What you always wanted to know about...

Data Acquisitions, Trigger, Controls

(… but never dared to ask.)

Martin L. Purschke, Brookhaven National Laboratory

Data Acquisitions, Trigger, Controls

About Martin

- Studied nuclear physics at the University of Muenster, Germany
- WA80 - WA93 – WA98 Experiments at CERN
- Graduated in 1990
- Spent 11 years at CERN with the SPS Heavy-Ion Program until it ended in 1996
- Then I moved “with the program” to Brookhaven National Laboratory
- BNL has the Relativistic Heavy Ion Collider called “RHIC”

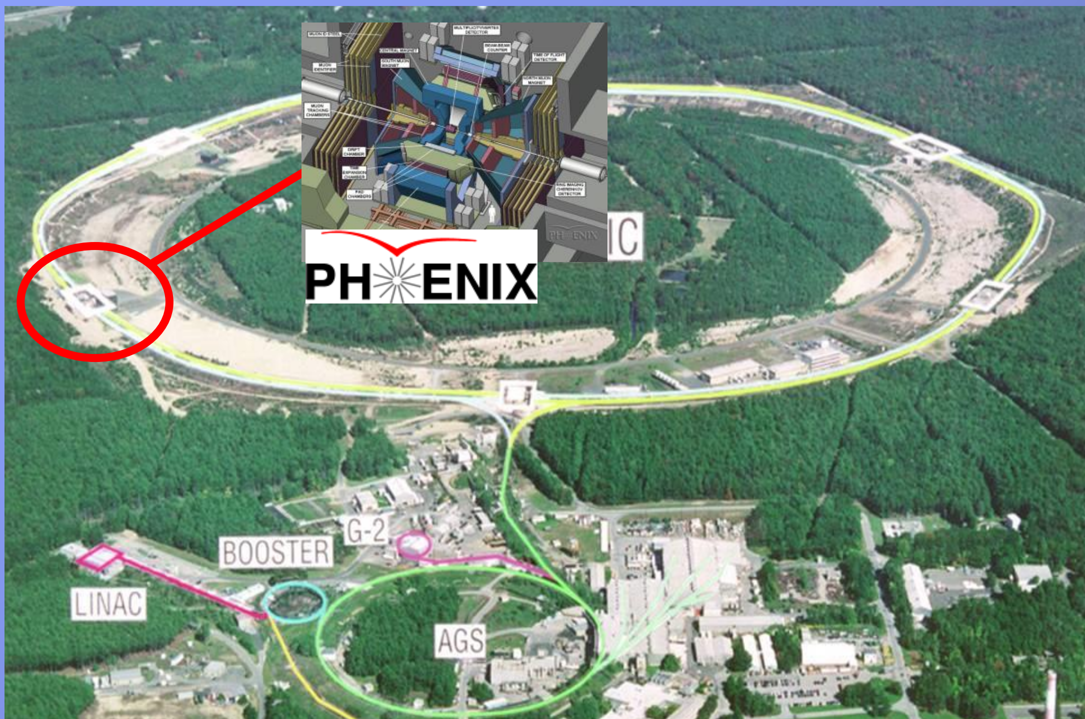
New York City

Manhattan

Long Island, NY

RHIC from space

RHIC/PHENIX at a glance



PHENIX:

4 spectrometer arms

12 Detector subsystems

2500,000 detector channels

Lots of readout electronics

Data rate ~7KHz (AuAu) , 9KHz (pp)

Data Logging rate ~900-1200 MB/s 1600MB/s max

RHIC:

2 independent rings, one beam clockwise, the other counterclockwise

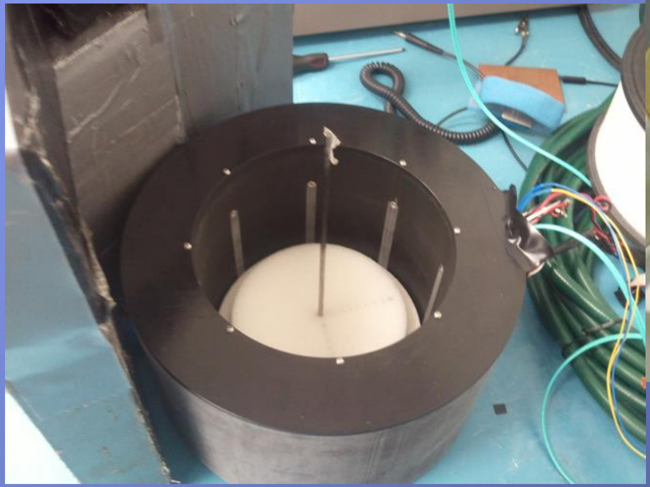
$sqrt(S_{NN})$= 500GeV * Z/A

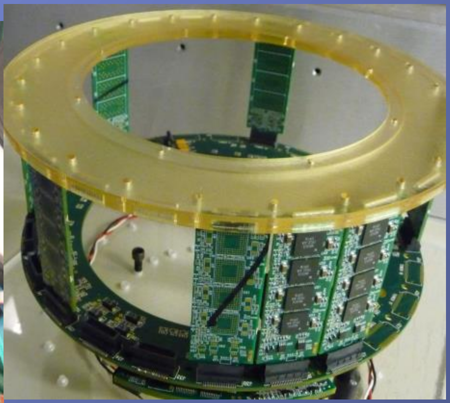
~200 GeV for Heavy Ions

~500 GeV for proton-proton (polarized)

Medical Imaging / PET @BNL

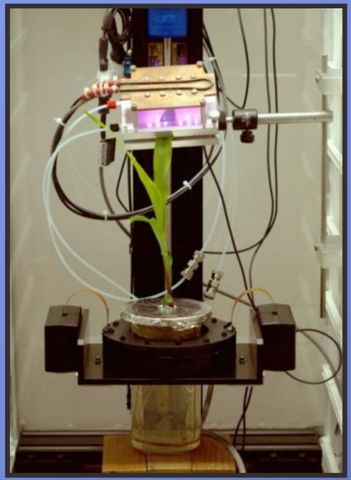
Original Ratcap V1





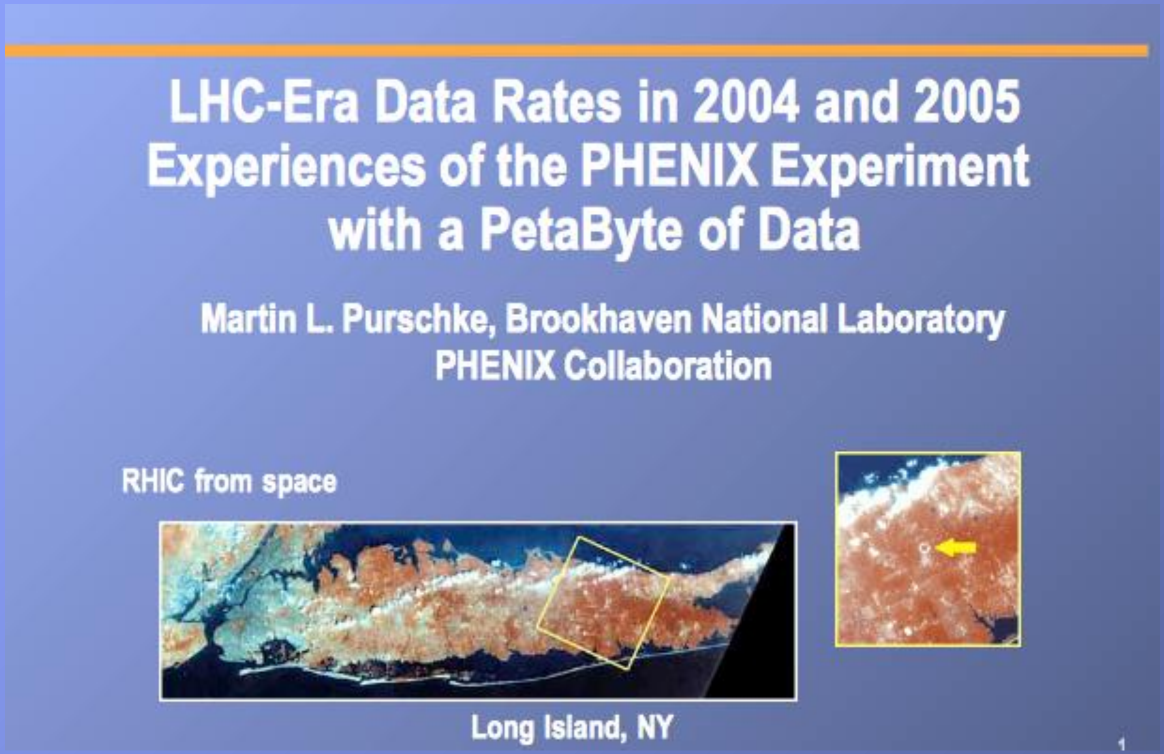
Breast Scanner

UPenn Scanner   400MB/s DAQ application



Plant Scanner

PHENIX - an “early” high-rate experiment



My opening slide at the Computing for High-Energy Physics Conference in Mumbai, India, 2006

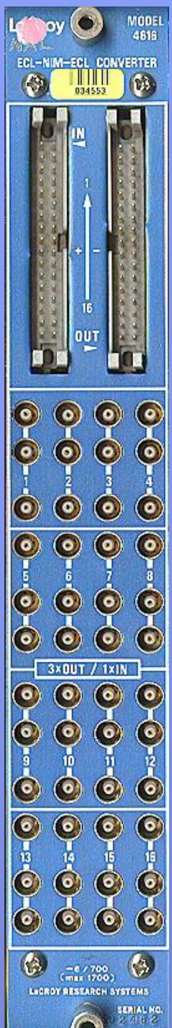
I am the Data Acquisition Coordinator for PHENIX and our successor experiment “sPHENIX”

… and that's why I'm here today.

DAQ Timelines

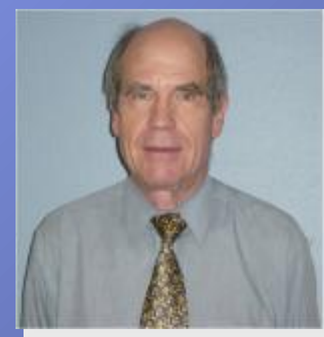
1970	Minicomputers, PDP-11, Tracor
	CAMAC and NIM electronics emerge as the de-facto standards for instrumentation
1980	VME and Fastbus, VAX-VMS as standard OS, Digital Equipment dominates scientific computing and DAQ
	data acquisition hardware from standard building blocks
	VME Processors with CAMAC and Fastbus.
1990	UNIX becomes the OS for DAQs
	custom solutions for (by then-standards) high-bandwidth DAQ’s.
	Single VME crates are no longer big enough
2000	VME Crate Interconnect, VME Taxi
	standard networks for interconnect
2010	Trigger farms, commodity hardware for DAQ, GB/s data speeds

There is a name...



There are many manufacturers (CAEN, …), but this era of physics instrumentation is really associated with…

… **Walter LeCroy**



Even today, many modern detector elements and prototypes see their first test using LeCroy electronics

"I did it in Blue Logic", referring to the LC blue color

Also, a prestigious series of "Electronics for Future Colliders" conferences held at LeCroy's headquarters in the early 90's

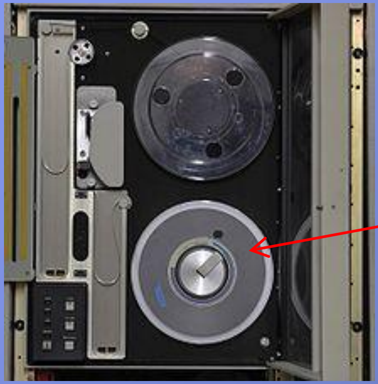
Computing ca. 1985

Our flagship mainframe computer, a Digital Equipment VAX 780

About 1/8 as much computing power as my Nexus 5 smartphone these days

Not as much memory though... 4MB

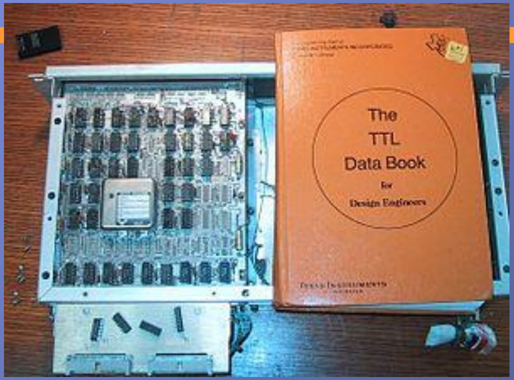
But a great OS, OpenVMS



This is a RA81 harddisk. 600MB, just enough to hold the contents of one data tape

And this is a DEC VT100 terminal, where most of the work took place in those days.

3 Fundamental Signal Standards

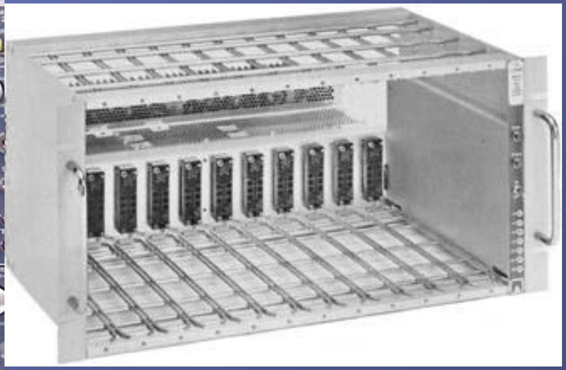


TTL – Transistor-Transistor Logic

0-5V digital signal range

Popular in circuit boards because of a wide range of IC (74LSxxxx)

Poor timing characteristics, high currents (= power) needed – largely obsolete



NIM – Nuclear Instrumentation Module (AEC Standard)

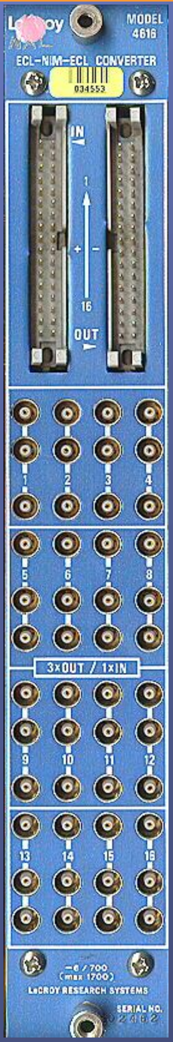
Defines a crate standard, connectors, and power/voltage supply levels, as well as a signal standard

The signals are defined as currents (-16mA into 50 Ohm – makes about -800mV). Negative signals

Virtually every experiment has them. This what made standardization in instrumentation possible

Modules can be inserted and removed “hot”

Signal Standards - ECL



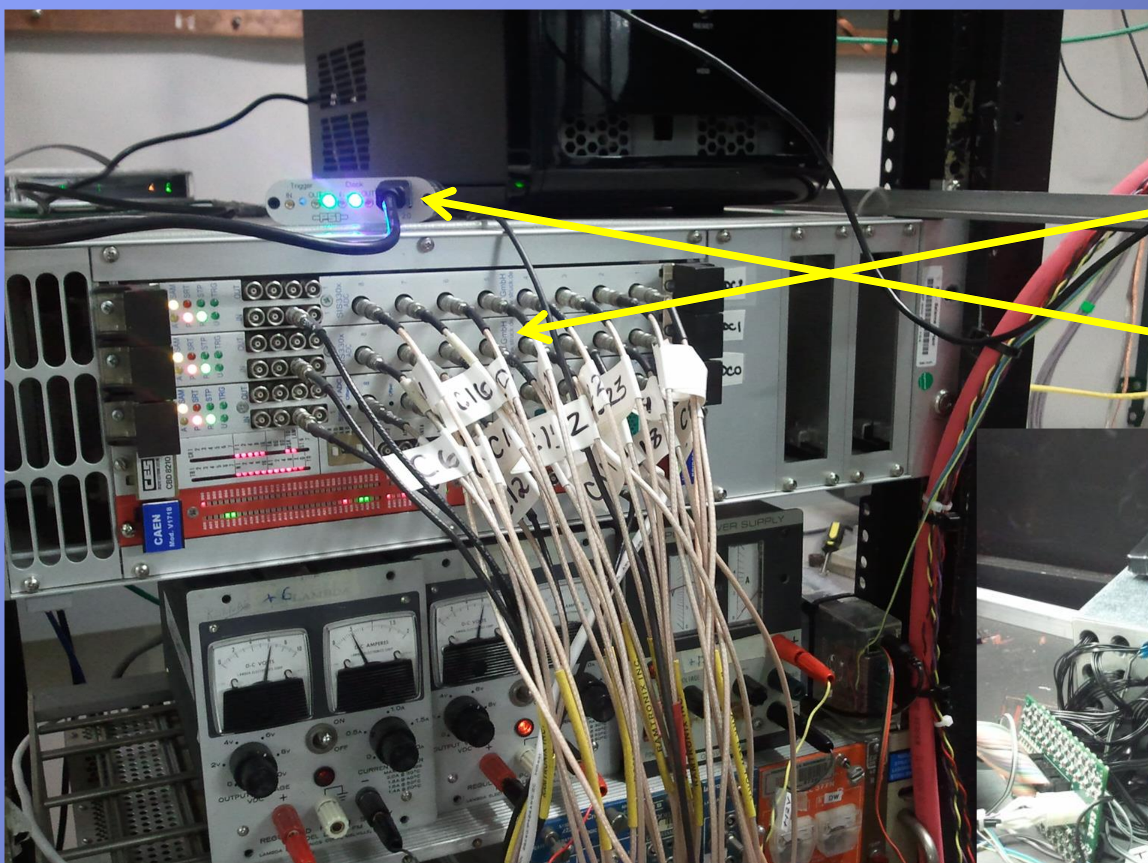
- ECL – Emitter Coupled Logic
- Part of the NIM standard
- Excellent timing characteristics – constant current gets routed on way or another, no capacitance charging
- High-Density (well, back some years) connectors with twisted-pair or short flat cables
- A "bus" of ECL lines can connect to multiple inputs, last one gets terminated – convenient at times
- Flat cables make it harder to make wiring mistakes
- But mostly chosen for speed and density.
- Constant current makes for high power consumption though

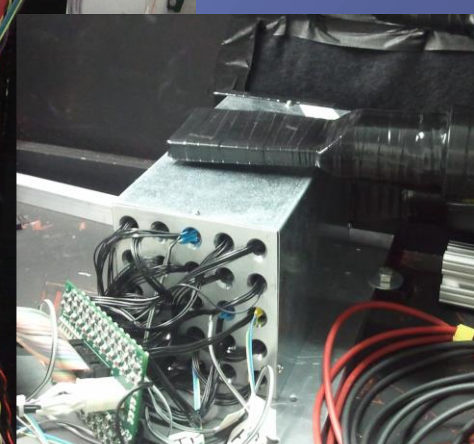
Why do we need to know the "classic" things?

Even in 2014, you are likely to use CAMAC / VME for the initial tests of the detector

Results obtained with "known" electronics drive the development of your final readout

That final readout is likely not available by the time you go to test beams





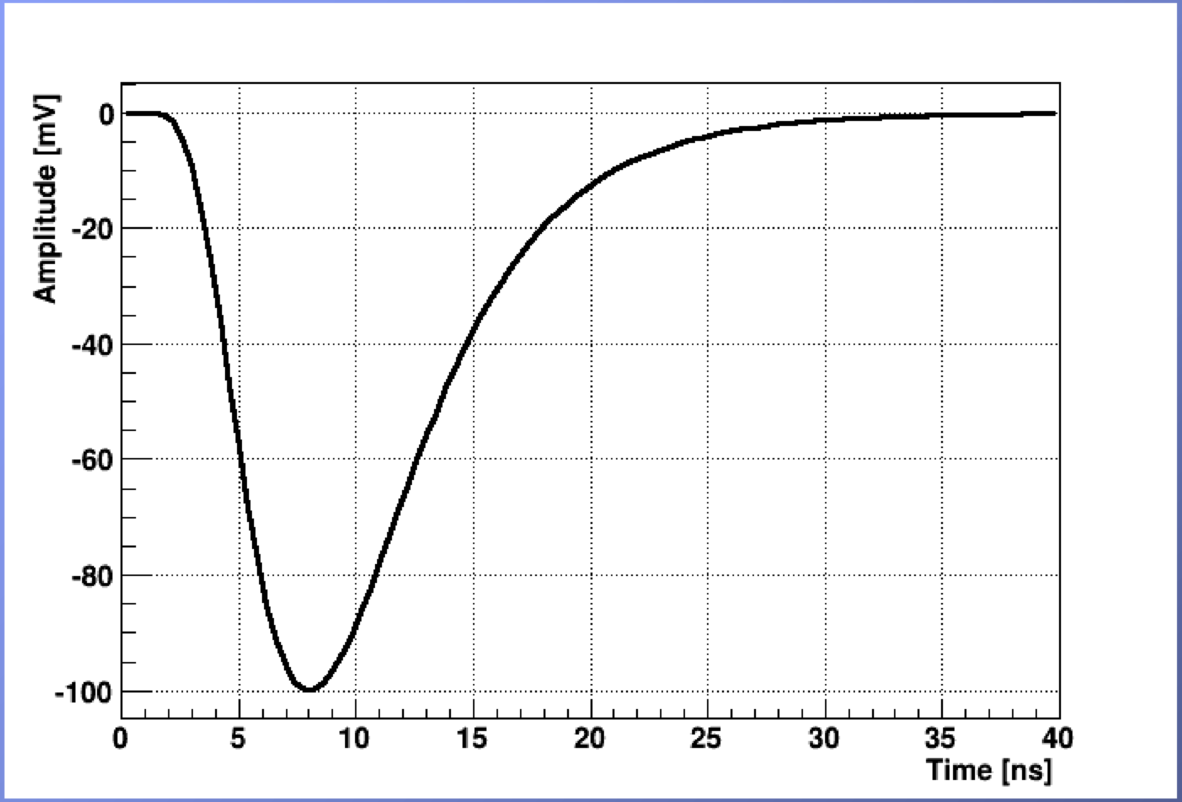
FermiLab test beam Sep. 2013

For the PHENIX-MPCEX detector

Struck SIS3300 Flash ADCs (VME)

(Also a DRS4 eval. Board...)

Signal Discriminators

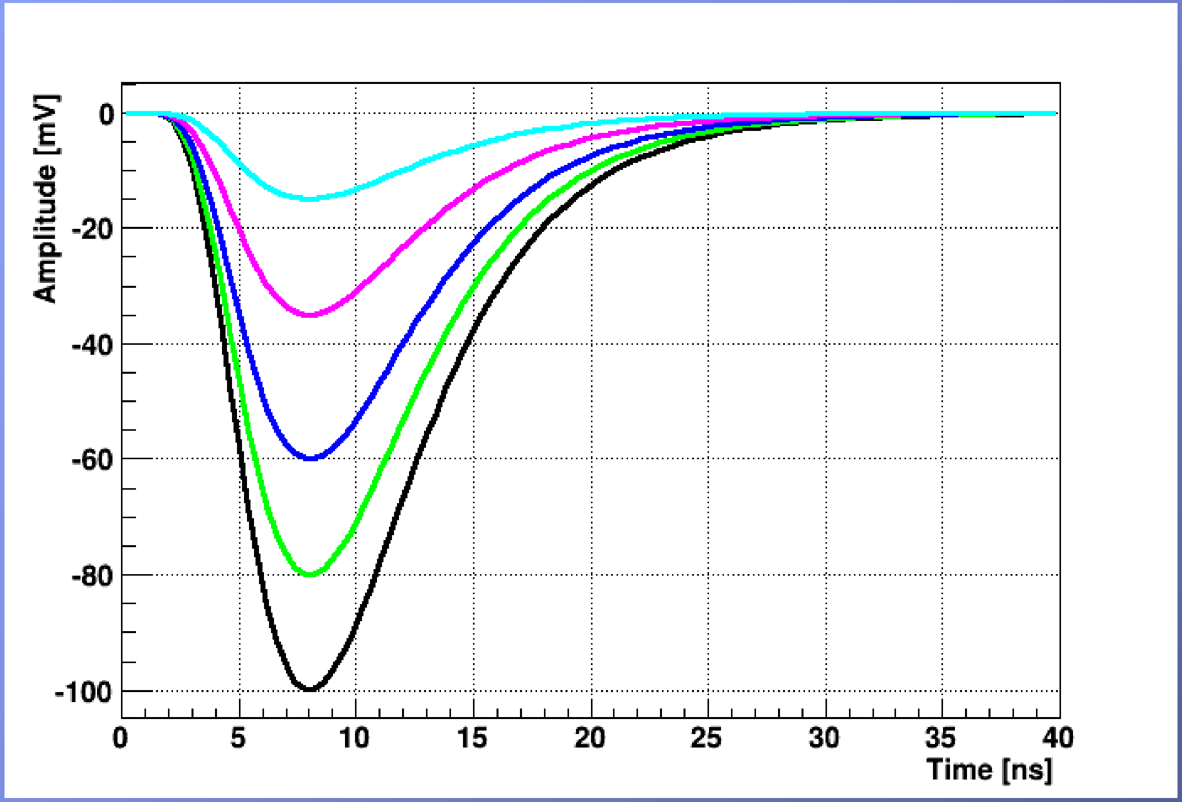


This is a parameterized "typical" signal from a photomultiplier.

It usually has a fast rise and returns to the baseline more slowly.

We almost always deal with negative pulses, so we usually say "rise", although it technically falls. In the same spirit, we always say "signal height"...

Signal Discriminators



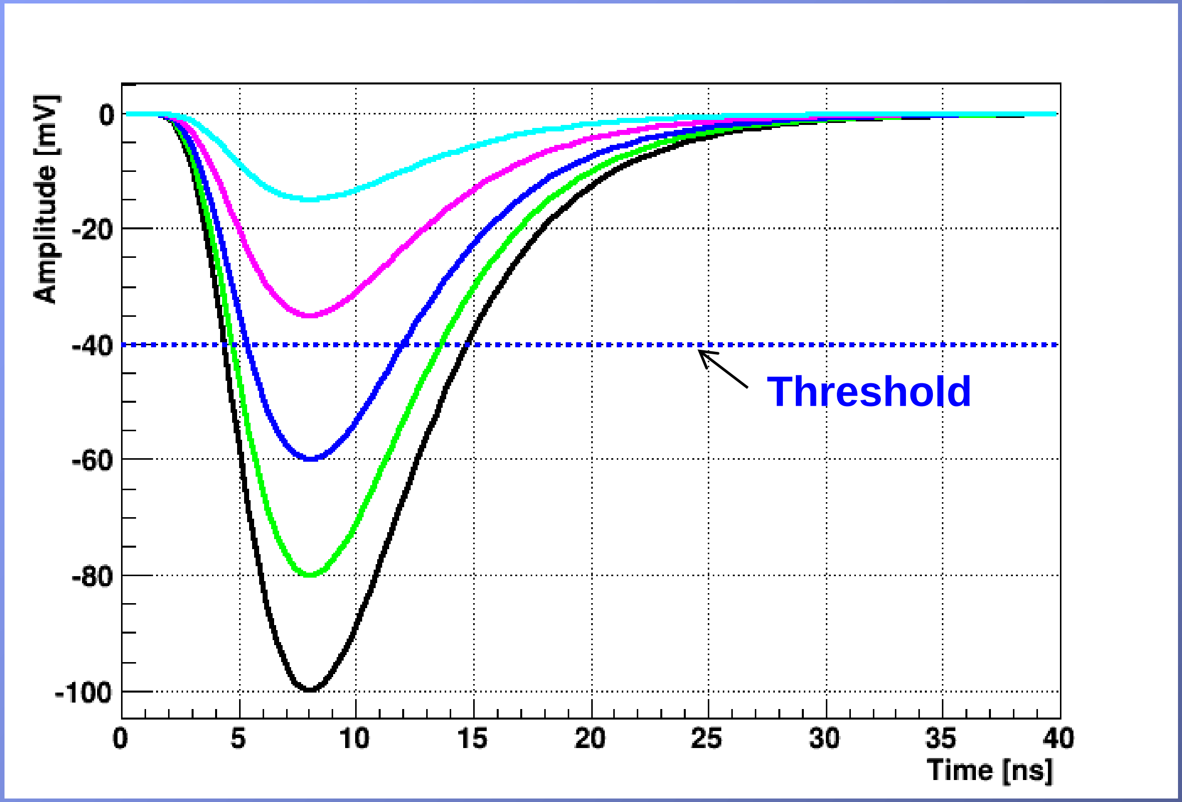
Of course the signal heights vary from pulse to pulse

There is also noise – a myriad of tiny pulses which have nothing to do with a signal in your detector

You want to know whether or not a signal is higher than a certain threshold – this could translate into a minimum required energy deposited, for example

All signals on the left have the same form, just a different amplitude

Signal Discriminators

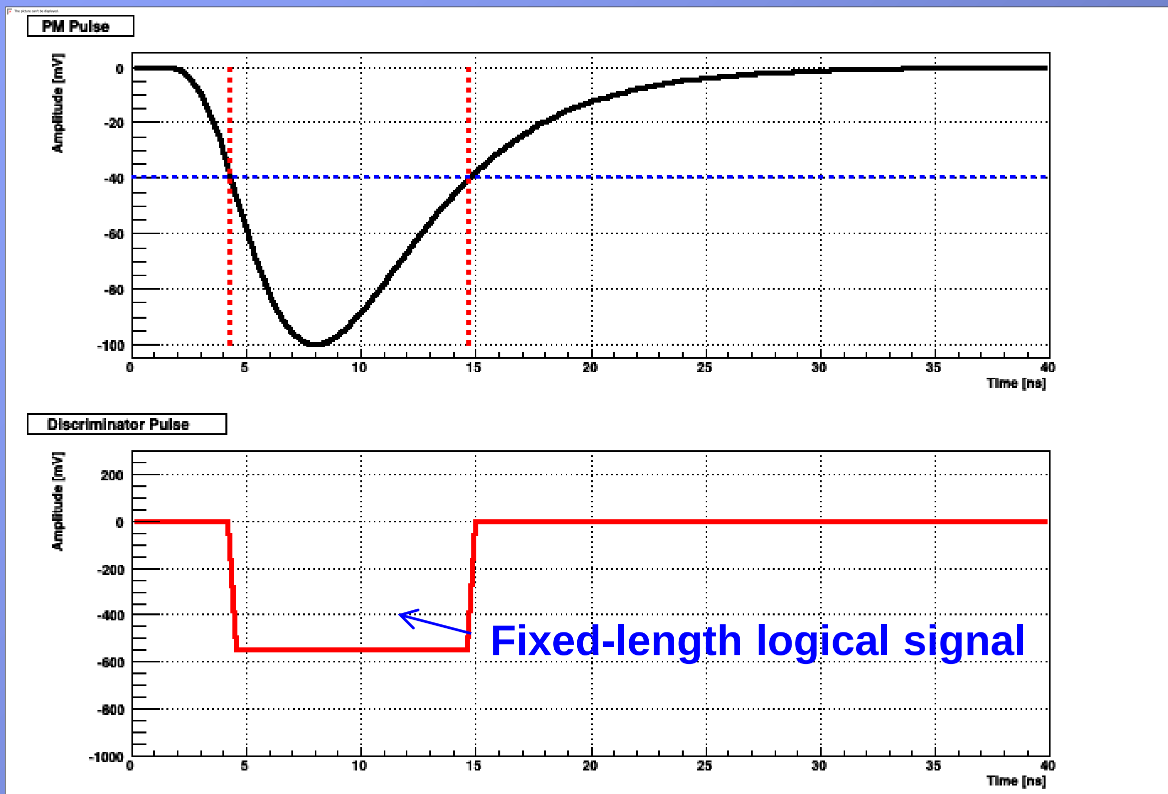


In this example, we set a threshold of -40mV.

The black, green, and blue signals would make the cut here.

We would ignore the magenta and light blue signals here.

Signal Discriminators

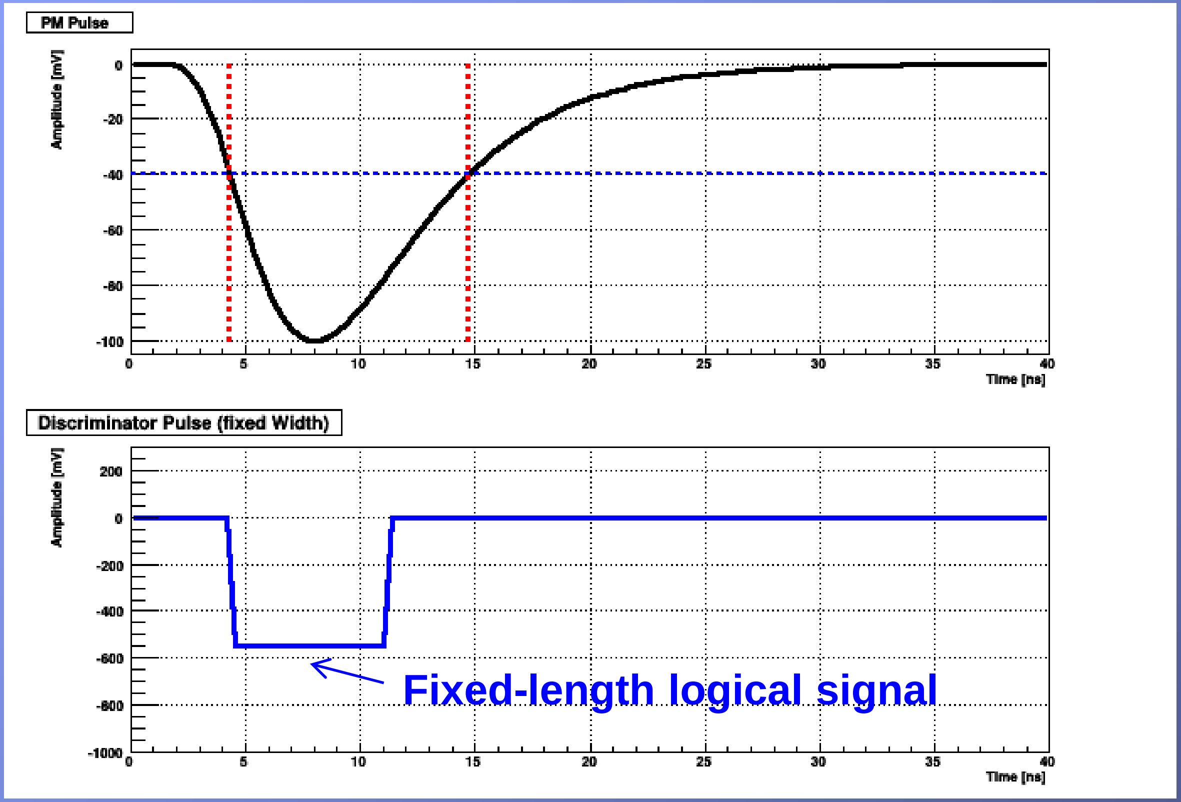


This is what you might see on your scope.

Where the signal exceeds the threshold, you get the discriminator to fire.

Most discriminators give a logic pulse with a fixed length, independent of the "above-threshold-time" of the signal. Has many advantages.

Signal Discriminators



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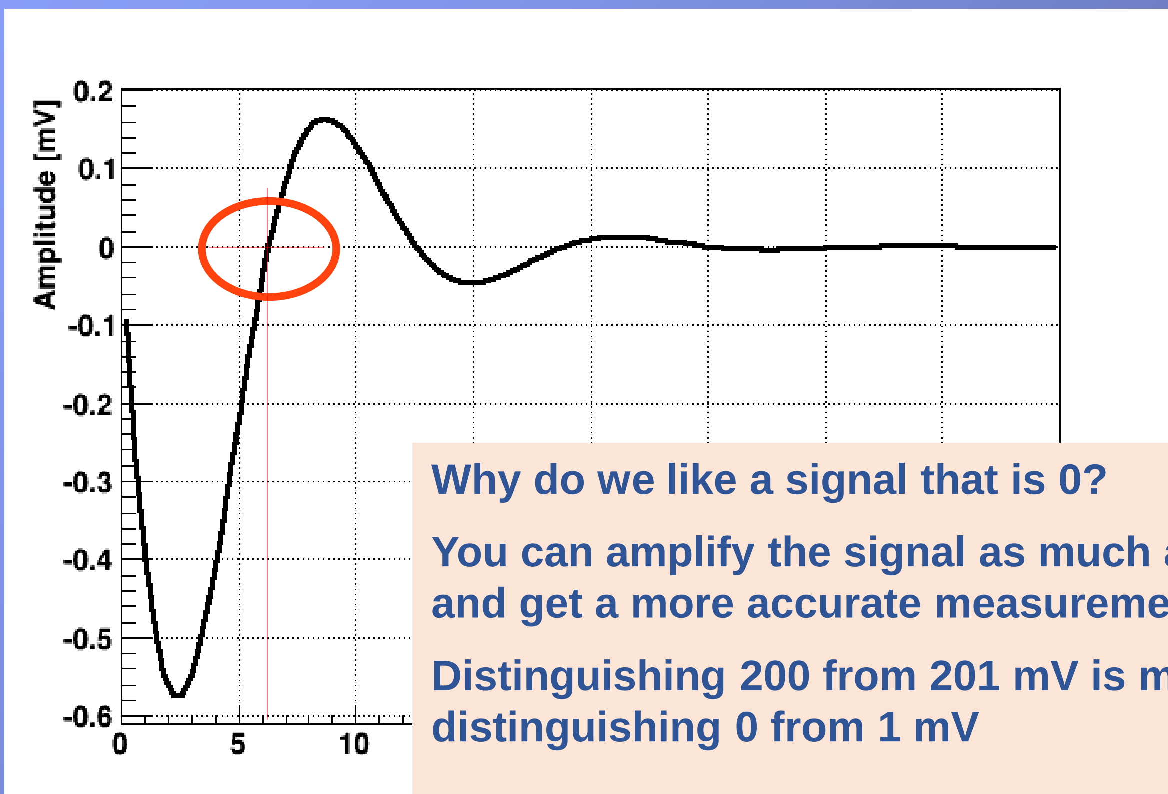
Zero-Crossing Discriminator

Just to mention this...



There are many ways to discriminate a signal – I just want to mention a zero-crossing discriminator.

Fires when a signal goes through zero.

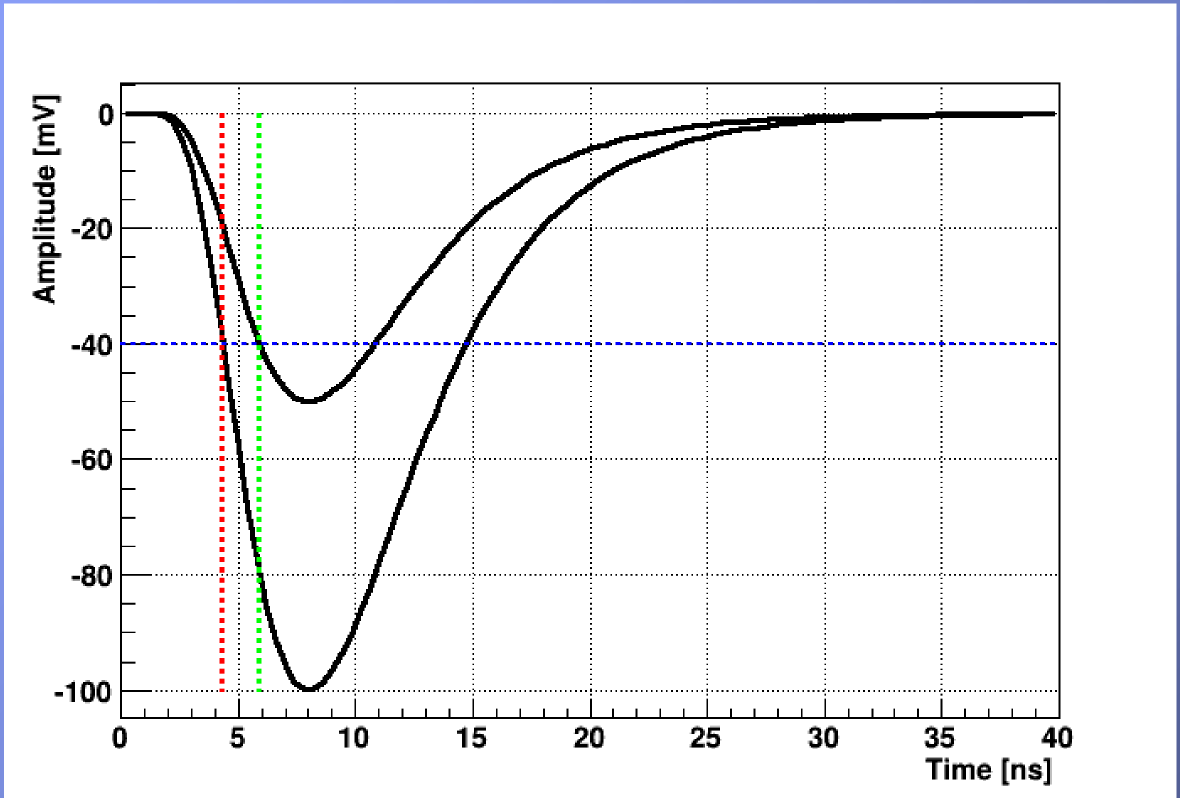
Typically involves a shaper,

Why do we like a signal that is 0?

You can amplify the signal as much as you need and get a more accurate measurement.

Distinguishing 200 from 201 mV is much harder than distinguishing 0 from 1 mV

A big problem: Walk



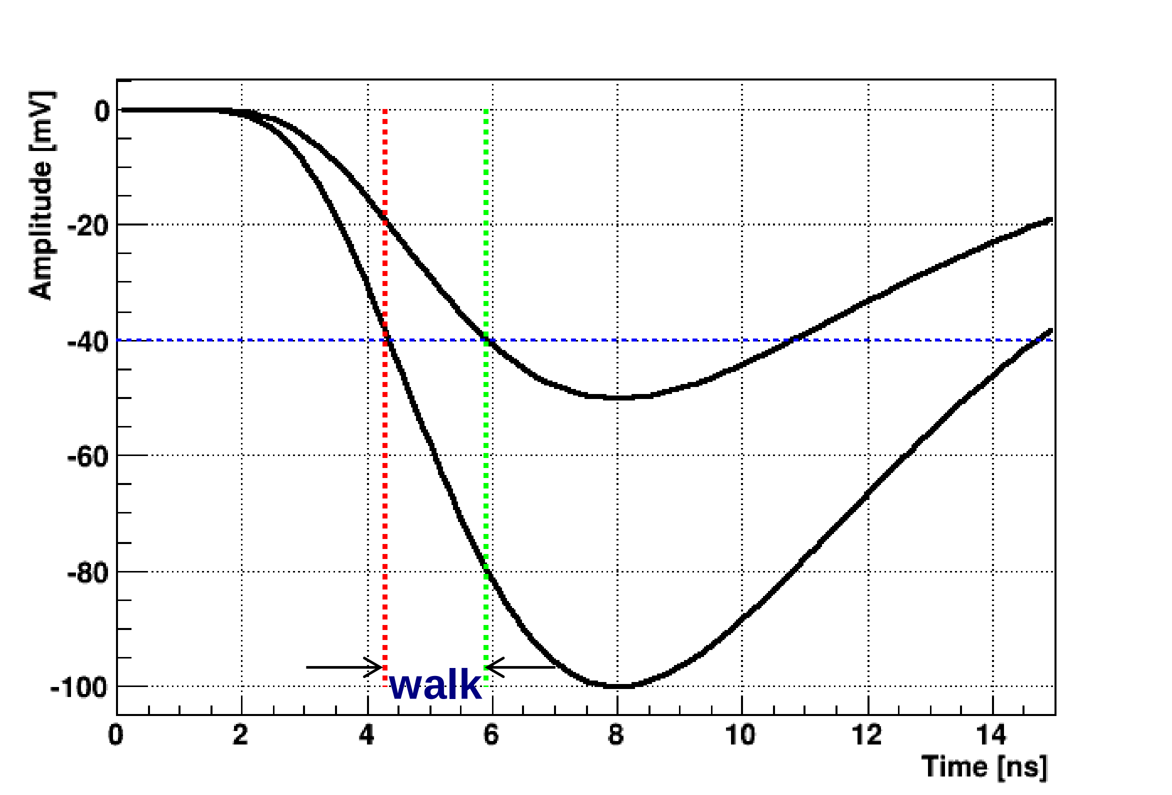
A larger pulse will cross the threshold earlier than a smaller pulse which will ultimately be above the threshold.

So the timing when we cross the threshold "walks" around depending on signal height

By and large, physicists don't use threshold discriminators in their setups because of the significant walk problem.

Basically unusable for timing measurements.

A big problem: Walk



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Constant Fraction Discriminators

Well, a Constant Fraction Discriminator sounds like the golden solution

instead of a fixed threshold, you “adjust” the threshold pulse by pulse so it fires at, say, 40% of the peak amplitude

No matter what the peak is, if the pulse shape is always the same, a signal reaches its 40% level at the same time. Walk eliminated.

Problem solved... well, not so fast.

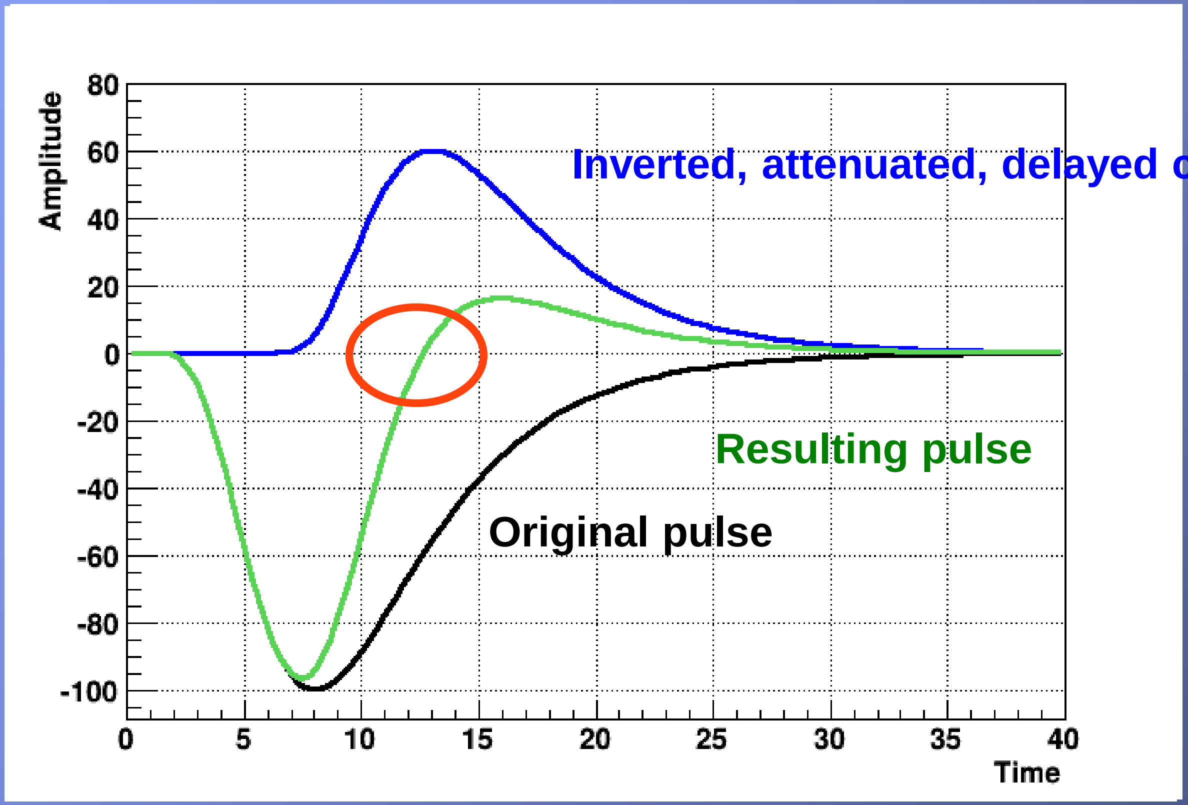
How do you know the peak amplitude? How do you do that?

Luckily, someone figured that one out...

The Constant Fraction Discriminator (CFD)

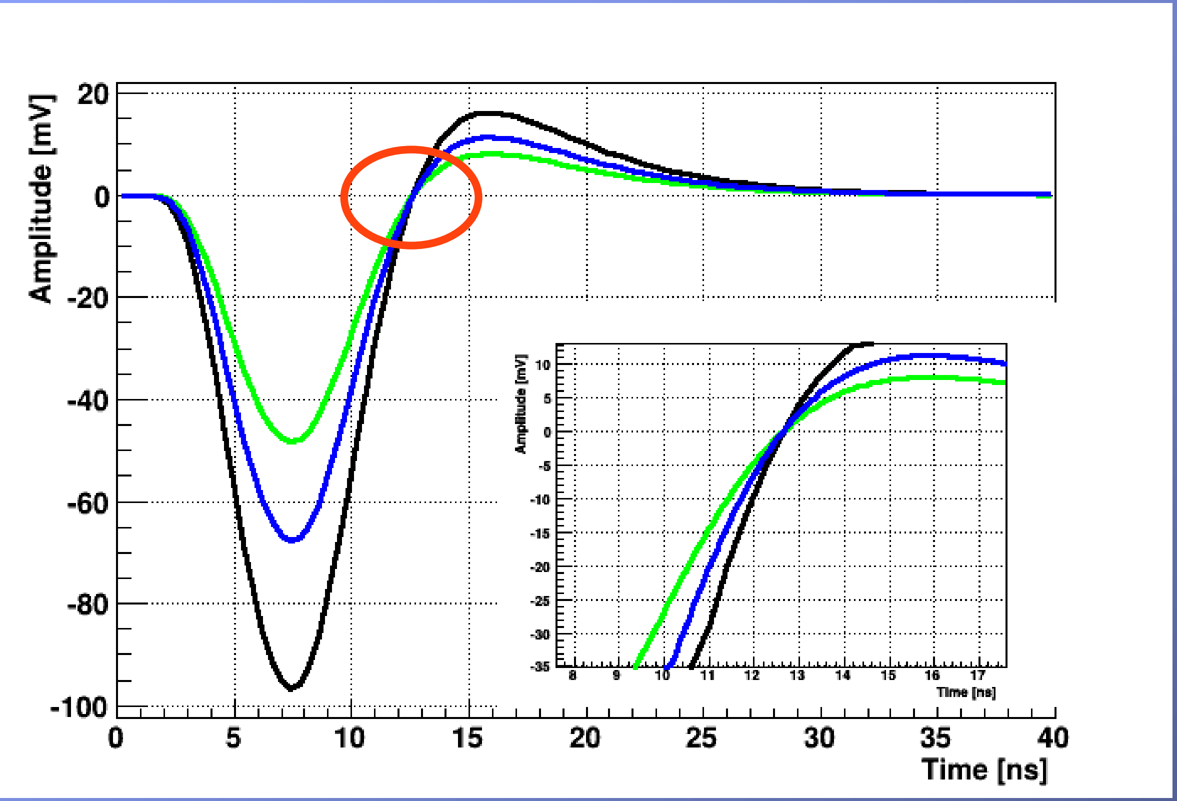
You take the signal, and subtract a delayed and attenuated copy from it

(or: you add an inverted, delayed and attenuated copy to it)



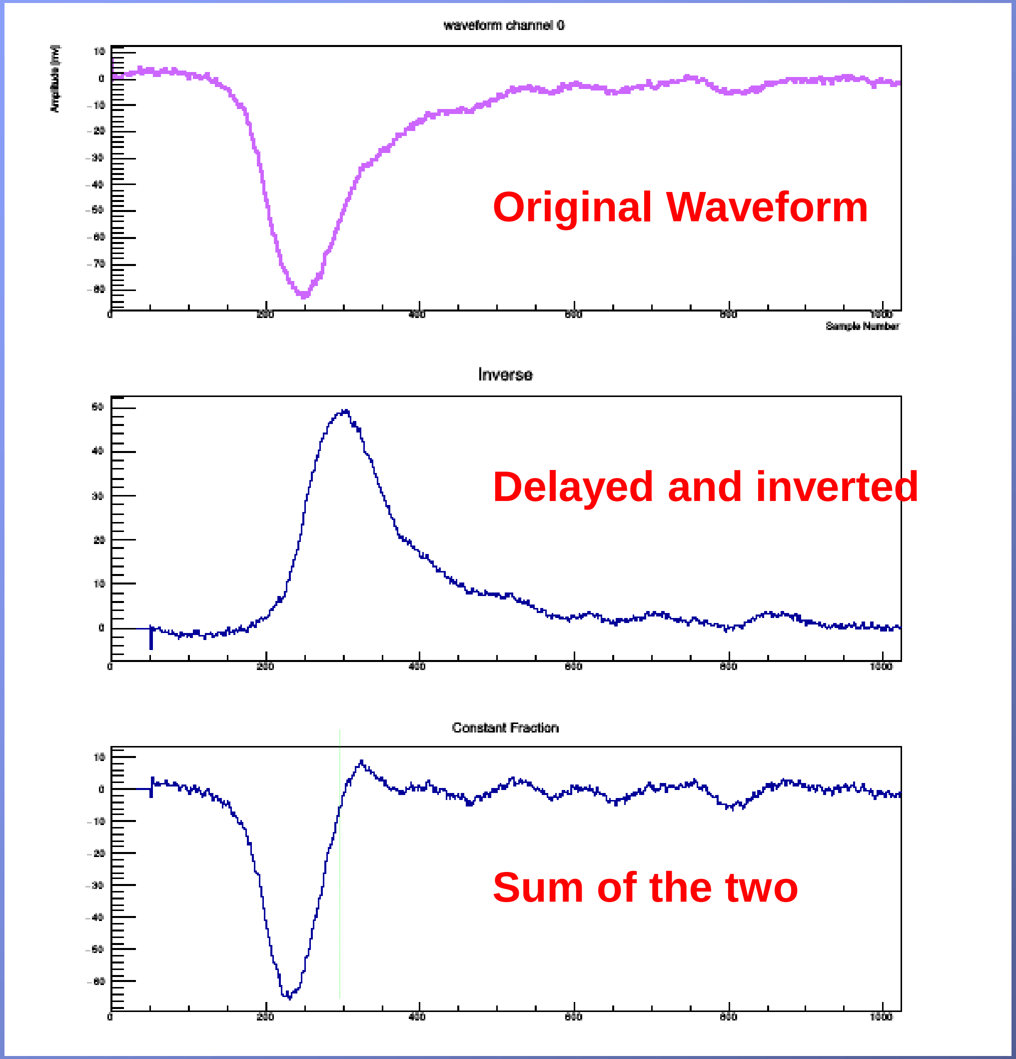
And then you use a zero-crossing discriminator to find the spot

Look, no walk!



- This shows the zero-crossing time of 3 different pulses
- They all go through 0 at exactly the same time
- If the signals are amplified copies (all the same shape), this is mathematically exact
- Of course, we are dealing with real-life signals...

Data from our Time-of-Flight Setup



This are data taken by us here at the school with the TOF setup.

I picked a 0.6 fraction, 50 samples delay

That can still be improved...

Slewing Correction

Real-life signals do usually not completely fulfill the “scaling rule”

They do not have the exact same shape (still good enough for many applications)

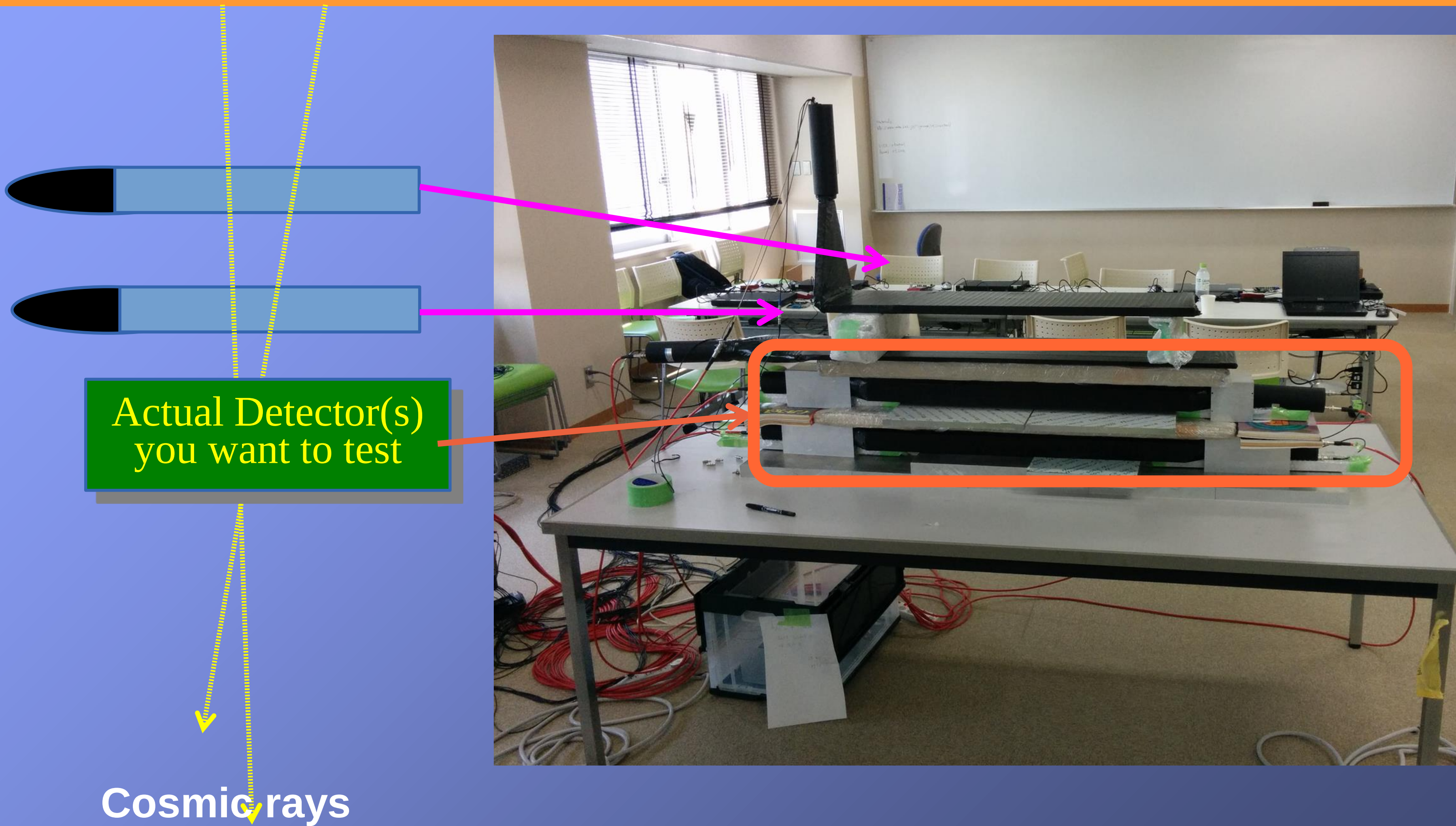
Example: Scintillator light does not simply “scale” - depending on energy the light profile varies, and so does the final pulse shape

For picosecond-level timing, one still needs to eliminate a residual timing dependence on the pulse height

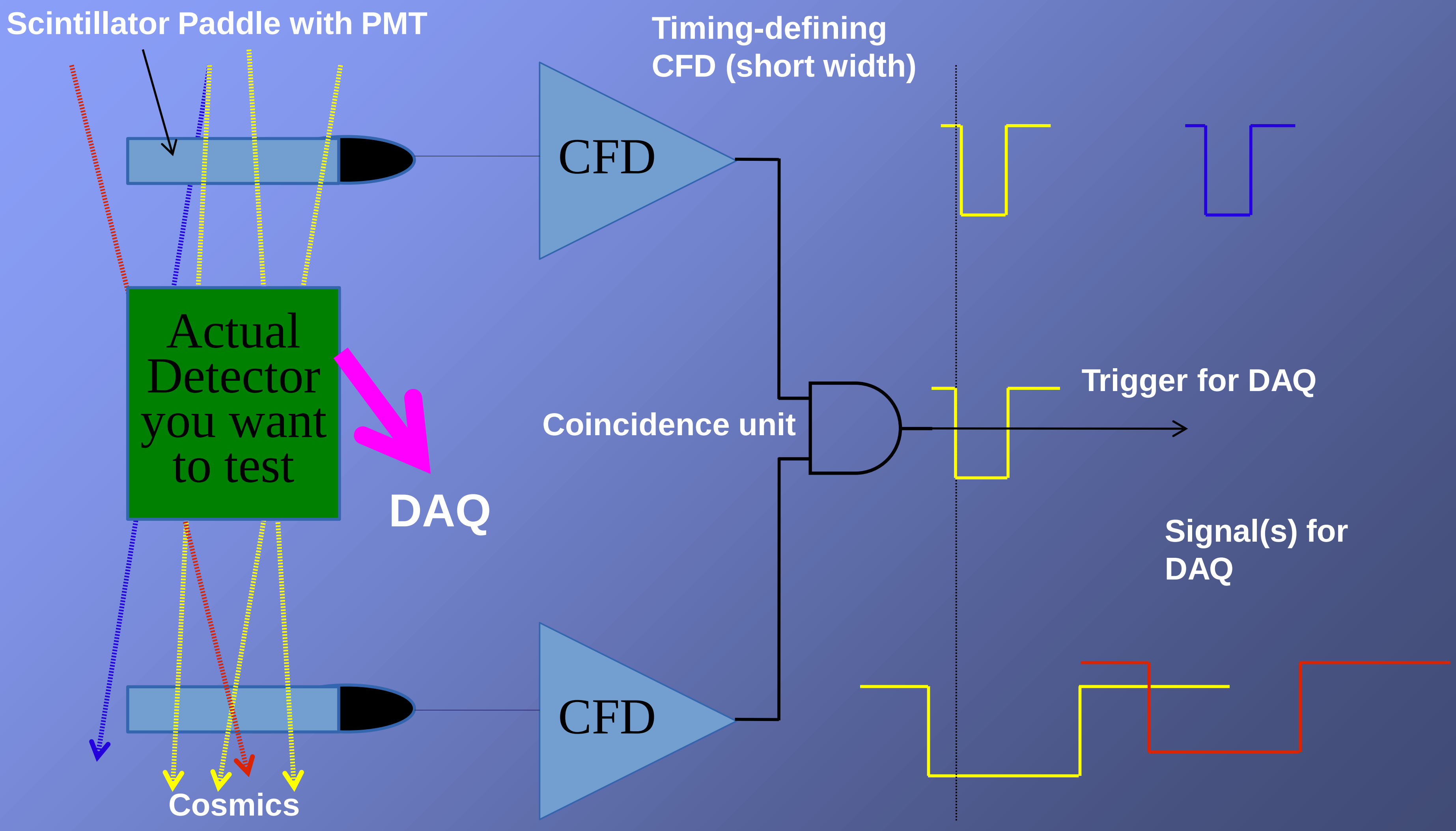
Measure the pulse height and perform a amplitude-dependent correction -

“Slewing correction” - part of your offline analysis

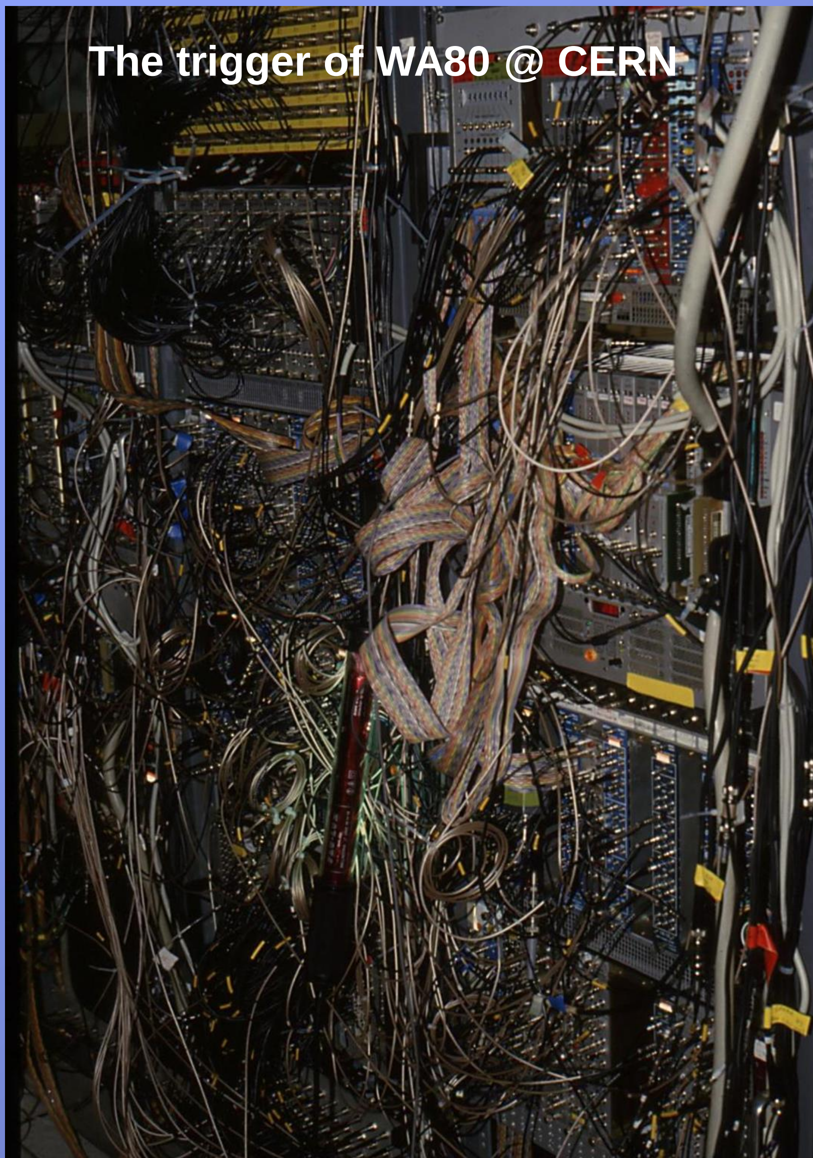
A Cosmic Ray Test Stand

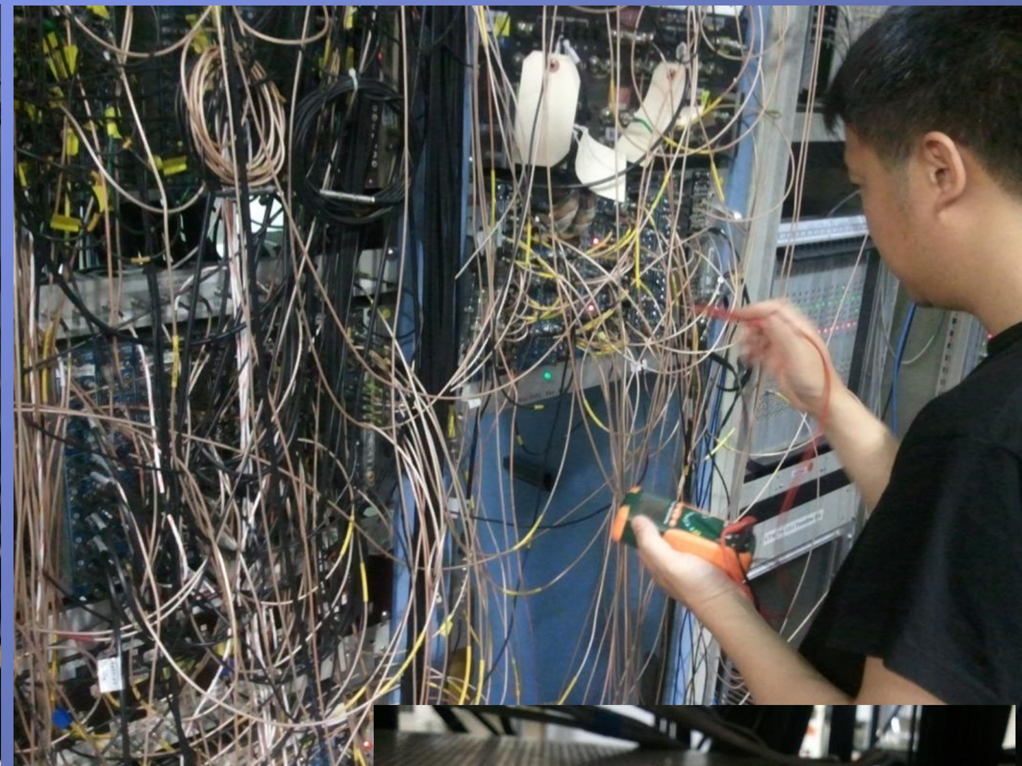


Let's Build a Cosmic Ray Teststand



More BLTs...


The trigger of WA80 @ CERN




LeCroy
MODEL 623B
LeCroy
LeCroy
DUAL GATE
FULL SCALE WIDTH
MODEL
755

How to measure signals?

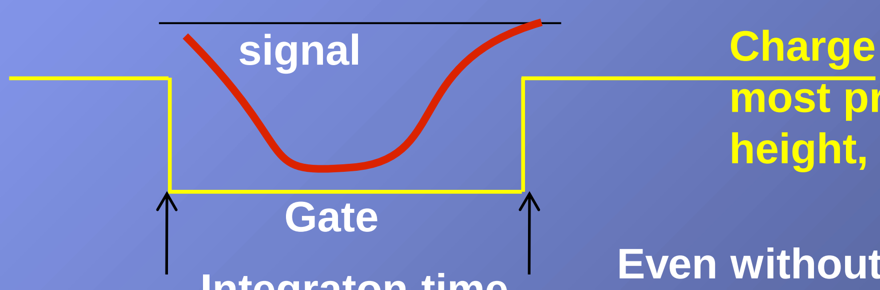
Two main devices:

An ADC – Analog to Digital Converter - converts a pulse height or integrated charge in to a number

A TDC – Time to Digital Converter - converts the time difference between a start and a stop signal into a number

You'll hear “10 bit” or “12 bit resolution” - how many bits that number has. This is one contributor to the real resolution – with 10bit you can get at most 0.1% (1/1024). Typically your detector's resolution is much worse than that.

ADC – “charge integrating” or “Peak Sensing” … PS is rare, charge-integrating is the most common ADC



Charge integrating ADC are often the most precise ADCs (you can lose signal height, but you can't lose charge)

Even without an actual signal, an ADC does not measure 0 - noise, dark currents, etc make a “pedestal”. Needs to be measured and subtracted

Flash ADCs

Rather than measuring one number, a Flash ADC samples the signal at a specific frequency (10, 100 MHz, 1, 2, 5 GHz)

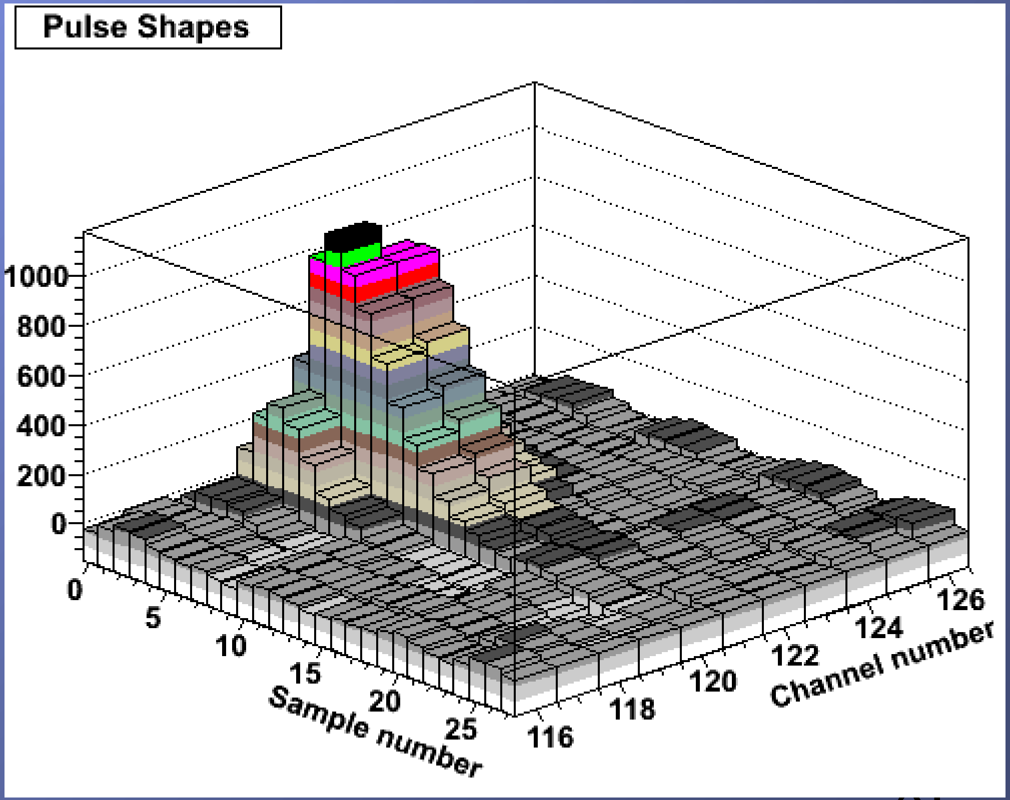
FADC gives you a waveform just like a scope

You can measure pedestals signal-by-signal (select samples before the actual pulse)

Perform Waveform analysis

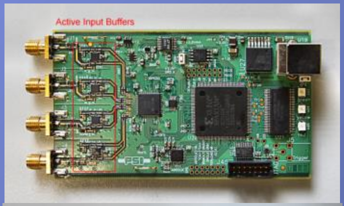
Much higher data volume though

FADCs are expensive



Switched-capacitor arrays can be a cheaper alternative

we will use here the DRS4 chip



More Standards

Now what? Can I buy one of those ADC's and read it out?

Depends. There are a few standards for such instrumentation so you can buy stuff off the shelf.

CAMAC

VME

FASTBUS

Custom-made (most of PHENIX)

uTCA (I'll get back to this later)

CAMAC

- “Computer Automa
- A standard crate w
- Up to 25 slots per
- A standard comm
- Function (F), Crat various platforms
- To the extent that controllers – not i
- But many R&D pr
- Most prominent: t
- Virtually each Inst (“HEEP” at BNL)
- Also many “contr computer-control
- At CERN we did w of CAMAC registe less operation

Example: 2280 ADC System

- My workhorse ADC system back at CERN
- To the best of my knowledge, the densest ADC system in CAMAC
- Up to 960 ADC channels with a common gate in one crate
- System processor subtracts pedestals, zero-suppresses, delivers data in a compact format
- Used to read out what is today our Lead Glass Calorimeter (and other Calos at CERN)

FASTBUS

Attempt to overcome some of CAMAC's limitations

Larger crate, more space, hot-swappable modules...

I have not used FB that much, so I'm not the expert

The reason that I skipped FB, however, is the “wrong sex” of the backplane

The backplane is by far the most expensive item in a crate

In FB the backplane has the pins. What??? You bend or break one while inserting a module, and the backplane is shot

That said, JH's 787 experiment was all in FastBus... so it cannot be that bad

VME

"Virtual Memory Extender", designed as a digital / computing device

Bus allows to memory-map modules and access them

Different modules can access each other's memory across the backplane

Many attempts to use VME for analog-type instrumentation (denser, faster, cheaper than CAMAC)

However, standard VME crates don't have the proper clean power for analog electronics

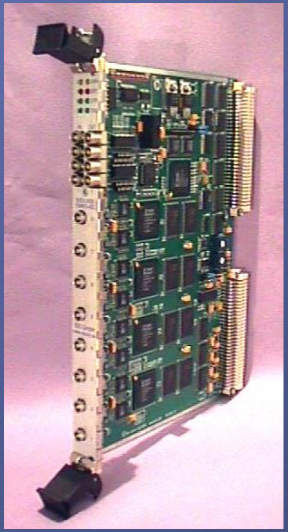
CERN's add-on standard "VIPA" guarantees certain limits, but makes VME crates really expensive

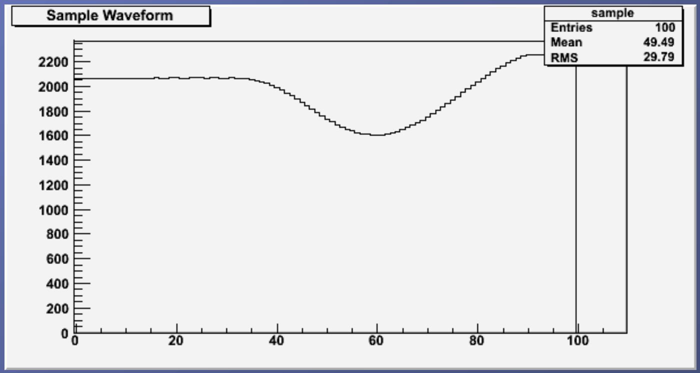
Still, a wealth of modules in VME

All of PHENIX's DCMs, DCM2s, Partitioners are in VME (e.g VME crate controllers, such as iocondev1a). All use of VME in the PHENIX DAQ is digital-only

I like(ed) VME a lot for its ease of use

Easy to understand





Struck SIS3300 8-channel Flash ADC

New(er) Developments

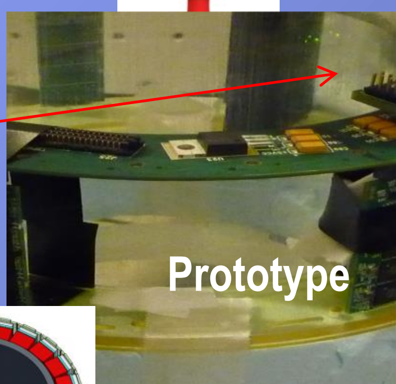
For various groups (medical imaging, GEM R&D, Stony Brook GEM Cherenkov, Yale...) I'm providing a modern DAQ system running on a PC.

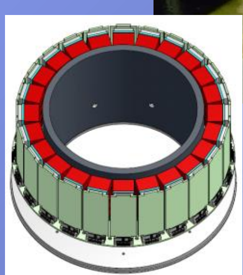
The principal data streams into a PC are network, USB, and PCI/PCIe

Most folks planning some test beam will likely interact with it. SB@SLAC (now), MPC-EX...

RCDAQ

"TSPM"



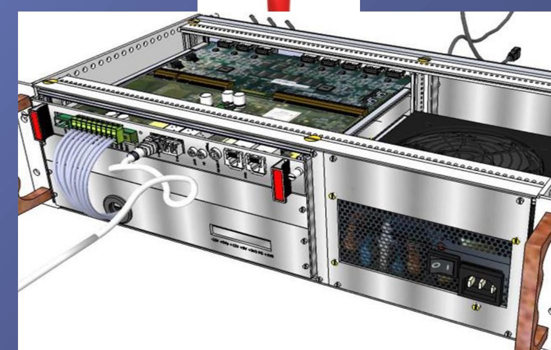


PET Scanner for Mammography / Rodents (3072 LYSO crystals)

DRS4 Eval board

"USB Oscilloscope"

Nice for triggering, say, for cosmics



The SRS System

Dead Time

UNITE the UNION
against Deadtime
Less than 10%!
Less than 10%!
NO CUTS
NO EVICTIONS
More Than 10%!
Don't let Deadtime
data
Scientists for less Deadtime
Scientists for less Deadtime
Deadtime is Evil!

Dead Time

It takes some time to actually read out your detectors. You have to transfer the data, package it, store it

Many “small” data acquisitions run in the neighborhood of 1 millisecond – so you can get an event rate of about 1KHz max.

During the time the DAQ is reading out, it cannot accept another signal - “dead ”.

An event / signal arriving during that time is lost.

We measure dead time (or live time) in percent – 10%, 20%, …

If your dead time is 50%, a given signal has a 50% chance to be accepted.

If your dead time is 10%, the chance is 90%.

Dead Time

If you have truly rare interesting events which you want to measure in your overall data stream, you cannot afford such a high dead time.

Example: PHENIX takes data at about 7KHz. We get about 300 J/Psi particles /day among all the millions of other events.

If we would be running at 50% dead, we would lose 150 out of the 300.

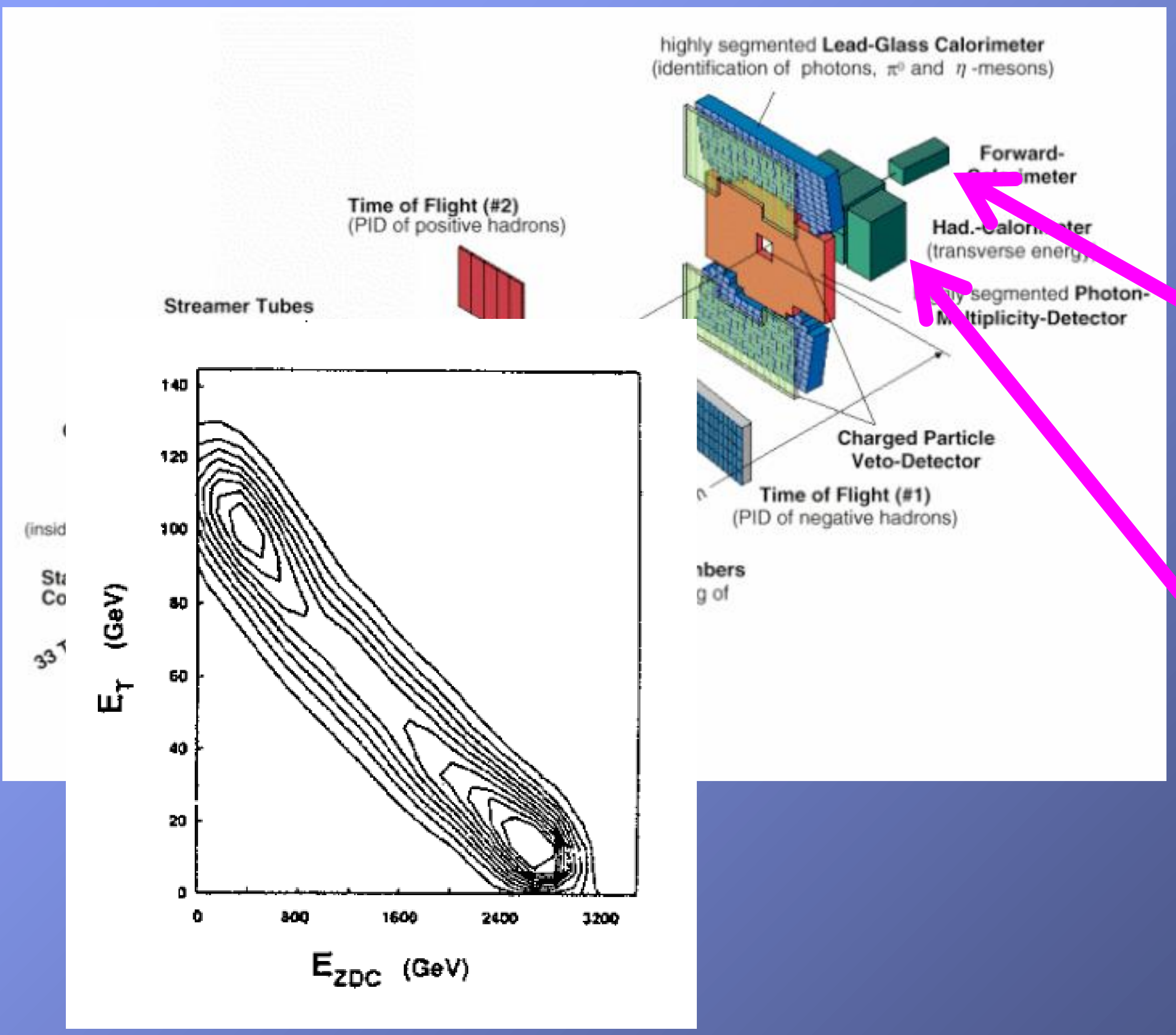
We are running about 88% live, so we are losing 36 of the 300.

Of course we would like to run 99% live.

But then we would not take not a lot of data, and the J/Psi is not the only thing we measure

→ Always a compromise.

An example from my past



WA98 @ CERN

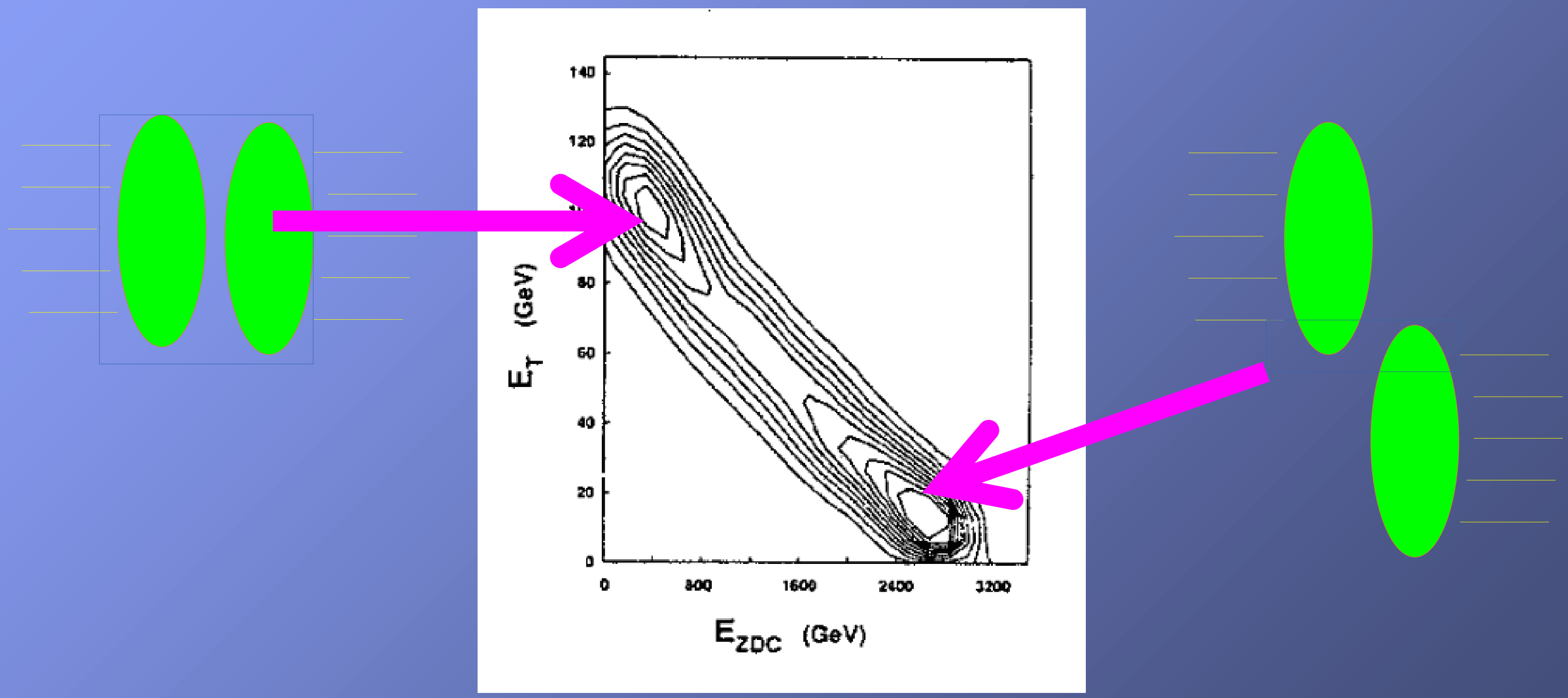
Heavy-Ion Experiment at th

Zero-Degree Calorimeter (me

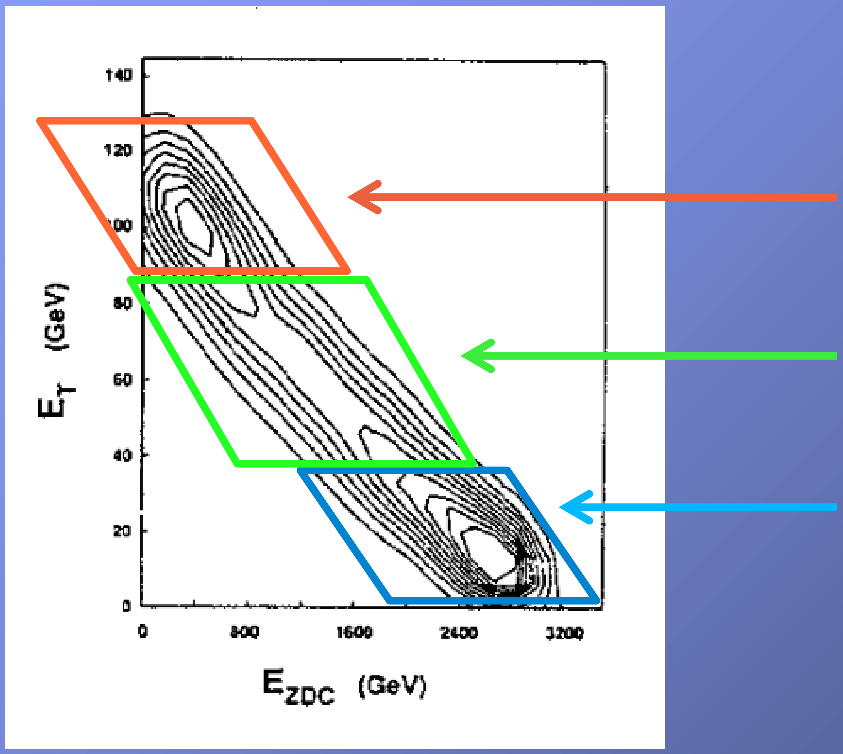
Mid-Rapidity calorimeter. No
More violent collision – more

Centrality Trigger

High Centrality → small impact parameter
Low Centrality → large impact parameter



Centrality Regions



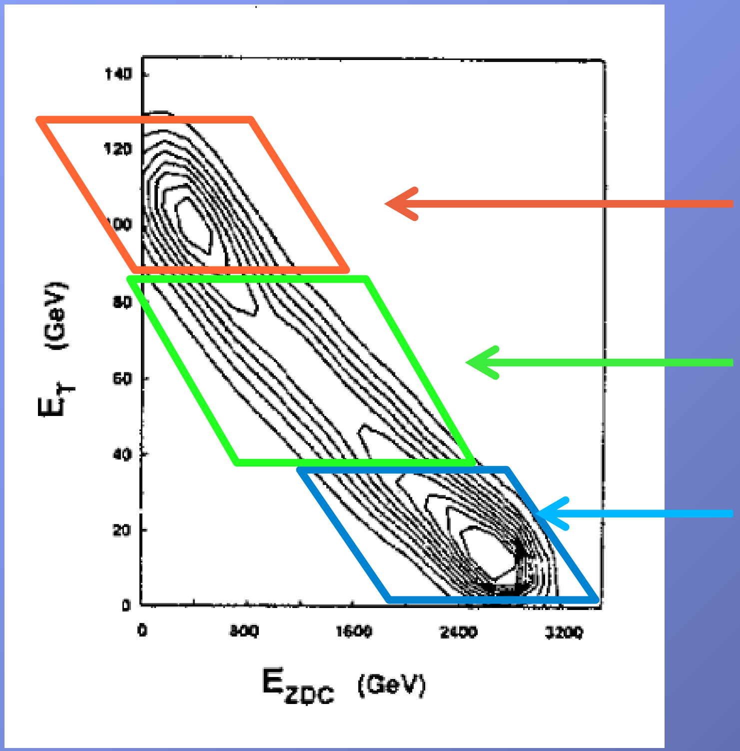
High

Medium Centrality

Low

What is the problem?

For each high-centrality collision, you get



1

10^5

10^8

Such a central collision is somewhat rare

If you can take 1000 event/s – and your DAQ is 10% live –

You capture ***one*** of those events every 4 hours and 40 minutes

You will never complete your measurement!

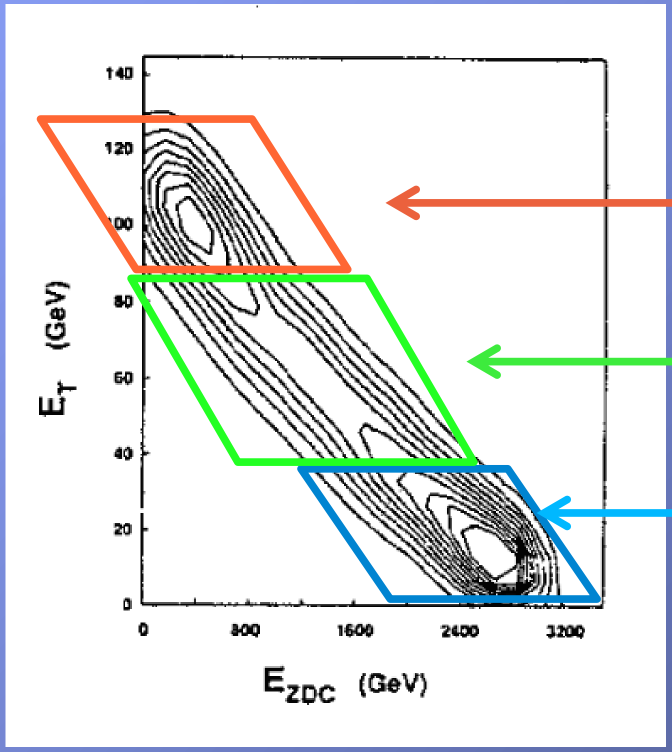
You need to do something different...

How do we fix this?

The low-centrality collisions are abundant. There are plenty available, and they look pretty much **all the same**.

You divide your trigger in the 3 regions, and scale down the trigger rate for the low-C triggers

Now you play with the numbers until your DAQ live time is right – for example, 90%



1 / 1 = 1

10^5 / 1000 = 100

10^8 / 100000 = 1000

Pitfalls of the Scaledown

You offer your DAQ fewer events of the “abundant” types by “scaling them down”

You offer the DAQ only each 5th, 100th, or 1000th event

VERY IMPORTANT: You can only count the events which arrived during the live time of your DAQ.

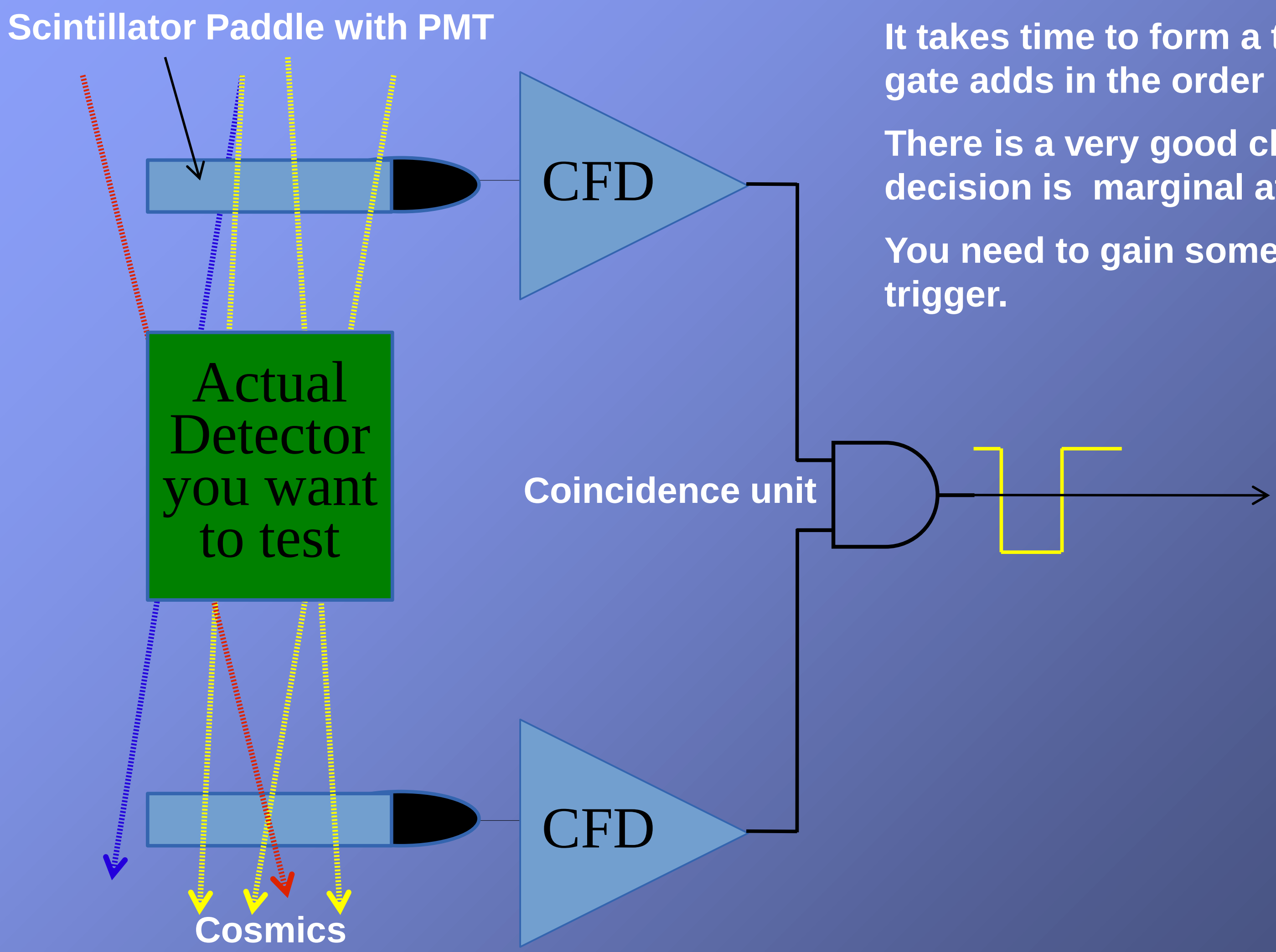
The Event *could have been taken* (we just decided not to).

Then (and ONLY then) such an event represents 5, 100, or 1000 others of the same kind (that's pretty much how a poll for politics works – you poll 5000 representative people)

When you analyze the data, you assign a weight of 5, 100, or 1000 (in this example) to it to account for the scaledown

End of Part 1.... I hope we made it here....

Let's go back here for a second



It takes time to form a trigger decision. Each gate adds in the order of 20ns.

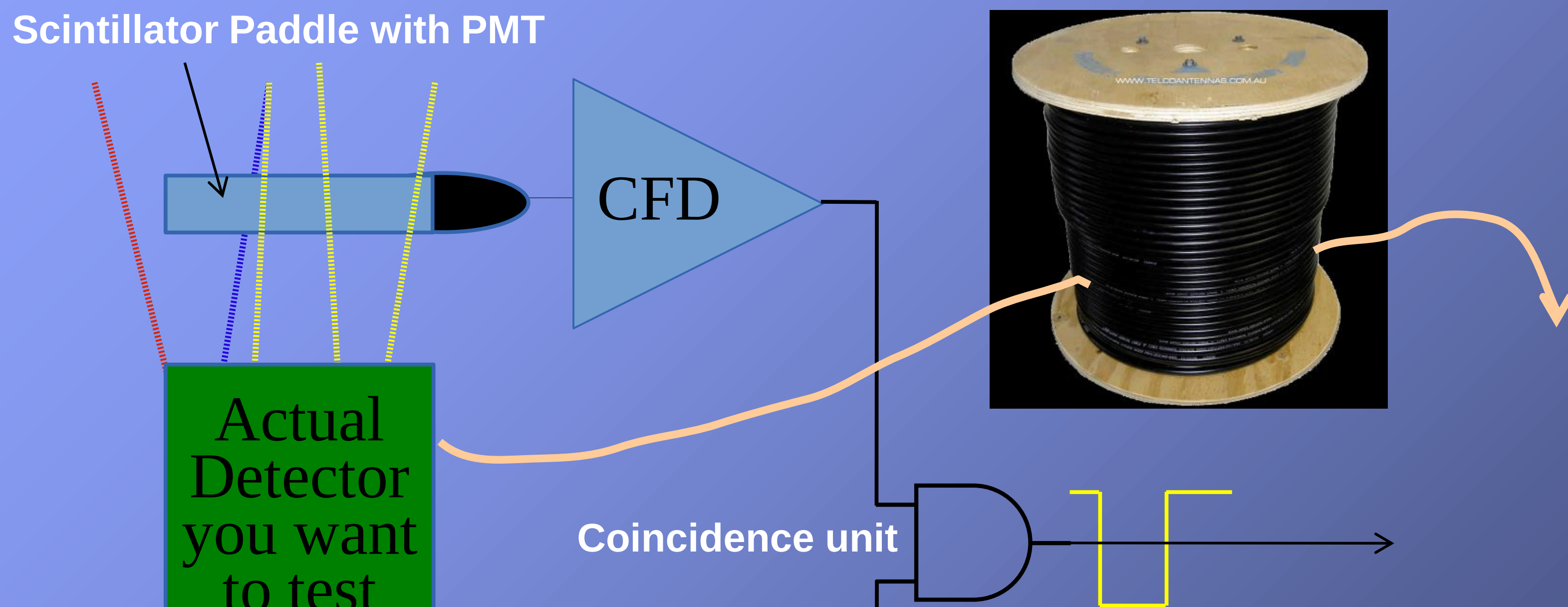
There is a very good chance that your trigger decision is marginal at best

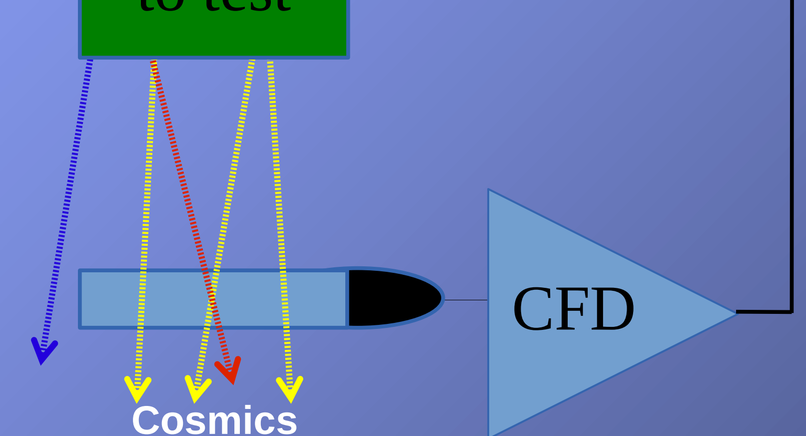
You need to gain some time for making the trigger.

Too Late!

This is a screenshot where we see that our gate would be too late for a “classic” ADC

So what can you do?





In the 80's, we sent all signals through a long cables (WA98 – 108 m) so the signals would arrive only after the trigger decision has been made

Expensive and ultimately limited – 600Km cables

To remember: RG58 and RG174 cables have a speed of 5ns/m

108m → 540 ns   trigger signals 30m, subtract 150ns

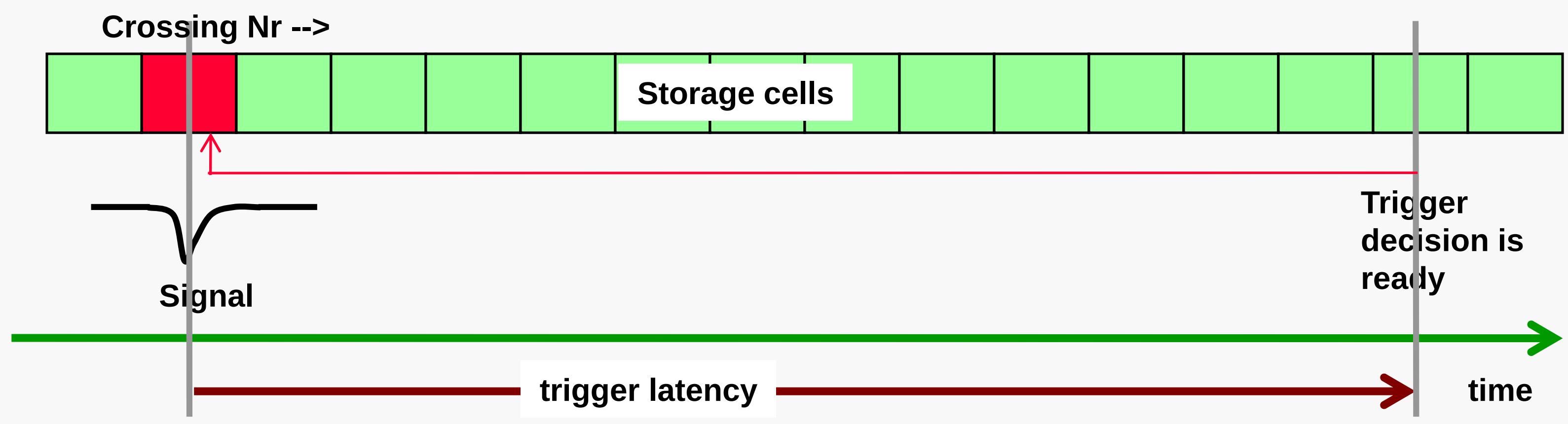
Electronic delays instead

Here's what we concluded.

Move all analog electronics (ADCs, TDCs, etc) to the detector.

Those front-end modules (FEM) have some analog storage which allows to keep the data from a certain number of crossings (e.g.% 64)

When the trigger decision finally arrives, we go back a number of storage cells, digitize the signal in there, and transmit the number. Delay problem solved.



At each bunch crossing, store the signal in the next "memory" location. When the trigger decision is made, get the stored value that corresponds to that crossing

Pipelines

Volkswagen assembly line.

It takes about 18 hours for a given car to be assembled.

If VW would let just one car through at a given time, they would produce 1.3 cars /day

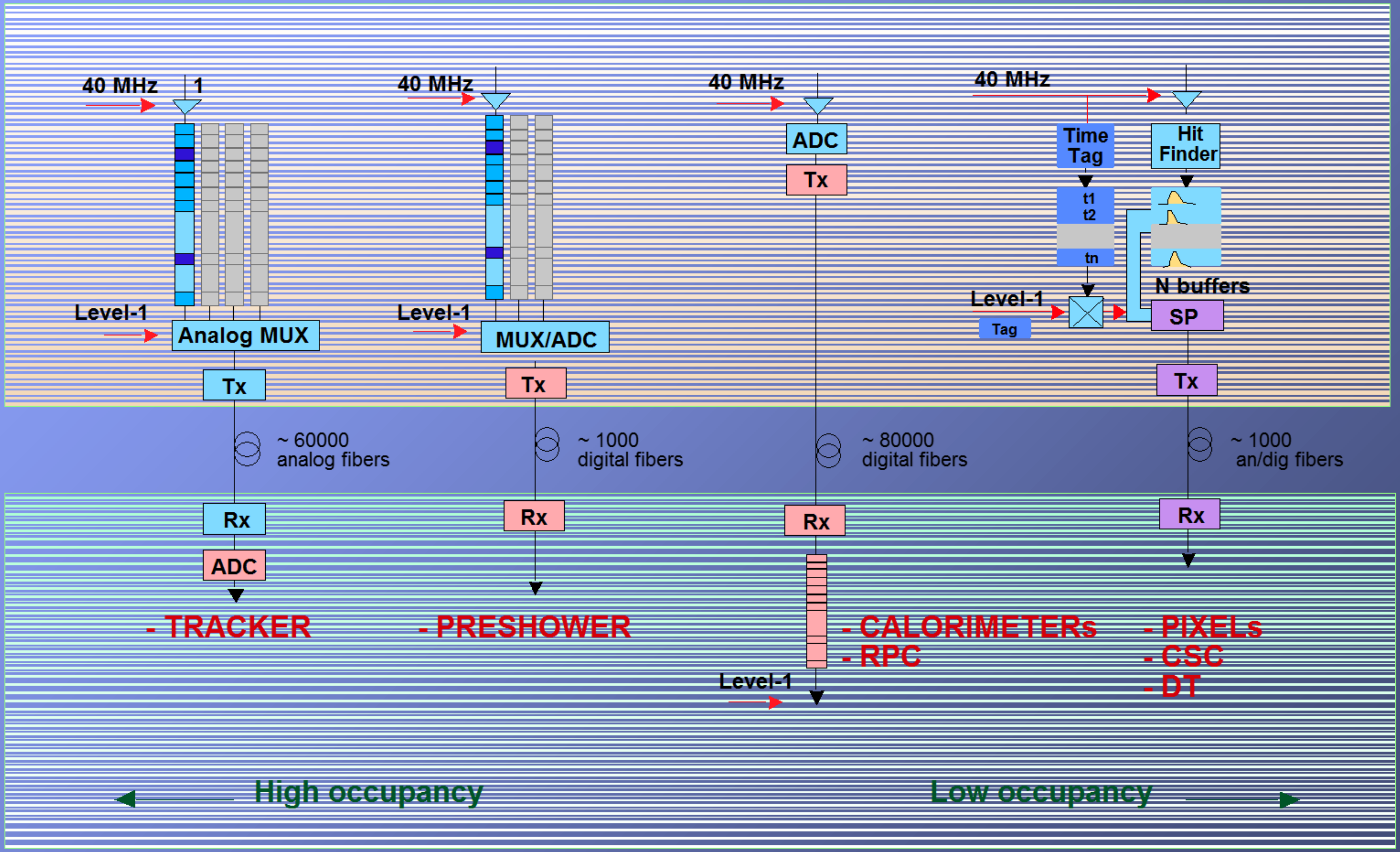
Of course they can put the next chassis on the line as soon as the first station clears

Each time a car is done at a station, the next car can move forward

So they assemble about 280 cars/day

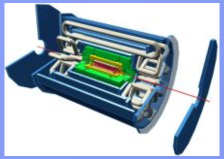
→ Pipelined assembly

Types of Pipelines - CMS

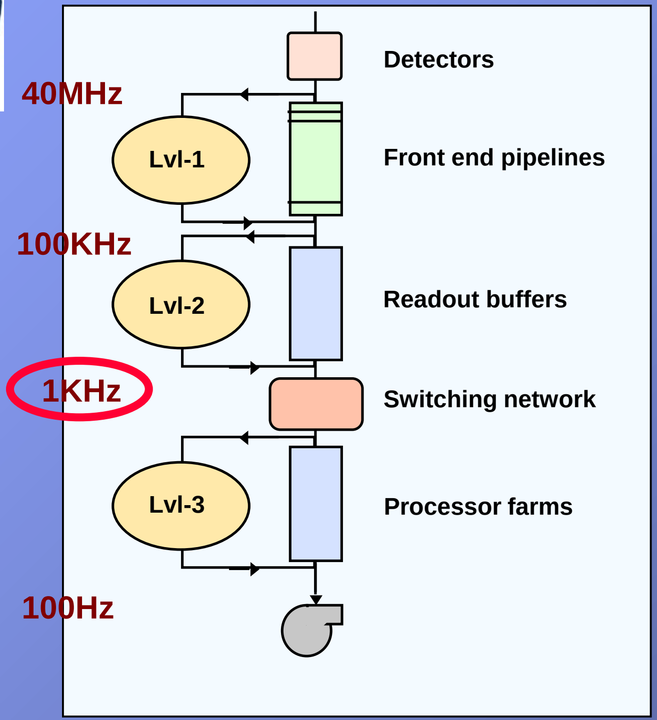


Higher-Level Triggers

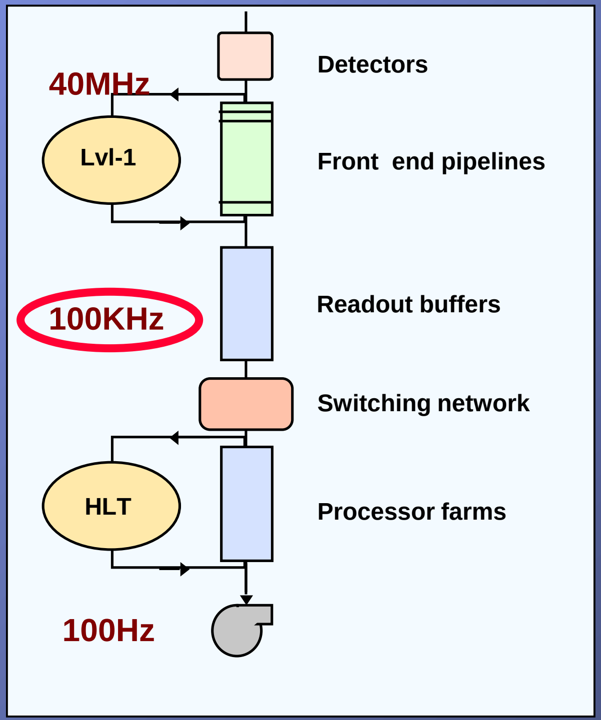
ATLAS



ATLAS: 3 physical levels



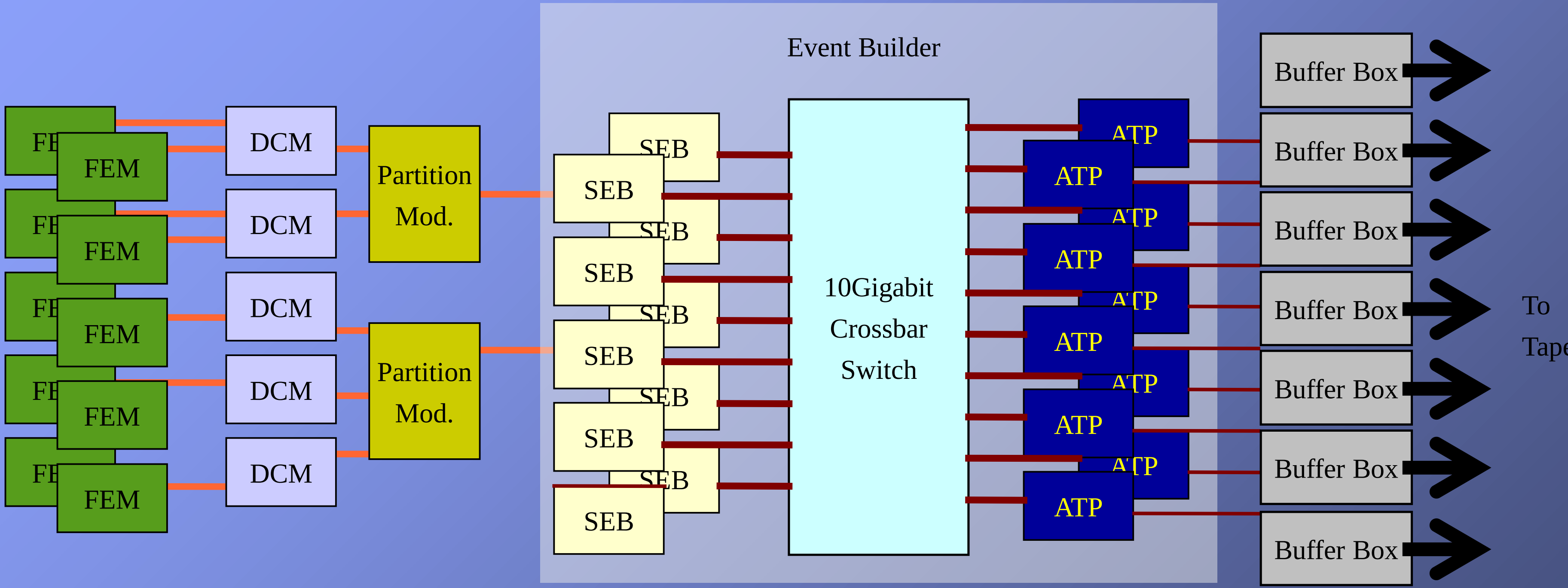
CMS: 2 physical levels



CMS

- Atlas has 3 levels with "Regions of Interest"
- CMS has only 2 levels.
- CMS' Switching Network needs to perform at much higher throughput (1000 GB/s vs 1/100 of that for 3 levels)
- But the processor farm has the full view of all L1 events

PHENIX DAQ Event builder



Front-End Module

Digitizes data

Partition Module and Sub-Event Buffer

Combines data from several DCMs

Assembly and Trigger Processor

Builds full events

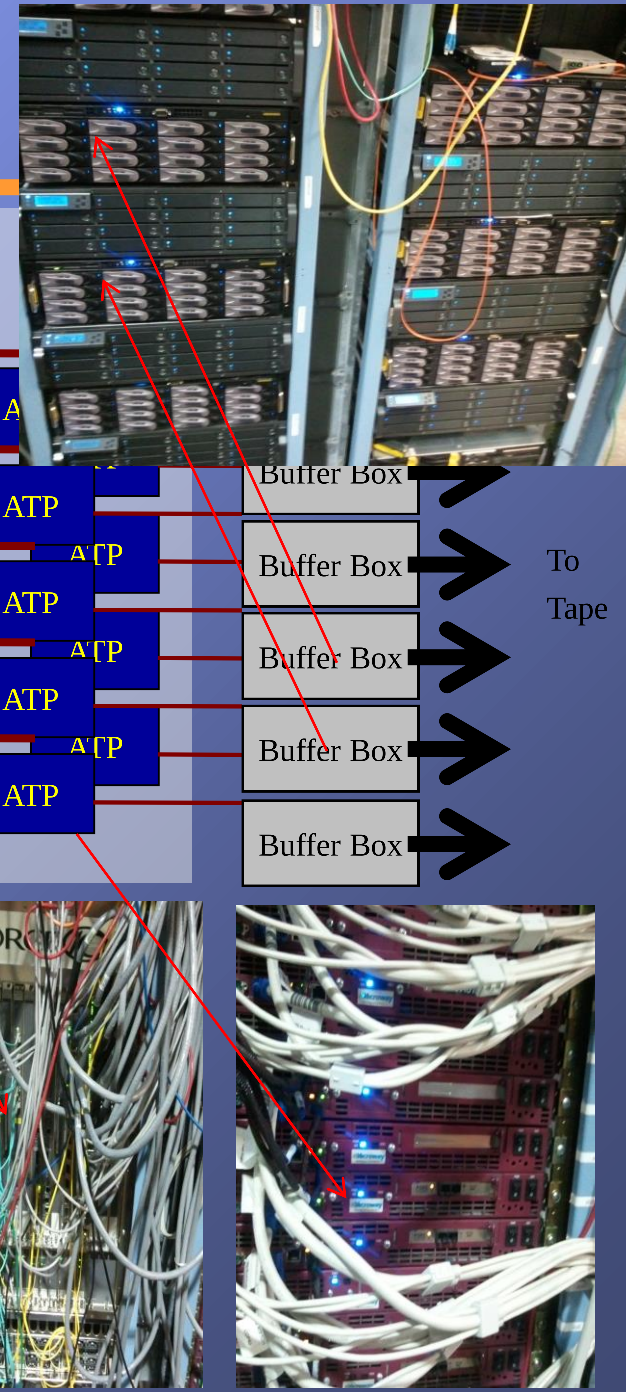
Data Collection Module

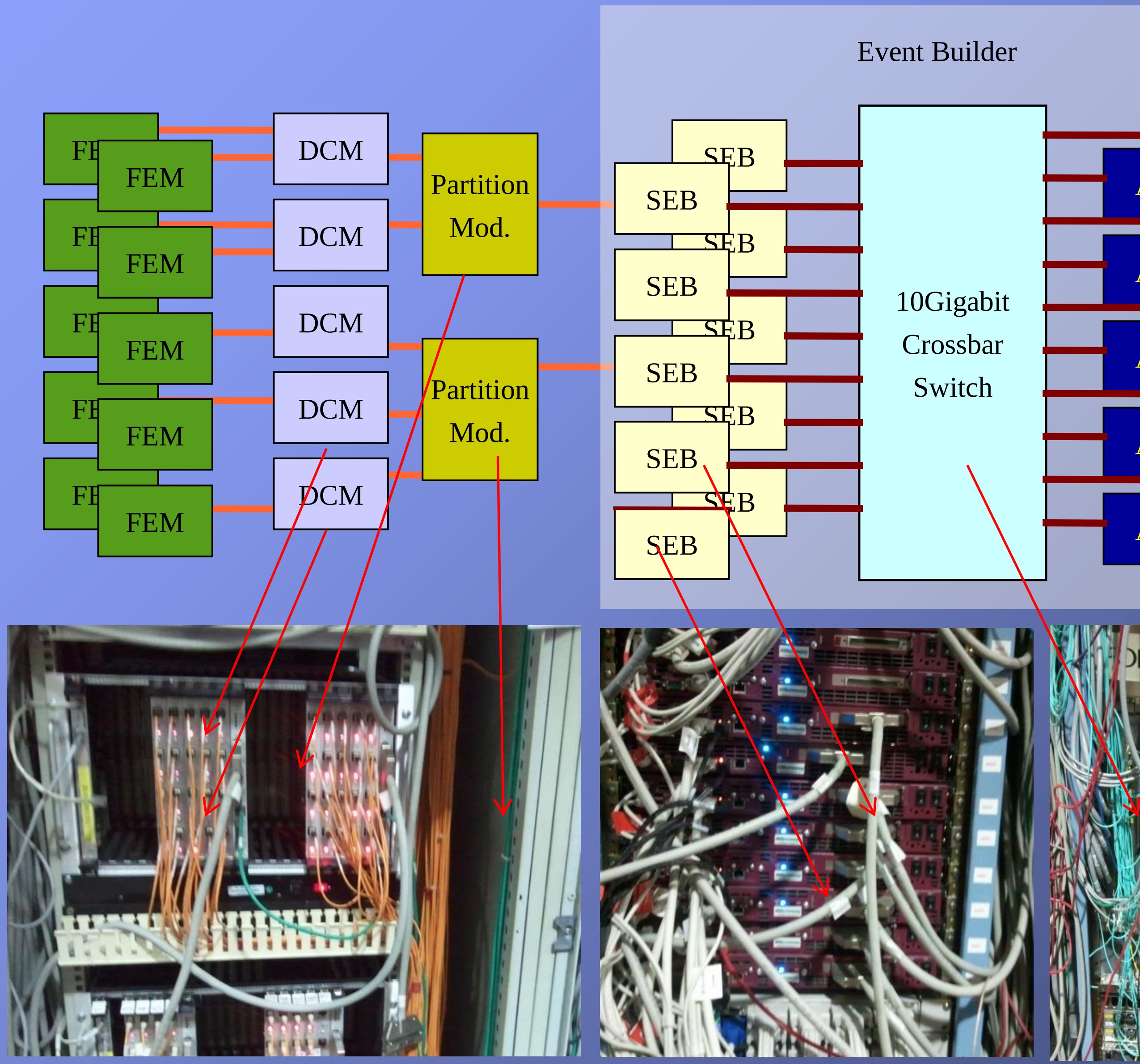
Zero-Suppression, packaging

Buffer Box

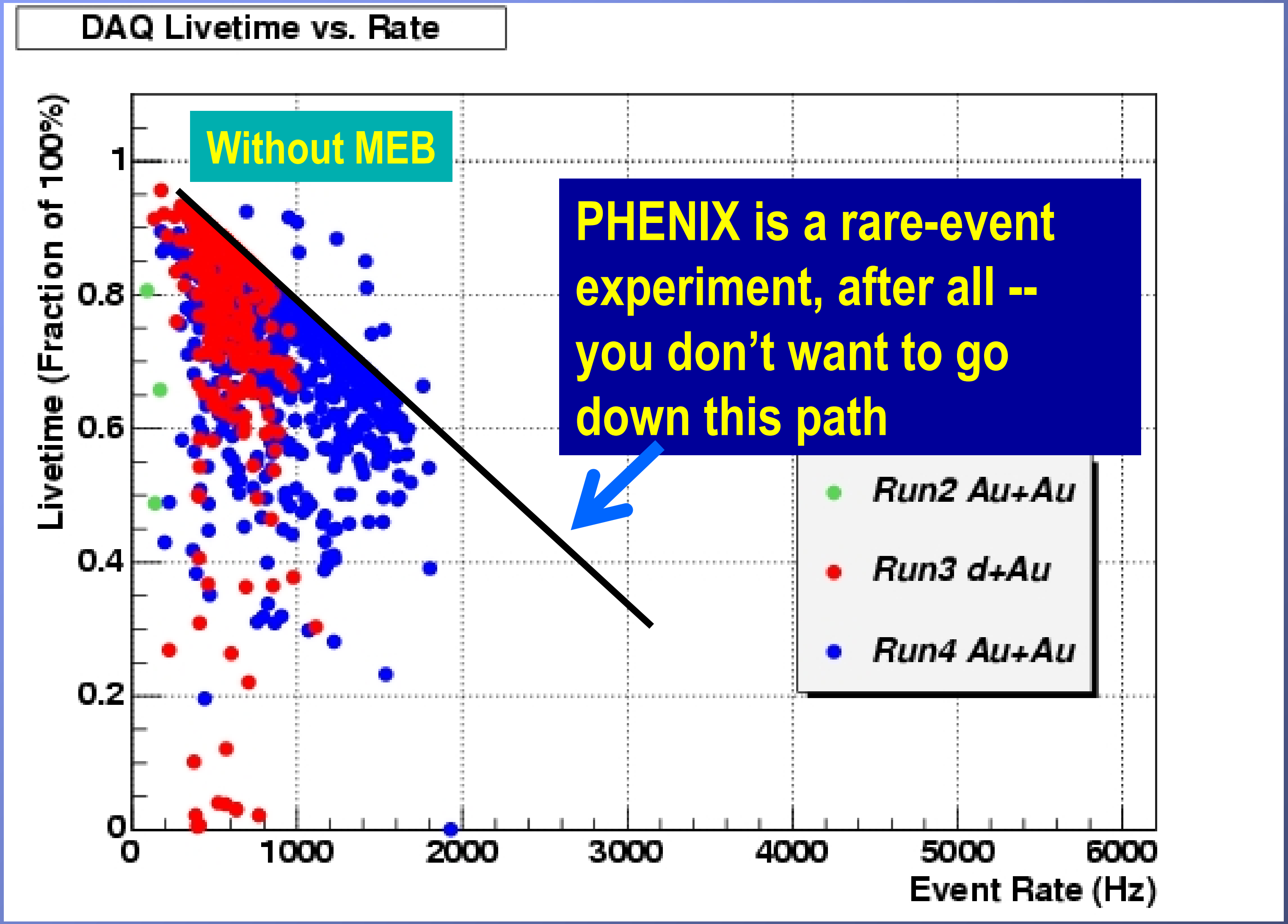
Buffers data O(40h) - steady data stream for the tape robot

PHENIX DAQ




Event Builder
FEM
FEM
FEM
FEM
FEM
DCM
DCM
DCM
DCM
DCM
Partition Mod.
Partition Mod.
SEB
SEB
SEB
SEB
SEB
SEB
SEB
SEB
SEB
SEB
SEB
10Gigabit Crossbar Switch
ATP
ATP
ATP
ATP
ATP
ATP
ATP
ATP
Buffer Box
Buffer Box
Buffer Box
Buffer Box
Buffer Box
To Tape

Multi-Event Buffering aka pipelining



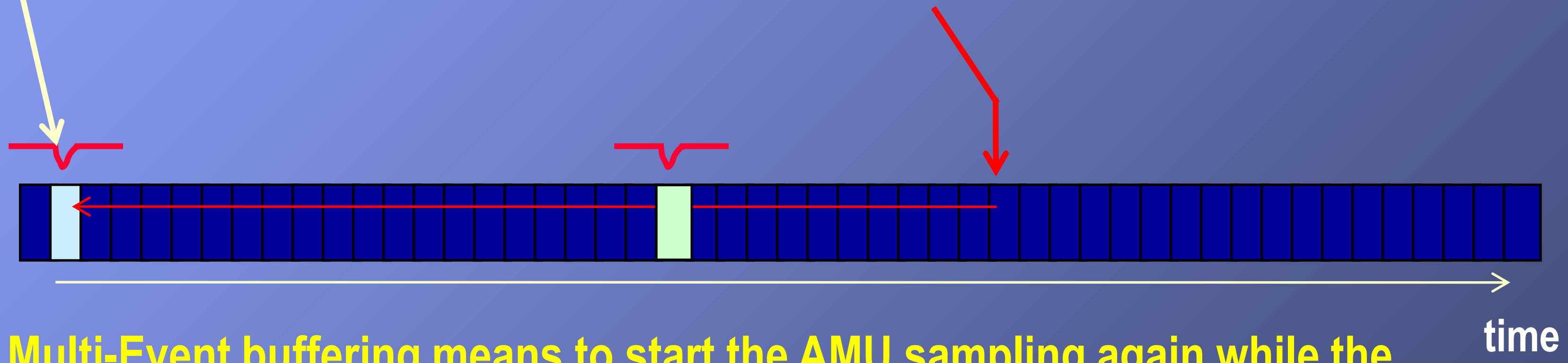
MEB: trigger delays by analog Memory

trigger electronics needs to buy some time to make its decision

done by storing the signal charge in an analog memory (AMU)

Memory keeps the state of some 40us worth of bunch crossings

Trigger decision arrives. FEM goes back a given number of analog memory cells and digitizes the contents of that memory location

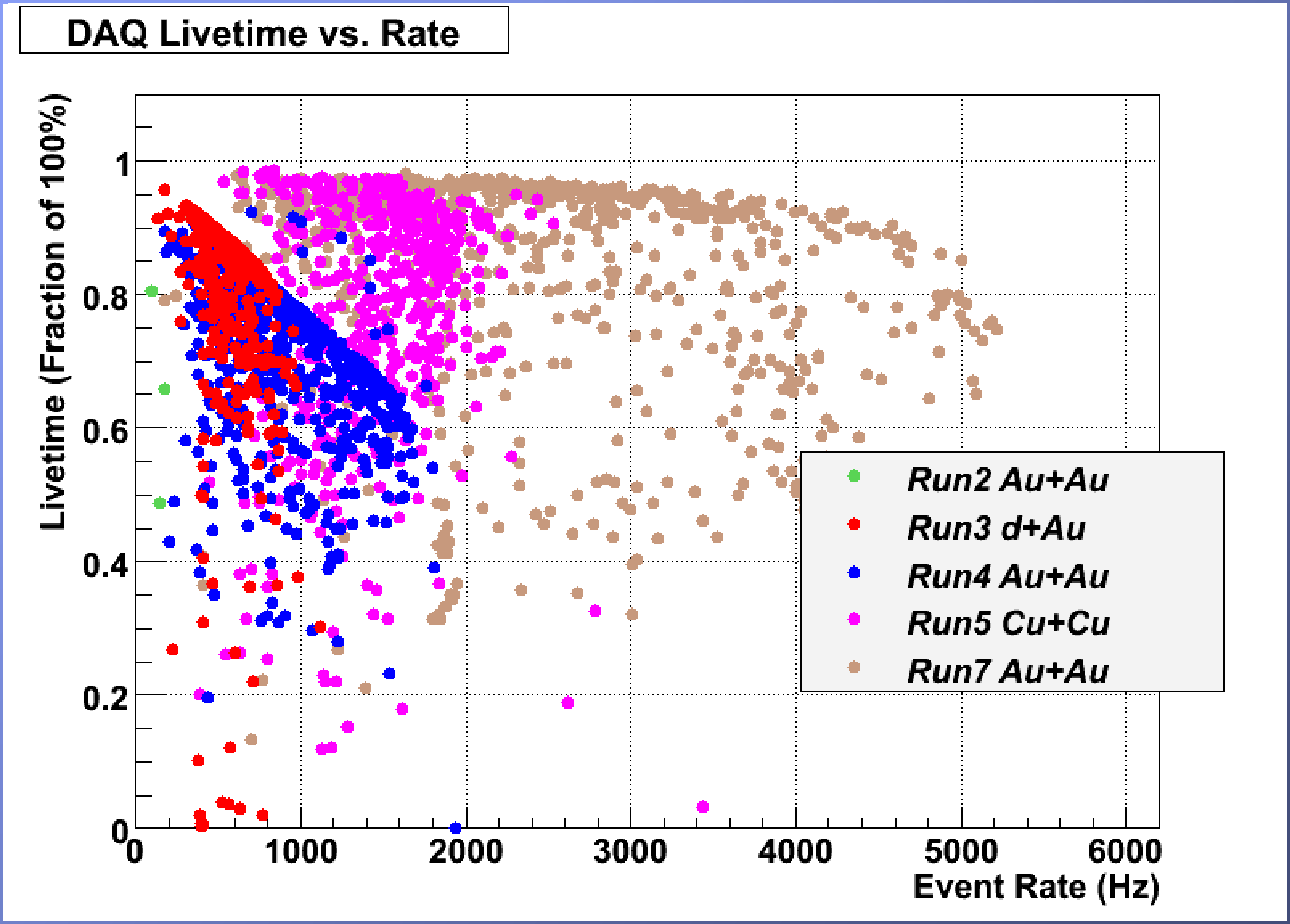


Multi-Event buffering means to start the AMU sampling again while the current sample is still being digitized.

Trigger busy released *much* earlier

deadtime greatly reduced

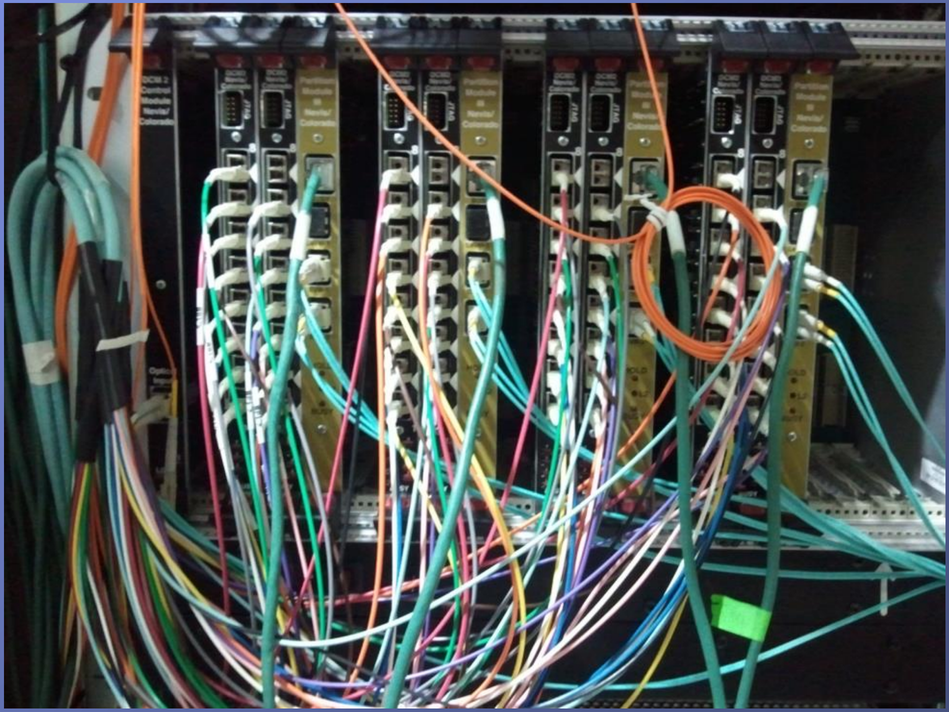
The Multi-Event Buffering Effect



FPGAs, FPGAs, and Networks

- I believe that the typical physicist will be able to program FPGAs and know VHDL just like we all know C++ these days
- We already see FPGAs enter the commodity HPC market (driven by $$$ or course)
- That, and networks will drive most DAQs
- We already see this in the (F)VTX readout – the entire front-end is FPGAs
- A well-designed board can be used for an astonishing variety of things.

DCM2 +
Partitioner 2



Controls

•At some point, you need to add controls (usually called slow controls) to your setup.

•Control the data taking

•Control and configure the front-end

•Set High Voltages, bias voltages, magnetic fields, etc

•If you are a BIG experiment (think LHC), there's a comprehensive solution

•If you rig up something smaller, you are typically on your own

•Also think of the need to log all such data

Communication methods

If you work for an LHC experiment, this is all taken care of for you.

If not, well, some pointers.

These are some methods to communicate between processes on a machine

Shared Memory	Named Semaphores	Remote Prodecure Calls	CORBA

These work only on the same machine

(yes, there are add-ons to get around that, but it's a bit of a kludge)

Few people use shared memory any more.

These work in a network-transparent fashio

If I want, I can control my DAQ at BNL from h

RPC

- Remote Procedure Call
- Widely established standard (RFC 1831) for remote execution of code controlled by a client
- Makes it look like a local function call, but the function executes on a server
- The ubiquitous NFS is based on RPC, it is available virtually everywhere
- It is a network protocol, so client and server don't have to be on the same machine, can have DAQ and control machine in different rooms (or as far apart as you like as long as the connection traverses the firewalls)
- Very robust and easy, and an open standard built into virtually any OS
- Linux, Android, Windows, …. works on any Linux flavor, for example the Raspberry PI

CORBA

- Attempt to take a C-style remote procedure call (like a function call) to calling methods on a remote object
- Fundamentally a good idea, but in many cases overkill and really complicated to implement
- Not very widespread availability
- No good “vendor” (it's usually open source, but different implementations) interoperability (supposed to be, but not so)

I'm using RPCs unless there's a good reason not to.

My first choice.

Log. Log. And log some more

Everyone has used a paper logbook. In this day and age, this is not an adequate solution anymore.

I'm talking about “environmental” data logging here, the logging of “slow controls” data

I will use a DAQ of mine as an example, but this goes for all setups.

Logging data about the data

- “reading out your detector” does not yet make a data acquisition
- It lives and dies by its ability to capture... well, everything
- What was the HV? Was the light on? What was the temperature?
- In many cases, it's there only for forensics in case there's something wrong
- Was the HV where it was supposed to be?
- Often, you need to get parameters which in the old days you had to type in from a paper logbook
- You could add a webcam picture so we have a visual confirmation of things (say, you want to move the detector with step motors)
- When you log these things automatically, no one can forget to do it.

Metadata Example

"It appears that the distributions changes for Cherenkov counter 1 at 1,8,12,and 16 GeV compared to the other energies. It seems that the pressure is changed. [...] Any help on understanding this would be appreciated."

Martin: "Look at the info in the file!"

```
$ ddump -t 9 -p 910 beam_00002298-0000.prdf
S:MTNRG  = -1      GeV
F:MT6SC1 =  5790        Cnts
F:MT6SC2 =  3533        Cnts
F:MT6SC3 =  1780        Cnts
F:MT6SC4 =  0           Cnts
F:MT6SC5 =  73316       Cnts
E:2CH    =  1058  mm
E:2CV    =  133.1 mm
E:2CMT6T =  73.84 F
E:2CMT6H =  32.86 %Hum
F:MT5CP2 =  .4589 Psia
F:MT6CP2 =  .6794 Psia
```

```
$ ddump -t 9 -p 910 beam_00002268-0000.prdf
S:MTNRG  = -2      GeV
F:MT6SC1 =  11846       Cnts
F:MT6SC2 =  7069        Cnts
F:MT6SC3 =  3883        Cnts
F:MT6SC4 =  0           Cnts
F:MT6SC5 =  283048      Cnts
E:2CH    =  1058  mm
E:2CV    =  133   mm
E:2CMT6T =  74.13 F
E:2CMT6H =  37.26 %Hum
F:MT5CP2 =  12.95 Psia
F:MT6CP2 =  14.03 Psia
```

A picture tells more that 1000 words

Was XXXx's contraption in the beam in run 2743? There is a higher fraction of showering than before."
Martin: "Look at the cam pictures we automatically captured for each run."

Summary

The End