Putting it all together

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http://conferences.fnal.gov/edit/

Focus of this talk

- Given limited time, I will "put it all together" for the experiments I have been working on most recently
  - Compact Muon Solenoid in Large Hadron Collider at CERN
    - Currently in operation
  - Mu2e at Muon Campus at FNAL
    - Currently under construction

- Apologies if your favorite experiment isn't represented
  - Fortunately, many of the concepts you have been exposed to over the past couple of weeks, including this talk, are applicable to almost all experiments

Outline

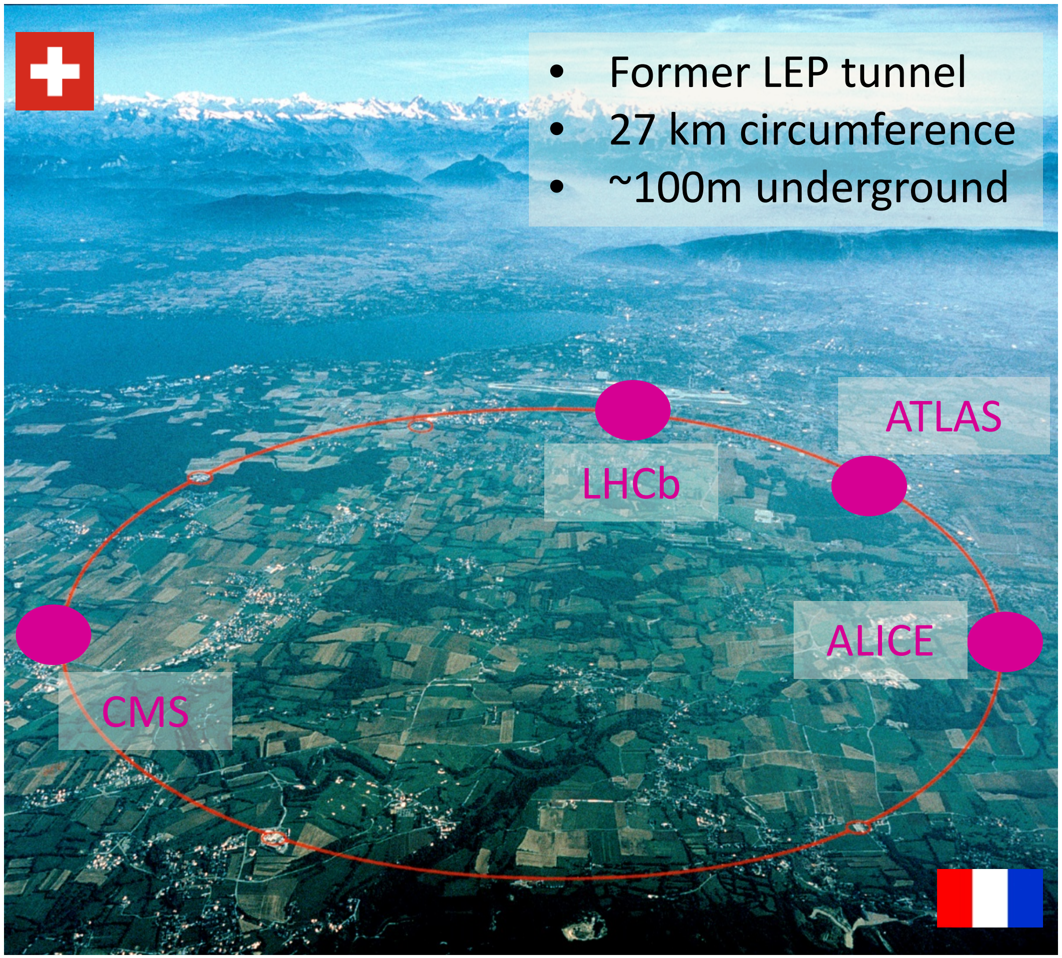
- Where to assemble your detectors
  - Particle accelerators
- How to assemble your detectors
  - Install, integrate, commission, calibrate, …
- Operate your detectors (run!)
  - … as a coherent unit in concert w/ the accelerator

Where to assemble your detectors

Particle accelerators

Large Hadron Collider (LHC) @ CERN

Multi-purpose hadron collider: p+p, Pb+Pb, p+Pb

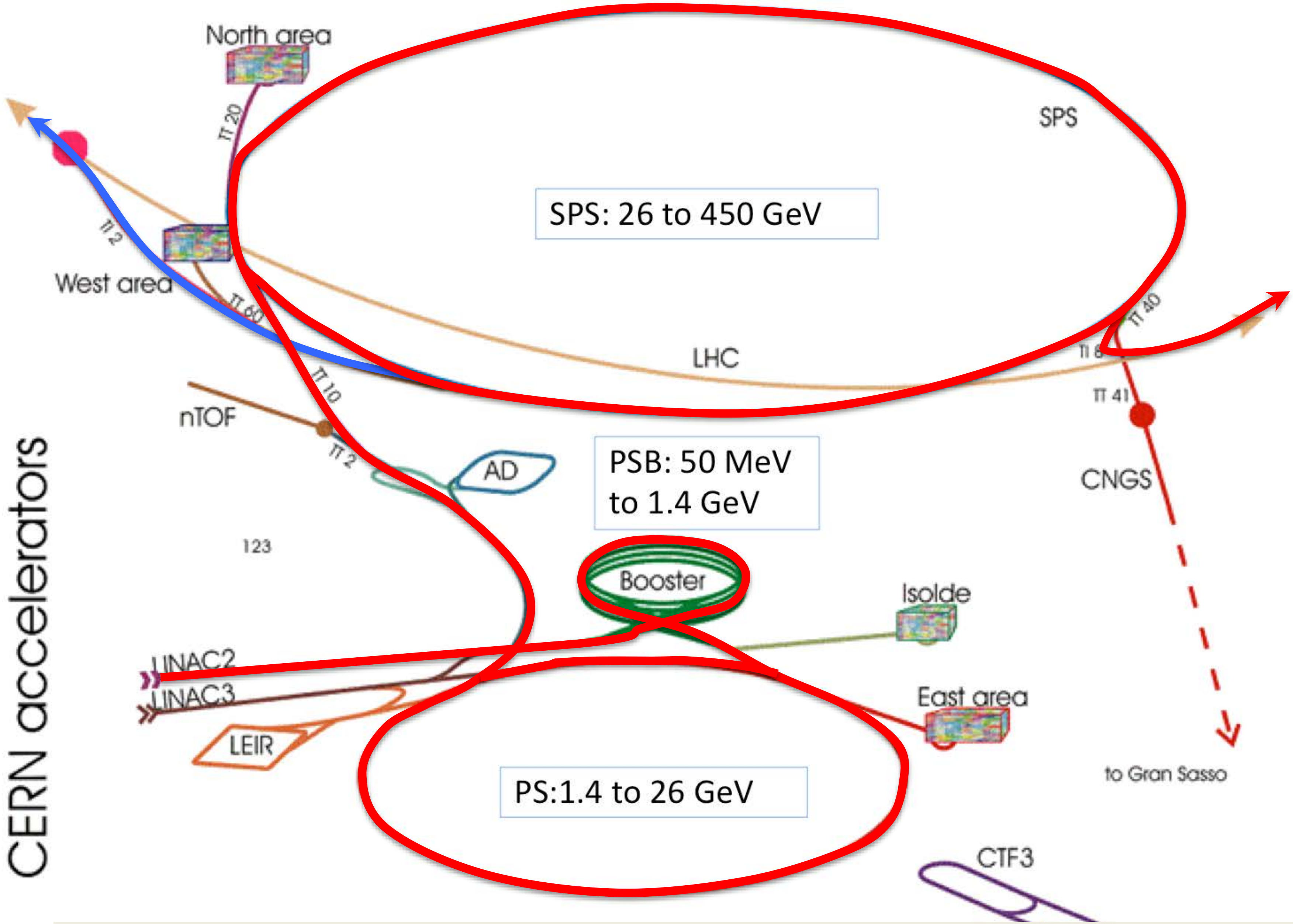


Searches for new physics at four Interaction Points

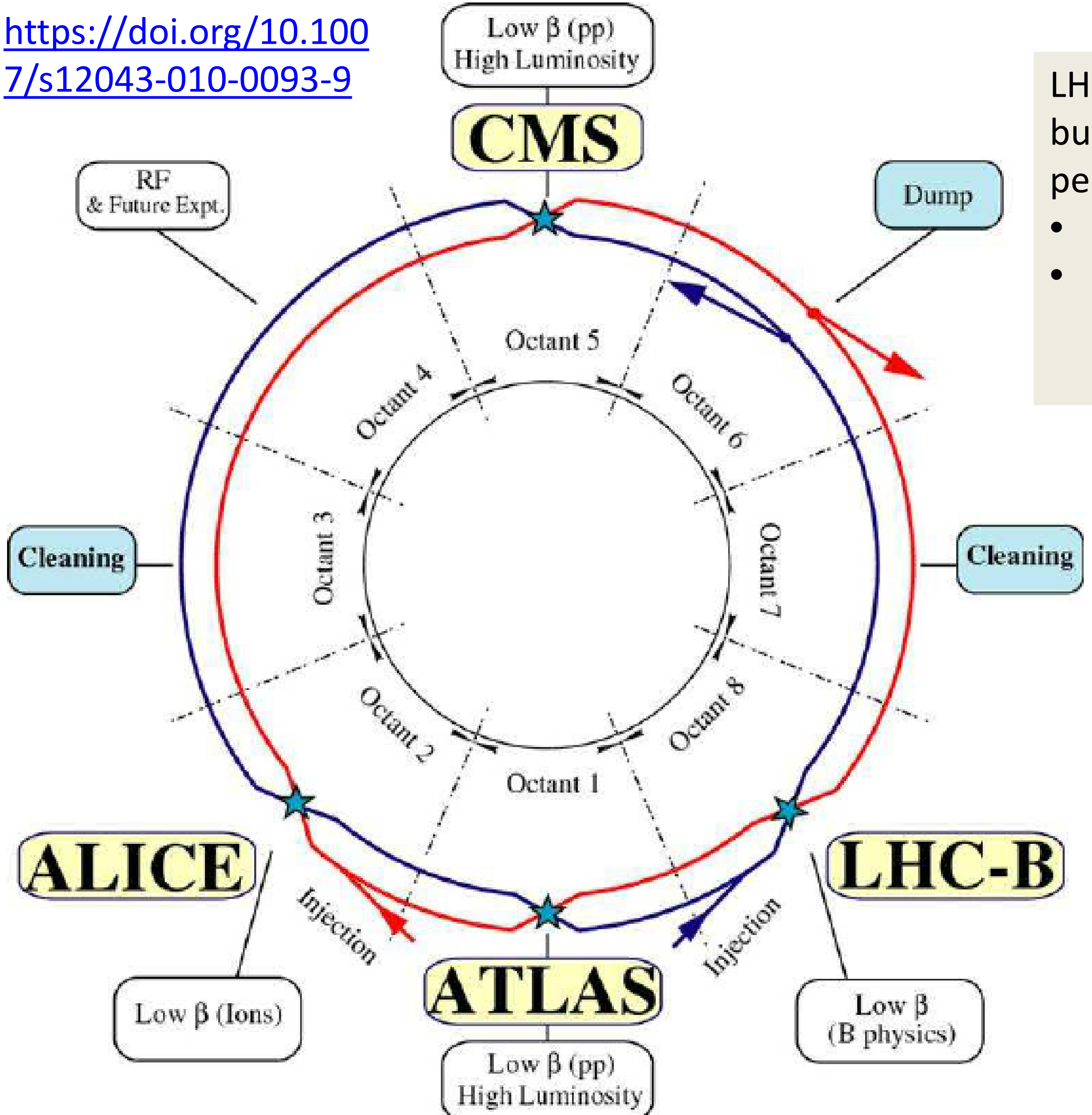
CMS and ATLAS…
- General purpose detectors for precision Higgs studies and searches for physics beyond the Standard Model

LHCb…
- Detailed studies of b-quark

ALICE…
- Focus = heavy ions



A complex chain of accelerators is required to get the particles to the right energy with the correct timing to perform a typical particle physics experiment https://doi.org/10.1007/s12043-010-0093-9

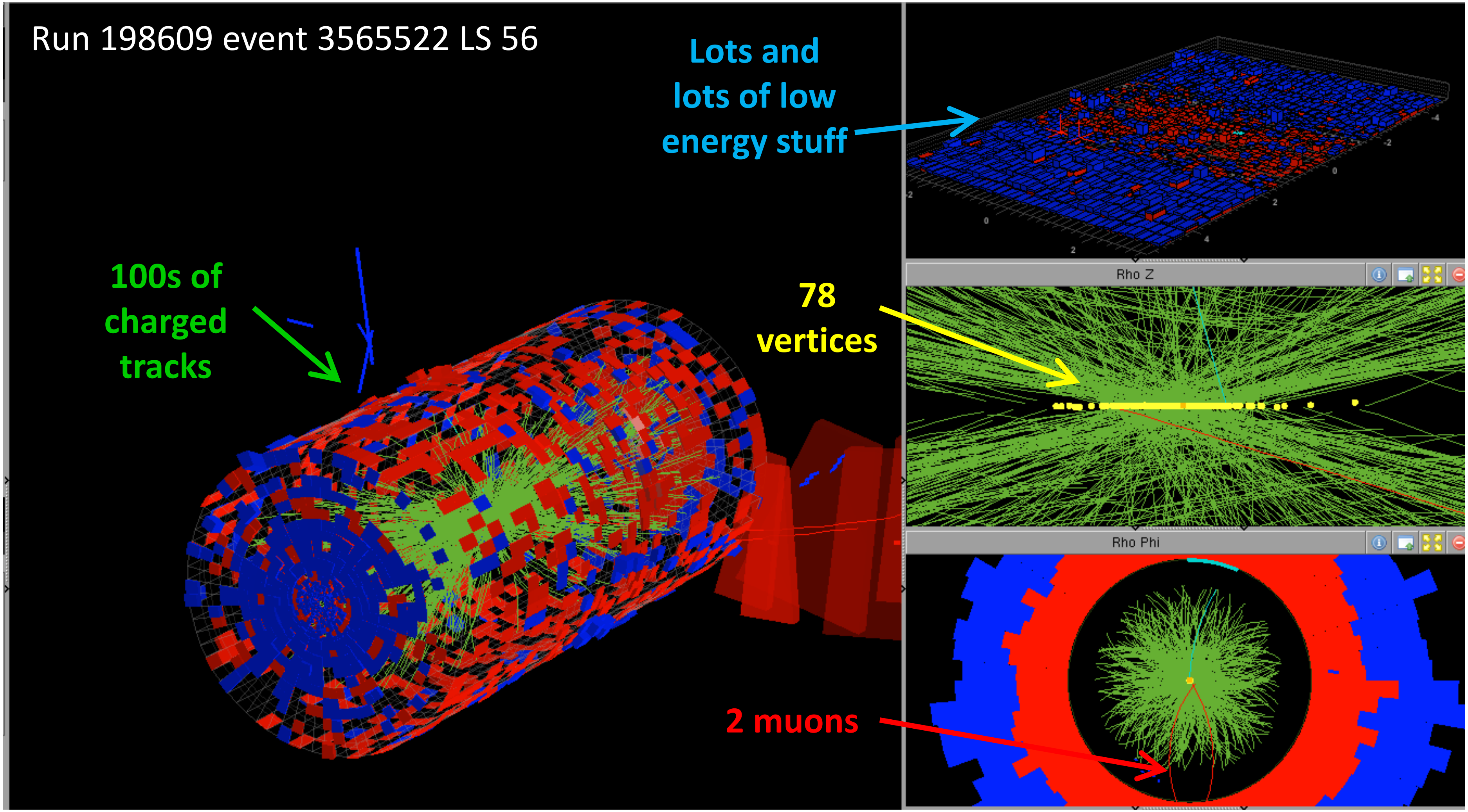


LHC: ~2500 counter-rotating bunches of protons (~1x10^{11} per bunch)

- 450 GeV → 6.5 TeV
- Steered into collision at four Interaction Points located around the ring

Watch first 1:15 of… https://www.youtube.com/watch?v=pQhbhpU9Wrg

A "typical" p+p crossing at LHC (CMS data)



http://cms.web.cern.ch/news/reconstructing-multitude-particle-tracks-within-cms

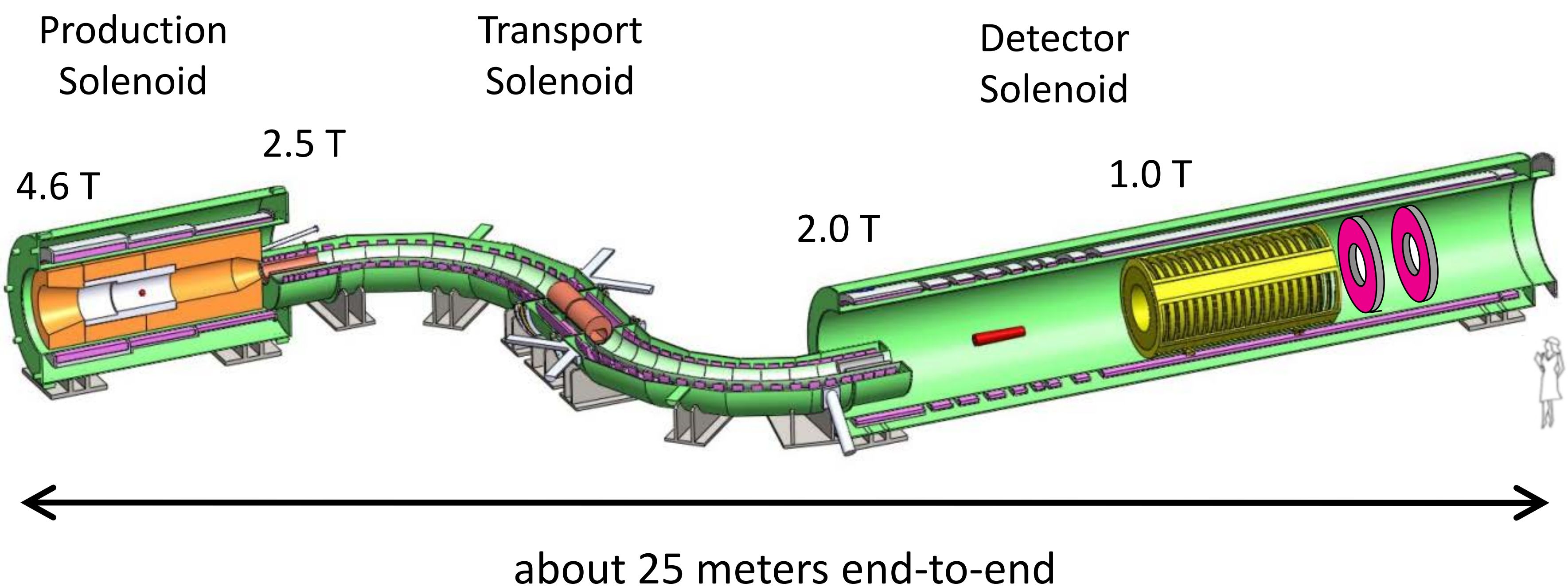
Muon campus @ FNAL

Searches for rare and hidden phenomena with muons

http://mu2e-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=4005

A complex chain of accelerators is required to get the particles to the right energy with the correct timing to perform a typical particle physics experiment

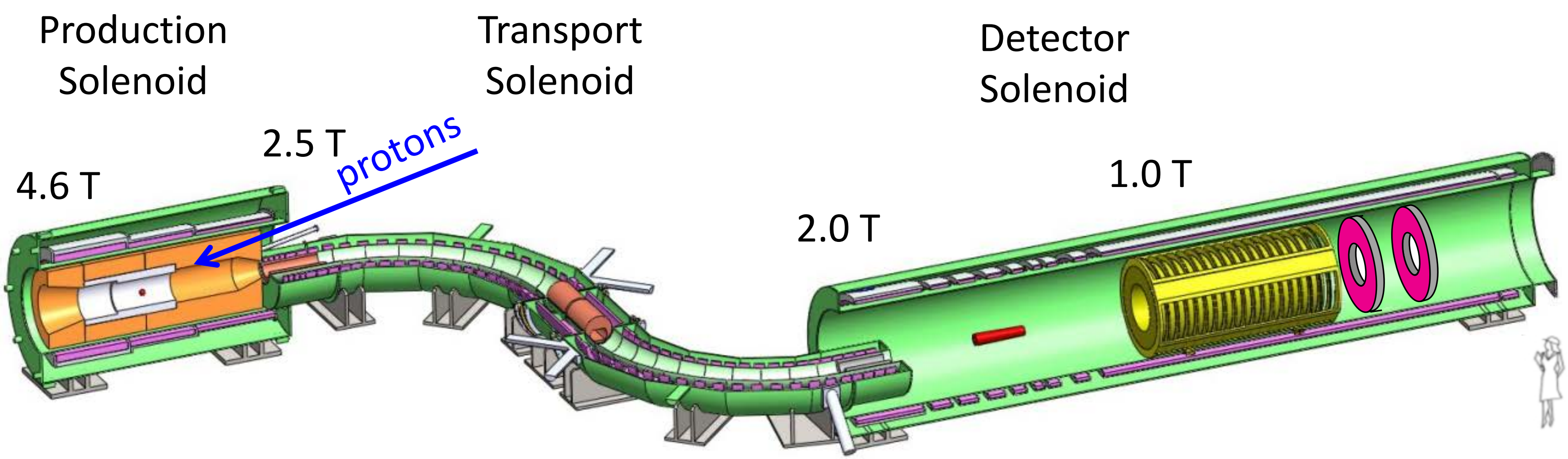
Mu2e: muon production, transport, capture, and conversion/decay



Consists of 3 solenoid systems

Tuned from original by D. Glenzinski (FNAL) at
http://www.lnf.infn.it/meetings/seminars.php

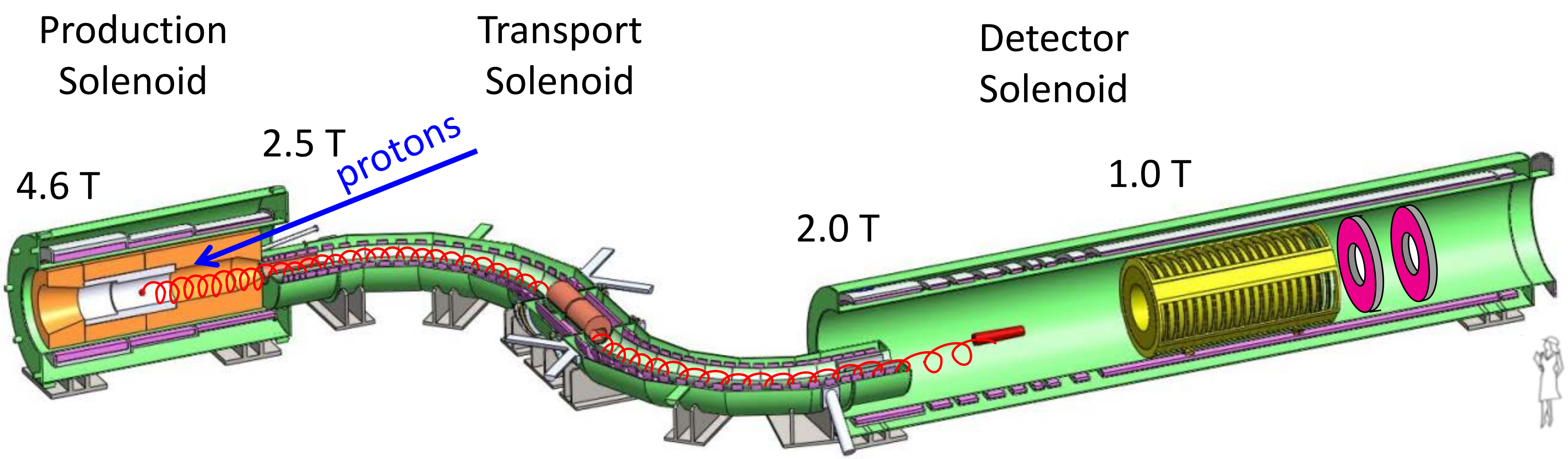
Mu2e: muon production, transport, capture, and conversion/decay



8 GeV protons interact with a tungsten target to produce μ^{-} (from π^{-} decay)

Tuned from original by D. Glenzinski (FNAL) at
http://www.lnf.infn.it/meetings/seminars.php

Mu2e: muon production, transport, capture, and conversion/decay

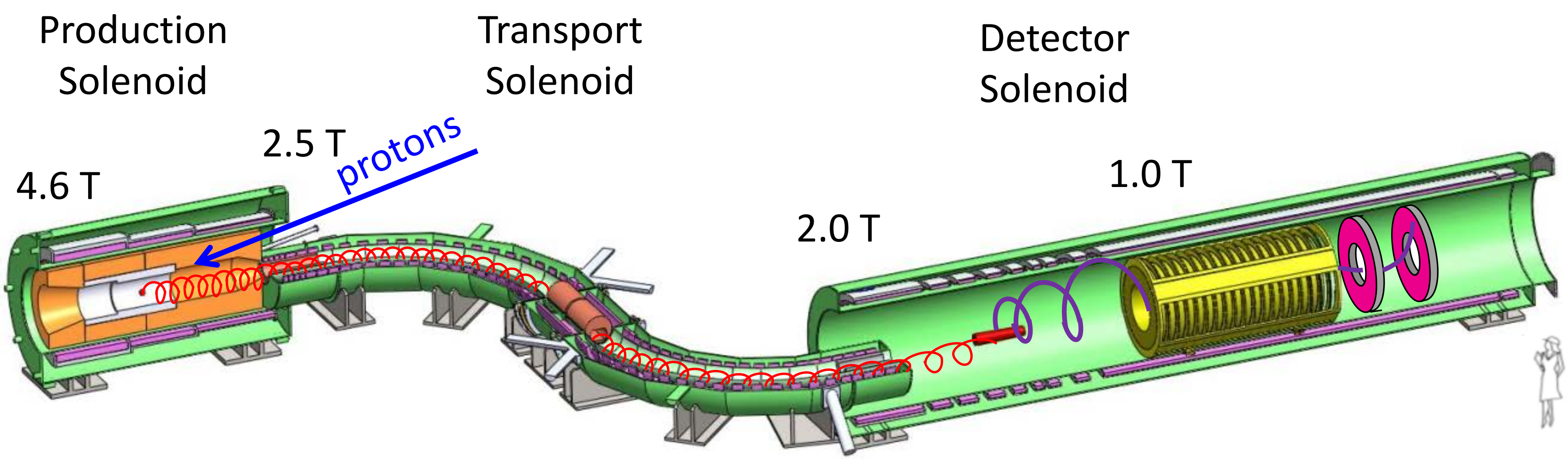


Production and transport solenoid systems:

- capture backwards-going μ– (and π–)
- momentum- and sign-selects beam
- transports to an aluminum target where the μ– is stopped (muonic aluminum)

Tuned from original by D. Glenzinski (FNAL) at http://www.lnf.infn.it/meetings/seminars.php

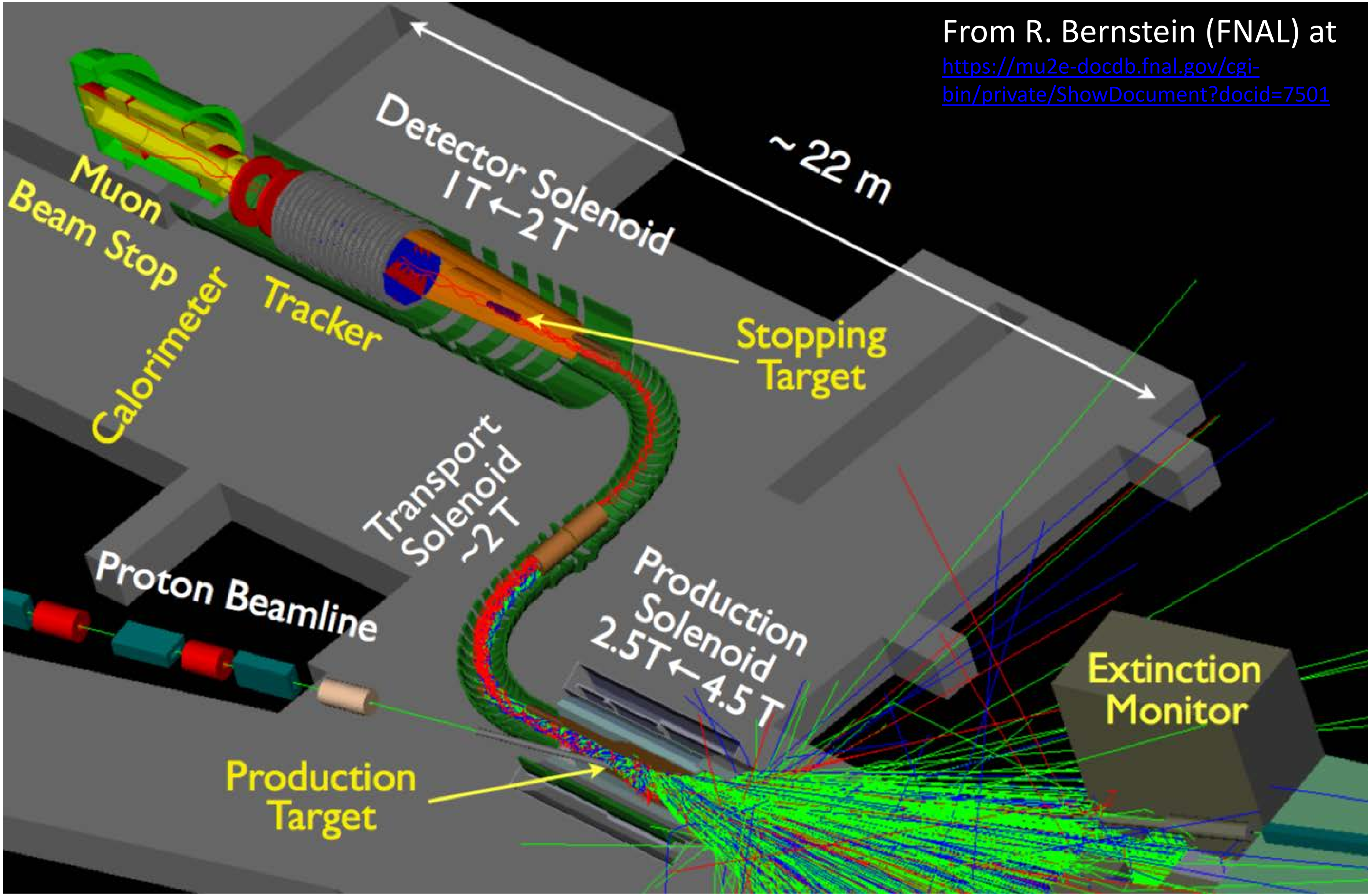
Mu2e: muon production, transport, capture, and conversion/decay



Detector solenoid system directs decay $\mu^- \rightarrow e^-$ (or, if we're lucky, directly converted $\mu^- \rightarrow e^-$) towards detector and bends them in a circle so as to measure their momentum

Tuned from original by D. Glenzinski (FNAL) at http://www.lnf.infn.it/meetings/seminars.php

"Typical" beam pulse at Mu2e (simulation)



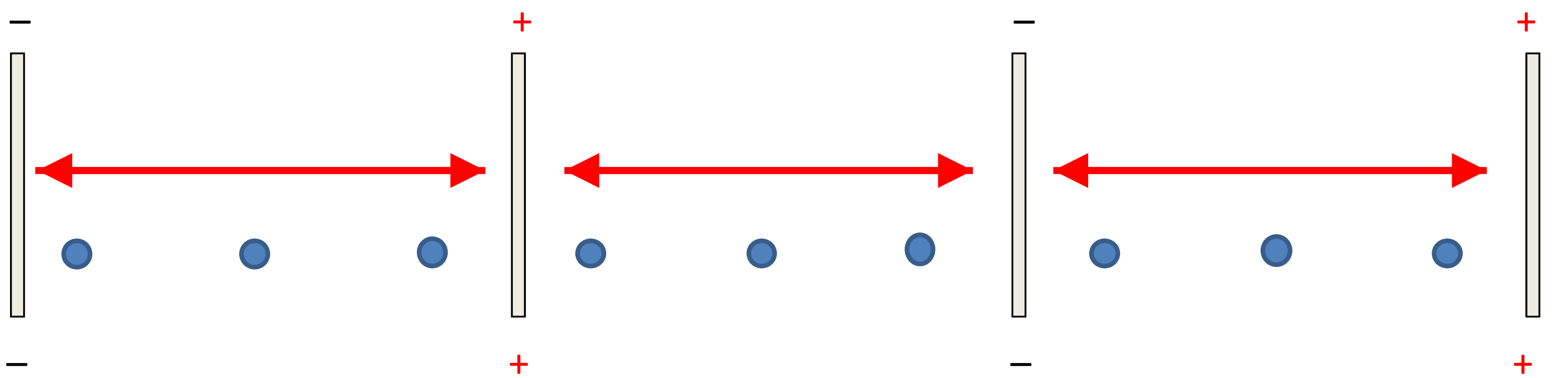
A couple of words on particle acceleration

Note: these words do not even begin to touch this topic… it is a full physics curriculum itself!

(You can get a PhD in accelerator physics and make a career out of it, if you are so inclined…)

RF acceleration

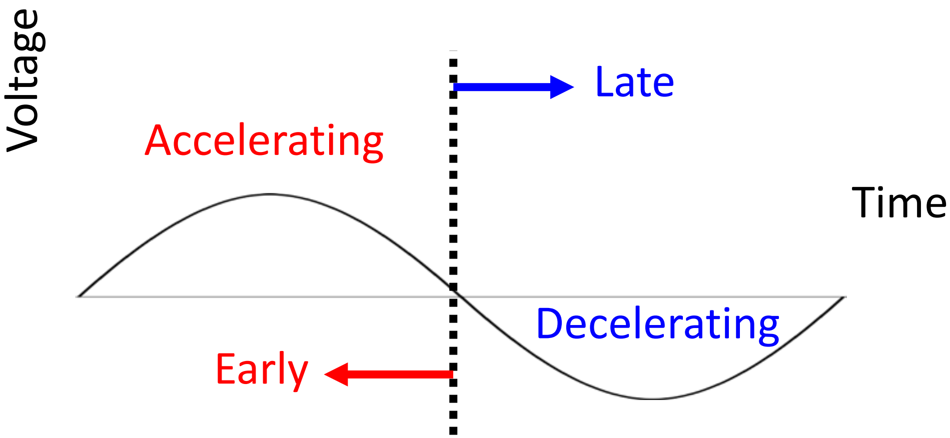
Animation tuned from original by G. Burt (Lancaster U.) https://www.cockcroft.ac.uk/wp-content/uploads/2015/04/Lecture1_Cavities.ppt

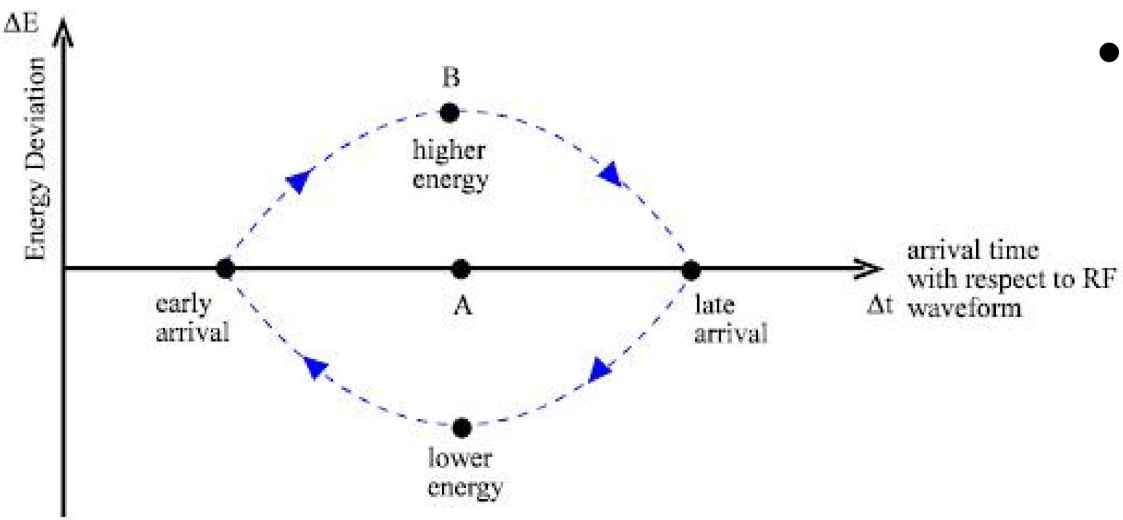


By switching the charge on the plates in phase with the particle motion, the particles always see an acceleration

RF acceleration → bunching (1/2)

https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.buckets_and_bunches

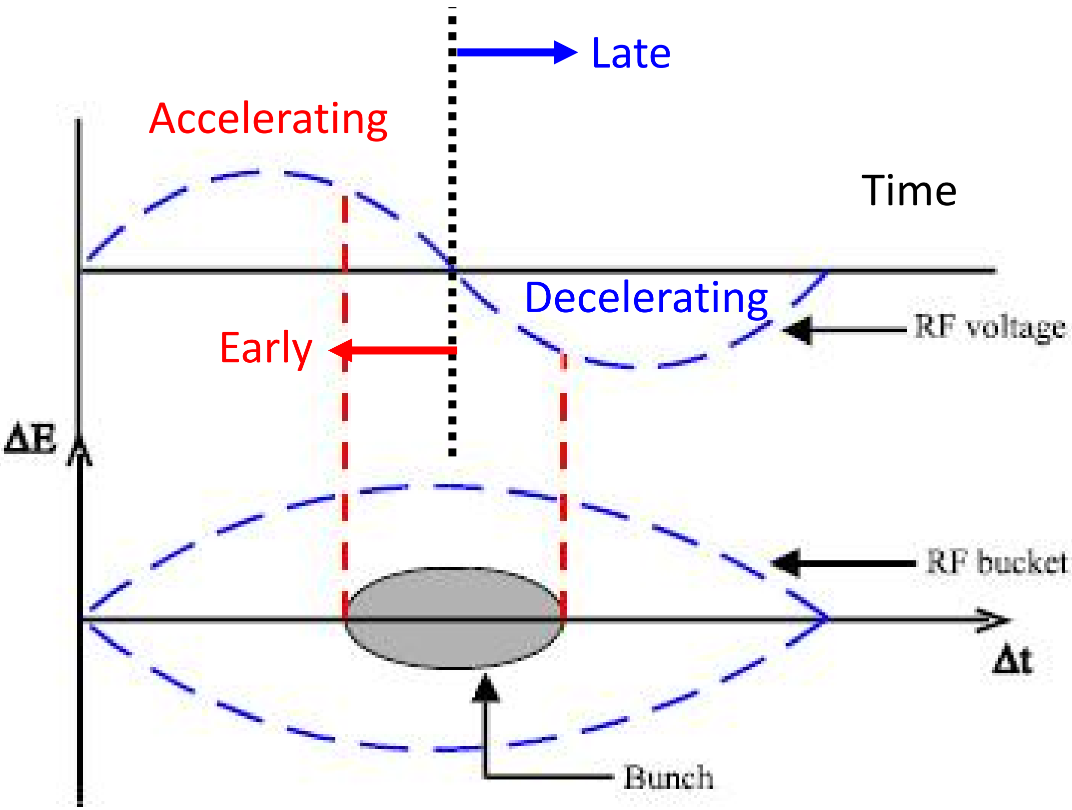




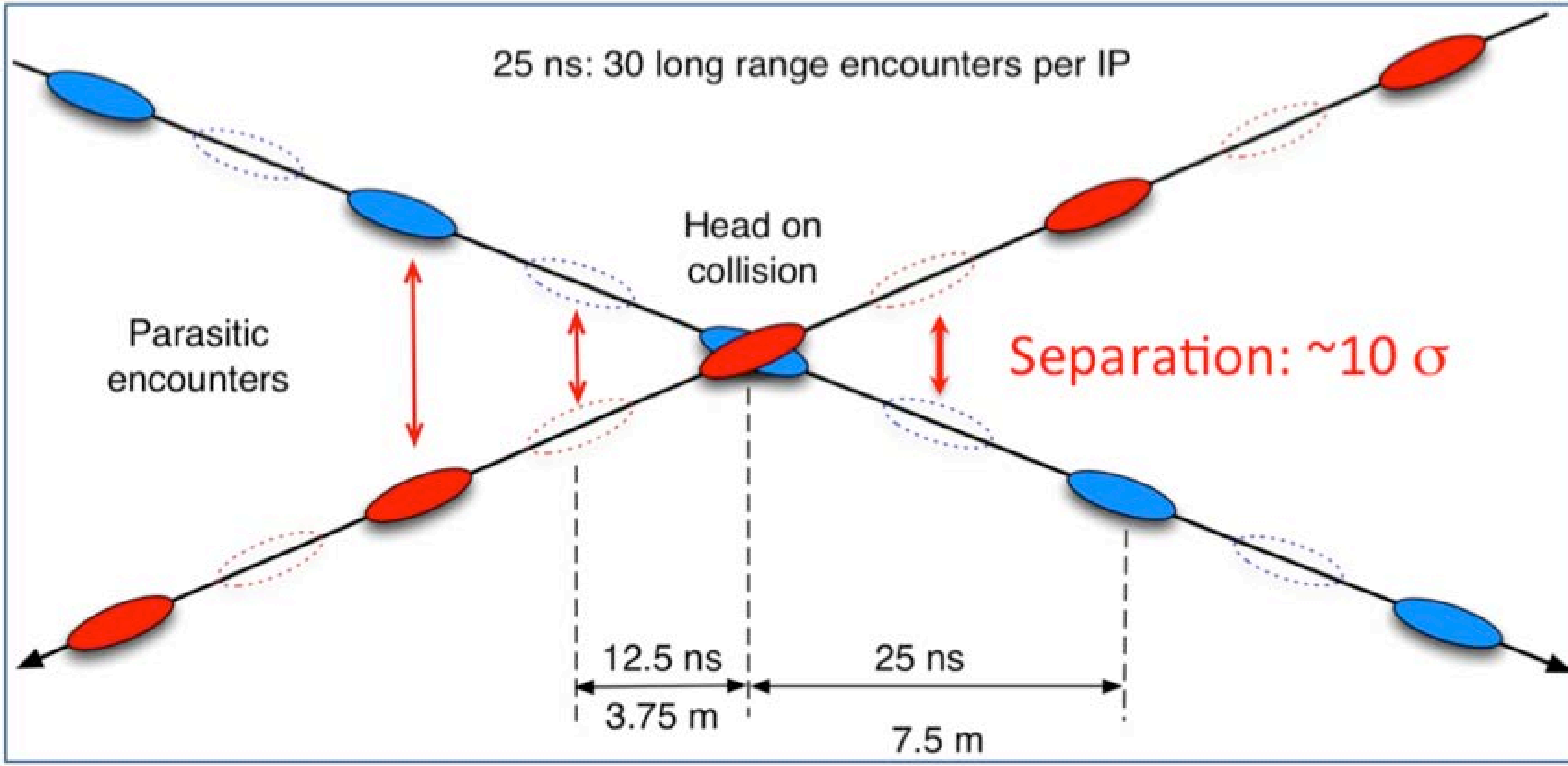
- Proton timing w.r.t. RF determines acceleration
  - Later → decelerate
  - Early → accelerate
- Since magnet bend ∝ 1/p, higher energy protons travel farther around in a circular accelerator
  - Higher energy → later
  - Lower energy → earlier

RF acceleration → bunching (2/2)

https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.buckets_and_bunches



- At top energy, the ideally timed proton with exactly the right energy will see no acceleration
- Protons with slightly different energies, arriving earlier or later, will be accelerated or decelerated so that they stay close to the energy of the ideal particle
- This sorts the particle beam into discrete packets called "bunches"



The LHC collides bunches of protons every 25ns
(25ns = bunch spacing = BX → 40MHz)

Short aside: what is a "nanosecond"?

- Nanosecond [**nan**-*uh*-sek-*uh*-nd, ney-nuh-]
  - *Noun:* one billionth of a second
  - British: one thousand-millionth of a second
  - Informal: a very short time; a moment.
    - "he replied without a nanosecond's hesitation"

- Recall: speed of light = 30 cm/ns ~ 1 foot/ns
- Nanoseconds are the correct unit of time for…
  - … particles traveling at relativistic speed
  - … in detectors whose size is measured in meters

Back to business…

- Chains of accelerators are used to reach high energies
- Chains of magnets within each accelerator are used to
  - Bend the particles in a circle (dipoles)
  - Focus the beams (quadrupoles)
  - Stabilize the beams from resonances (octupoles)
- They operate in ultra high vacuums
  - 10^{-9} Pa at interaction regions (mean free path ~10,000 km)
- Many of the magnets are superconducting
  - Liquid He cryogenics use ~1/3 of electrical power at LHC

What could possibly go wrong?

Part 1

Next page →

https://en.wikipedia.org/wiki/Beech_marten

Large Hadron Collider [edit]

On 29 April and 21 November 2016, two beech martens shut down the Large Hadron Collider, the world's most powerful particle accelerator, by climbing on 18–66 kV electrical transformers located above ground near the LHCb and ALICE experiments, respectively.[29][30][31] The second marten was stuffed and put on display in the Rotterdam Natural History Museum.[32]

Beech Marten

- Car starter cable ✅
- 66kV transformer ❌

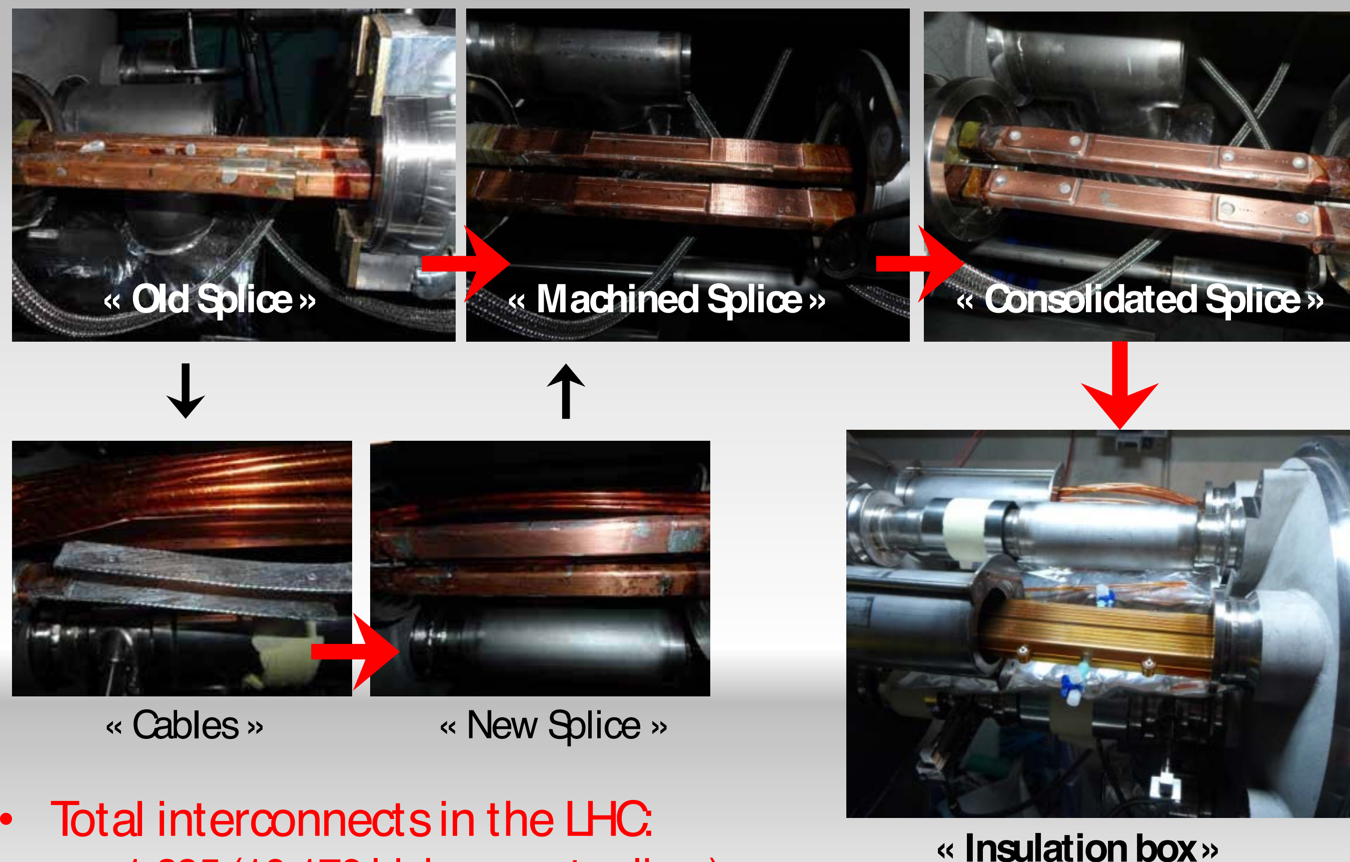
19 Sept 2008: “The LHC incident”

- From http://press.cern/press-releases/2008/10/cern-releases-analysis-lhc-incident
  - “During powering tests of the main dipole circuit in Sector 3-4 of the LHC, a fault occurred in the electrical bus connection in the region between a dipole and a quadrupole, resulting in mechanical damage and release of helium from the magnet cold mass into the tunnel.
  - “... The forces on the vacuum barriers attached to the quadrupoles at the subsector ends were such that the cryostats housing these quadrupoles broke their anchors in the concrete floor of the tunnel and were moved away from their original positions, with the electric and fluid connections pulling the dipole cold masses in the subsector from the cold internal supports inside their undisplaced cryostats…”

- Lessons learned for the experimental physicist: be challenging in concept and conservative in implementation, question yourself, talk to everyone, think of every possible failure mode, ALWAYS maintain safe practices, and… be ready for the unexpected…

Splices re-worked in 2013-2014 to allow magnets to power up to 6.5 TeV

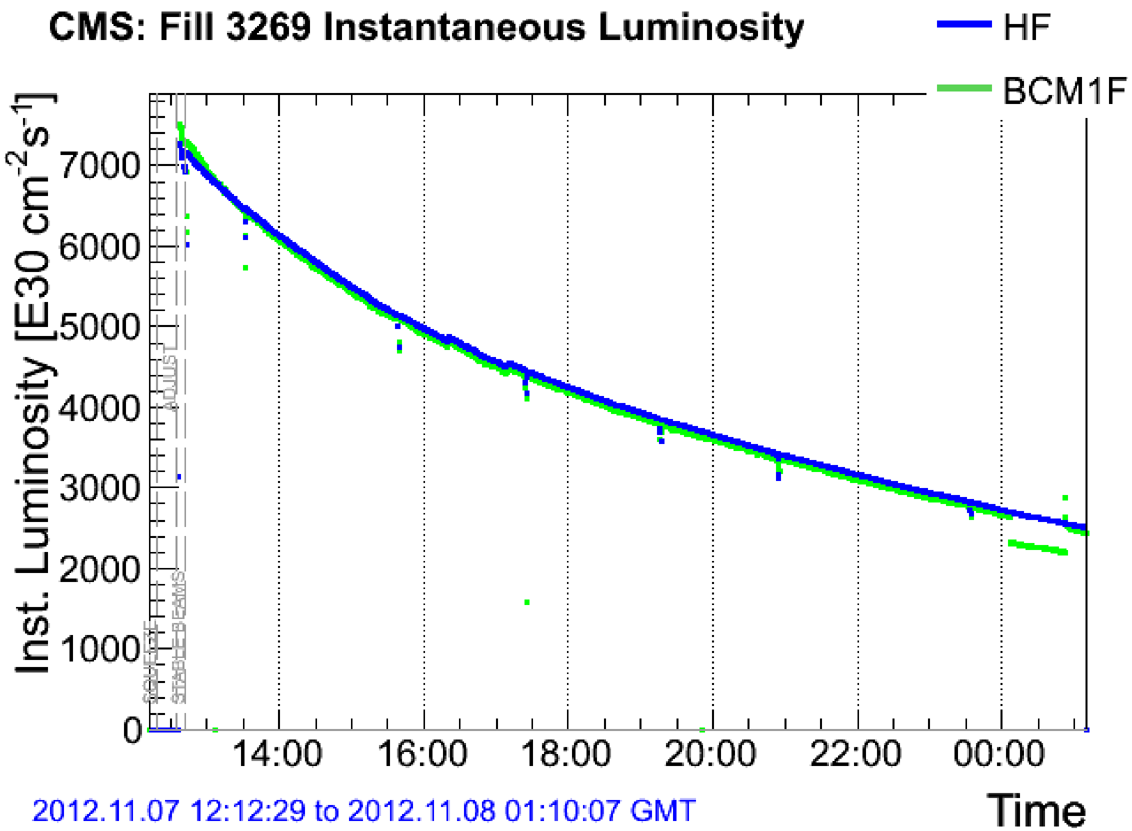
M. Lamont (CERN) at 2015 Moriond (https://indico.in2p3.fr/event/10819/)



- Total interconnects in the LHC:
  - 1,695 (10,170 high current splices)
- Number of splices redone: ~3,000 (~30%)
- Number of shunts applied: >27,000

And a lot more besides…

And when it all goes right:
Inject, Ramp, Squeeze, Adjust, Stable Beams…



If they can, LHC will typically keep a fill until the luminosity drops to ~1/2 the initial value

Summary (so far)

- Many particle physics experiments look at particles coming from accelerated beams

- Accelerator physics is very hard and very fun

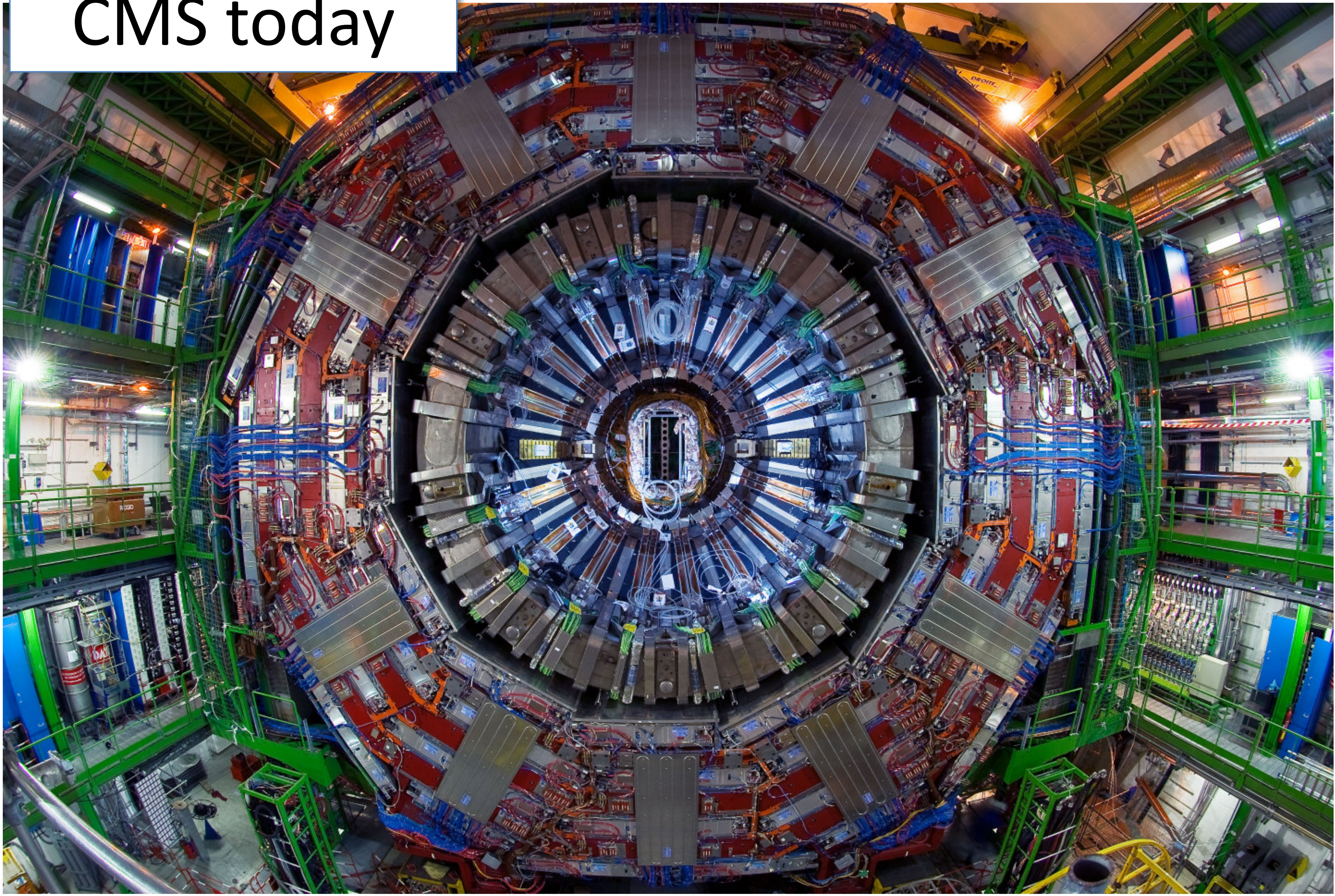
Be on the lookout for the unexpected!

How to assemble your detectors

Install, integrate, commission, calibrate, …

1998-2005: excavation of CMS cavern

CMS today



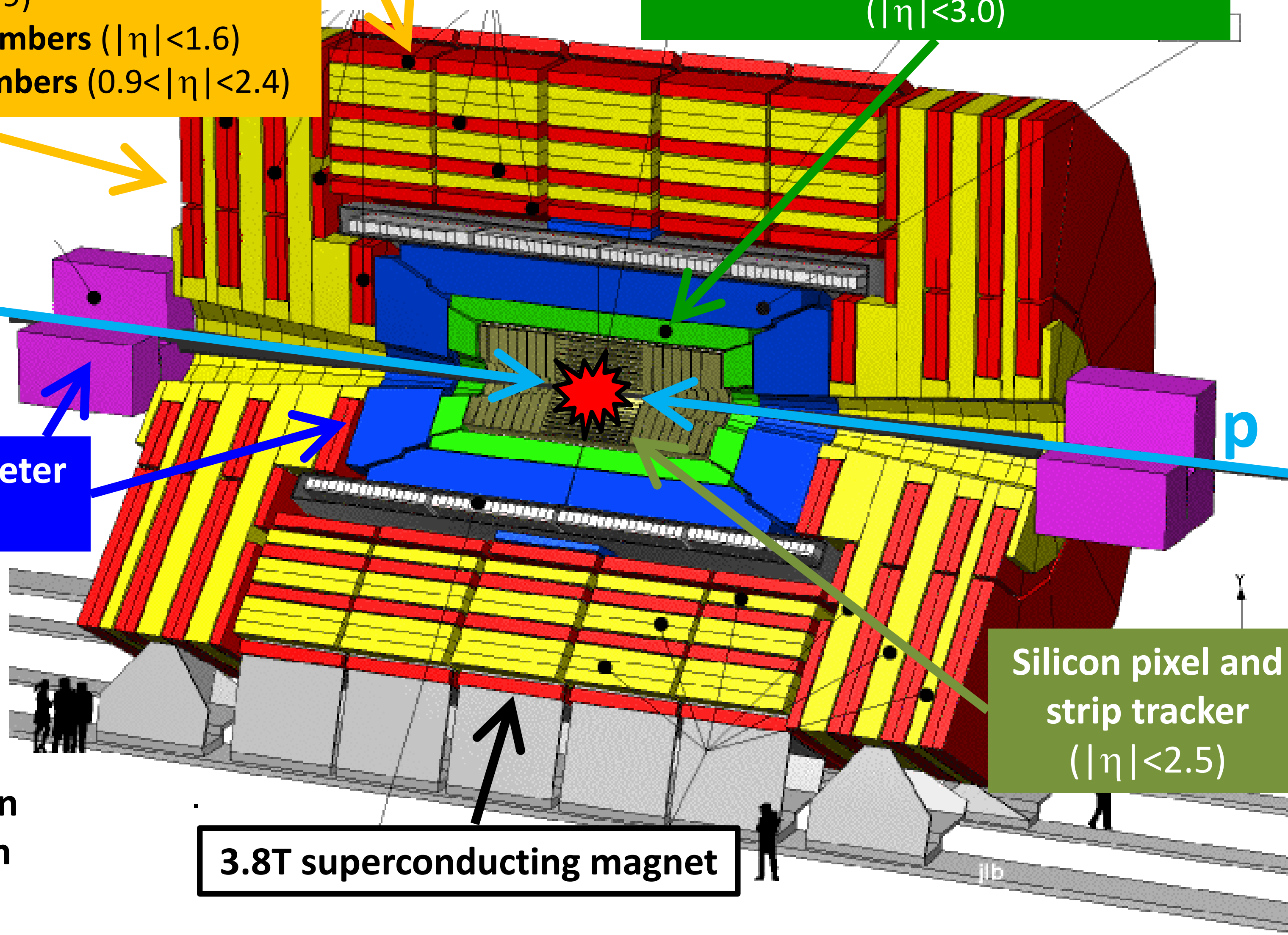
Particle identification by design

From A. Korytov (UF) at http://conferences.fnal.gov/edit/edit2018/plenary-lectures/

- **Nine particles that matter:**
  - out of hundreds different particles produced in high energy collisions, only the following few that can actually be directly observed via their interactions with a detector in general purpose experiments: γ, e, μ, $\pi^{\pm}$, $K^{\pm}$, K_L, K_S, p, n
  - all others are too short lived and three neutrinos; there are inferred...

- To detect, identify, and reconstruct particles produced in proton collisions, CMS was assembled with:
  - Inner tracker embedded within a magnetic field
  - Electromagnetic calorimeter
  - Hadronic calorimeter
  - Muon detector

Compact Muon Solenoid detector



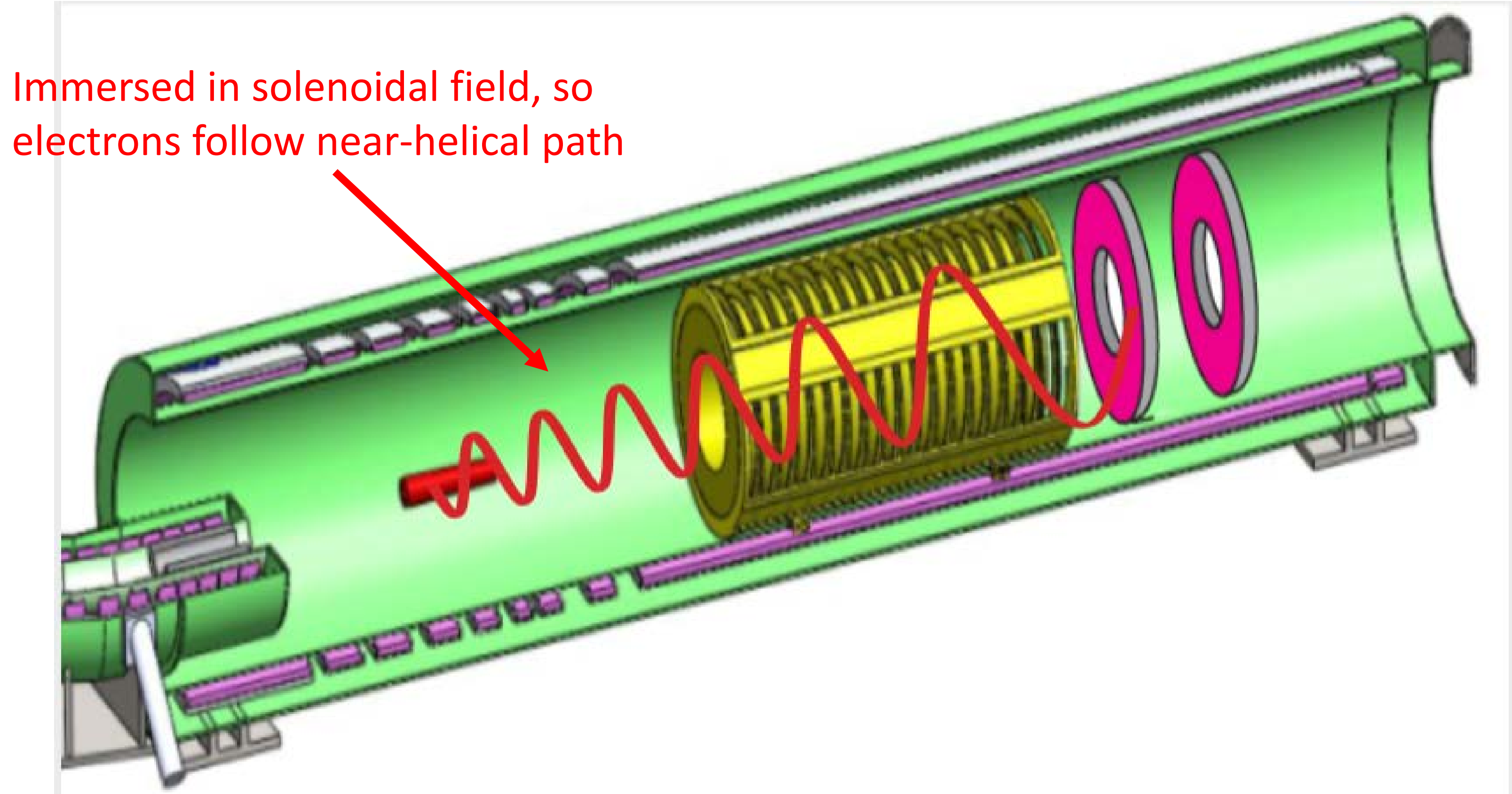
Weight = 14.5kton
Diameter = 14.6m
Length = 21.6m

Quiz: what have you detected?

- Identify the particle you have most likely detected if you see the following signals…
  - Possible answers: electron, photon, muon, $\pi^{+/-}$, $K^{+/-}$, K^0_L, K^0_S, proton, neutron

Signal / Most probable particle?	Inner tracker	Electromagnetic calorimeter	Hadronic calorimeter	Muon detector
electron	Yes	Yes	No	No
photon	No	Yes	No	No
charged hadron	Yes	Minimal	Yes	No
muon	Yes	Minimal	Minimal	Yes

Mu2e Detector



- Goal: detect e^- with p=105 MeV/c from target
- Tracker: measure radius of curvature
- Electromagnetic calorimeter: identification and timing

A couple of words on commissioning and calibration

Note: if you don't do these things, your detector will not work

If your detector doesn't work, you will not discover anything

Some general commissioning steps (1/2)

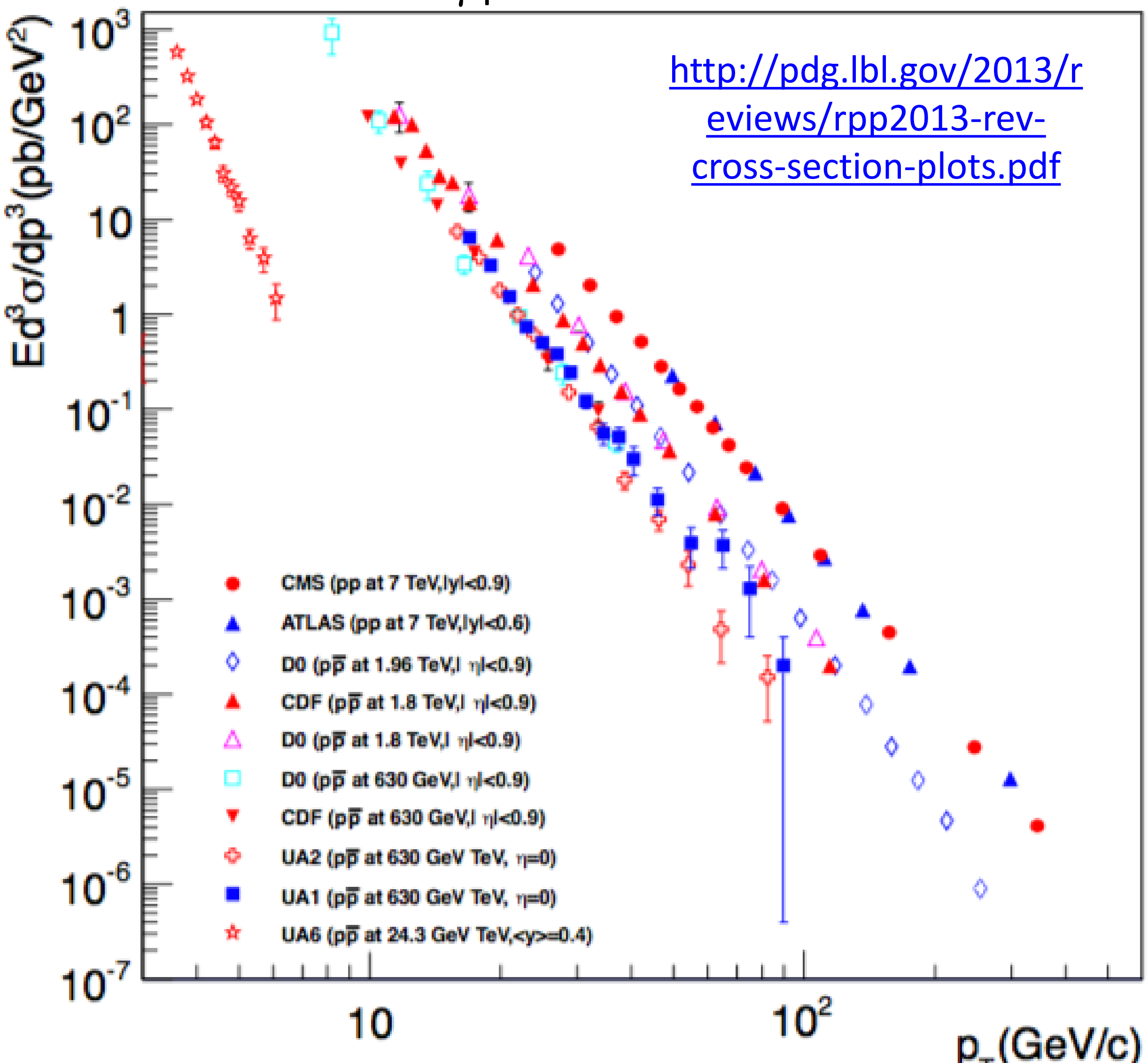
- Turn on and configure (robustly)
  - This is harder than it sounds
- Test interfaces
  - Both within system and with other systems…
  - This is a *lot* harder than it sounds
- Measure timing, efficiency, latency, …
  - Iterative and usually needs other detectors
- Align and calibrate
  - Iterative and may need a lot of data

Some general commissioning steps (2/2)

- Test system robustness under known stresses
  - Do not get caught by the same bug twice
- Take data at every new condition
  - Likely to learn every time something changes, no matter how small the change appears to be…
- Understand detector response
  - Histograms depend on trigger & conditions
- Take lots and lots of data…
  - … including under the most stressful conditions

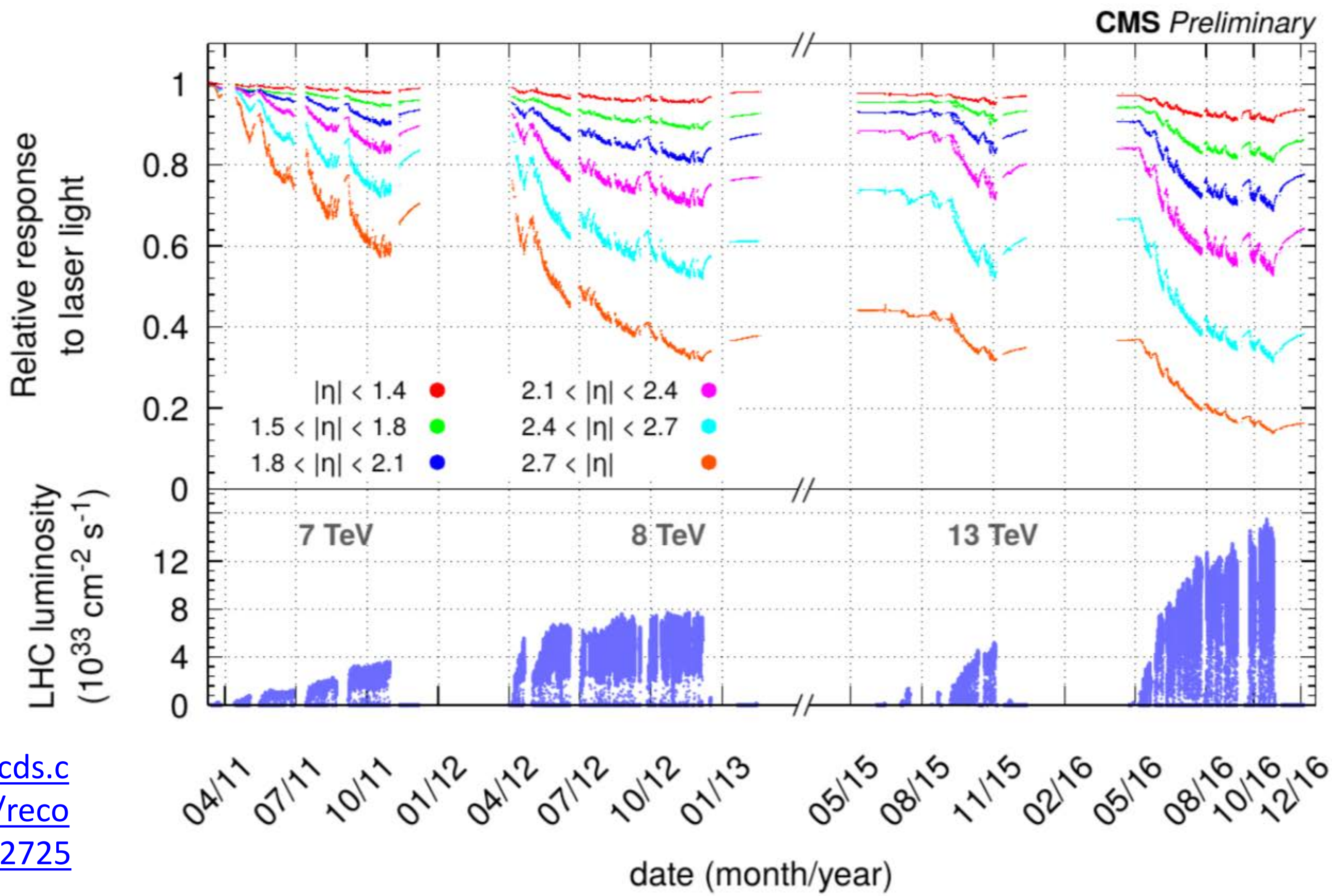
Example 1/3: energy calibration (1/2)

Direct γ production cross section



An uncertainty in the photon energy (~x-axis) translates directly into an uncertainty in the production cross section (y-axis)

Example 1/3: energy calibration (2/2)

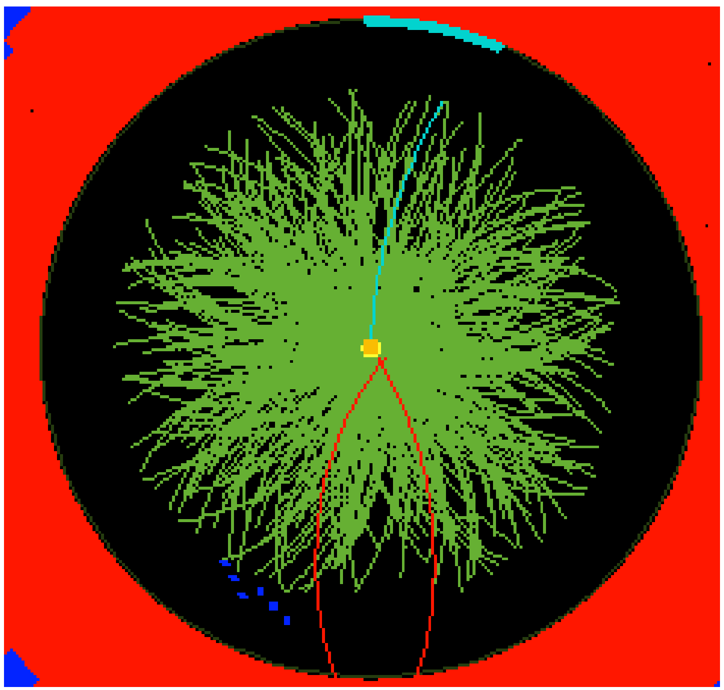


http://cds.cern.ch/record/2252725

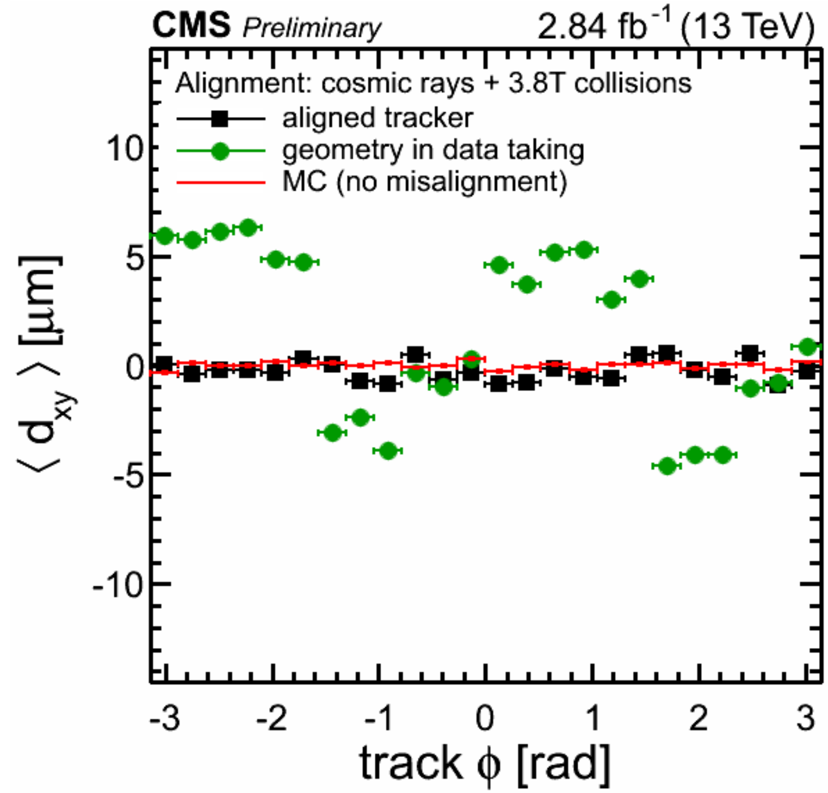
Continuous monitoring + calibration to get correct energy response

Example 2/3: tracker alignment

Question: How well can we specify the transverse position of the collision vertex?



Answer:



2x10^5 alignment parameters determined using collision and cosmic ray tracks

JINST 9 (2014) P06009

Example: trigger synchronization

- It's fundamental
  - Experiments often use an architecture of a *synchronous trigger* with a pipeline readout
  - A mis-timed detector will make you miss the event

- It's hard
  - A typical subsystem has 1000's of knobs to turn
  - Requires a well-defined procedure to converge

What does "synchronous trigger architecture" mean?

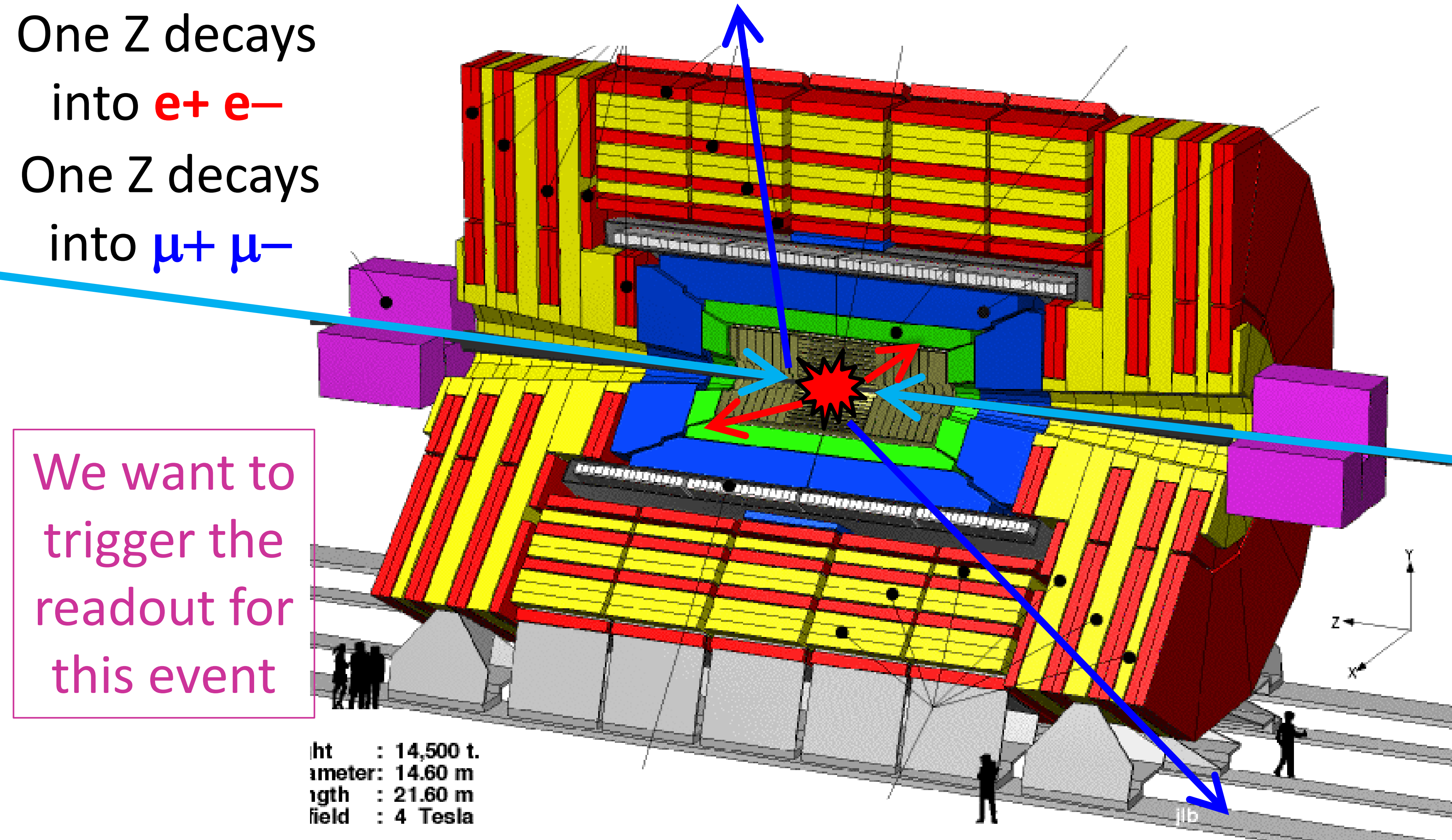
Next page →

proton + proton → Higgs → Z + Z

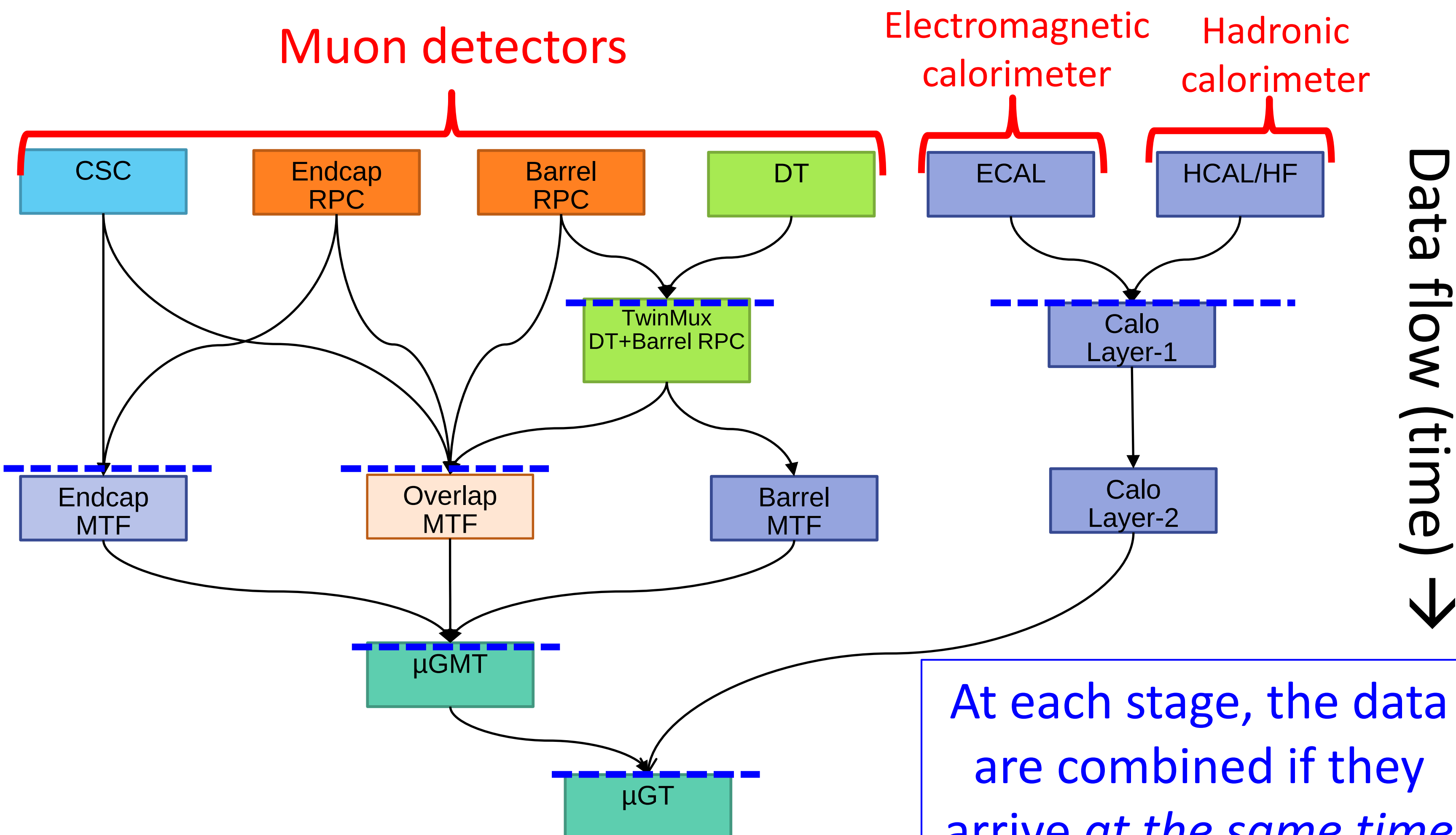
One Z decays into **e+ e–**

One Z decays into **μ+ μ–**

We want to trigger the readout for this event

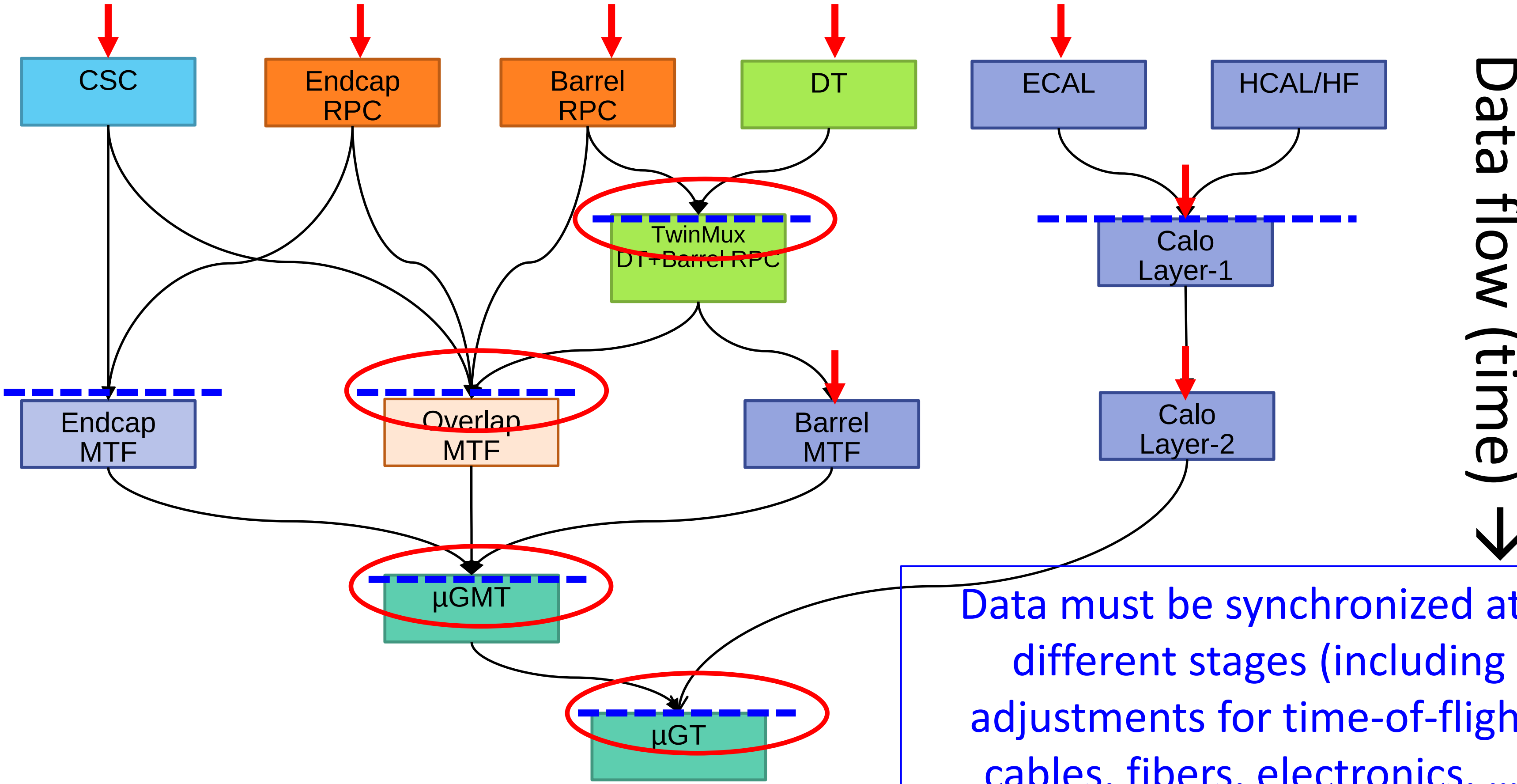


Data from subsystems are combined in stages to make more complicated objects



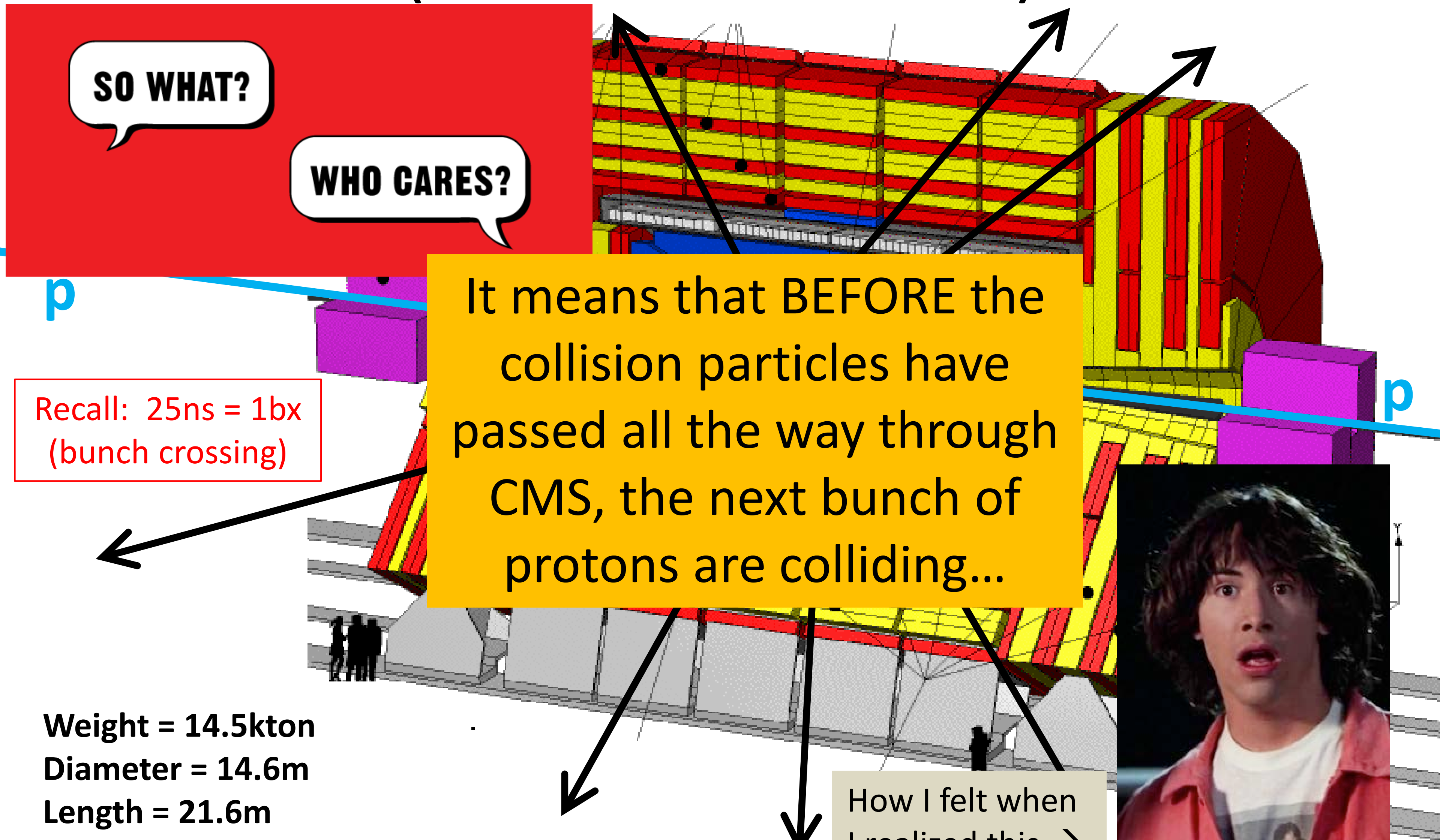
At each stage, the data are combined if they arrive *at the same time*

Data from pp → H → ZZ → $e^+e^-\mu^+\mu^-$



Data must be synchronized at 4 different stages (including adjustments for time-of-flight, cables, fibers, electronics, …) … otherwise we miss the event!

CMS: height = 25ns, length = 35ns (from the IP → out)



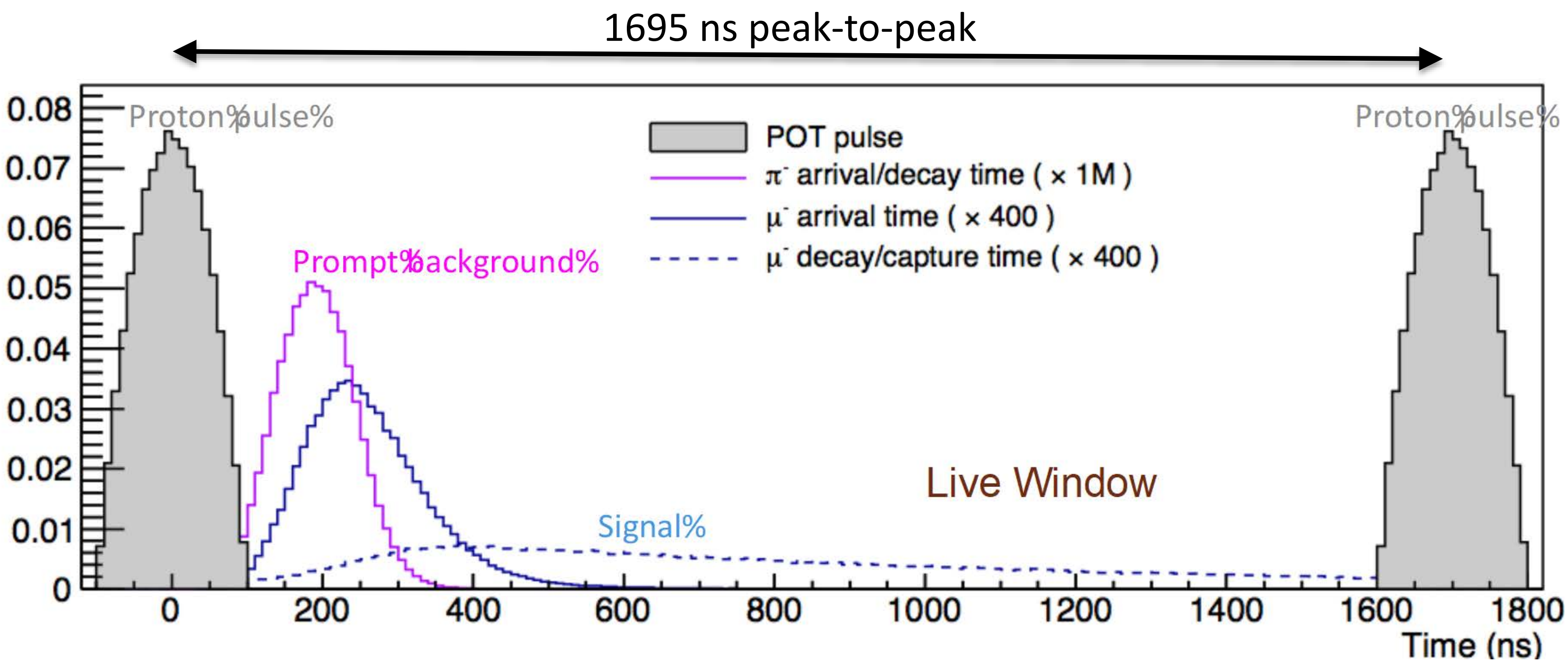
It means that BEFORE the collision particles have passed all the way through CMS, the next bunch of protons are colliding…

Recall: 25ns = 1bx (bunch crossing)

Weight = 14.5kton
Diameter = 14.6m
Length = 21.6m

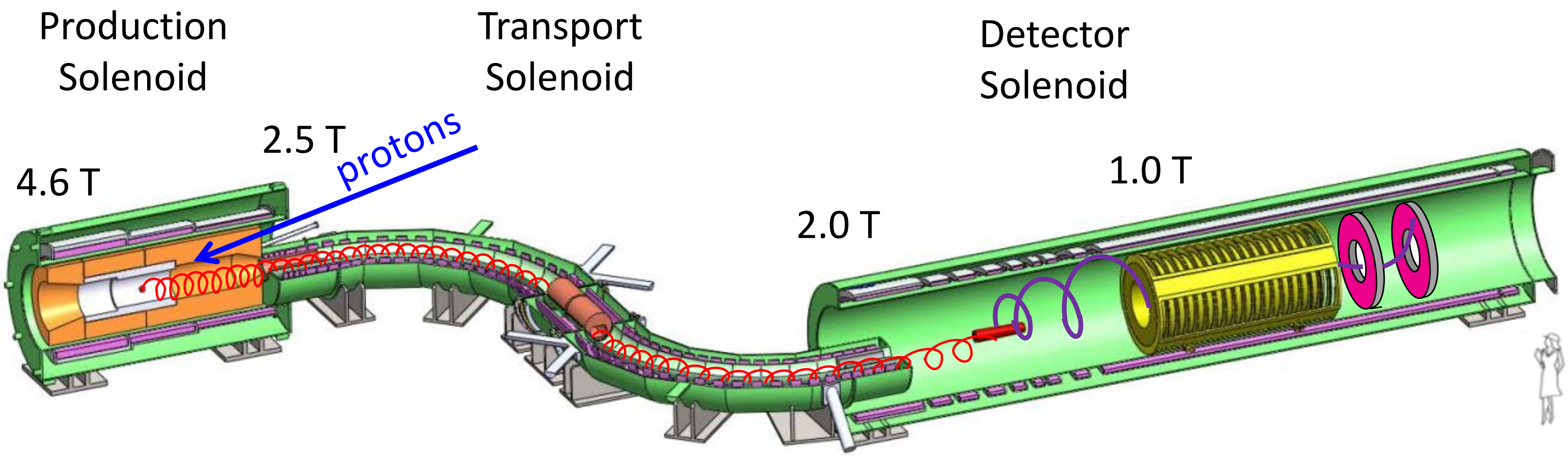
How I felt when I realized this →

Mu2e: time structure



- Pulsed proton beam with a delayed live gate to suppress prompt backgrounds from pions ("flash")
  - 700 ns delay reduces pion background by $>10^{-9}$

Asynchronous clocks



Since the protons incident on target are far removed from stopped muons that decay/convert into electrons, it was decided that the Mu2e experiment clock (40MHz) would not be locked to the accelerator clock (590kHz)

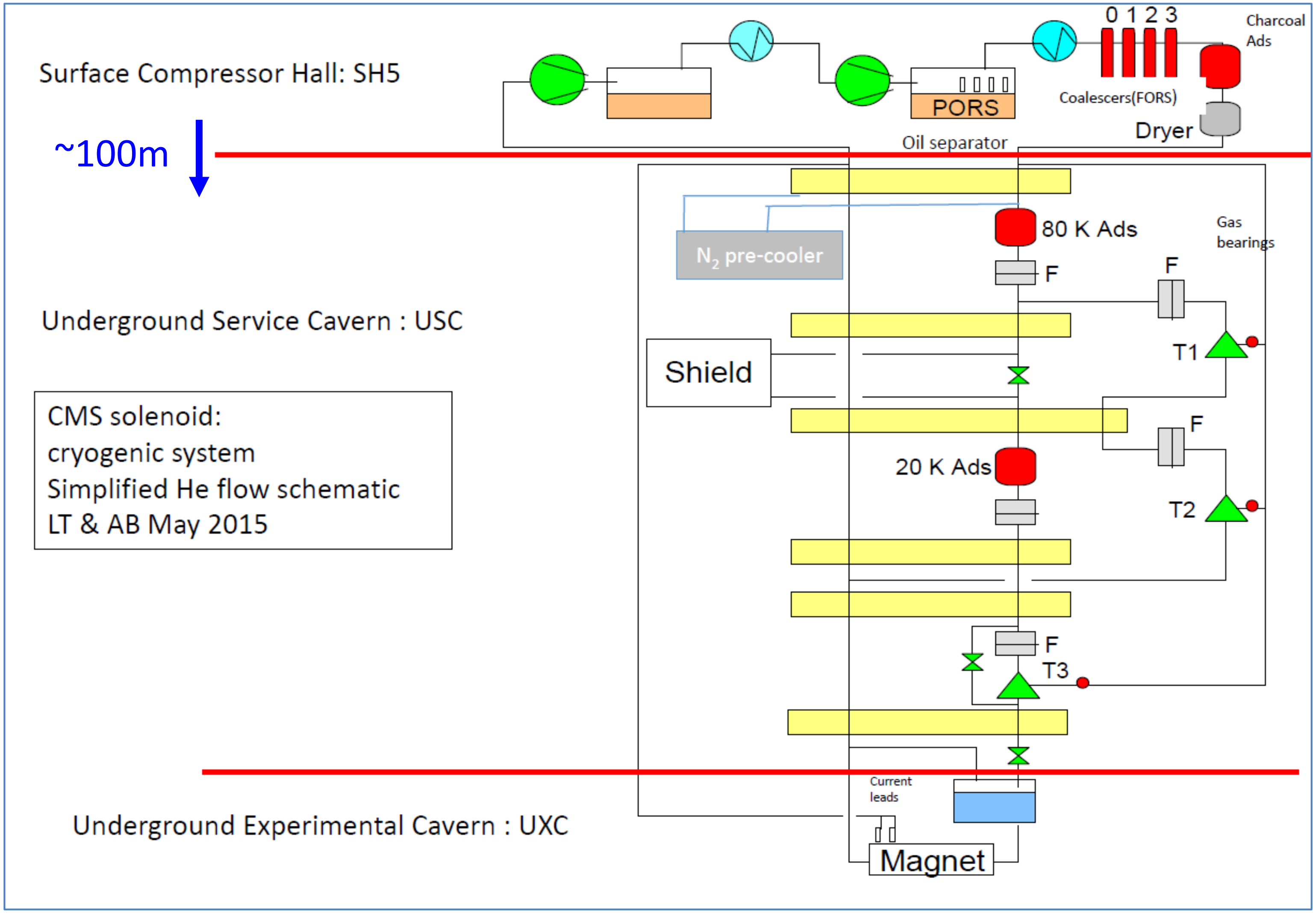
→ Must measure the relative phase for each proton pulse

What could possibly go wrong?

Part 2

Next page →

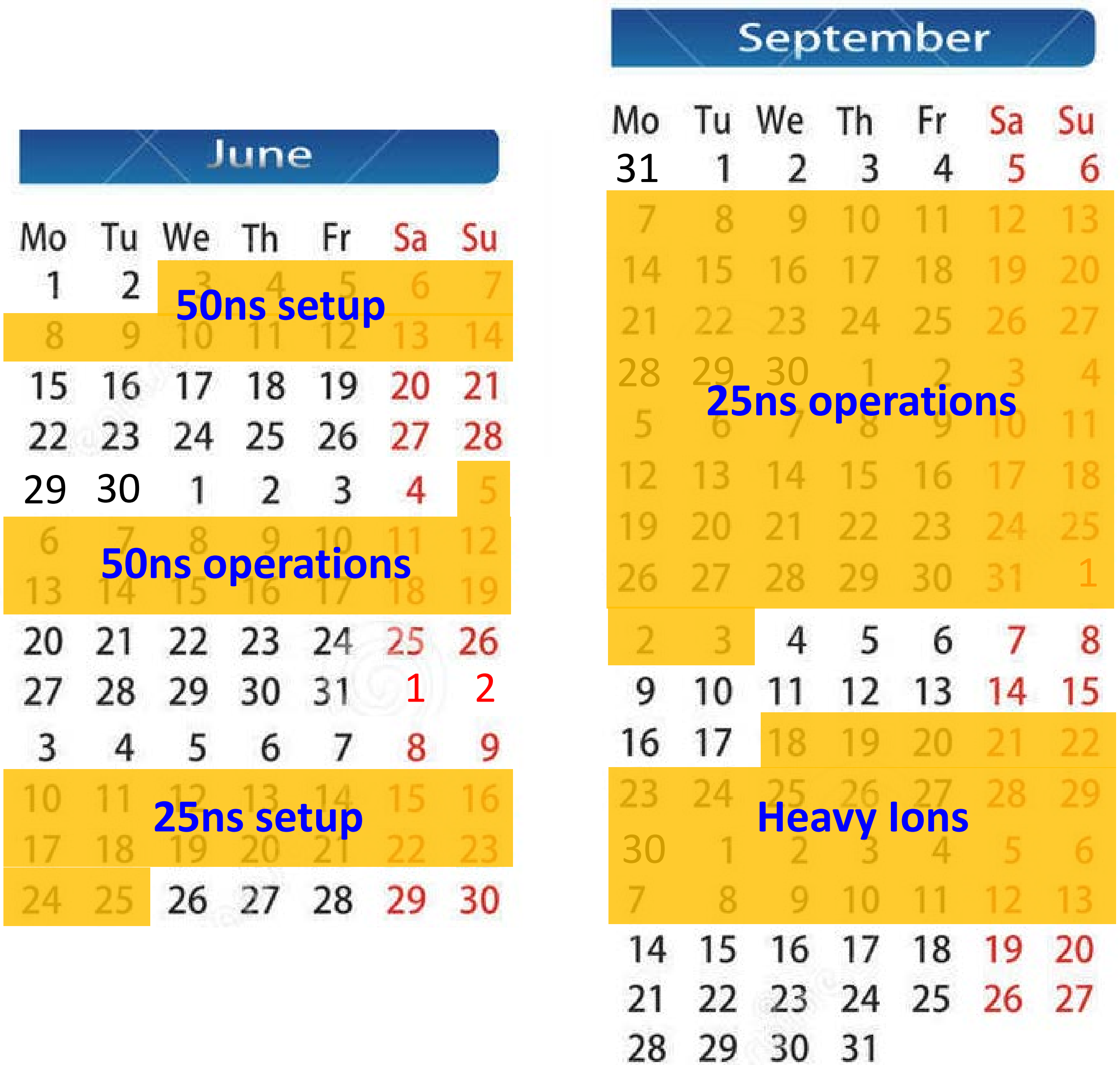
Schematic of CMS cryo cold box



At start of 2015, about one cup of oil was accidentally introduced into the Primary Oil, Recovery, and Separation system

Oil clogs filters

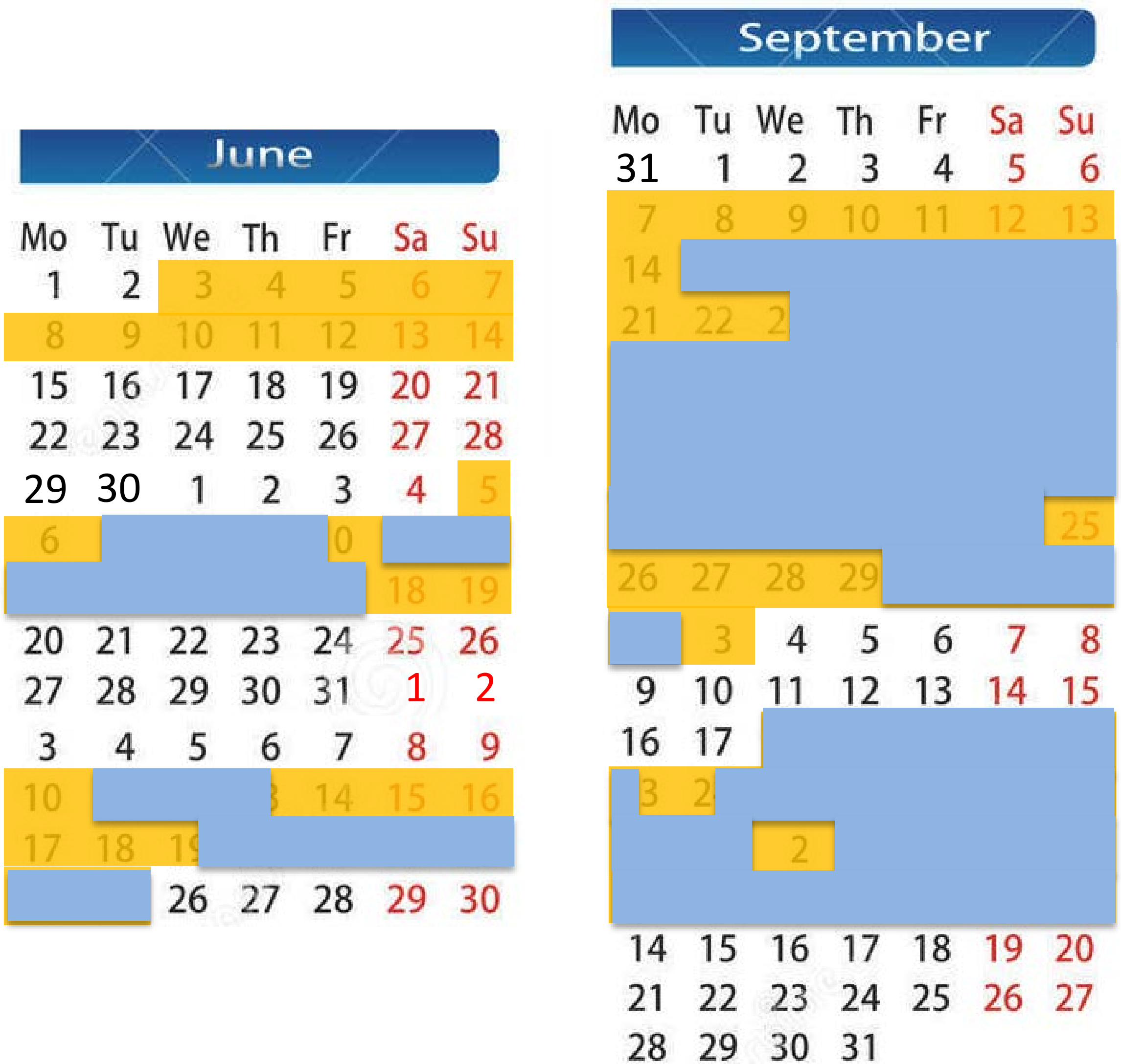
2015 LHC operation



= LHC collisions

These are the times when CMS needs to be fully operational

CMS operation during LHC operation



= LHC collisions

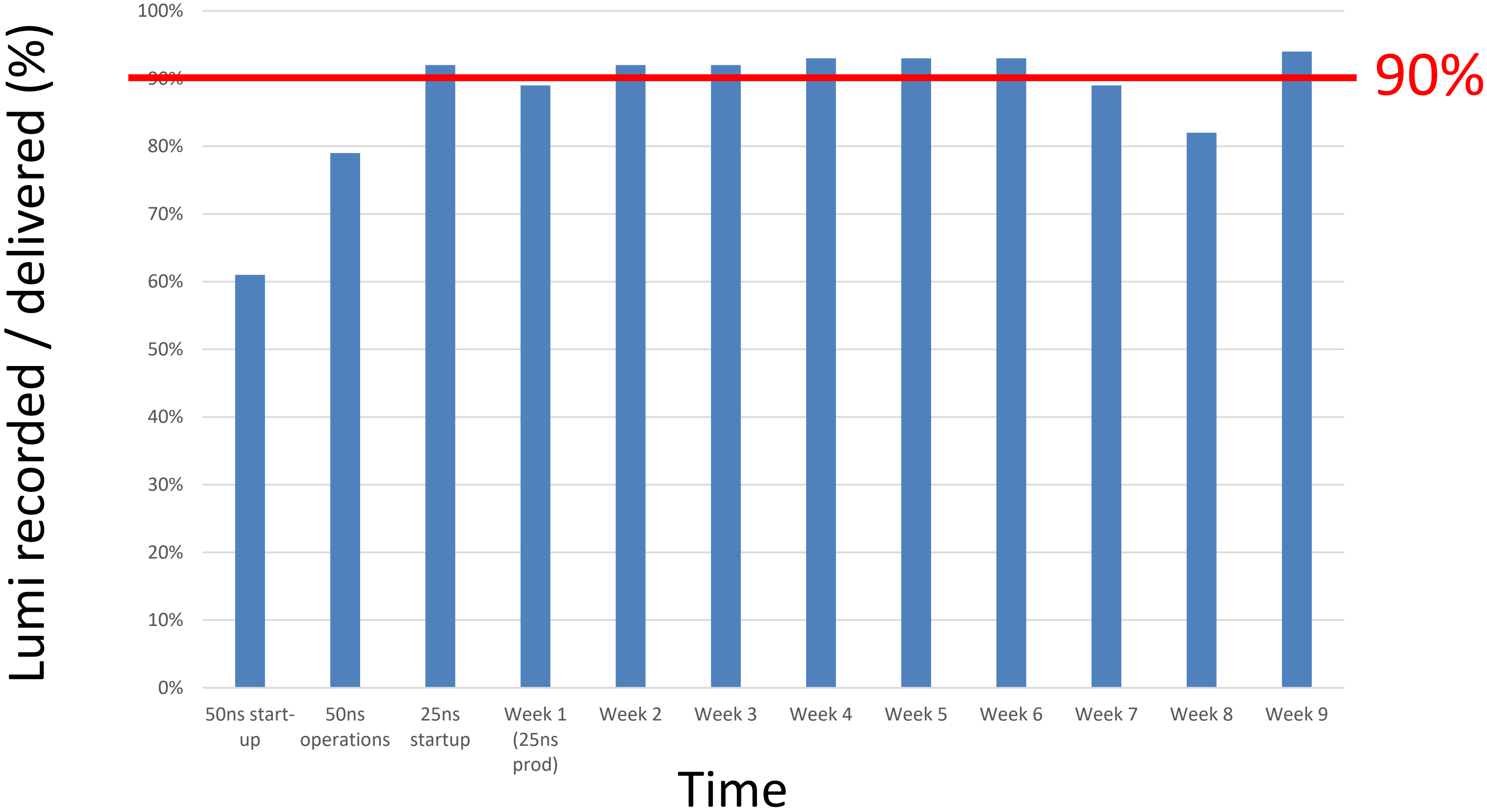
= CMS magnet B=3.8T

When cryogenic filters clog, liquid He production stops and the superconducting magnet is ramped down…

2015 was a tough year

System was cleaned at start of 2016 → back to stable operations

In spite of magnet issues…



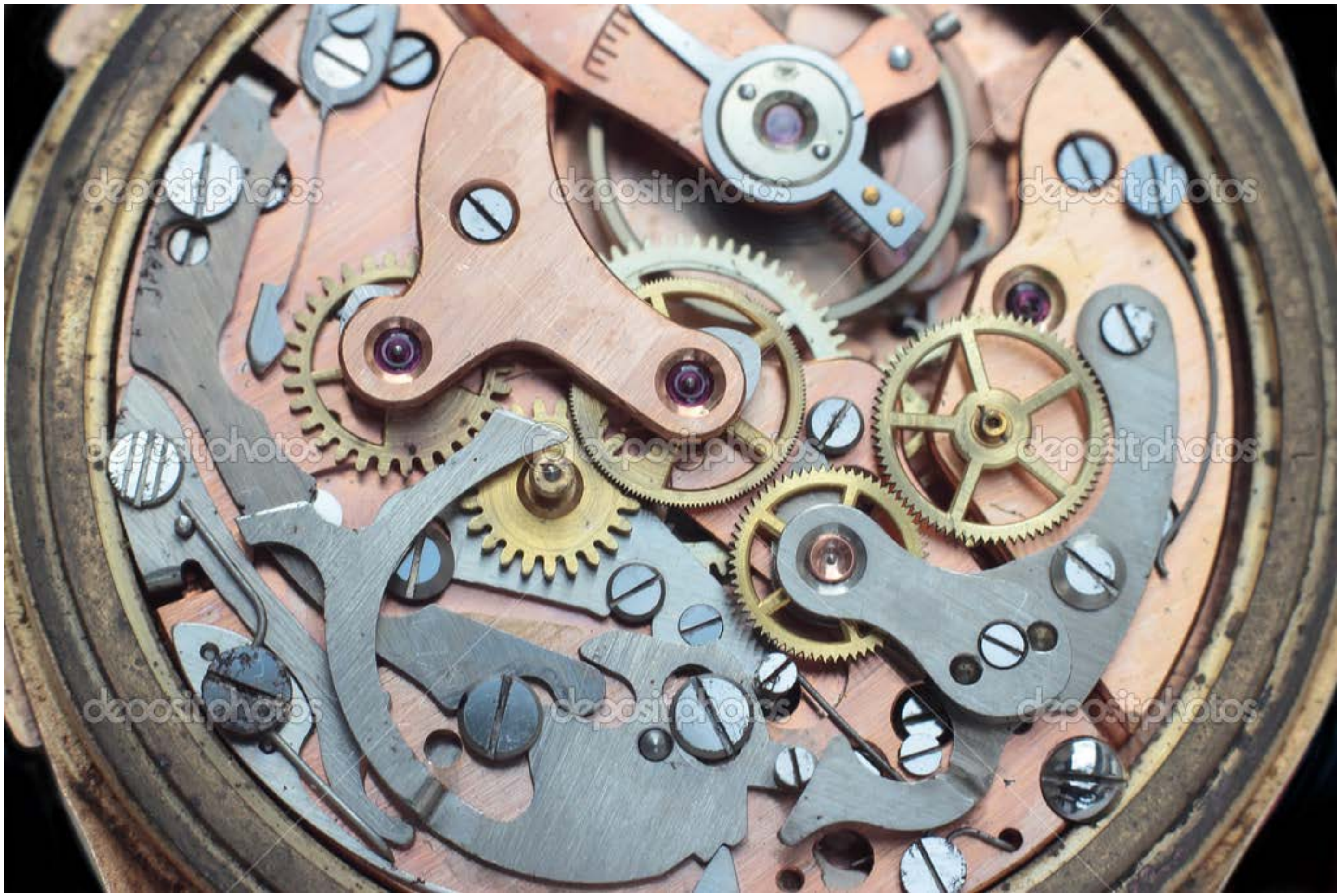
→ 2015 steady-state recording efficiency > 90% ←

Summary (so far)

- Many particle physics experiments look at particles coming from accelerated beams
  - Accelerator physics is very hard and very fun
- Detectors are assembled to reconstruct and identify specific final states
  - Commissioning and calibration is fundamental to make the reconstruction and identification possible

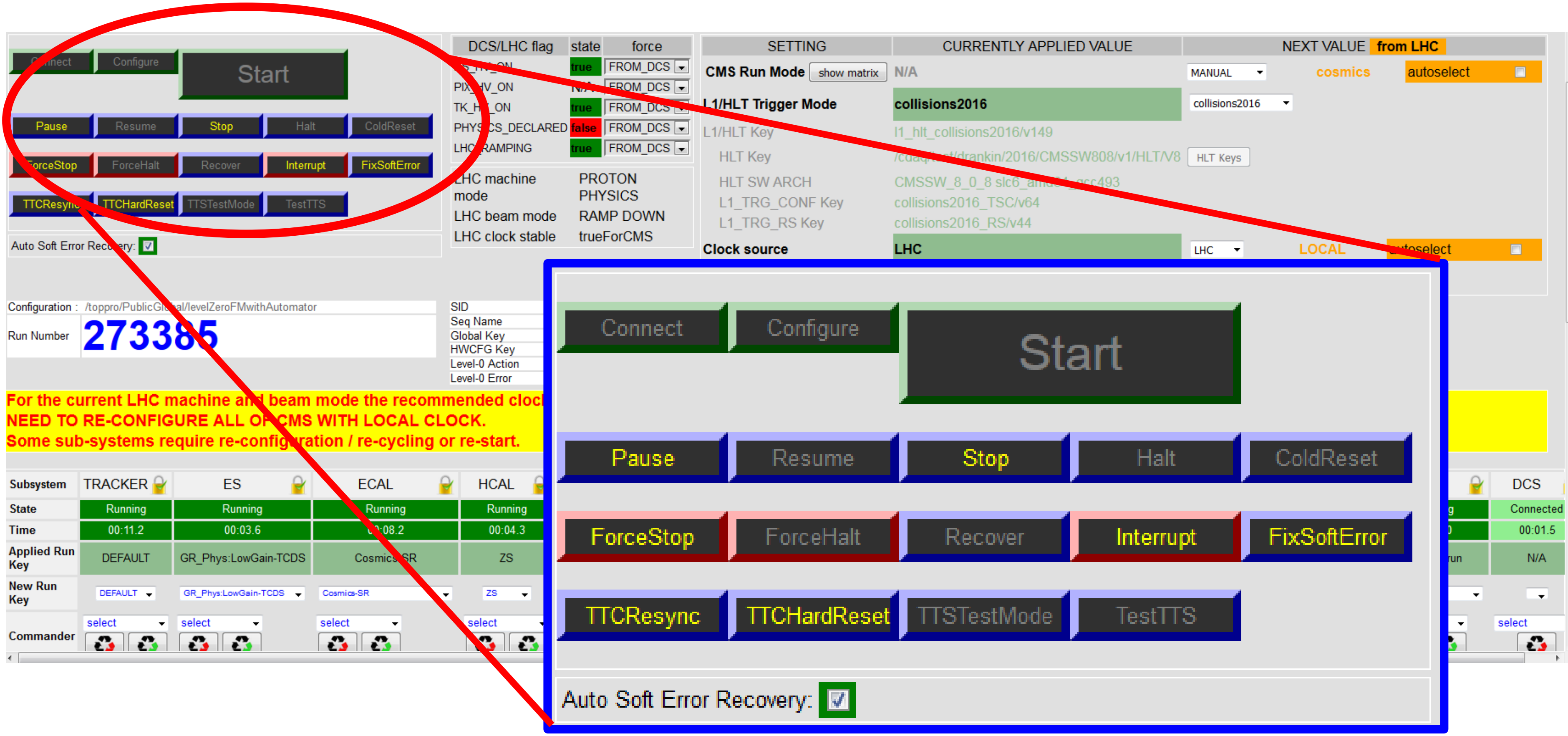
Be on the lookout for the unexpected!

Run!



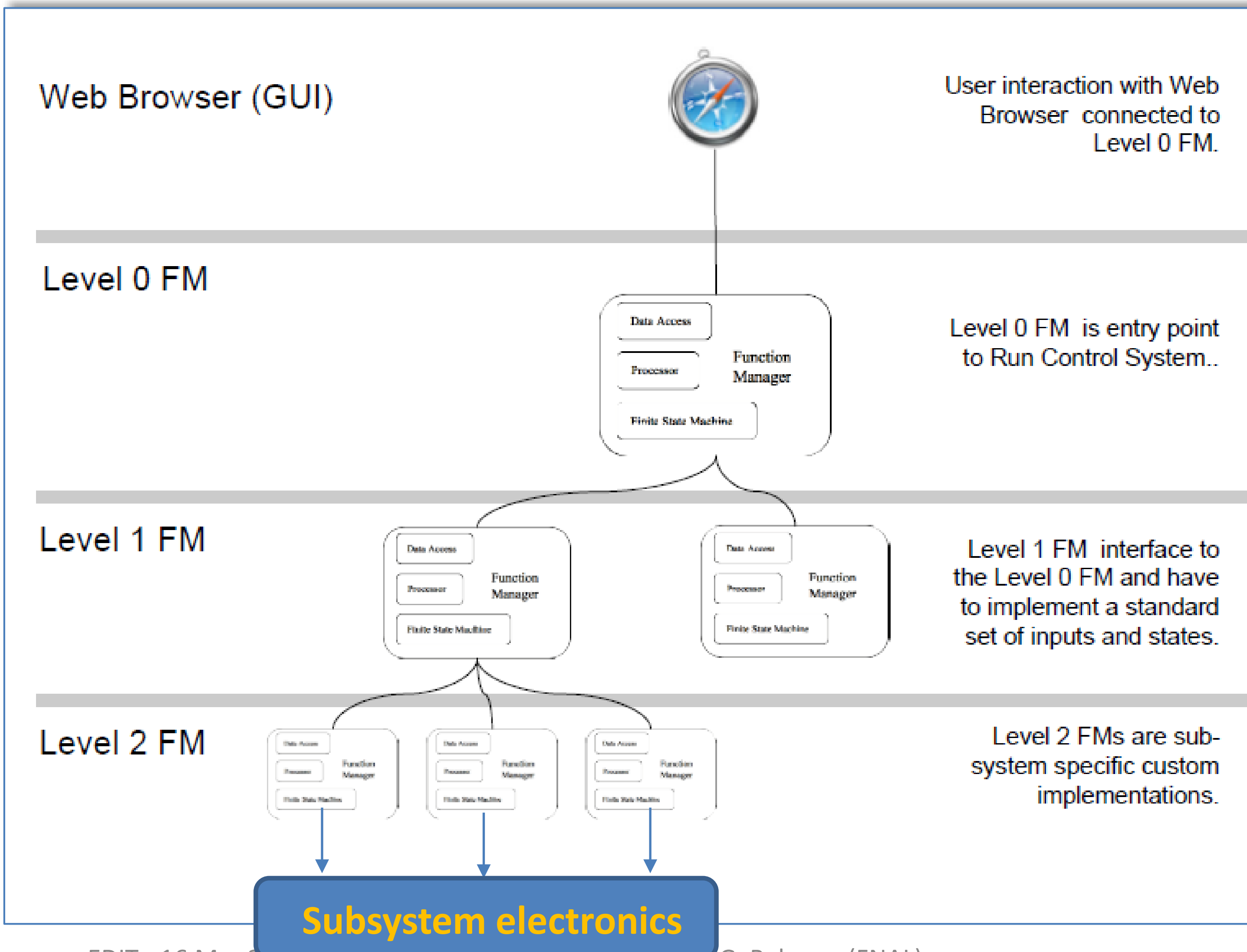
Snapshot of DAQ shifter station

Commands



Software architecture

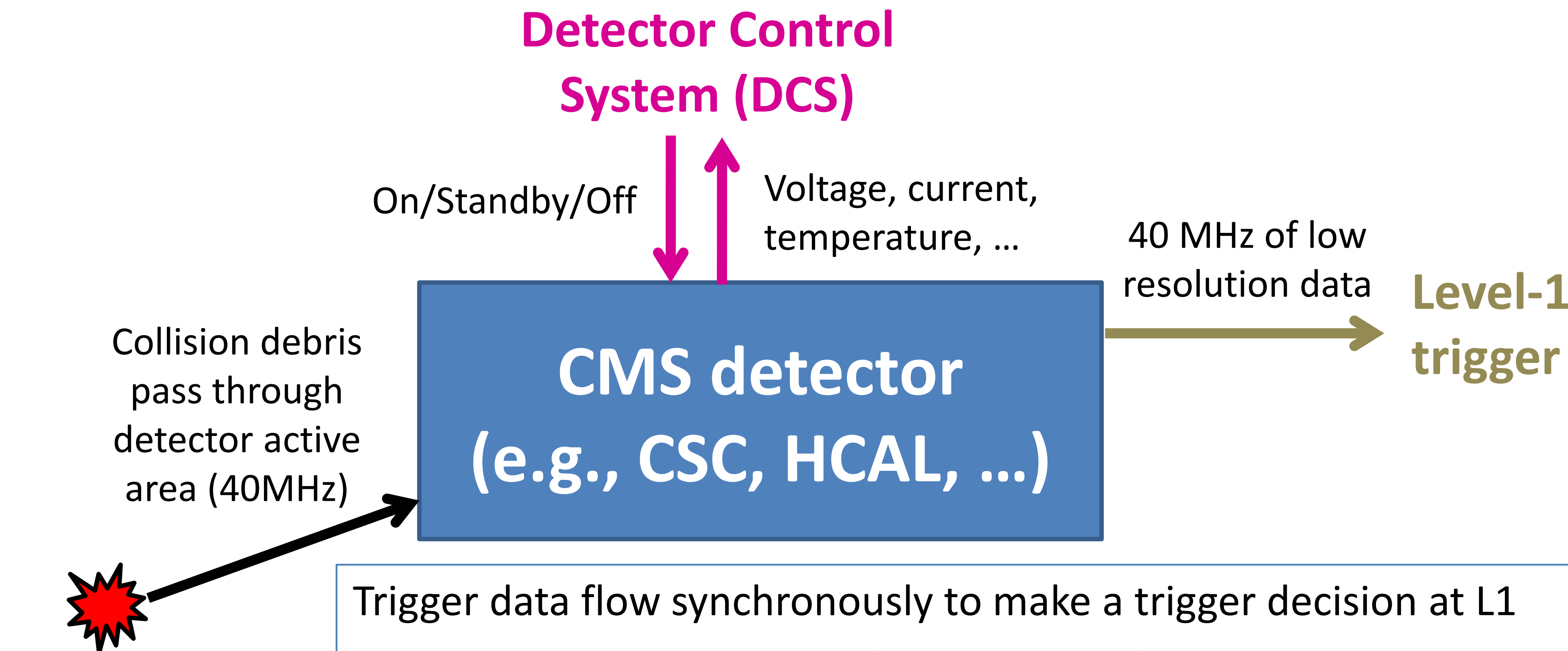
From A. Oh (CERN) (https://indico.cern.ch/event/3580/contributions/1768398/attachments/712547/978188/aohchep07.pdf)



Subsystem control software instantiated by a top-level "Function Manager"

To operate the subsystems as a *coherent whole*, commands are sent from the top to drive the each subsystem through a Finite State Machine
(e.g., "Configure", "Start", "Stop")

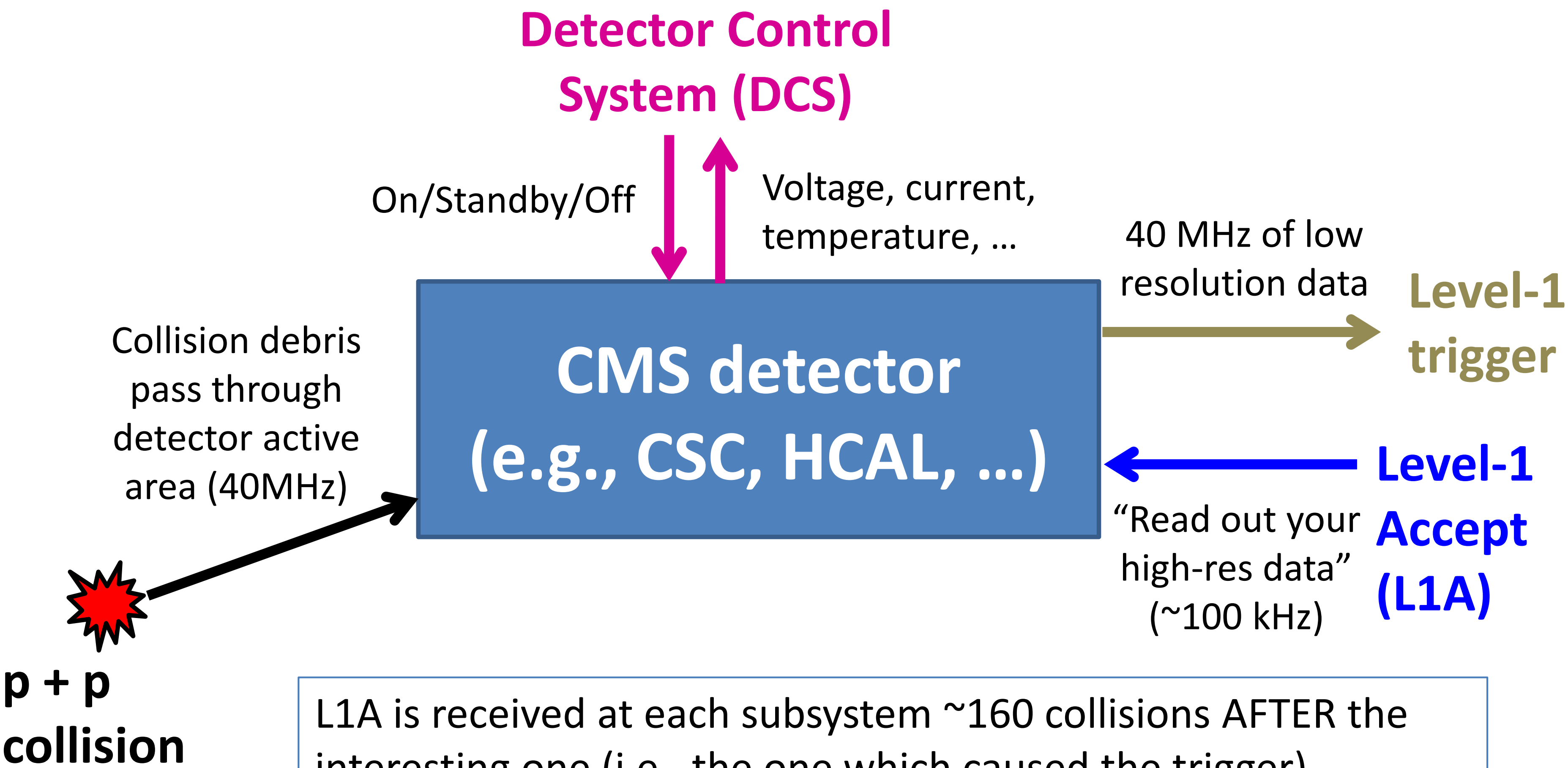
Box diagram of a typical CMS detector



Trigger data flow synchronously to make a trigger decision at L1

- Low resolution "snapshots" (taken at 40MHz) analyzed within 3.2μs to select events likely to contain interesting physics
- As described before, **muons, jets, electrons, and gammas must be *synchronized* in order to trigger correctly**

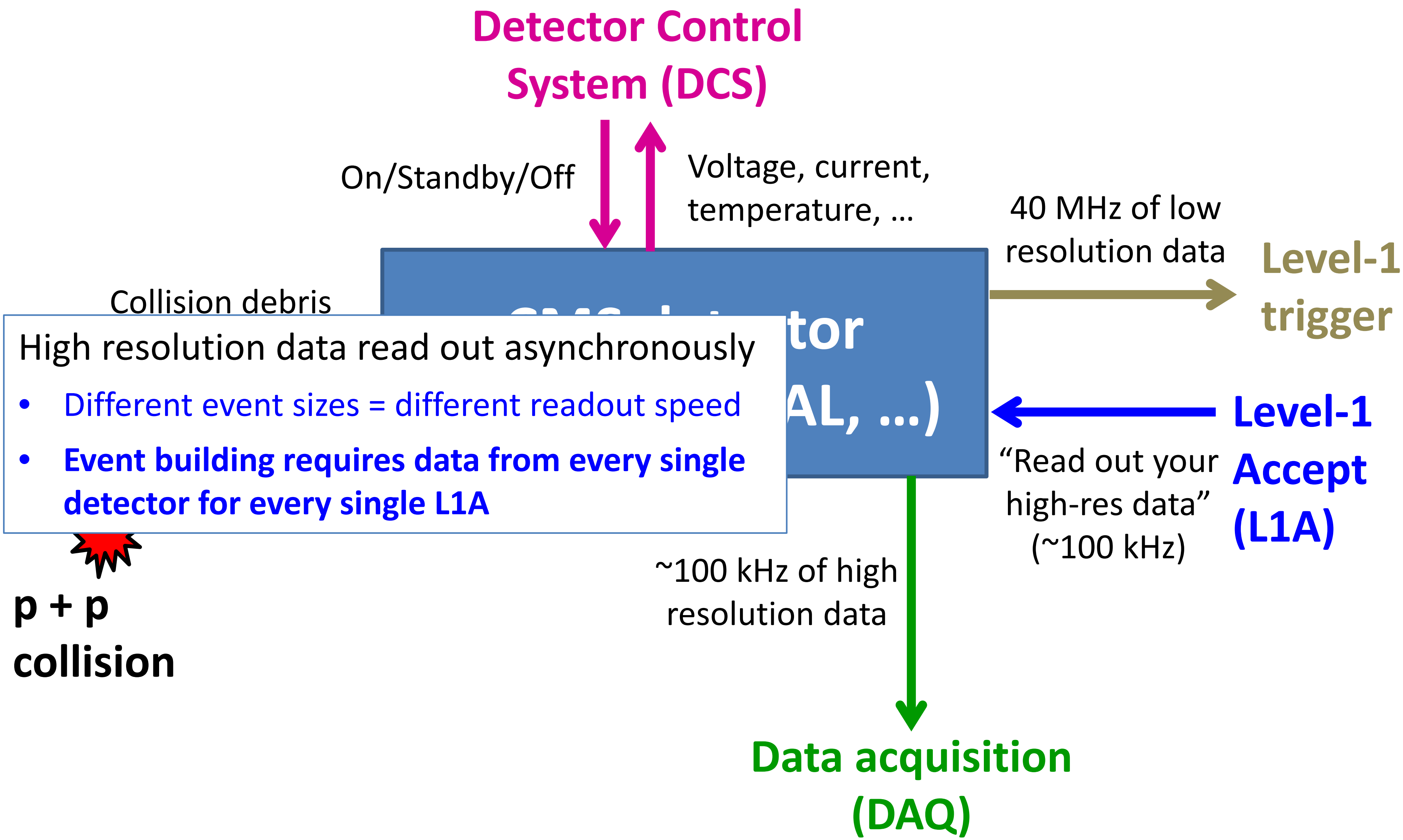
Box diagram of a typical CMS detector



L1A is received at each subsystem ~160 collisions AFTER the interesting one (i.e., the one which caused the trigger)

- **Data stored in a pipeline to be able to select the right one**
- Scope: analyze 400 events and select 1 (throw away 399) in 3.2μs

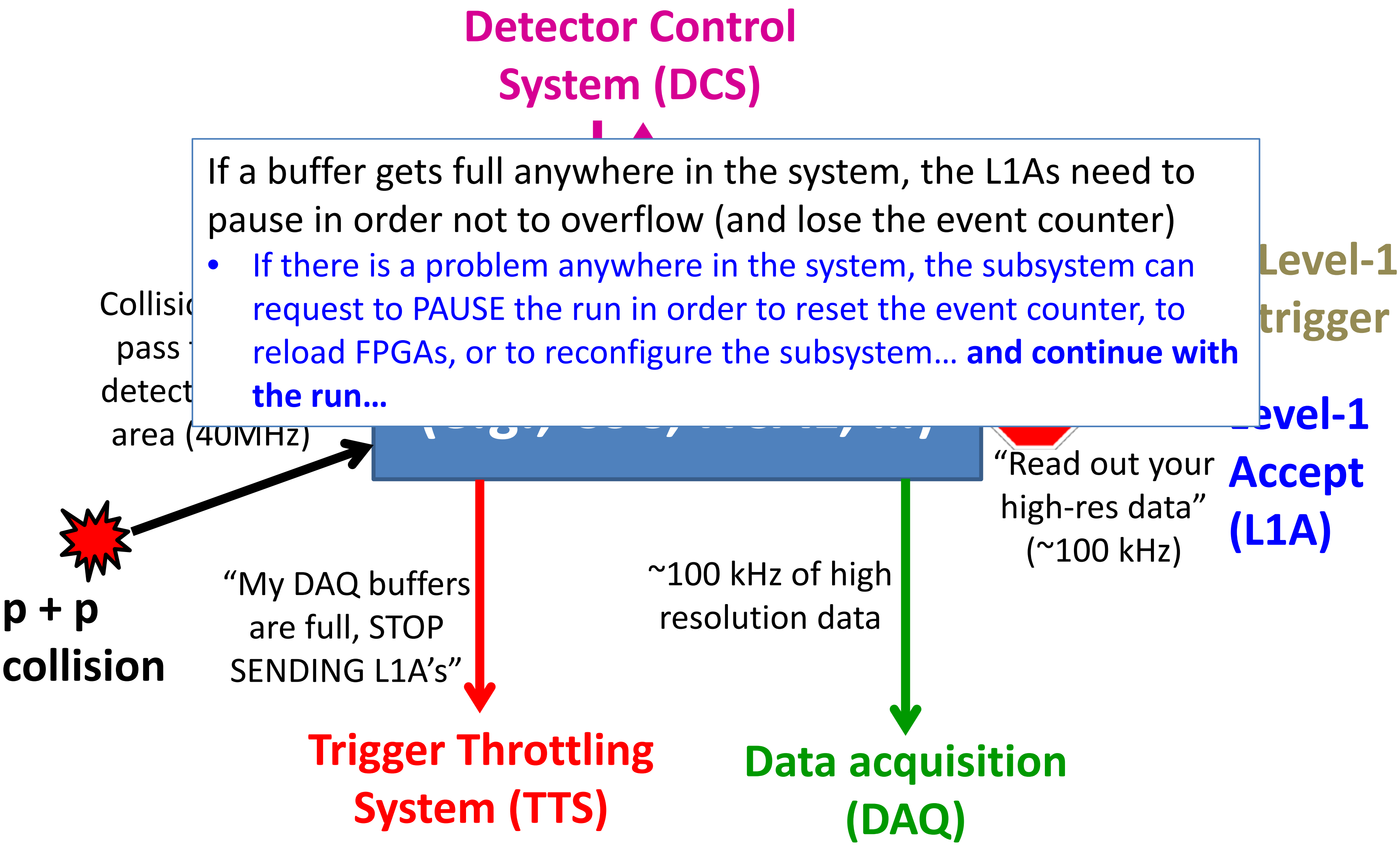
Box diagram of a typical CMS detector



High resolution data read out asynchronously

- Different event sizes = different readout speed
- **Event building requires data from every single detector for every single L1A**

Box diagram of a typical CMS detector



If a buffer gets full anywhere in the system, the L1As need to pause in order not to overflow (and lose the event counter)

- If there is a problem anywhere in the system, the subsystem can request to PAUSE the run in order to reset the event counter, to reload FPGAs, or to reconfigure the subsystem… **and continue with the run…**

Take a look at these slides and think about what it takes for each of these steps to be successful

The more you think about it, the more you will be amazed that it works at all

The trigger and data acquisition machine of a particle physics experiment is a marvel of technology

Summary

- Many experiments look at particles from accelerated beams
  - Accelerator physics is very hard and very fun

- Experiments assemble detectors to measure specific final states
  - Commissioning, calibration, timing, and alignment are fundamental to making this possible

- The simultaneous operation of an experiment in concert with an accelerator is an amazing phenomenon
  - Each step of this activity is worth to understand in detail

Be on the lookout for the unexpected!

(You are likely to discover something…)

Last words…

Mu2e collaboration

http://mu2e.fnal.gov/collaboration.shtml

CMS collaboration

https://cms.cern/collaboration

http://www.bbc.com/news/science-environment-32976838

3 June 2015: first “Stable Beams” (collisions) at $\sqrt{s}$=13 TeV at CMS

Science & Environment

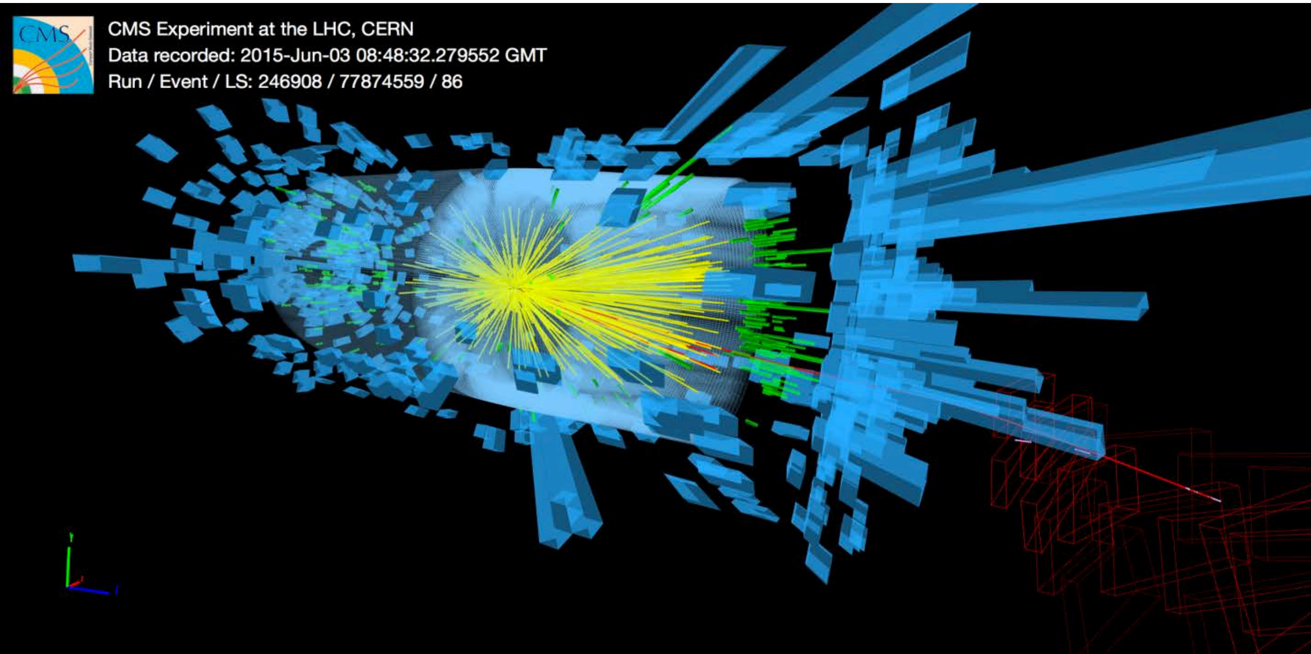
Large Hadron Collider turns on 'data tap'

By Paul Rincon
Science editor, BBC News website

3 June 2015 | Science & Environment

The CMS experiment team celebrated when the first collisions occurred e-environment-32976838

ns on 'data tap'



Appreciating the success of hard work

The CMS experiment team celebrated when the first collisions occurred

We are looking forward to seeing you at the experiment!

Backup slides

Drivers of US particle physics research

- Use the *Higgs Boson* as a new tool for discovery
- Pursue the physics associated with *neutrino mass*
- Identify the new physics of *dark matter*
- Understand cosmic acceleration: *dark energy* & *inflation*
- Explore the *unknown*: new particles, interactions, and physical principles

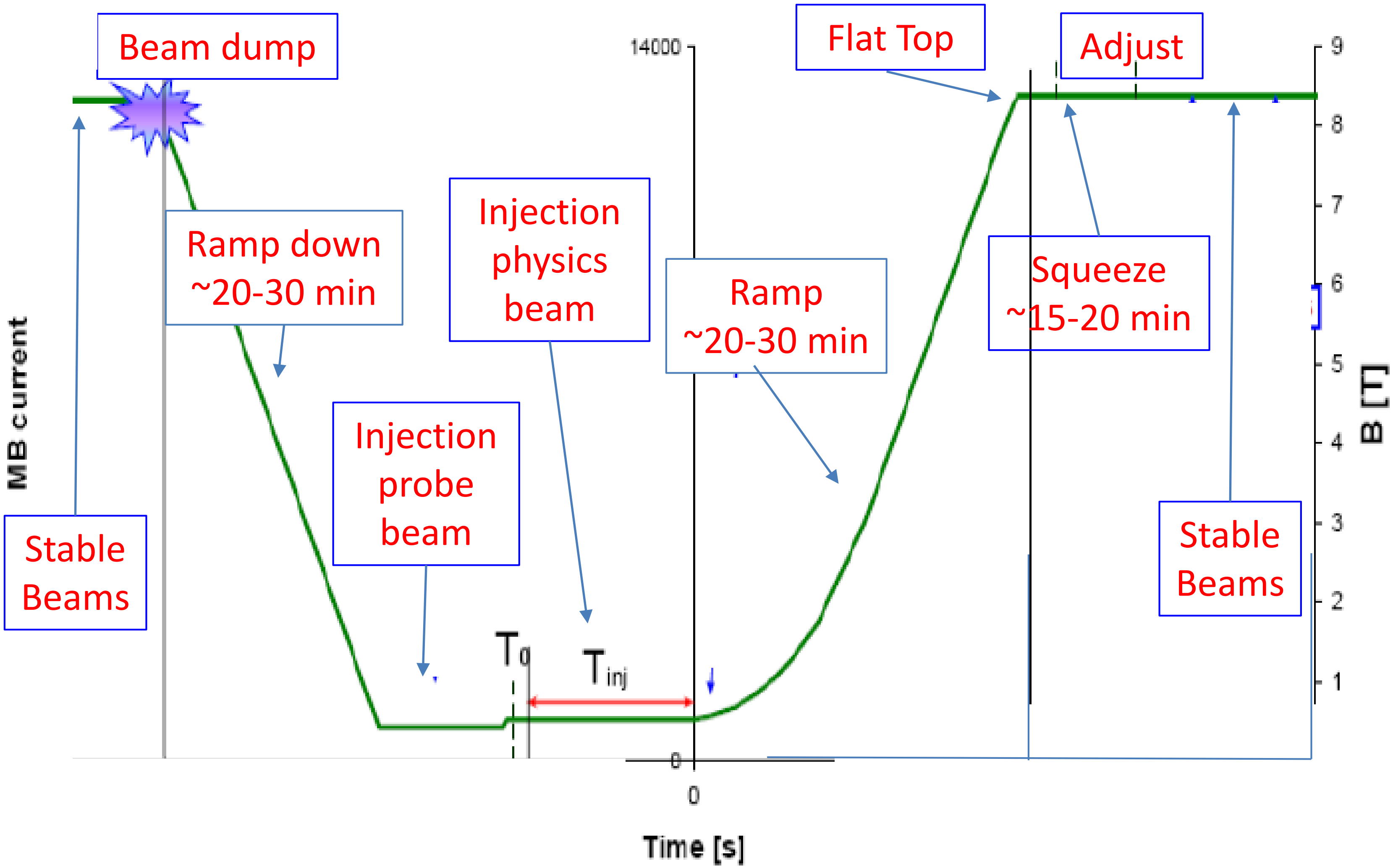
https://science.energy.gov/hep/research/

Frontiers of physics

- Experimental strategy organized along three inter-related frontiers
  - **Energy frontier:** accelerate particles to highest-energies ever made by humanity and collide them… *Sophisticated detectors*, some the size of apartment buildings, observe the newly produced particles
  - **Intensity frontier:** intense particle beams and *highly sensitive detectors*… study some of the rarest particle interactions
  - **Cosmic frontier:** highest-energy particles ever observed have come from cosmic sources… *Ultra-sensitive detectors* deep underground may glimpse the dark matter wind

https://science.energy.gov/hep/research/

LHC: Fill Cycle



HV state of CMS depends on LHC state

CMS DCS automatically responds to the LHC Accelerator:Beam mode…

http://cmsonline.cern.ch/portal/page/portal/CMS%20online%20system/DCS/Automation

Light blue = Go to Standby   Green = Go to Physics   White = Do nothing

Injection | Ramp | Squeeze | Adjust | Stable Beams | Beam dump

Group	-	SETUP	ABORT	INJECTION PROBE BEAM	INJECTION SETUP BEAM	INJECTION PHYSICS BEAM	PREPARE RAMP	RAMP	FLAT TOP	SQUEEZE	ADJUST	STABLE BEAMS	UNSTABLE BEAMS	BEAM DUMP	RAMP DOWN
Silicon Tracker	PIXEL	DO NOTHING	DO NOTHING	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	GO TO PHYSICS *	PROTECT STANDBY	DO NOTHING	DO NOTHING
	STRIPS	DO NOTHING	DO NOTHING	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	GO TO PHYSICS *	PROTECT STANDBY	DO NOTHING	DO NOTHING
ECAL	ECAL EM	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING
	ECAL BM	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING
	ECAL BP	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING
	ECAL EP	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING
	ECAL ESM	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING
	ECAL ESP	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING
HCAL	HCAL	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING
	ZDC	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING
	CASTOR	GO TO PHYSICS / mode=muonHV	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	DO NOTHING	GO TO PHYSICS / mode=ppHV	GO TO PHYSICS / mode=ppHV	DO NOTHING	DO NOTHING	DO NOTHING
Muons	DT	DO NOTHING	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	GO TO PHYSICS	GO TO PHYSICS	GO TO PHYSICS	DO NOTHING	DO NOTHING	DO NOTHING
	RPC	DO NOTHING	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	PROTECT STANDBY	GO TO PHYSICS	GO TO PHYSICS	GO TO PHYSICS	DO NOTHING	DO NOTHING	DO NOTHING
	CSC	DO NOTHING	GO TO STANDBY	GO TO STANDBY	GO TO STANDBY	GO TO STANDBY	GO TO STANDBY	GO TO STANDBY	GO TO STANDBY	GO TO PHYSICS	GO TO PHYSICS	GO TO PHYSICS	DO NOTHING	DO NOTHING	DO NOTHING
	SETUP	ABORT	INJECTION PROBE BEAM	INJECTION SETUP BEAM	INJECTION PHYSICS BEAM	PREPARE RAMP	RAMP	FLAT TOP	SQUEEZE	ADJUST	STABLE BEAMS	UNSTABLE BEAMS	BEAM DUMP	RAMP DOWN	

When LHC wants to inject…

1. LHC issues "Injection Warning"
   - Communicated over DIP (communication protocol between "very loosely coupled heterogeneous systems")
   - https://wikis.web.cern.ch/wikis/display/EN/DIP+and+DIM

2. DCS automatically puts the CMS detector to "Standby" (see previous)
   - Safe state to allow injection of beams into LHC

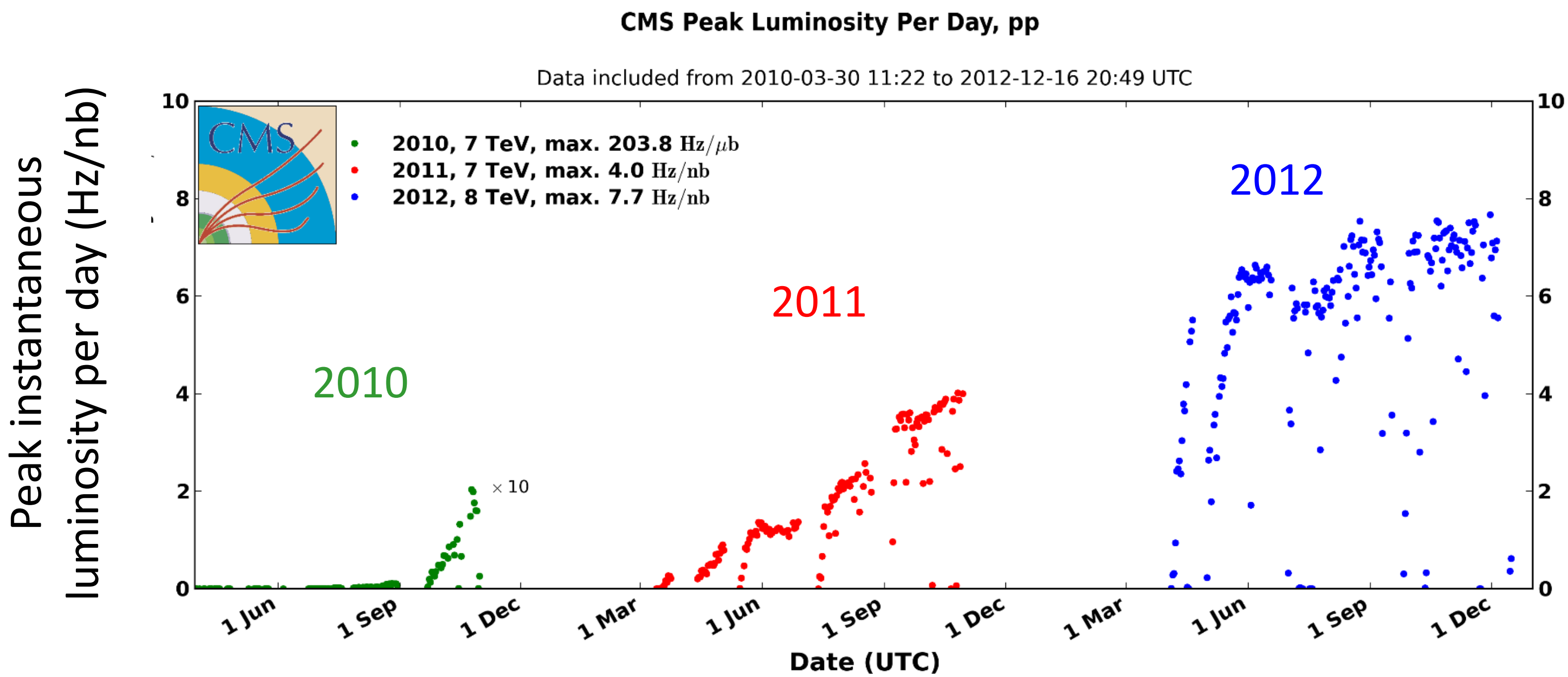
3. Shift leader pulls injection inhibit button to allow LHC to inject

Beam abort
Do not push this button!

Injection inhibit:
Green light ON
→ injection allowed

Run-1: instantaneous lumi evolution

https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

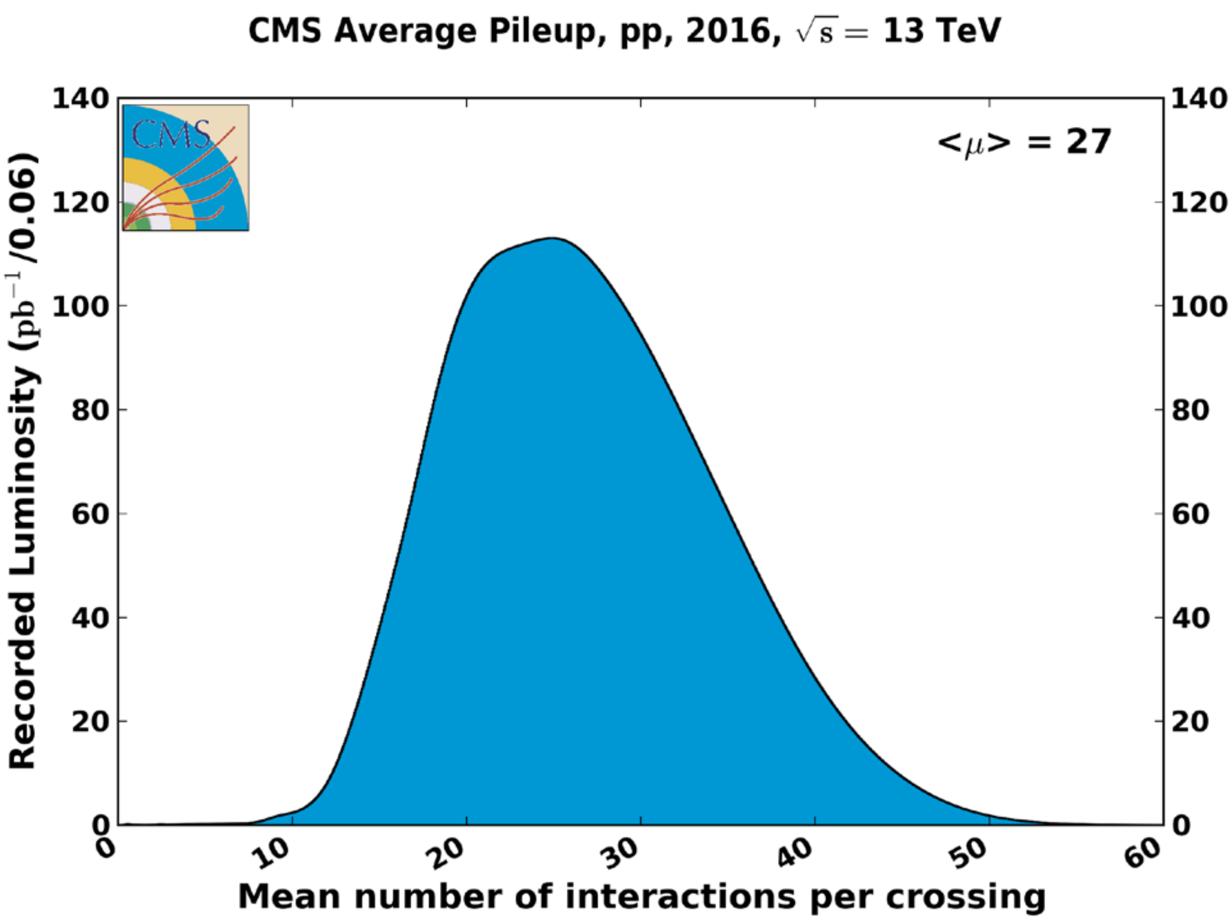


Run-1 peak performance numbers

- Max. inst. lumi = $7.7 \times 10^{33}/cm^2/s$ (design = 1×10^{34})
- Number of bunches = 1380 (design ~ 2200)
- Bunch spacing = 50ns (design = 25ns)

From the point of view of peak instantaneous luminosity *per bunch*, LHC Run-1 **exceeded the specs by ~140%**

Higher luminosity = higher pileup



The number of interactions per crossing is called **pileup**

The original design of CMS and ATLAS was for an average pileup of about 20 (!)

LHC changes from Run-1 → Run-2

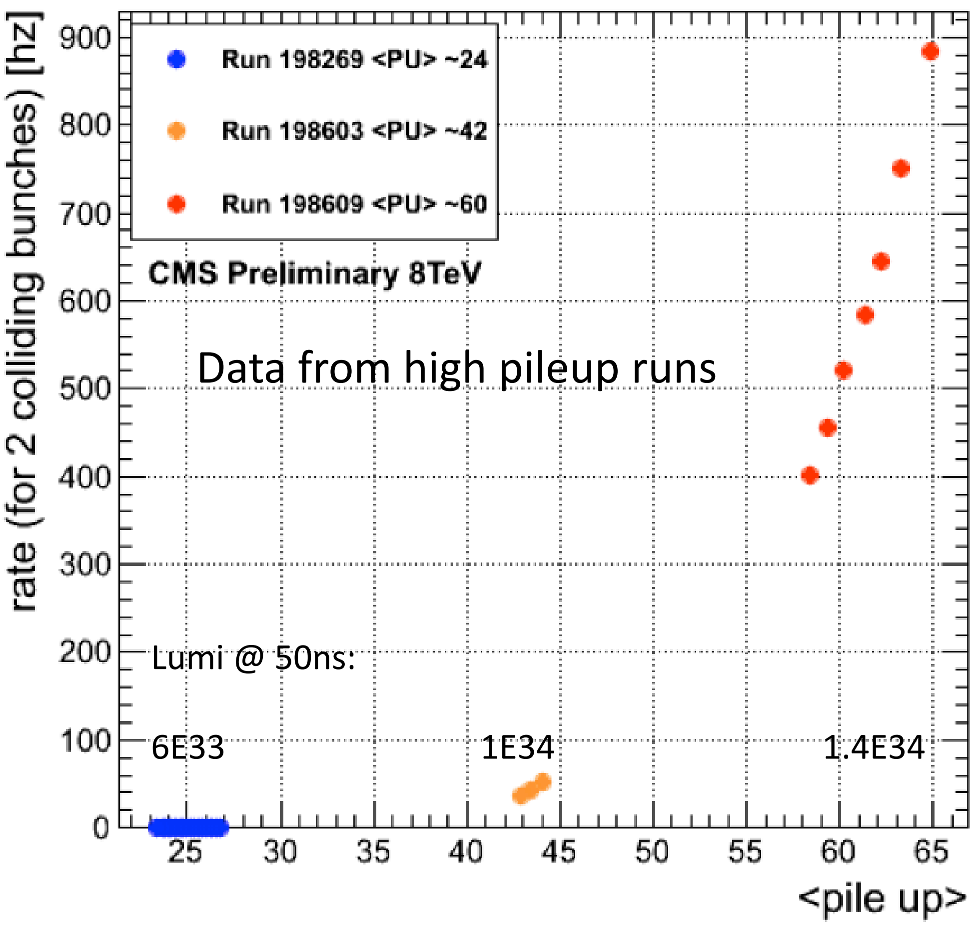
From M. Solfaroli (CERN) at LHCC 23 Sept 2015 (https://indico.cern.ch/event/443017/)

- 160% larger collision energy → $\sqrt{s}$=13 TeV
- 50% smaller bunch spacing → 25ns
- 200% larger number of bunches → 2800 bunches
- 200% larger pileup → 40 interactions/crossing
- 66% smaller β^* → 40cm
- 170-220% larger peak lumi → (13-17)x10^{33}cm^{-2}s^{-1}

"Priority for 2015 is to prepare 2016 as a 'physics production run' at 25ns" – M. Solfaroli (CERN)

The pileup problem

Look at triggers of clustered hadronic energy > 200 GeV



CMS was designed to sort out the wheat from the chaff, as long as there isn't too much chaff

→ This is why increasing the bunch intensity to increase the luminosity doesn't increase the luminosity which is *useful* to CMS

CMS plan: upgrade the detector to match the LHC performance

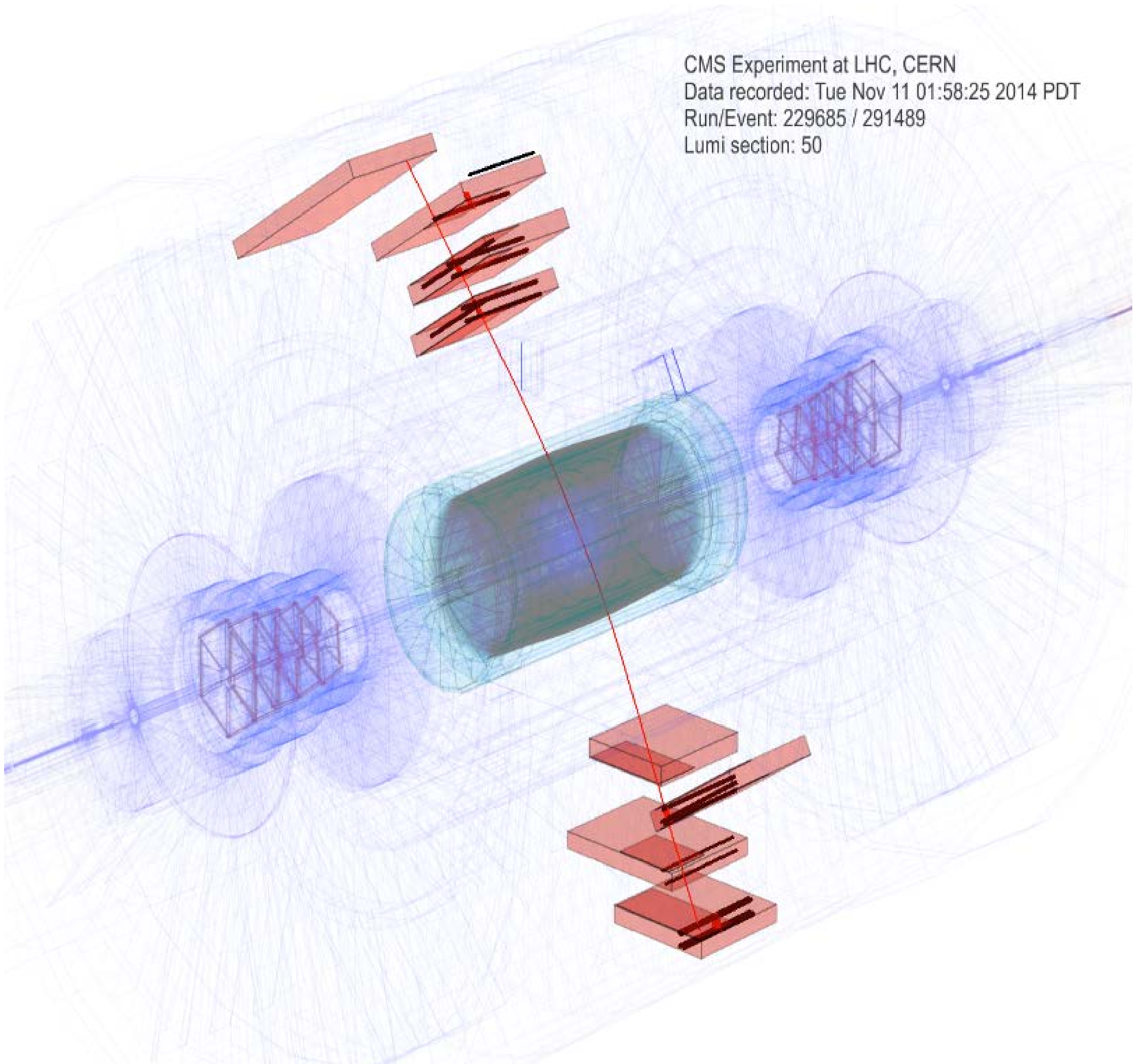
- CMS "Phase-1" upgrade (2014-2016): handle increased pileup…
  - Add another layer of silicon tracking (vertices)
  - Add processing power to the Level-1 trigger (jets)
  - Refine granularity of the hadron calorimeter (jets)
  - But I'm not going to talk about this…

- LS1 (2013-2014): complete and maintain the detector, and lay the foundation for Phase-1…
  - Next page →

CMS upgrades during LS1

- Data acquisition: new architecture
- Trigger Control and Distribution System: new
- Level-1 trigger: new calorimeter trigger
- Silicon pixels: new modules
- Silicon tracker: new temperature (–15°C)
- Electromagnetic calorimeter: new optical trigger links
- Hadronic calo: new SiPMs, front-, & back-end (uTCA)
- Drift Tube chambers: new trigger electronics
- Resistive Plate Chambers: new chambers
- Cathode Strip Chambers: new chambers & electronics

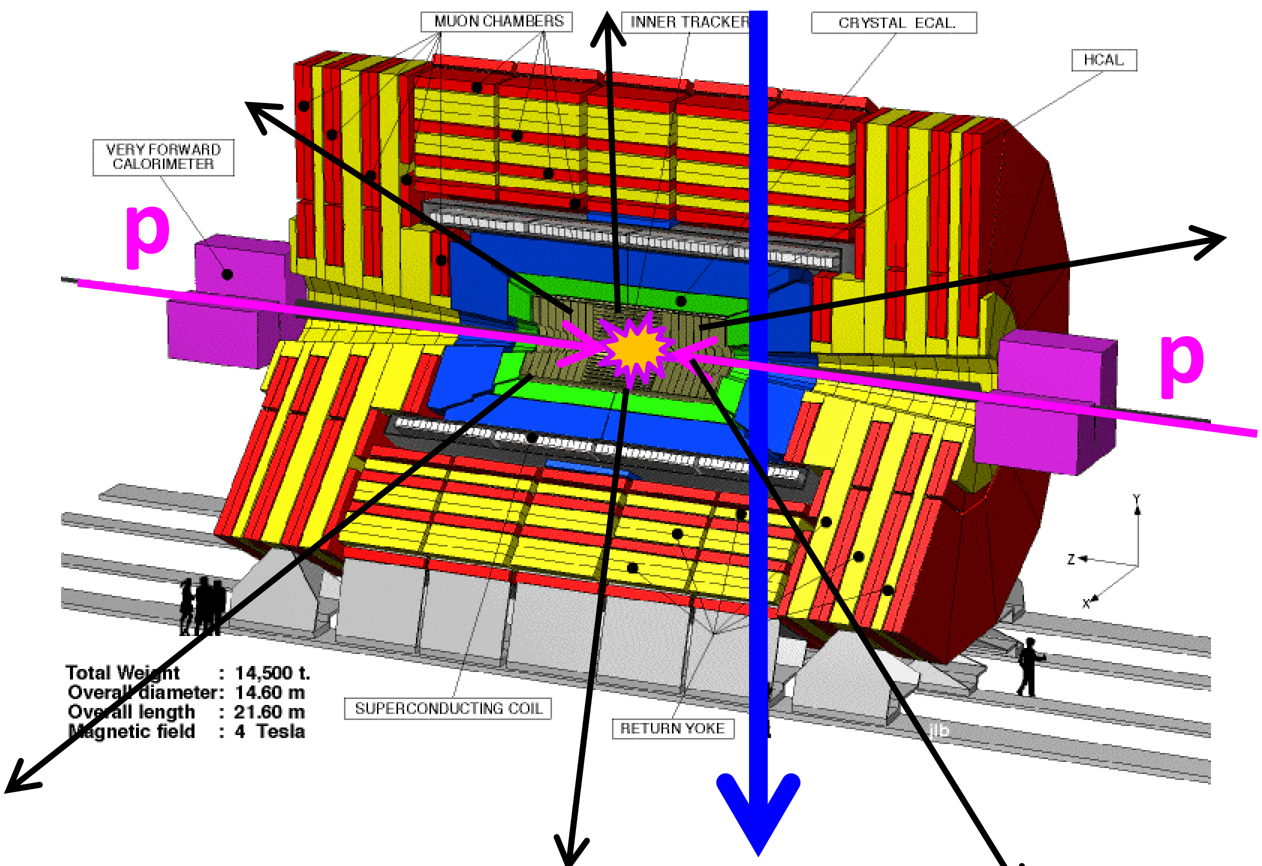
Not stretching the truth to say that CMS is a new detector!


CMS Experiment at LHC, CERN
Data recorded: Tue Nov 11 01:58:25 2014 PDT
Run/Event: 229685 / 291489
Lumi section: 50

Timing 101: place "scintillator" correctly

Since cosmic rays traverse CMS from top → bottom, triggers coming from top muon chambers will have timing wrong by

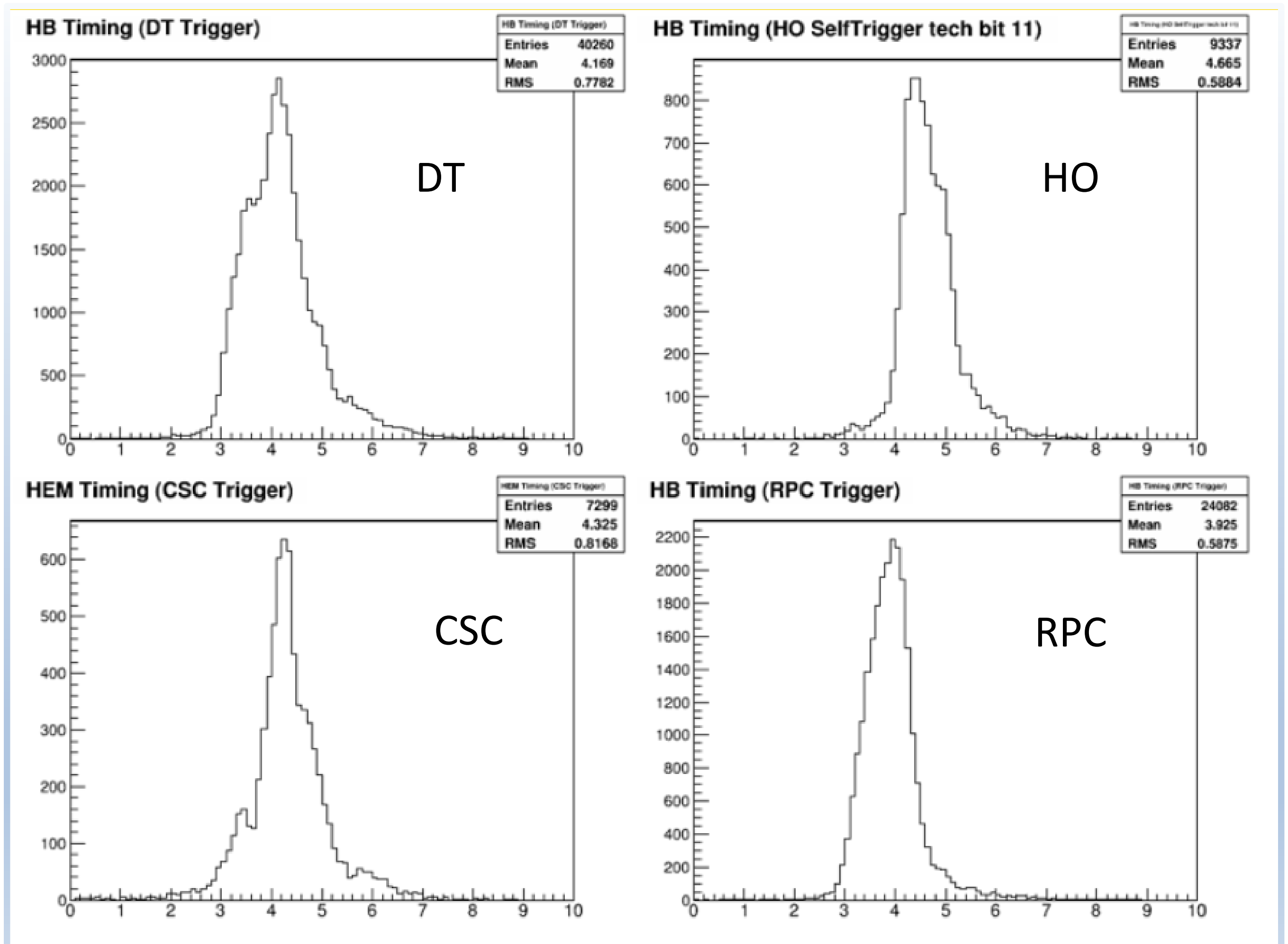
(2 x time-of-flight) ≈ 2bx



To make cosmic rays work "for free" with collision timing, trigger on the bottom half of the detector

Timing 201: use one trigger at a time

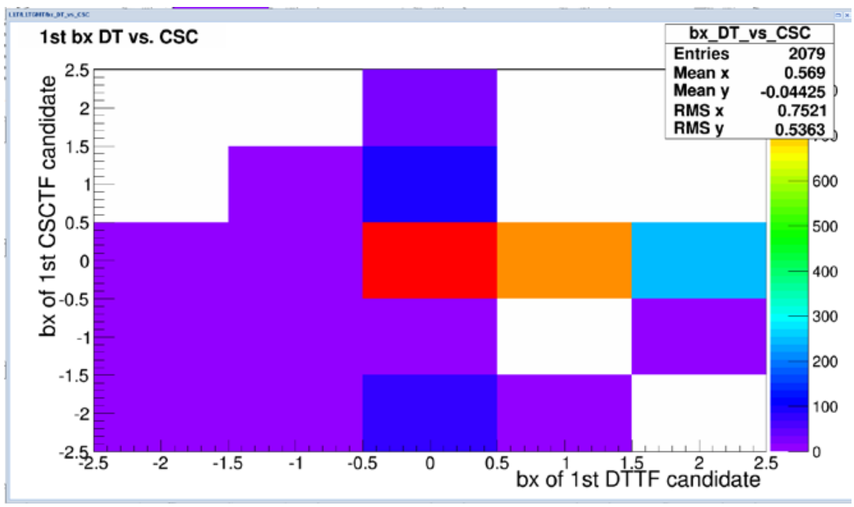
Timing of Hadronic Calorimeter ~equal with different muon triggers



Timing 301: increase complexity

Enable muon sources pair-wise → look at relative timing of triggers at Global Muon Trigger

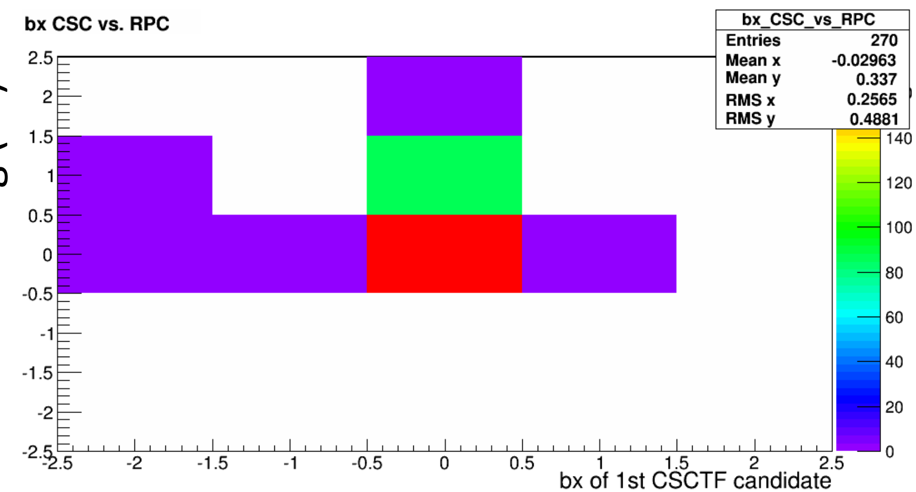
CSC vs. DT (run 228579)



CSC Track Finder timing (bx)

DT Track Finder timing (bx)

RPC vs. CSC (run 228677)

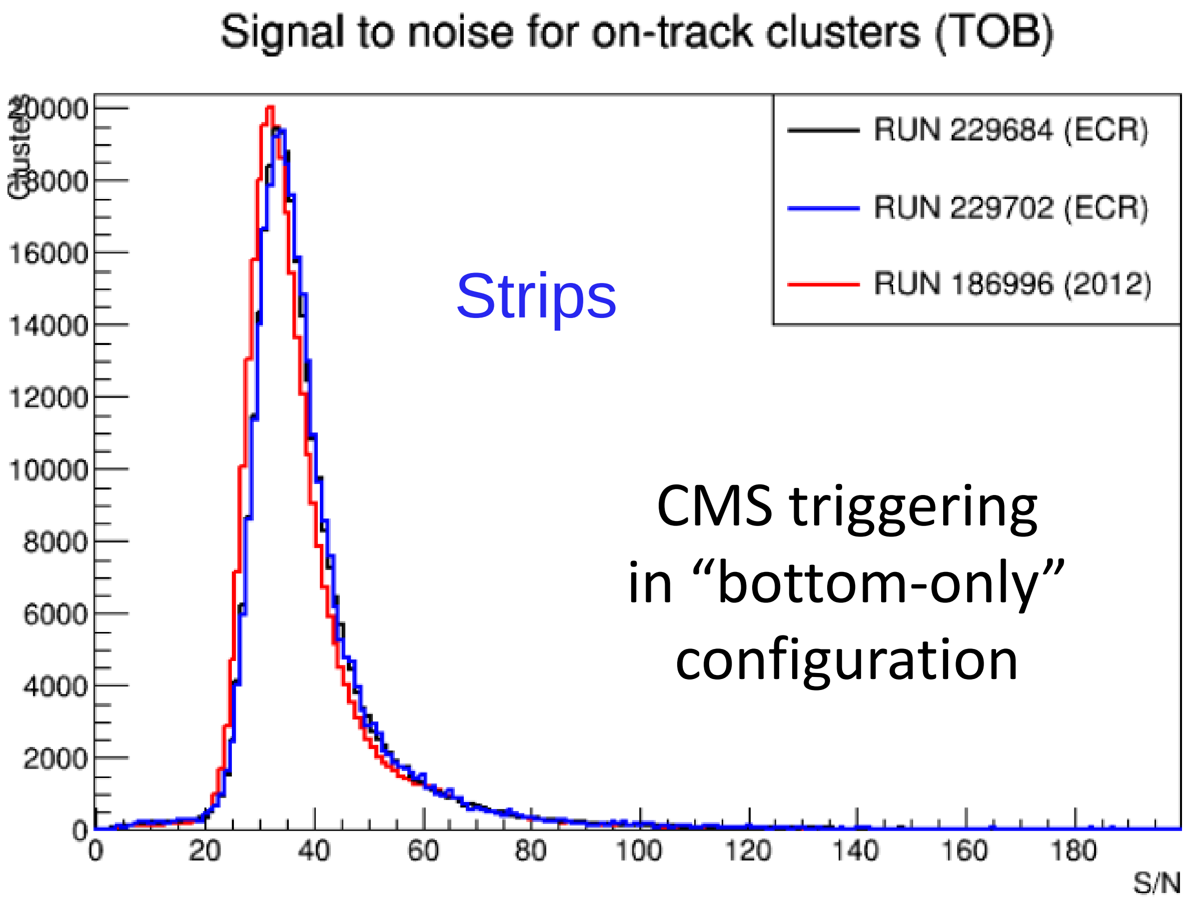


RPC timing (bx)

CSC Track Finder timing (bx)

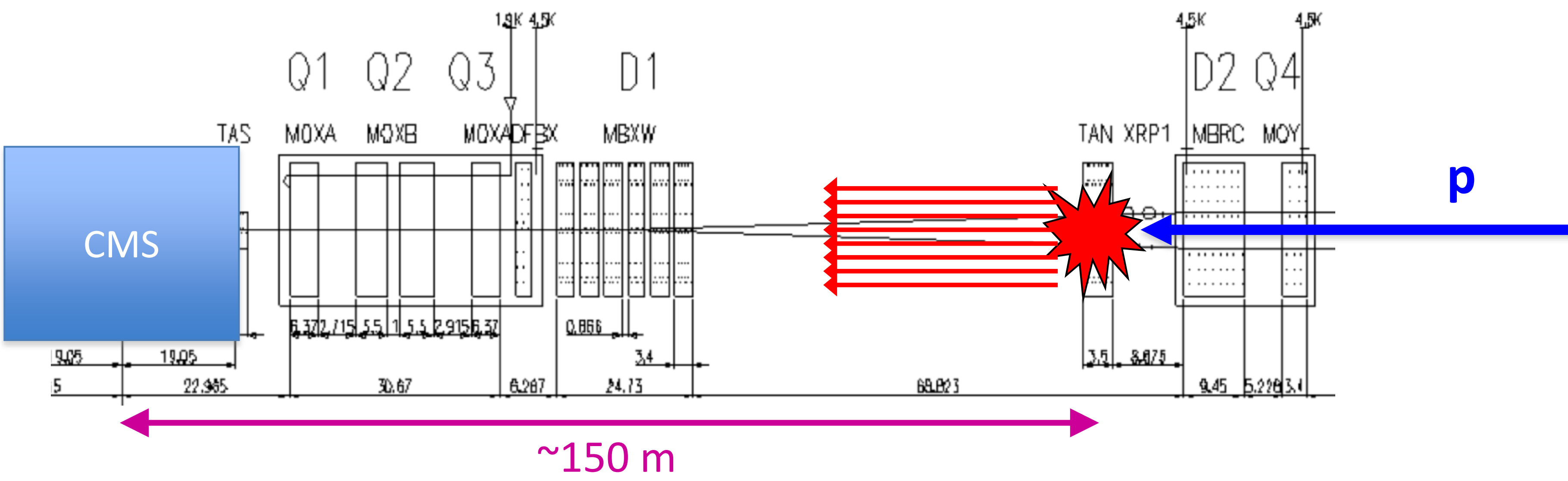
Each muon path confirmed to be ~synchronous with the others

Cosmic rays with “bottom-only” triggers = OK



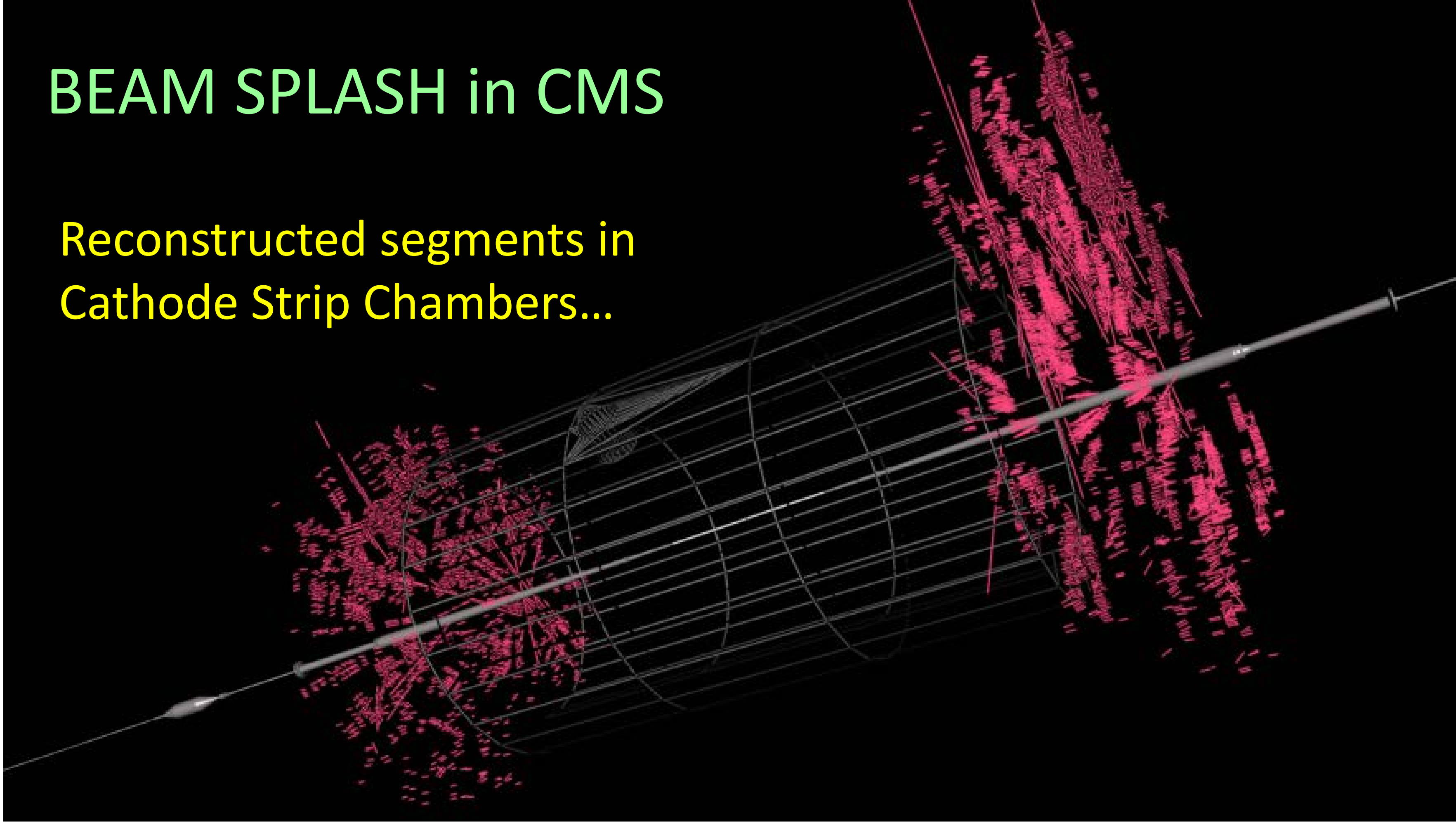
CMS timing with LHC
"Beam Splash" events

Beam splash = ~2 x 10^9 protons at 450 GeV/c incident on collimators ~150m upstream of CMS

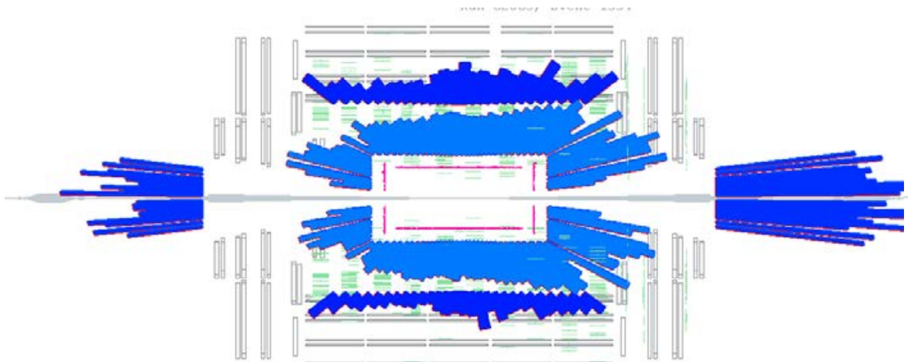


BEAM SPLASH in CMS

Reconstructed segments in Cathode Strip Chambers…

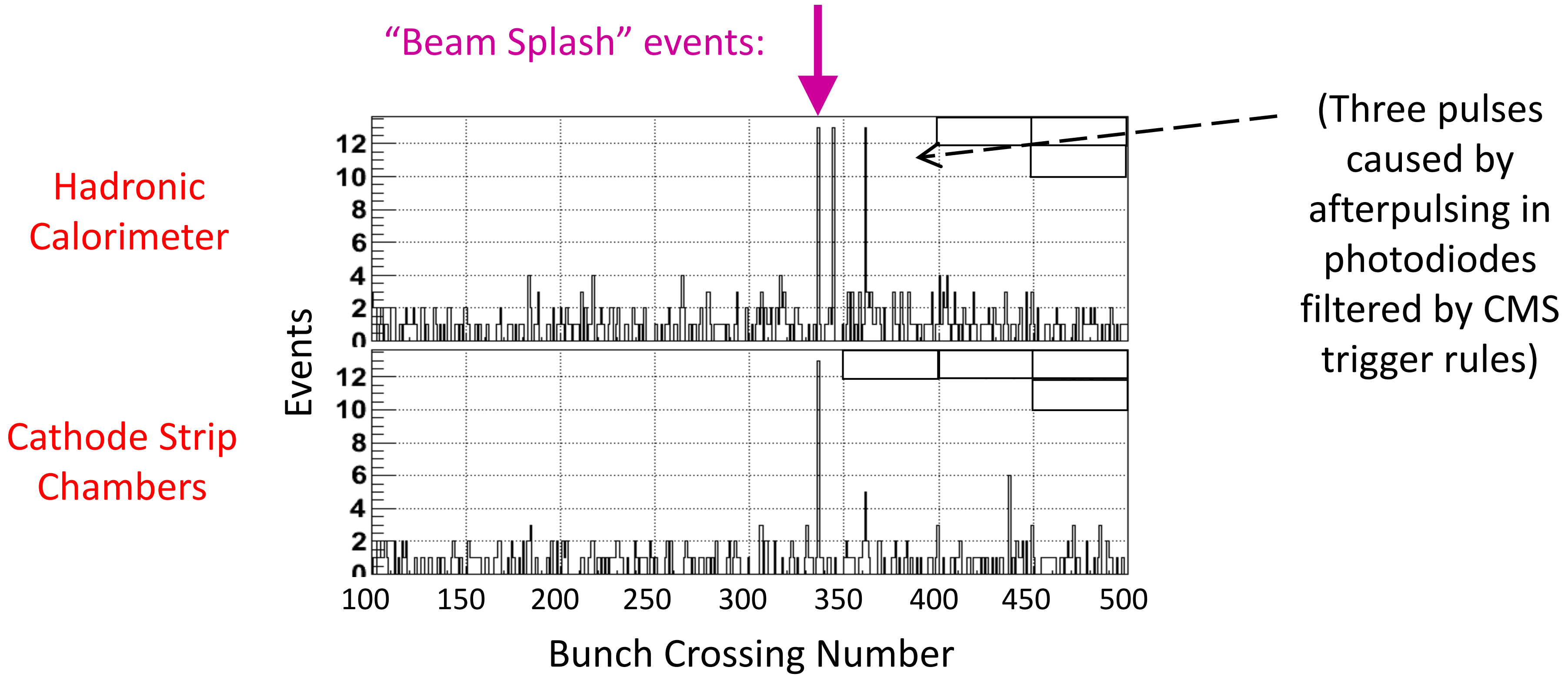


Energy in Hadronic Calorimeter:



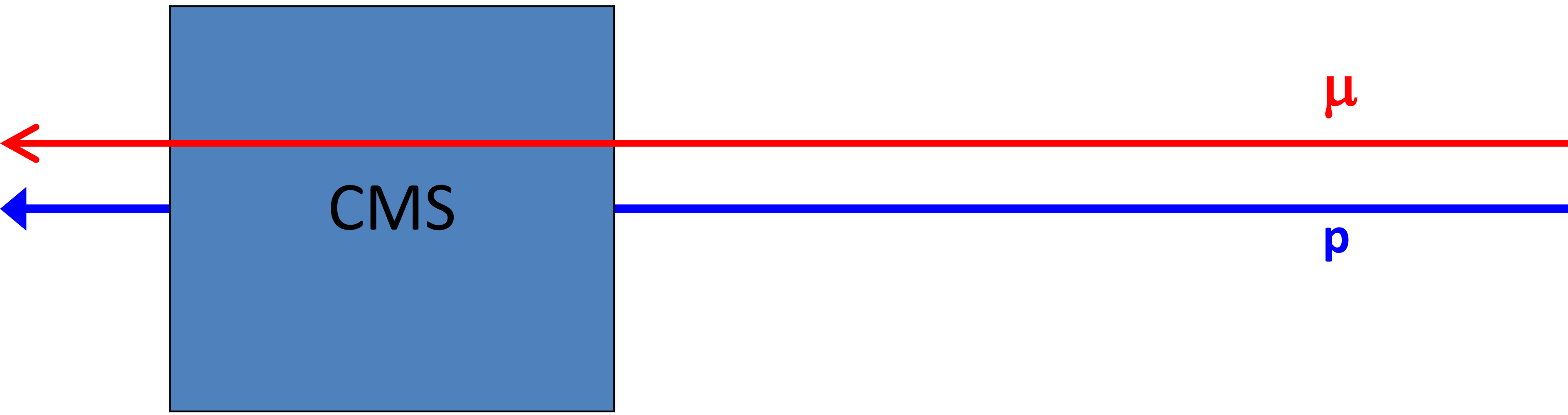
Energy in Electromagnetic Calorimeter:

Different subsystems triggering on LHC Beam Splash

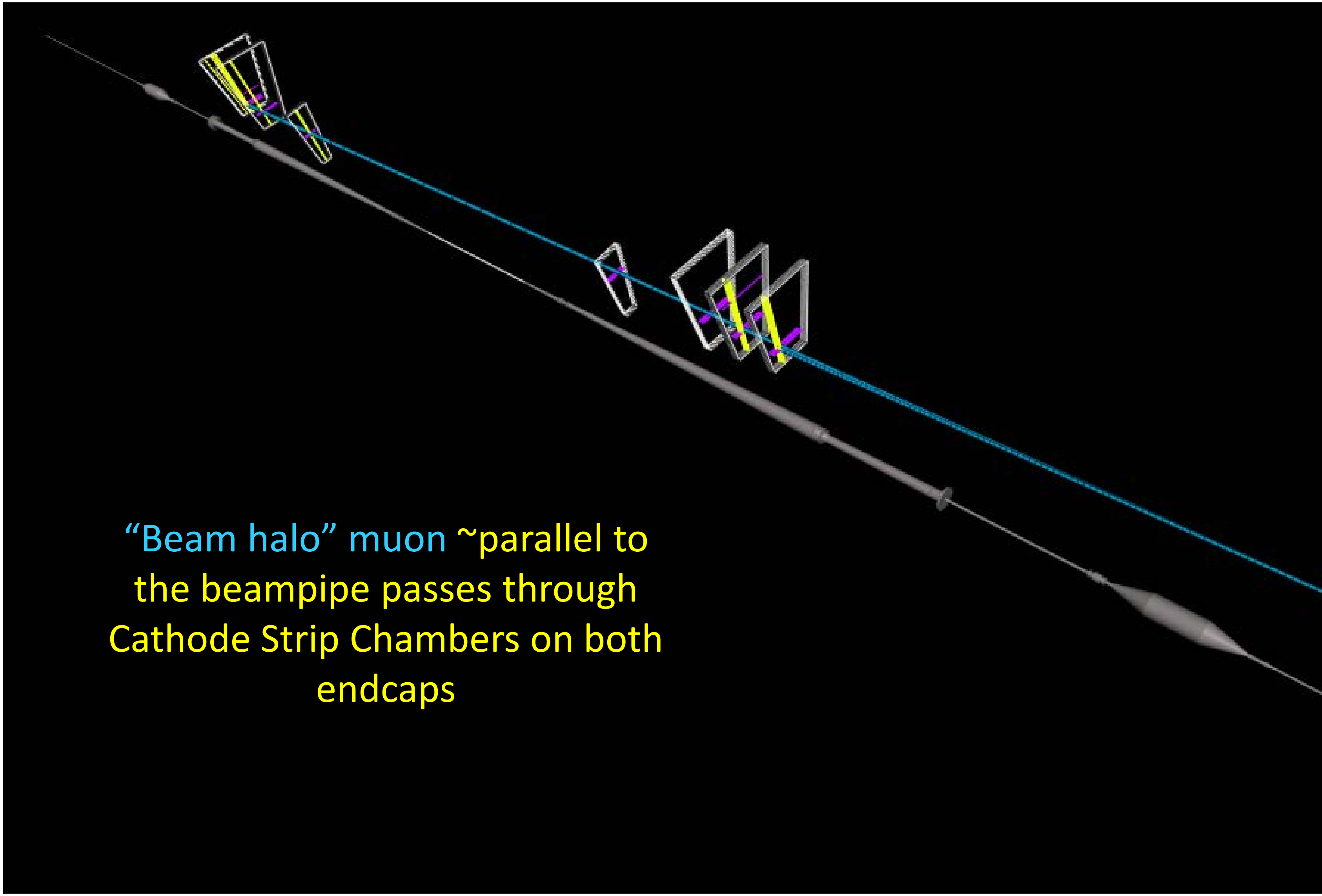


→ Detector synchronization **much** easier with synchronous beam

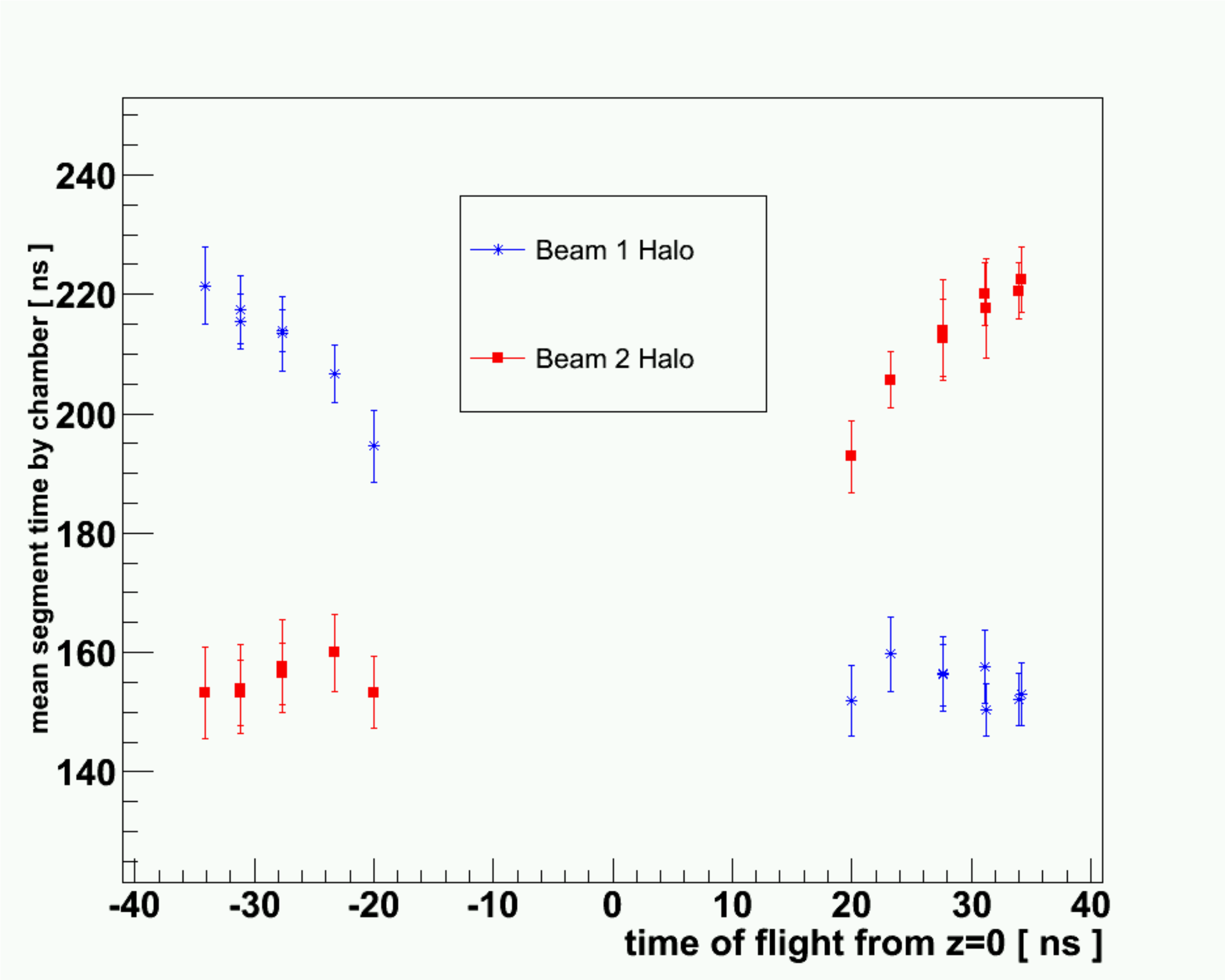
CMS response to LHC beam circulating without colliding:
"Beam Halo"



“Beam Halo” Muon Traversing CMS



Beam halo muons with collision timing



Beam halo "sees"…

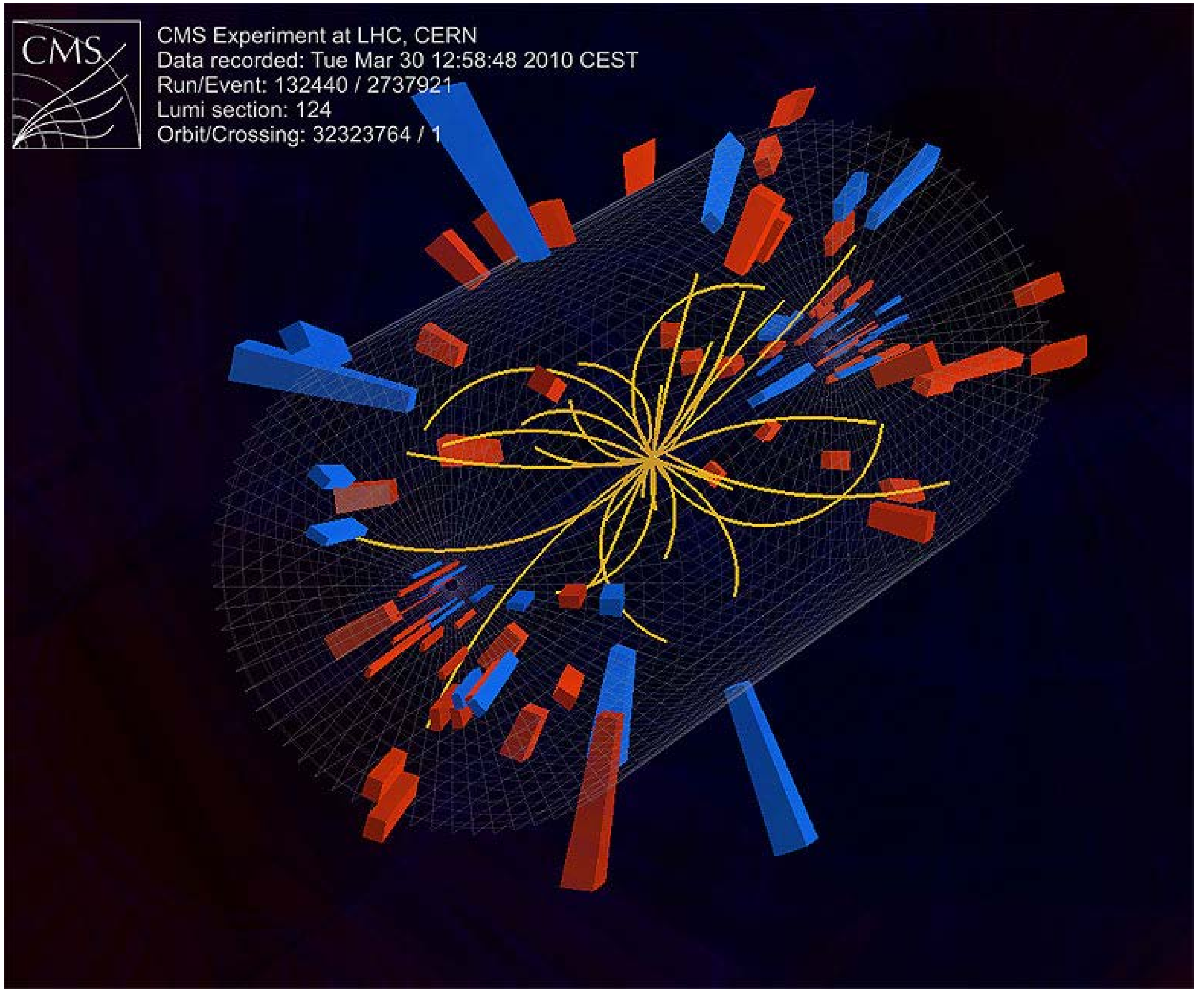
1. Upstream detectors
2. Interaction Point
3. Downstream detectors

Thus, similarly to cosmic rays, upstream chambers are early by…

(2 x time-of-flight)

… while those in the downstream chambers are ~in-time with collisions

CMS timing with collisions



http://www.fnal.gov/pub/today/images/images10/CMS1stEvent.jpg

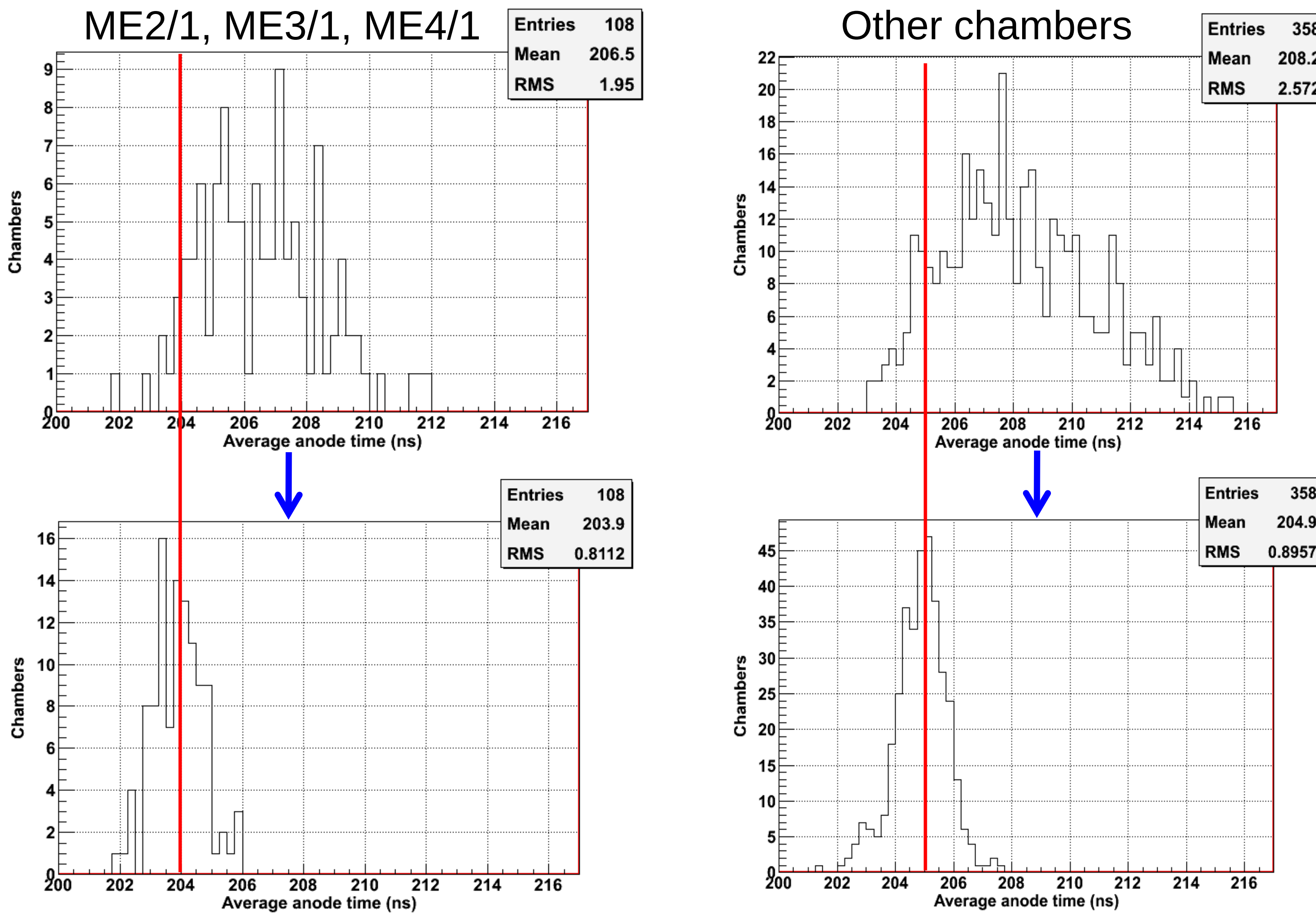
Fine tuning trigger timing

Plot average CSC anode time per chamber

Before

Changes implemented 17 Aug 2010

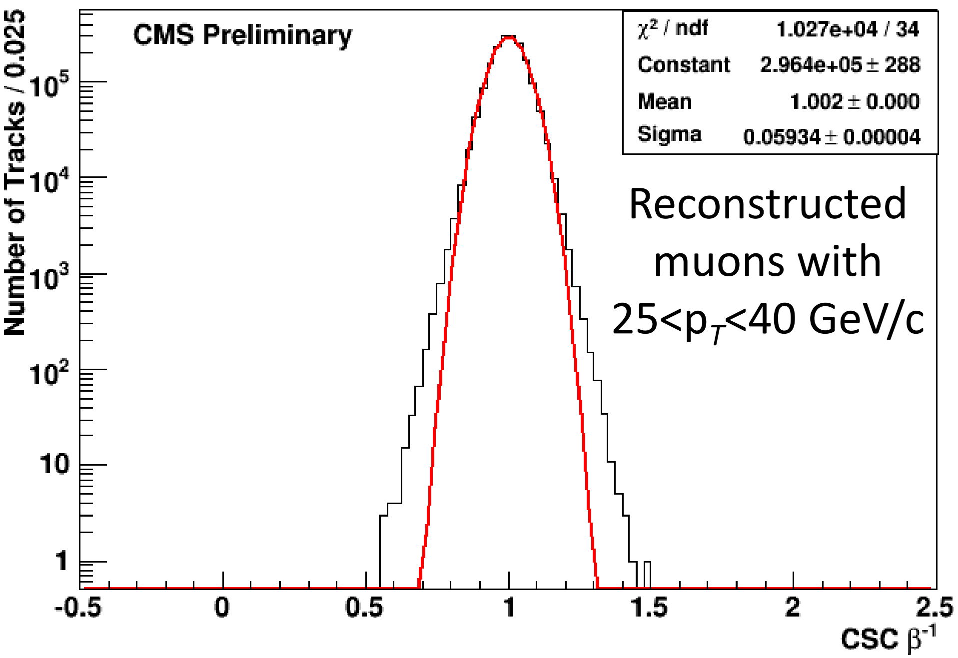
After



What happens when we get it all to work?

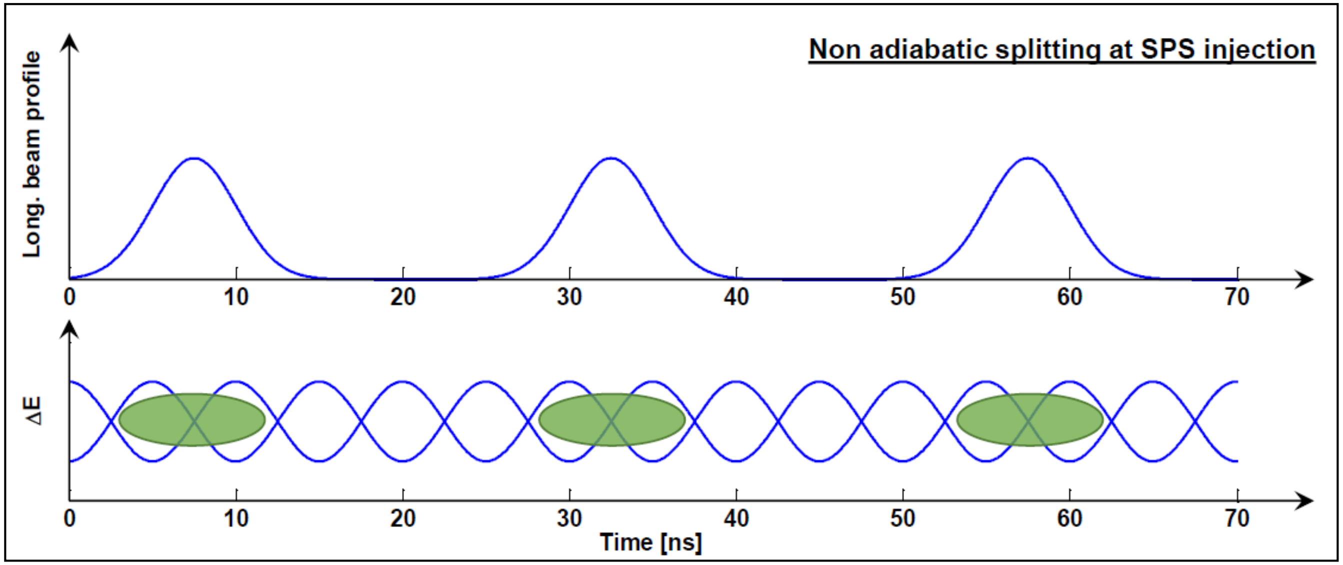
Combine all timing measurements from all layers used to reconstruct the track
→ 4 chambers * 6 layers * (anode + cathode) ~ 48 measurements per event

- Calculate $\beta^{-1} = 1 + c^*t/d$ per measurement
- Combine β^{-1} to create one value per track
  - Weight each measurement by square of the distance from the IP to minimize RMS
  - Timing quality cuts done for preselection

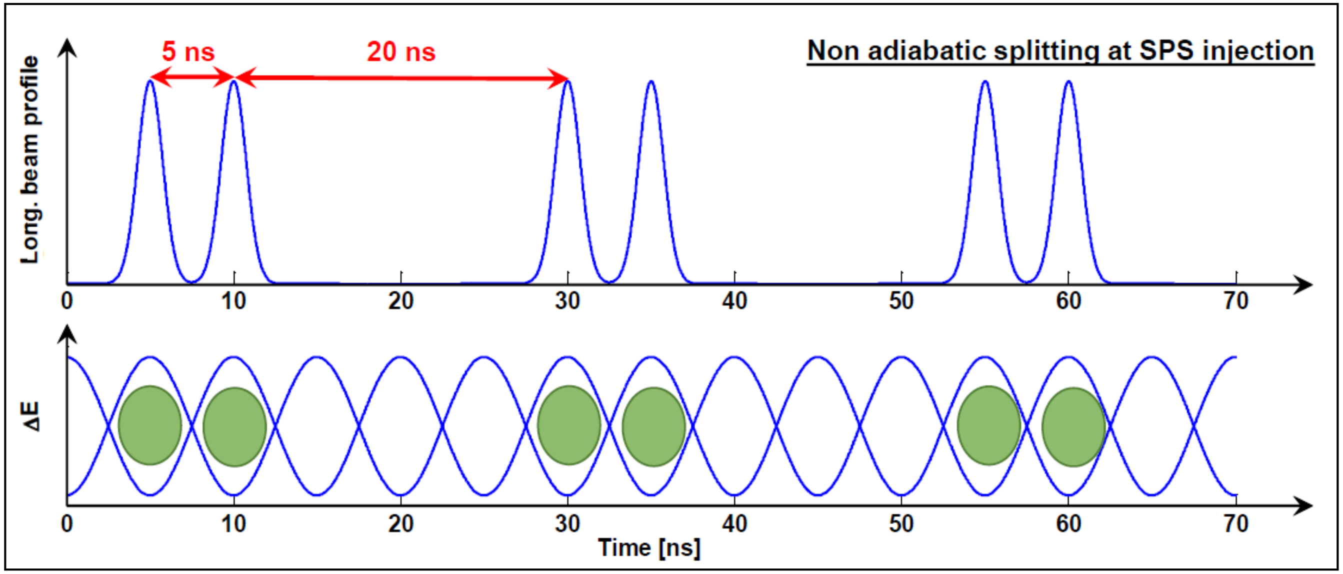


Measure the speed of light with 6% accuracy using the CSCs…

Creation of "doublets"



Create "long" bunches in the PS and inject them into the SPS



The RF in the SPS captures the long bunches into two bunches separated by 5ns (spaced every 25ns)