UNIVERSITY OF NOTRE DAME

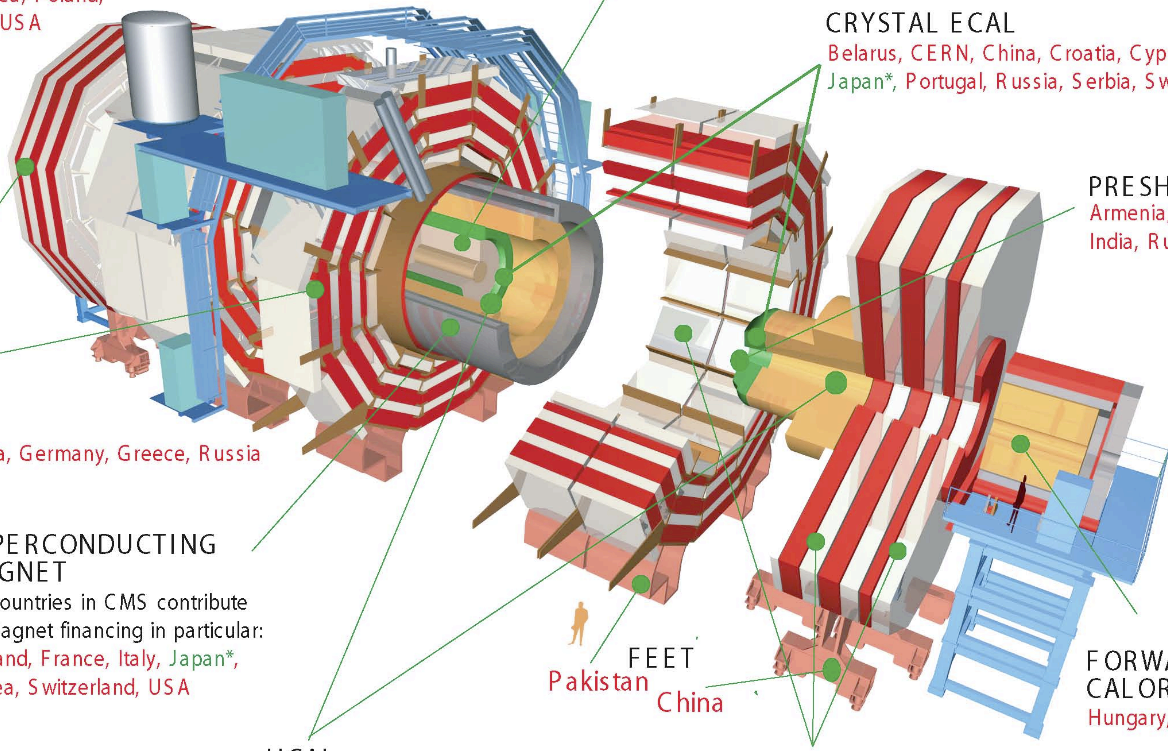
Physics with Electrons and Photons at the CMS experiment

Colin Jessop

University of Notre Dame

The CMS Collaboration

37 Countries, 155 Institutes, 2000 scientists (including about 400 students) October 2006



Total weight	:	12500 T
Overall diameter	:	15.0 m
Overall length	:	21.5 m
Magnetic field	:	4 Tesla

Contents

- Motivation: Why e/γ are important to CMS program. What are the challenges.

- Brief revision of Energy Loss Mechanisms for electrons and photons

- Choice of ECAL technology. Construction and Current Status

- Some first plots with electrons and photons

- The longer term: Reconstruction of Photons and Electrons used in case studies of H->$\gamma\gamma$, H->ZZ

NB: My groups contributions are to e/γ reco software, ECAL commissioning and operation, testbeams, DAQ. Physics

Notre Dame Jessop Group

Faculty: Colin Jessop

Nancy Marinelli*

Postdoc: Jeff Kolb*

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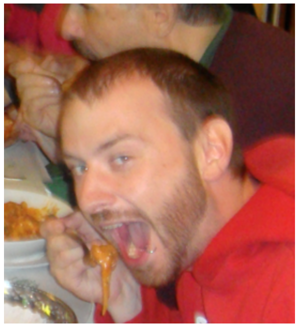
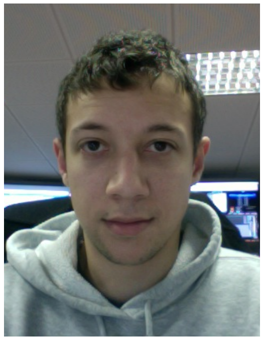
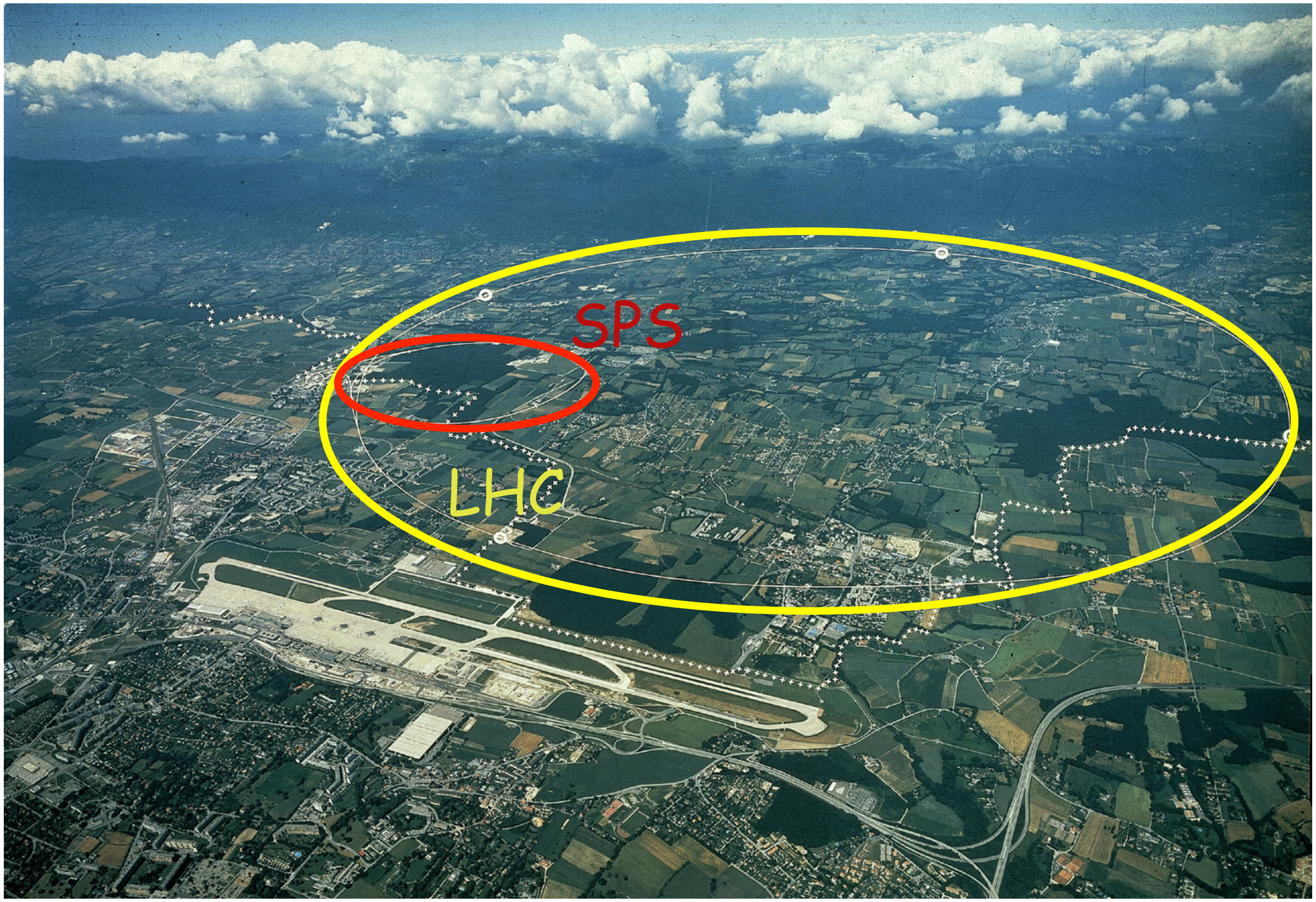
Grad Students: Ted Kolberg* Jamie Antonelli Sean Lynch* Doug Berry*





Primary Goal of LHC



14 TeV pp

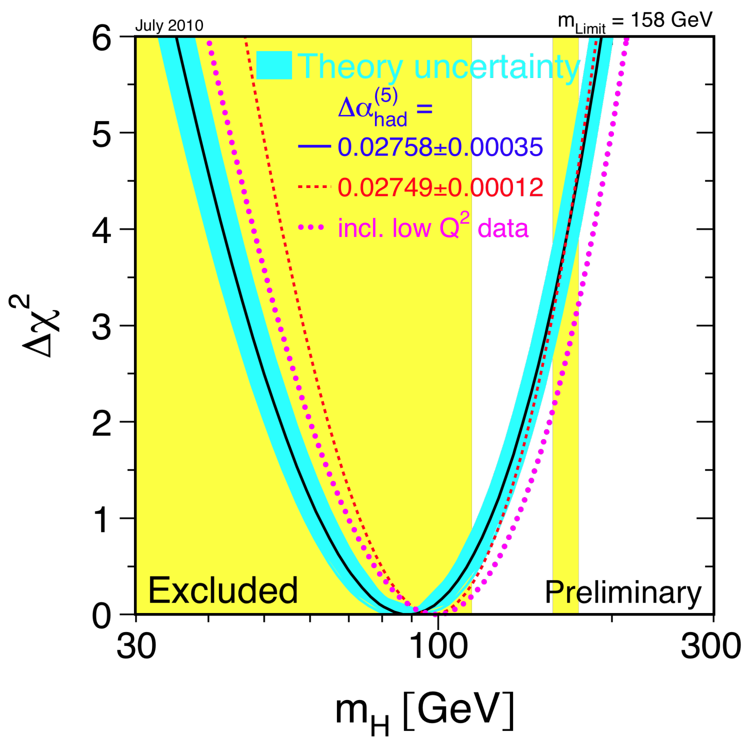
$L = 10^{34}\ cm^{-2}\ s^{-1}$

Effectively a high energy gluon collider

To Understand the Mechanism of Electroweak Symmetry Breaking - The Higgs

Standard Model Higgs Constraints

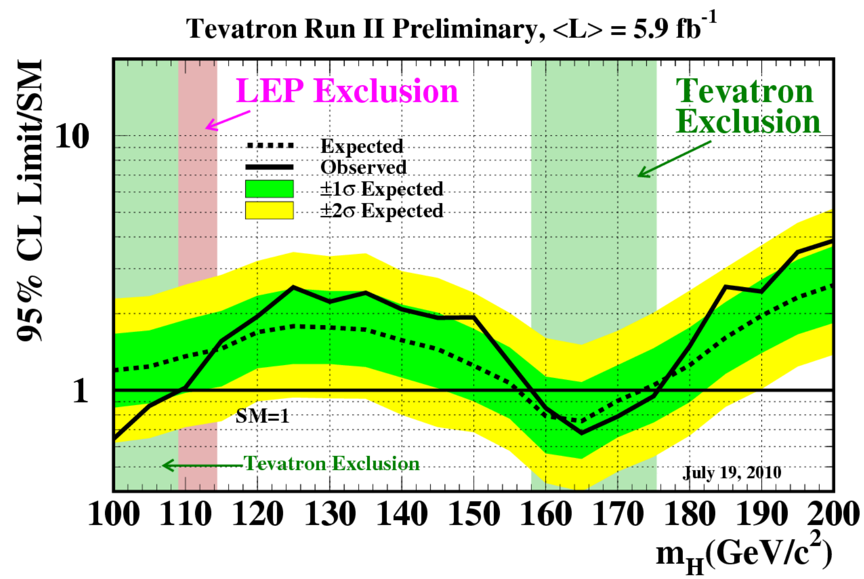
(LEP EWWG July 10)



95% Confidence Limits (July 2010)

m_H > 114.4 GeV (Direct Search)

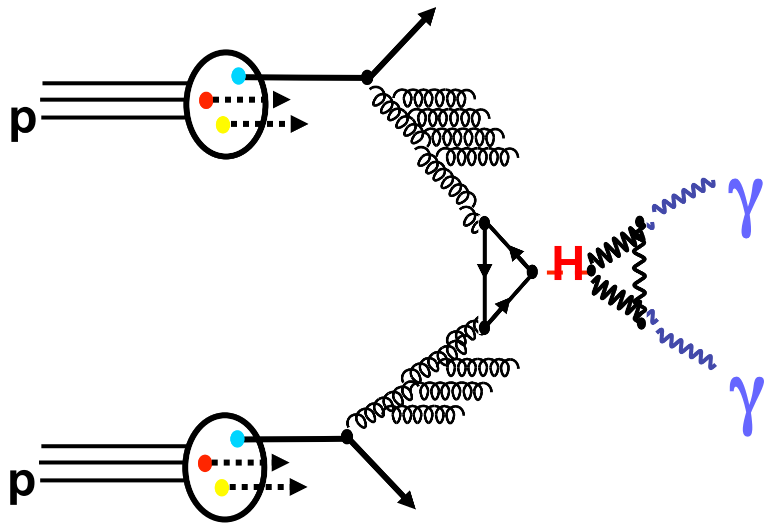
m_H < 182 GeV (*Inferred from constraints on radiative corrections to measured M_w,M_t …. + Direct search limit*)



If the minimal standard model is correct expect a "low" mass Higgs (~100 to 200 GeV)

Higgs Production and Decay

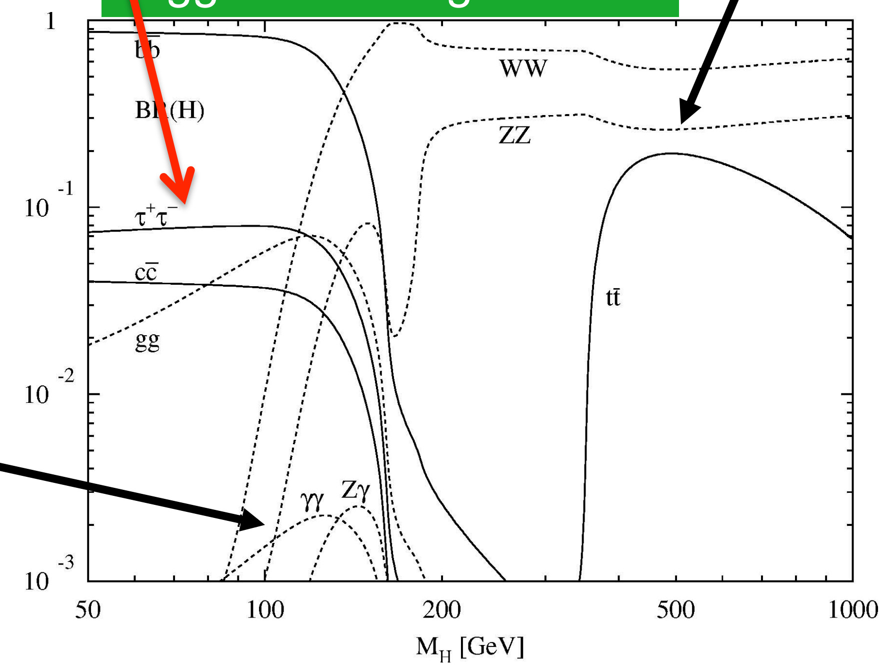
Dominant Higgs Production Mechanism



H->ττ

H->ZZ*, Z->e+e-

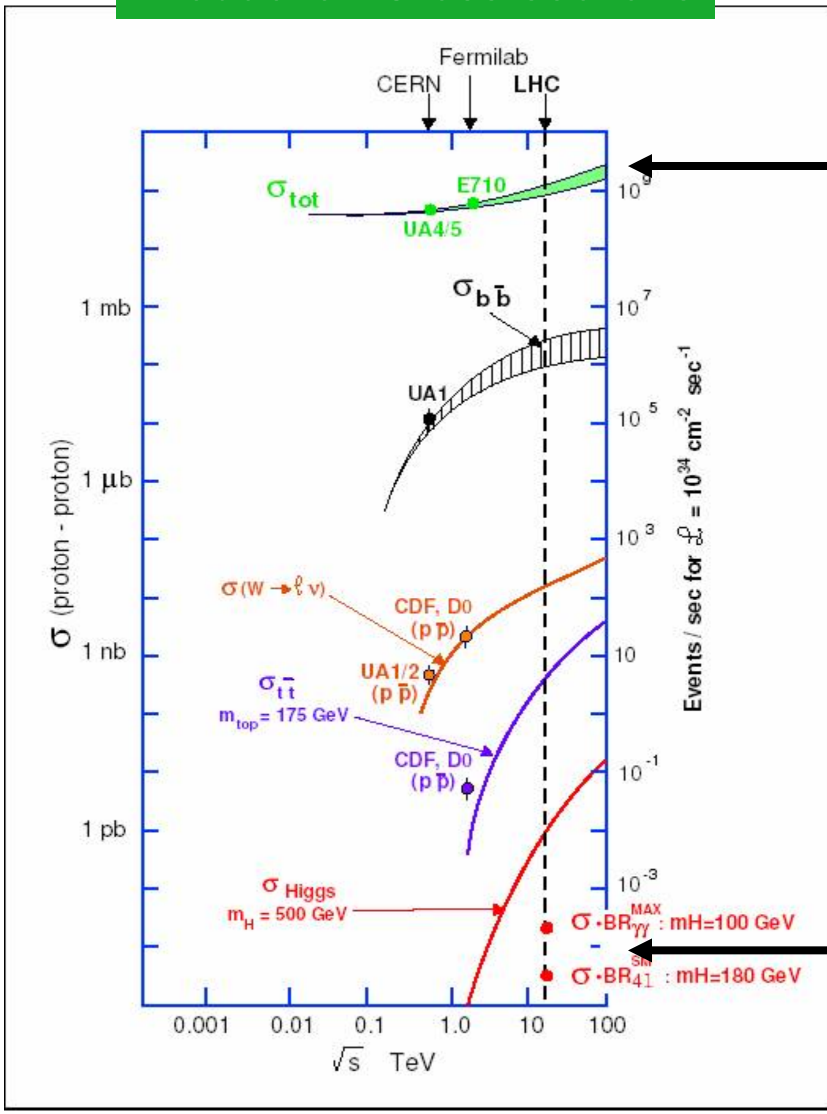
Higgs Branching Fraction



Br(H->γγ)~0.1% but can fully Reconstruct this decay from the photons

The Challenge

Production Cross-sections



σ_{total} ~ 100mb

Find one event in 10^{13}

$\sigma.Br(H\text{->}\gamma\gamma) \sim 10^{-11}$mb

Backgrounds

Most of σ_{total} is due to jet production

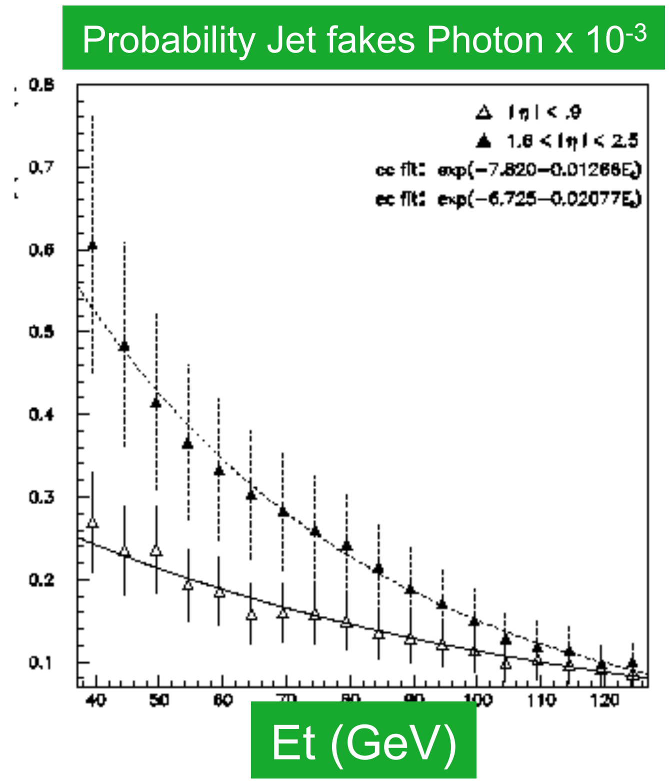
From D0 at Tevatron:

Probability Jet to fake photon ~ 1 in 10^4

Jet to fake electron ~ 1 in 10^5

(*Early indications at CMS point to slightly higher rates)*

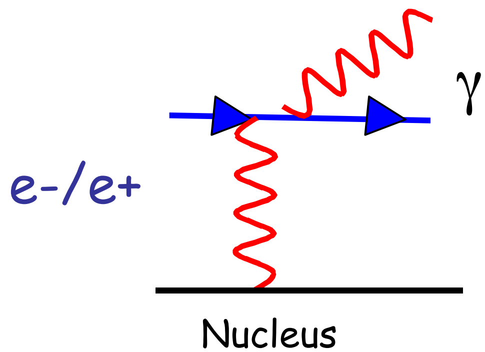
Also backgrounds from real e/γ but these tend to be smaller and more manageable



Need very selective trigger and excellent e/γ reconstruction capabilities and jet rejection

Very Brief Revision of Electron/Photon energy loss in matter

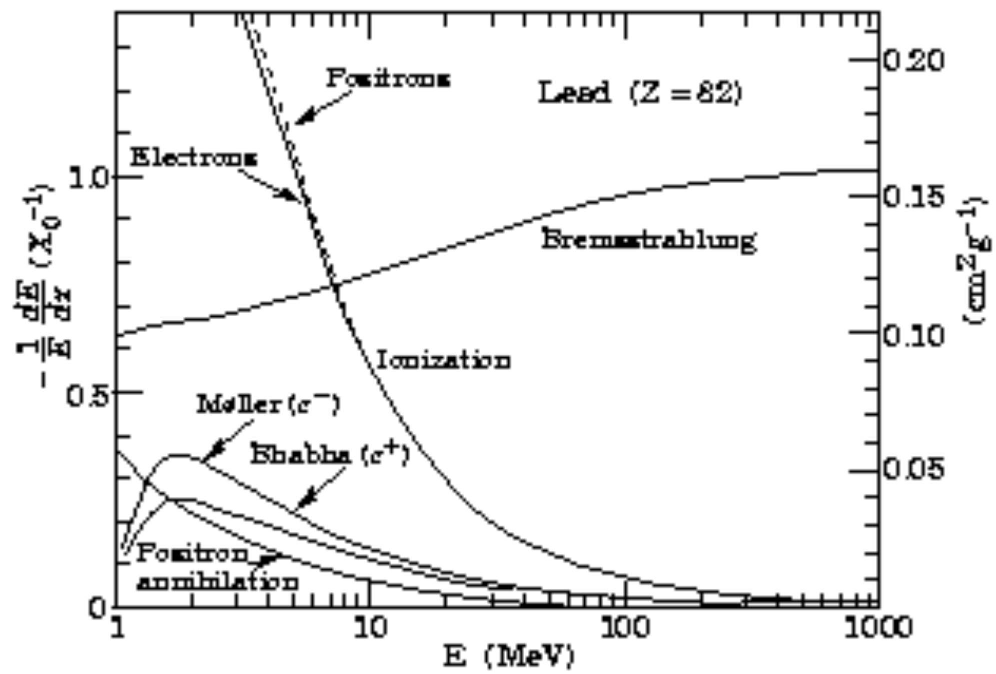
Electron/Positron Energy Loss in matter



Bremstrahlung (radiation of photon)

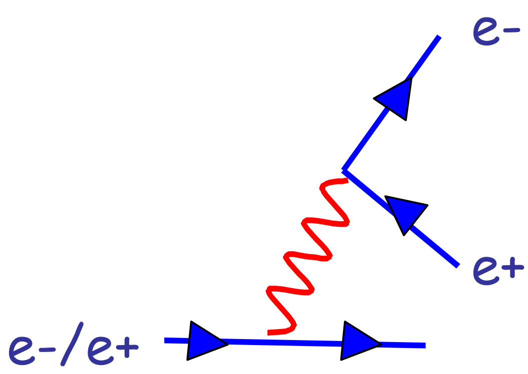
$$\frac{dE}{dx} = -\frac{E}{X_0} \qquad X_0 = \frac{180A}{Z^2}$$

Correctly described by Bethe-Heitler Model



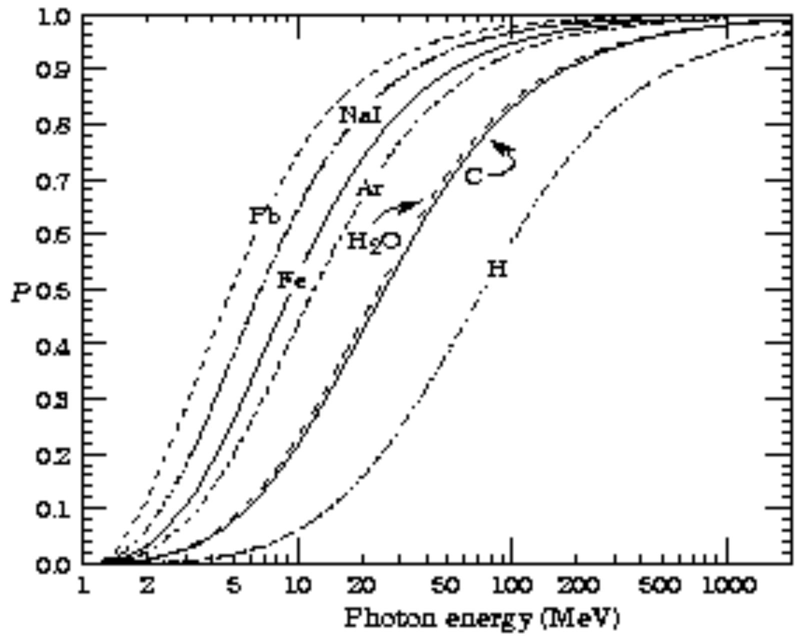
Electron energy loss primarily by Brem at E > E_c (~20 MeV) and ionization below. Brem Radiation probability depends on radiation length X_0

Photon Energy Energy Loss



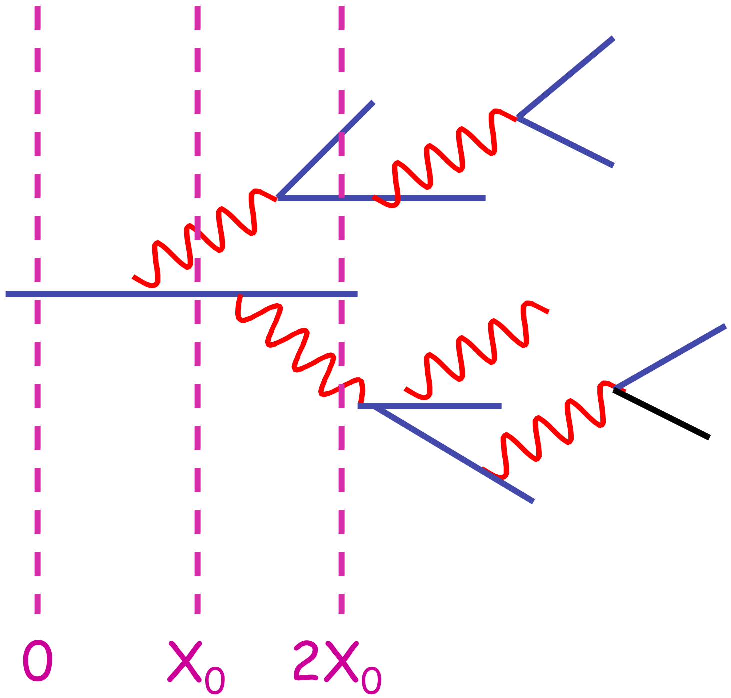
Pair Production

P=probability of pair production



Photon energy loss primarily pair production at $E > E_c$ (~20 MeV) and Compton Scattering below

Brem+ Pair Production = Electromagnetic Showers



A reasonable model of this process:

1. Each electron $E > E_c$ travels $1\ X_0$ and gives up 50% E to photon

2. Each photon travels $1\ X_0$ and pair produces with 50% E to each

3. Electrons with $E < E_c$ lose energy by ionization

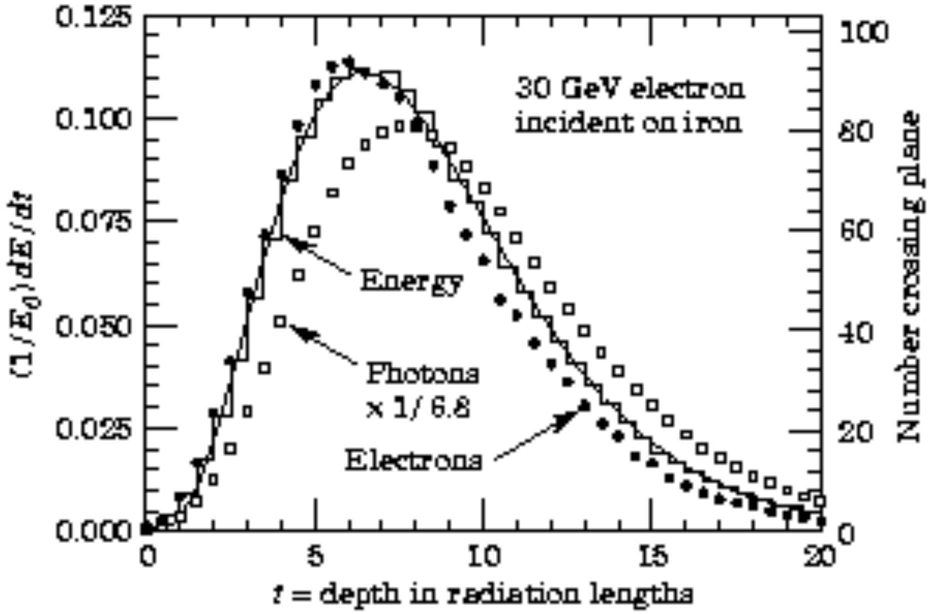
Can show that Max number of shower particles occurs at: $X_{max} \propto \ln(E_0 / E_c)$

Total charged track length: $L \propto \frac{E_0}{E_c}$

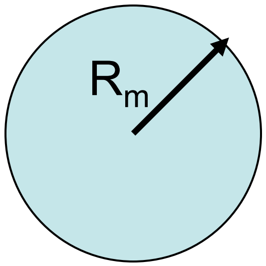
Measure Energy by measuring L with ionization or scintillation

Electromagnetic shower Profile

Longtitudal Profile



Lateral Profile



Moliere Radius: $R_m \approx X_0$

(from multiple scattering)

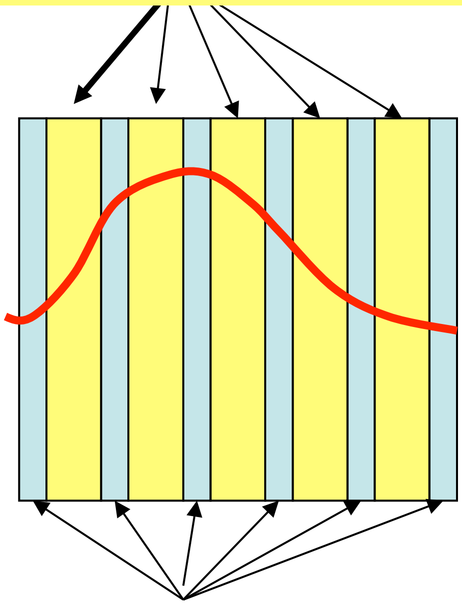
To contain >99% shower need depth of material ~ 25 X_0

To measure lateral position accurately need segmentation ~ X_0

Sampling vs Total Absorption Calorimeter

Sampling Calorimeter

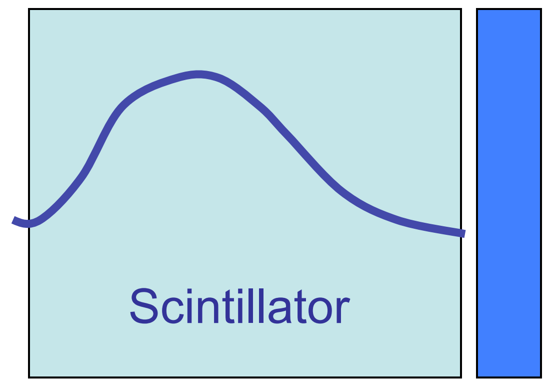
Lead- causes shower



Active Detector (ionization chamber or scintillator) to measure total track length L

Cheap with poor resolution
~2.5% for 100 GeV Photon

Total absorption calorimeter



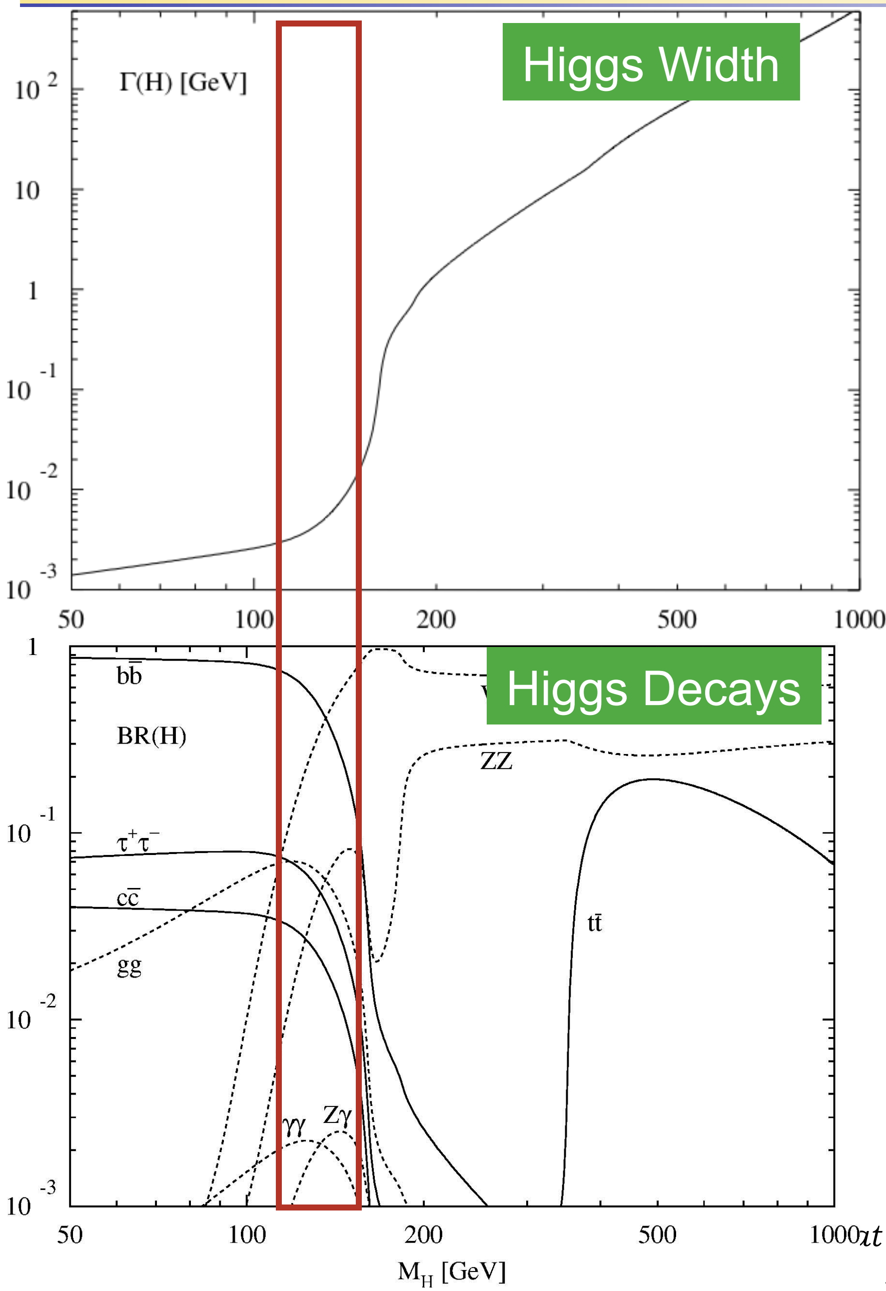
Photon Detector

Scintillator both causes shower and is active detector

Expensive with good Resolution ~0.5% at 100 GeV

CMS ECAL Technology Choice

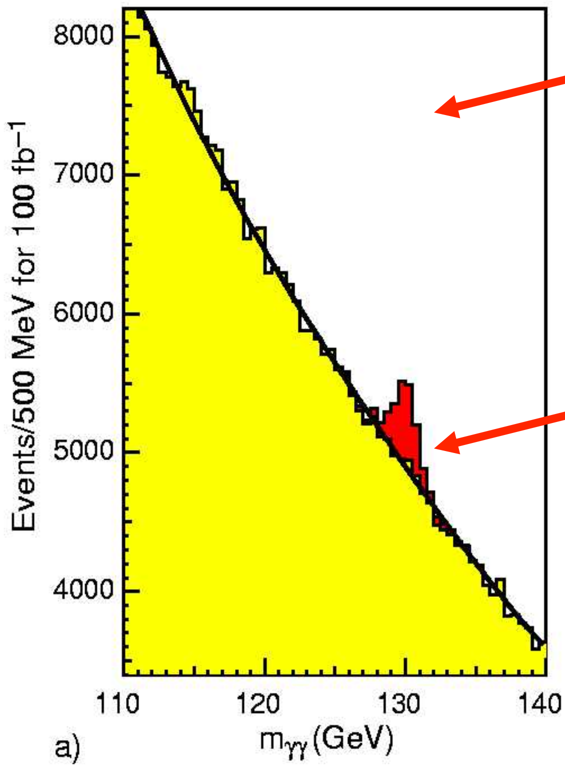
Higgs Width



Less than 10 MeV (0.01% of M_H) in H->γγ range

When reconstruct the resolution of $M_H(\gamma\gamma)$ will be dominated by experimental resolution

Reconstruction of H->γγ



Measure photons in ECAL and form invariant mass mγγ

$$m_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}\left(1-\cos\theta_{\gamma 1,\gamma 2}\right)}$$

Width of peak determined by Energy resolution

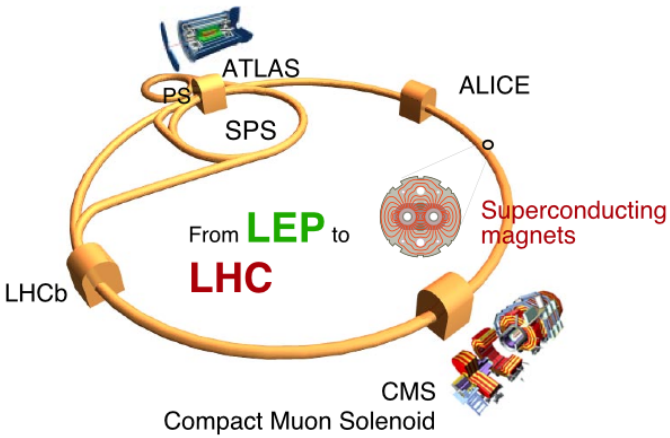
$$\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \frac{1}{2}\left[\frac{\Delta E_{\gamma 1}}{E_{\gamma 1}} \oplus \frac{\Delta E_{\gamma 2}}{E_{\gamma 2}} \oplus \frac{\Delta \theta_{\gamma\gamma}}{\tan\left(\theta_{\gamma\gamma}/2\right)}\right]$$

(angular resolution also but limited by vertex resolution)

The significance of signal maximized by best possible energy resolution in calorimeter. Use total absorption calorimeter

(Note this plot for 100 fb^{-1} = year 2015)

The LHC Environment (Phase 1 to 2020)



Year	Energy TeV	Luminosity $x10^{34}$ $cm^{-2}s^{-1}$	Integrated Luminosity fb^{-1}	
2011	7	0.01	200	
2012		Shutdown	Shutdown	Fix Dipoles
2013-15	14	0.1	100	
2016		Shutdown	Shutdown	Replace Pixels
2016-19	14	1.0	500	

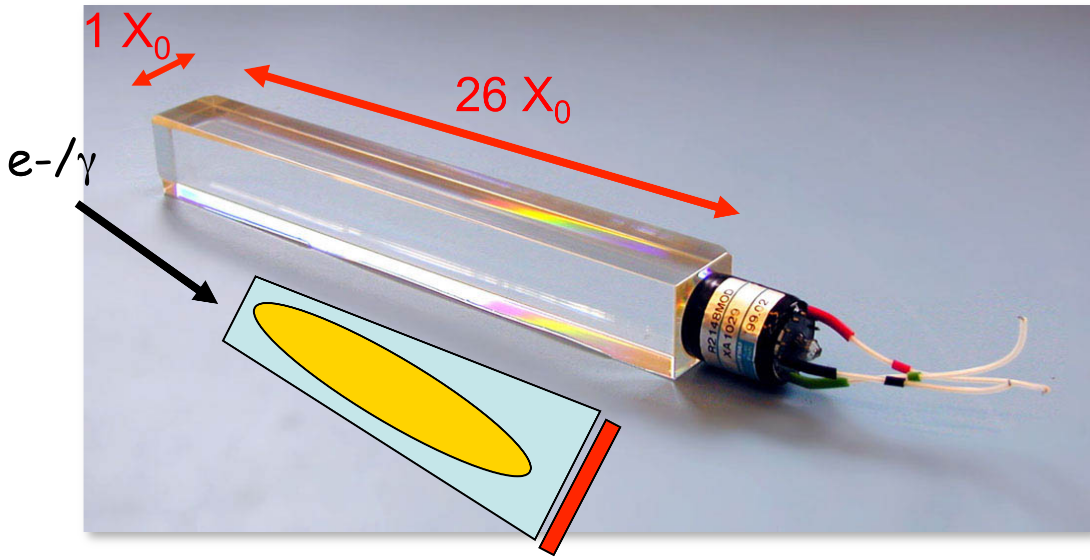
At Luminosity of 10^{34}

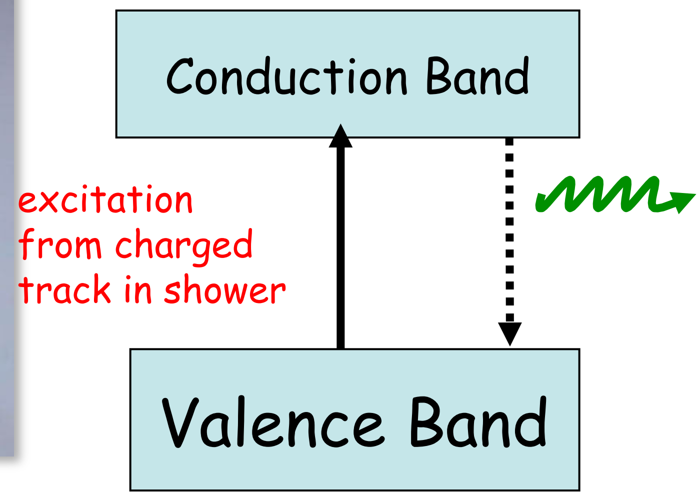
Bunch crossing rate : 40 MHz

Every 25 ns : up to 20 p-p interactions and up to 1000 charged particles

Need fast and highly segmented detectors to avoid pileup of events and detectors must be radiation tolerant

Lead Tungstinate ($PbWO_4$) Scintillating Crystal





Very Dense (X_0 = 0.9 cm) – it's a transparent lead brick

Single Crystal which emits fast green scintillation light

Crystal acts as optical waveguide and light internally reflected onto photo-detector

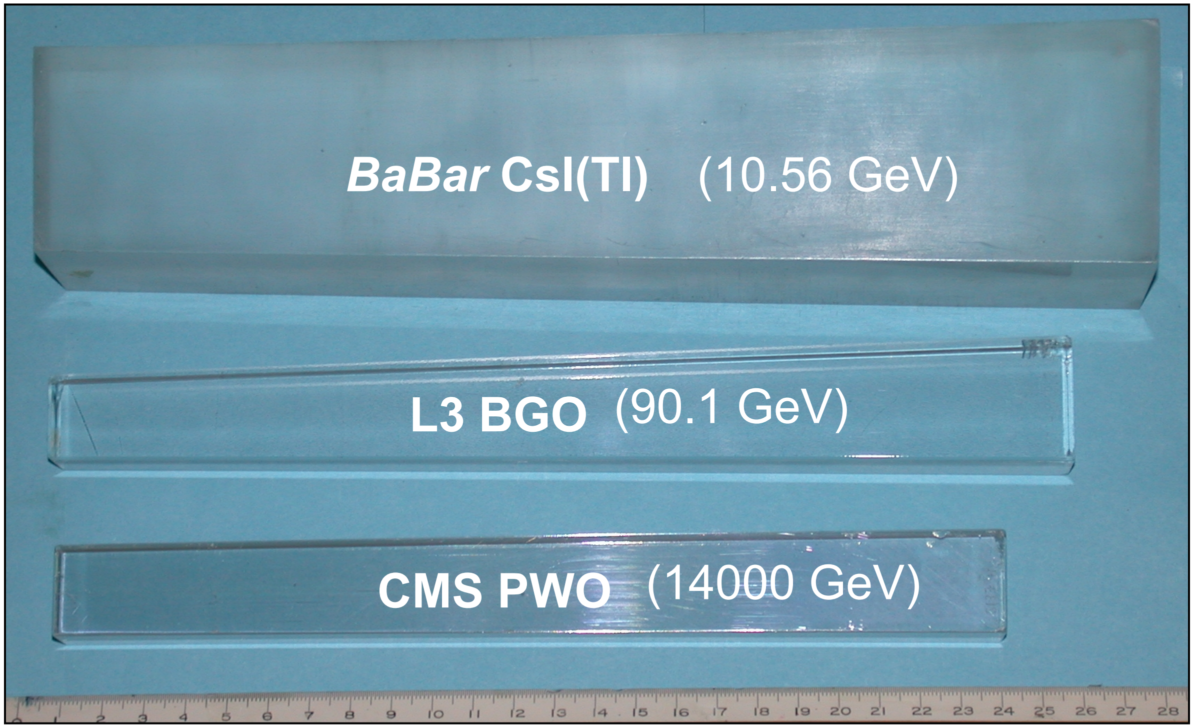
Crystal Calorimeters in HEP

Date	75-85	80-00	80-00	80-00	90-10	94-10	94-10	95-20
Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	LEAR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	-	0.5	1.5	1.5	-	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	1.0	0.27	-	1.0	1.25	1.29
Number of Crystals	672	11,400	7,800	1,400	3,300	6,580	8,800	76,000
Crystal Depth (X_0)	16	22	16	16	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	1	1.5	7	1	2	5.9	9.5	11
Light Output (p.e./MeV)	350	1,400	5,000	2,000	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	WS[a]+Si PD	PMT	Si PD	Si PD	APD[a]
Gain of Photosensor	Large	1	1	1	4,000	1	1	50
σ_N/Channel (MeV)	0.05	0.8	0.5	0.2	small	0.15	0.2	40
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^4	10^5

CMS: High Granularity to decrease occupancy but increases cost (~$80-100 M)

PbWO is fast and radiation hard but has low light yield

Crystal Density: Radiation Length



Full Size Crystals:

BaBar CsI(Tl): 16 X_0

L3 BGO: 22 X_0

CMS PWO(Y): 25 X_0

CMS Crystals: (X_0=0.9cm) 23cm in length

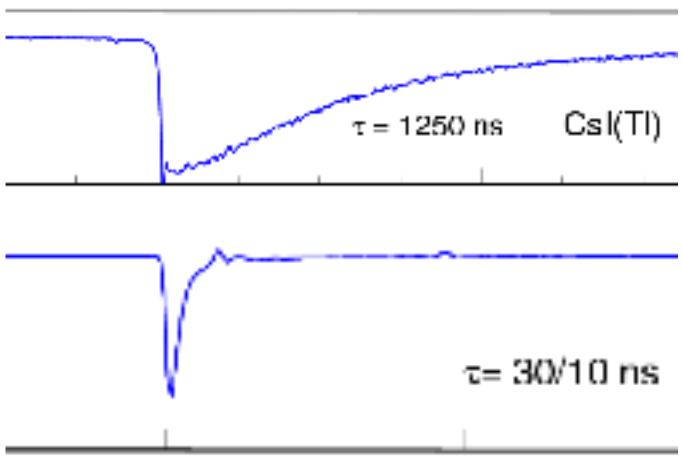
Transverse size of CMS crystals ~ 2.2 cm x 2.2 cm (Moliere Radius = 2.2 cm)

Fast Scintillation to reduce Pileup

Comparison of Signal Pulse from Crystals

CsI(tl)
BaBar

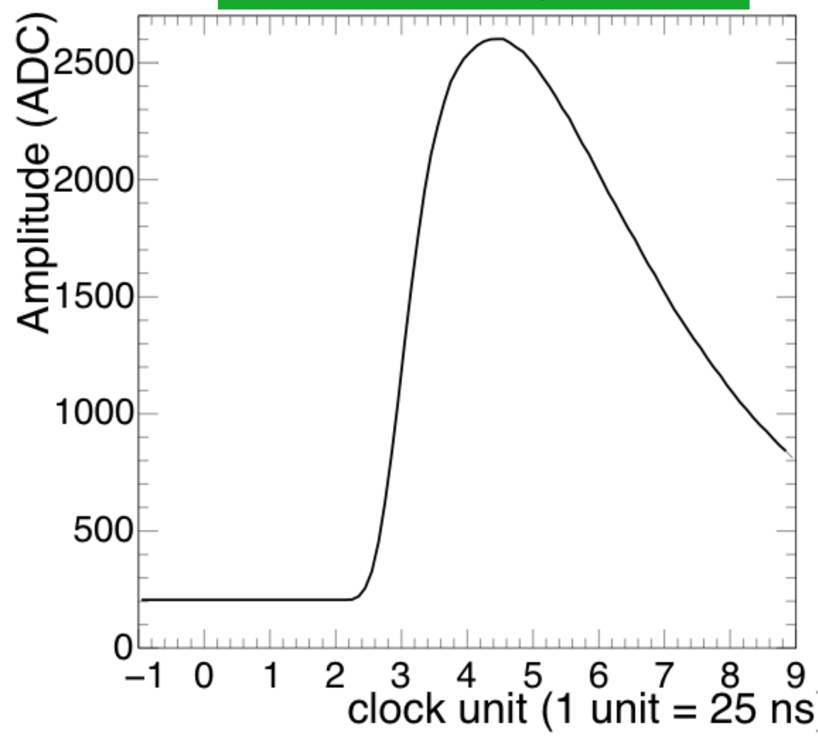
PbW0
CMS



Pileup reduced by fast pulse, granularity.

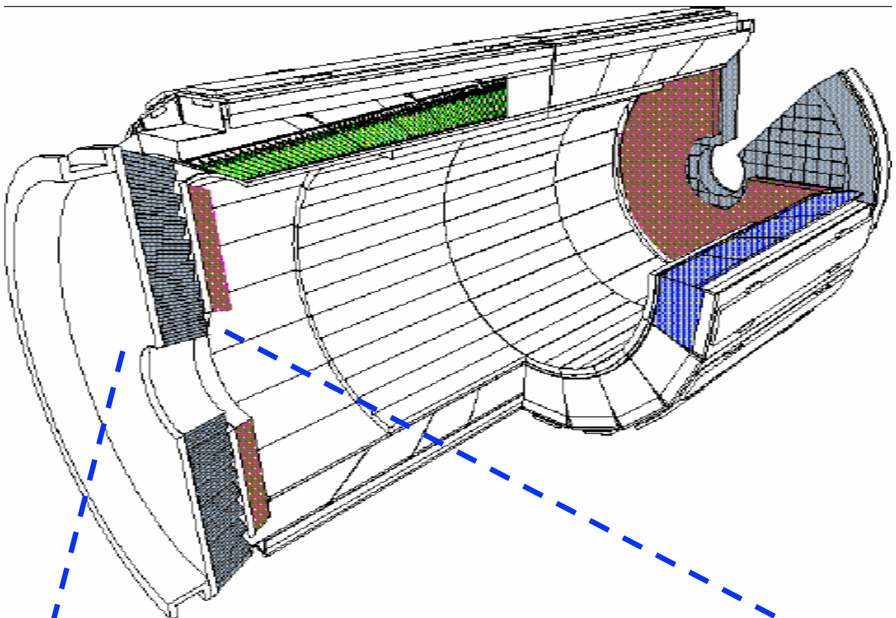
Effects of pileup reduced to negligible with digital filtering of 10 sample (25ns each) Window.

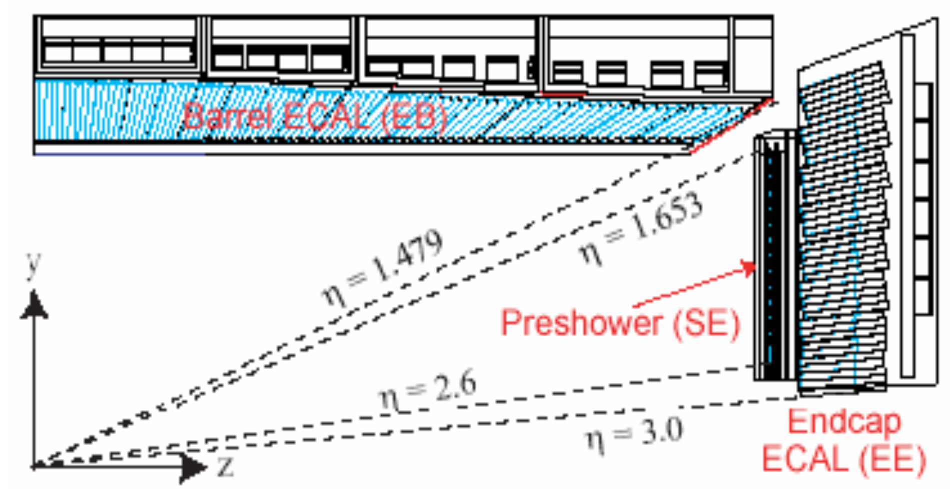
CMS Sampling window

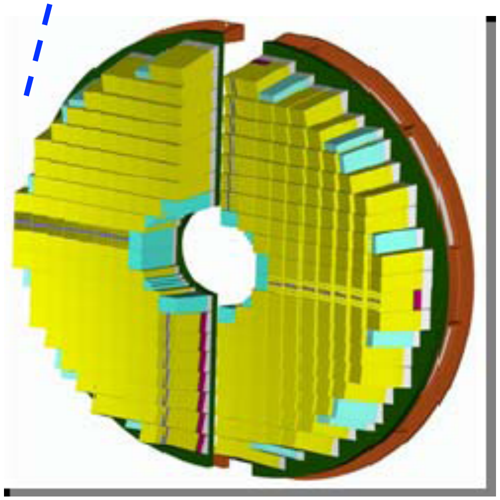


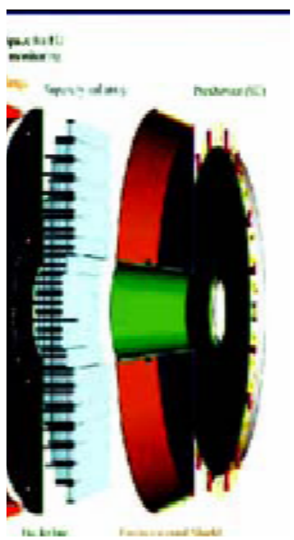
CMS ECAL Construction and Status

The ECAL



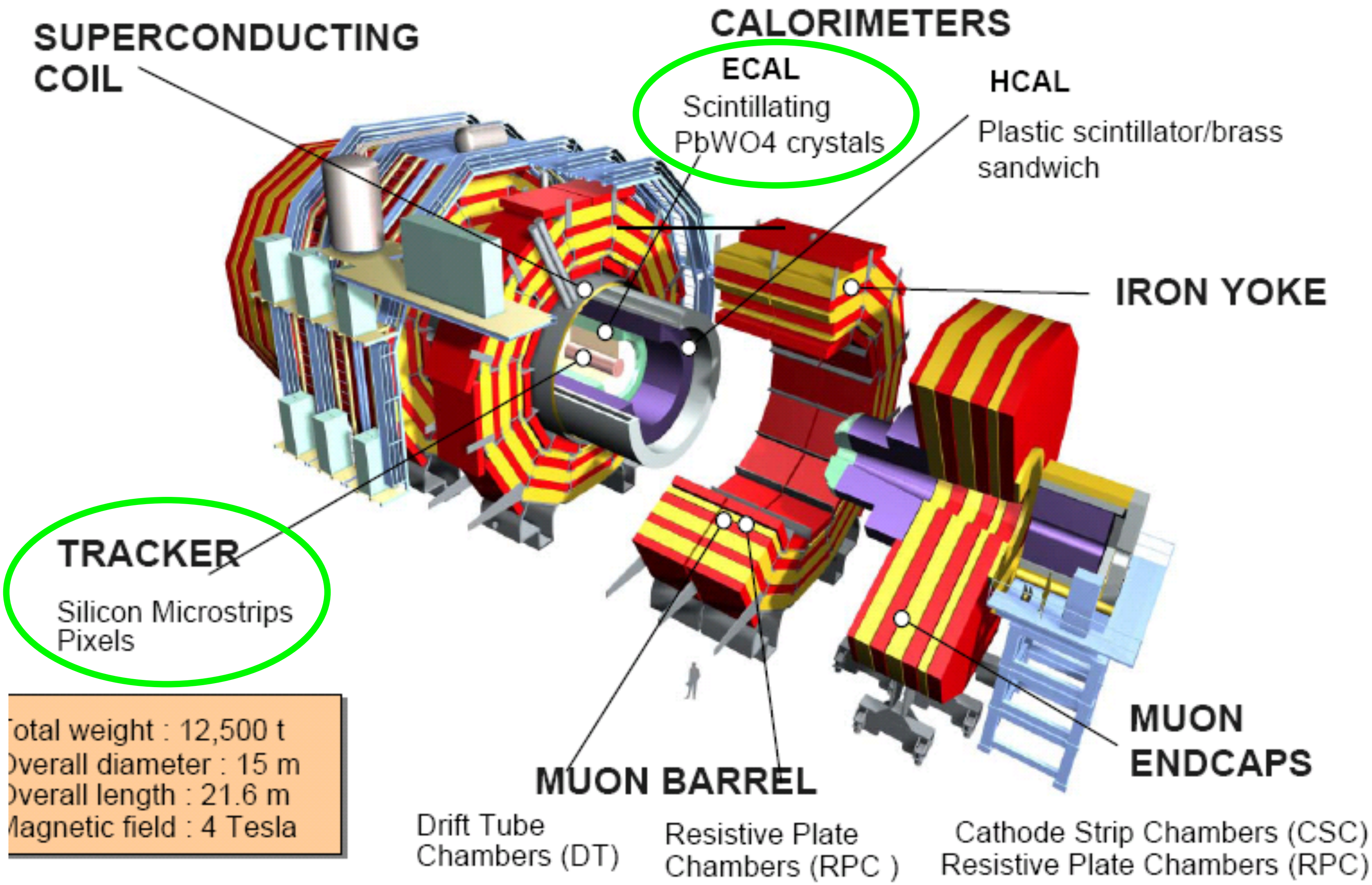




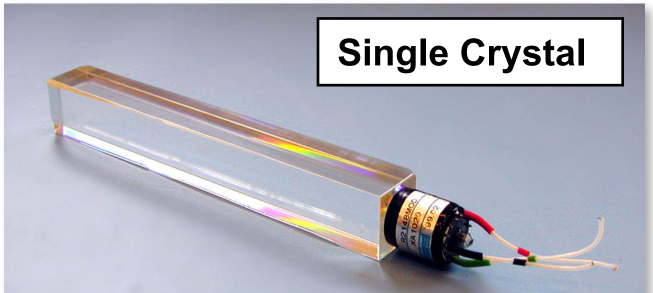


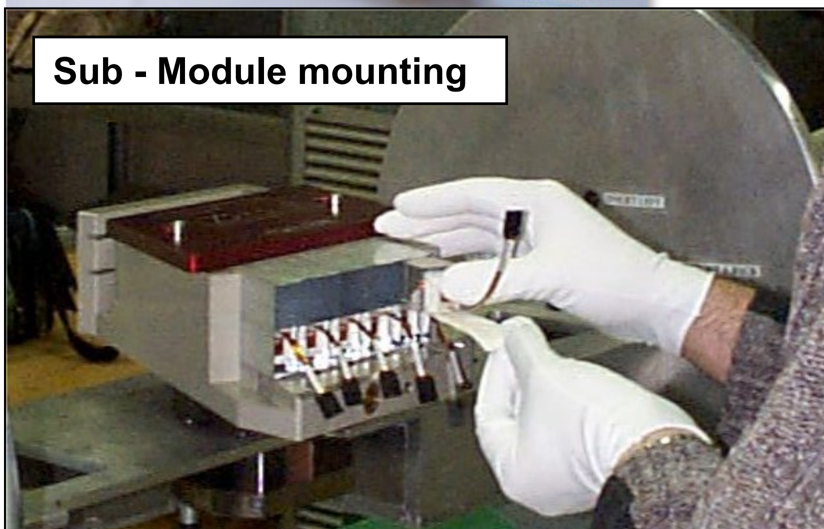
Parameter	Barrel	Endcap
η Coverage	|η|<1.48	1.48|η|<3.0
Granularity (ΔηxΔφ)	0.0175x0.0175	varies in η
Crystal dim (cm^3)	2.18x2.18x23	2.85x2.85x22
Depth in X_0	25.8	24.7(+3)
No. of crystals	61.2 K	14.9K
Modularity	36 supermodules	4Dees

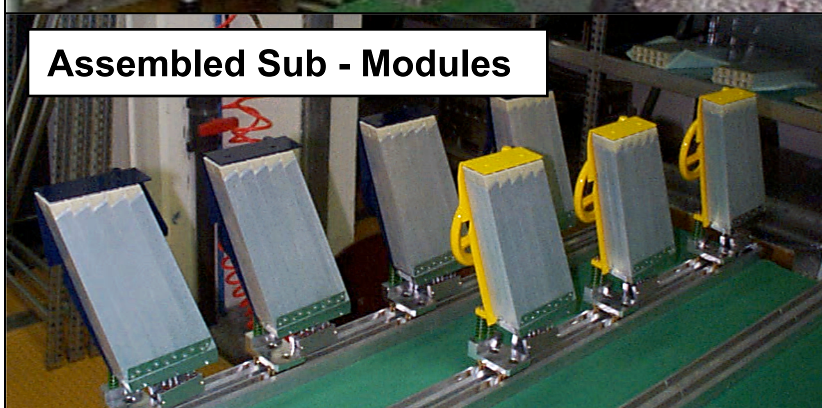
The CMS experiment

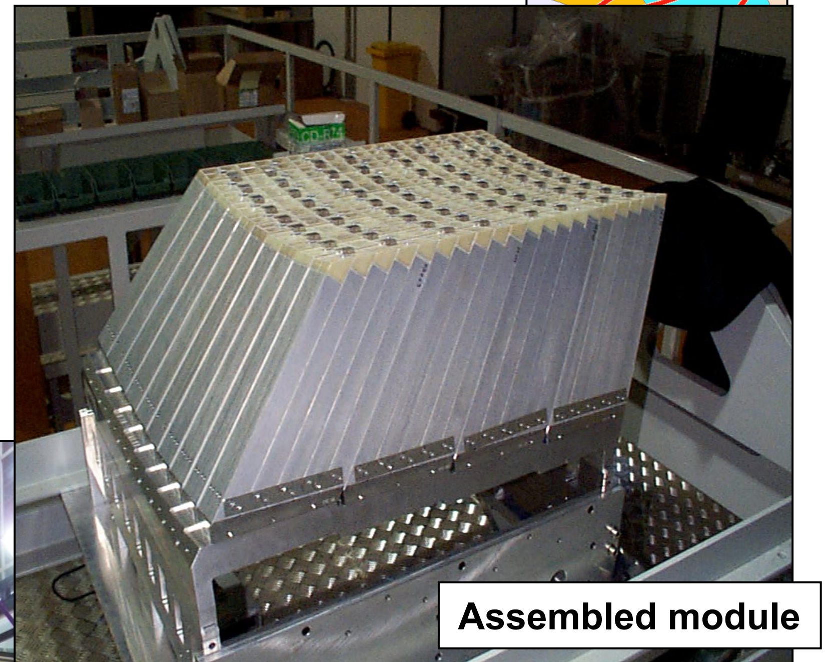


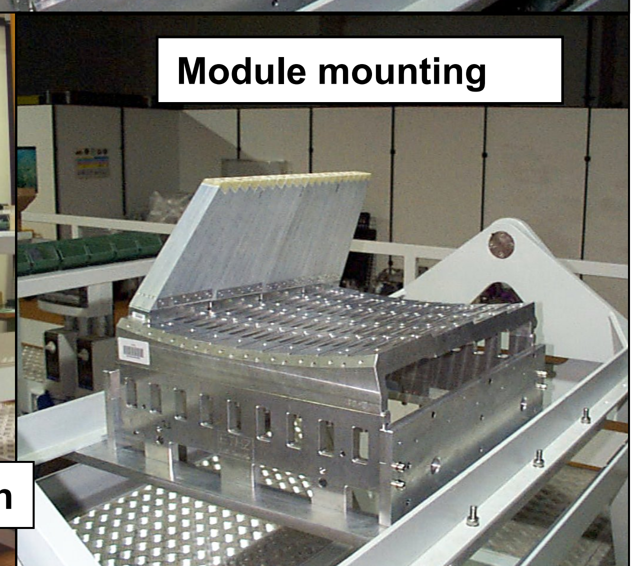
ECAL Crystal Matrix Production



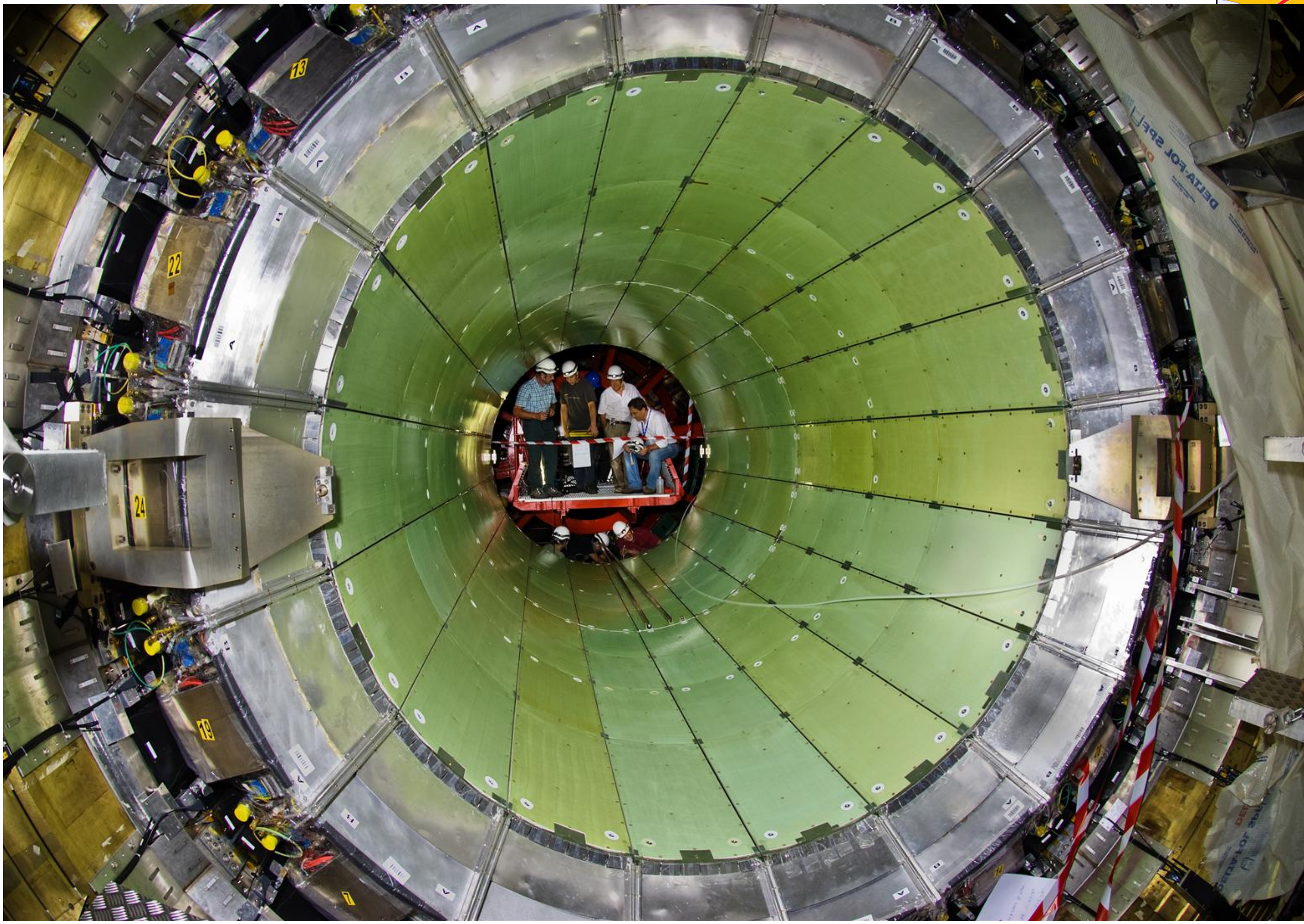




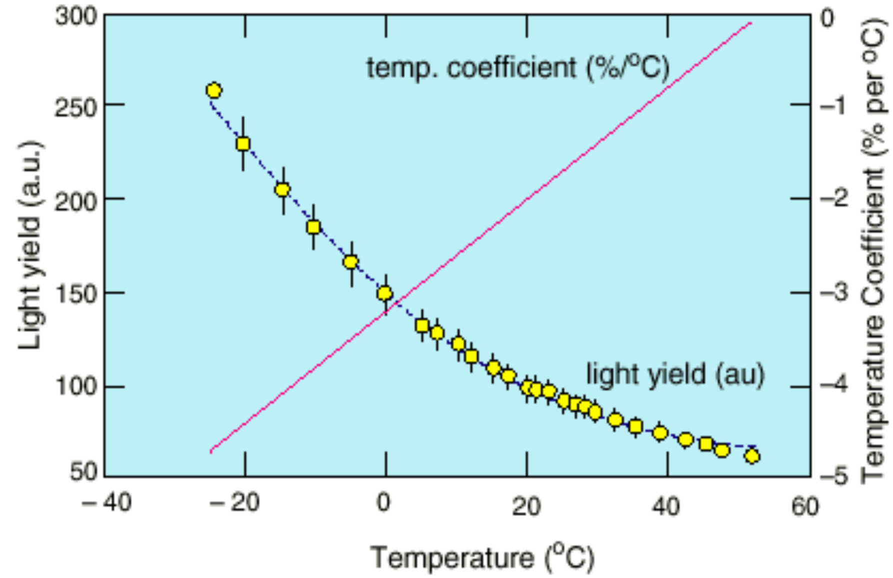




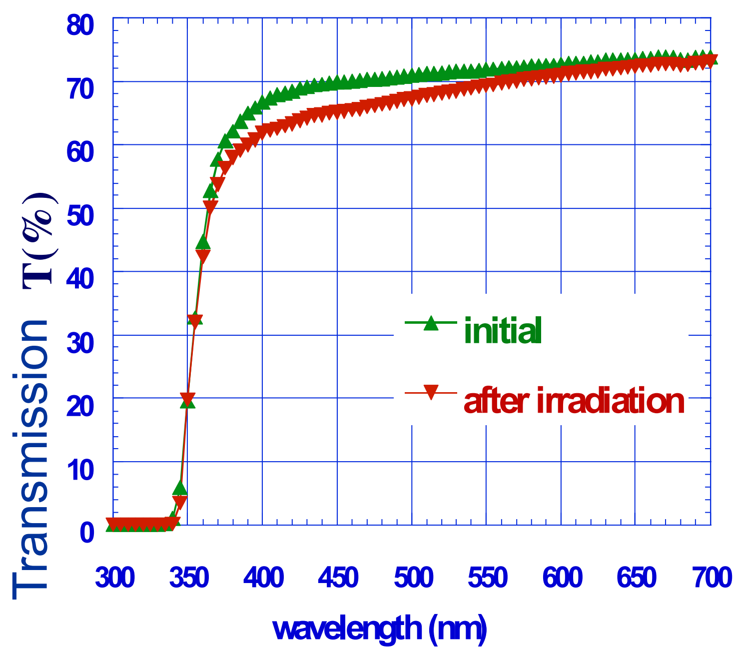
CMS Barrel Installation



Lead Tungstate Properties



Radiation resistant to very high doses.



But:

Temperature dependence ~2.2%/°C
→ Stabilise Crystal Temp. to ≤ 0.1°C

Formation and decay of colour centres in dynamic equilibrium under irradiation
→ Precise light monitoring system

Low light yield (~1% NaI)
→ Photodetectors with gain in mag field

Specially Developed Photodetectors

Barrel : Avalanche photodiodes

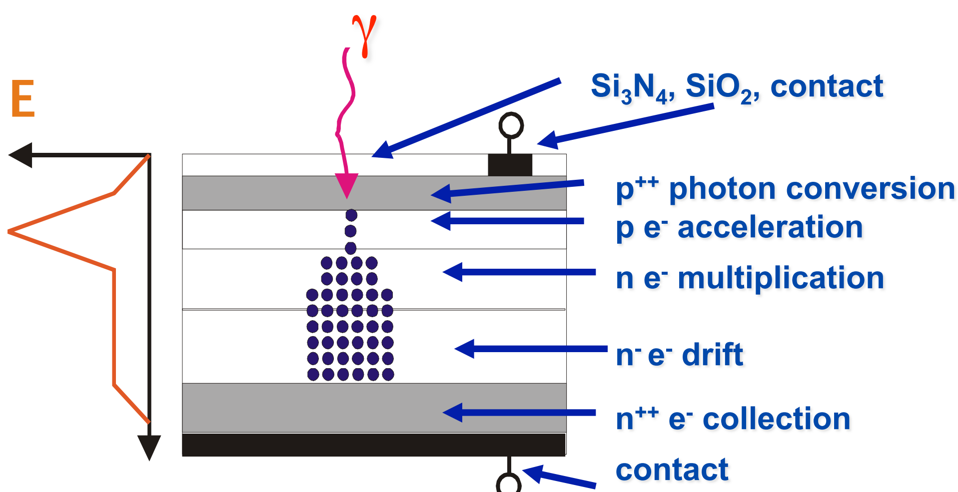
Two 5x5 mm^2 APDs/crystal

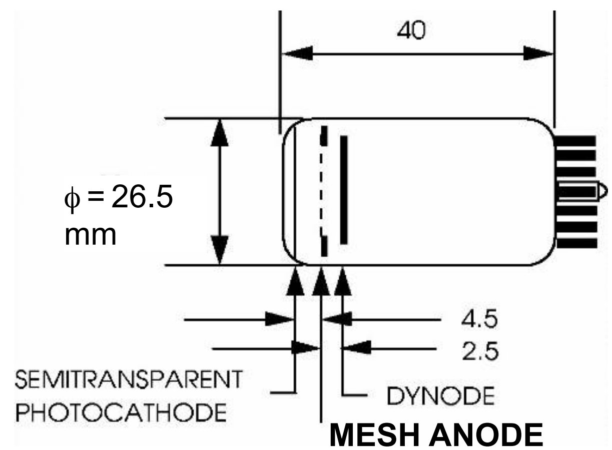
- **Gain: 50 QE: ~80%**
- **Temperature dependence: -2.4%/^{O}C**

Endcaps: Vacuum phototriodes

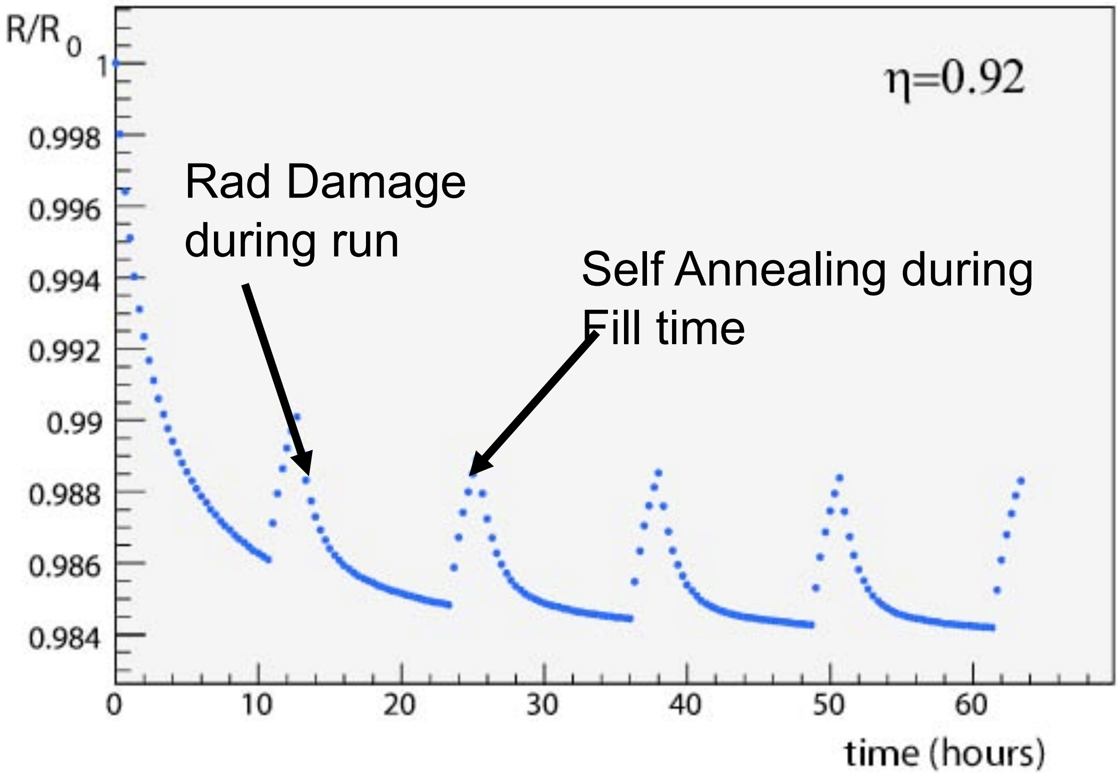
More radiation resistant than Si diodes (with UV glass window)

- **Active area ~ 280 mm^2/crystal**
- **Gain 8 - 10 at B = 4 T Q.E. ~ 20% at 420 nm**





Monitoring and Calibration



Transparency changes from 1-2% (Barrel) to > 10% (endcap) over course of a run

Precision Laser Monitoring System essential to avoid Severe resolution degradation

In situ Calibration from W->eν, π^0->$\gamma\gamma$, Z^0 ->e+e-, Z->$\mu\mu\gamma$ essential to Achieve design performance

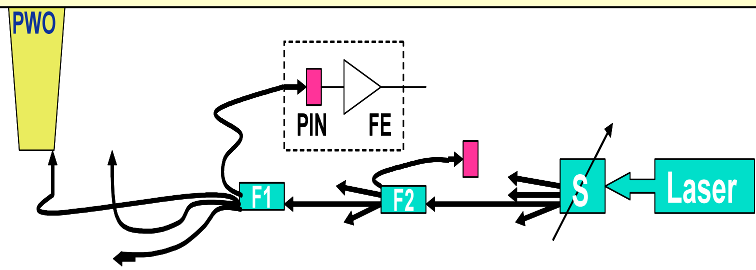
Laser light monitoring system

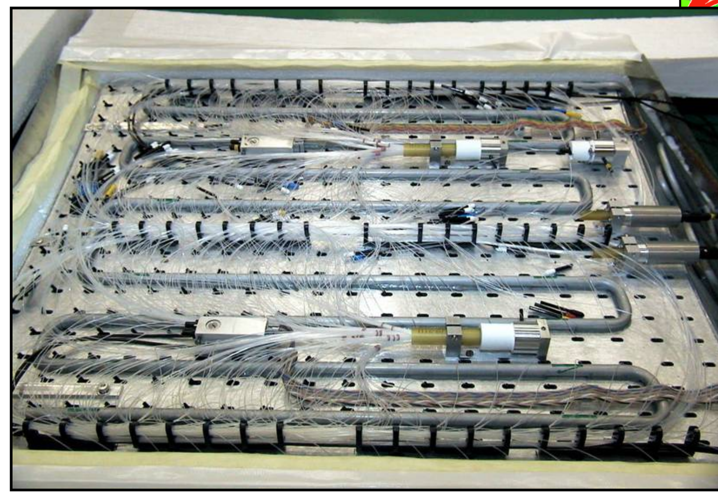
Colour centres

These form in $PbWO_4$ under irradiation
Partial recovery occurs in a few hours

Damage and recovery during LHC cycles tracked with a laser monitoring system

2 wavelengths: 440 nm and 796 nm

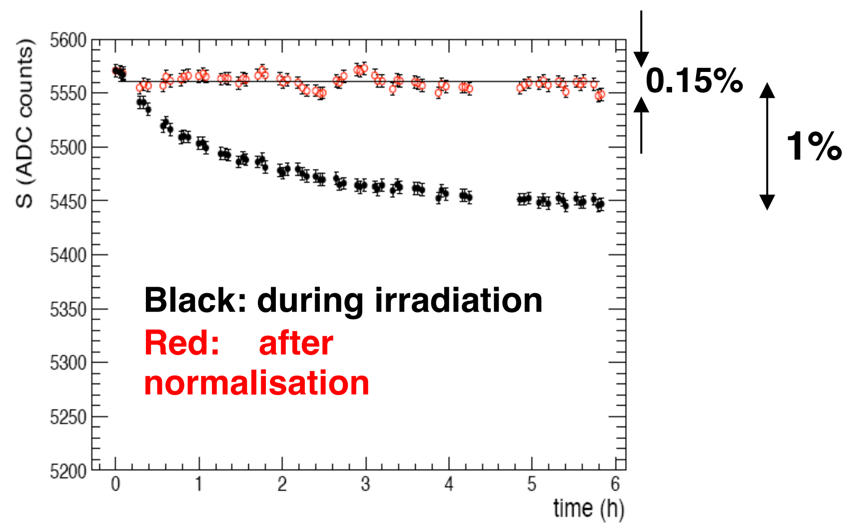




Light injected into each crystal using quartz fibres, via the front (Barrel) or rear (Endcap)

Laser pulse to pulse variations followed with pn diodes to 0.1%

Normalise calorimeter data to the measured changes in transparency

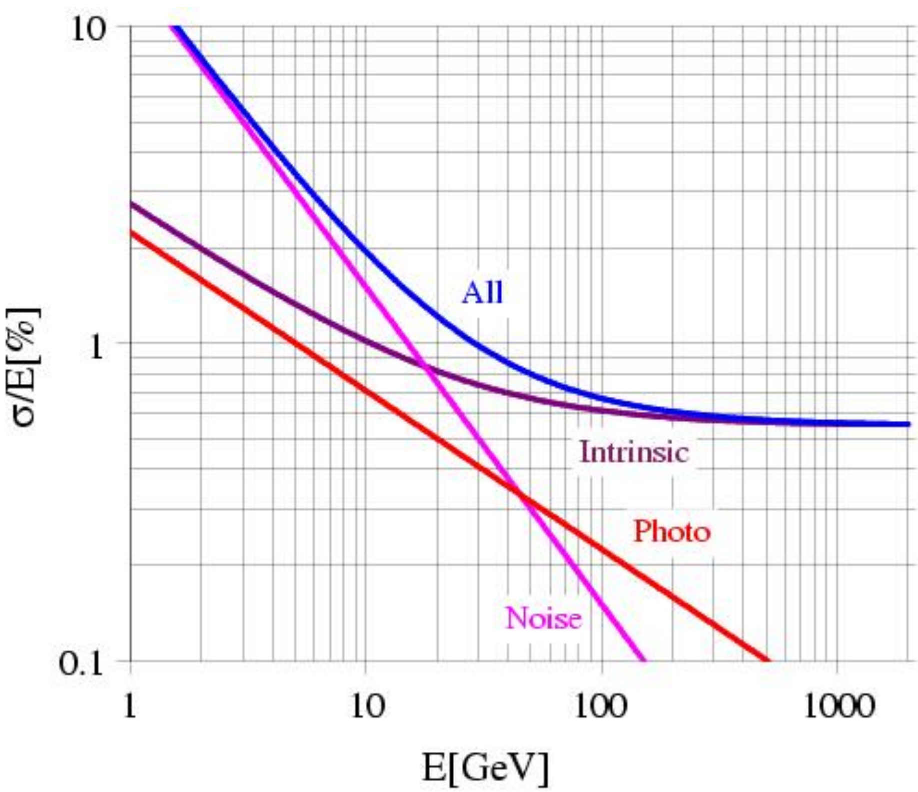


Electron signal in crystal versus time (h)

PWO Crystal ECAL Resolution

(Measured in Ideal conditions at testbeam. Reality later.)

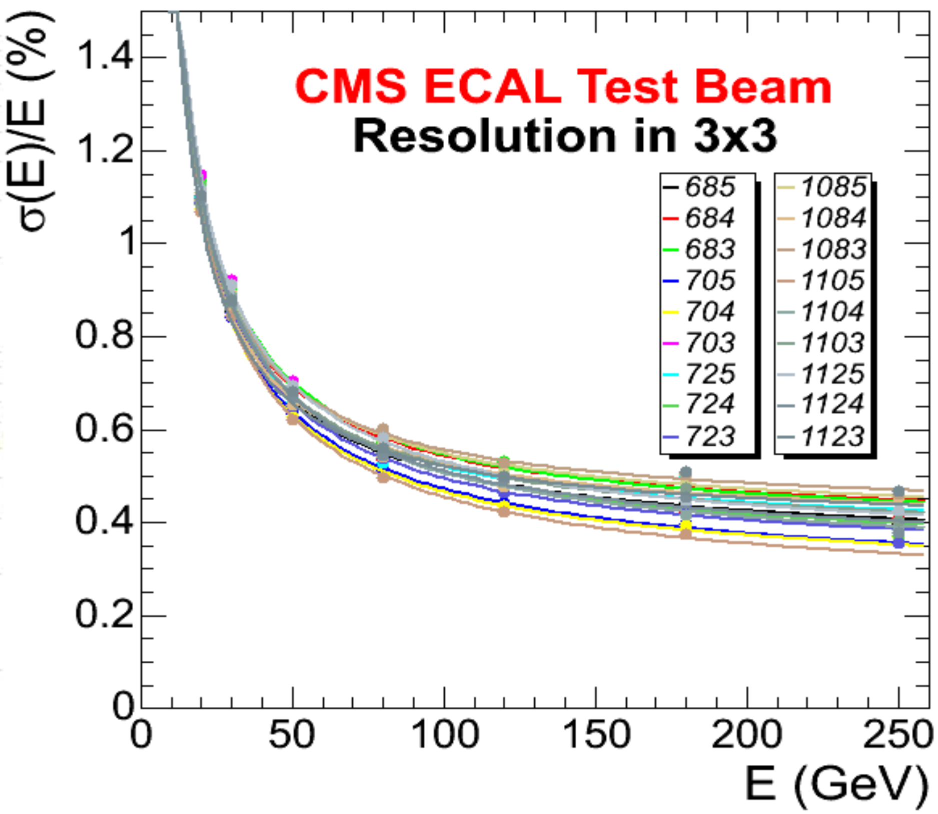
Designed Resolution



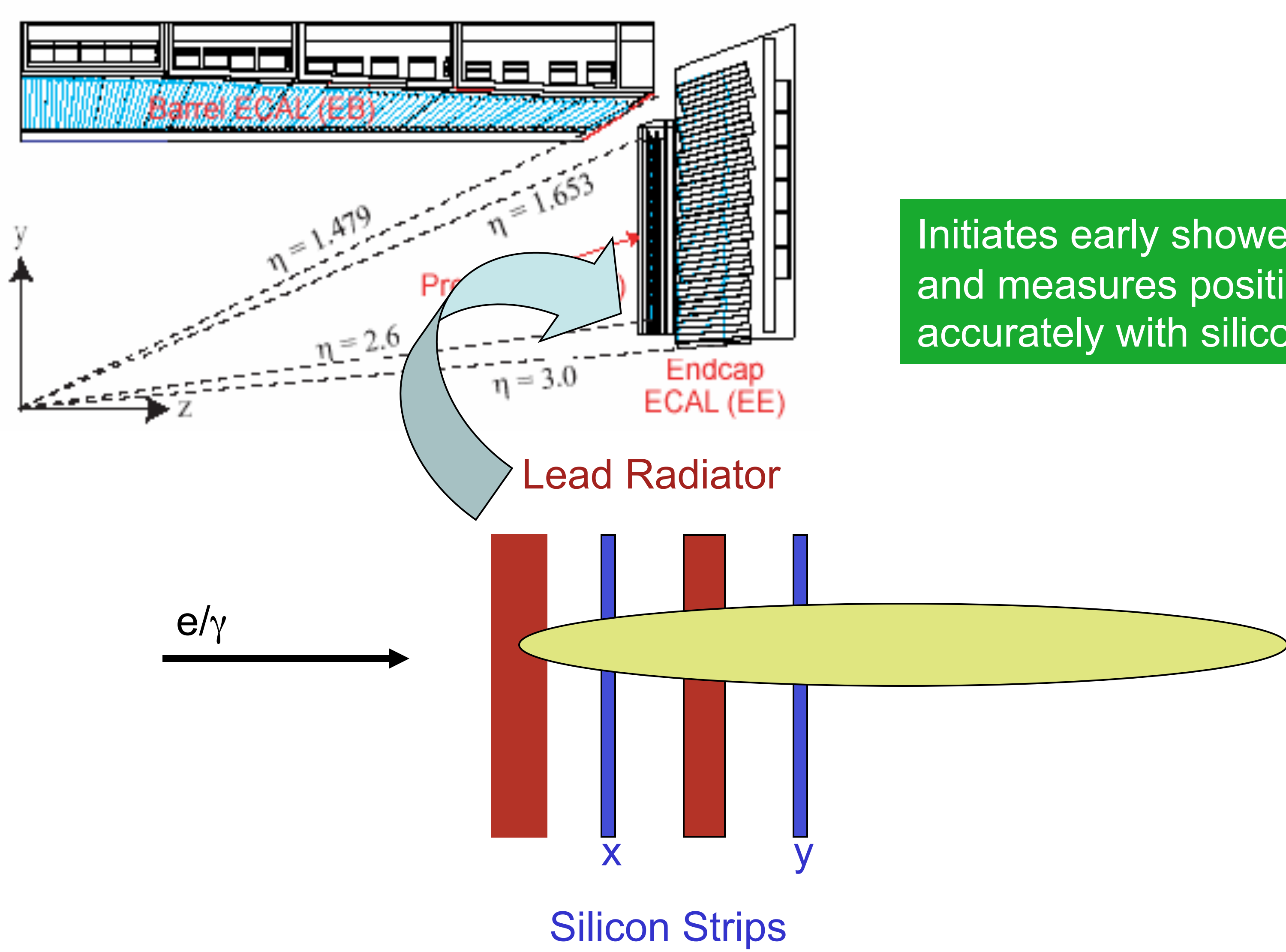
Measured Resolution

$\sigma(E)/E < 1\%$ if $E > 25$ GeV

$\sigma(E)/E \sim 0.5\%$ at 120 GeV



Preshower Detector



Initiates early showering and measures position accurately with silicon strips

Preshower Detector for π^0 rejection

H->$\gamma\gamma$ photons: Barrel 20-50 GeV
Endcap 50-100 GeV
(50% γ in endcap)

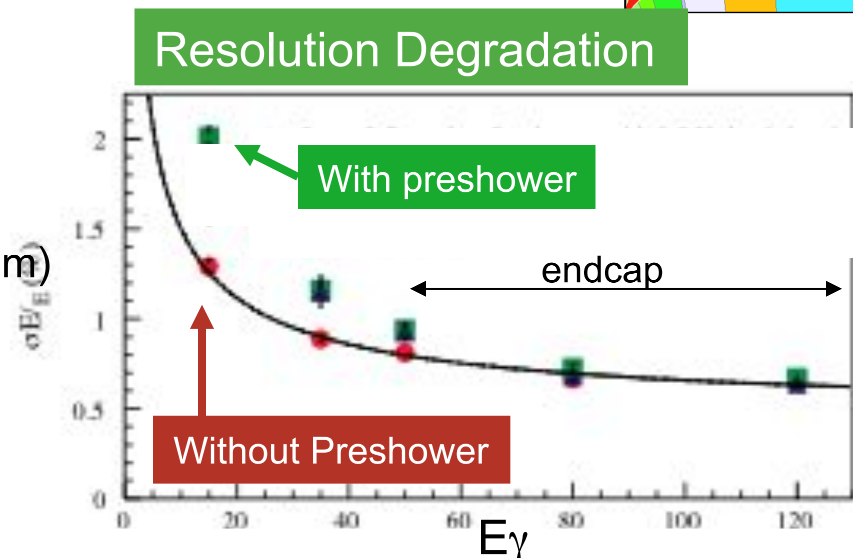
Photon Seperation (crystals 22mm x22mm
Preshower Si strips 1.9 mm)

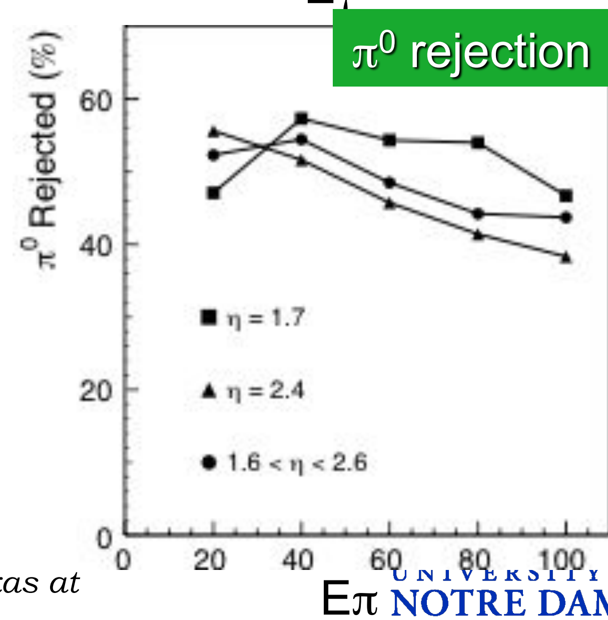
$E_{\pi}0$ (Gev)	< Δx $\gamma\gamma$> (mm)
25	25
50	15
200	4

Resolution degradation due to shower fluctuations significant at low E only

Barrel - lateral shower profile
Endcap - Preshower

For endcap, rejection improved by x2 with little degradation in resolution





Early Operational Experience

LHC Startup

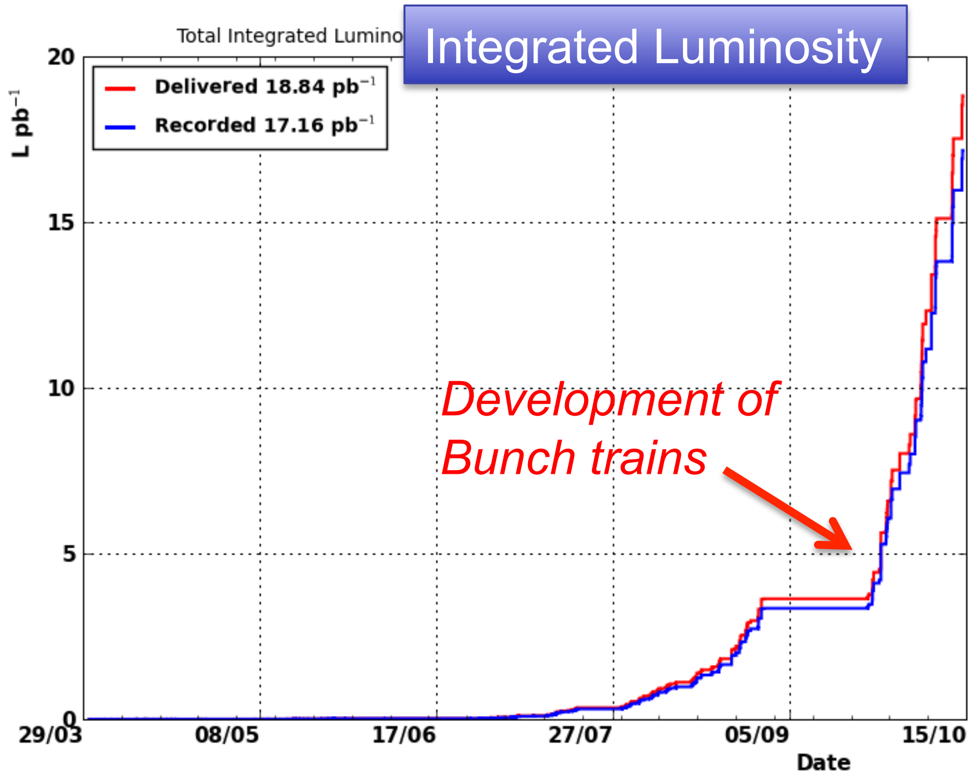
Data taking at 7 TeV since March 2010

Currently 10^{11} p per bunch and L=1.03 x 10^{32} cm^2s^{-1} (Oct 15 2010)

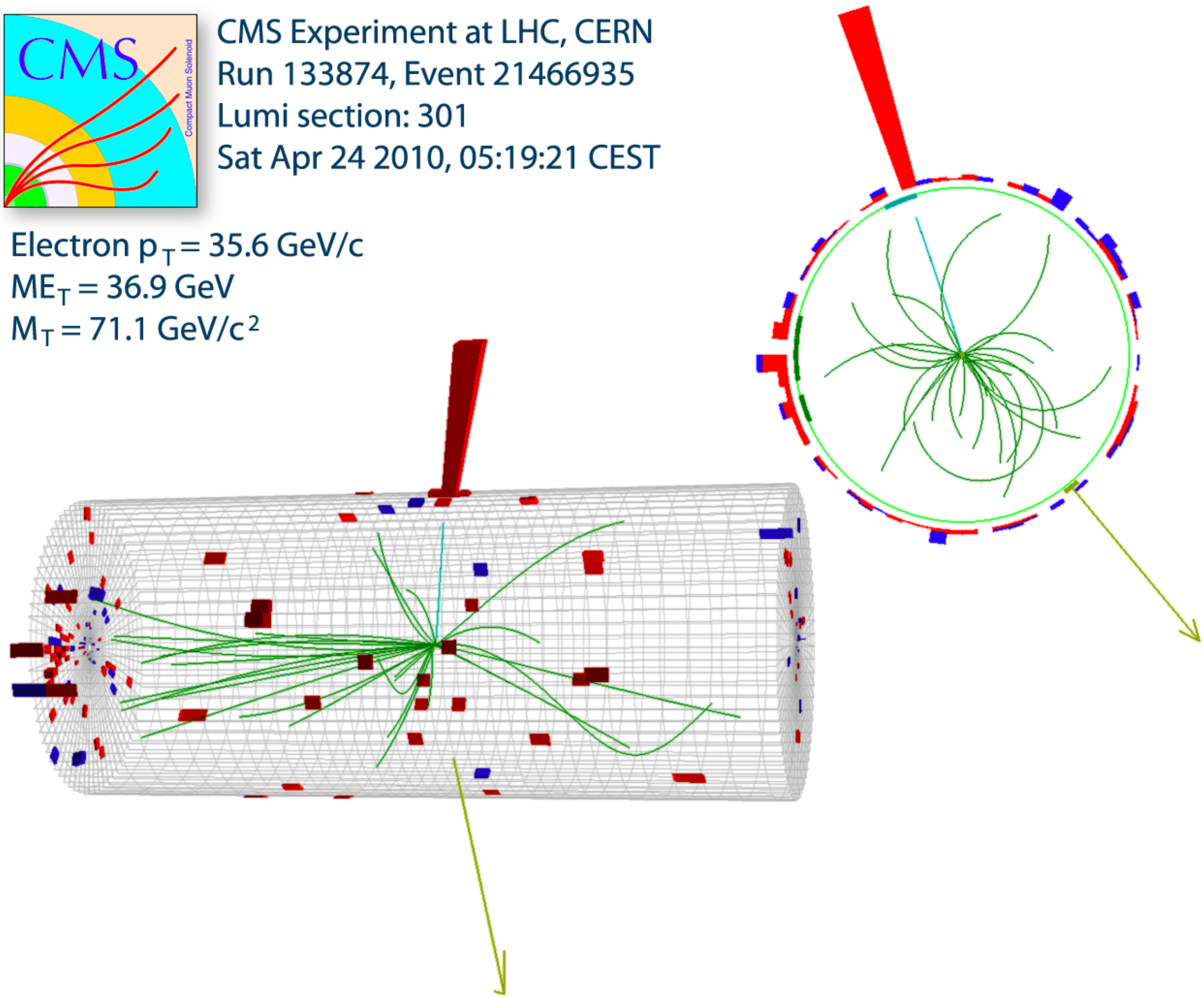
N= 248 bunches in trains with 233 bunches colliding (nominal LHC 2808/beam)

Adding 48 bunches per week

Expect 50 pb^{-1} by end 2010
$1fb^{-1}$ by end 2011



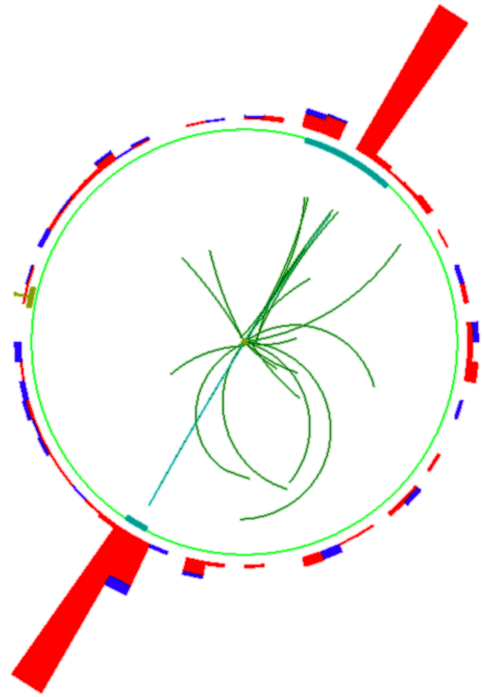
$W^- \rightarrow e^- \nu_e$ candidate

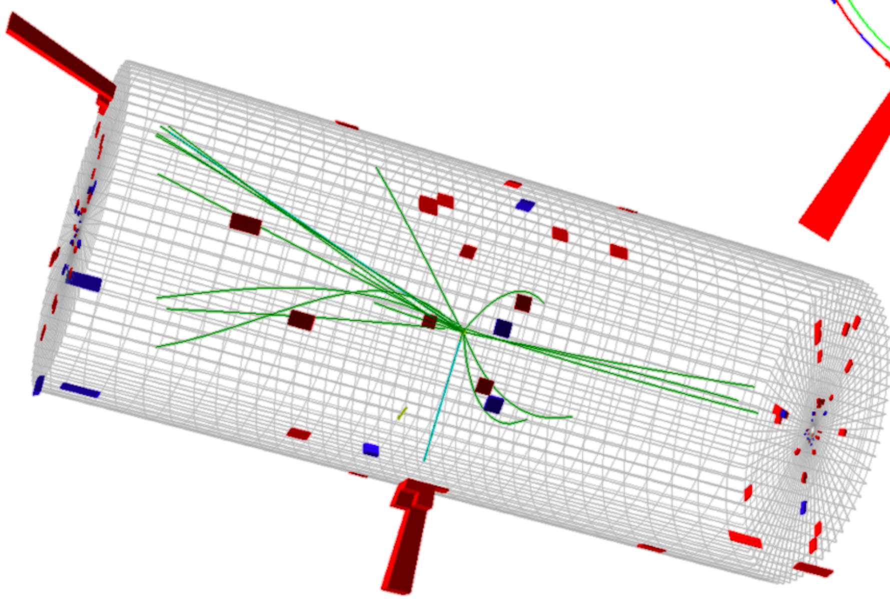


Z→e^+e^- candidate

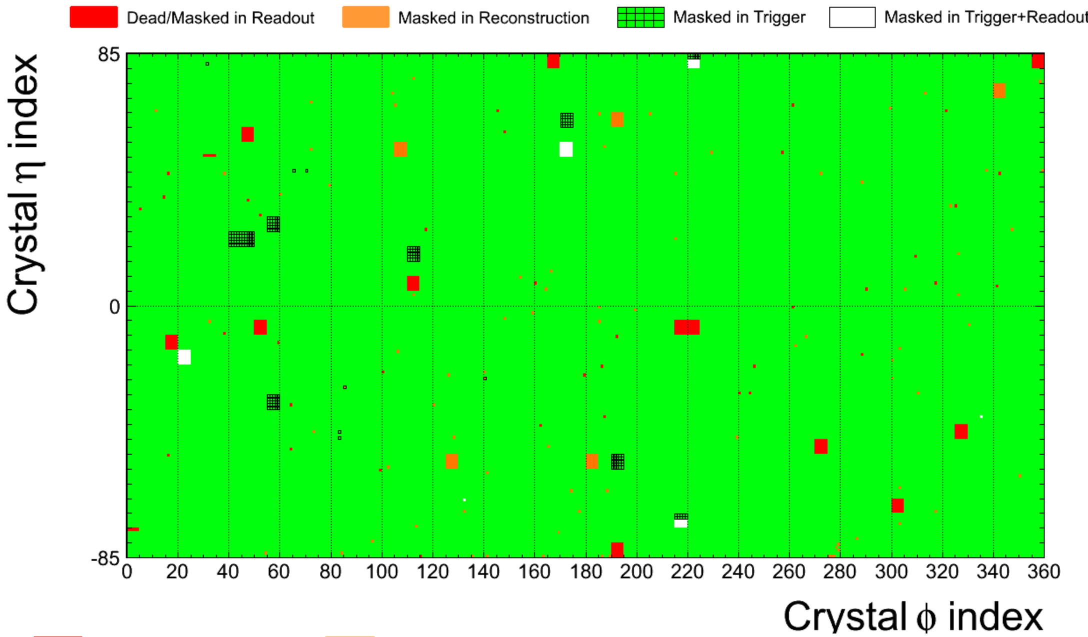
CMS Experiment at LHC, CERN
Run 133877, Event 28405693
Lumi section: 387
Sat Apr 24 2010, 14:00:54 CEST

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

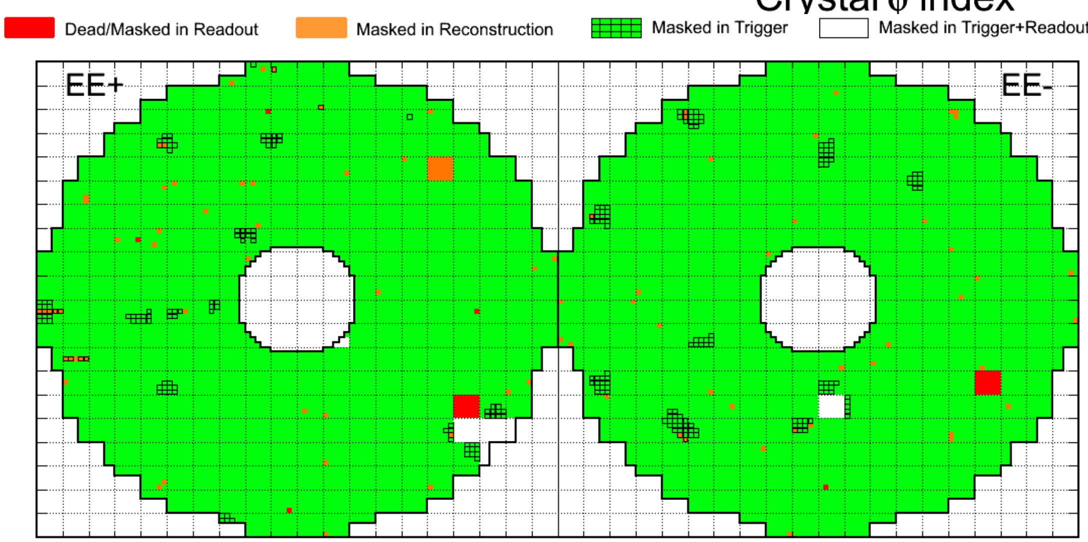




Dead Channels

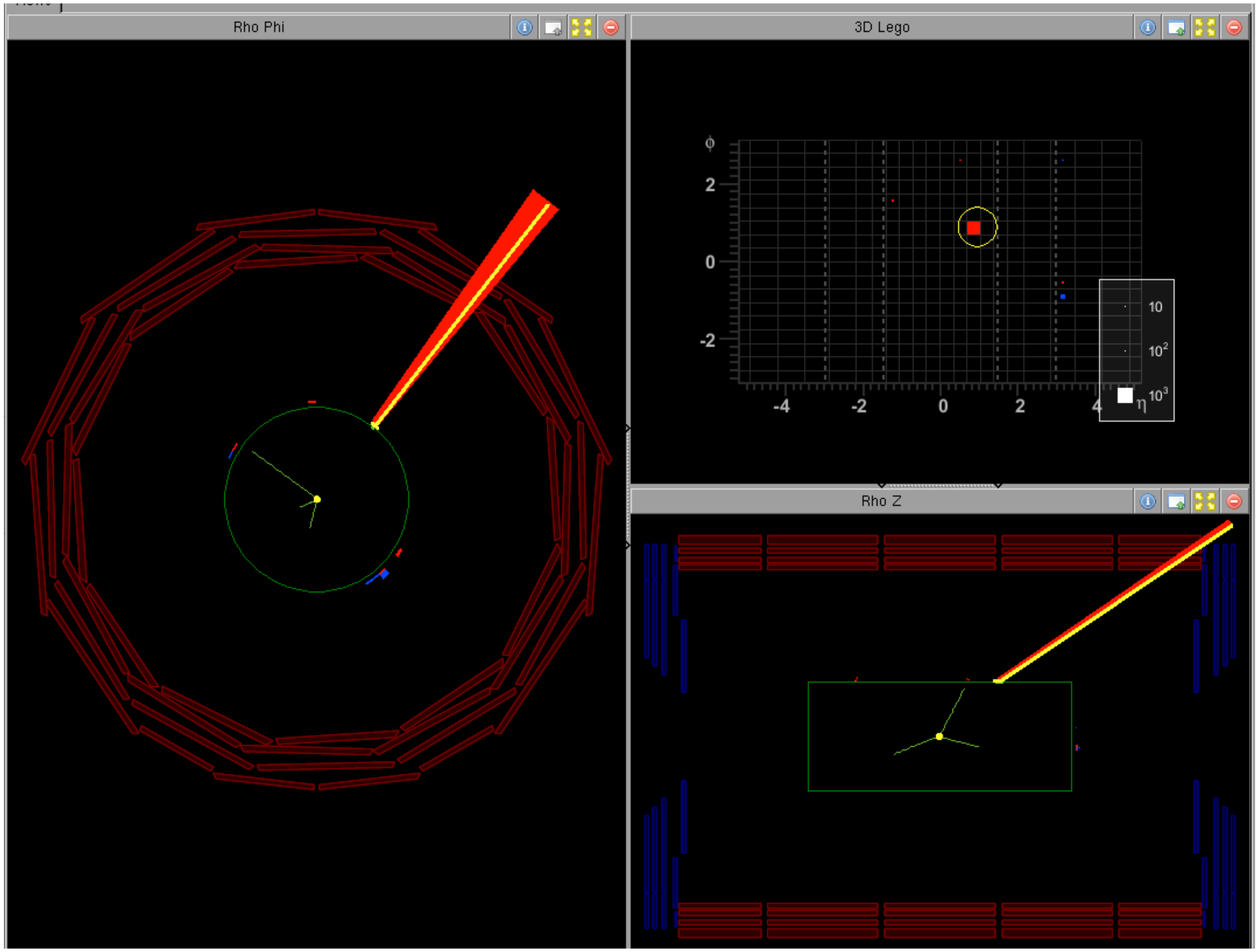


99.3% good channels in barrel



99.94% good channels in endcap

Spikes !



As soon as we started running we started seeing huge (1TeV) energy deposits in single crystals (approx 1 in every 1000 min bias events)

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Origin of spike signals

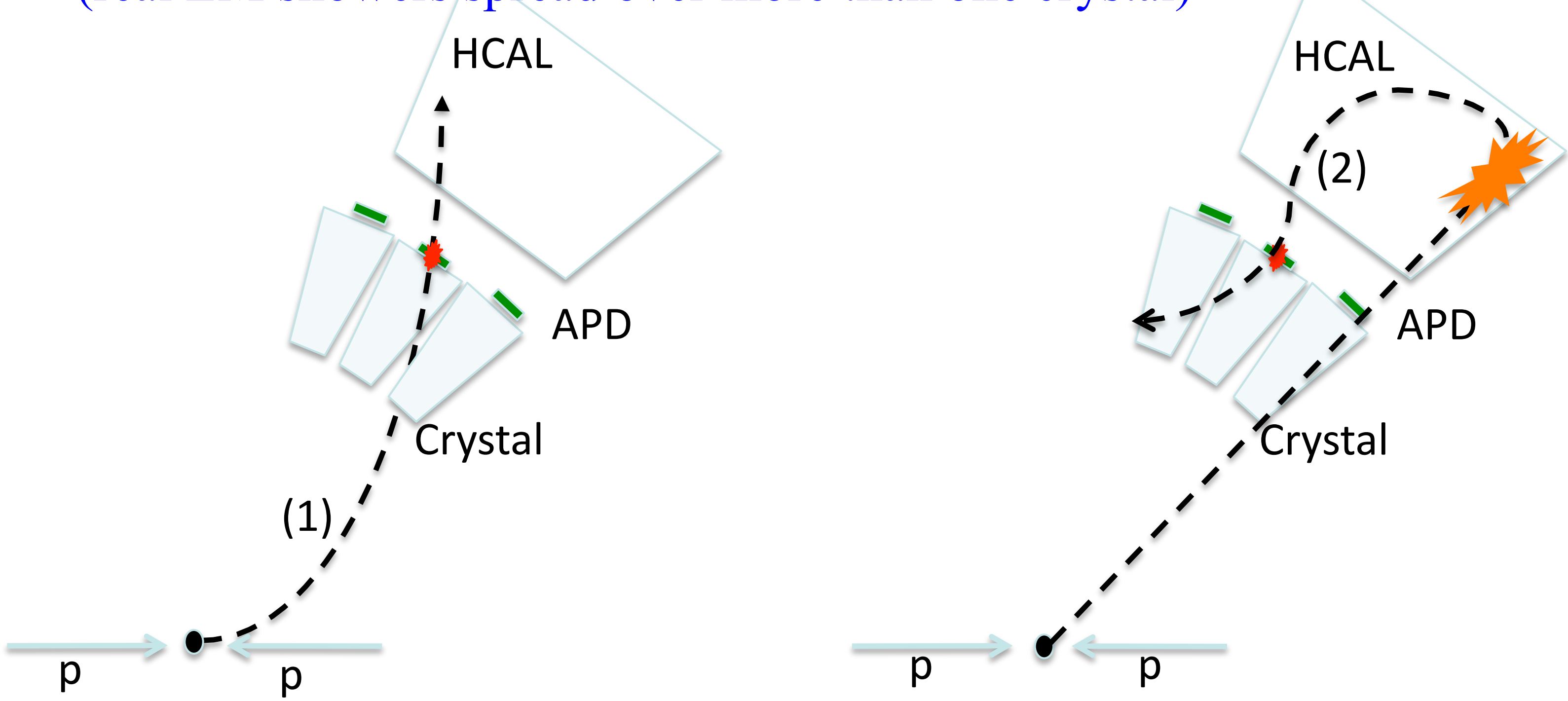
Spikes are due to a deposition of energy in the depleted silicon bulk of the Barrel photodiodes which fakes a much larger energy deposition in the corresponding crystal.

The *mother* particle can be produced:

① At the IP => early signal

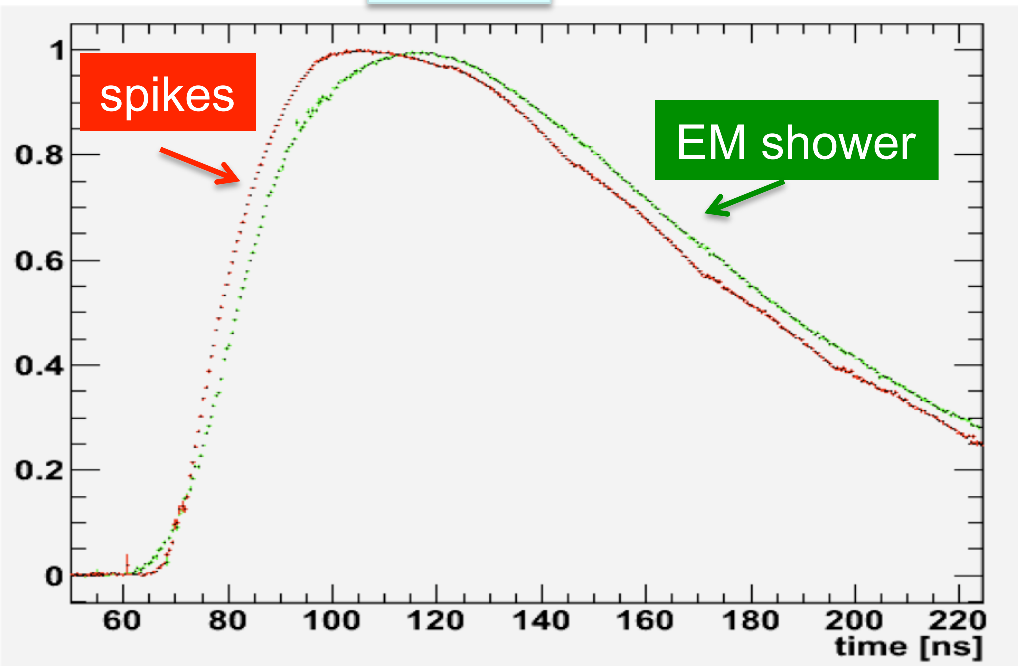
② In secondary interaction => wide timing spectrum

Spike signals are recognizable by their timing and unusual shower shape profile
(real EM showers spread over more than one crystal)

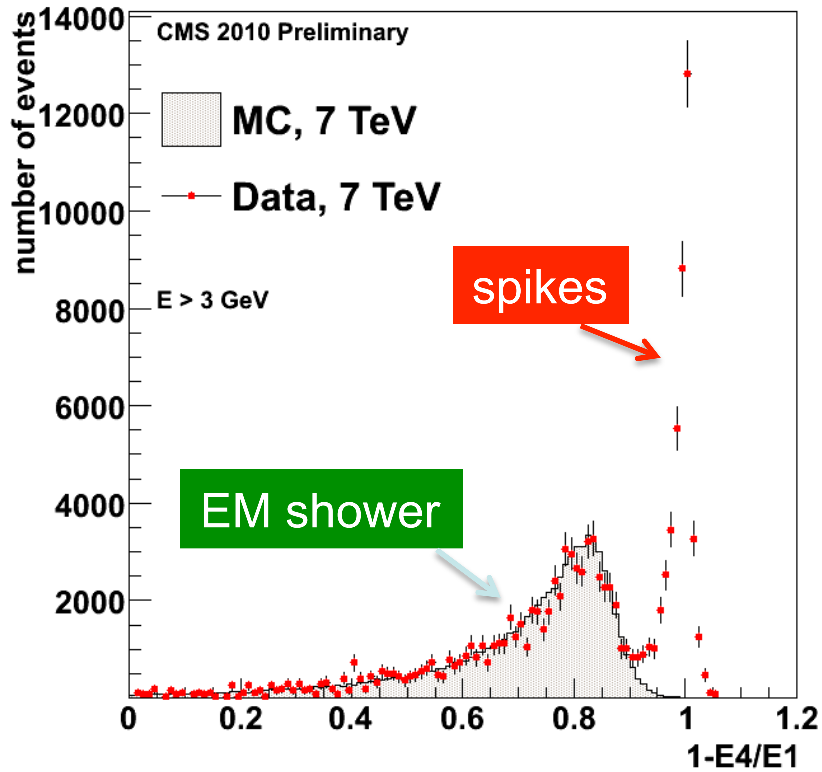


Removing Spikes

Timing



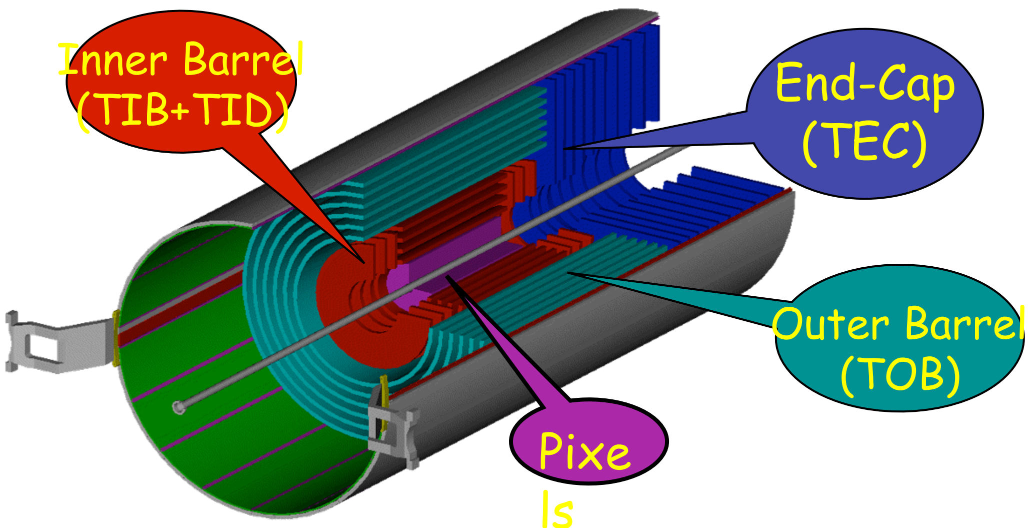
Isolation

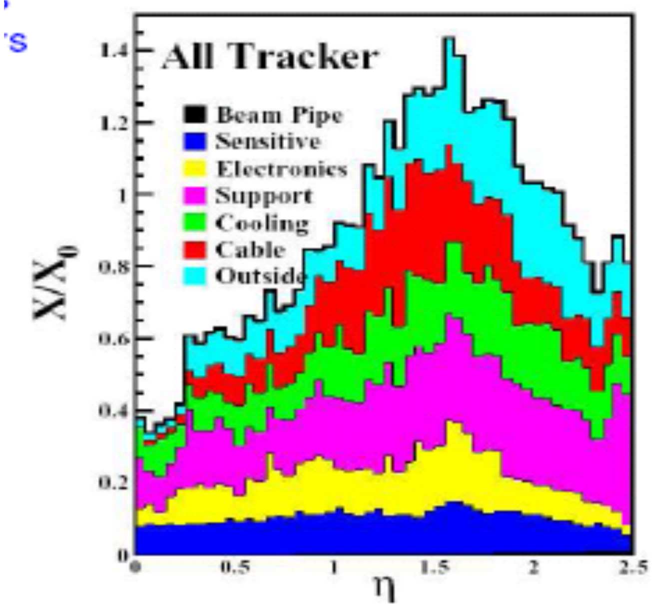


At present we can remove spikes offline but they may become a serious issue for triggering

Selection and reconstruction of e/γ

Material in Front of Calorimeter



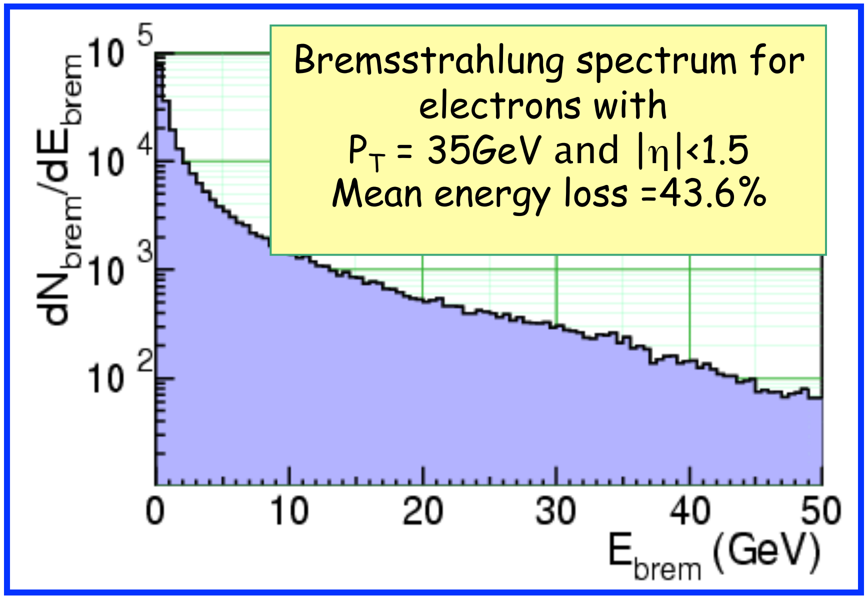


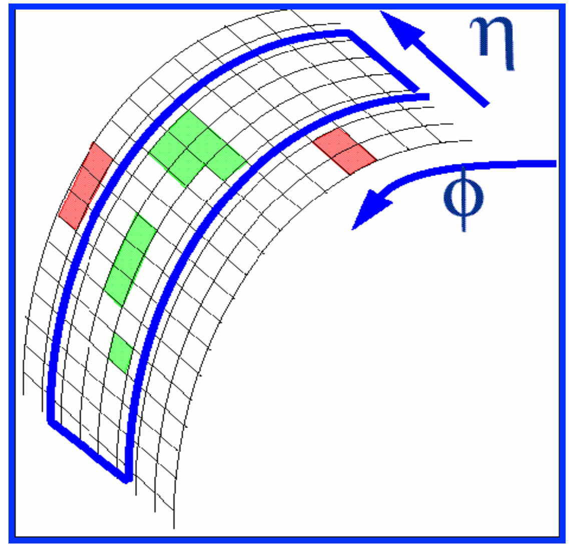
Unusually large amount of material in front of Calorimeter (0.4 to 1.4 X_0) from Silicon tracker (c.f. BaBar 0.4 X_0)

1. Causes Electron Bremstrahlung
2. Causes Photons to pair produce

Significantly degrades resolution and Efficiency to reconstruct good e/γ

Electron Bremstrahlung

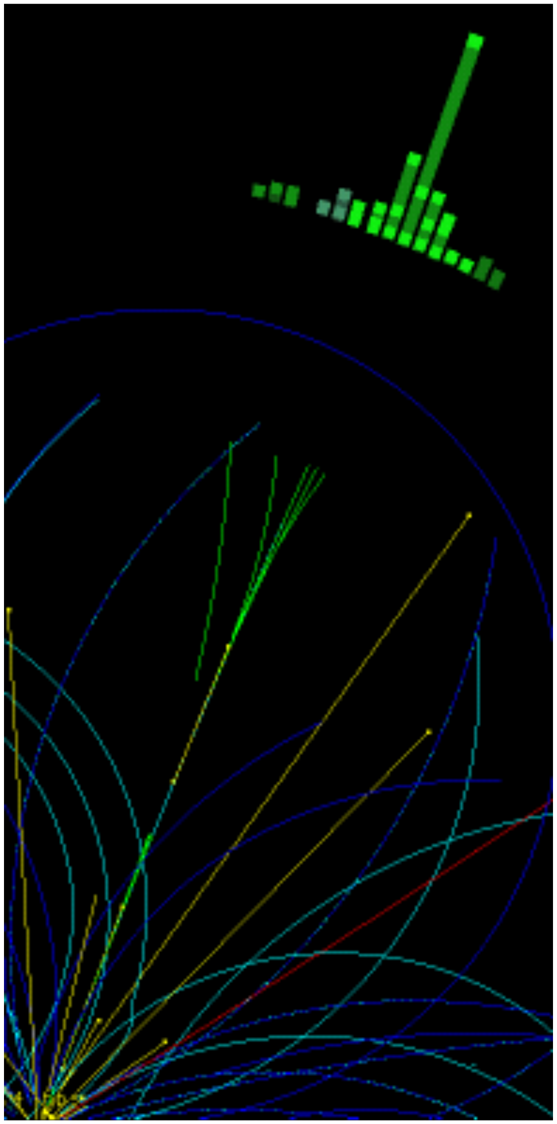


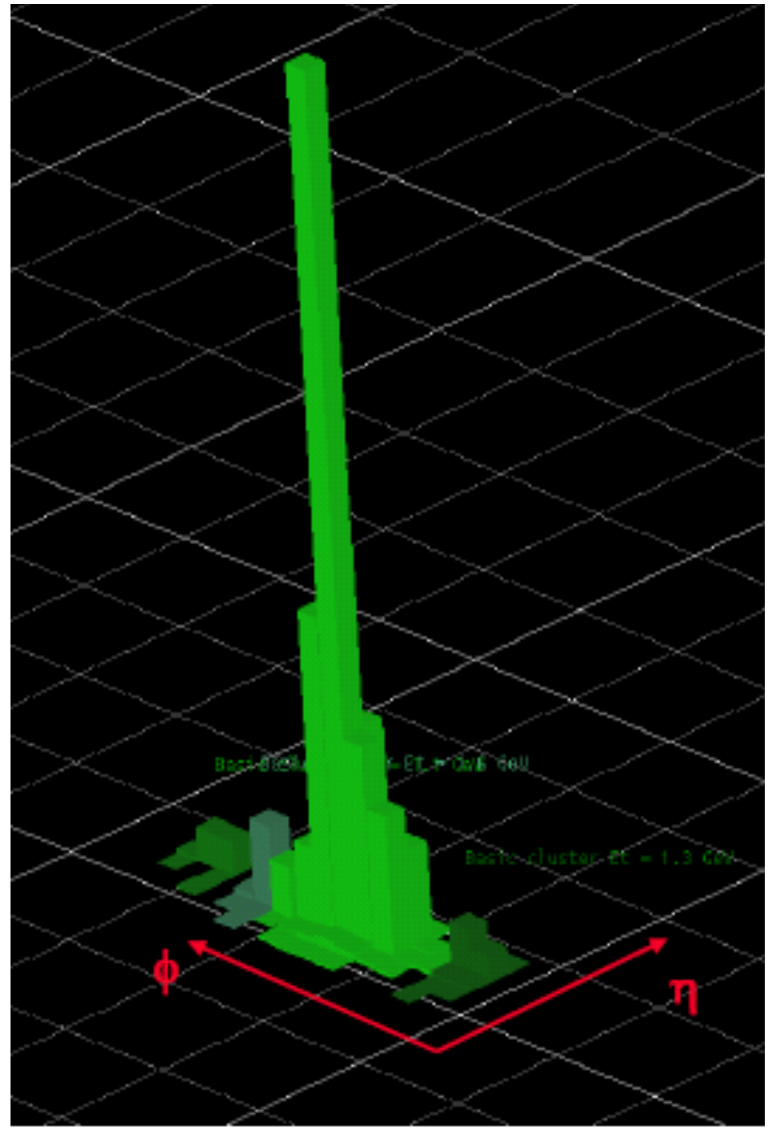


Electrons brem in tracker material and bend in φ in 4T mag field so cluster energy is distributed in φ.

35% electrons radiate more that 70% of energy before ECAL
10% 95%

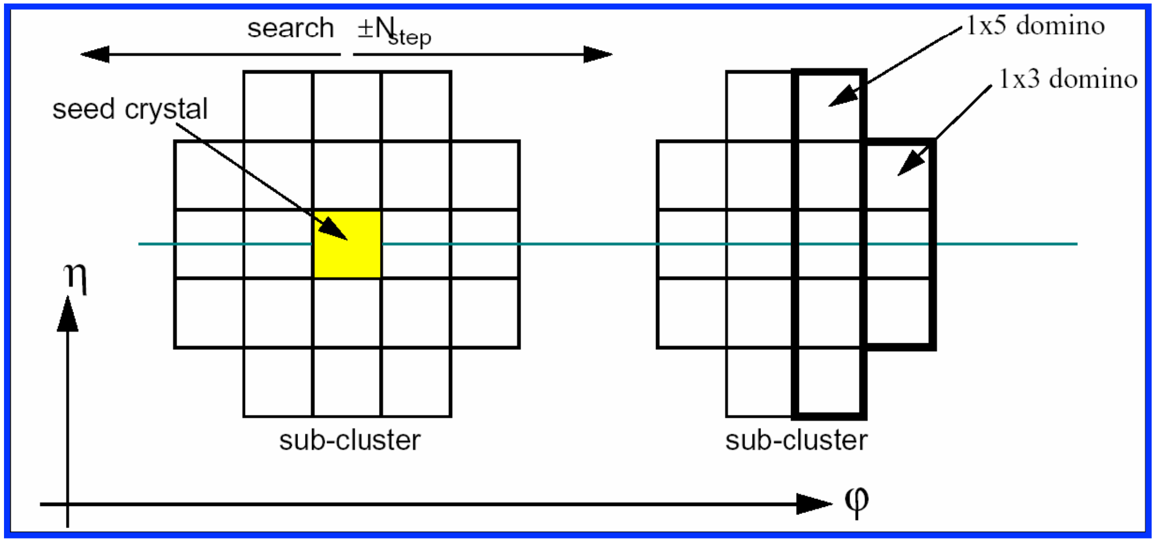
Example of an Electron reconstructed in ECAL

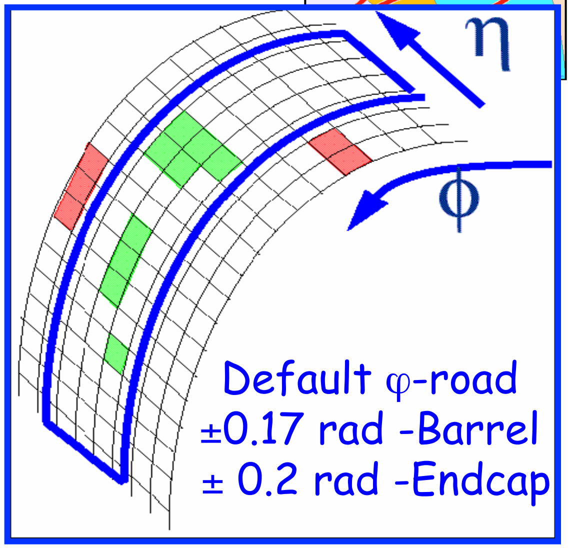




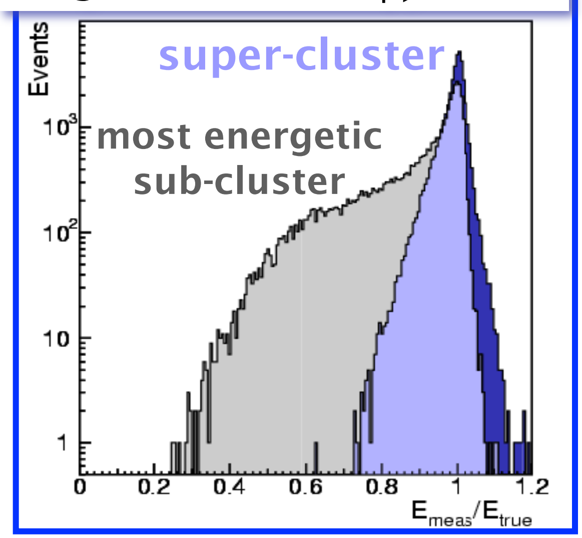
Bremsstrahlung recovery in clustering

For a single e/γ that does not brem or convert cluster size is typically about 3x3 crystals (94% Energy contained)





Single electrons $P_T > 30$GeV

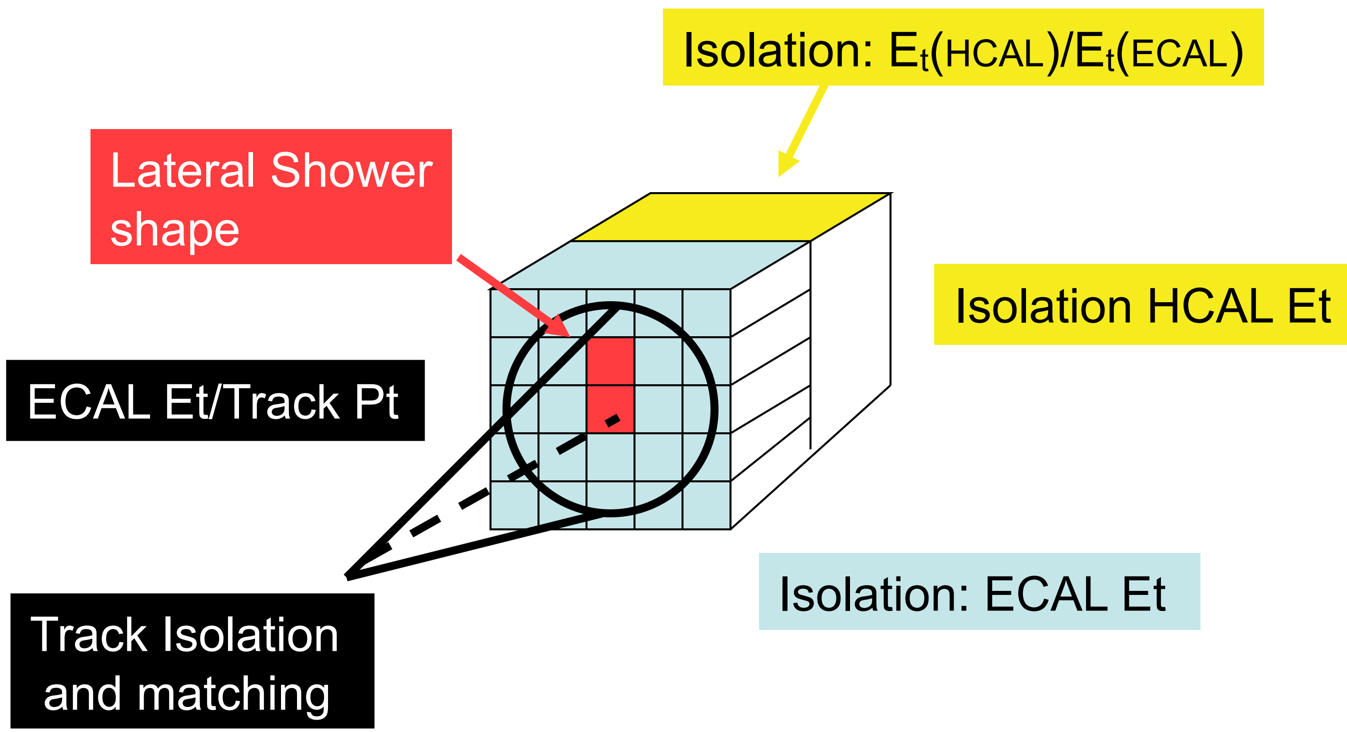


Recover Brem by making "superclusters" which are a cluster of clusters in ϕ.

(Hydrid/Island algorithms for Barrel/endcap)

Reducing Jet background to e/γ

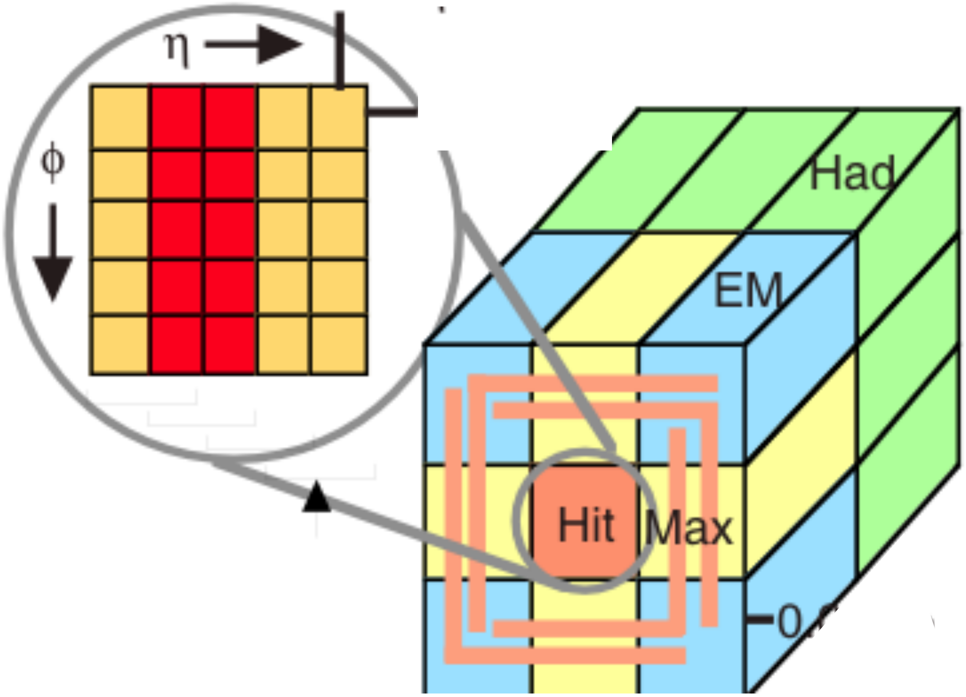
Four tools: Shower Shape, Isolation, Track Matching, E/P

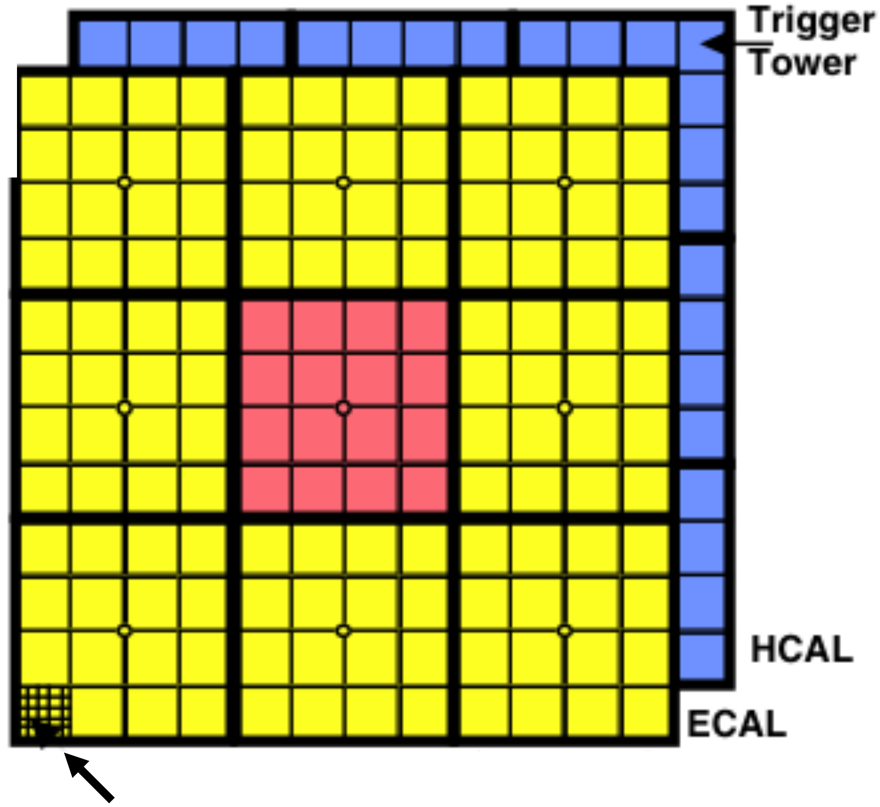


Level 1 Triggering (Hardware)

Lateral profile in η slices

Isolation using trigger towers





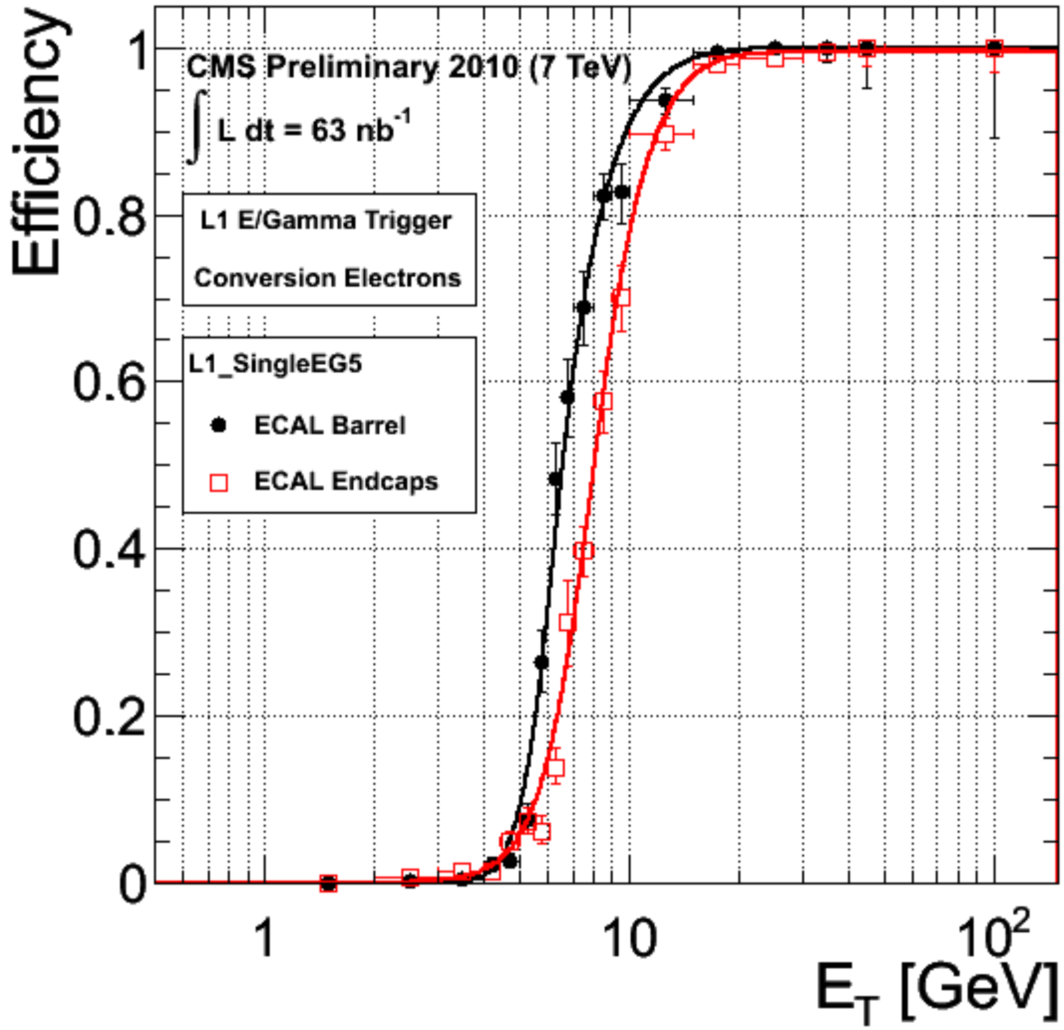
No tracks in trigger so e/γ is just a cluster. Use isolation and lateral shape to reduce jet background.

Level 1 Triggering Efficiency

From Minumum bias Events

Using 5 GeV threshold (nominally 19 GeV at full luminosity)

Turn on is as expected



1. Find SuperCluster in ECAL

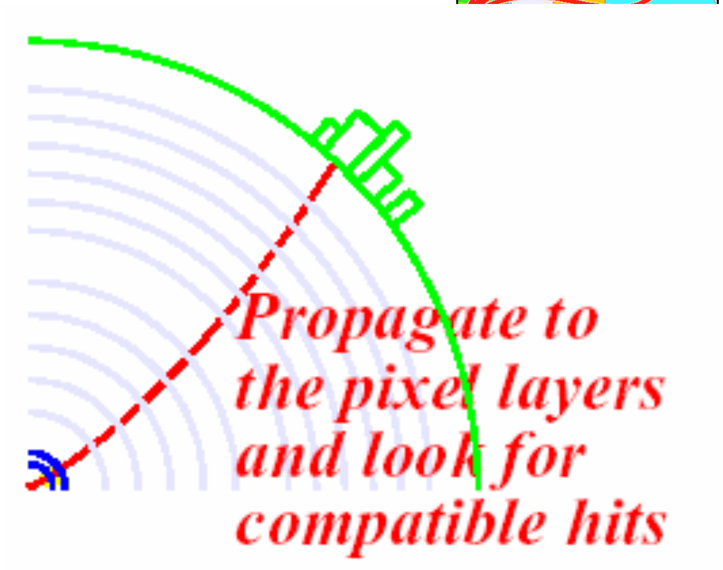
2. Use primary vertex to construct a presumed trajectory between SuperCluster and Vertex

3. Look for pixel hits in window about trajectory

4. Using pixel seeds build trajectory in to out and look for associated silicon tracker hits

5. Fit trajectory

6. Correct Cluster Energy for energy loss in material

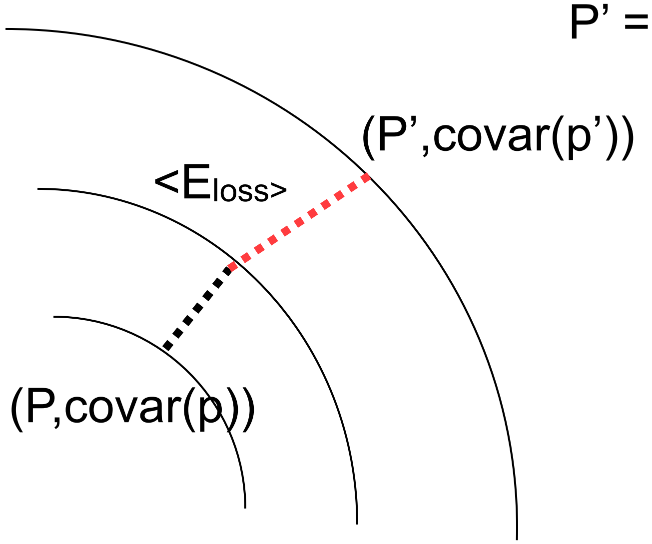


Electron tracking uses Gaussian Sum Filter (GSF) which takes into account the effect of the interaction of the material in the tracker on the trajectory

The Gaussian Sum Filter (GSF)Tracker

Kalman Filter introduced to take into account of energy loss in material when technology moved from gas to denser silicon trackers.

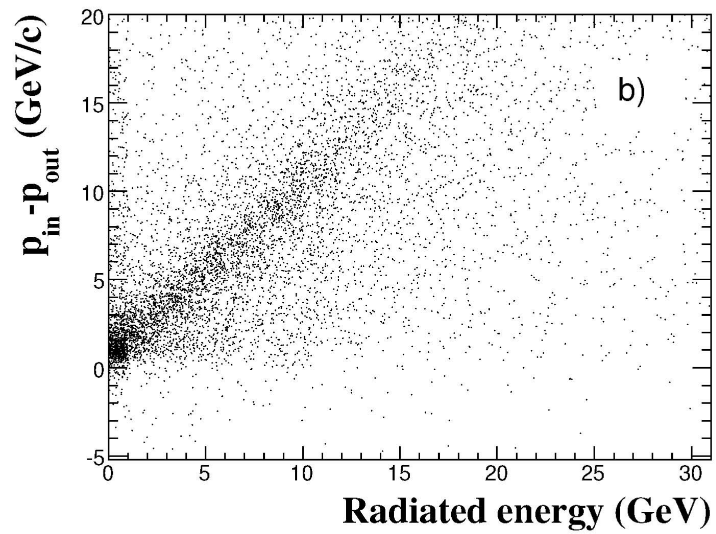
$P' = P - \langle E_{loss} \rangle$ $\quad$ $covar(p') = covar(p) - covar(E_{loss})$



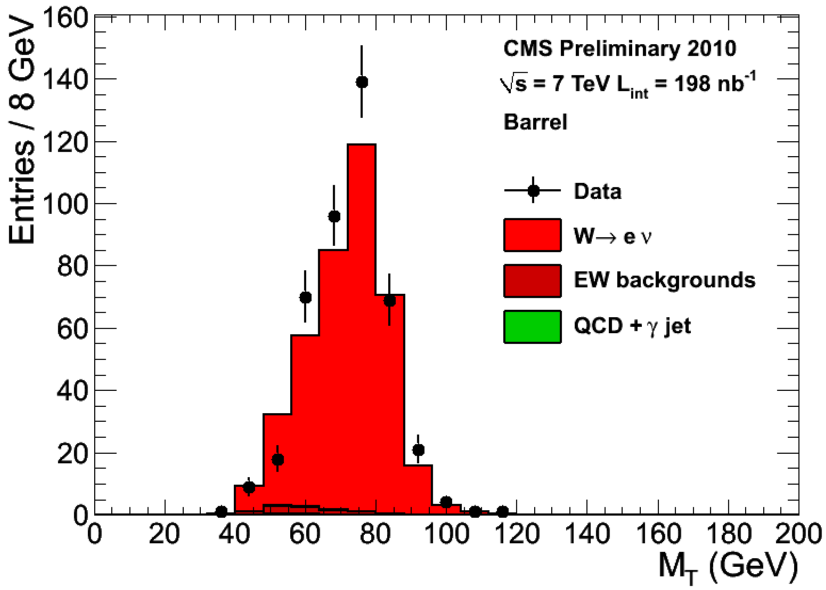
More efficient, better covariance matrix, get measure of P_{in} at vertex and at P_{out} at ECAL

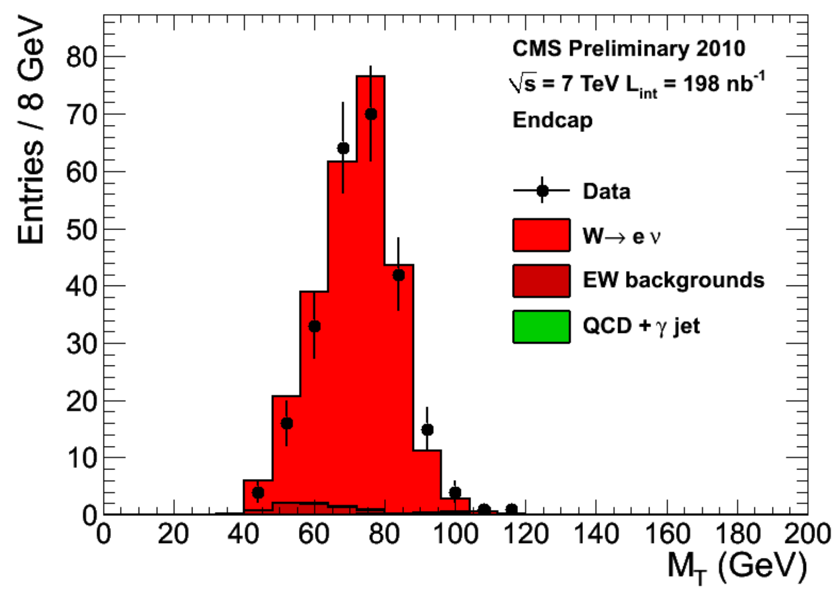
Kalman uses Gaussian model of losses. GSF approximates correct Bethe-Heitler model of loss with sum of Gaussians

Compare P_{in}-P_{out} (tracks) with E_{brem} (ECAL)



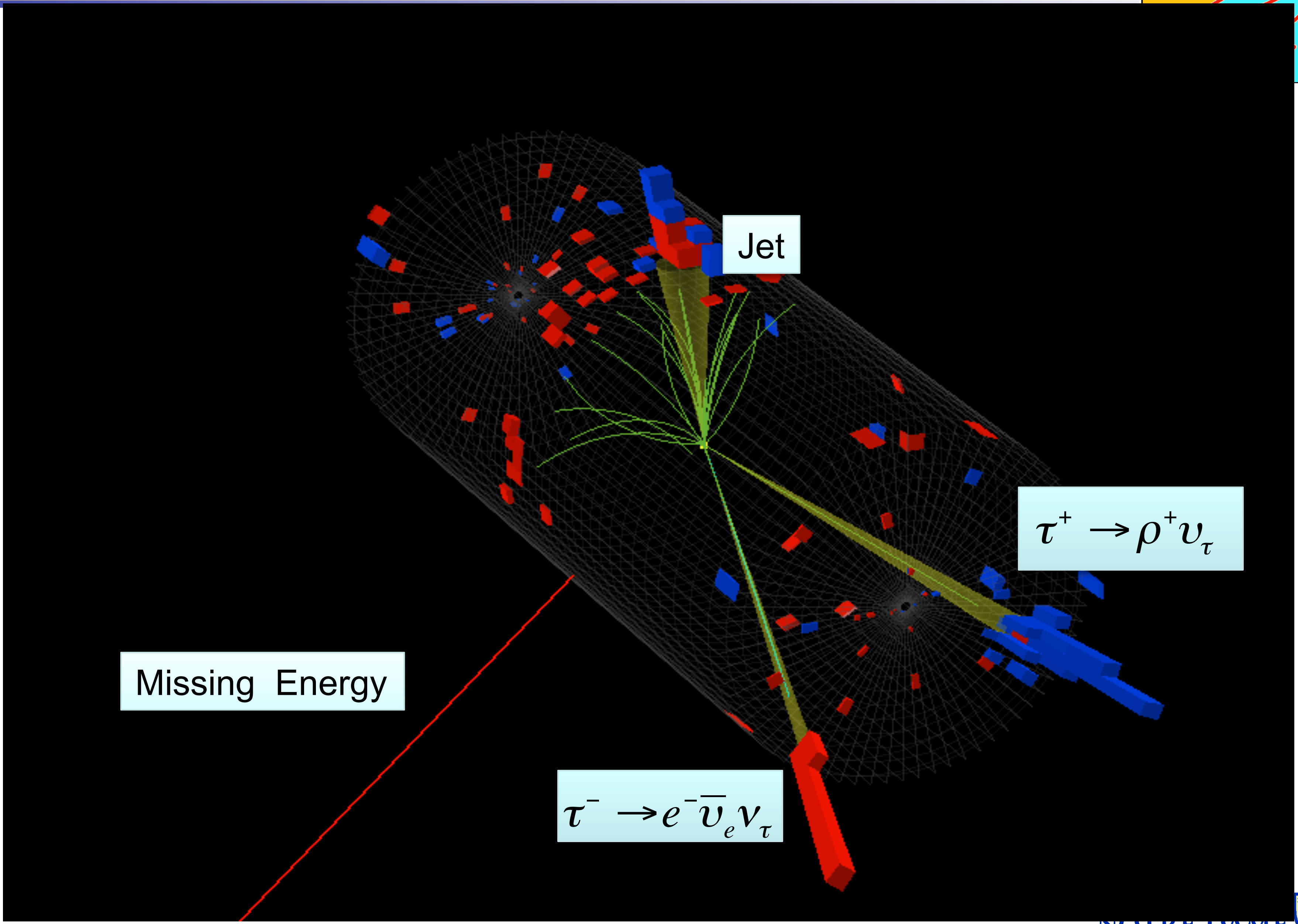
Transverse Mass $W^- \rightarrow e^- \nu_e$



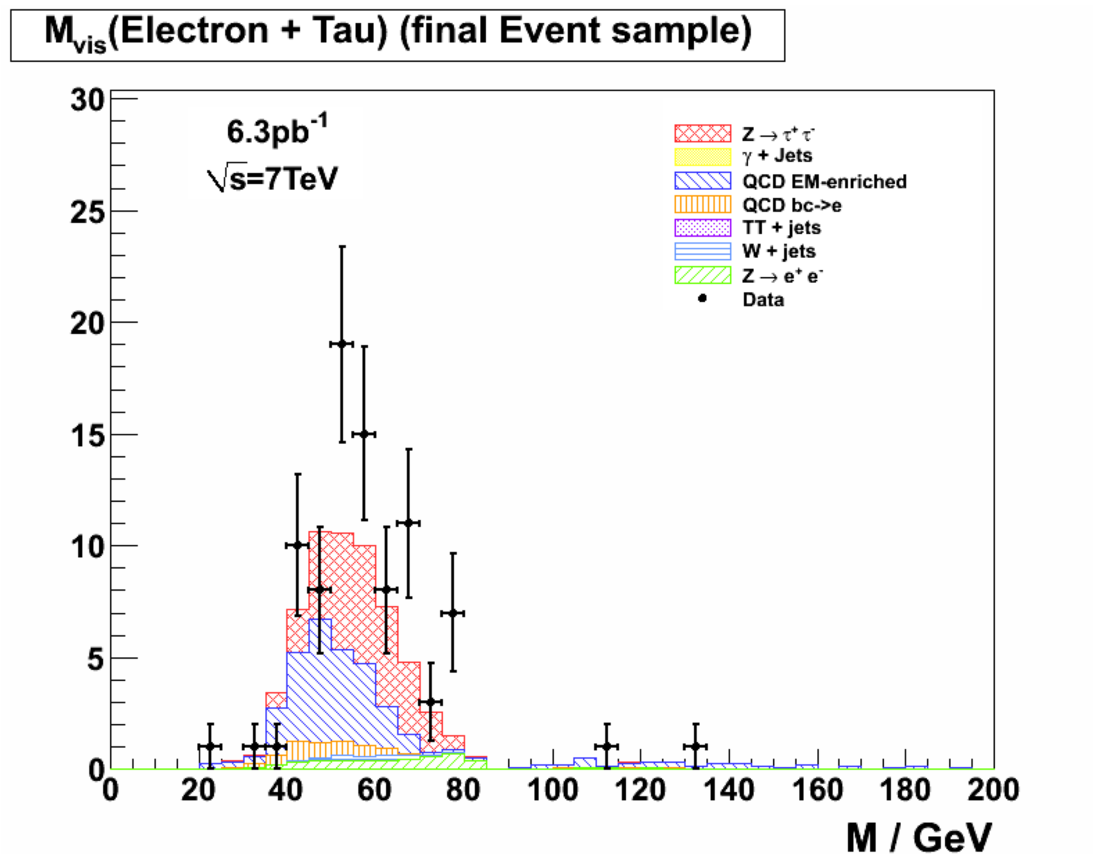


Definition of Mt

$Z \to \tau^+\tau^-$ Cross-section Measurement



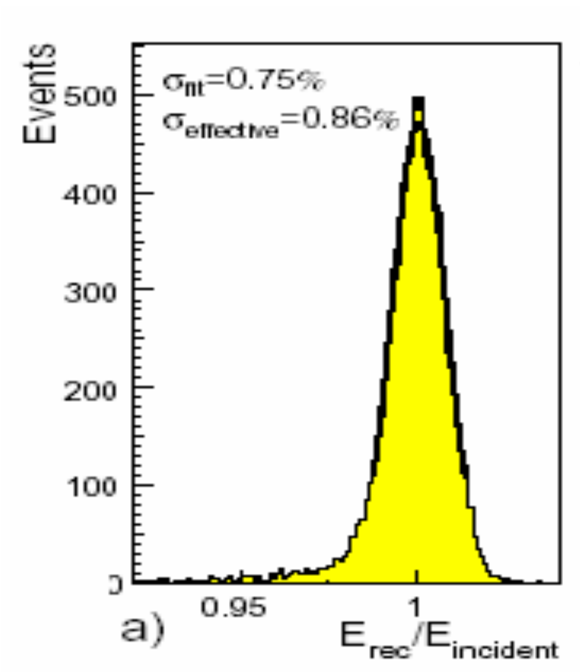
Z->$\tau^+\tau^-$ Cross-section Measurement

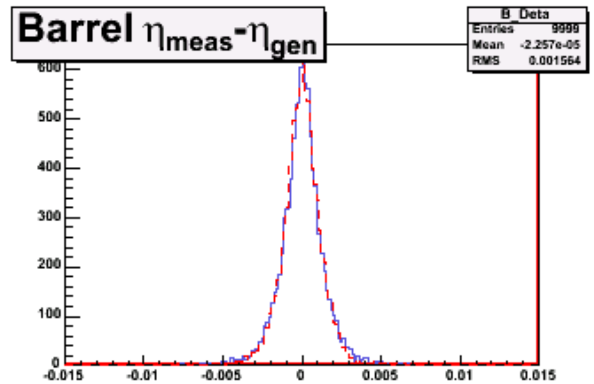


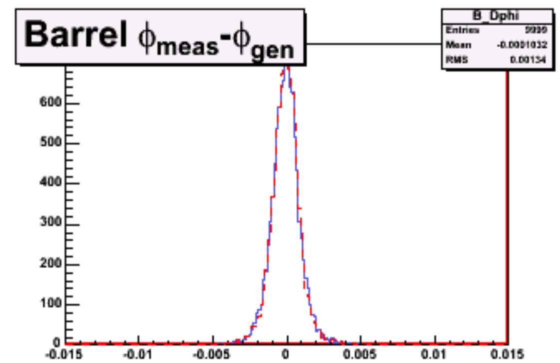
*Not an approved plot

First step towards H->$\tau^+\tau^-$

Photon Reconstruction - Unconverted Photons



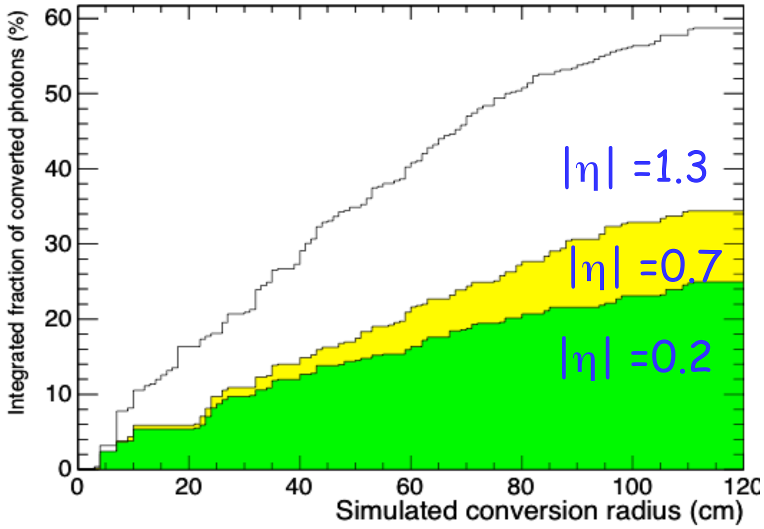




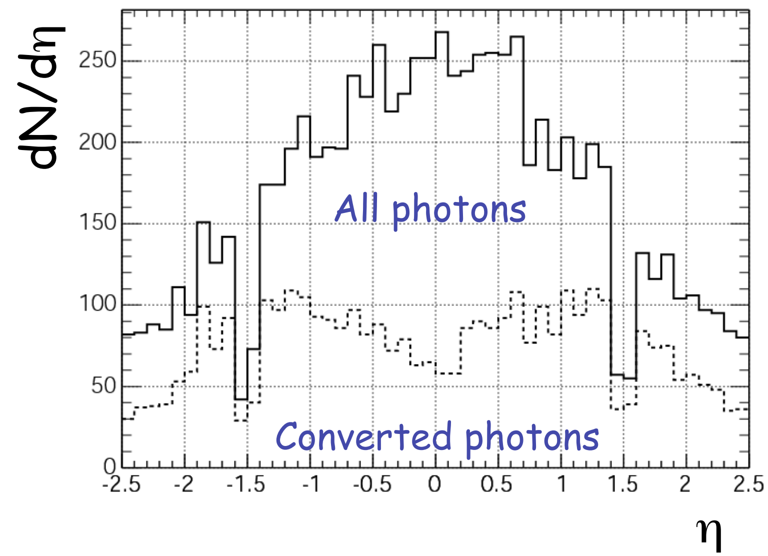
Unconverted photons are easily reconstructed with good Energy and position Resolution but a significant fraction convert due to material

Photon Conversions in H->γγ

Integrated fraction of converted photons (%)



Simulated photons from H→ γγ



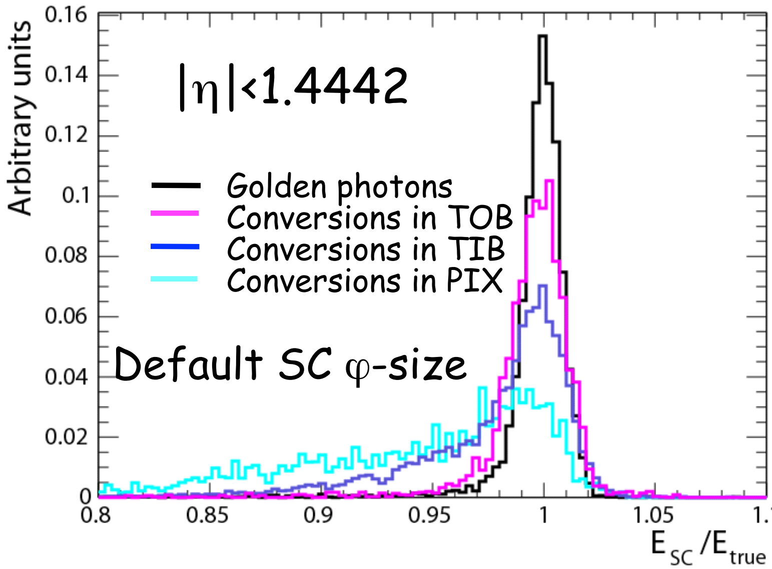
~44% of photons from H→ γγ events convert

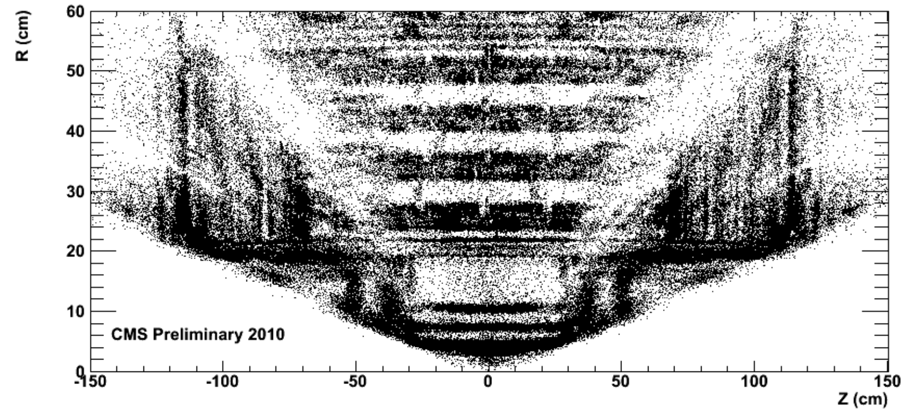
Of all conversions

~25% occur late in the tracker (i.e. with R_{conv} > 85 cm or Z_{conv} > 210 cm) → good as un-converted photons as for energy resolution in ECAL

~20% occur very early in the pixel detector

Photon Conversions

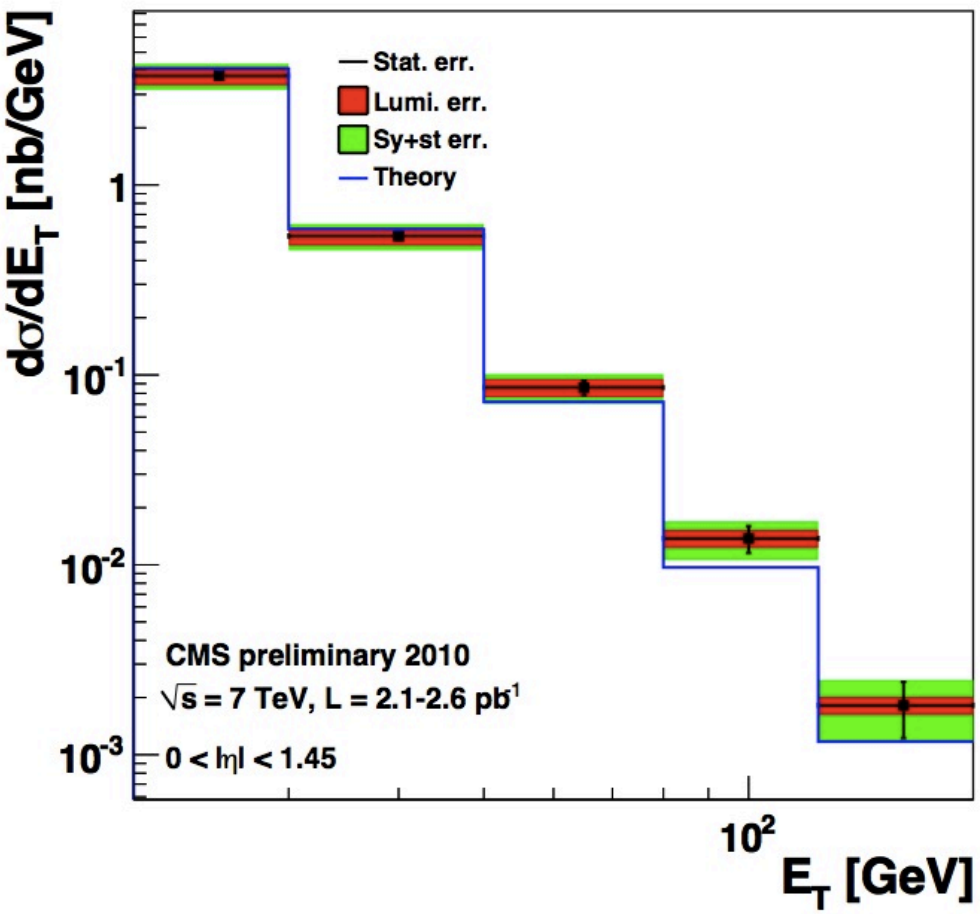




Early conversions (near vertex) degrade resolution significantly if use standard clustering algorithm. Need conversion finder.

Currently being used to map material which is critical for tracking and reconstruction

Measurement of γ+jets x-section



*Not an approved CMS plot

First step towards H->γγ

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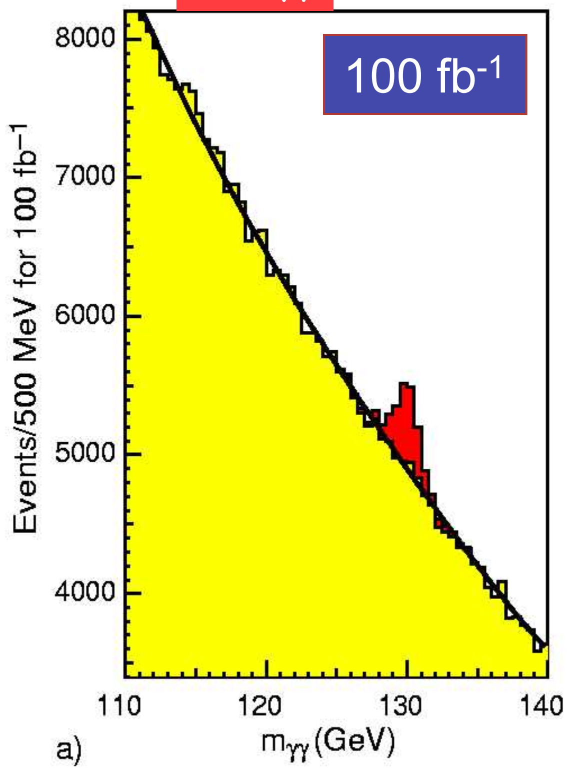
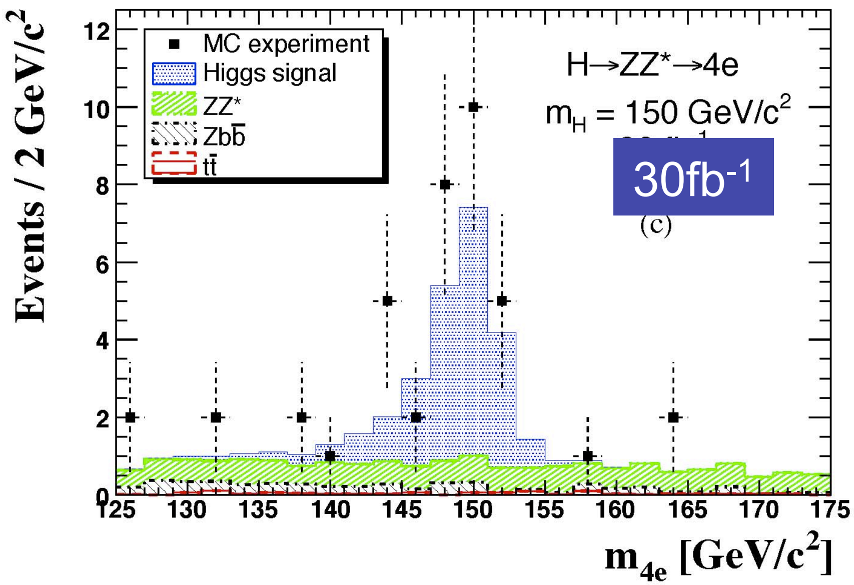
Conclusion

Straight forward counting analysis using e/γ described

H->γγ



H->ZZ*->4e



US Institutes in ECAL / e/γ

CMS ECAL Project Manager: Roger Rusack (U. Minn)
US ECAL manager: Brad Cox (U Virginia.)
US ECAL Institution Board Chair: Colin Jessop (Notre Dame)

Hardware R&D

Caltech: Laser Monitoring System, Crystals
Minnesota: APD readout

Testbeams, Construction and Commissioning

Caltech,FNAL,KSU,FSU,Minnesota,Notre Dame,Virginia

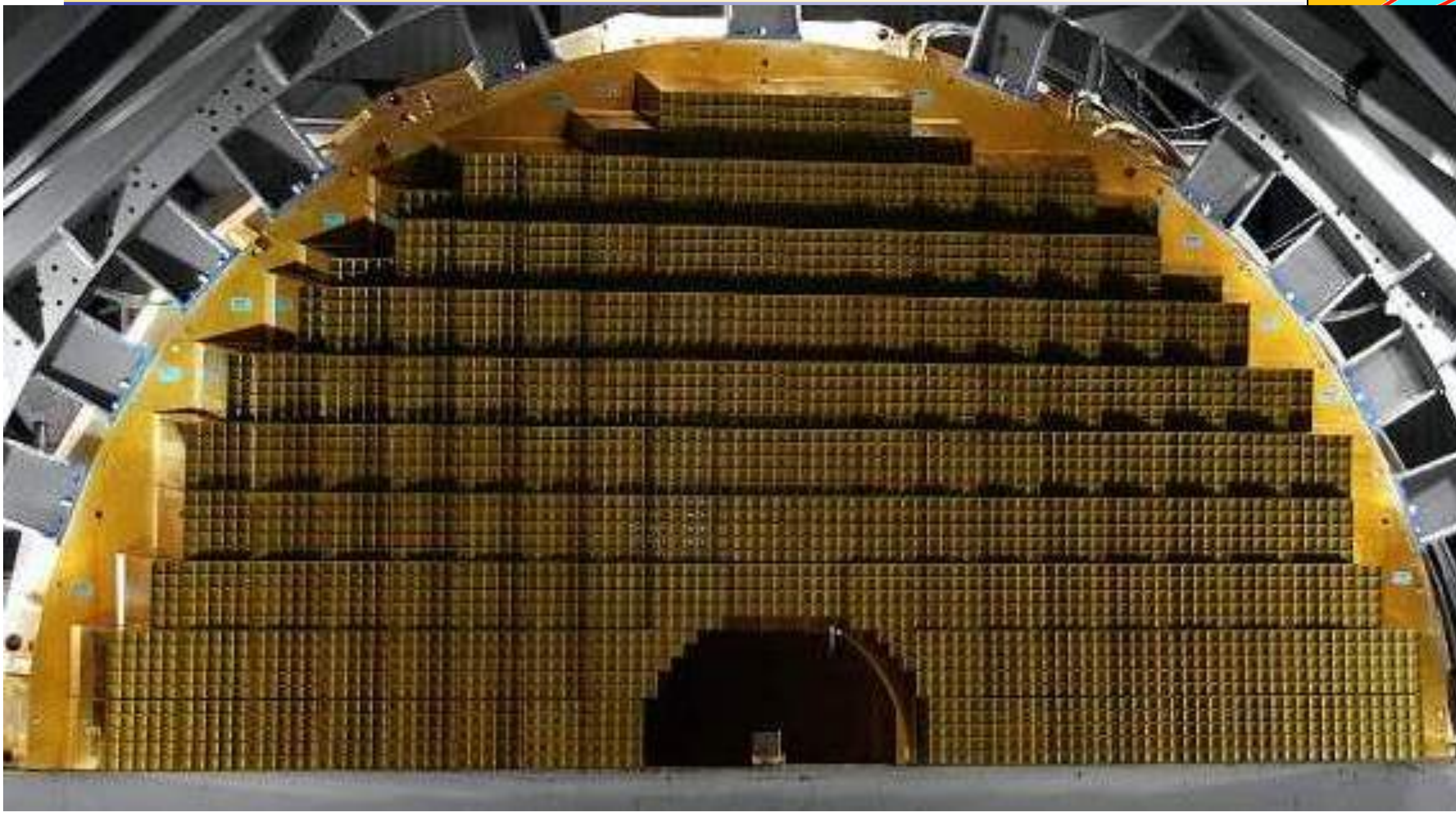
Calibration, Reconstruction Software and Data Analysis with electrons and photons

Caltech,FNAL,KSU,FSU,Minnesota,Notre Dame,Virginia

All in close collaboration with the many institutes comprising the CMS collaboration !

Backup Slides

CMS Endcap ECAL

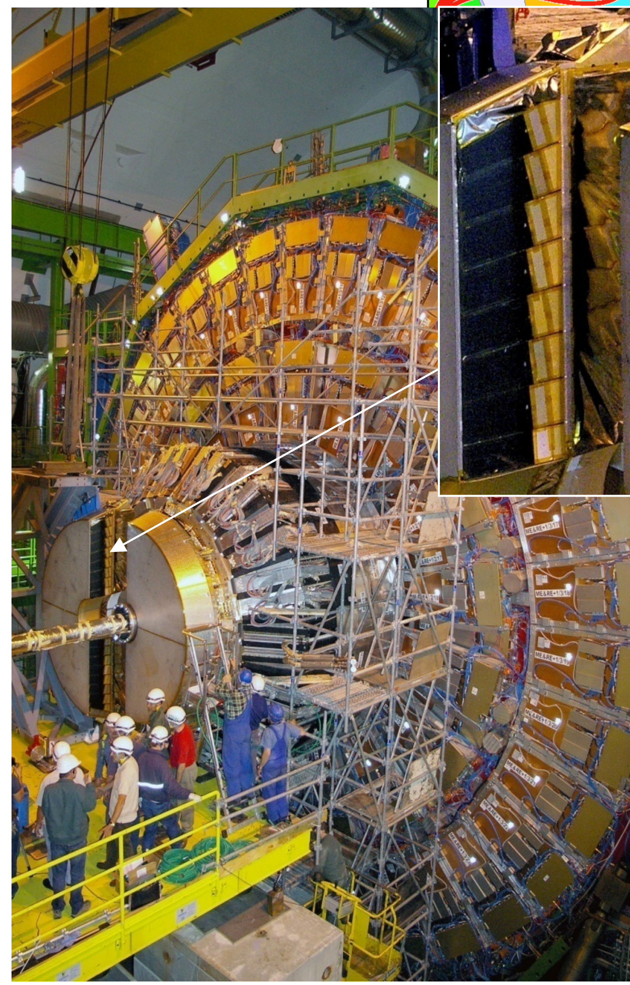


A completed Dee with all Supercrystals

CMS Endcap ECAL

Dee1 lowering and rotation 19 July 08

Dee1 mounting on HE 22 July 08



Dee2 mounting on HE 24 July 08

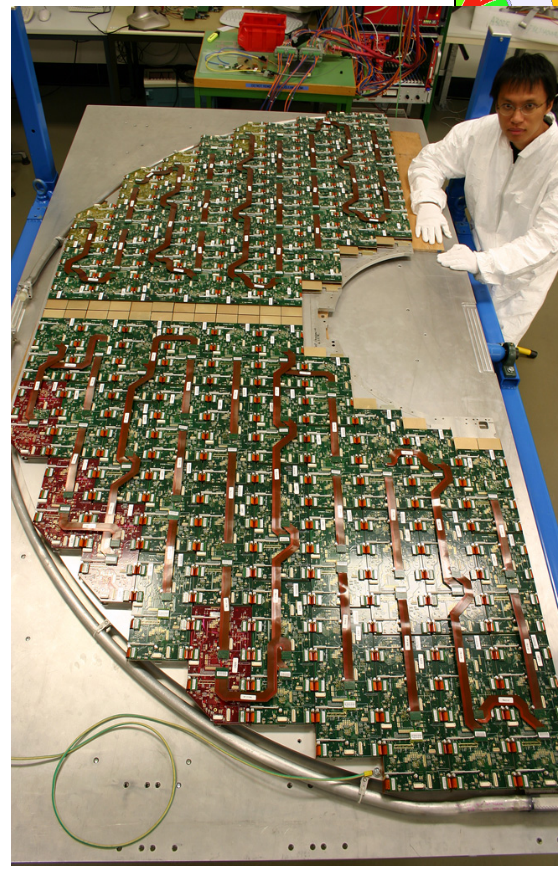
Preshower detector

Motivation: Improved π^0/γ discrimination
Rapidity coverage: 1.65 $< |\eta| <$ 2.6 (End caps)

2 orthogonal planes of Si strip detectors behind 2 X0 and 1 X0 Pb respectively

Strip pitch: 1.9 mm (63 mm long)
Area: 16.5 m^2 (4300 detectors, 1.4 x10^5channels)

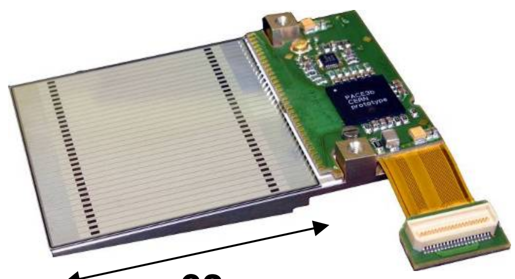
High radiation levels, dose after 10 yrs:
2 x 10^{14} n/cm^2, 60 kGy => operate at -10^{o}C



The first full Dee absorber with a complete complement of sensors

A micromodule with its silicon sensor (32 channels)

90% of micromodules have been produced



Preshower installation expected during winter shutdown 2008/9

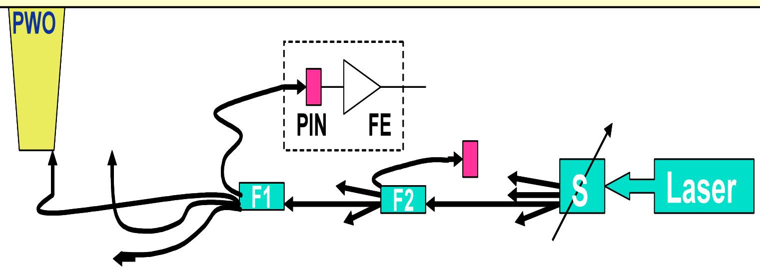
Laser light monitoring system

Colour centres

These form in $PbWO_4$ under irradiation
Partial recovery occurs in a few hours

Damage and recovery during LHC cycles tracked with a laser monitoring system

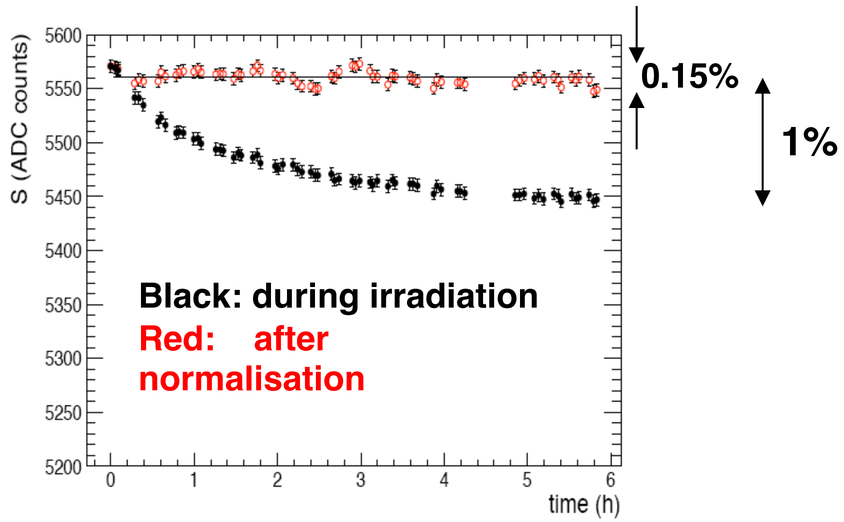
2 wavelengths: 440 nm and 796 nm



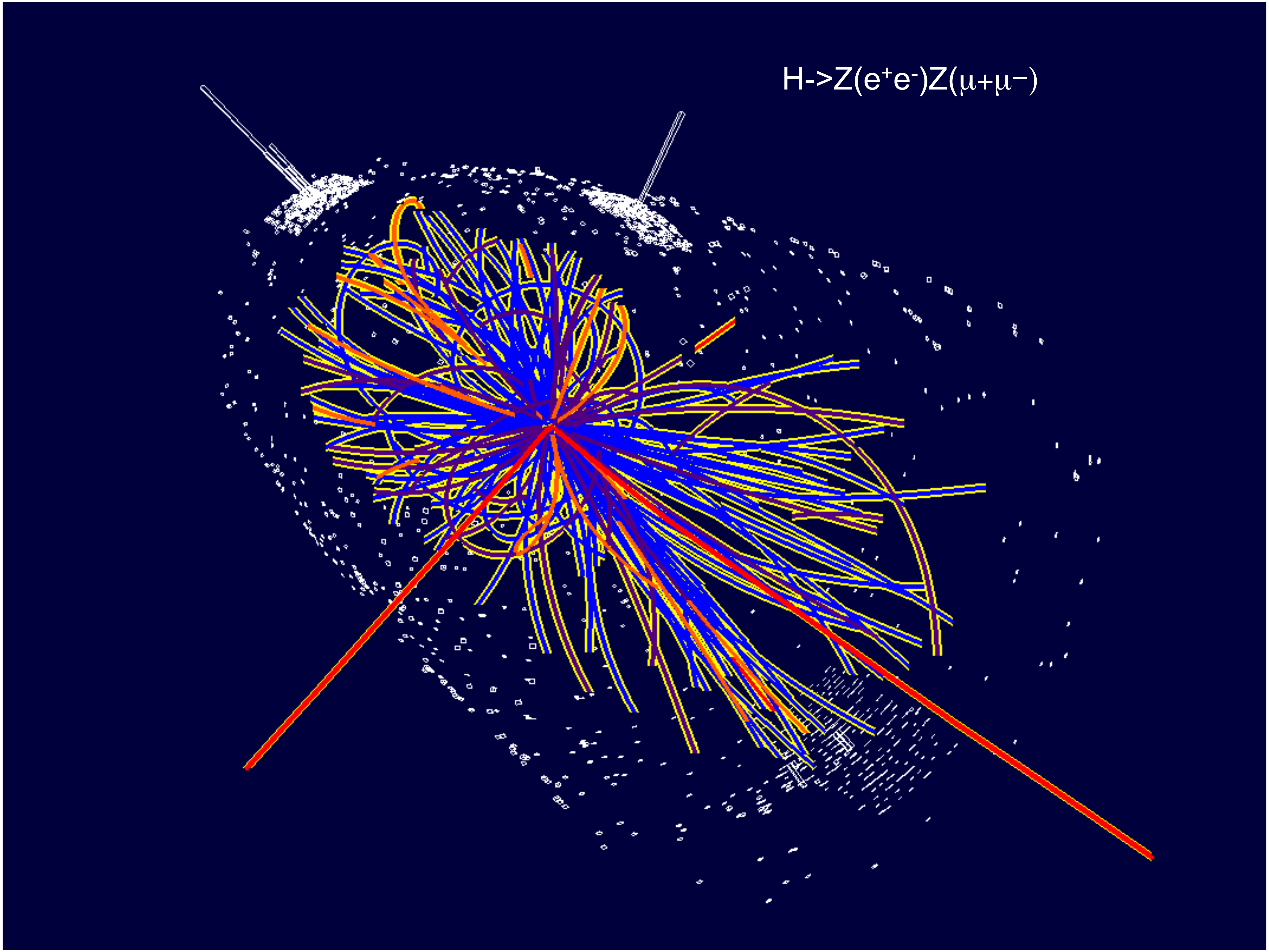
Light injected into each crystal using quartz fibres, via the front (Barrel) or rear (Endcap)

Laser pulse to pulse variations followed with pn diodes to 0.1%

Normalise calorimeter data to the measured changes in transparency



Electron signal in crystal versus time (h)


H->Z(e+e-)Z(μ+μ−)

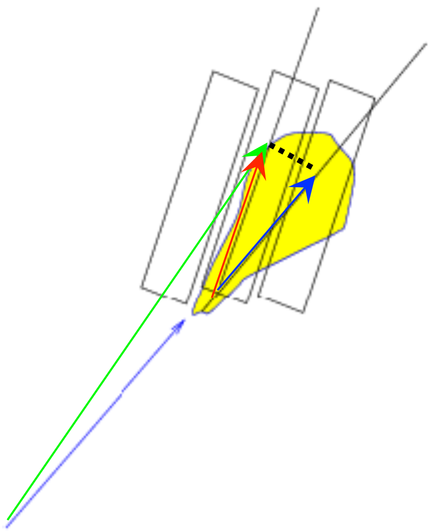
High Level Trigger (HLT)

L1: Possible to trigger on combination of up to four isolated or non isolated clusters.

Thresholds: (~100% efficient for H->$\gamma\gamma$ and H->Z(ee)Z(ee) with e/γ in fiducial region)
Single Isolated: Et > 23 GeV
Double Isolated: Et > 12 GeV
Double Non-Isolated: Et > 19 GeV

HLT: Software trigger that adds, superclustering, tracking and partial or full reconstruction to give a full set of analysis tools for jet rejection.

Cluster Position Algorithm



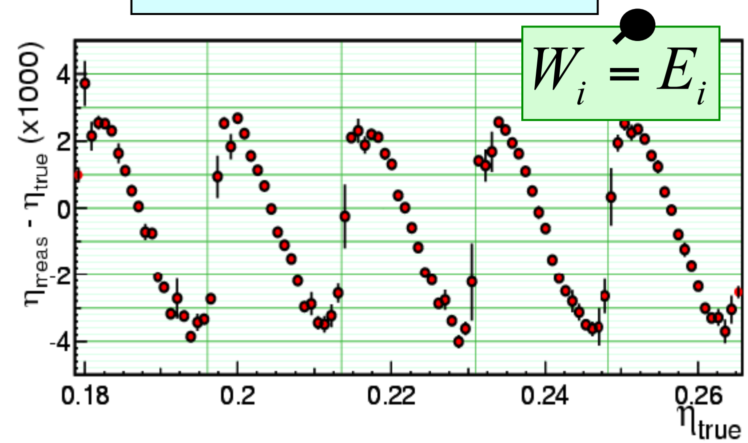
Off-pointing Xstals

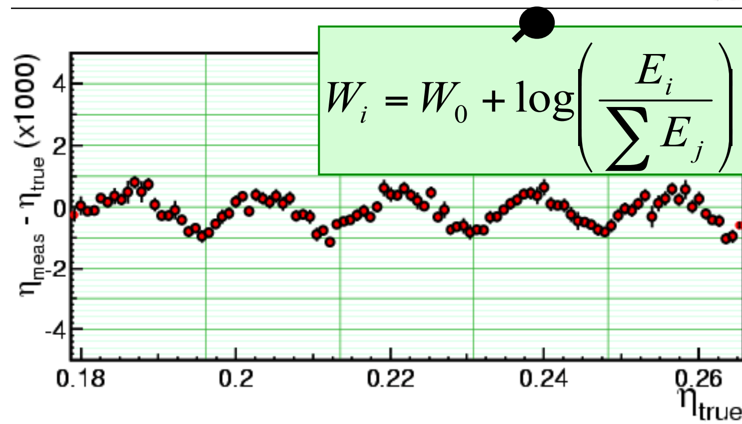
Cluster position

Crystals are non-projective to avoid Leakage in cracks

Position of Xstal: shower max projected onto xstal axis

Use log E weighting to calculate centroid as E degrades exponentially

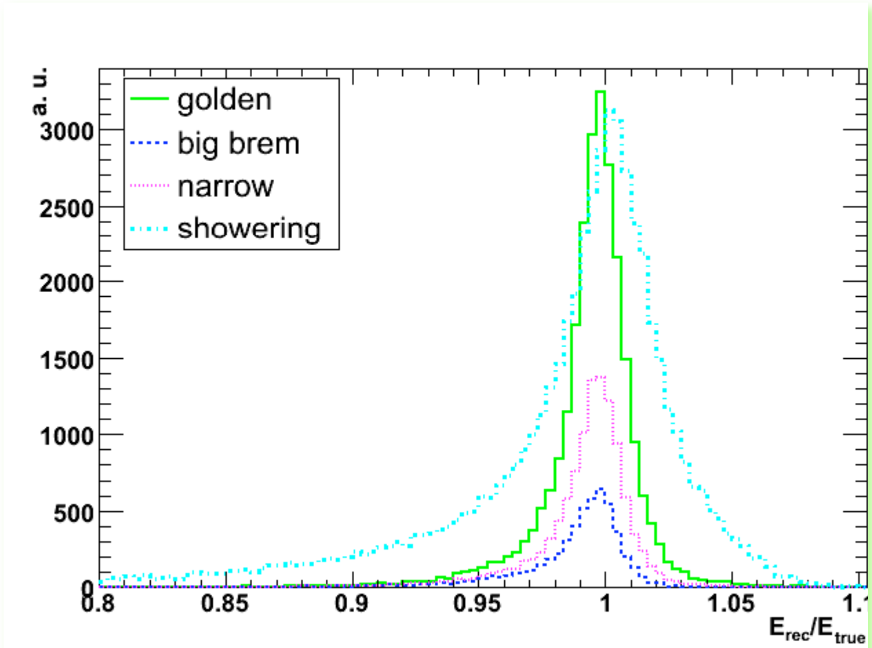




Classification of Electrons

Classified according to whether Brem has been fully
Recovered and whether emitted photon has converted
Correlates to resolution

1. Golden Electrons: less than 20% brem which is fully recovered
2. Big Brem: >50% brem which is fully recovered
3. Narrow: 20-50% brem which is fully recovered
4. Showering (Bad). Brem which is not recovered due to photon conversion

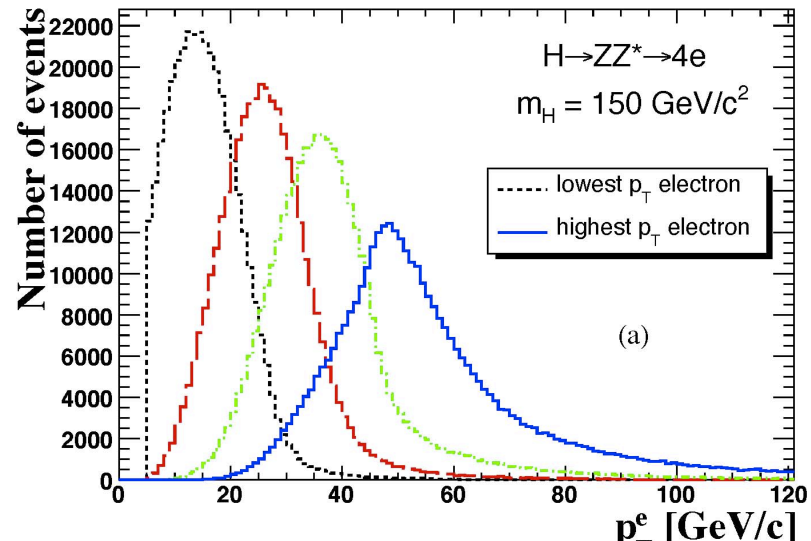


About 60% of electrons between 5 and 100 GeV are in class 4 (Bad)

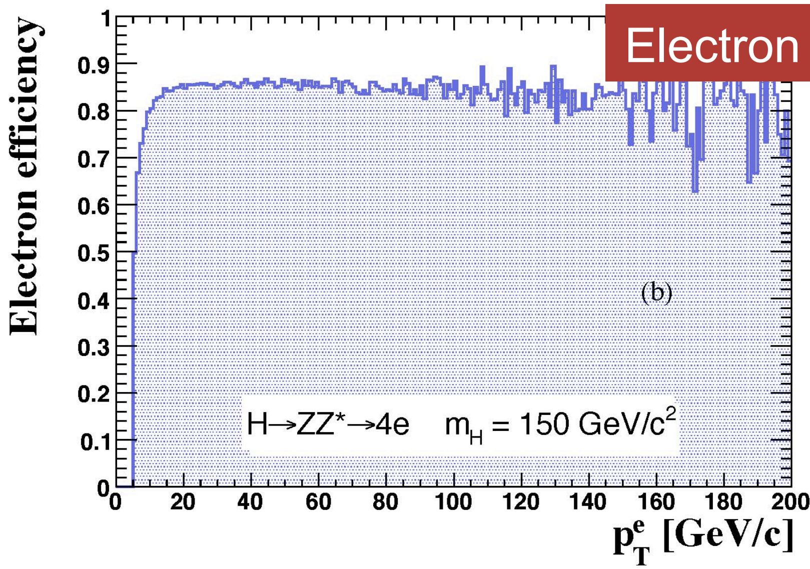
Electron Efficiency for H->Z(ee)Z(*)(ee)

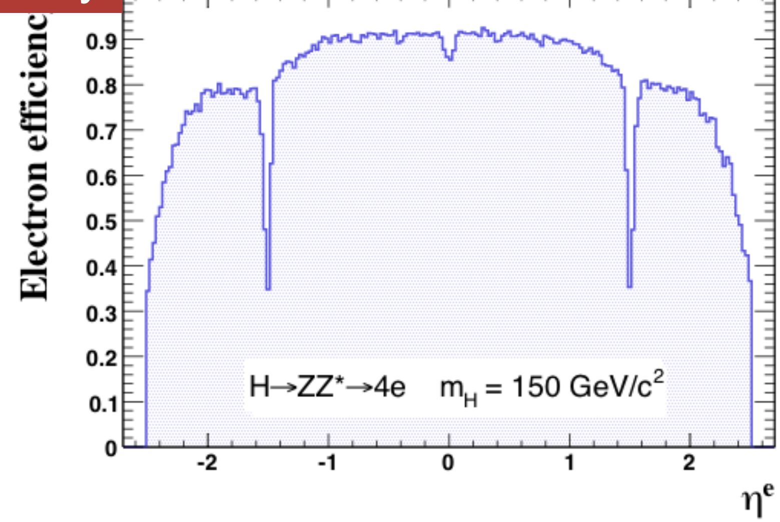
H→ZZ(*)→4e

Using all classes of electron (after Triggering)



Electron Efficiency



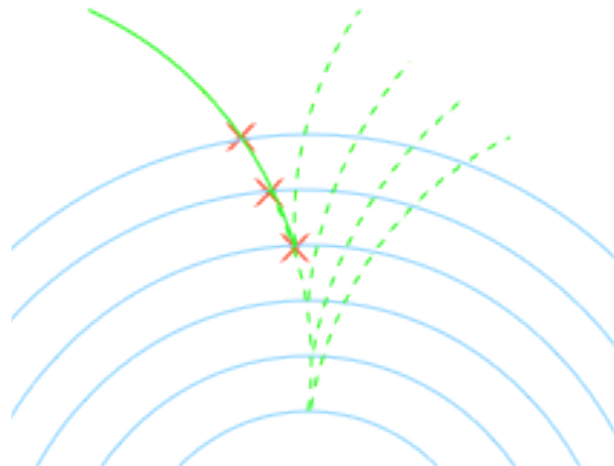


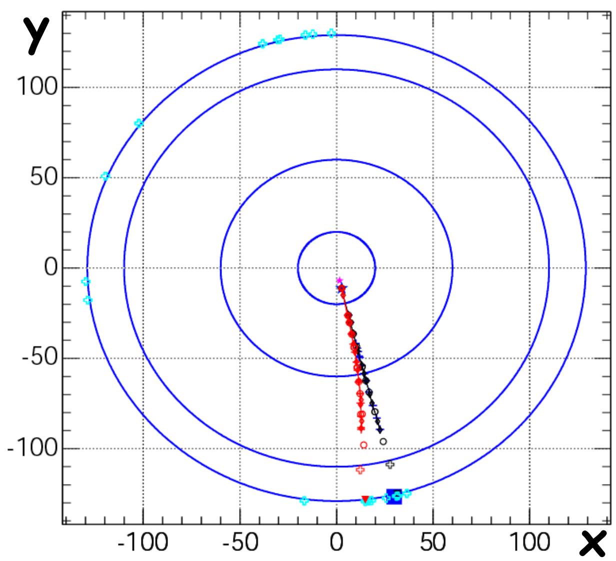
Finding Photon Conversions

Start from SuperCluster

Do out to in tracking with GSF

Find tracks that intersect





About 75% efficient for R < 0.85 cm (trackers extends to 120cm) Significant Improvement in resolution but still worse than unconverted photons

For R > 0.85 conversions do not degrade resolution since electrons tend to fall within normal supercluster