CMS ECAL Basics

(For grad students and new collaborators)

Colin Jessop

LPC &

University of Notre Dame

(Thanks to A. Borheim, N. Marinelli, R. Zhu and others for plots and slides)

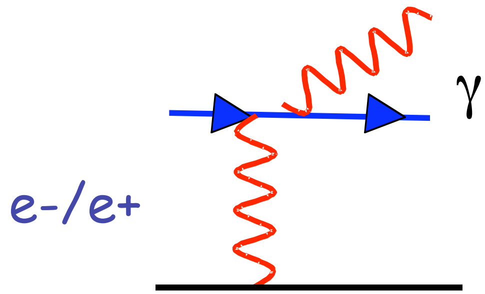
Contents

- Electromagnetic Calorimetry Primer
- Choice of ECAL technology
- Construction and Current Status
- Reconstruction of Photons and Electrons

* Will not cover   Triggering with ECAL or Calibration

Calorimetry Primer

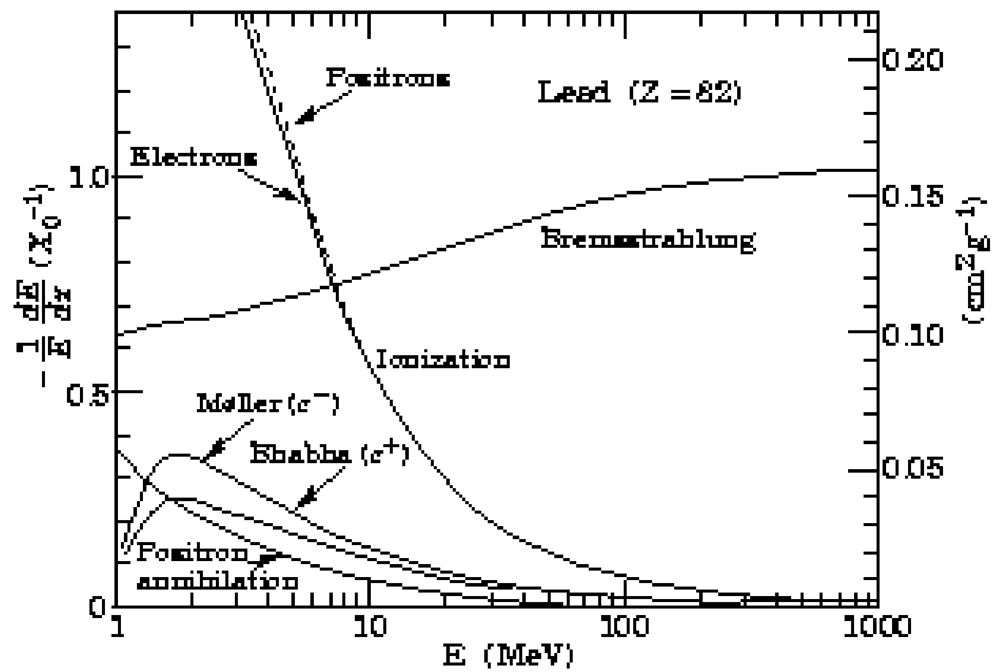
Electron/Positron Energy Loss in matter



Nucleus

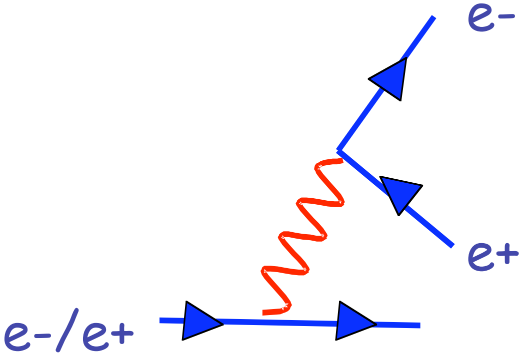
Bremstrahlung (radiation of photon)

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



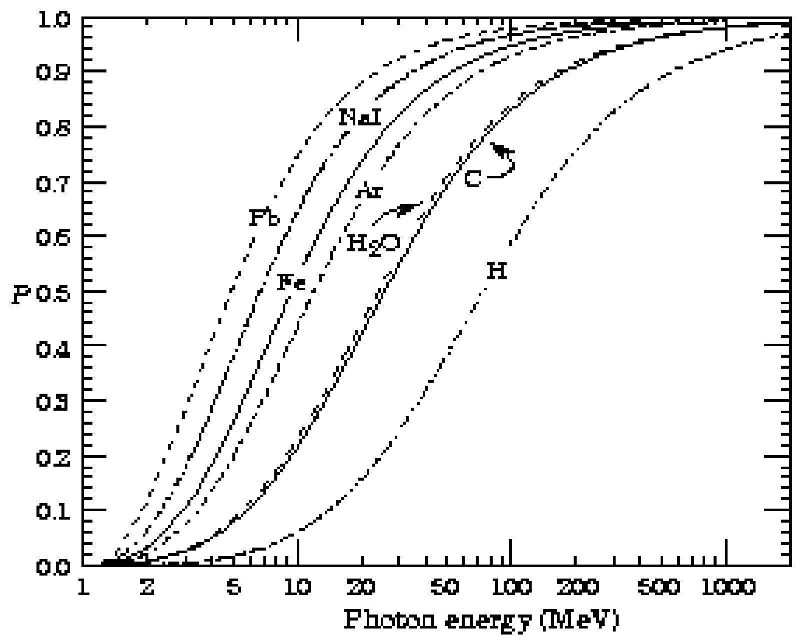
Electron energy loss primarily by Brem at E > E_c (~20 MeV) and ionization below. Brem Radiation probability depends on radiation length X_0

Photon Energy Energy Loss



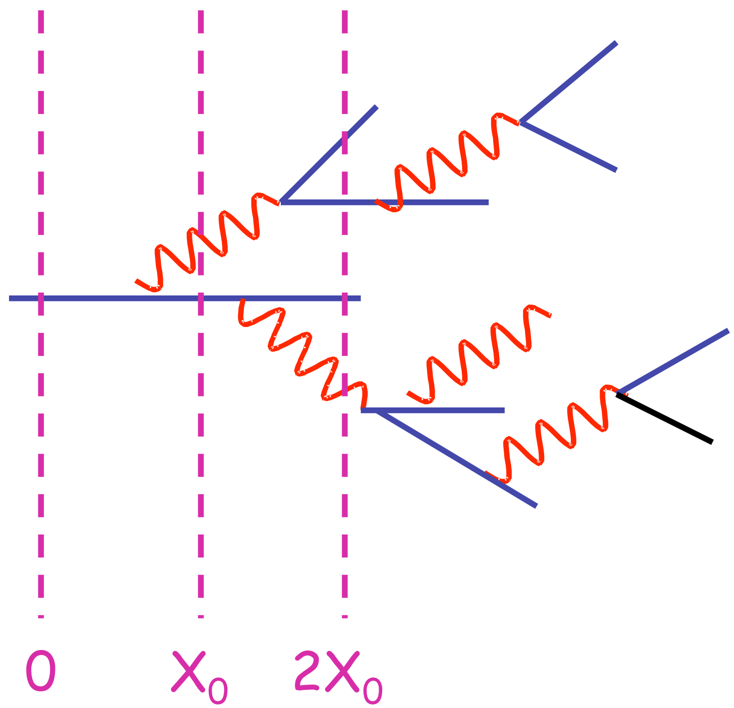
Pair Production

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

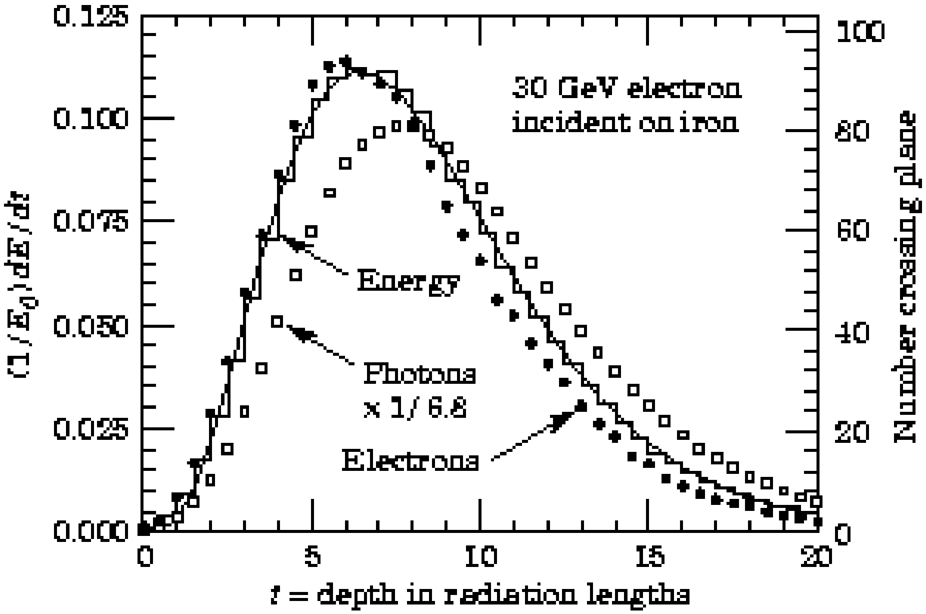
Can show that Max number of shower particles occurs at: $X_{\max} \propto \ln(E_0 / E_c)$

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

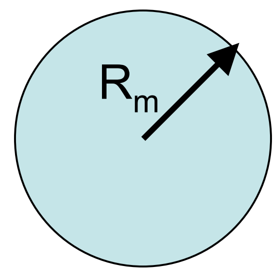
Measure Energy by measuring L with ionization or scintillation

Electromagnetic Shower Profile

Longtitudal Profile



Lateral Profile



Moliere Radius: $R_m \approx X_0$

(from multiple scattering)

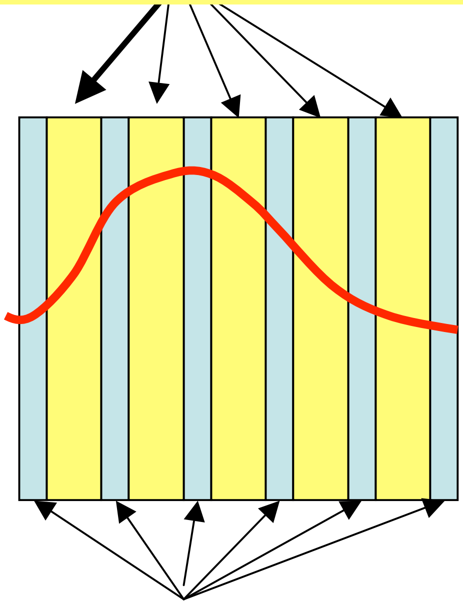
To contain >99% shower need depth of material ~ 25 X_0

To measure lateral position accurately need segmentation ~ X_0

Sampling vs Total Absorption Calorimeter

Sampling Calorimeter

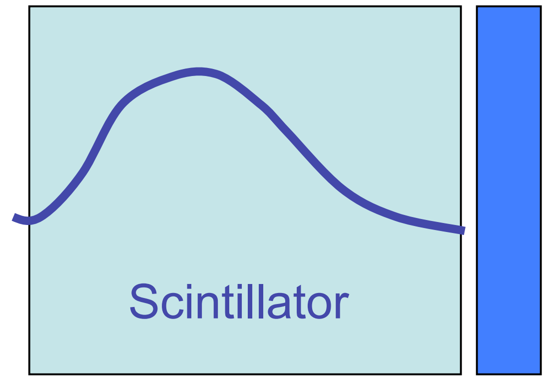
Lead- causes shower



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



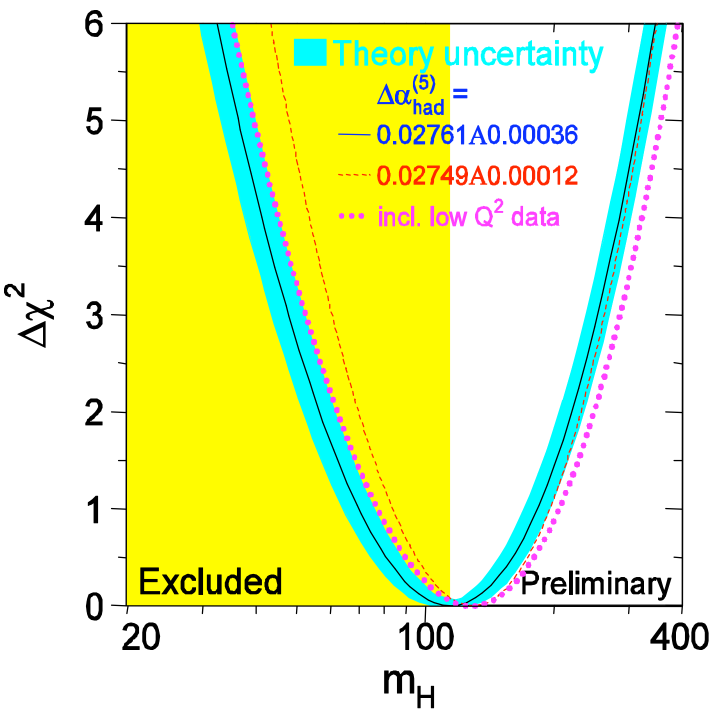
Photon Detector

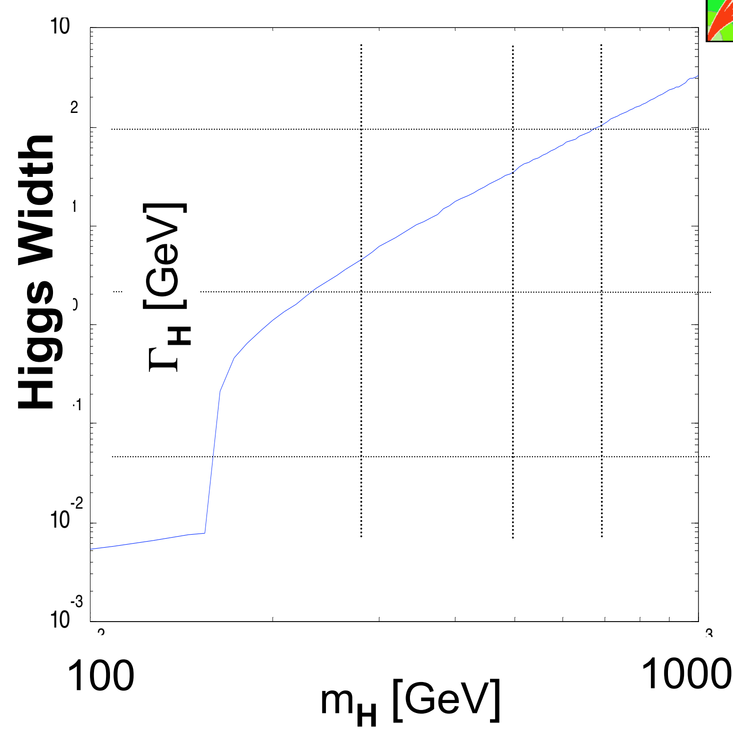
Scintillator both causes shower and is active detector

Expensive with good Resolution ~0.5% at 100 GeV

CMS ECAL Technology Choice

Standard Model Higgs Search

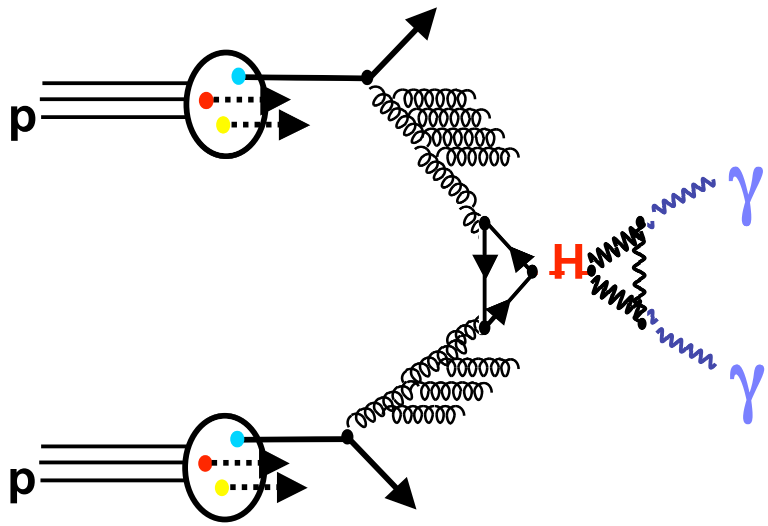




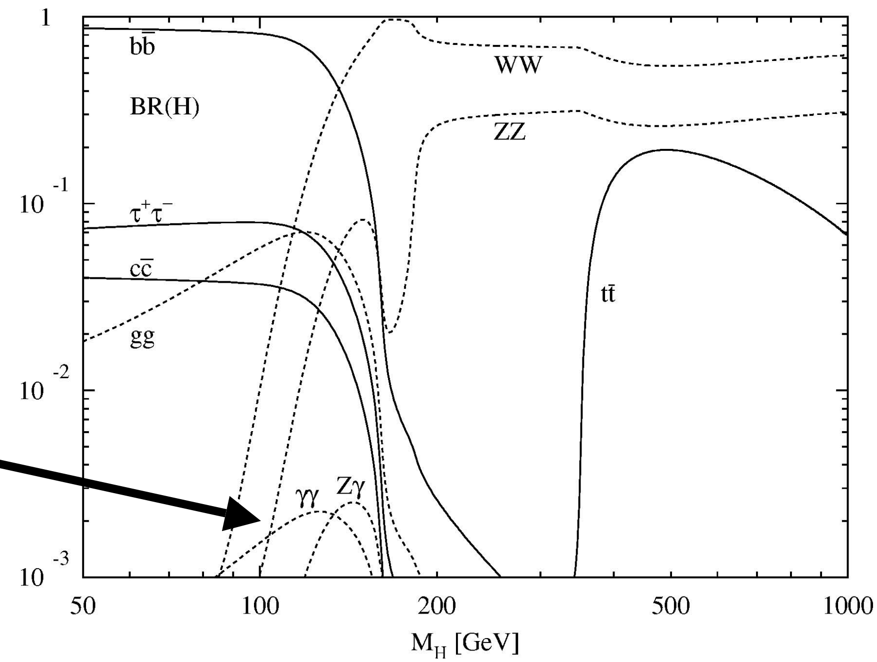
Expect a low mass Higgs (< 150 GeV) with a natural width < 0.01%

Need to reconstruct Higgs decays with excellent detector resolution
(ideally detector resolution < natural width)

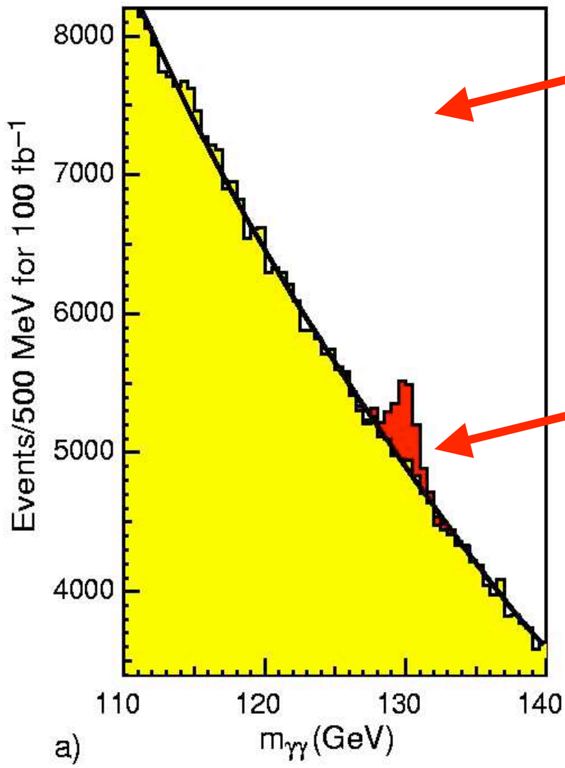
Higgs Production and Decay



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



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

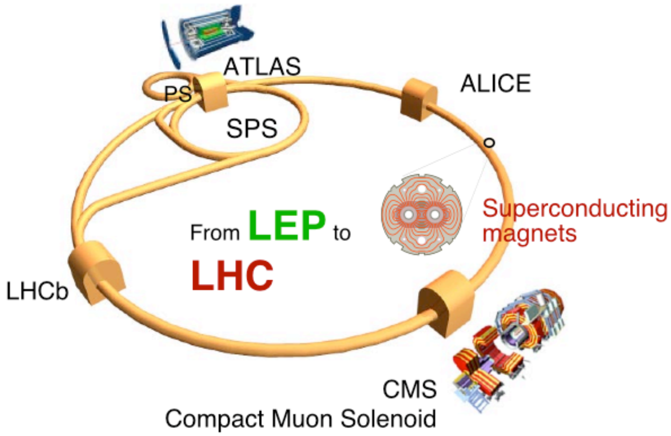
$$\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \frac{1}{2}\left[\frac{\Delta E_{\gamma 1}}{E_{\gamma 1}} \oplus \frac{\Delta E_{\gamma 2}}{E_{\gamma 2}} \oplus \frac{\Delta\theta_{\gamma\gamma}}{\tan\left(\theta_{\gamma\gamma}/2\right)}\right]$$

(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 2012-2013)

The LHC Environment

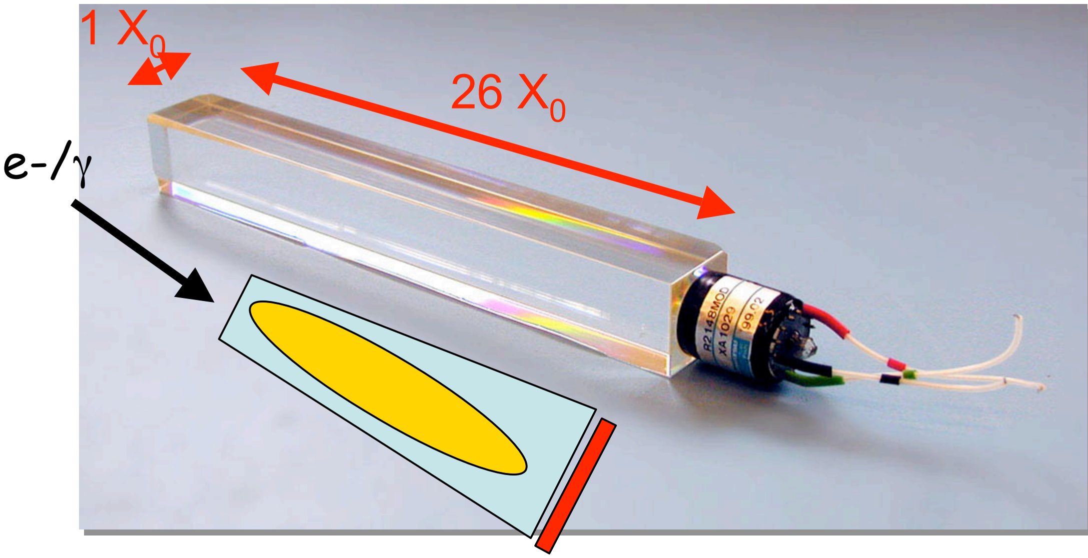


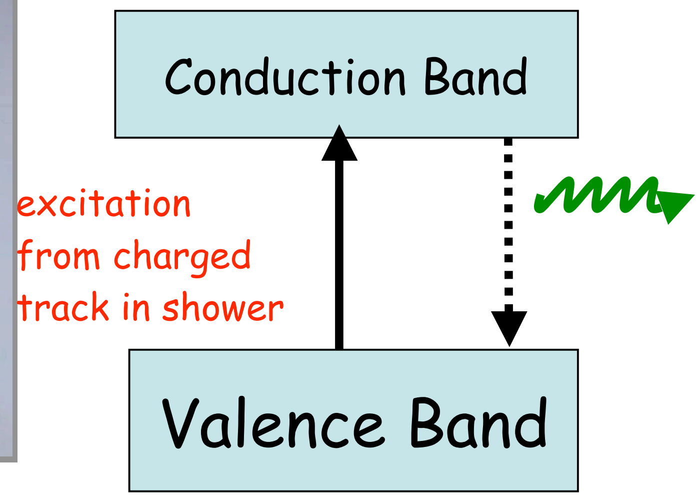
Year	Luminosity $\times 10^{34}$ $cm^{-2}s^{-1}$	Integrated Luminosity fb^{-1}
2007	0.005	0.02
2008	0.03	1.2
2009	0.1	4
2010+	1.0	40

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

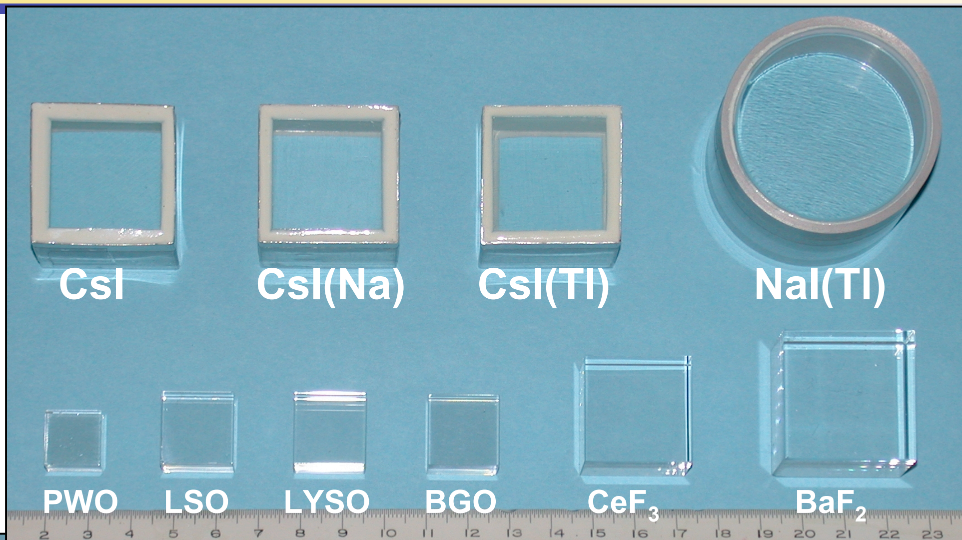
Crystal Calorimeters in HEP

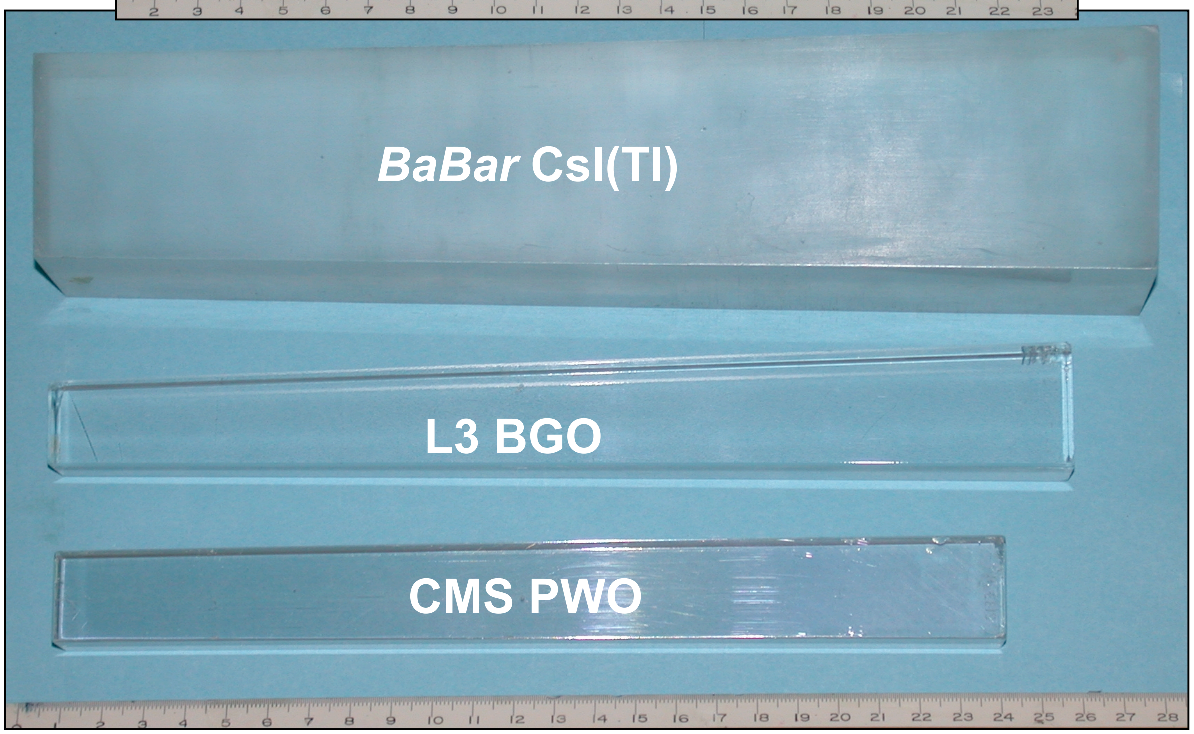
Date	75-85	80-00	80-00	80-00	90-10	94-10	94-10	95-20
Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	LEAR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	-	0.5	1.5	1.5	-	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	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 is largest most granular crystal calorimeter ever built.

PbWO is fast and radiation hard but has low light yield

Crystal Density: Radiation Length





1.5 X_0 Samples:

Hygroscopic Halides

Non-hygroscopic

Full Size Crystals:

BaBar CsI(Tl): 16 X_0

L3 BGO: 22 X_0

CMS PWO(Y): 25 X_0

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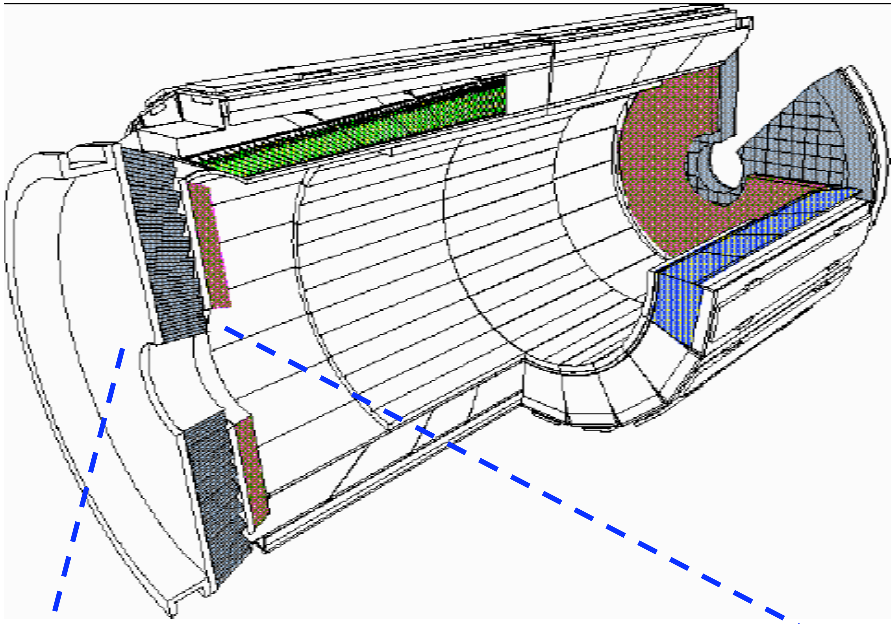
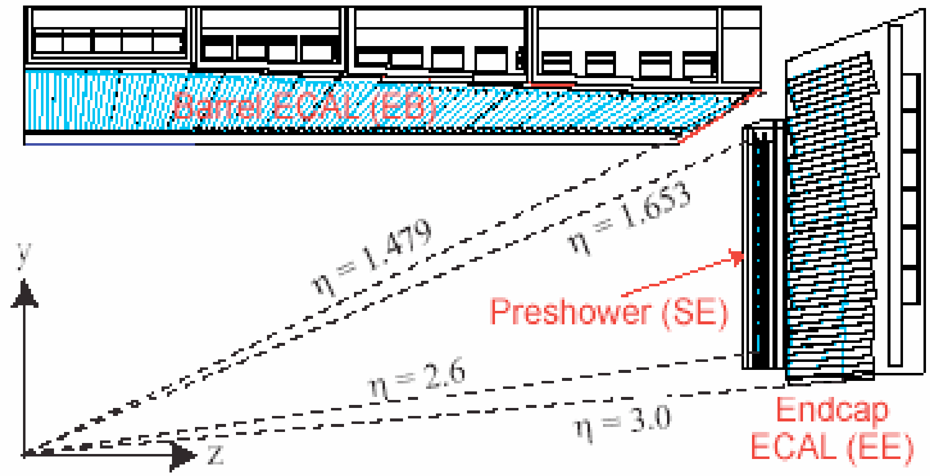
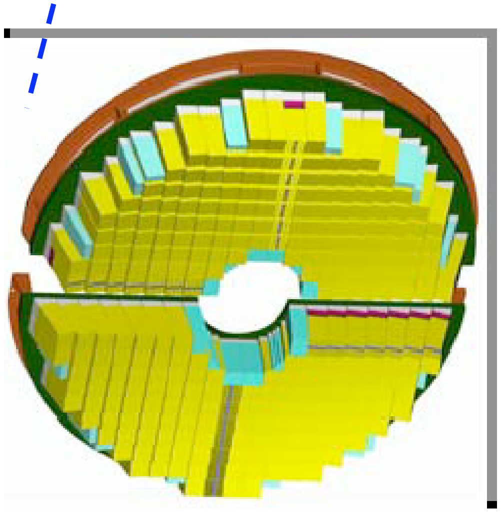
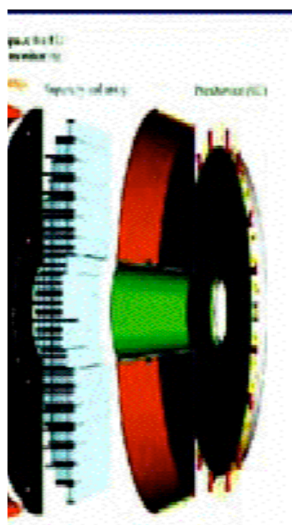
CMS ECAL Construction and Status

ECAL



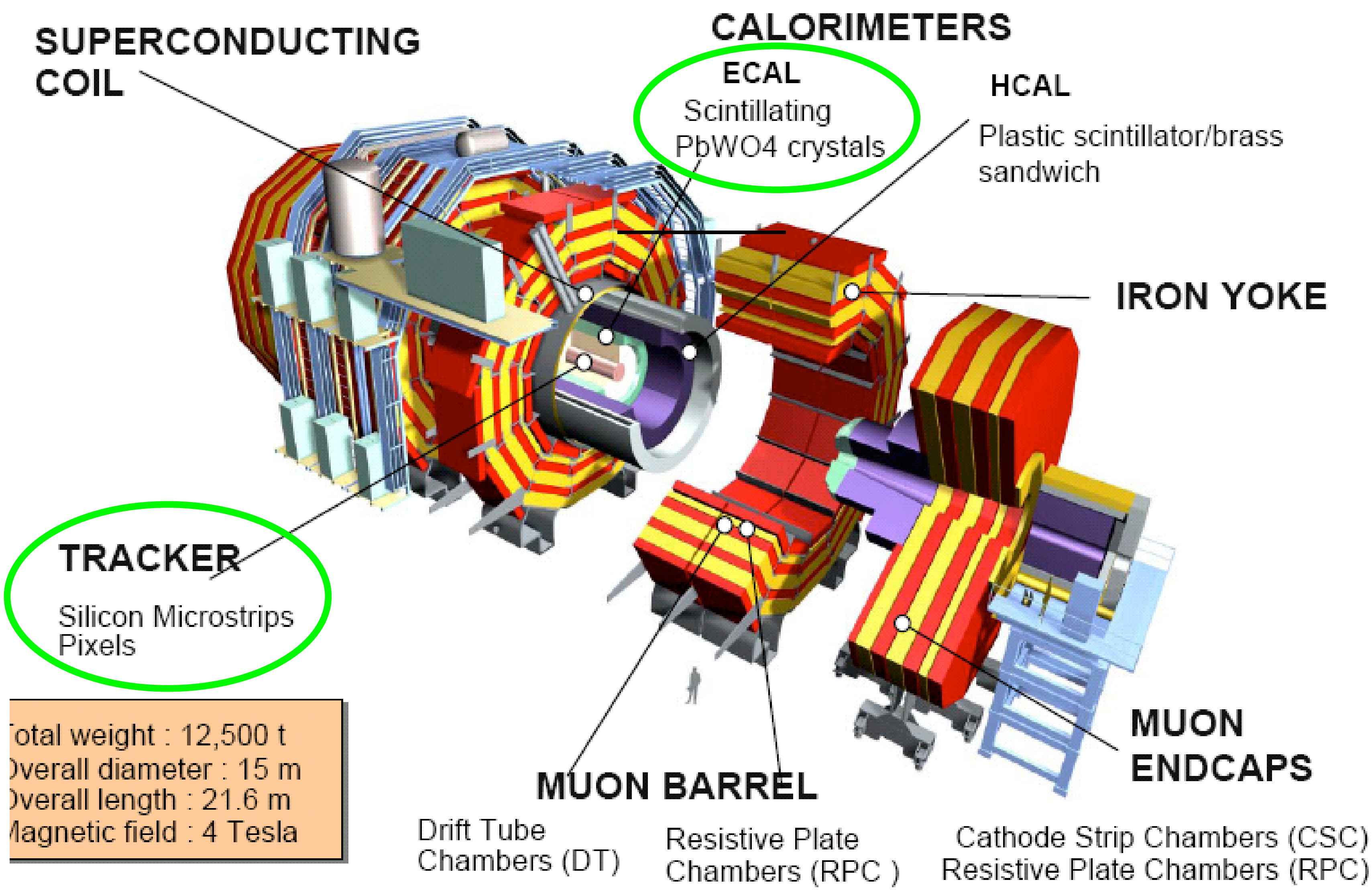




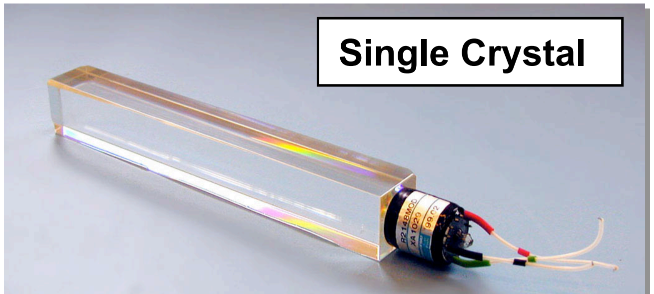


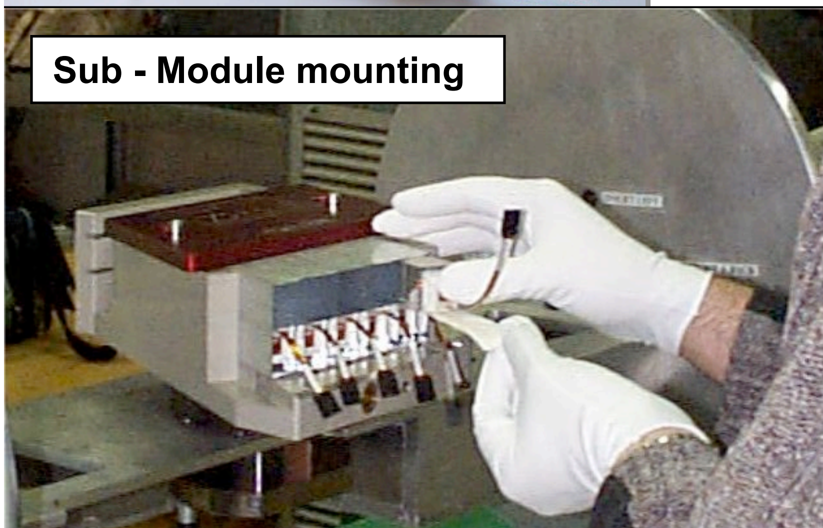
Parameter	Barrel	Endcap
η Coverage	|η|<1.48	1.48|η|<3.0
Granularity (ΔηxΔφ)	0.0175x0.0175	varies in η
Crystal dim (cm^3)	2.18x2.18x23	2.85x2.85x22
Depth in X_0	25.8	24.7(+3)
No. of crystals	61.2 K	14.9K
Modularity	36 supermodules	4Dees

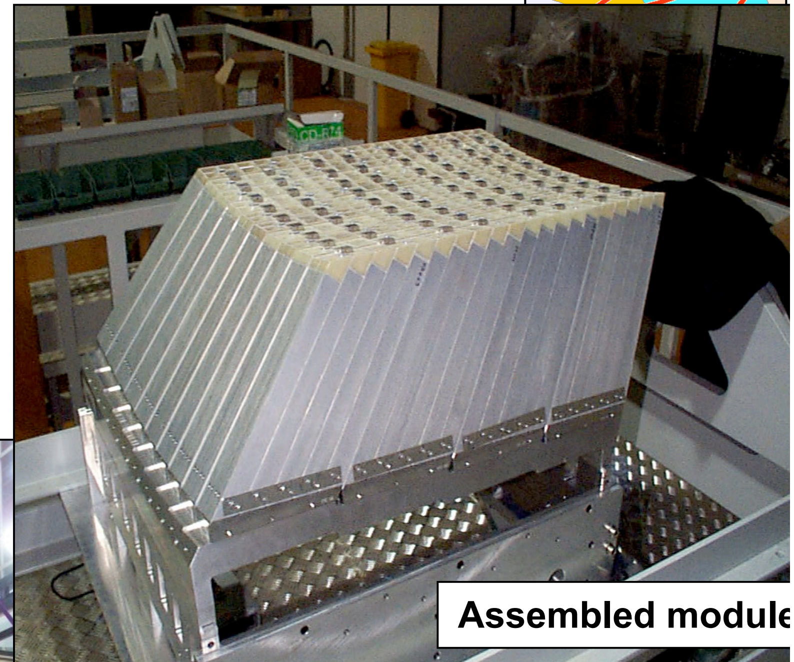
CMS Experiment

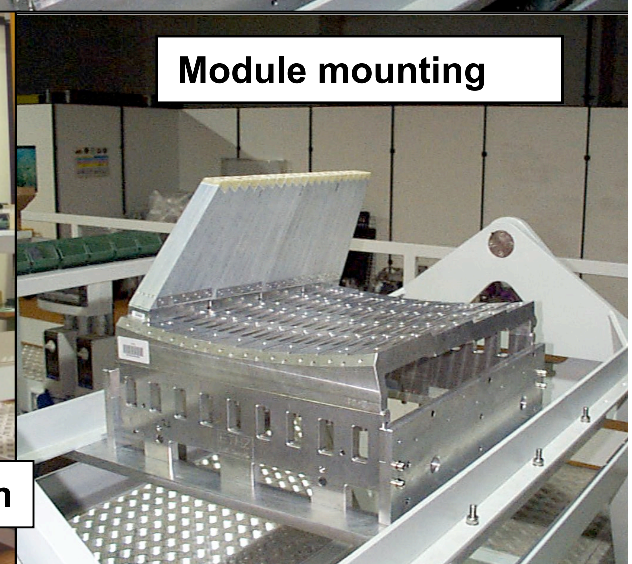


ECAL Crystal Matrix Production

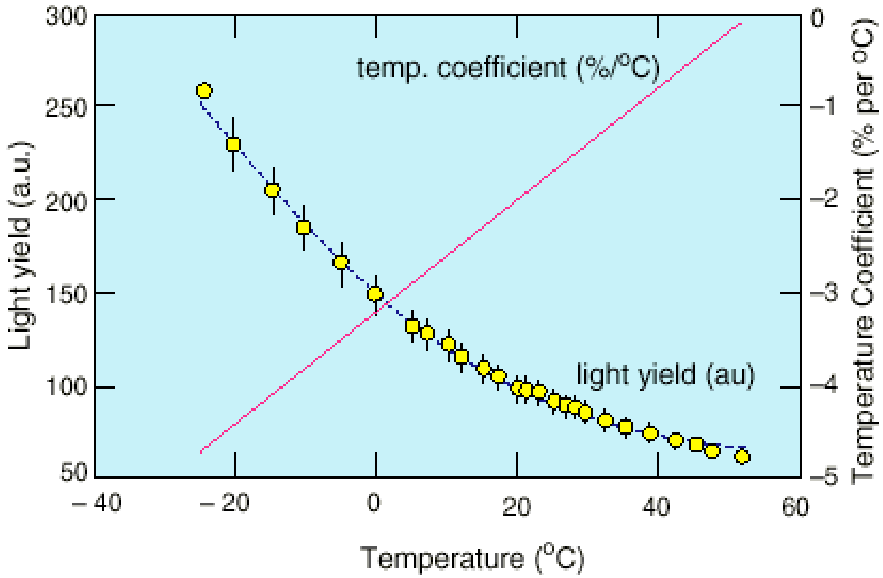




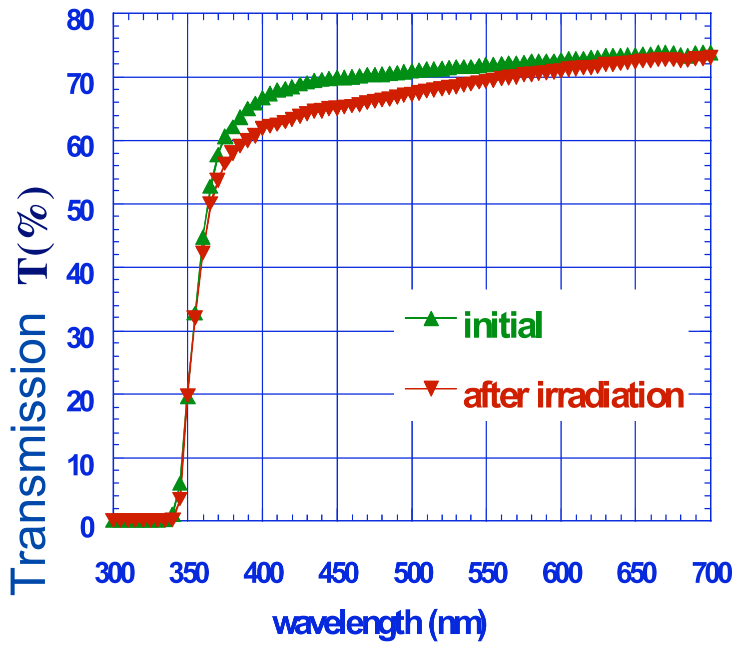




Lead Tungstate Properties



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

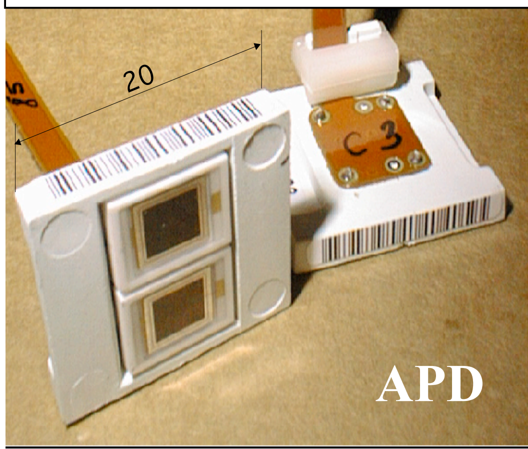
Low light yield (~1% NaI)
→ Photodetectors with gain in mag field

Photodetectors

Barrel : Avalanche photodiodes

Two 5x5 mm² APDs/crystal

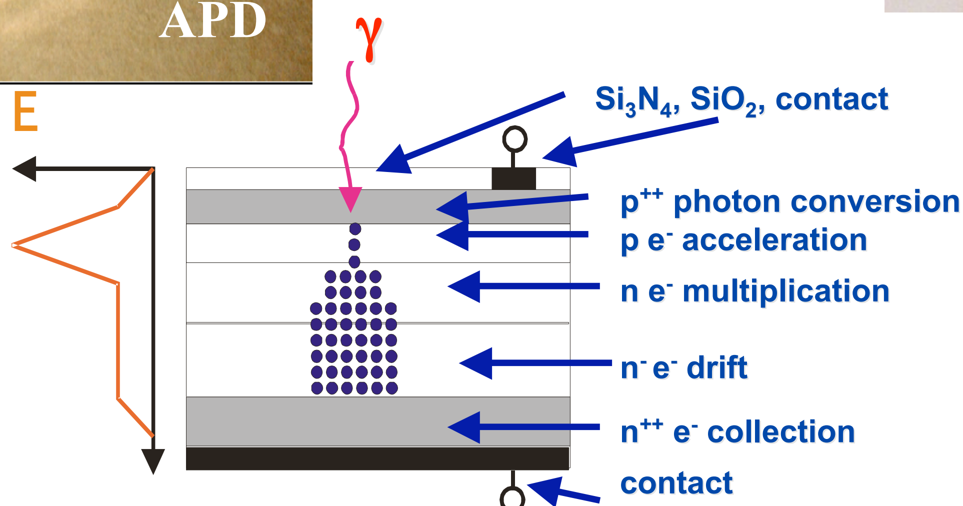
- **Gain: 50   QE: ~80%**
- **Temperature dependence: -2.4%/°C**
- **Work well in strong B fields**

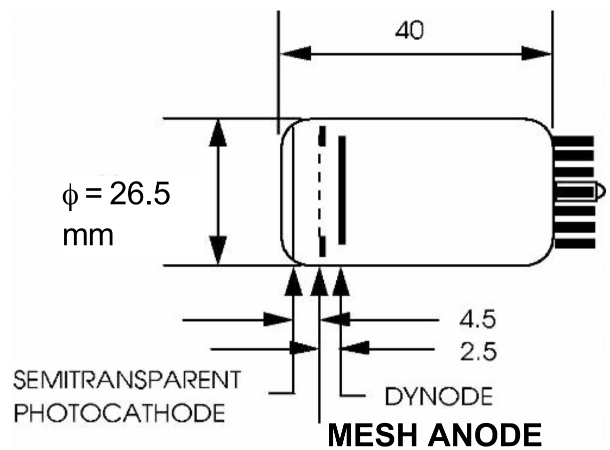


Endcaps: Vacuum phototriodes

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

- **Active area ~ 280 mm²/crystal**
- **Gain 8 - 10 at B = 4 T   Q.E. ~ 20% at 420 nm**

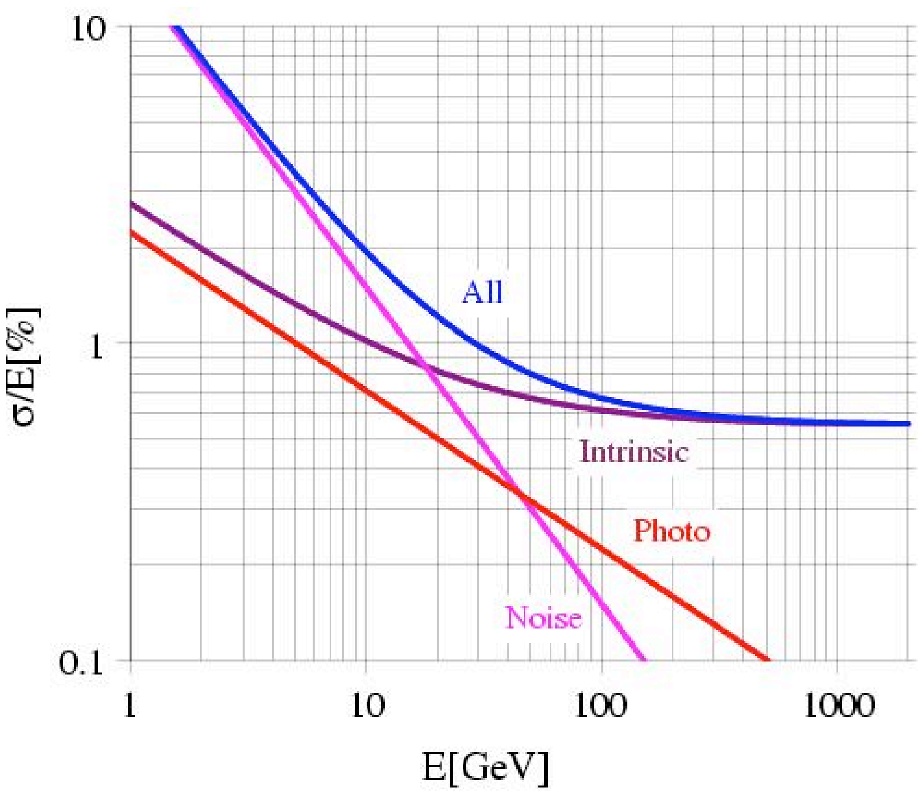


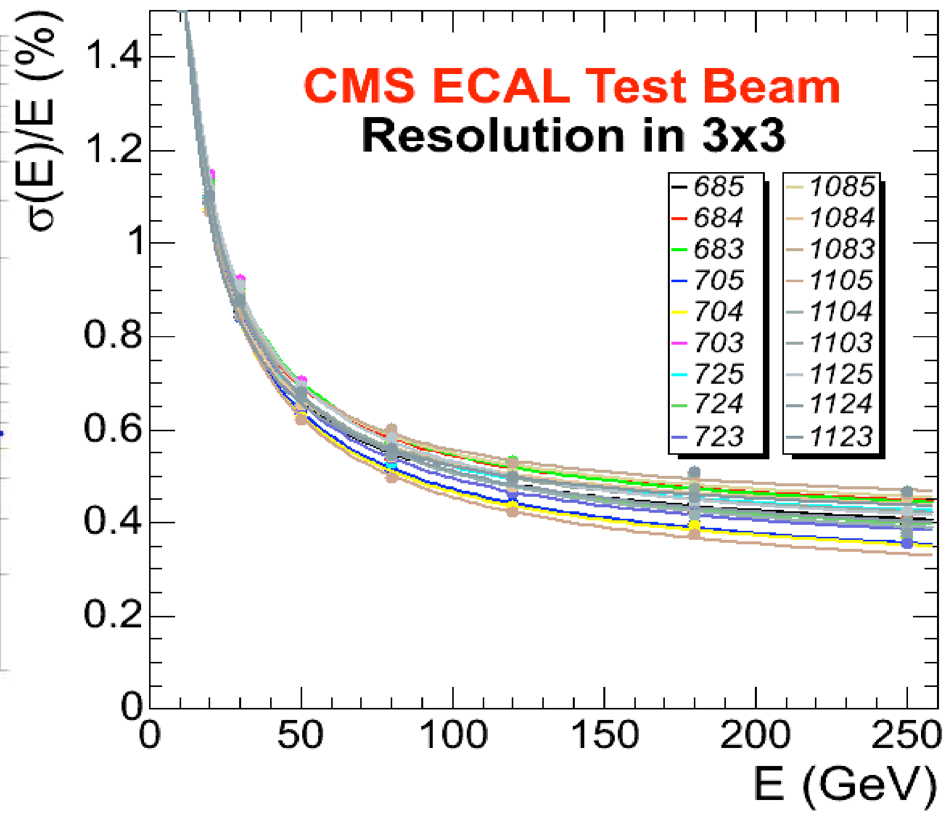


PWO Crystal ECAL Resolution

Design Resolution

Measured Resolution
σ(E)/E < 1% if E > 25 GeV
σ(E)/E ~ 0.5% at 120 GeV





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Current Status

All Barrel crystals delivered. Barrel installation starts April 26th

Delivery of endcap crystals concludes later this year. Endcaps will not be in place for the pilot run

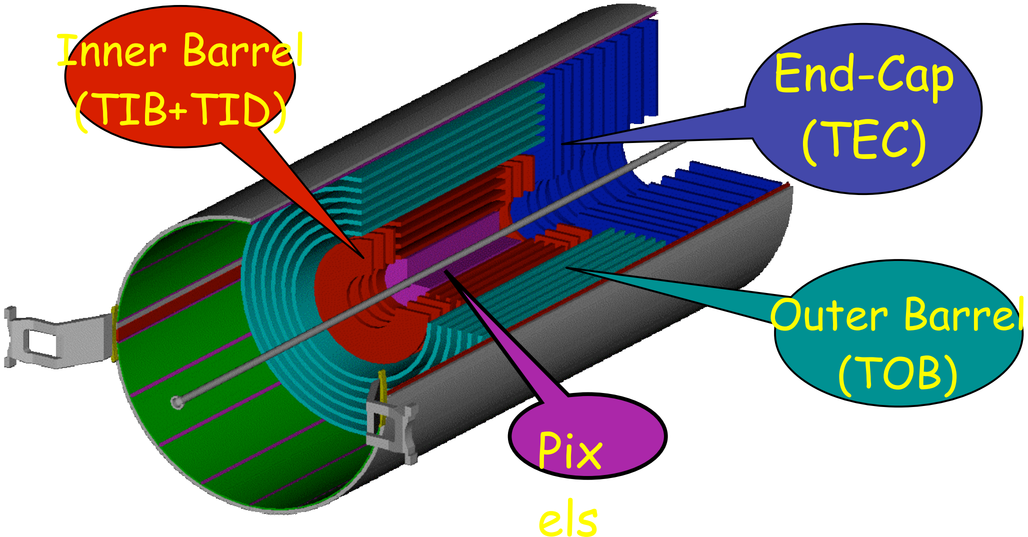
Testbeams at CERN to precalibrated endcap crystals later this year

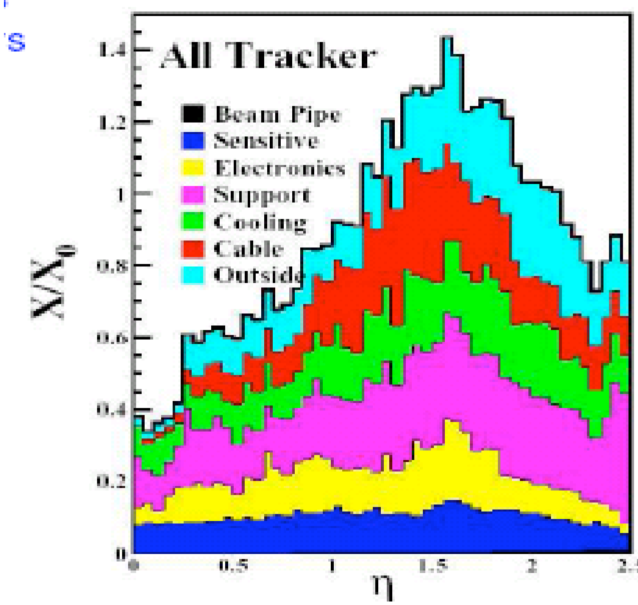
Detailed status reports in recent CMS week meeting

U.S contributes to hardware: crystals & monitoring (Caltech), readout (Minnesota). Roger Rusack (Minnesota) is U.S ECAL manager. Most Other US ECAL groups involved in testbeams

Reconstruction of e/γ

Material in Front of Calorimeter





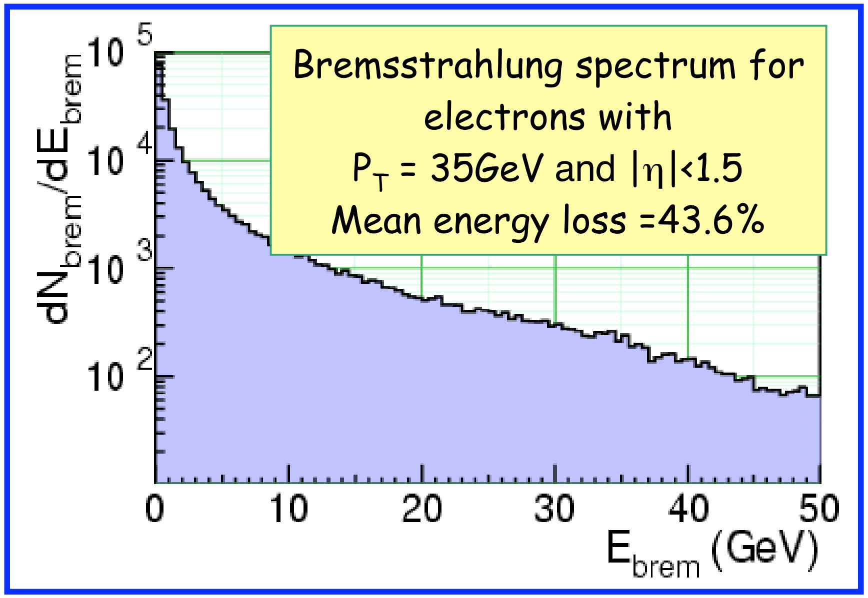
Unusually large amount of material in front of Calorimeter (0.4 to 1.4 X_0) from Silicon tracker (c.f. BaBar 0.4 X_0) (caused by redesign of tracker)

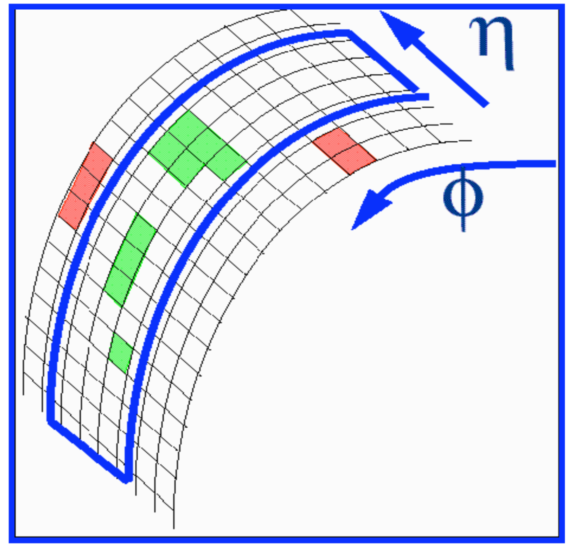
1. Causes Electron Bremstrahlung

2. Causes Photons to pair produce

Significantly degrades resolution and Efficiency to reconstruct good e/γ

Energy clustering/bremsstrahlung



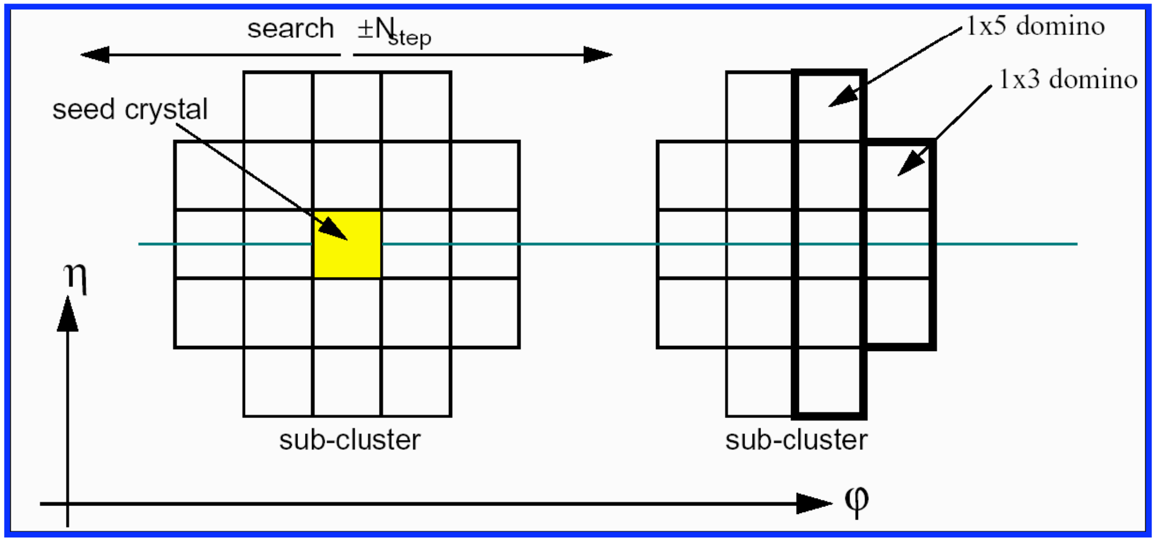


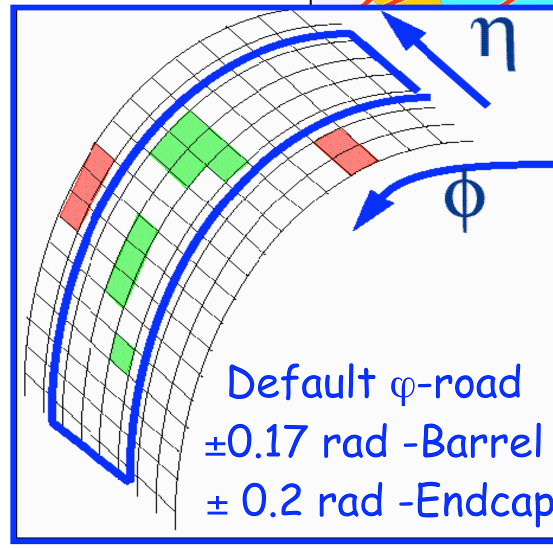
Electrons brem in tracker material and bend in ϕ in 4T mag field so cluster energy is distributed in ϕ.

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

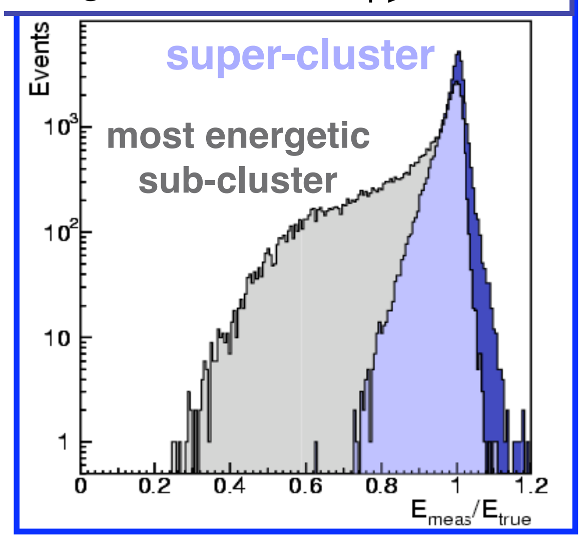
Bremsstrahlung recovery in clustering

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



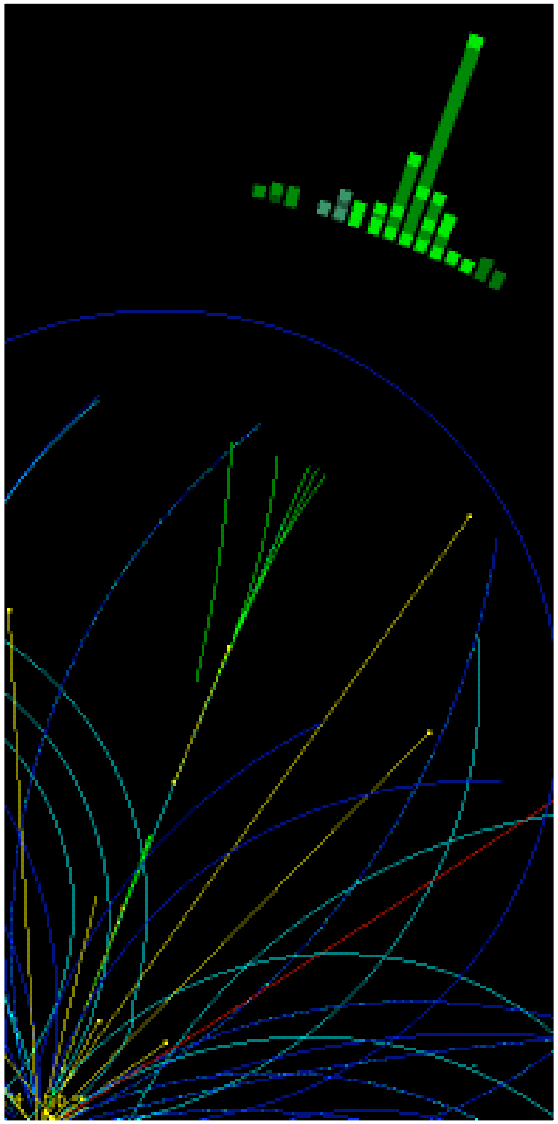


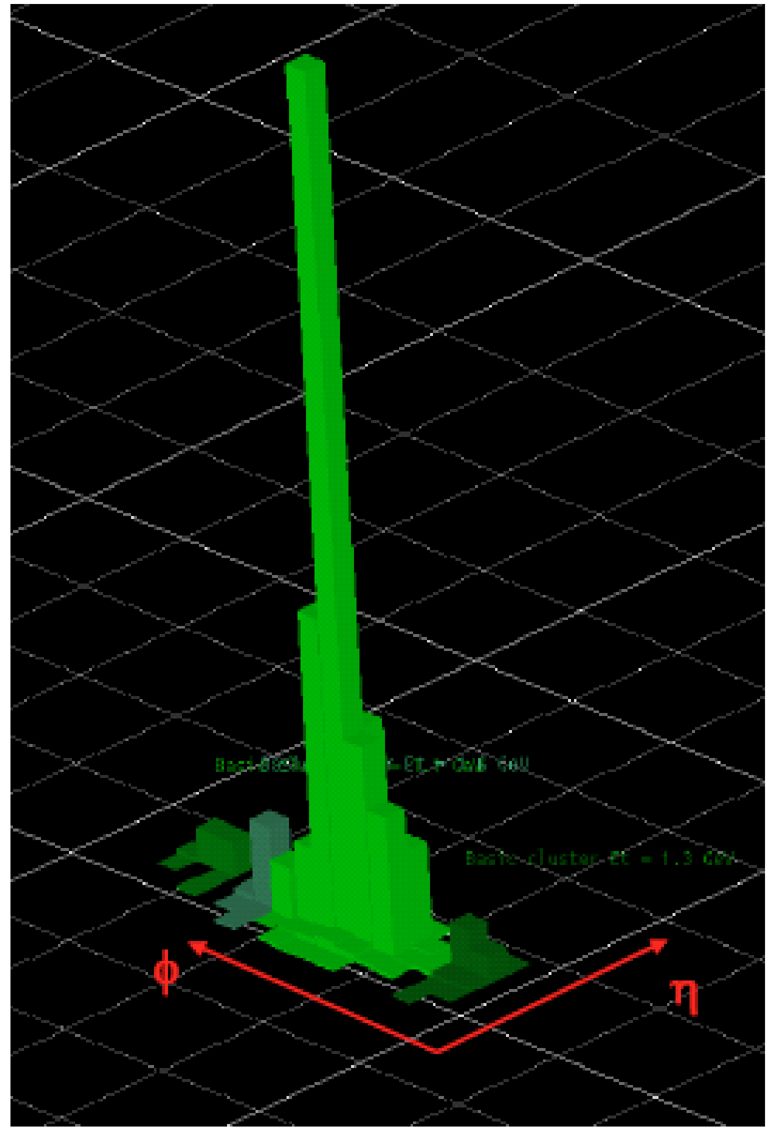
Single electrons $P_T > 30$GeV



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

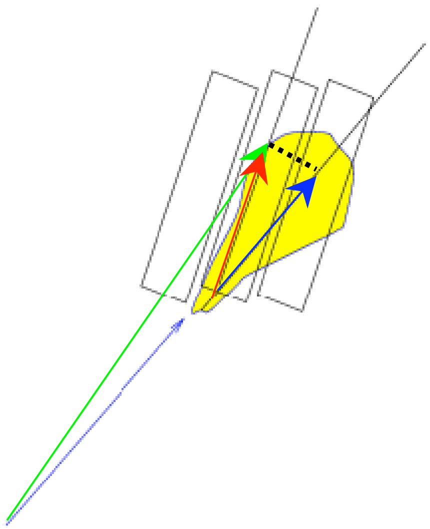
Example of an Electron reconstructed in ECAL



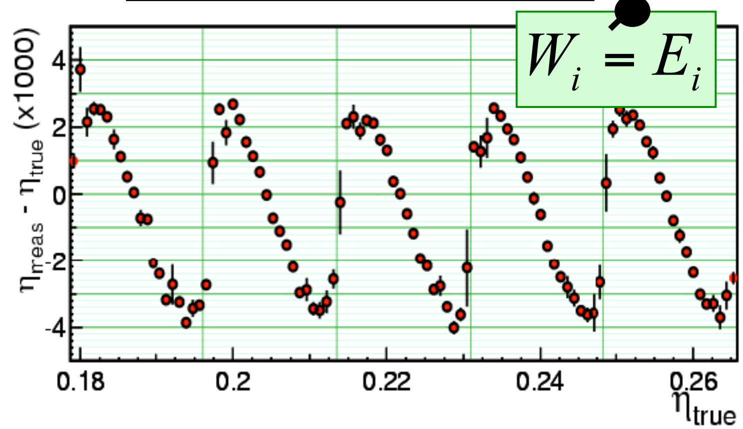


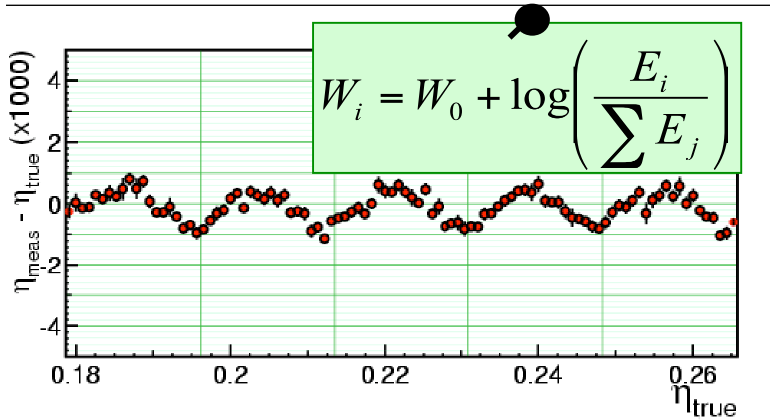
Cluster position

Cluster position



Off-pointing
Xstals





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

Current Electron Reconstruction using ECAL and tracker

1. Find SuperCluster in ECAL

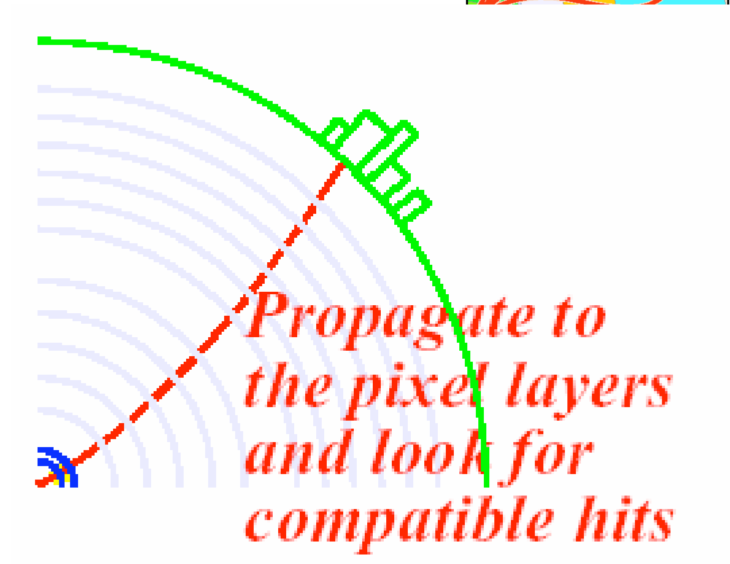
2. Use primary vertex to construct a presumed trajectory between SuperCluster and Vertex

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

Classification of Electrons

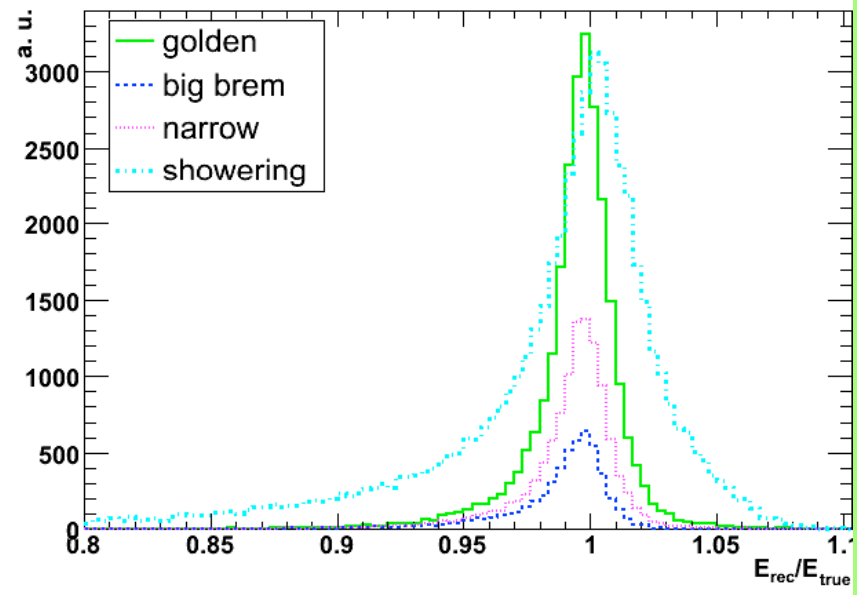
Classified according to whether Brem has been fully Recovered and whether emitted photon has converted
Correlates to resolution

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

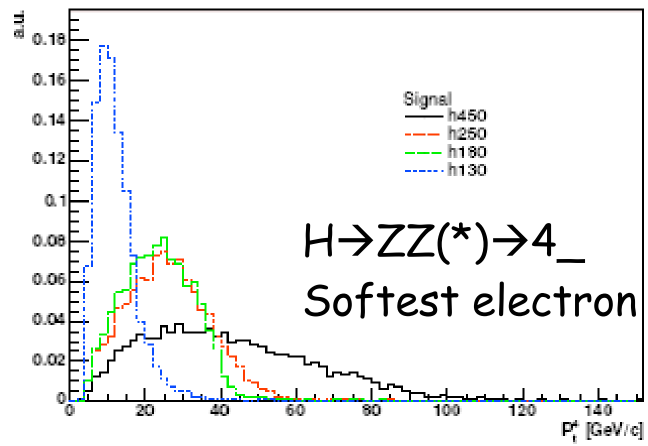


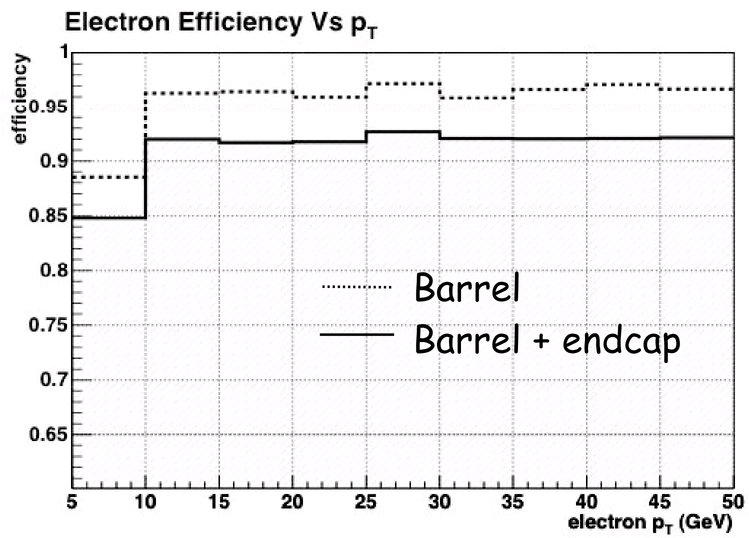
About 60% of electrons between 5 and 100 GeV are in class 4 (Bad)

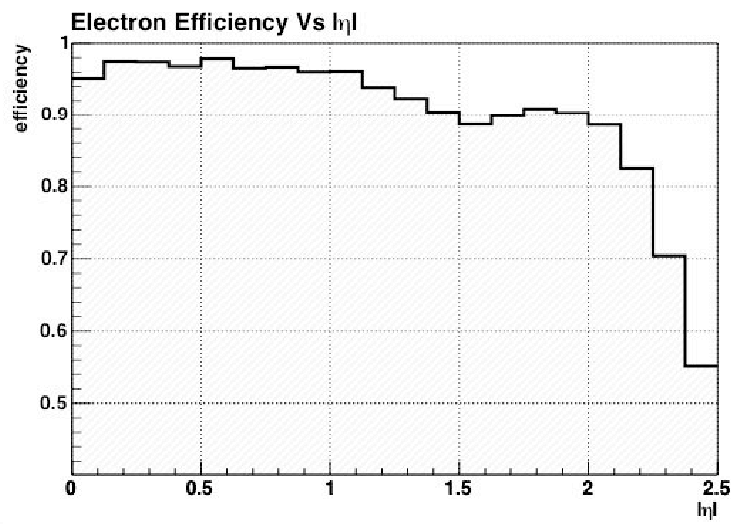
Electron efficiency in a prototype analysis from Phys TDR

H→ZZ(*)→4_

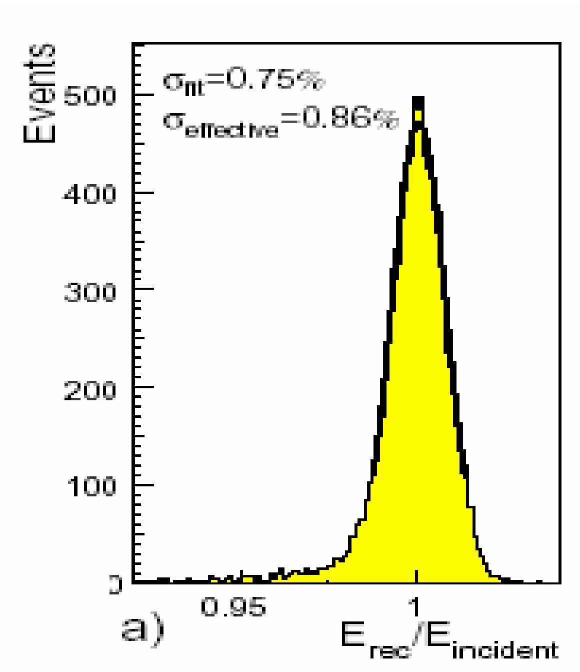
Using all classes of electron

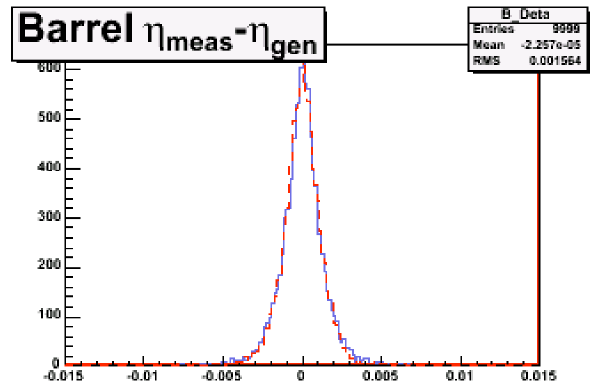


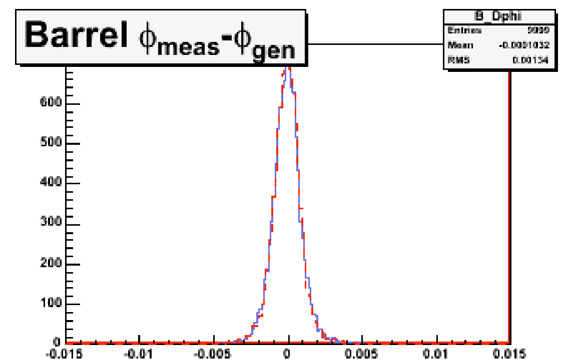




Photon Reconstruction - Unconverted Photons



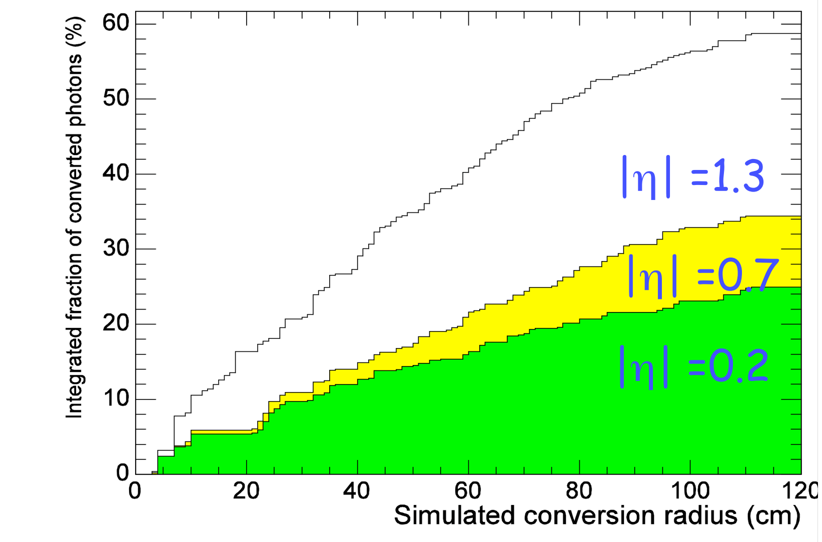




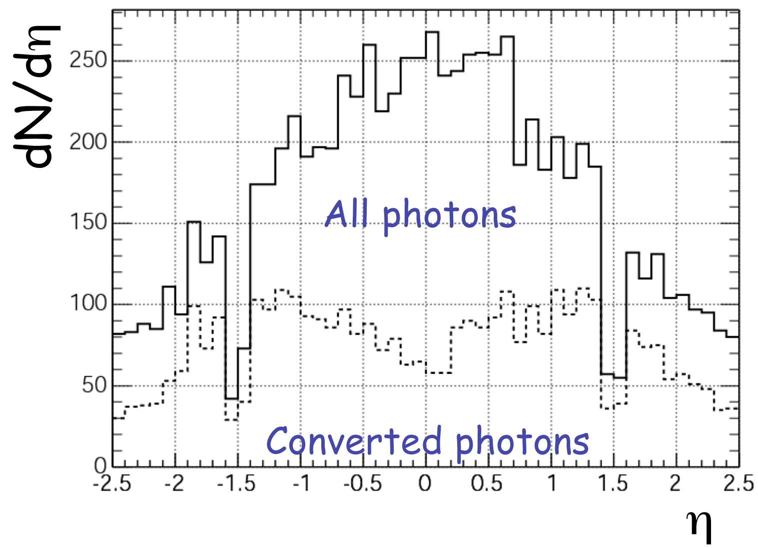
Unconverted photons are easily reconstructed with good Energy and position Resolution but a significant fraction convert due to material

Photon Recontruction

Integrated fraction of converted photons (%)



Simulated photons from H→ γγ



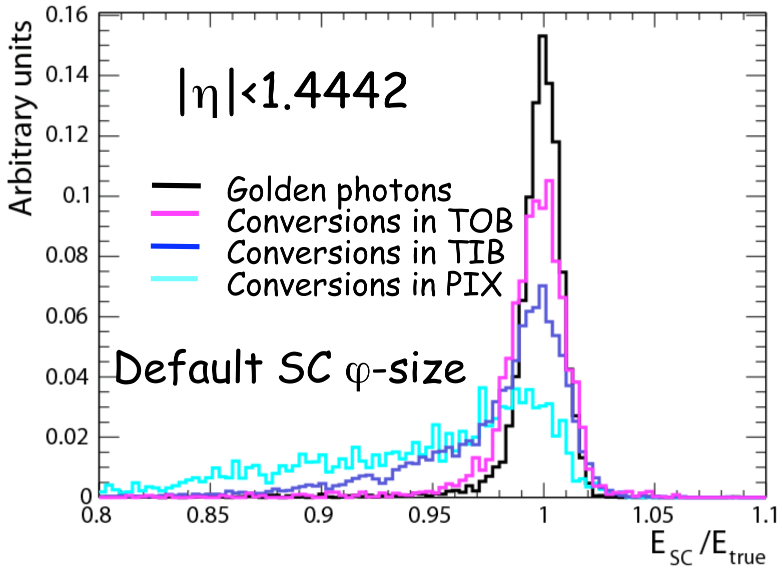
~44% of photons from H→ γγ events convert

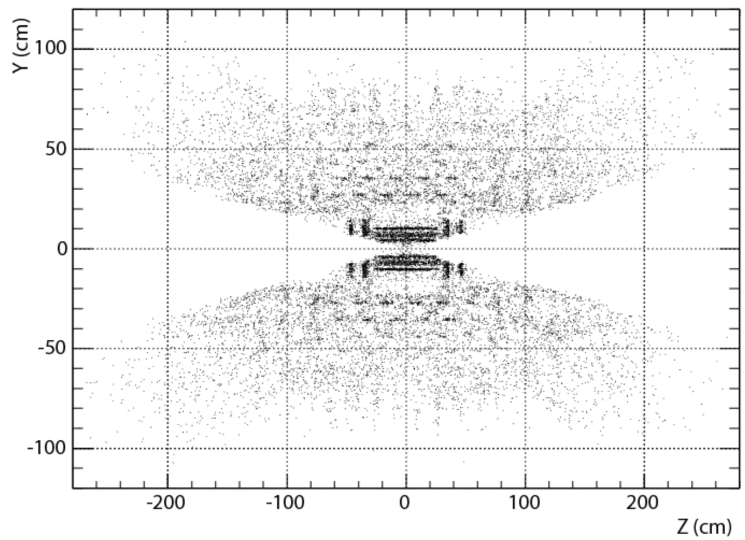
Of all conversions

~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





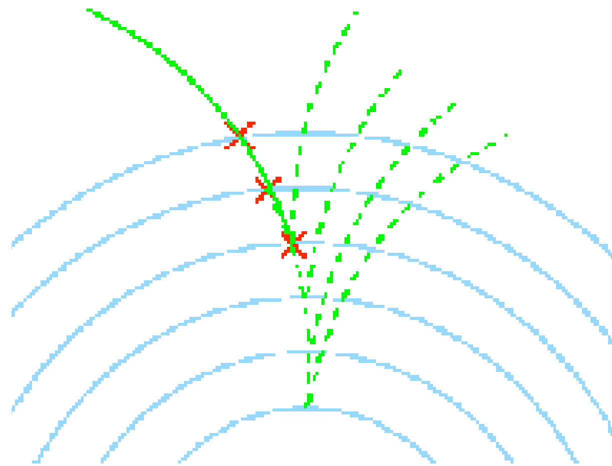
Early conversions (near vertex) degrade resolution significantly if use standard clustering algorithm. Need conversion finder.

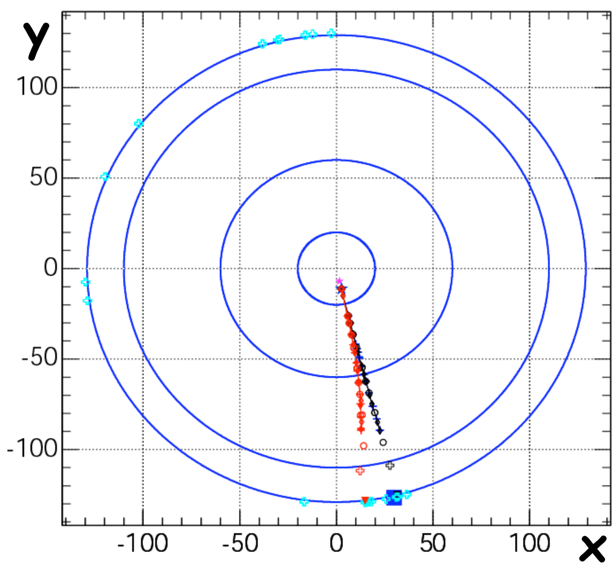
Finding Conversions

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

Current Status of e/γ

Preceding plots were all made with ORCA but currently at the End of the conversion from ORCA to CMSSW:

See the workbook Wiki:

electrons:
https://twiki.cern.ch/twiki/bin/view/CMS/WorkBookElectronReco

Photons:
https://twiki.cern.ch/twiki/bin/view/CMS/WorkBookPhotonReco

Many of the tools are under development but you do basic things

LPC e/γ group

Leaders: Jeff Berryhill (berryhil@fnal.gov) Yuri Gershtein (gerstein@hep.fsu.edu) & Colin Jessop (jessop@fnal.gov)

US Institutes involved: Caltech,Cornell,KSU,FSU,Notre Dame, Minnesota,Virginia

Projects: Reco algorithms and development, calibration & monitoring material estimation, validation and control samples.

Meetings: LPC e/gamma biweekly Friday 11am Sunset and VRVS – next meeting March 23.

CMS central management for ECAL e/γ

ECAL: Project Manager: Phillippe Bloch (CERN)

US PI's have membership of ECAL Institutional Board

Roger Rusack (Minnesota) is US ECAL manager

Physics:

Detector Performance Group: (Calibration and commisioning)
Chris Seez and Paolo Meridiani

Physics Object Group:
David Futyan and Pascal Vanlaer

References

Calorimetry: Fabjan&Gianotti Rev. Mod Phys 75 2003
Calorimetry by R. Wigmans published by Oxford University Press
Calor 2006 website for latest Calorimetry developments

CMS Detector: CMS ECAL TDR CERN/LHCC 97-33

Electrons: CMS Notes 2001/034,2005/001,2006/40

Photons: CMS Notes 2006/005

Nice talks by N. Hadley & Adi Borheim at LPC J-Term in January 2006 (online)