Particle Detectors

Part 2

Lectures at the CHIPP winter School 2013

Roberto Carlin (University of Padova and CERN)

SCINTILLATORS AND DETECTION OF LIGHT

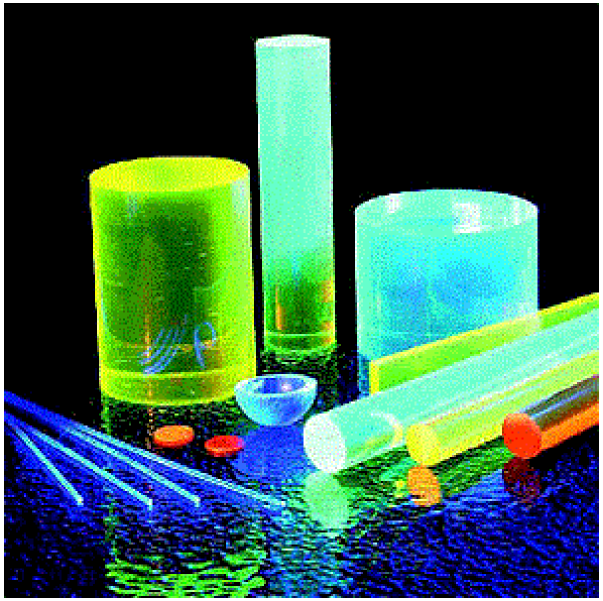
Scintillation

- Production of visible or UV light produced by atomic or molecular excitation from a charged particle
  - Fluorescence = prompt signal)
  - (Phosphorescence = delayed signal)

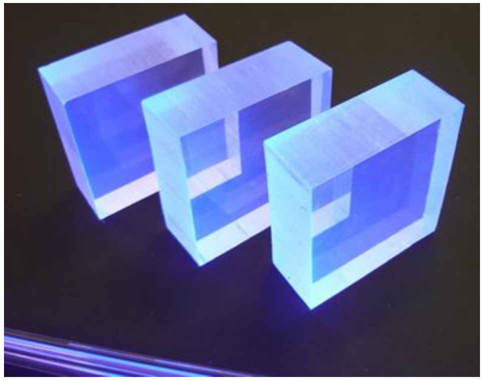
$$\frac{dN(t)}{dt} = \frac{N_{TOT}}{t_D} e^{-\frac{t}{t_D}}$$

$$\frac{dN(t)}{dt} = N_{TOT}\left(\frac{A}{t_F} e^{-\frac{t}{t_F}} + \frac{B}{t_S} e^{-\frac{t}{t_S}}\right)$$

  - Prompt signal decays exponentially, sometimes with two components



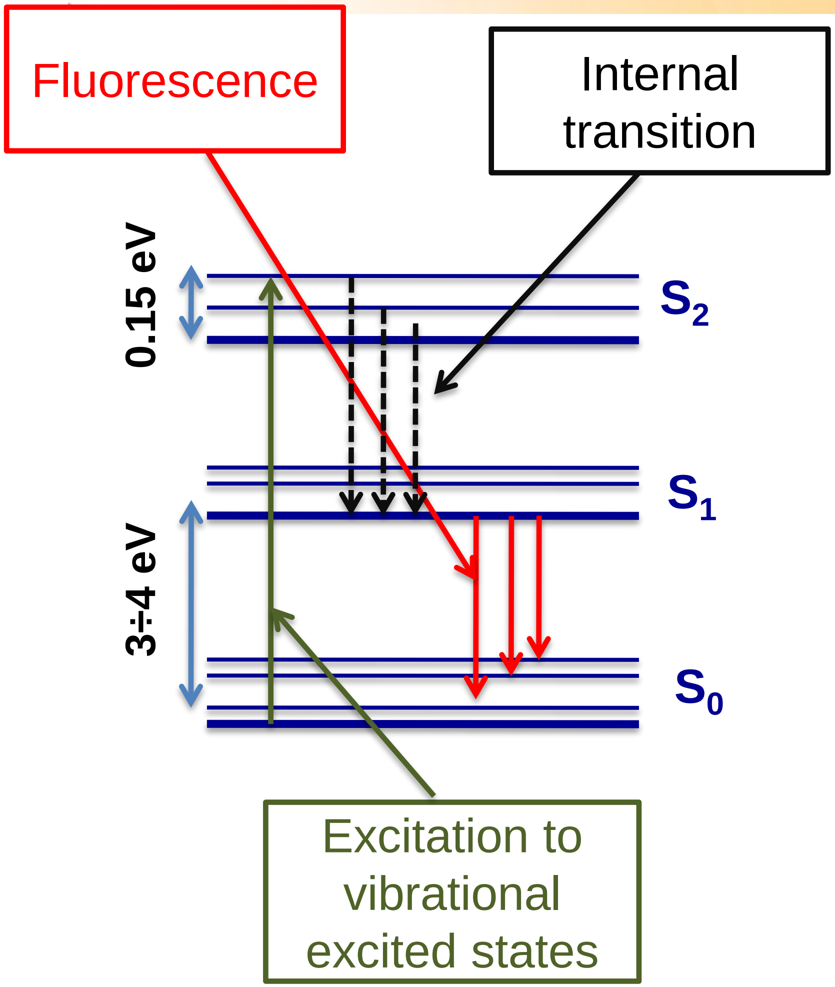
Scintillation



- Important features of a scintillator
  - Light Yield (number of photons/energy lost)
  - Transparency to the radiation
  - Light colour compatible with the photon detectors
  - Linearity (particularly for calorimeters)
  - Speed (particularly for trigger)
    - Goes from ns to μs

- Scintillator classes
  - Organic
    - Plastic
    - Liquid
    - Crystals
  - Inorganic crystals
  - Inorganic liquids and gases
  - Glasses

Scintillation



- How can a scintillator be transparent to their *own* radiation ?
  - Light emitting transitions are to vibrational excited states
  - Energy not enough to excite from S0 to S1

Plastic scintillators

	σ (ns)	τ (ns)
NE102A	0.7	2.4
NE111	0.2	1.7
NE110		3.3
Naton 136	0.5	1.87

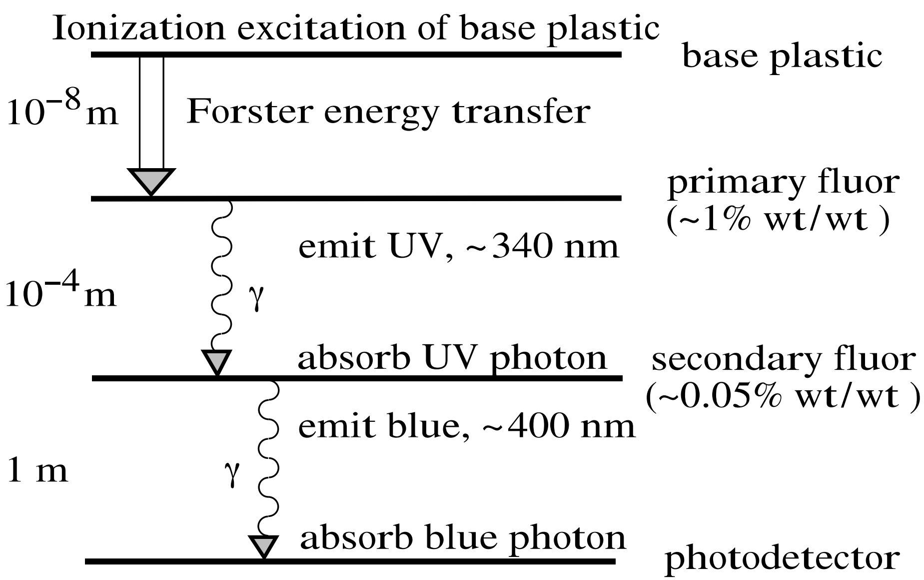
- Problems
  - Light attenuation
  - Radiation damage
  - Aging
  - Not dense

- The most common
  - Organic scintillator in a plastic solvent
  - Good LY
  - Very fast

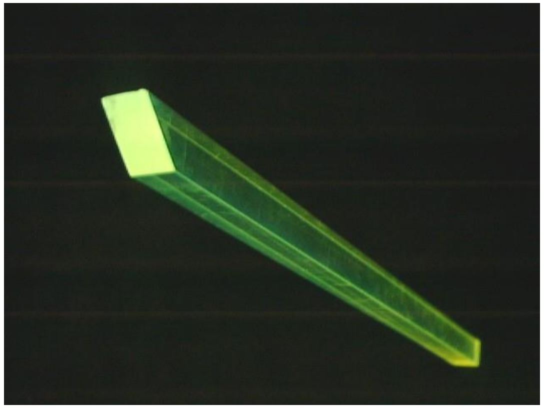
$$N(t) = N_0 g(s,t) e^{-\frac{t}{t_D}}$$

  - Contain hydrogen
    - Suited to detect fast neutrons (proton recoil)

Plastic scintillators



- Typically the fluorescence is in the UV
  - Added other molecules that shift the light to the visible
  - Wavelength Shifters (WLS)

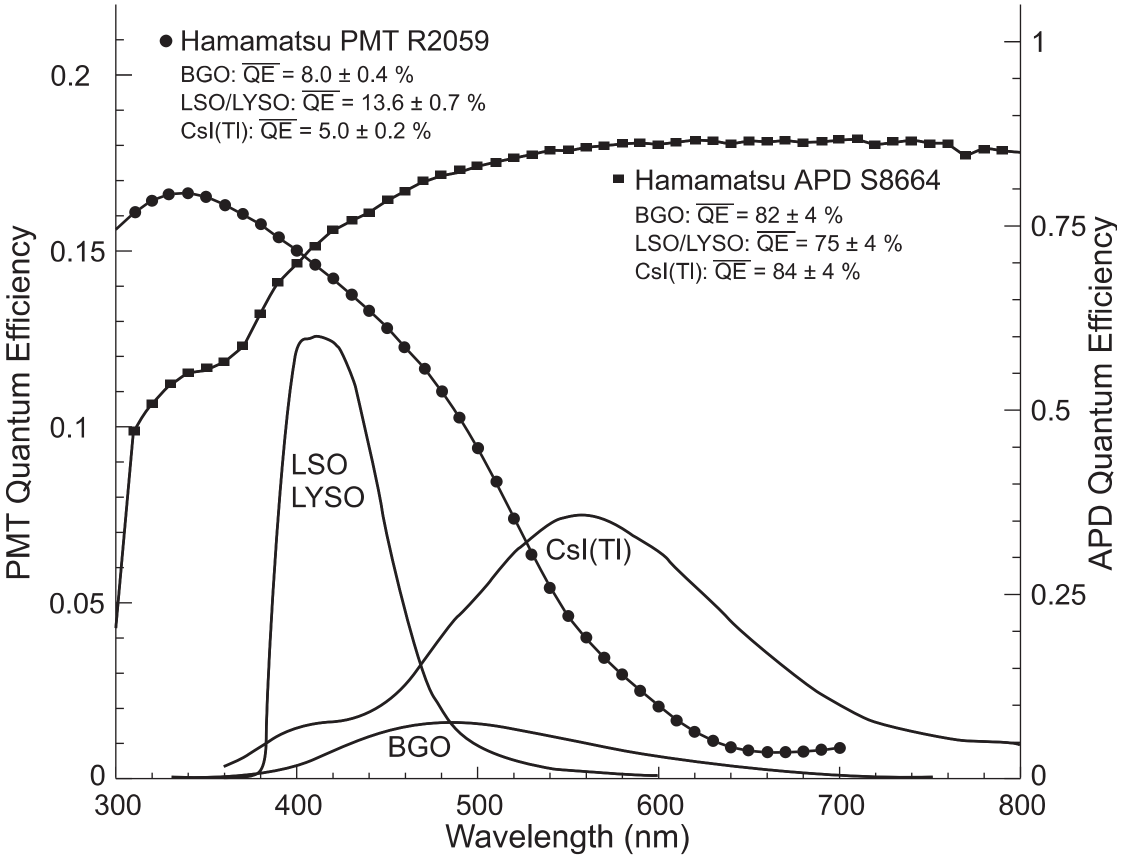


- Sometimes it is useful to have WLS as a separate function element
  - Absorbs light and emit isotropically at a different colour

Inorganic crystals

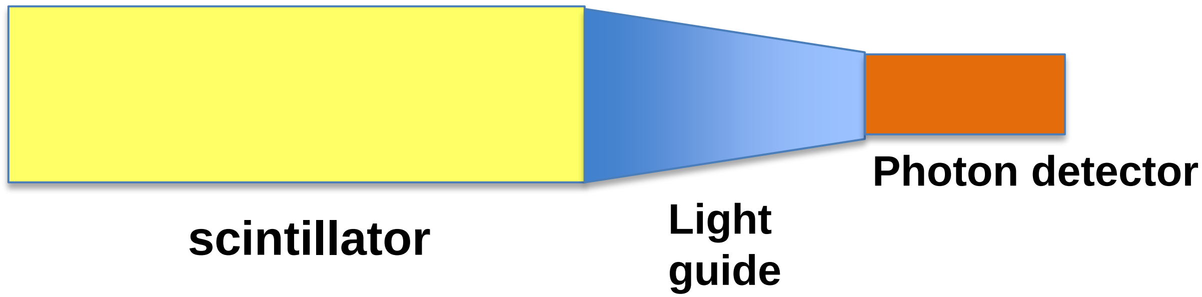
Parameter:	ρ	MP	X_0^*	R_M^*	dE/dx	λ_I^*	$\tau_{\rm decay}$	$\lambda_{\rm max}$	$n^\natural$	Relative output†	Hygro-scopic?	$d(\mathrm{LY})/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	230	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.6	30.7	630^s	300^s	1.50	36^s	no	-1.3^s
							0.9^f	220^f		3.4^f		$\sim0^f$
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1300	560	1.79	165	slight	0.3
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	35^s	420^s	1.95	3.6^s	slight	−1.3
							6^f	310^f		1.1^f		
$PbWO_4$	8.3	1123	0.89	2.00	10.2	20.7	30^s	425^s	2.20	0.083^s	no	−2.7
							10^f	420^f		0.29^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	420	1.82	83	no	−0.2
GSO(Ce)	6.71	1950	1.38	2.23	8.9	22.2	600^s	430	1.85	3^s	no	−0.1
							56^f			30^f		

Inorganic crystals



- Need to use photon detector tuned to their emission spectrum

Light detection

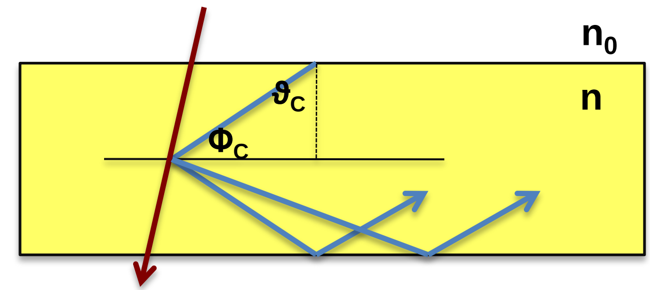


- Light produced by a plastic scintillator
  - density ≈ 1g/cm, 1.7MeV/cm for MIP
  - about 10^4 photons/MeV
    - $E_v = hc/\lambda \approx 3eV$ with $\lambda = 420nm$
    - Energy transformed to light ≈ 30keV/MIP
    - About 2% of the energy lost by the particle (taking a monochromatic light spectrum 420nm)

- Effect that reduce the signal
  - Attenuation in the scintillator
  - Light loss on contact surfaces and light guides
  - Quantum efficiency of the detector
    - Number of electrons generated per photon

Light detection

- Light attenuation
  - $\lambda_{ATT} = 1 \div 2$m
    - For new, undamaged scintillator (radiation, aging)
- Transport of light
  - Total reflection, F= fraction of light reflected forwards
  - For n=1.58 one gets F=20%



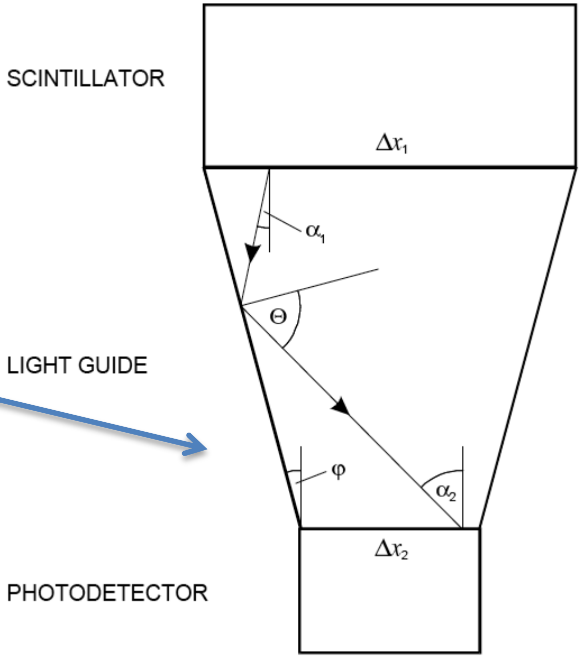
$$\sin\vartheta_L = \frac{n_0}{n}$$

$$F = \frac{\Omega}{4\pi} = \frac{1}{4\pi}\int_0^{\varphi_L} d\Omega = \frac{1}{4\pi}\int_0^{\varphi_L} 2\pi\sin(\varphi)\,d\varphi$$

$$F = \frac{1}{2}\left(1 - \cos\varphi_L\right) = \frac{1}{2}\left(1 - \sin\vartheta_L\right) = \frac{1}{2}\left(1 - \frac{n_0}{n}\right)$$

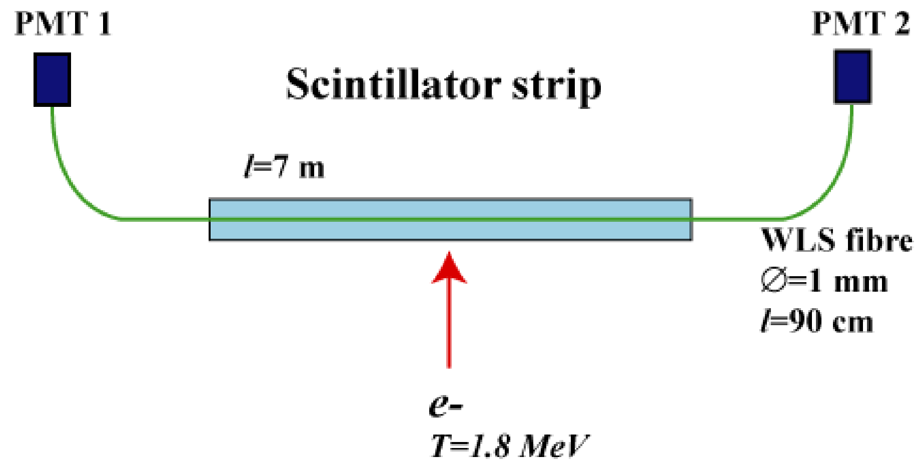
Light detection

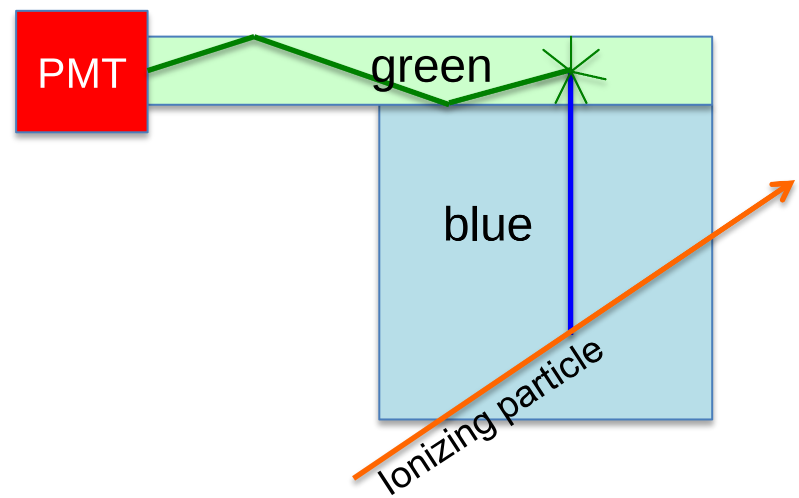
- Scintillator often cannot be coupled directly to the photon detector
  - Matching geometry of scintillator and photo-detector
  - Environmental conditions
    - E.g. high magnetic field
- Use of transparent light guides
  - If the cross section of the guide get reduced, the fraction of transmitted light reduces accordingly
  - Liouville's theorem (conservation of phase space), valid for all refraction indexes n



Light detection

- Another option is to use wavelength shifters
  - Light is absorbed by the WLS and emitted isotropically at different wavelength
- Different geometries are used
  - Fibres in the scintillator
  - Bars at the end of it

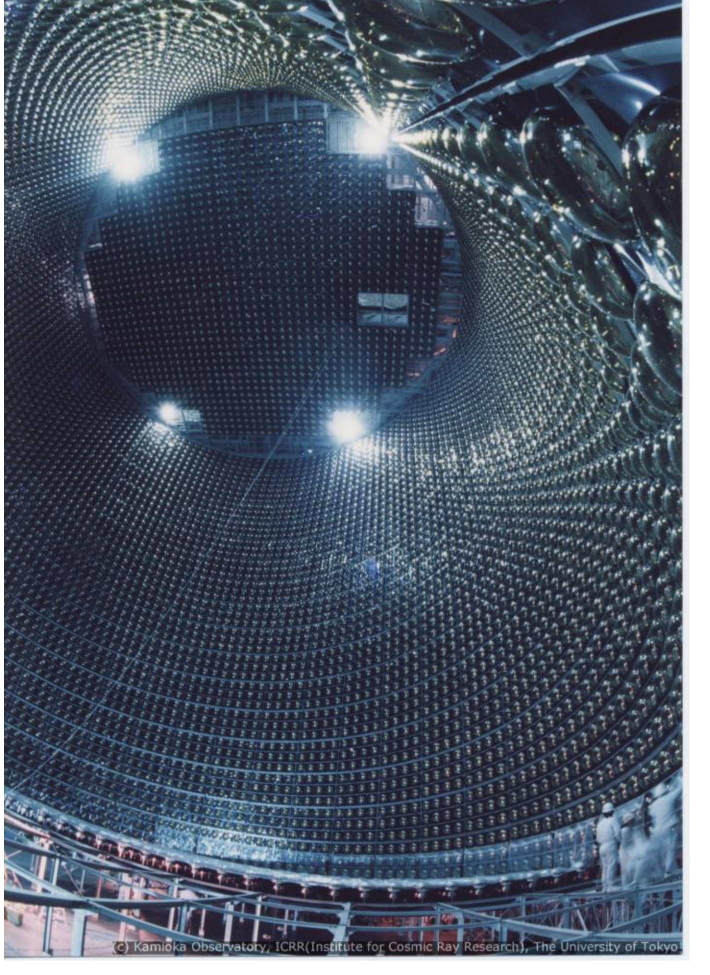




Photon detectors

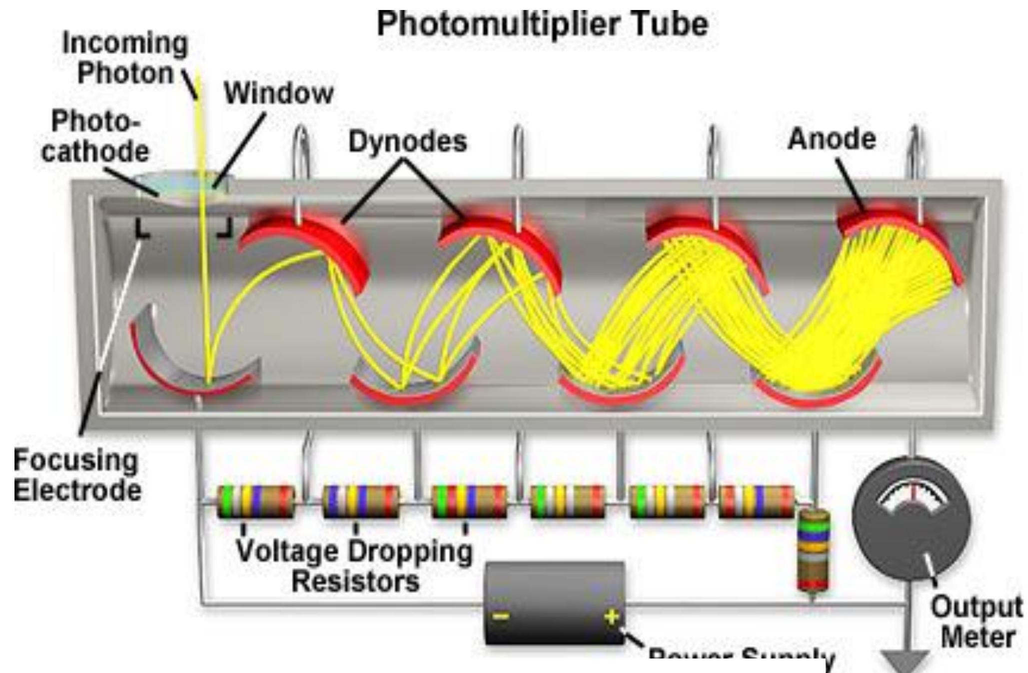
- The process
  - Photon is absorbed producing a photoelectron, or a electron-hole pair
  - Signal is amplified with secondary emission or avalanches
  - Signal is collected on a electrode
- Important features
  - Quantum efficiency (QE)
    - Probability that photon produce an electron
  - Efficiency of collection
  - Gain
  - Noise
  - Transit time fluctuation
  - Dynamic range and linearity
- Main classes
  - vacuum detectors
    - PMT, MCP, HPD
  - Gas detectors
    - Photocathode followed by a gas chamber, GEM
  - Solid state
    - SiPD, APD, SiPM

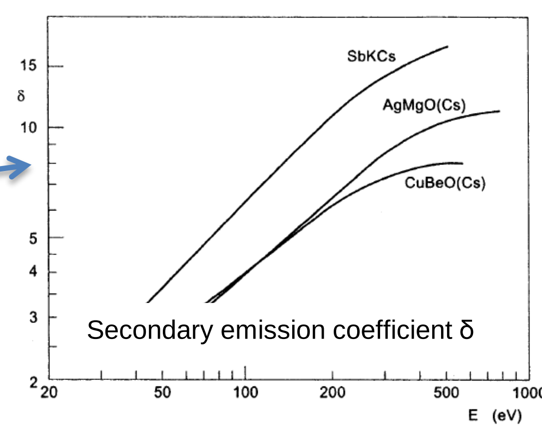
Super-Kamiokande



Photon detectors

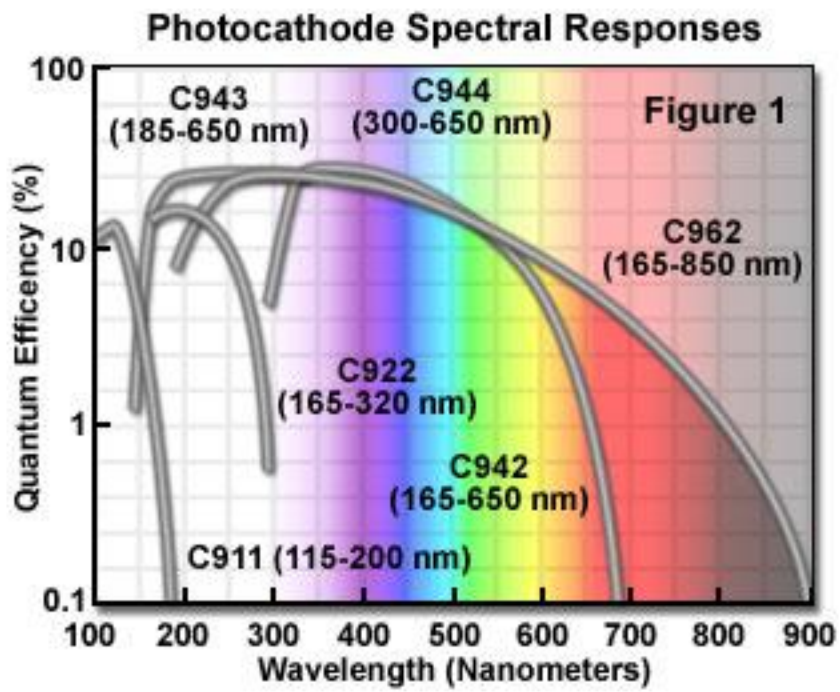
- The PMT
  - Transparent window (glass, quartz)
  - Photocathode
    - Bialkali (SbKCs)
    - An electron is extracted for photoelectric effect
  - Electron is accelerated and impacts on dynodes, extracting more electrons
  - Finally the signal is collected
  - Gain depends on the number of dynodes and on the acceleration voltage
    - Single dynode gain δ = 2-10
    - Number of dynodes n_D = 8-15
    - **Total gain $n_D^{\delta} = 10^6 - 10^8$**





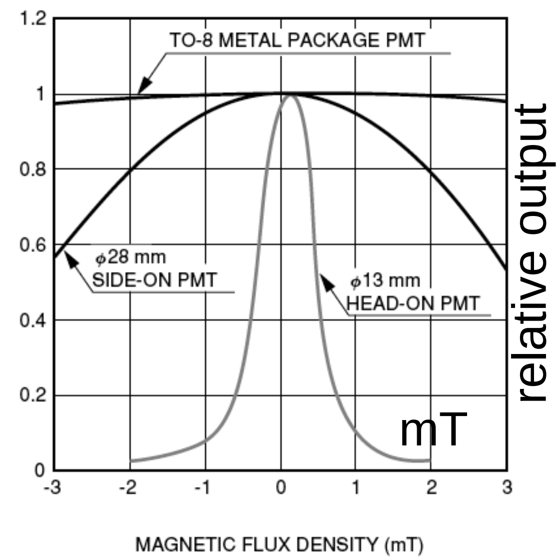
Photon detectors

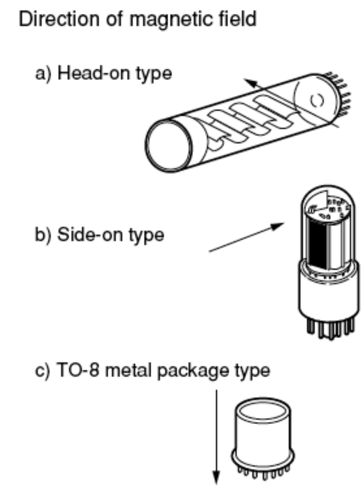
- Efficiency in PMT depends mostly from QI of the photocathode
  - Depends on the wavelength
    - Up to 27% on the peak of the sensitivity
  - Photocathode has to be adapted to the spectrum of the light
  - Typically sensitive mostly to short wavelengths
    - The higher the sensitivity to red, the lower the work function, the higher the “dark noise” induced by thermal effects
- Another factor is the efficiency of collection of the first dynode
  - Focusing, strongly effected by magnetic field



Photon detectors

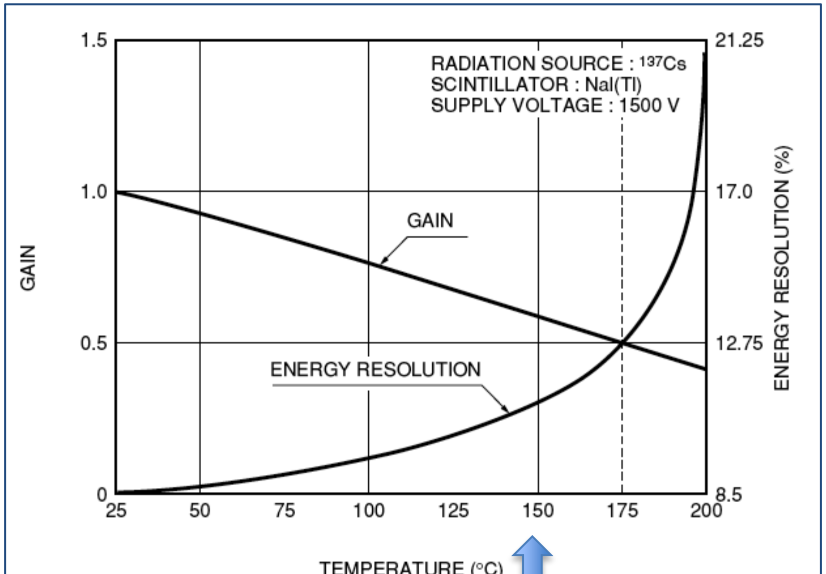
- Example
  - 1cm thick scintillator ≈ 10^4 γ
    - light transport in the scintillator 20%
    - Light transport in the guides and interfaces 20%
    - 400 γ left
  - QE of the photocathode 25%
    - 100 photoelectrons
  - Gain PM = 10^7
    - 10^9 electrons, 0.16nC
    - 5ns signal, 32mA
      - 1.6V on 50 Ω
  - Signal can be very large
    - At high rate, saturation problems, “sagging” or thermal problems in the resistor array
      - Voltage drops lead to non linearity



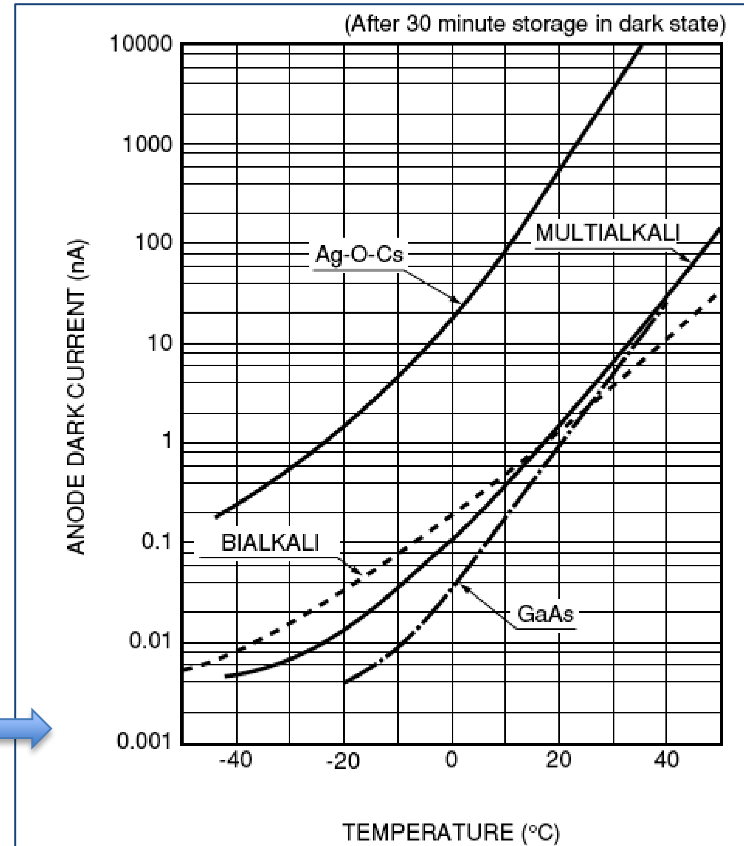


- PMT are extremely sensitive to magnetic field
  - 25% decrease in gain for 0.1mT
- Have to be shielded, and kept outside region with high B
- Or, other γ detectors have to be used

Photon detectors

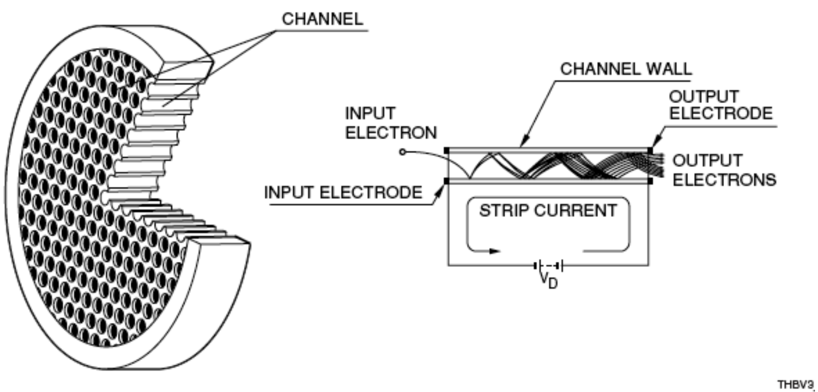


- T effects
  - Limited on the gain
  - Very strong on the dark current”
    - Depending on the photocathode
    - PMT sensitive to red may have to be cooled



Micro Channel Plates

- PMT with small resistive channels replacing the dynodes
  - Diameter ≤ 10μm
- Advantages
  - Very fast, rise time ≈ 100ps and transit < 1ns
  - More tolerant to magnetic field
    - Up to 2T axial, 70mT transverse
- Disadvantages
  - Linearity more limited (saturation effects)

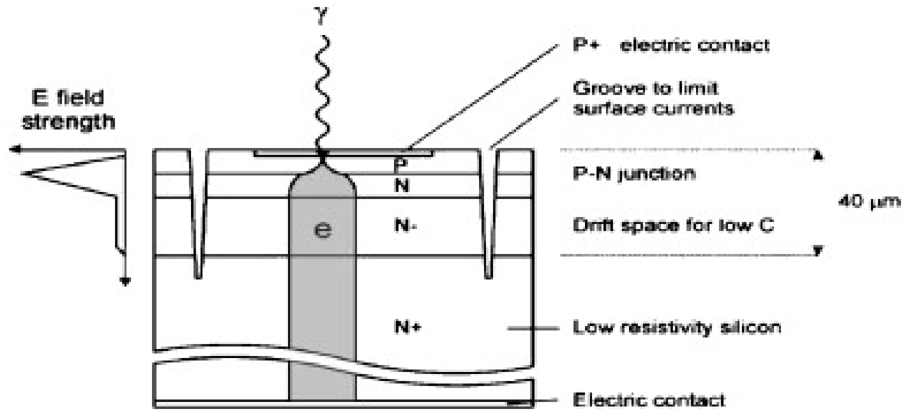


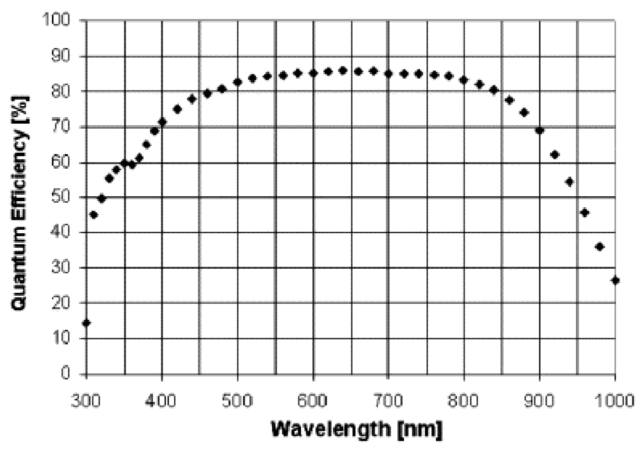
(a) Schematic structure of an MCP

(b) Principle of multiplication

APD

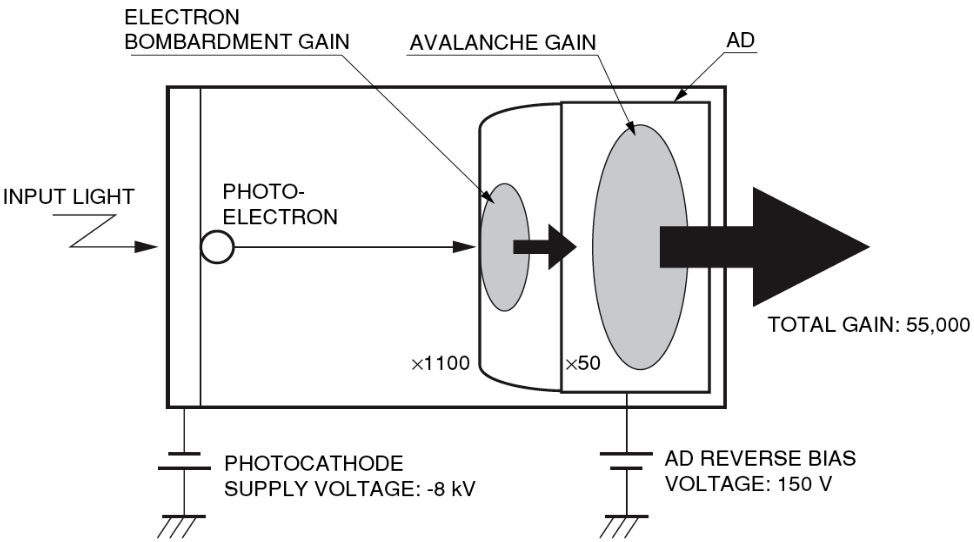
- Semiconductor diodes with high reverse bias voltage
    - The electrons are accelerated in the depletion region and undergo multiple collisions generating an avalanche
    - Gain ≤ 1000 in linear mode
    - Up to 10^6 in Geiger mode
        - Generalized discharge that has to be dumped actively or with a resistor
        - Total loss of linearity, higher recovery time
- Much better Q.E. than a PMT
    - Above 70%
    - Sensitive to larger light spectrum
- Excess noise factor (w.r.t. Poisson expectation) F≈ 3-10





HPD

- Hybrid Photodiode
  - Cathode and acceleration in vacuum like in the PMT
  - High acceleration voltage in a single step
    - ≈ 10 kV
  - Energetic electron hits a silicon diode, generating a cluster of electron-holes pair
    - bombardment gain ≈ 1000
  - This step sometimes is followed by a further avalanche gain in the silicon (HAPD)
    - Further gain ≈ 50
    - Allows lower HV in the first section



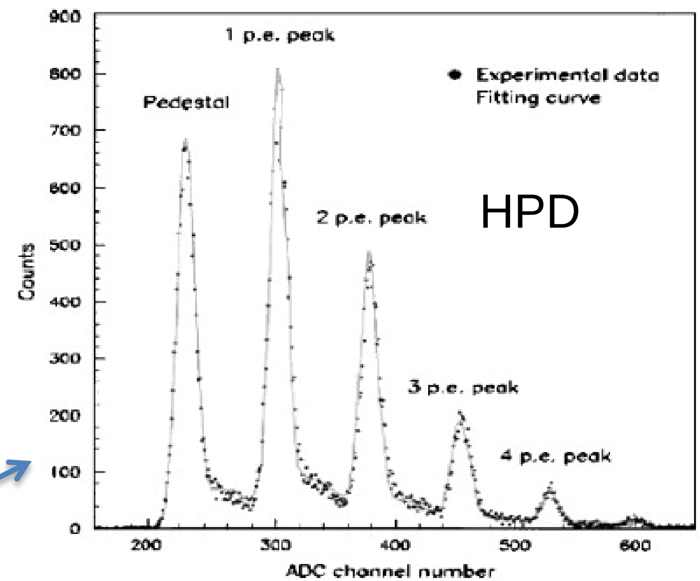
HPD

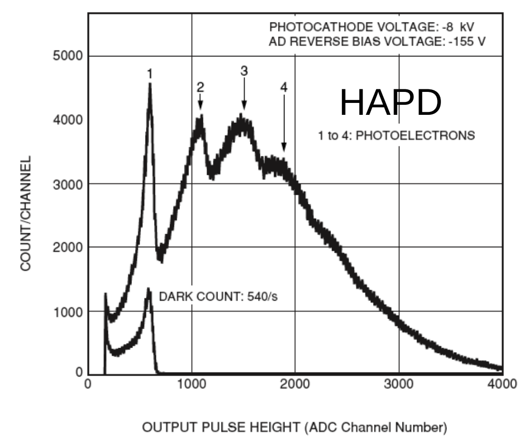
- Very good resolution
  - Stochastic fluctuations limited by the high gain in the first (or only) step

$$\frac{\sigma(n)}{n} \propto \frac{1}{\sqrt{n}}$$

$$n \sim 1000 \rightarrow \frac{\sigma(n)}{n} \sim 3\%$$

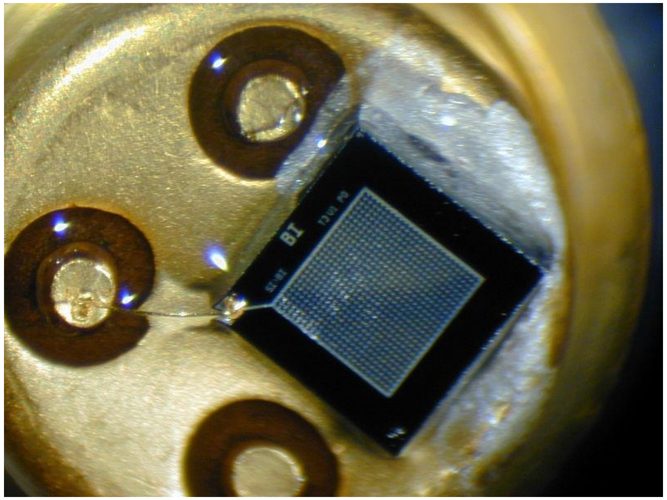
  - Easy to separate 1,2,3 photons signals
    - Possible in PMT only of special high-dynode gain classes
  - Gain is limited
  - Sensitive to transverse B field
    - CMS is using them in the hadron calorimeter (inside 4T magnetic field)
    - Sensitive to stray B field, plan to upgrade with SiPM





SiPM

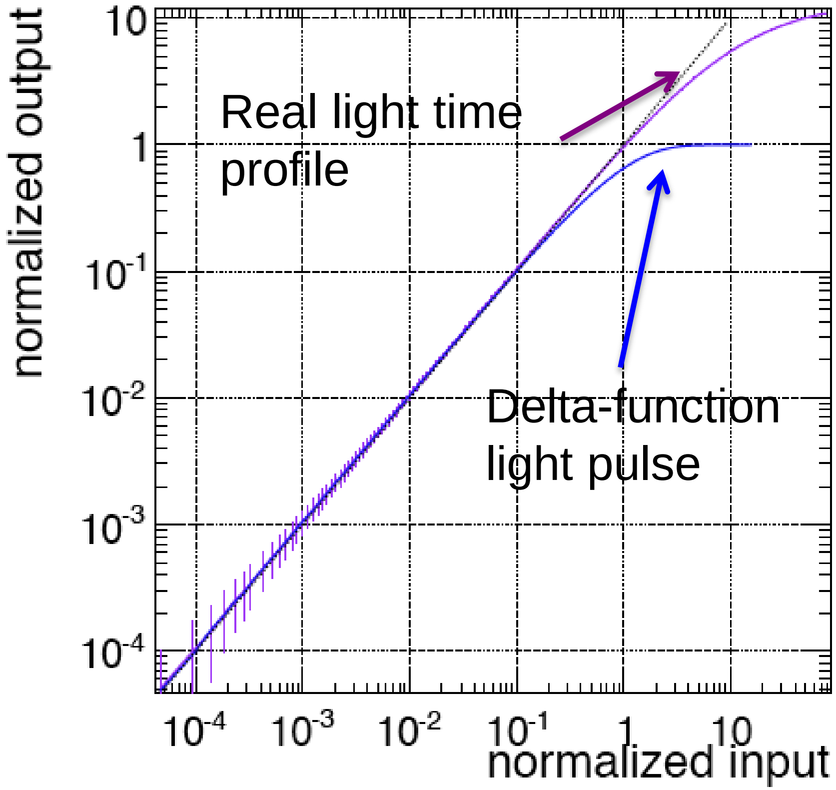
- Silicon PhotoMultiplier
    - Most trendy photon detector
  - Array of APD working in Geiger mode
    - Current limited by a quench resistor per each pixel
    - Fast recovery time possible
      - Needed in high Pile-Up application al LHC
  - Every photon hits a pixel, number of photon proportional to the pixel hit
    - Linearity recovered, with obvious saturation effects
  - Low Voltage device
  - Insensitive to magnetic field
  - Quantum efficiency 20%



Parameter	Spec Value	Hamamatsu 15 μm 500 kΩ	[a]KETEK 20 μm 400 kΩ	[a,b]KETEK 15 μm 500 kΩ
Size	2.2 mm^2 or 2.5 mm round	2.2X2.2	2.2X2.2	2.2X2.2
Gain	6×10^4	2×10^5	9×10^5	5×10^5
Effective number pixels (per device)	> 20K per device	58K	12K	44K
Recovery Time RC	< 10 ns	4 ns	29 ns	8 ns
PDE at 515 nm	> 15%	18%	21%	12%
Leakage Current (after 2E12 n)	< 200 μA	120 μA	900 μA	388 μA
Fractional Gain X PDE (after 2E12 n)	> 65%	80%	80%	85%
ENF	< 1.4	1.3	1.2	1.1
Optical Cross Talk	< 15%	15%	15%	10%
Neutron noise sensitivity	NO	yes	no	no
Bias Voltage	< 100 V	75 V	25 V	29 V
Operating temp	22^{o}C	22^{o}C	22^{o}C	22^{o}C
Temperature Dependence	< 5% per ^{o}C	4%	1%	1.5%

SiPM

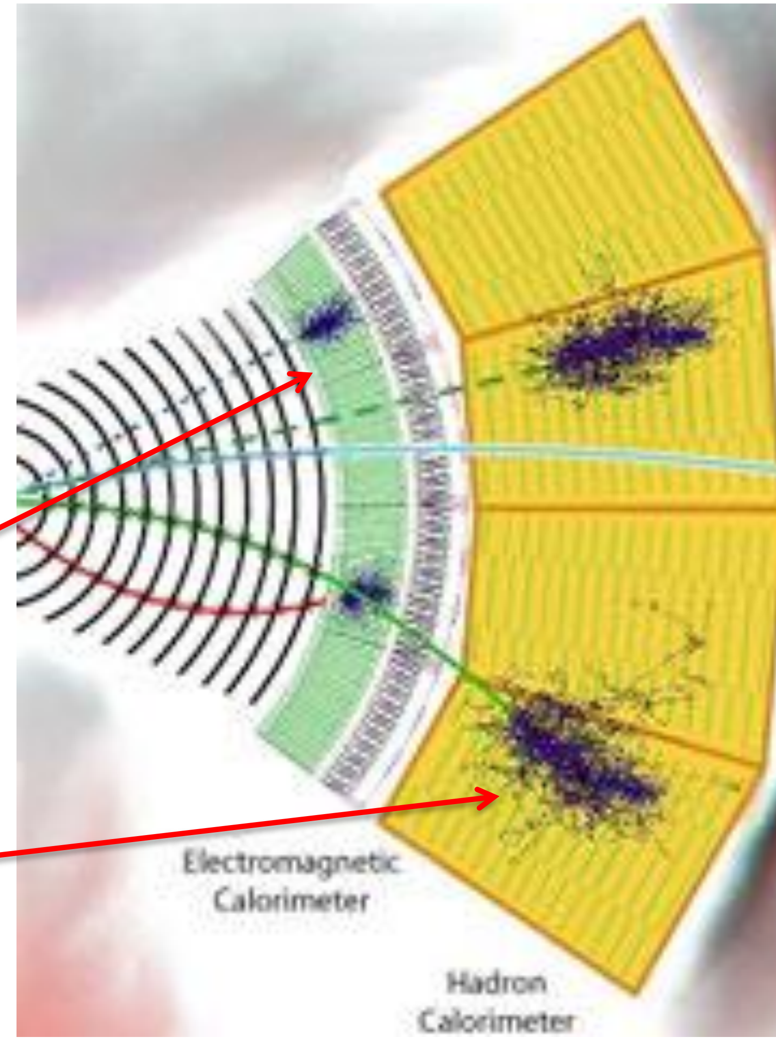
- Fast SiPM and linearity
  - Recovery time <10ns, shorter than the time distribution of scintillator light
  - Each Geiger cell can fire more than once, recovering dynamic range



CALORIMETERS

CALO classification

- Calorimeters
  - Measure the energy of a particle by totally absorbing it
    - Particle can be charged or neutral, as long as it get stopped
  - Two main classes
    - Electromagnetic calorimeters
      - Electrons, photons
    - Hadronic calorimeters

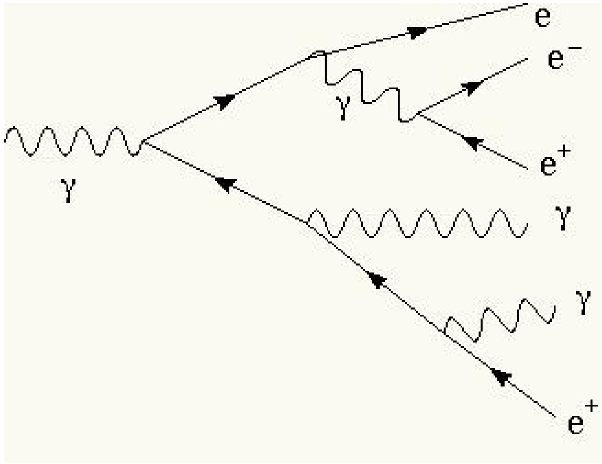


EM showers

- Remember $\lambda_{Pair} \approx X_0$
  - EM shower is very symmetrical
  - On average one can think that every X_0 the number of particles double and they energy halves
  - The process stops when the particle energy gets below E_C

$$E = \frac{E_0}{2^{t_{MAX}}} = E_C$$

$$t_{MAX} = \frac{\ln(E_0/E_C)}{\ln 2}$$



- At the end, after t radiation lengths, the number of particles is $N \approx 2^t$ and the energy per particle is $E \approx E_0/N$
- The depth of the shower (in X_0) grows logarithmically with the particle energy

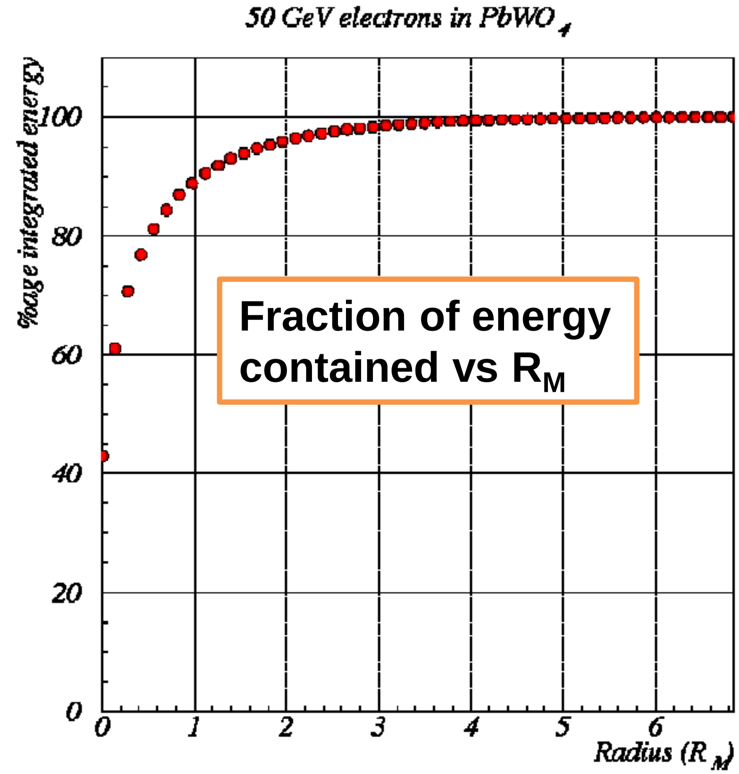
EM showers

- Lateral development of the shower is measured by the "Moliere" radius

$$R_M \approx X_0 \frac{21.2 MeV}{E_C}$$

$$R_M \approx 0.0265 X_0 (Z + 1.2)$$

- More than 90% of the energy is contained in a cylinder of diameter $2R_M$, more than 99% within $3.5R_M$



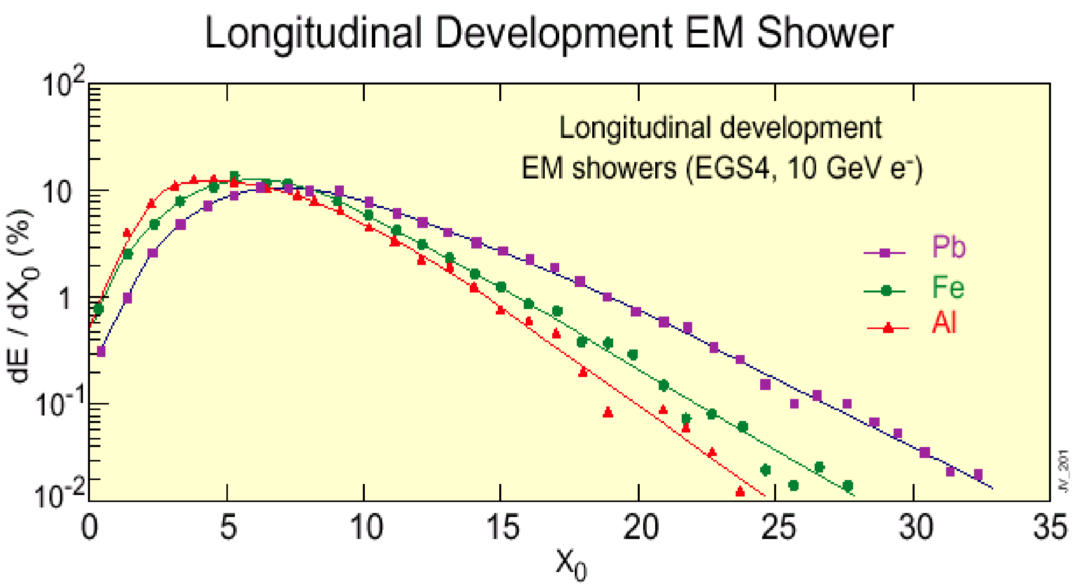
- Example for Pb
  - $R_M = X_0 \times 21.2/7.8 = 2.7X_0$
  - $R_M = 0.0265X_0(82+1.2) = 2.2X_0$

EM showers

- Longitudinal development

$$t_{95\%} \approx t_{max} + 0.08Z + 9.6$$

  - Length in X_0 containing 95% of the energy
  - Enery containment important for the energy resolution



EM calorimeter resolution

$$\frac{s(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

$$(E \text{ in } GeV)$$

- Calibration
  - Limits at high energy

- Noise (constant)
  - Dominates at low energies

- Stochastic term
  - Theoretical limit is a=0.01 GeV$^{1/2}$

- Stochastic term

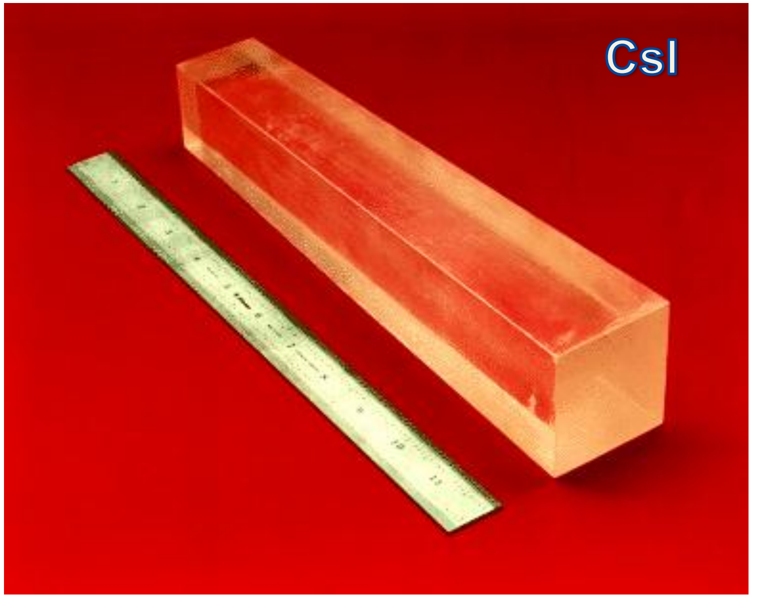
$$s(n) \propto \sqrt{n} \rightarrow s(E) \propto \sqrt{E}$$

$$\frac{s(E)}{E} = \frac{a}{\sqrt{E}}$$

  - Energy is proportional to the number of photon you measure

Homogeneous EM calorimeters

- Longitudinally one piece of homogeneous material
  - Act as absorber → has to be dense enough
  - Generate a detectable signal → typically light
- Choice essentially limited to
  - Inorganic scintillating crystals
  - Lead-glass producing Cherenkov light
  - Heavy noble liquefied (cold) gasses (Xe)



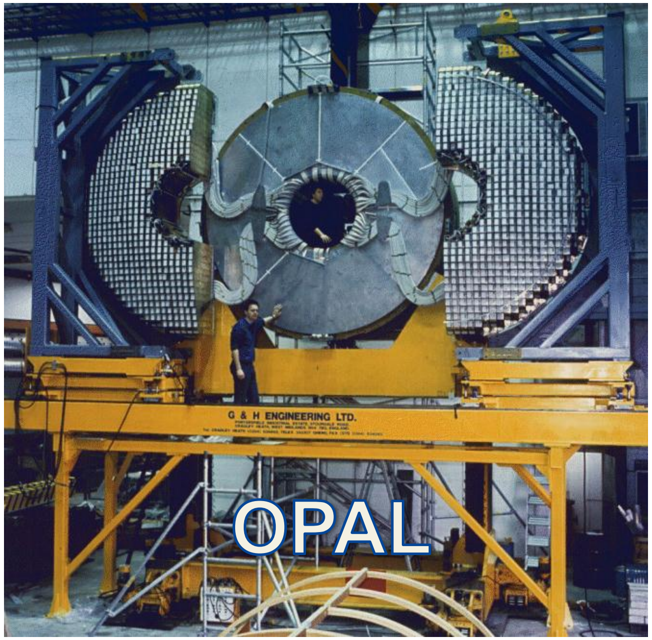
Inorganic crystals

	NaI(Tl)	BaF2	CsI(Tl)	CsI	CeF3	BGO	PWO	
ρ	3.67	4.88	4.53	4.53	6.16	7.13	8.26	g/cm^3
X0	2.59	2.05	1.85	1.85	1.68	1.12	0.89	cm
RM	4.5	3.4	3.8	3.8	2.6	2.4	2.2	cm
τ	250	0.8/620	1000	20	30	300	15	ns
λp	410	220/310	565	310	310/340	480	420	nm
n (λp)	1.85	1.56	1.80	1.80	1.68	2.15	2.29	
LY	100%	15%	85%	7%	5%	10%	0.2%	%NaI

- Dense, suited for an homogeneous calorimeter
- Different LY and speeds (from fast to very slow)
  - LY sensitive to temperature

Lead glass

Cherenkov Radiator	Density	X0 (cm)	λ (cm)	Index of refraction
SF2 lead glass	3.85	2.76	38	1.65
SF6 lead glass	5.2	1.7	30	1.81
SF57 lead glass	5.5	1.5	28	1.85
PbF_2 crystal	7.8	0.93	20	1.82
UVT acrylic	1	40	80	1.5



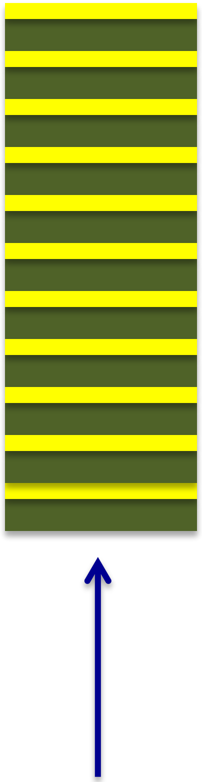
- Also Lead Glasses have been used for homogeneous calorimeters
  - Much cheaper than crystals
  - LY much lower, ≈ 1 photon/MeV , 10^{-4} w.r.t the best crystals

Sampling calorimeters

- Many layers of
  - Passive absorber to develop the shower
  - Active detector
- Advantages
  - More flexibility in the choice of materials → lower cost
  - Possibility to use position-sensitive detectors
    - Good angular resolution, extrapolation to the vertex
- Disadvantages
  - Less visible energy → larger stochastic fluctuation, lower resolution

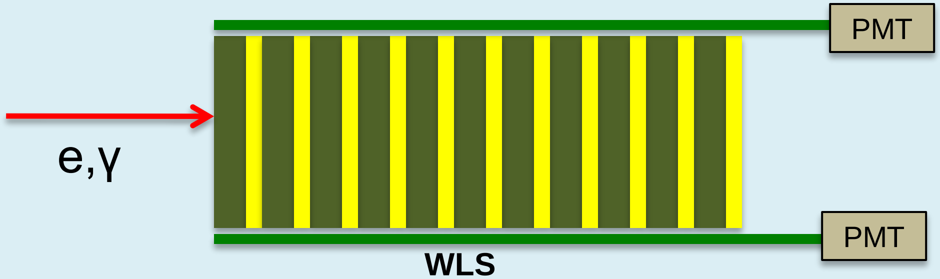
$$\frac{s(E)}{E} \mu \frac{\sqrt{t/f}}{\sqrt{E}}$$

  - Resolution depends on the sampling fraction (ratio between active and passive material)
    - Stocastic contribution around 10%-15%

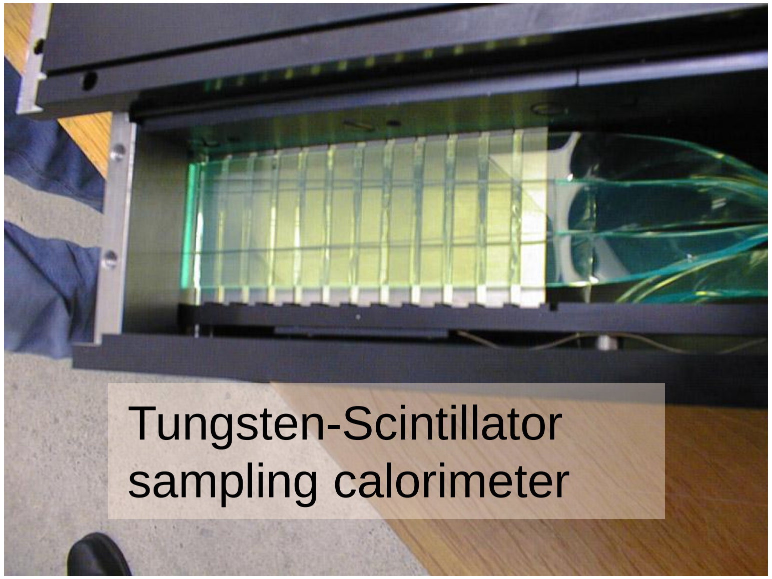


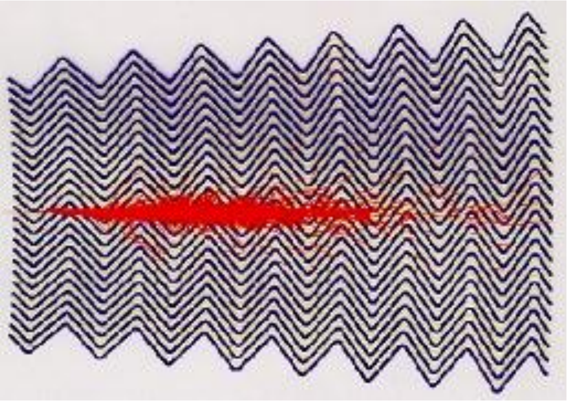
Sampling calorimeters

- Common technologies
  - Lead/scintillator
    - Light readout with wave length shifter on the sides, or with fibres inserted longitudinally



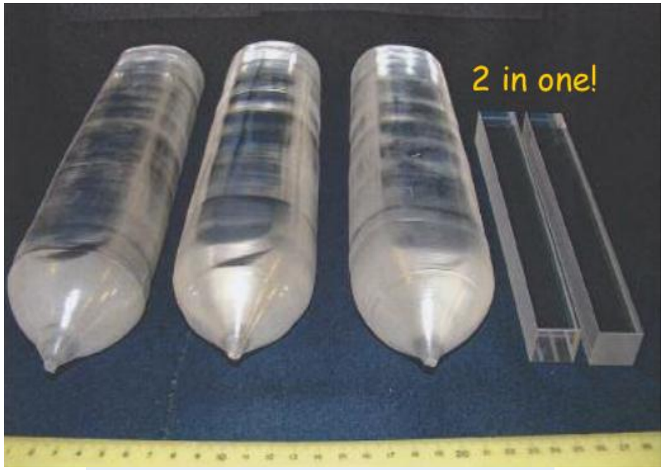
  - Lead/Lar
    - Liquid argon, readout as an ionization chamber



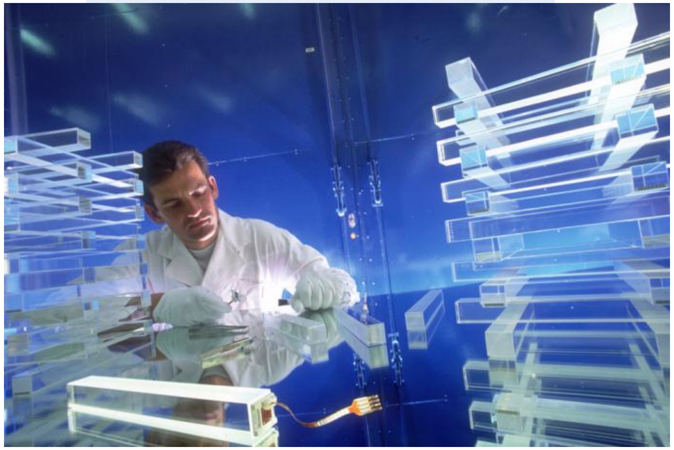


CMS calorimeter

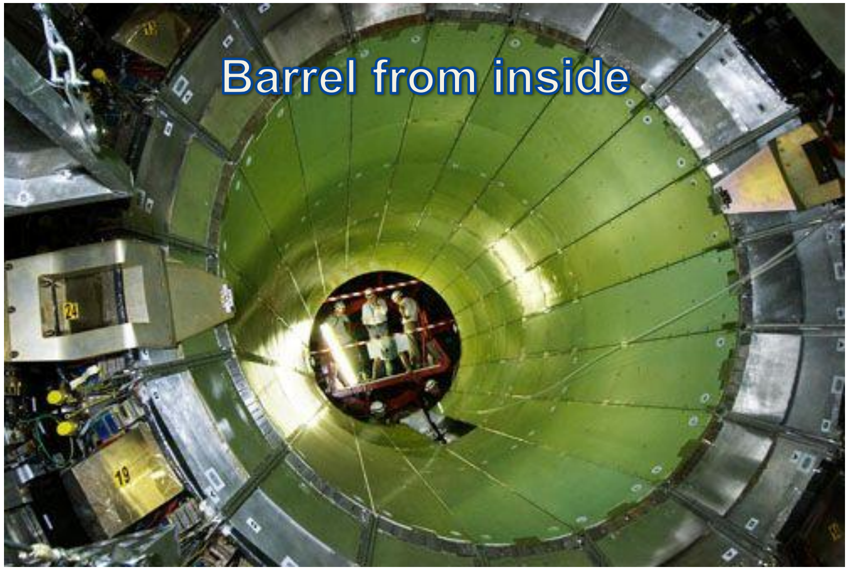
- Homogeneous, using $PbW0_4$ crystals
  - Very dense, X_0=0.89cm
  - Fast, 20ns response time
    - Needed at LHC with its 25ns bunch crossing rate
  - good radiation tolerance
  - Very sensitive to temperature
    - Need extremely sophisticated T control, to within ±0.1°C
  - Limited LY w.r.t. other crystals
    - ≈ 100 photons/MeV



$PbWO_4$ ingots and machined crystals



CMS calorimeter



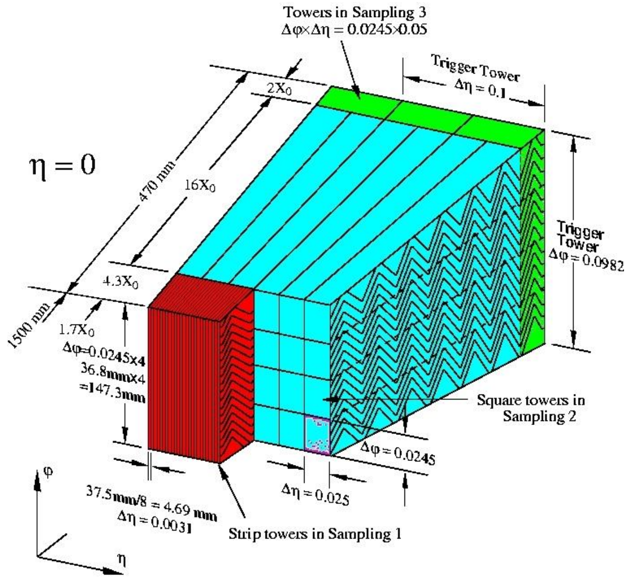
- 80 thousands crystals, 2.2×2.2×23cm (26X_0)

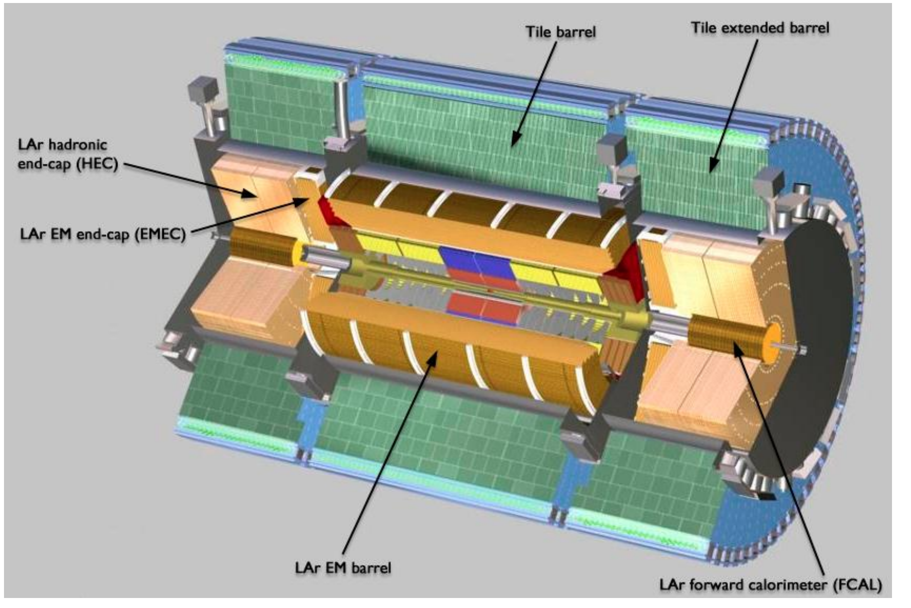
$$\frac{s(E)}{E} = \frac{2.75\%\left[GeV^{1/2}\right]}{\sqrt{E}} \oplus \frac{150\,MeV}{E} \oplus 0.5\%$$

$(E \text{ in } GeV)$

- Extremely good resolution

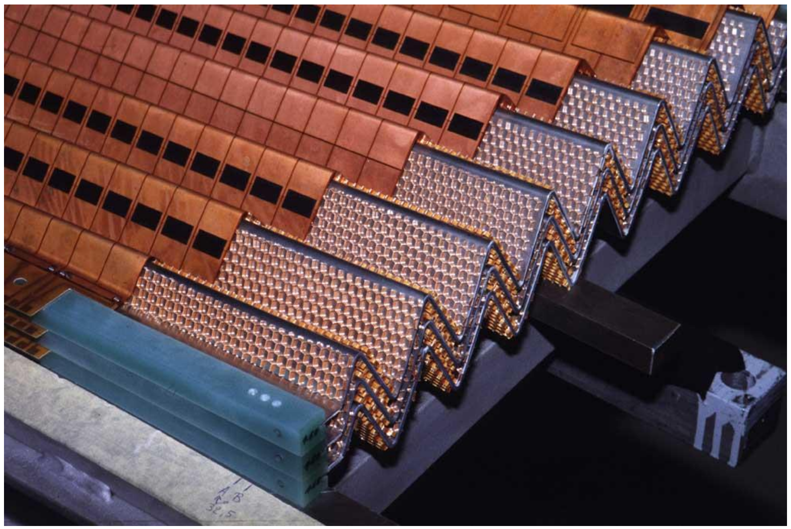
Atlas EM calorimeter





- LAr sampling calorimeter
  - “accordion” geometry, segmented in 3 regions
    - S1 (Strips) $6X_0$: angle and position measurement
    - S2 (Middle) $16X_0$ main energy measurement
    - S3 (Back) $2X_0$ “tail catcher”

Atlas calorimeter



resolution

$$\frac{s(E)}{E} = \frac{10\%\left[GeV^{1/2}\right]}{\sqrt{E}} \oplus \frac{300\,MeV}{E} \oplus 0.7\%$$

$(E \text{ in } GeV)$

- Advantages
  - Radiation hard
  - Fine longitudinal and transverse segmentation
  - No cracks, good uniformity

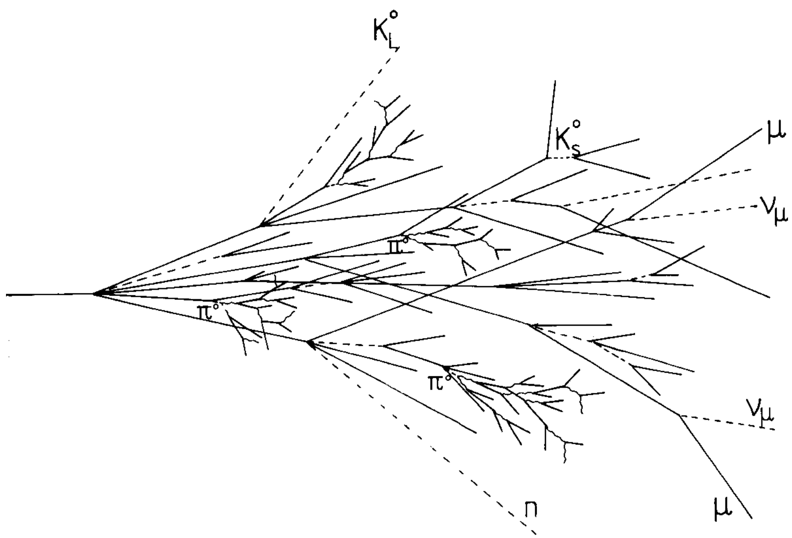
Summary of EM calorimeters

Technology (Exp.)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2/\%\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

Homogeneous

Sampling

Hadron calorimeters



- Energetic charged and neutral hadrons interact with nuclei of the absorber, giving rise to a particle shower

$$\sigma_{inel} \approx \sigma_0 A^{0.7} \qquad \sigma_0 \approx 35\ mb$$

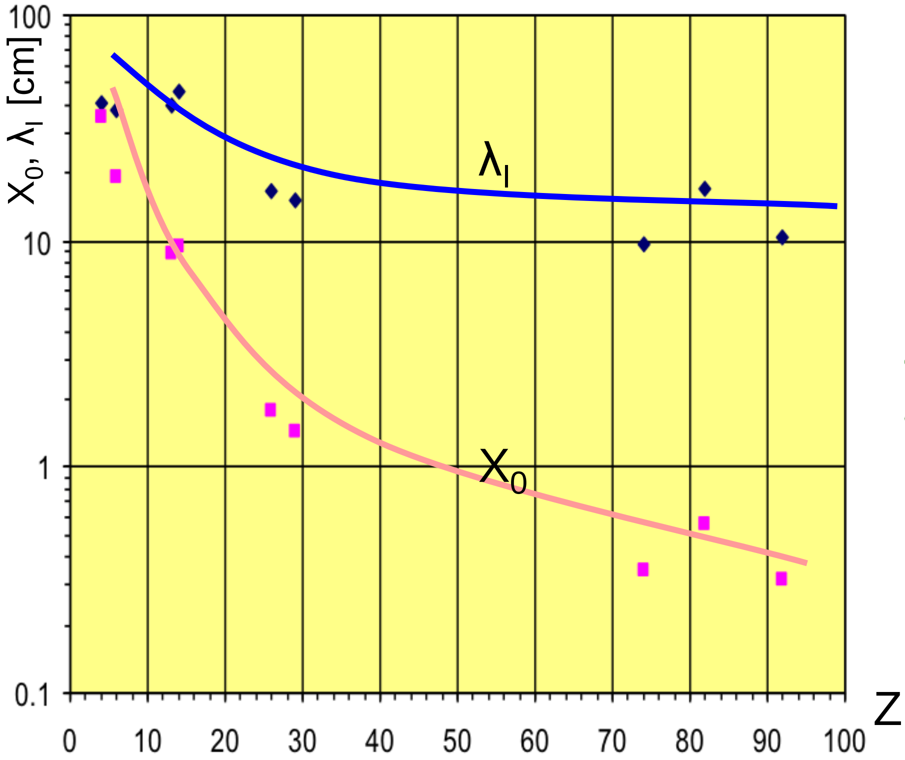
$$\lambda_I = \frac{A}{N_A \sigma_{inel}} \approx \frac{A}{N_A \sigma_0 A^{0.7}} \approx \frac{A^{1/3}}{N_A \sigma_0}$$

$$N = N_0 e^{-\frac{x}{\lambda_I}}$$

- The interaction probability is governed by a formula similar to the photon, with λ_I replacing X_0.
- λ_I is the mean distance travelled by a hadron before undergoing an inelastic nuclear collision

- $\lambda >> X_0$
- Hadron showers are much longer and larger than EM
- processes much less homogeneous than in the EM shower

Hadron calorimeters

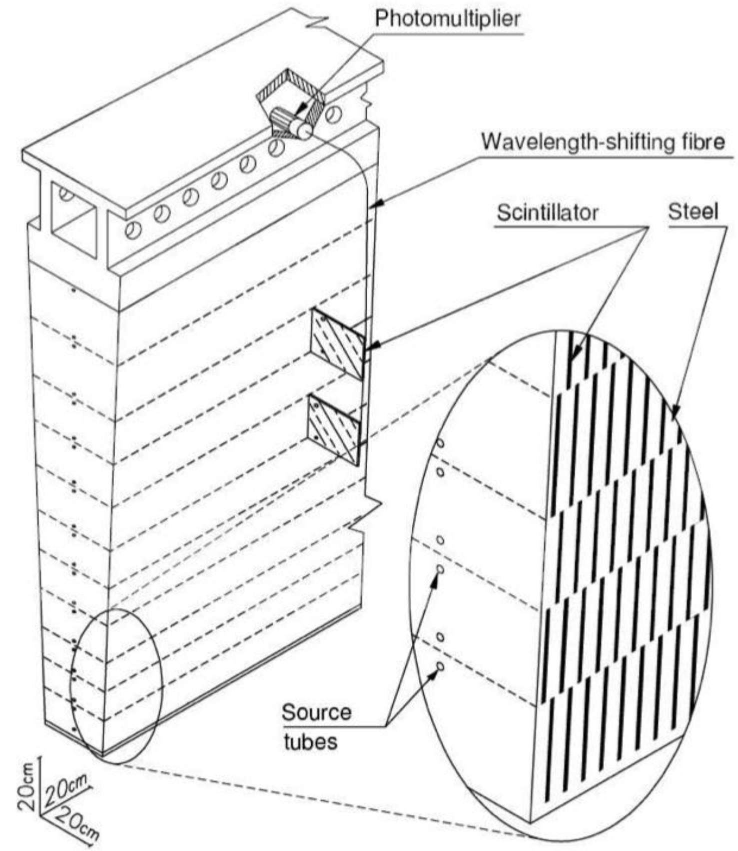


- λ_I is flatter in Z for high Z

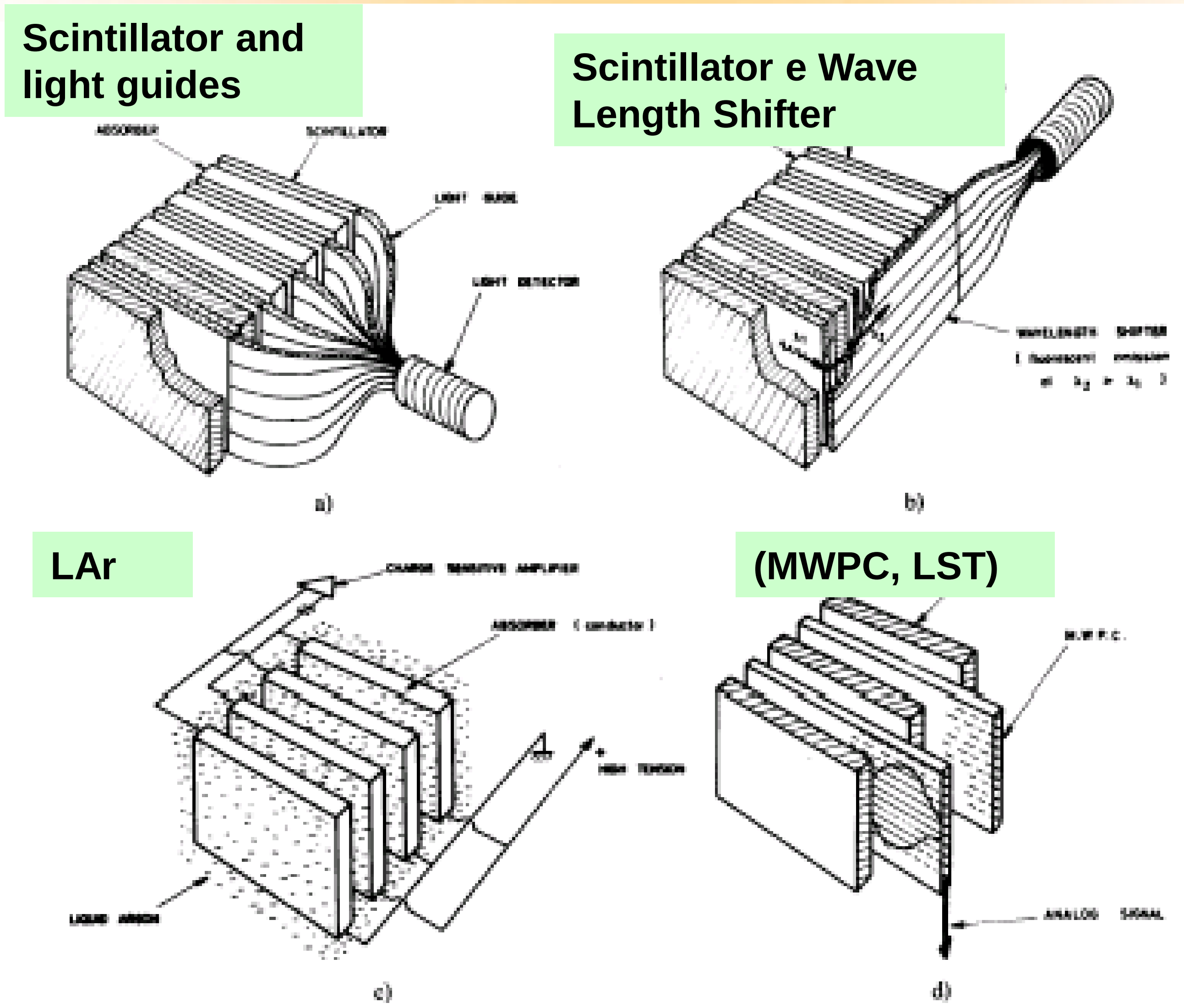
Material	Z	A	ρ [g/cm^3]	X_0 [g/cm^2]	λ_a [g/cm^2]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0

Hadron calorimeters

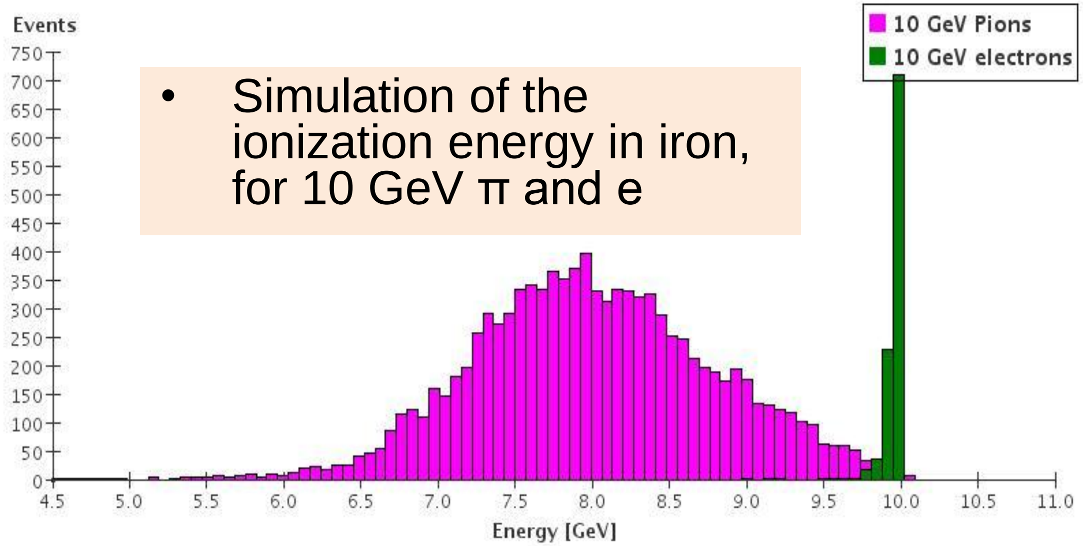
- All hadron calorimeter are sampling
  - Showers are too long and large
  - Some fraction of the energy is not detectable
    - Neutron from spallation and nuclear evaporation
    - Nuclear recoils
    - Weak decays with neutrinos and muons production
  - The fraction is variable (20% - 35%) so the resolution is intrinsically limited



Hadron calorimeters



Hadron calorimeters



- Simulation of the ionization energy in iron, for 10 GeV π and e

- The response e/h to hadrons and electron is very different
  - e/h = 1.2 – 1.5
- When π_0 are produced, their decay into γγ transform a fraction of the shower into EM
  - This fraction is variable and influences a lot the resolution
  - electromagnetic fraction f_e is very important for the resolution
- Usually resolutions ≈60%/√E

Compensating calorimeters

- A solution to f_{em} problem
  - Compensating calorimeter: e/h=1
    - Reduce EM signal
      - As σ_{EM} grows faster with Z than σ_{HAD} (see X0 vs λ_I), increasing high Z absorber thickness w.r.t the active part reduces e/h
    - Increase hadron signal
      - Use detector containing hydrogen (plastic scintillator) to increase sensitivity to fast neutrons

- Zeus built a Uranium-scintillator compensating calorimeter
  - 3.3mm U
  - 2.5mm scintillator

$$\frac{s(E)}{E} = \frac{35\%}{\sqrt{E[GeV]}} \oplus 2\%$$

  - NB the compensation has nothing to do with the nuclear properties of the uranium

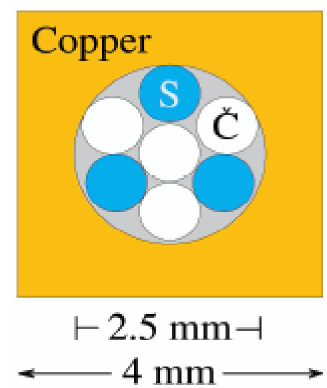
Dual-readout calorimeter

- Two independent readouts with very different e/h
  - Scintillator
    - Sensitive to all charges
  - Quartz fibres
    - Generate Cherenkov light, so more sensitive to relativistic electrons of the EM showers
  - One gets two signals Q,S

$$Q = E\left[f_{em} + \left.\frac{h}{e}\right|_Q \left(1 - f_{em}\right) \right] \qquad S = E\left[f_{em} + \left.\frac{h}{e}\right|_S \left(1 - f_{em}\right) \right]$$

  - Solving one gets E and f_{em}

DREAM



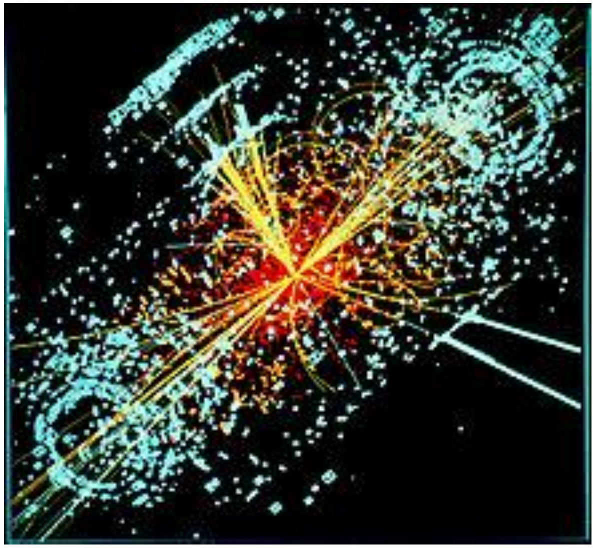
$$\frac{\sigma(E)}{E} = \frac{36.9\%}{\sqrt{E}} \oplus 1\%$$

Particle-flow calorimetry

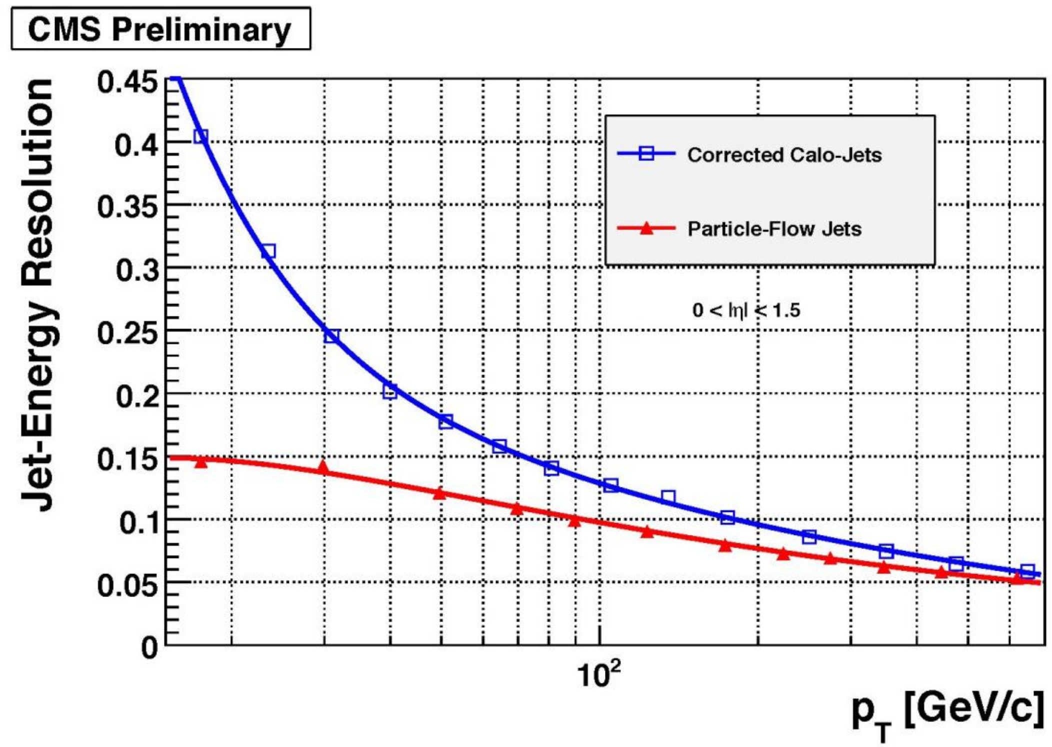
- In modern experiments the hadron calorimeters mostly measure energy from Jets
    - 60% of energy in charged hadrons
    - 30% in photons (mostly from $\pi_0 \rightarrow \gamma\gamma$)
    - 10% in neutral hadrons
  - With large variations
- Profit from the other detectors
  - Charged particles measured in the central tracker (very well)
  - Photon measured in the EM calorimeter
  - Neutral hadrons have to be measured in the hadron calorimeters

- Only the latter suffer of the bad H-CAL resolution
  - overall much improved resolution

- Easy to say
  - One has to disentangle the different particles contributing energy in the calorimeter
  - Need high granularity

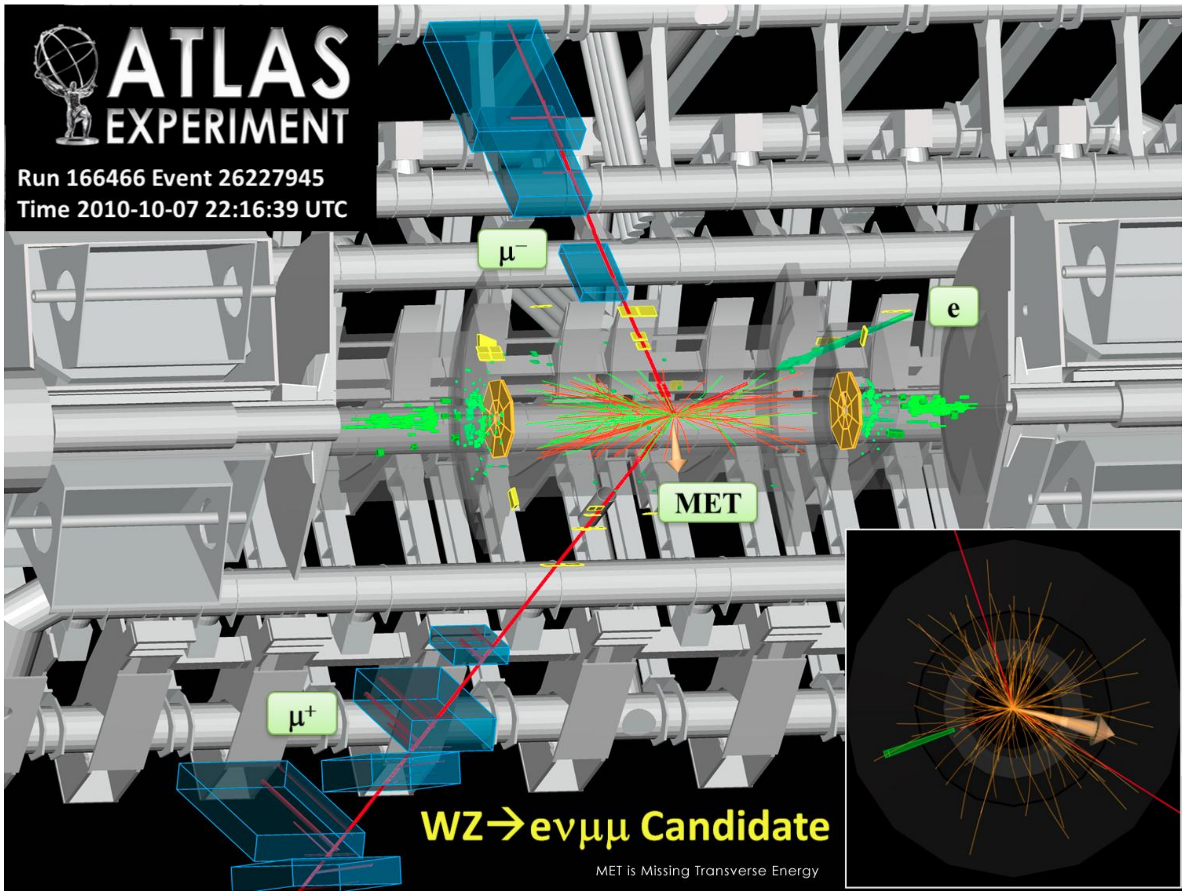


Particle-flow calorimetry



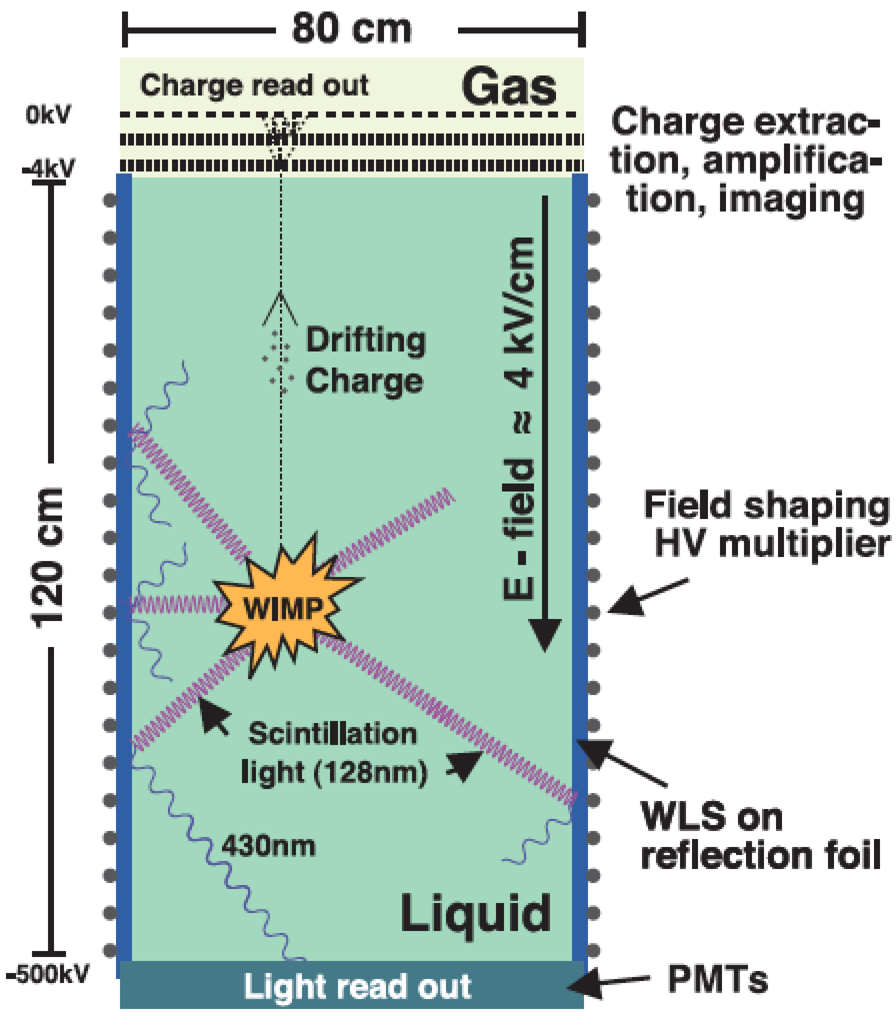
- It works
  - And it is routinely used, also at high trigger levels

Neutrinos



- What about neutrinos?
  - Energy escapes
  - vector sum of the energy and identifies the missing transverse energy (MET)
- Need an hermetic detector

Double-phase calorimeters



- Noble gases (Ar,Xe) can be used as
    - Ionization chambers in liquid phase
    - Gas chamber
    - Scintillator
- **Or all three together**
    - Double phase detectors: the liquid works as drift volume of a TPC, here the amplification is done in the upper area in gas phase
        - Measurement of x,y (gas) z (drift) position of the hit
    - The hit generates also scintillation light in Ar, at very small λ=128nm
        - Light is shifted to 430nm by a WLS covering the wall
        - And readout by PMTs on the bottom

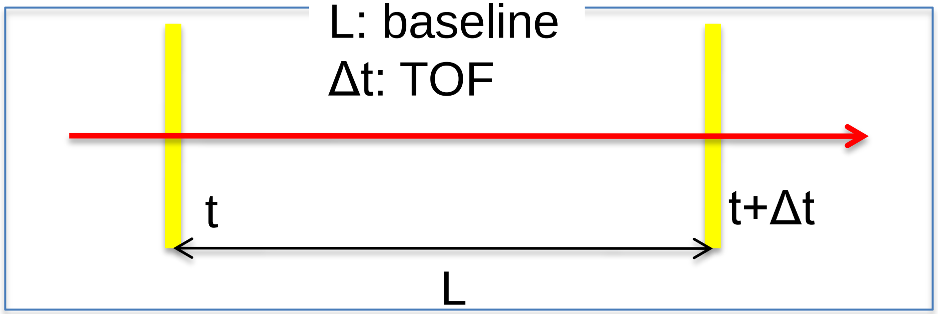
PARTICLE ID

PID

- Identification of a particle, measuring p and another kinematical quantity
    - Mostly β, sometimes γ
  - Time of flight (TOF)
  - dE/dx
  - Cherenkov
  - TRD

- Other ways to identify particles
  - EM Shower
    - e (charged)
    - γ (neutral)
  - Penetration through thick material
    - μ
  - Missing E_T
    - ν

TOF



$$\frac{L}{\Delta t} = \beta c = \frac{pc^2}{E} = c^2 \frac{p}{\sqrt{p^2c^2 + m^2c^4}} = c\frac{p}{\sqrt{p^2 + m^2c^2}}$$

$$\frac{\Delta t}{L} = \frac{1}{c}\sqrt{\frac{p^2 + m^2c^2}{p^2}} = \frac{1}{c}\sqrt{1 + \frac{m^2c^2}{p^2}}$$

$$\text{per } \frac{m^2c^2}{p^2} << 1 \text{ one has } \sqrt{1 + \frac{m^2c^2}{p^2}} \approx 1 + \frac{m^2c^2}{2p^2}$$

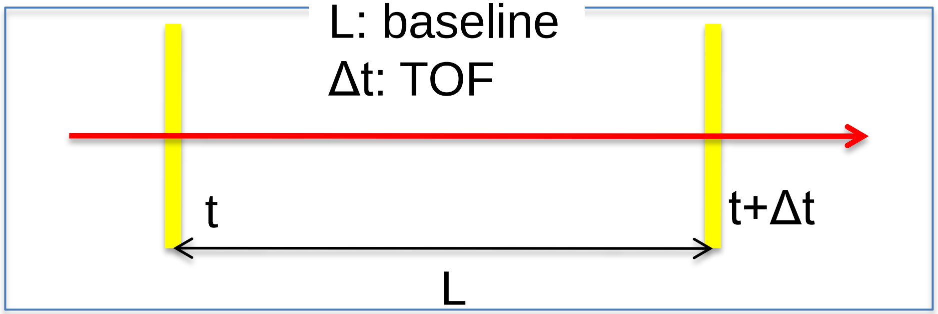
- If one has two particles selected with the same momentum and different masses m_1 and m_2

$$\Delta t_1 - \Delta t_2 = \frac{L}{c}\left(1 + \frac{m_1{}^2c^2}{2p^2} - 1 - \frac{m_2{}^2c^2}{2p^2}\right)$$

$$\Delta t_1 - \Delta t_2 = \frac{Lc}{2p^2}\left(m_1{}^2 - m_2{}^2\right)$$

- TOF is a function of the difference of the masses squared, decreases with p^2

TOF



- Example
  - σ_T=100ps, consider the signal distinct when $\Delta T \geq 4\sigma_T$
  - What is the baseline L to distinguish 1GeV π from k

$$m_k \approx 0.5 GeV/c^2 \quad m_\pi \approx 0.14 GeV/c^2$$

$$\frac{\Delta t_k - \Delta t_\pi}{L} \approx \frac{5}{3}\frac{\left(m_1{}^2 - m_2{}^2\right)}{p^2} \approx 0.4\, ns/m$$

- L=1m

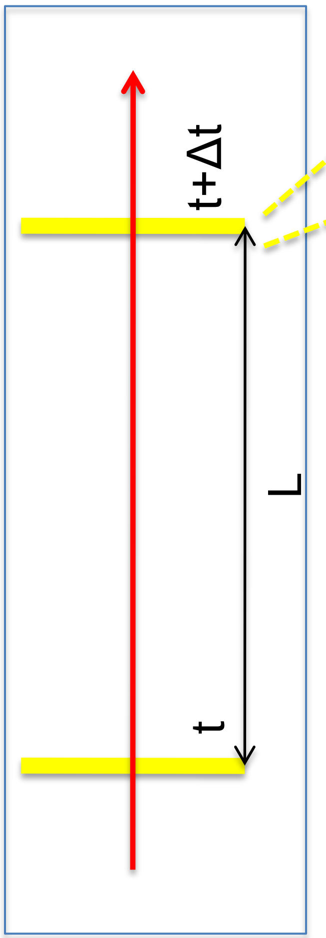
$$\Delta t_1 - \Delta t_2 = L\frac{c}{2}\frac{\left(m_1^2 - m_2^2\right)}{p^2}$$

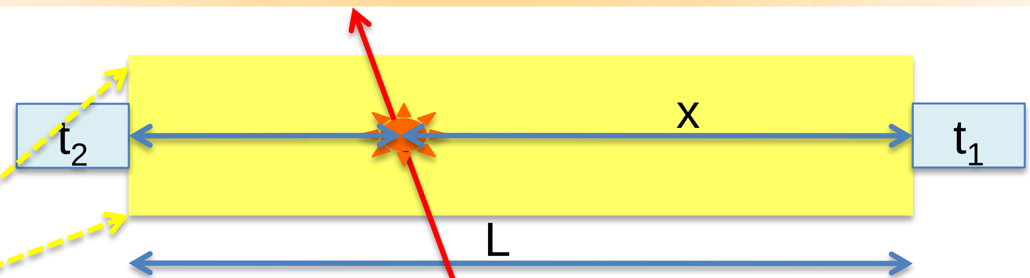
- Measuring TOF in ns, L in meters, m in GeV/c²:

$$\Delta t_1 - \Delta t_2 = L\frac{1}{2c}\frac{\left(m_1^2 - m_2^2\right)}{p^2} \approx L\frac{5}{3}\frac{\left(m_1^2 - m_2^2\right)}{p^2}$$

Time separation is function of 1/p², at high momenta need very long baseline or extreme time resolutions

TOF





- Problem: propagation time in the scintillator if the scintillator is long
  - Would worsen time measurement precision

$$t_1 = t_0 + \frac{x}{v} \qquad t_2 = t_0 + \frac{L - x}{v}$$

t_0 impact time
v= velocity of light in the scintillator ≈ c/2

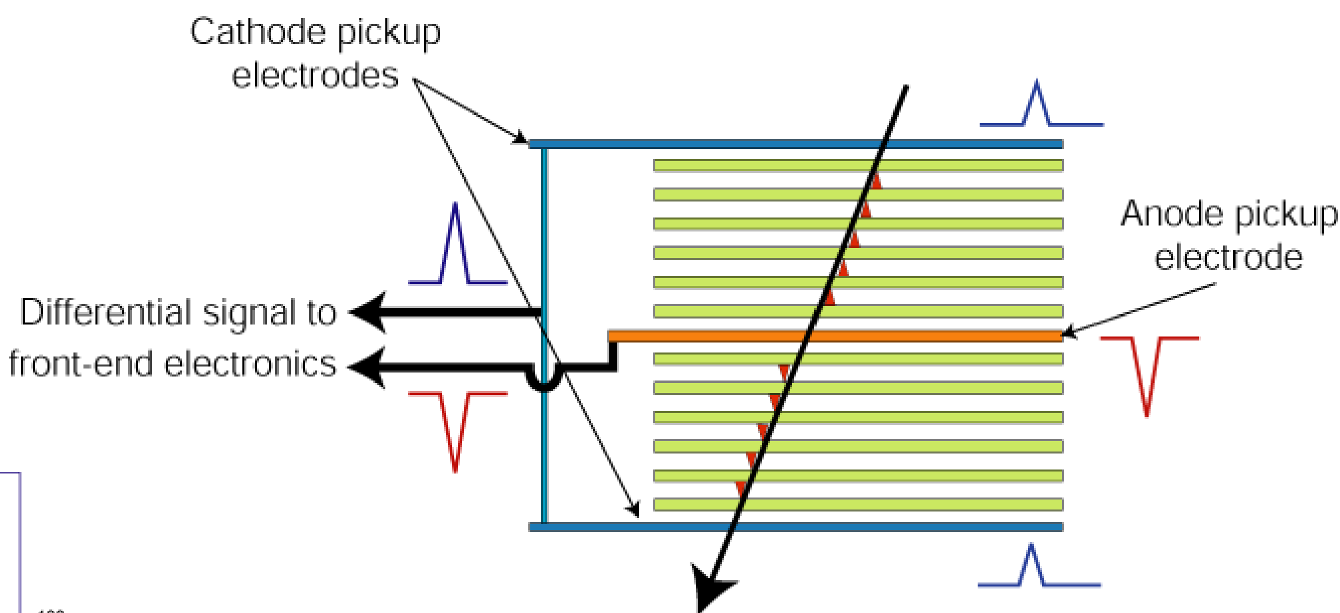
$$t_1 + t_2 = 2t_0 + \frac{L}{v} \rightarrow t_0 = \frac{t_1 + t_2 - \frac{L}{v}}{2} \qquad t_2 - t_1 = \frac{L}{v} - \frac{2x}{v} \rightarrow x = \frac{v}{2}\left(\frac{L}{v} + t_1 - t_2\right)$$

  - Measuring on both sides gets both <u>mean time</u> and position along the scintillator

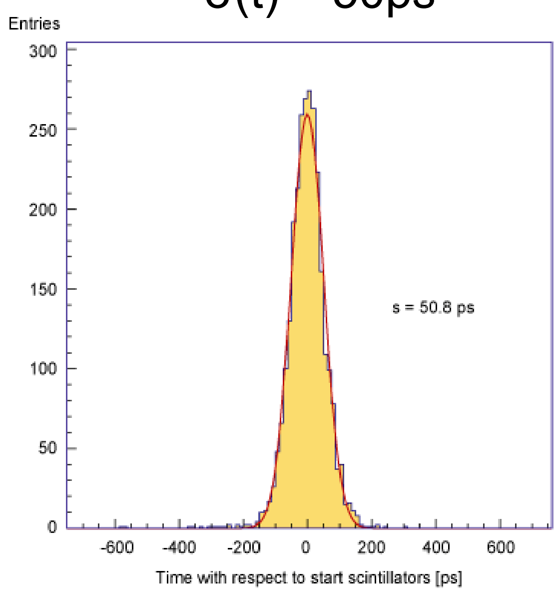
$$s(t) = 100\,ps \rightarrow s(t_1 - t_2) = 150\,ps$$

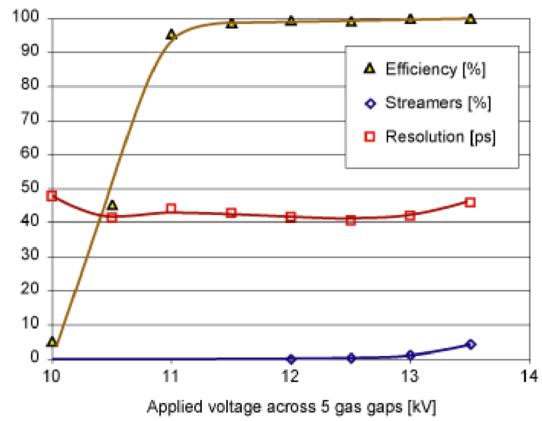
$$s(x) = \frac{v}{2} s(t_1 - t_2) = \frac{c}{4} \times 0.15 \cdot 10^{-9} \approx 1cm$$

ALICE at LHC: TOF with multi-gap RPC

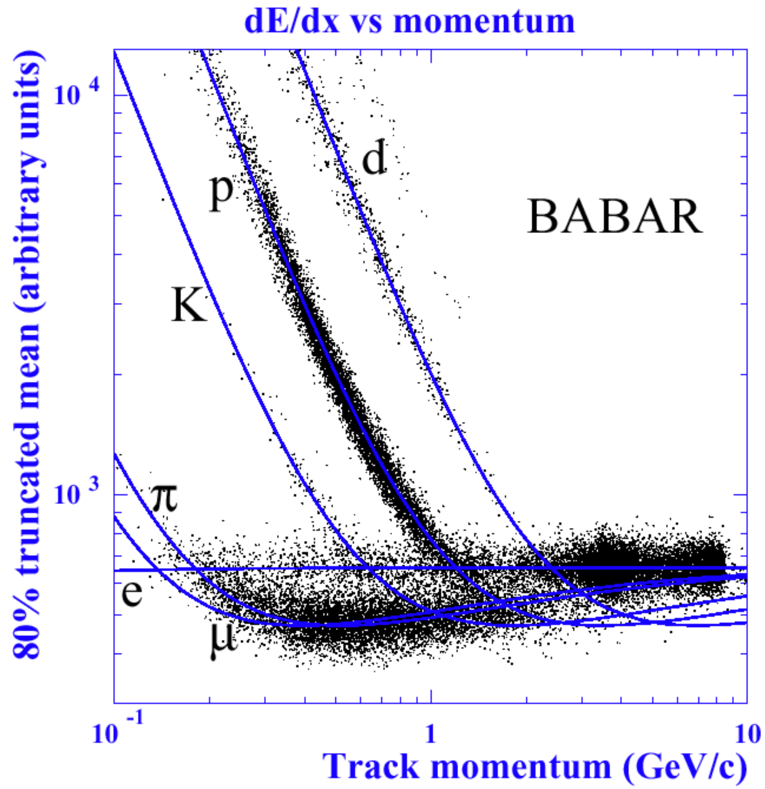


σ(t) ≈ 50ps



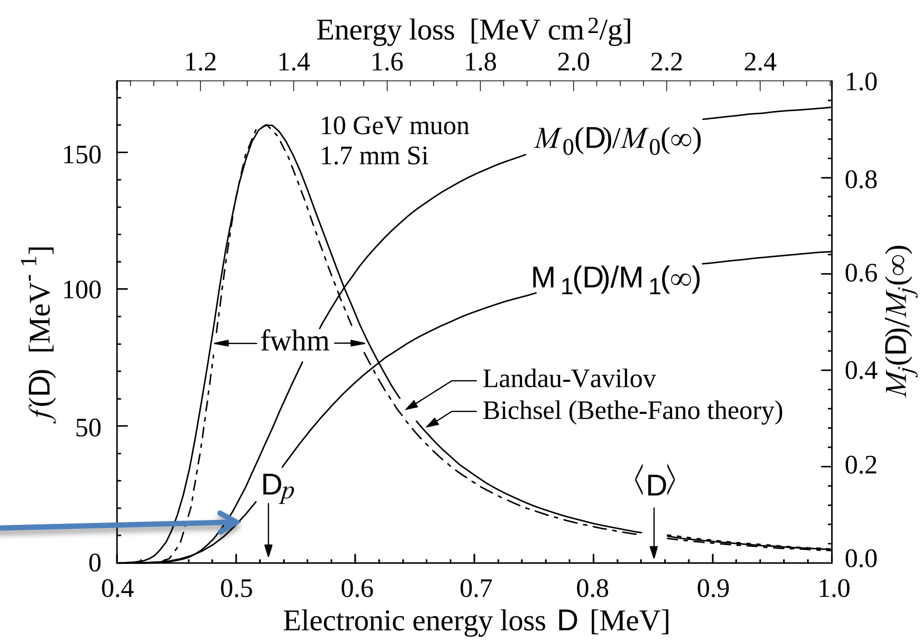


PID with dE/dx

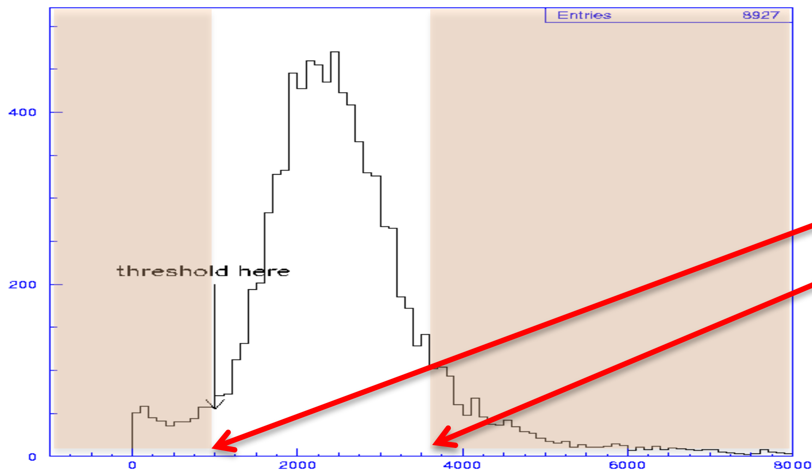


- Often as by-product of the momentum measurement in a tracking detector
  - Many thin samples (≈ 1cm Ar)
  - Large statistical fluctuations

- Landau distribution of energy loss in a think material layer
  - Long tails, most probable value is much lower than average



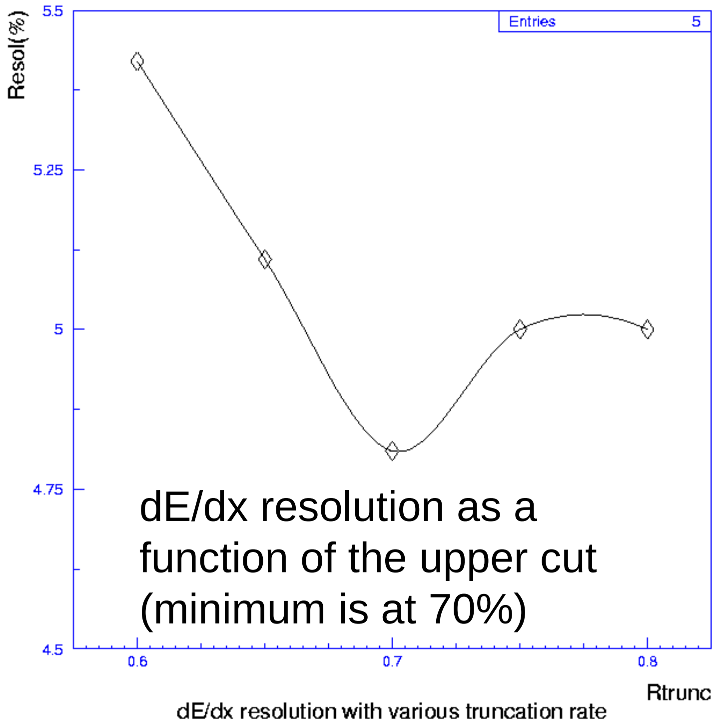
dE/dx truncated mean



dE/dx (arbitrary unit)

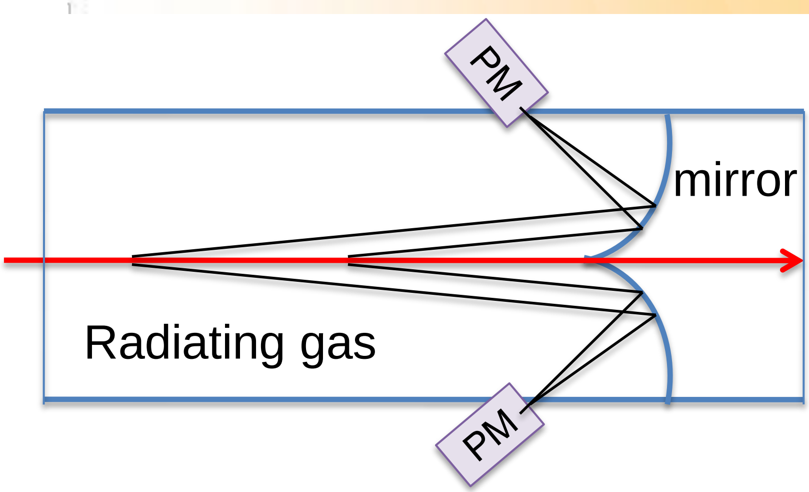
Many measurement/track, one can use selection cuts

- Lower cut removes noise
- Higher cut removes tails



dE/dx resolution as a function of the upper cut (minimum is at 70%)

Cherenkov



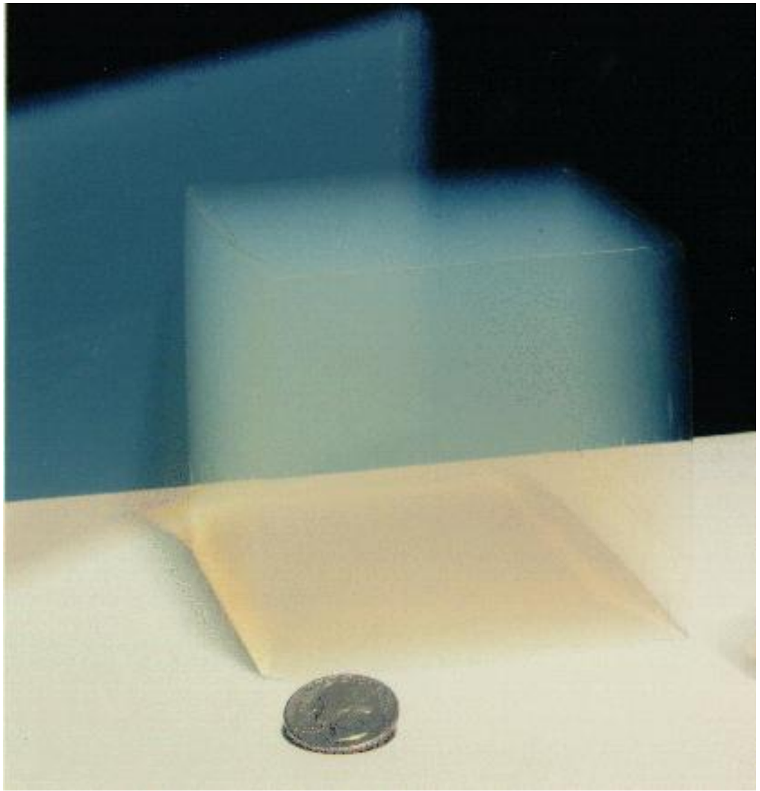
$$\frac{dN}{dx} = 2\pi\alpha z^2 \cdot \sin^2\theta_C \cdot \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

for z=1, $\lambda_1 = 400nm$, $\lambda_2 = 700nm$

$$\frac{dN}{dx} = \frac{490}{cm} \cdot \sin^2\theta_C \qquad \left(\cos\theta_C = \frac{1}{n\beta}\right)$$

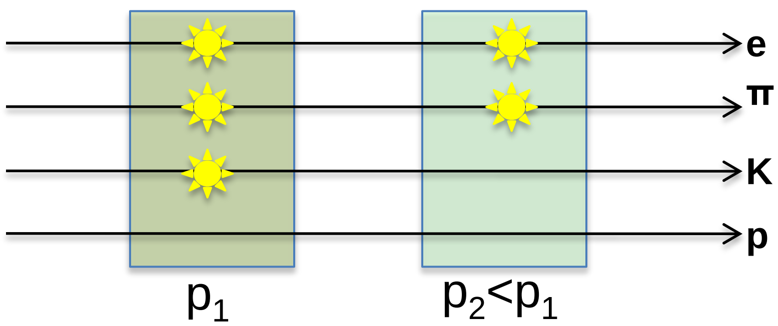
- Threshold Cherenkov
  - Given the refraction index n, only particles with $\beta > \beta_{min} = 1/n$ give signal
    - Glass, Plexiglas: n=1.5
      - $\beta_{min}=0.67$, $\gamma_{min}= 1.37$
    - Water: n=1.33
      - $\beta_{min}=0.75$ $\gamma_{min}= 1.52$
    - Aerogel n=1.007÷0.13
      - $\beta_{min}=0.993 \div 0.884$, $\gamma_{min}= 8.5 \div 2.1$
    - Air STP: n=1.0003
      - $\beta_{min}=0.9997$, $\gamma_{min}=41.2$
      - $n \approx 1+\alpha p$, can use pressure to tune the threshold in β

Aerogel



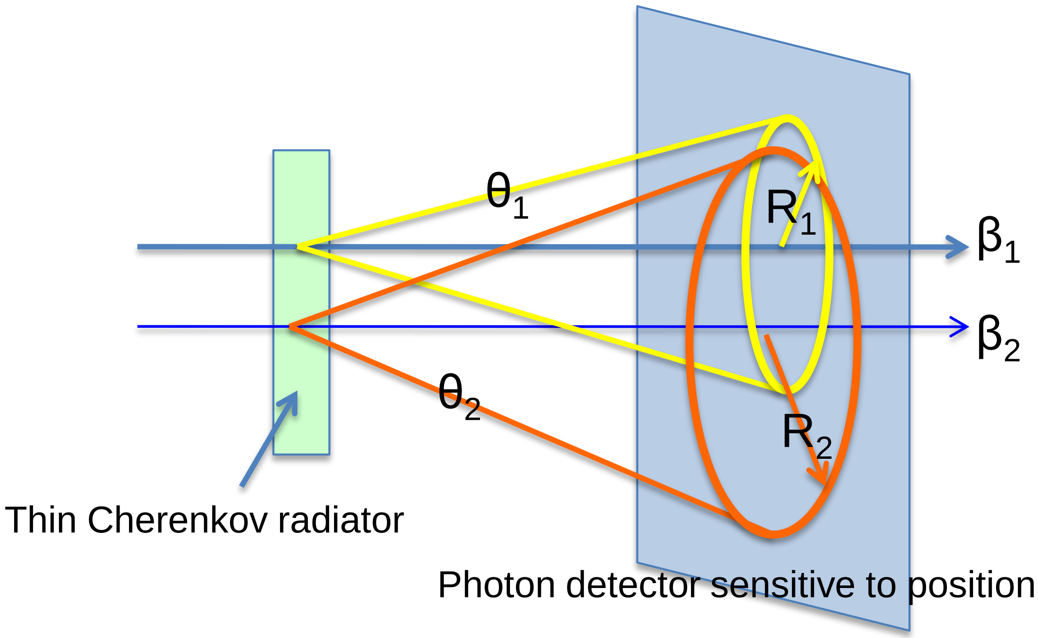
- Silica aerogel
  - “frozen smoke”
  - n function of density
    - $n \approx 1+0.21\rho$
  - Mostly used industrially as thermal ultra-insulator

Cherenkov



- Cascades of Cherenkov detectors
  - Different thresholds
  - Can tag different particles
  - Lightest particle fires the highest threshold
- Often used in secondary beam lines trigger on different particles
  - Momentum has to be selected by a bending magnet and collimator

Imaging Cherenkov

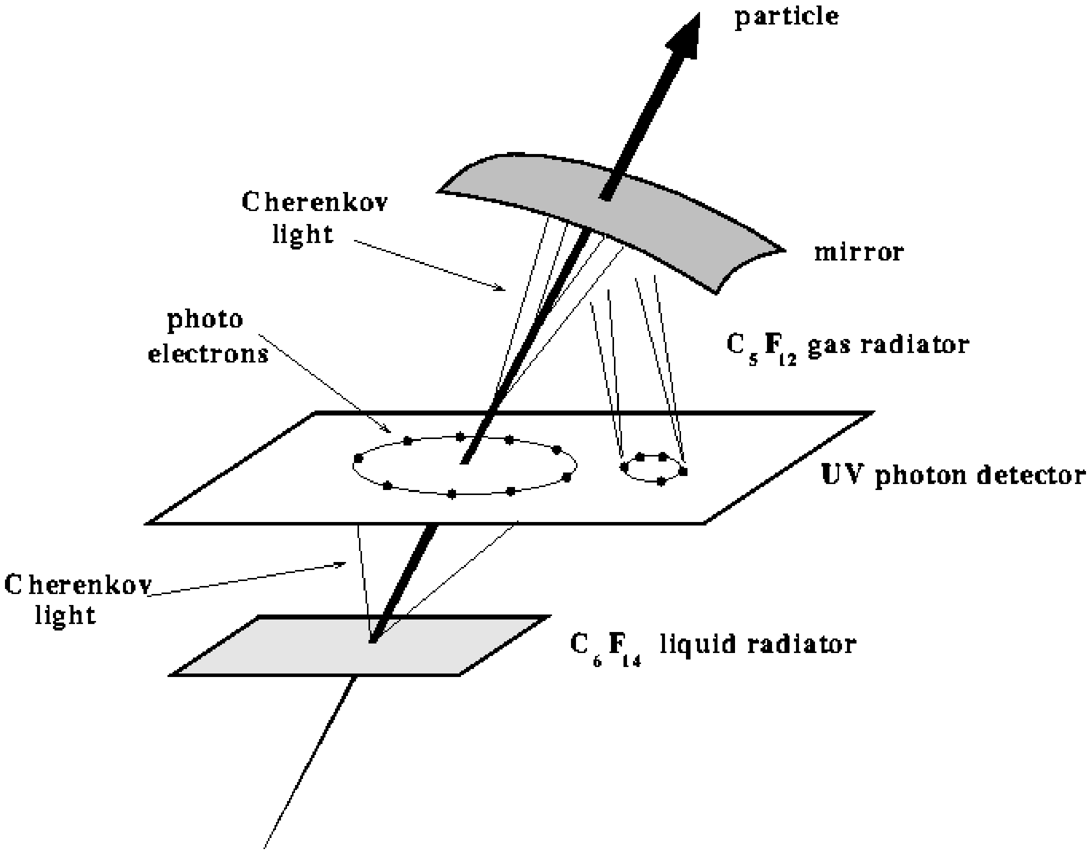


$$\cos q_C = \frac{l}{\sqrt{l^2 + R^2}} = \frac{1}{nb}$$

$$b = \frac{1}{n \cos q_C} = \frac{\sqrt{l^2 + R^2}}{\mathrm{ln}}$$

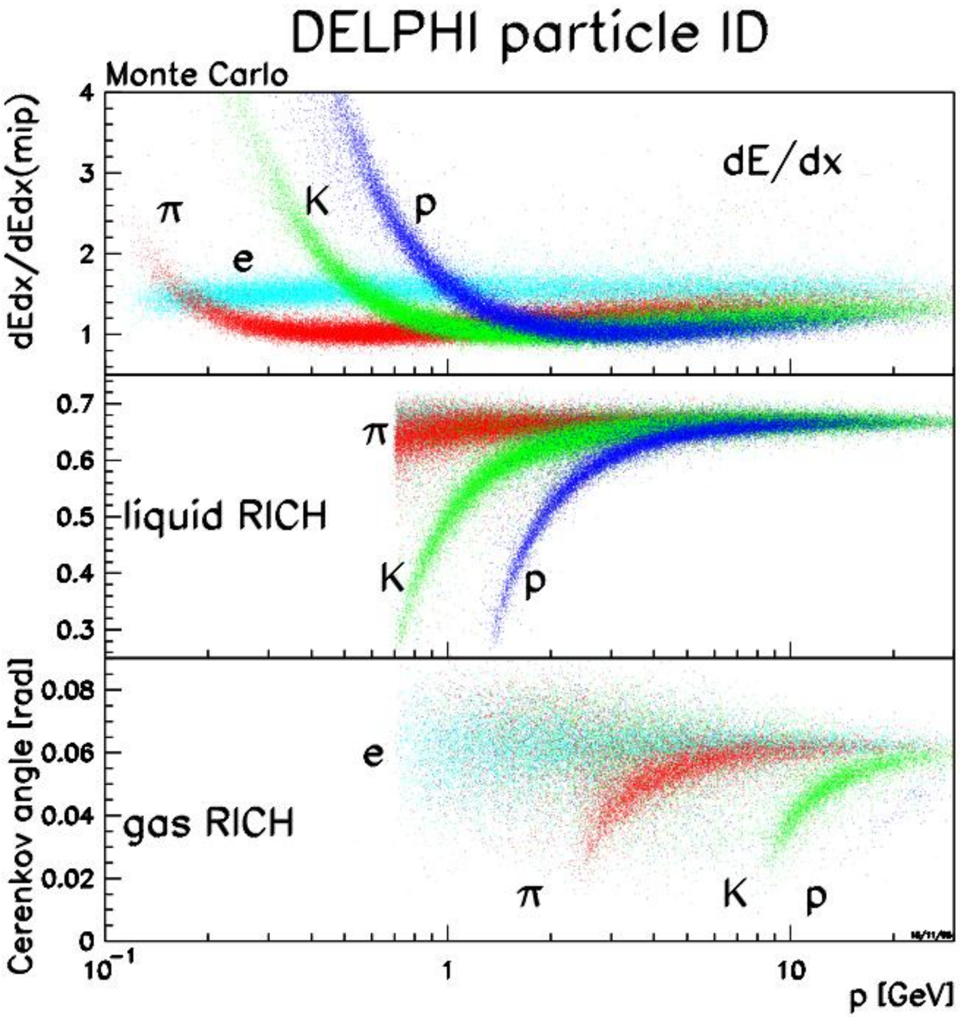
- RICH Ring Imaging Cherenkov
  - Thin radiator (proximity focusing)
  - Photons define a circle, measure ϑ_C from radius, direct measurement of β
    - Small number of photons, possible confusion between circles at high densities

Imaging Cherenkov



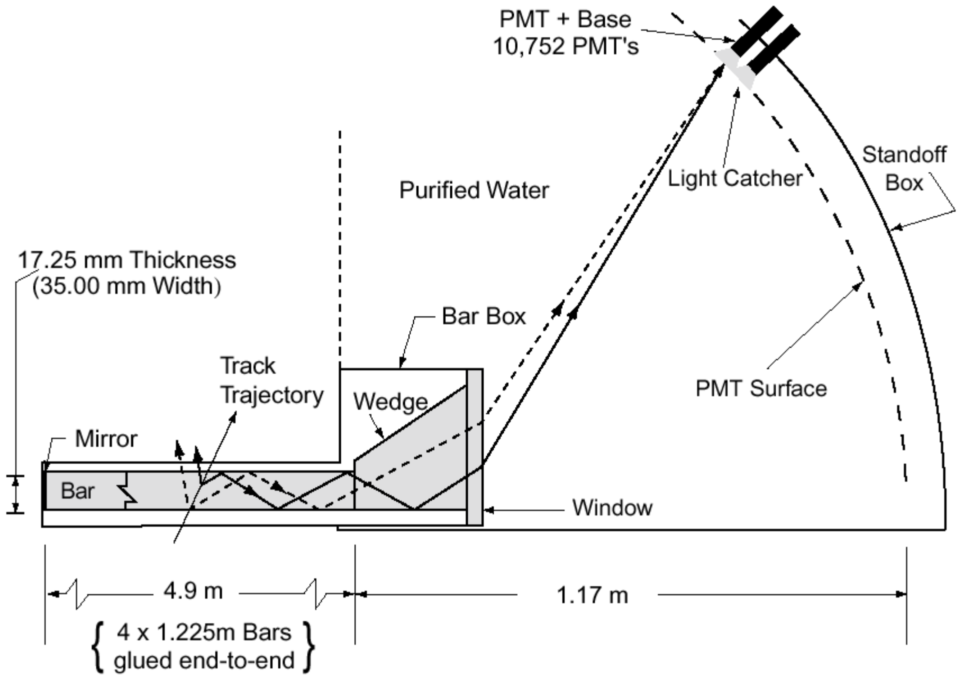
- DELPHI
  - Double radiator
    - Liquid, gas
  - Single position detector
    - Think layer converting photons to electrons (CsI) then wire chamber

Imaging Cherenkov



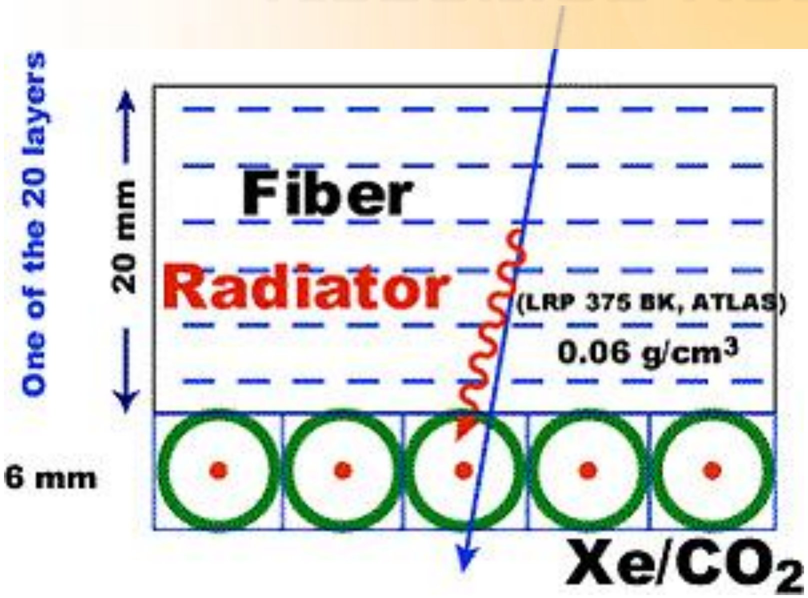
- Set of PID measurements in Delphi
  - TPC, liquid and gas RICH
  - Notice the different β range of the two RICH

Imaging Cherenkov



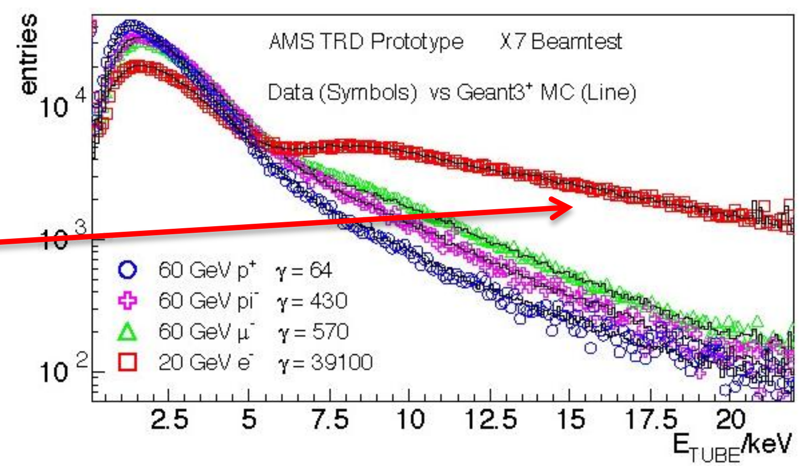
- DIRC (BaBar at SLAC)
  - Quartz fibres with internal reflection of Cherenkov light (angle is conserved)
  - External detector made of 11000 conventional PMTs

Transition Radiation Detector

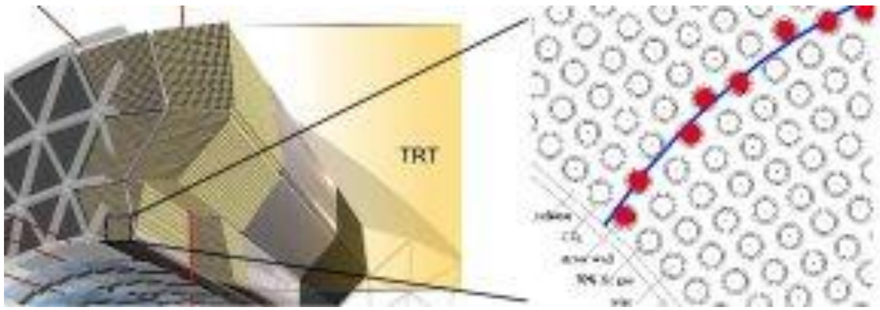


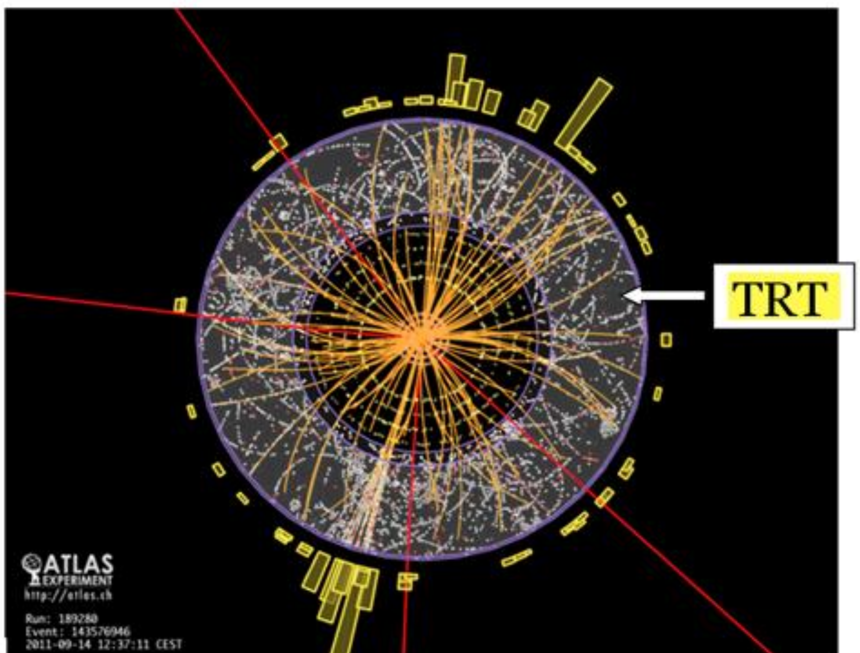
- Example of TRD (AMS)
  - Stack of many layers to increase the probability of photon emission
  - Gas detector using Xe as noble gas
    - High Z increases sensitivity to photons

TRD sensitive to Lorentz γ, suited to discriminate energetic electrons from other charged particles



Atlas TRT





- Tracking detector outside the silicon tracker
  - Straw tubes, thin (4mm diameter) cylindrical wire chambers
- Uses Xe as noble gas
- Radiators between the straws
- Energetic electrons are tagged
  - TR photons produced in the radiators are measured in the straw tubes

AN EXPERIMENT

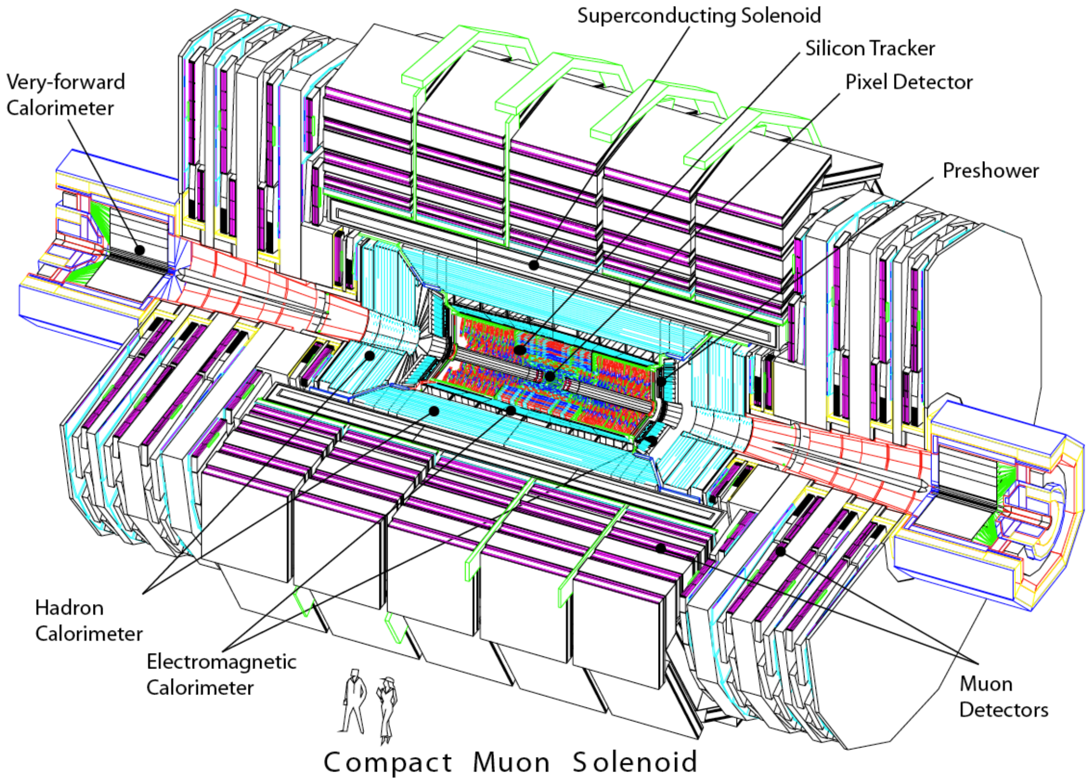
CMS

- Requirements
  - Good muon identification
    - External detector
      - Trigger
      - Momentum and position matching with track detector

$$\frac{\Delta p}{p} \approx 10\% \text{ a } 1\text{TeV} \;\rightarrow\; \frac{\Delta p}{p} \approx 10^{-4}\, p[GeV]$$

  - Good EM energy resolution
  - Good resolution for jets and MET
    - Hermeticity of the calorimeters
    - Good segmentation for PF measurements
  - Long lived particles tagging
    - High resolution pixel detector
  - Separation of vertexes in high PU events
      - High resolution pixel detector

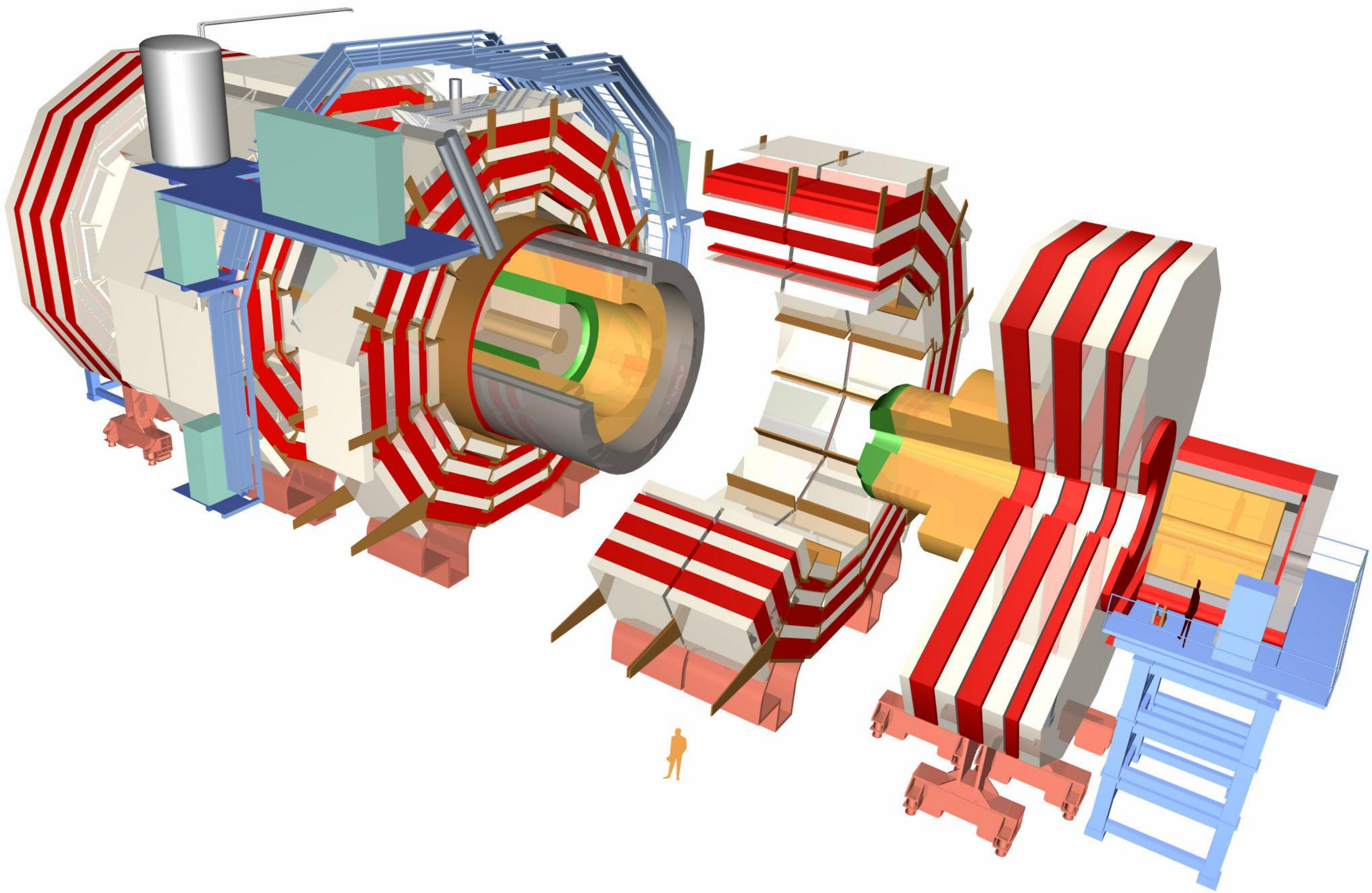
CMS



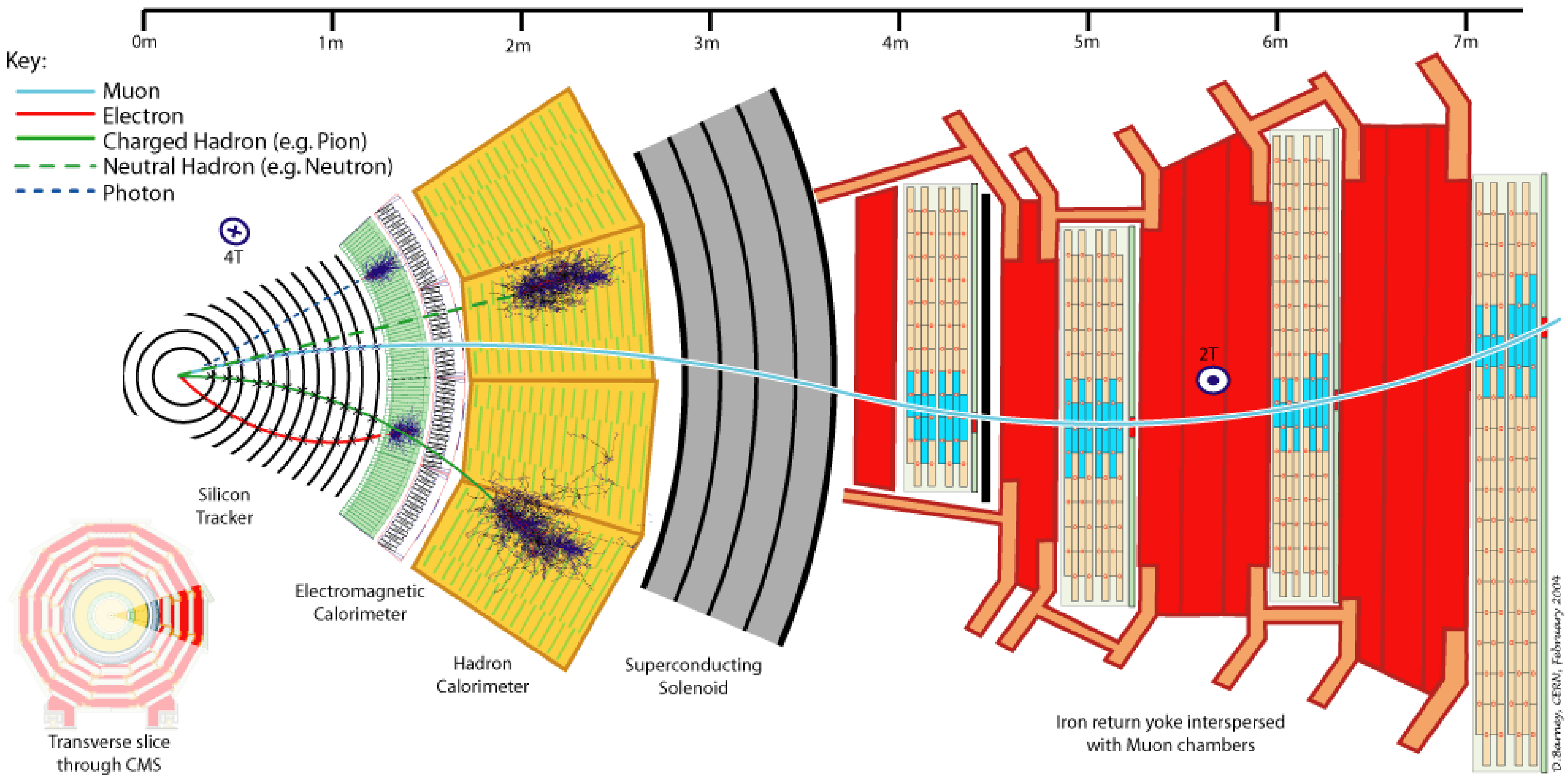
- Compact Muon Spectrometer
  - Length 21.6 m
  - Diameter 14.6 m
  - Weight 12500 tons

- It is "compact" …
  - ATLAS
    - Length 46 m
    - Diameter 25 m
    - Weight 7000 tons

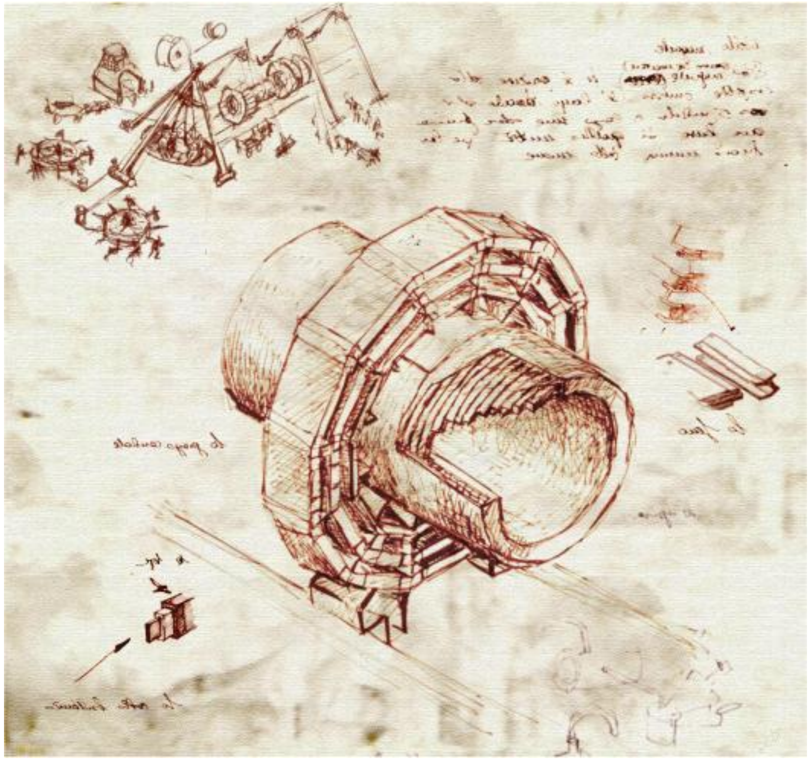
CMS



CMS: a φ sector



CMS: the magnet



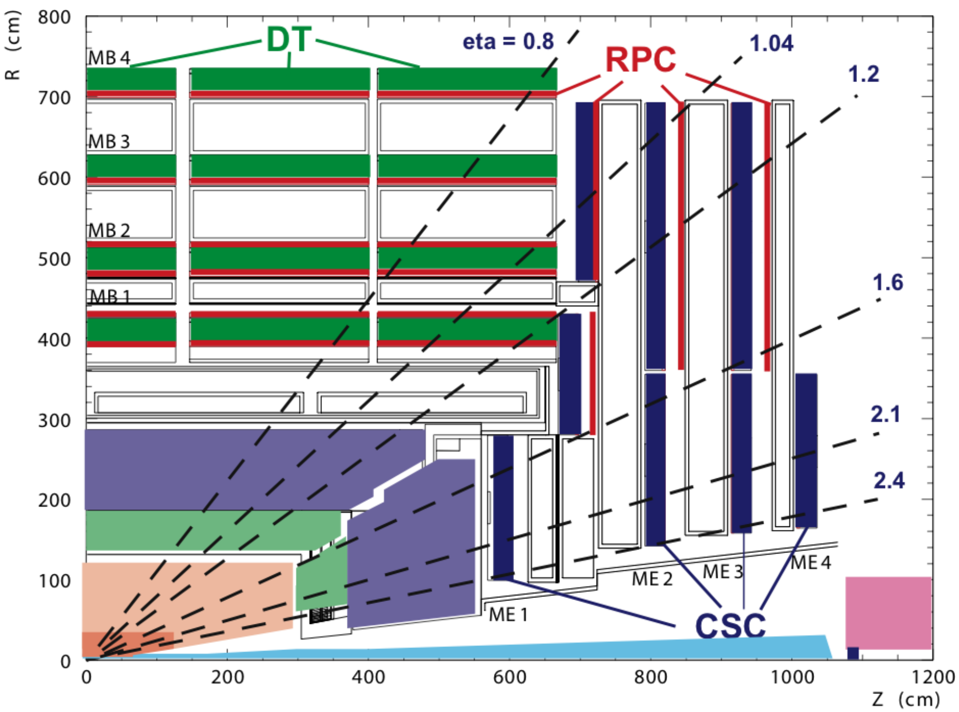
- Features of the superconducting solenoid

Magnetic field	3.8 T
Internal diameter	5.9 m
Length	12.9 m
Current	18 kA
Stored energy	2.7 GJ

- Very large magnet
  - Tracker and full calorimetry inside

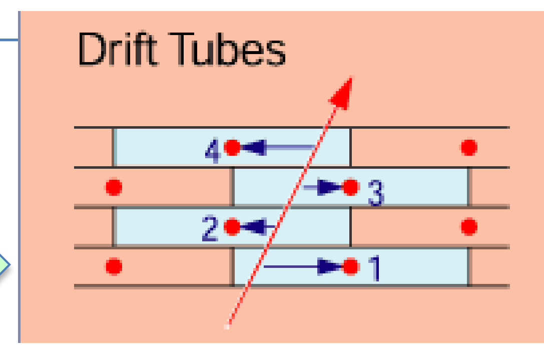
- The return flux of the magnet magnetizes also the iron yoke of the muon detector
  - Differently from Atlas which uses a large toroid magnet system, with muon bending in air

CMS: the muon detectors

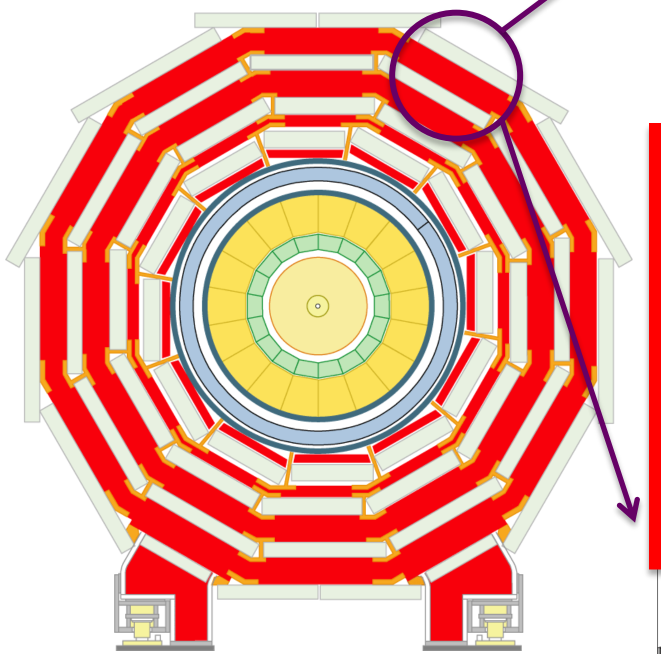


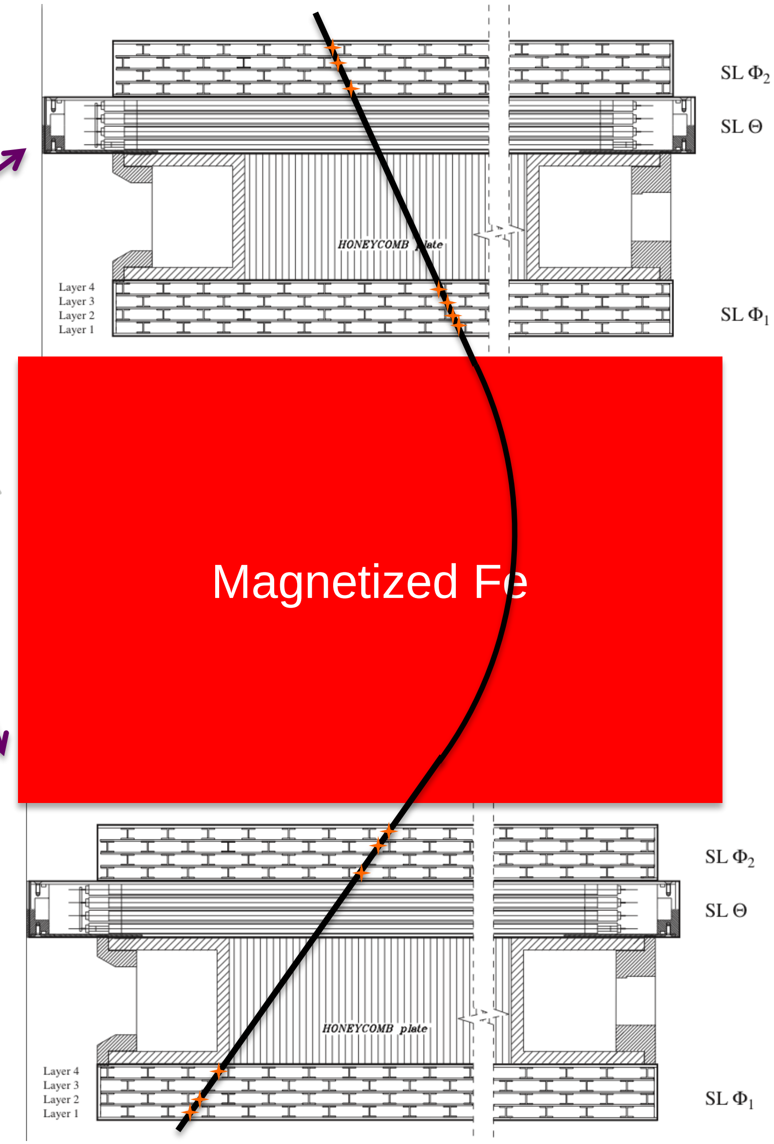
- Barrel
  - 4 station of drift chambers
    - Each measuring bending with 4+4 planes
  - 6 planes of RPC chambers
- End-caps
  - 4 stations of MWPC
  - 3 planes of RPC
- Trigger
  - All system contribute to the trigger
  - RPC are very fast, redundant trigger with very good bunch discrimination

- In the barrel the drift chamber have 400ns drift time, but can identify the collisions at 25ns using a special geometry arrangement of the channels
  - "mean timer" used in the first level fast trigger



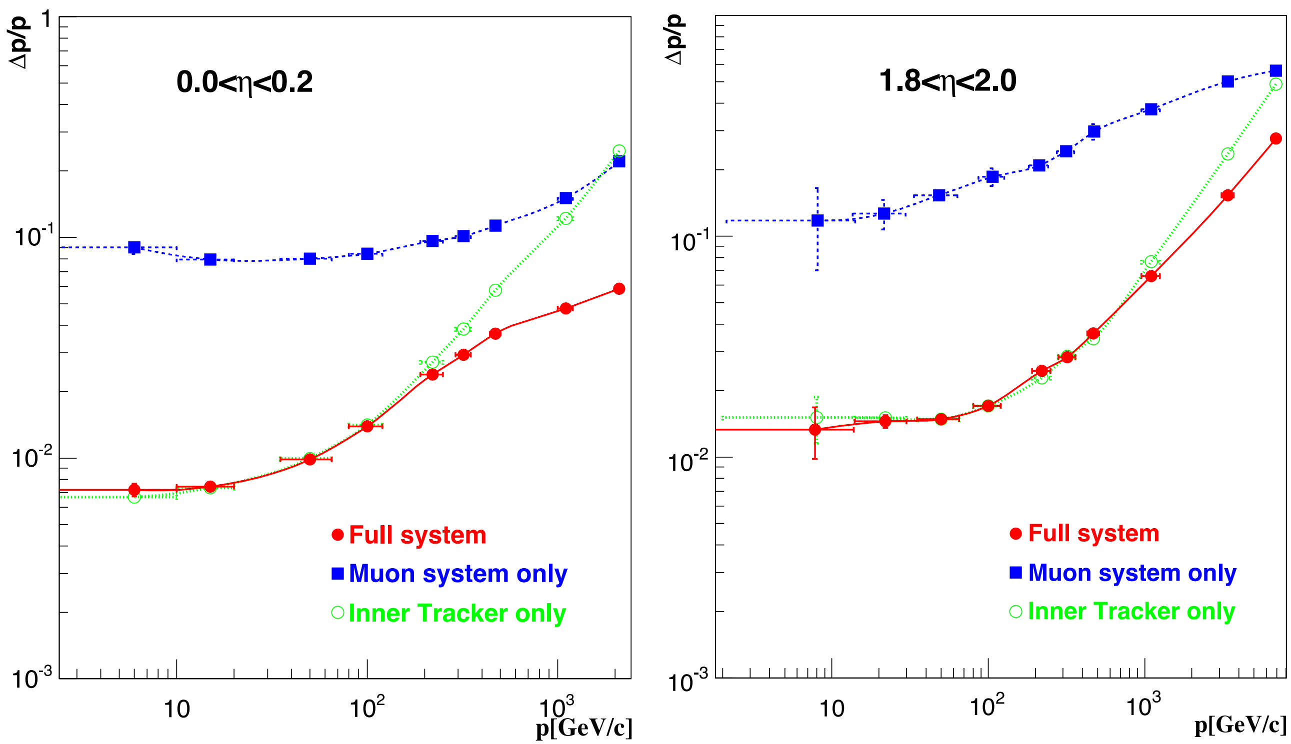
CMS: barrel muon





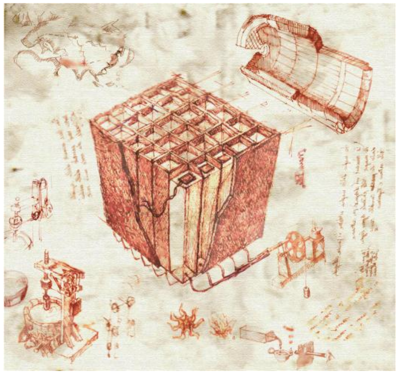
- Bending measurement with drift chambers

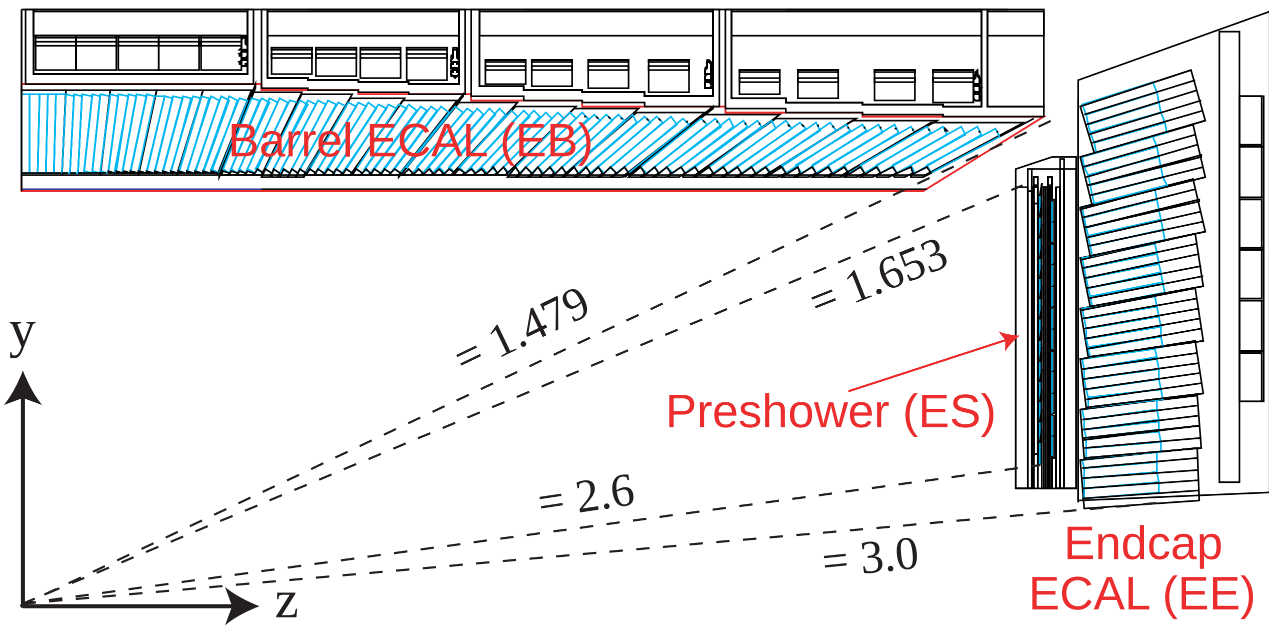
CMS: barrel muon



- The resolution is clearly dominated by the tracker
  - **Multiple scattering** in iron prevents good resolutions at low pt
  - Muon system contribute to improve the resolution above 100 GeV/c

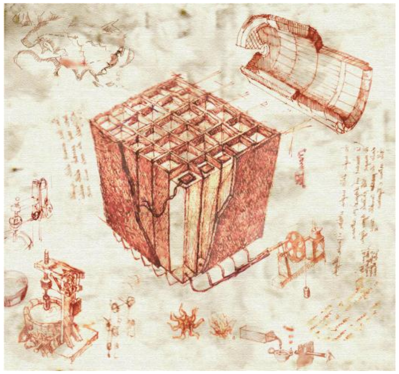
CMS: Ecal

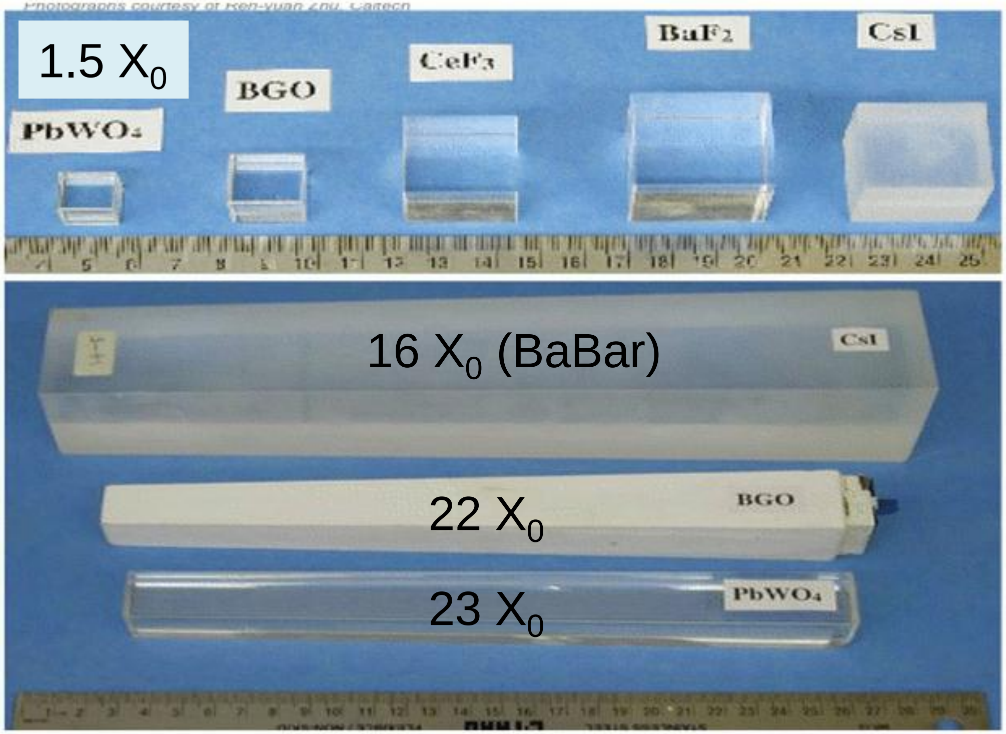


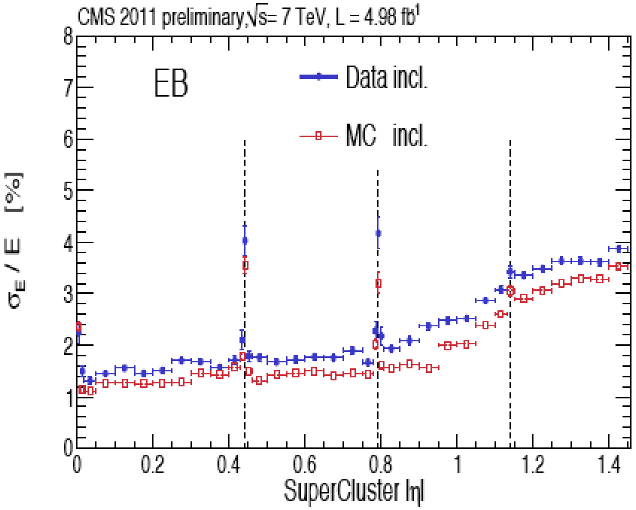


- Homogeneous calorimeter with $PbWO_4$ crystals
  - Very good resolution
  - Need very accurate calibration and radiation damages tracking

CMS: Ecal







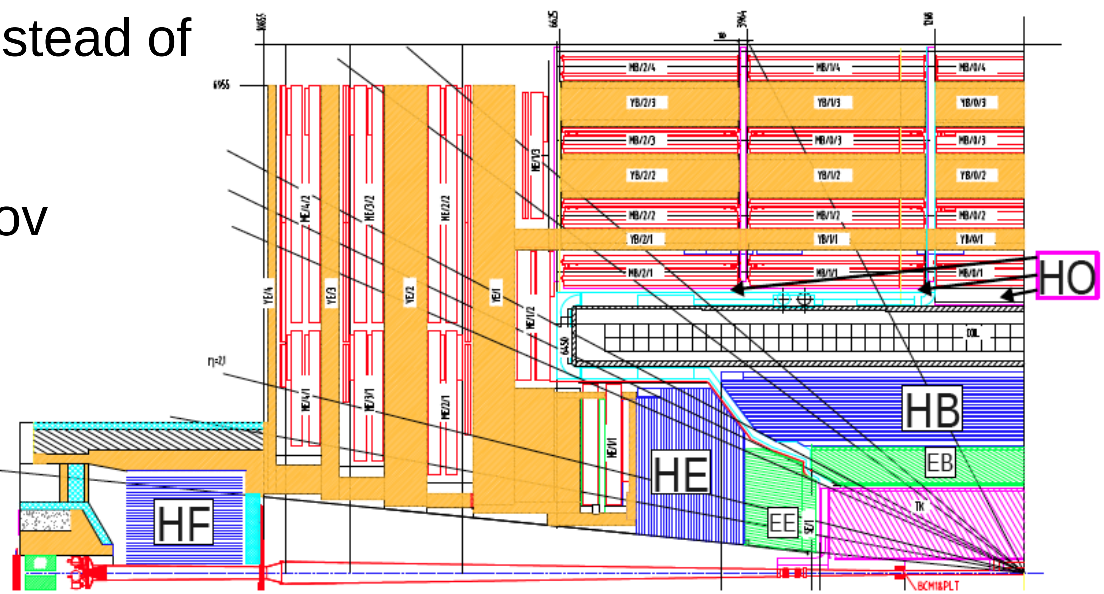
ECAL barrel resolution (2011) approaching MC expectation

- Why $PbWO_4$?
  - Very dense
  - Very fast (15ns)

CMS: Hadron Calorimeter

- Sampling calorimeter
  - Barrel and End-cap
    - Brass/scintillator
    - WLS fibres readout
    - Segmented HPD readout
  - Forward
    - Use quartz fibres instead of scintillator
    - Much rad-harder
    - Signal via Cherenkov
    - PMT readout

Barrel layers	Scintillator	Absorber
Layer 0	9mm	61 mm steel
Layer 1-8	3.7 mm	50.5 mm brass
Layer 9-14	3.7 mm	56.5 mm brass
Layer 15-16	3.7 mm	75 mm steel

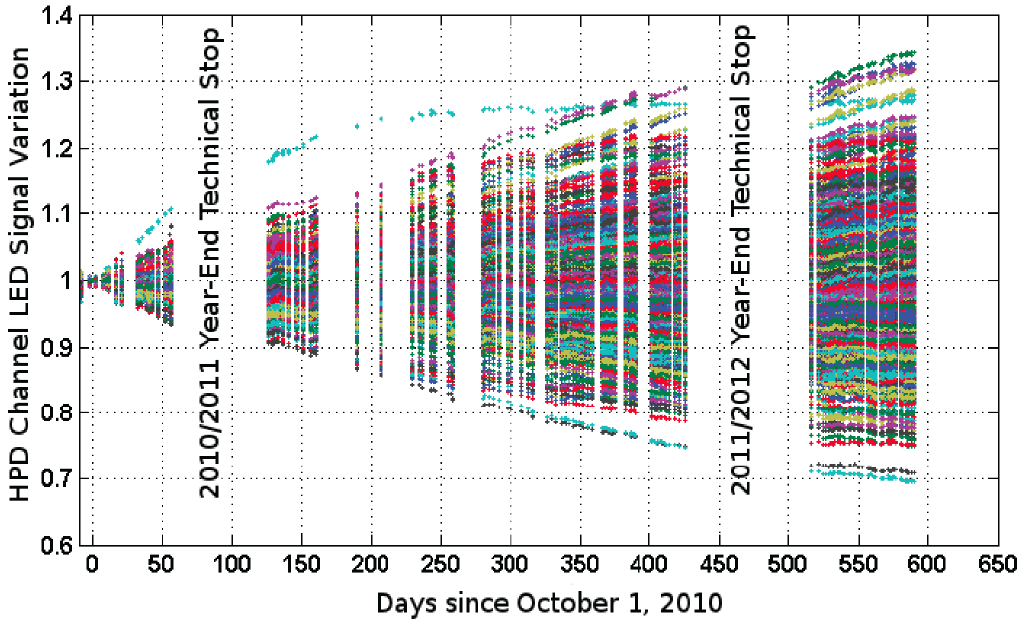


- Detector thickness
  - 5.82 λ_I at 90 degrees
  - Increases with η

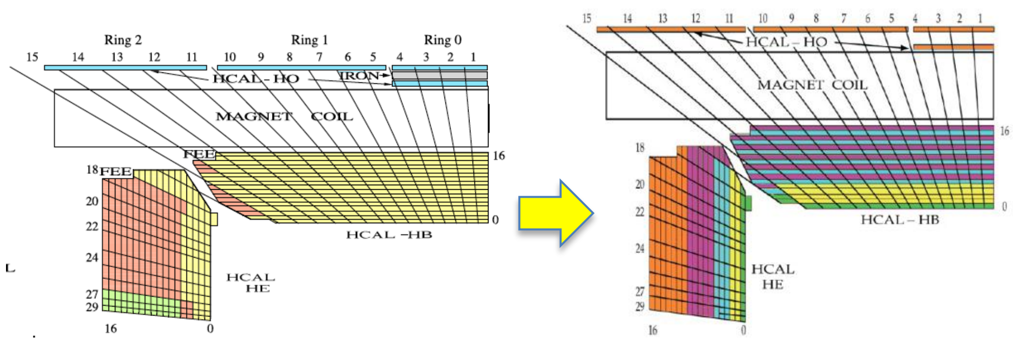
CMS: Hadron Calorimeter

- Brass was provided by Russia
  - 1 million of shells from Russian navy converted in calorimeter absorber plates

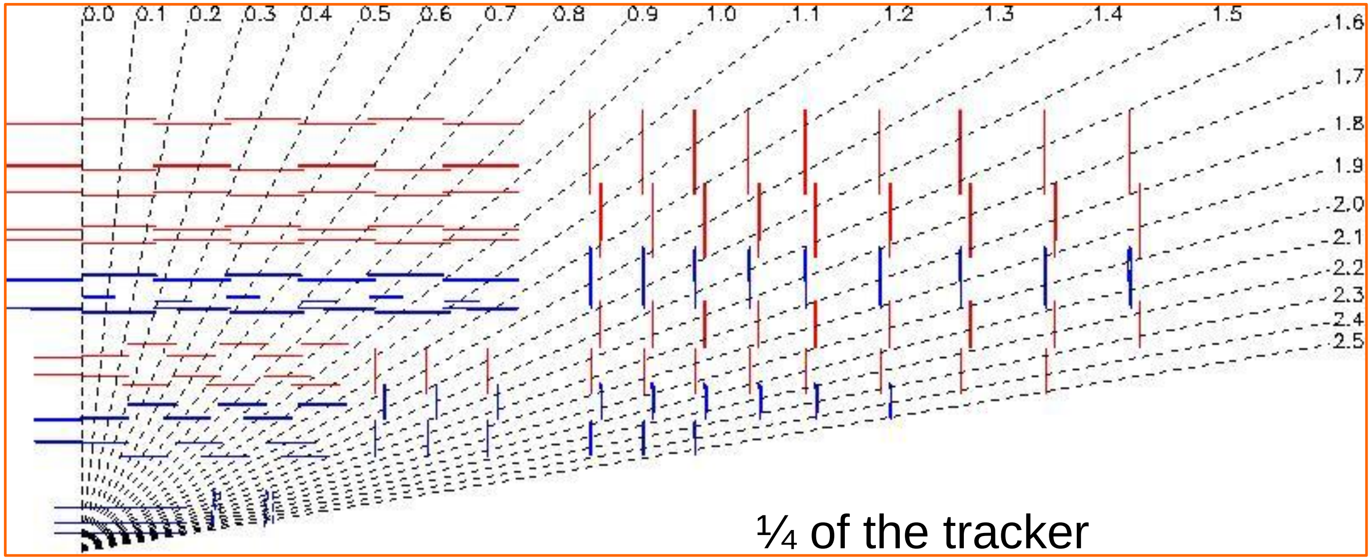
CMS: Hadron Calorimeter Upgrade



- HPD deteriorate with radiation
  - Photocathode response
  - And are sensitive to stray magnetic field
    - Small HV discharges can generate noise
- Plan to replace them with SiPM
  - Improving also the longitudinal segmentation
    - Better control of low-energy PU



CMS: tracker

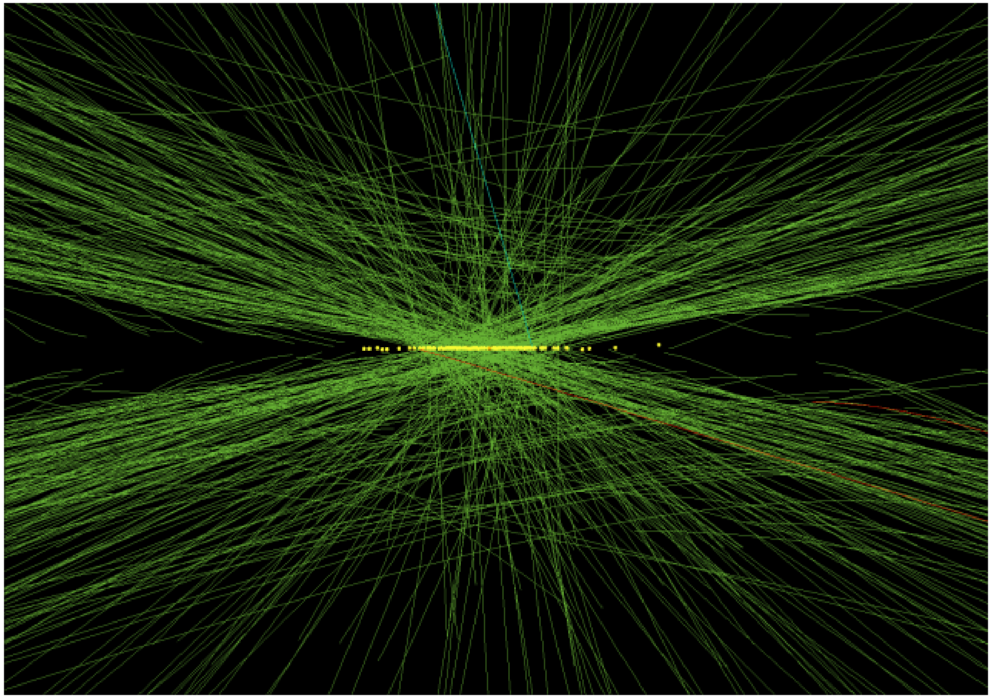


- Full Si tracker
  - Pixel detector
    - 100µm × 150µm
  - 20-r-55 cm TIB
    - Si micro strips, strip pitch 80µm
    - 300µm thick
  - R>55cm TOB
    - Si micro strips, strip pitch 180µm
    - 500µm thick. Improves SNR reducing C

- Similar structure in the end caps

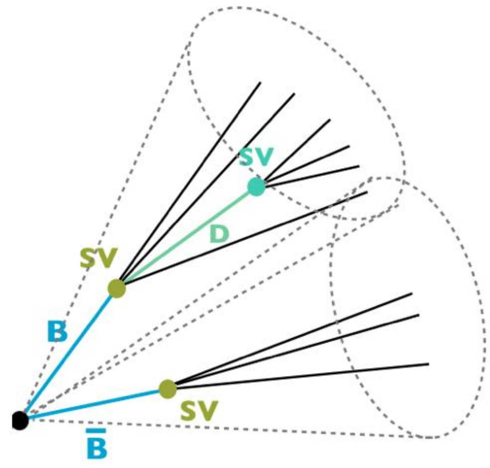
- Total
  - **66 millions pixels ≈ 1 m^2**
  - **9.6 millions strips ≈ 200 m^2**

CMS: tracker



- Event with 78 vertices reconstructed in CMS

- Pixel detectors are essential at LHC
  - Not only to tag b-physics with a secondary vertex
  - But to disentangle the vertex of the hard scattering in an high PU interaction
    - Track- based isolation
    - PF measurement



Conclusion

- We touched the surface of many detectors
- Many other not even mentioned
  - “vintage detector”: bubble chambers, spark chambers …
  - Open Air Shower detectors
  - Emulsions
  - …
- Hope if was useful
- As usual, you learn (and have fun) only by working on them

Thanks

To the organizers of the school
in this wonderful place!