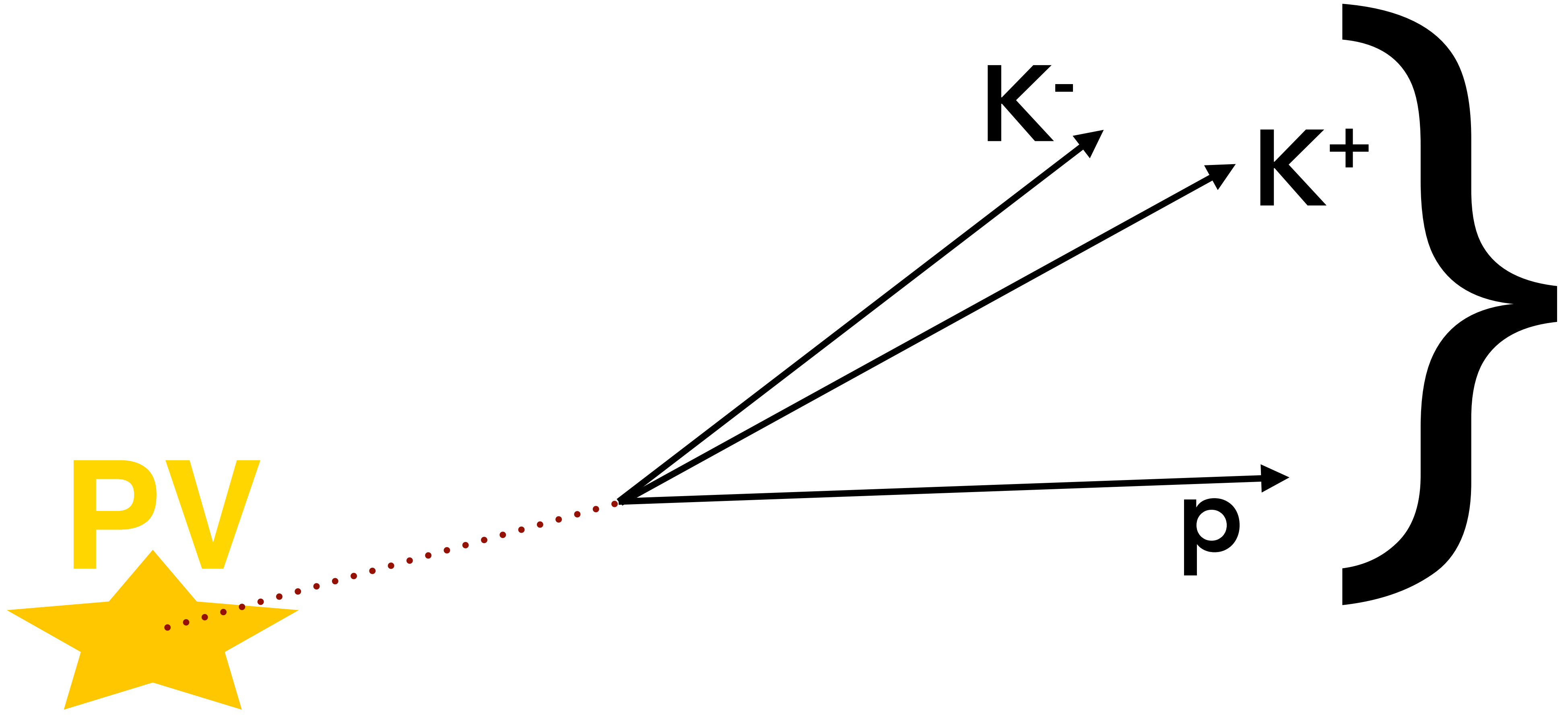
How does an exclusive selection help?

Poor compressability : use an inclusive real-time selection and write entire output of detector to permanent storage	Medium compressability : use a semi-inclusive real-time selection and write signal candidate & other interesting parts of event which can be used in a final exclusive selection to permanent storage	Good compressability : use an exclusive real-time selection and write the signal candidate which it identifies to permanent storage

How compressable is your analysis?

In two ways. Firstly you can discriminate against other b-hadron decays better, so the rate goes down. Secondly you can now exploit event compression to reduce the event size and write more events.

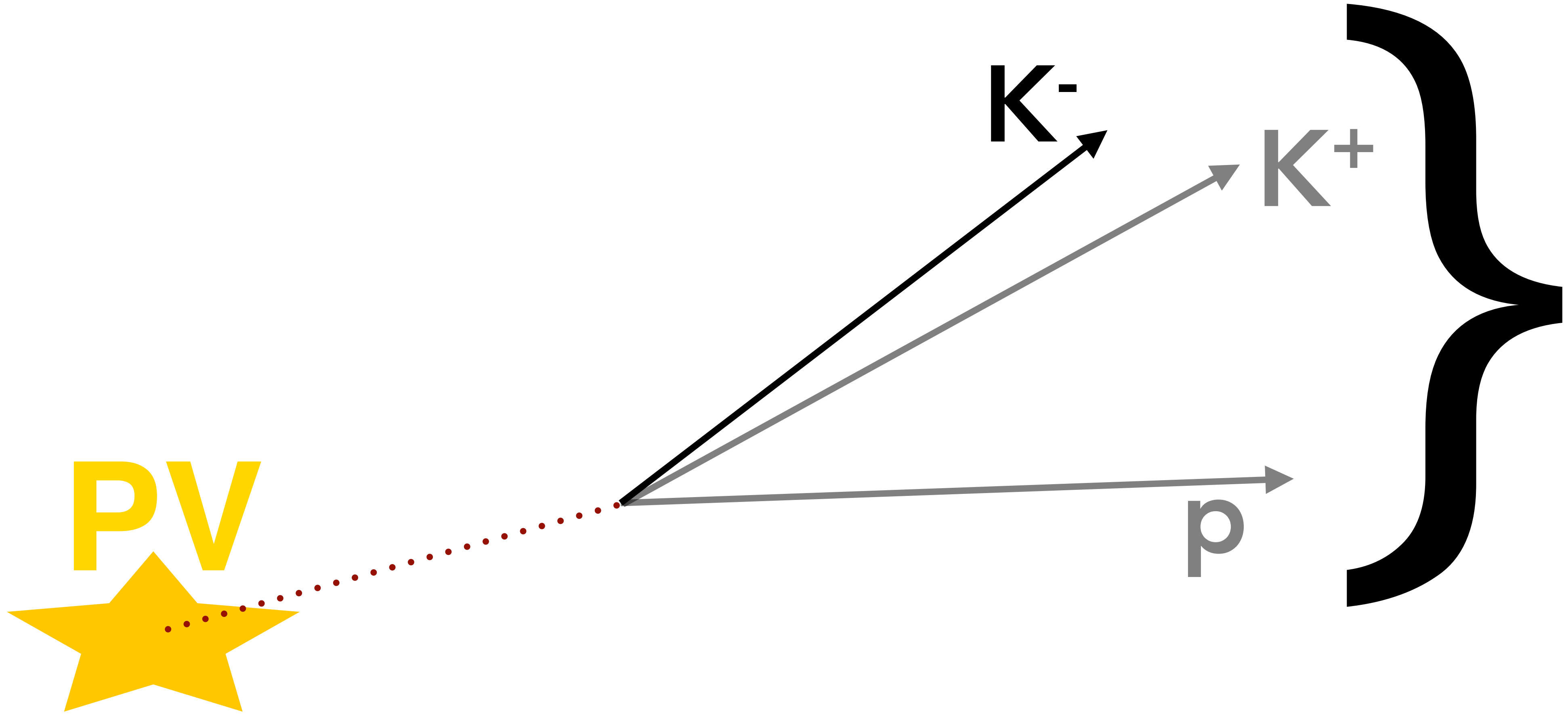
Combinatorics & inclusive/exclusive



EXCLUSIVE : MUST AFFORD COMBINATORICS OR RECONSTRUCTION TO REDUCE THEM

Remember our earlier discussion about reducing the time of combining reconstructed objects into signal candidates? This is usually more severe for exclusive selections

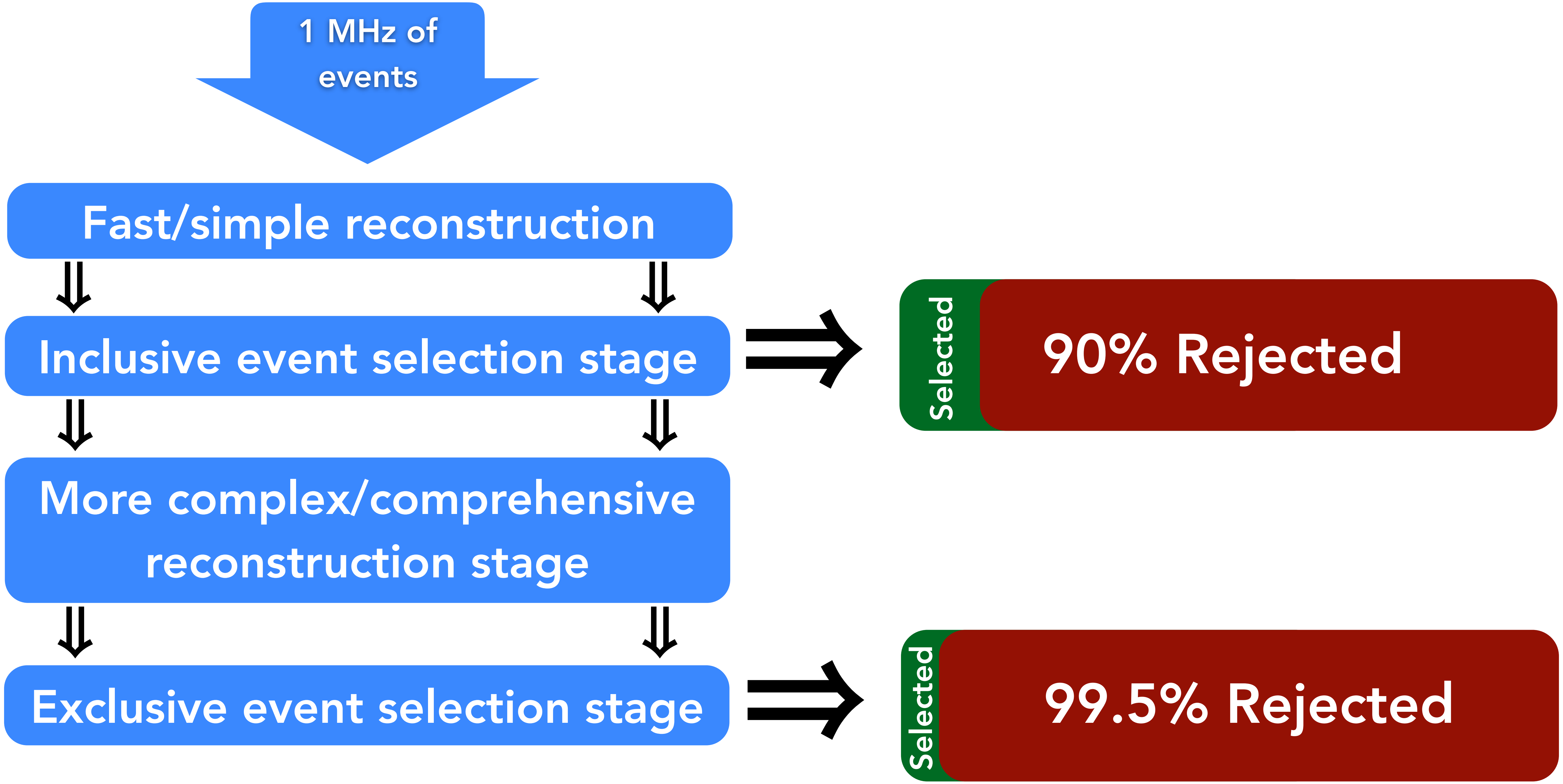
Combinatorics & inclusive/exclusive



INCLUSIVE : GENERALLY SIGNIFICANTLY FEWER OR NO COMBINATORICS TO PERFORM

Remember our earlier discussion about reducing the time of combining reconstructed objects into signal candidates? This is usually more severe for exclusive selections than inclusive ones where only part of signal is built

Can you use a mixture?



Absolutely and in fact you often will do exactly that : an inclusive selection for the first cascade stages where rate can be higher, exclusive later. This is in fact logical because the more complex reconstruction gives access to the additional information needed for the exclusive selection to be efficient.

Do inclusive selections enable new ideas?

You will often hear your colleagues say that unless the real-time selection is inclusive, you will not be able to develop new analysis ideas once the data is already taken.

This is absolutely correct.

However the other side of this is that for precision measurements where your selection rate is dominated by your signal, you will not be able to achieve the full physics potential (sensitivity) without exclusive real-time selections and without event compression.

Recap : inclusive & exclusive selections

Inclusive selections are great if signal is rare, and/or partially unknown, and/or expensive to fully reconstruct

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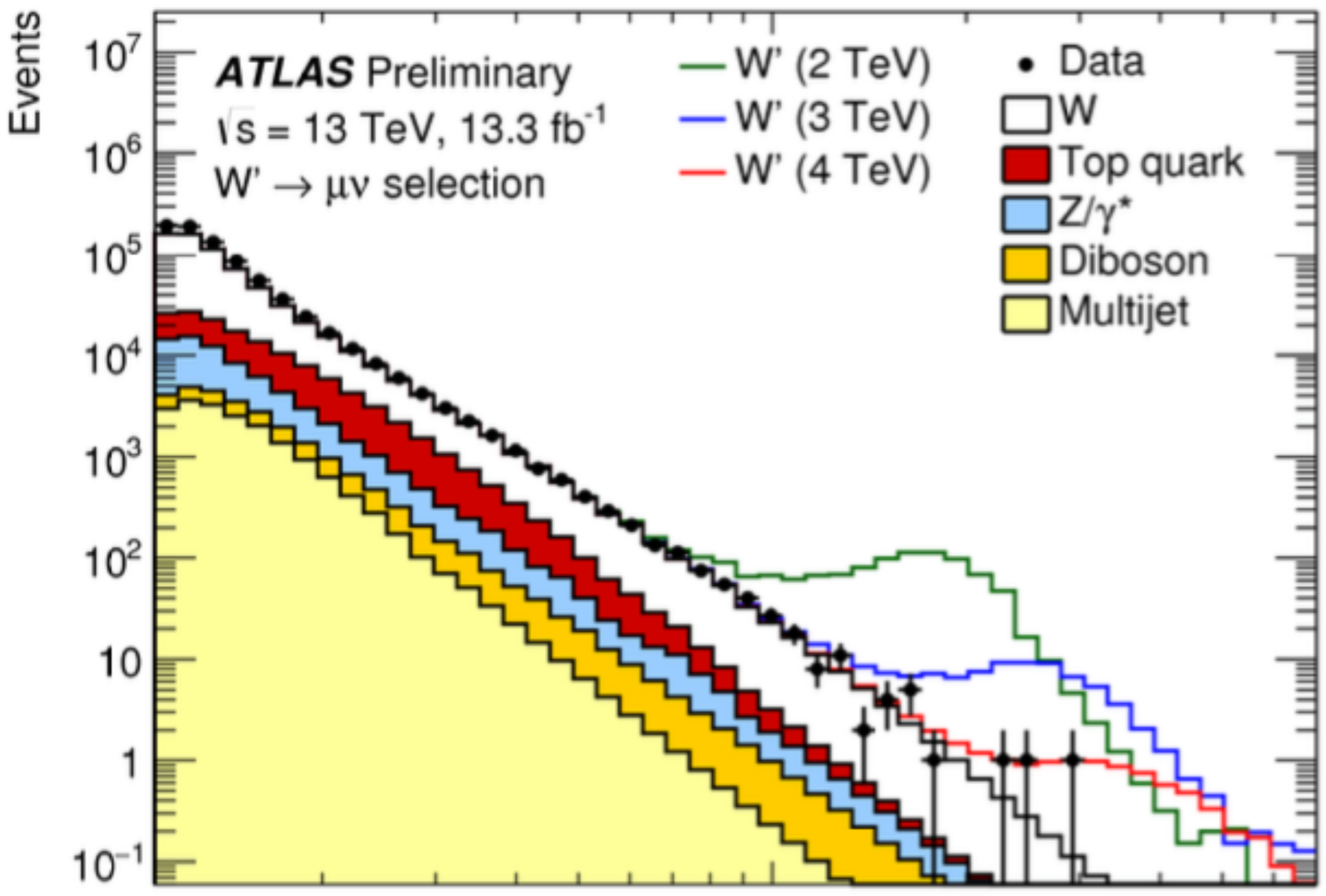
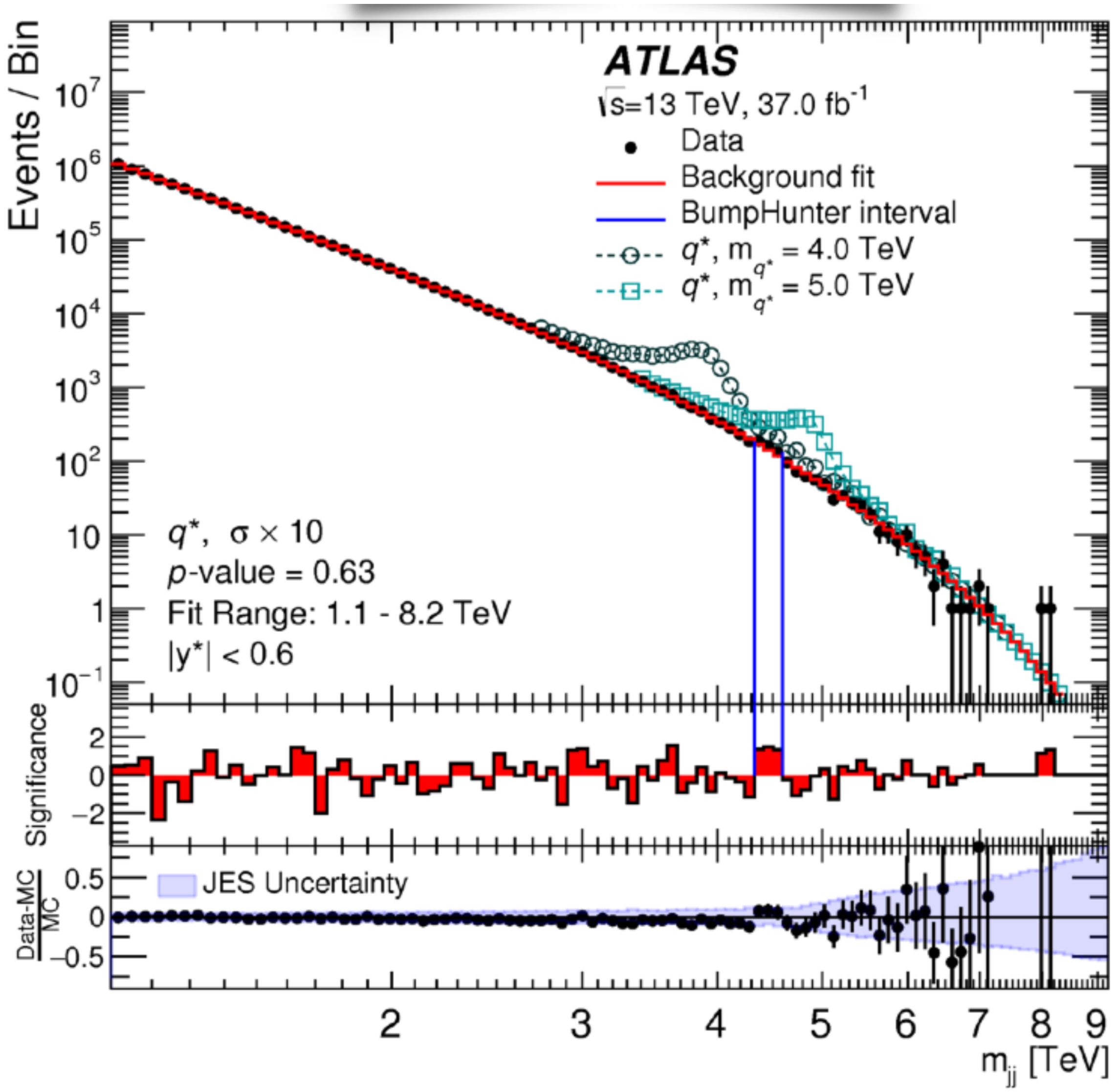
So how to calibrate & understand this processing?

Calibrating the reconstruction and selection and understanding their performance

Remember our two analysis components?





Almost every analysis has two basic components :

1. Combine&select building blocks to observe a signal above background
2. Understand the efficiency of step (1) to measure signal properties

Can’t you just use detector simulation?

If detector simulation matches data perfectly, just process the simulation identically to data and obtain the efficiencies that way. *It often doesn’t.*

Examples of hard problems for simulation

Occupancies near the beampipe or around magnets

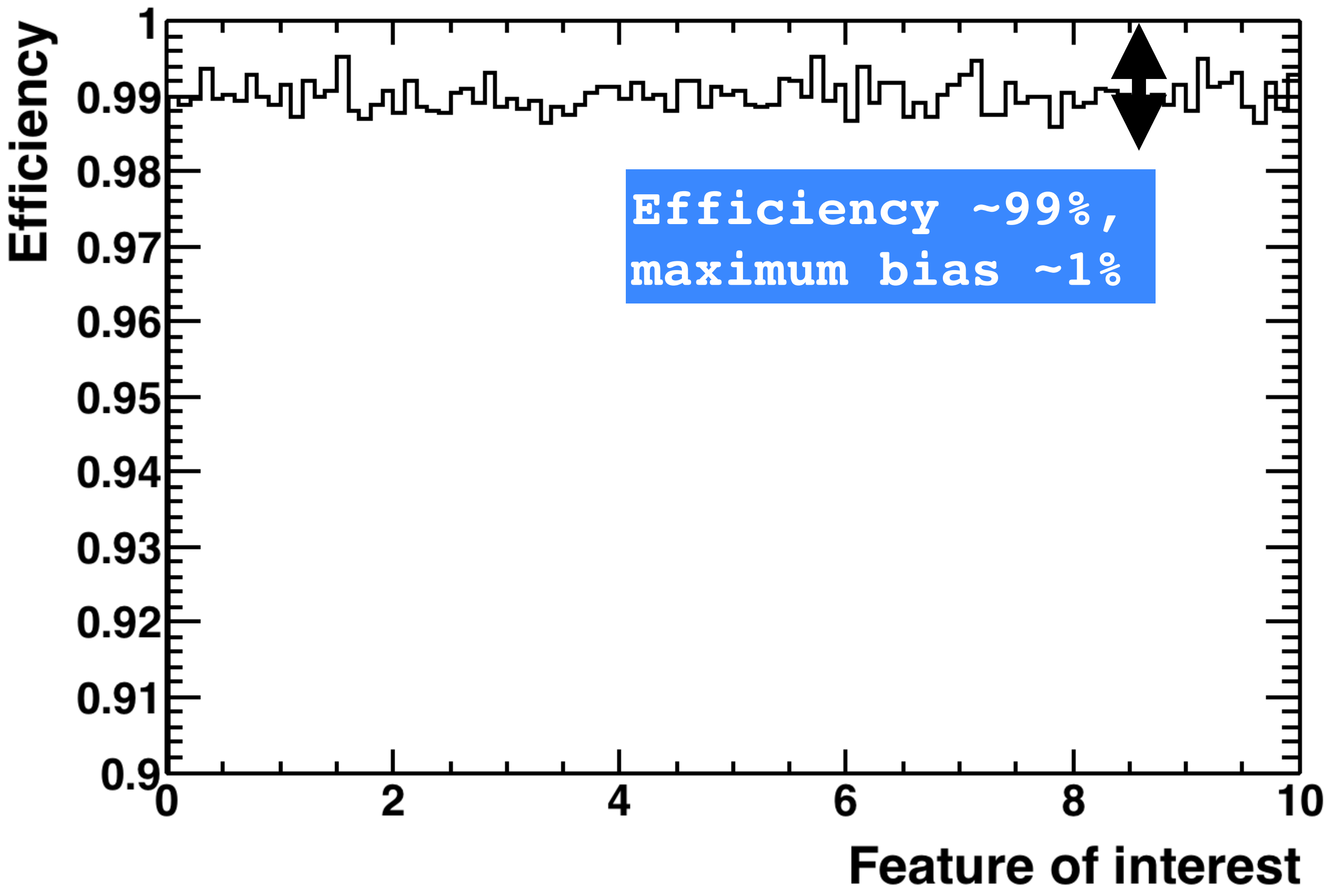
Shower shapes and ageing in the calorimeters

If the real-time reconstruction and selection evolve over time, it can be hard to simulate the correct mixture

Momentum and pseudorapidity spectra, especially of light particles in the event

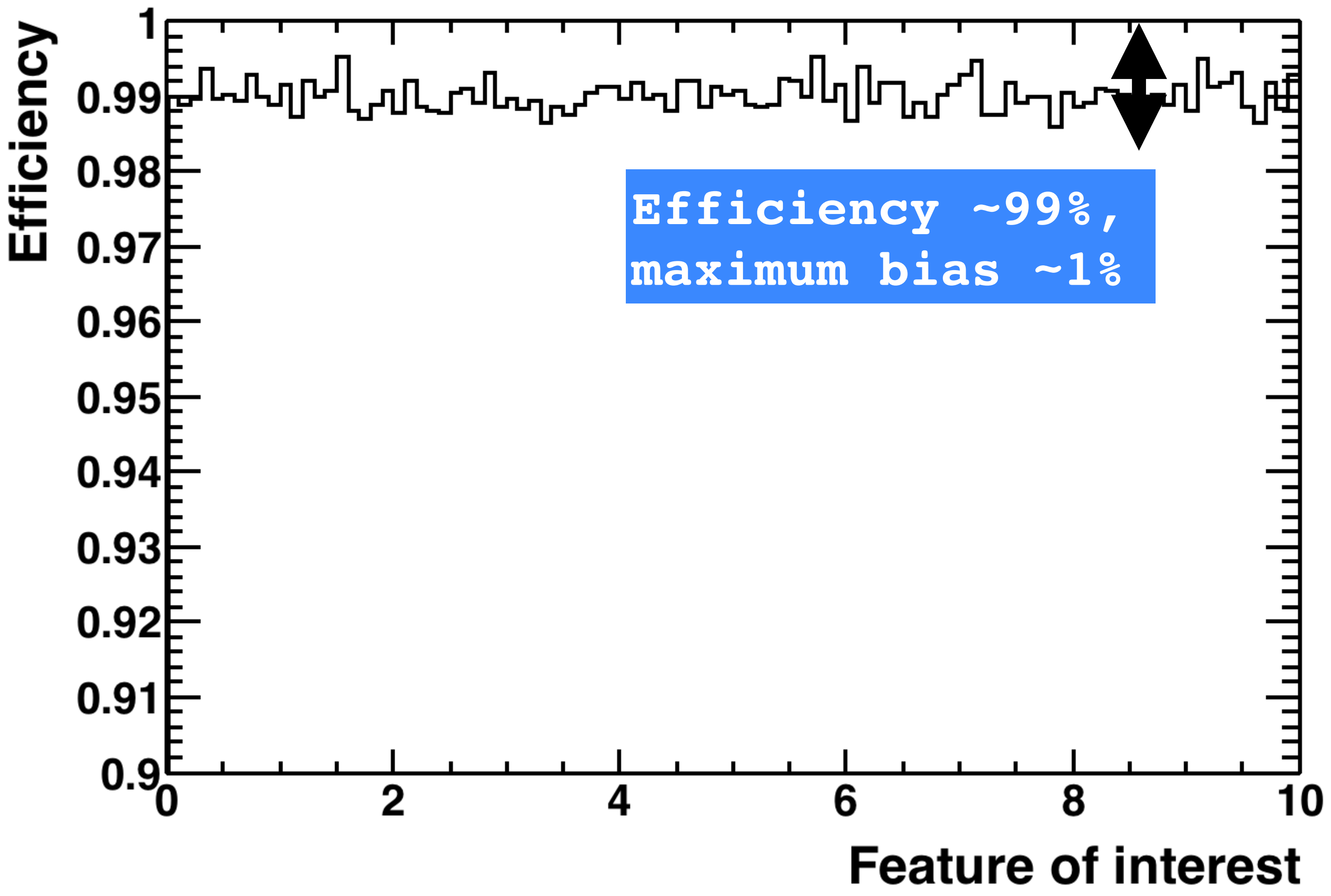
In general therefore, we will need to use data-driven ways to figure out what our efficiency was and how to correct the simulation to match data

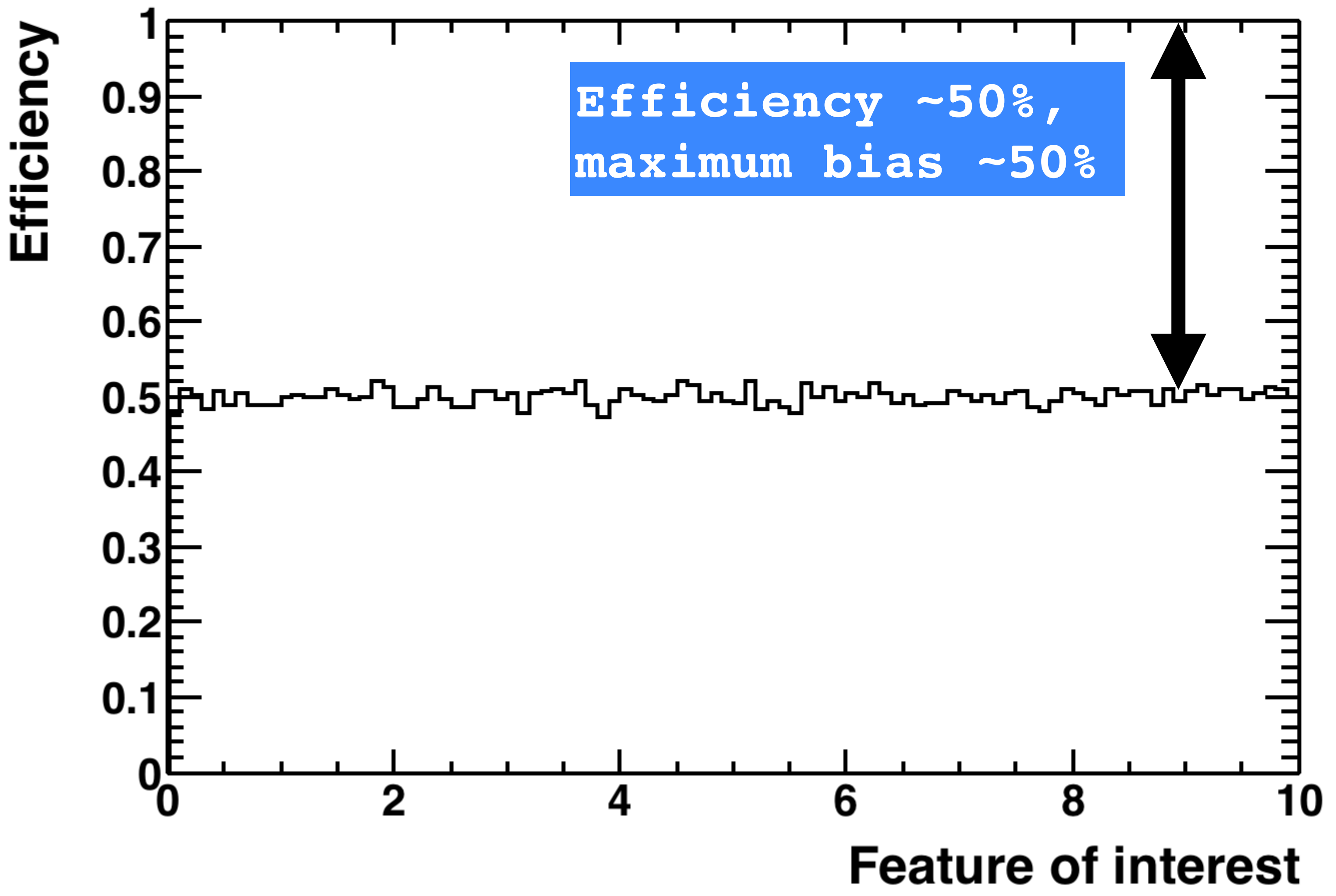
Better performance is easier to calibrate



All other things being equal, higher efficiencies are easier to calibrate than lower ones, and better detector resolutions easier than worse ones.

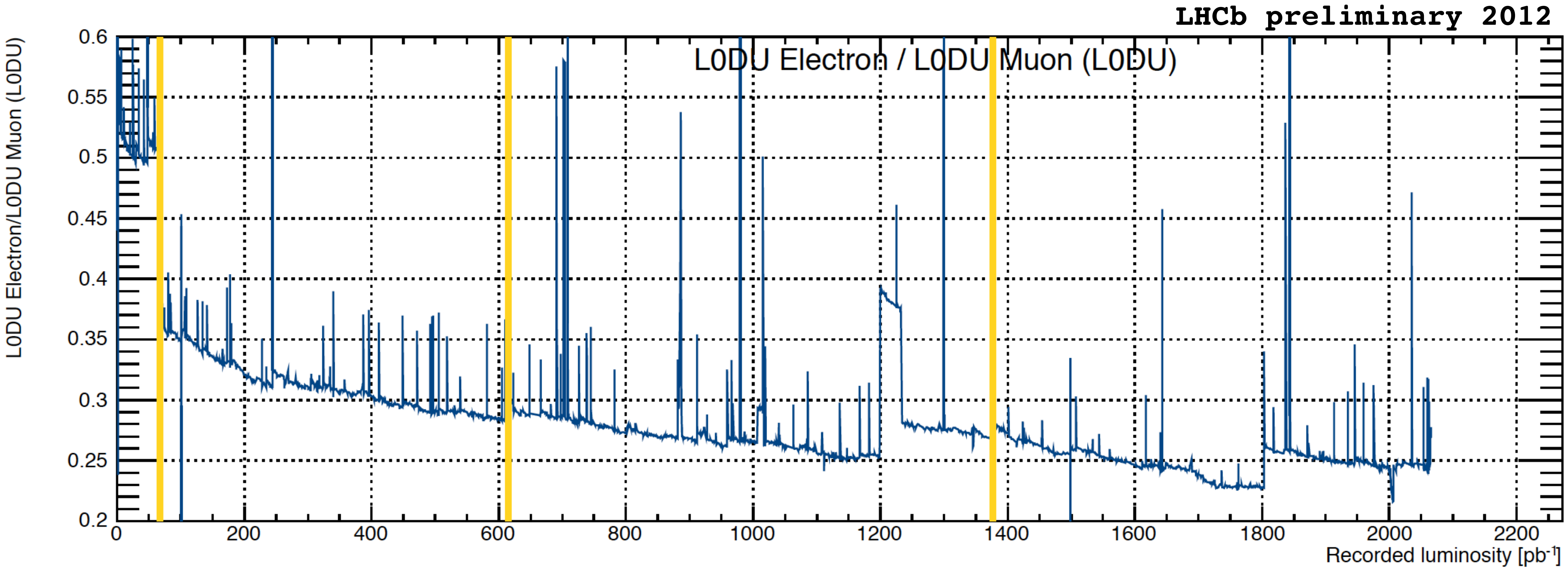
Better performance is easier to calibrate





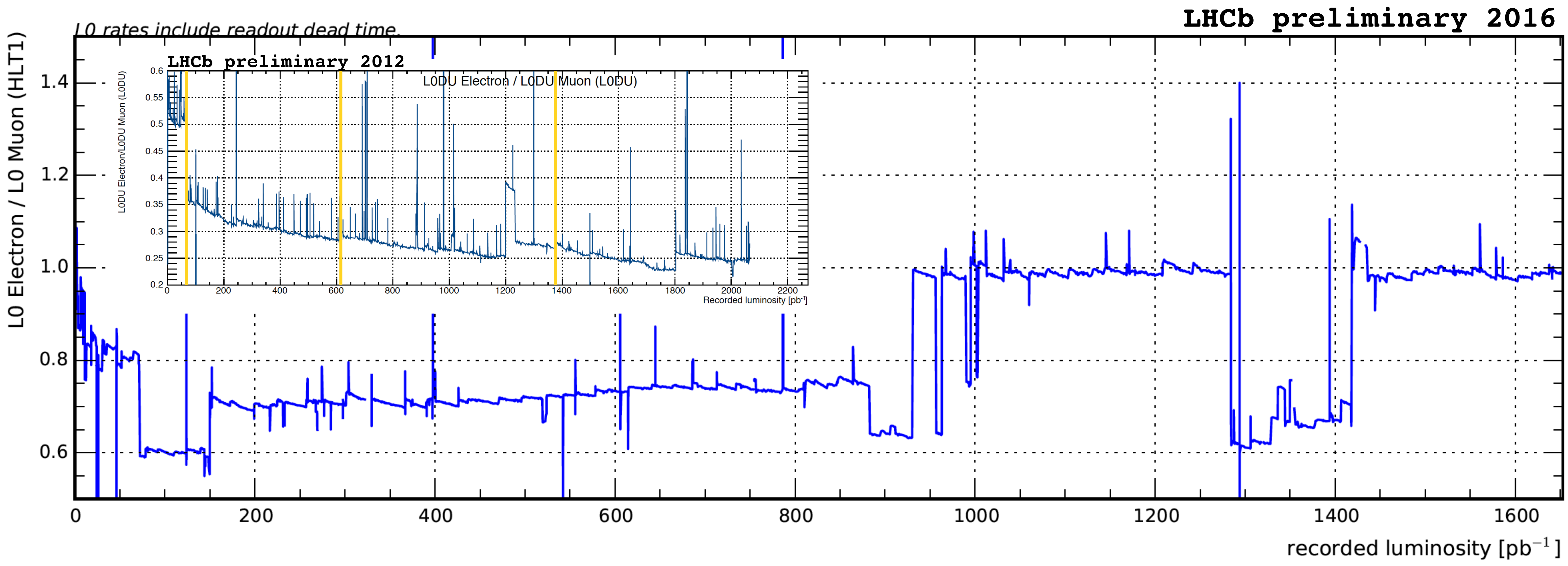
All other things being equal, higher efficiencies are easier to calibrate than lower ones, and better detector resolutions easier than worse ones. This is because simulation is almost always optimistic, so the better the intrinsic performance the smaller the systematic this can generate in your analysis.

The performance should also be stable



This is the ratio of electron vs. muon rates at the first (fixed latency) level of the LHCb real-time selection in 2012. It changed significantly during the year mainly because of calorimeter ageing, so hard to simulate an average.

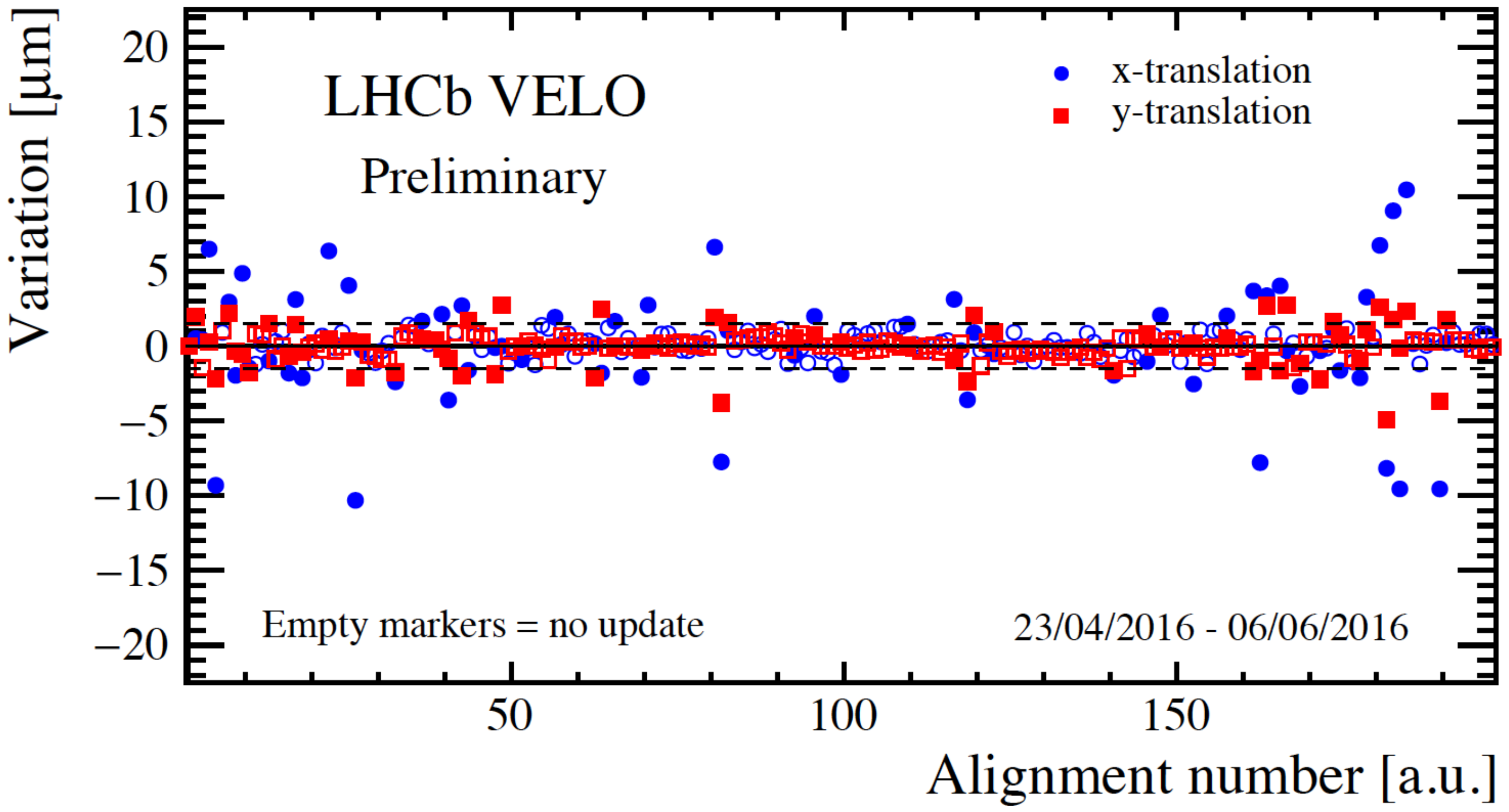
in order to minimize the corrections



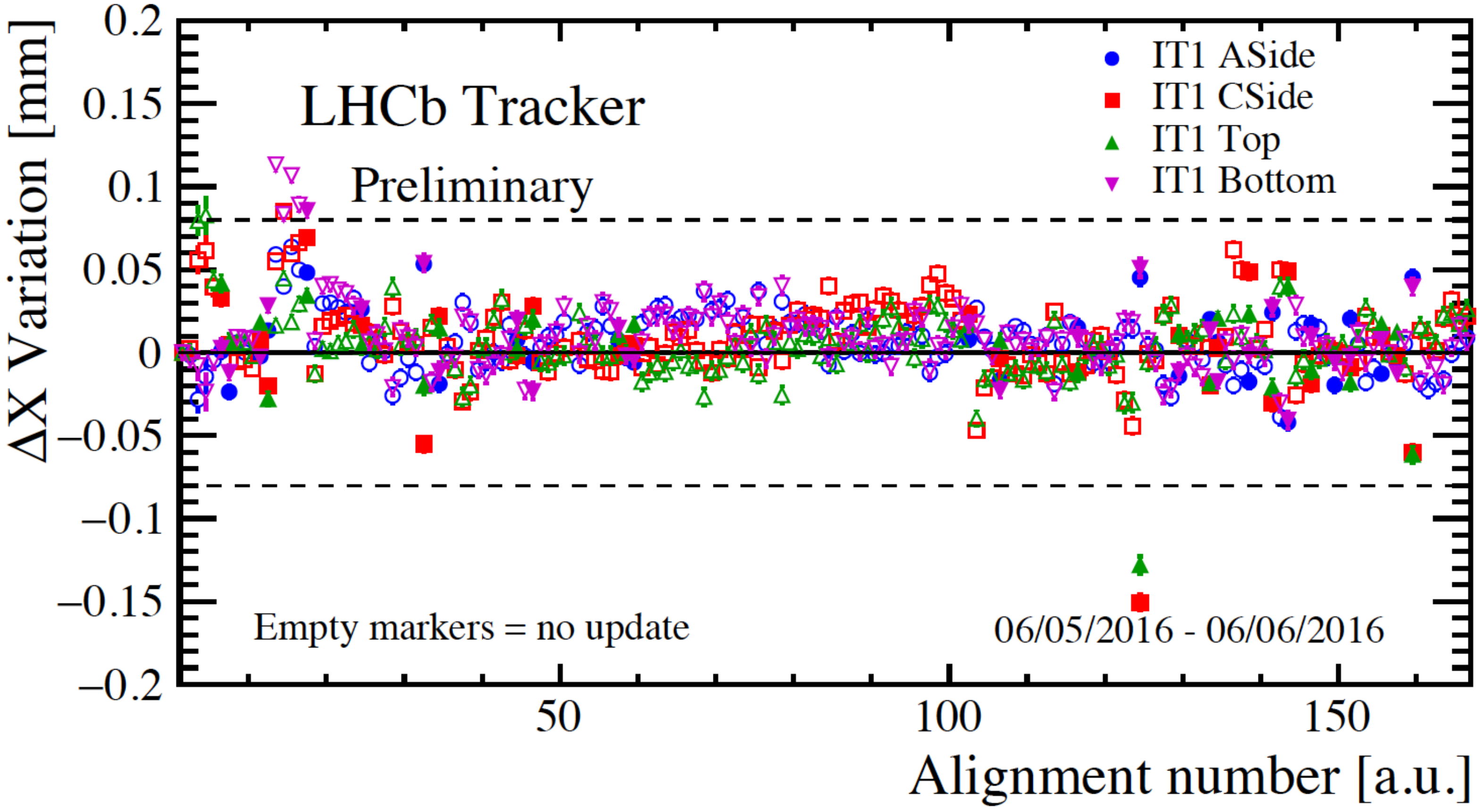
In 2015 LHCb introduced a new procedure for following the ageing of the calorimeter, which led to much more stable ratios of electron to muon rates. The jumps you see are deliberate selection changes, not ageing.

So if you can, align & calibrate in real time

Randomly selected events align the vertex detector



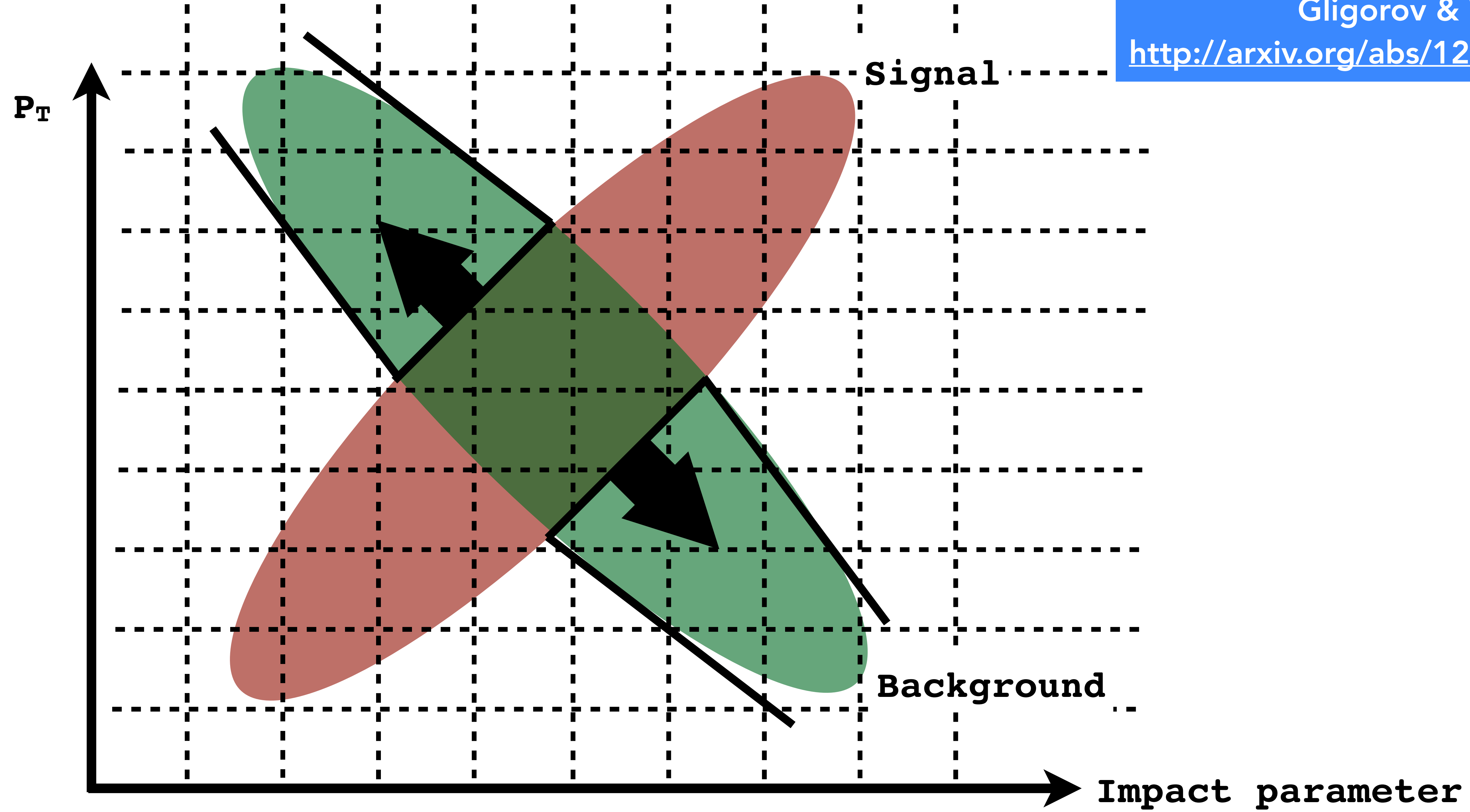
Selected $D^0 \to K\pi$ events used to align the full tracker



Aligning a detector can be slow, but you can speed it up by parallelizing the alignment process across a compute farm. Then you have to select the right events to feed the alignment algorithms, depending on the detector.

Make selections simpler to calibrate

Gligorov & Williams
http://arxiv.org/abs/1210.6861



Consider a two-variable BDT : this is like a binned selection where the BDT algorithm picks the optimal bin sizes and boundaries

by matching selection & reconstruction

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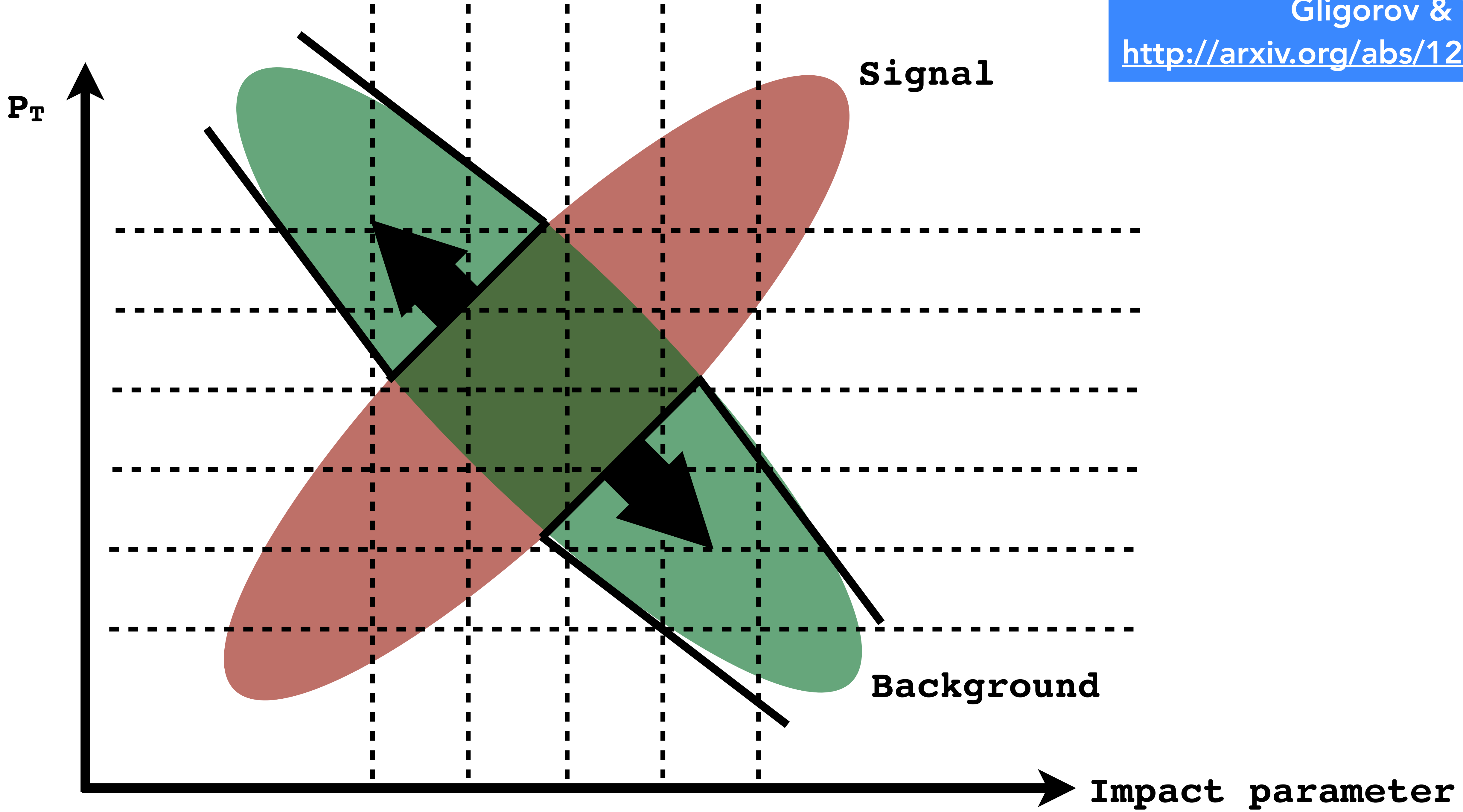
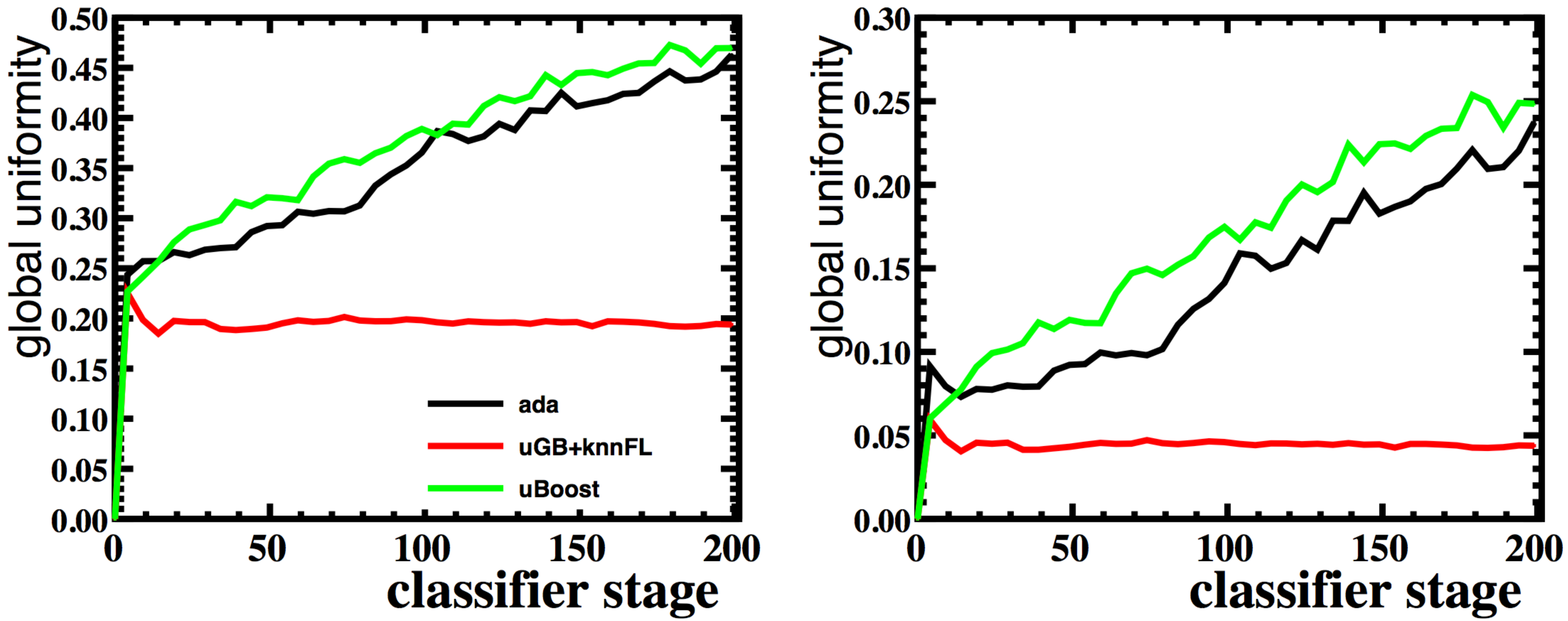


If you pick the binning yourself based on detector resolution and observed variations in the detector performance over time, you will lose some 5-10% of overall discriminating power but you get a selection which is simple(r) to calibrate and much faster to implement (becomes 1D lookup table).

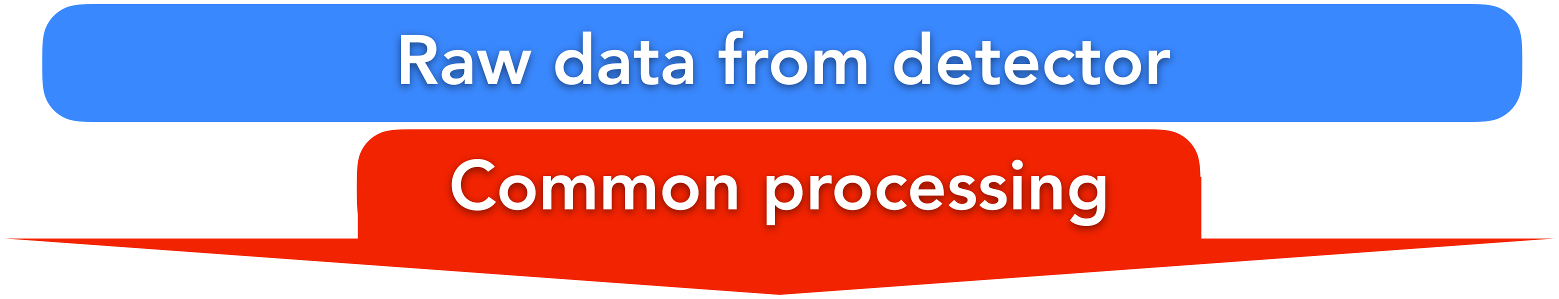
Further reducing selection biases

Rogozhnikov et al.



You could also use classifiers which can be pre-calibrated to have a uniform efficiency or background rejection with respect to any variable/feature of interest for a marginal (few percent) loss in absolute performance. This is especially powerful and useful when you are selecting the signal with multivariate classifiers, which can distort kinematic/geometric distributions if not handled with care.

So which efficiency do you need to know?

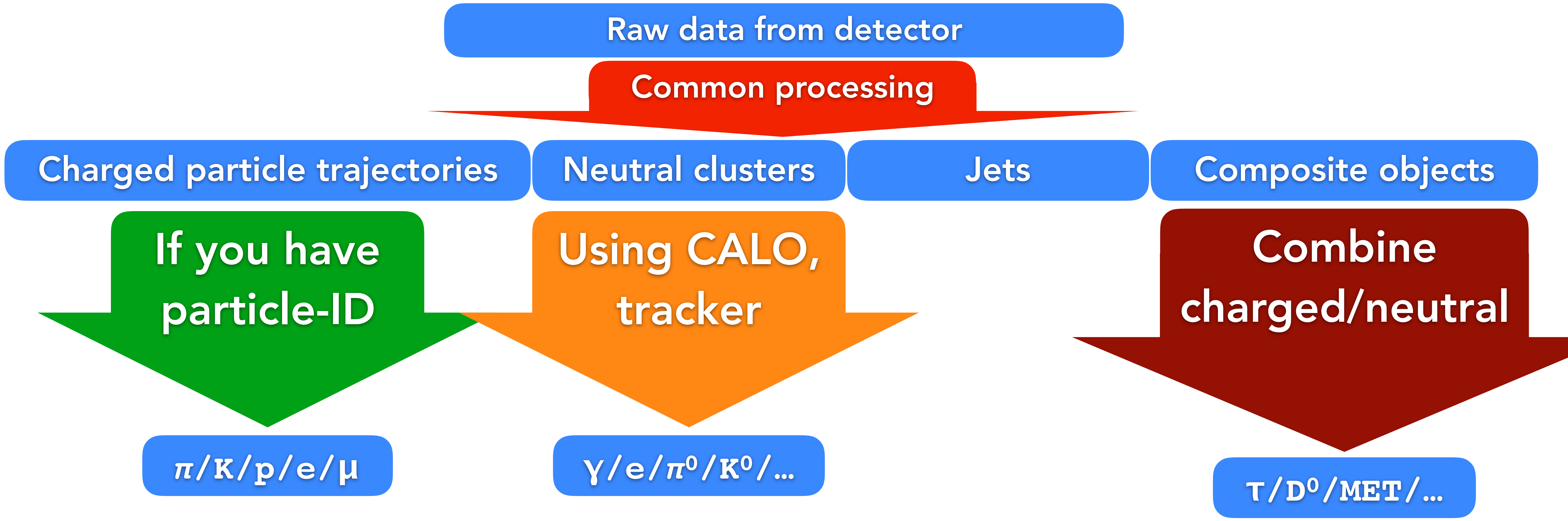


That depends on what you are selecting and indeed compressing!

The common object efficiency?

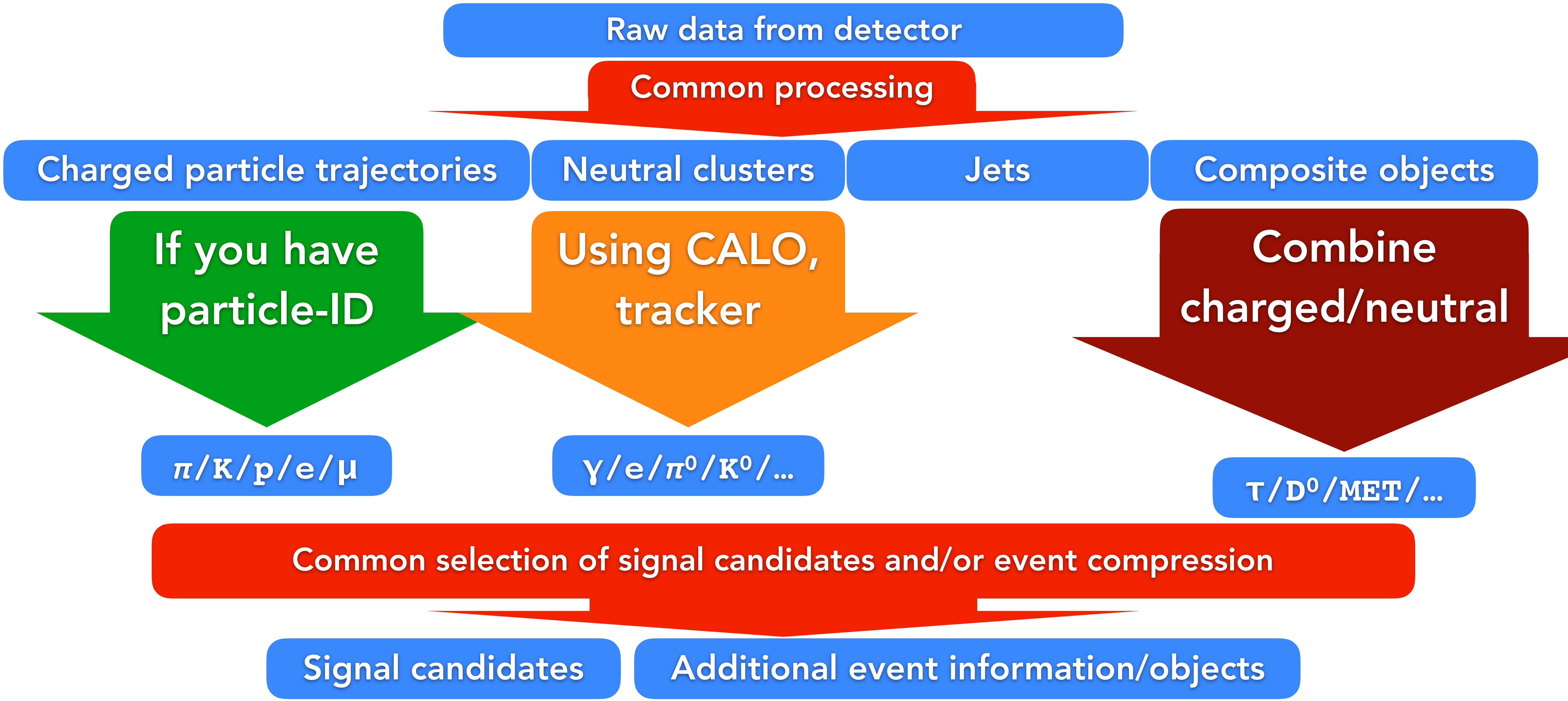
You may need to know efficiency to reconstruct the basic common objects

The composite object efficiency?



You may need to know efficiency to make more complex common objects

The signal selection efficiency?

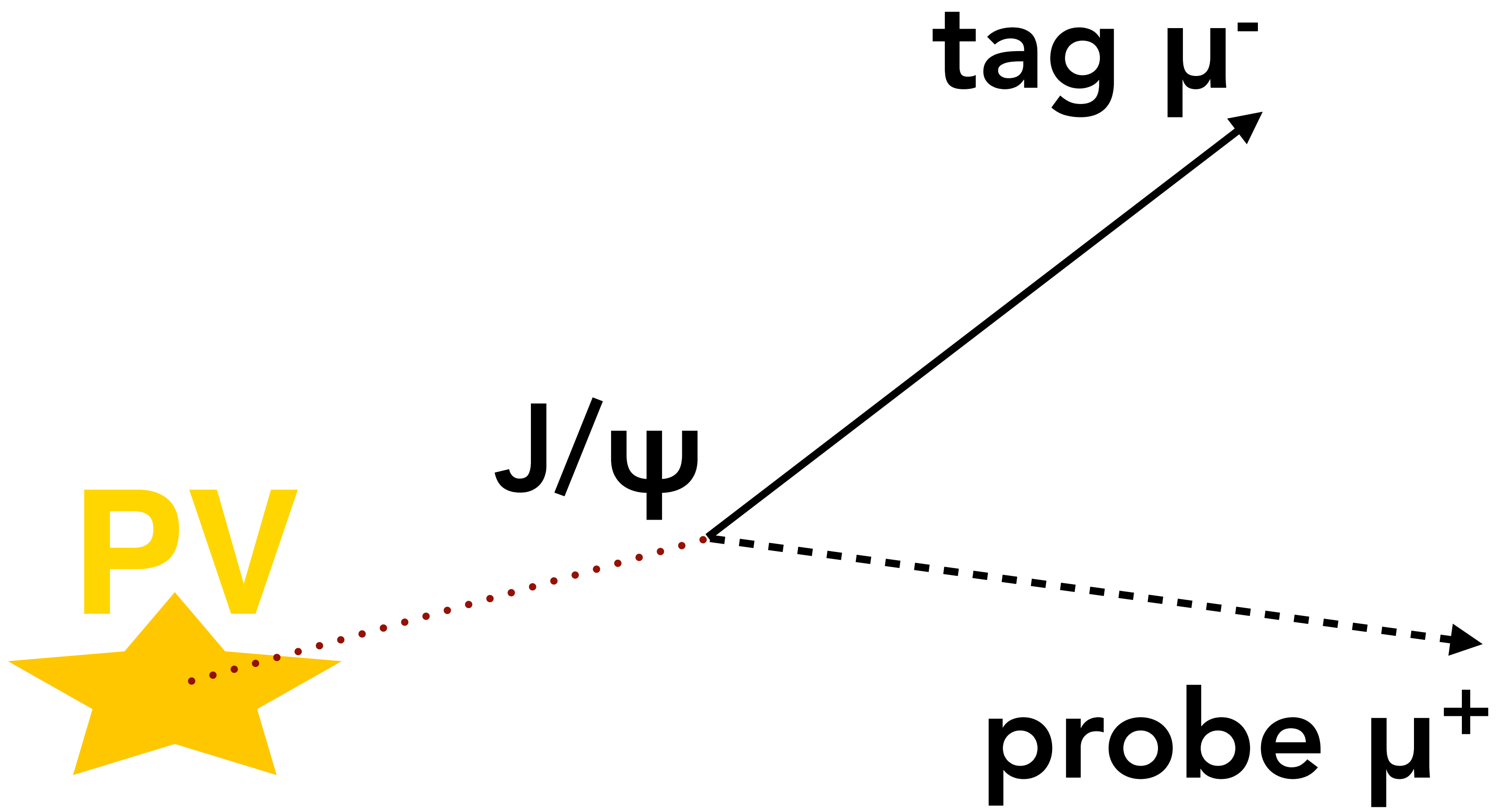


And/or you may need to know the efficiency to perform the final selection.

Tag & probe, the basic tool for efficiencies

The most basic technique which you can use for determining efficiencies is called tag&probe. You select the "probe" object for which you want to measure an efficiency using a separate "tag" object, and then count how frequently (efficiently) you also select the probe.

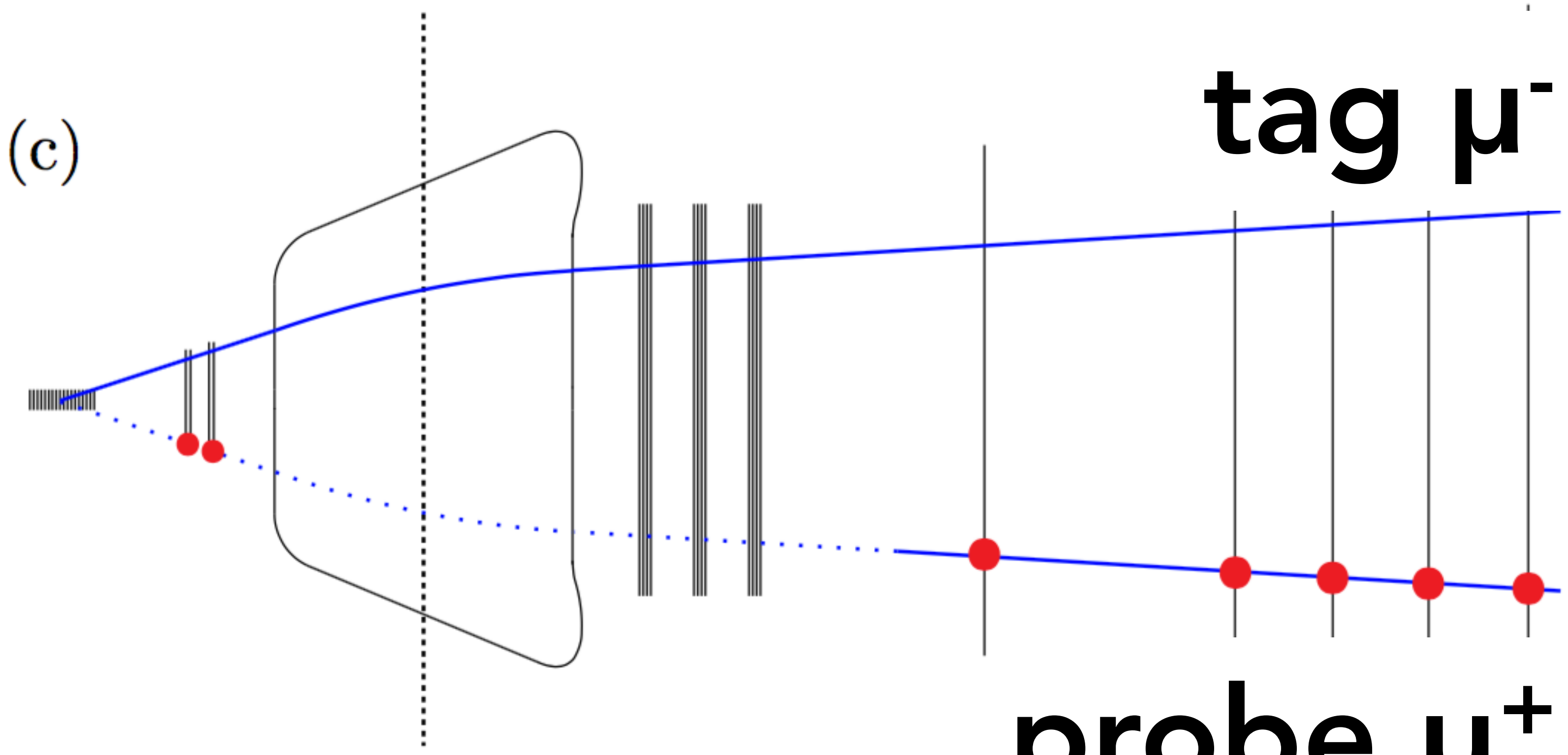
Tag & probe for tracking efficiencies

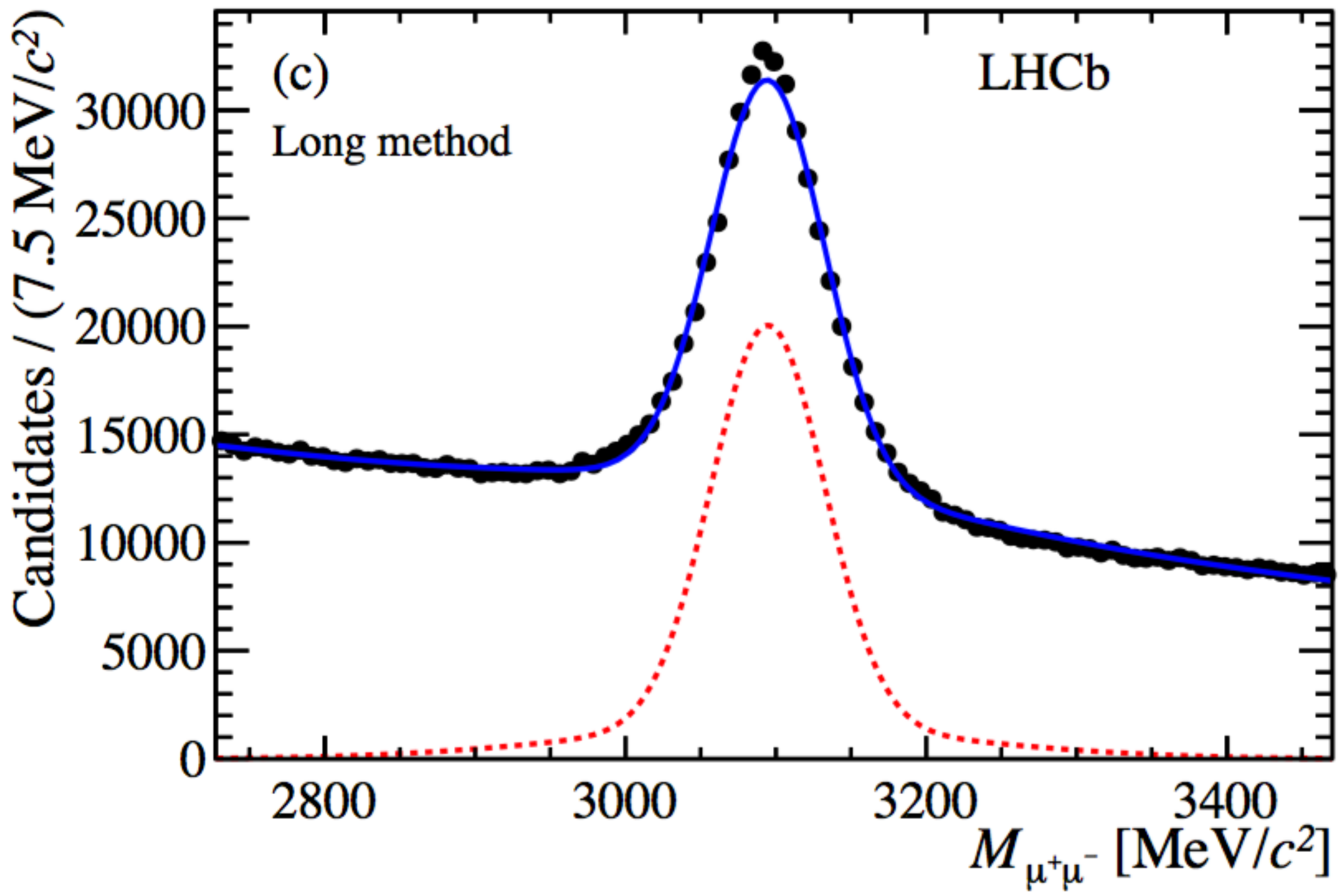


Let's take as an example the efficiency of charged particle reconstruction ("tracking"). One of the most common tag-and-probe pairs is J/ψ→μμ, because muons are rare so the tag can be selected cleanly.

You must partially select the probe

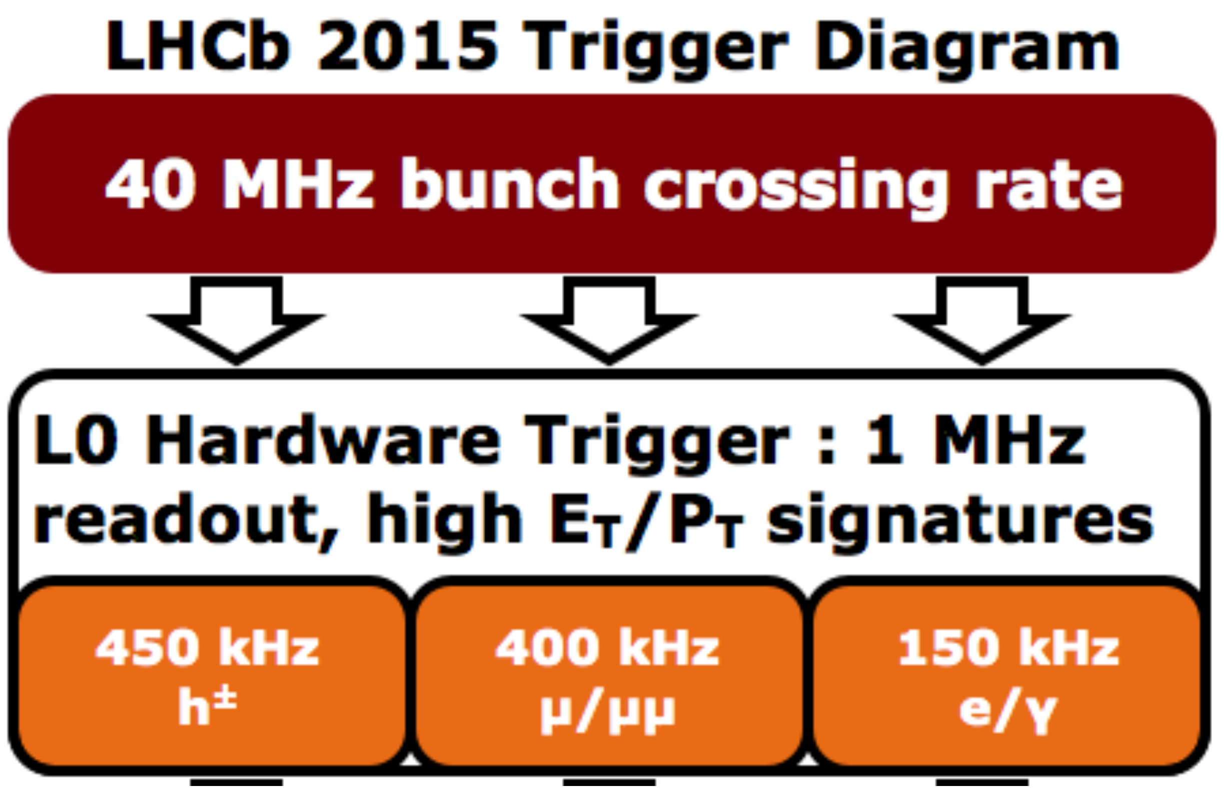
LHCb-DP-2013-002





You of course need to partially select the probe, because otherwise how can you tell the tag muon came from a J/ψ? But you don't need much resolution to see a mass peak so typically you can simply reconstruct the muon track in the muon detector, and rely on the standalone momentum measurement to get a mass peak (for the LHCb peak shown it is a bit more complicated but the idea is the same).

What about the full selection efficiency?



If you need to know the full efficiency of a specific real-time selection for your signal, the most common technique is also a kind of tag&probe. Let's take as an example LHCb's fixed latency selection which requires either an energetic calorimeter cluster, or an energetic muon or dimuon.

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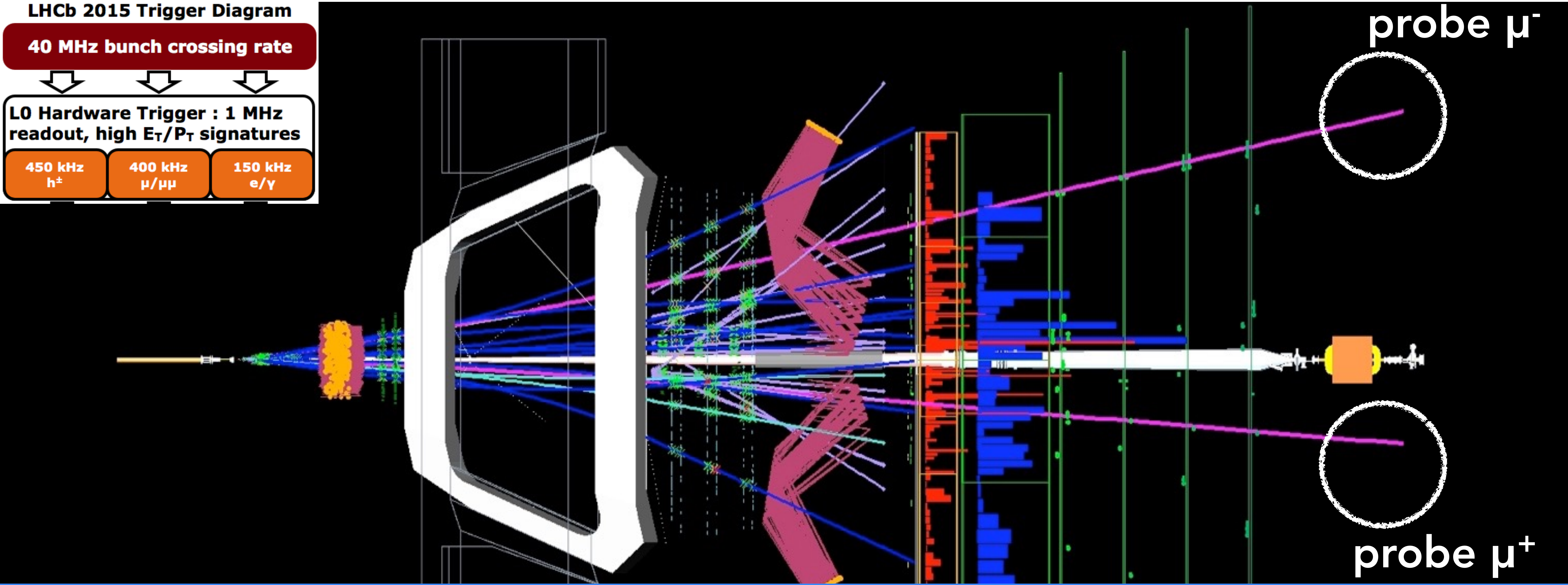

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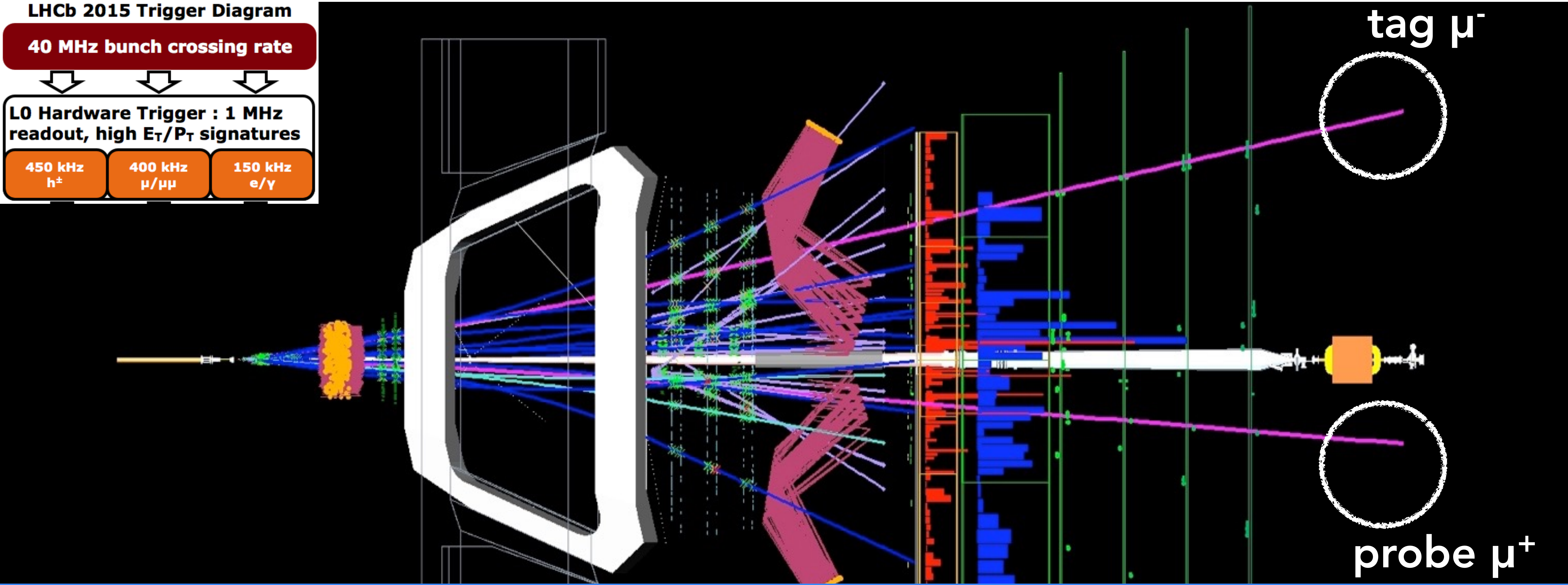

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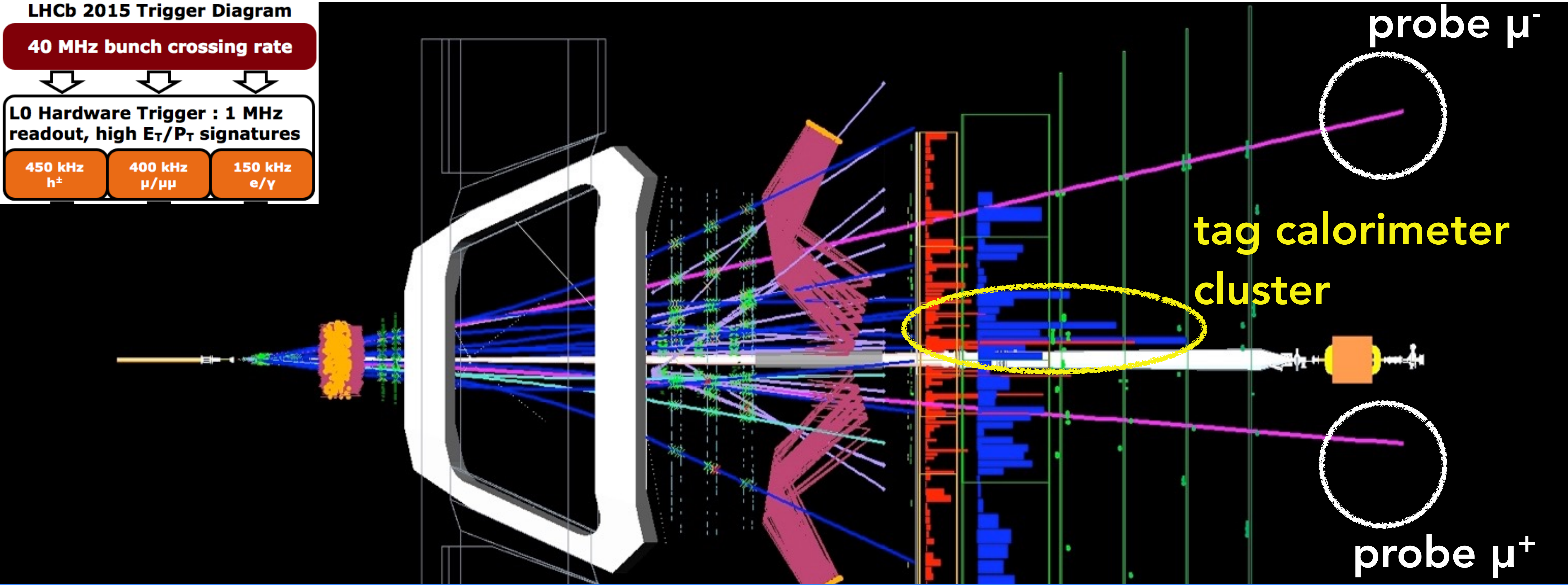
What about the full selection efficiency?



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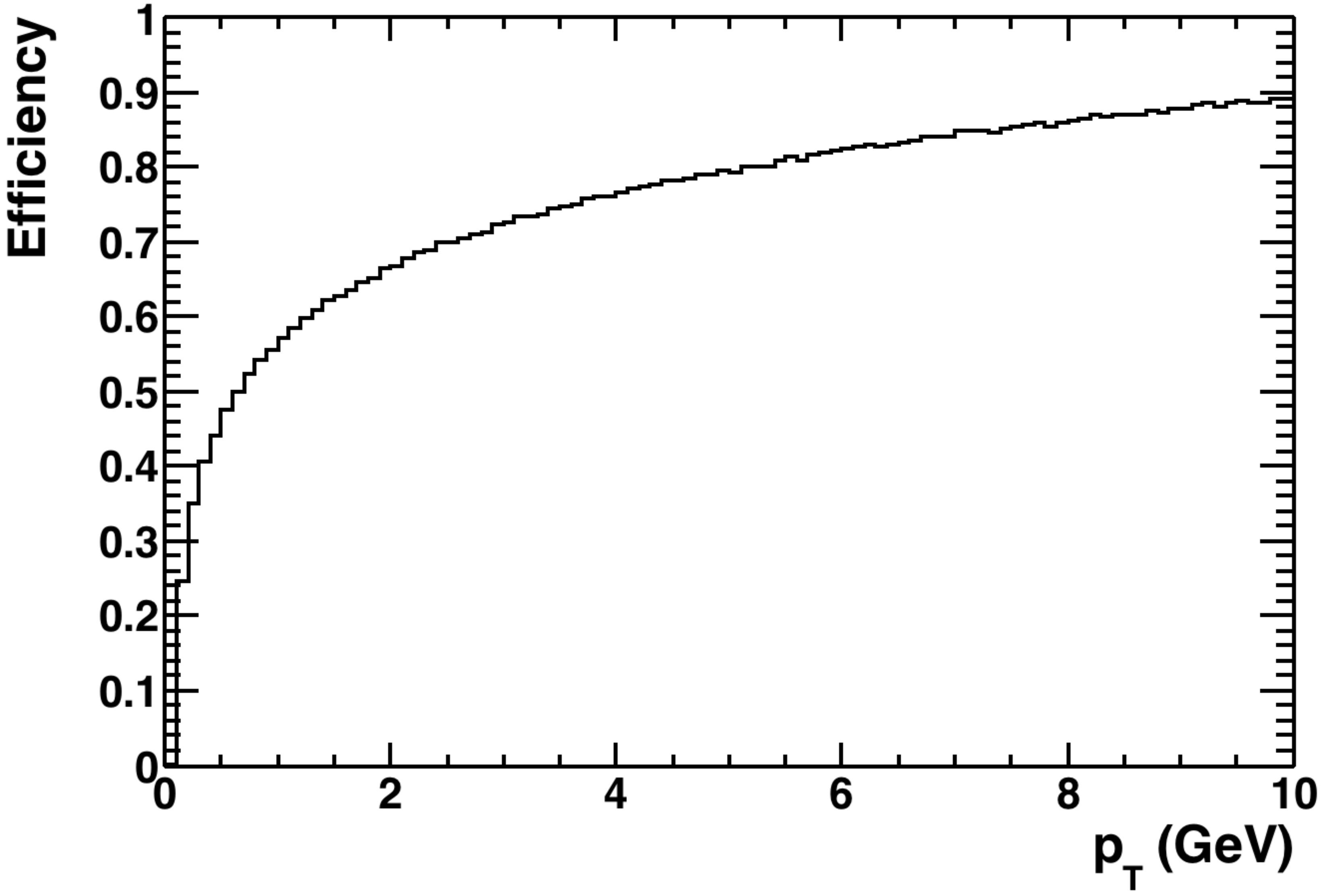
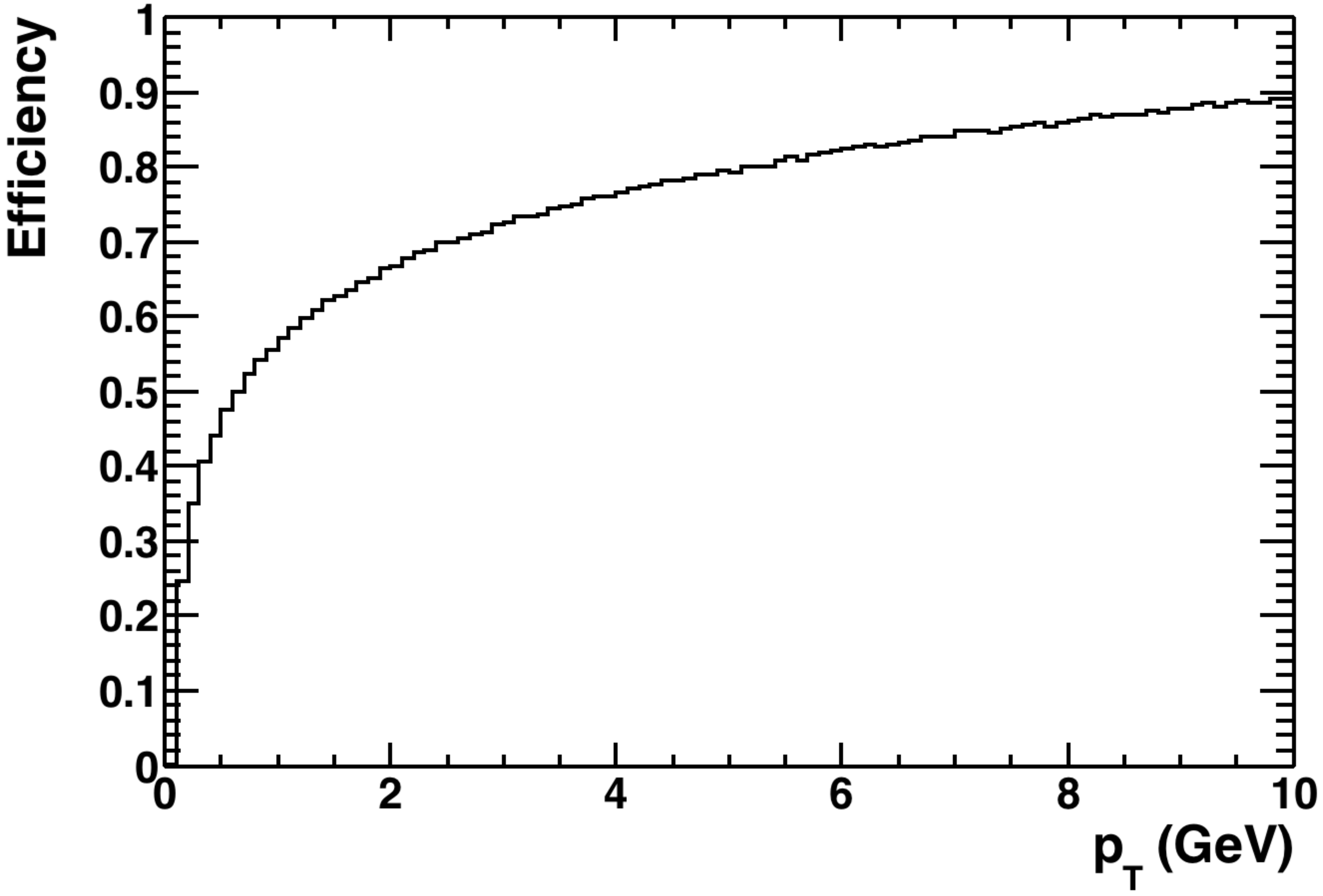
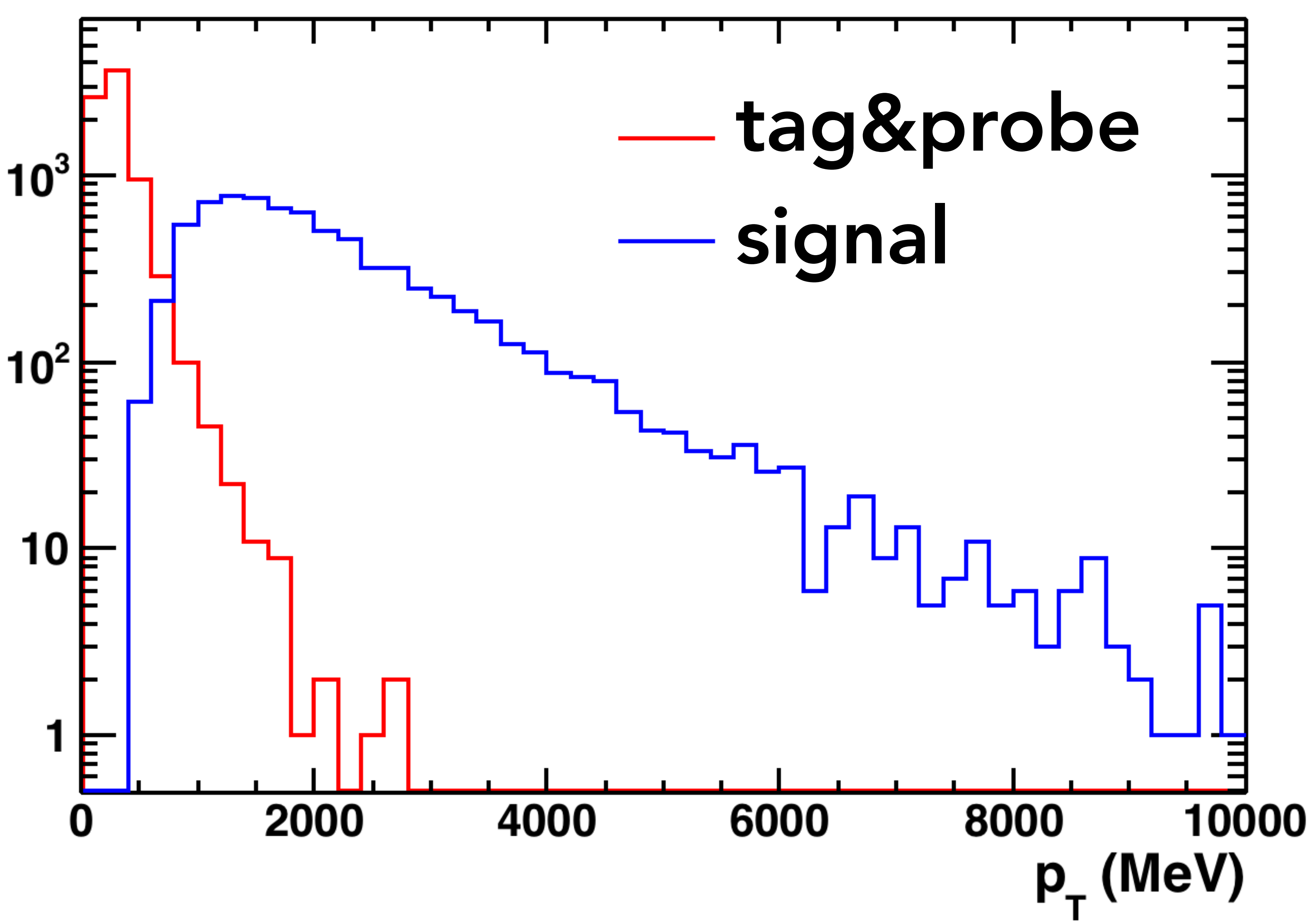
And if efficiencies depend on kinematics?



Most efficiencies you need will vary as a function of your kinematics. It is therefore important that your calibration (tag&probe) and signal samples have matching kinematics.

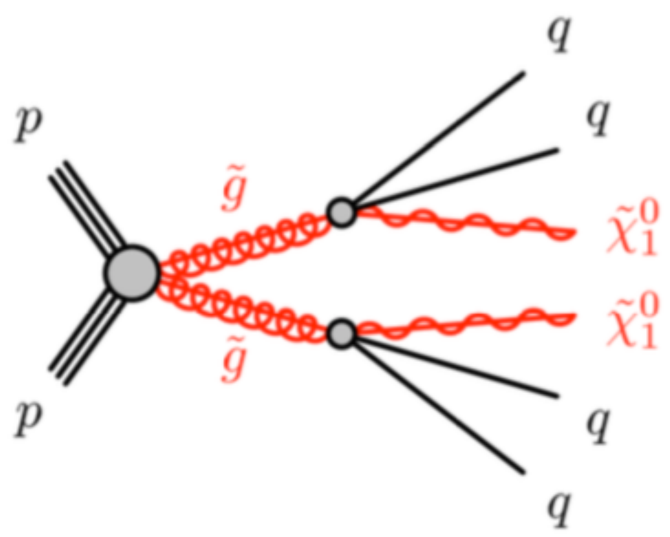
You need to match the calibration&signal





Most efficiencies you need will vary as a function of your kinematics. It is therefore important that your calibration (tag&probe) and signal samples have matching kinematics. If they don't, the calibration is not of much use.

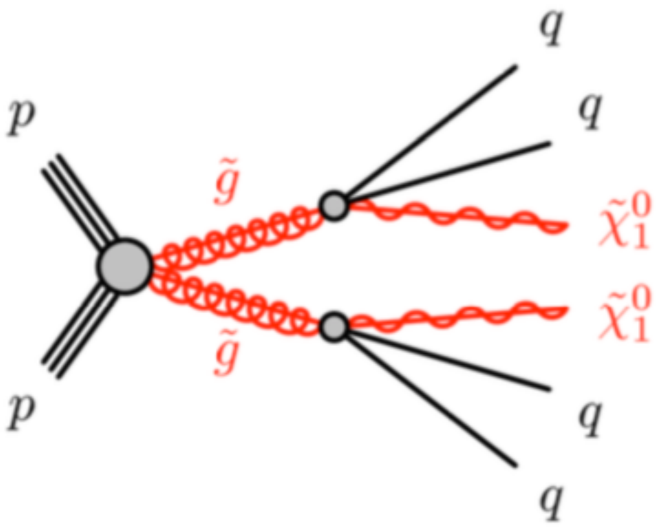
Reweighting calibration or simulation

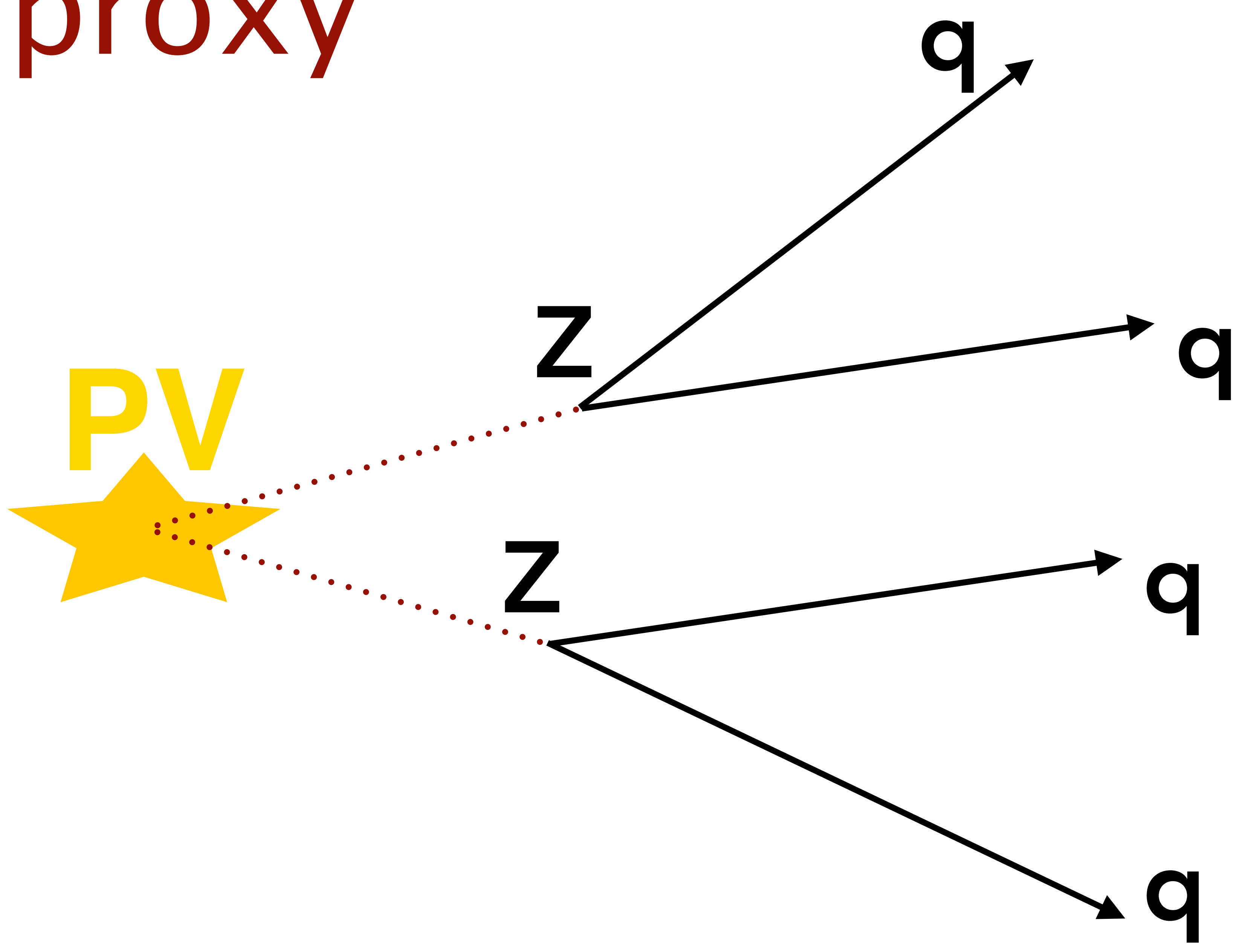


But if you are looking for a new beyond standard model signal, how do you know its kinematics in data?

This mismatch problem can also occur because the simulation kinematics don't match the signal kinematics. In both cases you need to reweight the calibration or simulation samples to match your signal before using them.

You need to use a proxy





You don't, but you can use a related well-known SM control channel which you are able to select cleanly, and derive data/simulation correction factors from this to port to your signal.

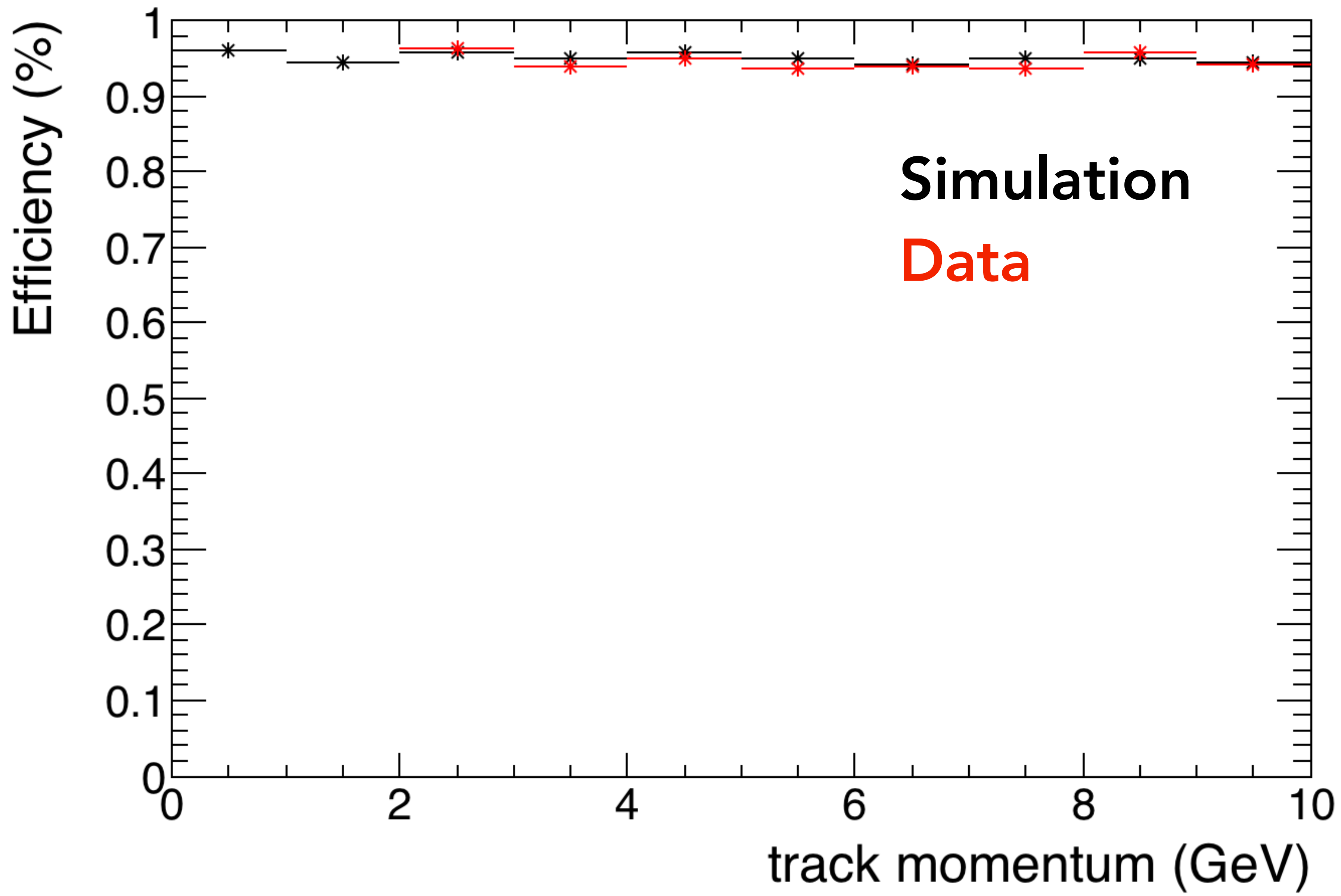
Some boobytraps when reweighting

If using an exclusive selection strategy you have to remember to write selections for all the control and calibration signals as well!

Be careful with kinematic regions which are not covered by your calibration samples. If your correction factors are close to 1, it may be safe to use a nearest-neighbour region as a proxy and assign a generous systematic uncertainty. If not consider removing them.

If the signal and control samples are very different from each other and their distributions vary rapidly, you need to bin more finely when reweighting in order to avoid biases.

Danger of regions not in calib sample



Say you are calibrating data-simulation differences and get the above plot for efficiency on data/simulation. Would you feel comfortable extrapolating into the region not covered in the data sample?

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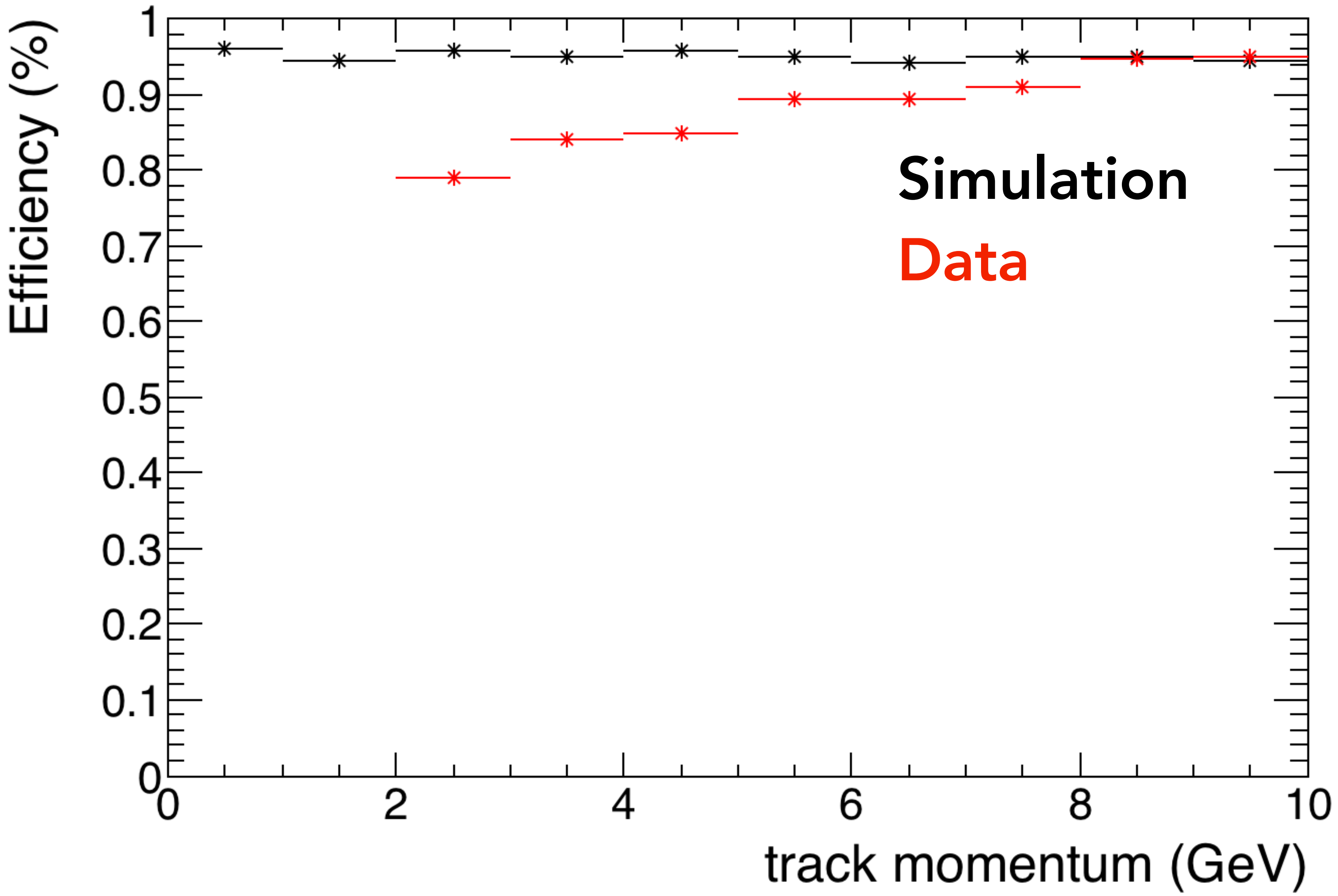

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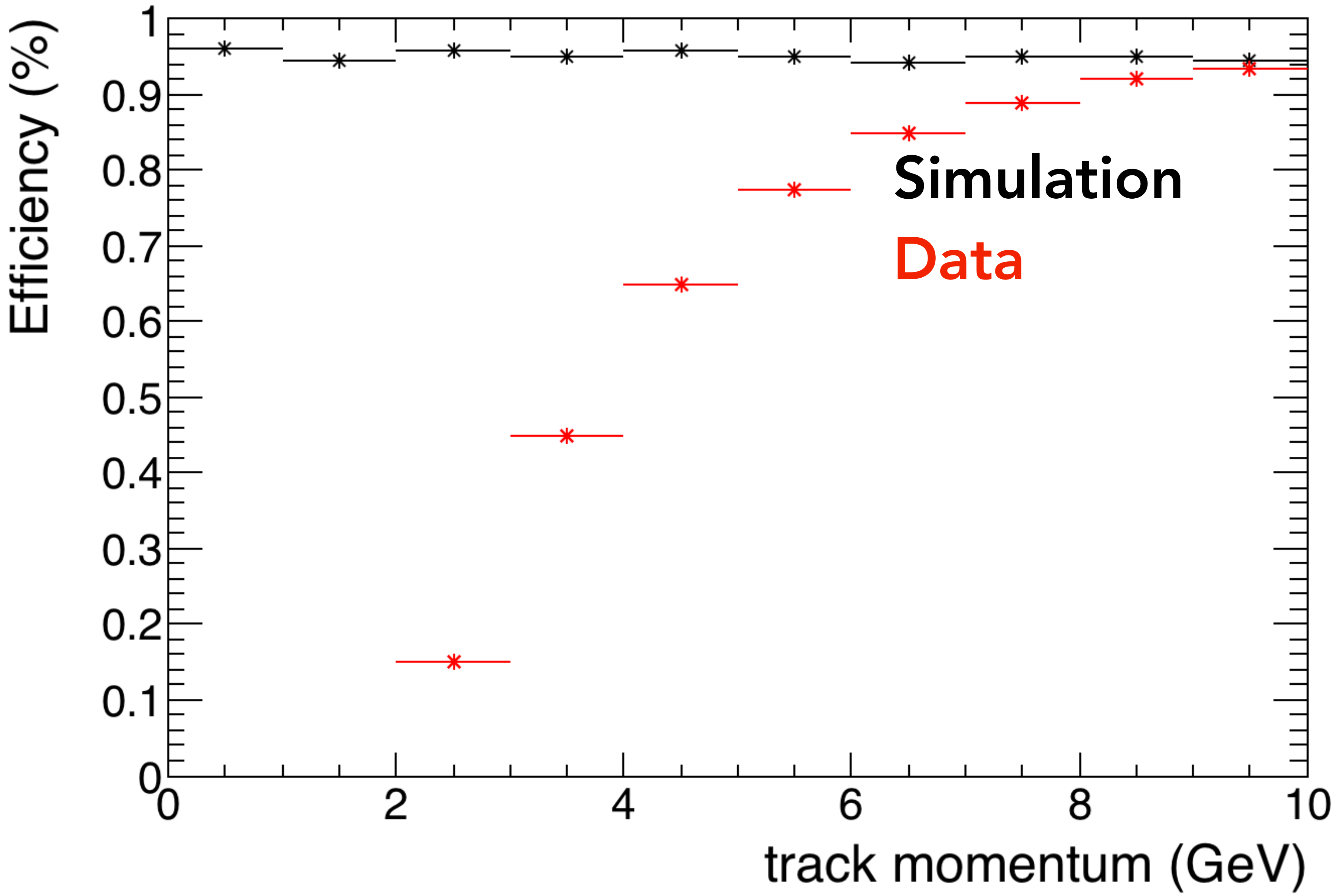

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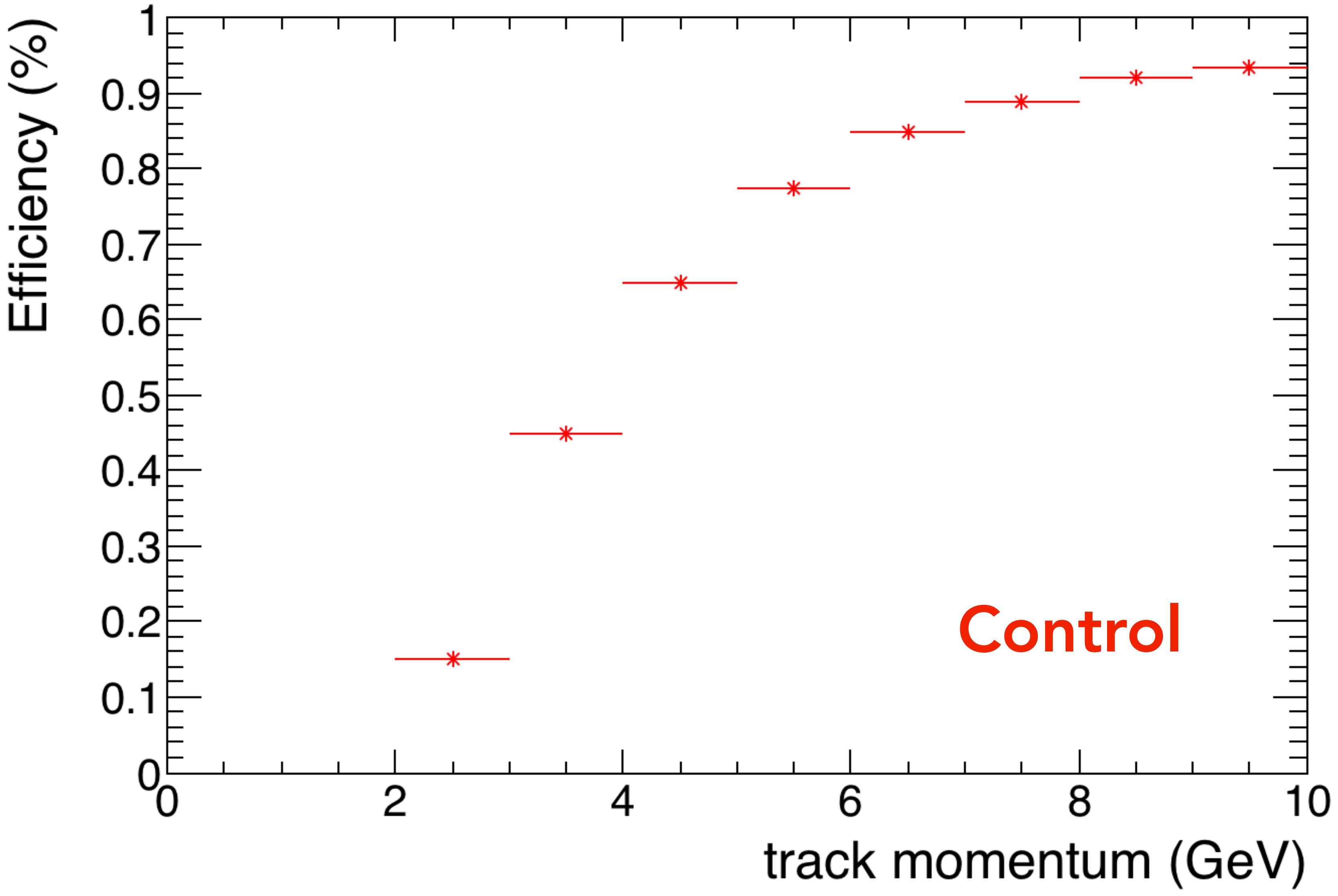
Danger of rapidly varying distributions



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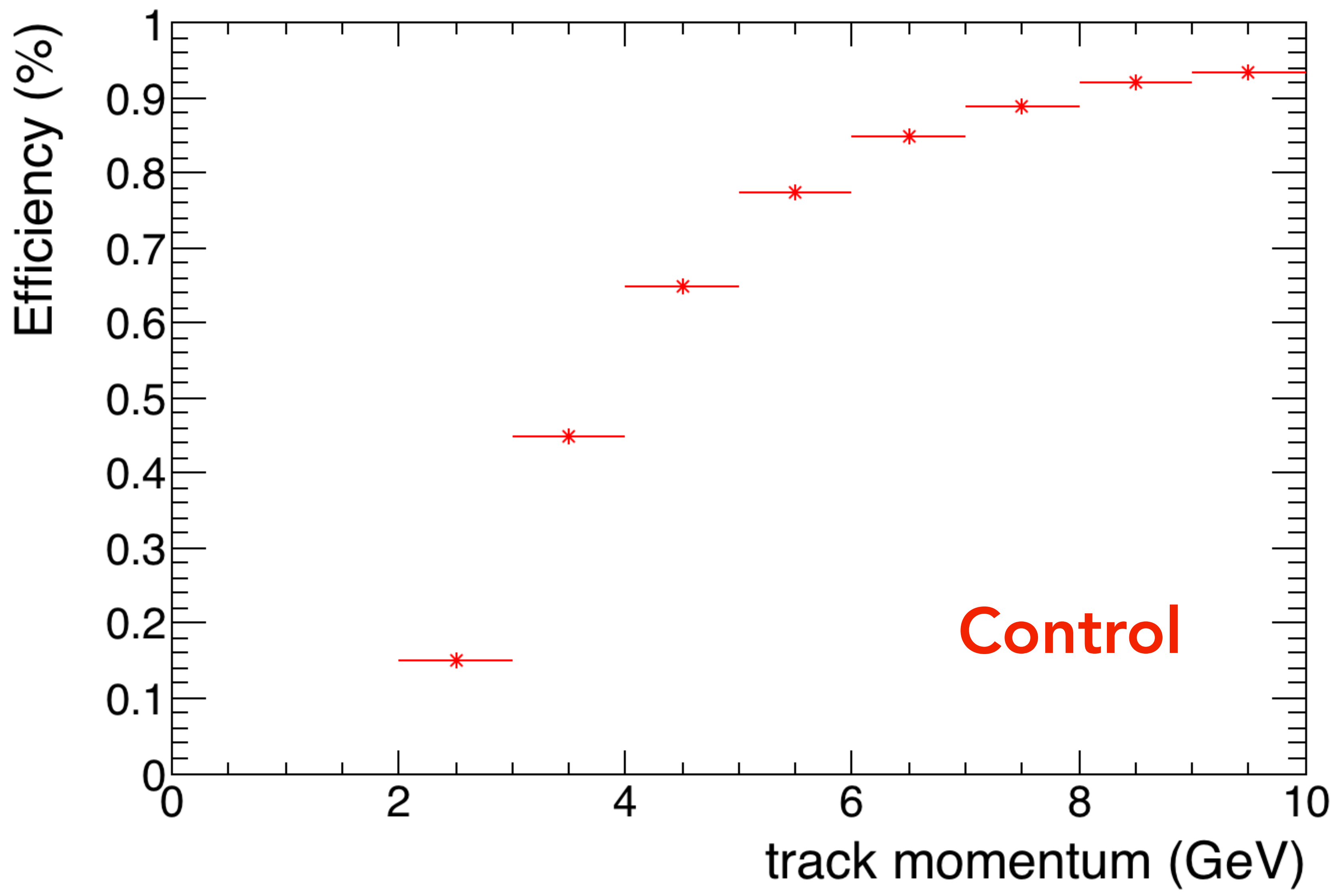

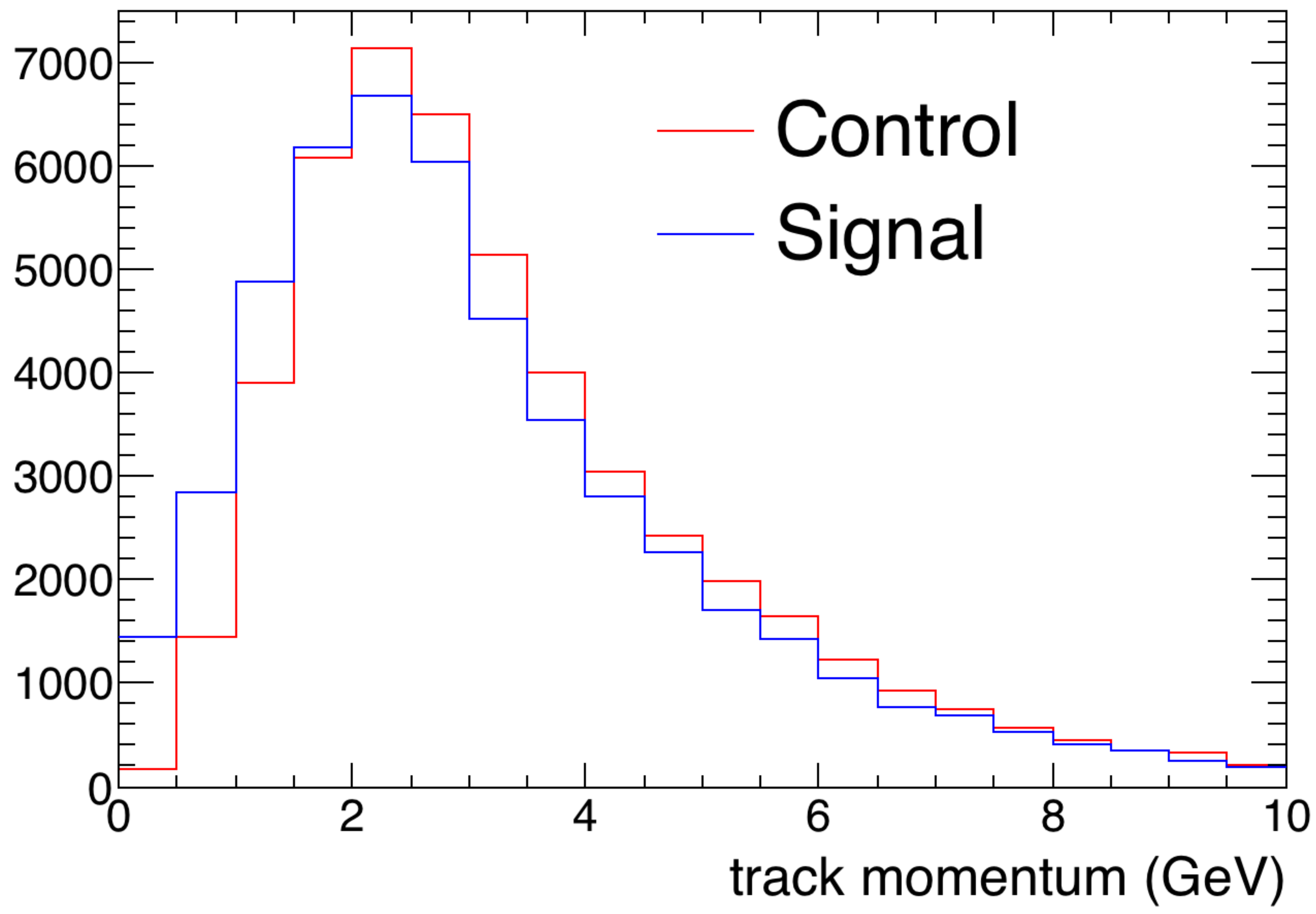

Another pitfall with a binned plot is that each entry is the average efficiency in a given bin. But this assumes signal and control samples have roughly the same kinematics *in each bin*! If not, bin more finely or reweight.

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Thanks for listening!