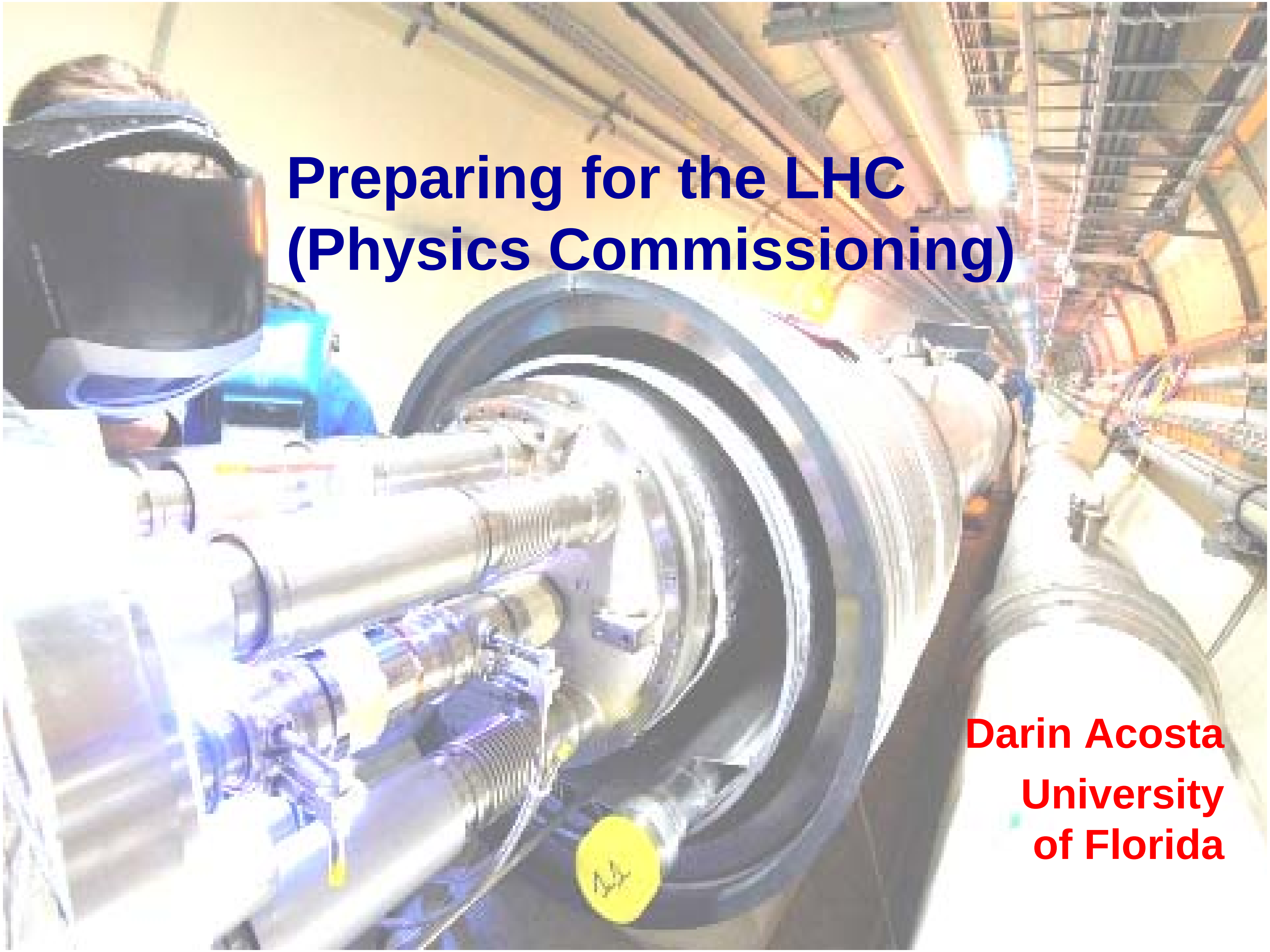


Preparing for the LHC (Physics Commissioning)

Darin Acosta

University of Florida

Outline of Lectures

- What is commissioning?
- Scale of the problem
  - Detectors, electronics, software, computing
- Commissioning activities
  - Test beam programs
  - Detector "Slice Tests"
  - Magnetic field measurements

Lecture 1

- Detector performance
  - Temporal alignment (synchronization)
  - Spatial alignment
  - Material budget
  - Calibration

Lecture 2

- Operating the Experiment
  - What it takes to run a large experiment
  - Data quality monitoring

Lecture 3

Outline, Cont'd

Lecture 3

- Preparing for physics measurements
  - Luminosity measurement & beam conditions
    - Impact of pile-up
  - Understanding the detector performance from data
    - Impact of instrumental issues (noisy/dead channels, zero suppression) on basic physics objects
    - Missing Transverse Energy – catch-all of instrumental problems
    - Jet Energy scale
- Early LHC physics measurements
  - Underlying event
  - Calibrating the Standard Model backgrounds
    - e.g. QCD jet production, Electroweak measurements, Top quark measurements

Lecture 4

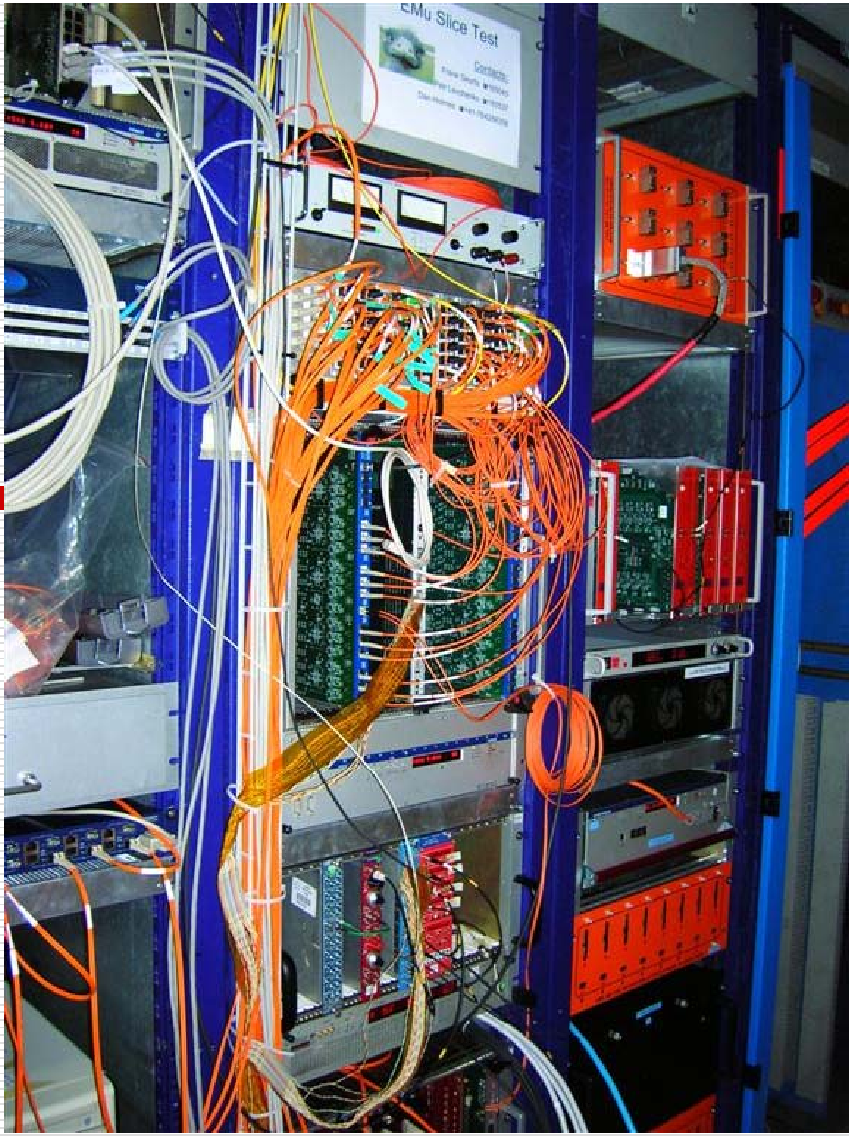
Summary of Commissioning Exercises

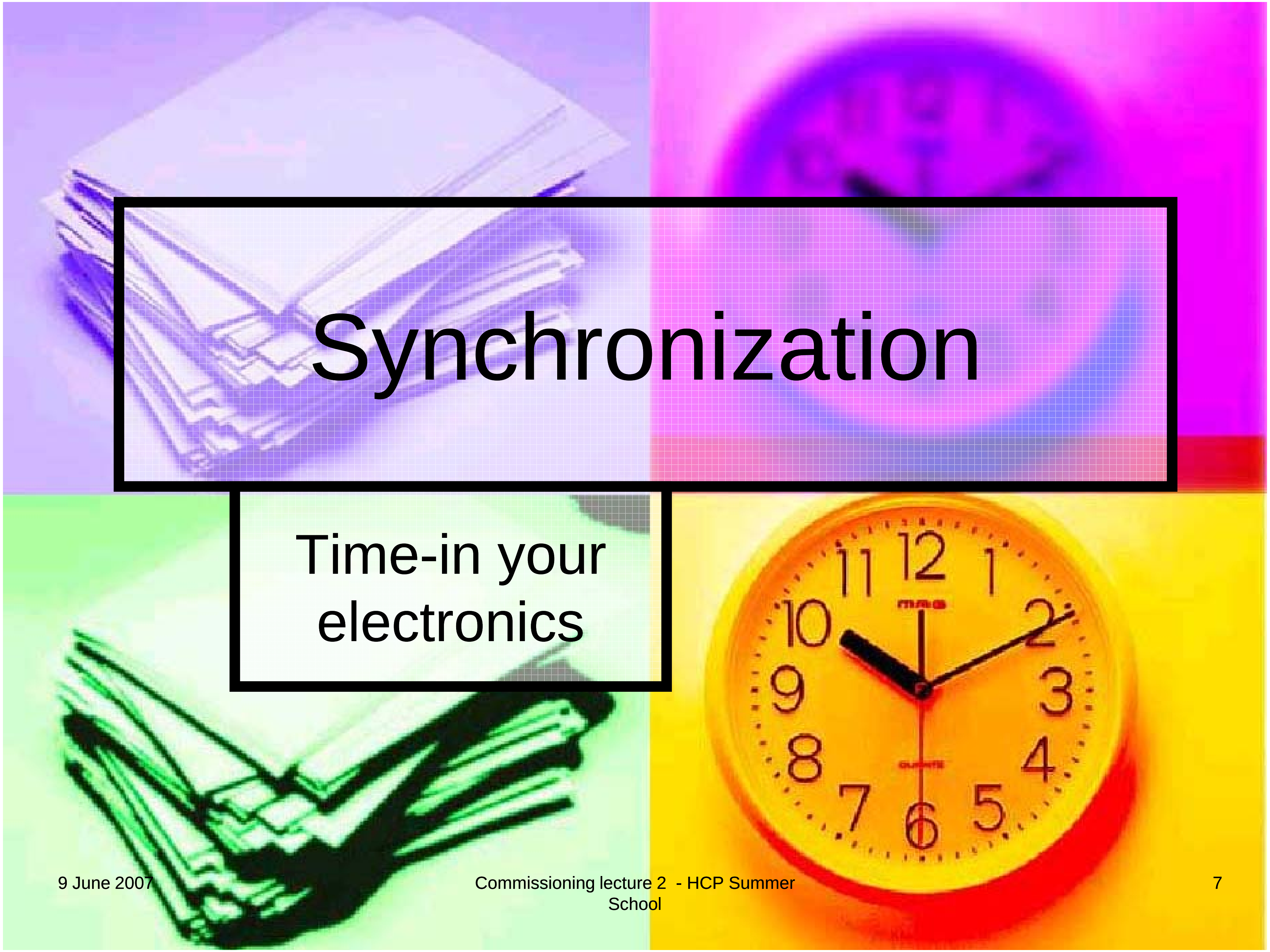
- You always learn something!
  - Expect the unexpected (electronics failures, detector noise, …)
- It is important to test slices of the complete system for functionality (vertical slice tests), and the portions of the full system for scale (horizontal slice tests)
- Because of the importance of the LHC turn-on, and the possibility of new discoveries right at the beginning, we are trying to pre-commission as much as we can before beams
- But this implies trade-offs:
  - Commissioning exercises vs. installation activities
  - Global data-taking exercises vs. subsystem commissioning
- It's a "chicken-or-egg" problem:
  - If we wait for installation to be over, we have not pre-commissioned in time
  - We can't commission until we are installed…

Detector Performance

Success in commissioning will be judged quantitatively by achieving the design performance from the detector subsystems

First things first:
Check the connections

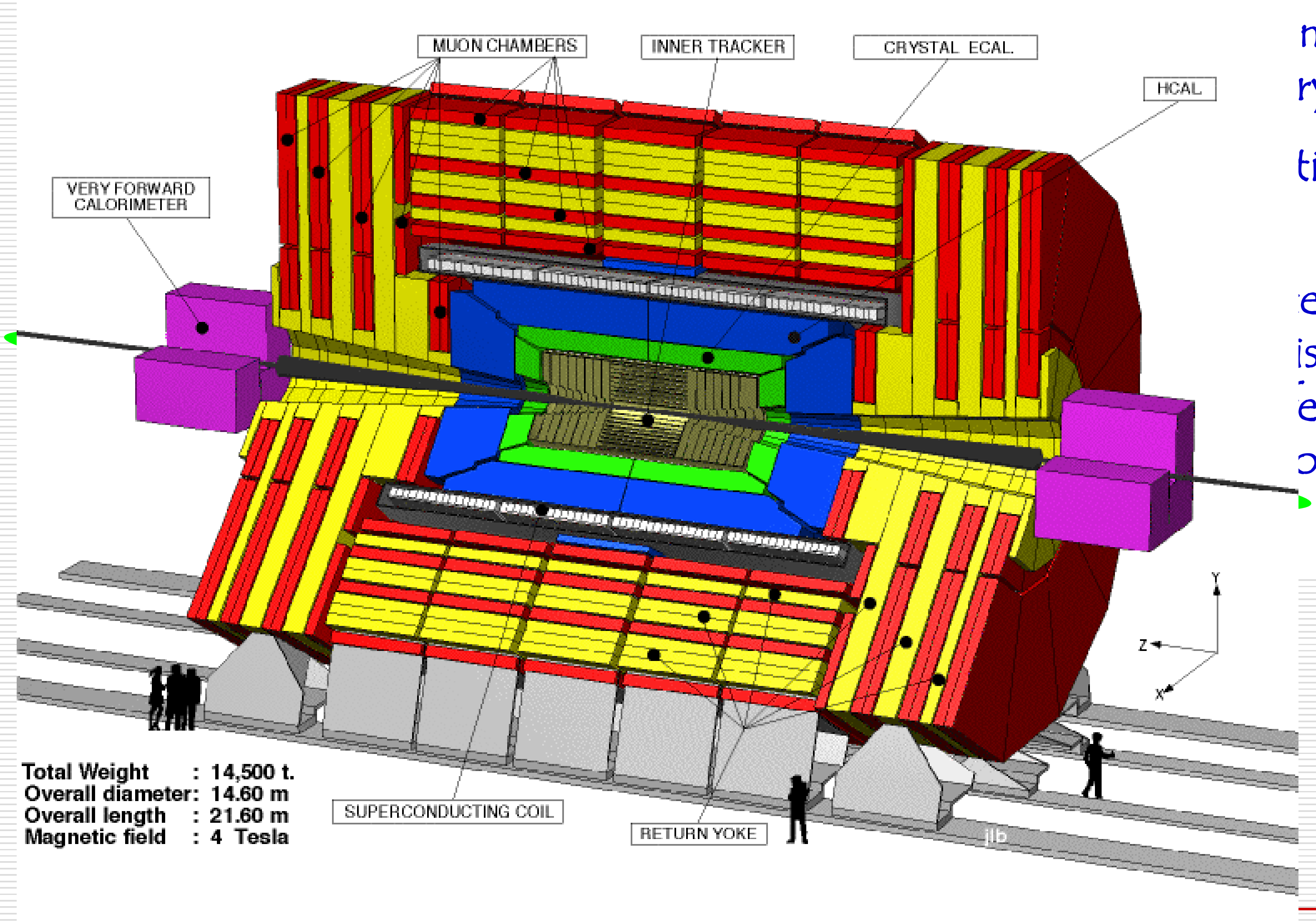




Synchronization

Time-in your electronics

Collisions @ CMS



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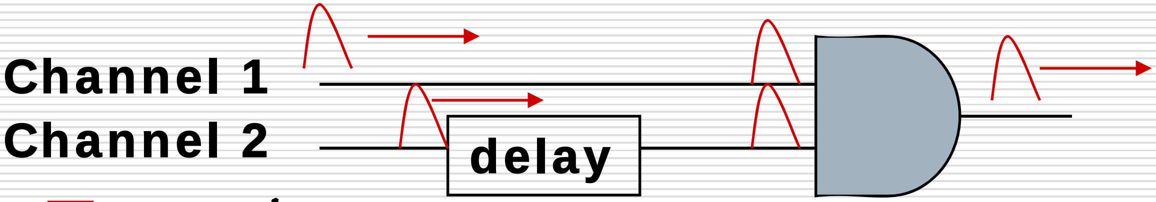
Synchronization: General Picture

- Synchronization means making fine delay adjustments to the electronics signals from the various detector components so that the data from a single beam crossing are received and processed in coincidence, despite different flight times



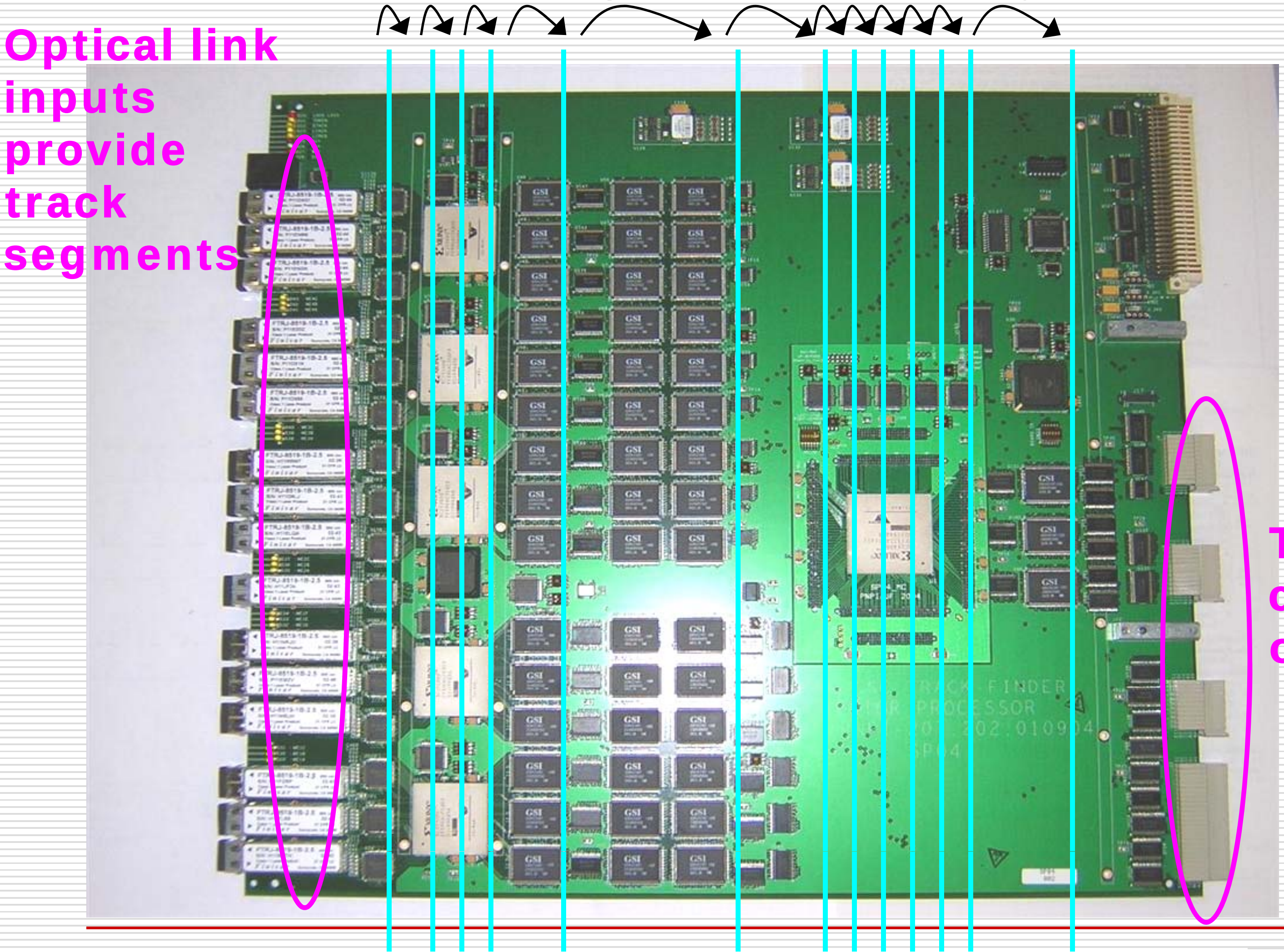
- Need to time in:
  - The synchronous Level-1 trigger system so inputs are coincident
  - The capture of pulses for the data acquisition system (DAQ) based on the trigger signal
  - The time assignment & association of captured data (BX, event number)
- There is one master reference clock that drives everything→

The Clock

- Is the heartbeat of the experiment
- Most of the front-end detector electronics and the Level-1 trigger electronics march to its beat
- LHC bunch crossing frequency: 40.0788 MHz
  - Approximately 25 ns bunch crossing (BX) spacing
- Since this is a very short interval, cannot complete the full Level-1 trigger decision within 1 BX (actually takes ~100)
- Thus, the digital electronic systems are pipelined, with the clock synchronized (via phase-locked loops, PLLs) to the LHC frequency
  - Each clock edge marks the arrival of data from the next collision
- Catastrophic error if the experiment clock is disrupted, or the frequency changes

Dataflow of a synchronous digital electronic board (Level-1 Muon Track-Finding Board)

Data moves to next step on each clock edge

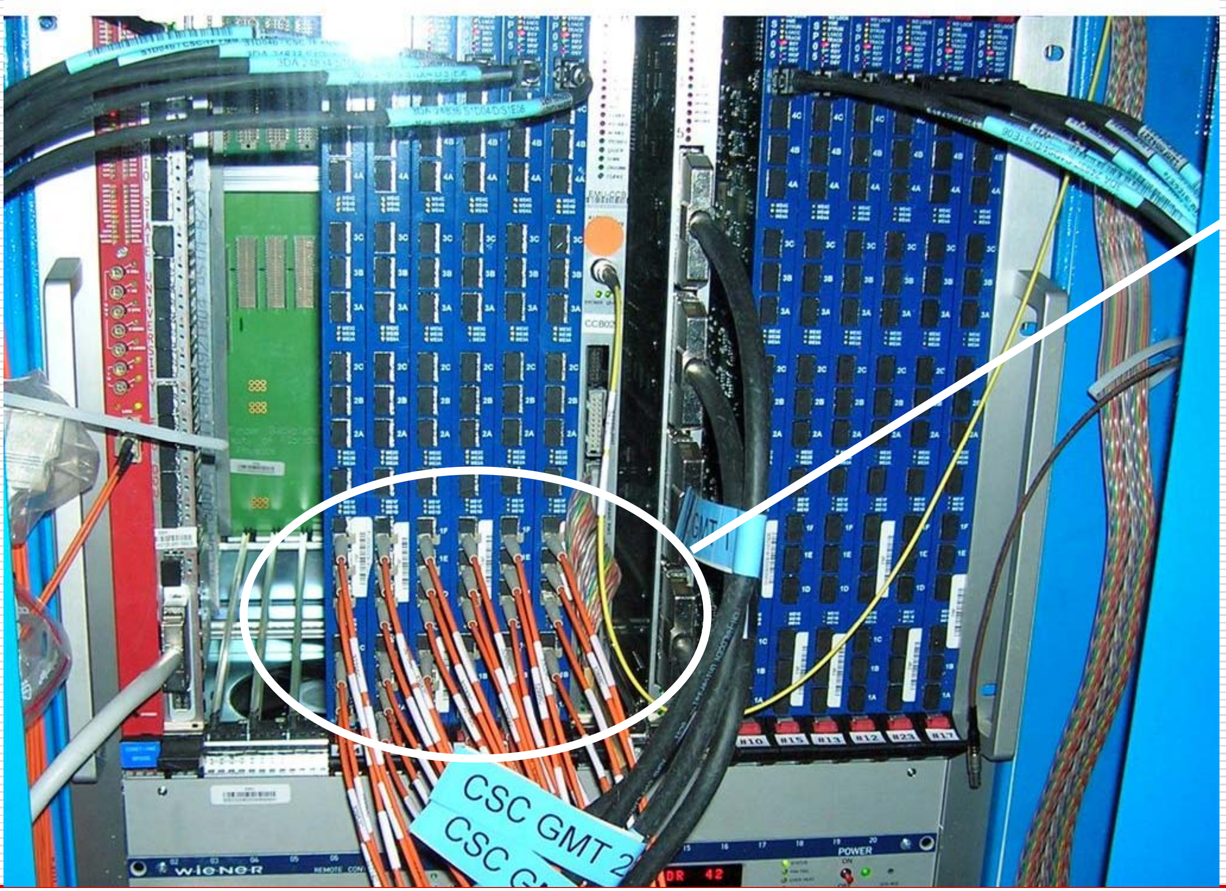


- A complex task is partitioned into individual steps
- Register output of each step so that data can be processed every BX even though entire operation takes >1BX

Data from 13 BX on board at any one time, latency: 13*25ns=0.33µs

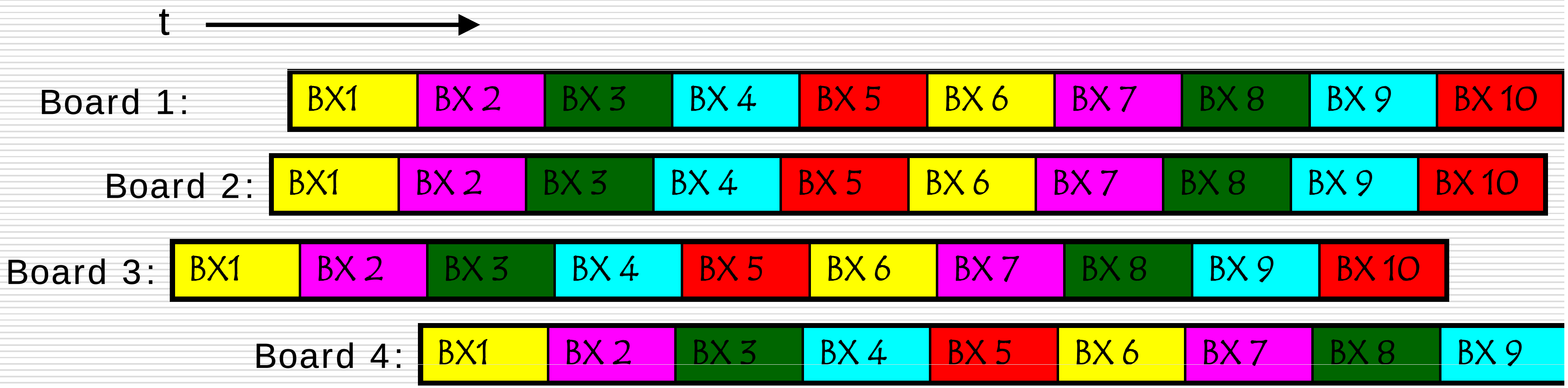
Multiple boards, crates, racks

- Single board is embedded within a system of many crates and racks of electronics



Even the optical links connecting the detectors to the electronics add delays due to the finite speed of light, and hold many collisions (20 BX in this case)

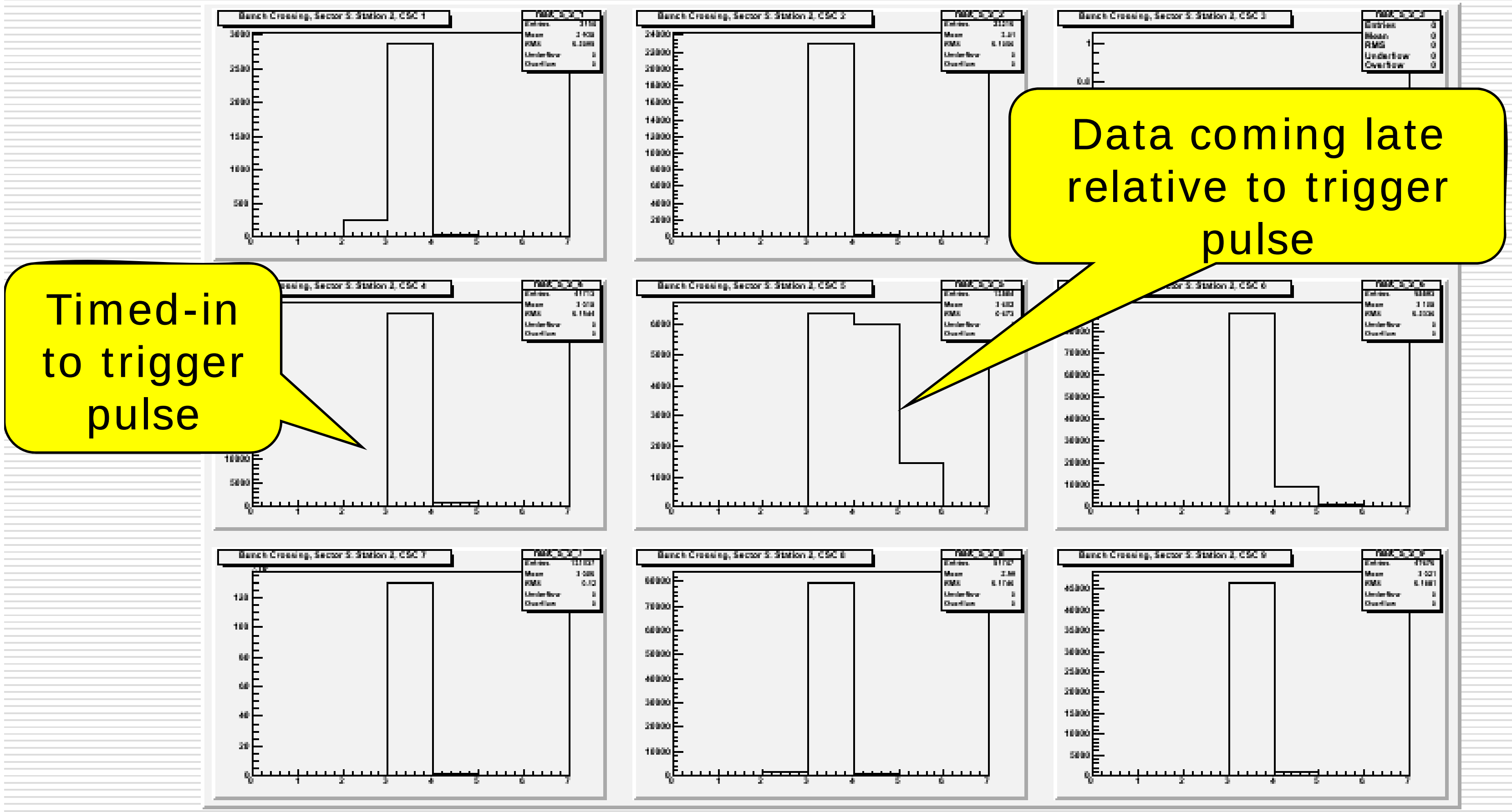
Level-1 Trigger Synchronization



- For a synchronous system, one needs to add delays and adjust phases to keep data synchronized when collecting data from multiple boards (e.g. at the Global Trigger)
  - If not, you will be mixing up different events!
- This can be tricky
  - There are a lot of boards! But some delays can be calculated (cables, logic)
- Need to send periodic pulses to check time alignment, and look at the data itself for coincidences

Example of (mis)timed trigger electronics

- ☐ Cosmic ray signals from muon detector trigger electronics



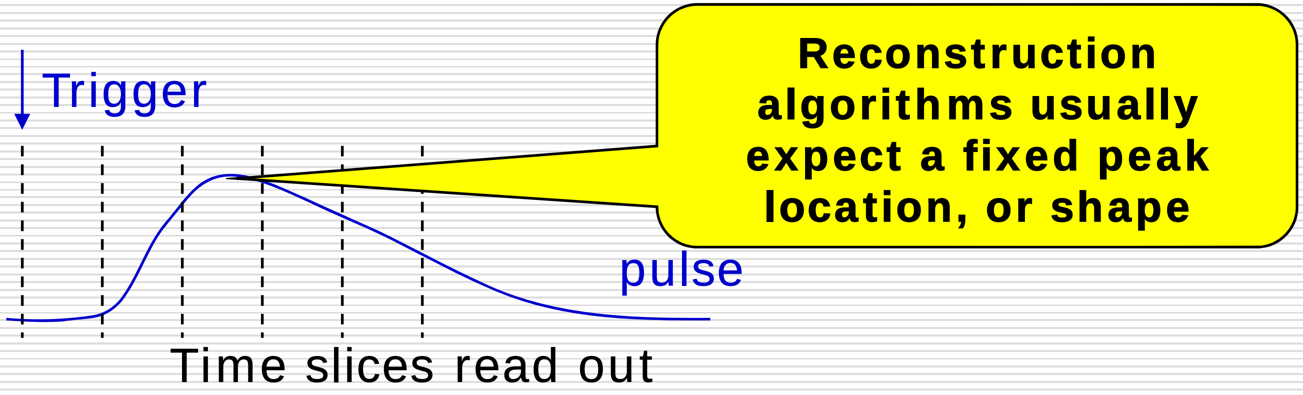
Timed-in to trigger pulse

Data coming late relative to trigger pulse

Relative BX →

Signal Capture and Synchronization to Trigger

- The analog pulses coming from the detectors must be delayed or otherwise stored, and then digitized (ADC, TDC) after a Level-1 trigger accept decision arrives

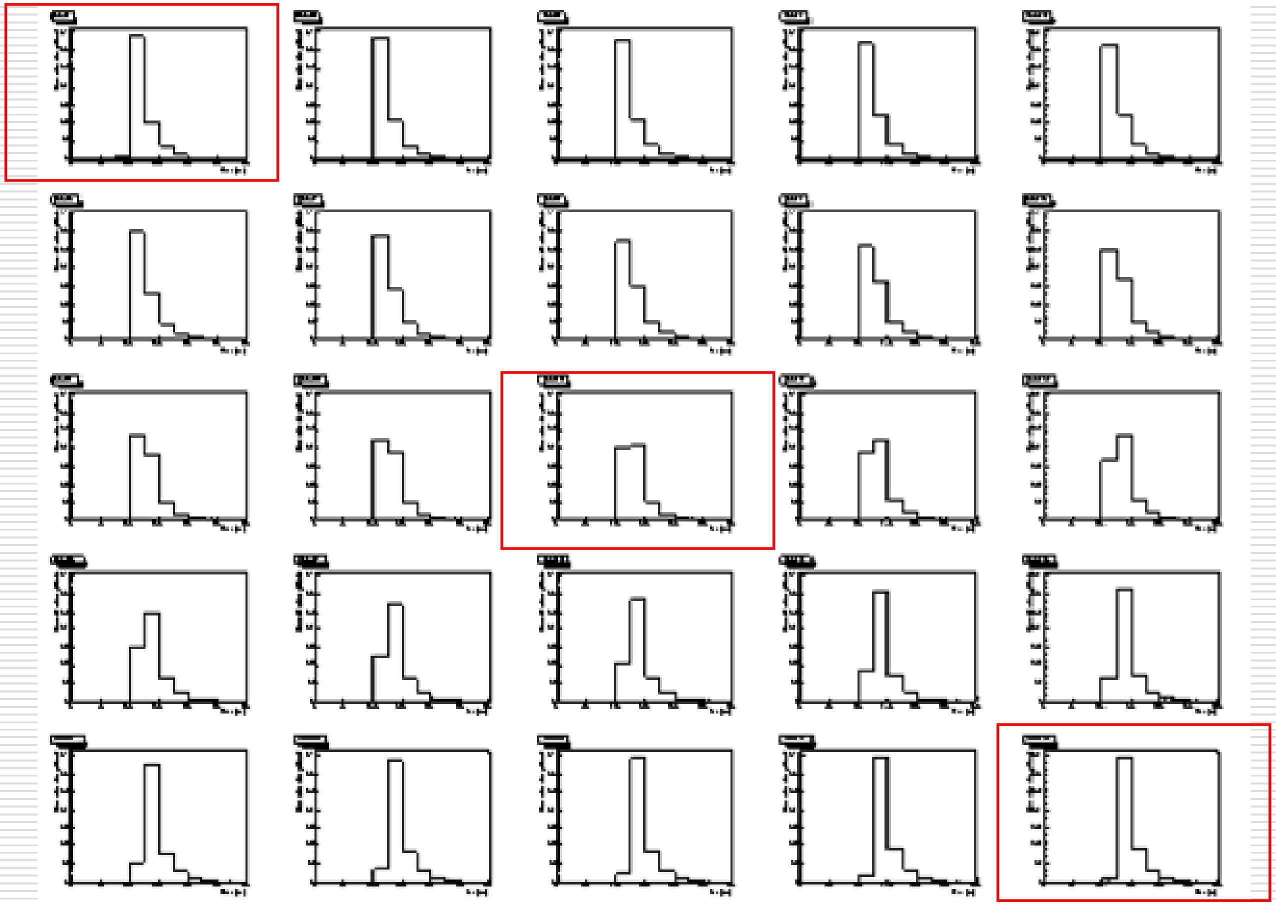


Reconstruction algorithms usually expect a fixed peak location, or shape

- So timing-in the data acquisition electronics generally means capturing the data inside a certain time window defined relative to the trigger signal, with the clock phase adjusted so that the peak is in a fixed, desired position
  - Otherwise you are in danger of losing your detector signals, or misinterpreting the integral of the pulse (the charge)

Adjusting phases of calorimeter signals

- Adjusting the clock phase in 1ns steps to align pulse in window
  - One channel of CMS hadron calorimeter responding to laser pulse

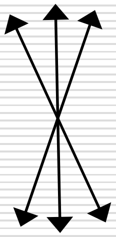


Peak is ½ clock later

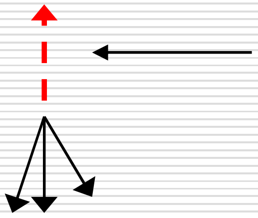
Peak is 1 clock later

Synchronizing Event fragments

- Once your trigger is synchronized, and pulses captured, one should ensure that the data captured by the DAQ actually corresponds to the same collision
- Time markers include the Level-1 event number and the bunch crossing (BX) number
- There could be a lot of interesting discoveries at the LHC if data fragments are not properly aligned!
  (e.g. momentum imbalance)



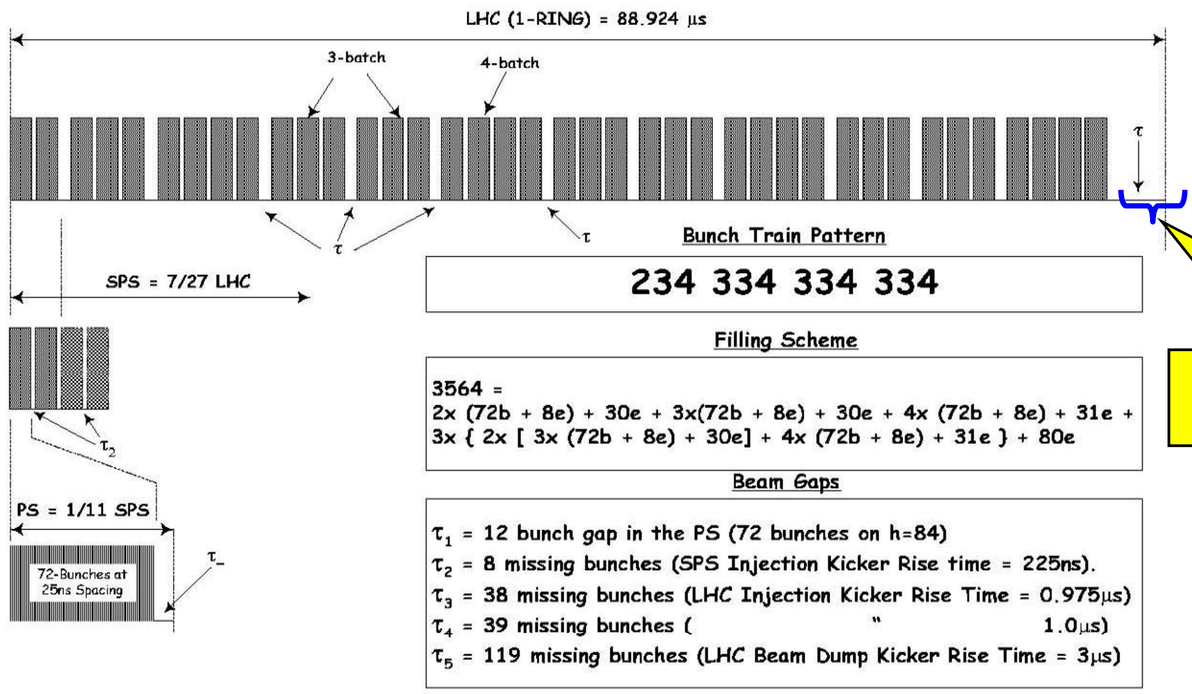
Dijet event becomes…



Presumed invisible SUSY particle because data associated to wrong event!

LHC Bunch Structure (another handle)

- ☐ 3564 "buckets" spaced 25ns apart span one LHC orbit
- ☐ 2808 (80%) buckets to be filled with protons per LHC design
- ☐ Structure of gaps provides a useful "fingerprint" to check synchronization of electronics



Bunch Train Pattern

234 334 334 334

Filling Scheme

3564 =
2x (72b + 8e) + 30e + 3x(72b + 8e) + 30e + 4x (72b + 8e) + 31e +
3x { 2x [3x (72b + 8e) + 30e] + 4x (72b + 8e) + 31e } + 80e

Beam Gaps

τ_1 = 12 bunch gap in the PS (72 bunches on h=84)
τ_2 = 8 missing bunches (SPS Injection Kicker Rise time = 225ns).
τ_3 = 38 missing bunches (LHC Injection Kicker Rise Time = 0.975µs)
τ_4 = 39 missing bunches (" 1.0µs)
τ_5 = 119 missing bunches (LHC Beam Dump Kicker Rise Time = 3µs)

Long"abort gap"

Time alignment of BX structure

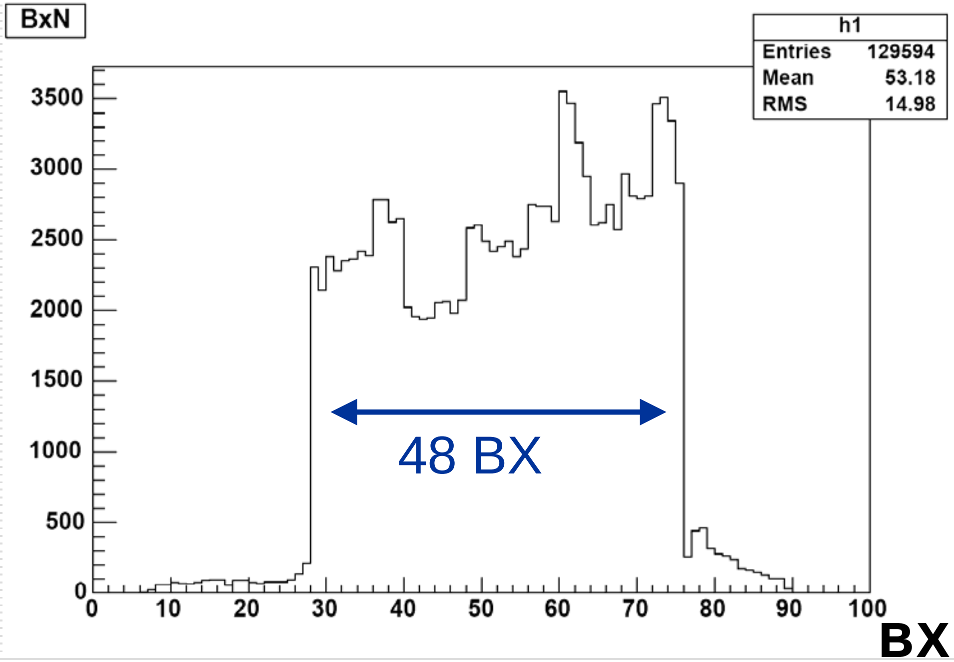
channel 1

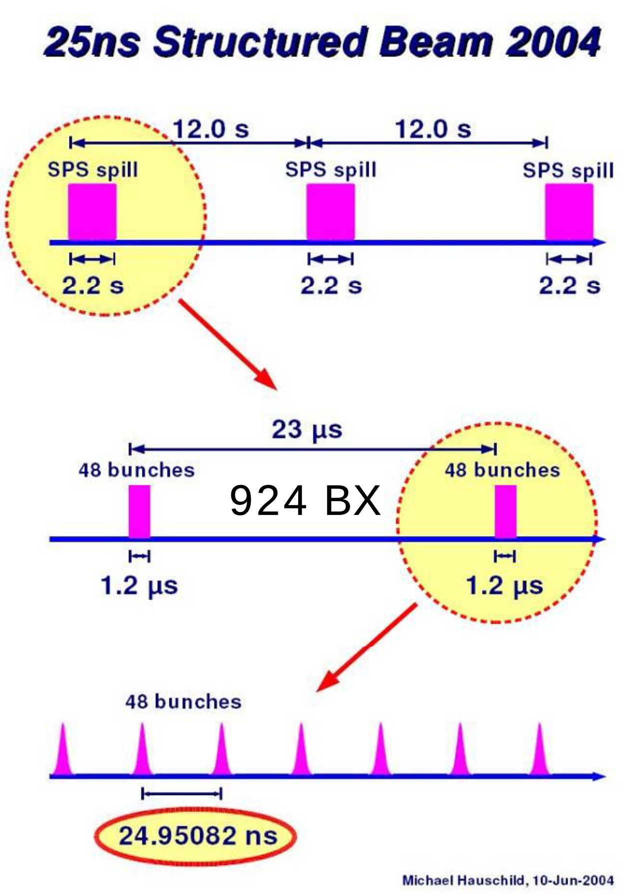
channel 2

- ☐ Accumulate data from each electronic channel and bin occurrences vs. BX number
- ☐ Look for offsets in the fingerprint, then adjust delays or counters to match

Bunch Crossing Structure Example

- For example, the SPS provided a testbeam with bunches synchronized to the LHC frequency (48 BX train)
- CMS muon detector electronics (cathode strip chambers) exhibited this structure during 2004 tests



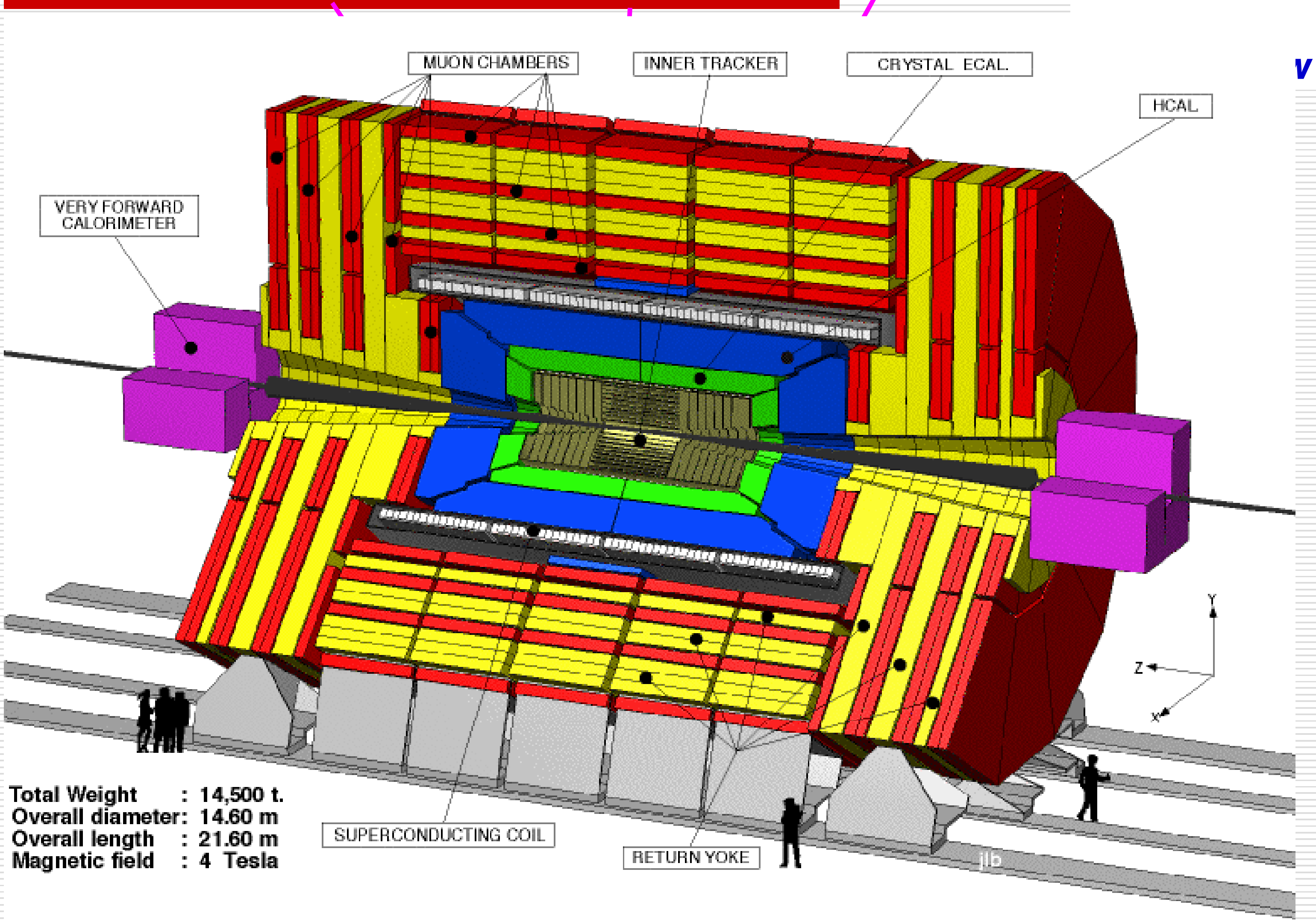


Synchronization with particles

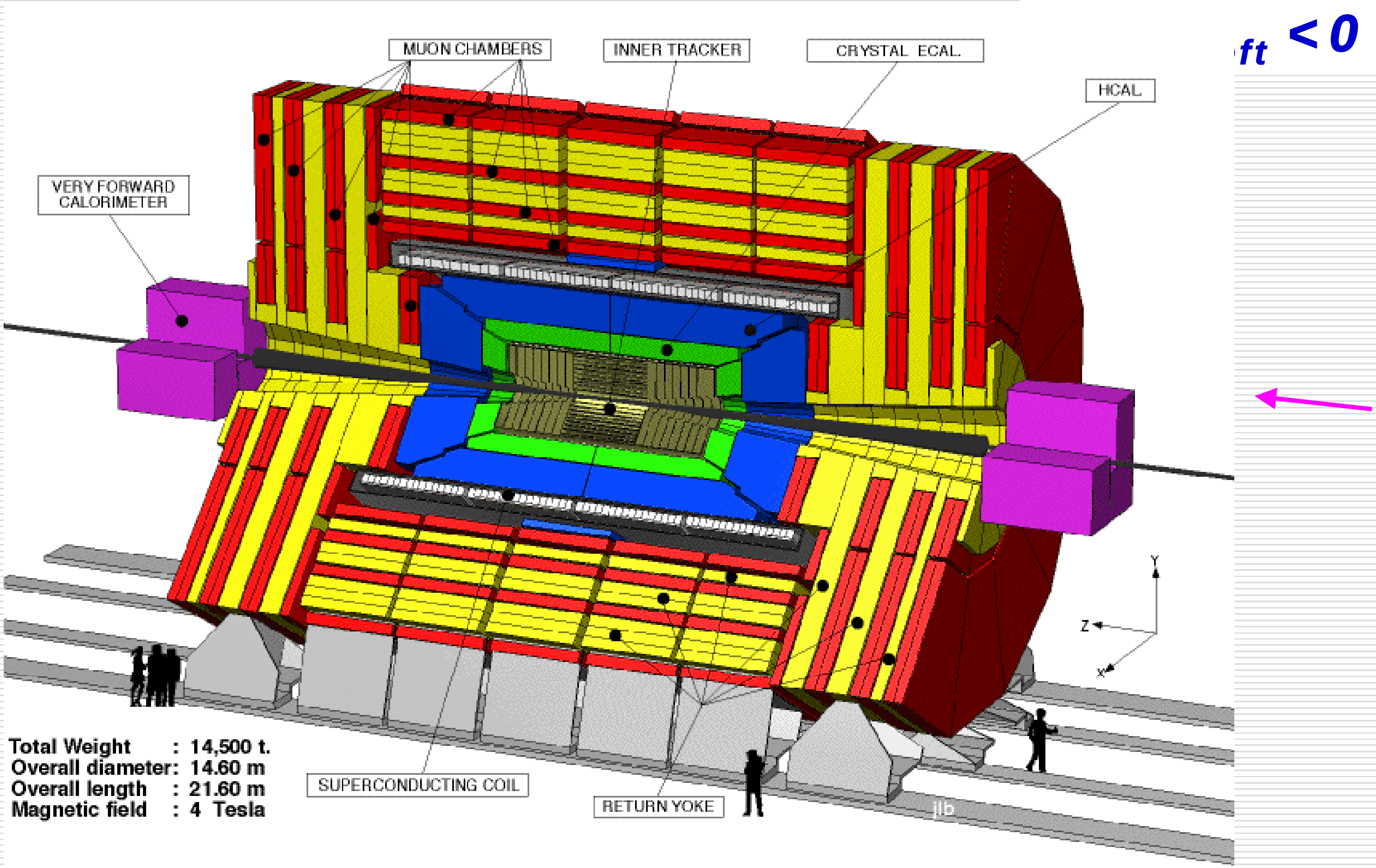
- Of course to achieve synchronization requires some particles!
- Three possible sources of particles for synchronizing detectors in-situ in the collision hall:
  - Cosmic ray muons (all we have at the moment…)
    - Asynchronous (random), and with asymmetric time-of-flight timing
  - Beam halo particles (single beam or collision operation)
    - Synchronous with 25ns bunch spacing, but asymmetric time-of-flight timing
  - Collision particles
    - Synchronous with 25ns bunch spacing, nominal timing
- The first two have biases, thus we need LHC collisions to complete the synchronization of the detectors

Cosmic ray timing (asymmetric)

$vn < 0$



Beam halo (asymmetric)



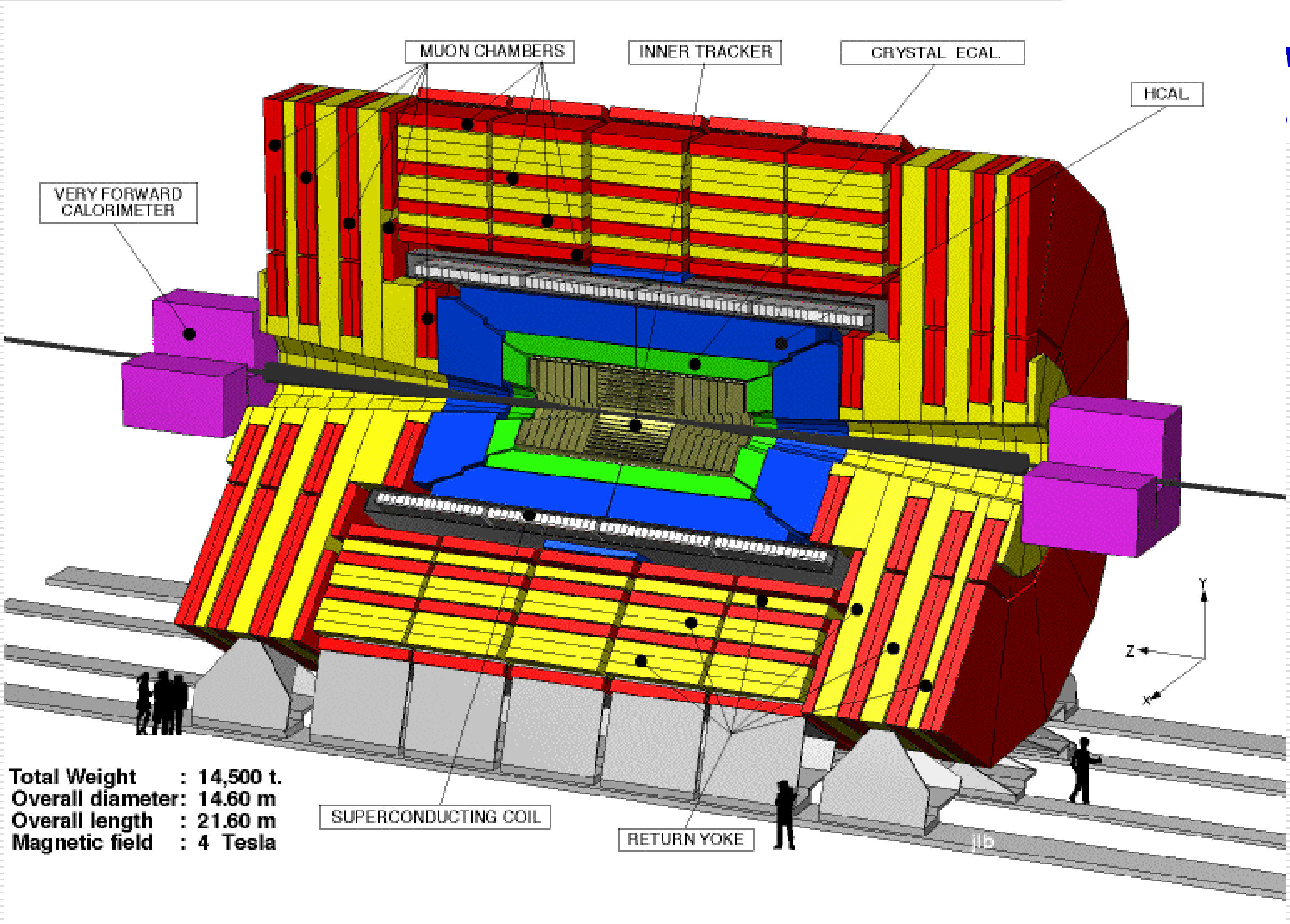
Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

ft < 0

Collision particle timing

vn ~ 0

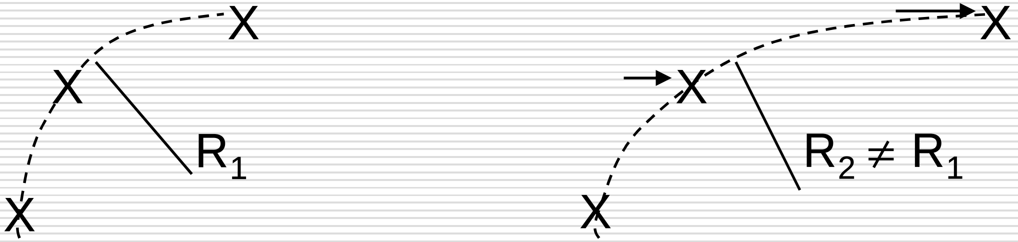
ft ~ 0



Spatial Alignment

Why alignment?

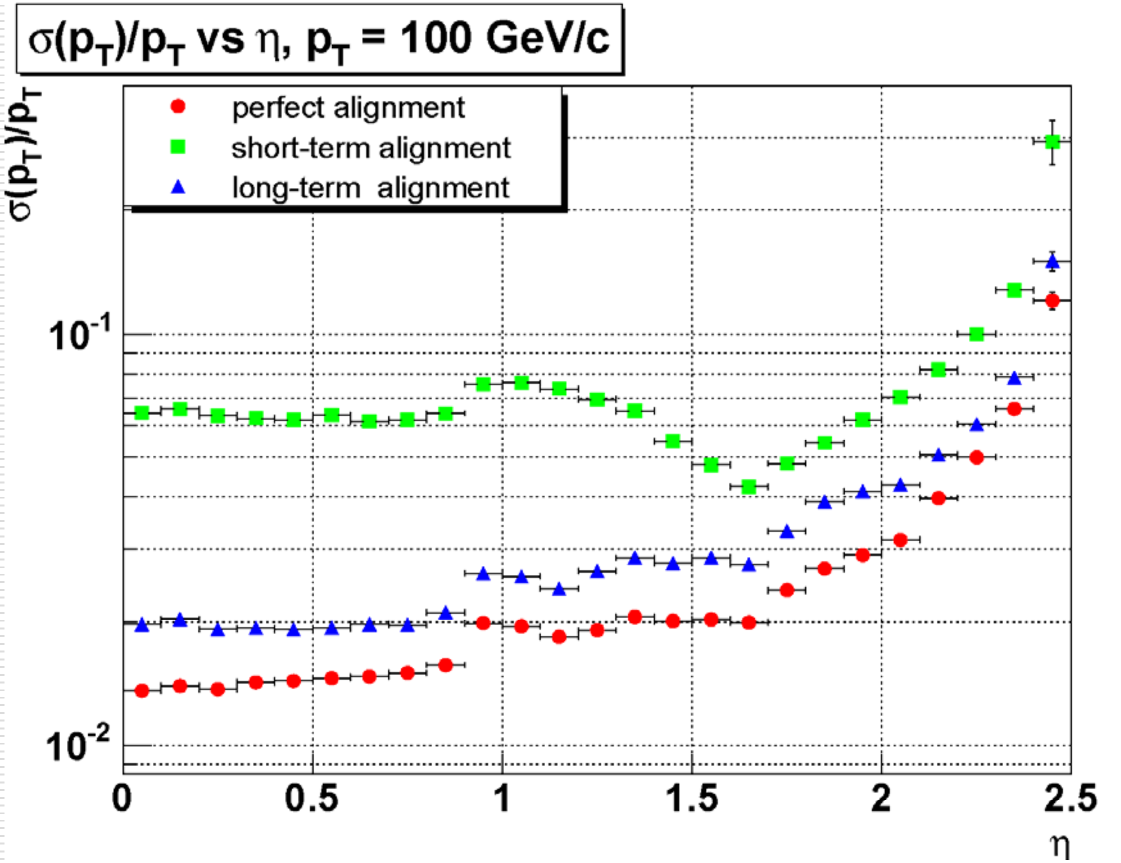
- Efficiency of associating correct detection "hits" to a charged particle's trajectory depends on proper understanding of detector alignment (for severe displacements)
- Even more importantly, the assignment of the momentum of a charged particle via its curvature in a magnetic field depends on the precise alignment
  - $p_T = q\,B\,r$,   q=charge, B= magnetic field, r=radius



- So we must align our detectors to get optimum performance for physics measurements

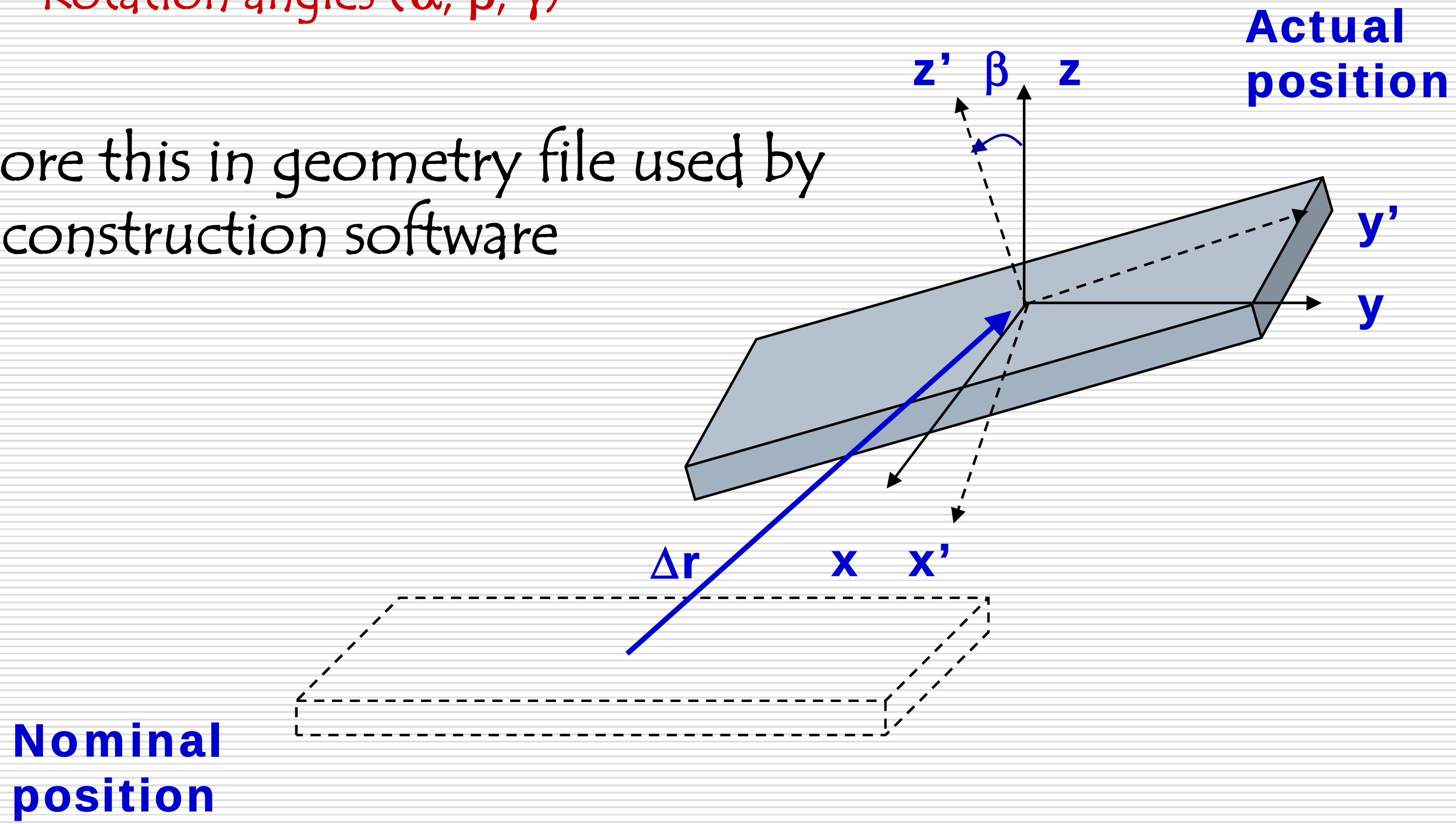
P_T Resolution

- Study of effect on P_T resolution due to misalignment of CMS Tracker



What needs to be measured

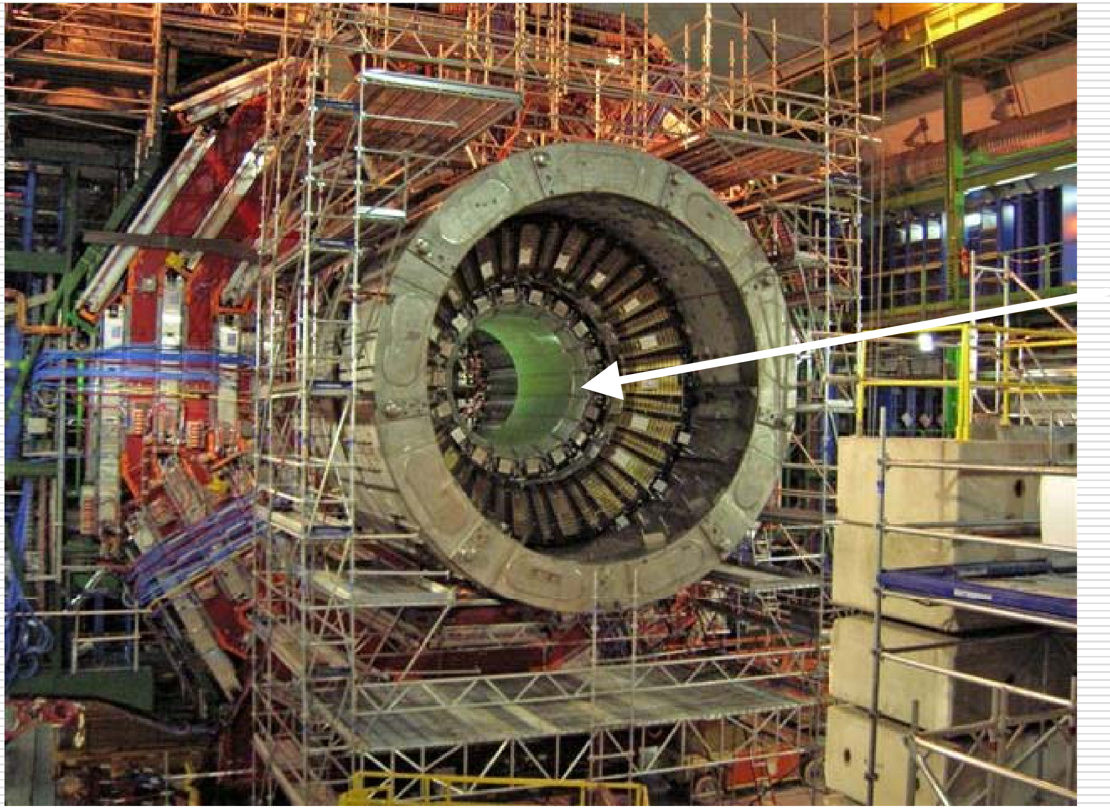
- For every active detector element, 6 degrees of freedom:
  - Translation vector $\Delta r = (\Delta x, \Delta y, \Delta z)$
  - Rotation angles (α, β, γ)
- Store this in geometry file used by reconstruction software



Survey

- First step is to survey the placement of your installed detector elements
  - Positioning of detector modules or chambers (collections of individual sensor elements)
  - Deviates from nominal position by placement accuracy, gravity, magnetic forces, …
- Complemented by careful measurements of the detector internal geometry during construction phase as well
  - Positioning of individual strips, cells, towers within a module
  - This can be very accurate for some systems

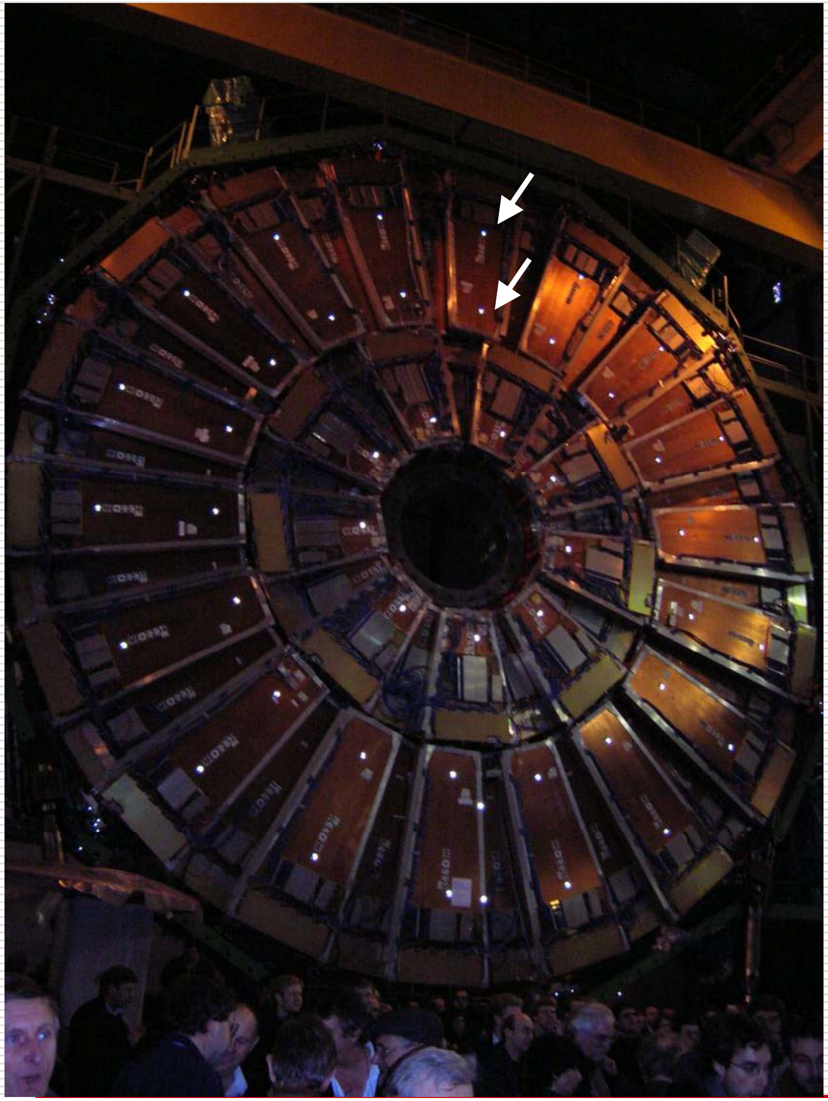
Survey



Newly installed CMS electromagnetic calorimeter (half-barrel) inside solenoid

Surveyor

Photogrammetry
(Or why do I get those bright spots when I take a flash picture?)



- Photogrammetry is the determination of 3D geometry from photographic images (taken at various angles) of pre-positioned reflective targets
- Precision of survey and photogrammetry data can reach 300µm (0.3mm) even for large objects

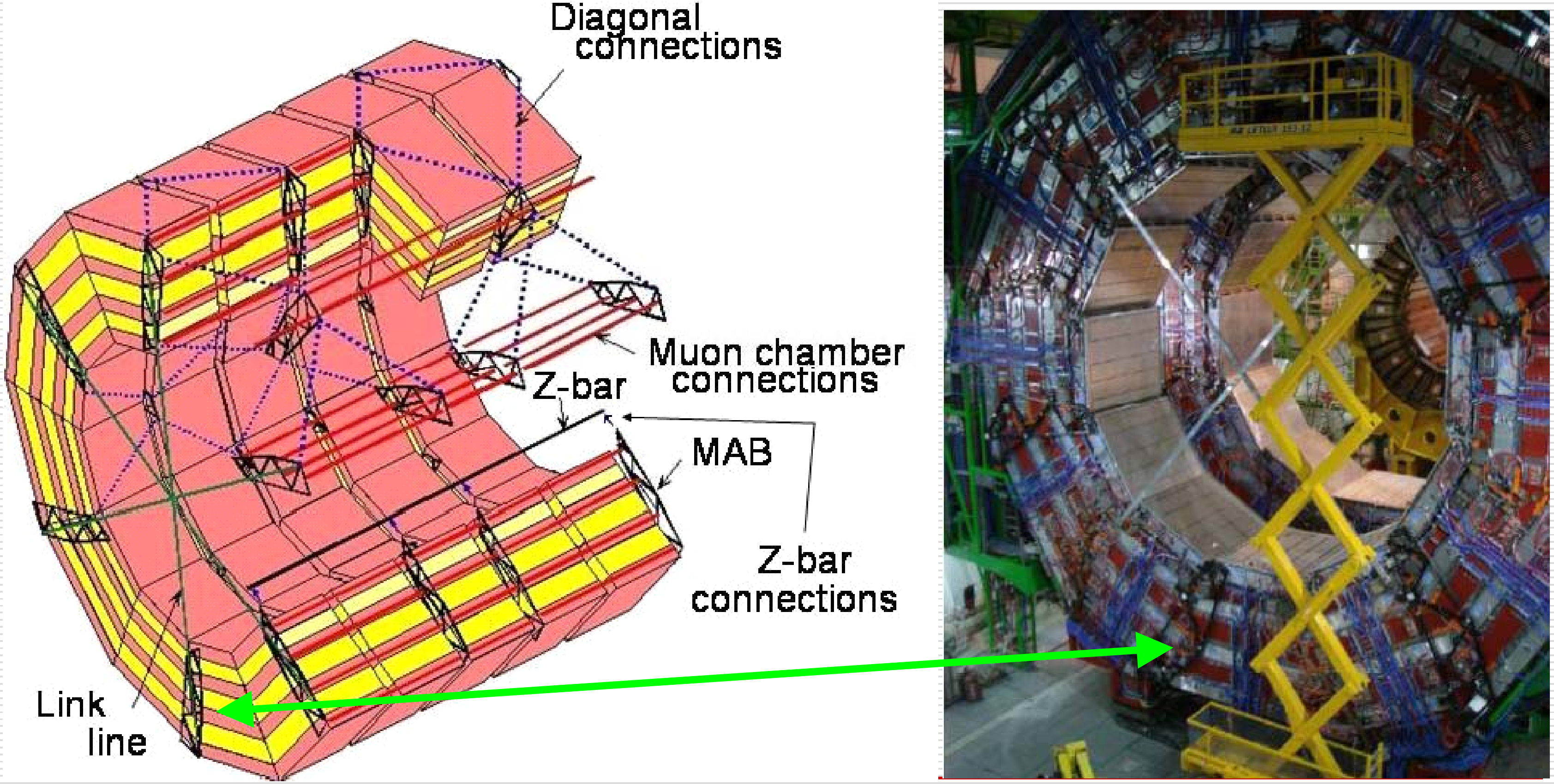
Picture taken of a complete disk of CMS cathode strip chambers (muon detectors) – 2 alignment pins per chamber

Optical alignment systems

- To monitor changes in the detector alignment due to changing conditions (temperature, magnetic field), need dedicated optical systems
- Precision down to ~100μm
- Along with survey/photogrammetry information, optical alignment information is complementary to information from in-situ track-based alignment (next topic)
  - Can remove some invariants of the problem

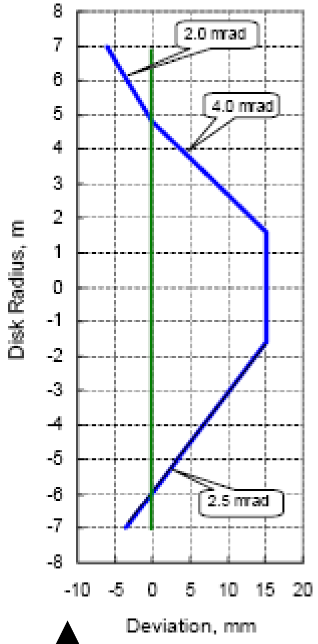
CMS Muon Barrel Alignment system

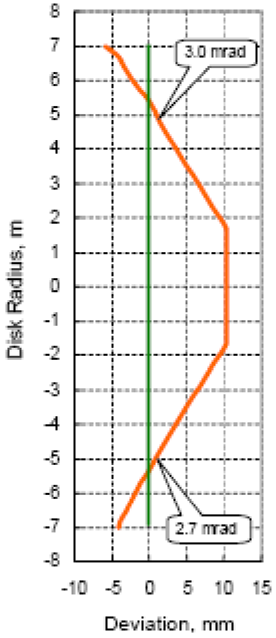
- LED+laser sources with precision distance and angle sensors
  - Position and orientation of 250 chambers → 3000 d.o.f.
  - 4000 measurements

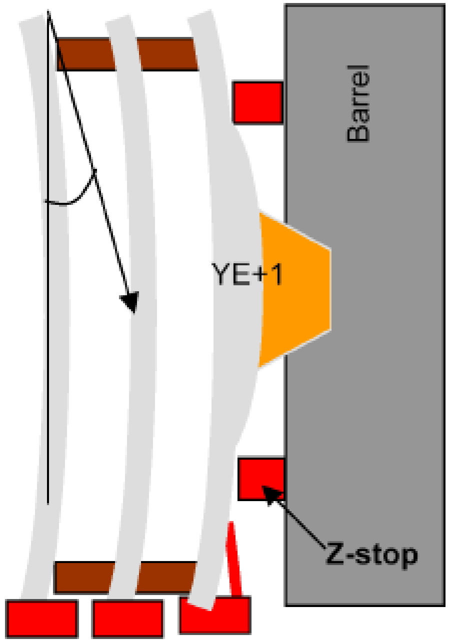


Measured distortion of endcap iron disks

- Test of alignment system during test of CMS 4T solenoid





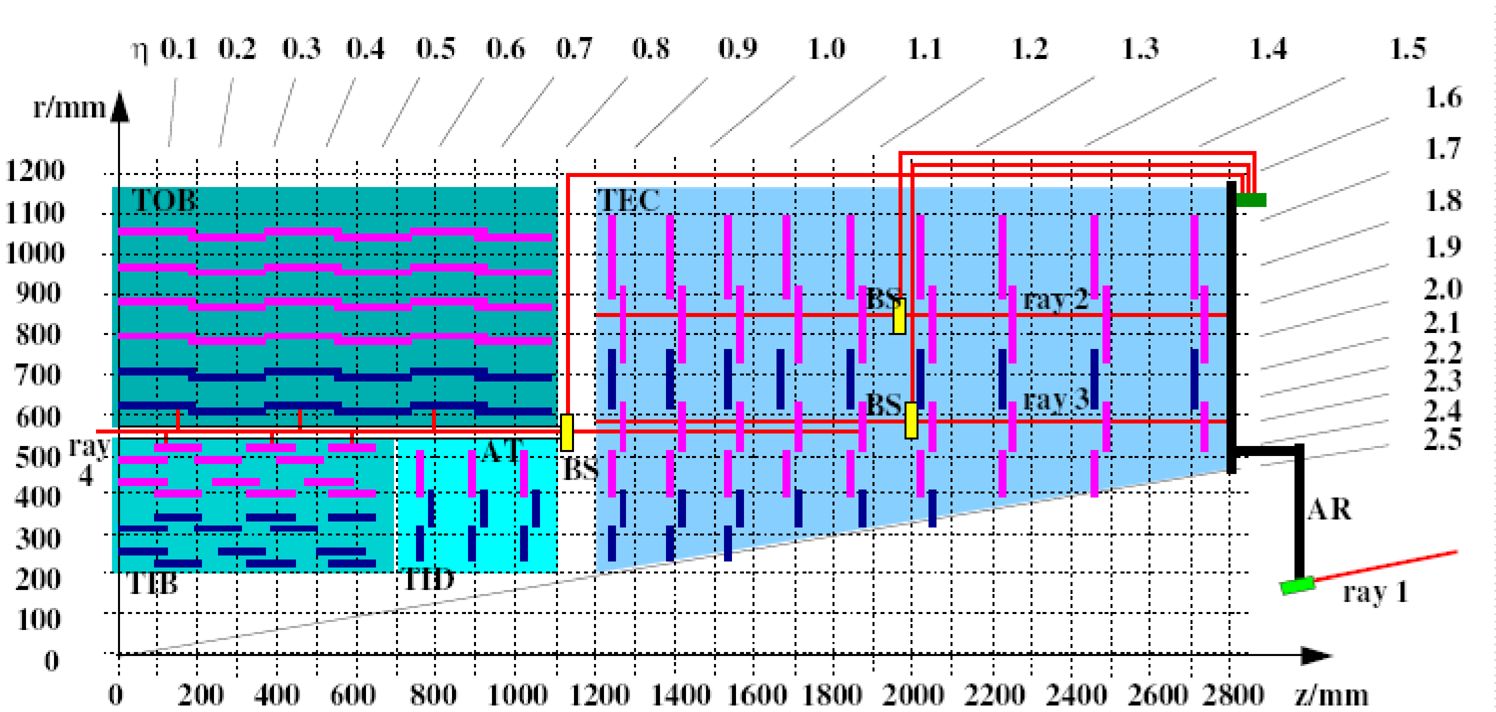


Measurements

FEA calculations

- 15mm inward "bow" of 1000 ton disk by 10g magnetic force!

Laser Alignment System extends into Inner Tracker



Track-based alignment

- Align sensors using in-situ tracks
  - Generally yields the ultimate precision, O(10μm) for tracking
  - Requires data
- General principle:
  - Every track has a series of measurements in detector sensors that we are interested in aligning to better precision
  - Take the residual difference between the measured position and the fitted track trajectory for each hit on the track and for all tracks
  - Minimize the sum of the squared residuals, normalized by the measurement error, over all hits and all tracks by adjusting the alignment parameters
- The problem:
  - The number of modules to align, N, is very large
    - N=15K for CMS strip tracker, 6 d.o.f., → 100K alignment parameters!
  - Computationally intensive (but solvable!)

Some details

$$\chi^2(\Delta\mathbf{p}) = \sum\nolimits_{events}\sum\nolimits_{tracks}\sum\nolimits_{hits}\frac{\Delta_i^2}{\sigma_i^2} \quad + \quad G(\Delta\mathbf{p})$$

p = alignment parameters for all modules

Δp = alignment corrections

$G(\Delta\mathbf{p},\mathbf{q})$ = Lagrange multiplier for external constraints (survey, laser alignme

- Ignoring correlations between measurements and dependence on track parameters (q)
  - Which generally implies that one iterates the minimization procedure several times with the position information improved from the previous calculation

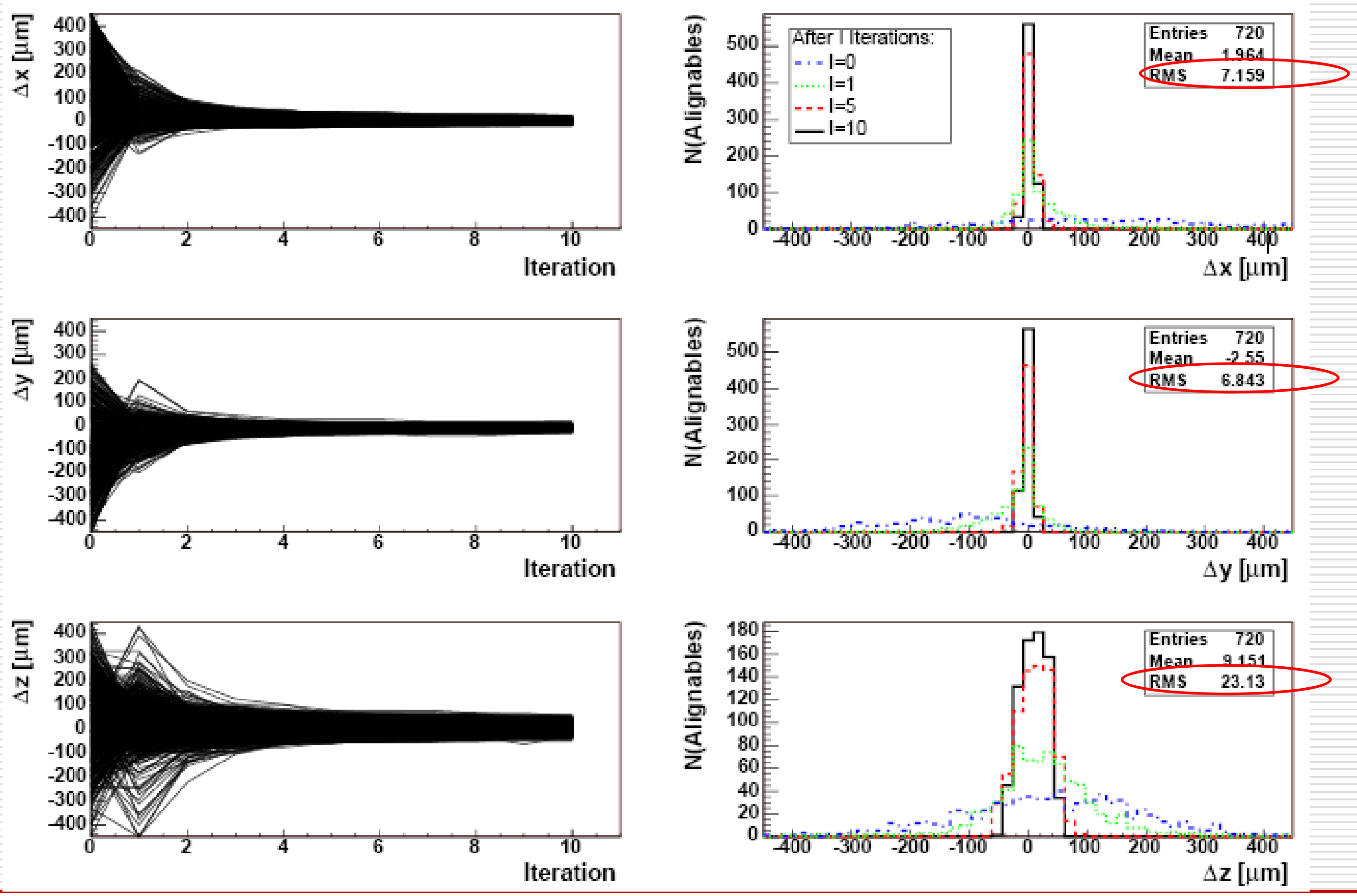
- Minimize function to solve for alignment corrections
  - Generally the solution involves solving a large matrix equation, which is block diagonal 6N x 6N

Approaches to solve problem

- Exactly solving the full matrix equation (i.e. inverting a large matrix) only feasible for O(1000-10000) parameters
  - CPU time goes as N^3, memory as N^2
- MILLEPEDE algorithm (V.Blobel) does that (since 1996)
  - Has been used successfully for tracking alignment at the H1 experiment (vertex detector and drift chamber), as well as at CDF, HERA-b, and LHC-b
- To solve higher-dimensional matrices (100K), need to go to iterative procedures
  - e.g. MILLEPEDE-2, started 2005, but also:
  - Hits and Impact Points algorithm (HIP)
    - V. Karimaki, A. Heikkinen, T. Lampen, and T. Linden – works with only 6x6 matrix blocks rather than inverting full 6N x 6N
  - Kalman filter approach
    - R. Fruhwirth, E. Widl, and W. Adam – updates alignment information after each track is processed

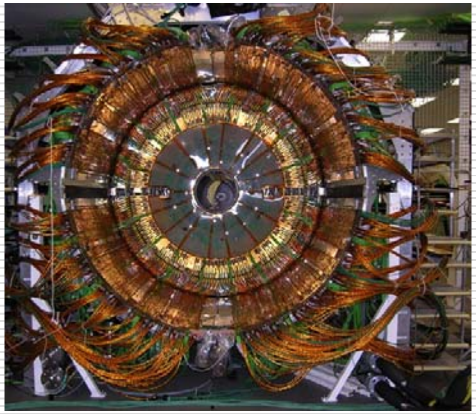
HIP alignment demonstration on CMS Pixels

- 720 pixel barrel modules, assuming strip tracker aligned
  - Monte Carlo study of 200K $Z^0 \rightarrow \mu\mu$

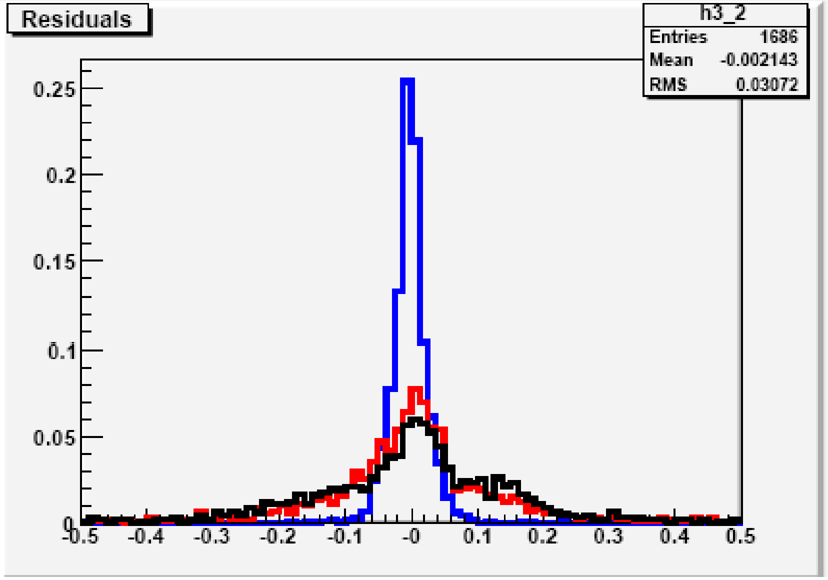


~25μm stand-alone pixels

Tracker Alignment: Cosmic Muons at CMS TIF



- First alignment results on small data sample (50K events) from the CMS Tracker Integration Facility
  - Only HIP algorithm used so far
  - Recall about 20% of strip tracker instrumented
- TIB residual: ~600 μm with no alignment, ~170 μm after 30 iterations
  - 30 hours, 3.6 GHz Xeon dual CPU
- Analysis ongoing with more data, and other algorithms



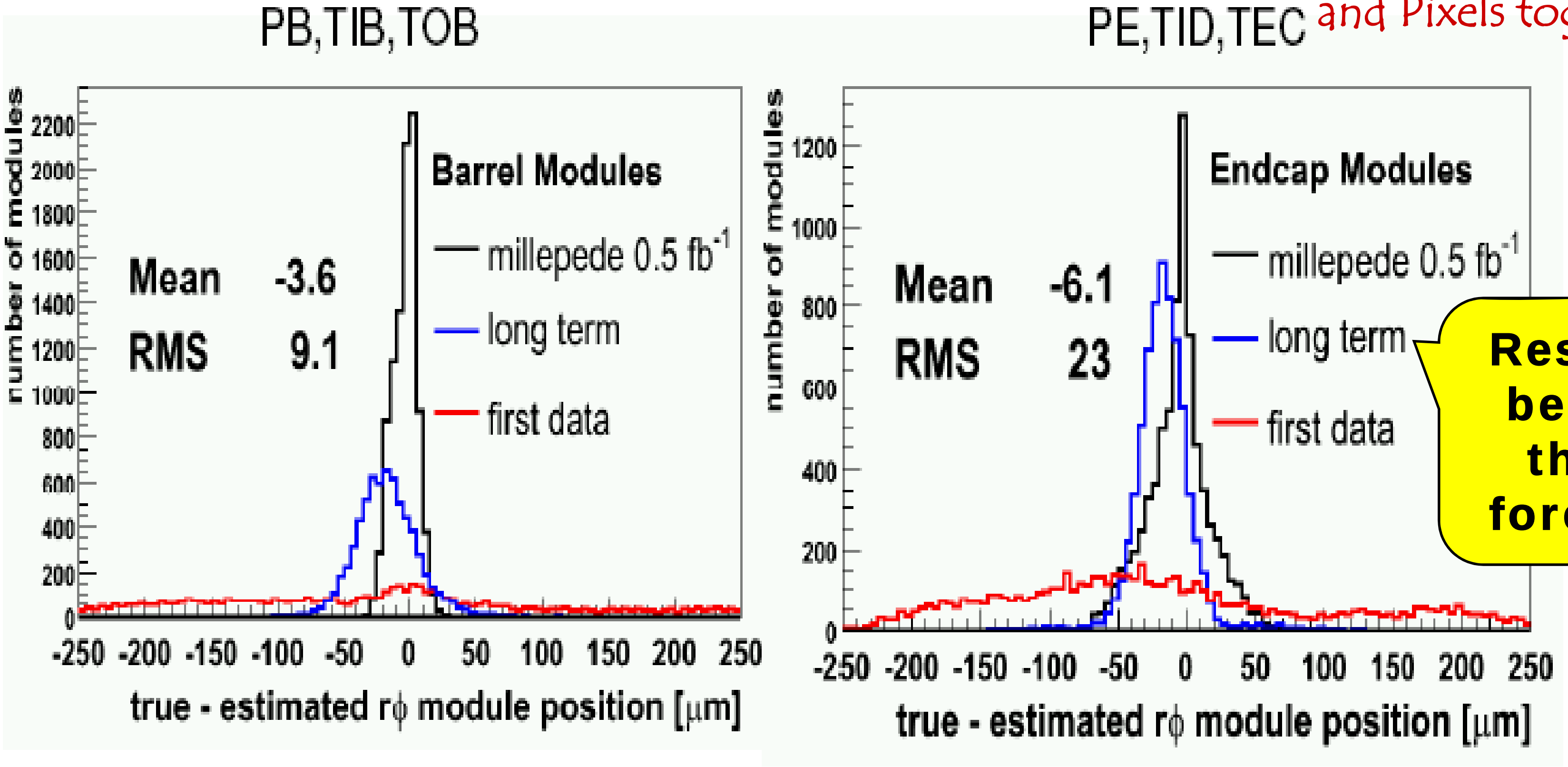
Iteration 0
Iteration 3
Iteration 20

Demonstration of alignment of Complete CMS Tracker!

L ~ 0.5 fb^{-1}

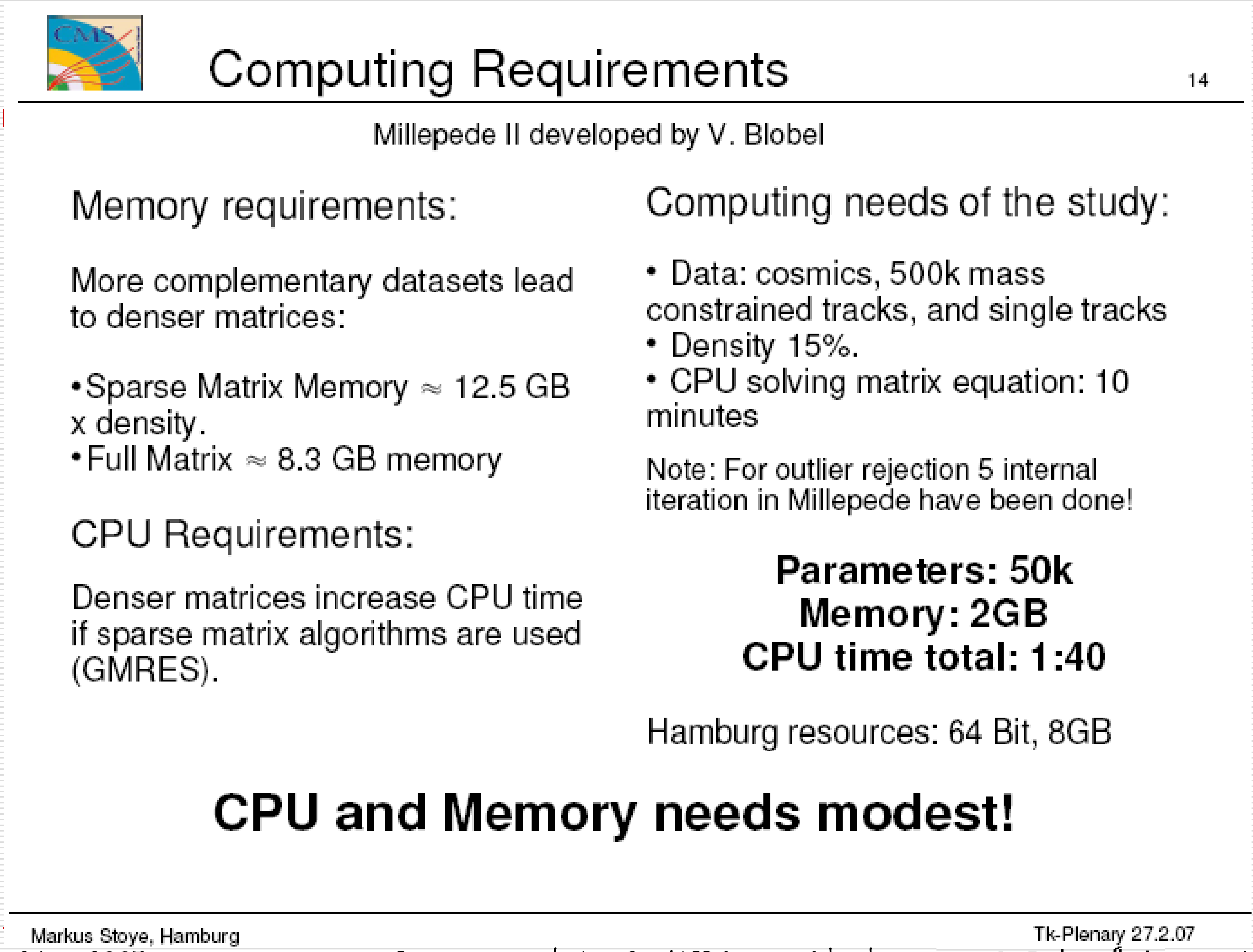
Cosmics and single muons of 2 mio. Z^0 events used.

Monte Carlo study, MILLEPEDE-2. Strips and Pixels together



Results better than foreseen

Pixels RMS to 2μm or better



Computing Requirements

14

Millepede II developed by V. Blobel

Memory requirements:

More complementary datasets lead to denser matrices:

- Sparse Matrix Memory ≈ 12.5 GB x density.
- Full Matrix ≈ 8.3 GB memory

CPU Requirements:

Denser matrices increase CPU time if sparse matrix algorithms are used (GMRES).

Computing needs of the study:

- Data: cosmics, 500k mass constrained tracks, and single tracks
- Density 15%.
- CPU solving matrix equation: 10 minutes

Note: For outlier rejection 5 internal iteration in Millepede have been done!

Parameters: 50k
Memory: 2GB
CPU time total: 1:40

Hamburg resources: 64 Bit, 8GB

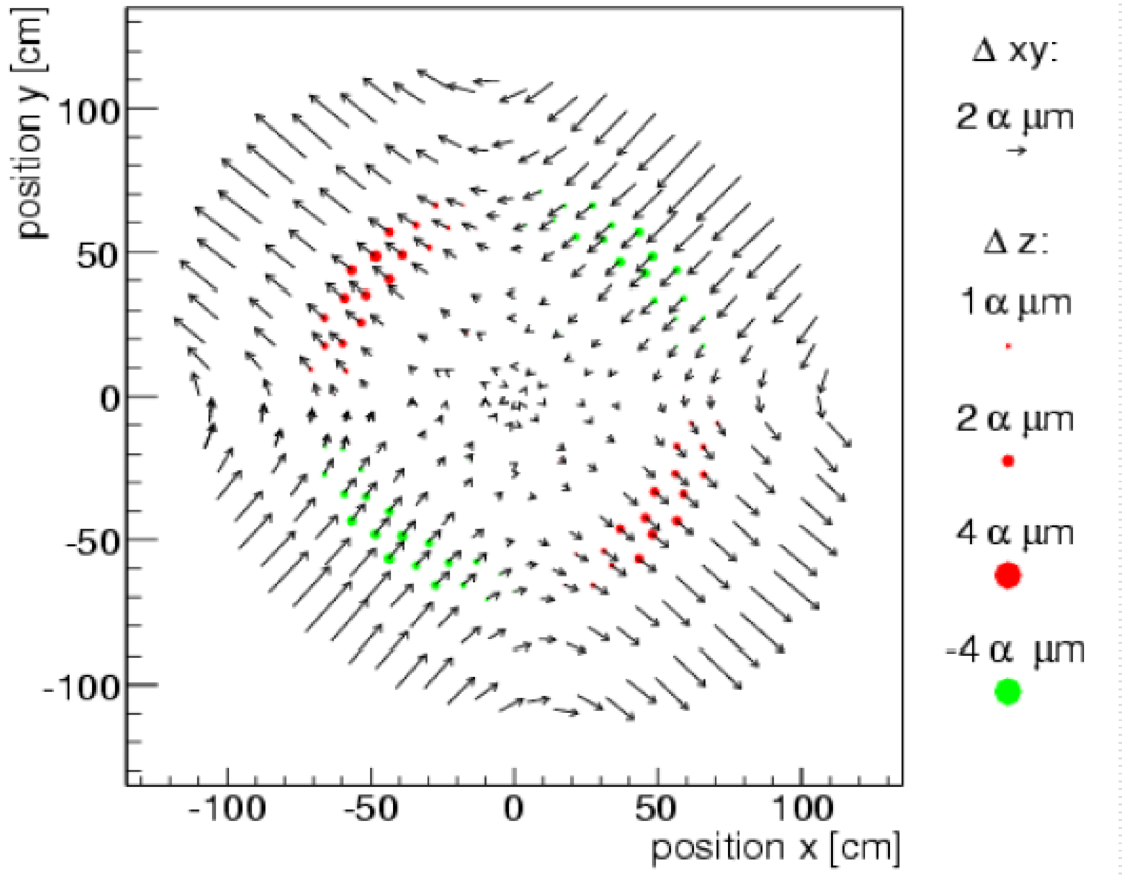
CPU and Memory needs modest!

Markus Stoye, Hamburg

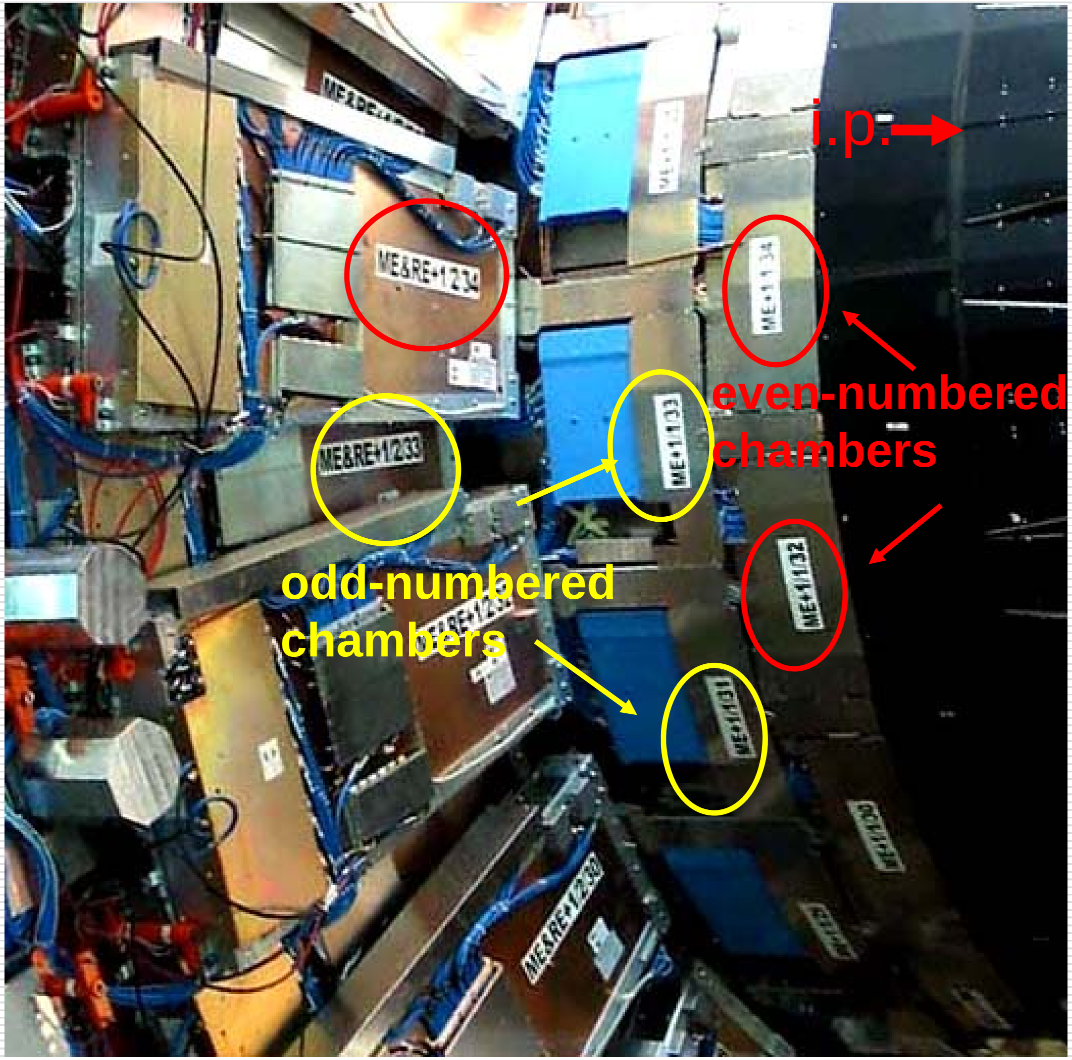
Tk-Plenary 27.2.07

Why cosmic muons, beam halo muons, and other constraints are necessary

- ☐ The track-based alignment methods have some invariants using only one class of tracks, i.e. particles coming from interaction point
- ☐ Some deformations leave the χ^2 sum invariant
- ☐ Need tracks at other angles to solve these ambiguities



Despite all that precision, don't forget to check the actual installed geometry!



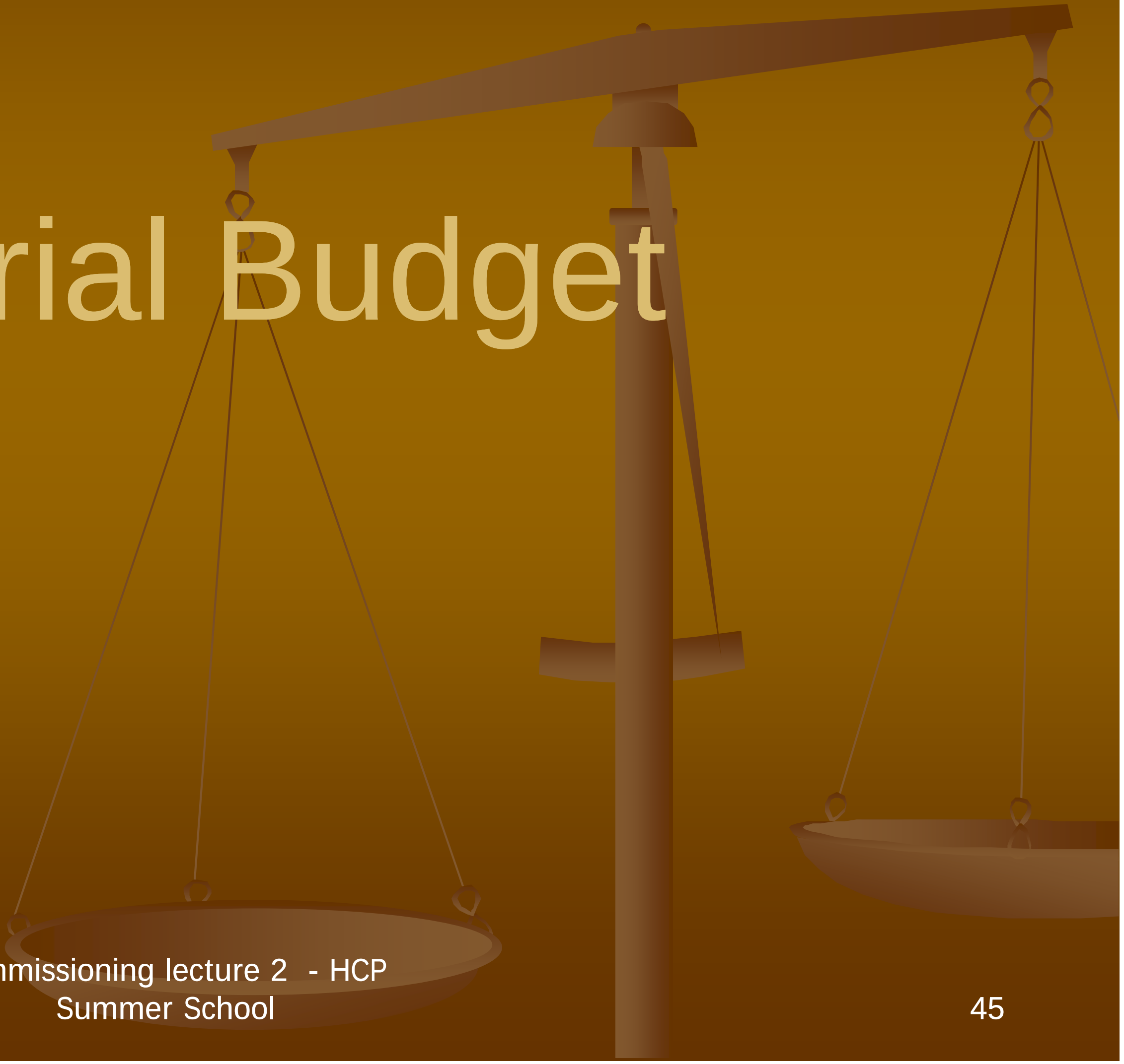
Sometimes large, but subtle, effects such as the symmetry in the offset staggering of detectors can be missed !

- A pure Monte Carlo simulation and reconstruction would have been self consistent
- But analyzing real data with the coded reconstruction geometry can point out problems

Other examples:

- Which side of the cavern the shaft is located
- Where the "chimney" is for the cryogenic pipes

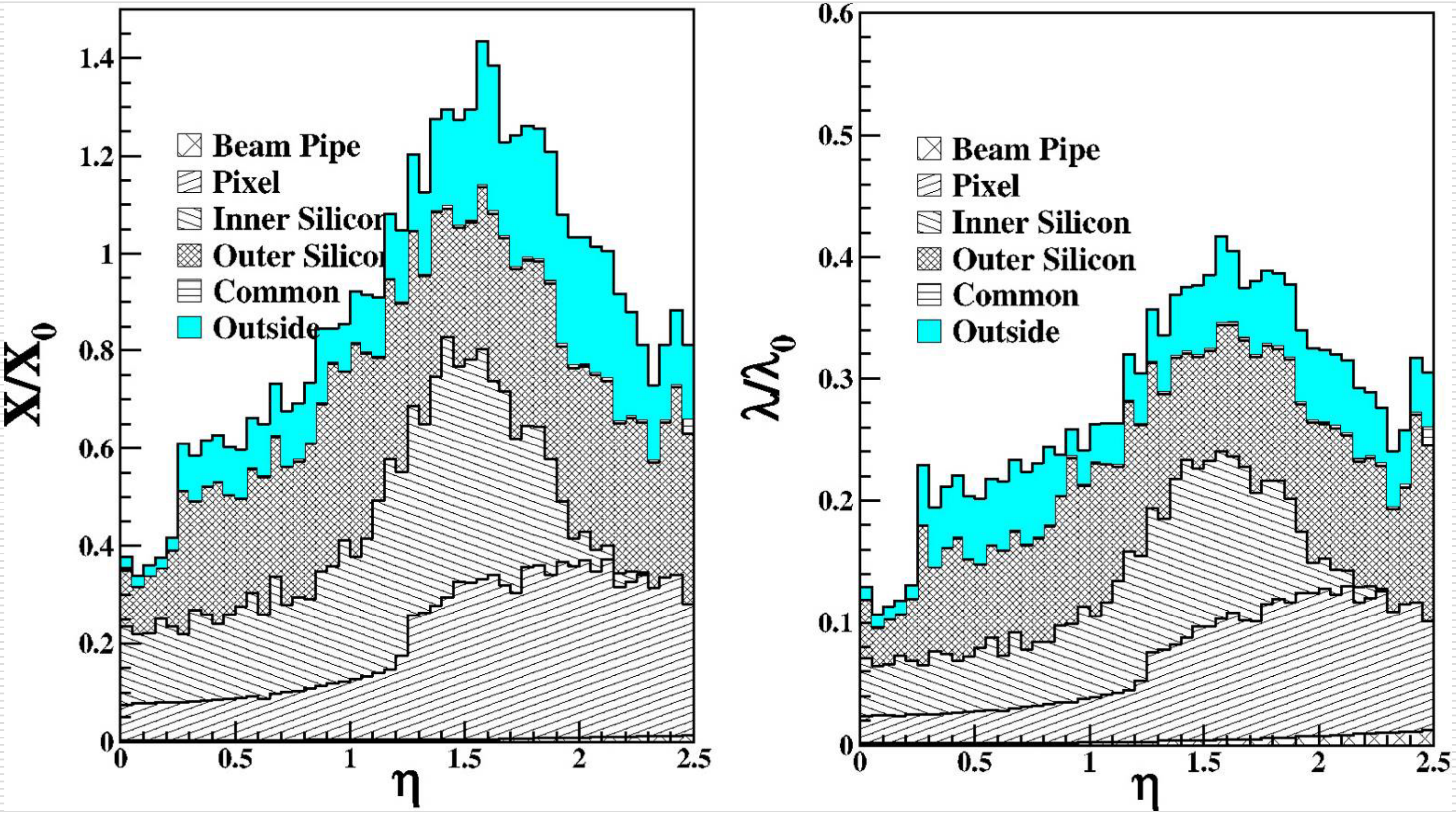
Material Budget



Material Budget

- Along with knowing where everything is, it also helps to know just how much of everything you have!
- Reason: the tracking system must meet contradictory goals of having sensors to measure particle trajectories whilst using as little material as possible to minimize scattering, which would disturb the measurement
    - In addition, precision electron and photon measurements benefit from minimizing the material in front of the calorimeter, which otherwise will cause
        - Electrons to bremsstrahlung (causes poor energy measurement)
        - Photons to convert (causes electron fakes)
- At a minimum, one needs to know how much material is there to simulate its effects
    - Historically, experiments get this wrong a priori and significantly underestimate the amount of material
    - Hard to know where every cable and pipe is that gets installed

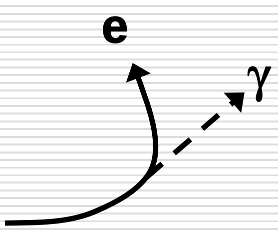
Estimated CMS Tracker Material Budget

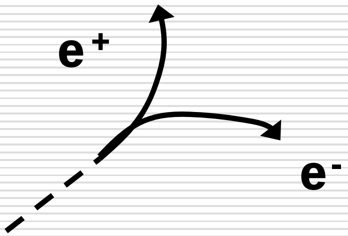


- X_0 = radiation length
  - ☐ Electron radiates all but e^{-1} = 37% of its energy in $1X_0$
  - ☐ Mean free path of photons is 9/7 X_0

Methods to Measure Material in Data

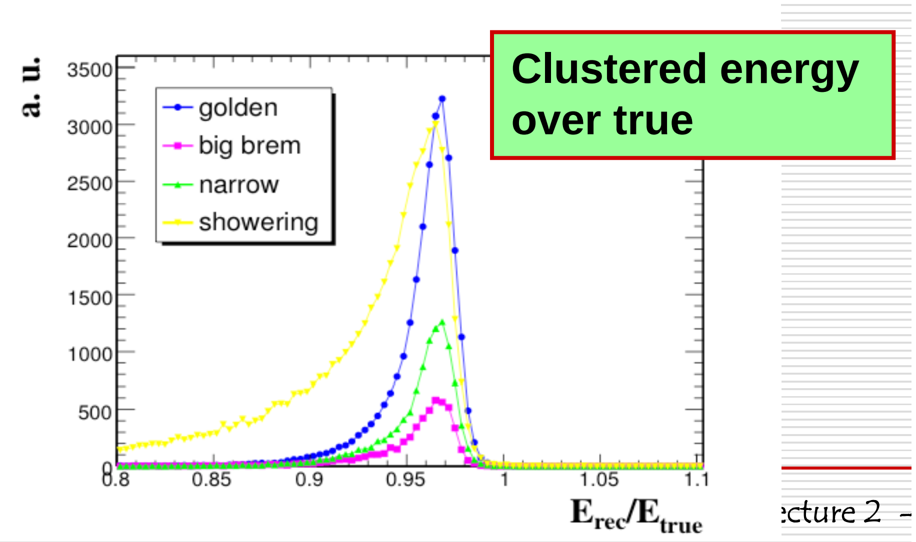
- Weigh the components of your built detector and services (pipes, supports, etc.) and compare with the "weight" in your geometry model used by simulation and reconstruction
  - e.g. CMS has a systematic campaign for the final Strip Tracker to measure this to accuracy < 10%
- Measure processes sensitive to the material budget, e.g.
  - Electrons will radiate photons due to the material in their path
    - Measure amount of bremsstrahlung
  - Photons (from π^0 for example) will convert (pair produce e^+e^-)
    - Measure fraction of converted photons



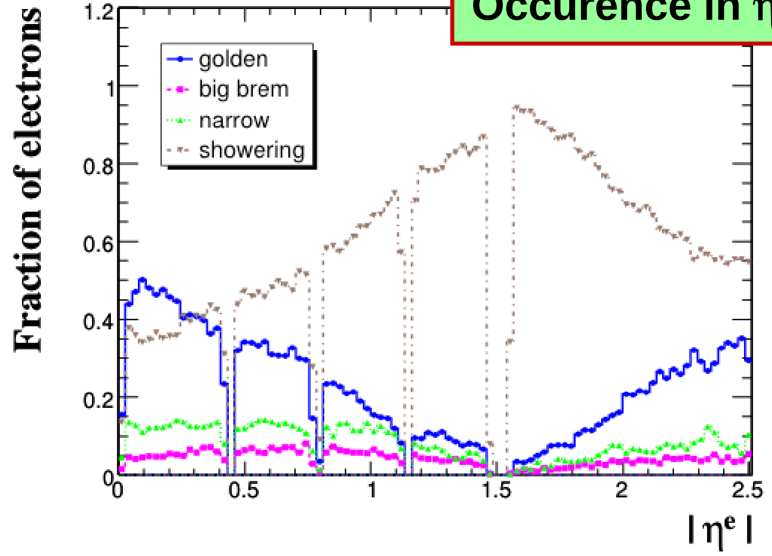


CMS Electron Reconstruction

- ☐ Uses a type of track reconstruction called "Gaussian Sum Filter"
  - ■ Ability to associate silicon tracker hits to trajectory even with bremsstrahlung all the way to the ECAL
    - ☐ More hits attached → better measurement
  - ■ Provides momentum measurement at vertex (before bremsstrahlung) and at outer radius of helix (after)
    - ☐ Ratio of P_{in}/P_{out} indicates bremsstrahlung
  - ■ Classification of electrons based on this



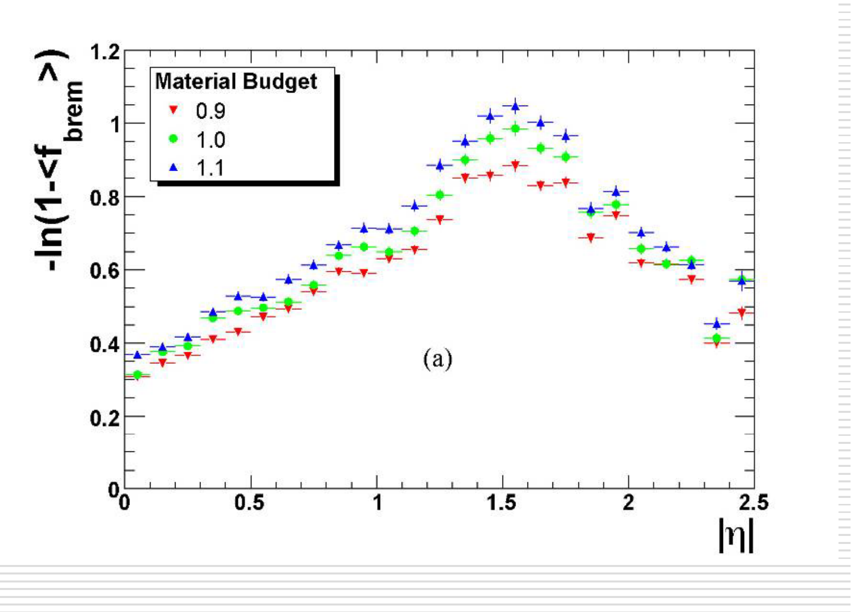
Clustered energy over true

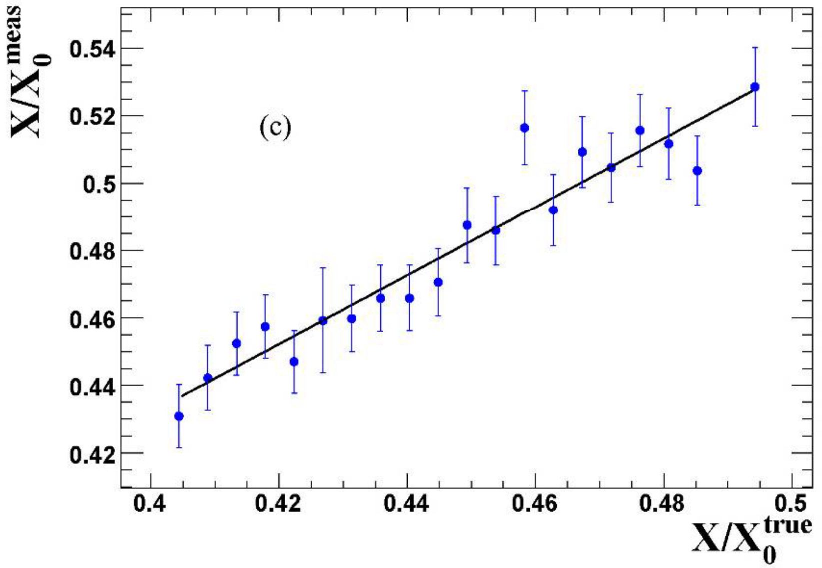


Different classes Occurence in η

Material budget from electrons

- ☐ Since $\exp(-X/X_0)$ is fraction of energy not radiated $(1-f_{brem})$
- ☐ $X/X_0 = -\ln(1 - f_{brem})$
- ☐ So measuring this quantity from electrons on average gives the material budget distribution (statistical accuracy ~2%)





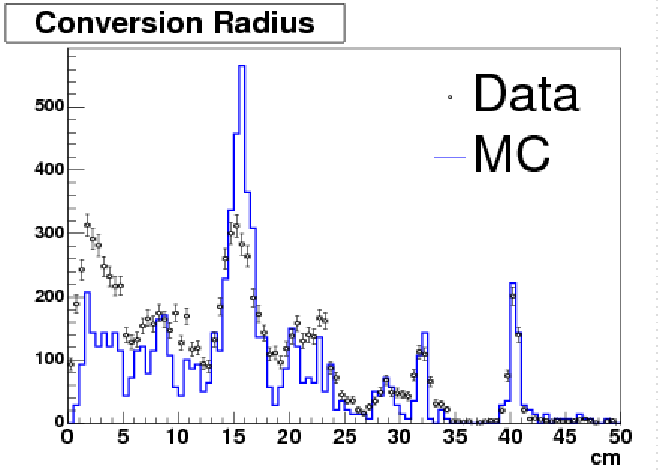
- Tracks changes in budget; tracks true value, with some scaling

Physics Example: Chargino-Neutralino Search

- Search for production of supersymmetric fermions

$$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0} + X \to \ell^{\pm}\ell^{+}\ell^{-} + X$$

- Topologies to search:
  - Trileptons: eee, μμμ, eμμ, eeμ
  - Dileptons with same charge
- Like-sign dimuons fairly clean
- Electron categories sensitive to fake electrons from converted photons
  - Need tight electron id requirements, ways to cross-check contamination from data
    - e.g. control regions to enhance conversion selection, compare in detail radius of conversions, absolute yield for a control region, etc.



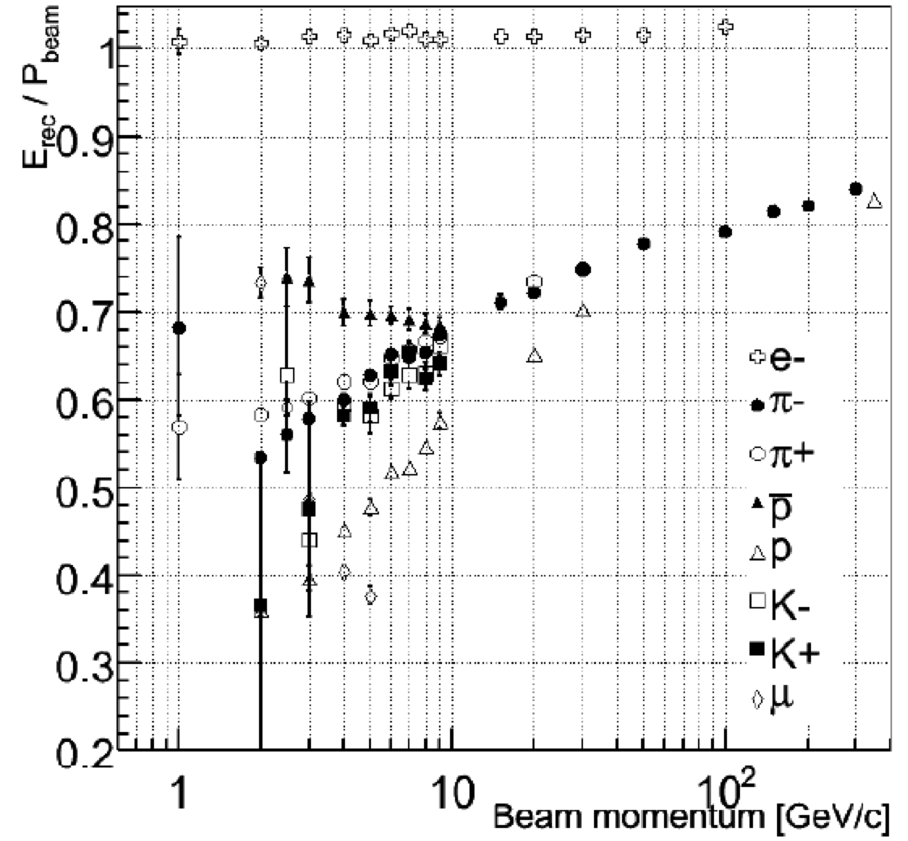
Calibration

Calorimeter Calibration

- Intercalibration:
  - Process of adjusting the scale factors (gains) used in converting the recorded detector signals (i.e. ADC counts) into energy so that the detector gives <u>uniform</u> response for particles of the same incident energy and type
- Absolute calibration
  - Adjusting the calorimeter energy scale so that the reconstructed energy corresponds to the actual energy of the incident particle
- Complicating matters, absolute calibration is not always well defined. The calorimeter response depends on the incident particle type, as well as the material upstream of the calorimeter
  - i.e. a 5 GeV pion does not give the same signal in a calorimeter as a 5 GeV electron, unless it is a perfectly "compensating" calorimeter
  - See Dr. Froidevaux's lectures

CMS Barrel Calorimeter response

- From a 2006 testbeam, combined electromagnetic and hadronic calorimeters
- Absolute calibration requires knowledge of the incident particle type

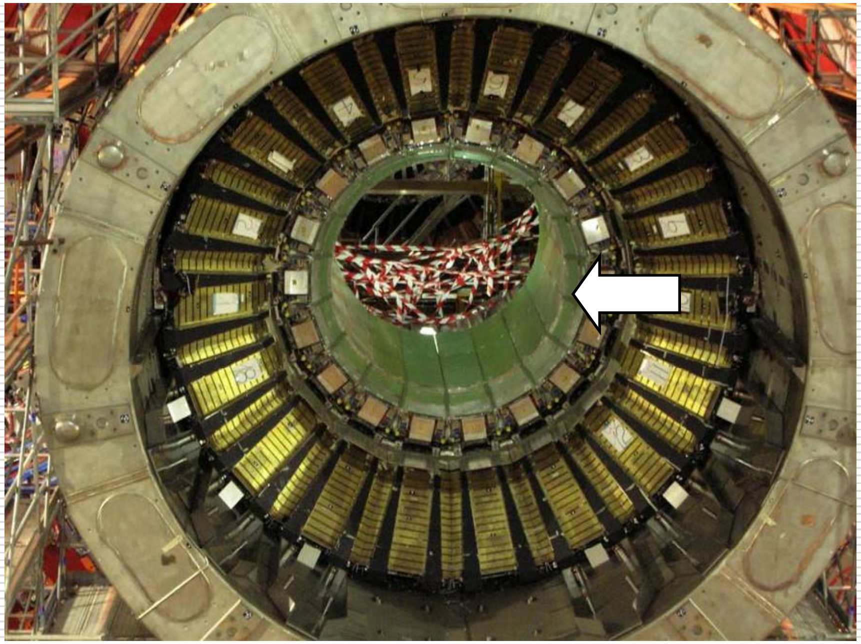


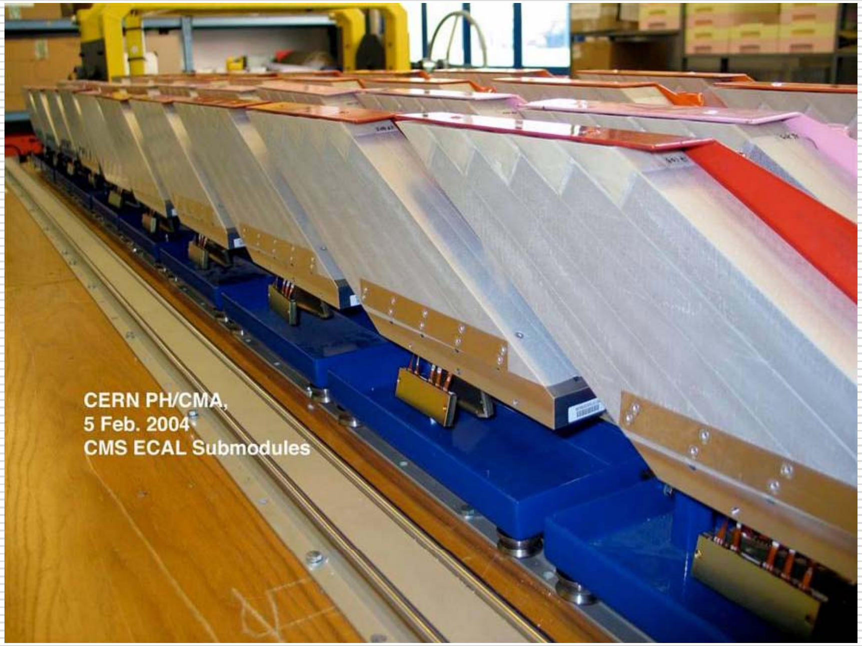
Calorimeter Cell Intercalibration Program

- To homogenize the response across all cells (aka "towers")
- Without LHC collisions:
  - Test beam experiment and studies (dedicated beams of particles at specific energies)
    - Generally not feasible for all cells – too much beam time needed (e.g. there are 61K crystals comprising the CMS barrel electromagnetic calorimeter, though about 15K were calibrated in a testbeam)
    - Forms an excellent reference sample to compare against other methods
  - Radioactive source measurements
  - Cosmic ray energy deposition
- In-situ approaches based on LHC collisions
  - Momentum balance ("phi symmetry") of minimum bias events
  - Single isolated particles
    - Electrons and pions with tracker momentum measurement

Calibration Case Study: CMS ECAL

- Lead Tungstate crystals (61K barrel, 15K endcap)





  - Designed for precision (< 0.5%) electron/photon energy measurements
  - But:
    - Scintillation light-yield varies ~8% from crystal-to-crystal
    - Vacuum phototriode readout for endcap varies 25% channel-to-channel
    - Temperature sensitivity (2% / °C), and radiation sensitivity (transparency)

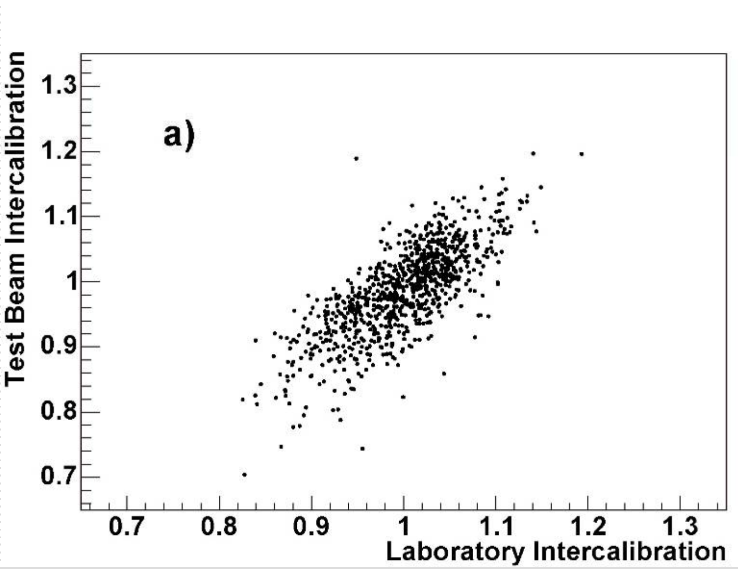
ECAL Calibration Decomposition

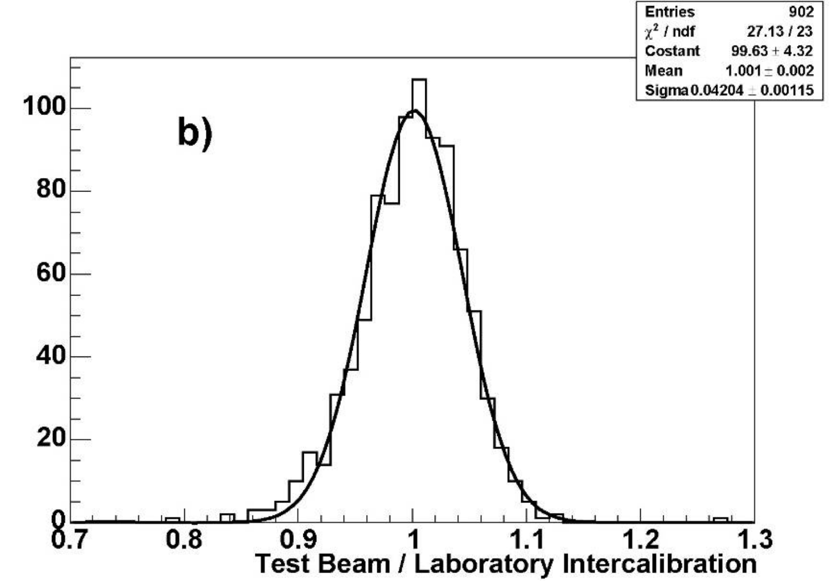
$$E_{e,\gamma} = G \times F \times \sum_i c_i A_i$$

- G = absolute global energy scale
- F = correction function for type of particle (e,γ), position, momentum, and energy clustering algorithm (e.g. 5x5 cells)
- c_i = intercalibration coefficient for channel i
- A_i = amplitude of channel i in ADC counts

Lab Measurements

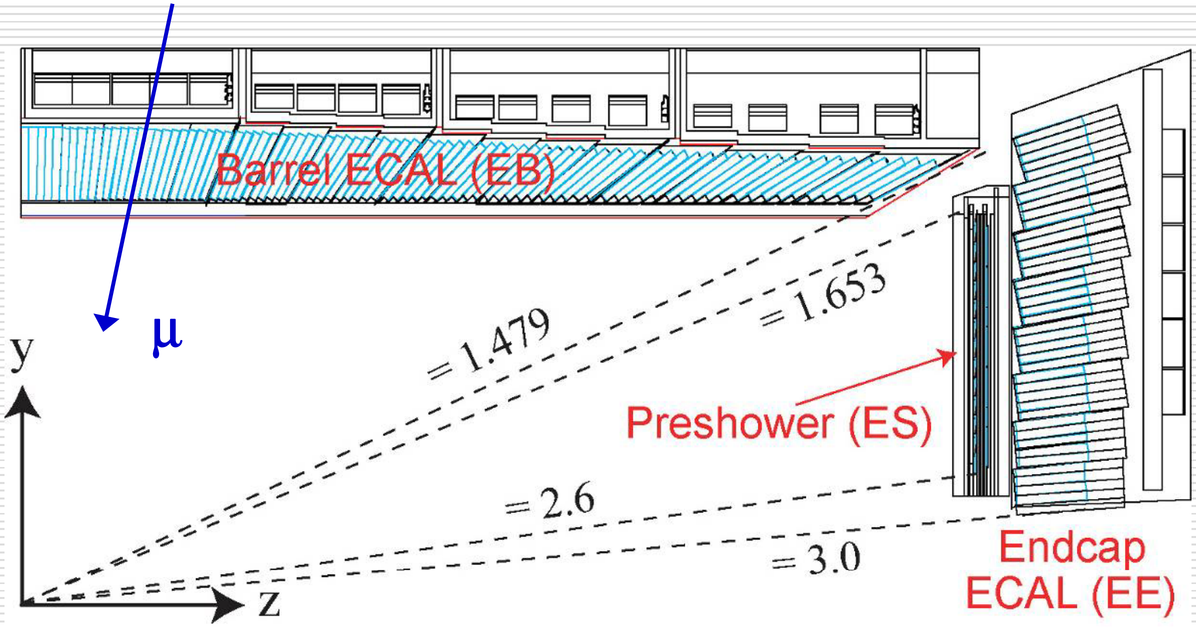
- ☐ Light-yield of crystals can be carefully measured with a ^{60}Co radioactive source combined with knowledge of the photodetector sensitivity and electronic readout calibration
  - ■ Determine calibration constants c_i to normalize yields
- ☐ By comparison to beam test measurements (of a few supermodules), RMS of lab calibration determined to be 4%

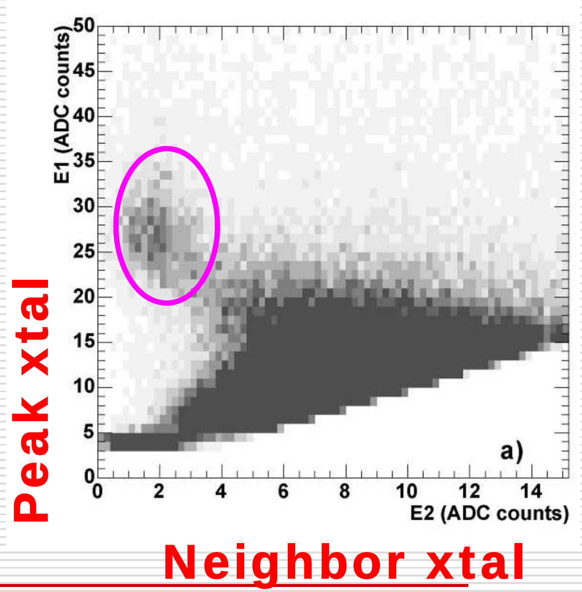




Cosmic Ray Muon Measurements

- Collect data from muons traversing crystals
    - Select those muons contained within a single crystal
    - Normalize responses of all crystals
    - Comparison to test beam data shows 3% RMS variation
        - Already completed for all CMS barrel crystals





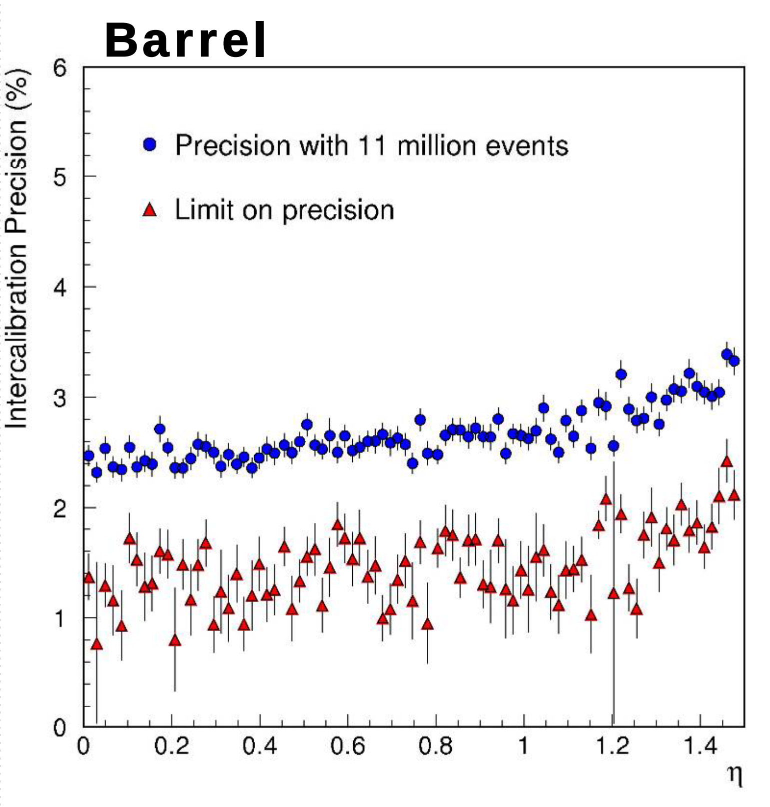
In-Situ Calibration: Phi Symmetry

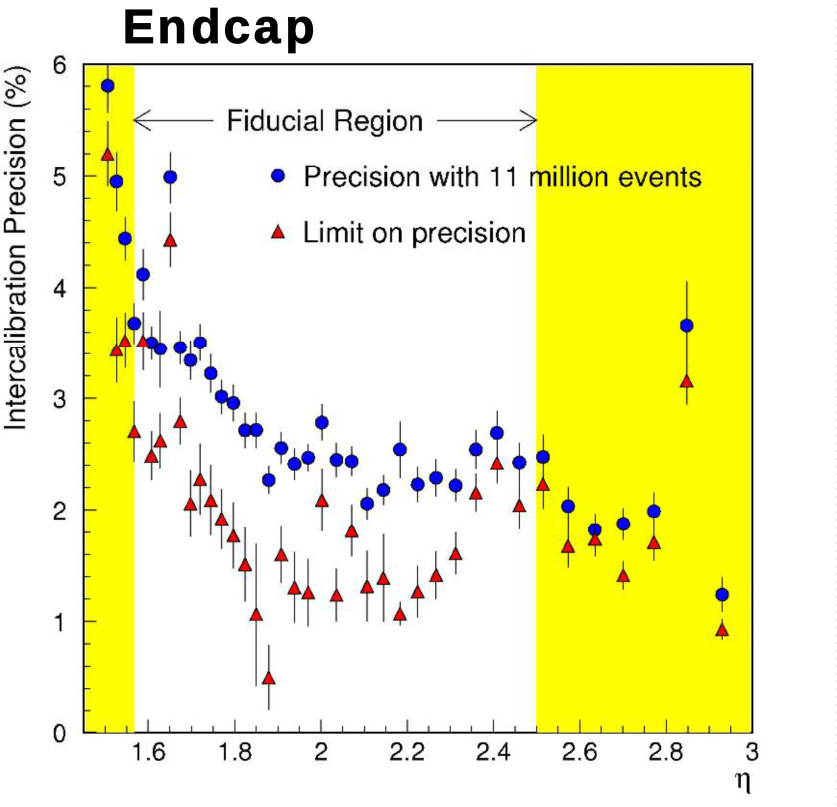
- Collider physics, and the collider experiment, should be symmetric in azimuth (ϕ) on average!
- Collect collision data with minimum trigger bias ("minbias"), or jet triggers, and plot the average energy deposit in calorimeter cells
- Can do this for each ring in ϕ at constant pseudorapidity (η) to get the intercalibration constants per cell in that ring
  - Different rings in η having differing amounts of energy deposit, so you still have to intercalibrate the rings (but it is far fewer constants)
- Advantage of this technique is that it uses very high cross section processes, and so can be done with little integrated luminosity

ECAL Phi Symmetry Intercalibration

- Blue: a few hours of data-taking
- Red: a full day of data at low LHC luminosity
  - ☐ Assuming 1 kHz calibration stream from jet triggers (just crystal data)
- Precision is limited by violation of phi symmetry by tracker material

Can achieve 2 % precision in early running





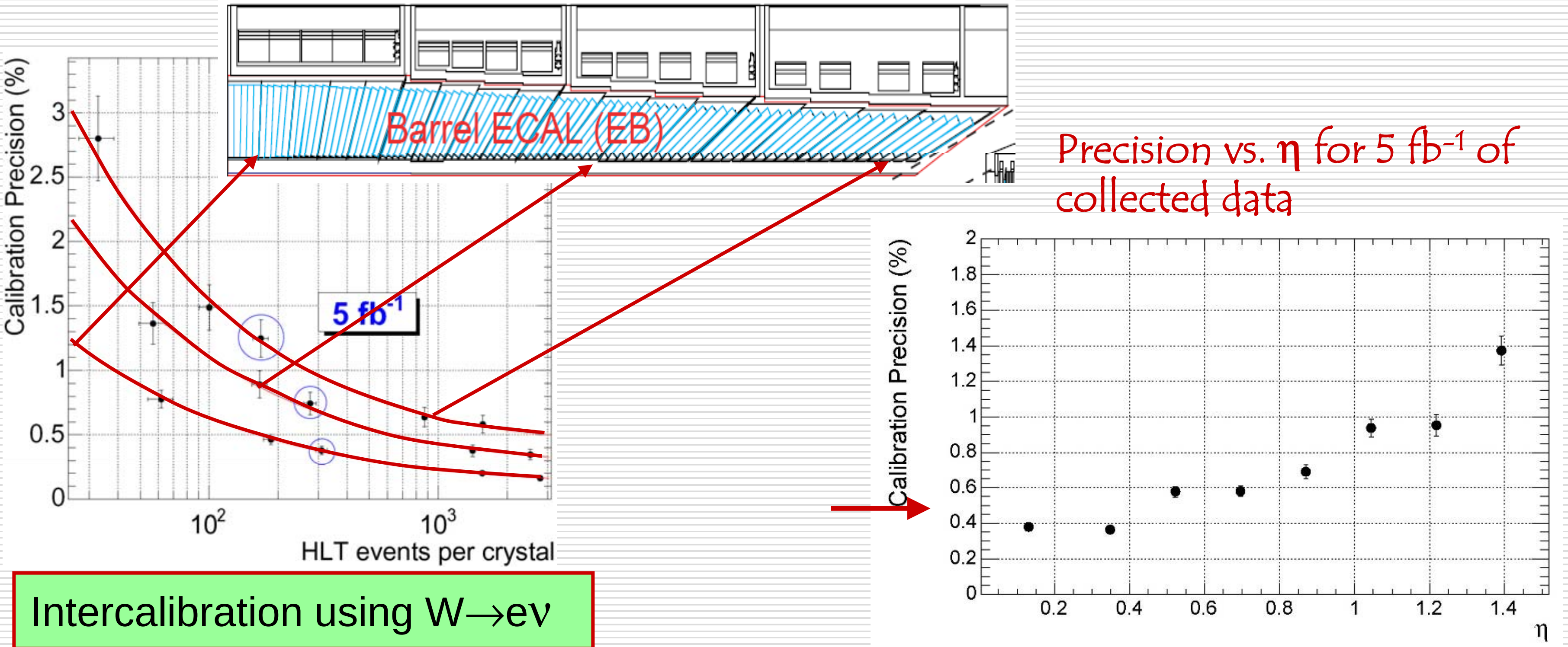
In-Situ Calibration: Single Electrons

- A key identifying signature of an electron in an experiment is the presence of a charged track with a measured momentum about equal to deposited energy: $E/p\sim1$
- Assuming the tracker is aligned and the momentum measurement calibrated, select a sample of isolated electrons and calibrate the calorimeter cells
  - e.g. $W\rightarrow e\nu$, $Z\rightarrow ee$, produced plentifully at LHC ($\sim$11Hz, $L=10^{33}cm^{-2}s^{-1}$)
- Complicating factors:
  - Electrons bremsstrahlung and shower in the tracker material, spreading the shower into multiple clusters and biasing the momentum measurement
    - Need to take care in selecting good tracks, and cut tightly on shower shape
- Can deliver the ultimate precision in intercalibration factors

Precision from single electrons

- ☐ Calibration precision improves as $\text{prec} = \dfrac{A}{\sqrt{\#\text{events/xtal}}} \oplus C$

- ☐ Monte Carlo study of barrel region of CMS ECAL:



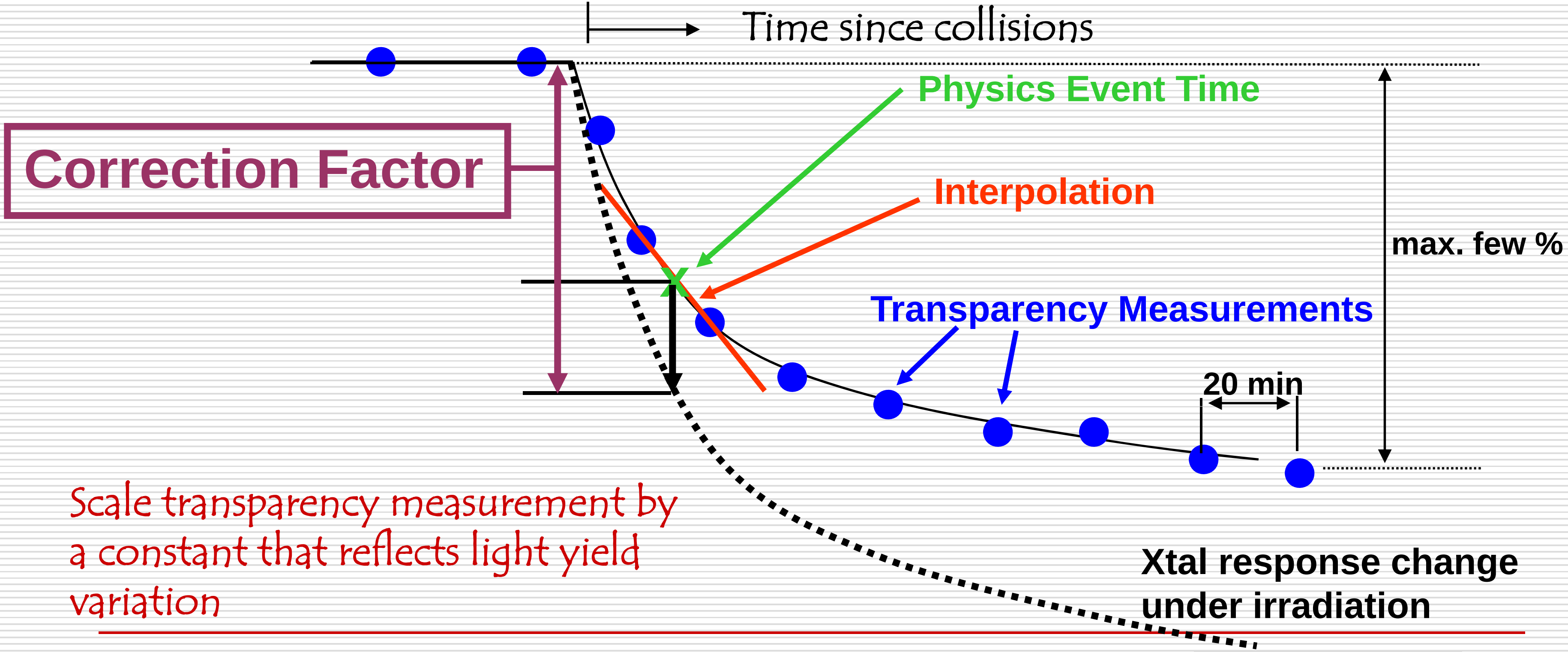
Precision vs. η for 5 fb^{-1} of collected data

Intercalibration using W→eν

Reached goal for central region by second LHC year

Monitoring Calibration

- Recall that the CMS ECAL is sensitive to temperature and radn. dose rate
- Need to monitor the transparency changes of the crystals frequently – every 20min
- Measure transparency changes by pulsing a laser distribution system to each crystal during the "abort gap" (no collision period) during each orbit



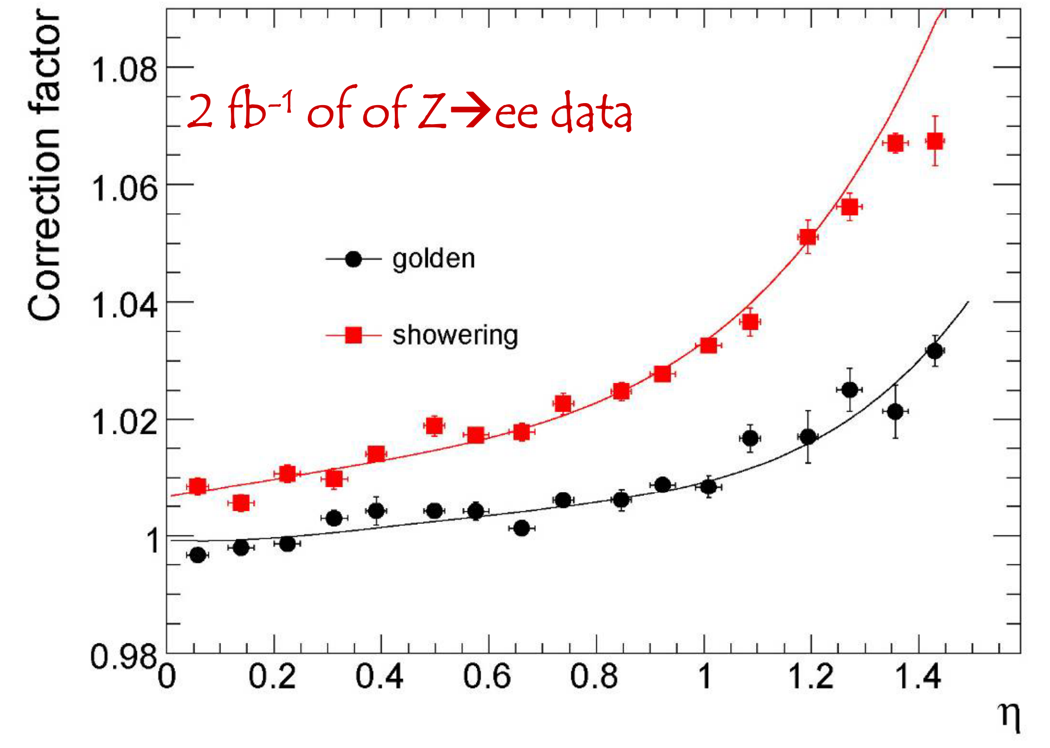
Scale transparency measurement by a constant that reflects light yield variation

Electron/Photon Absolute Calibration

- To obtain an absolute calibration, need a "standard candle" as a gauge
  - e.g. Z→ee, fixed mass of 91.188 GeV
- Keep in mind that the object we are calibrating depends on the reconstruction algorithm (clustering in this case)
  - Some energy may leak outside your cluster
  - Depends on how much bremsstrahlung electron radiated
- Nevertheless, generate a calibration for a specific algorithm
  - Correction function "*F*"

Electron Energy Scale from Z→ee

- ☐ Correction function f(η) from CMS ECAL study
  - ■ Differs for different classes of electrons
  - ■ Similar shape, little spread
- ☐ Scale determined to about 0.1%



2 fb^{-1} of of Z→ee data

Hot, Dead, or Saturated Electronic Channels

- Dead channels – no signal
- Not expected to be large
  - e.g. only 20 out 30K CMS barrel crystal channels are dead (< 0.1%)
- But should account for energy lost in these regions

Other Calibrations

- Much of previous discussion applies to calorimeter calibration in general
  - Hadron calorimeters
  - Different calorimeter technologies
- There are also many other things to calibrate too
  - Drift velocities in muon chambers
  - Strip response in cathode strip chambers
  - Signal response in silicon tracking detectors
  - The ADC→pC conversion factors for electronic amplifiers/digitizers

Operating the Experiment

Congratulations, you've commissioned the experiment!
Now what?

Credits

- ATLAS
- CDF
- CMS
- Angela Acosta
- Christoph Amelung
- Paolo Bartalini
- Victor Blobel
- Adolf Bornheim
- Rick Cavanaugh
- Sergio Cittolin
- Pawel De Barbaro
- Domenico Giordano
- Marcus Stoye
- Slawek Tkaczyk
- Jim Virdee