Z Boson Cross Section Measurement using CMS at the LHC

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Outline

- Standard Model
  - $Z \rightarrow ee$
- Large Hadron Collider
- Compact Muon Solenoid
- Simulation
- Event Selection
- Results
- Conclusions

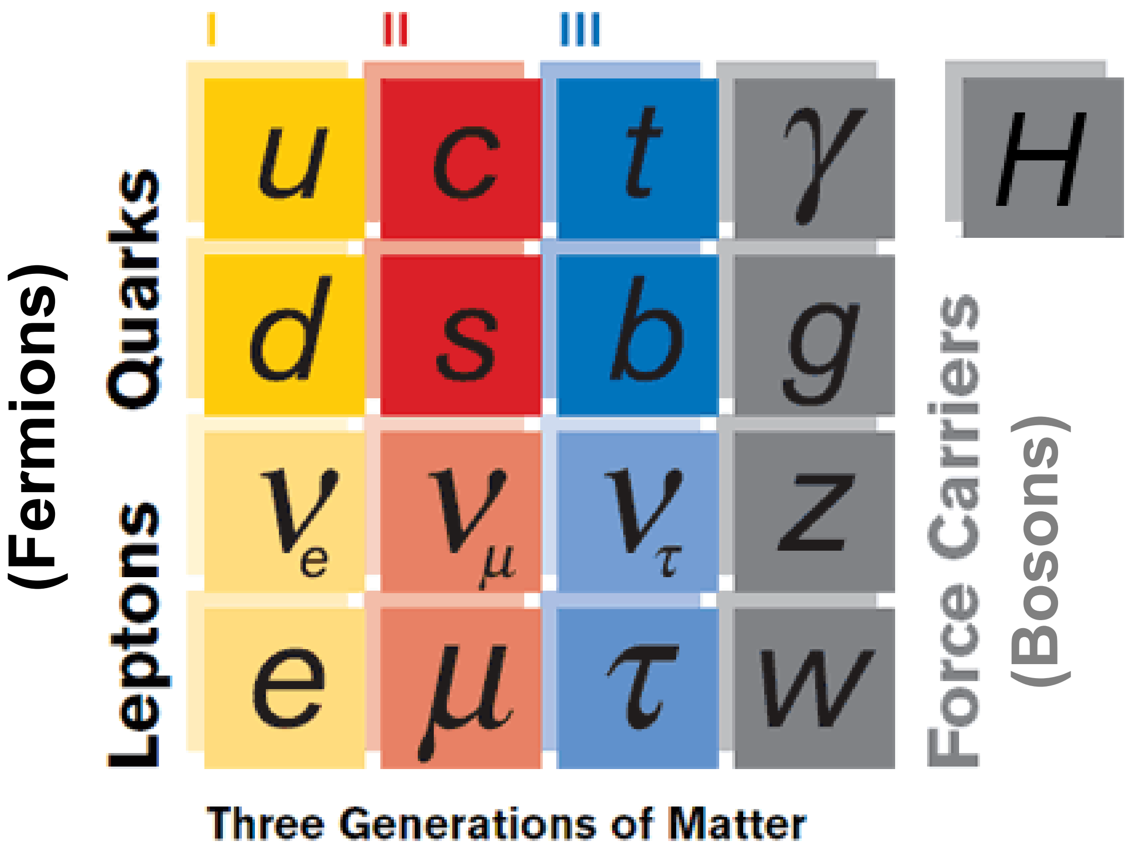
Standard Model

Current framework of knowledge about fundamental particles

Matter particles
- Leptons
- Quarks

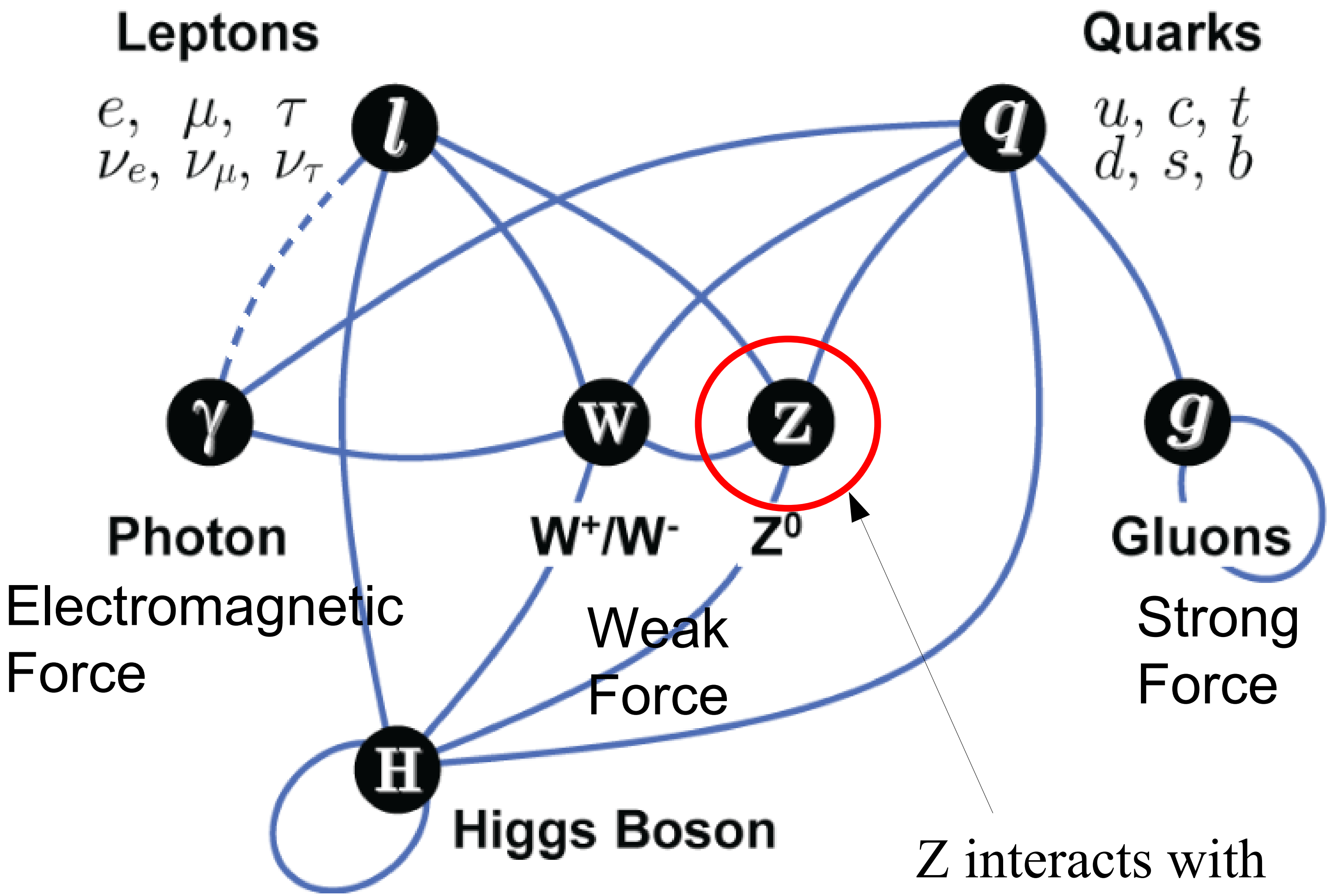
Force carriers
- Photons
- Gluons
- W,Z

Everyday matter



Antiparticles: similar properties, opposite charge

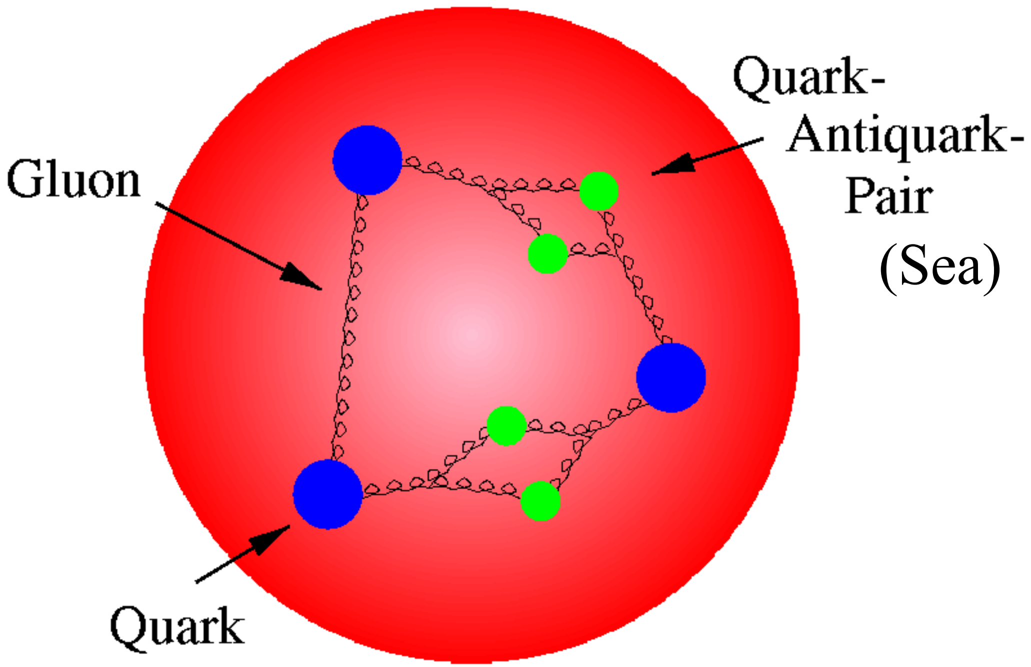
Particle Interactions



Z interacts with all fermions

Proton Structure

- Proton: *uud*
- Constituents (quarks, gluons) = "partons"
- Parton distribution functions $f_i(x)$ (PDFs)
- i = quark flavor
- x = quark's fraction of proton momentum
- PDFs measured experimentally

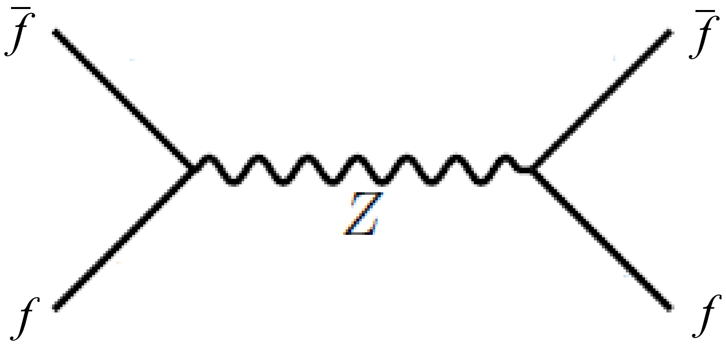


Proton includes *all* quark flavors

The Z Boson

History

- Proposed in 1968 for unification between electromagnetic and weak forces
- Discovered in 1983 at CERN in UA1 and UA2 experiments



M_Z = 91 GeV

Lifetime = 3 x 10^{-25} s

f = u,d,...

e,μ,τ,

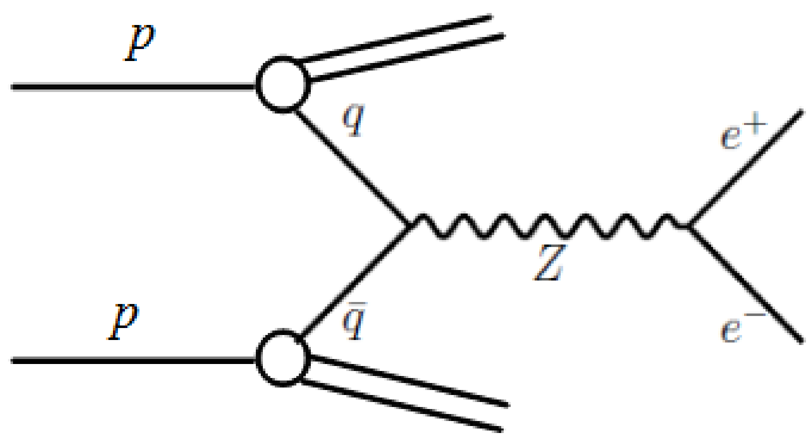
ν_e,ν_μ,ν_τ

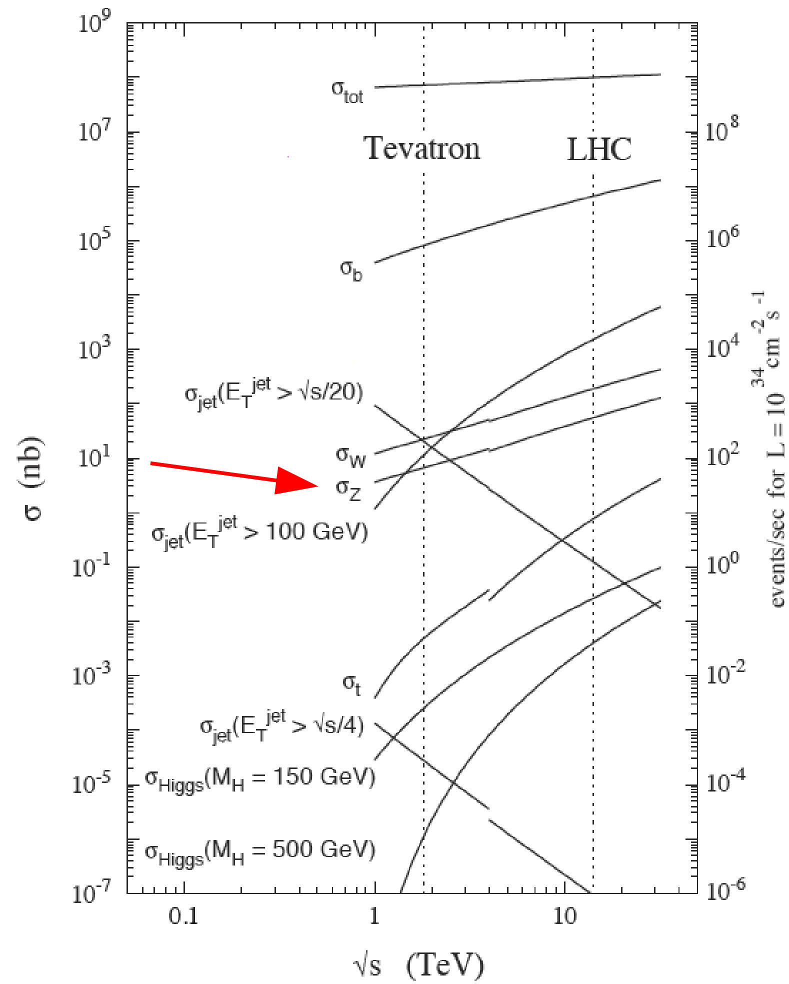
Branching ratio (BR): likelihood of Z decaying to given final state

Role in physics

- Mediates weak force (interacts with all fermions)
- Lifetime gives prediction for number of neutrino flavors

$Z \to ee$





Why look at $Z \to ee$?

- High rate, very clean signal, virtually no background → ideal "standard candle" for detector calibration
- Clean signal → test between PDF sets
- High end of mass spectrum may show signs of new physics

$$M_{inv} = \sqrt{(E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2}$$

Electron invariant mass peaked around Z mass

$Z \rightarrow ee$ Cross Section

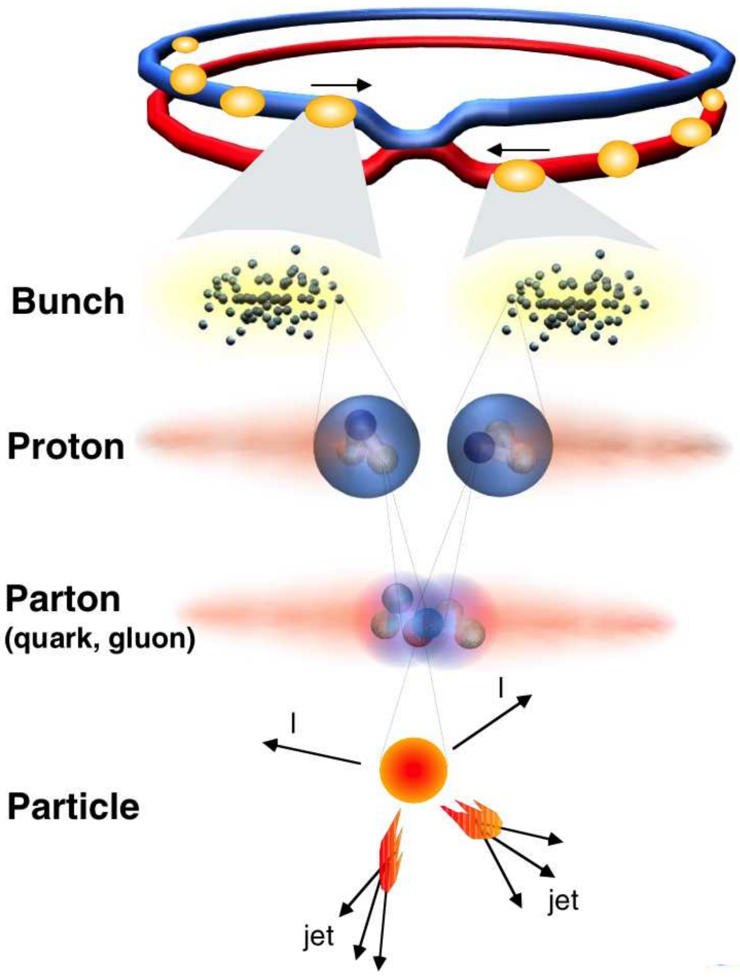
Aim: Measure cross section of $Z \rightarrow ee$ within detector acceptance and mass window $60 < M < 120$ GeV

– Cross section σ: "probability" of interaction

$$\sigma_Z \times \mathrm{BR}\,(Z \rightarrow ee) = \frac{n_{Z\rightarrow ee}}{\mathcal{L} \times \epsilon \times A}$$

- $n_{Z\text{->}ee}$: number of Z candidate events
- A: acceptance, fraction of events visible in CMS
- ε: efficiency of event reconstruction
- L: luminosity, total data taken

Proton-proton interactions at LHC



	Design	Achieved
Proton-Proton	2835 bunch/beam	1380
Protons/bunch	10^{11}	1.3×10^{11}
Beam energy	7 TeV (7×10^{12} eV)	3.5 TeV
Luminosity	10^{34} cm^{-2} s^{-1}	1.55×10^{33} cm^{-2}s^{-1}
Crossing rate	40 MHz	
Collisions ≈	10^7 - 10^9 Hz	

Luminosity L = particle flux/time, units of 1/(area*time) (cm^{-2}s^{-1})

Integrated luminosity *L*: total over period of time, units of 1/area ("barn" b= 10^{-28}m^2)

Interaction rate $dN/dt = L\sigma$

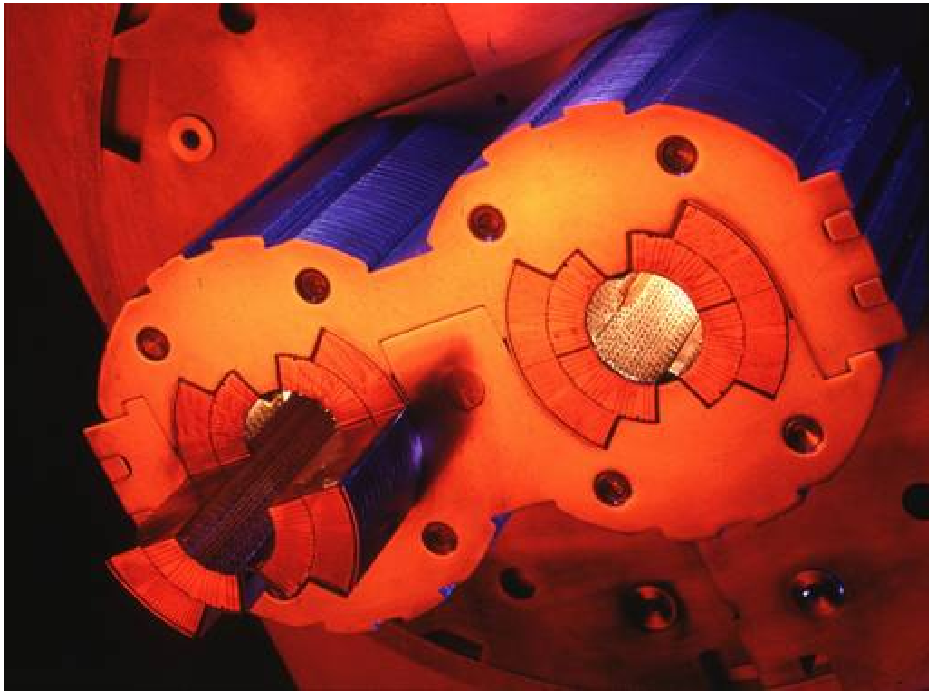
Cross section σ = "effective" area of interacting particles

During 2010
3.5 TeV
2×10^{32} cm^{-2}s^{-1}

LHC Magnets

Superconducting NbTi magnets require T = 1.9K

- 1232 dipoles bend proton beam around ring, B = 4T
- Quadrupoles focus beam



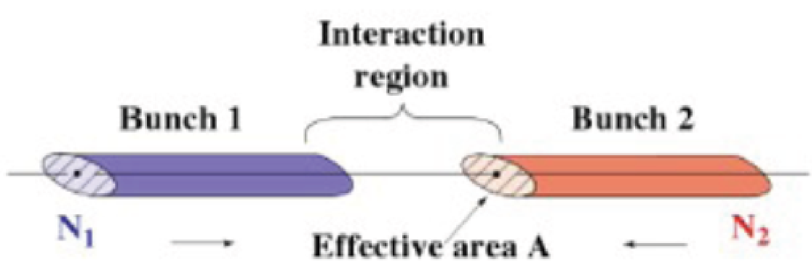
Measurement of Luminosity

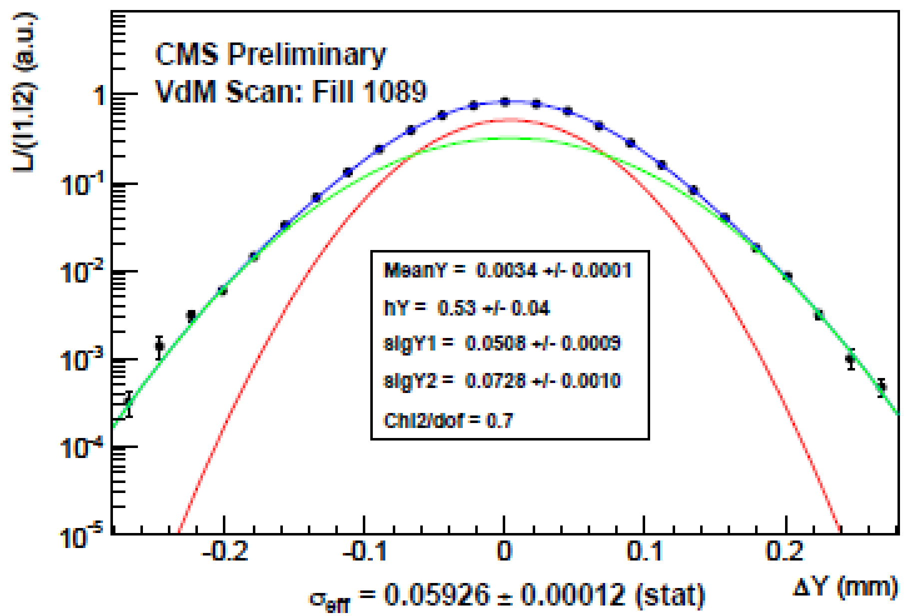
- Instantaneous measurement done using CMS forward hadronic calorimeter (HF)
  - Average transverse energy per HF tower
- Normalized via van der Meer scan

$$\mathcal{L} = N_1 N_2 f n_b \int \rho_1(x,y)\rho_2(x,y)dxdy$$

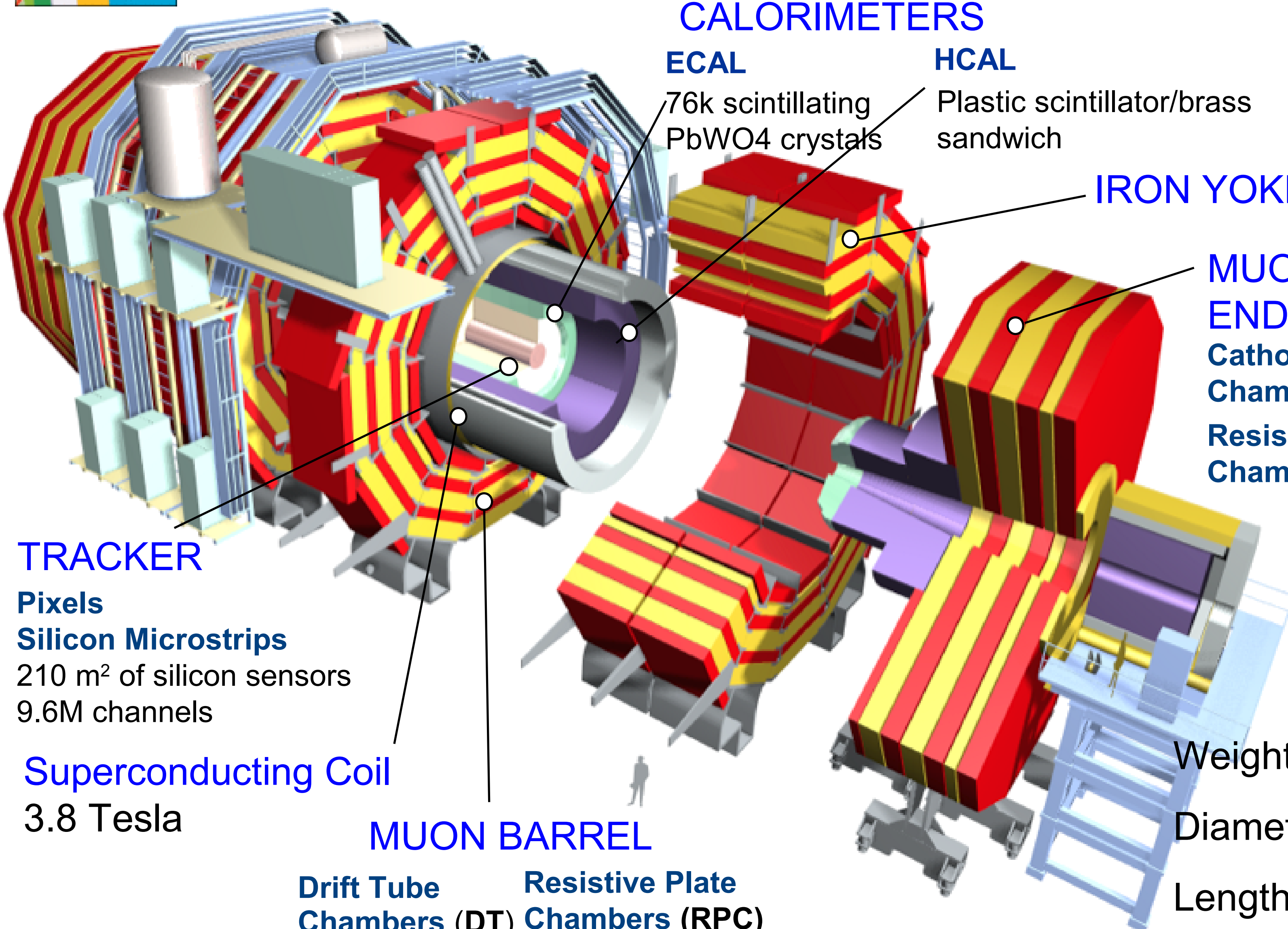
$$\mathcal{L} = \frac{N_1 N_2 f n_b}{A_{eff}}$$

$$A_{eff} = 2\pi\sigma_x\sigma_y$$





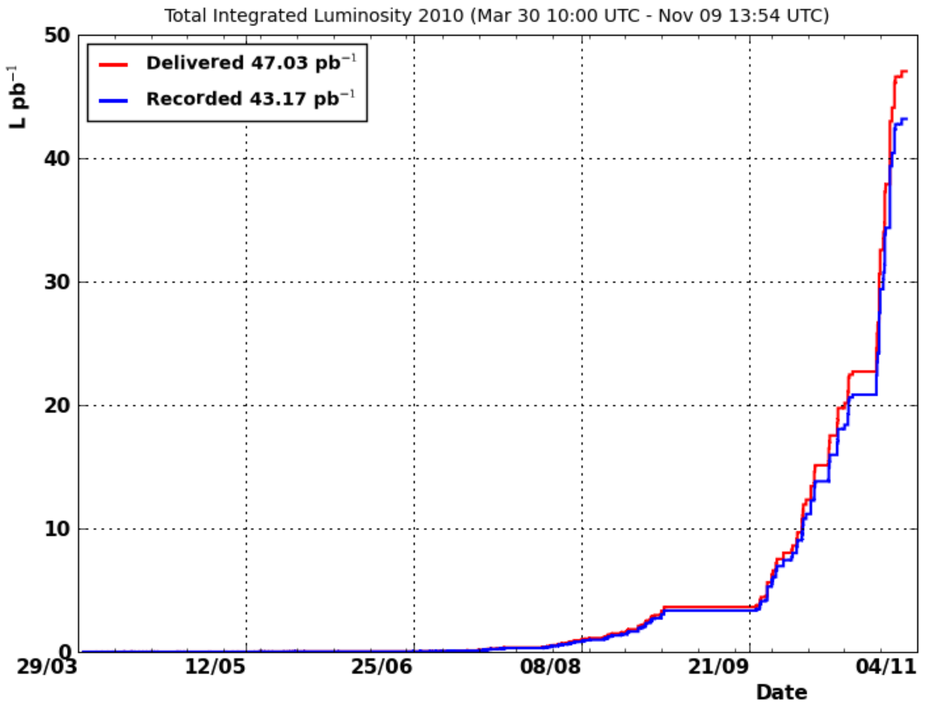
Compact Muon Solenoid (CMS)



Current CMS Status

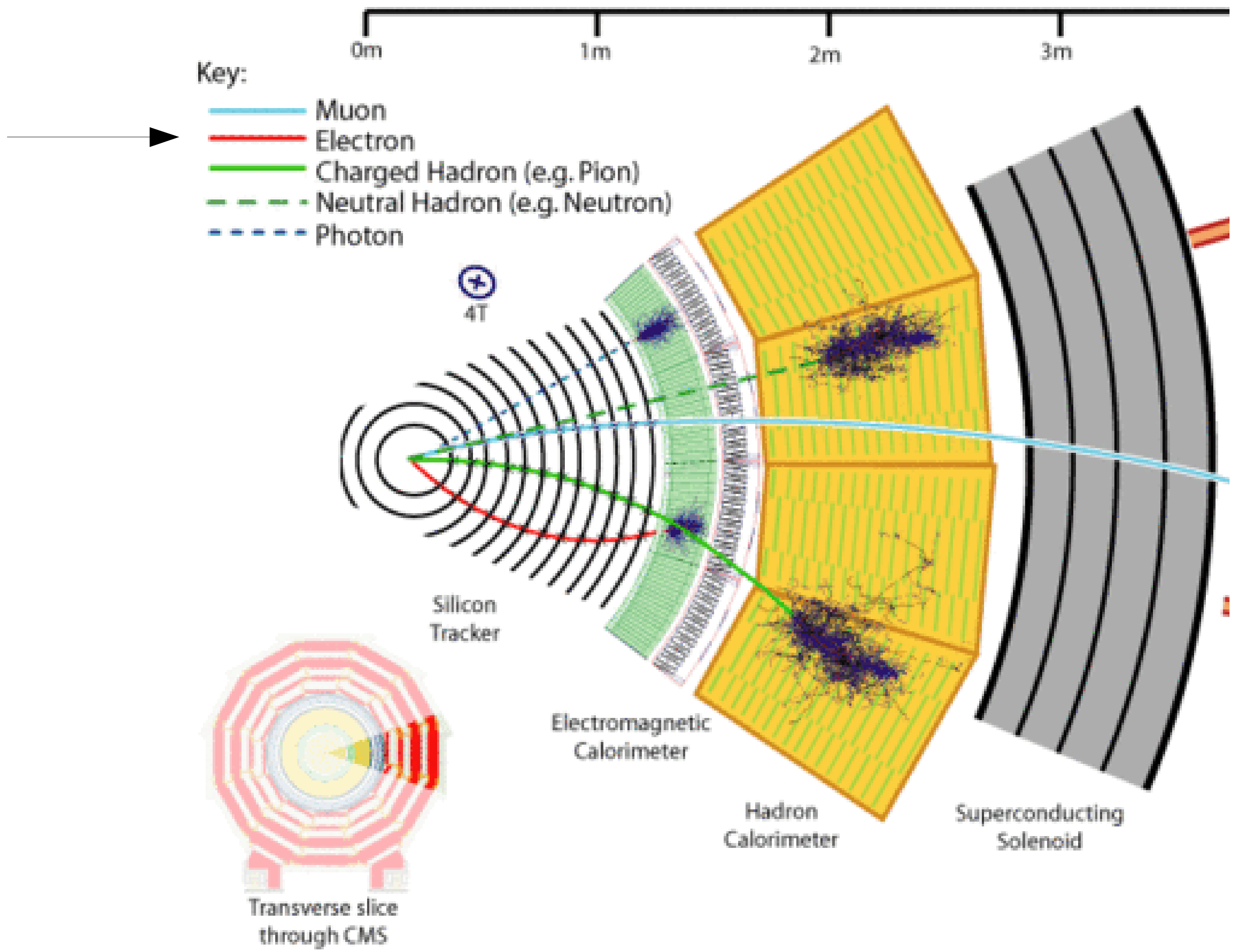
7 TeV collision run began March 2010

- 2010: 36.1 pb^{-1} good data recorded, all subdetectors good (43 pb^{-1} total recorded)



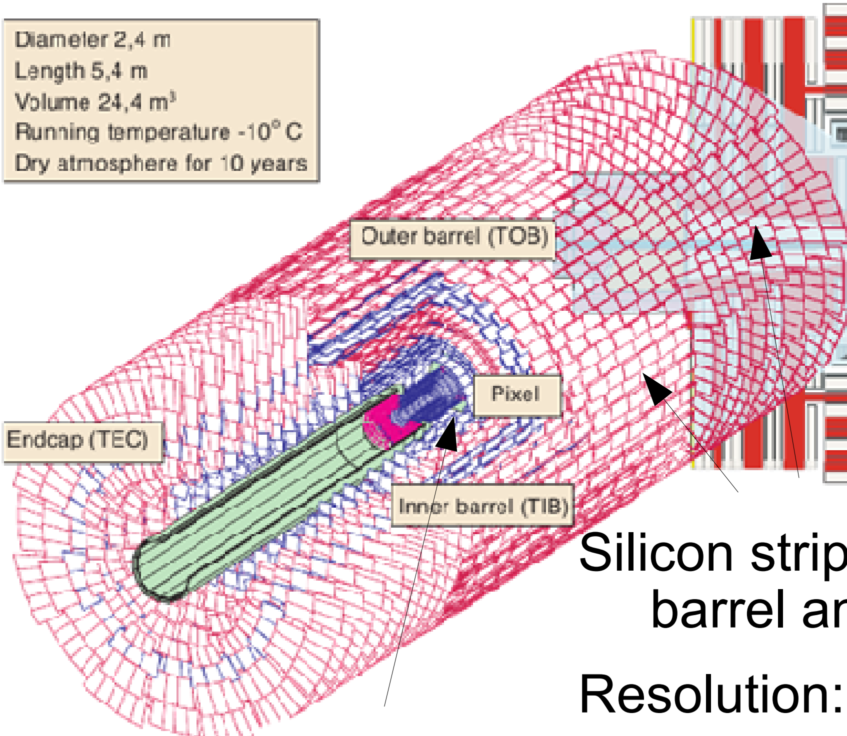
- Z cross section analysis first electroweak analysis published. Many more analyses published, as well
- 2011: 1.23 fb^{-1} and counting...

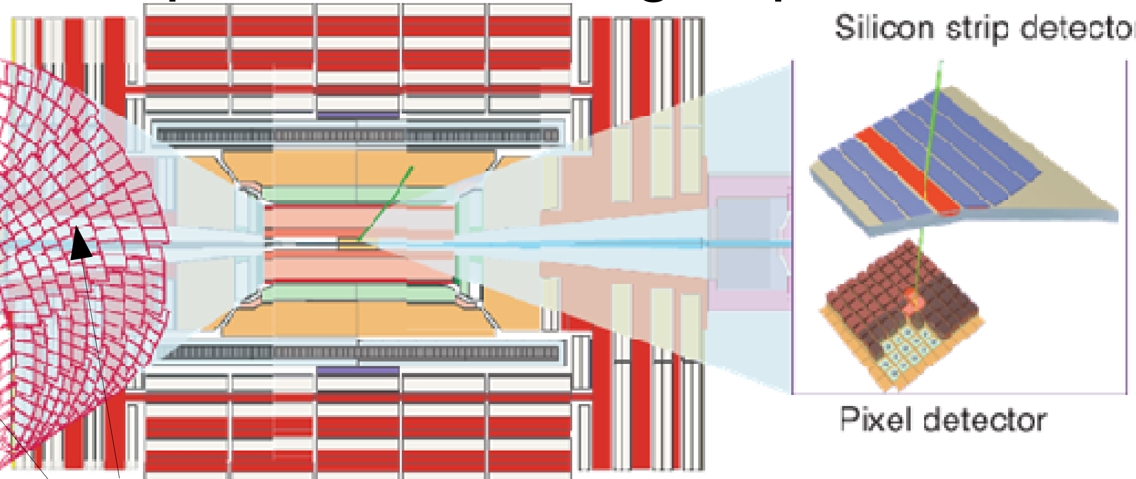
Seeing Particles in CMS



Tracker

Measures momentum and position of charged particles





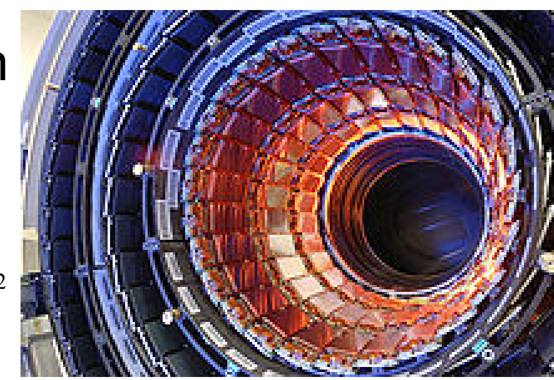
Silicon strip detectors used in barrel and endcaps

Resolution: 15-50 μm

Silicon pixel detectors used closest to the interaction region

$$\left(\frac{\sigma}{p_T}\right)^2 = (0.5\%)^2 + (0.015\, p_T)^2$$

Resolution: 15 μm



75 million total channels

Tracker coverage extends to |η|<2.5, with maximum analyzing power in |η|<1.6

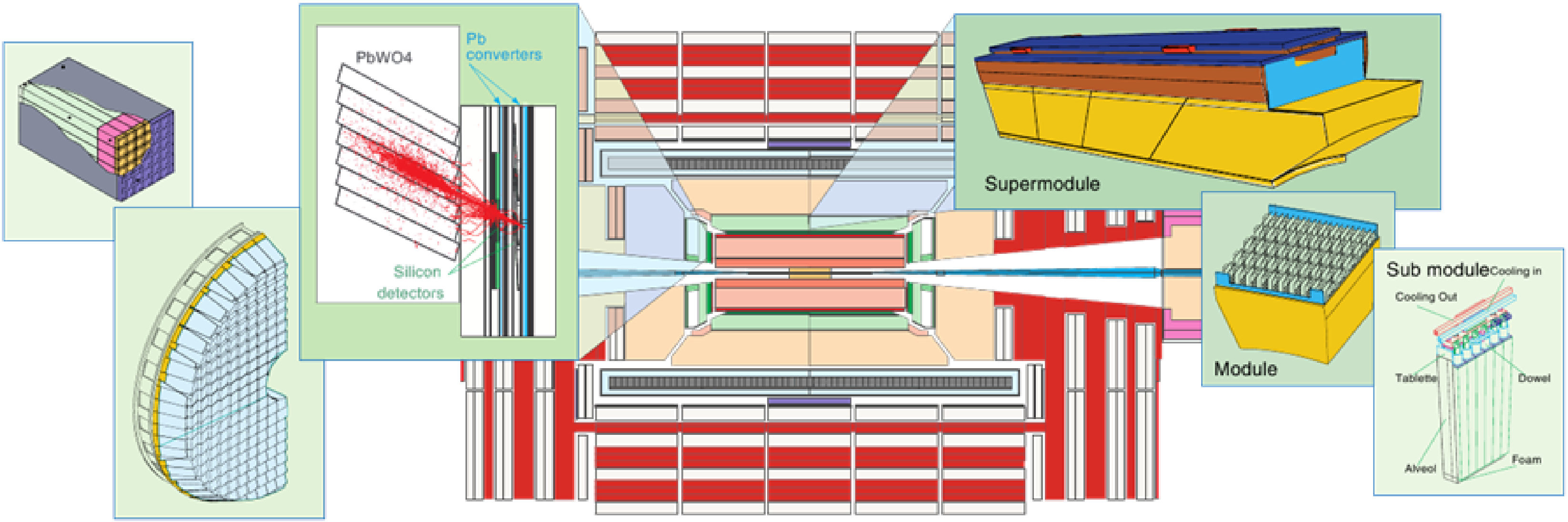
Electromagnetic Calorimeter (ECAL)

Measures electron/photon energy and position to $|\eta| < 3$

~76,000 lead tungstate ($PbWO_4$) crystals

- High density
- Small Moliere radius (2.19 cm) compares to 2.2 cm crystal size

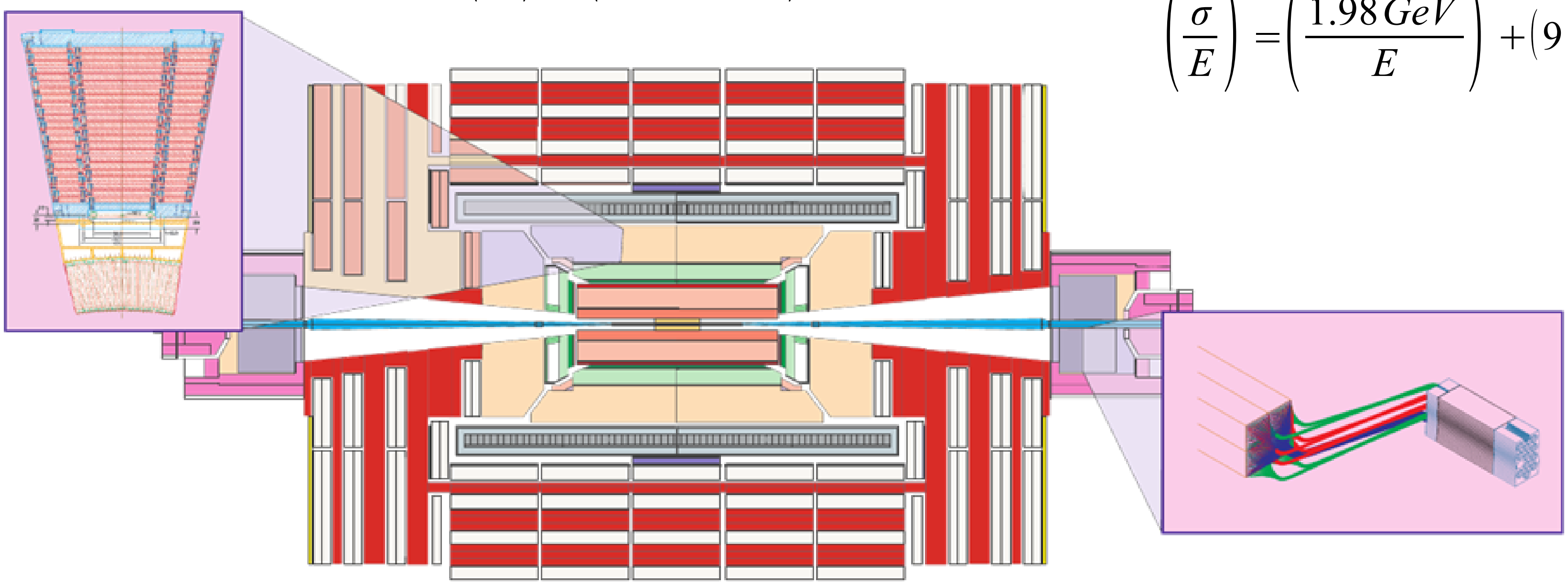
Resolution: $$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{41.5\,MeV}{E}\right)^2 + \left(0.30\%\right)^2$$



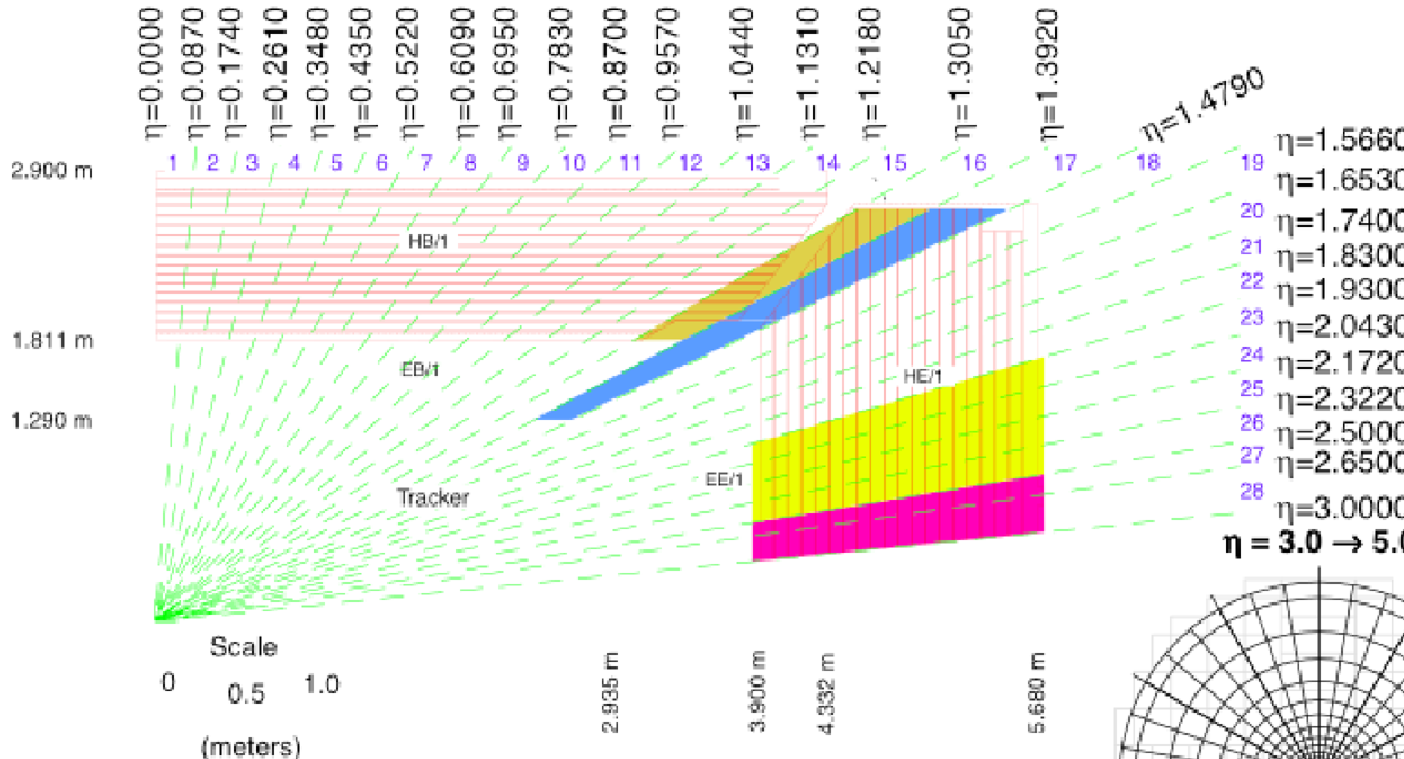
Hadronic Calorimeter (HCAL)

HCAL samples showers to measure energy/position of hadrons, vetoes electrons

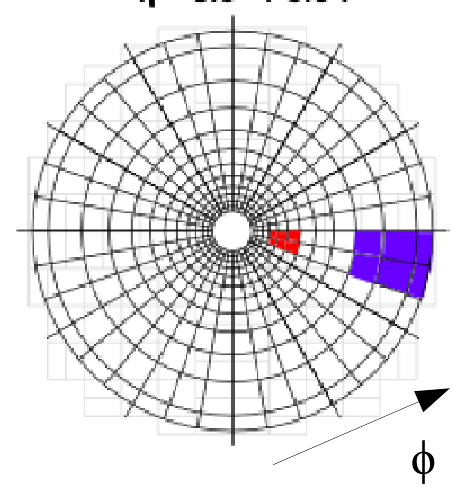
- HB/HE -- barrel/endcap region
  - Brass/scintillator layers
  - Eta coverage $|\eta| < 3$
  - Resolution: $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{0.847\,GeV}{E}\right)^2 + (7.4\,\%)^2$
- HF -- forward region
  - Steel plates/quartz fibers
  - Eta coverage to ±5
  - Resolution: $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{1.98\,GeV}{E}\right)^2 + (9\,\%)^2$



Calorimeter Geometry



η = 3.0 → 5.0 :



$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

2 CMS HF Calorimeters mapping onto Trigger System Jet/Summary Card

Readout segmentation: 36ϕ × 12η × 2z × 2F/B

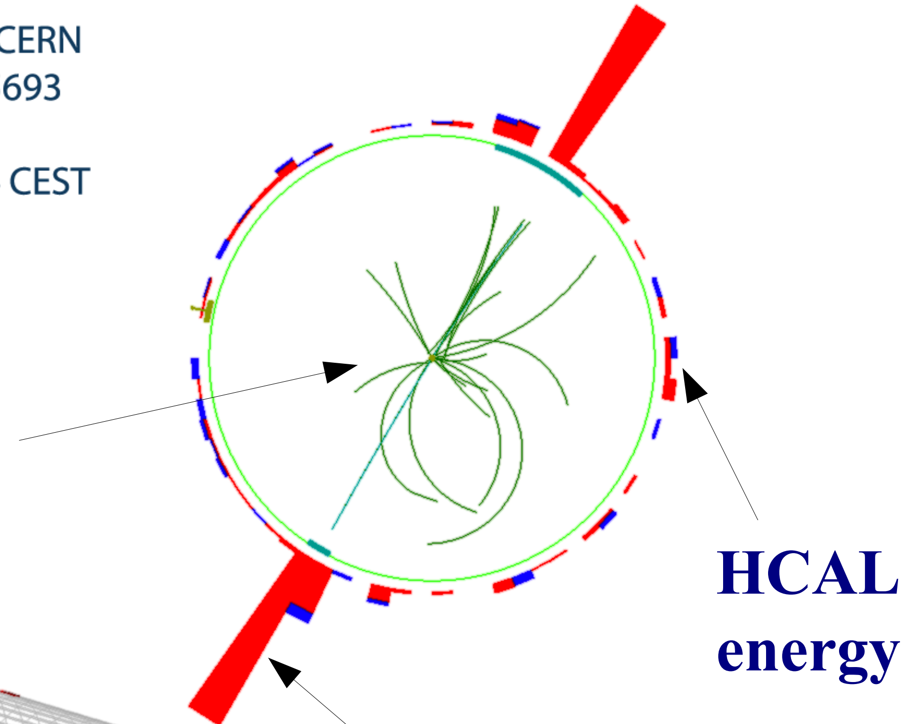
Trigger Tower segmentation: 18ϕ × 4η × 2F/B

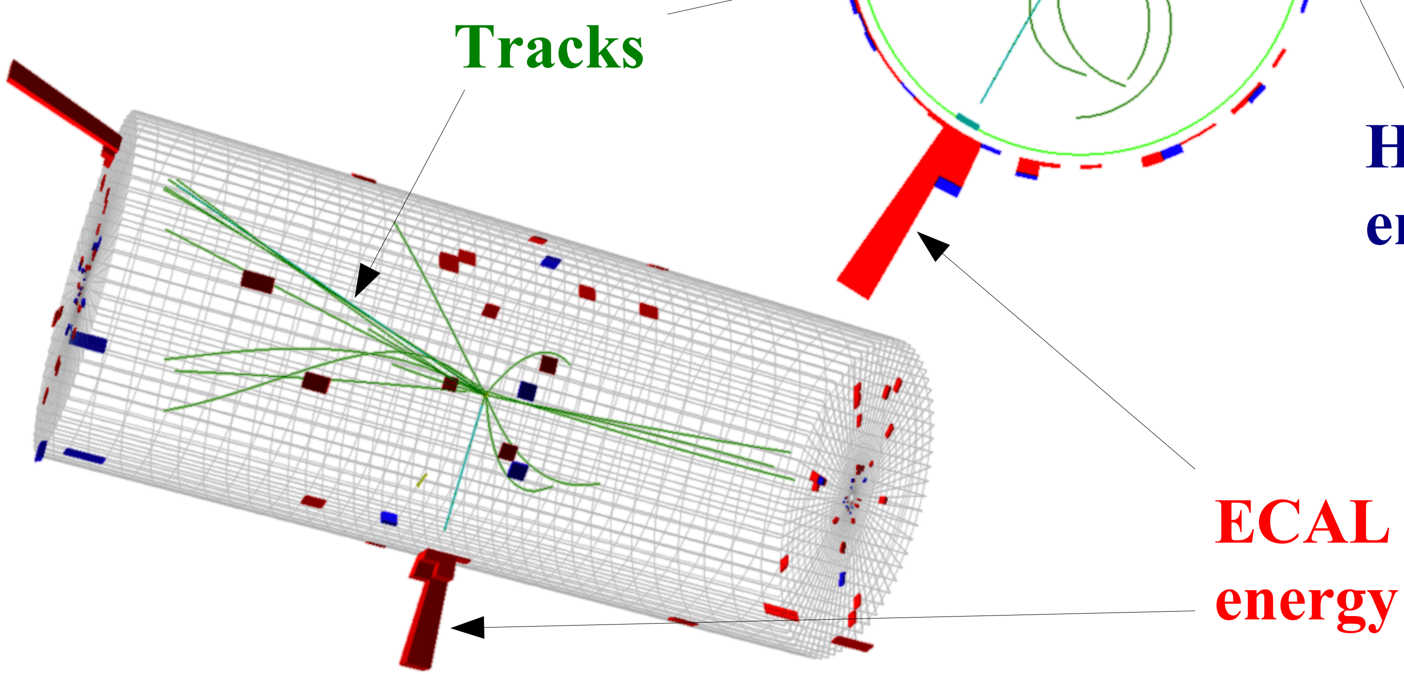
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

Z→ee Event Display

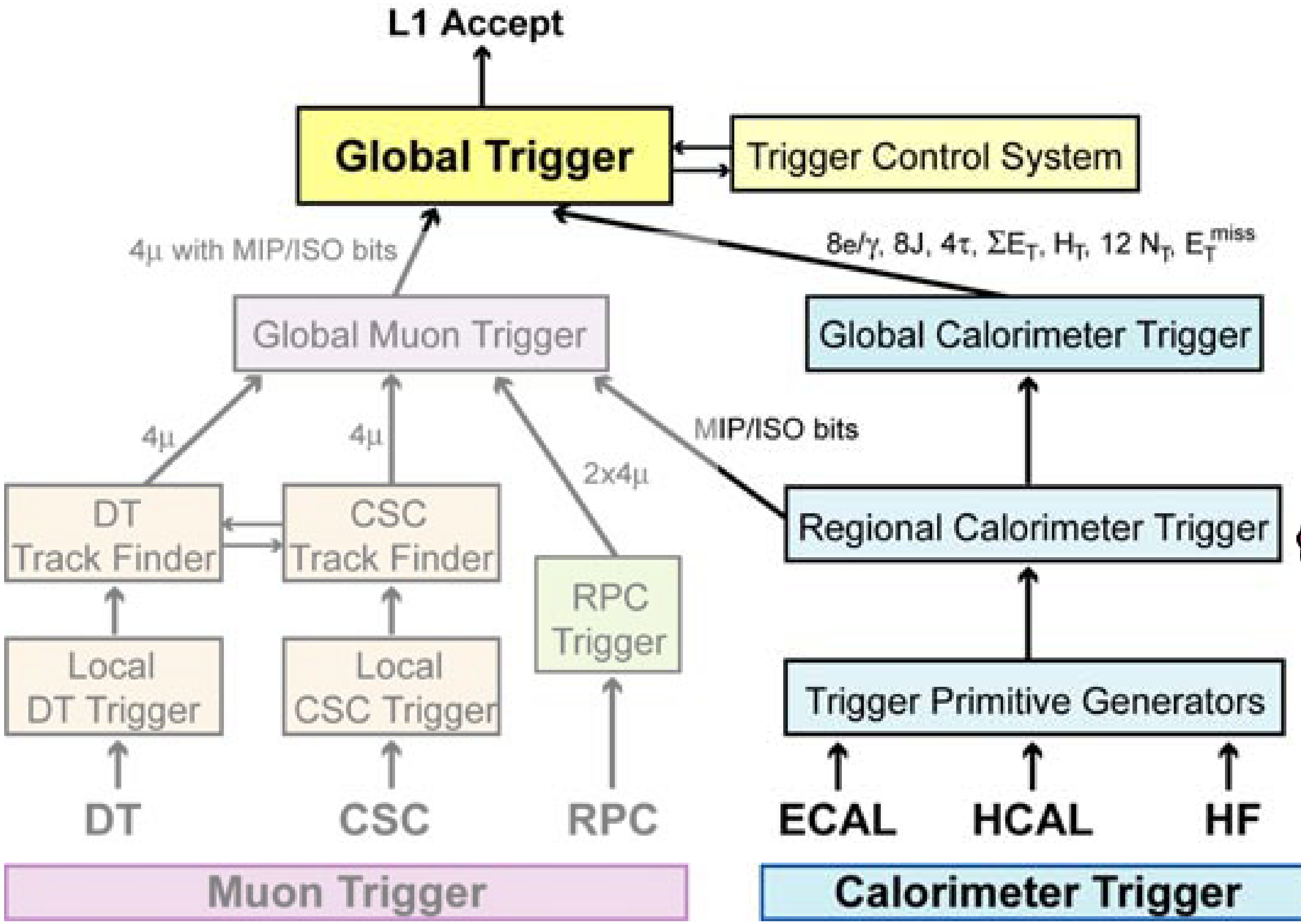
CMS Experiment at LHC, CERN
Run 133877, Event 28405693
Lumi section: 387
Sat Apr 24 2010, 14:00:54 CEST

Electrons p_T = 34.0, 31.9 GeV/c
Inv. mass = 91.2 GeV/c^2

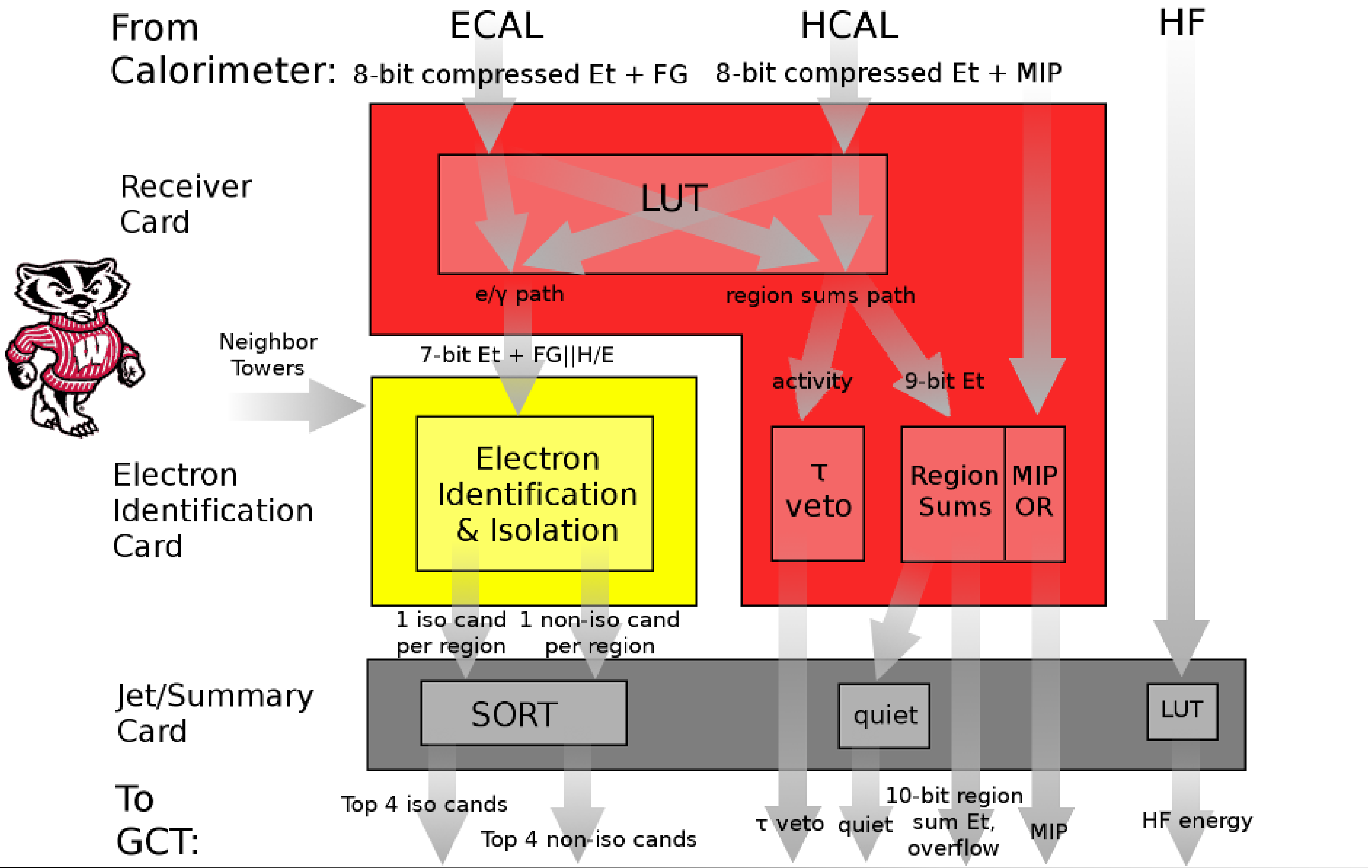




Level-1 Trigger



Regional Calorimeter Trigger



Level-1 Electron Algorithms

Electron (Hit Tower + Max)

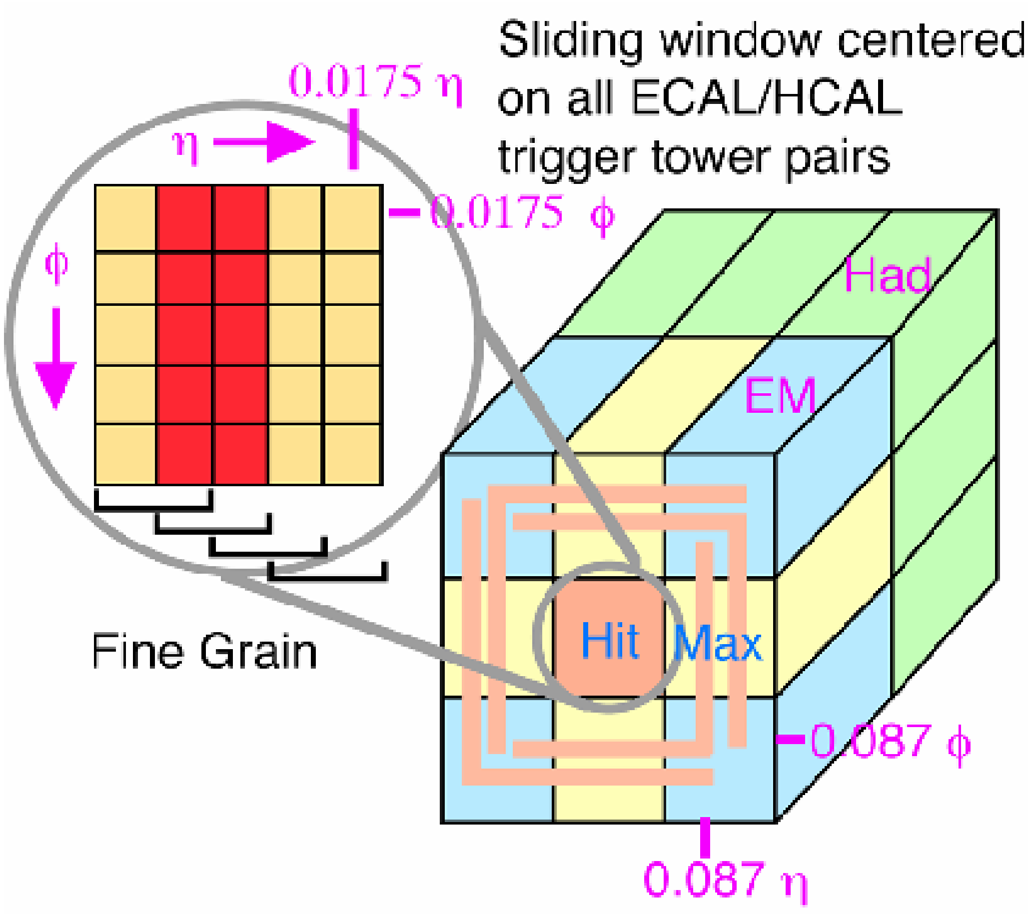
- 2-tower $\sum E_T$ + Hit tower H/E
- Hit tower 2x5-crystal strips >90% E_T in 5x5 (Fine Grain)

Isolated Electron (3x3 Tower)

- Quiet neighbors: all towers pass Fine Grain & H/E
- One group of 5 EM E_T < Threshold

Electron triggers

- Required one electron object above 5 or 8 GeV (evolved with luminosity)

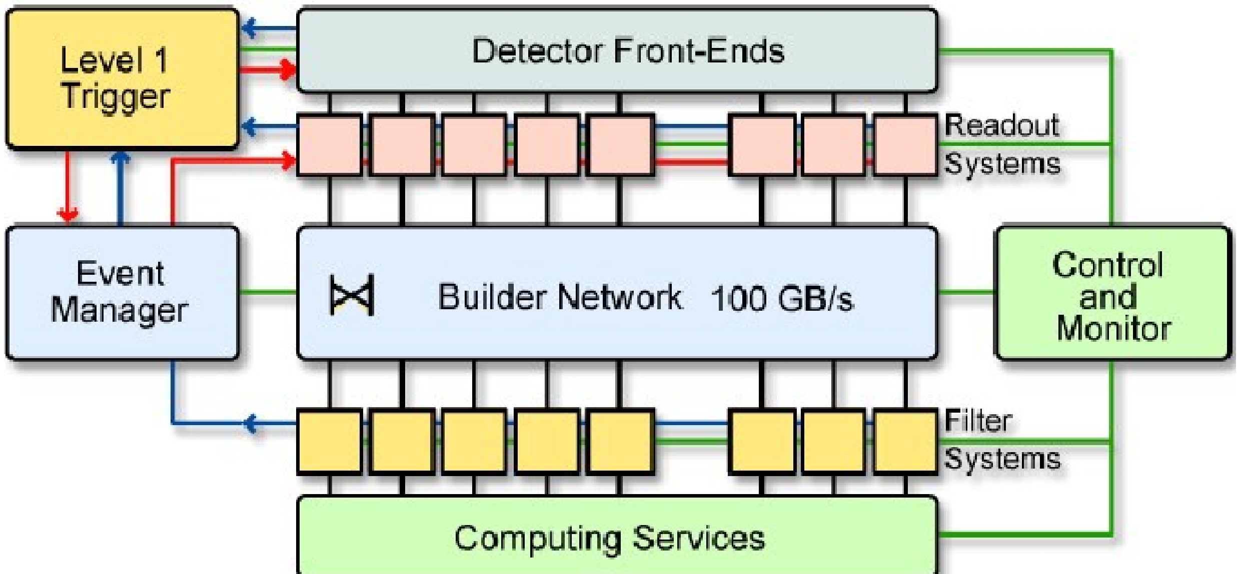


High-Level Trigger

Reconstruction done using High-Level Trigger (HLT) -- computer farm

Reduces rate from Level-1 value of up to 100 kHz to final value of ~300 Hz

Slower, but determines energies and track-cluster matching to high precision

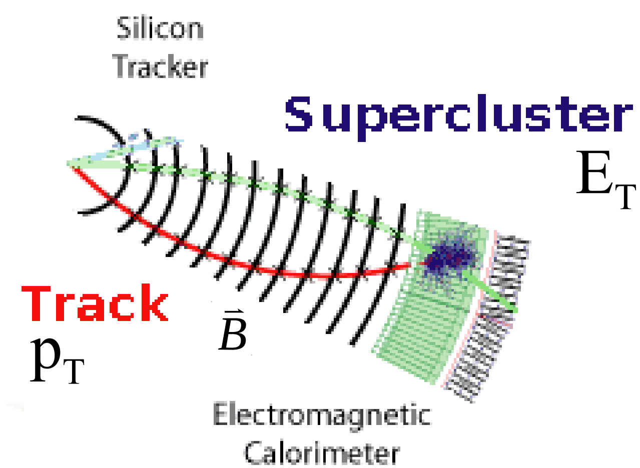


Electron triggers: one reconstructed electron above threshold (15 or 17 GeV), later triggers had stricter requirements (higher luminosity)

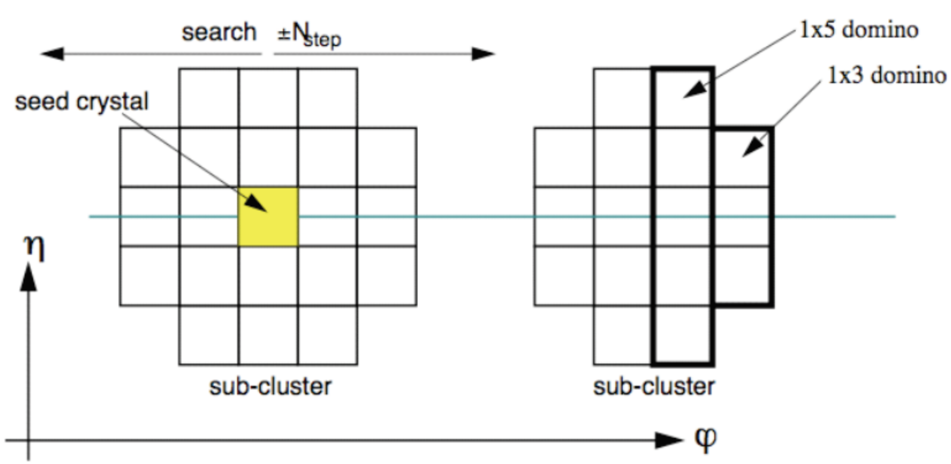
Electron Reconstruction: Energy Clustering

Create "superclusters" (SC) from clusters of energy deposits in ECAL

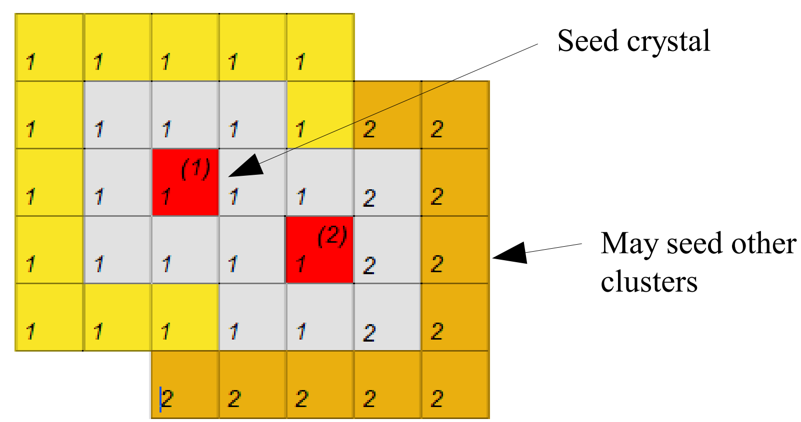
- Must have E_T greater than some threshold
- Seed crystals: E_T higher than neighboring crystals
- Energy grouped into clusters, which make up superclusters



Hybrid (barrel)

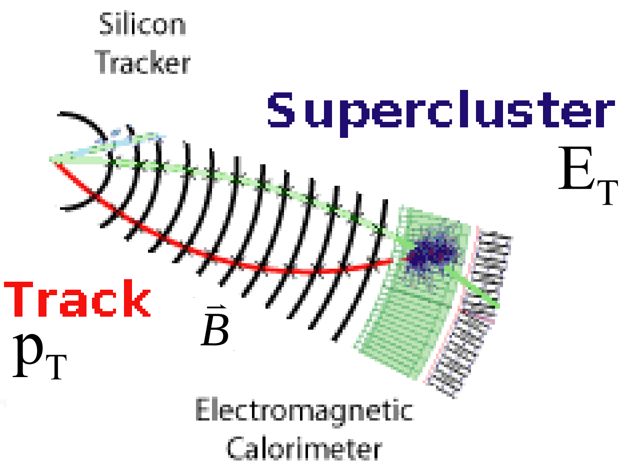


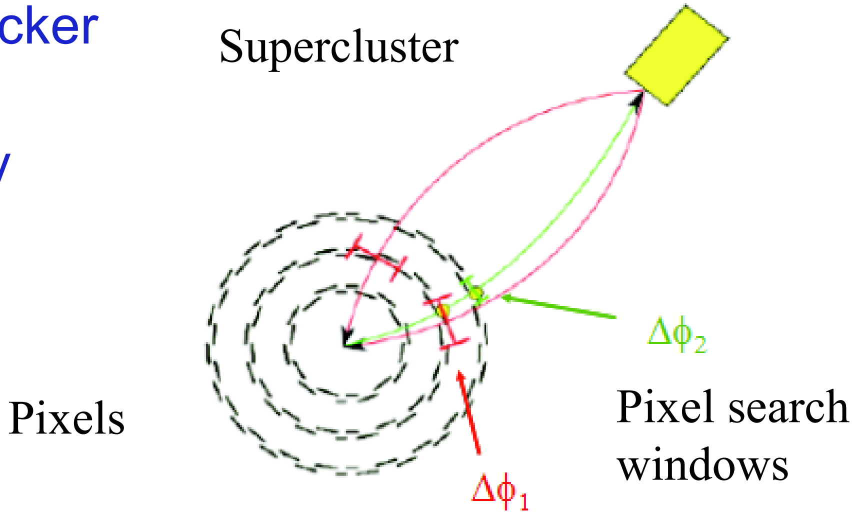
Multi5x5 (endcap)



Electron Reconstruction: Tracking

- Match superclusters to hits in pixel detector
  - Electrons create a hit (photons do not!)
  - Search for successive pixel hits
- Combine with full tracking information
  - Track seeded with pixel hit
  - Hits sought in successive tracker layers
  - Series of hits forms trajectory





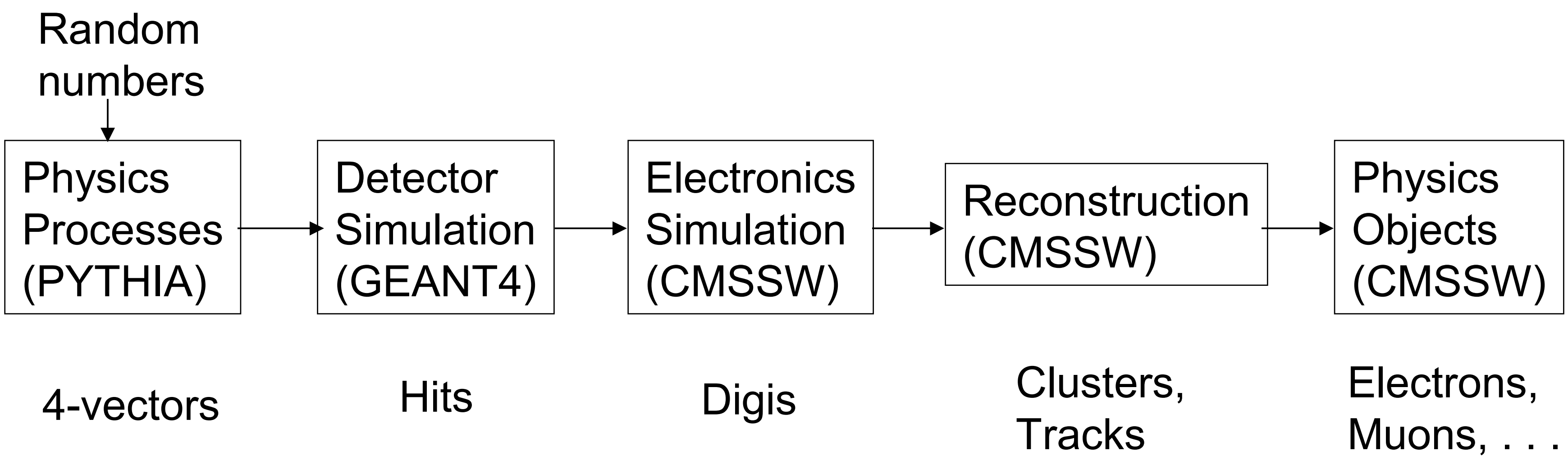
Simulation

How do we know all our algorithms actually work?

- Simulate the entire event
- Run it through the actual reconstruction.

We know what the “right” answer is, so we can tell how well our reconstruction algorithms work.

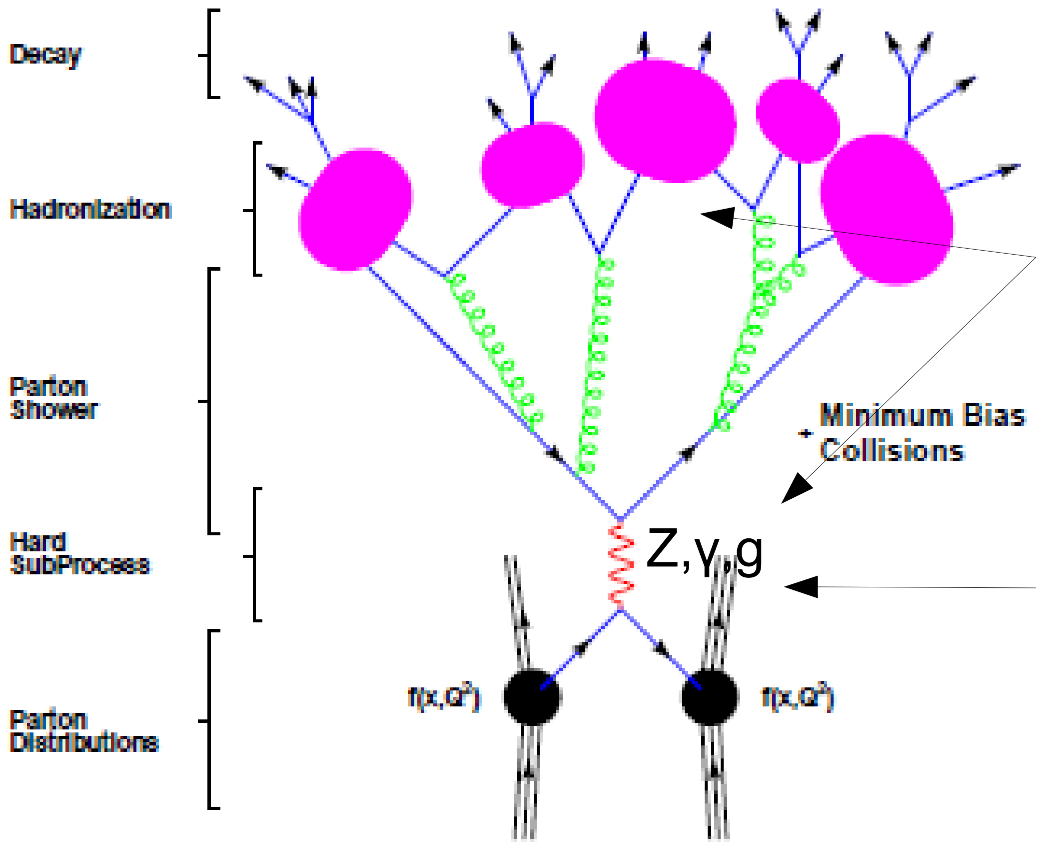
Framework for reconstruction is CMS SoftWare (CMSSW)



Monte Carlo (MC)

Modular design of parton shower MC

MC: Simulate events, distributions from random numbers



PYTHIA

- General-purpose workhorse event generator
- Background events

POWHEG

- Specialized NLO event generator
- Signal events

Acceptance: Definition

Acceptance (A): Fraction of events that can theoretically be seen by detector

- Determined by solid-angle coverage, low end of energy sensitivity

Must be determined from MC: need to know how many events the detector *didn't* see

Acceptance Calculation

Sample used: Z → ee POWHEG

Generator-level acceptance:

- In Z mass window 60 GeV < M_{inv} < 120 GeV:
- 2 final-state electrons from Z, E_T > 25 GeV, |η| < 2.5
- A: 0.423

"ECAL Acceptance" (matched to supercluster) to account for SC reconstruction efficiency:

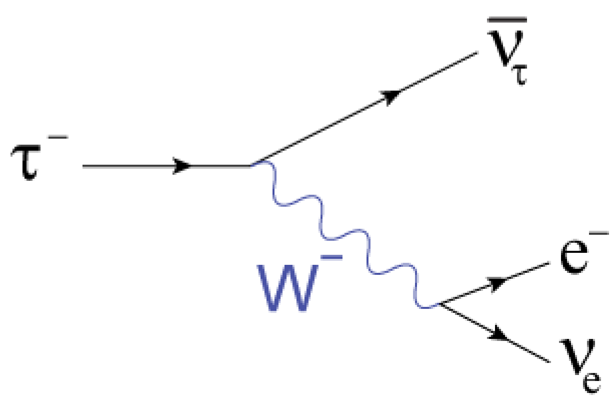
- 2 final-state electrons from Z matched to supercluster within ΔR = 0.2.
- SC: E_T > 25 GeV, |η| < 1.4442 or 1.566 < |η| < 2.5
- A_{ECAL}: 0.387

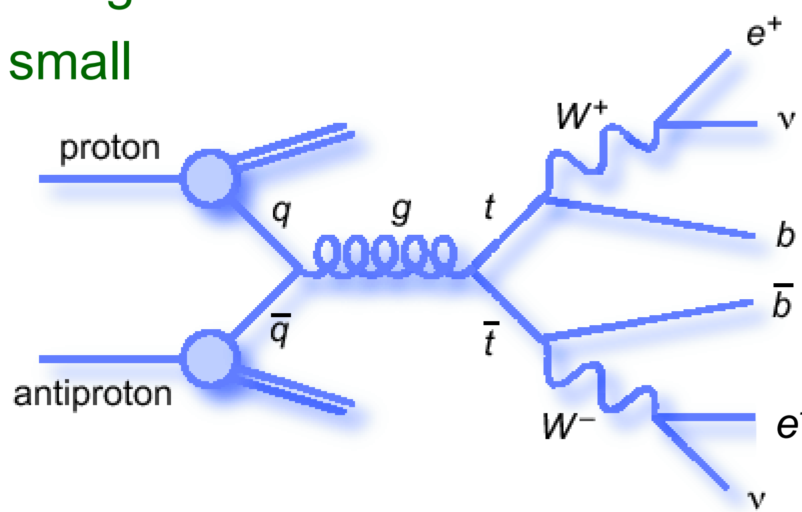
Avoid problematic boundary

Backgrounds

Anything that can look like two electrons from a Z

- Jets faking electrons: QCD
- Real electrons from τ's
- 1 real electron from W decay, one fake electron
- Real or fake electrons from top pair decays
- Diboson (WW, WZ, ZZ)
  - Includes Z production, but considered background because can't distinguish electrons
  - Contribution very small





Selection Strategy

Differentiate signal from background, then cut out background

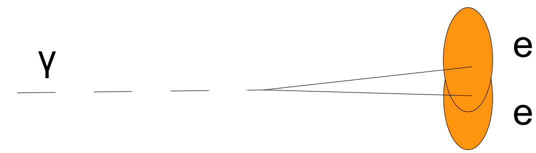
Requirements = “cuts”

Background electrons

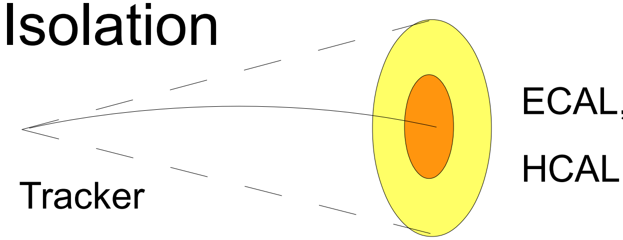
- From photons (γ->ee, photon “converts”): far from interaction point, tracks close together
- Within jets: too much surrounding energy
- Fake (electron-like signatures): spread out, potential bad match between track and cluster

Signal electrons: well-reconstructed tracks, narrow energy deposit mostly in ECAL, good track-cluster match

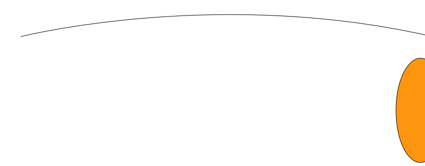
Conversion rejection



Isolation



Electron Identification



Therefore:

Pick events with two “signal” electrons

Electron Selection Variables

Conversion rejection

- Require track in full tracker: number of missing hits
- Require no partner tracks: distance (dist) or angle (Δcotθ)

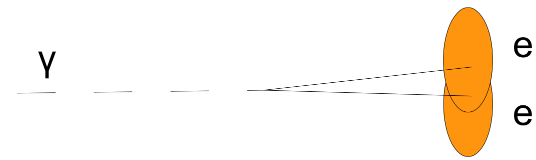
Isolation: make sure electron isolated in

- Tracker cone
- ECAL radius
- HCAL radius

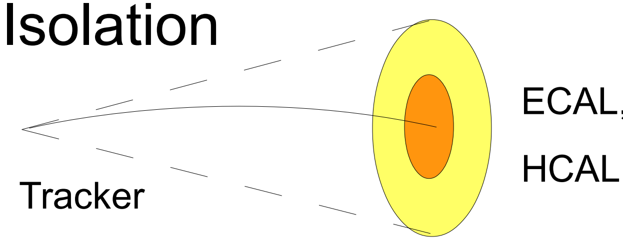
Electron Identification

- Match track to cluster in η: $\Delta\eta_{in}$
- Match track to cluster in ϕ: $\Delta\phi_{in}$
- Require cluster to be narrow: $\sigma_{i\eta i\eta}$
- Require cluster to be mostly in ECAL (H/E ratio)

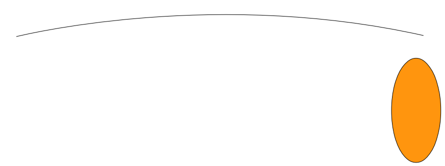
Conversion rejection



Isolation



Electron Identification



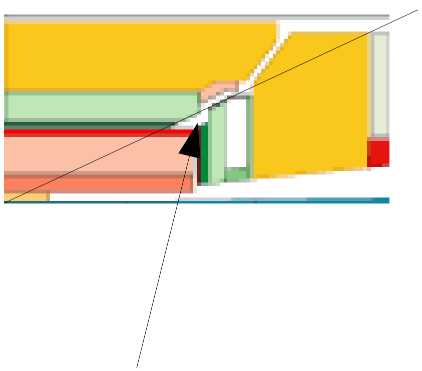
$$\sigma_{i\eta i\eta} = \sqrt{\frac{\sum_i (\eta_i \times 0.0175 + \eta_{seed} - \eta_{5\times5}^{avg})}{\sum_i w_i}}$$

$$w_i = 4.2 + \ln \frac{E_i}{E_{5\times5}}$$

Event Selection

Require two electrons

- $|\eta| < 1.4442$ or $1.566 < |\eta| < 2.5$
- Supercluster $E_T > 25$ GeV
- Passing “good electron” selection cuts
- At least one electron passing trigger
- Mass window: $60 < M_{inv} < 120$



$|\eta| \sim 1.5$: ECAL barrel/endcap overlap region, poor electron reconstruction performance

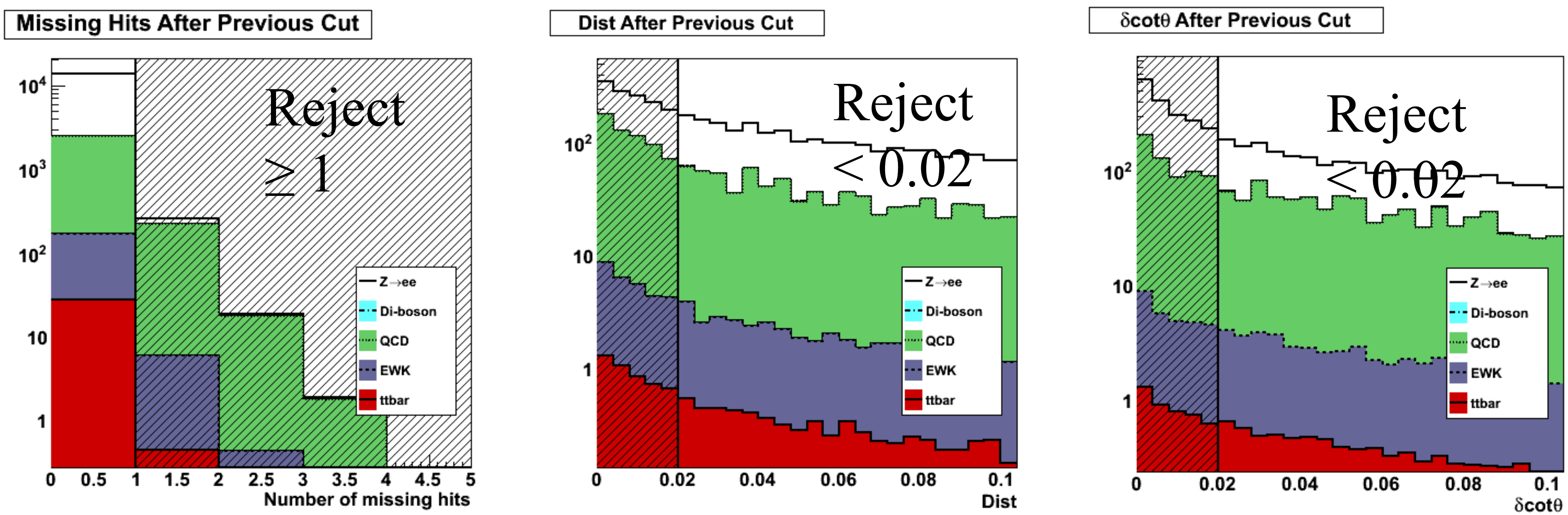
WP80	Barrel	Endcap
Conversion Rejection		
Missing Hits	0	0
dist	0.02	0.02
$\Delta cot\theta$	0.02	0.02
Relative Isolation		
ECAL	0.07	0.05
HCAL	0.10	0.025
Track	0.09	0.04
Electron Identification		
$\sigma_{i\eta i\eta}$	0.01	0.03
$\Delta\phi_{in}$	0.06	0.03
$\Delta\eta_{in}$	0.004	0.007
H/E	0.04	0.025

* Selection plots on following slides show MC only (QCD MC samples include isolation cuts, disagree with data until all cuts applied)

Conversion Rejection Cuts

Reject electron pairs from photon conversions (γ->ee)

- These electrons originate far from interaction point, are very close together



Require electron to pass missing hits requirement and either dist or Δcotθ requirement (allows for anomalous dist or Δcotθ value)

38553 out of 49962 events kept

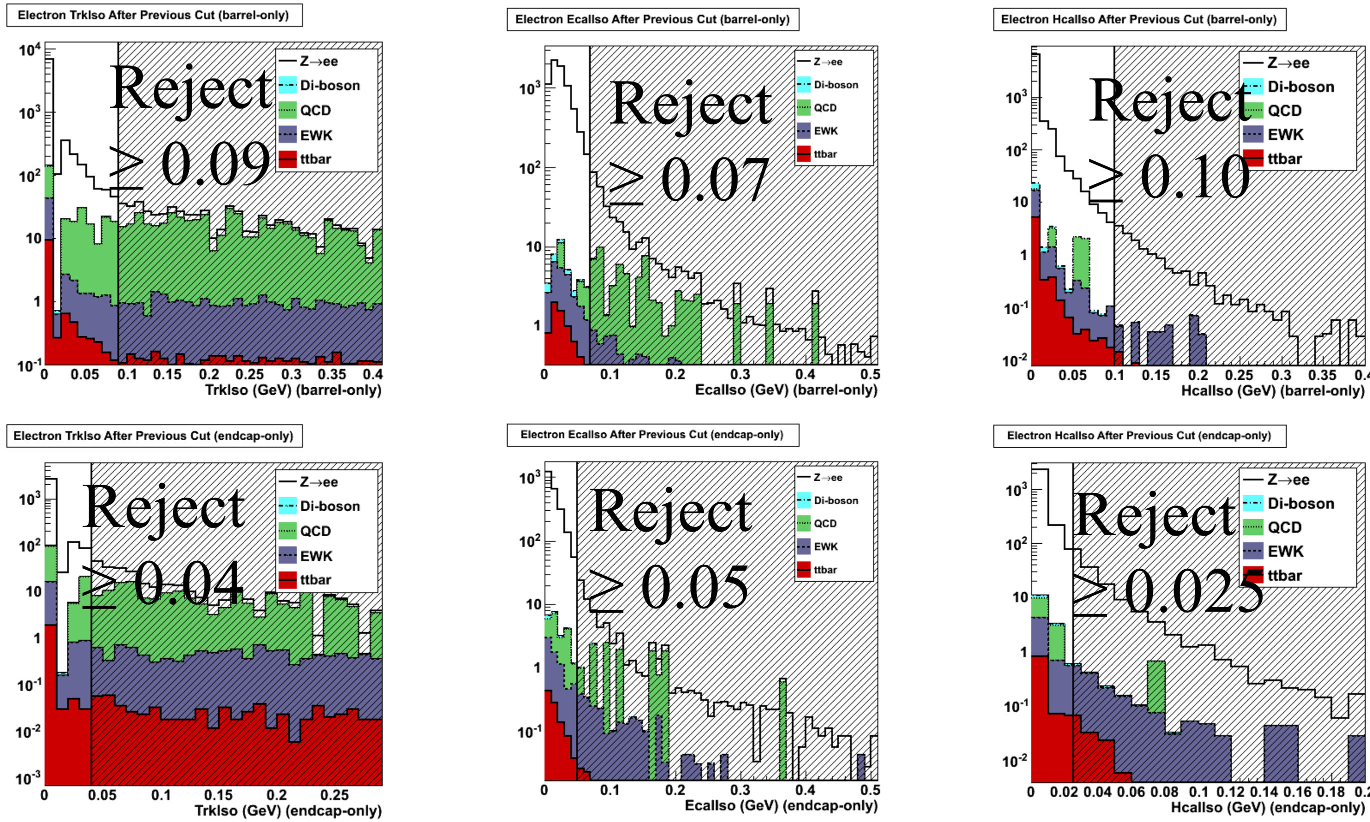
Isolation Cuts

Surrounding energy

Track | ECAL | HCAL

Barrel

Endcap



Electrons from background (esp. QCD) more likely to have surrounding energy

Keep only events with isolated electrons to cut out backgrounds

10529 out of 38553 events kept

Electron Identification Cuts
Cluster-Track Matching

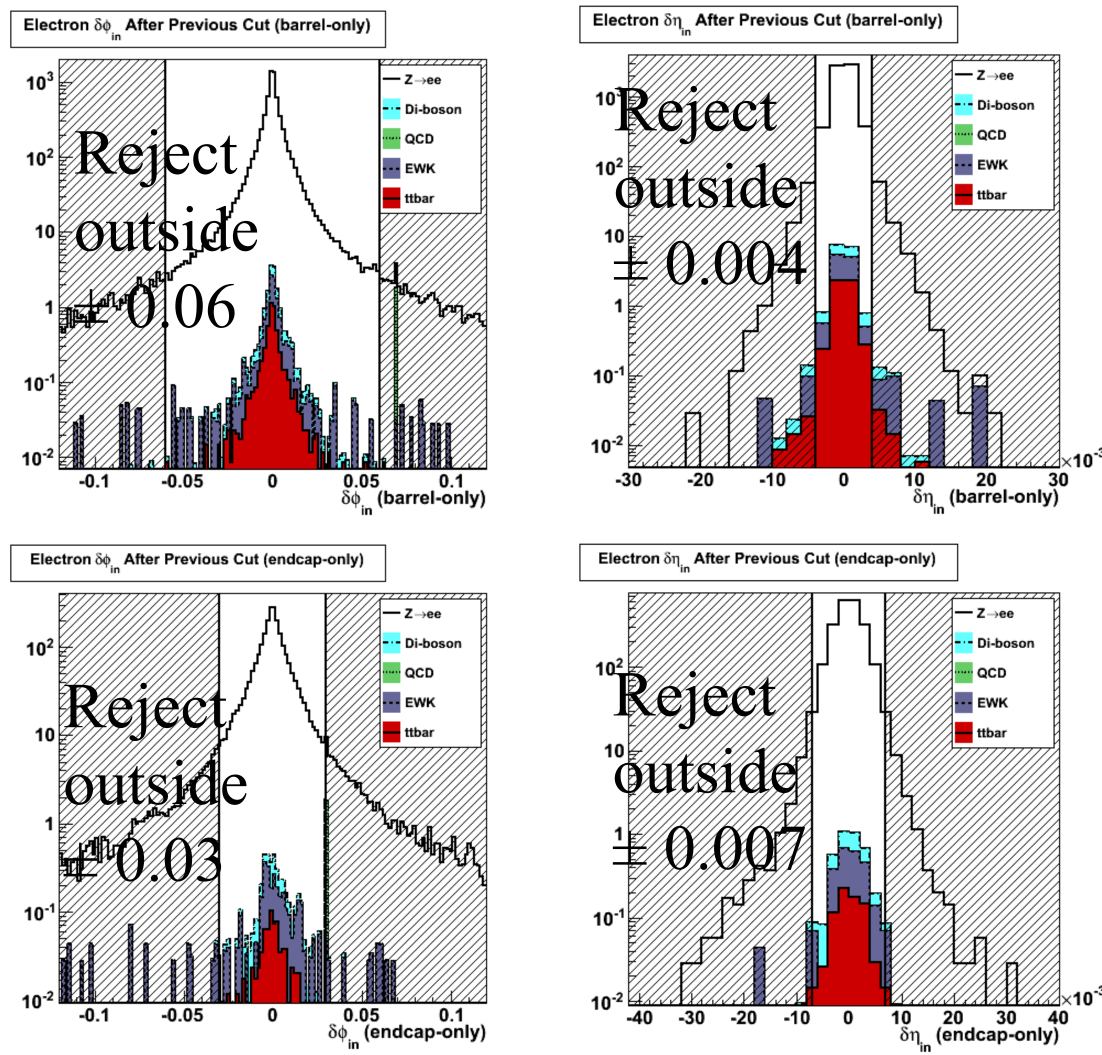
Δη and Δϕ between track and cluster

- Ensure a clean sample
- 9086 out of 10529 events kept

$\Delta\phi_{in}$ $\Delta\eta_{in}$

Barrel

Endcap



Electron Identification Cuts: Energy Deposit Shape

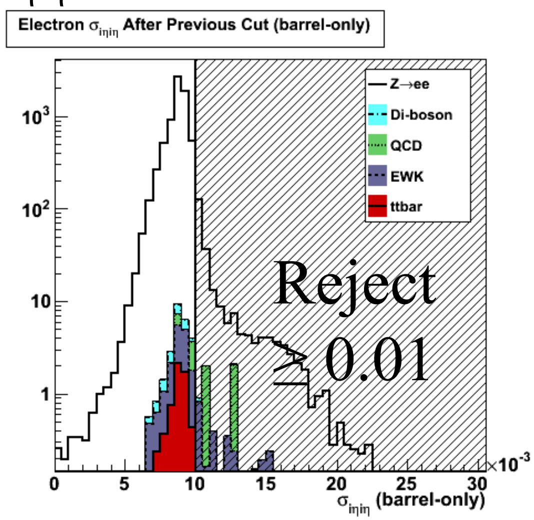
Energy deposit width ($\sigma_{i\eta i\eta}$) and length (H/E)

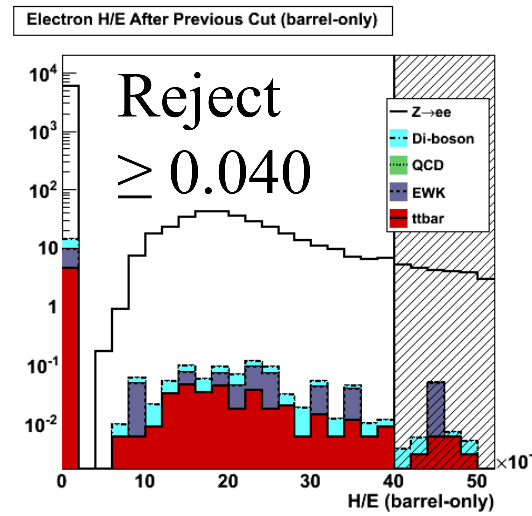
Ensure a clean sample

8453 out of 9086 events kept

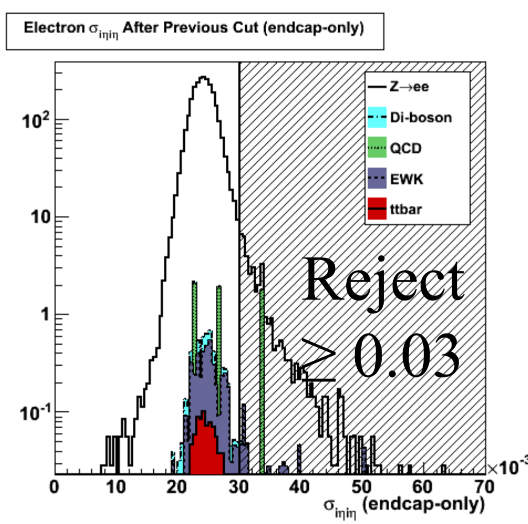
$\sigma_{i\eta i\eta}$ H/E

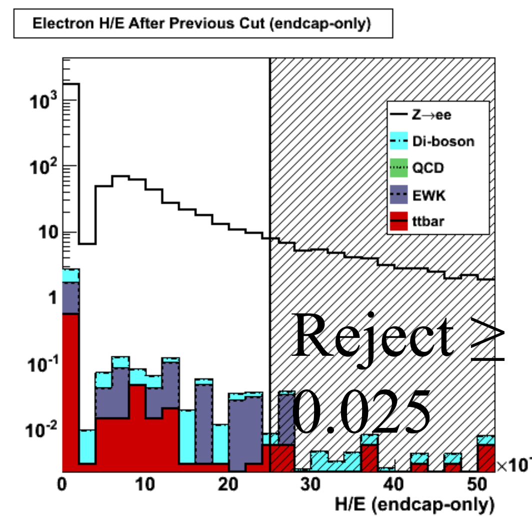
Barrel





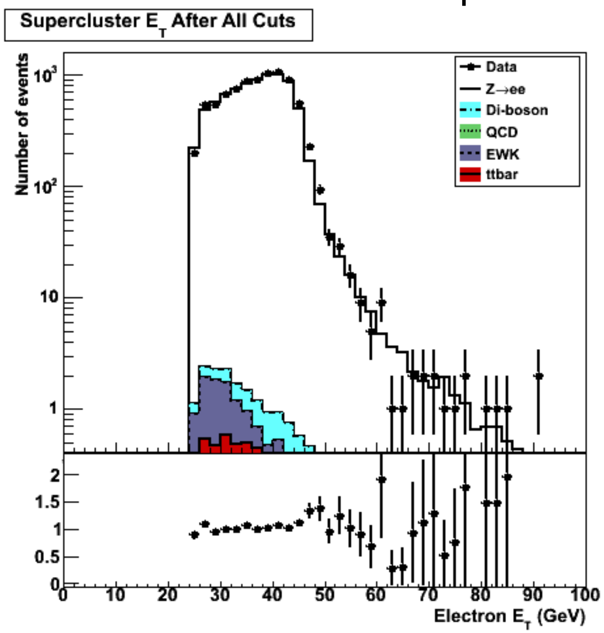
Endcap



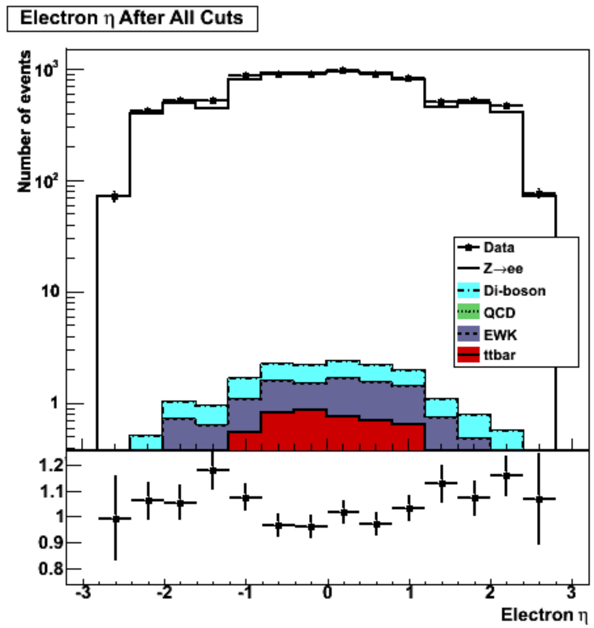


Electron Distributions

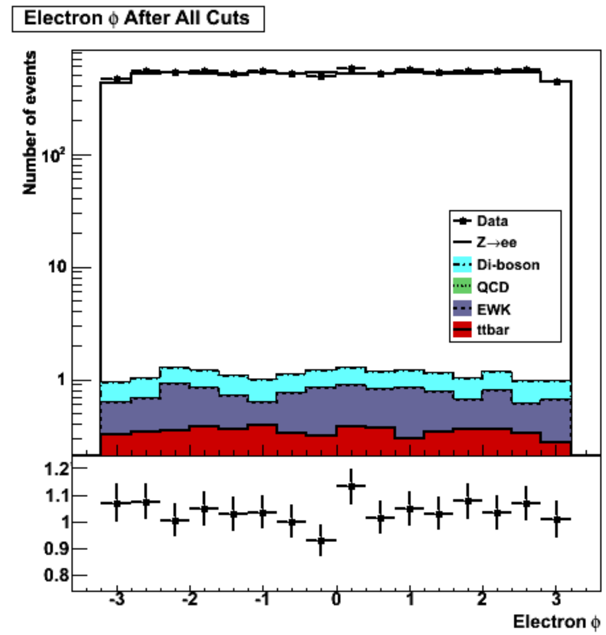
Electron SC E_T



Electron η



Electron ϕ



Good agreement between data and MC after all cuts

– MC models data well

Calculation of Efficiency

Tag and Probe method:

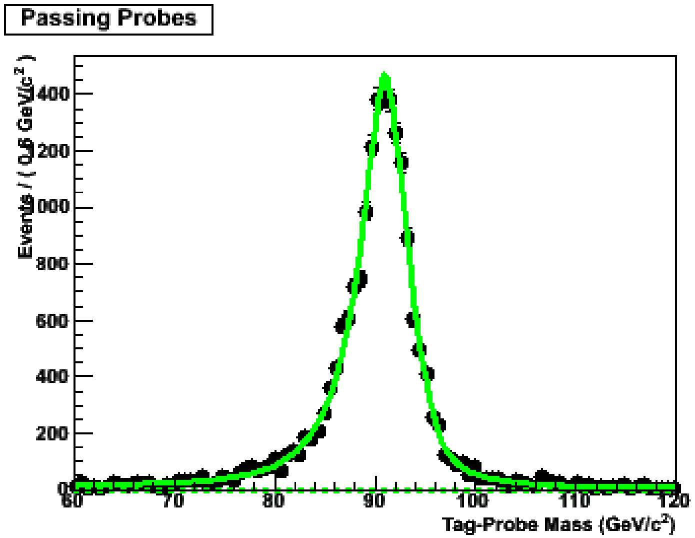
- Select sample of probable Z $\rightarrow$ ee events using mass window 60-120 GeV
- Identify well-reconstructed electron object as “Tag”
- Partner object is “Probe”
- Efficiency = (probes passing given selection)/(total probes)

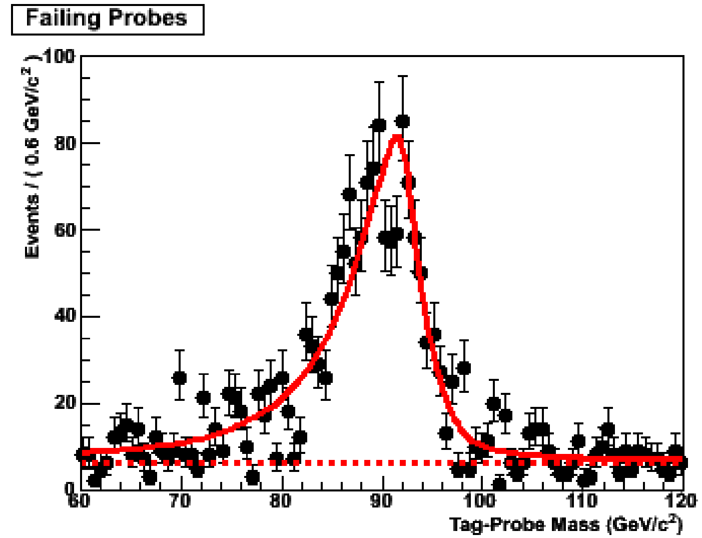
Determined by simultaneous fit to Tag+Passing Probe and Tag+Failing Probe invariant mass spectra

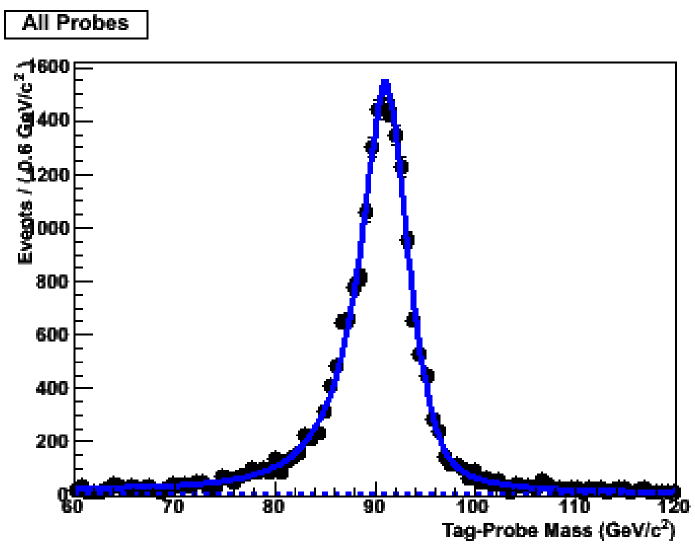
- Signal: Z mass distribution from simulation, convolved with function to describe detector behavior
- Background: exponential function

Strategy: Identify Monte Carlo “true” efficiency, correct by data/MC ratio from Tag and Probe

Example of Efficiency Fit Plots







Very good fit to passing probes, all probes

General agreement for failing probes – very few events

Efficiency Results

Step	True MC	MC T&P	Data T&P	Ratio	Eff
Reconstruction	0.965	0.972	0.971 +/- 0.002	0.999 +/- 0.002	0.964 +/- 0.002
Isolation	0.926	0.927	0.910 +/- 0.003	0.976 +/- 0.003	0.905 +/- 0.003
Electron ID	0.906	0.907	0.897 +/- 0.003	0.989 +/- 0.003	0.896 +/- 0.003
Trigger	0.959	0.941	0.972 +/- 0.001	1.032 +/- 0.001	0.991 +/- 0.001
Event selection	0.654	0.665	0.621 +/- 0.005	0.933 +/- 0.007	0.610 +/- 0.005

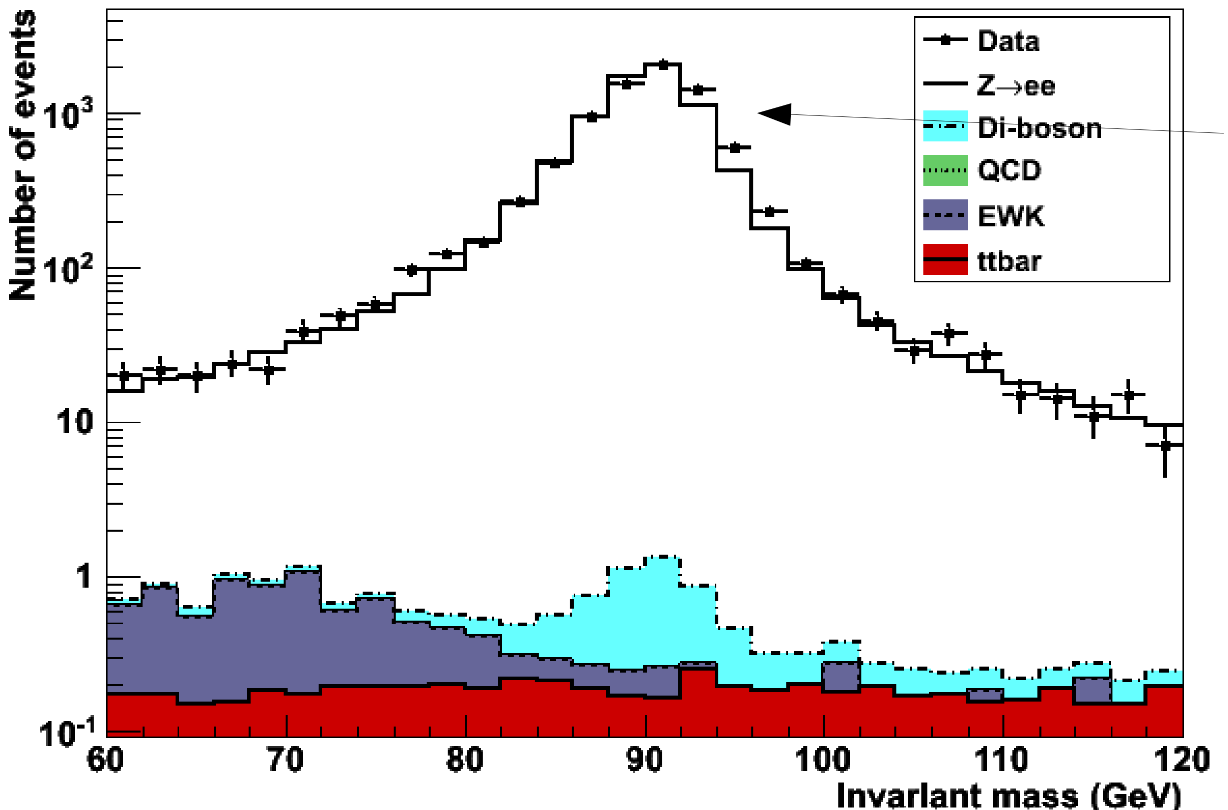
$$\epsilon^{corrected} = \epsilon_{MC}^{true} \times \left(\frac{\epsilon_{data}^{T\&P}}{\epsilon_{MC}^{T\&P}} \right)$$

Overall event efficiency: 0.610 +/- 0.005

- Errors include statistical and fit systematic uncertainties
- Relative uncertainty: 0.005/0.610 = 0.76%

Invariant Mass

Dielectron Invariant Mass After All Cuts



Peak shift: data does not include transparency corrections. Very small effect, accounted for in systematic errors.

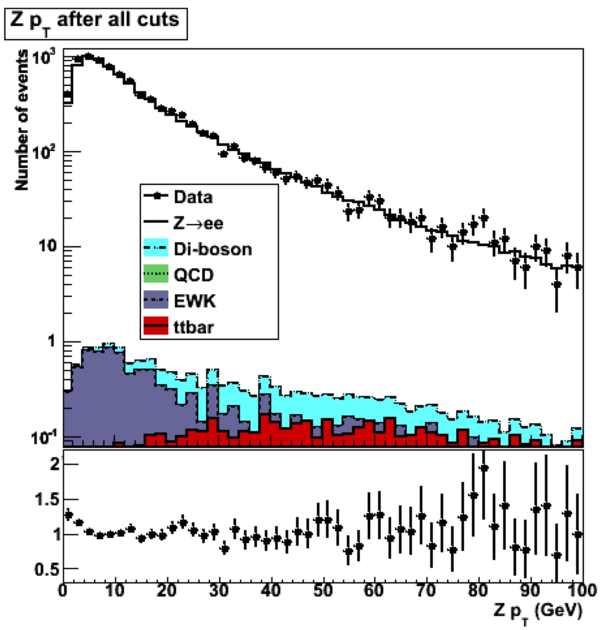
Data yield: 8453

Estimated BG from MC: 18.5

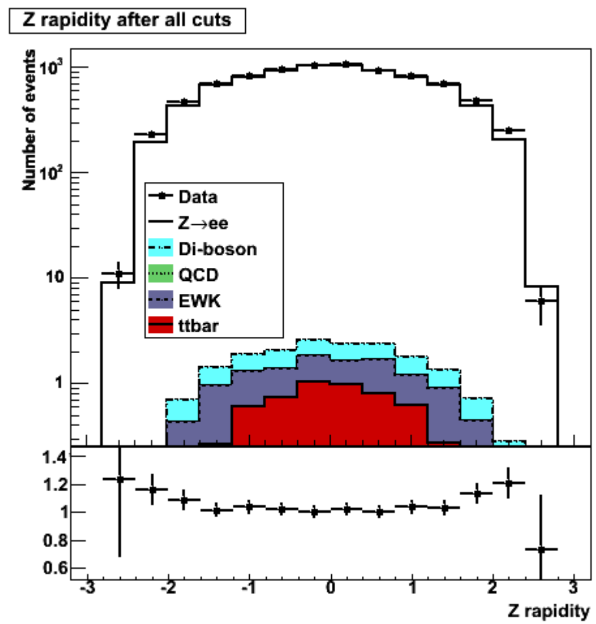
- EWK: 6.7, ttbar: 5.8, Diboson: 6.0, QCD: 0

Z Boson Distributions

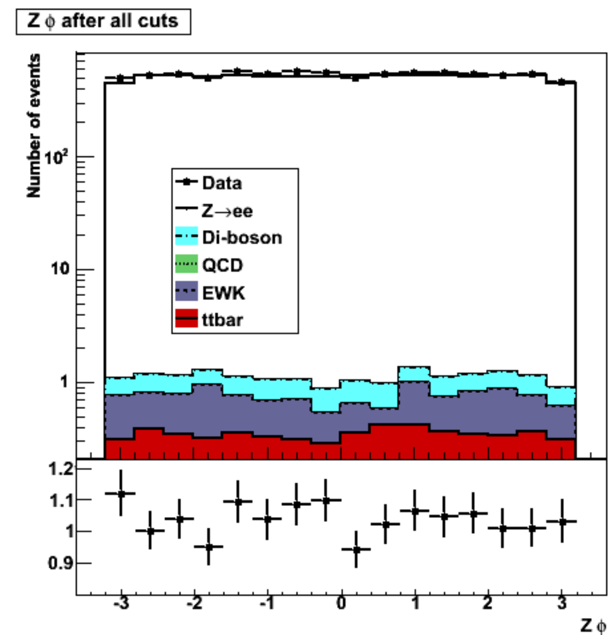
Z boson p_T



Z boson rapidity



Z boson ϕ



Good agreement between data and simulation

– Data well-understood

Confirmation of Background Estimate

Verify MC prediction of zero QCD background

Template Technique

1. Choose variable with different signal/background distributions (here, track isolation)
2. Get “signal-rich” and “background-rich” data samples with adjusted selections, as well as “standard data” sample
3. Find composition of signal+background samples that best fits standard data sample

Only useful for QCD background (EWK background too similar to signal)

Template Method Implementation

Working Point:

WP80	Barrel	Endcap
Conversion Rejection		
Missing Hits	0	0
dist	0.02	0.02
$\Delta cot\theta$	0.02	0.02
Relative Isolation		
ECAL	0.07	0.05
HCAL	0.10	0.025
Track	0.09	0.04
Electron Identification		
$\sigma_{i\eta i\eta}$	0.01	0.03
$\Delta\phi_{in}$	0.06	0.03
$\Delta\eta_{in}$	0.004	0.007
H/E	0.04	0.025

Modified working points for data/template selections:

- Semi-Tight: working point without track isolation
- Tight: Semi-Tight plus several thresholds modified
  - $\Delta\phi_{in}$: 0.03 (barrel), 0.02 (endcap)
  - $\Delta\eta_{in}$: 0.005 (endcap)
  - H/E: 0.025 (barrel)
- Loose: thresholds x 5 for all isolation, ID variables
  - Additional loosening for better statistics:
  - ECAL isolation: 2.5 (barrel), 1.0 (endcap)
  - SC E_T cut (25 → 20 GeV)

Data and template selections

- Data: two electrons passing Semi-Tight
- Signal: two electrons passing Tight, opposite sign
- Background: two electrons, one passing Semi-Tight, one passing Loose, same sign

Template Method Results

Results over full range:

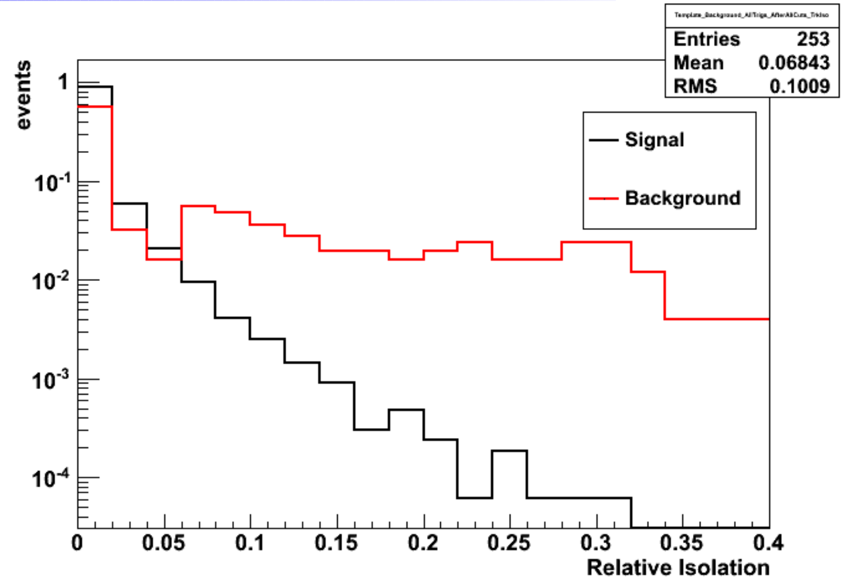
- Signal fraction: 0.998 +/- 0.014
- Background fraction: 0.0016 +/- 0.0020

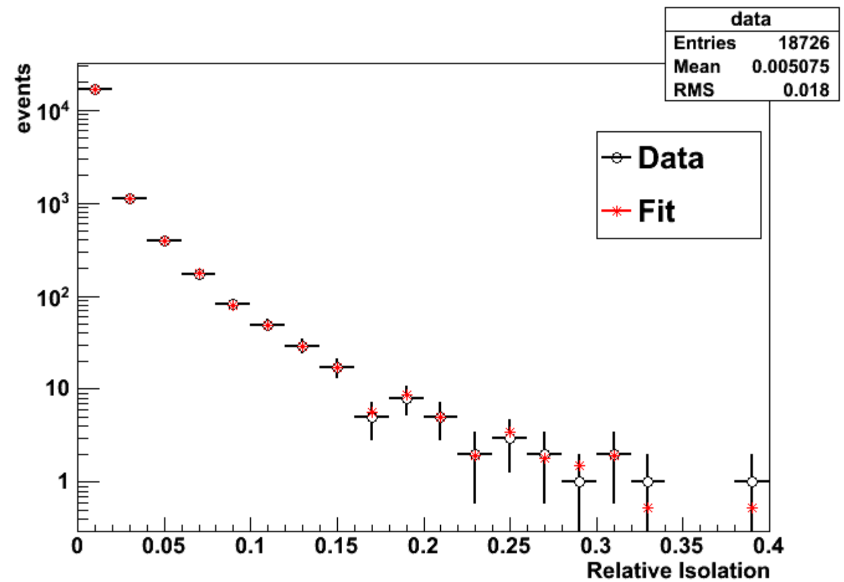
Results below threshold (re-adding track isolation cut)

- Signal fraction: 1.000 +/- 0.014
- Background fraction: 0.000 +/- 0.002

Estimated number of QCD background events:

- 0 +/- 16.8
- Relative uncertainty on number of signal events: 0.2%





Signal Extraction Fit

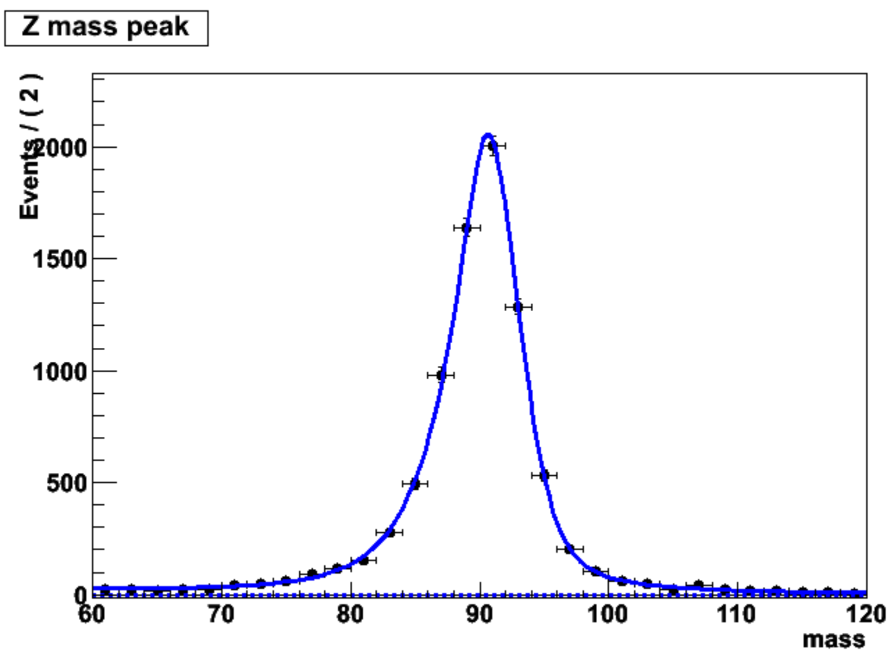
Verify MC prediction for all backgrounds

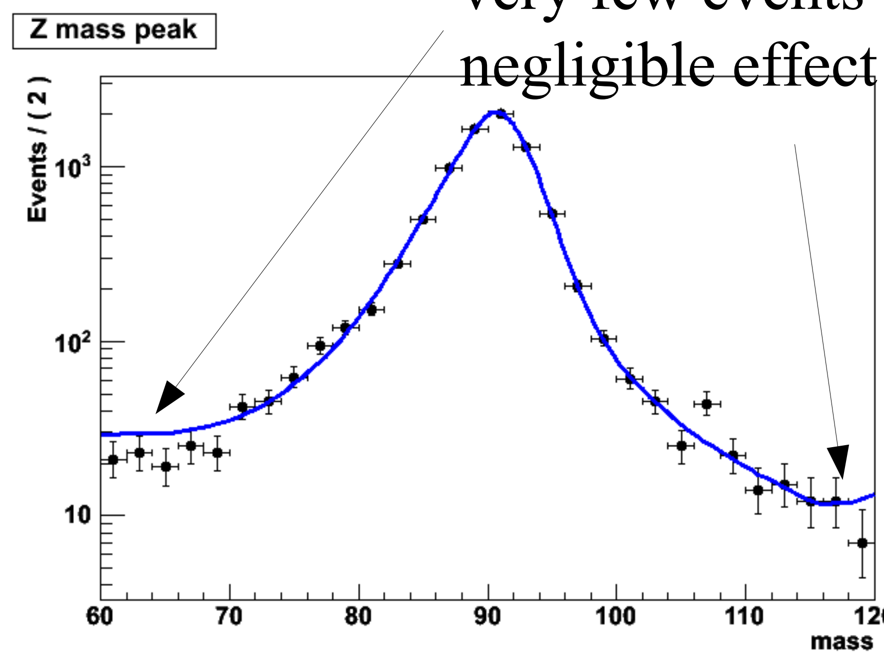
Fit invariant mass spectrum with signal+background shape

- Same lineshapes as for Tag and Probe
- Signal: 8453 +/- 18, Background: 0 +/- 14

Zero background, confirms MC prediction

Upticks due to fluctuations in base lineshape, but very few events – negligible effect





Background Estimation Summary

All estimates consistent:

- MC: 18.6 events
- Template fit: 0 +/- 16.8
- Z mass fit: 0 +/- 14

Take most conservative value, error

- Value: 19 events (MC estimate)
- Error: 17 events (template method)

Systematic Errors

Theoretical uncertainty

- Varied PDF, renormalization scale; calculated ISR/FSR corrections, other >LO corrections
- Total theoretical uncertainty on yield: +/-1.7%

Electron energy scale

- Varied electron energy by ECAL energy scale uncertainty: 2/3% in barrel/endcap (conservative)
- Uncertainty on yield: +0.82%, -1.1%. Average = 0.95%

Varied sample for MC efficiency

- POWHEG vs. PYTHIA, different parameter sets for underlying event
- Evaluated efficiency using each sample
- Systematic = spread/2 between values for the three samples
- Syst = 1.2%

Summary of Uncertainties

Source	Value
Luminosity Uncertainty	4%
Statistical Uncertainty	1.1%
Theoretical Systematics	1.7%
Experimental Systematics	1.7%
Electron Energy Scale	0.95%
MC Sample for Efficiency	1.2%
Efficiency Fitting	0.76%
Background Subtraction/Modeling	0.2%
All error sources combined	4.8%

Cross Section

Cross section:

Quantity	Value
A	0.387
ϵ	0.610
L	36.1
n_{Total}	8453
n_{BG}	19

$$\sigma \times BR = (n_{Total} - n_{BG}) / A * \varepsilon * L$$

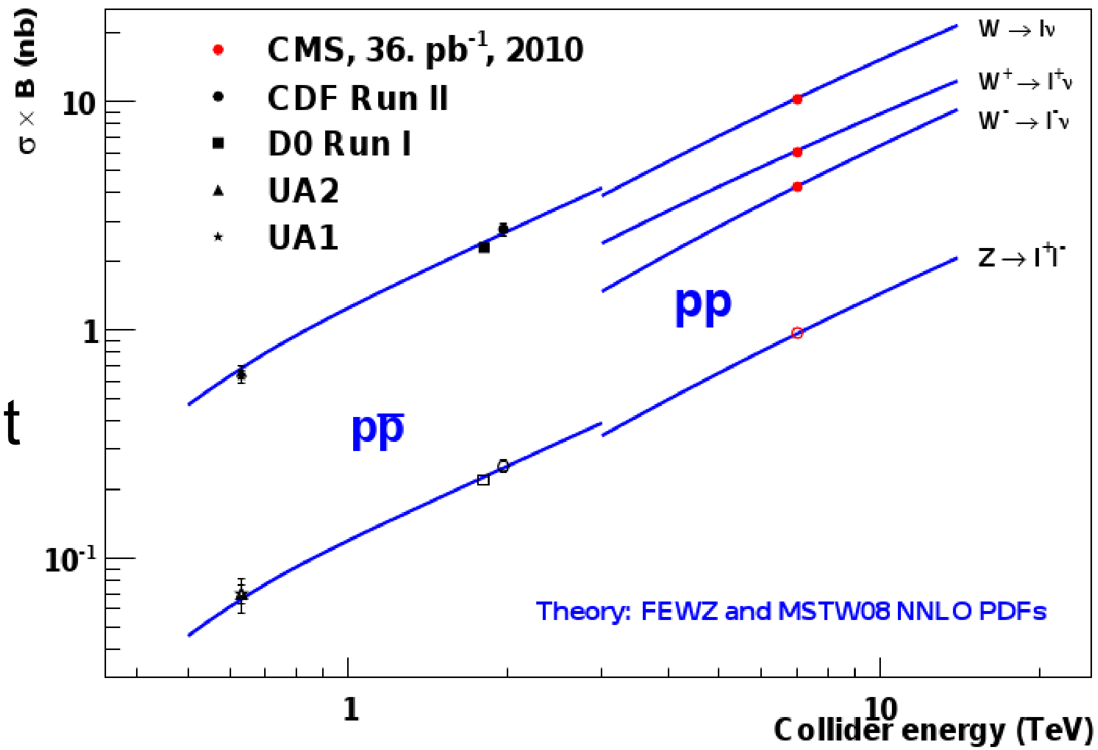
$$= 990 \pm 48 \text{ pb}$$

NNLO theoretical from FEWZ: 972 ± 40 pb

Agreement to theory within errors

Comparison with Other Experiments

- This analysis
  - $990 \pm 48\ pb^{-1}$
- CMS published result
  - $992 \pm 48\ pb^{-1}$
- ATLAS published result
  - $972 \pm 62\ pb^{-1}$
- Very good agreement



Conclusions

Cross section of $Z \rightarrow ee$ measured with 36.1 pb^{-1} 7 TeV data

- $\sigma = 990 \pm 48$ pb

Uncertainties determined to be reasonable

Measured value agrees with theoretical value within errors

This measurement laid the ground for measurements and searches being completed this summer

Samples

Data
/EG/Run2010A-Dec22ReReco_v1/AOD
/Electron/Run2010B-Dec22ReReco_v1/AOD

Monte Carlo	Generator	Number of Events	Cross section (pb)
Signal			
Z -> e e	POWHEG	1998990	1666.
Background			
QCD EM 20 to 30	PYTHIA	36920242	235500000.
QCD EM 30 to 80	PYTHIA	71834019	59300000.
QCD EM 80 to 170	PYTHIA	8073559	906000.
QCD BCtoE 20 to 30	PYTHIA	2243439	235500000.
QCD BCtoE 30 to 80	PYTHIA	1995502	59300000.
QCD BCtoE 80 to 170	PYTHIA	1043390	906000.
TTbar	PYTHIA	1099550	94.3
Z -> tau tau	PYTHIA	2057446	1666.
W -> e nu	PYTHIA	4856474	6153.
W -> tau nu	PYTHIA	5207750	7899.
WW	PYTHIA	110000	2.9
WZ	PYTHIA	110000	0.34
ZZ	PYTHIA	2113368	4.297

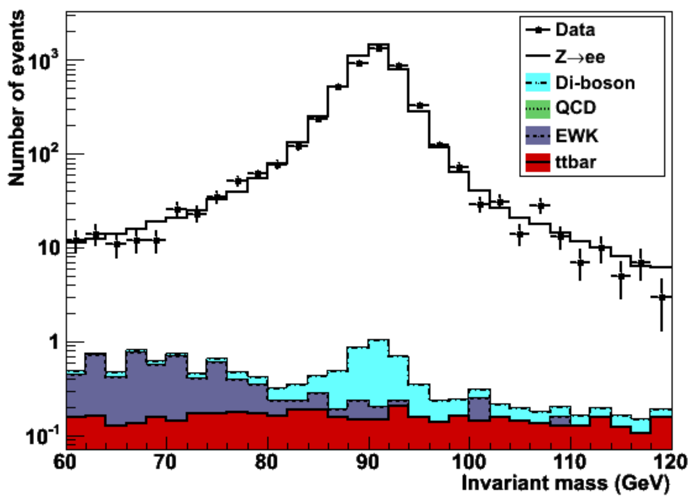
Trigger Efficiencies

Trigger efficiencies from T&P method on data

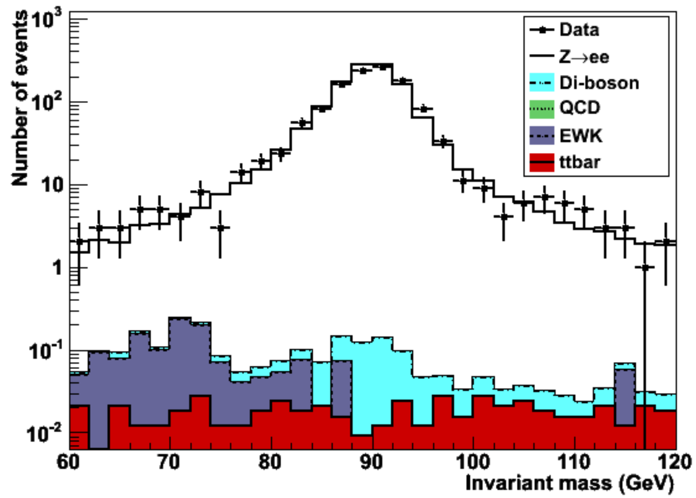
Trigger	Efficiency	Error (fit)
HLT_Photon15_Cleaned_L1R	0.976	0.002
HLT_Ele15_LW_L1R	0.961	0.005
HLT_Ele15_SW_L1R	0.981	0.003
HLT_Ele15_SW_CaloEleId_L1R	0.986	0.003
HLT_Ele17_SW_CaloEleId_L1R	0.992	0.002
HLT_Ele17_SW_TightEleId_L1R	0.973	0.002
HLT_Ele17_SW_TighterEleIdIsol_L1R_v1	0.973	0.003
HLT_Ele17_SW_TighterEleIdIsol_L1R_v2	0.977	0.002
HLT_Ele17_SW_TighterEleIdIsol_L1R_v3	0.974	0.003
Overall	**0.9763**	**0.0009**

Invariant Mass by η

Dielectron Invariant Mass After All Cuts, Barrel-Barrel



Dielectron Invariant Mass After All Cuts, Barrel-Endcap



Dielectron Invariant Mass After All Cuts, Endcap-Endcap