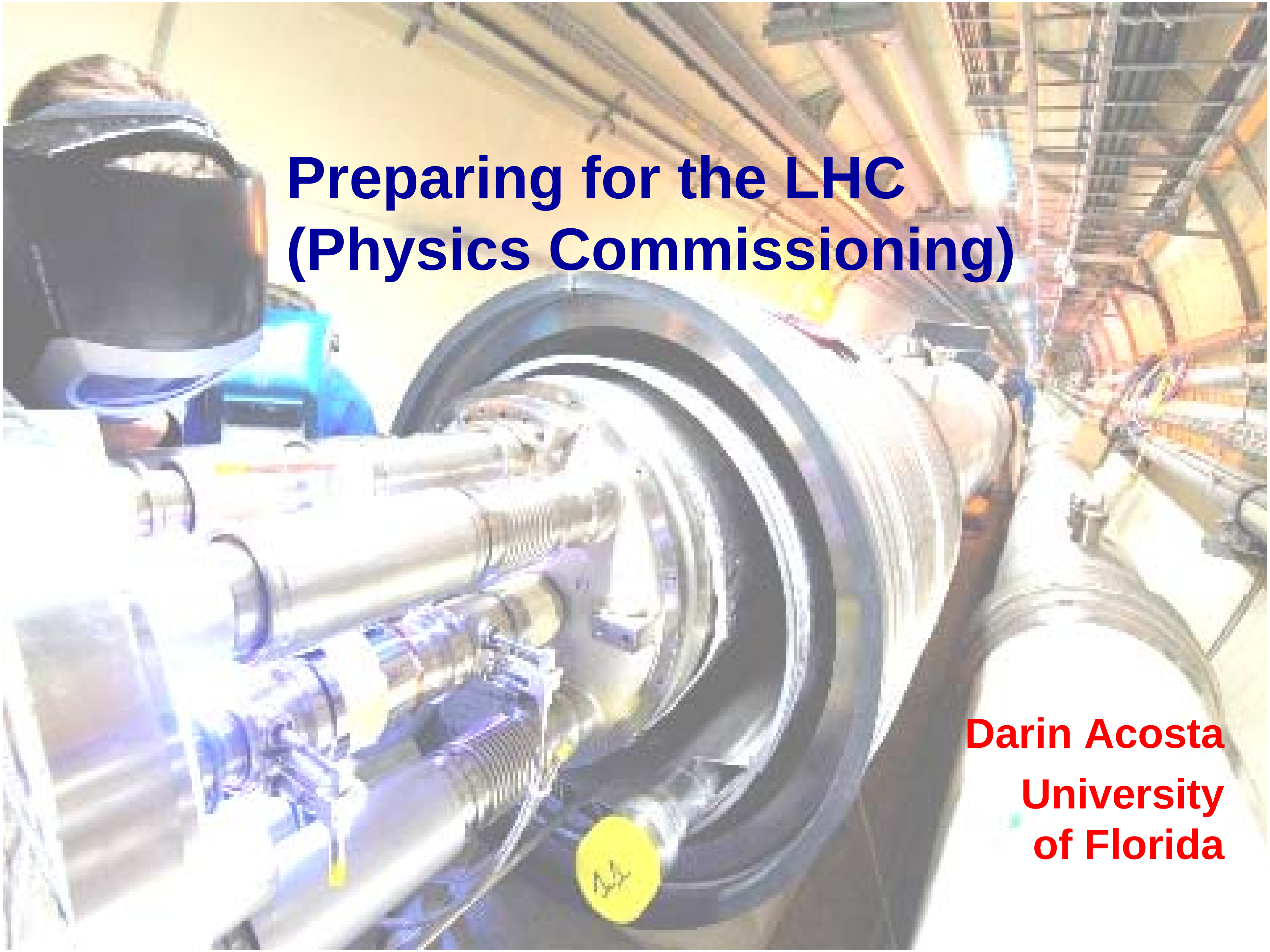


Preparing for the LHC (Physics Commissioning)

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
- Detector performance
  - Temporal alignment (synchronization)
  - Spatial alignment
  - Material budget
  - Calibration
  - Zero suppression
- Operating the Experiment
  - What it takes to run a large experiment
  - Data quality monitoring

Lecture 1

Lecture 2

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

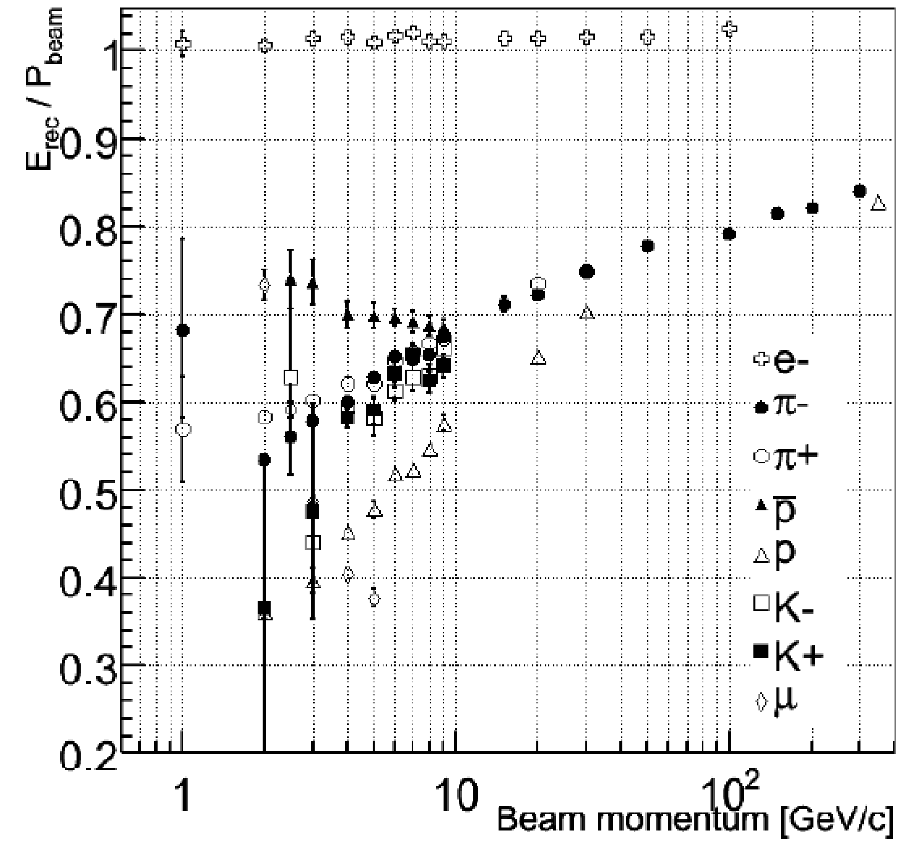
Calibration

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 uniform 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

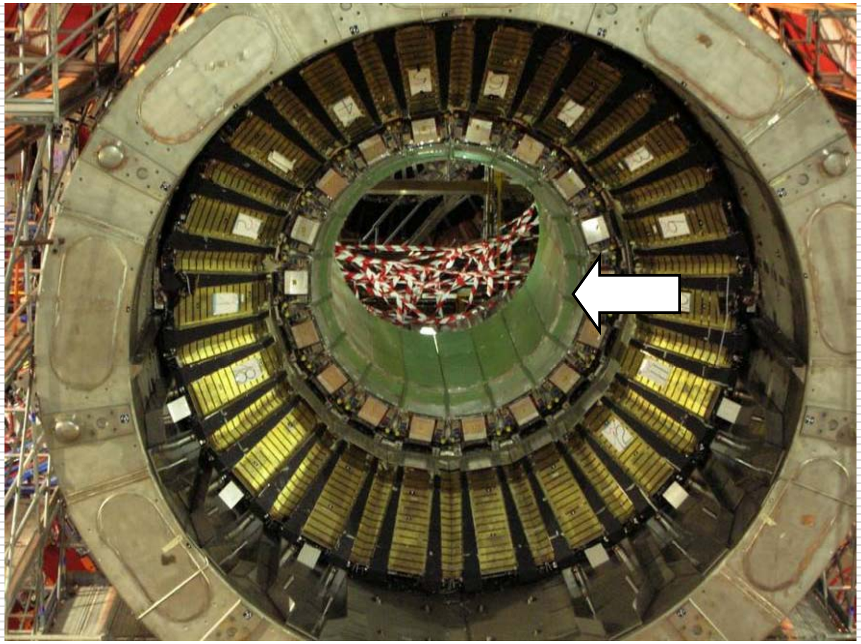


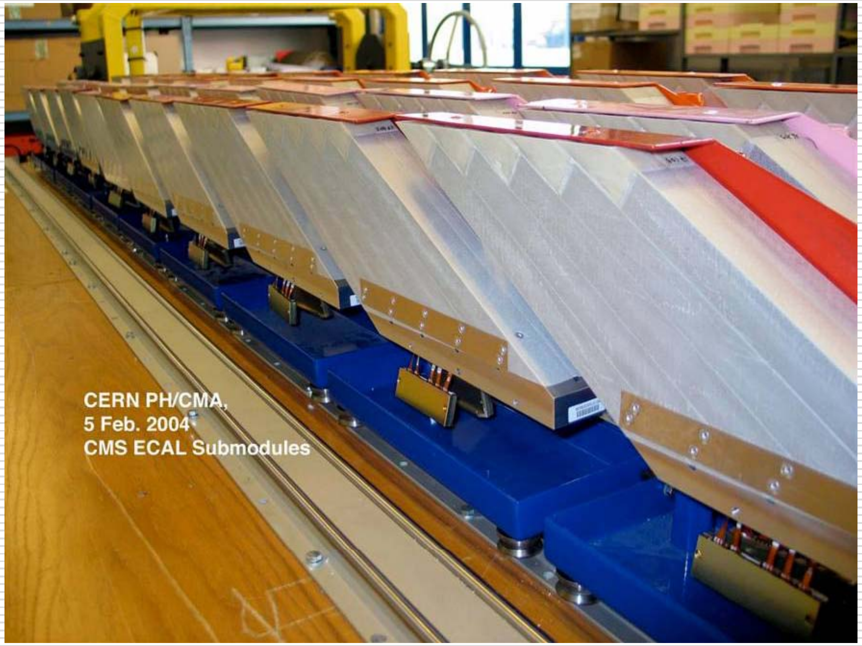
Calorimeter Cell Intercalibration Program

- 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)

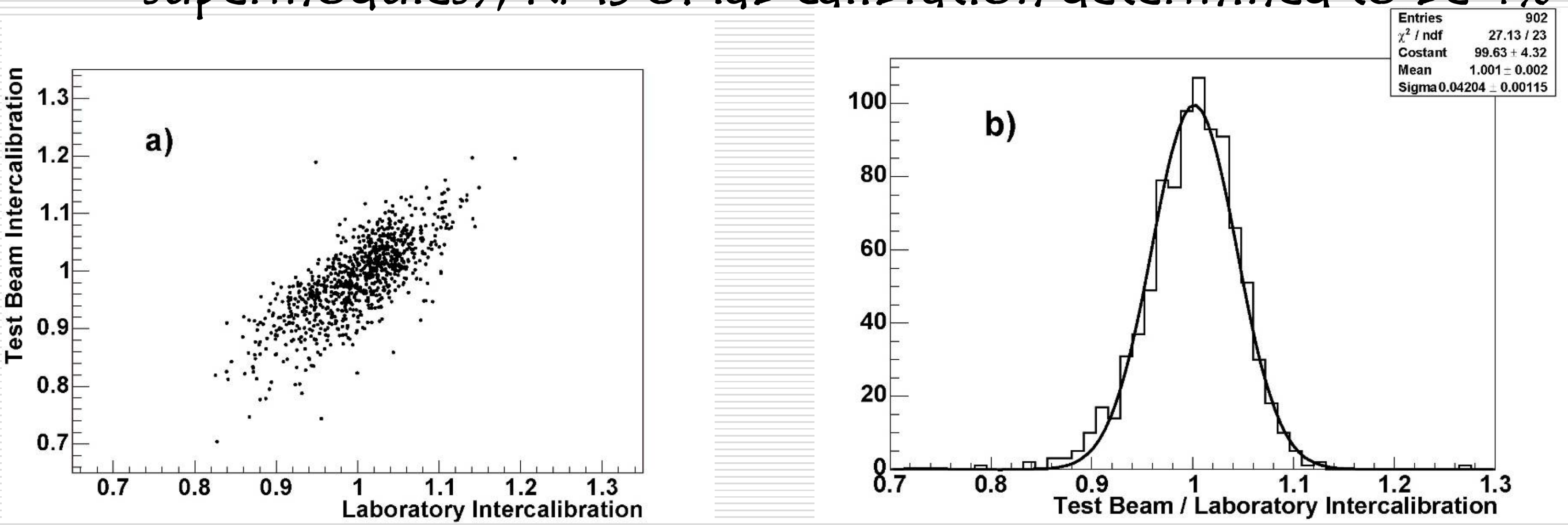
ECAL Calibration Decomposition

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

- G = absolute global energy scale
- F = *correction function* for type of particle (e,γ), position, momentum, and energy clustering algorithm (e.g. 5x5 cells)
  - i.e. this becomes dependent on your definition of a physics object
- c_i = intercalibration coefficient for channel *i*
- A_i = amplitude of channel *i* in ADC counts

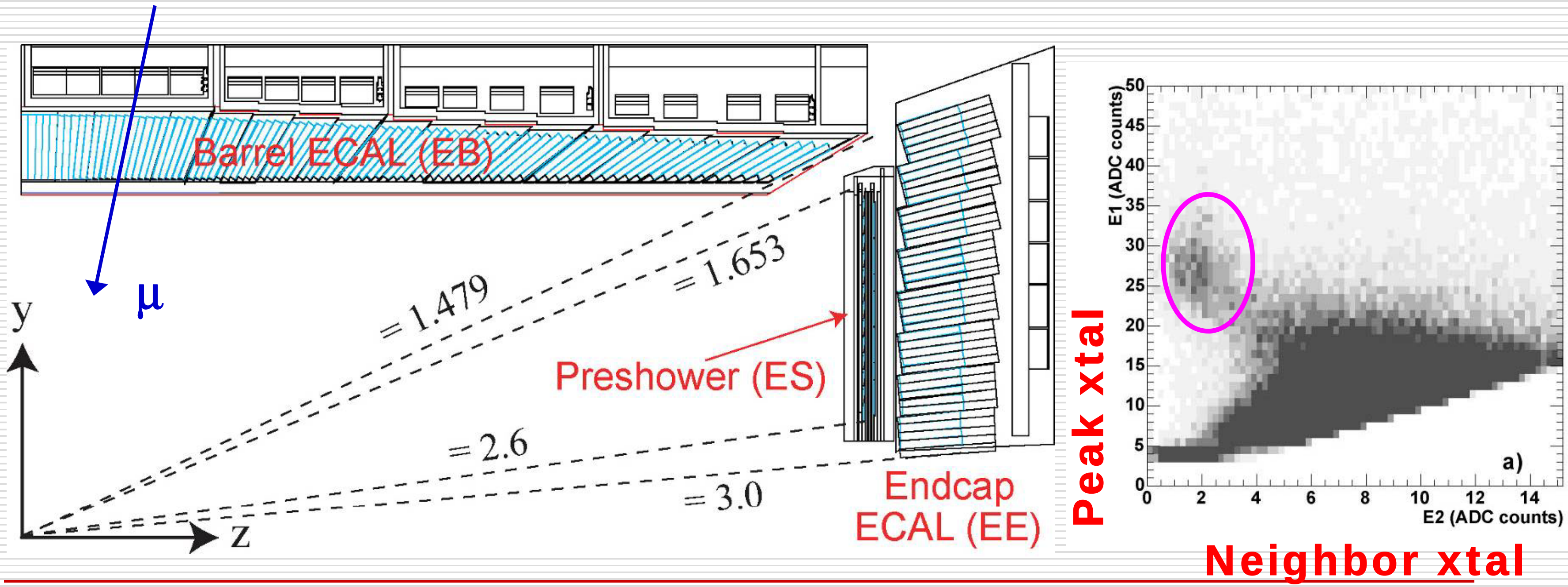
Lab Measurements

- 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

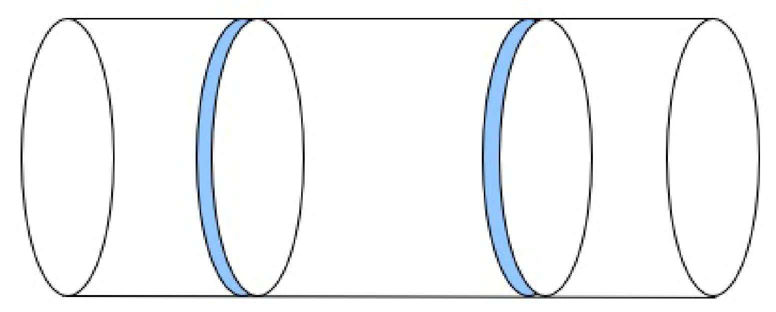


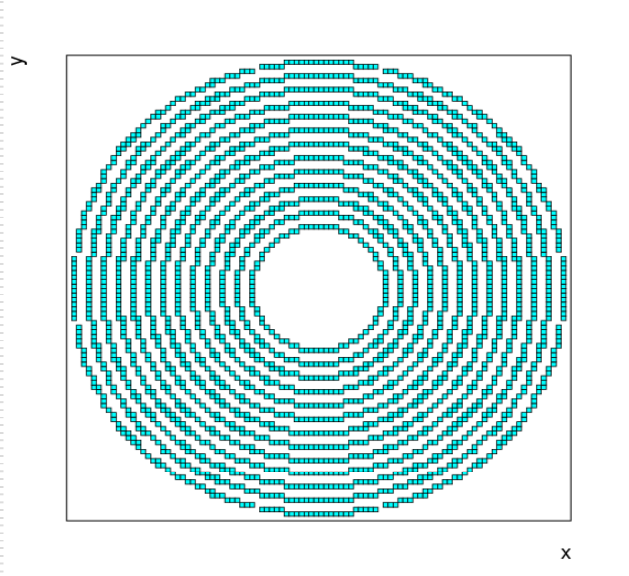
In-Situ Calibration: Phi Symmetry

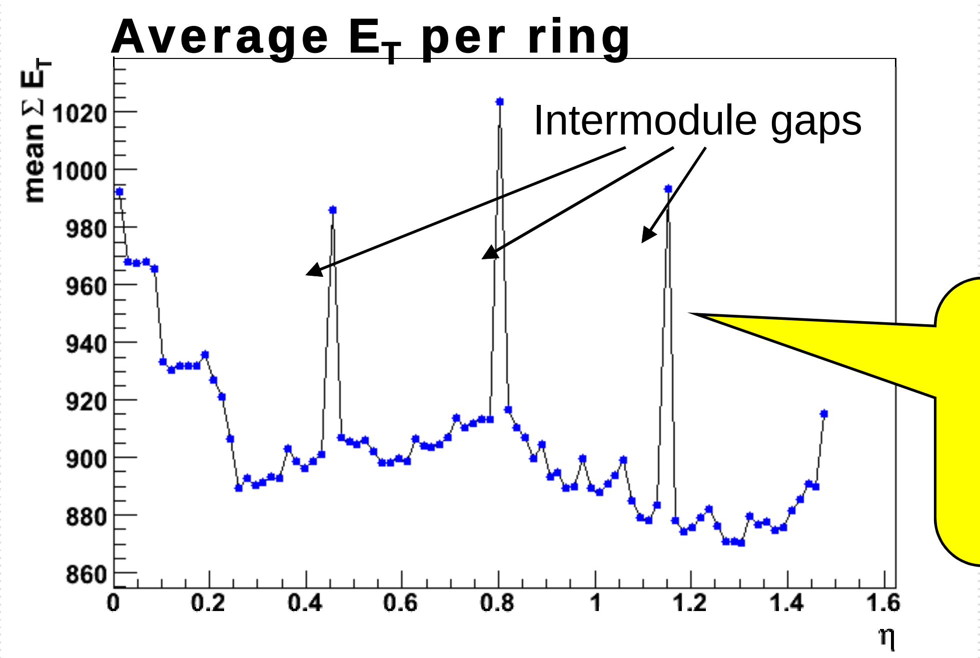
- Collider physics, and the collider experiment, should be symmetric in azimuth (ϕ) on average!
- Collect collision data with minimum trigger bias ("minbias"), or jet triggers, and plot the average energy deposit in calorimeter cells
- Can do this for each ring in ϕ at constant pseudorapidity (η) to 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

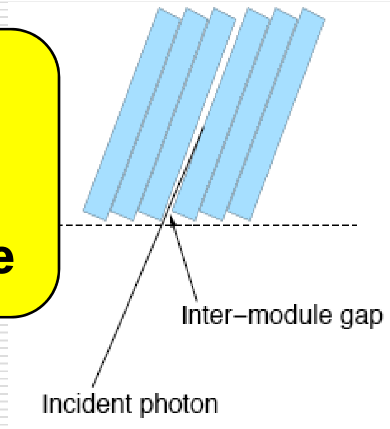
- Barrel Endcap→







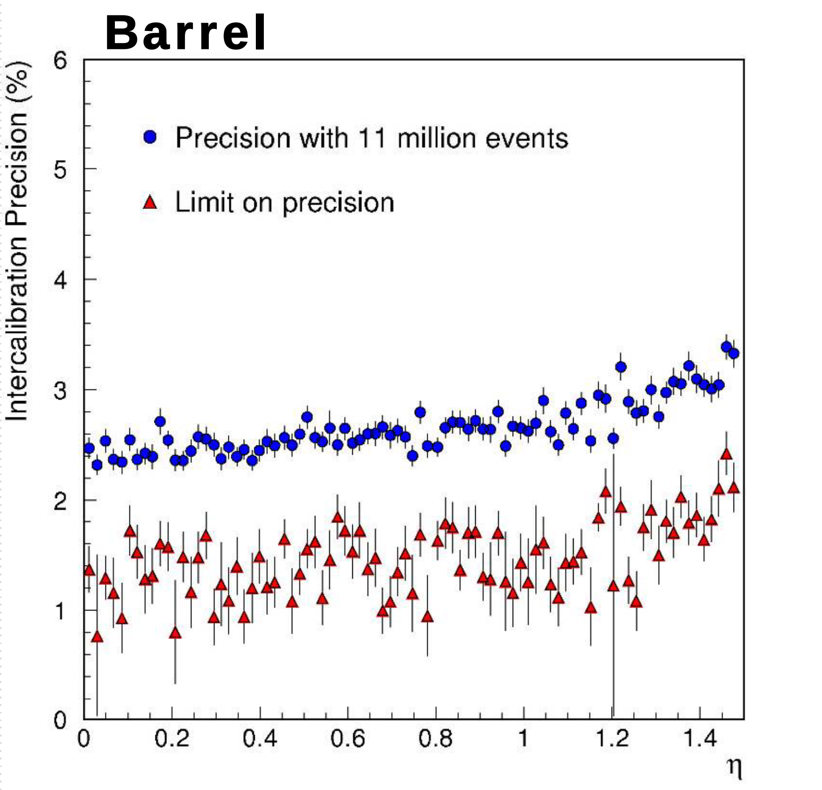
Note that corrections for cracks must be done

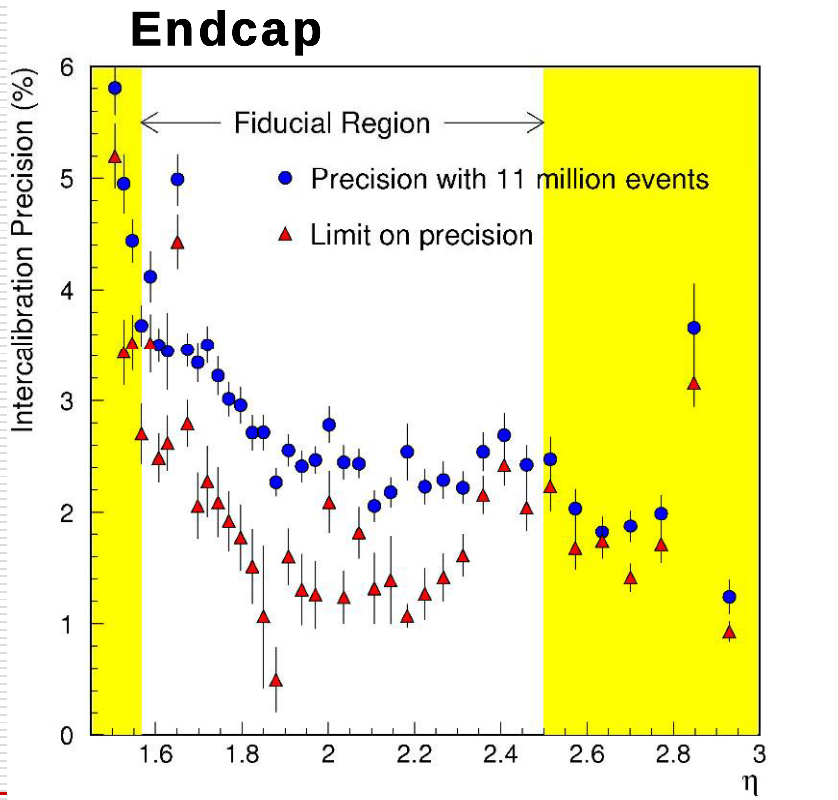


ECAL Phi Symmetry Intercalibration

- 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



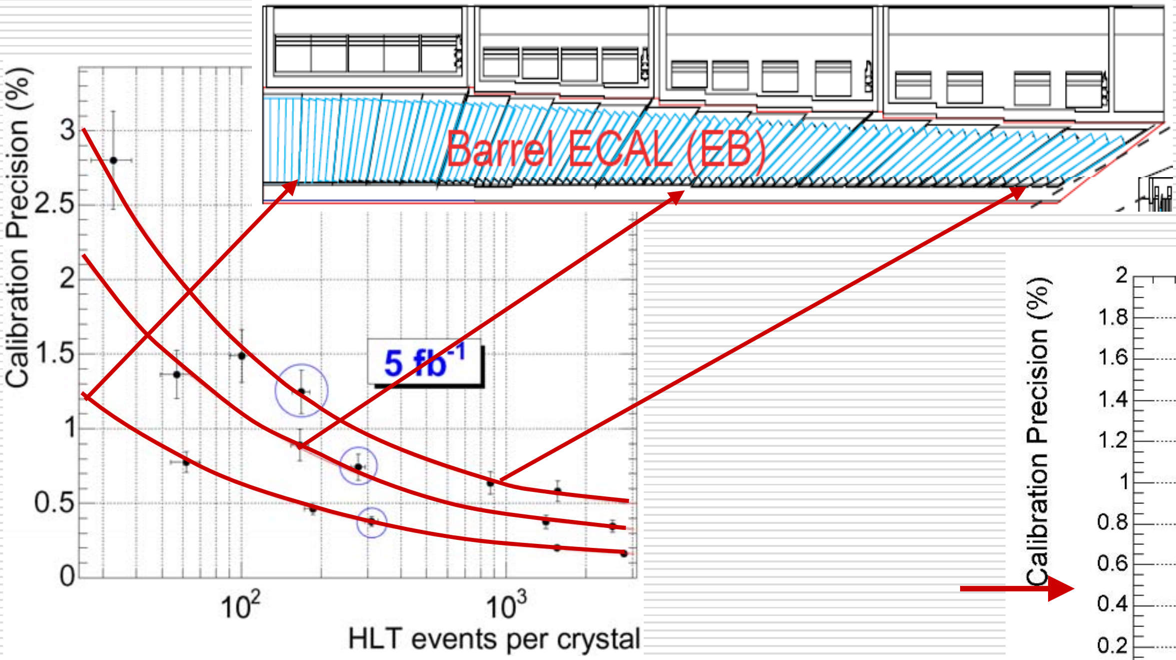


In-Situ Calibration: Single Electrons

- 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: $E/p \sim 1$
- 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 (~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

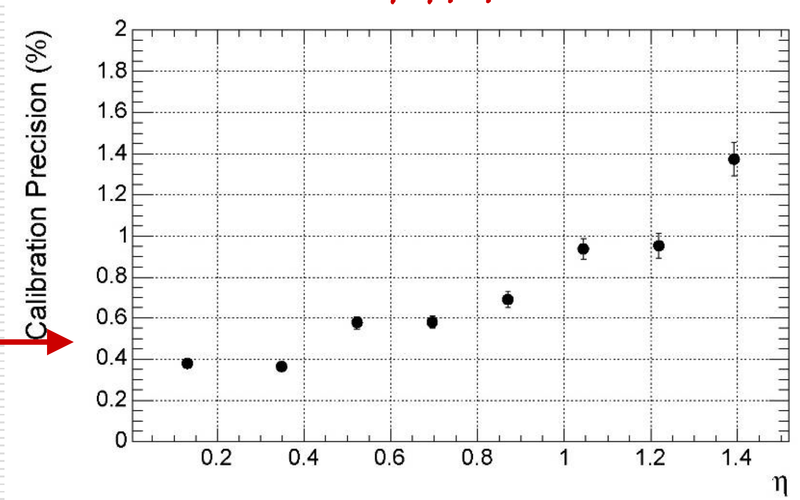
Precision from single electrons

- Calibration precision improves as $\text{prec} = \frac{A}{\sqrt{\#\text{events/xtal}}} \oplus C$
- Monte Carlo study of barrel region of CMS ECAL:



Intercalibration using W→eν

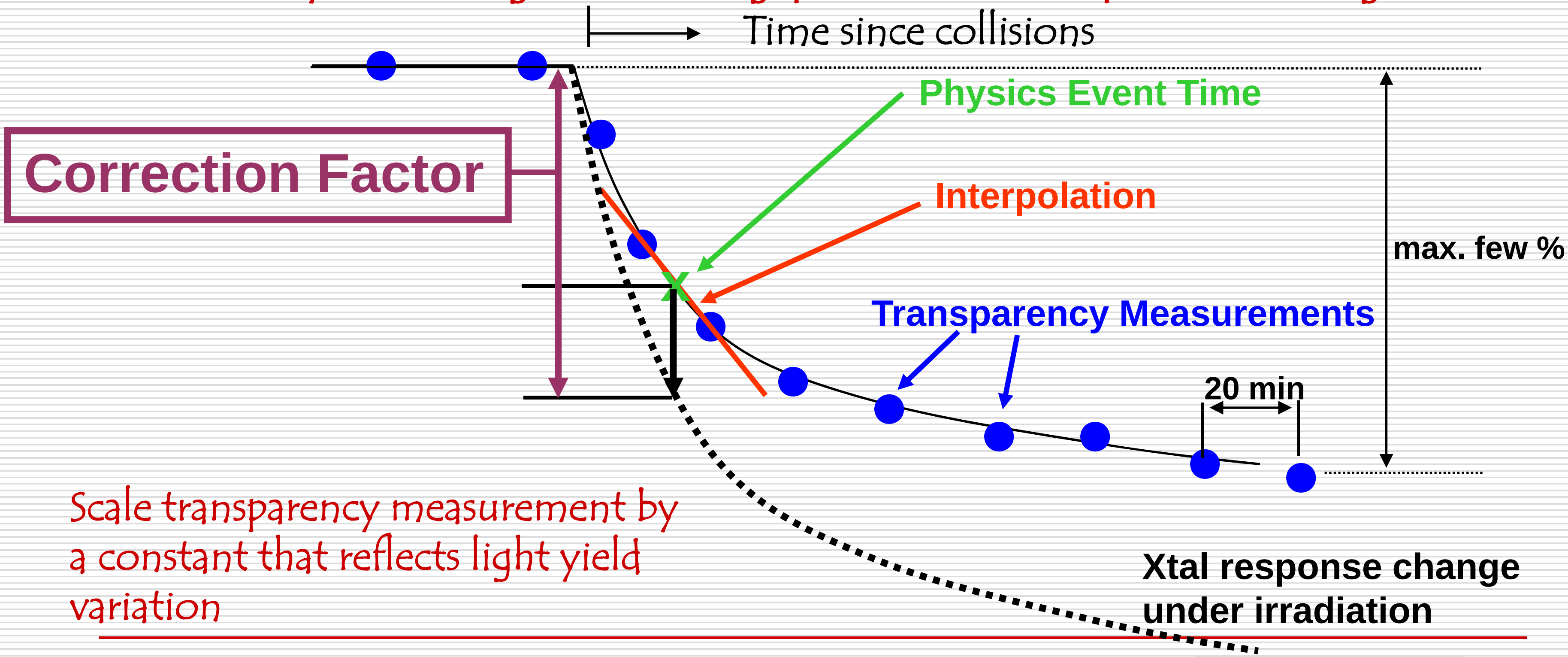
Precision vs. η for 5 fb^{-1} of collected data



Reached goal for central region by second LHC year

Monitoring Calibration

- Recall that the CMS ECAL is sensitive to radiation 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*"

Early results from Run 2 of Tevatron

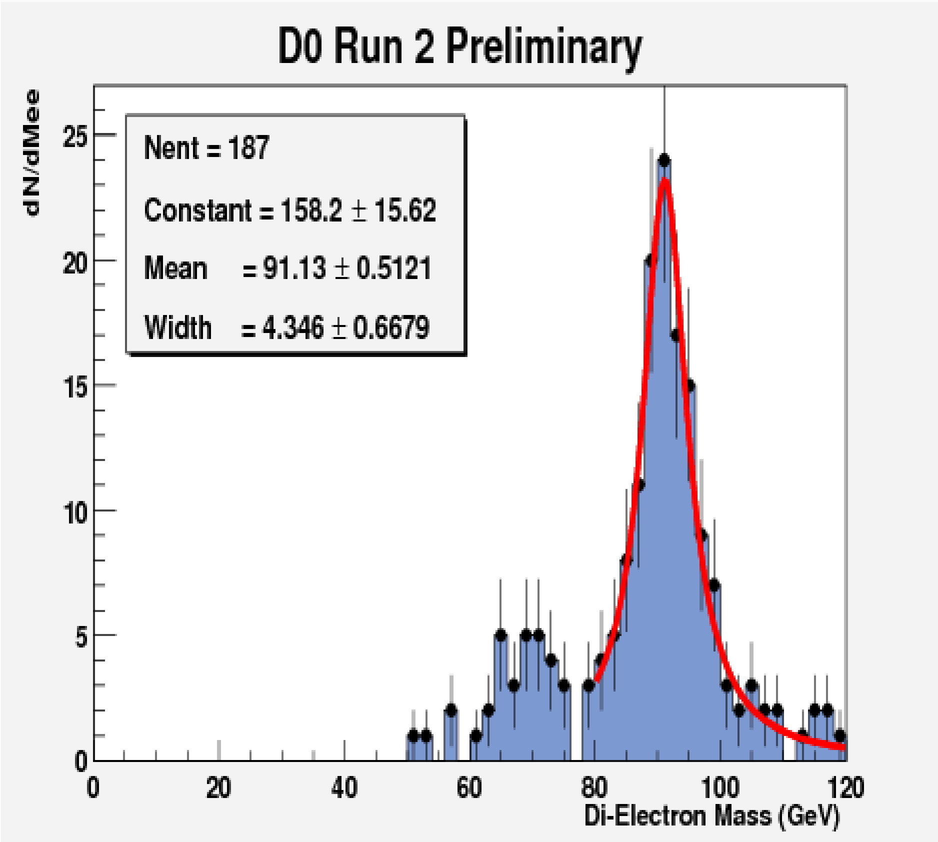
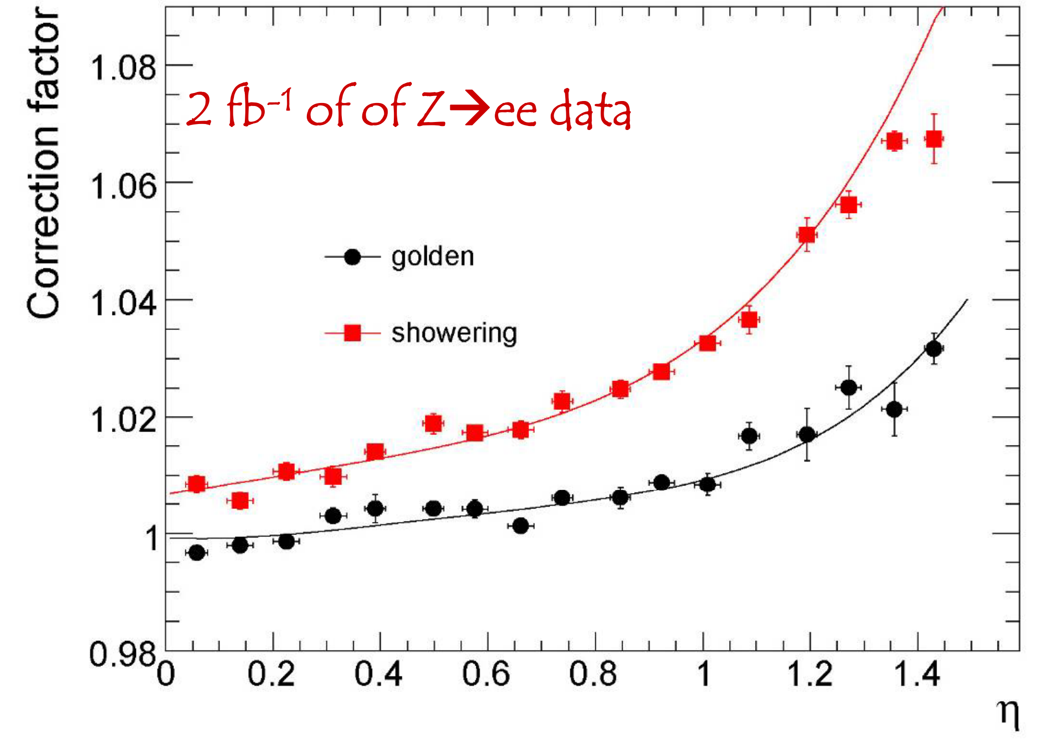


Figure 3: Di-electron invariant mass from $Z \to e^+e^-$ candidates after energy scale corrections.

- D0, May 2002 hep-ex/0205039
- 10 pb^{-1}, one year into Run 2 program
- "A significant fraction (25%) of this integrated luminosity has been devoted to detector commissioning."

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 0.3%



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

Some Types of Calibration samples

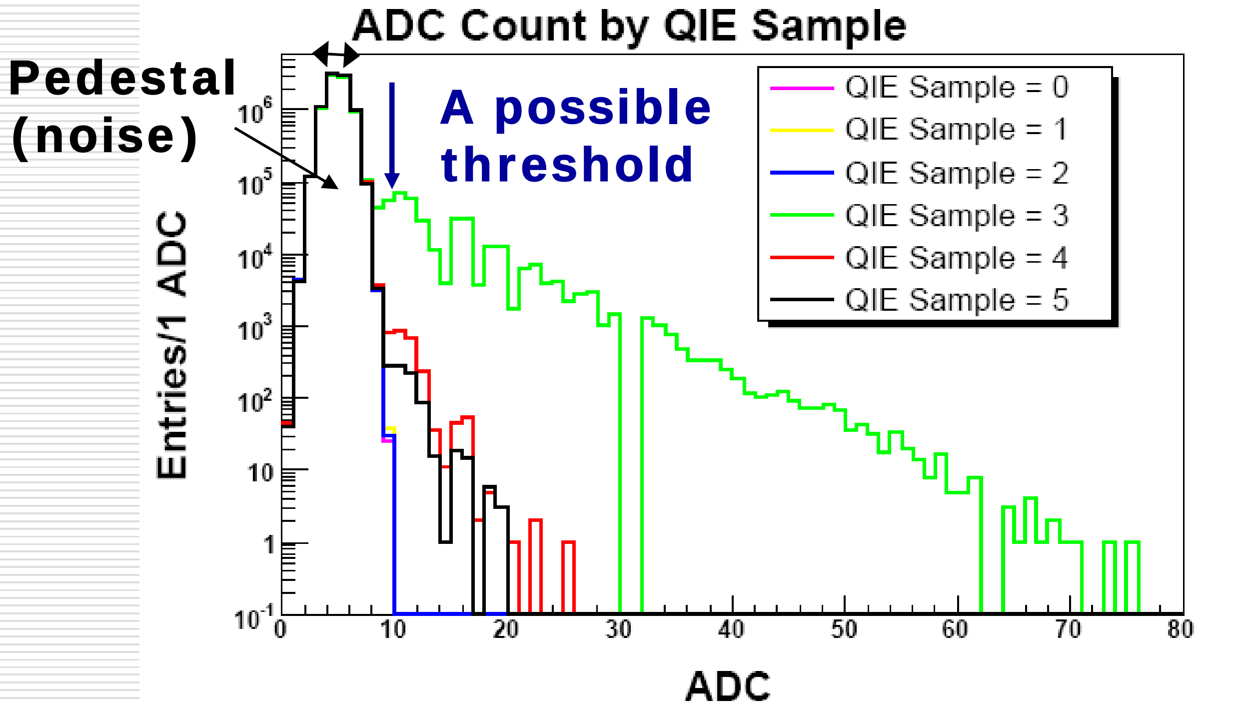
- Laser & LED pulsing of optical systems to monitor optical chain (not generally scintillation light yield)
  - Can be done during abort gap during running, or in special calibration runs
- Radioactive source scans
- Minimum bias or zero-bias datasets
  - For Phi-symmetry tower calibration
- Jet and gamma+Jet data samples
  - Jet calibration
- High P_T electrons (W, Z)
  - Electron calibration

Zero Suppression

- In general cannot read out all channels of an experiment every triggered event
  - 100M channels x ~1 byte = 100 MB !
    - And 10 GB/s at 100 Hz to tape ! (36 TB/hour)
- Generally suppress signals (noise) below a threshold
- Also can suppress based on topology
  - e.g. CMS cathode strip chambers require a local trigger segment in order to read out chamber
  - CMS ECAL applies a threshold, or otherwise takes cells without threshold if they neighbor a cluster above threshold (selective readout)
- Zero suppression also needs commissioning. You are throwing away data! Better make sure effects are fully understood first…
  - i.e. Trade trigger rate for increased event size given a fixed DAQ bandwidth in order to log data for further study at the beginning

Zero Suppression and Calibration

- Careful calibration generally requires not applying normal zero suppression
  - Either because the calibration is to measure the pedestals
  - Or need to disentangle noise contribution from signal



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%)
- Saturated channel
  - Signal exceeds dynamic range (e.g. multi-TeV electrons)
- But should account for energy lost in these regions
  - Murphy's Law will probably cause your Nobel-prize winning discovery to have an electron right next to a dead channel ☹
- Need to parameterize the energy in a calorimeter cell based on the energy deposit distribution in neighboring cells
  - For example, use ratios of energy: left vs. right and top vs. bottom
  - Interpolate to find shower position, then use parameterization of energy in dead cell from energy in surrounding cells

Operating the Experiment

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

Run Coordination

- Operating the experiment is operating a complex, high-tech facility
- Need a core team of people 24/7 in the control room:
  - Operating the trigger and data acquisition system
    - Run start, stop, pause – and diagnosis when problems arise
  - Monitoring the data quality
    - The health of the detectors – alert shift crew when problems
  - Monitoring and responding to the safety system
    - "SLIMOS" – Shift Leader in Matters of Safety
    - Safety of the experiment and of people
  - Shift Leader
    - Overall in charge of shift operations, tactical decisions
  - Run Coordinator
    - In charge of strategic decisions, setting the daily/weekly run plan

Shifts on Experiments

- CDF – mature experiment, 4 shifters → 3 recently
  - "SciCo" – scientific coordinator (shift leader)
  - "CO" – consumer operator, data quality monitoring shifter
    - May be remote
  - "Aces" – Two (now one) experts in running and monitoring DAQ and other expert-level detector operations
    - Generally 3 month commitment, with on periods and off
- ZEUS – mature, (but based on my aging memory from the 90s)
  - Shift Leader
  - Deputy shift leader – data quality monitoring
  - Safety shifter
  - Online shifter
- CLEO – very mature experiment, two shifters:
  - "Professional" in charge of running operations
  - Physicist in charge of data quality monitoring
    - This person can be remote

Outside the Control Room

- Need a small army of experts on-call to be responsible for responding to any problems that develop with their specific subsystem
  - In fact, during the commissioning period, these experts are also probably sitting in the control room
  - Can get crowded…
  - Several experiments still maintain detector expert shifts well into running

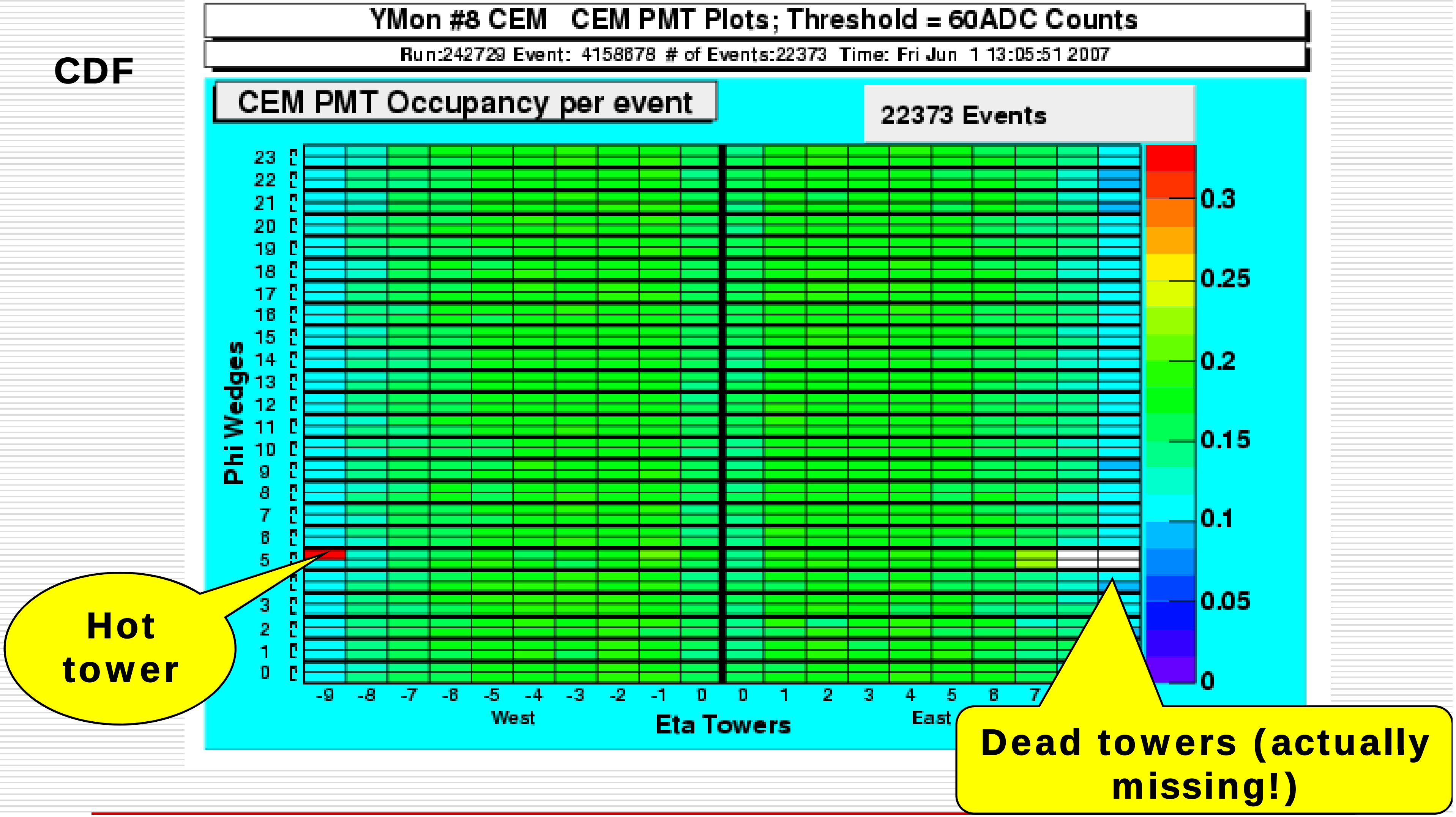
First global commissioning effort in the underground service cavern of CMS. Only Trigger, DAQ, and one detector system!

Data Quality Monitoring (DQM)

- It is important to monitor the performance of the detectors in order to catch and address problems promptly as they are encountered
  - Generally low-level, basic detector performance plots such as occupancy plots
- Remember, it is not the integrated luminosity delivered by the machine that matters for your analysis, but the luminosity that you accumulate while the experiment is functioning properly
  - Must keep the efficiency high for recording physics-quality data

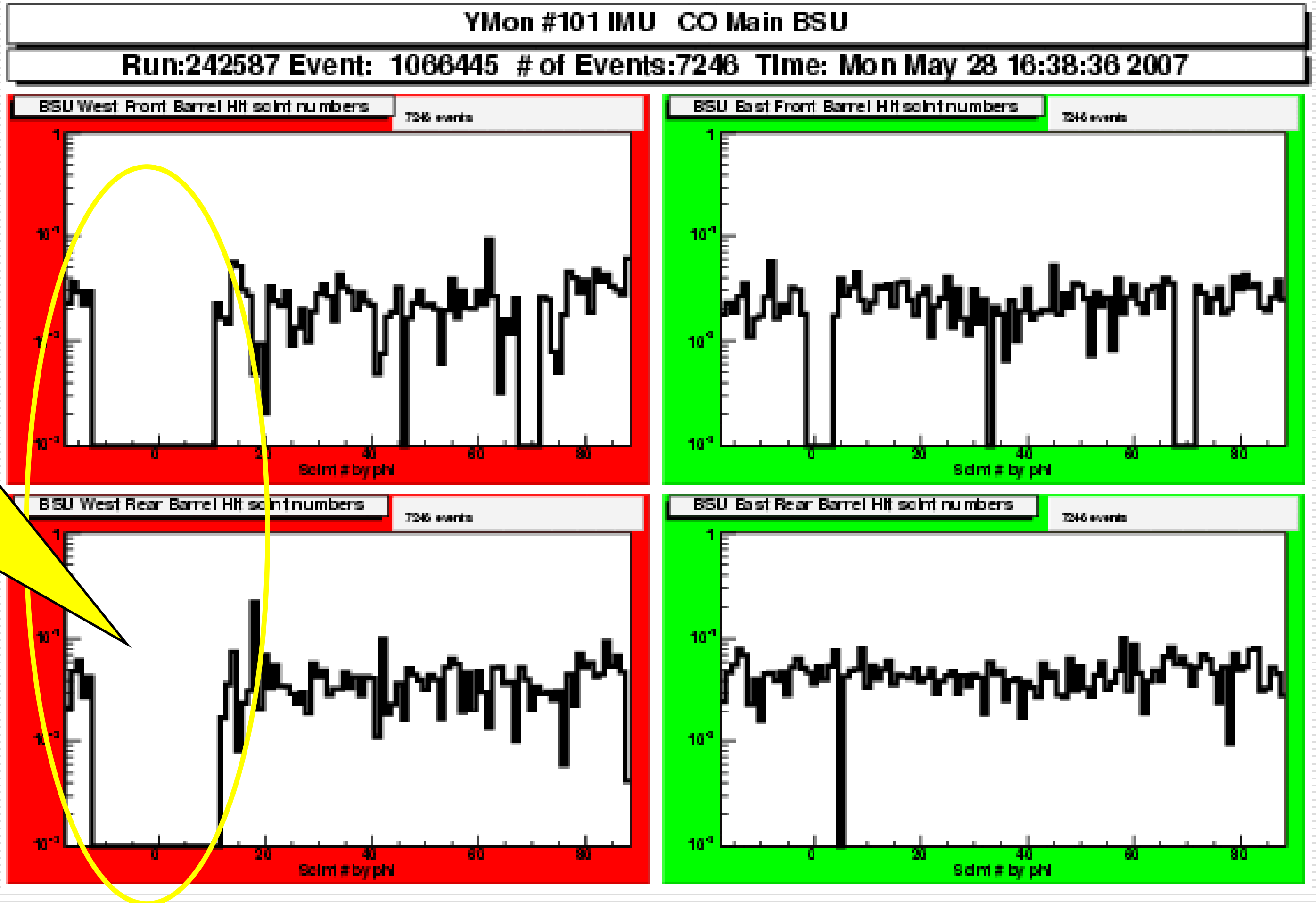
Example: Calorimeter Tower Occupancy

CDF



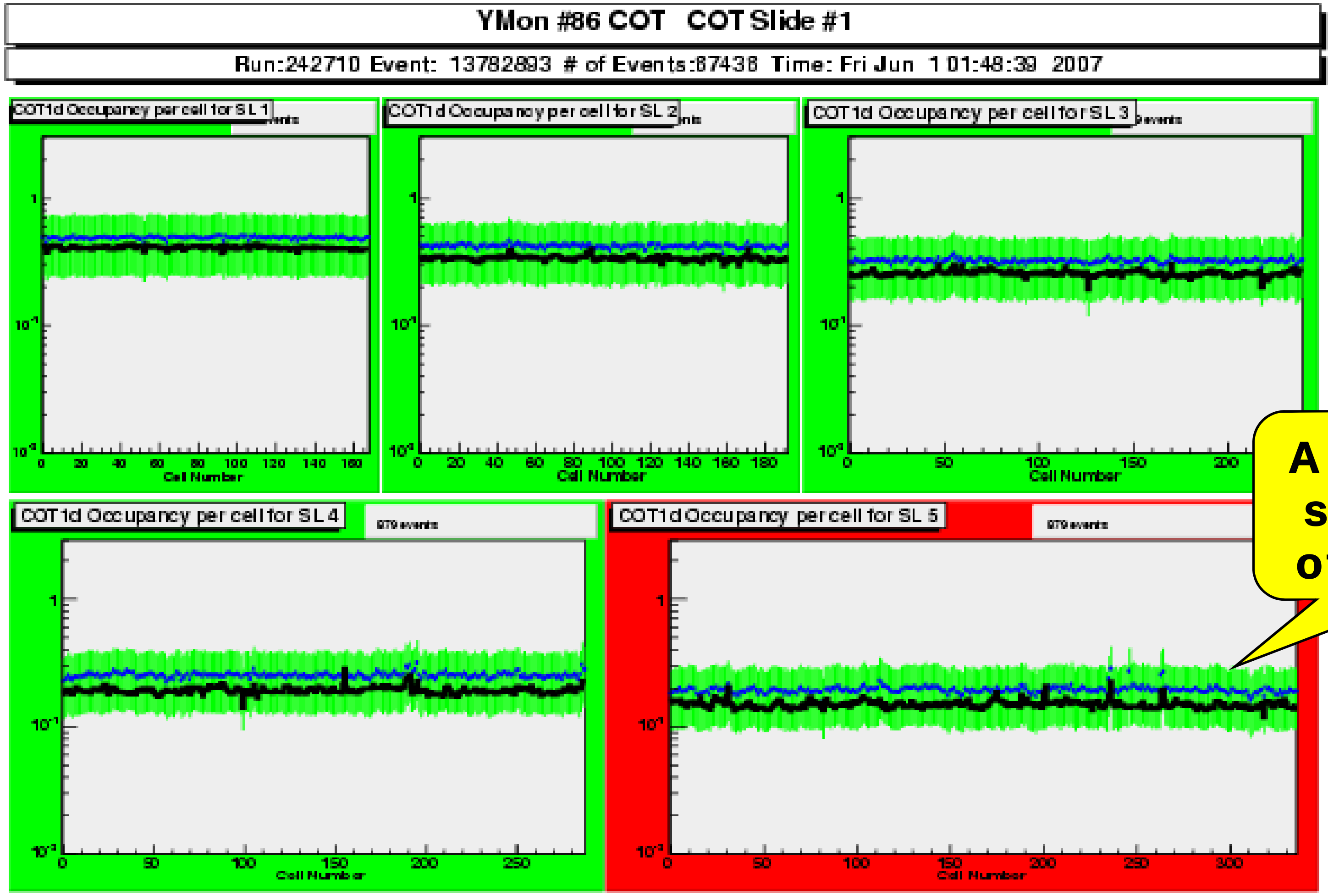
Example: Muon Scintillator Occupancy

CDF



Entire quadrant dropped out (automatically flagged red)

Example: Occupancy in Tracking Cells



CDF

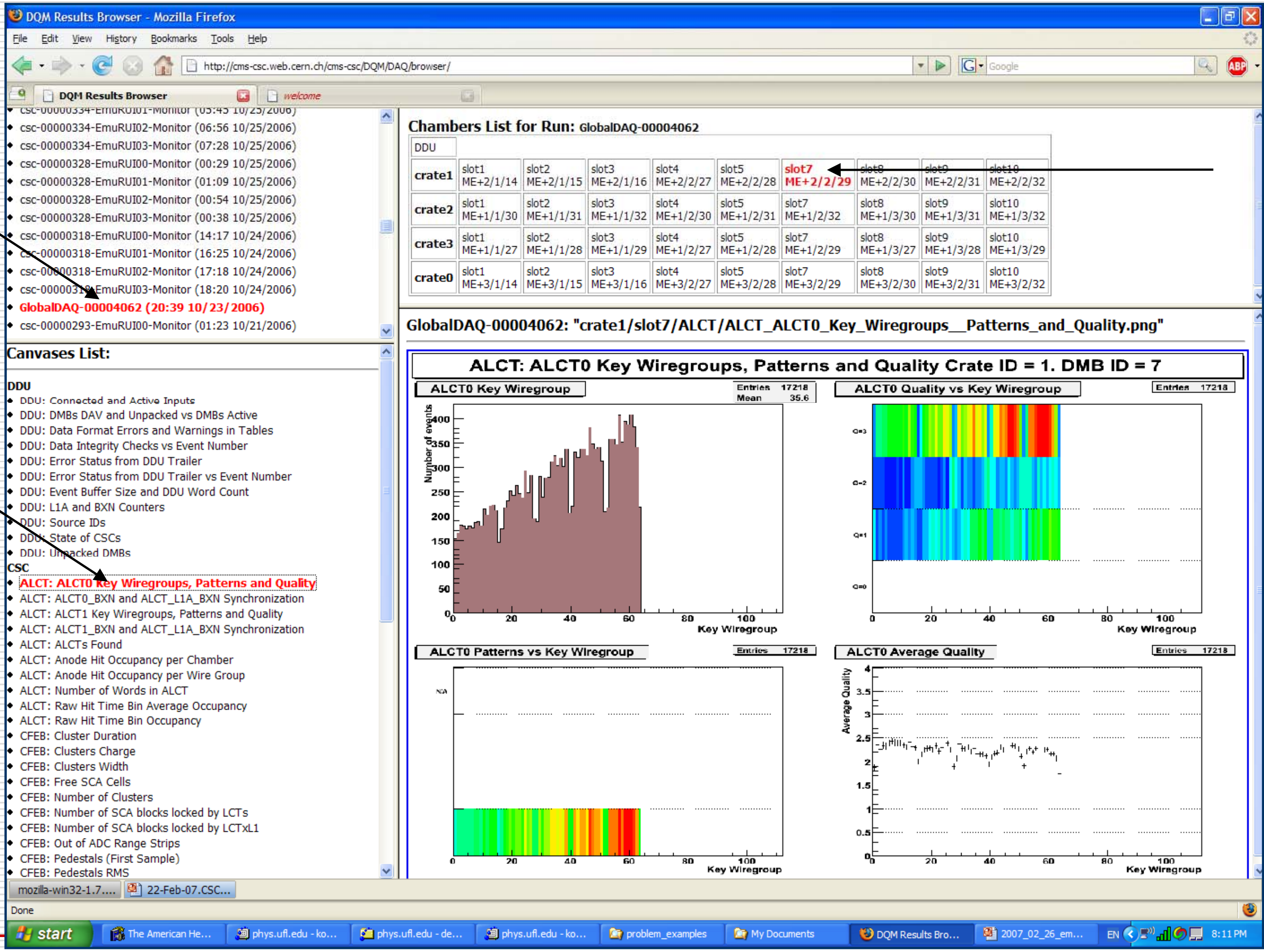
A cell or two slightly out of tolerance

CMS Cathode Strip Chamber DQM Browser (expert level – useful for diagnostics)

pick any published run

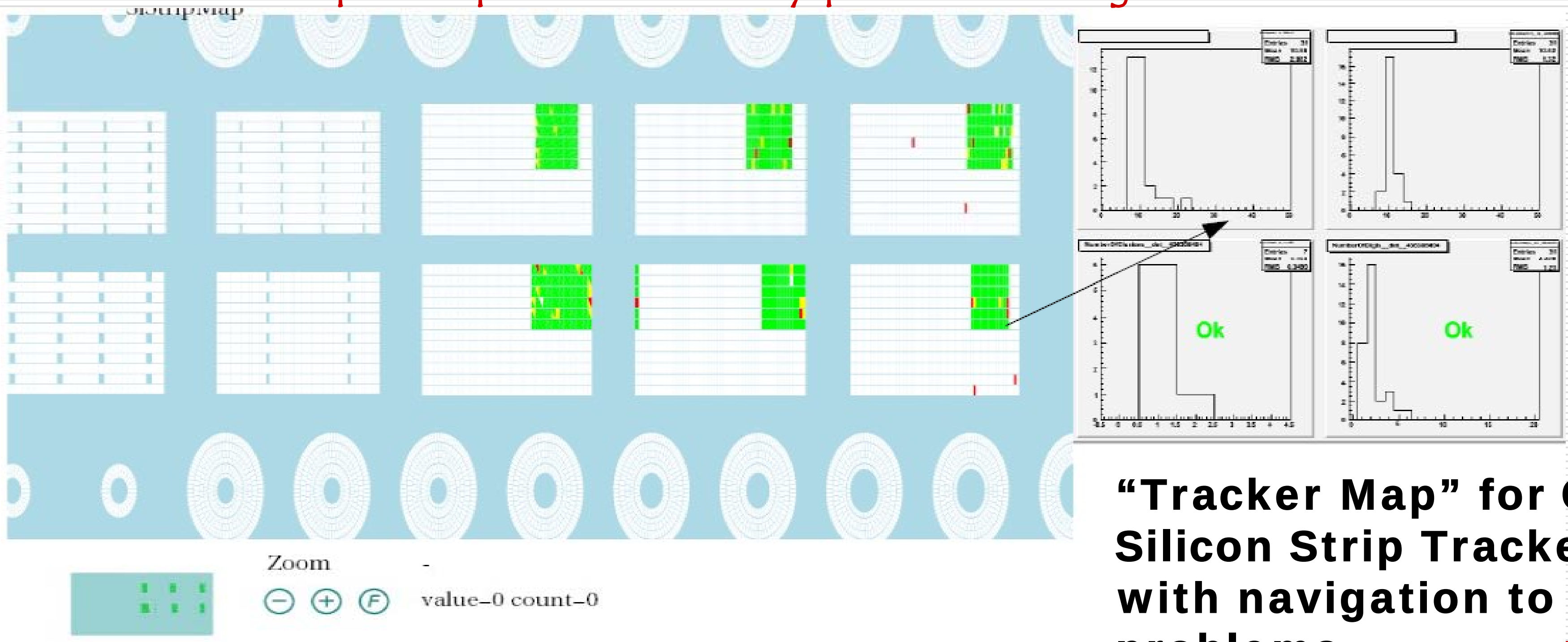
pick any canvas

pick any chamber



Automated DQM Checking

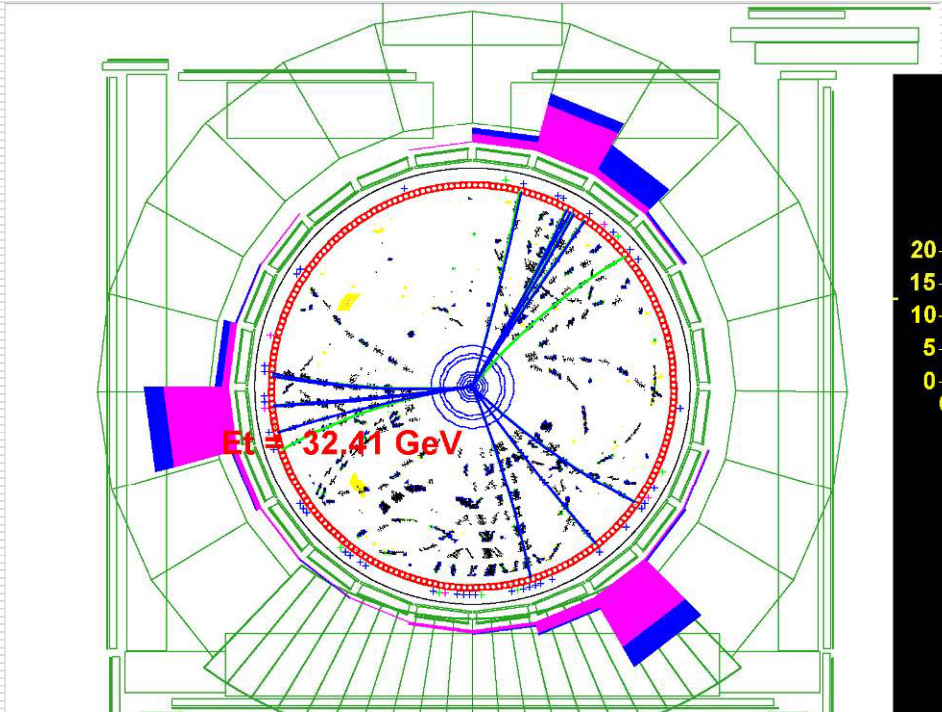
- Can easily have O(1 million) histograms in total to check for an LHC experiment like CMS or ATLAS !
  - Need to code fault patterns, or compare against reference histograms, to find errors (no human could possibly check all)
  - Prepare top-level summary plots indicating errors

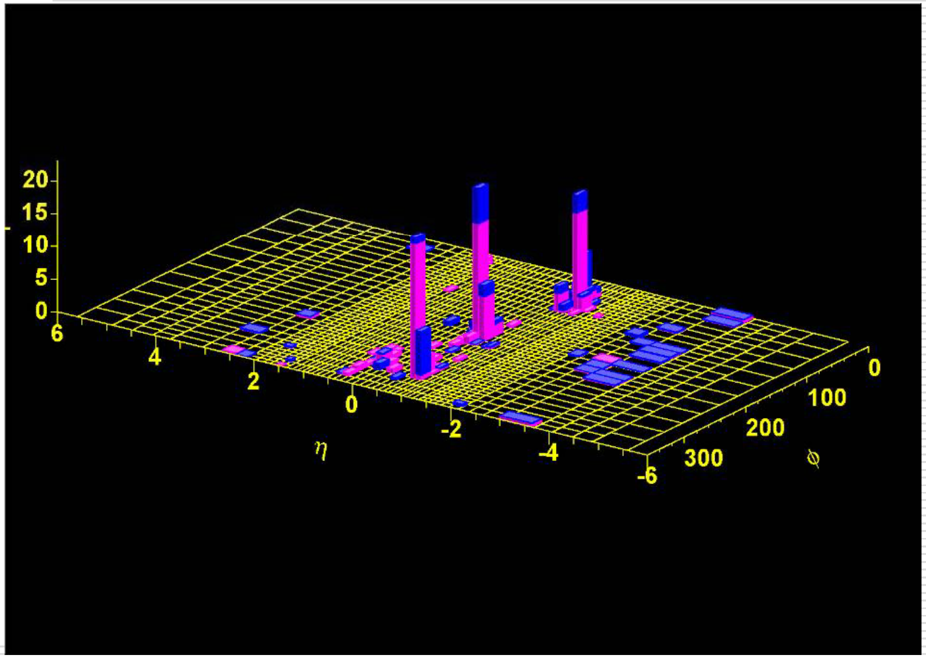


"Tracker Map" for CMS Silicon Strip Tracker, with navigation to problems

Event Display

- Don't underestimate the ability of a good event display for a visual inspection of problems online
  - Could see hot channels, dead channels, backgrounds, etc.

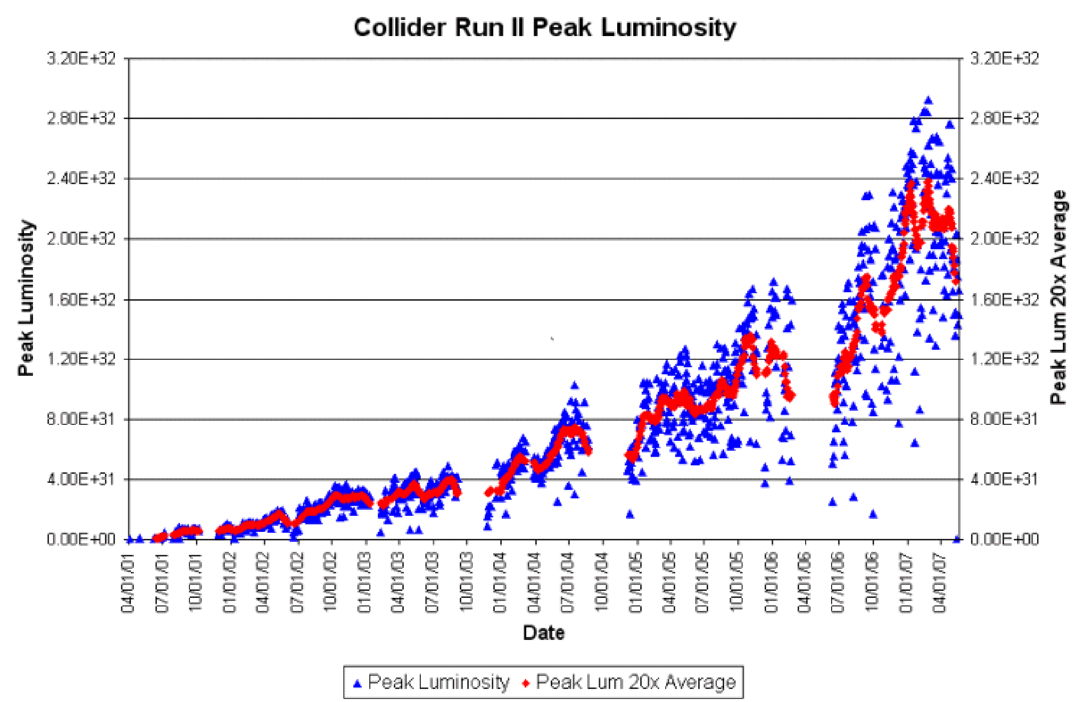





LHC
Luminosity
LBV 1806-20
The Sun
Tevatron

What is Luminosity?

- Luminosity is a measure of the "brightness" of the colliding beams at a collider
- It determines the rate of collisions and, integrated over time, the total number of events in our data samples



Tevatron peak luminosity:

$\mathcal{L}$ =2.8x10^{32} cm^{-2}s^{-1}

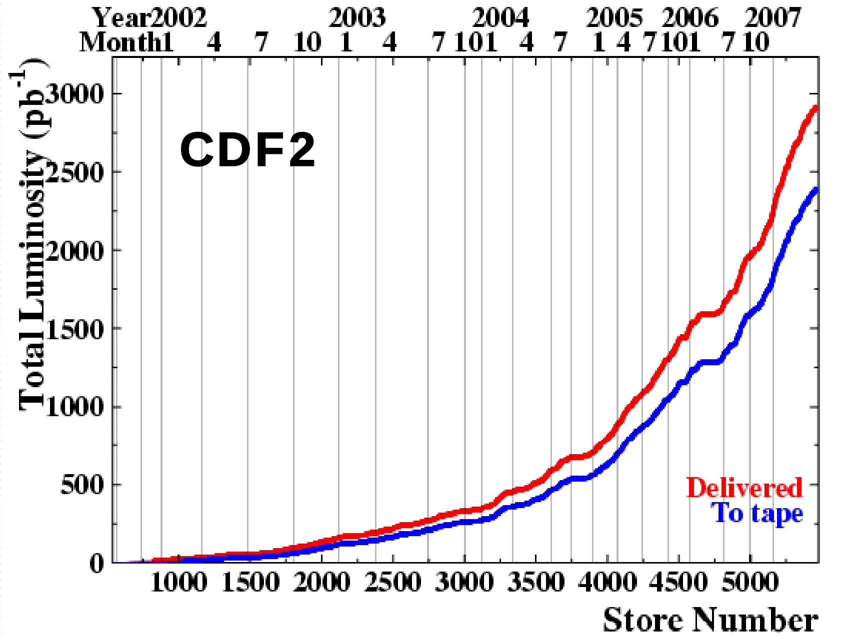
Rate=$\sigma\,\mathcal{L}$

LHC design goal:

$\mathcal{L}$ =10^{34} cm^{-2}s^{-1}

Why is luminosity important?

- You want to accumulate as much as possible to search for rare processes
  - Tevatron Run 2 integrated luminosity is nearly 3 fb^{-1}
  - Standard Model Higgs search requires several times more than that



- You need to know the denominator of your cross section measurement!

$$\sigma = \frac{N_{sel}}{\varepsilon L}$$

Luminosity from Machine Parameters

- $\mathcal{L} = (k\, N_p^2 f) / (4\pi\, \sigma_x \sigma_y)$
  - f = revolution frequency
  - N_p = number of protons per bunch (assumed equal)
  - k = number of bunches (2808)
  - σ_x, σ_y = transverse sizes of the beam
- Goal is to maximize $\mathcal{L}$
  - Increase N_p as much as possible
  - Increase bunch crossing frequency
  - Decrease beam cross section
- And if we can measure these parameters, we also have a measurement of the luminosity
  - "Van der Meer scan" of stepping beams through each other to determine parameters from count rates

See lectures by Dr. Wenninger for more information on LHC

Luminosity – Also a Critical Analysis Ingredient

- Generally one is interested in measuring the cross section of an interesting process at a collider:

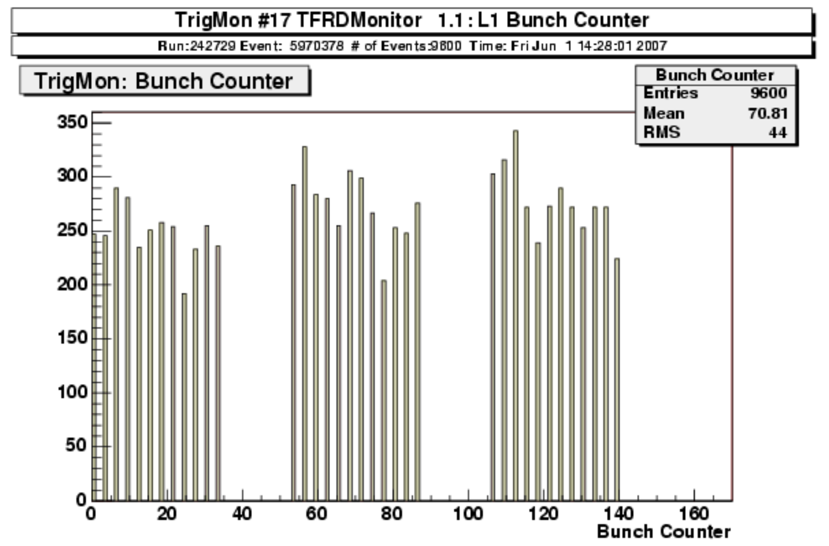
$$\sigma = \frac{N_{sel}}{\varepsilon L}$$

  - N_{sel} = number of selected interesting events
  - ε = efficiency to select those events
  - L = total integrated luminosity (cm^{-2}, or $fb^{-1} = 10^{-39}\ cm^{-2}$)

- Can spend a lot of time determining cuts to isolate the interesting events of a particular process from a myriad of ordinary Standard Model backgrounds, and measuring, or otherwise simulating, the efficiency of those cuts and estimating systematic uncertainties
- But it is also important and necessary to measure the luminosity accurately and precisely
  - Even better to have several handles cross-checking

Processes from which to Measure Luminosity

- The luminosity measurement should provide quick feedback to the accelerator operators and to the experiment, so need good statistics on short timescales
  - e.g. to provide bunch-by-bunch luminosity →



Filled bunches @ Tevatron from CDF measurement

- Choose high cross-section processes at colliders:
  - e^+e^- : Bhabha scattering $e^+e^- \rightarrow e^+e^-$
  - ep : ep bremsstrahlung $ep \rightarrow ep\gamma$
  - pp : inelastic scattering $pp \rightarrow X$

Luminosity from total inelastic cross section

- Rate of inelastic collisions: $R = \sigma \mathcal{L}$
  - σ = inelastic cross section (cm^2, or barns)
  - $\mathcal{L}$ = instantaneous luminosity ($cm^{-2} s^{-1}$)
- Rate is also $R = \mu f_{BC}$
  - μ = average number of inelastic collisions per bunch crossing
  - f_{BC} = frequency of bunch crossings
- So experimentally, instantaneous luminosity can be measured by:
  - $\mathcal{L} = \mu f_{BC} / \sigma$
  - f_{BC} comes from machine design
  - σ must be measured, or otherwise calculated, from the process used to measure luminosity
  - Measure μ from your detector

Methods to measure μ: Zero Counting Method

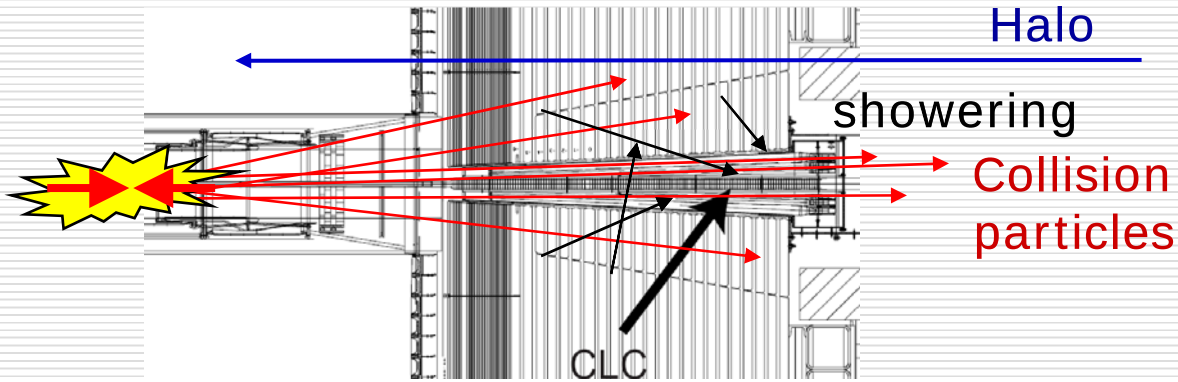
- The probability of n inelastic collisions in a given bunch crossing, given a mean number of collisions μ, is given by Poisson formula:
  - $P(n) = \exp(-\mu)\, \mu^n / n!$
- The probability of zero collisions is:
  - $P(0) = \exp(-\mu)$
- Thus, one can measure the fraction of empty bunch crossings to get μ:
  - $\mu = -\ln P(0)$
- In practice, a detector is not 100% efficient at detecting a collision due to limited angulae coverage and detection inefficiency
  - $P(0) = \exp(-\varepsilon\mu)$, ε = efficiency
- One also can have backgrounds or detector noise that can mimic a detector response from a collision
  - Trickier to deal with if cannot be removed
- Limitation:
  - "Zero starvation" at high luminosity (i.e. if $\mu \gg 1$, so that P(0) is small)
  - This makes the measurement susceptible to systematic uncertainties
    - e.g. Backgrounds or noise that mimic a collision and bias μ larger, or inefficiencies that bias μ smaller, have a fractionally larger bias

Methods to measure μ: Hit/Particle counting

- Rather than try to measure the fraction of empty events, measure the number of detector elements hit (counters, towers), or better the number of collision particles, in a beam crossing
- $\mu = \langle N_H \rangle / \langle N_H^1 \rangle$
- $\langle N_H \rangle$ = measured number of hits or particles
- $\langle N_H^1 \rangle$ = number of hits, or particles, for a single collision
  - Could be measured from counting a fraction of the charged particles in a collision, for example
  - Need good separation of one collision from two, and avoid saturation of counters at high luminosity

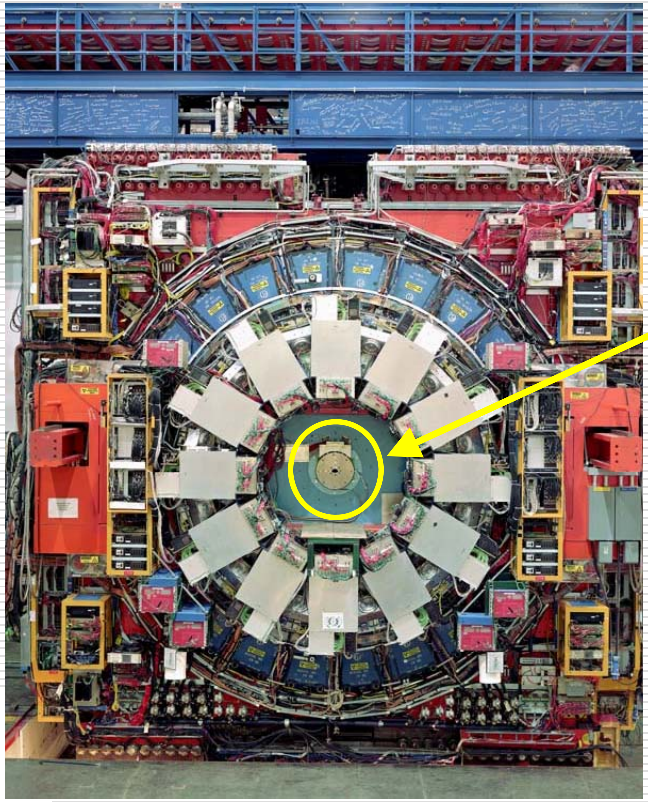
Detectors for Relative Luminosity Measurement

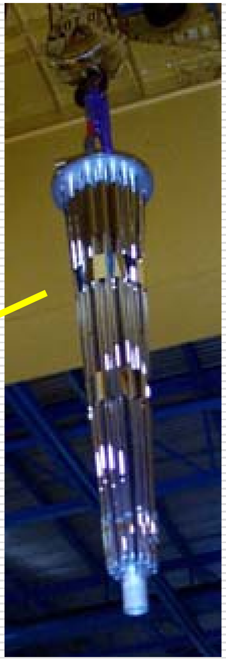
- A measurement of just about any process with any detector is sensitive to the luminosity
  - Inelastic scattering, W/Z production, J/Ψ production, …
  - Calorimeter occupancy/energy, tracking detector currents, tracks,…
- Choose a high cross section process for good statistics
- Choose high acceptance, low noise/background detector or technique to minimize systematic uncertainties
  - Generally means covering the forward regions of collider expt.

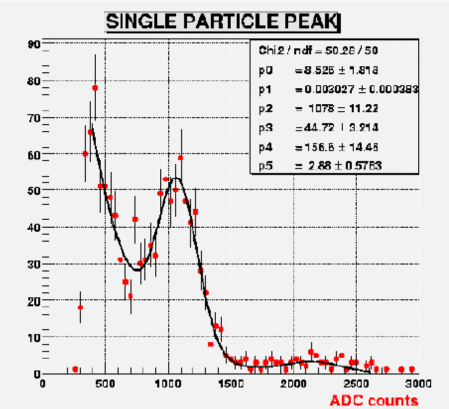


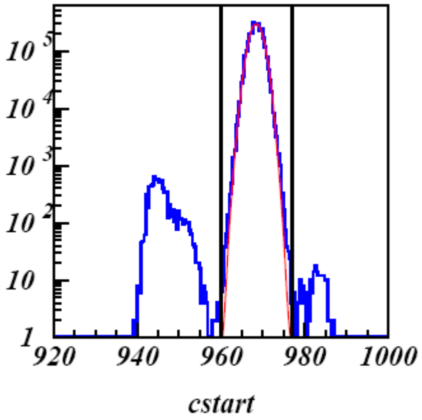
CDF Cherenkov Luminosity Counters

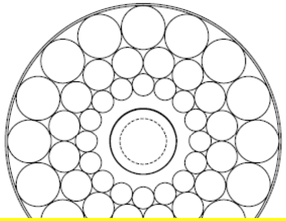
- Eta coverage: $3.7 < |\eta| < 4.7$
- Good acceptance: 60%
  - 95% of which is from hard-core inelastic collisions
- Cherenkov device :
  - Good signal:noise separation
  - Self calibrating
  - Excellent timing
  - Directionality









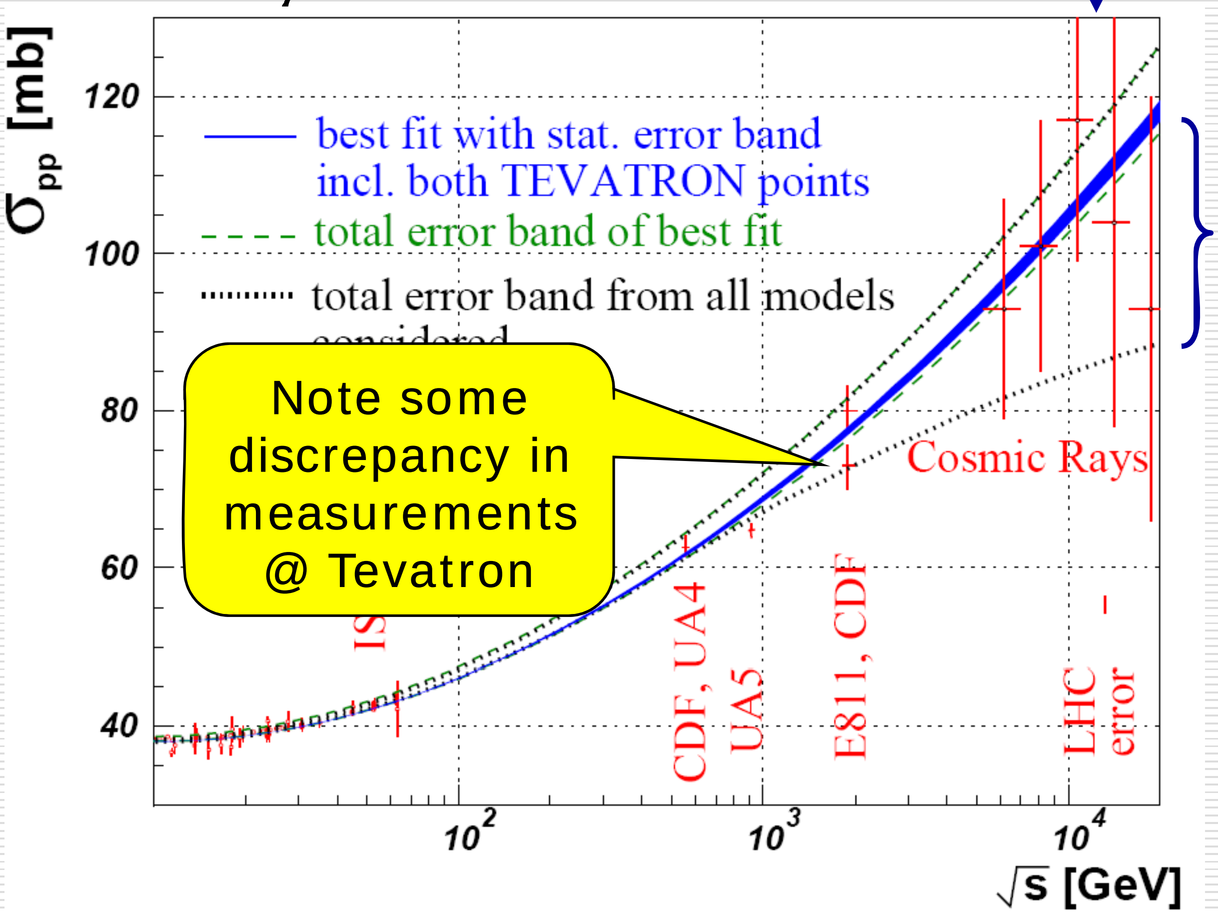


4.2% measurement uncertainty

(6% with cross-section uncertainty)

Total pp Cross Section @ LHC

- Large extrapolation from Tevatron to LHC, so large uncertainty until measured

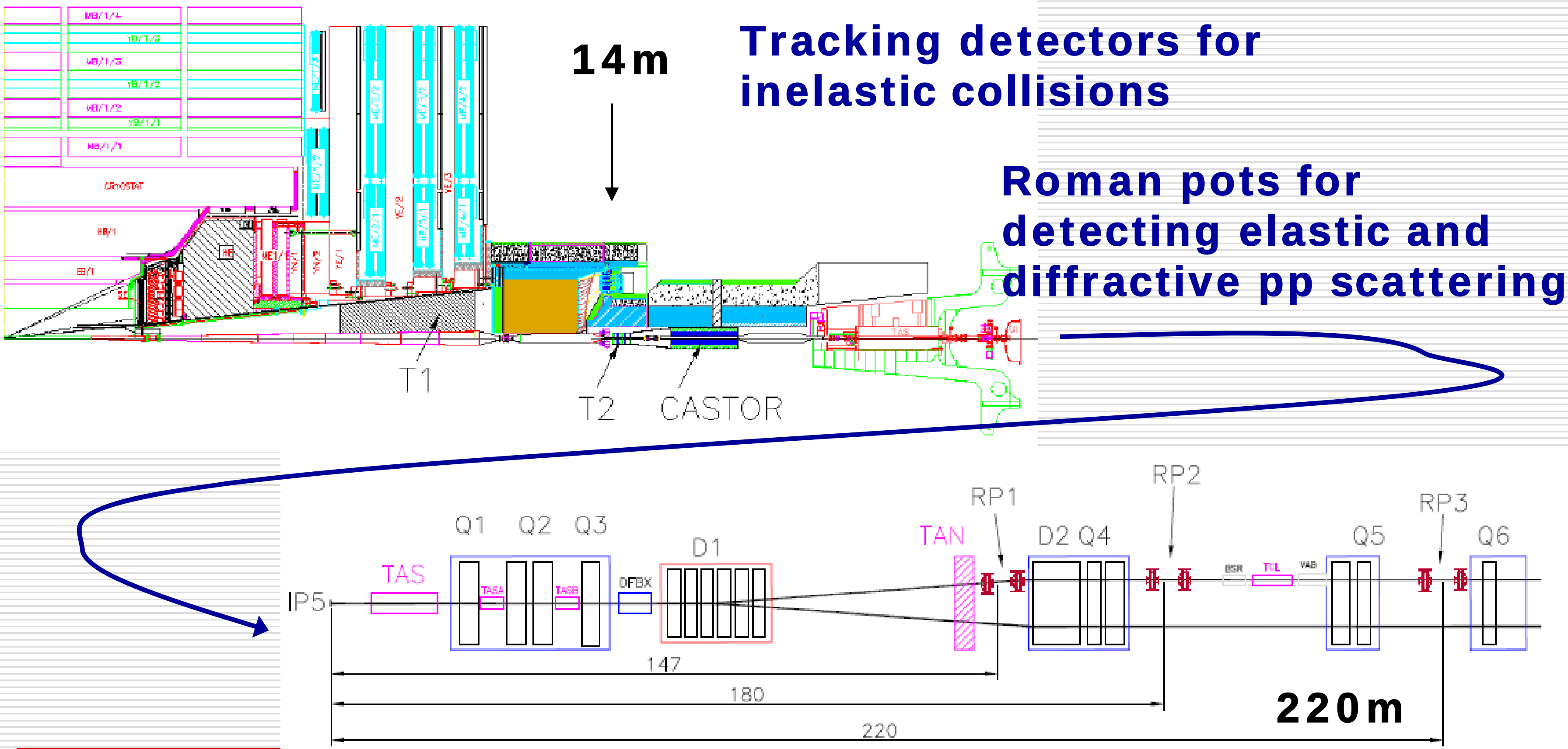


Conservatively 100 ± 15 mb

J.Cudell et al., PRL 89, 201801 (2002)
σ = 111.5 ± 4.2

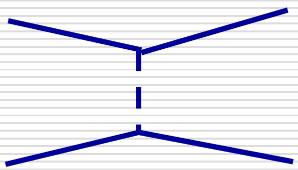
TOTEM Experiment

- Dedicated experiment @ LHC (shares P5 with CMS) devoted to measuring the total pp cross section and study elastic and diffractive dissociation



Total cross section & absolute luminosity measurement from elastic scattering

- Optical Theorem: the total cross section is related to the imaginary part of the elastic scattering amplitude extrapolated to zero momentum transfer:
  - Incident flux is removed by total xsec



$$\sigma_{tot} = 4\pi \,\mathrm{Im}\left[f_{el}(t=0) \right] \qquad -t \propto \theta^2$$

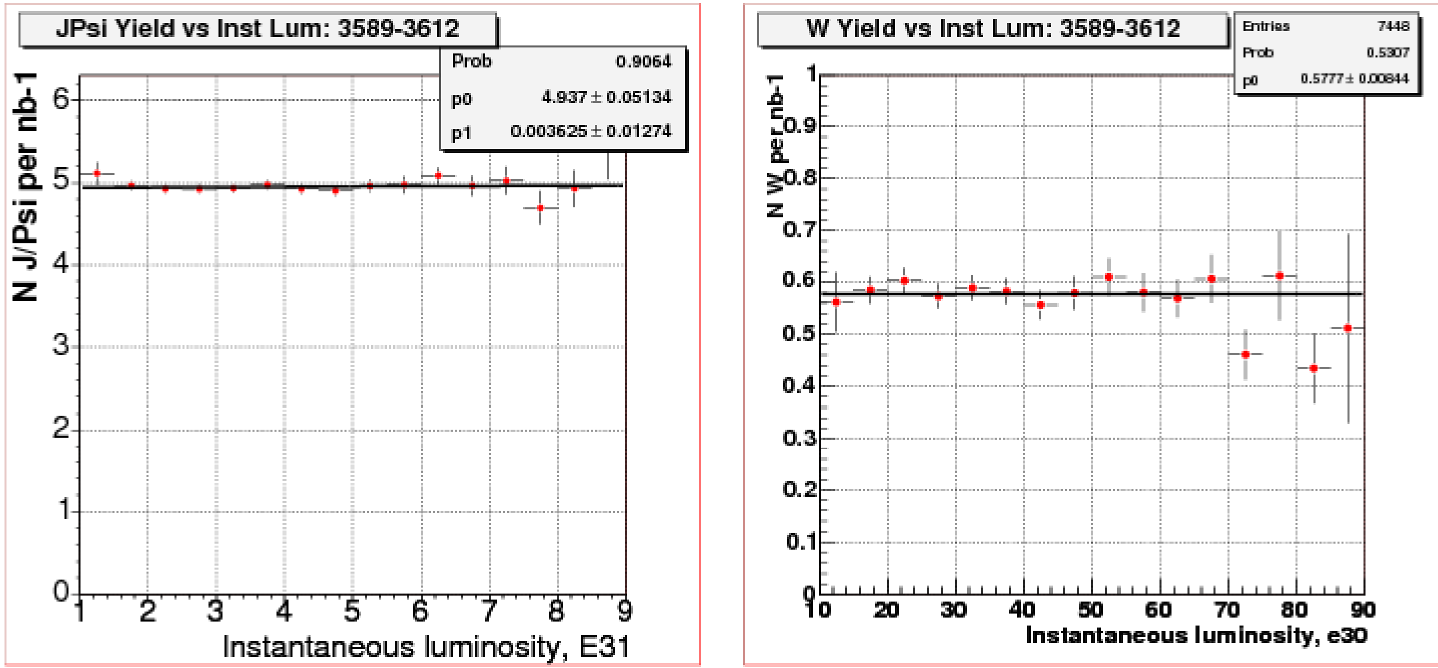
- Measure the total interaction rate R_{tot} and the elastic rate in the forward direction $(dR_{el}/dt)_{t=0}$

$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{(dR_{el}/dt)_{t=0}}{R_{tot}} \qquad \rho = \left. \frac{\mathrm{Re}\left[f_{el}(t) \right]}{\mathrm{Im}\left[f_{el}(t) \right]} \right|_{t=0} \approx 0.14$$

$$L = \frac{R_{tot}}{\sigma_{tot}} = \frac{(1+\rho^2) R_{tot}^2}{16\pi (dR_{el}/dt)_{t=0}}$$

Luminosity cross-checks

- With the luminosity measurement from the experiment, useful to make cross-check with other processeses



CDF

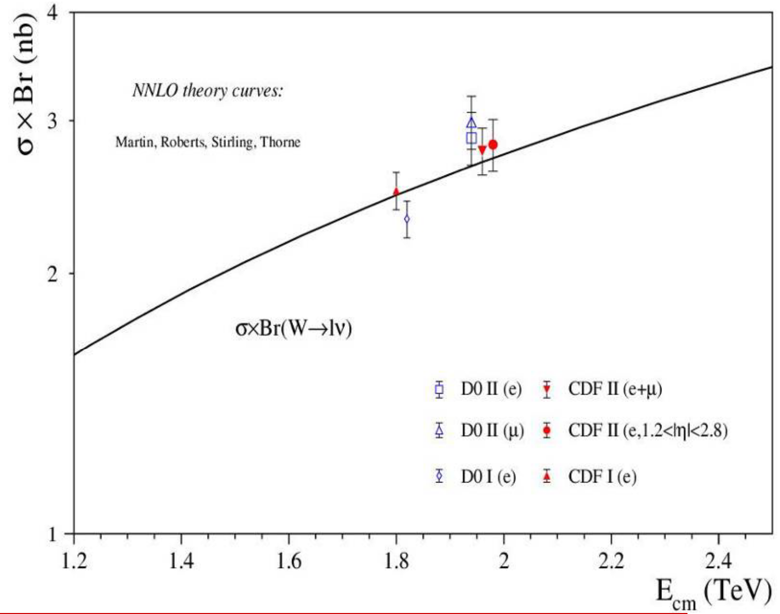
Pile-up conditions change

Figure 18: $J/\psi \to \mu\mu$ yield per instantaneous luminosity bin. The number of reconstructed J/ψs is flat versus luminosity.

Figure 19: $W \to e\nu$ yield per instantaneous luminosity bin. The number of reconstructed Ws is flat versus luminosity.

Luminosity from Standard Candles (W, Z)

- The W boson cross section has been measured to 7% at the Tevatron, and agrees very well with NNLO theory
  - 6% of this uncertainty comes from the luminosity measurement, and only 3.5% from the W measurement itself
- Thus, it may be appropriate to choose such a process to ultimately normalize the luminosity
  - But sacrifices W/Z cross section measurements at the LHC, and measurements of the proton parton densities
  - Also, it may take some time before all systematic uncertainties of this measurement are fully understood
    - CDF publication came 5 years after Run 2 start

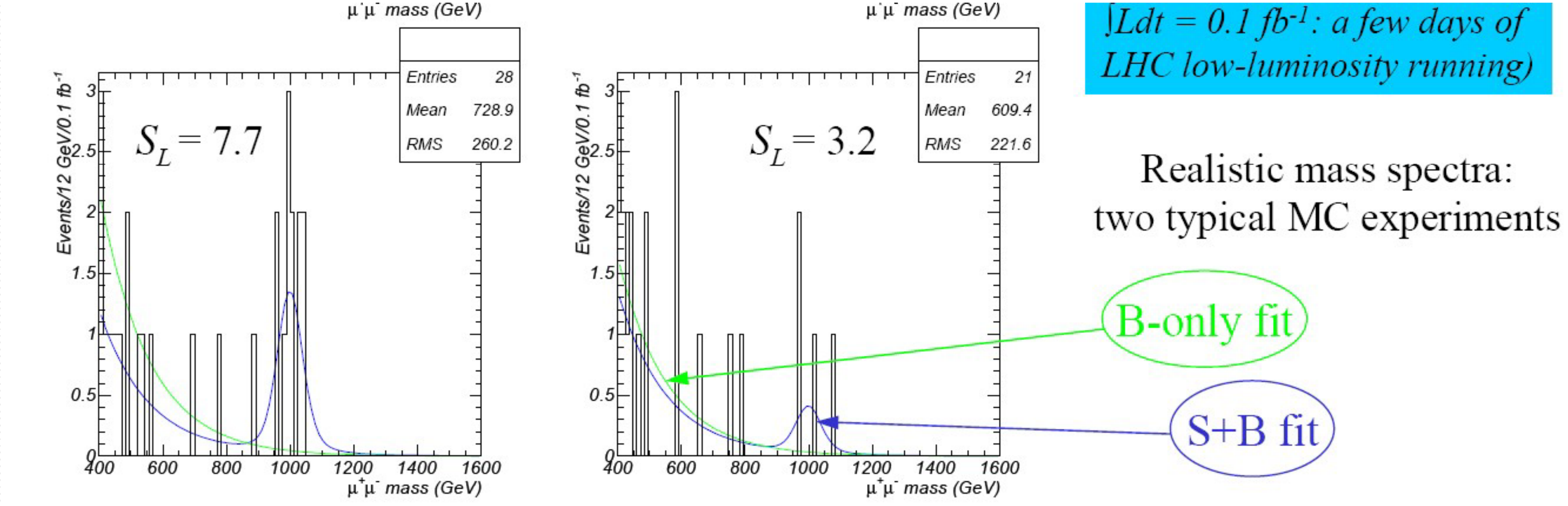


Or skip cross sections, measure relative rates

- Previous example shows that one can usually quote smaller experimental errors by measuring ratios
  - For example, at LHC, perhaps $\sigma(pp \rightarrow H \rightarrow ZZ \rightarrow 4\mu) / \sigma(pp \rightarrow Z \rightarrow \mu\mu)$
- Luminosity will cancel in the ratio
- Many common systematic uncertainties cancel as well
  - e.g. muon reconstruction efficiency (partly)
- Moreover, for new physics searches, generally can set stronger limits (because of smaller systematic uncertainties) by not doing a "dead reckoning" counting experiment
  - i.e. instead of setting an upper limit based on the number of observed candidates and the estimated number of background candidates, let the background float →

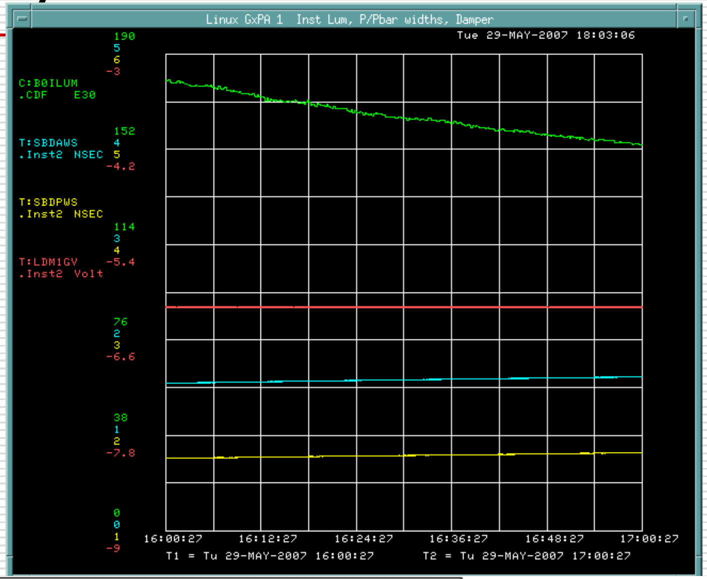
Z′→μμ Search Strategy

- Fit mass distribution to expected resonance and background <u>shapes</u>
- Extract significance of excess, and measured mass

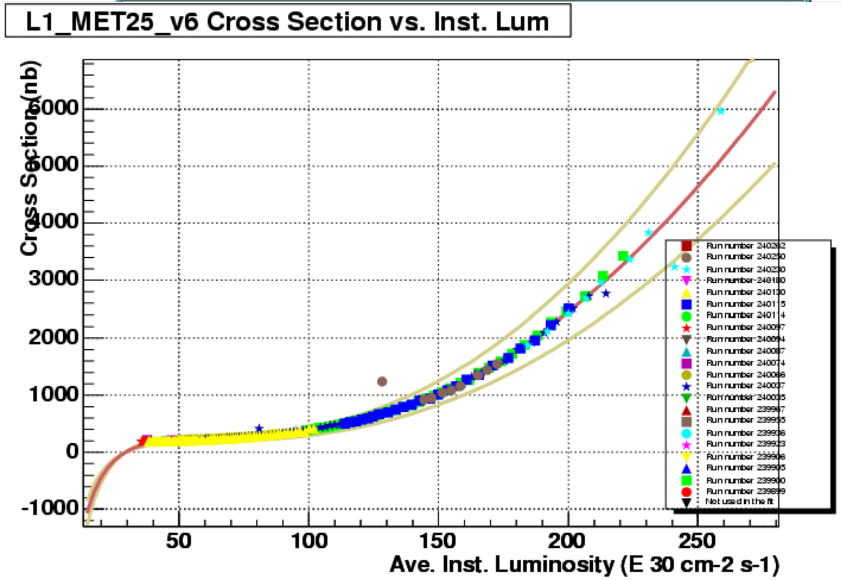


- Better than trying to estimate absolutely the background in a mass window for the signal

Finally, where to report luminosity information ?



- To the accelerator group for monitoring feedback →
  - Aiming for 1 Hz refresh rate
- Data quality monitoring
  - Online cross sections →
  - Conditions for detectors



- Into database for use in analyses
  - Tools to calculate integrated luminosity for given datasets

What is μ at the LHC anyway? (Pile-up Issues)

- Take total inelastic cross section (hard-core scattering plus diffractive scattering) to be about 80 mb
- In-time pile-up:
  - Time indistinguishable from collision of interesting signal process

$$\mu = \sigma L \Delta t \frac{N_{\text{tot}}}{N_{\text{filled}}}$$

$$= \left(80\times10^{-3}\times10^{-24}\ \text{cm}^2\right)\times\left(2\times10^{33}\ \text{cm}^{-2}s^{-1}\right)\times\left(25\times10^{-9}\ \text{s}\right)\times\frac{3564}{2808}$$

$$\mu = 5.1 \quad \text{for } L = 2\times10^{33}$$

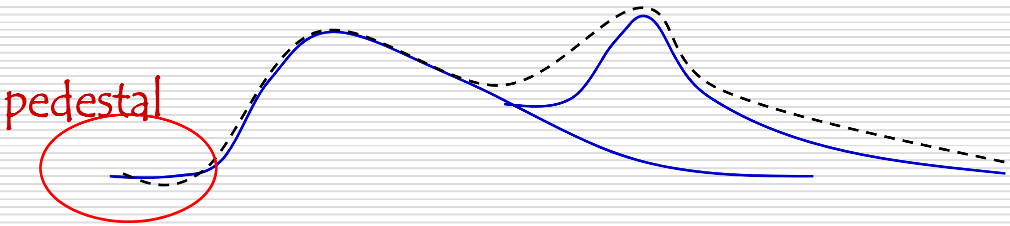
$$\mu = 25 \quad \text{for } L = 10^{34}$$

3.5
17.5
without diffraction

- In addition, pile-up from collisions in bunch crossings just before and just after the signal collision also can affect detector signals
  - Pulses come before or after those from signal process BX

Out-of-time pile-up

- Pulses on same electronic channel:



- If occupancy is high in detector (e.g. tracking and calorimeters), can affect measurement of pulse
- Ways to combat:
  - Good time resolution from detectors/electronics
  - Dynamic pedestal subtraction (sample signal before main pulse)
  - Use shape of pulse to determine if pile-up occurred, correct or remove
- For pulses on different channels:
  - If good time resolution, cut out signals not consistent with signal BX

Effect of pile-up on analyses

- If not otherwise removed electronically (not possible for in-time pile-up), adds energy and tracks to the recorded event
  - Adds underlying energy to jets (should be subtracted)
  - Adds underlying energy around otherwise isolated leptons (decreases isolation efficiency)
  - Worsens the resolution on missing transverse energy
  - Complicates calorimeter calibration
- Should be included into Monte Carlo simulations of detector performance
- Good tracking capability → reconstruct separate vertices for different collisions
  - Use vertex of signal lepton to determine which vertex, or make choice that highest P_T vertex is signal
  - Base isolation on tracks emanating from same signal vertex, not calorimeter energy

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