8.882 LHC Physics

Experimental Methods and Measurements

Detectors: Electrons and Particle Id

[Lecture 12, March 16, 2009]

Organization

Project 1: Charged Track Multiplicity

- no hand-ins as of yet

Project 2: Upsilon Cross Section

- all material is on the Web
- is due April 9 (in 3.3 weeks)
- please, try to find a partner if you do not yet have one

CP Travel plans

- at MIT in the flesh Wednesday/Friday
- April 8 - May 13 as well: find alternative time for Apr 8

Lecture Outline

Electron Identification

- electromagnetic calorimetry

Particle identification systems

- dE/dx in drift chamber
- TOF – Time-Of-Flight detectors
- RICH – Ring Imaging CHerenkov detectors
- DIRC – Detection of Internal Reflected Cherenkov light

Why Muons and Electrons?

Leptons

- rare in *pp* (<1% of the tracks), often related to very interesting physics processes
- taus special case (m = 1.777 GeV, $c\tau$ = 87.11 μm)
  - decay well before they reach the silicon detector, lifetime more then a factor of five smaller then for *B* mesons
  - can also produce hadrons in decay, more difficult to identify
  - always involve neutrino in decay (incomplete reconstruction)
- muons have very characteristic signature
  - penetrate the calorimetry, are detected in the muon chambers
  - leave minimally ionizing signature
- electrons have very characteristic signature
  - maximal ionization in tracking system
  - get absorbed completely in ECAL no signature in the HCAL
  - shower shape in ECAL is short and broad

Why Electrons/Photons at the LHC?

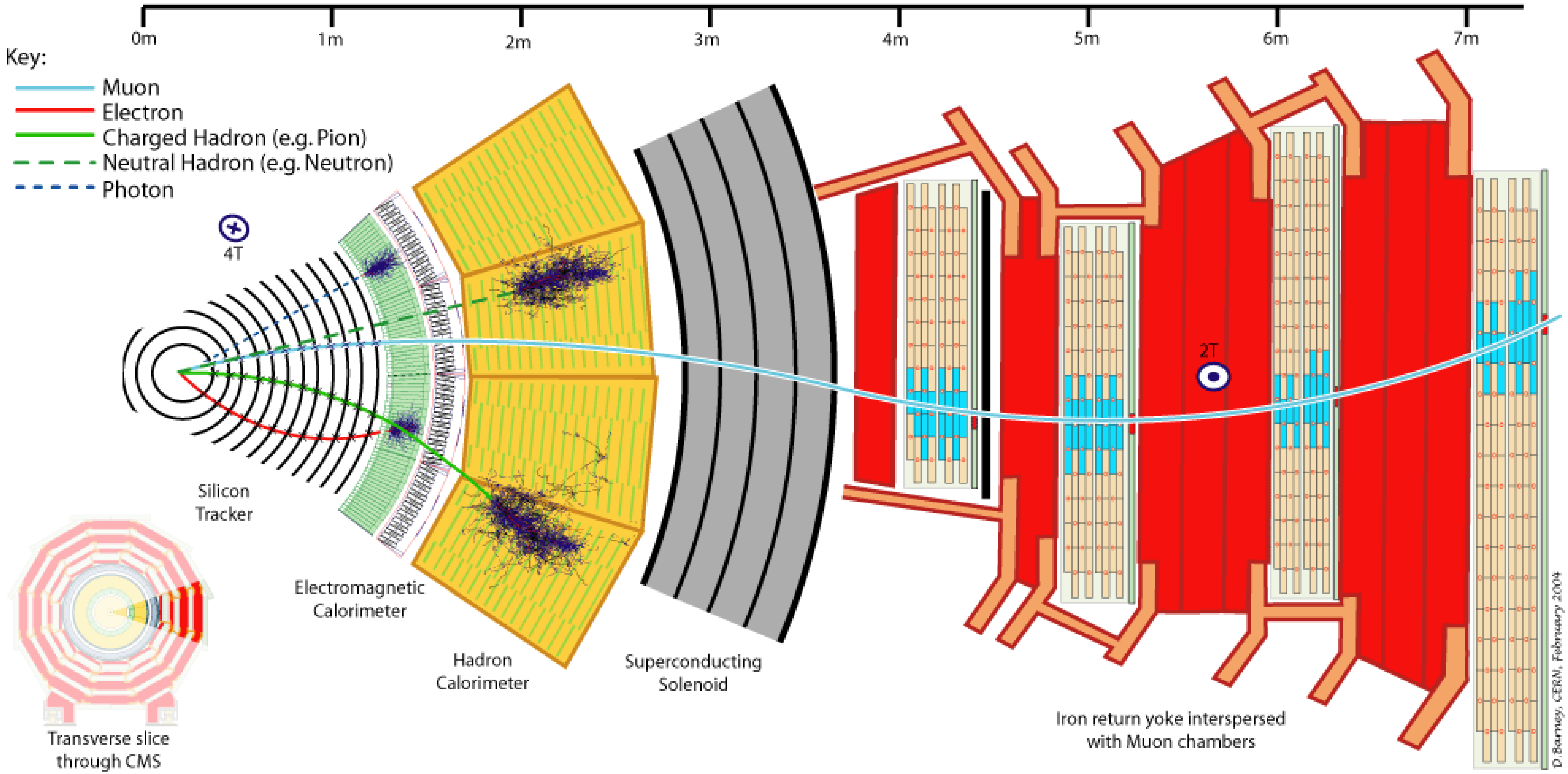
Physics opportunities

- very low Higgs masses (below 130 GeV): $H \rightarrow \gamma\gamma$
- most of other range: $H \rightarrow ZZ(^*) \rightarrow e^+e^- \, (\mu^+\mu^-/e^+e^-)$
- Z' decaying to e^+e^- final state, masses as high as possible

Requirements for the ECAL at LHC

- excellent resolution over very large dynamic range
  - CMS decided for crystal calorimeter
  - high light output
- capable of dealing with dense particle distributions
  - dense material to quickly contain shower
  - fine granularity
- capable to resist high radiation, maintaining performance
  - material research necessary

Particle Identification



Electron Signature: track + all energy in ECAL

- backgrounds: photons plus random track
- neutral pion: decays to 2 photons (shower shape)

Compare Electron and Muon Id

Muon identification

- by definition background is quite low
- few particles arrive in muon system: gold plated

Electron/Photon identification

- very large number of particles
- tracking essential (reject/select photons)
- electromagnetic calorimetry essential (reject neutral pions)
- hadron calorimetry essential (reject other hadrons)
- intrinsically more complex then muons but still very important

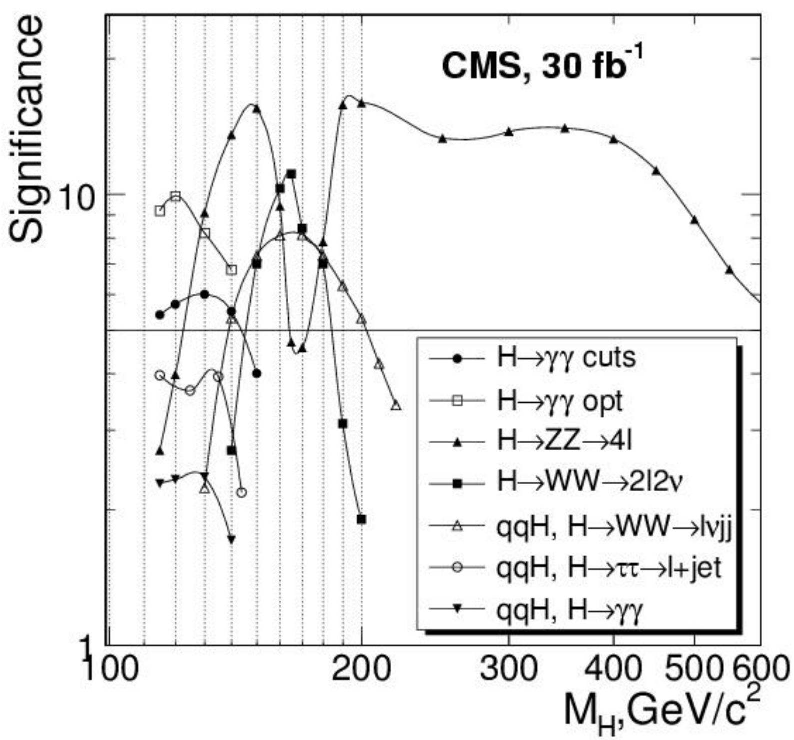
Higgs Mass Drives ECAL Design

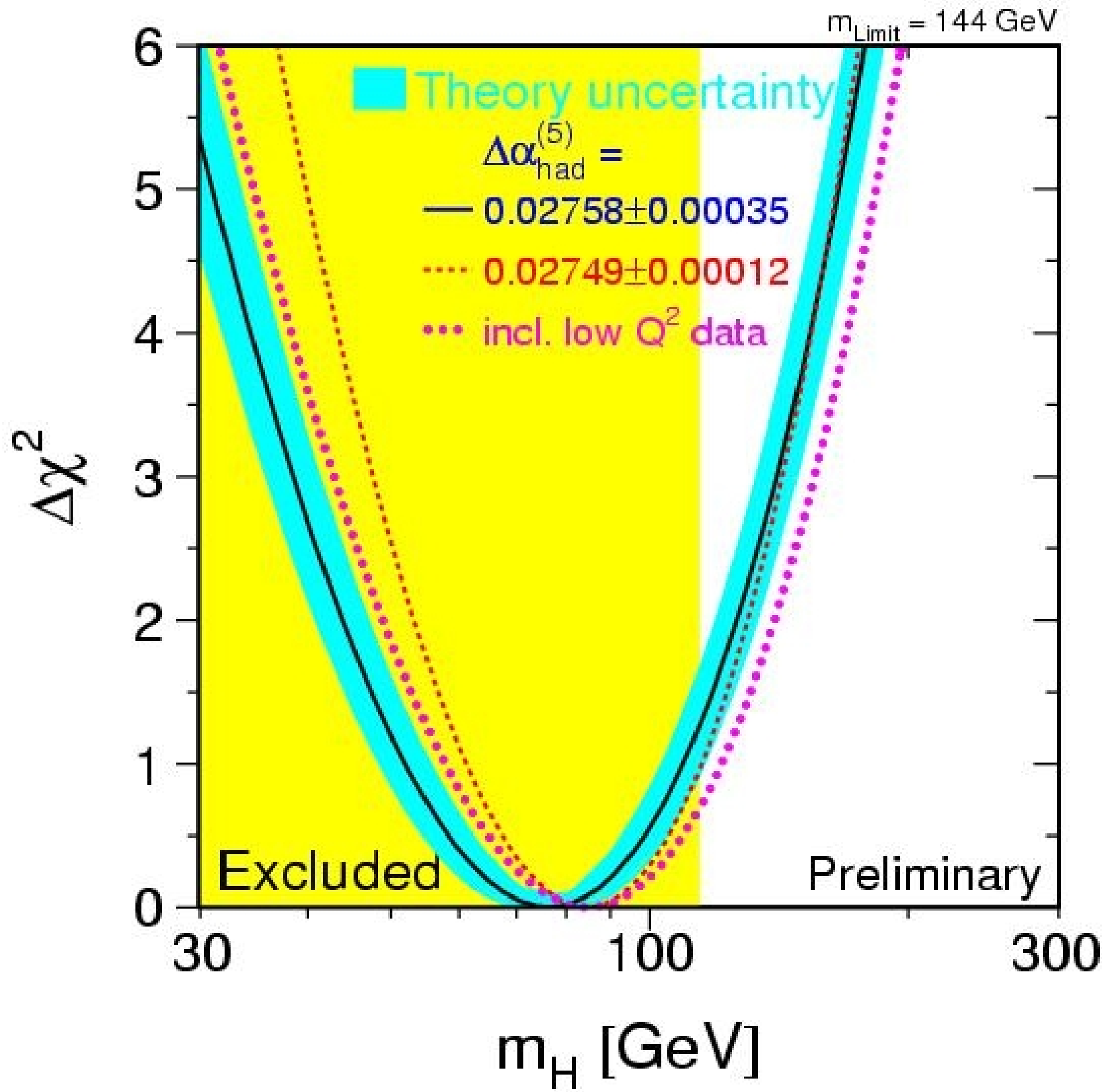
Electroweak data

- Higgs < 144 GeV

Direct searches

- Higgs > 114 GeV





ECAL Performance

Resolutions

- ECAL benchmark: mass resolution of $H \rightarrow \gamma\gamma$ process

$$\frac{\sigma_M}{M} = \frac{1}{2}\left(\frac{\sigma_{E_1}}{E_1} \oplus \frac{\sigma_{E_2}}{E_2} \oplus \frac{\sigma_\theta}{\tan\theta/2}\right) \quad \text{with} \quad \oplus = \text{quadr.sum}$$

Components: energy and angular resolutions

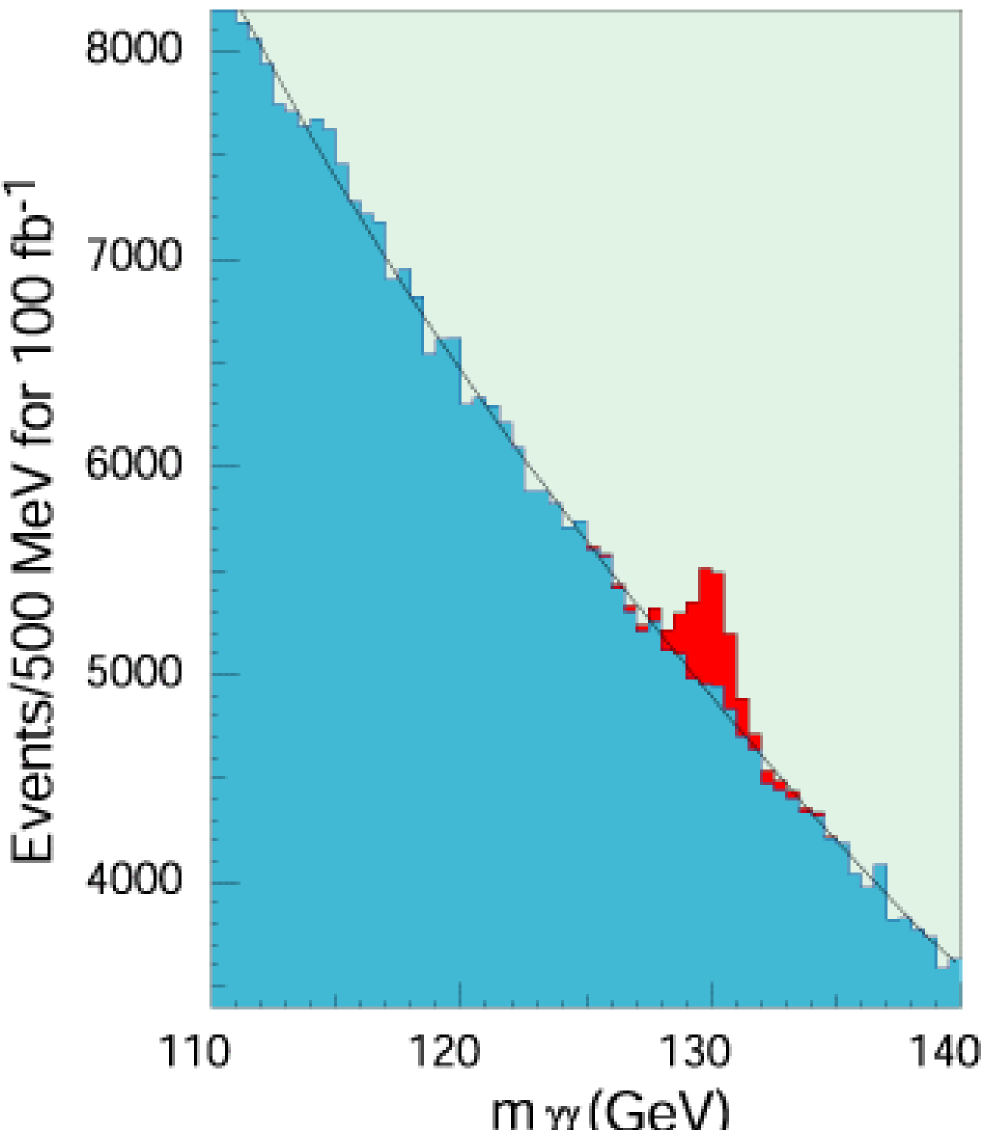
- angular resolution can be achieved without too much problems: more about this later
- energy resolution more complex

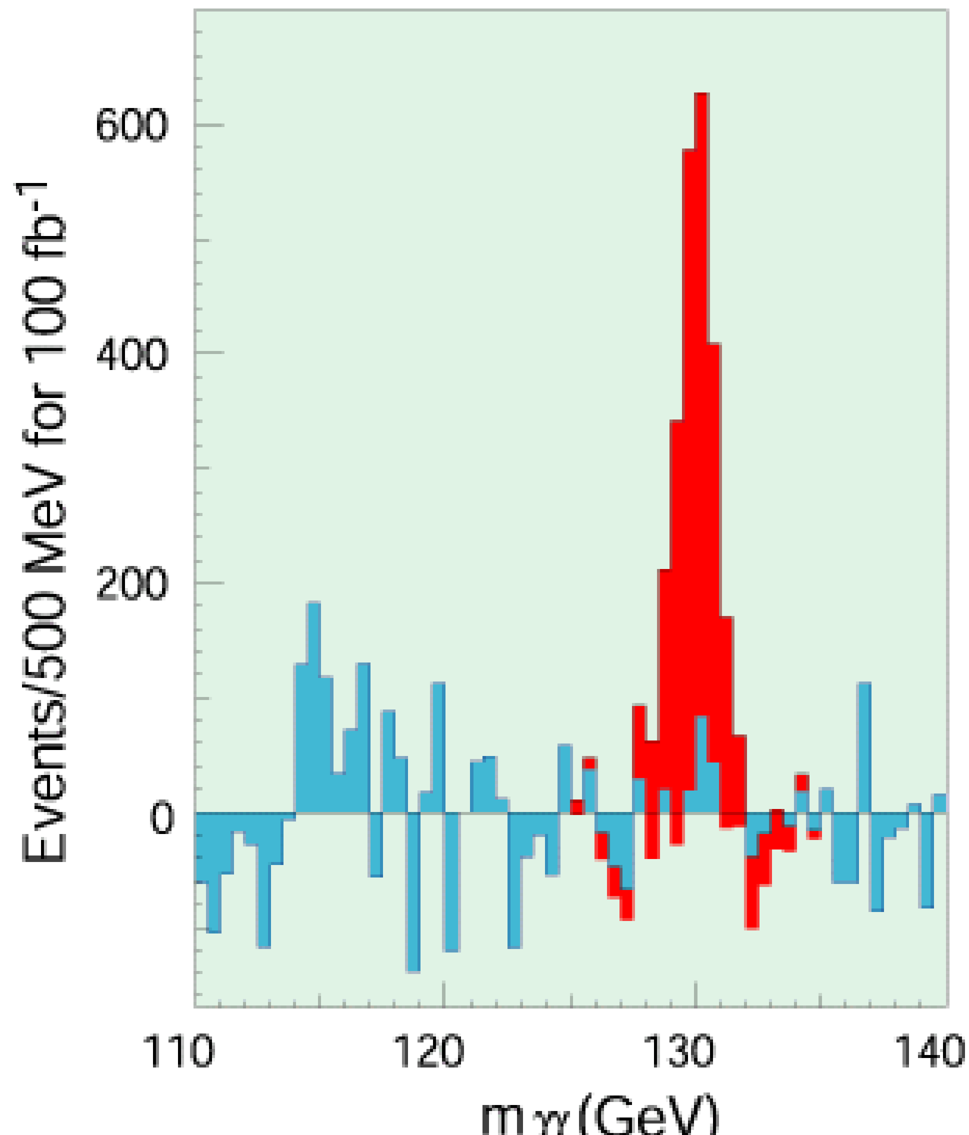
$$\frac{\sigma_E}{E} = \left(\frac{a}{\sqrt{E}} \oplus b \oplus \frac{\sigma_N}{E}\right)$$

a – stochastic proportionality factor
b – constant term (calibration, non-uniformities etc.)
σ_N – noise equivalent (electronics, pileup energy)

- a<10% difficult with sampling (pushes precise geometry)
- a=2% with active calorimeters (requires b<0.5%, tricky)

Higgs to gamma gamma



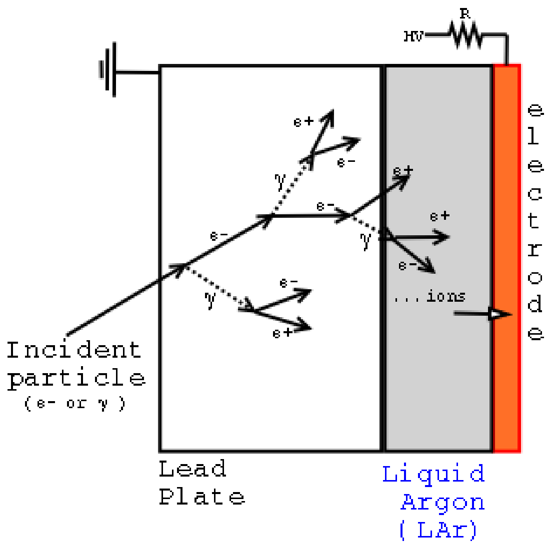


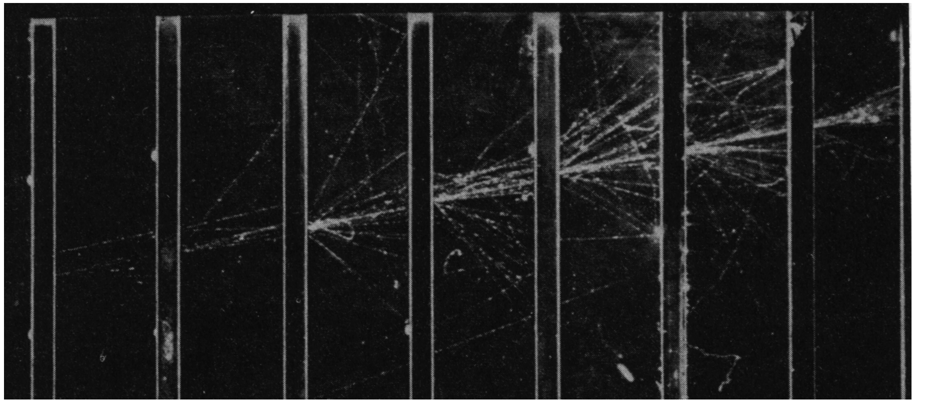
the narrower the mass peak the cleaner to separate

Electromagnetic Calorimeters

Sampling calorimeters

- Atlas: liquid Argon, accordion geometry

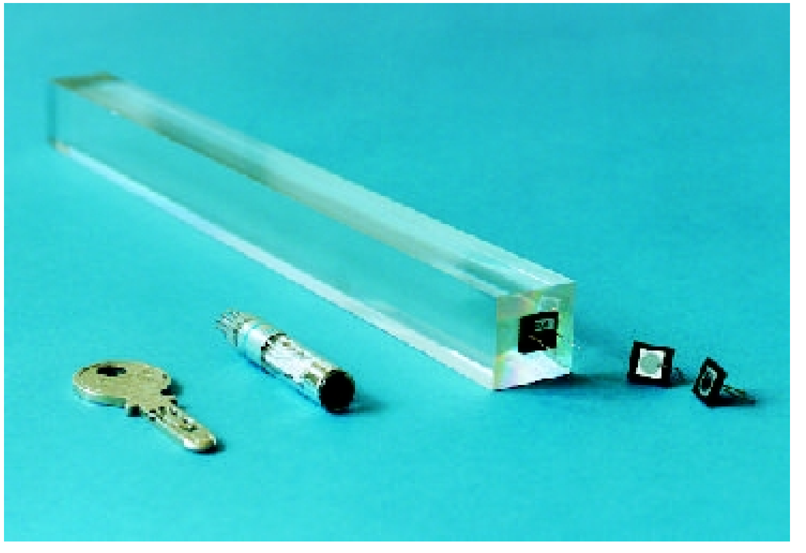




Cloud chamber with lead absorbers

Fully active calorimeters

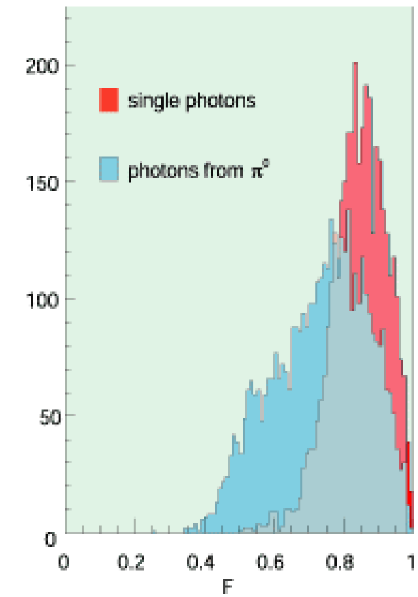
- CMS: $PbWO_4$ crystal calorimeter
- more sensitive to radiation
- online laser monitoring system
- also called homogeneous

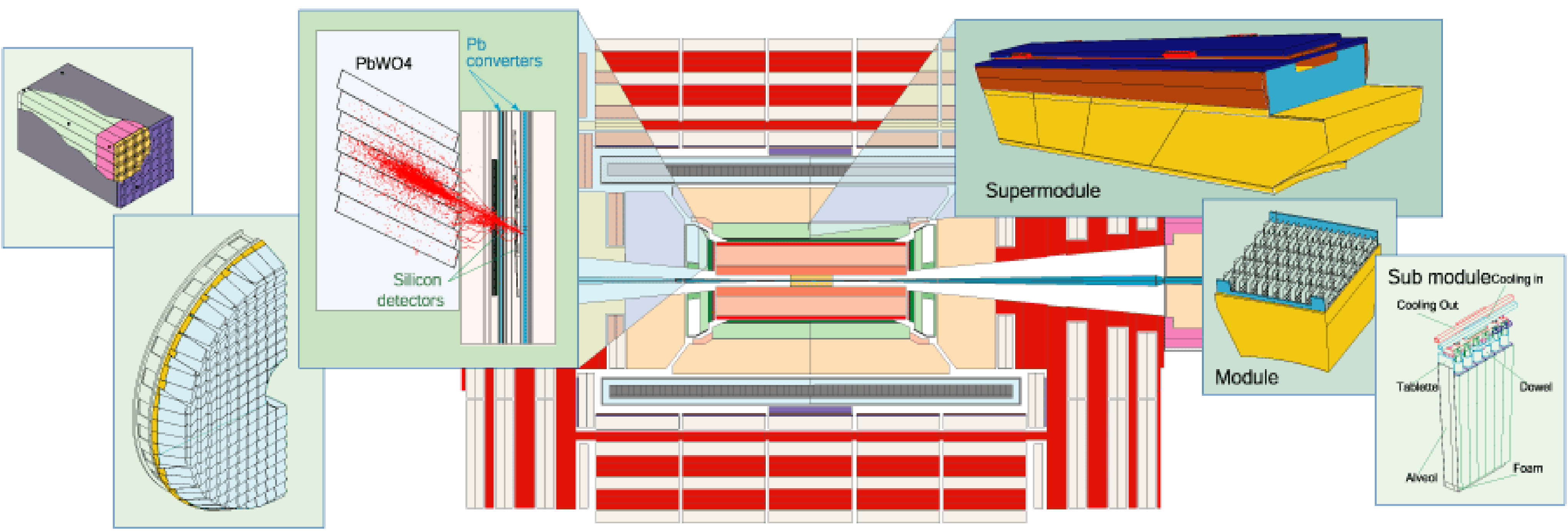


ECAL Layout in CMS

CMS choice

- crystal calorimeter: $PbWO_4$ (compact, fast, doable)
- $PbWO_4$ is optimal material, next page
- endcap has additional pre-shower: reject neutral pions as photon background





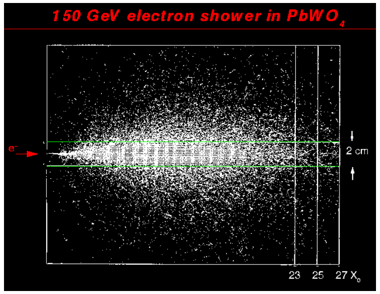
Crystal Comparison

Table 1.1: Comparison of properties of various crystals

	NaI(Tl)	BGO	CSI	BaF_2	CeF_3	$PbWO_4$
Density [g/cm^3]	3.67	7.13	4.51	4.88	6.16	8.28
Radiation length [cm]	2.59	1.12	1.85	2.06	1.68	0.89
Interaction length [cm]	41.4	21.8	37.0	29.9	26.2	22.4
Molière radius [cm]	4.80	2.33	3.50	3.39	2.63	2.19
Light decay time [ns]	230	60 300	16	0.9 630	8 25	5 (39%) 15 (60%) 100 (1%)
Refractive index	1.85	2.15	1.80	1.49	1.62	2.30
Maximum of emission [nm]	410	480	315	210 310	300 340	440
Temperature coefficient [%/°C]	~0	–1.6	–0.6	–2/0	0.14	–2
Relative light output	100	18	20	20/4	8	1.3

Moliere radius $R_M = 0.265\, X_0\, (Z+1.2)$

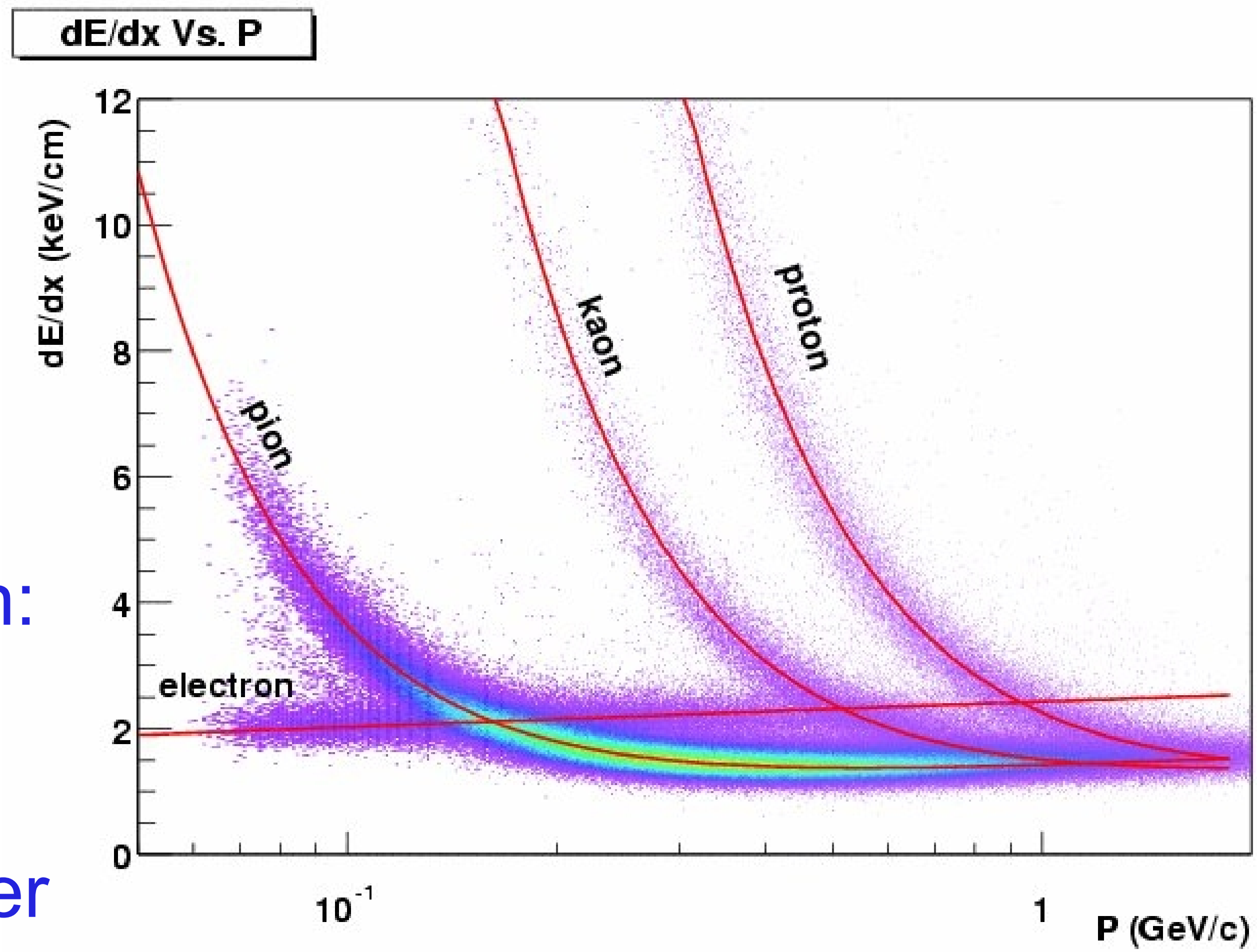
- 95% transverse shower contained in 2 R_M



Energy Loss in Trackers

Bethe Bloch

- depends on β only
- given *dE/dx* and momentum *p* determines and β thus the mass, *m*
- after mass correction: universal curve

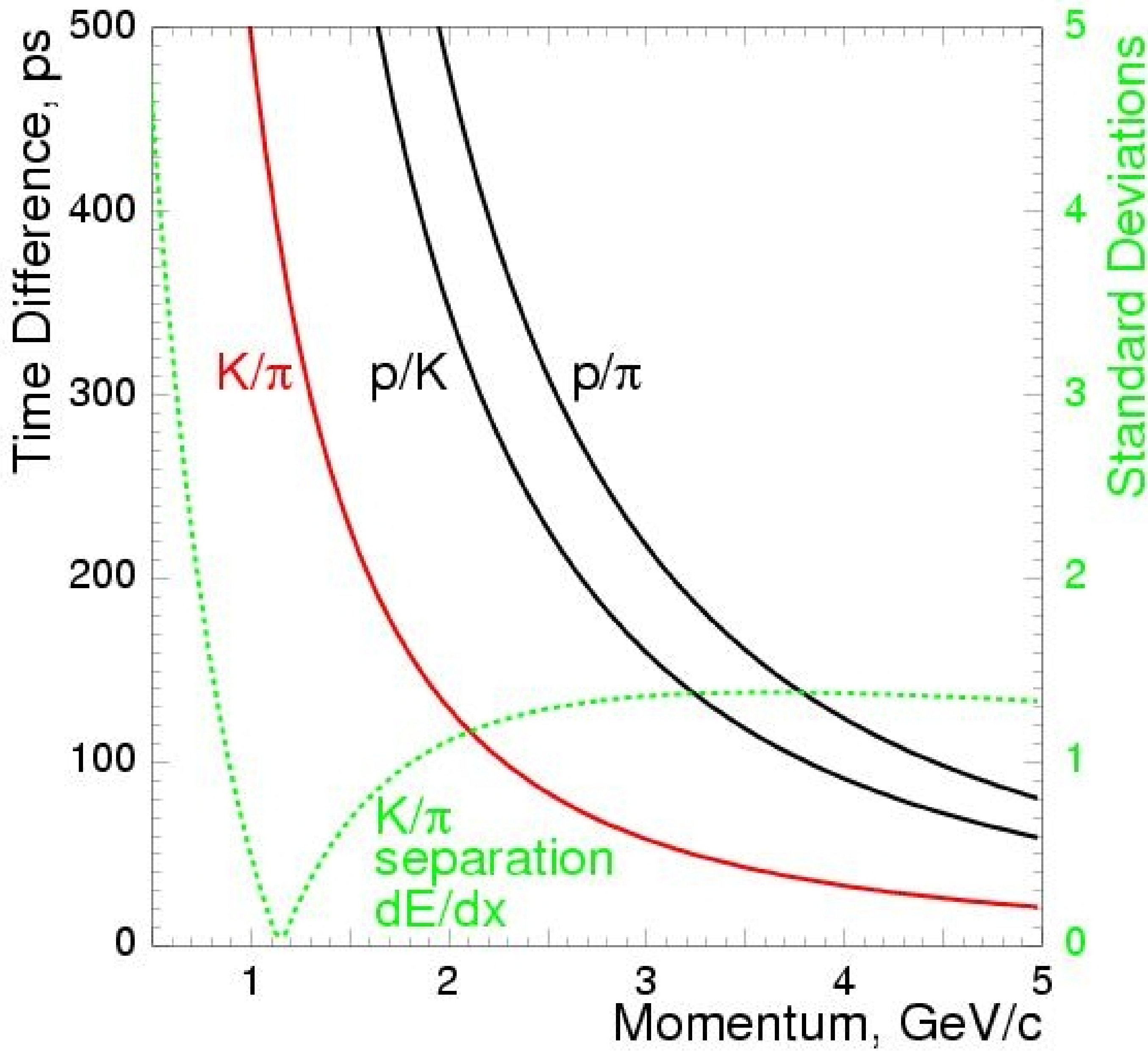


How to measure?

- pulse height in tracker
- lots of corrections ...

$$\frac{dE}{dx} = -4\pi N_A r_e^2 c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2}{I^2}T^{\max} - \beta^2 - \frac{\delta}{2}\right]$$

Time-Of-Flight Detectors



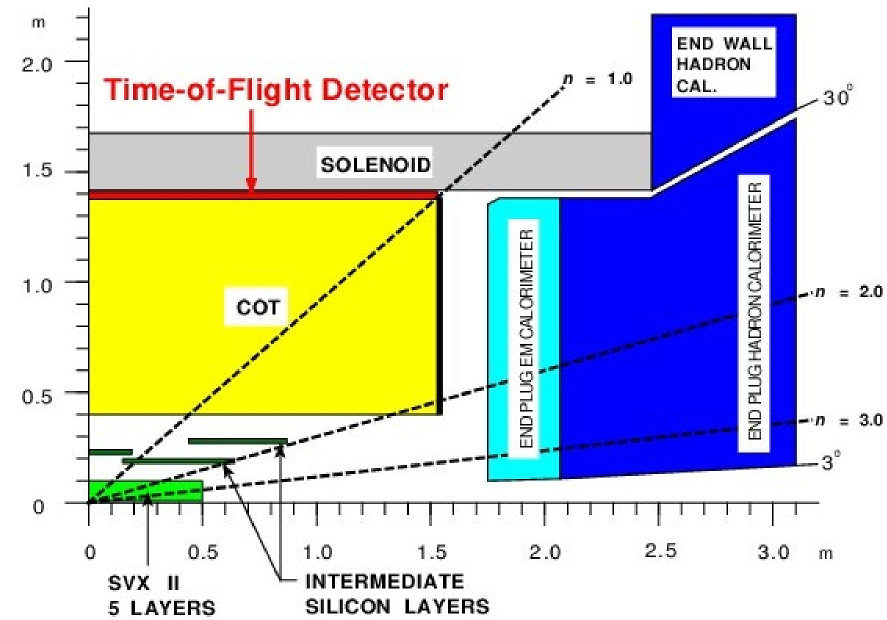
Principle

- arrival depends on velocity
- *p* + *v*: *m*

CDF: Time-Of-Flight Detector

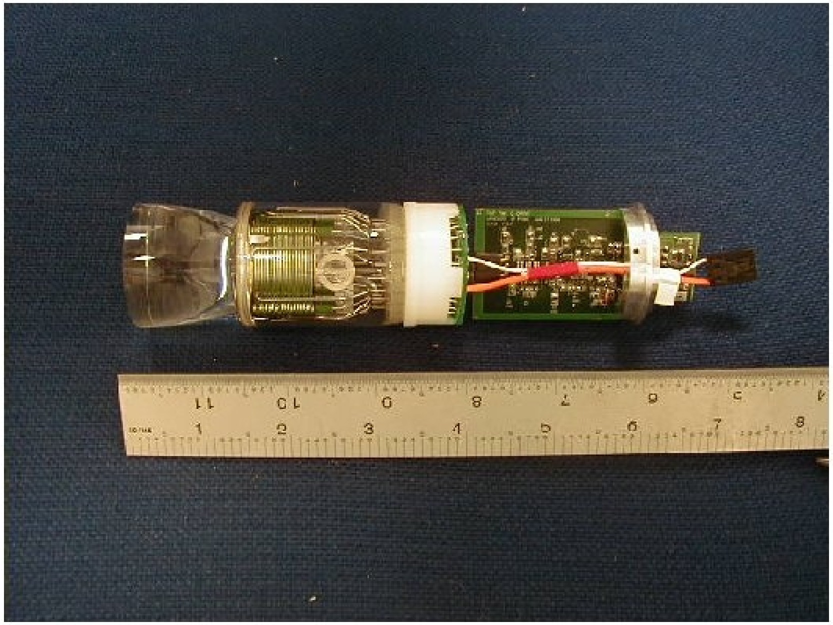
Characteristics of the system

Scintillator Bars	216 (1.7°)
Radius	140 cm
Bar Cross Section	4×4 cm^2
Bar Length Bar	300 cm
Coverage	$\|\eta\| < 1$
Scintillator Material	Bicron–408
Photomultipliers	Hamamatsu
Readout of the Bars	two–sided
Design Resolution	100 ps



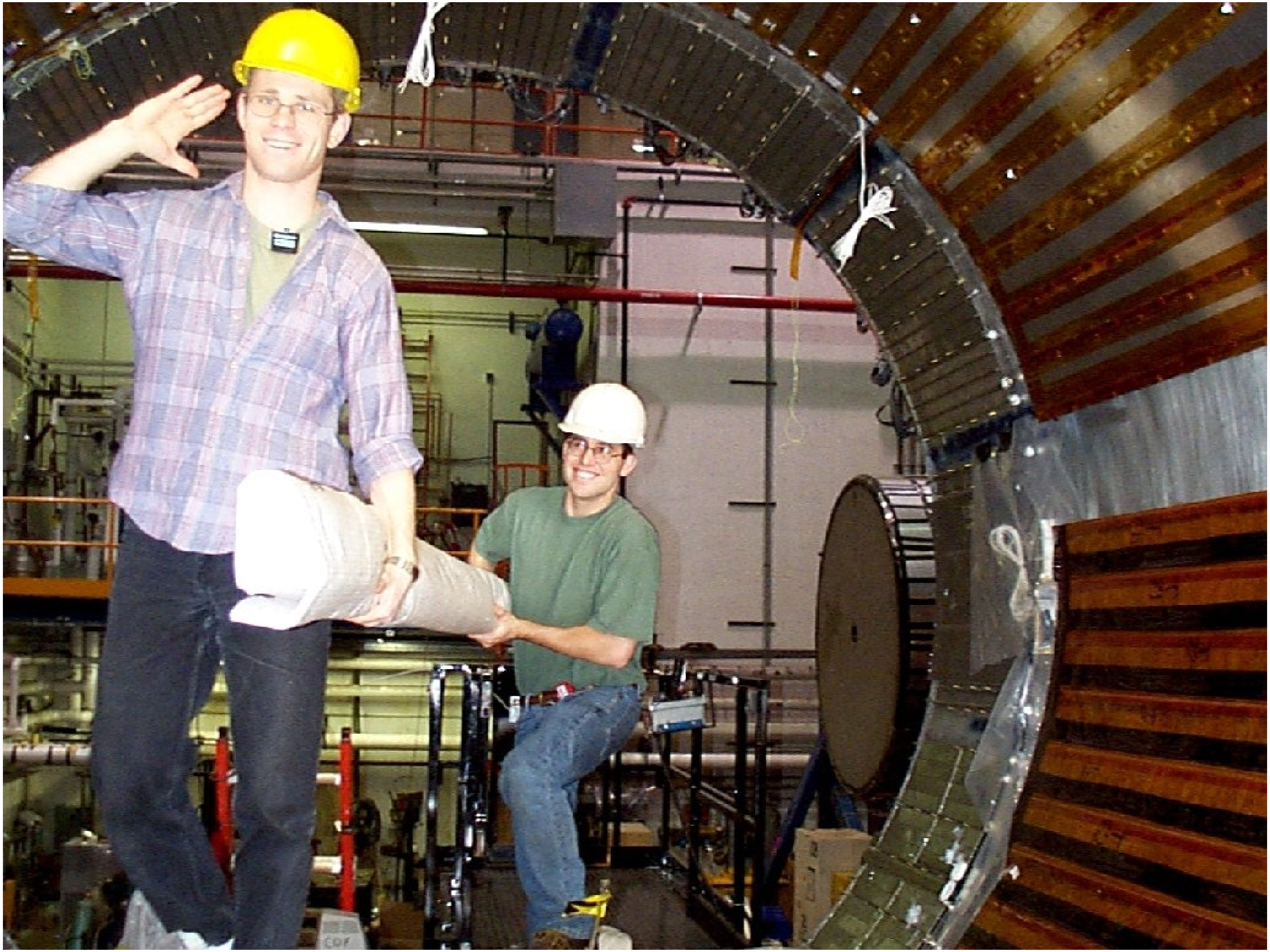
Hamamatsu photomultiplier

Type	fine mesh, R7761
Stages	19
Geometry	1.5 inch diam.



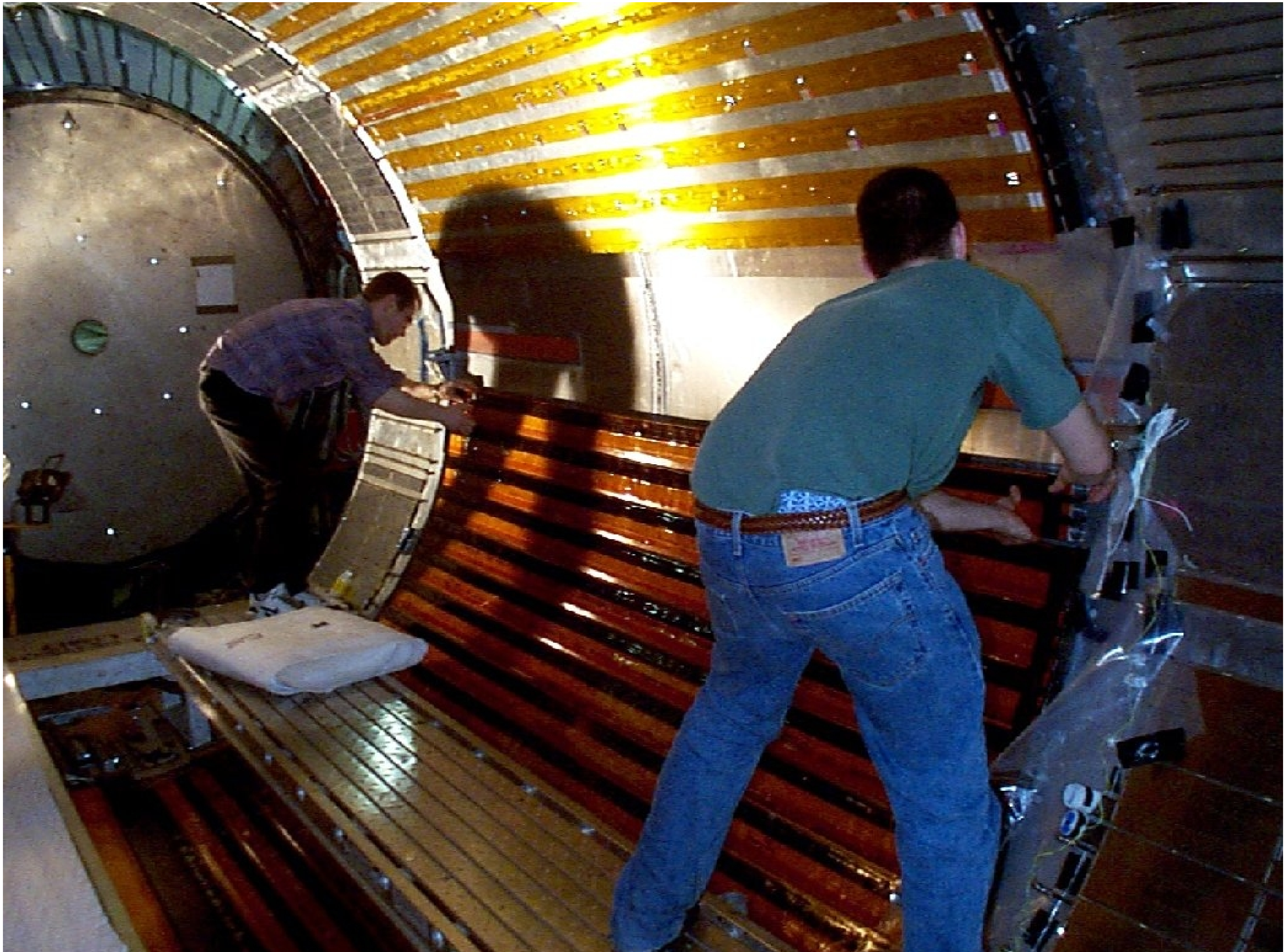
PMT operates in 1.4 T B field

Bar Arrive at the Bore

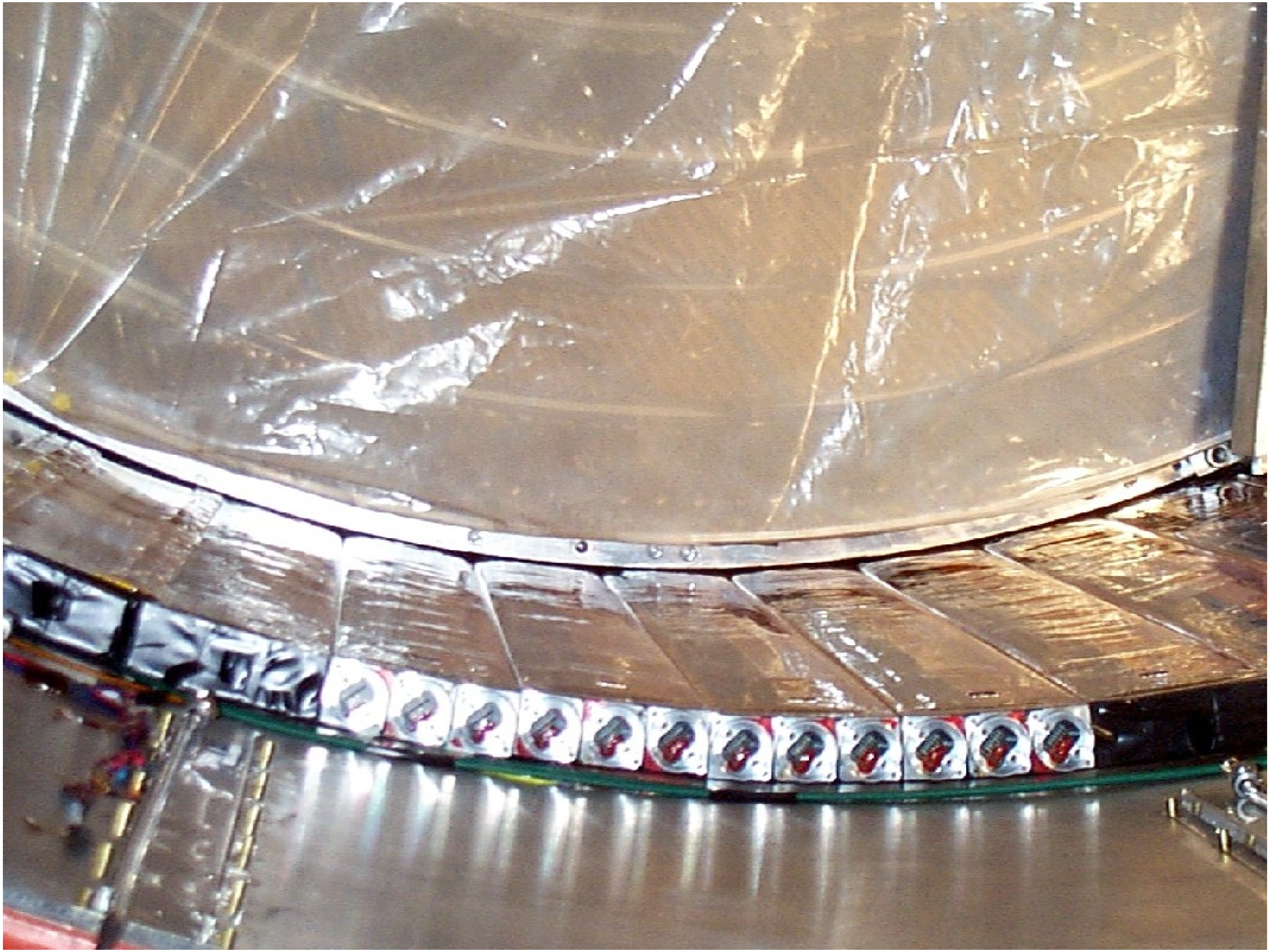


Bar Unpacking

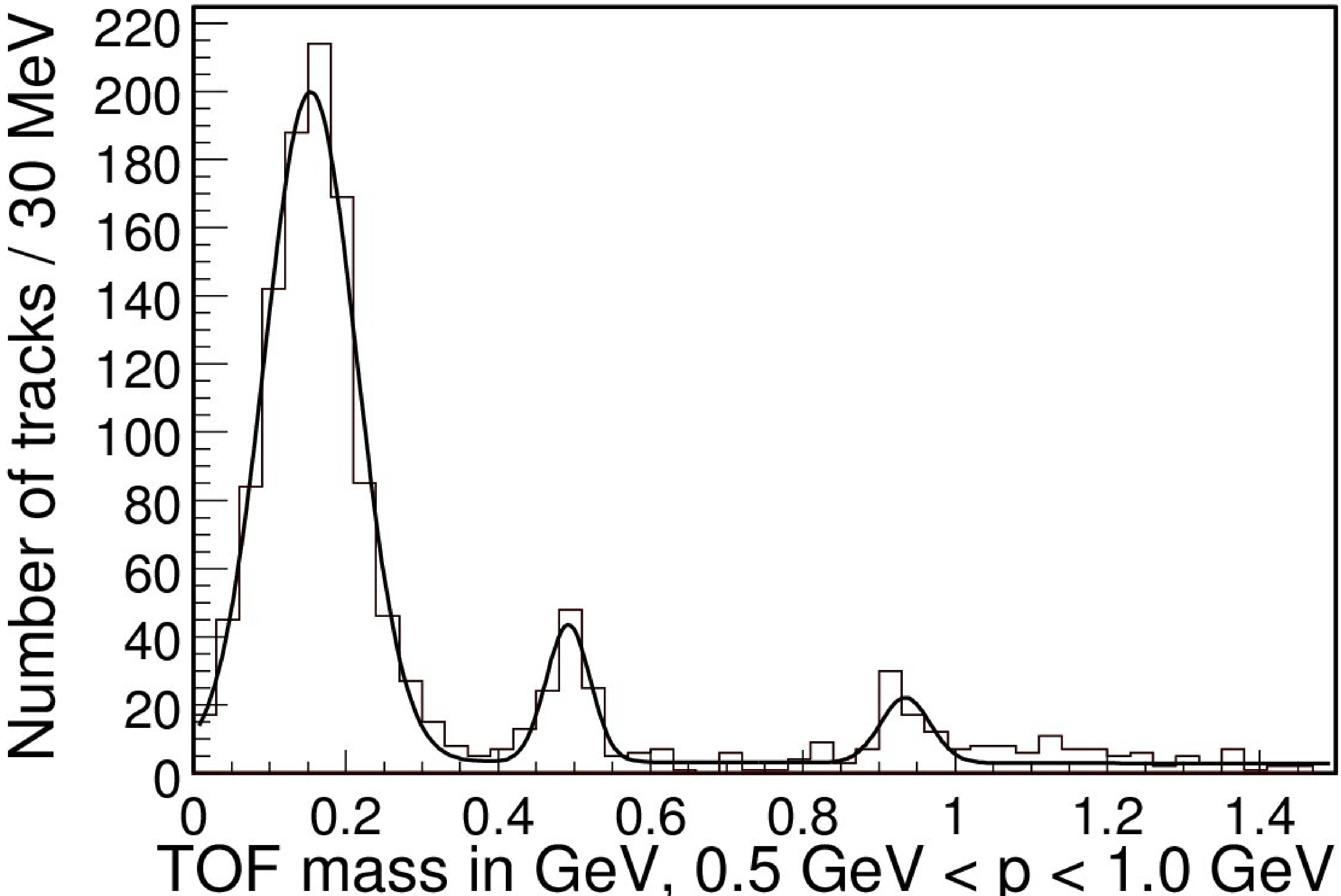
Inserting the Bar



And the Tracker still Fits



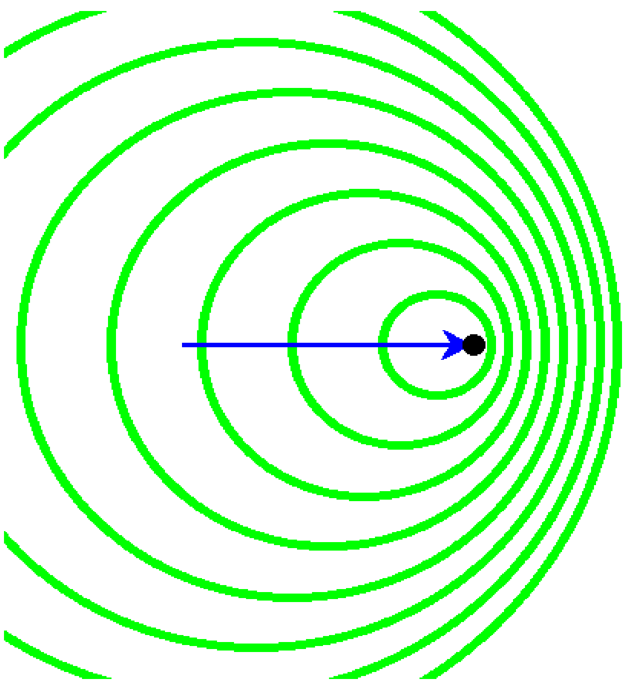
Particle Distinction with TOF

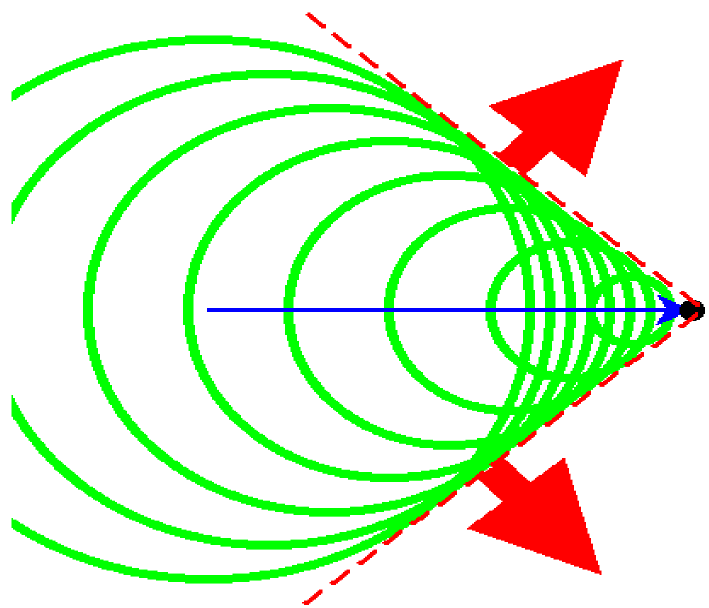


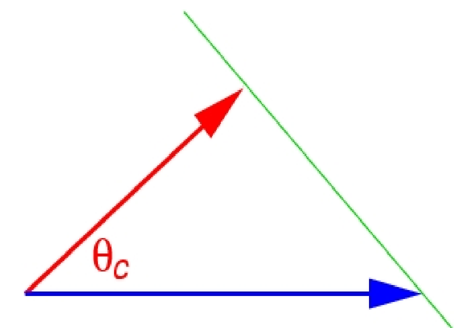
Cherenkov Light

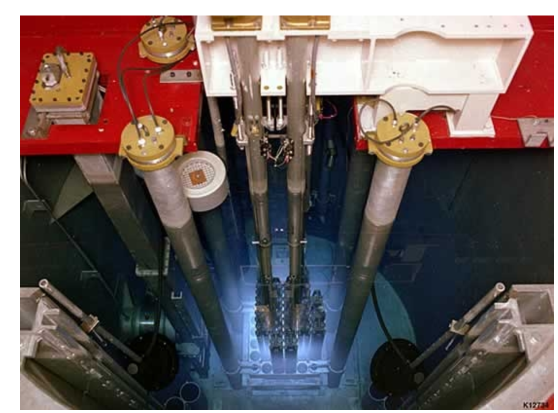
Particle travels through material

- weak EM wave spreads: polarizing/de-polarizing effect
- slower then wave speed: waves never interfere
- faster then wave speed: they will interfere and create conic light under characteristic angle: $\cos\theta_C = 1/\beta_n$





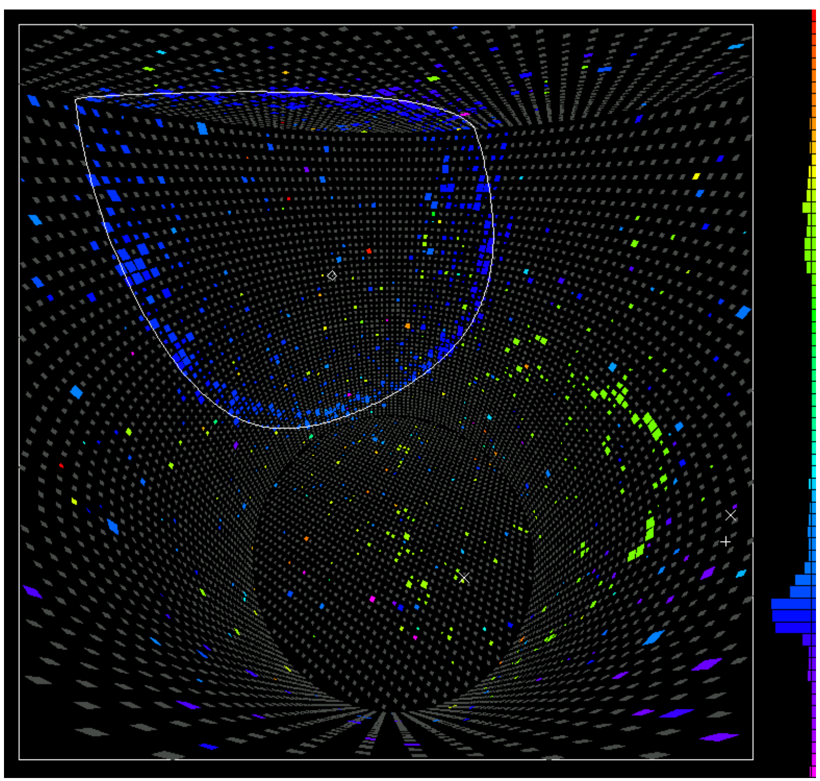




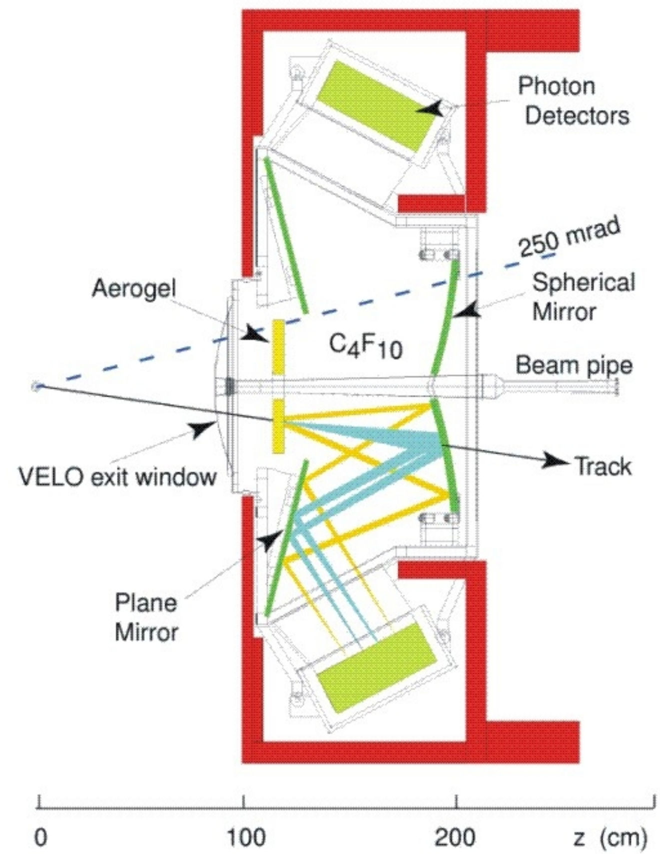
Ring Imaging CHerenkov Detectors

RHIC detectors

- particle velocity from the opening angle of light cone
- particle passes through proper type of material
- the light cone produces a ring image
- size of ring determines velocity



Super Kamiokande ring

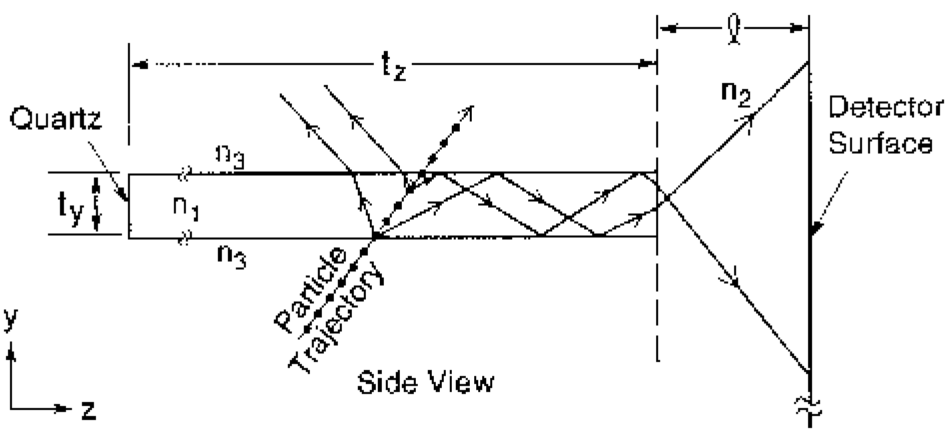


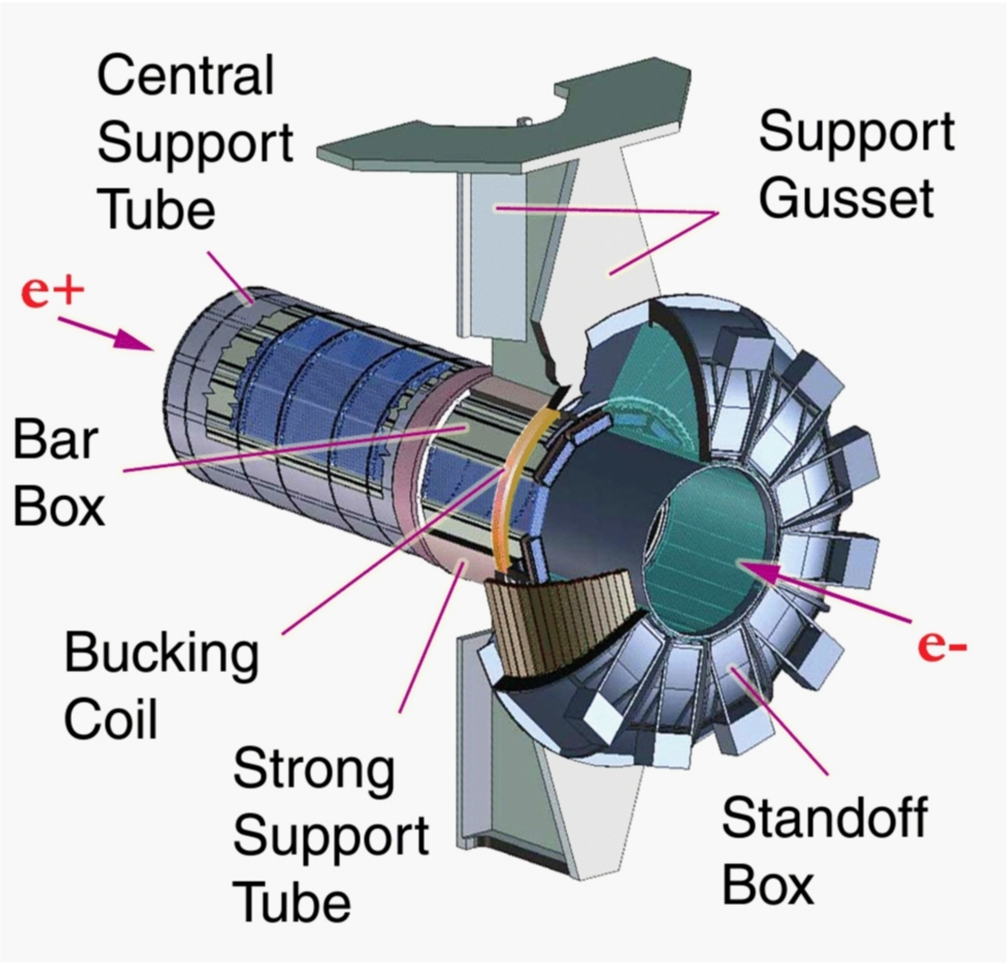
LHCb Aerogel RICH

DIRC at BaBar Experiment

Detection of Internally Reflected Cherenkov light

- quartz bar is used to transport light under Cherenkov angle
- light ring in water tank
- size determines β
- high surface quality needed
- angle has to be retained





Conclusion

Electron/Photon reconstruction crucial at LHC

- very low Higgs masses drive the ECAL design
- m_H below 130 GeV: $H \rightarrow \gamma\gamma$
- active calorimeter more precise then sampling type
- CMS and Atlas covers full Higgs range

Particle Id (mostly pion/kaon separation)

- dE/dx in tracking (solid and gaseous)
- time of flight measurements
- Cherenkov light cone do determine velocity
  - Ring Imaging CHerenkov detectors: RICH
  - Detection of Internally reflected Cherenkov light: DIRC

Next Lecture

Analysis Tips Bottomonium Analysis....