Particle physics: lecture 2
Particle detectors

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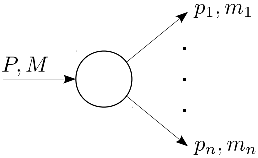
ELEMENTARY PARTICLE PROCESSES: DECAYS

Elementary processes are of two types: *decays* and *scattering*.

- Stable particles: proton, electron, neutrinos, photon

- All other hadrons and leptons, $W^\pm/Z$, and Higgs, *decay*, i.e., “break up” in various ways yielding ultimately stable particles.



- Quasi-stable final states, as far as particle detection goes: $\pi^\pm, K^\pm$, $\mu^\pm$

- These show up as charged tracks in trackers, but left alone long enough, they will ultimately undergo weak decay.

Q: check what are the allowed decays for $\pi^\pm, K^\pm$, $\mu^\pm$?

LIFETIME

Typical life span of unstable particles:

- Half-life, $t_{\frac{1}{2}}$: time in which half of a large sample of unstable particles of some type decays. Proper lifetime, $\tau = t_{\frac{1}{2}} / \ln 2$

Empirically, decay rate (prob. of decay/unit time/particle) is t-independent

$$dP = \Gamma dt$$

dP: probability for a particle to decay over infinitesimal time interval dt

$\Gamma = \sum_i \Gamma_i$: *total decay width*, time-independent total decay rate
Γ_i: *partial decay width*, decay rate in channel i

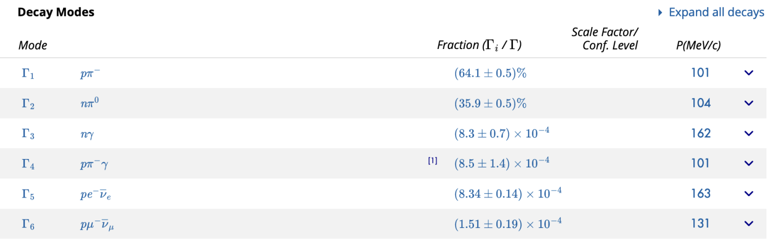
Particles decay independently from each other, sample size $N(t)$ obeys

$$dN(t) = -\Gamma N(t) dt \Rightarrow N(t) = N(0)e^{-\Gamma t} = N(0)e^{-\frac{t}{\tau}} \ , \quad \tau \equiv \Gamma^{-1}$$

Γ_i/Γ: *branching ratio* (or *fraction*) of channel i (relative probability that the decay will take place through channel i)

Partial widths

- The Particle Data Group (PDG) lists the known decay modes and their partial widths.
- Shown below for the $\Lambda(1115)$ strange baryon (link):



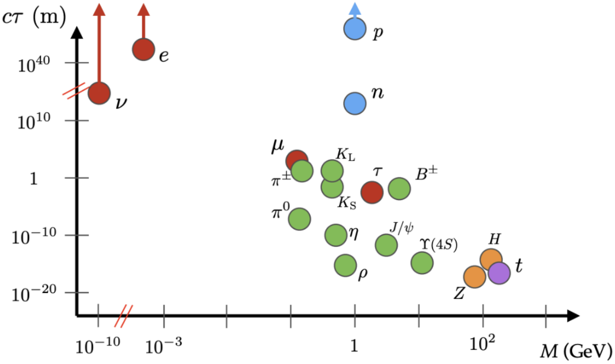
Decay Modes

▸ Expand all decays

Mode			*Fraction* (Γ_i / Γ)	*Scale Factor/ Conf. Level*	*P(MeV/c)*
Γ_1	$p\pi^-$		$(64.1 \pm 0.5)\%$		101
Γ_2	$n\pi^0$		$(35.9 \pm 0.5)\%$		104
Γ_3	$n\gamma$		$(8.3 \pm 0.7) \times 10^{-4}$		162
Γ_4	$p\pi^-\gamma$	[1]	$(8.5 \pm 1.4) \times 10^{-4}$		101
Γ_5	$pe^-\overline{\nu}_e$		$(8.34 \pm 0.14) \times 10^{-4}$		163
Γ_6	$p\mu^-\overline{\nu}_\mu$		$(1.51 \pm 0.19) \times 10^{-4}$		131

TYPICAL LIFETIMES

- Fundamental particles have a wide range of lifetimes. The proton lifetime is $>$ age of the universe!



- Note: only *proper* lifetime (τ) is really meaningful. That is, the lifetime in the particle's rest frame.

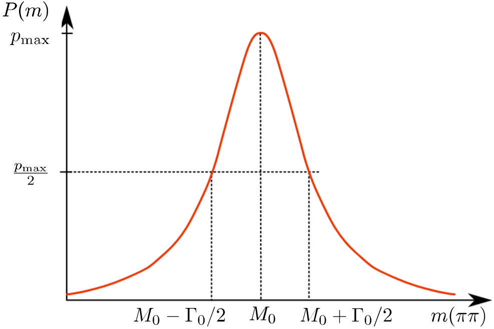
TYPICAL LIFETIMES (CNTD.)

particle	main decay mode	lifetime
μ^-	$\mu^- \to e^- \nu_\mu \bar{\nu}_e$	$2.2 \cdot 10^{-6} s$
n	$n \to p e^- \bar{\nu}_e$	$8.8 \cdot 10^2 s$
p	??	$>$ age of Universe
π^+	$\pi^+ \to \mu^+ \nu_\mu$	$2.6 \cdot 10^{-8} s$
π^0	$\pi^0 \to \gamma\gamma$	$8.4 \cdot 10^{-17} s$
Δ^0	$\Delta^0 \to p\pi^-, n\pi^0$	$5.6 \cdot 10^{-24} s$

- Long lifetimes: weak coupling or some sort of suppression (phase-space, Cabibbo, GIM).
- EM decays have intermediate lifetimes
- Strongly decaying particles have shortest lifetimes and therefore largest decay widths.

LINESHAPES

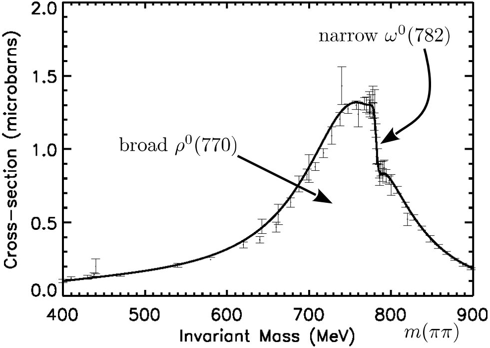
- Particles don't have a mass *per se*, but lineshapes.
- Uncertainty principle: lifetime $\propto$ 1/decay-width



- Broad resonance: $\rho^0(770) \to \pi^+\pi^-$: $M_0 \sim 770$ MeV, $\Gamma_0 \sim 145$ MeV.

LINESHAPES (CONTD.)

- Experimentally, what we see are often much more complicated.



- Two hadronic resonances "mixing" while decaying to $\pi^+\pi^-$.
- Lineshapes reveal underlying dynamics.

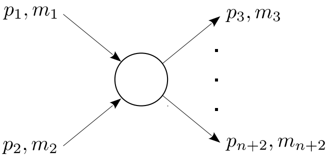
Q: check the properties of the ρ^0 and ω^0 mesons in PDG

ELEMENTARY PARTICLE PROCESSES: SCATTERING

- High energy collisions are our main tool to produce new heavy particles. Different colliders for different purposes.

- Highest energy collisions today are at the LHC: two proton beams at 7 TeV.

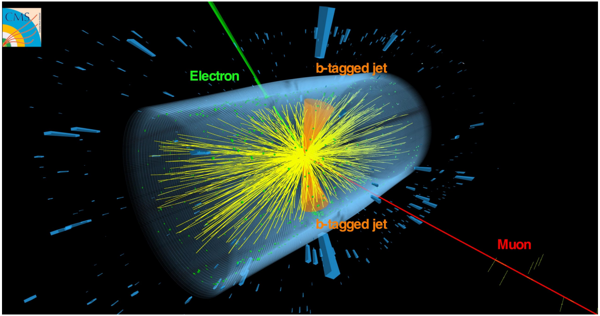
- Fixed-target and beam-dump experiments: high intensity photon/proton/pion/kaon beam on proton target



- SuperKEKB (Japan): e^+e^- collisions at precisely 10.58 GeV mass to produce only a B-meson pair. Clean environment.

- LBNF (Fermilab): protons on graphite → pions → muons + neutrinos. Intense neutrino beam!

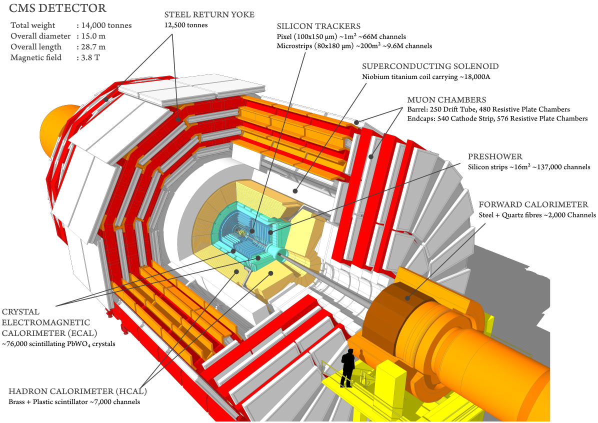
COLLISIONS TO PARTICLE DETECTORS



- Infer interesting physics from end products.
- Detector's job is to identify and measure energy/momentum of final state particles (stuff the detector "sees"): charged tracks ($\pi^\pm$, $K^\pm$, $e^\pm$, $p^\pm$, $\mu^\pm$), photons and may be neutrons.
- Detector interaction will be non-invasive (charged trackers) or absorbing (neutral calorimeters)?

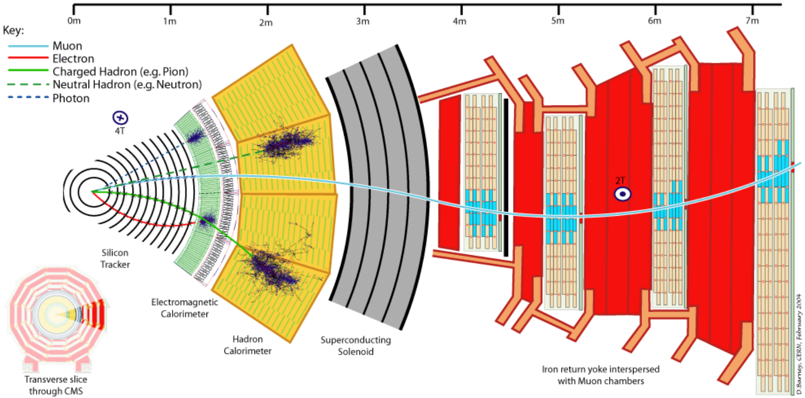
Modern particle detectors: "onion layers"

- Collision point cocooned inside layers of detectors.
- CMS detector at the LHC:



Slicing the “onion”

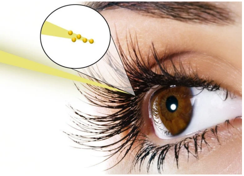
- Slice of the CMS detector at the LHC:

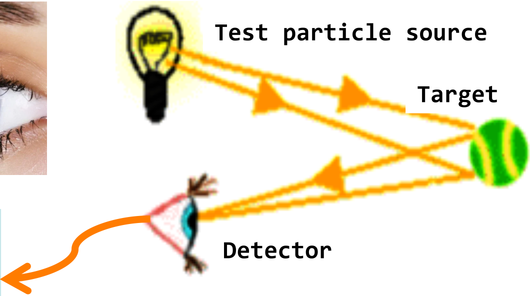


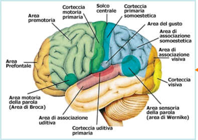
- Sequence of the onion shells have to be carefully planned: trackers come first...muon chambers last.

Early detectors: human eye

- The most obvious one. Sensitive and versatile photodetector.



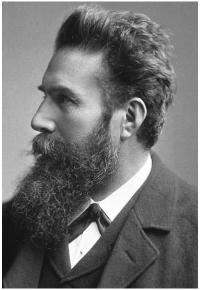


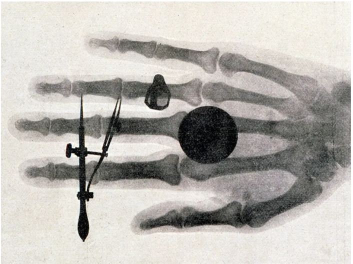


Data processing

- Can't measure the energy and works only at low rates.

EARLY DETECTORS: PHOTO PLATES

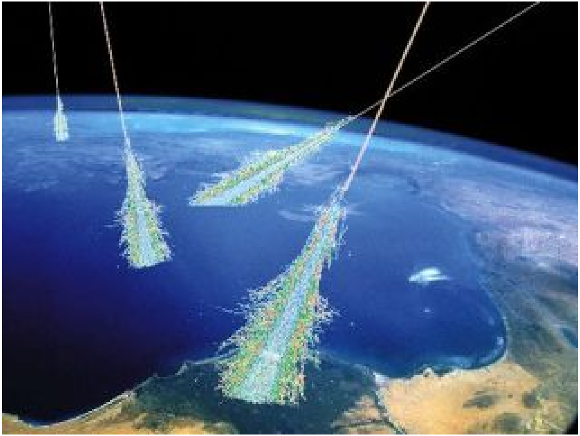




- X-rays discovered by Roentgen in 1895.
- AgBr/AgCl + energy ⇒ metallic (black) silver.

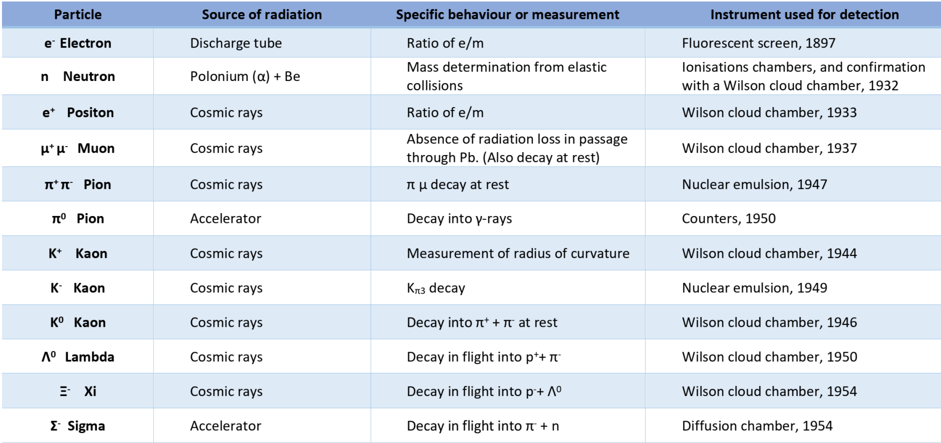
- Image era: photographs in cloud chambers, emulsions, bubble chambers. First 30 odd particles discovered this way.

COSMIC RAYS AS PARTICLE SOURCE



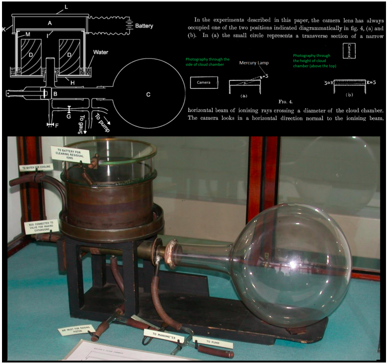
- How to produce new particles when we did not have accelerators? Cosmics are high;y energetic particles showering through the atmosphere. Mostly muons at sea level.
- Extremely useful source of “free” muons even today.

COSMIC RAYS AS PARTICLE SOURCE (CNTD.)



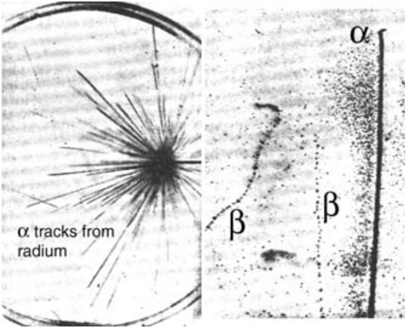
Particle	Source of radiation	Specific behaviour or measurement	Instrument used for detection
e^- Electron	Discharge tube	Ratio of e/m	Fluorescent screen, 1897
n Neutron	Polonium (α) + Be	Mass determination from elastic collisions	Ionisations chambers, and confirmation with a Wilson cloud chamber, 1932
e^+ Positon	Cosmic rays	Ratio of e/m	Wilson cloud chamber, 1933
$\mu^+ \mu^-$ Muon	Cosmic rays	Absence of radiation loss in passage through Pb. (Also decay at rest)	Wilson cloud chamber, 1937
$\pi^+ \pi^-$ Pion	Cosmic rays	π μ decay at rest	Nuclear emulsion, 1947
π^0 Pion	Accelerator	Decay into γ-rays	Counters, 1950
K^+ Kaon	Cosmic rays	Measurement of radius of curvature	Wilson cloud chamber, 1944
K^- Kaon	Cosmic rays	$K_{\pi 3}$ decay	Nuclear emulsion, 1949
K^0 Kaon	Cosmic rays	Decay into $\pi^+ + \pi^-$ at rest	Wilson cloud chamber, 1946
Λ^0 Lambda	Cosmic rays	Decay in flight into $p^+ + \pi^-$	Wilson cloud chamber, 1950
Ξ^- Xi	Cosmic rays	Decay in flight into $p^- + \Lambda^0$	Wilson cloud chamber, 1954
Σ^- Sigma	Accelerator	Decay in flight into $\pi^- + n$	Diffusion chamber, 1954

WILSON' CLOUD CHAMBER



In the experiments described in this paper, the camera lens has always occupied one of the two positions indicated diagrammatically in fig. 4, (a) and (b). In (a) the small circle represents a transverse section of a narrow horizontal beam of ionising rays crossing a diameter of the cloud chamber. The camera looks in a horizontal direction normal to the ionising beam.

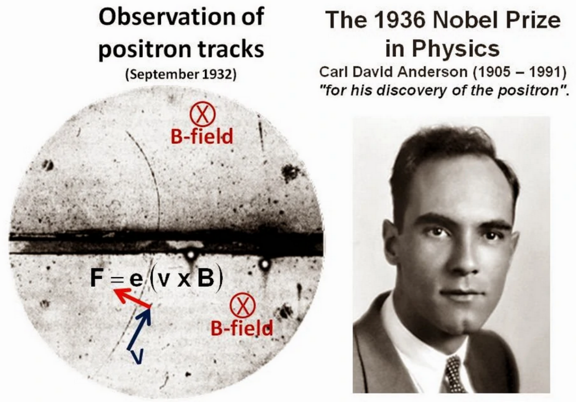
FIG. 4.



- Super-saturated water vapour. Charged particles traversing condense the vapour, leaving a trail.
- CTR Wilson discovered in 1911. Clean images led to many discoveries. Nobel Prize in 1927.

Wilson' cloud chamber (cntd.)

- First tracking detector: magnetic could chamber.
- Bending tells you the charge ⇒ discovery of antielectron.



Observation of positron tracks (September 1932)

The 1936 Nobel Prize in Physics
Carl David Anderson (1905 – 1991)
"for his discovery of the positron".

- Hard to make larger detectors for more penetrating tracks.

GLASER'S BUBBLE CHAMBER (1952)

- Same idea, replace medium with superheated liquid (H_2, D_2). Charged particles leave tracks of bubbles as liquid boils. Nobel prize in 1960.
- Larger volumes, sharper images and can be reset quickly.

- CERN bubble chamber, used to study weak decays in the '70's.
- Superconducting solenoidal magnet to bend tracks. Millions of photos!

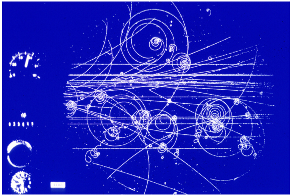
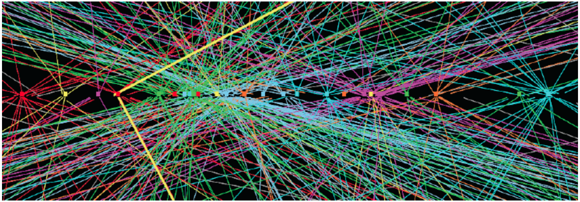


IMAGE ERA TO ELECTRONICS ERA: TRIGGERS

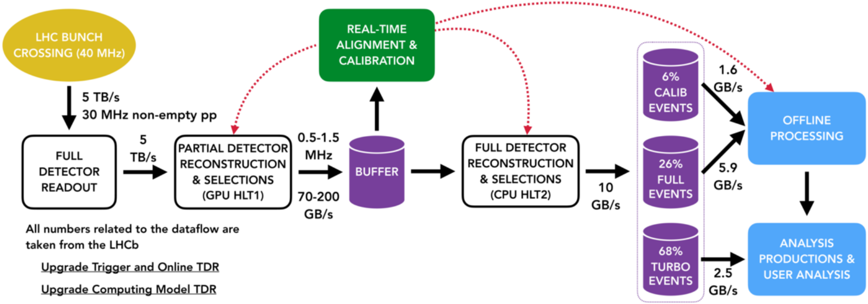
- Bubble chambers could provide $\sim 5\mu m$ track resolutions and full 4π hermetic acceptance. But impossibly slow rates (few Hz).
- No concept of trigger (selectively retain events) $\Rightarrow$ mandatory at LHC rates ($> 10^9$ Hz).



- Need electronic trigger logic. Since '70's, Geiger counters, scintillators+photomultipliers, spark chambers...

TRIGGER: PHYSICS IN A HEARTBEAT

- e^+e^- colliders (BaBar/Belle): every collision is clean signal. Detector records (almost) everything.
- Hadron colliders (LHC): huge rates, but mostly uninteresting events. Triggering is key. Need to decide which events to write out to tape...



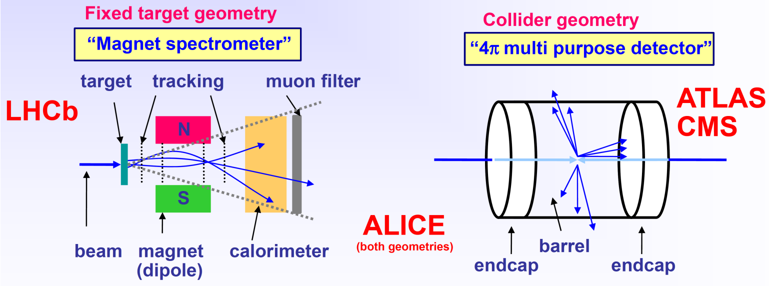
All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

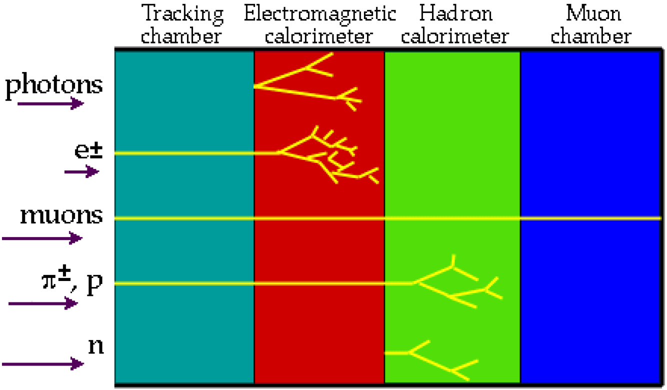
DETECTOR ACCEPTANCE

- Acceptance (or efficiency) $= N_{\text{reconstructed}}/N_{\text{incident}}$
- Uninstrumented regions (holes): invariably lead to loss of acceptance (c.f. bubble chambers).
- Can also be due to geometry (motivated by physics):



- Must recover back the full acceptance: simulation of the detector geometry/material + physics processes (`Geant4` toolkit) key.

TYPICAL SIGNATURES OF PARTICLES



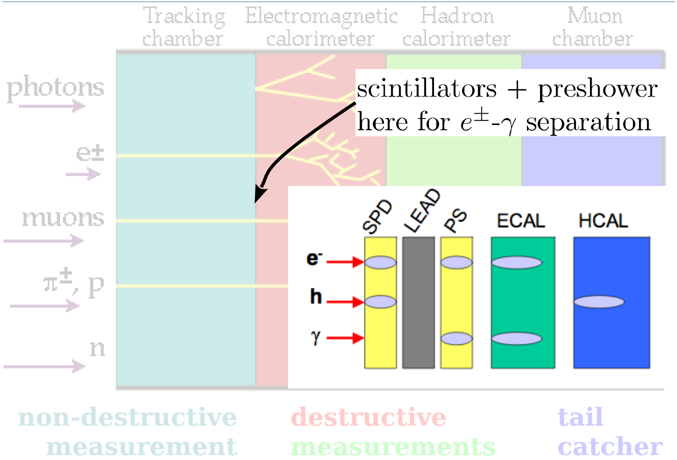
non-destructive measurement

destructive measurements

tail catcher

- Neutrino ⇒ missing energy @ colliders.

TYPICAL SIGNATURES OF PARTICLES (CNTD.)



scintillators + preshower here for $e^{\pm}$-γ separation

- Neutral photons leave no hits in the SPD (scintillating pad detector). Enables separation between EM clusters due to photons from electrons.

CHARGED PARTICLE INTERACTIONS

- (Multiple) elastic scattering in the detector material. Nuisance mostly – degrades resolutions.
- Ionisation of electrons inside material atoms producing minuscule currents that have to be amplified. Basis of tracking detectors (silicon, drift chambers).
- Photon emission:
    - Bremsstrahlung: fast particles (especially electrons) loses energy by radiation due to interaction with nuclei. Major problem for electron tracking, compared to muons.
    - Cherenkov radiation: charged particle travelling in dense medium a speeds greater that speed of light in the medium, emits cone of light. Used for $K/\pi/p$ separation.
    - Scintillation light: optical photons emitted (plastic or inorganic) that are read out and amplified. Fiber trackers, calorimeter readouts.

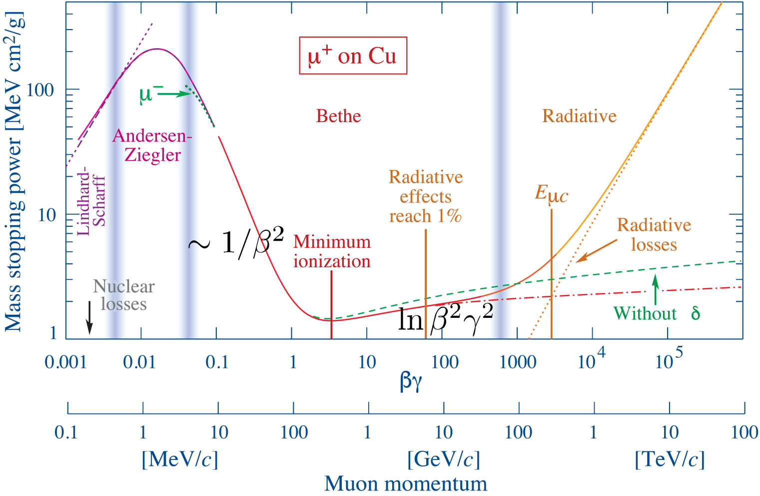
$\langle dE/dx \rangle$ AND BETHE-BLOCH

- Energy loss by ionisation for $m \geq m_\mu$ given by Bethe-Bloch:

$$\boxed{-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]}$$

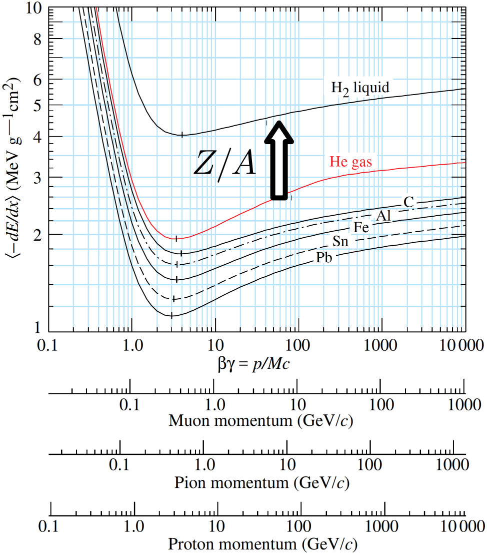
- Material effectively described by Z/A (Z is atomic number, A is atomic mass)
- Loss is $\propto 1/\beta^2$, $\beta = v/c$. If the momentum is known (from tracking), $\langle dE/dx \rangle$ gives the mass.
- PID: particle identification.

$\langle dE/dx \rangle$ DEPENDENCE ON MOMENTUM



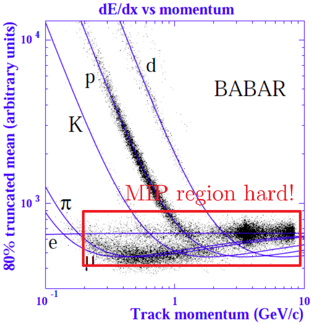
- MIP: minimum ionising particle (relativistic).

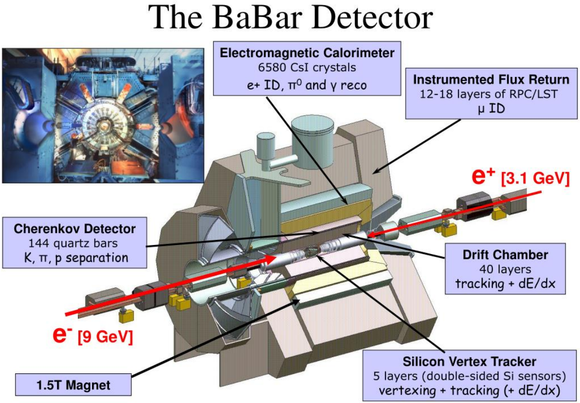
$\langle dE/dx \rangle$ DEPENDENCE ON Z/A



$\langle dE/dx \rangle$ for PID

- $\langle dE/dx \rangle$ measurements from the BaBar drift chambers

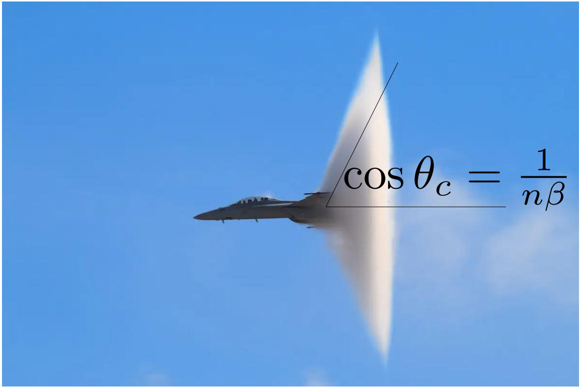




- Several sub-detectors contribute to multivariate PID discriminator. In particular, Cherenkov (RICH) detectors...

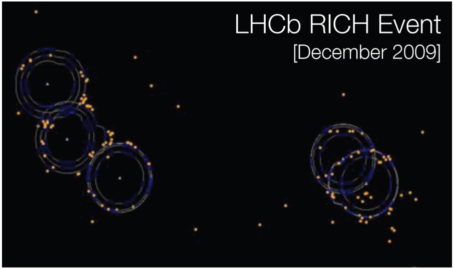
RING IMAGING CHERENKOV DETECTORS

- Just like sonic boom. n is the refractive index of the medium.
- Cone angle produces rings, for different momenta.

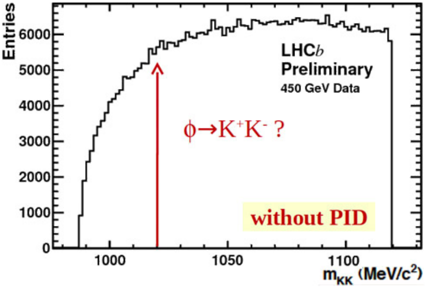


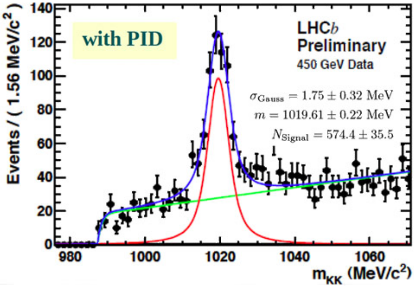
$$\cos\theta_c = \frac{1}{n\beta}$$

RICH PID IN ACTION...



pions/kaons/protons produce distinguishable rings
critical to “flavor” physics



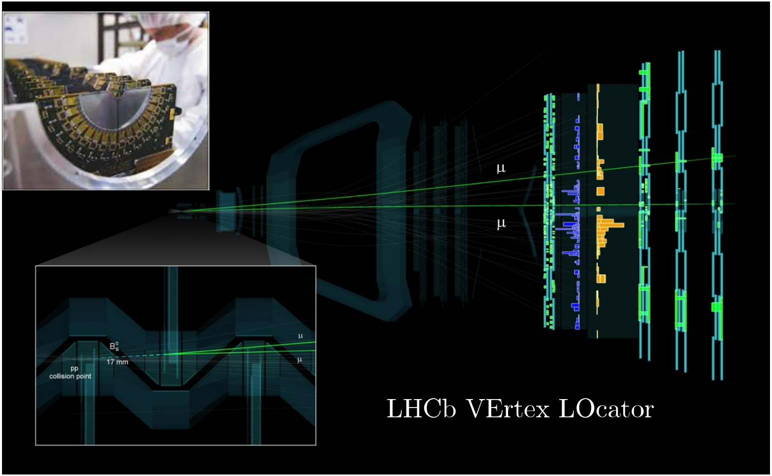


THE SILICON REVOLUTION

- Silicon trackers: Indispensable in almost any modern particle detector today.
- Huge improvements, closely tied to the semi-conductor industry
- Cost-effective, high granularity (pixels, microstrips), high resolution (μm), radiation-hard, low material budget: effectively the *only* solution close to the collision point.
- Cons: needs cooling (often $< -40^\circ$ C), and gets expensive for very large areas. Large number of readout channels (10^7 at ATLAS/CMS Si trackers).

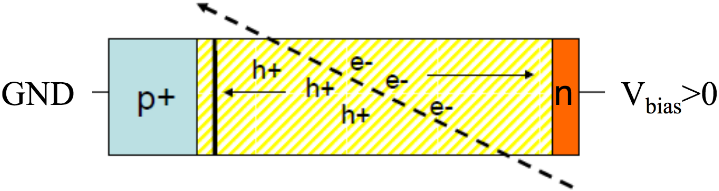
PRECISION VERTEXING

- VeLo sits just 7 mm away from the LHC beam! Femtosecond decay-time resolution



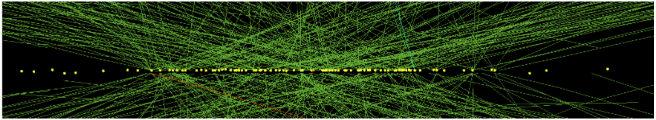
SILICON TECHNOLOGY

- Silicon is a semiconductor and can be doped. *p*-type and *n*-type. *p*-*n* junction is depleted of charge carriers.
- Reverse bias (*p*-type to $-$, and *n*-type to $+$) further increases this depletion region.
- Ionization due to charged particle creates e^{-}-h^{+} pairs and a current (3.6 eV/pair, 80 pairs/μm).

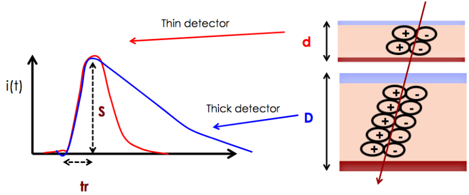


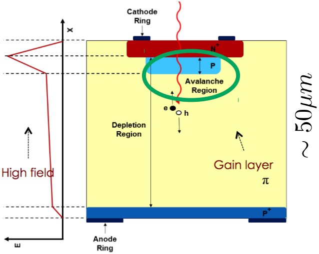
TOWARDS THE FUTURE: TIMING INFO (LGAD)

- High-luminosity LHC: *pp* bunch crossing every 25 ns. Pileup (interactions/bunch crossing) > 200.



- Just high spatial granularity won't do: primary vertices (*pp* collision point) are also separated in time. Need $\mathcal{O}(20)$ps res.





Low Gain Avalanche Diode

CALORIMETERS

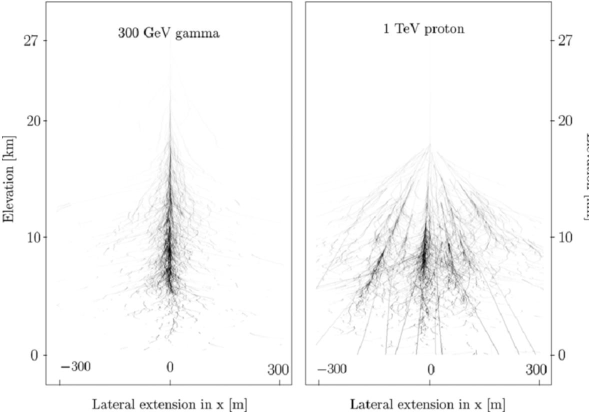
- Till now we wanted the detector material to be as less invasive as possible, to limit loss of resolution.
- Calorimeters: opposite. Ensure that all the energy is absorbed (and measured) inside detector. Resolution improves with energy.

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \otimes \frac{b}{E} \otimes c$$

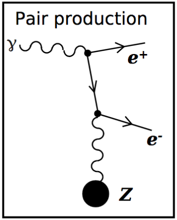
- a: $\frac{\sigma_E}{E} \sim 1/\sqrt{n} \sim 1/\sqrt{E}$. Stochastic term, intrinsic property. For sampling calorimeters, 5-20%.
- b: noise term. Electronic noise from readout chain $\sim 1\%$.
- c: constant term. Non-uniformities in the material/readout.
- Note: energy resolution (σ_E) improves with energy, unlike trackers where the momentum resolution is poorer at high momentum.

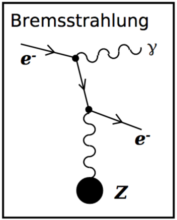
SHOWER PROPAGATION: ECAL AND HCAL

- Shower shape: photon/electron (EM, ECal) vs proton/pion/kaon (nuclear, HCAL). Different calorimeters to "catch" the particles.



RADIATION LENGTH FOR EM SHOWERS

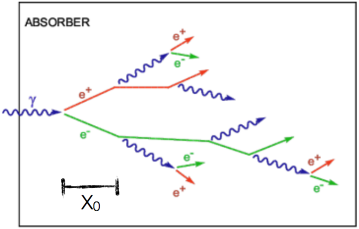




- Dominant processes at high energies. $\sigma_\gamma^{\text{pair}} = 7/9\sigma_e^{\text{brem}}$.

$$\sigma_\gamma^{\text{pair}} = 7/9\sigma_e^{\text{brem}} \approx \frac{7}{9}4\alpha r_e^2 Z^2 \ln\frac{183}{Z^{1/3}} = \frac{7}{9}\frac{A}{N_A X_0}$$

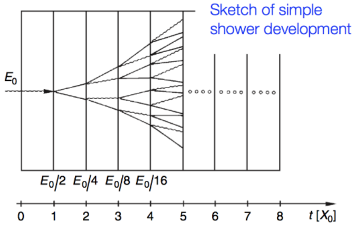
- Brem energy loss: $E = E_0 e^{-x/X_0}$. $X_0 \sim 180A/Z^2$ [g/cm^{-2}]
- High Z material for EM calorimetery. For Pb, $X_0 \sim 5.6$ mm.

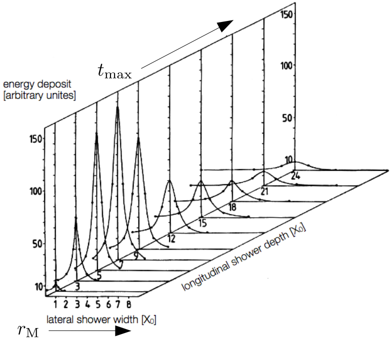


- Critical energy E_c: bream + pair prod dominates $E > E_c$. Below, ionisation, Compton eff. and photo el. eff.

- $E_c = 610/(Z + 1.24)$ MeV. For Pb, $E_c = 7.3$ MeV.

Shower propagation and shapes

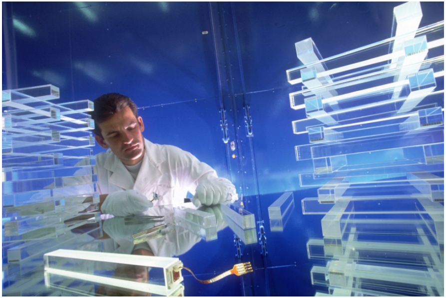

Sketch of simple shower development



- Depth is in units of X_0
- Longitudinal: $t_{\max} = \frac{ln E_0/E_c}{ln 2}$ where the profile peaks.
- Transverse size given by $R_M = \frac{21 MeV}{E_c} X_0$.
- Smaller R_M is preferred $\Rightarrow$ compact showers
- Radial shower containment: $90\%(95\%)$ at $R_M(2R_M)$

EXAMPLES OF CALORIMETERS: HOMOGENOUS

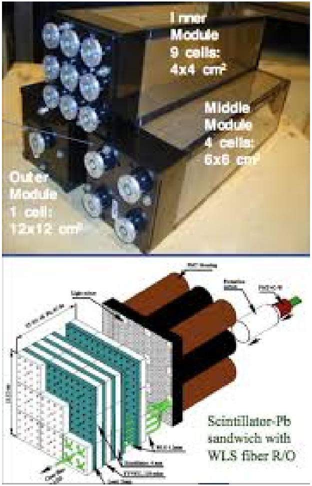
- Primarily two types: homogenous and sampling.
- Homogenous detector: single medium, both absorber and detector. Entire energy absorbed. Excellent resolutions.
- Liq. Ar/Xe/Kr. Dense crystals ($PbWO_4$, CsI(TI)), or organic scintillators.



CMS $PbWO_4$

- Almost entirely for ECal.
- 3-d shower profile not accessible (important for shower effective position).

EXAMPLES OF CALORIMETERS: SAMPLING TYPE

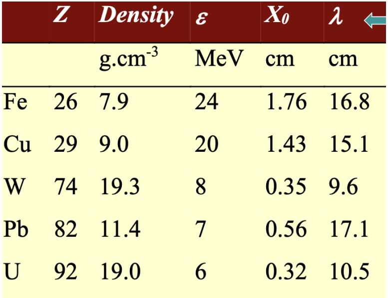


LHCb ECal

- Sandwich absorbers (Pb/W/Cu) by active detectors like scintillators
- Poorer resolutions since only part of the full energy sampled.
- Used in both ECal and HCal.
- Rule of thumb: at least $25X_0$ thick absorbers needed.

NUCLEAR INTERACTION LENGTH

- Similar to X_0, but for hadronic interactions, nuclear interaction length, $\lambda_n \sim A^{1/3}$.
- For the same material, $\lambda_n > 6X_0$. Therefore, hadronic showers start much later, than EM showers.

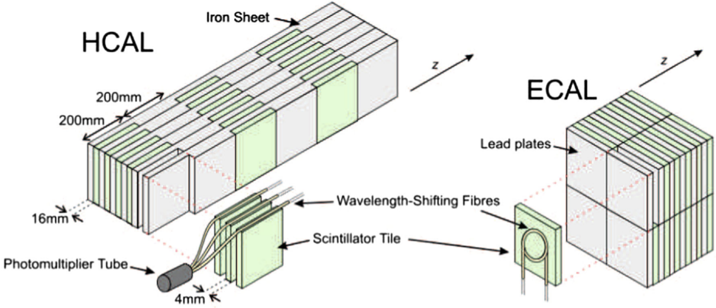


	Z	Density	ε	X_0	λ
		g.cm^{-3}	MeV	cm	cm
Fe	26	7.9	24	1.76	16.8
Cu	29	9.0	20	1.43	15.1
W	74	19.3	8	0.35	9.6
Pb	82	11.4	7	0.56	17.1
U	92	19.0	6	0.32	10.5

- Typically $> 9\lambda_n$ of material to fully contain the showers. HCal's are always sampling type.

LHCb ECal/HCal comparison

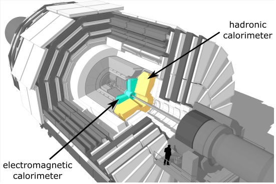
- Schematic comparison between ECal/HCal at the LHCb experiment:

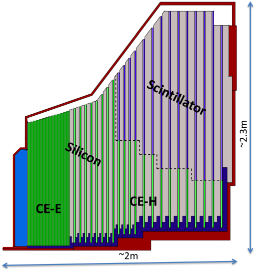


Next paradigm: 5D calorimetry

- At HiLumi-LHC, tracker + calorimeter + timing: detailed jet reconstruction.

CMS HGCAL





Electromagnetic calorimeter (**CE-E**):
Si, Cu & CuW & Pb absorbers, 28 layers, 25 X_0 & ~1.3λ
Hadronic calorimeter (**CE-H**):
Si & **scintillator**, steel absorbers, 22 layers, ~8.5λ