Physics with Electrons and Photons at the CMS experiment

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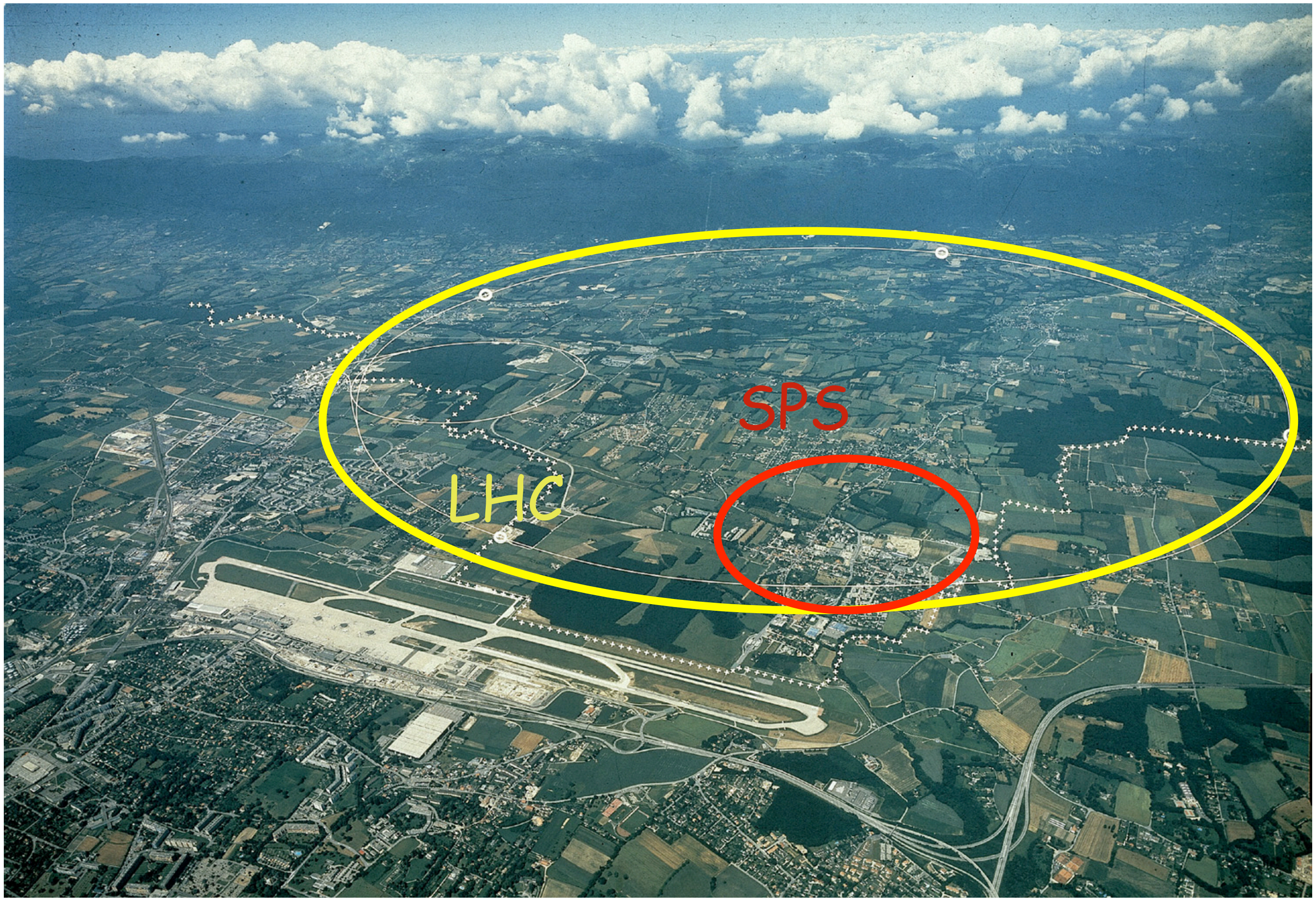
Contents

- 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
- Reconstruction of Photons and Electrons
- Case Studies H->$\gamma\gamma$, H->ZZ , SUSY

* Try to avoid duplication with Lorenzo Agostino Journal club 1/19/07

Primary Goal of LHC



14 TeV pp

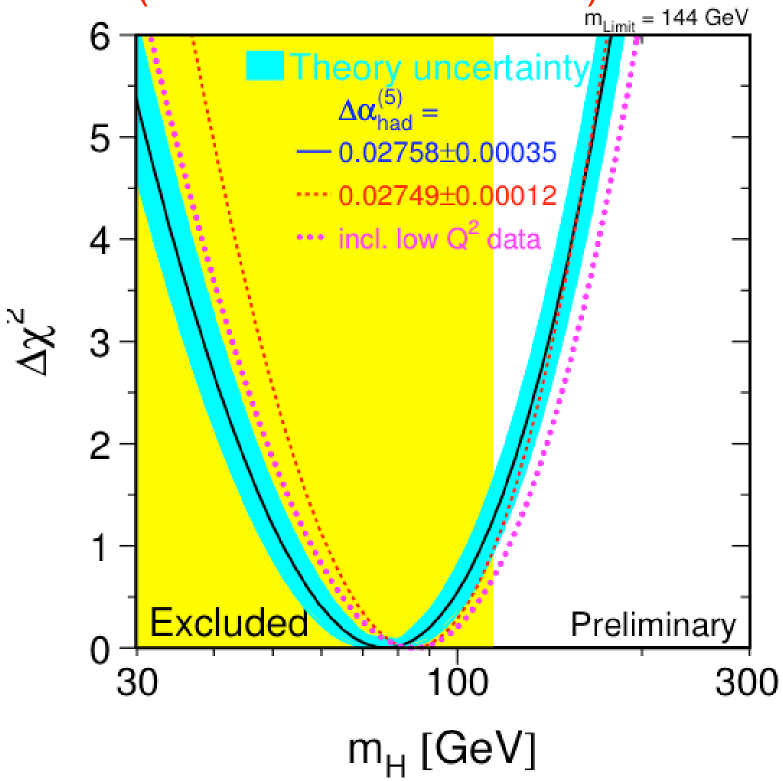
$L=10^{34}$ cm^{-2} s^{-1}

Effectively a high energy gluon collider

To Understand the Mechanism of Electroweak Symmetry Breaking - The Higgs

Standard Model Higgs Constraints

(LEP EWWG March 07)



95% Confidence Limits (Spring 2007)

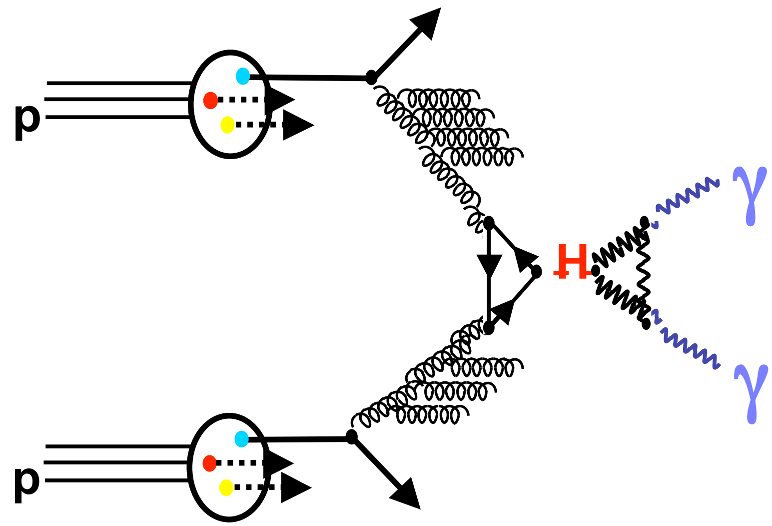
m_H > 114.5 GeV (Direct Search)

m_H < 182 GeV (Inferred from constraints on radiative corrections to measured M_W,M_t ….)

If the minimal standard model is correct expect a "low" mass Higgs

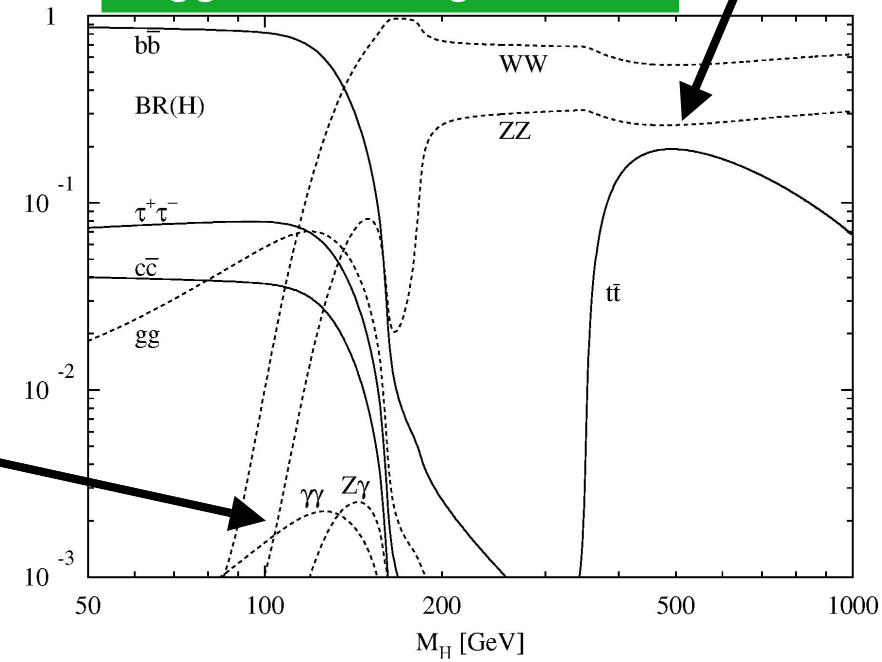
Higgs Production and Decay

Dominant Higgs Production Mechanism



H->ZZ uses ECAL for Z->e+e-

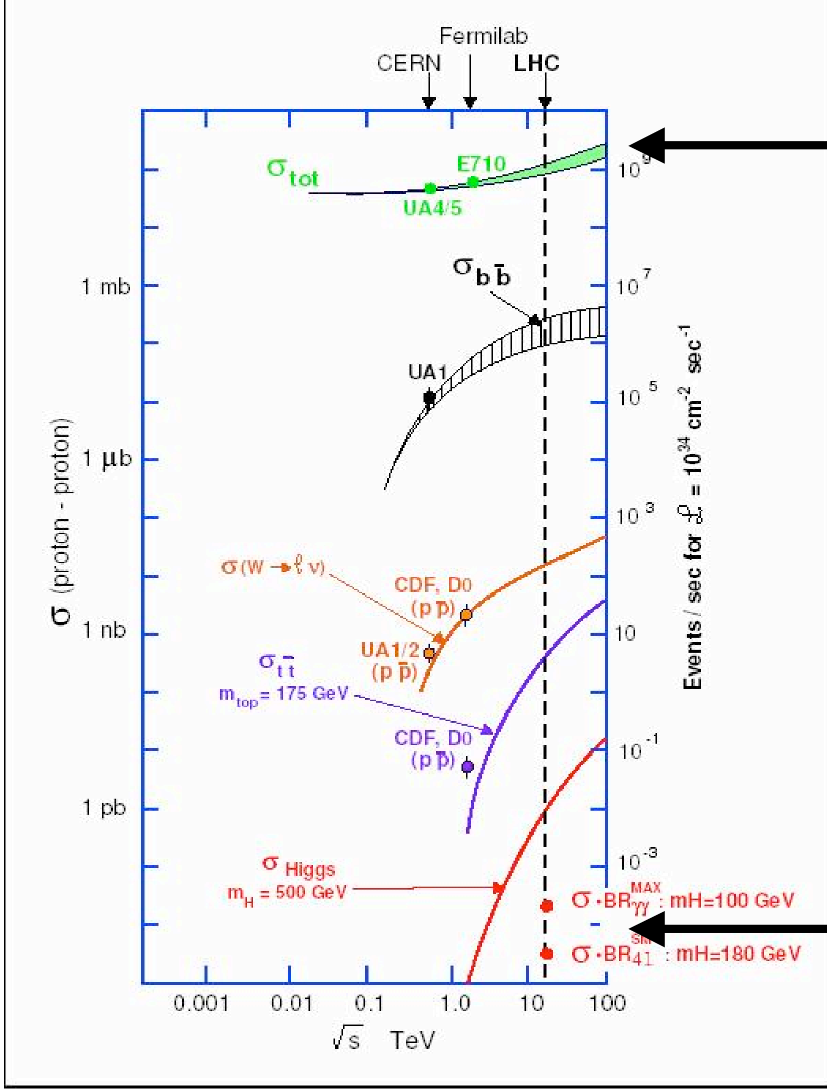
Higgs Branching Fraction



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}

σ.Br(H->$\gamma\gamma$) ~10^{-11}mb

Backgrounds

Most of σ_{total} is due to jet production

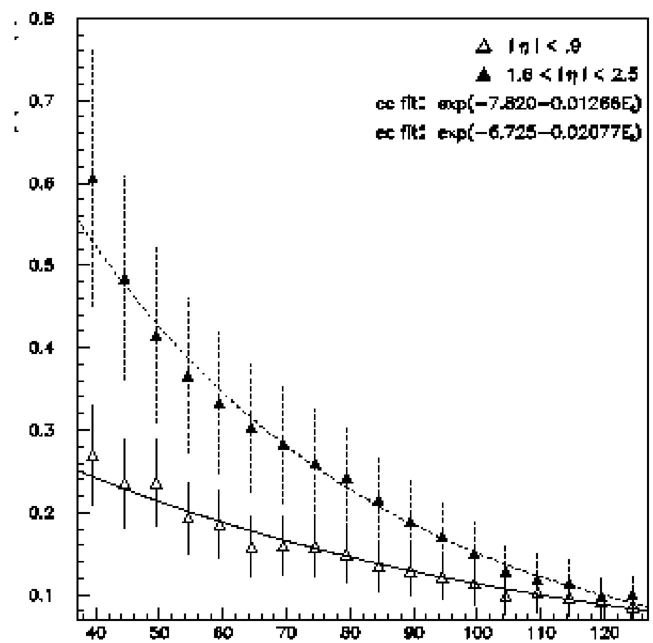
From D0 at Tevatron:

Probability Jet to fake photon ~ 1 in 10^4

Jet to fake electron ~ 1 in 10^5

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

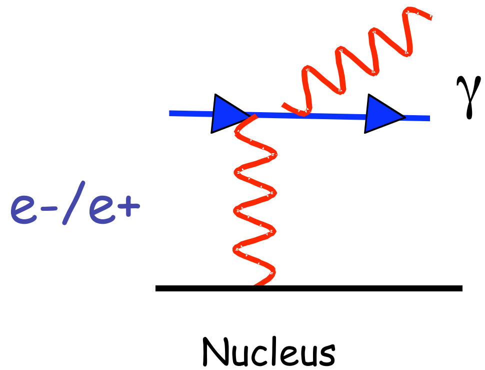
Probability Jet fakes Photon x 10^{-3}



Need very selective trigger and excellent recontruction capabilities for e/g

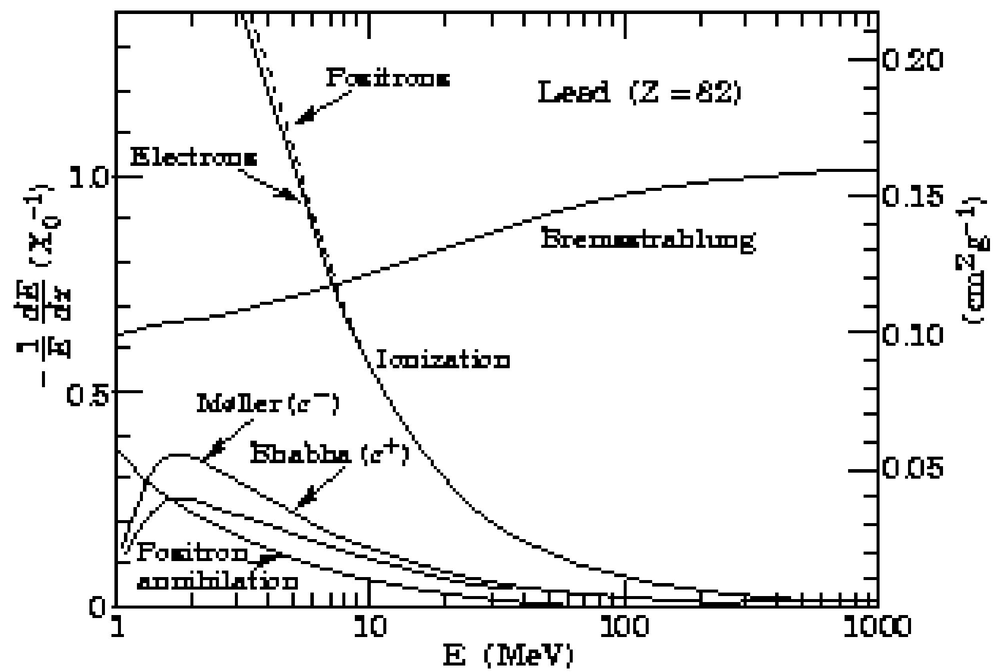
Very Brief Revision of Electron/Photon energy loss in matter

Electron/Positron Energy Loss in matter



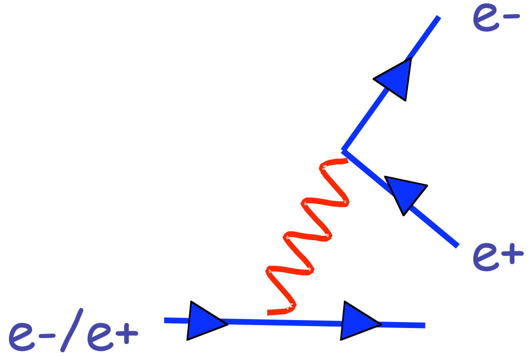
Bremstrahlung (radiation of photon)

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



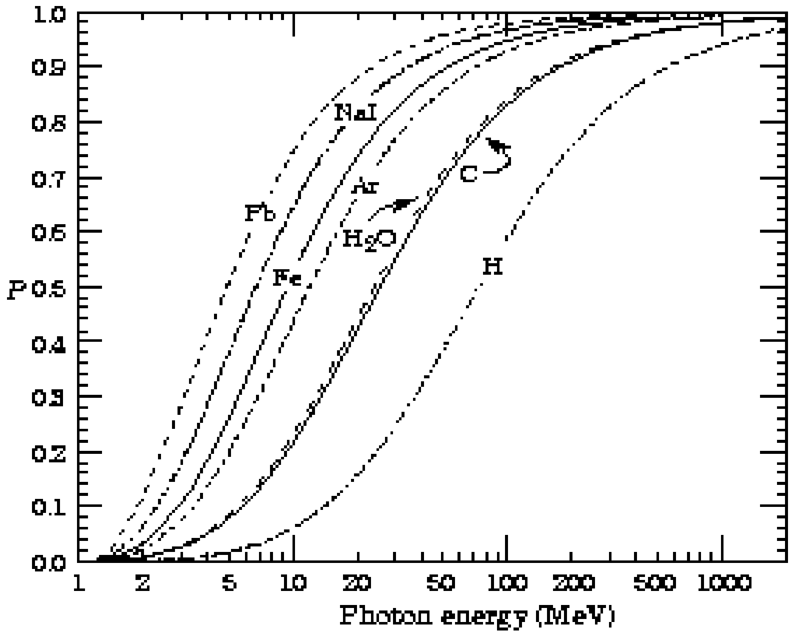
Electron energy loss primarily by Brem at E > E_c (~20 MeV) and ionization below. Brem Radiation probability depends on radiation length X_0

Photon Energy Energy Loss



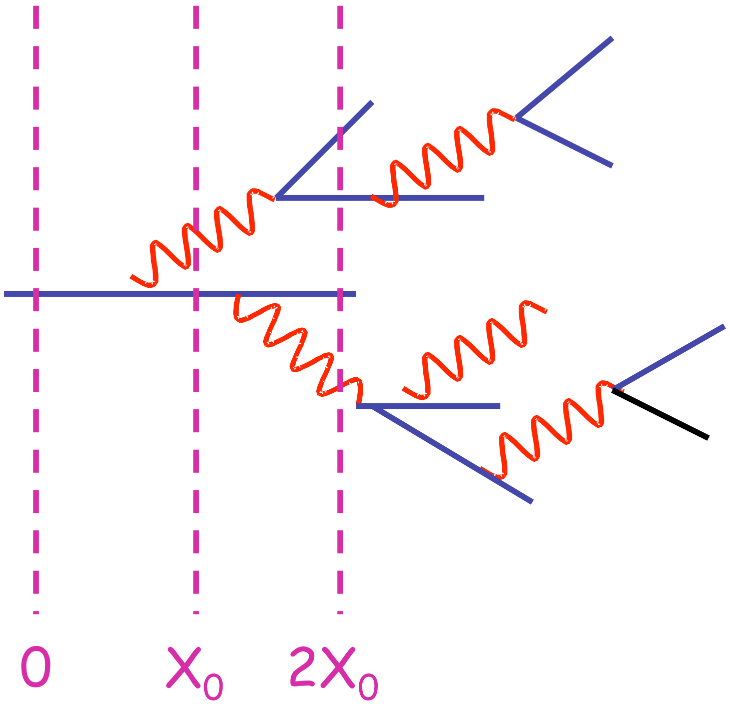
Pair Production

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

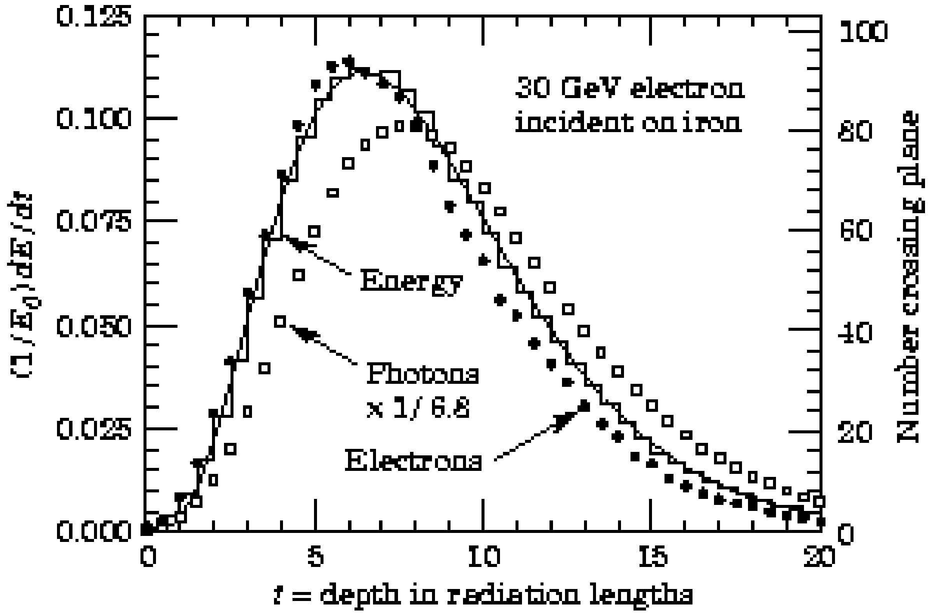
Can show that Max number of shower particles occurs at: $X_{\max} \propto \ln(E_0 / E_c)$

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

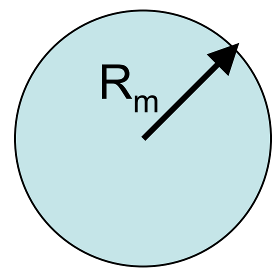
Measure Energy by measuring L with ionization or scintillation

Electromagnetic Shower Profile

Longtitudal Profile



Lateral Profile



Moliere Radius: $R_m \approx X_0$

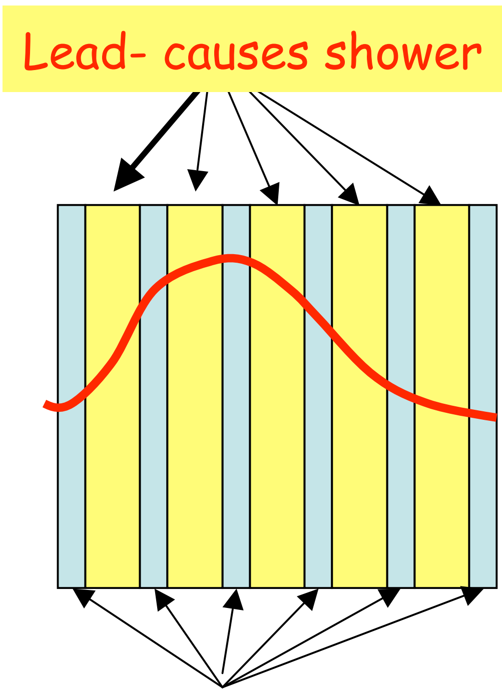
(from multiple scattering)

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

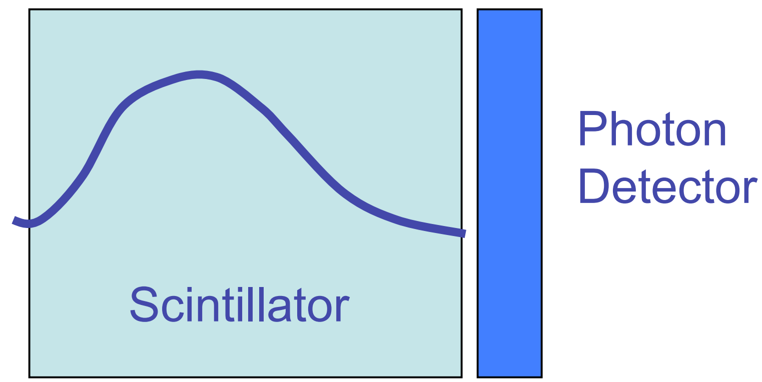
Sampling Calorimeter



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

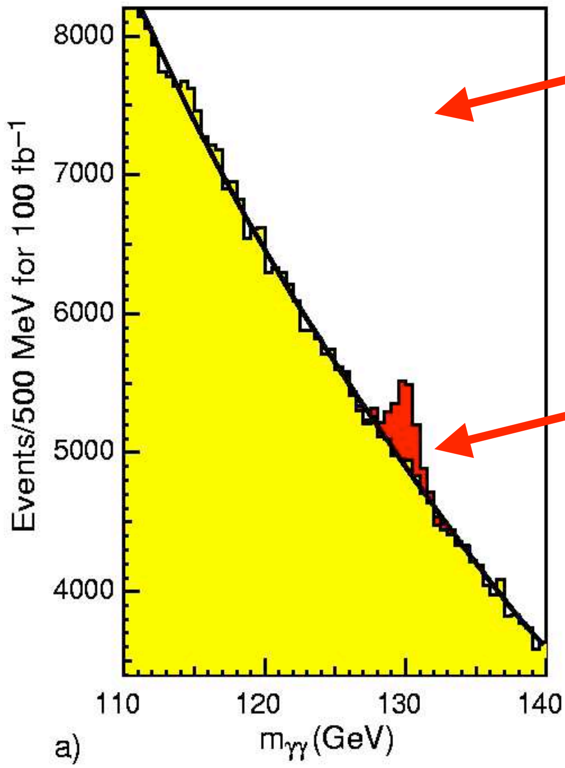


Scintillator both causes shower and is active detector

Expensive with good Resolution ~0.5% at 100 GeV

CMS ECAL Technology Choice

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

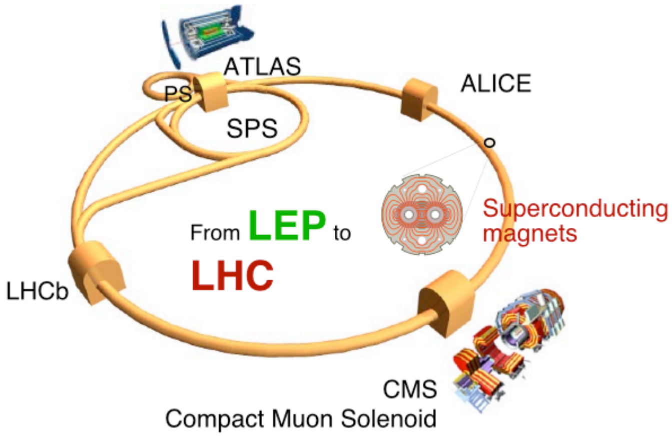
$$\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \frac{1}{2}\left[\frac{\Delta E_{\gamma 1}}{E_{\gamma 1}} \oplus \frac{\Delta E_{\gamma 2}}{E_{\gamma 2}} \oplus \frac{\Delta\theta_{\gamma\gamma}}{\tan\left(\theta_{\gamma\gamma}/2\right)}\right]$$

(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



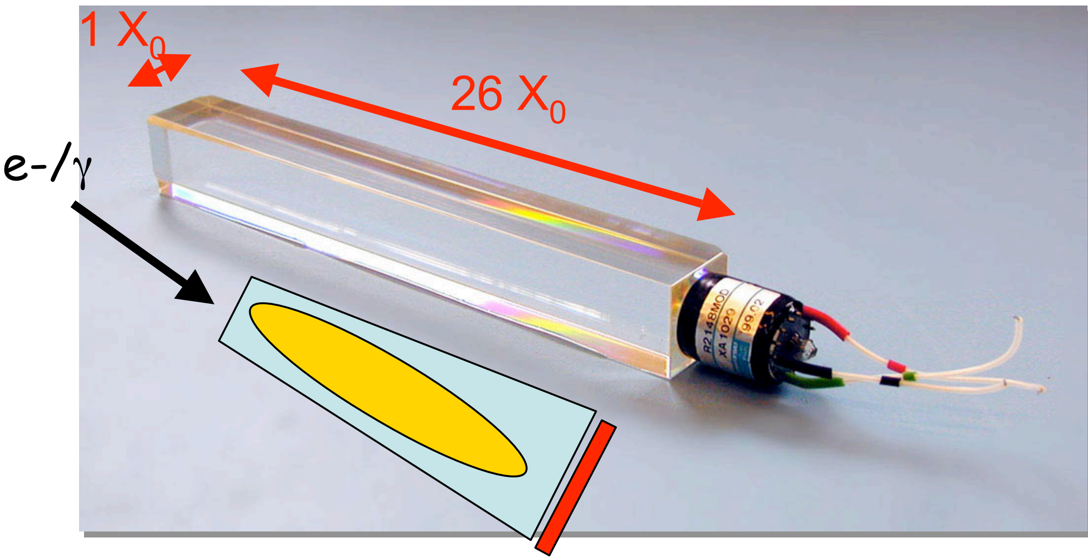
Year	Luminosity $x10^{34}$ $cm^{-2}s^{-1}$	Integrated Luminosity fb^{-1}
2007	0.005	0.02
2008	0.03	1.2
2009	0.1	4
2010+	1.0	40

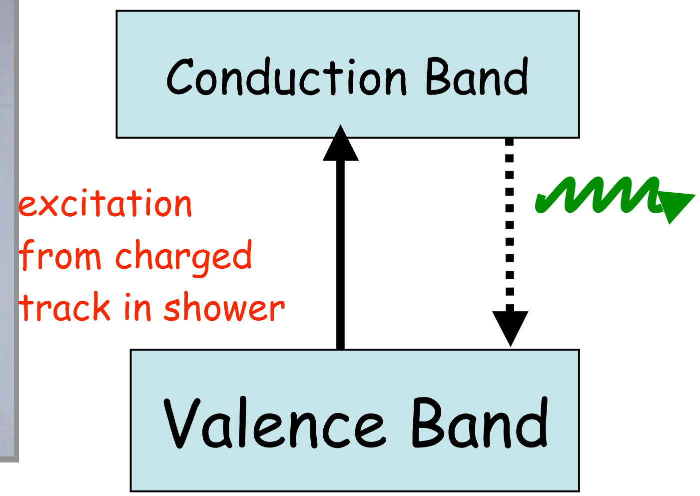
Bunch crossing rate : 40 MHz

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

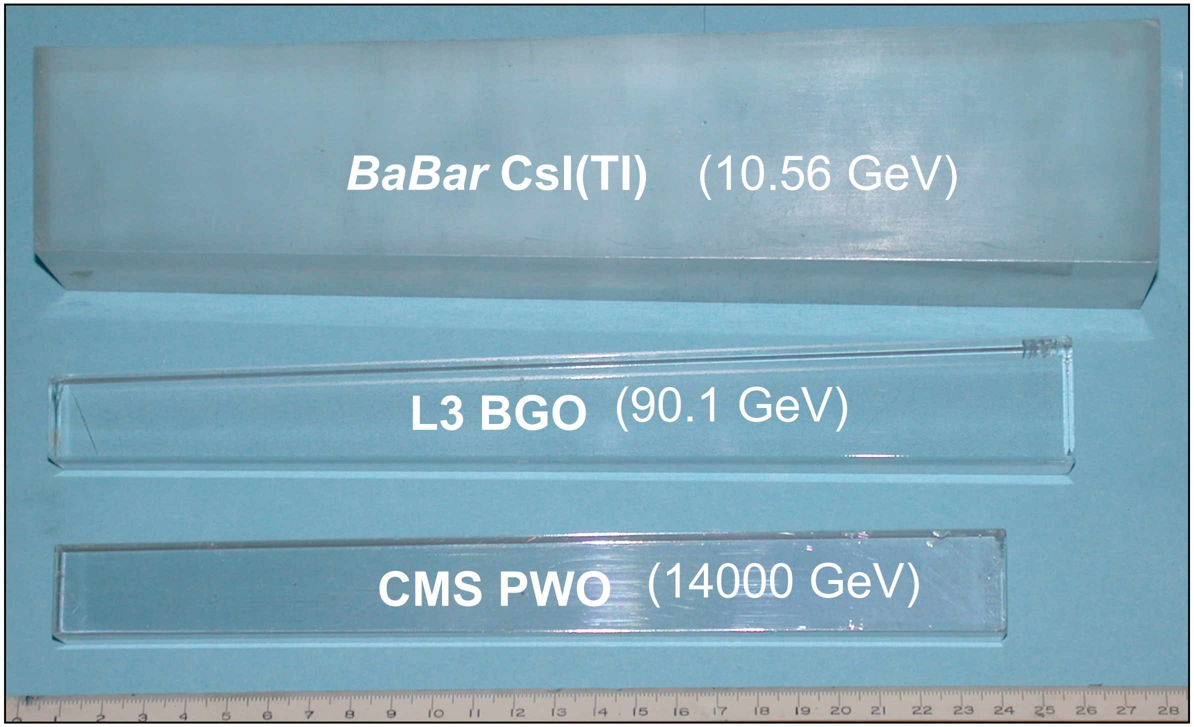
Crystal Calorimeters in HEP

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

High Granularity to decrease occupancy

PbWO is fast and radiation hard but has low light yield

Crystal Density: Radiation Length



Full Size Crystals:

BaBar CsI(Tl): 16 X_0

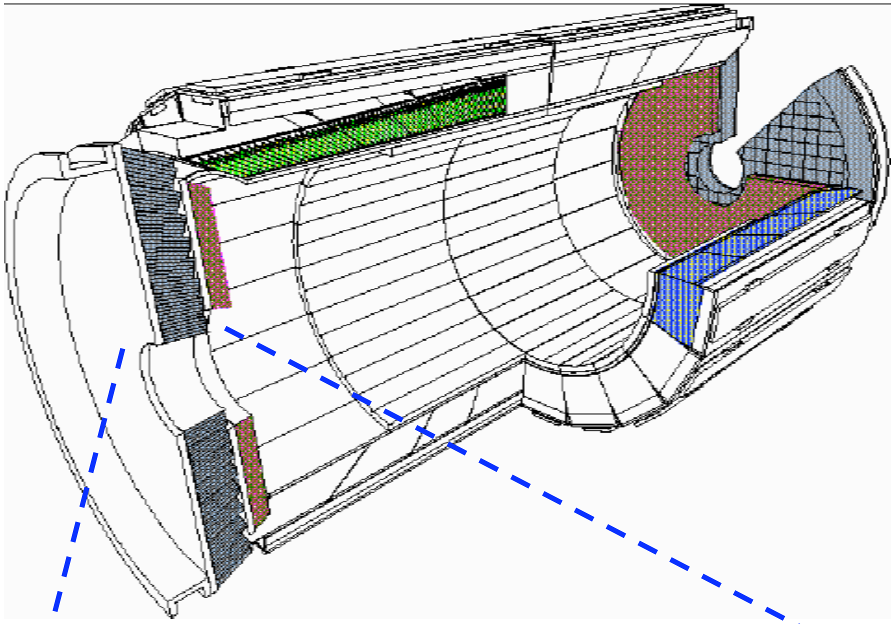
L3 BGO: 22 X_0

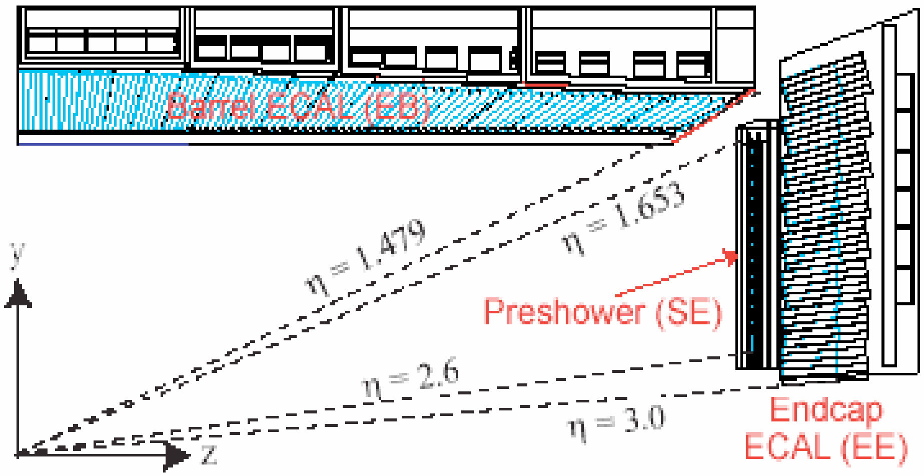
CMS PWO(Y): 25 X_0

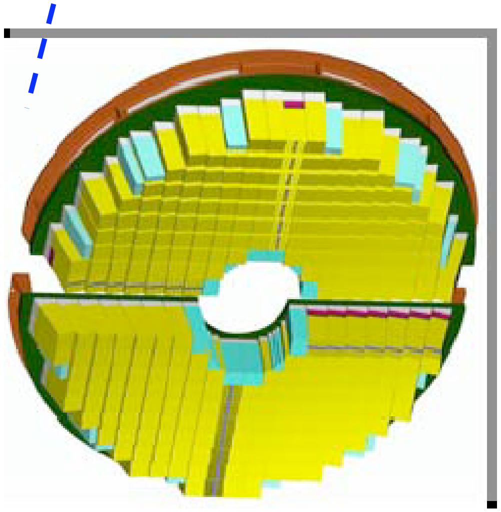
Tranverse size of CMS crystals ~ 3cm x 3cm

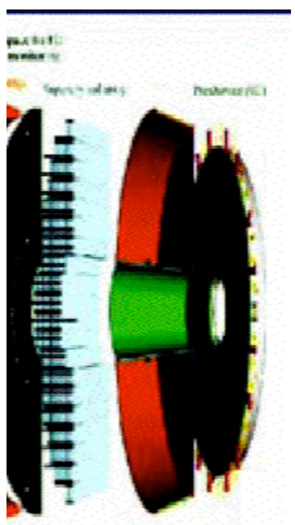
CMS ECAL Construction and Status

ECAL



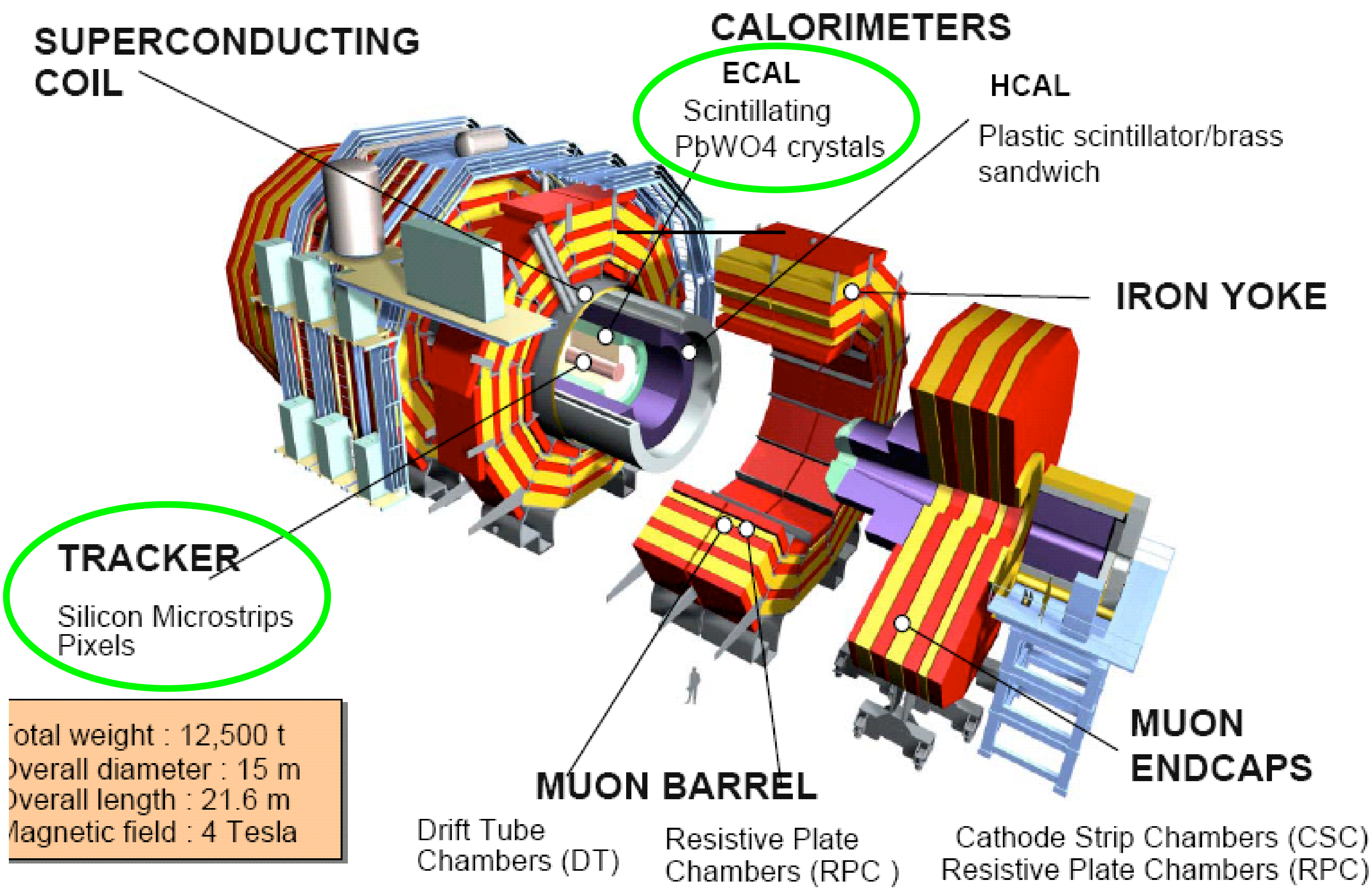






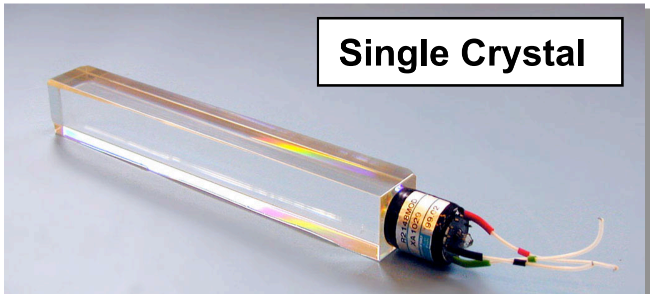
Parameter	Barrel	Endcap
η Coverage	|η|<1.48	1.48|η|<3.0
Granularity (ΔηxΔφ)	0.0175x0.0175	varies in η
Crystal dim (cm^3)	2.18x2.18x23	2.85x2.85x22
Depth in X_0	25.8	24.7(+3)
No. of crystals	61.2 K	14.9K
Modularity	36 supermodules	4Dees

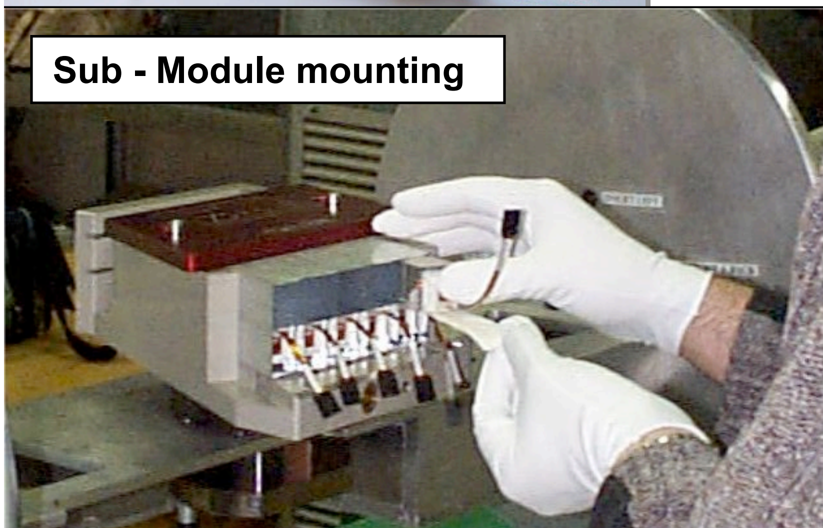
CMS Experiment



Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

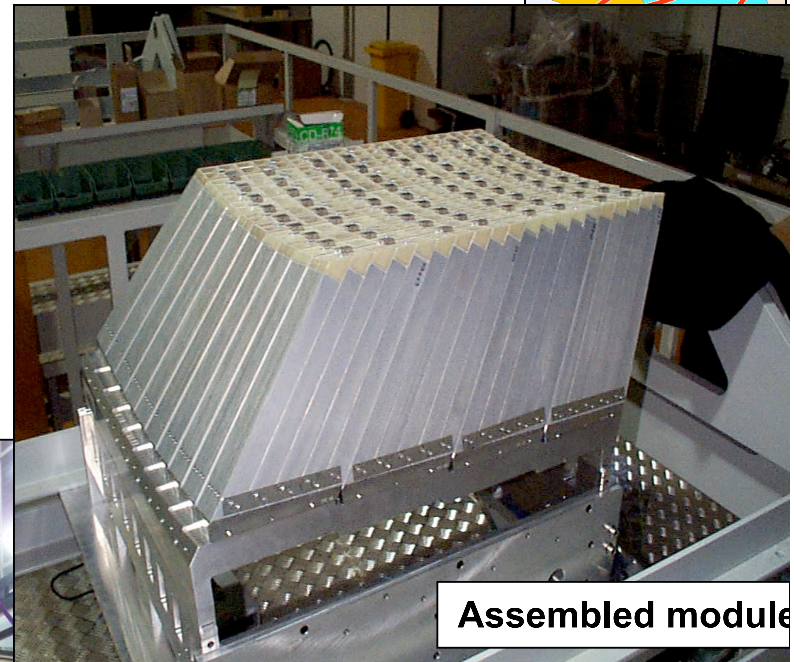
ECAL Crystal Matrix Production

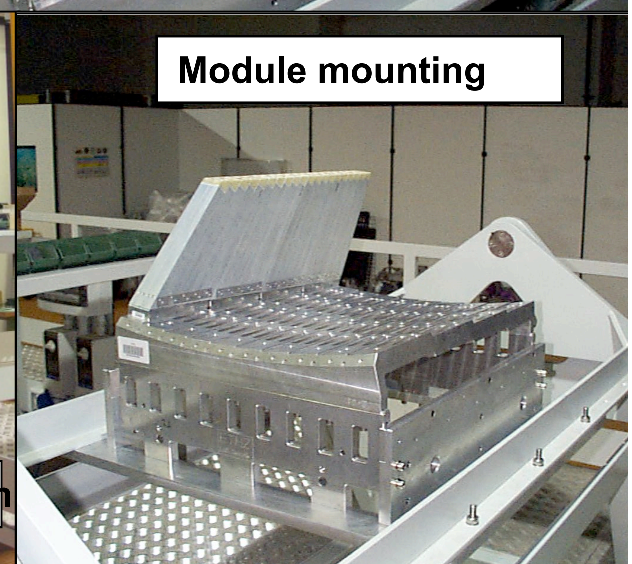

Single Crystal


Sub - Module mounting


Assembled Sub - Modules

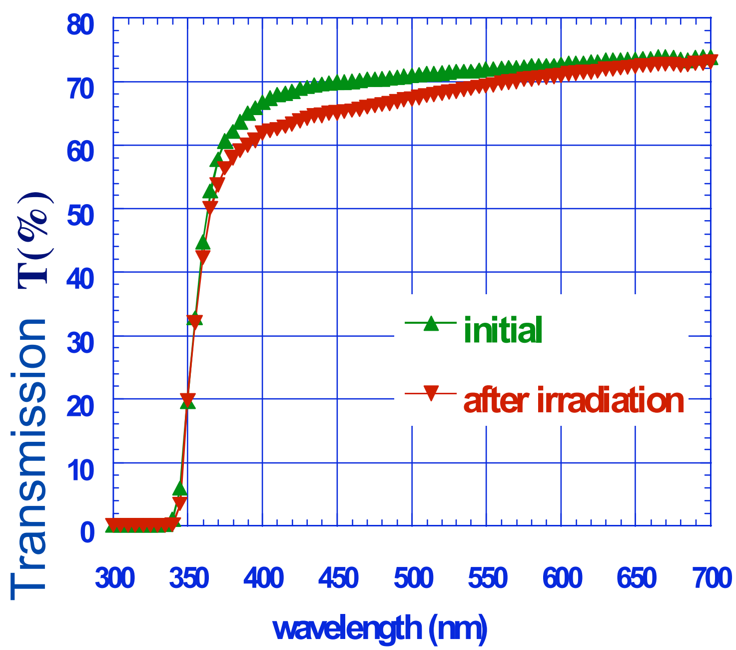

Free mounting bench

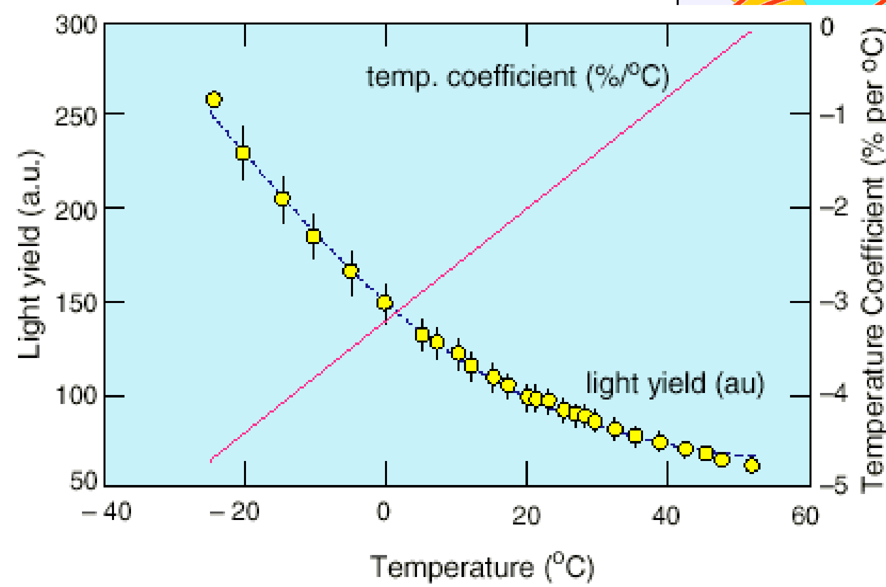

Assembled module


Module mounting

Lead Tungstate Properties

Radiation resistant to very high doses.





But:

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

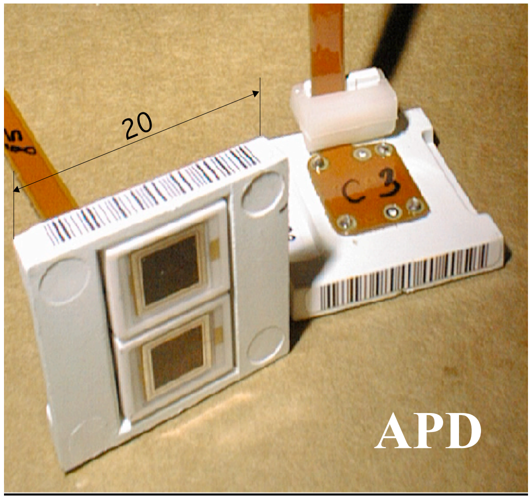
Formation and decay of colour centres in dynamic equilibrium under irradiation
→ Precise light monitoring system

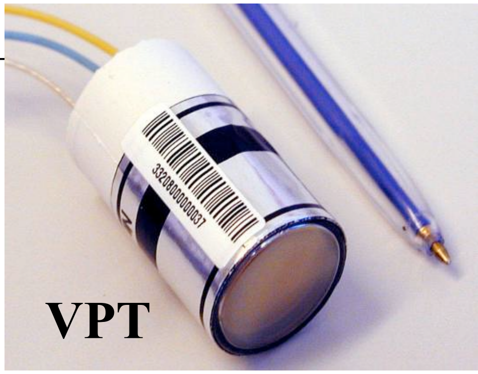
Low light yield (~1% NaI)
→ Photodetectors with gain in mag field

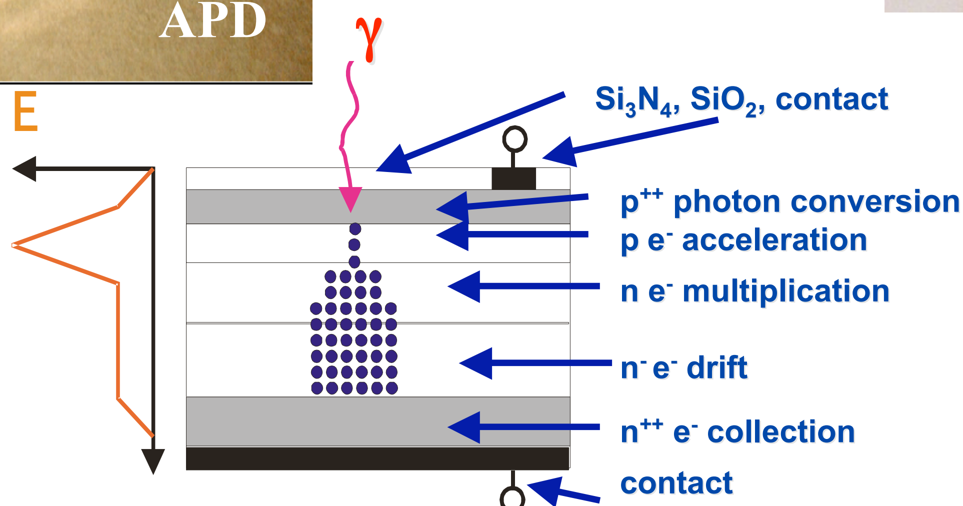
Specially Developed Photodetectors

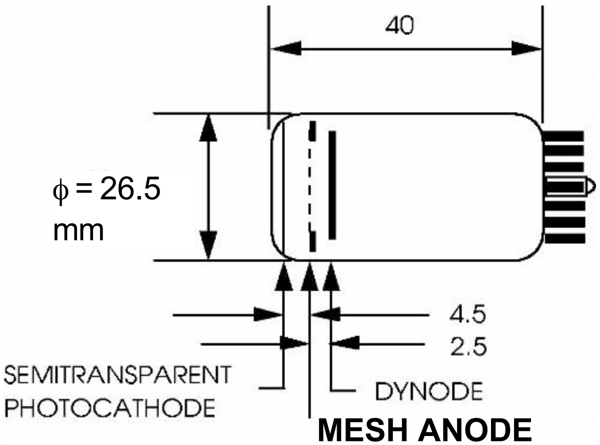
Barrel : Avalanche photodiodes
Two 5x5 mm^2 APDs/crystal
- **Gain: 50 QE: ~80%**
- **Temperature dependence: -2.4%/^{O}C**

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**







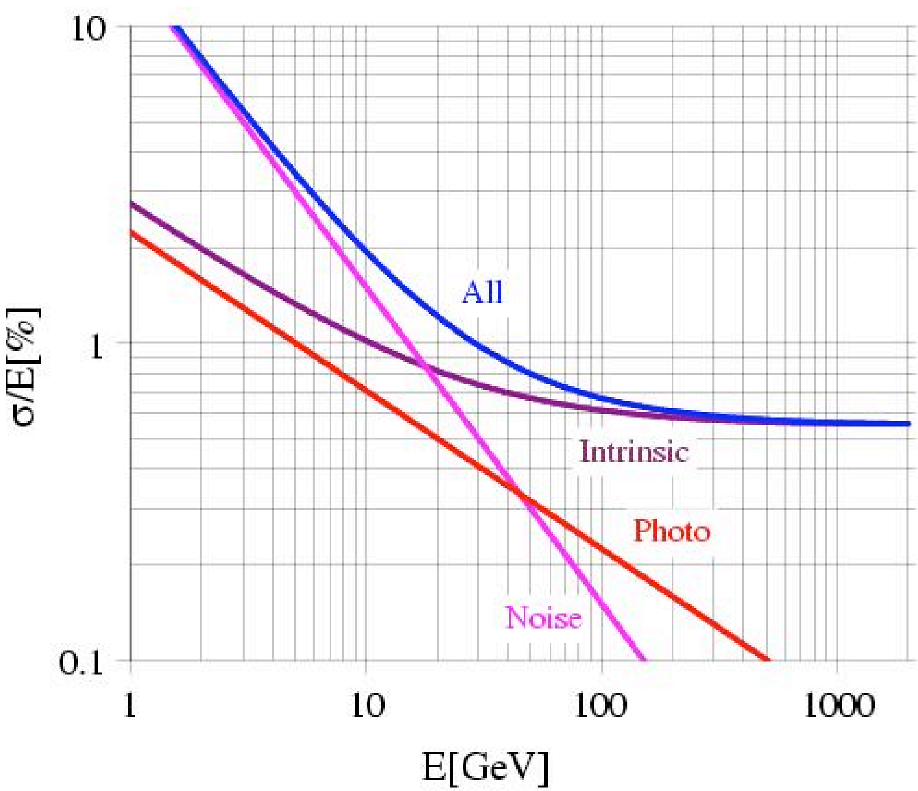


Monitoring and Calibration

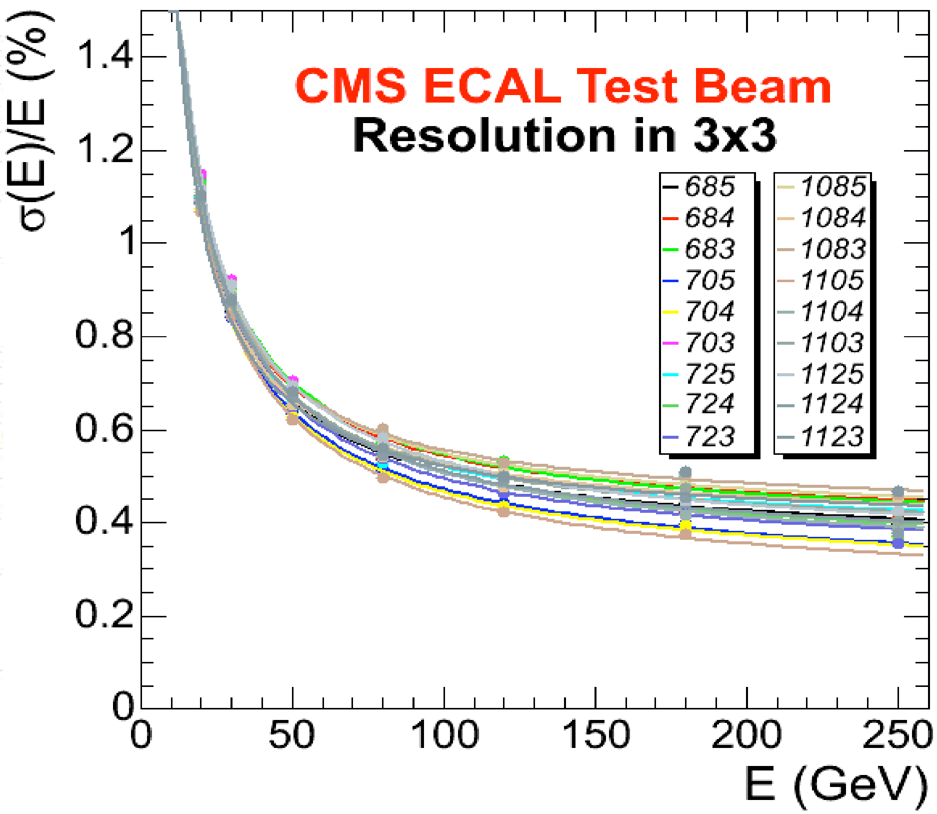
PWO Crystal ECAL Resolution

(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



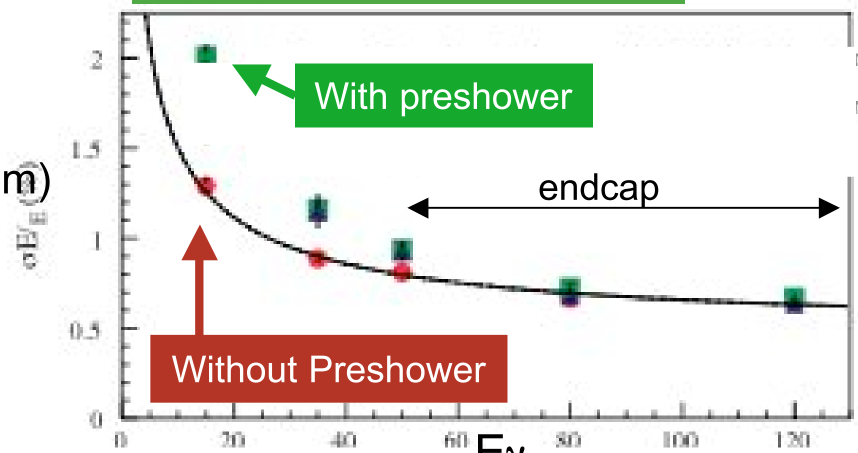
Preshower Detector for π^0 rejection

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

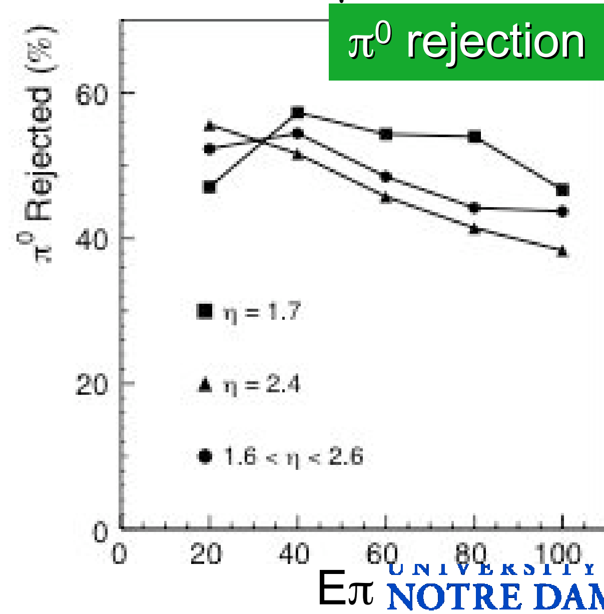
Photon Seperation (crystals 22mm x22mm
Preshower Si strips 1.9 mm)

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

Resolution Degradation



π^0 rejection



Barrel - lateral shower profile
Endcap - Preshower

For endcap, rejection improved by x2-3 with little degradation in resolution

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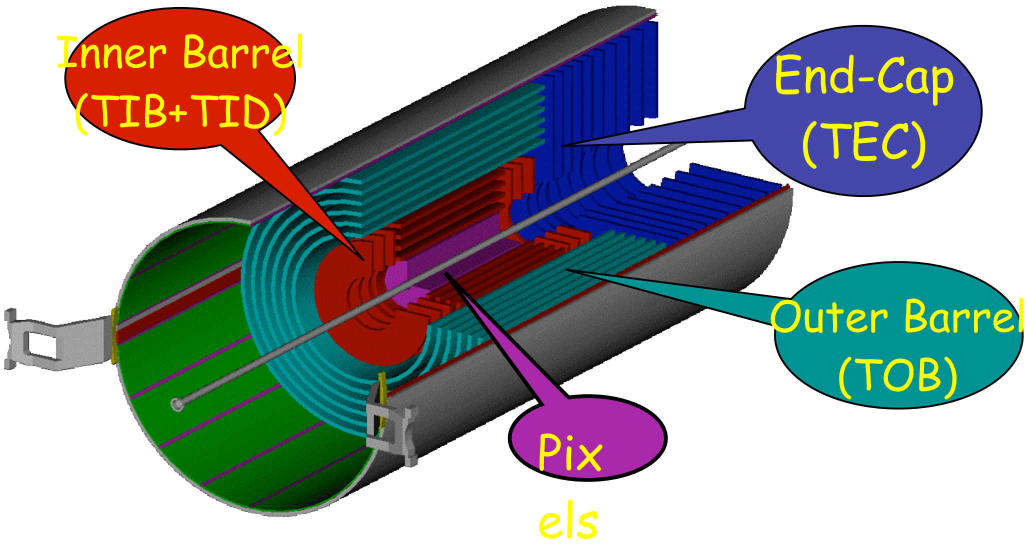
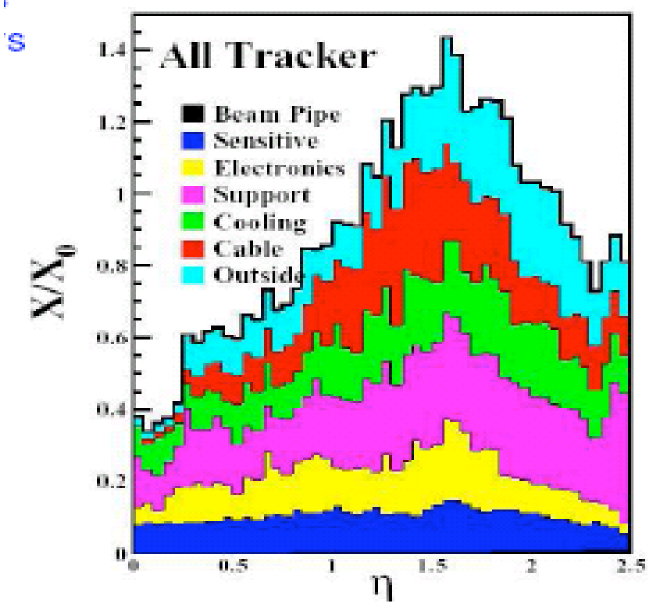
CMS

Reconstruction of e/γ

Material in Front of Calorimeter



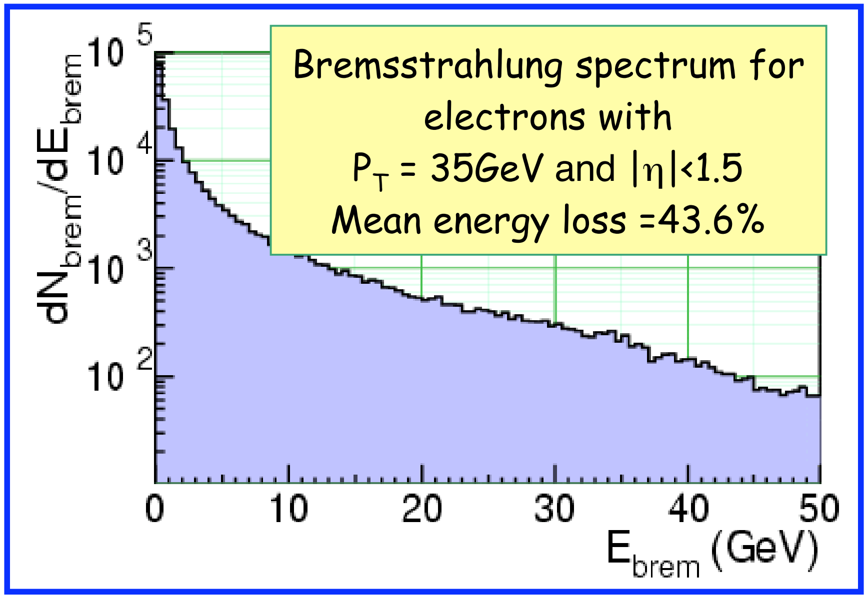


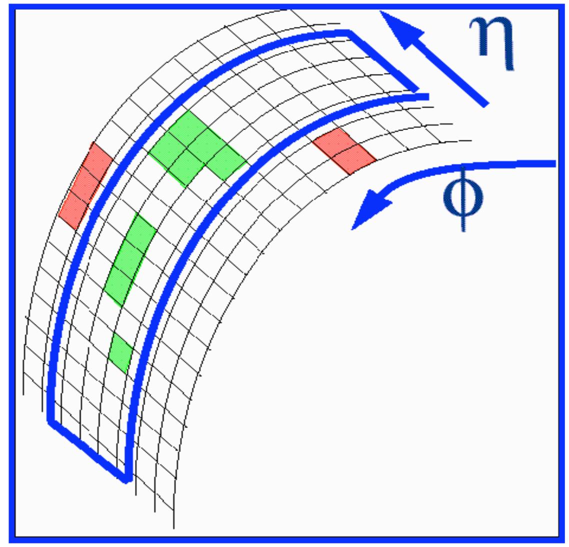
Unusually large amount of material in front of Calorimeter (0.4 to 1.4 X_0) from Silicon tracker (c.f. BaBar 0.4 X_0)

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

Significantly degrades resolution and Efficiency to reconstruct good e/γ

Energy clustering/bremsstrahlung



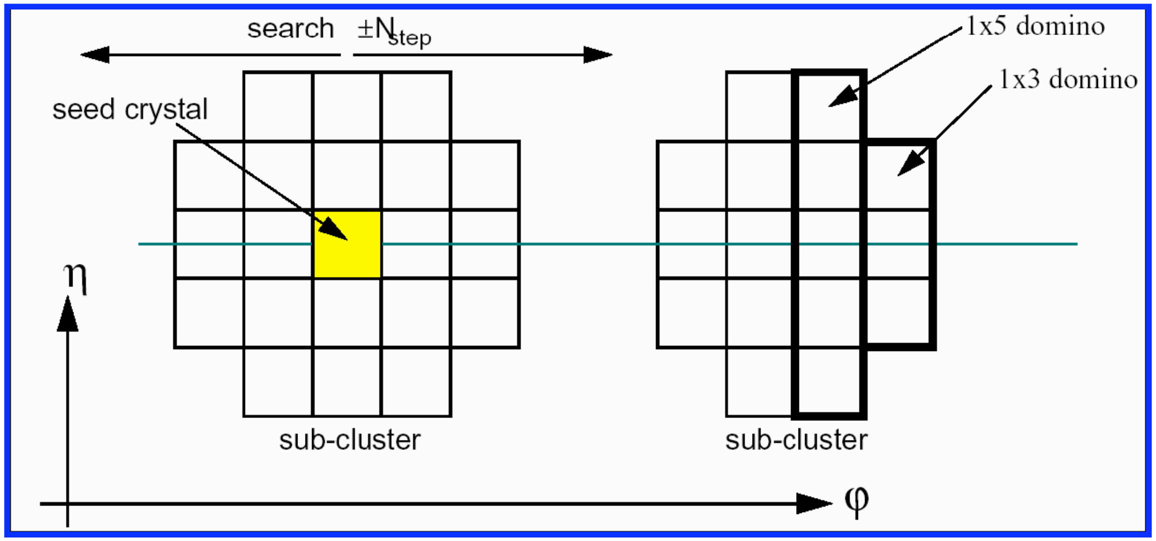


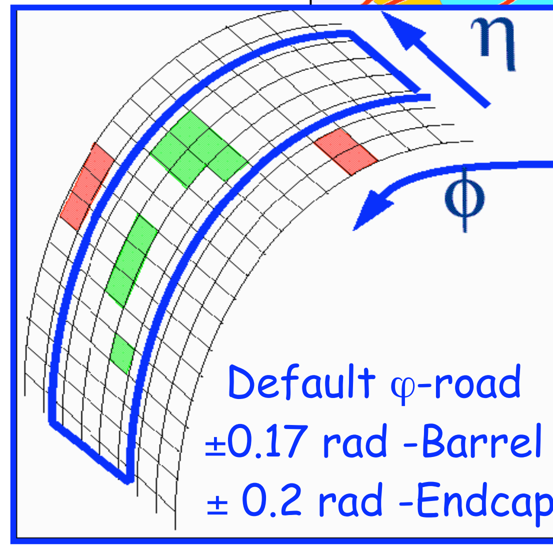
Electrons brem in tracker material and bend in ϕ in 4T mag field so cluster energy is distributed in ϕ.

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

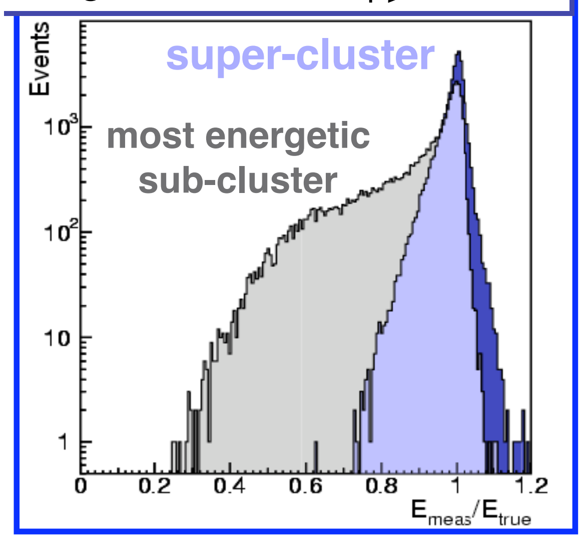
Bremsstrahlung recovery in clustering

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



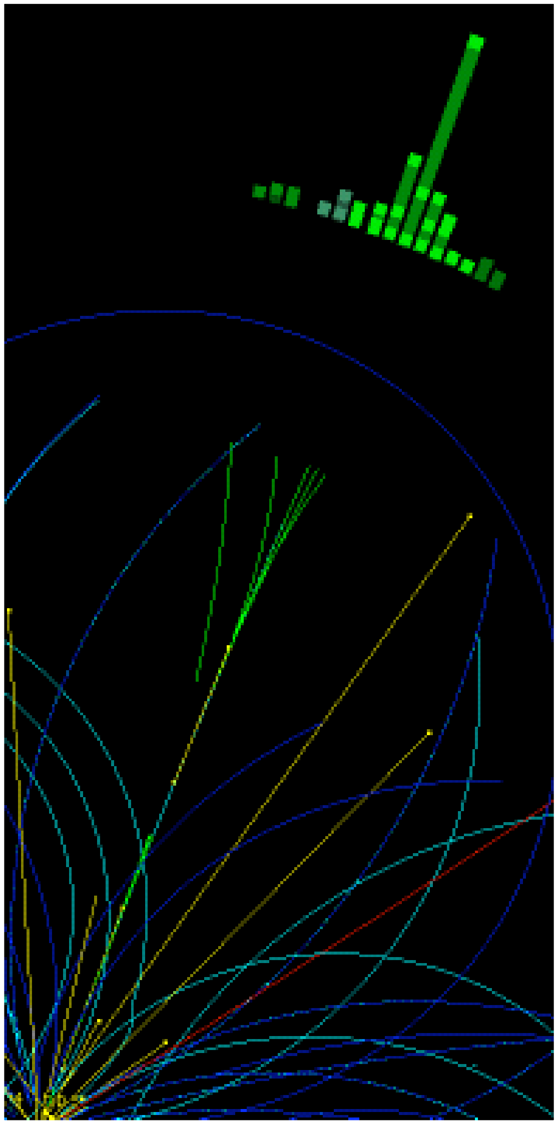


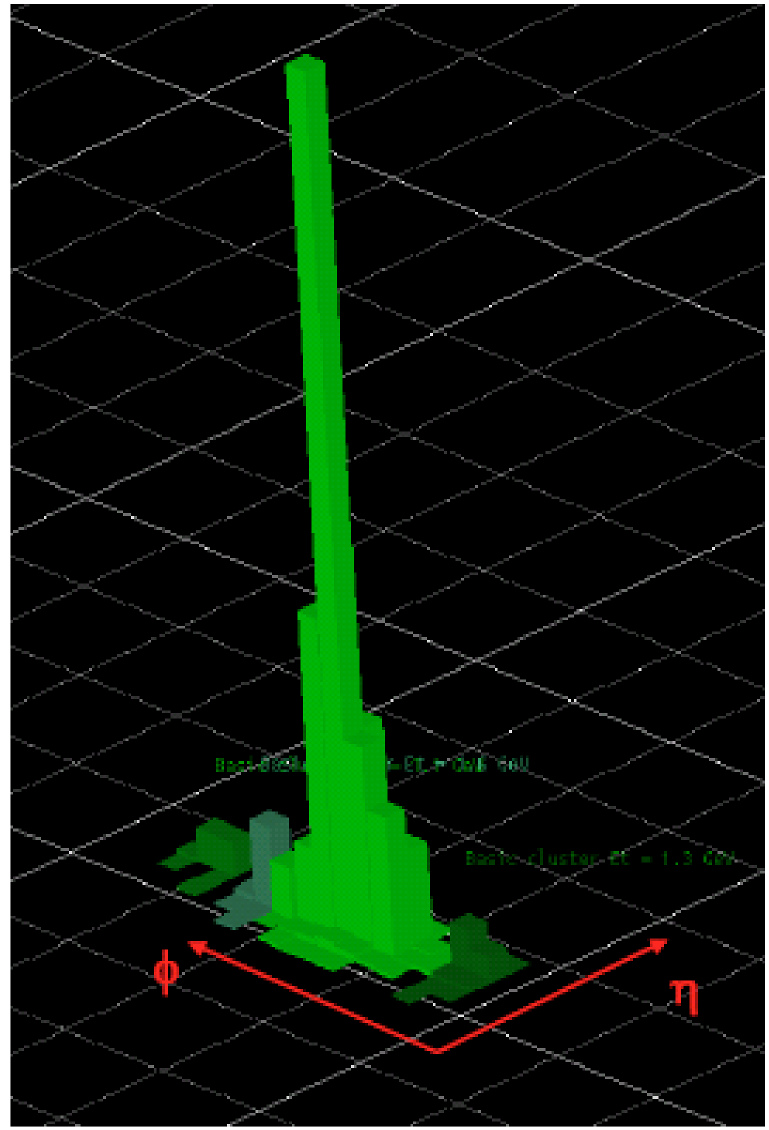
Single electrons $P_{T} > 30GeV$



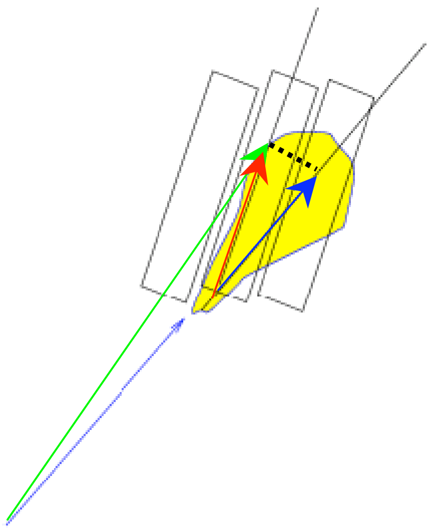
Recover Brem by making "superclusters" which are a cluster of clusters in ϕ

Example of an Electron reconstructed in ECAL



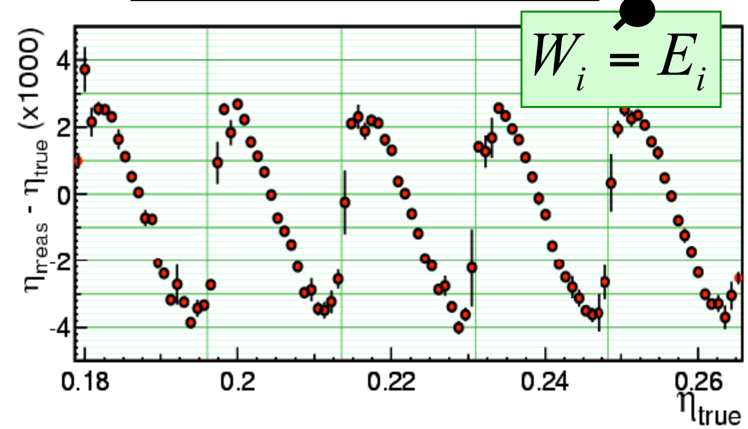


Cluster position

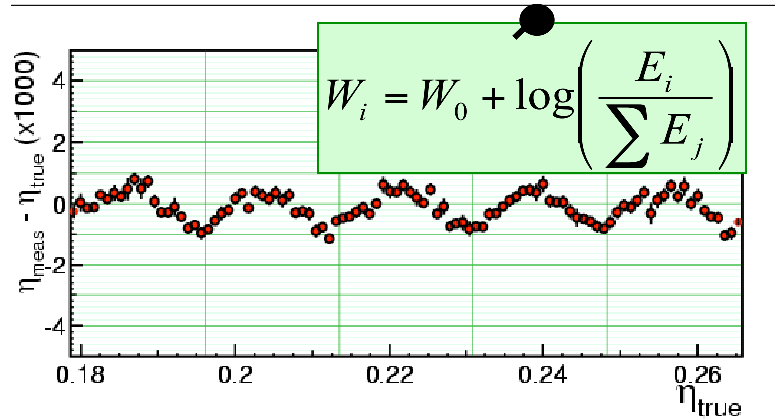


Off-pointing Xstals

Cluster position



$$W_i = E_i$$



$$W_i = W_0 + \log\left(\frac{E_i}{\sum E_j}\right)$$

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

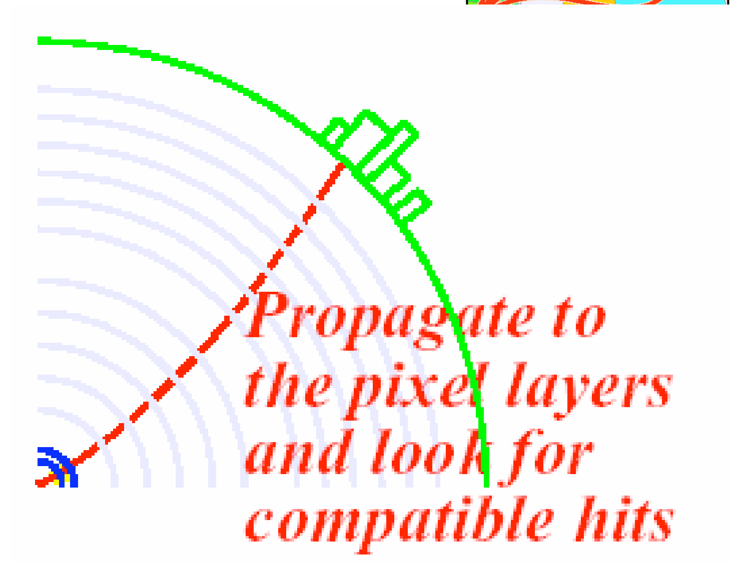
2. Use primary vertex to construct a presumed trajectory between SuperCluster and Vertex

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

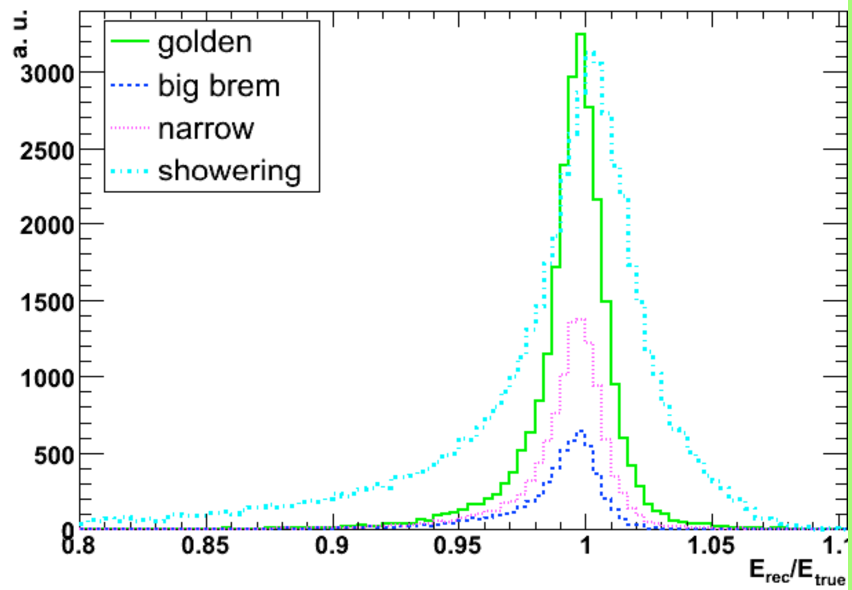


Electron tracking uses Gaussian Sum Filter (GSF) which takes into account the effect of the interaction of the material in the tracker on the trajectory

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

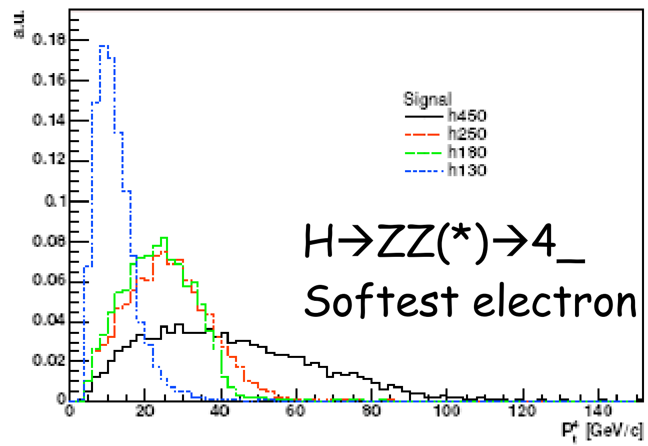


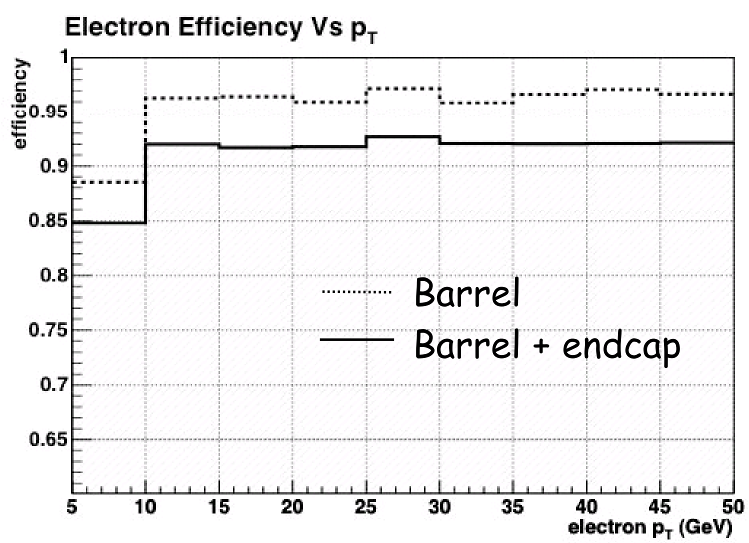
About 60% of electrons between 5 and 100 GeV are in class 4 (Bad)

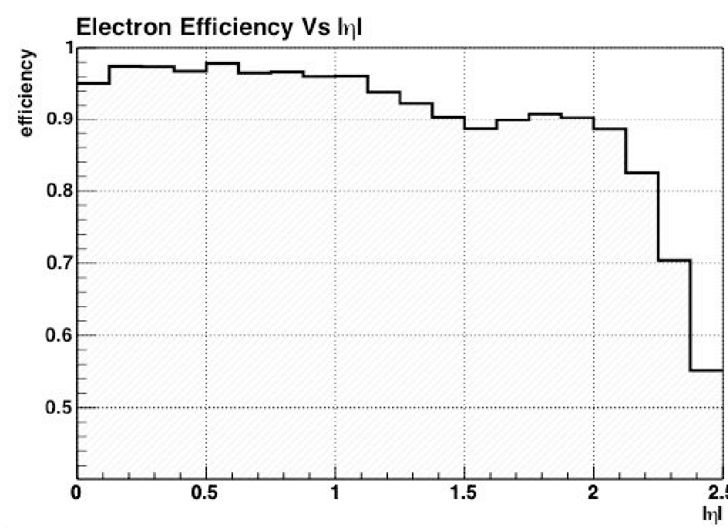
Electron efficiency in a prototype analysis from Phys TDR

H→ZZ(*)→4_

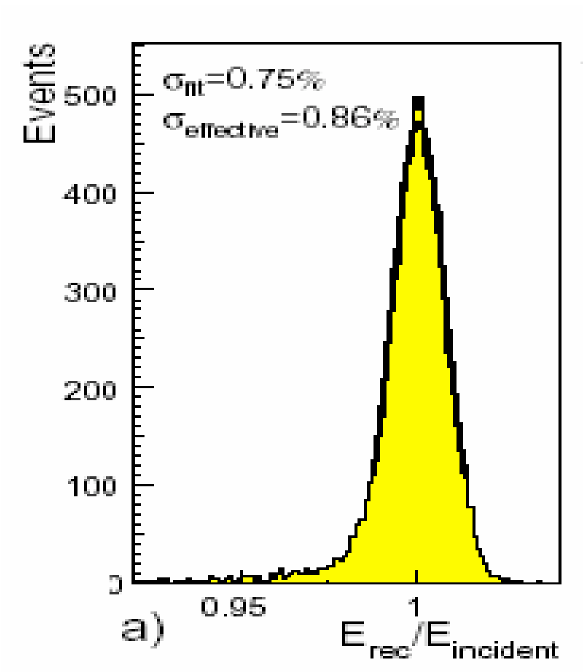
Using all classes of electron

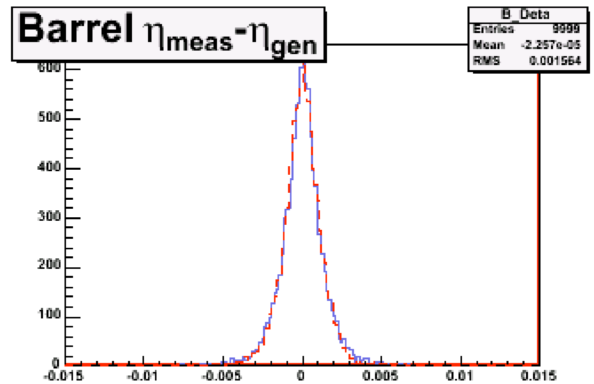


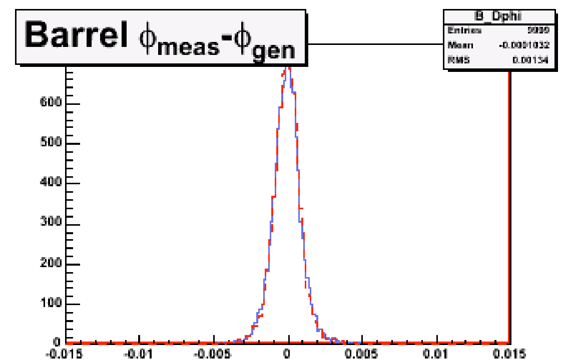




Photon Reconstruction - Unconverted Photons



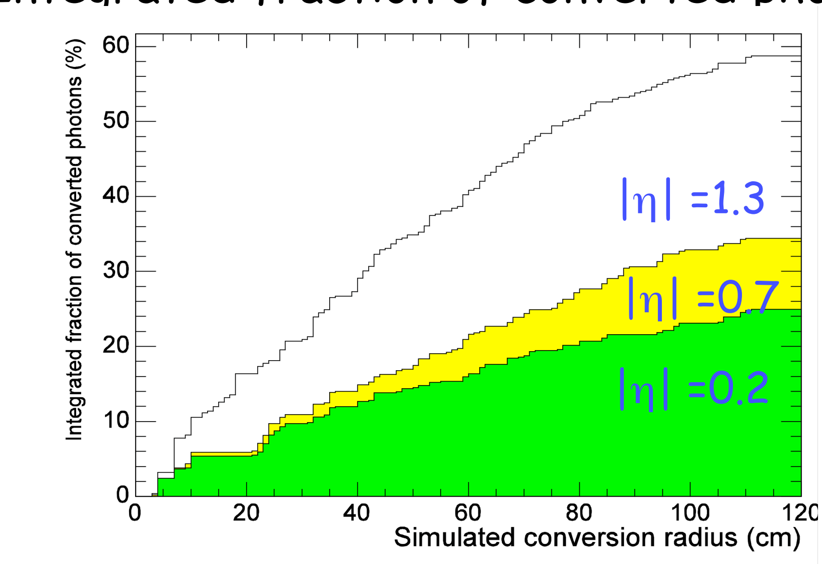




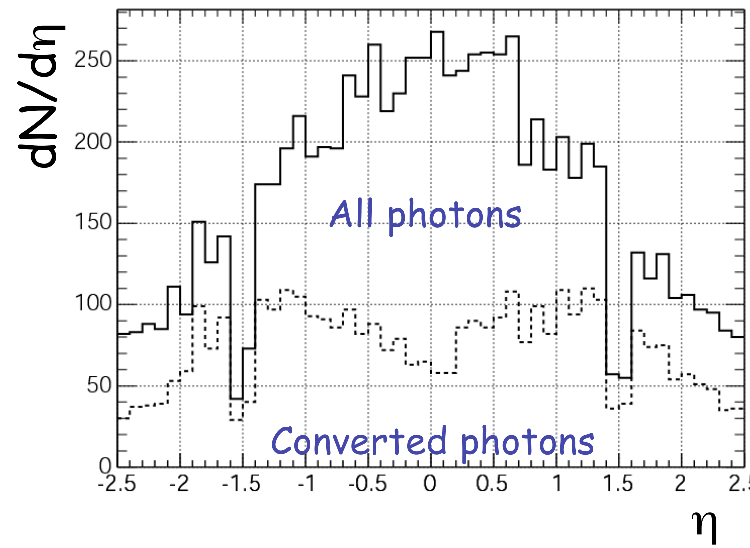
Unconverted photons are easily reconstructed with good Energy and position Resolution but a significant fraction convert due to material

Photon Recontruction

Integrated fraction of converted photons (%)



Simulated photons from H→ γγ



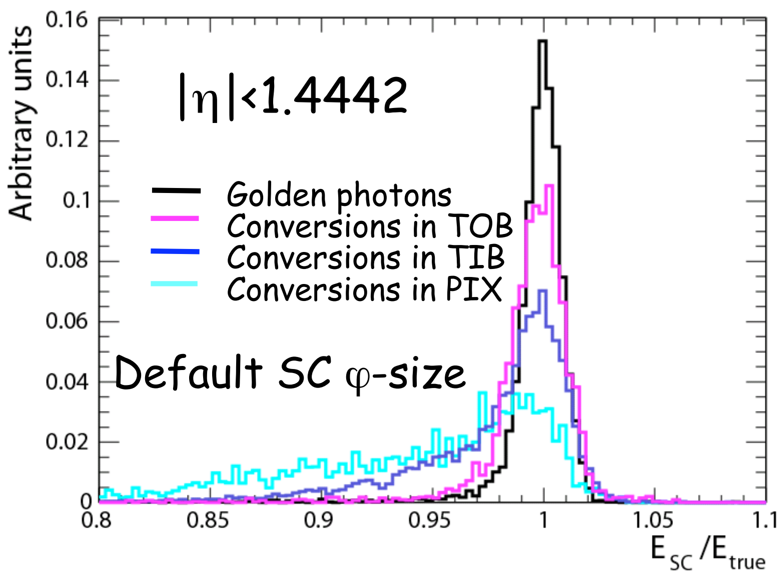
~44% of photons from H→ γγ events convert

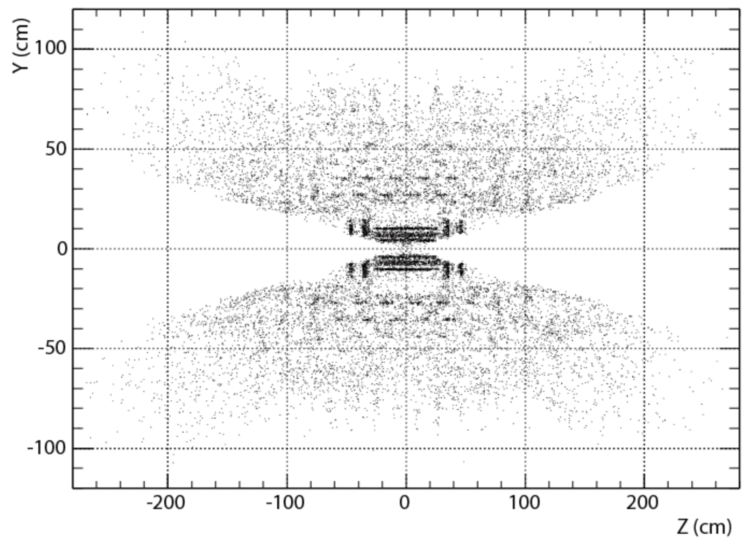
Of all conversions

- ~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





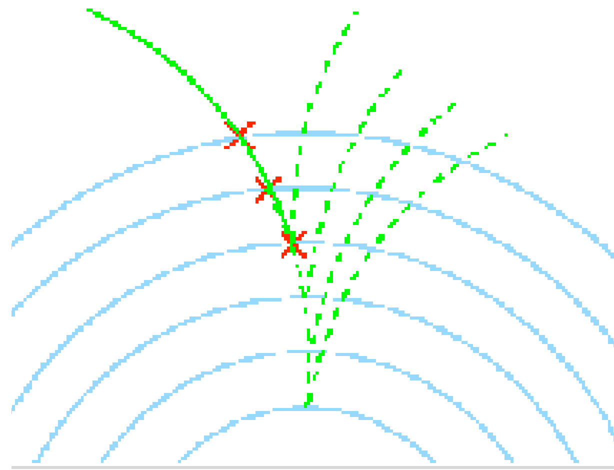
Early conversions (near vertex) degrade resolution significantly if use standard clustering algorithm. Need conversion finder.

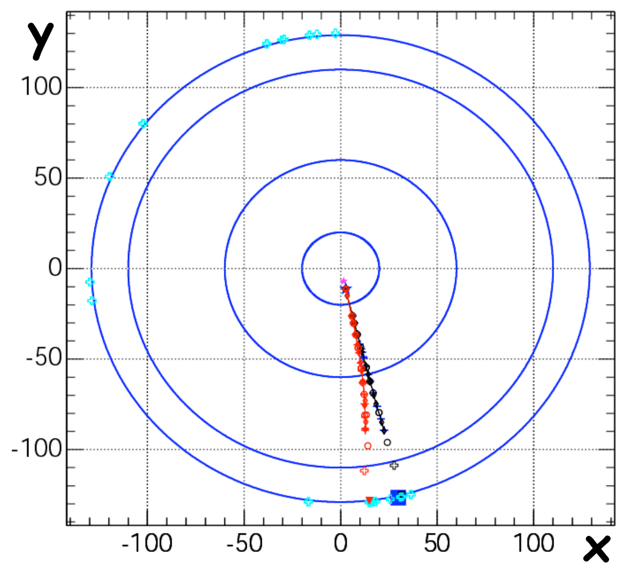
Finding Conversions

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 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

Algorithms are currently being ported to CMSSW and validated
(LPC egamma group heavily involved in this)

For new collaborators it is recommended that you wait for CMSSW Implementation to be completed (~2 months) before trying to use electrons or photons. Though tutorials to make clusters are available. Overhead to learn ORCA is not worth the effort.

LPC e/γ group

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

Institutes involved: Caltech,Cornell,UC Davis,KSU,FSU,Notre Dame,
Minnesota,Virginia,Yale

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

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

Also: CERN egamma meetings take place biweekly Wednesday at 4pm CST
(Contact: C.Seez & Y. Sirois)

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)