11th CERN LATIN-AMERICAN SCHOOL OF HIGH-ENERGY PHYSICS
San Esteban, Chile
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Collider Experiments

the LHC & beyond

Roger Forty (CERN)

Lecture 2

Outline

Lecture 1: Accelerators & experiments

Lecture 2: Detectors & data

1. Tracking detectors
   Particle interactions, gaseous/silicon/vertex detectors
2. Calorimeters
   Electromagnetic/hadron, photon detection
3. Particle identification
   particle signatures, hadron identification
4. Data taking
   Trigger, data acquisition, analysis

Lecture 3: LHC physics highlights

Lecture 4: Looking beyond

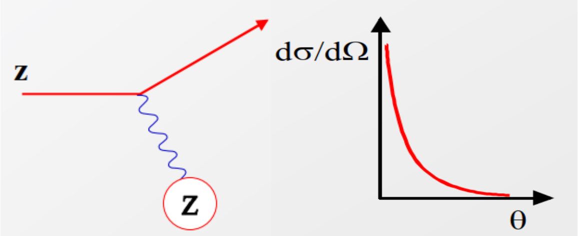
This is the most technically applied of the lectures:
for those working on theory, you could treat this as broadening your scientific culture, to understand how experiments actually *work*

Introduction

- We wish to reconstruct as fully as possible the events, where particles from the colliding beams have interacted, and typically many particles emerge from the interaction point
- **Tracking** detectors determine whether the particles are charged, and (in conjunction with a magnetic field) measure the sign of the charge and the momentum of the particle
- **Vertex detectors:** a subset of tracking detectors that are very precise, mounted close to the interaction point, to measure the vertex structure of the event: e.g. to see if there are short-lived decays
- **Calorimeters** detect neutral particles, measure the energy of particles, and determine whether they have *electromagnetic* or *hadronic* interactions: typically with separate sub-detectors for the two interactions
- **Particle identification** detectors determine what *type* of particles were produced: most experiments have muon detectors, and use information from their tracking detectors such as the amount of ionization
  Others have dedicated sub-detectors for this, such as RICH detectors

Interaction with matter

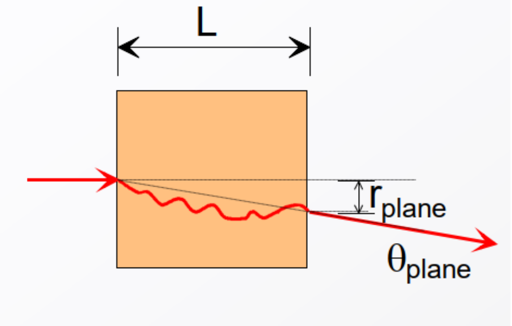
- Particles can only be detected if they deposit energy in the material of the detector
- The cross-section for a particle with charge *z* to interact *elastically* with a target of nuclear charge *Z*:



$$\frac{d\sigma}{d\Omega}(\theta) = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4\theta/2}$$

Rutherford formula

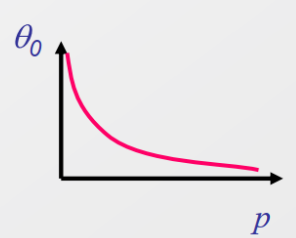
- But scattering does not lead to significant energy loss (nuclei are heavy)
- In a sufficiently thick layer of material a particle will undergo **Multiple Scattering**, relevant to tracking:

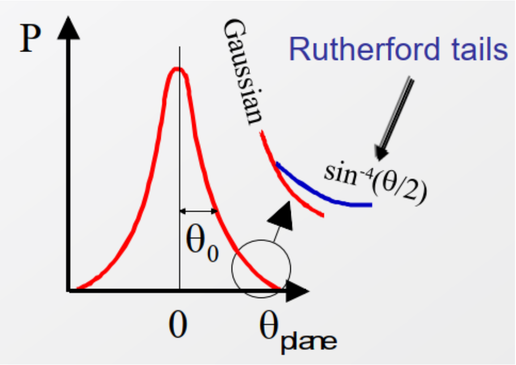


- Final displacement is result of many random scatters → Gaussian distribution (by the central limit theorem)

$$\theta_0 \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$$

X_0 = "radiation length" of the medium

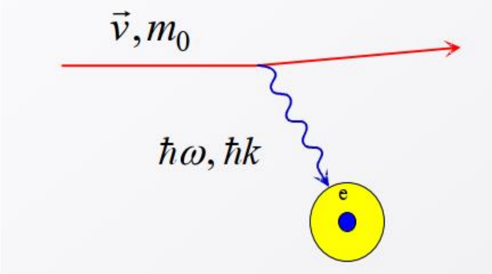




Ionization

- Energy is deposited through discrete collisions with the *atomic electrons* of the absorber material (collisions with nuclei not important for energy loss)
- *Bethe-Bloch* formula for energy loss by ionization ***dE/dx*** depends only on velocity β = *v/c* of particle:

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



$$\left\langle \frac{dE}{dx} \right\rangle = -\int_0^\infty NE \frac{d\sigma}{dE} \hbar\, d\omega$$

N : electron density

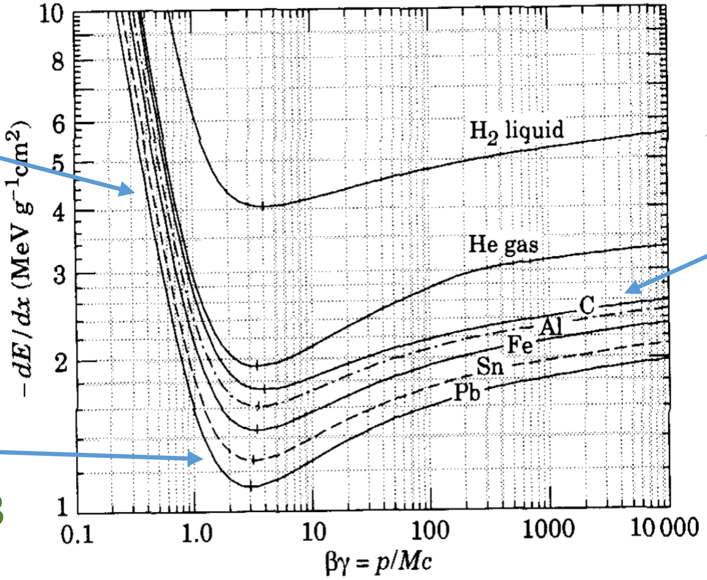
Recall: relativistic *boost*

γ = *E/mc* = 1/√(1–β²)

Increase at low βγ

$$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{1}{\beta^2}$$

“minimum-ionizing particles” (MIPs) βγ ~ 3



“relativistic rise”

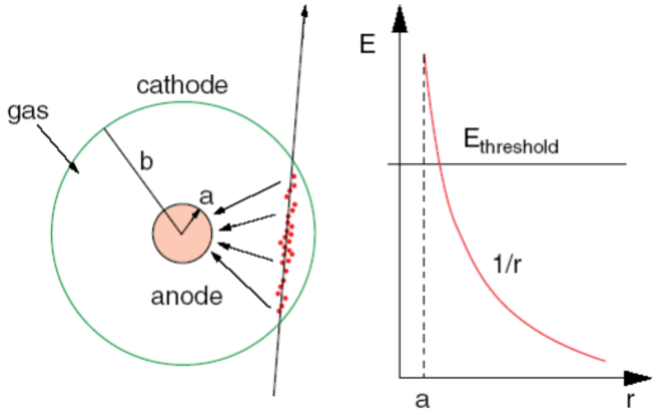
$$\left\langle \frac{dE}{dx} \right\rangle \propto \ln \beta^2 \gamma^2$$

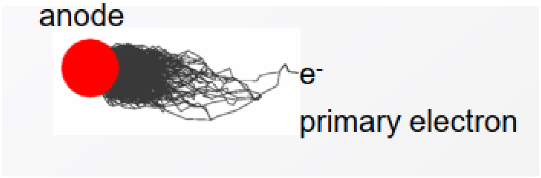
1. Tracking detectors

- **Wire chamber**: place an anode wire at HV in a gas volume – electrons liberated by ionization drift towards the anode wire
- Electrical field close to the wire sufficiently high (above 10 kV/cm) for electrons to gain enough energy to ionize further → avalanche: exponential increase of number of electron-ion pairs to several thousand
  → signal becomes detectable with electronics
- Simply repeat the cell using multiple wires
  → Multi-Wire Proportional Chamber

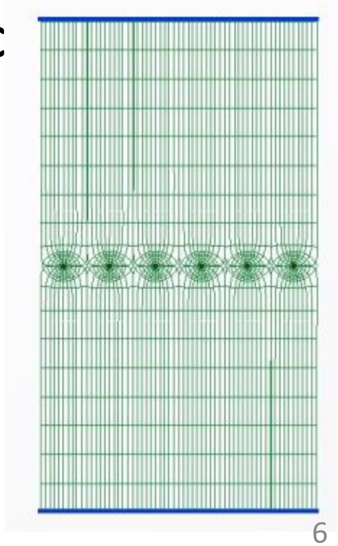
Nobel prize 1992
(G. Charpak)

- **Drift chamber**: measure *time* taken to reach the wire → determine the position more accurately





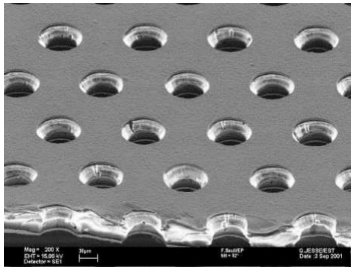
MWPC

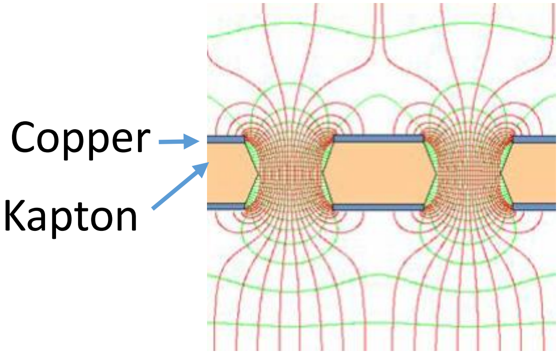


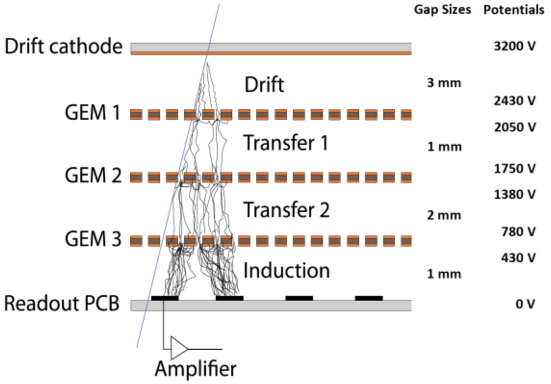
Micro-Pattern Gas Detectors

- Wires are not the only way to provide the accelerating field required
- Modern versions of gaseous tracking detectors use MPGDs: allow higher precision, operate at a higher rate, survive longer
- **GEM** (Gas Electron Multiplier) use holes in a foil

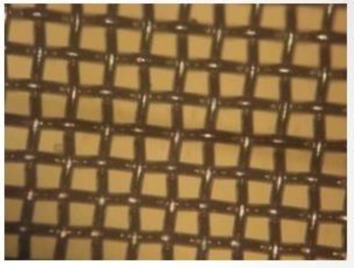
Ø 50-70 µm

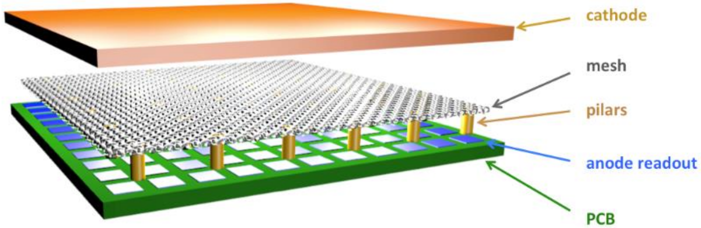


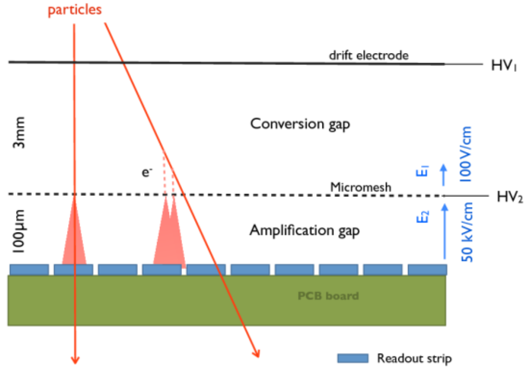




Micromegas use a fine wire mesh



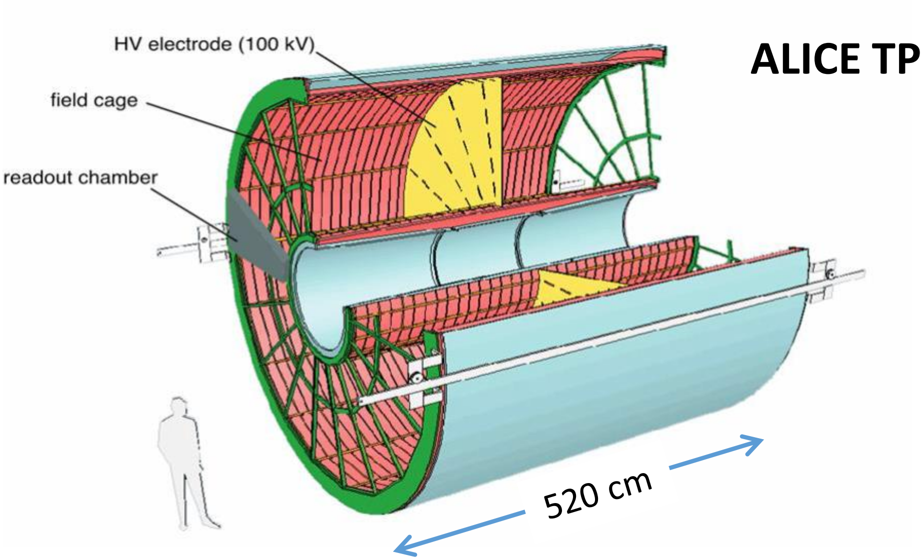


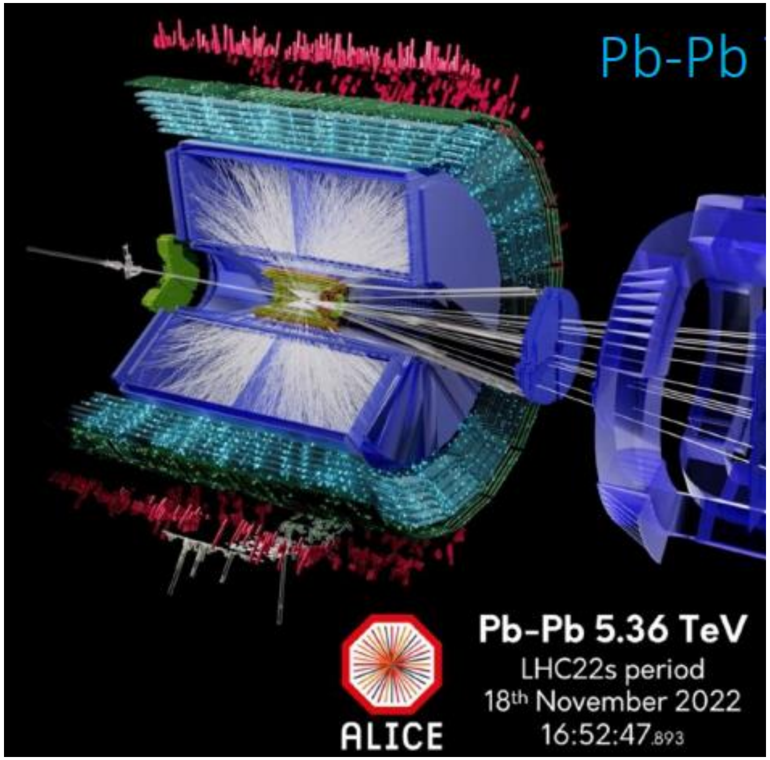


Time Projection Chamber

- The ultimate gaseous detector: move the detection planes (wire chambers or MPGDs) to the endplates and drift the ionization across the full volume, measure its arrival time to determine the longitudinal coordinate

ALICE TPC



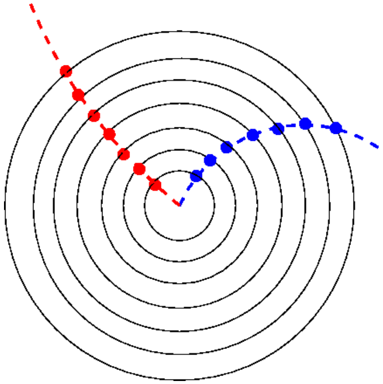


ALICE TPC readout replaced with MPGDs as part of its upgrade for Run 3 (“ALICE 2”)

- *Limitations* of gaseous detectors:
  Small primary signal needs amplification
  → ageing, rate limitations
  Limited resolution (~ 100 µm);
  require massive frames, HV, gas flow

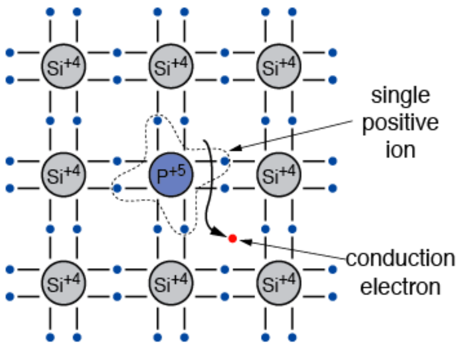
Silicon trackers

- Silicon trackers address some of those limitations, and are at the heart of many modern collider detectors
- Need to be radiation hard and low mass, to minimize multiple scattering of detected tracks
- Trajectories reconstructed from consecutive measurements as particles traverse detector volume

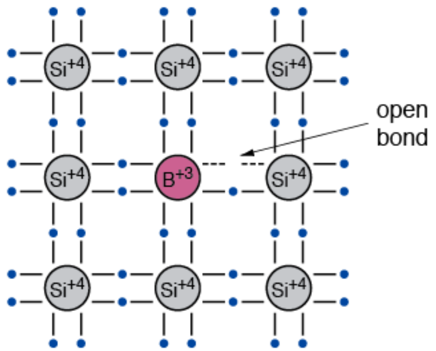


Solid-state detectors

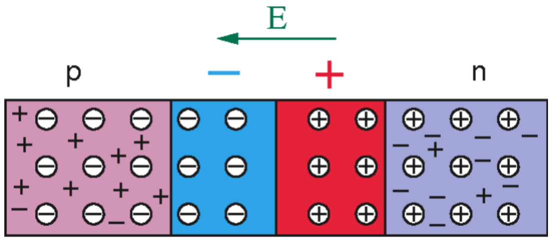
- Semiconductors such as silicon crystals are doped with impurities to alter their band structure (*n* or *p*-type, typically using phosphorus or boron)



n-type
charge carrier negative



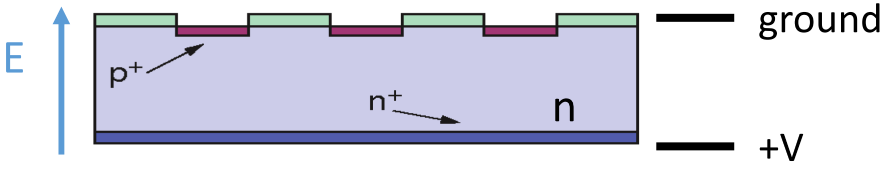
p-type
charge carrier positive

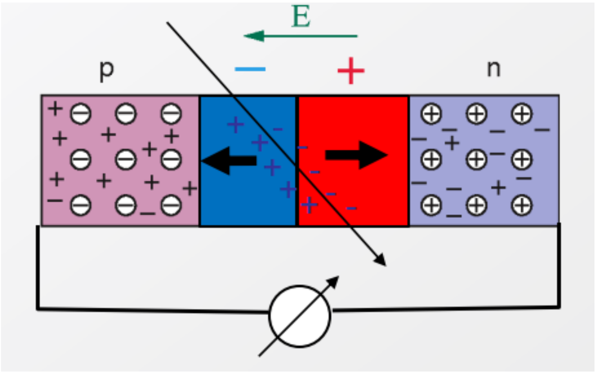


Bringing two doped regions in contact → depletion zone

Resulting electric field separates any newly created free charges → signal current

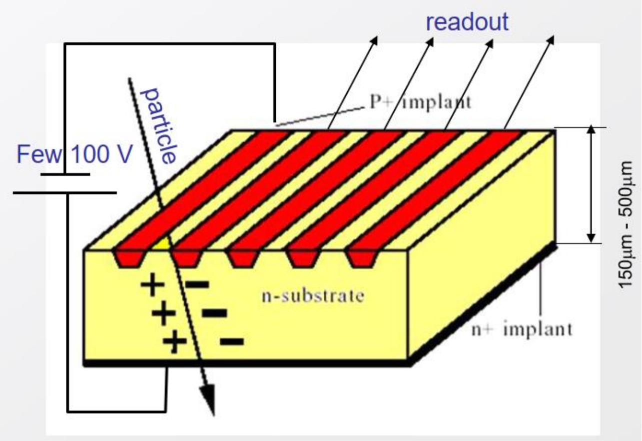
- implant features with different doping to bulk
  Applying external reverse voltage to *p-n* junction depletes the bulk material of free charges



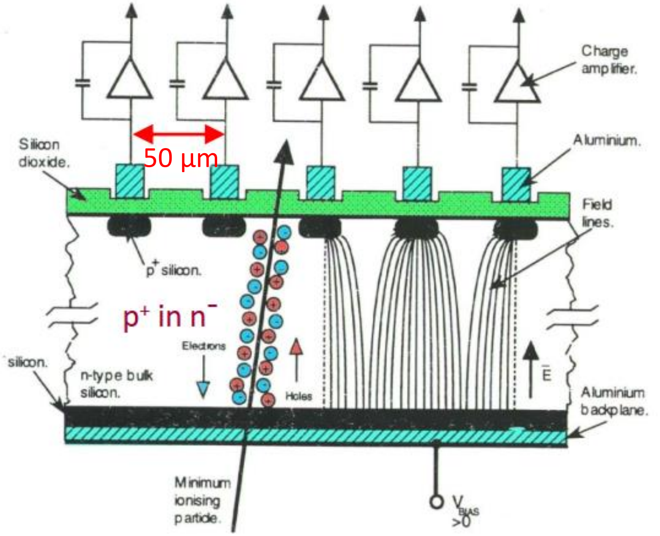


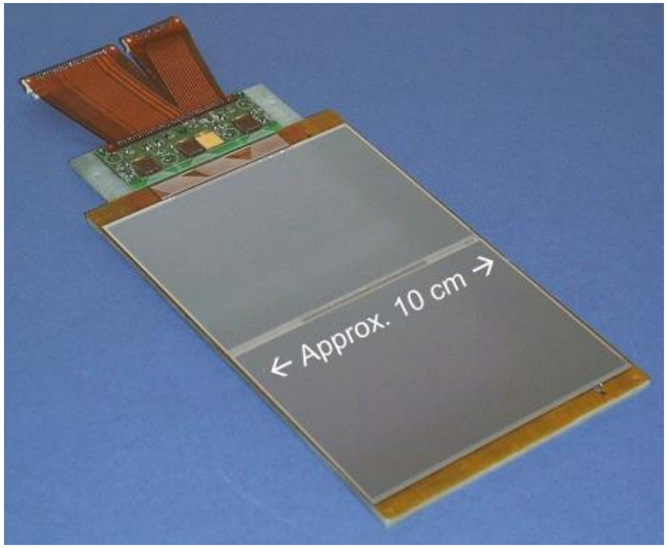
Silicon strip detectors

- Can choose the implants to be microstrips with pitch ~ 50 µm → accurate measurement of one coordinate



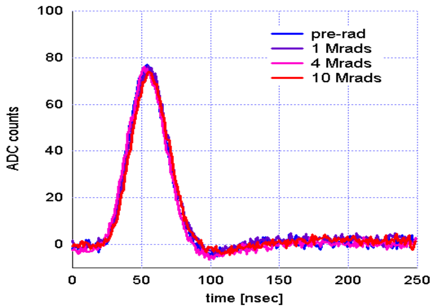
- The other coordinate can be measured with strips at a different angle → track passed where the hit strips cross
- At high occupancy this can lead to ambiguities → move to pixel detectors

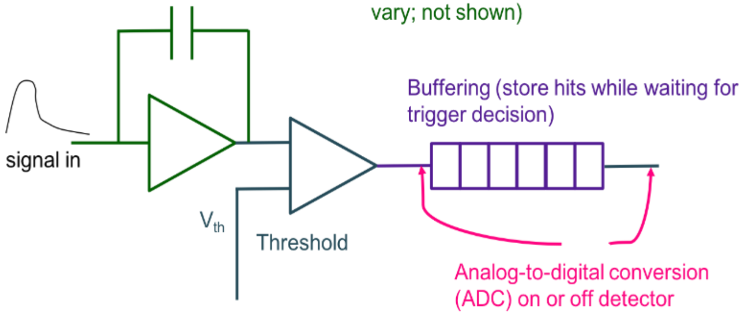




Readout electronics

- The signals are readout via dedicated **ASICs** (Application-Specific Integrated Circuits)
  Pulses are small: 80 electron-hole pairs per μm x 150 μm-thick detector = 12,000 electrons = 2 fC
- Measure the time-over-threshold or just the presence of charge (binary)
- LHC bunch crossing rate of 40 MHz → time between successive bunches = 25 ns
  Fast electronics is therefore required
  Shaping time < ~ 25 ns to avoid overlapping events from previous bunch crossing
- Electronics also needs to be *radiation resistant:* Dose from pp collision products is high, especially in forward region > 10^{15} n/cm^2 over 10 years → *deep sub-micron* chip technology
  (0.25 μm CMOS, or now smaller feature sizes)




Amplification – integrator with return-to-baseline (details vary; not shown)

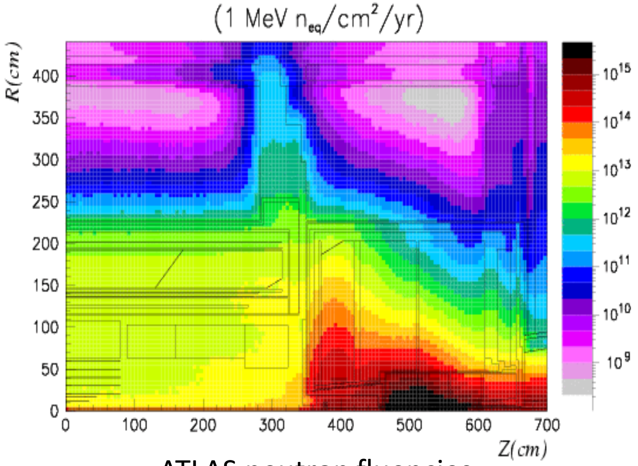
signal in

V_{th}

Threshold

Buffering (store hits while waiting for trigger decision)

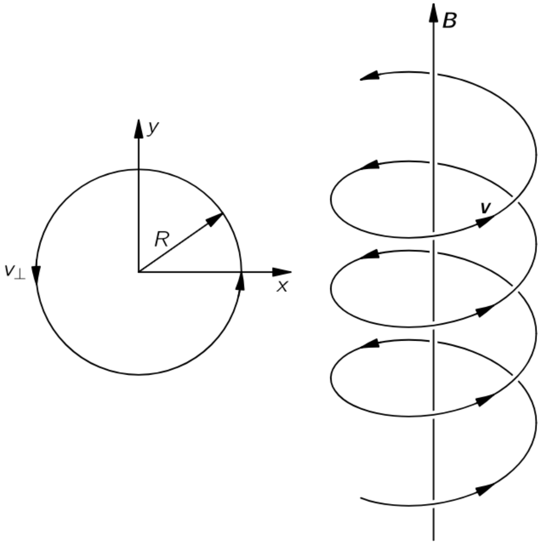
Analog-to-digital conversion (ADC) on or off detector



ATLAS neutron fluencies

Magnetic field

- Experiments use a magnetic field to separate charges of particles and measure their momenta
  The choice of magnet configuration determines the overall experiment layout



- In a uniform magnetic field, charged particles follow circular trajectories in the transverse plane

  $R = p_T / 0.3\,B$ using units [m], [GeV], [T]

  In 3D the trajectories are **helical**

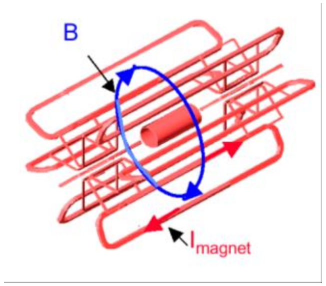
- The tracks of charged particle are measured using particle detectors with given spatial precision σ(*x*)
  To measure to higher momentum, need to increase field *B* or length *L* that track is measured over

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} \propto \frac{\sigma(x)\cdot p_T}{BL^2}$$

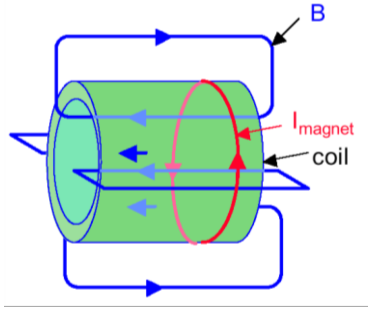
- General-purpose experiments at the LHC were designed to measure muons out to 1 TeV: use highest available field (superconducting magnets, up to 4 T) but still need to be very large, $L \sim O(20\text{ m})$
- The type of magnet construction dominates their appearance

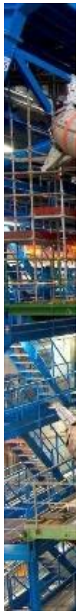
Magnets

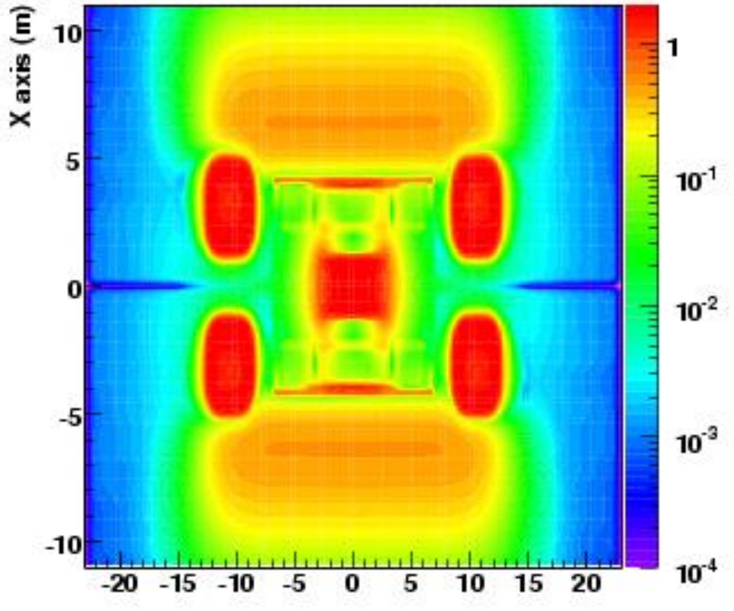
ATLAS toroidal field

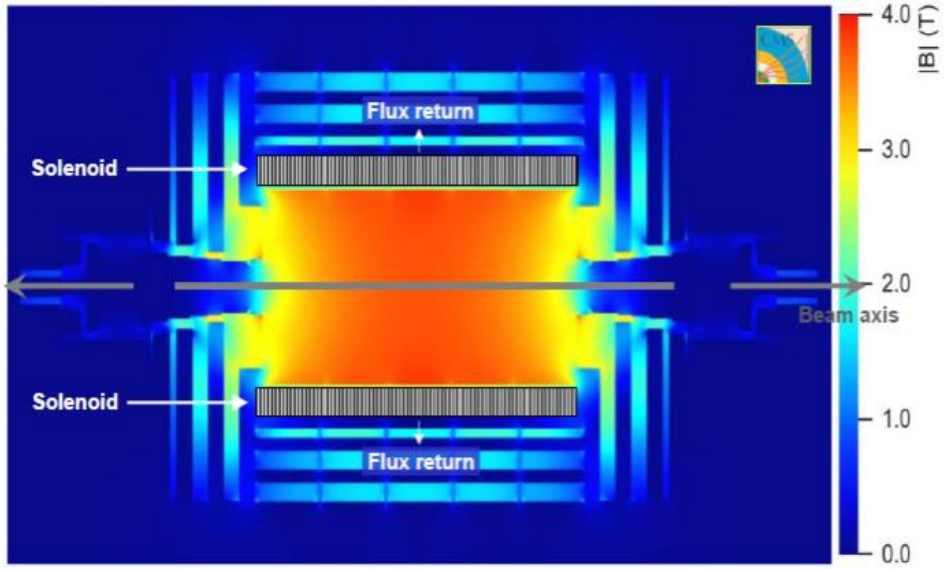


CMS solenoidal field









⊕ Standalone muon measurement

⊖ Tricky endcaps
Requires additional solenoid for central tracking

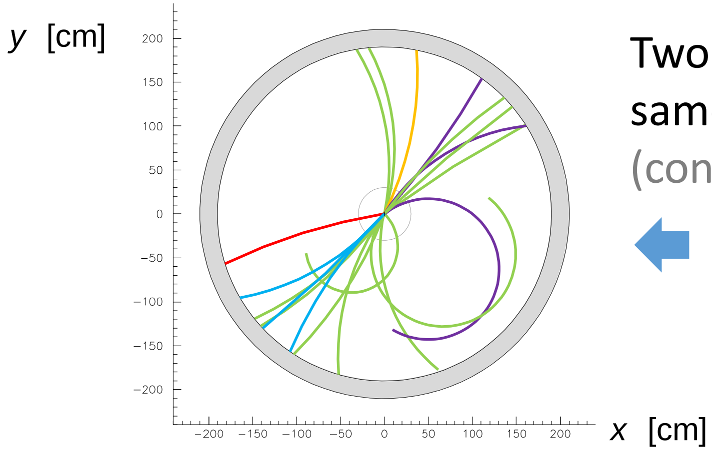
⊕ Higher flux density (4T) → more compact "traditional" design

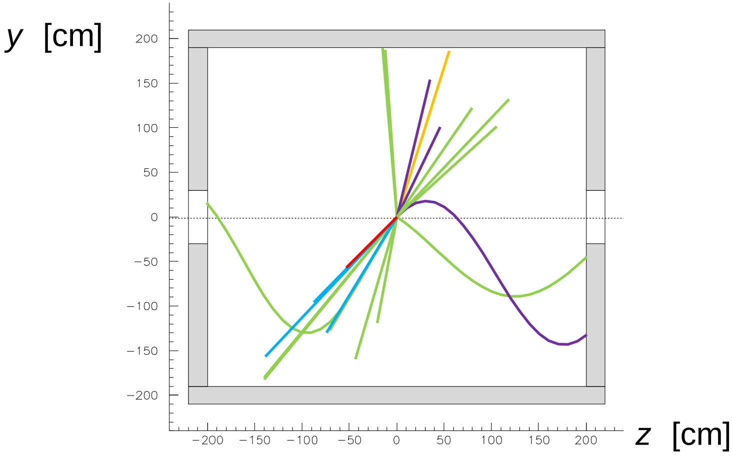
⊖ Very heavy (iron for return yoke)
Limited space for calorimeter inside coil

Track parameters

- In *projection*, helical tracks give circular segments (*x, y*) or sinusoids (*y, z*) → ~ straight lines for high p_T tracks in longitudinal plane of the beam axis

Two projections of the same tracks in a Z decay (constant B-field along *z*)



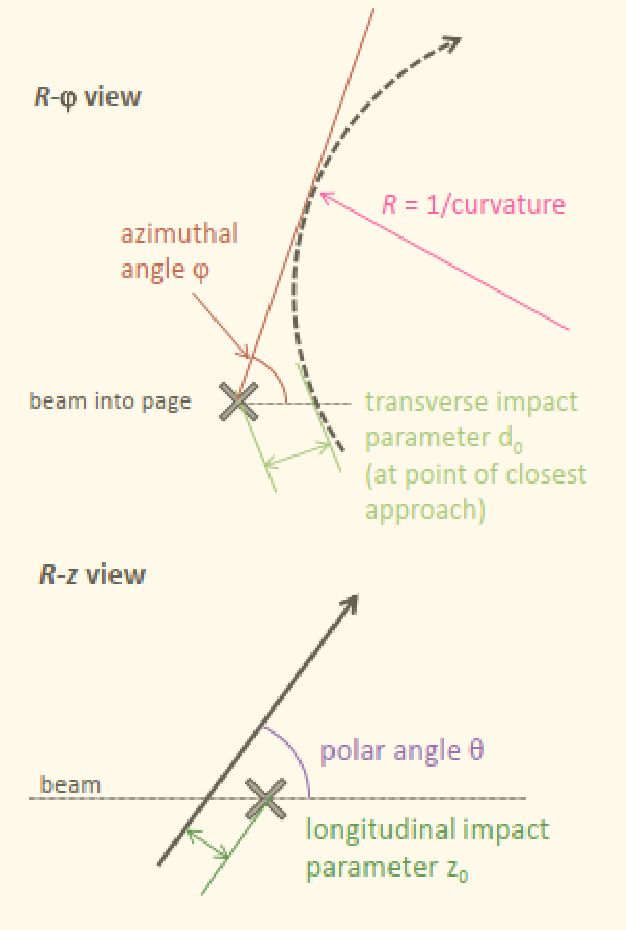


Helical trajectory defined by 5 track parameters:

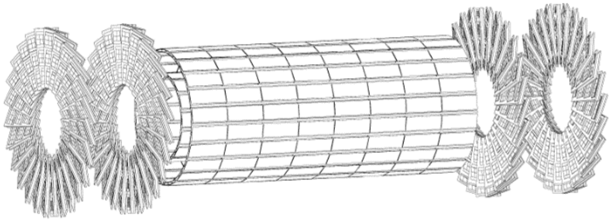
2 impact parameters (d_0, z_0)

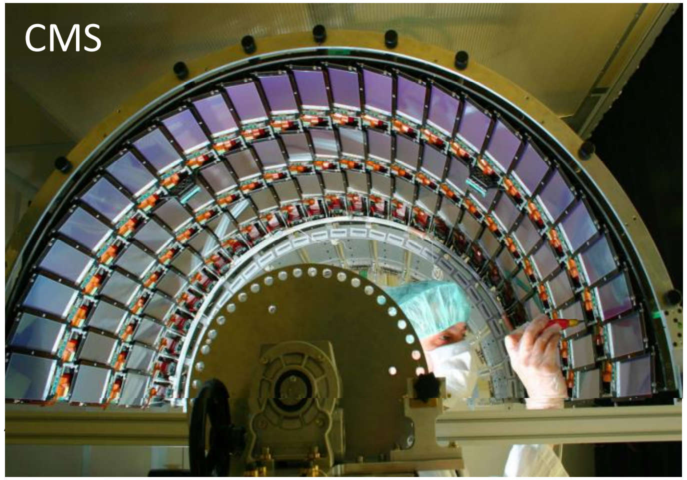
2 angles (θ, ϕ)

+ curvature ∝ $1/p_T$



Central tracking

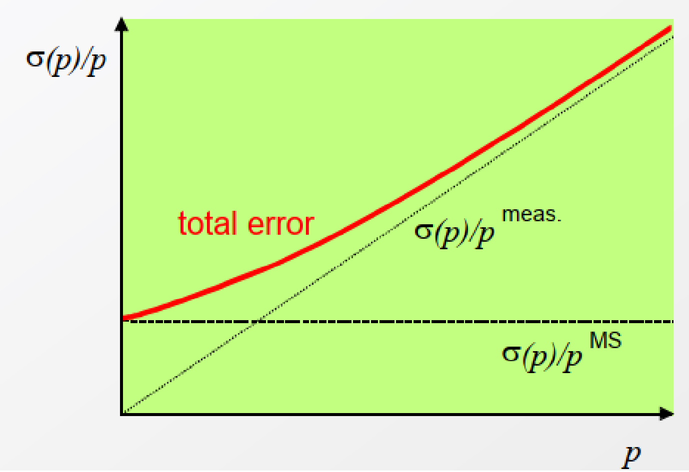




- The CMS tracker has 210 m^2 of silicon detectors!
- Thousands of wafers all have to be carefully *aligned* to each other e.g. using tracks that pass through overlap region
- Tracks are seeded with hits in the vertex detector, then a *Kalman filter* is used for track extrapolation, with subsequent fit to helical trajectory
- Remember: $$\frac{\sigma(p)}{p_T} \propto \sigma(x)\cdot p_T$$

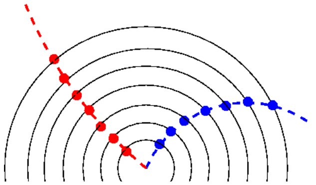
  and $$\sigma(x)\Big|^{MS} \propto \theta_0 \propto \frac{1}{p}$$

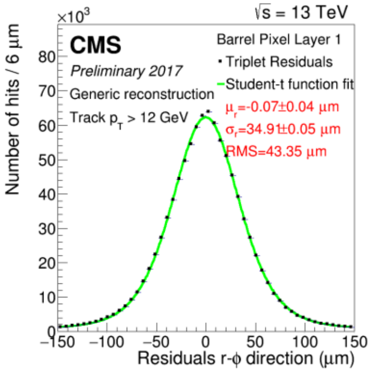
  so contribution to resolution from multiple scattering: $$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = \text{constant}$$

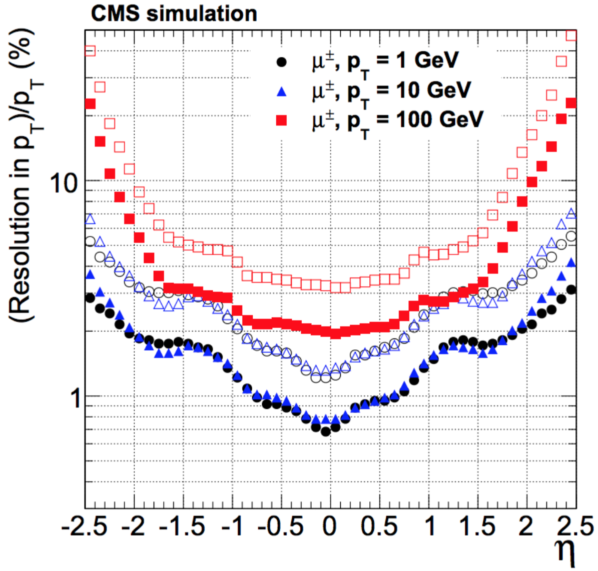


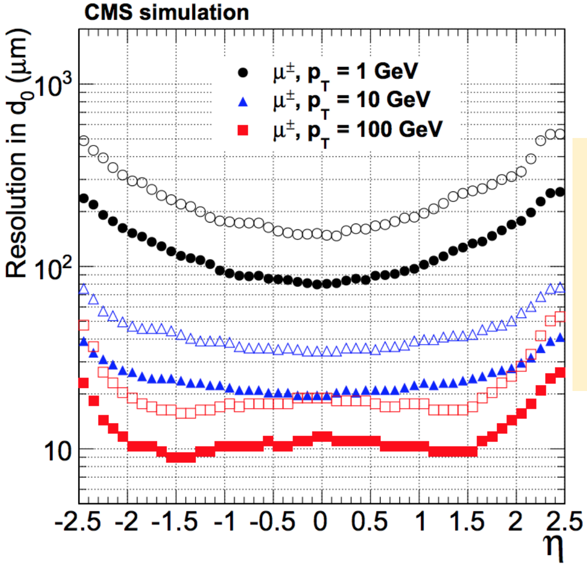
Tracking performance

- Measuring the resolution: refit the track after removing a hit, and compare the “residual” distance between the hit and the refitted track









arXiv:1405.6569

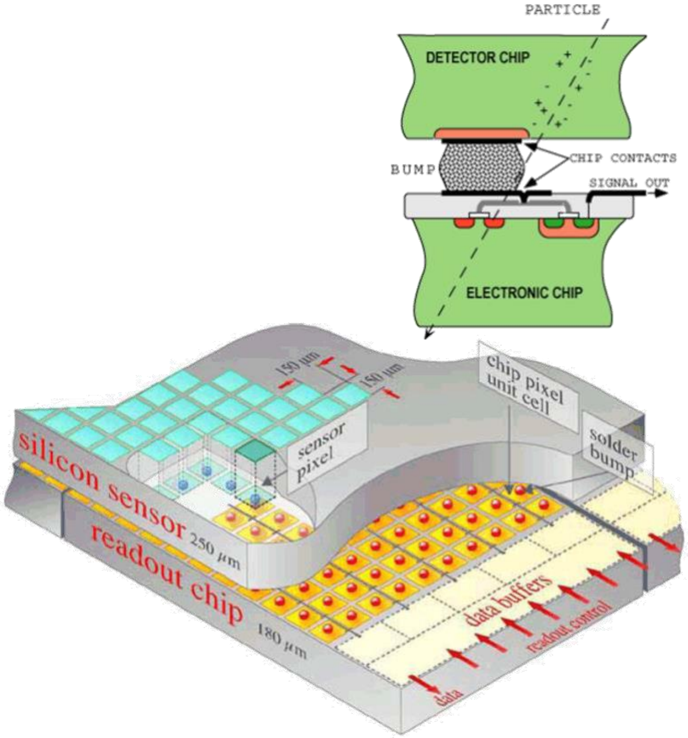
Harder to measure curvature of straighter (higher-momentum) tracks
Harder to extrapolate lower-momentum tracks: scattering in material matters

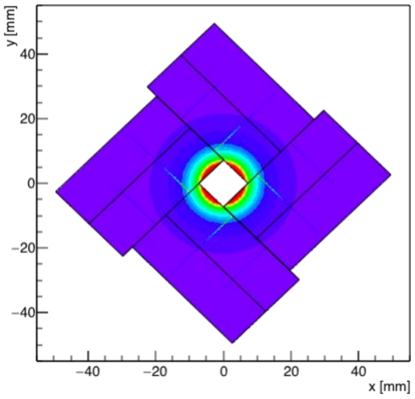
$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 \propto \underbrace{\boxed{c_1 \cdot \left(\frac{p_T}{BL^2}\sqrt{\frac{720}{N+4}}\right)^2}}_{\textbf{curvature}} + \underbrace{\boxed{c_2 \cdot \left(\frac{1}{B\sqrt{LX_0}}\right)^2}}_{\textbf{multiple scattering}}$$

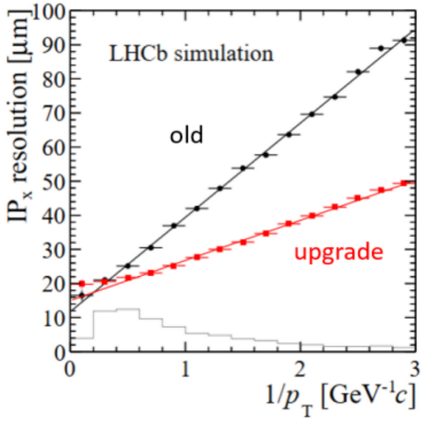
For CMS: magnetic field B = 3.8 T
tracker radius L = 1.2 m
number of measurements N >10

Vertex detectors

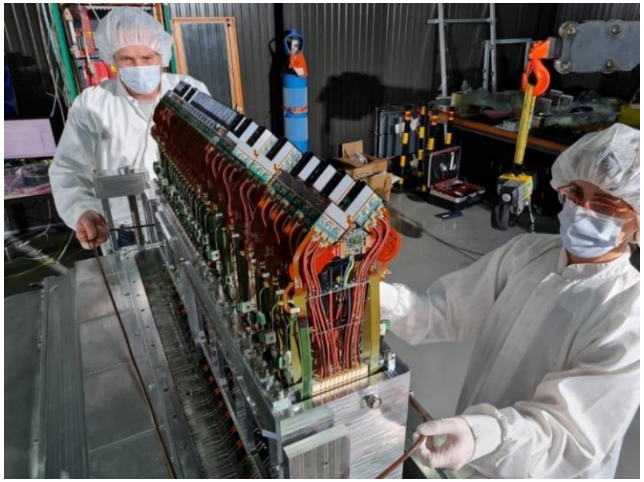
- Silicon pixel detectors are used for the precise vertex detectors
- Two major varieties: *hybrid* (with separate sensor and electronics chips) or *monolithic* (where on same Si wafer)
- Example of LHCb **VELO**: 55 µm x 55 µm pixels, bump-bonded to readout chip Approach to a few mm from the LHC beams with complex motorized system to retract detector while beams injected



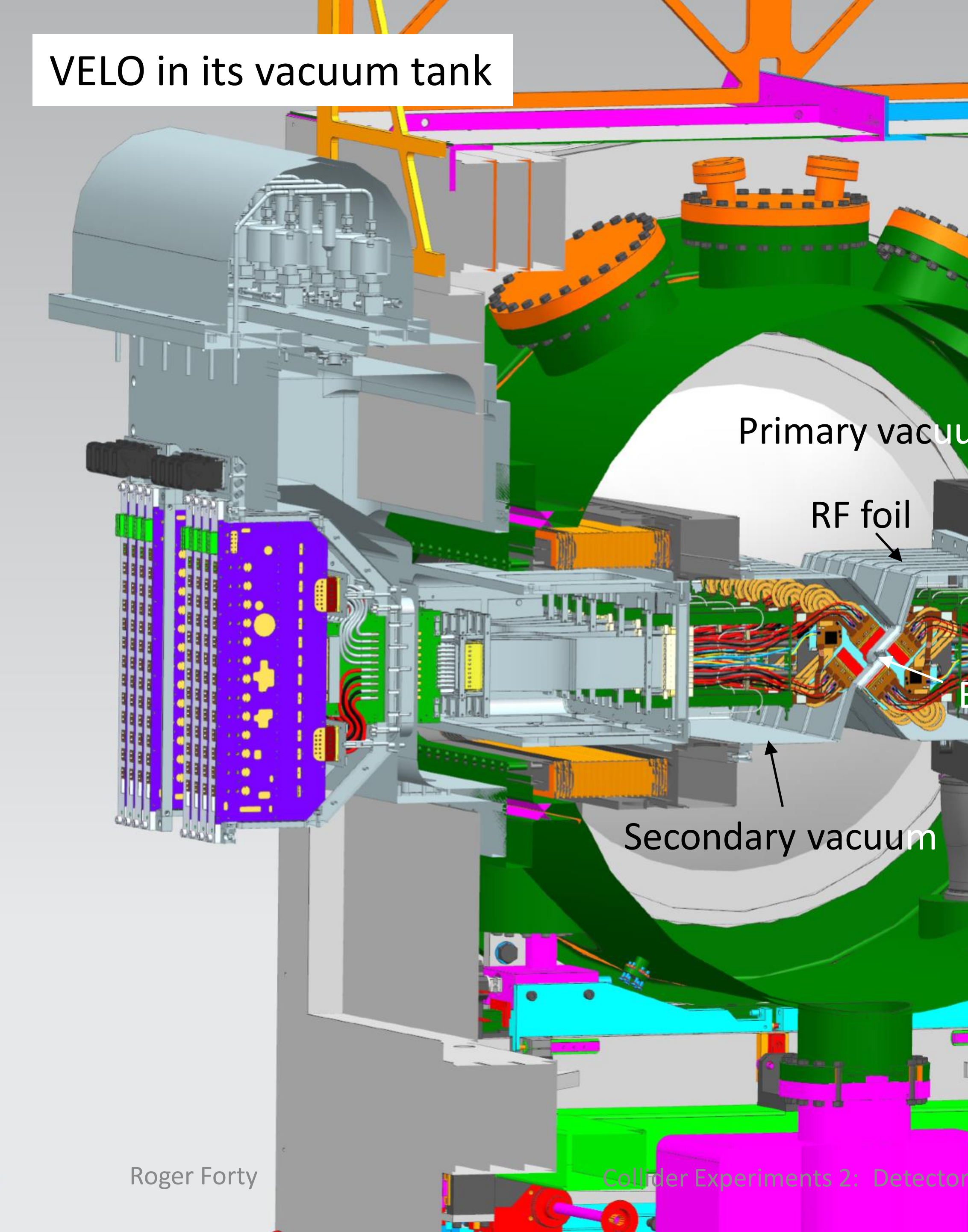


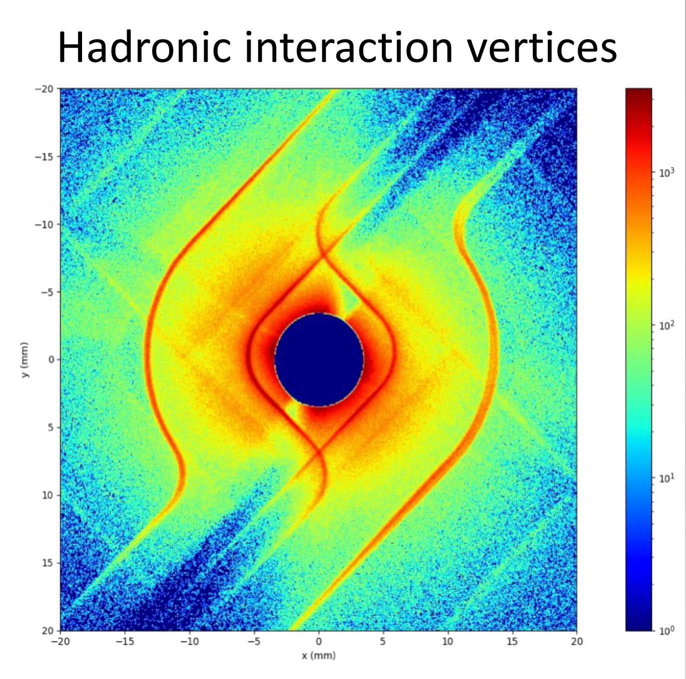


LHCb vertex locator (VELO)

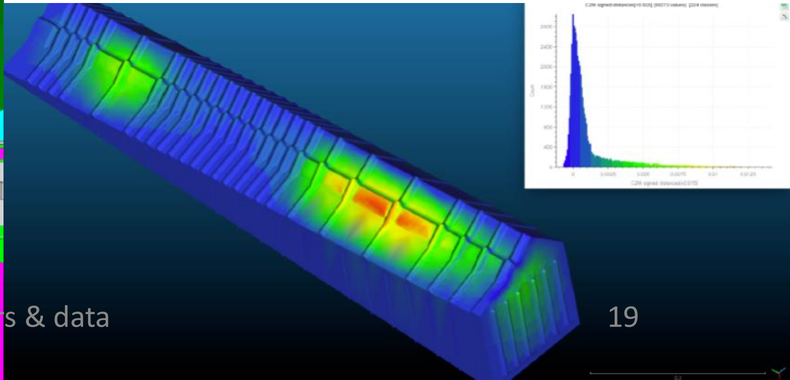


VELO in its vacuum tank



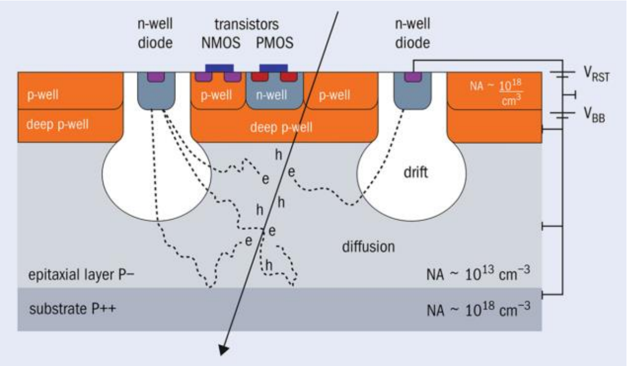


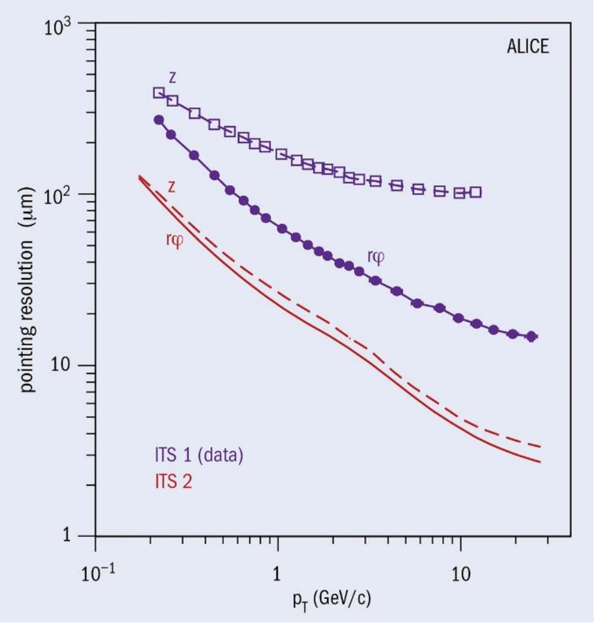
Incident with vacuum system (Jan 2023):
RF foil has been deformed by ~ 1 cm
Will have to be replaced at end of the year

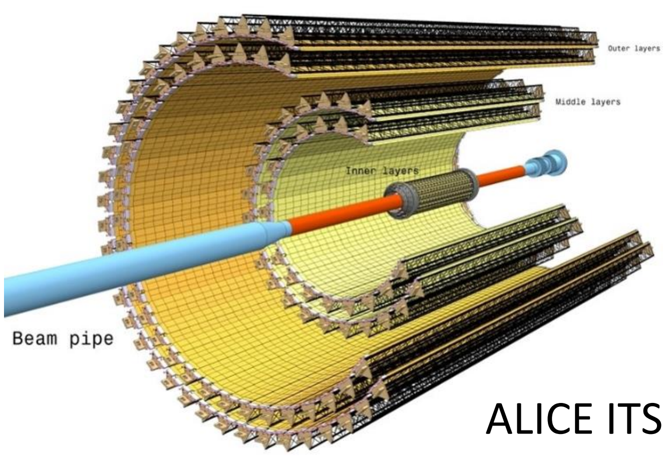


Monolithic Active Pixel Sensors

- ALPIDE chip of ALICE **ITS** is an example of a monolithic vertex detector: each chip has 15 × 30 mm^2 area with over half a million pixels organised in 1024 columns and 512 rows
- Sensitive volume is a 25 µm-thick layer of high-resistivity p-type silicon (> 1 kΩ cm) grown epitaxially on top of a standard CMOS wafer
- Radiation tolerance to beyond 10^{13} n/cm^2 (1 MeV equivalent), sufficient for ALICE



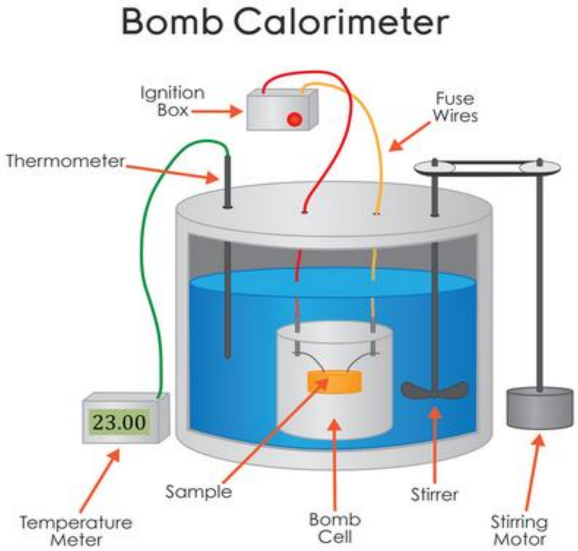




ALICE ITS

2. Calorimeters

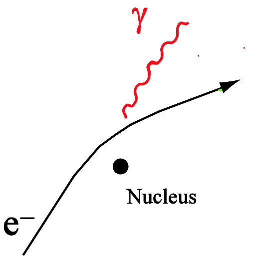
- Calorimeters measure *energy*: in a thermodynamics lab the temperature change of a known volume of water can be measured to determine the energy released in a reaction, sharing the reaction energy with many molecules evenly to determine its total
- HEP calorimeters convert the energy of an incoming single particle into many lower-energy particles Count the number of particles to determine the total original energy



- Basic properties:
  - Use dense material to cause particles to interact
  - Active material to produce measurable quantity: ionization charge or light
  - Thick to completely *contain* energy in calorimeter
- Calorimeters complement the magnetic spectrometers
  - They also measure the energy of *neutral* particles
  - Energy resolution *improves* with energy while track resolution degrades

Electromagnetic interactions

- **Electrons** are stable particles and have low mass (m_e = 0.51 MeV) When passing through matter they produce *Bremsstrahlung* radiation



$\Delta E \propto 1/m^2$
Dominates over ionization for electrons with E > 100 MeV

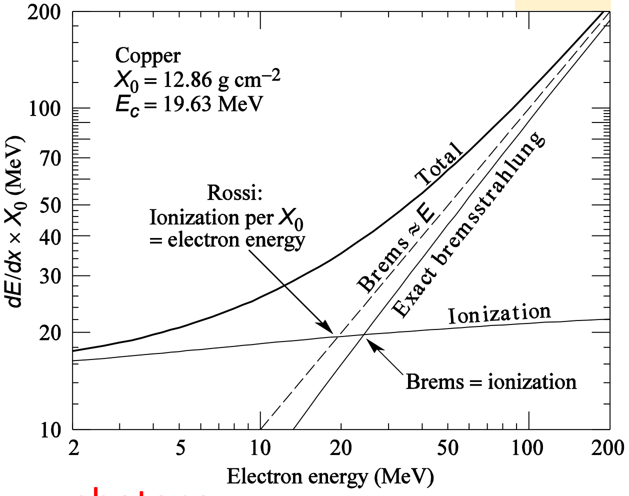
- Scales with radiation length X_0 of material = mean distance to reduce energy by 1/*e*

  e = base of natural logarithms ≅ 2.718

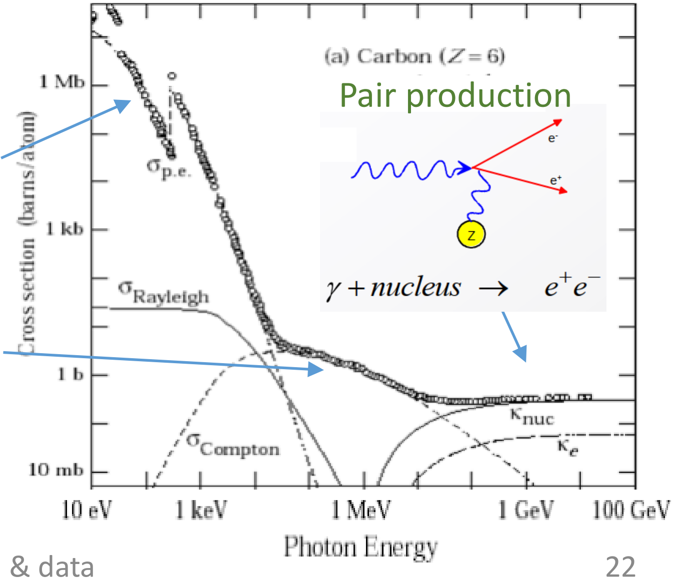
- **Photons** interact with material via various processes, dominating at different energies – at *high* energy they produce e^+e^- pairs

electrons

PDG

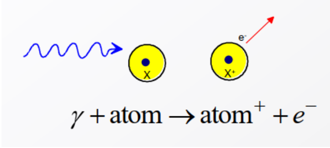


photons



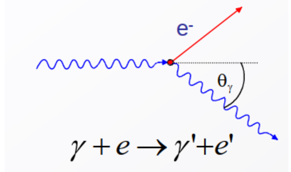
$\gamma + \text{nucleus} \rightarrow e^+e^-$

Photoelectric effect



$\gamma + \text{atom} \rightarrow \text{atom}^+ + e^-$

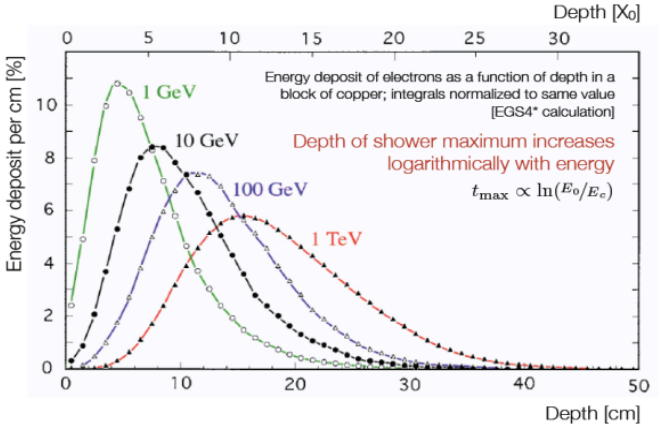
Compton scattering



$\gamma + e \rightarrow \gamma' + e'$

Calorimeter showers

- Put those effects together at high energy:
  1γ → 2e → 2γ → 4e… → **shower** of particles
- Calorimeters convert the energy of incoming particle into many lower-energy particles until reach critical energy E_c at which showering stops
- Eventually, low-energy particles deposit their kinetic energy by ionizing or exciting absorber
- Basic principle is to determine total number of particles produced in the shower, proportional to position of the peak of the energy deposit

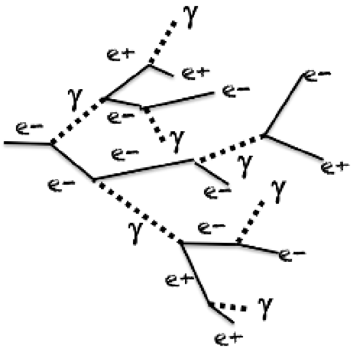


Energy deposit of electrons as a function of depth in a block of copper; integrals normalized to same value [EGS4* calculation]

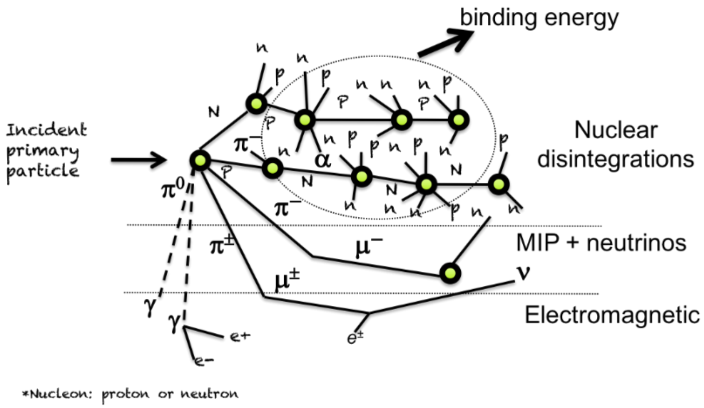
Depth of shower maximum increases logarithmically with energy

$t_{\max} \propto \ln(E_0/E_c)$

- **Electromagnetic** showers:
  pair production + radiation



- **Hadronic** showers:
  due to nuclear reactions



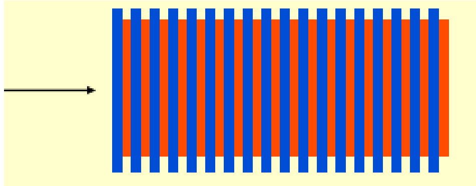
*Nucleon: proton or neutron

Calorimeter types

- **Homogeneous:** a single medium serves as both absorber and active detector Plastic scintillators or glass produce light that is read out by photodiodes or photomultipliers – expensive

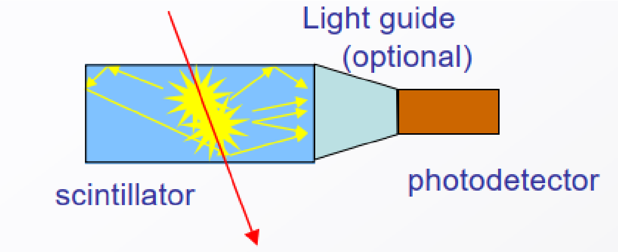
e.g. CMS ECAL

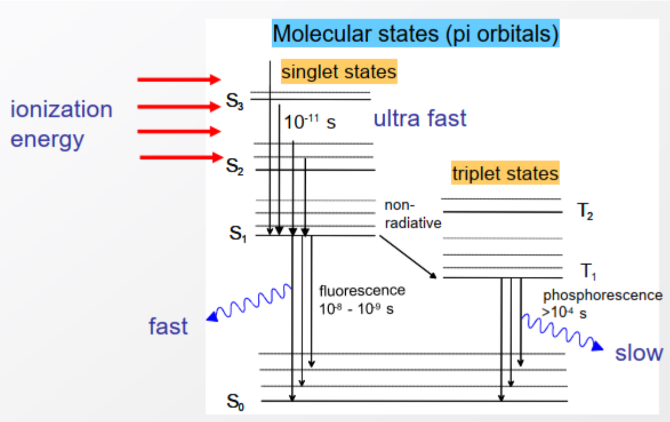
- **Sampling:** reduce cost – layers of cheap, dense passive absorber (Pb, Cu, Fe) for shower development alternated with active detector layers (silicon, scintillators or liquid argon) for signal measurement



e.g. ATLAS ECAL

- *Scintillators* are materials that convert ionization energy into light, typically by excitation of molecular energy levels:





Energy resolution

- Electromagnetic showers scale with the *radiation* length X_0 e.g. = 1.8 cm for Fe
  Hadronic showers scale with the *nuclear interaction* length λ_I e.g. = 17 cm for Fe
- $\lambda_I >> X_0$ so hadronic showers are longer and hadron calorimeters are placed *behind* the electromagnetic ones
- General expression for energy resolution:

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

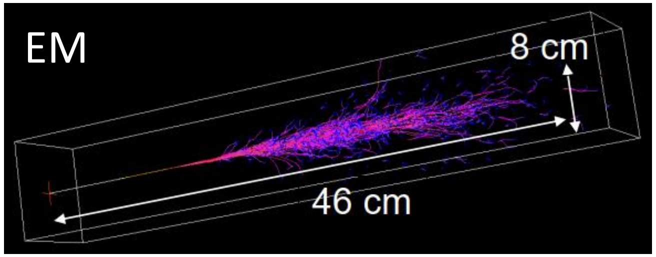
Stochastic term: fluctuations in the number of signal processes

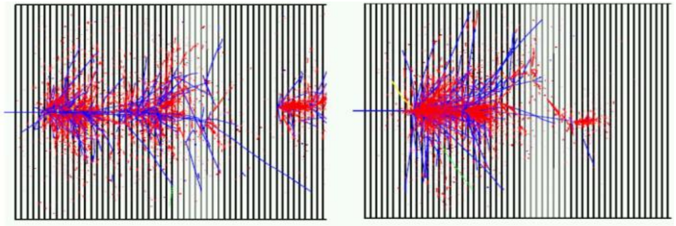
Constant term: inhomogeneities, bad cell inter-calibration, non-linearities

Noise term: electronic noise, radioactivity, pileup

Example: E_0 = 100 GeV in lead glass
E_c=11.8 MeV → $t_{max} \approx 13$, $R_M = 1.8 \cdot X_0 \approx 3.6$ cm

Simulation of showers





Hadronic: EM component, charged hadrons
note the less uniform energy deposition
EM component comes from $\pi^0 \rightarrow \gamma\gamma$ decays

Shower transverse size (Molière radius):

$$R_M = \frac{21\,\mathrm{MeV}}{E_c} X_0$$

Position of shower max: for EM calorimeters

$$t_{\max} = \frac{\ln E_0 / E_c}{\ln 2}$$

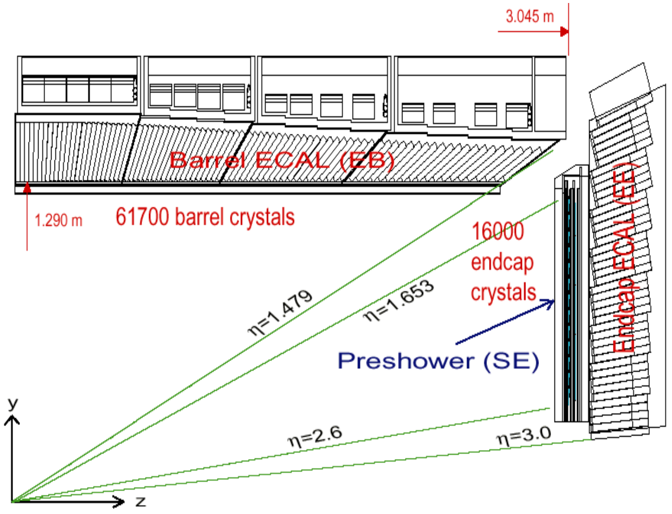
Electromagnetic calorimeters

- CMS uses scintillating crystals ($PbWO_4$)
  Very good energy resolution:

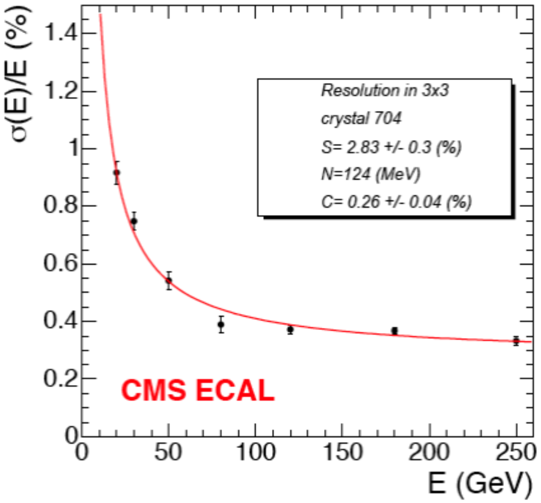
  $\sigma_E/E = 2.8\%/\sqrt{E} \oplus 0.3\% \oplus 0.128\ \mathrm{GeV}/E$

  but no longitudinal segmentation
- ATLAS uses a sampling calorimeter:
  Pb plates embedded in liquid argon
  to collect charge produced in showers

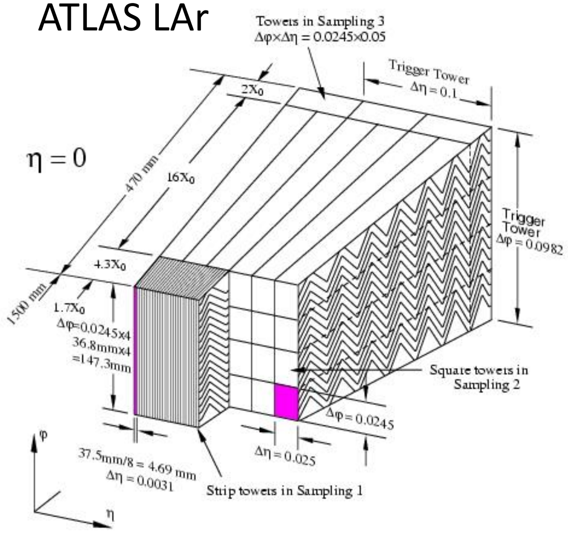
  $\sigma_E/E \sim 10\%/\sqrt{E}$



~ 80,000 crystals required

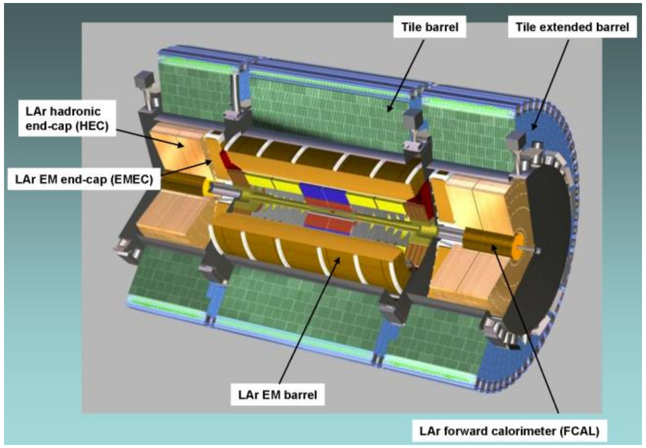


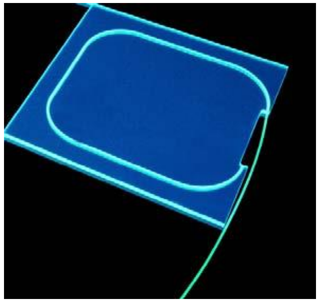
ATLAS LAr



Hadron calorimeters

- Due to the large size hadron calorimeters are usually sampling to save cost
  Example of the ATLAS HCAL: iron plates interleaved with scintillator
  Wavelength shifting fibers trap the light via internal reflection and transport it to photon detectors that convert it into electrical signals





$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$
$\sim 100\%$ for CMS

- In general the hadronic component (h) of a hadron shower produces a smaller signal than the EM component (e) so $\boldsymbol{e/h > 1}$

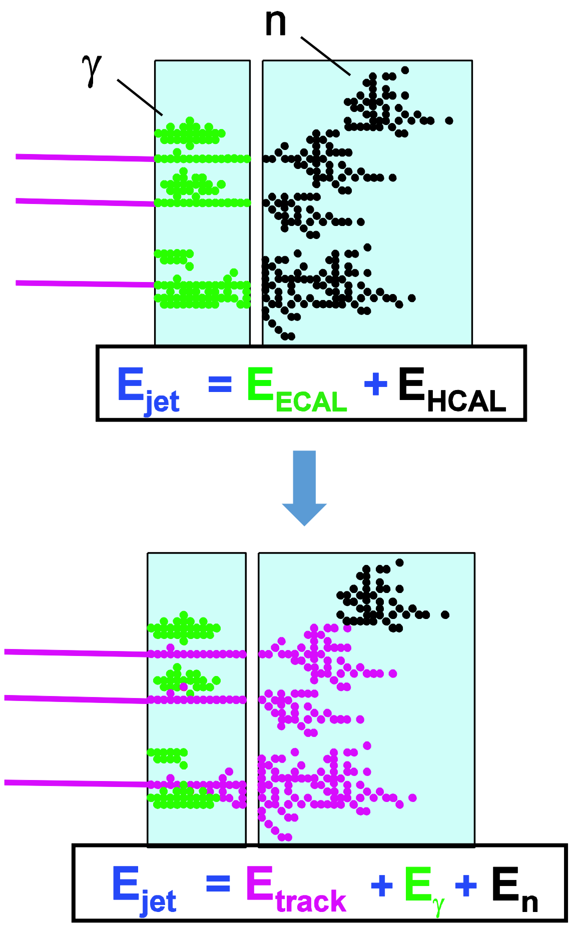
  Compensating hadron calorimeters seek to restore $e/h = 1$ to achieve better resolution and linearity e.g. using ^{238}U as absorber: fission releases additional neutrons (done in ZEUS and L3); or *dual readout* with different fibres (scintillating/Cherenkov) – discussed for future colliders

Particle Flow

- At borderline between tracking, calorimetry and particle ID: in a typical jet
  - 60% of jet energy is from charged hadrons
  - 30% is from photons (mainly from π^0)
  - 10% is from neutral hadrons (n and K_L^0)
- The traditional approach to jet reconstruction:

  Measure all of jet energy in calorimeters
  → ~ 70% of energy measured in HCAL
  HCAL limits jet resolution: $\Delta E/E \sim 60\% / \sqrt{E}$
- **Particle Flow** approach:
  - Charged particles well measured in tracker
  - Photons in ECAL
  - Neutral hadrons (only) in HCAL

  → Only 10 % of jet energy is taken from HCAL
  $\Delta E/E \sim 30\% / \sqrt{E}$ can be achieved



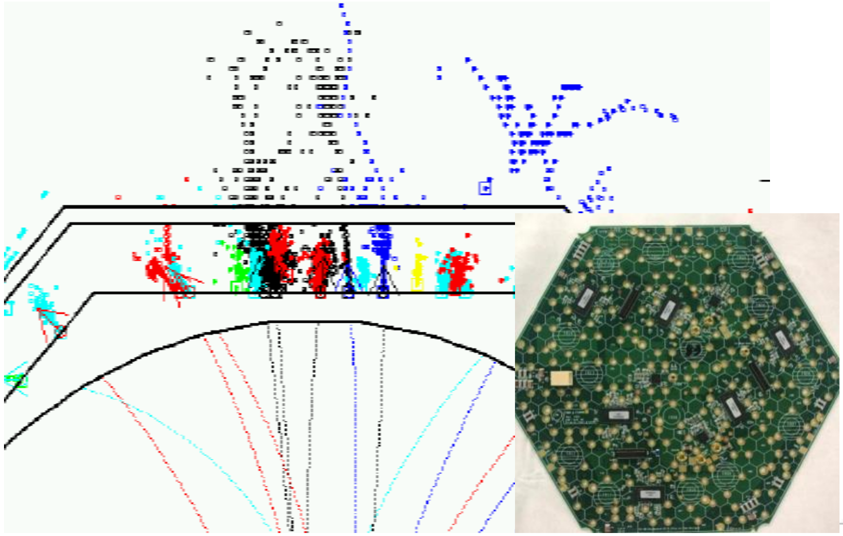
$E_{jet} = E_{ECAL} + E_{HCAL}$

$E_{jet} = E_{track} + E_{\gamma} + E_{n}$

Particle-flow calorimeters

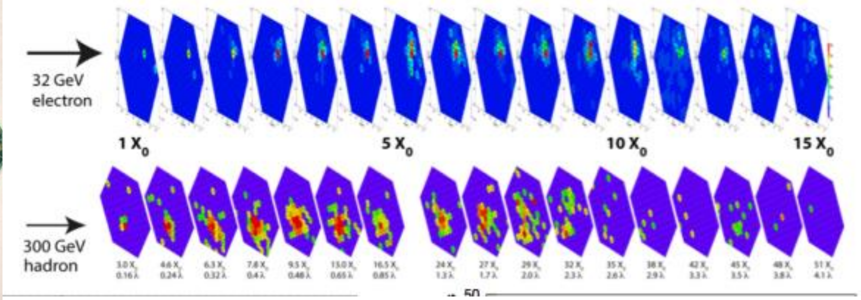
- The main remaining contribution to the jet energy resolution comes from the confusion of contributions, from overlapping showers etc.
- Most important is to have high *granularity* of calorimeters to help the (complicated) pattern recognition
- This is the approach being studied for detectors at a future e^+e^- collider Higgs Factory (e.g. ILC): will return to this in the 4th lecture

Simulated event in an ILC detector



Si wafer

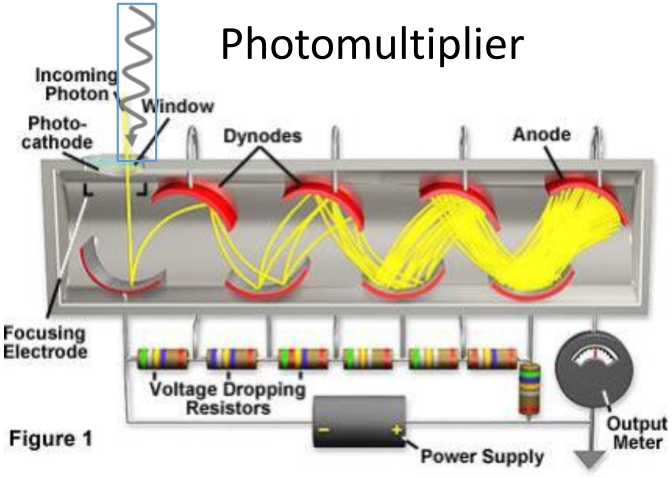
Similar technology (Si-W) has been adopted for the CMS forward calorimeter upgrade (**HGCAL**) for HL-LHC – with 6 million channels



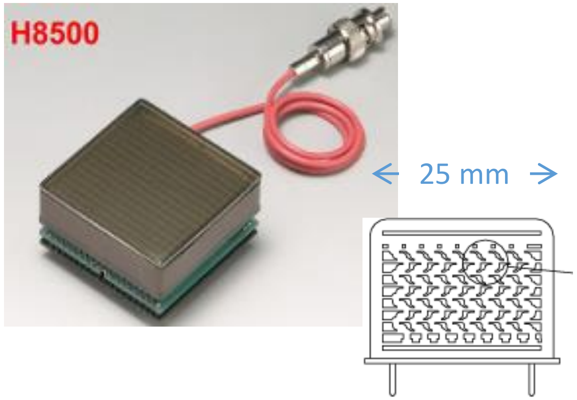
Photon detectors

- Photon detection necessary for many detectors performing calorimetry or particle identification
  Requirements: high efficiency, good spatial granularity, single-photon sensitivity (for RICH)
- Incident photon is converted to an electron by photoelectric effect in a *photocathode*, typically formed out of alkali metals e.g. Sb-Na-K-Cs
- Photoelectron signal needs to be amplified to give a measureable electronic pulse
  Achieved in traditional **photomultiplier** (PM) by dynode chain → charge multiplied at each dynode: e.g. if number of electrons triples at each stage of a 12 dynode chain → Gain = $3^{12} \sim 10^{6}$
- **Multianode PM**: a marvel of miniaturization
  up to 64 pixels in a single tube, each ~2×2 mm^2
  Dynodes formed from stack of metal foils

Photomultiplier



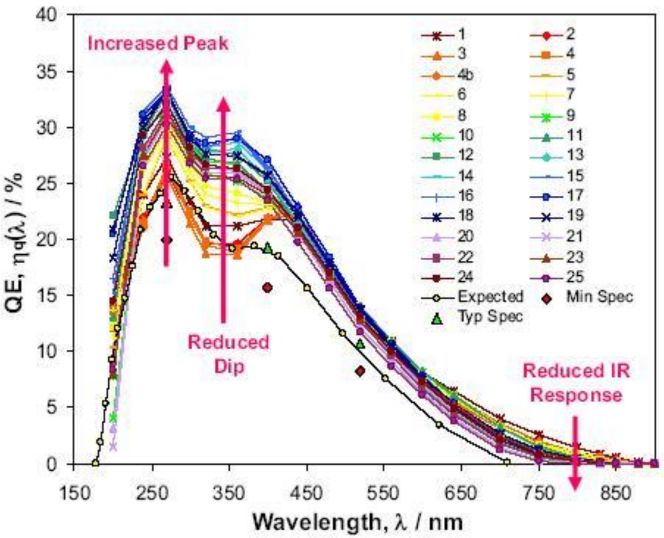
Multianode PM

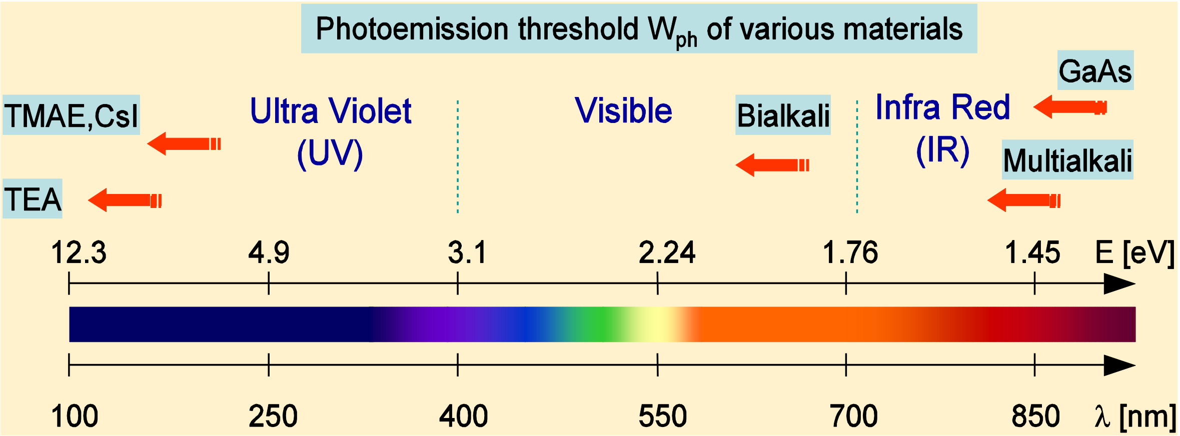


Photon detection efficiency

- *Quantum efficiency*: probability that an incident photon produces a photoelectron
  Peak value is typically 20–30%
- Needs to be multiplied by the *collection efficiency*: efficiency for detecting the photoelectron (typically 80–90 %)
- Photocathode type is chosen according to the desired spectral sensitivity
  (mostly near to *visible light*, E_γ = few eV)

QE curves for tubes with multialkali photocathode




Photoemission threshold W_{ph} of various materials

Remember: $E = hc/\lambda$
λ [nm] ≈ $1240/E$ [eV]

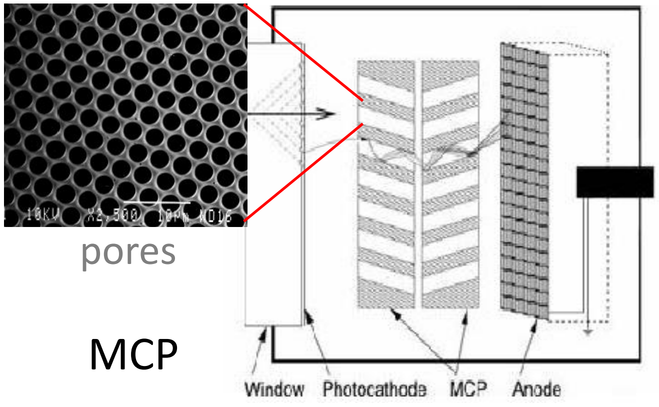
Wavelength

Other photon detectors

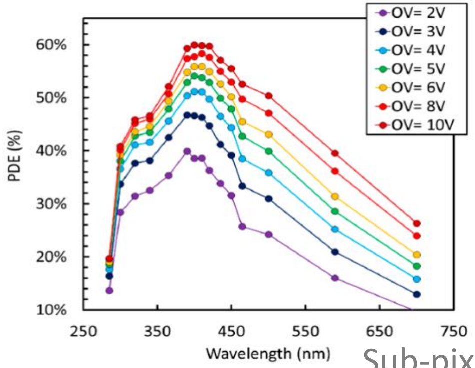
- Time Of Flight detectors need fast timing precision at *picosecond* (10^{-12} s) level
  1 ps ≈ 0.3 mm for a relativistic particle
  → requires small feature sizes
- **MCP** (micro-channel plate) photon detectors use electron multiplication in small (~ 10 μm) glass *pores*, as used in image intensifiers
  Timing precision of ~ 10 ps achieved
- **SiPM**: Fully solid-state photon detectors are a very active field of development

  Use a *p-n* junction in Geiger mode (above the breakdown voltage) → large gain, binary signal, long recovery – an array of ~100 such elements are combined to make up a single pixel

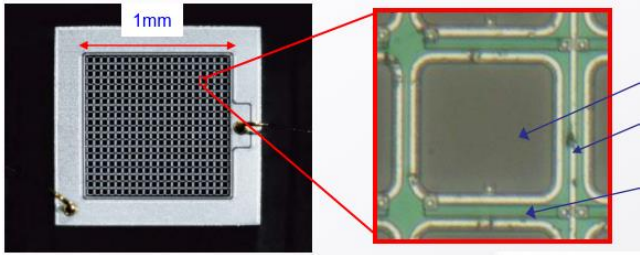
  Advantages: very compact, high QE
  Disadvantages: high noise, neutron damage



SiPM

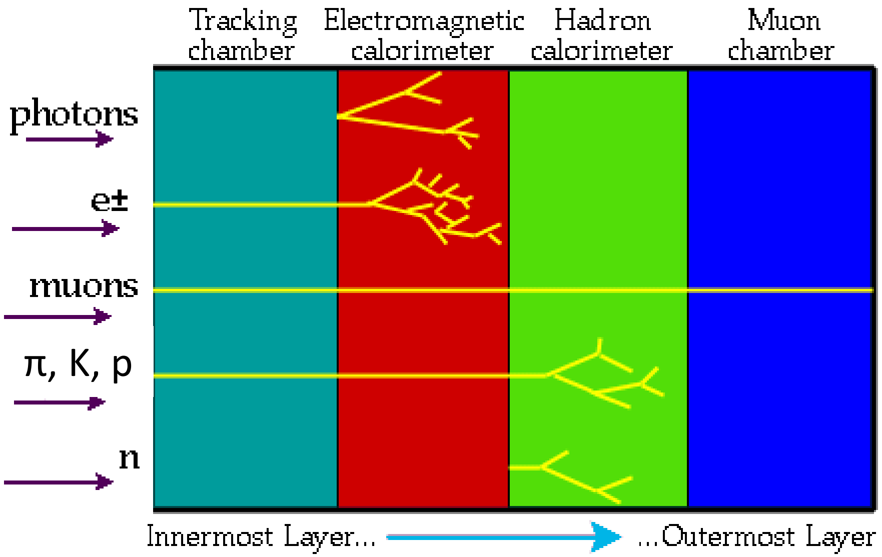


Sub-pixel



3. Particle identification

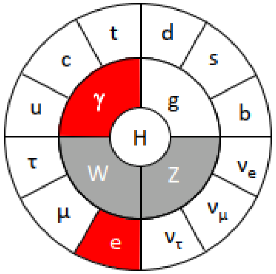
- Detectors arranged in successive layers, moving out from interaction point
  - **Tracking** detectors closest to beam pipe to minimize multiple scattering of tracks before they are measured → detect charged particles
  - Followed by **Electromagnetic calorimeter**: (e, γ) produce showers
  - Then a **Hadron calorimeter**: (π, K, p, n) produce showers
  - Finally **muon detectors**
- Neutrinos escape undetected → missing energy



Enough information provided to separate all of the particle types, except the charged hadrons (π, K, p) — for this require specialized detectors

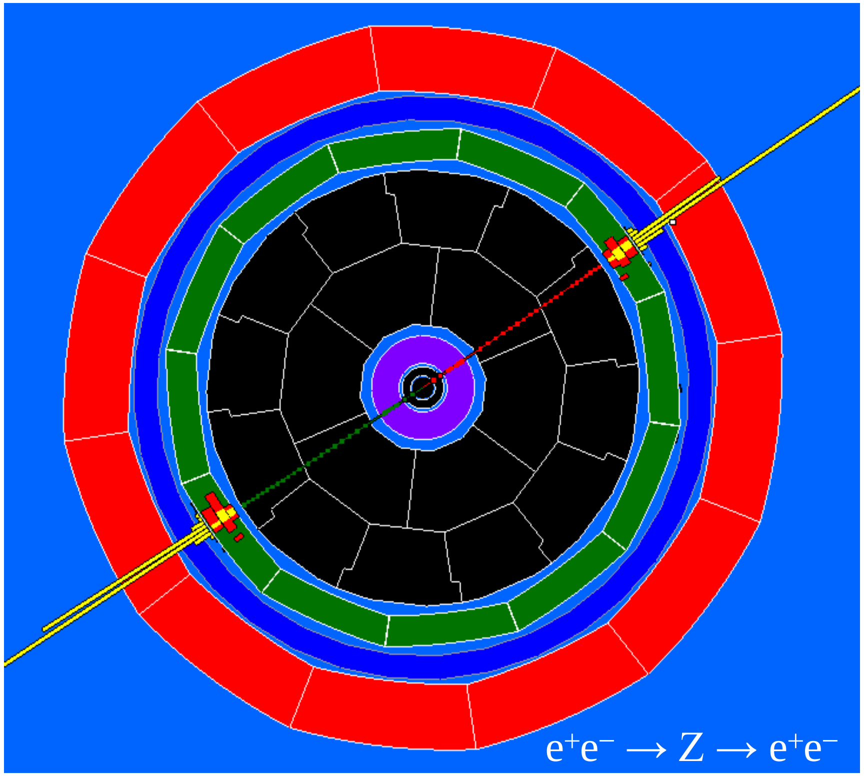
Will now briefly review how the different particles are seen

Electrons & photons

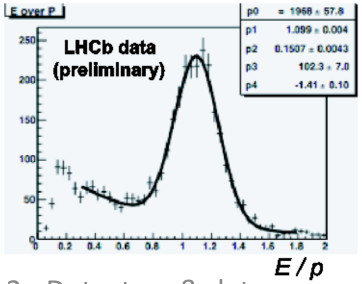


- Return to the event display shown in 1st lecture: ALEPH experiment at LEP – can now recognize the detectors
- Display is a fish-eye view in the plane transverse to the beams: use these “simple” events to illustrate how different particle types are identified
- **Electrons** & **photons** give similar showers in the ECAL (electromagnetic calorimeter)

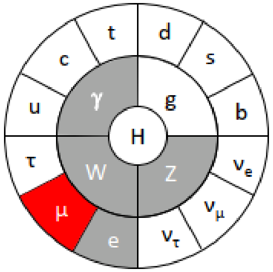
  Distinguished by the existence (or not) of an associated *track*
- For electrons, *E* (energy in the ECAL) and *p* (momentum from the tracker) should be equal: $E/p = 1$ —not the case for other particles



$e^+e^- \to Z \to e^+e^-$

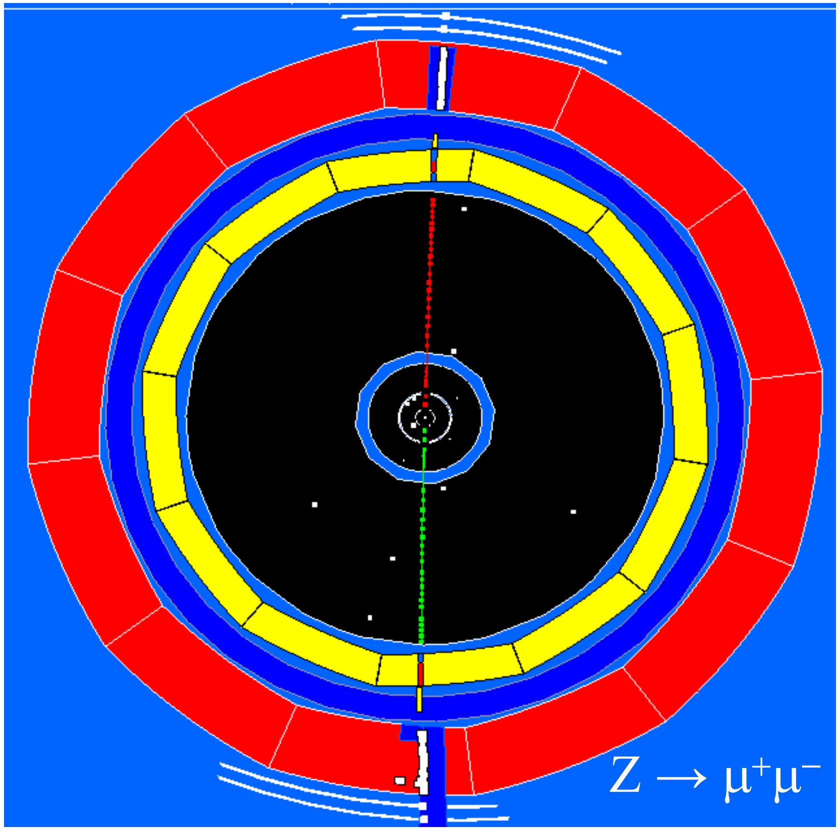


Muons



- Muons act like heavier versions of the electron, with mass 105.7 MeV
- They decay to electrons $\mu^- \rightarrow e^- \nu_e \nu_\mu$ with (proper) lifetime τ_μ = 2.2 μs
  = mean of their exponential decay distribution
- Distance they travel (on average) before decay: $d = \beta\gamma c\tau_\mu$
  where *velocity* $\beta = v/c$
  boost $\gamma = E/m = 1/\sqrt{(1-\beta^2)}$
- So a 10 GeV muon flies ~ 60 km before decay >> detector size
  → effectively stable
- Since mass is large, Bremsstrahlung radiation is small, and as a lepton it does not feel the strong interaction

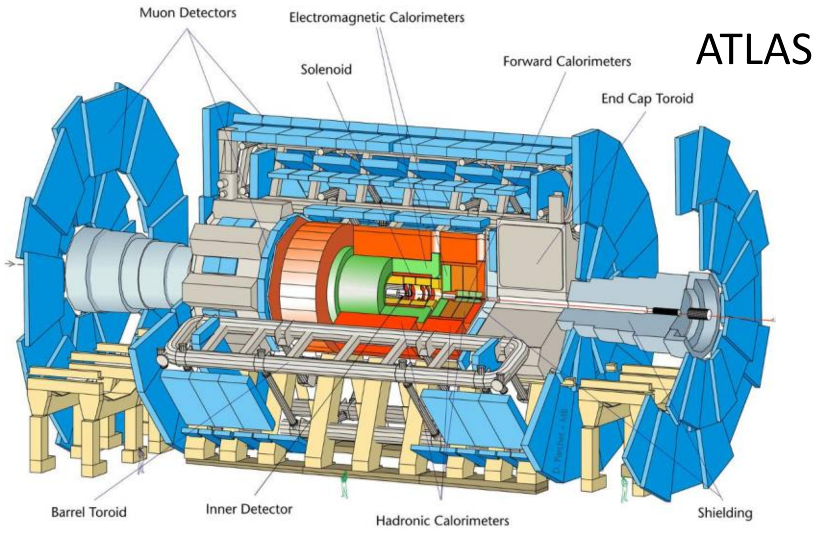
→ most penetrating charged particle

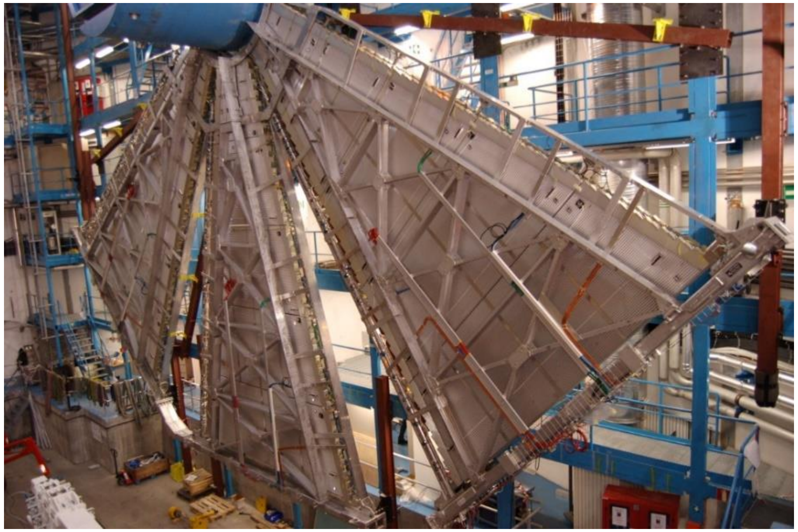


Muon detectors

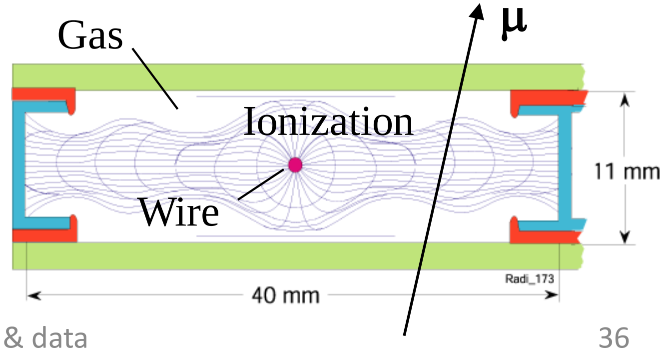
See lecture of George Mikenberg

- Since they are sited on the outside of an experiment, muon detectors tend to dominate their appearance
- Tracking for muons covers an area of ~ 10,000 m^2 in these detectors!

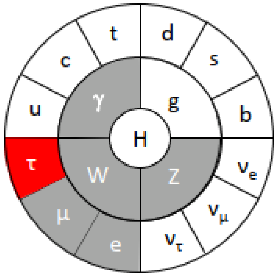




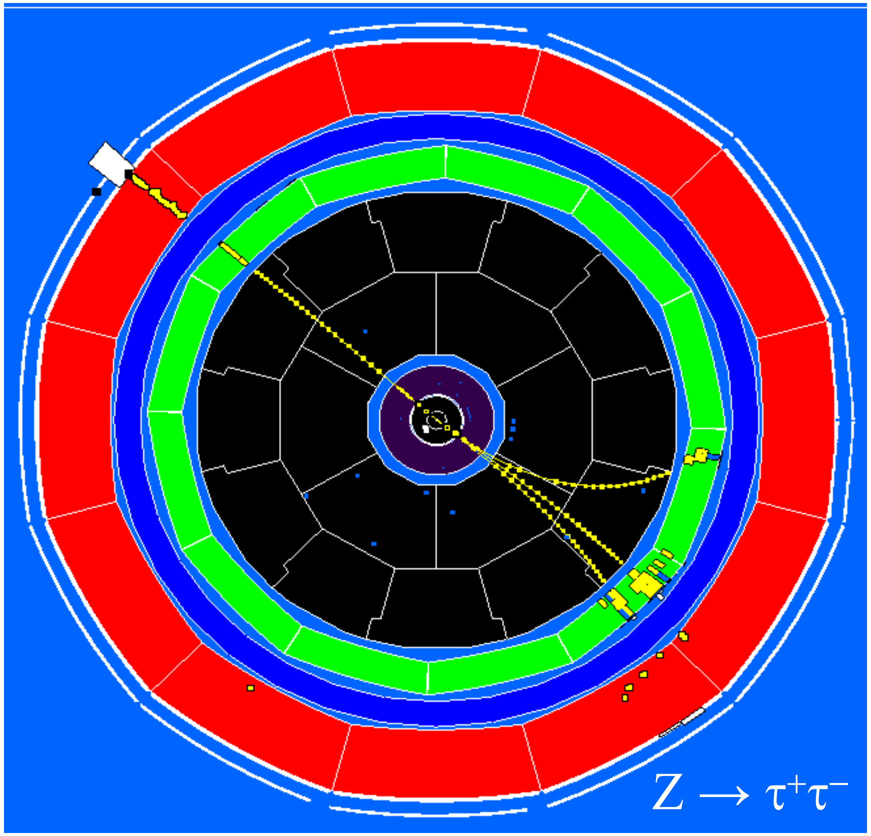
- They must be inexpensive, low granularity but precise enough for *p* measurement e.g. wire chambers with long drift volume (cross-section of a CMS chamber shown)



Tau leptons



- Tau is heavier still, $m_\tau = 1.78$ GeV
- Heavy enough that can decay to many final states: $\tau^- \to \mu^- \nu_\mu \nu_\tau$, $\pi^- \nu_\tau$, $\pi^- \pi^0 \nu_\tau$, $\pi^- \pi^- \pi^+ \nu_\tau$, …
- Lifetime $\tau_\tau = 0.29$ ps so a 10 GeV tau flies ~ 0.5 mm
- This is typically too short to be seen *directly* in the detectors
- Instead the decay products are seen: low multiplicity, "few prong" decays
- Accurate vertex detectors can detect that they do not come exactly from the interaction point (i.e. measure their *impact parameter*)



Neutrinos

See lectures of Renata Zukanovich Funchal

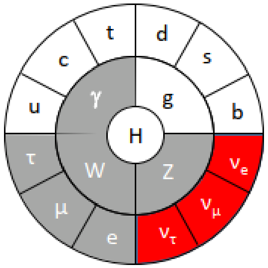
- Neutral (i.e. no track) and only weak interaction → pass though matter easily
- Interaction length $\lambda_{int} = A/(\rho\sigma N_A)$, cross-section $\sigma \sim 10^{-38}\ \mathrm{cm}^2 \times E$ [GeV]
  → a 10 GeV neutrino can pass through over a *million km* of rock
- Neutrinos are usually detected in HEP experiments through *missing energy* (applying *E* conservation to rest of the event, in the transverse plane E_T)
- Nevertheless their interactions can be detected if you produce enough of them, and the detector is sufficiently massive

> 1 kton of instrumented target mass!

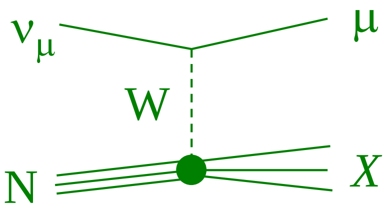
DUNE will be even bigger, aiming for 40 kton of liquid argon

Neutrino flavours

Nobel prize 1988
(Lederman,
Schwartz, Steinberger)

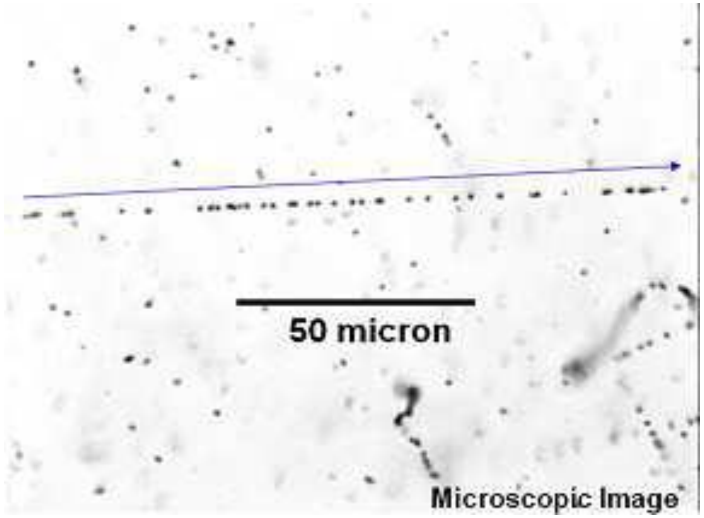


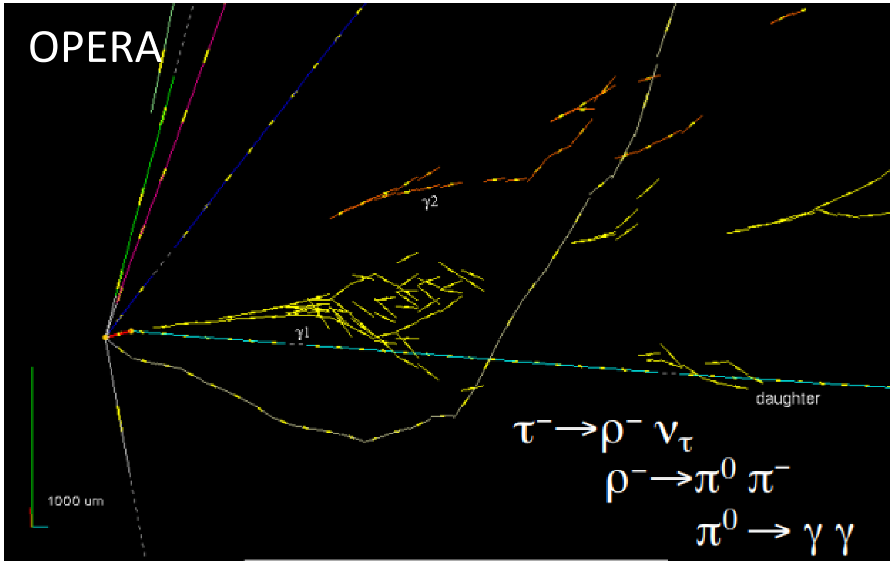
- Can determine the neutrino flavour (ν_e, ν_μ, ν_τ) from their charged-current interaction: $\nu_\mu \, N \to \mu^- X$, etc.



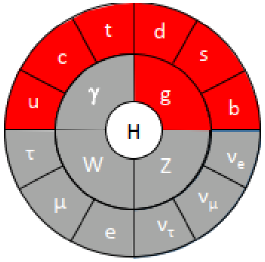
- OPERA searched for ν_τ created by neutrino oscillation from a ν_μ beam (sent 730 km from CERN to Italy)
- Tau decay seen as track kink in a high precision emulsion detector, interleaved with lead sheets to provide the high mass of the target

Emulsion image (like photographic film)

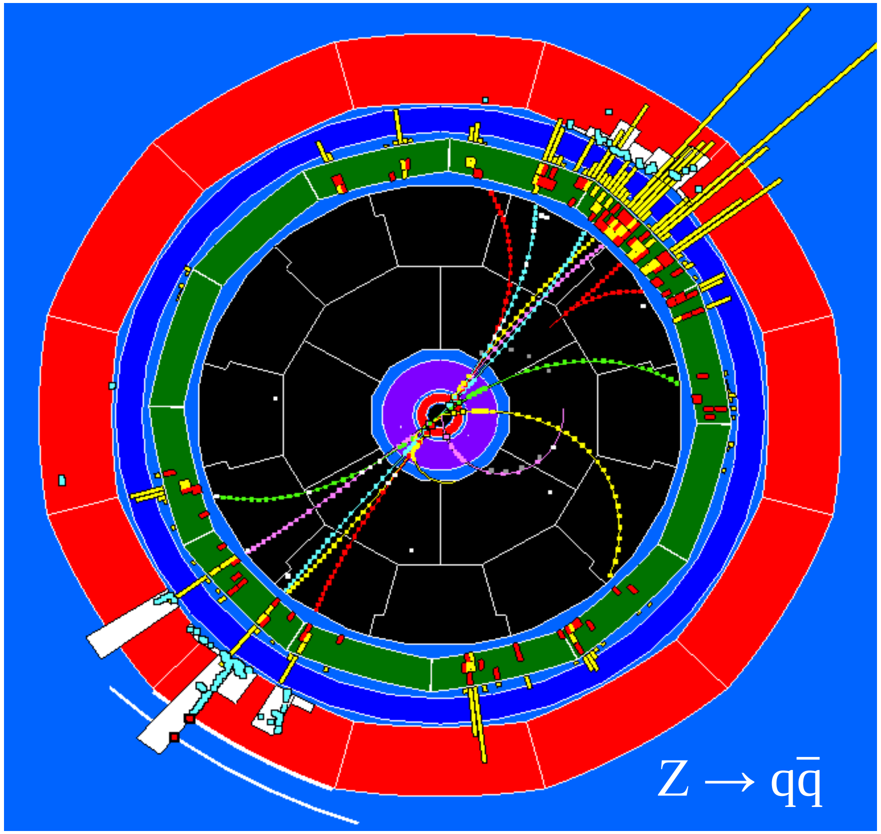




Quarks & gluons



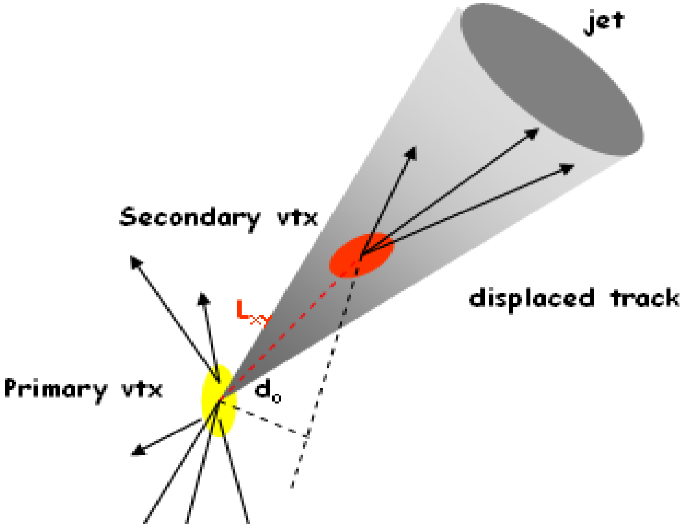
- Quarks feel the strong interaction, mediated by gluons
- Not seen (as bare partons) in the detector, due to the confinement property of QCD
- Instead, they *hadronise* into hadrons – mostly mesons ($q\bar{q}$) or baryons (qqq) – the lightest meson is the pion π ($u\bar{d}$) = most abundant particle at the LHC
- At high energy >> m_q the initial quark (or gluon) produces a "jet" of hadrons



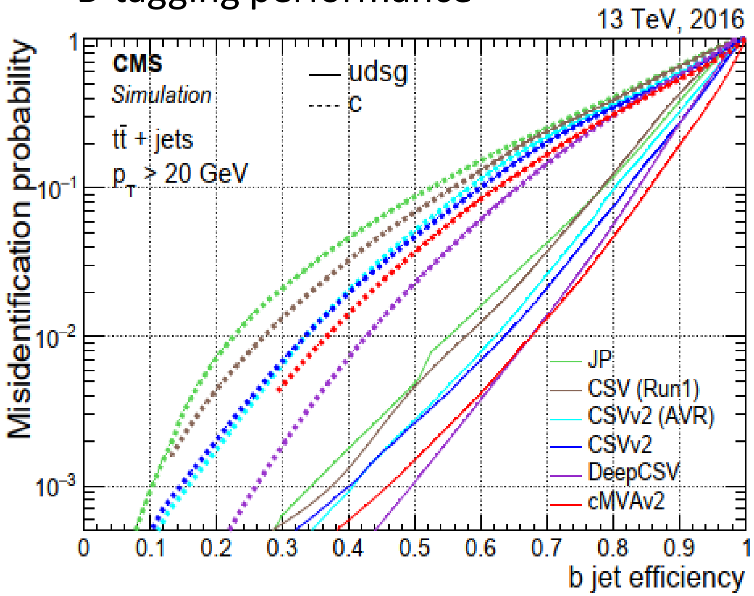
- Gluon and quark jets are difficult to distinguish: gluon jets tend to be wider, and have a softer particle spectrum

Jet reconstruction

- Jets are reconstructed by summing up the particles assigned to the jet
- Traditionally performed with a conical cut around the direction of a "seed" particle, or by iteratively adding up pairs of particles e.g. with lowest invariant mass
- Different quark flavours can be separated (at least statistically) by looking for displaced tracks from b- and c-hadron decays ($\tau \sim 10^{-12}$ s)
- Decay length $L = \gamma\beta c\tau \sim 1$ cm
  → tracks offset by $d_0 \sim 100\ \mu$m
  → *b-tagging* requires precision vertexing
- The jet properties can be used to approximate the quark or gluon
  Will return to jets in the next lecture



B-tagging performance



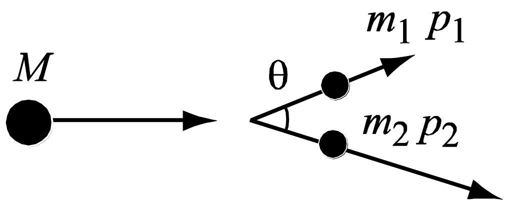
arXiv:1712.07158

Reconstructing particle decays

- The sub-detectors are designed to detect the products of the pp interactions i.e. the "stable" charged particles (e, μ, π, K, p) and neutrals (γ, ν, n)
  "Stable" means that they live long enough to travel through the tracker
  (although some π or K decay to μν before reaching calorimeters → kink in track)
- These are then used to reconstruct the short-lived *unstable* particles
  e.g. $\pi^0 \rightarrow \gamma\gamma$, $\rho^0 \rightarrow \pi^+\pi^-$, $K^0_S \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$, etc…
- From relativistic kinematics, the relation between energy *E*, momentum *p*, and (rest) mass *m* is:

$$E^2 = p^2 + m^2$$

(full expression $E^2 = p^2c^2 + m^2c^4$, but factors of *c* are often dropped)



- **Invariant mass** of two particles from a decay:

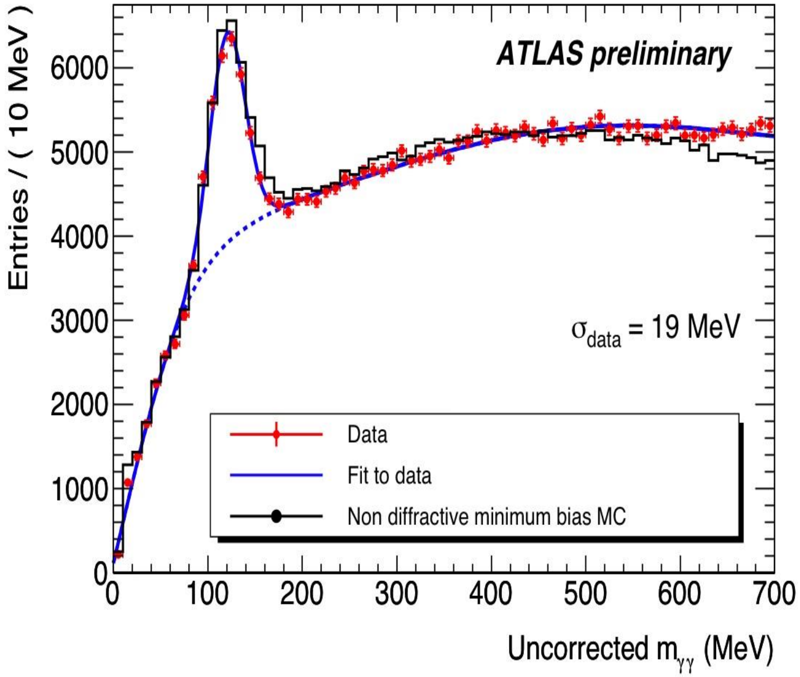
$$M^2 = m_1^{\,2} + m_2^{\,2} + 2\,(E_1E_2 - p_1p_2\cos\theta)$$

→ to reconstruct the parent mass need precise knowledge of momentum *p* and angle θ of decay products (as well as their particle type)

Mass reconstruction

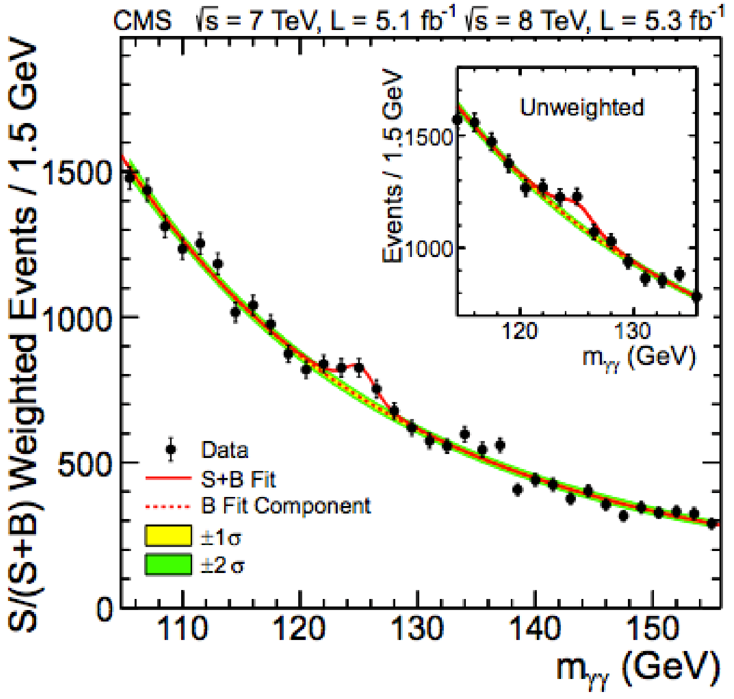
- Typical example of reconstruction of a particle decay: $\pi^0 \rightarrow \gamma\gamma$
  one of the first composite particles reconstructed in the LHC experiments
- This technique can also be used to search for more interesting signals:

$\pi^0 \rightarrow \gamma\gamma$



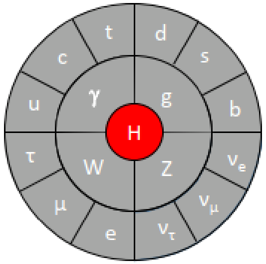
$m(\pi^0)$ = 135 MeV

$H \rightarrow \gamma\gamma$

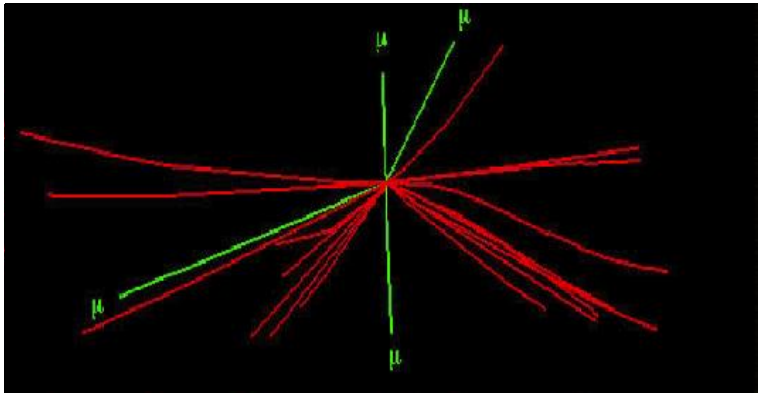


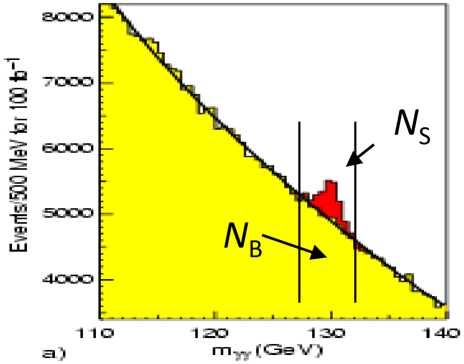
$m(H)$ = 125 GeV

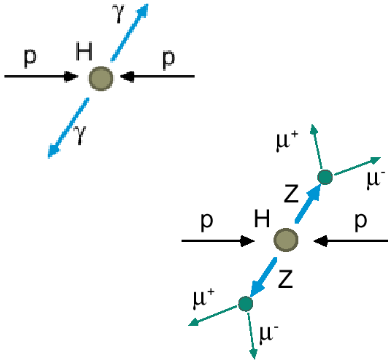
Higgs boson discovery



- Simulated $H \to 4\mu$ event with pileup
A mess, but applying cut $p_T > 25$ GeV:

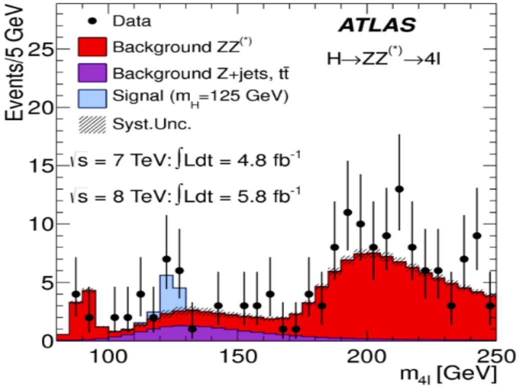






Significance of signal $S = N_S / \sqrt{N_B}$
(for high statistics)
N_S = number of signal events,
N_B = background events under peak

If $S > 5 \Rightarrow$ signal is more than 5x error on background → can claim discovery
(Gaussian probability that background fluctuates up by $> 5\sigma \approx 10^{-7}$)



Nobel prize 2013
(Englert, Higgs)

July 2012: "ATLAS and CMS observe a new particle compatible with the Higgs Boson"

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Hadron identification

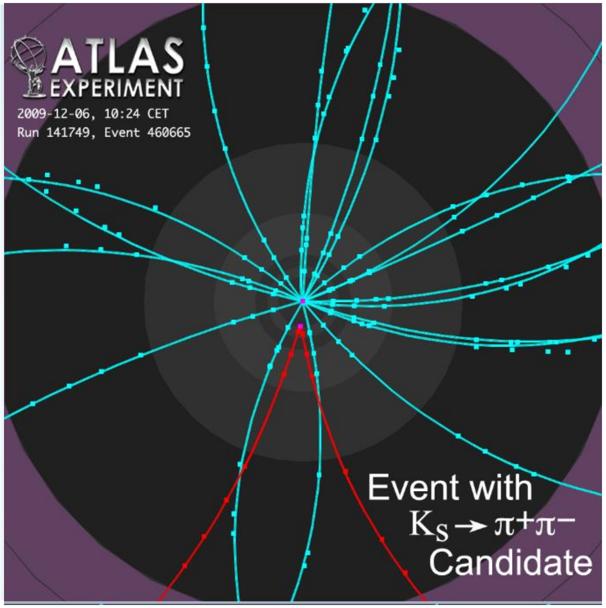
- Instead of making do with jet reconstruction, sometimes the physics under study requires the identification of *individual* hadrons
- There are *hundreds* of them, all listed in the PDG* (~ 1000 pages long)
- However, most are unstable, and decay into a few longer-lived particles:

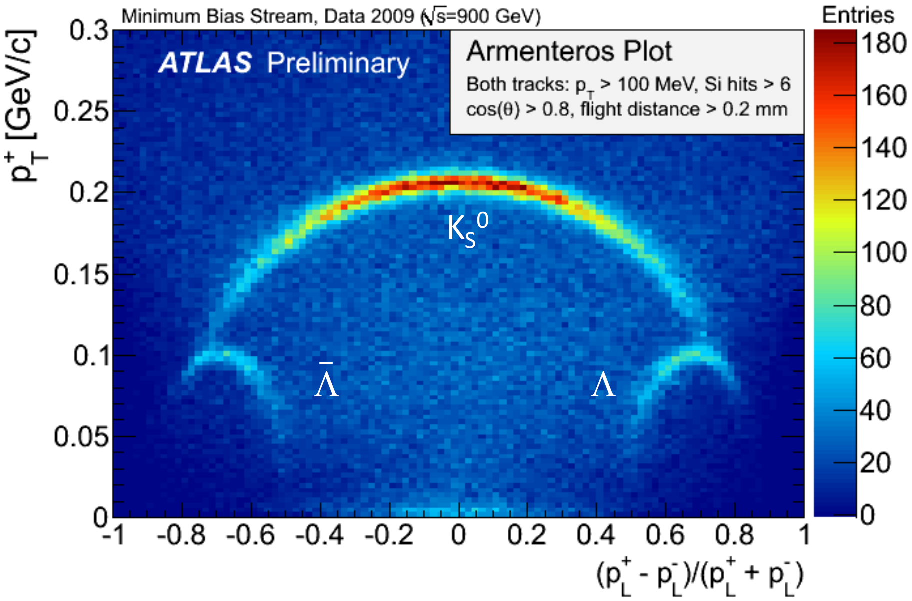
Particle	***m*** **[MeV]**	**Quarks**	**Main decay**	**Lifetime**	$c\tau$ **[cm]**
$\pi^\pm$	140	$u\bar{d}$	$\mu\nu_\mu$	2.6×10^{-8} s	780
$K^\pm$	494	$u\bar{s}$	$\mu\nu_\mu$, $\pi\pi^0$	1.2×10^{-8} s	370
K_S^0	498	$d\bar{s}$	$\pi\pi$	0.9×10^{-10} s	2.7
K_L^0	498	$d\bar{s}$	$\pi\pi\pi$, $\pi l\nu$	5×10^{-8} s	1550
p	938	uud	stable	$> 10^{25}$ years	∞
n	940	udd	$pe\nu_e$	890 s	2.7×10^{13}
Λ	1116	uds	$p\pi$	2.6×10^{-10} s	7.9

*Particle Data Group: https://pdg.lbl.gov/

Neutral hadrons

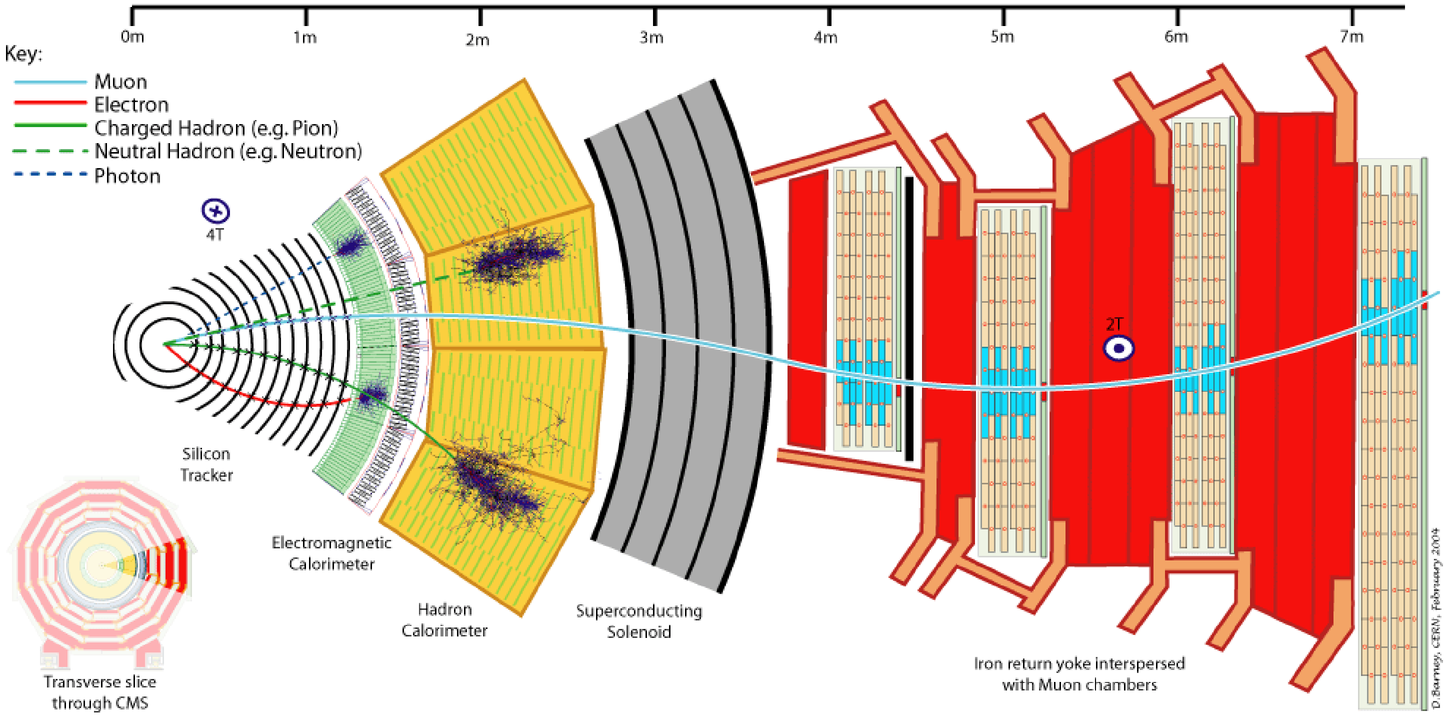
- K_S^0 and Λ are collectively known as V^0s, due to their characteristic two-prong decay vertex
- V^0s can be reconstructed from the kinematics of their positively and negatively charged decay products, without needing to identify the π or p
- K_L^0 and neutrons are detected as showers in the hadronic calorimeter without an associated charged track





General-purpose sub-detectors

- Have now discussed the set of sub-detectors used in a typical General Purpose experiment, such as ATLAS or CMS

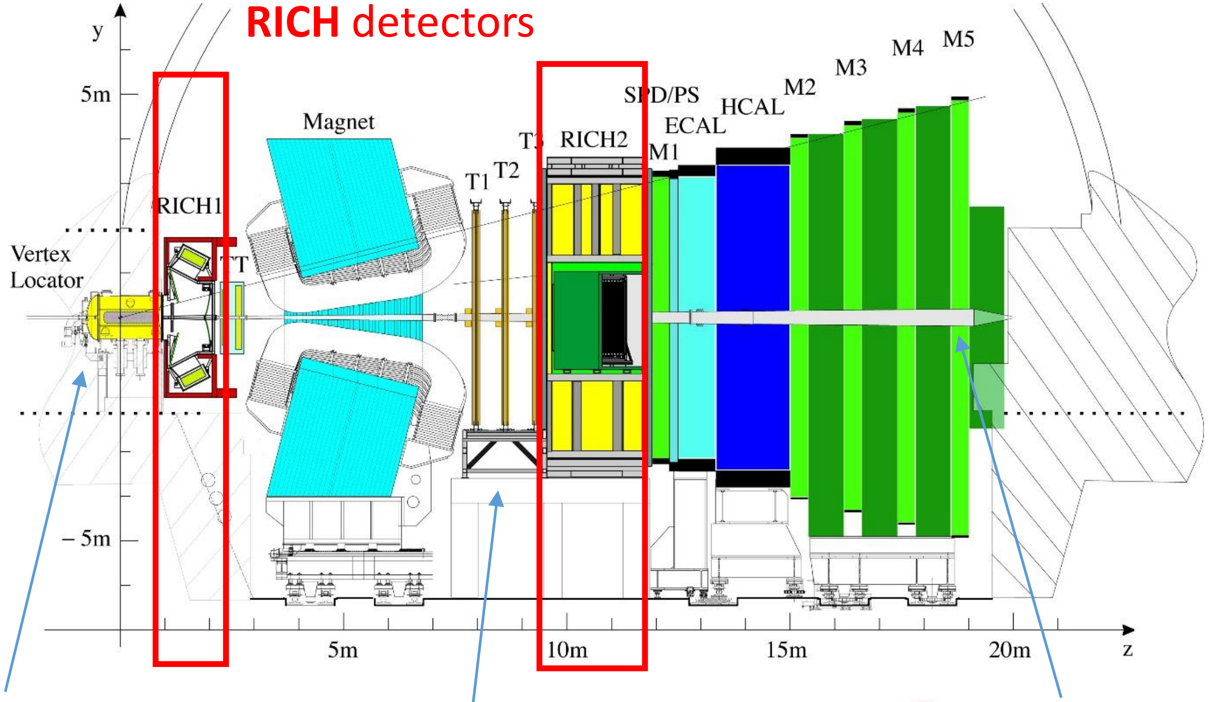


- One task that such General Purpose detectors do *not* do very well is to identify different charged hadrons (π, K, p)
This is the speciality of the dedicated experiments (LHCb, ALICE)

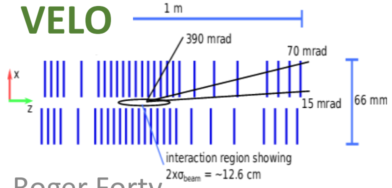
LHCb

- LHCb is the dedicated detector for flavour physics at the LHC
- It looks like the slice out of a General-Purpose experiment, apart from two extra detectors – for identifying charged hadrons

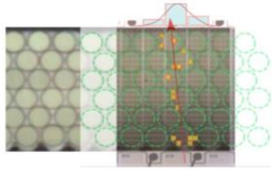
RICH detectors



VELO



Tracker made from 10,000 km of 250 μm Ø scintillating fibres

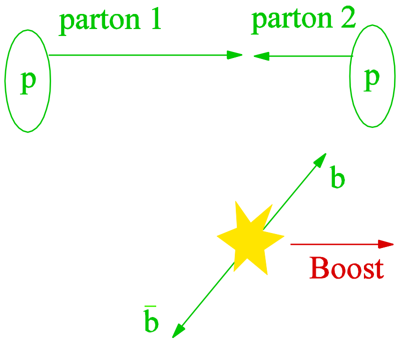


Fibre mat with SiPM

Beam-pipe conical, thin and made of Be (near IP) to minimize its effect on emerging particles

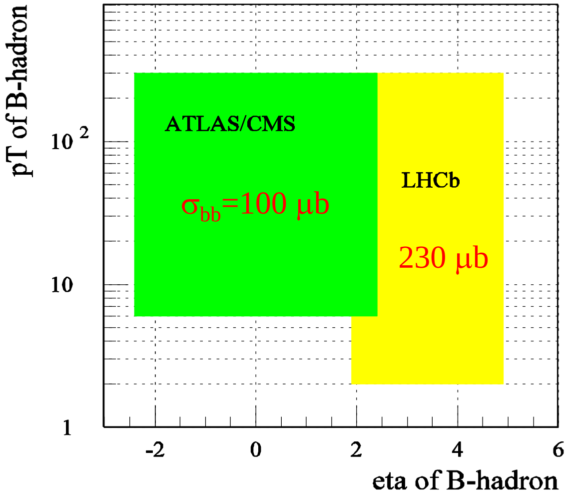
B-hadron production

- Production of a high mass object (like a W, Z or Higgs boson) requires large momentum fraction *x* for each parton → centrally produced
  Hence the general-purpose experiments ATLAS & CMS are designed to cover the central rapidity region |η| < 3

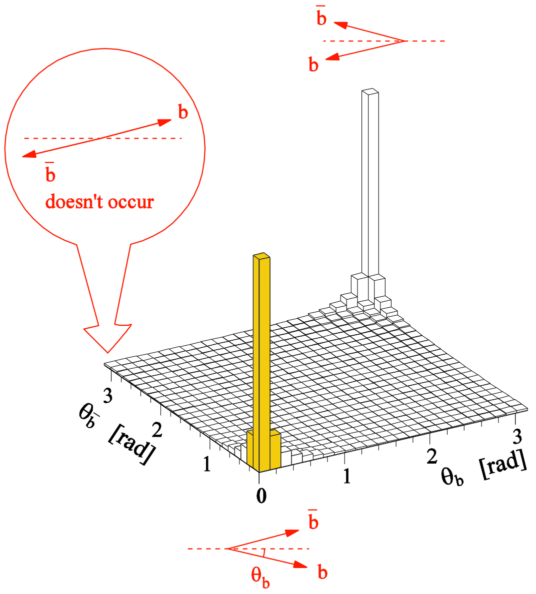


- B hadrons have a mass of ~ 5 GeV and therefore tend to be produced with asymmetric *x* values of the partons → boosted along the beam direction

  → **LHCb** covers the forward region
  (2 < η < 5)
  with a single-arm spectrometer, and triggers on lower p_T



Correlation between the b and $\bar{b}$ production angle (PYTHIA simulation)



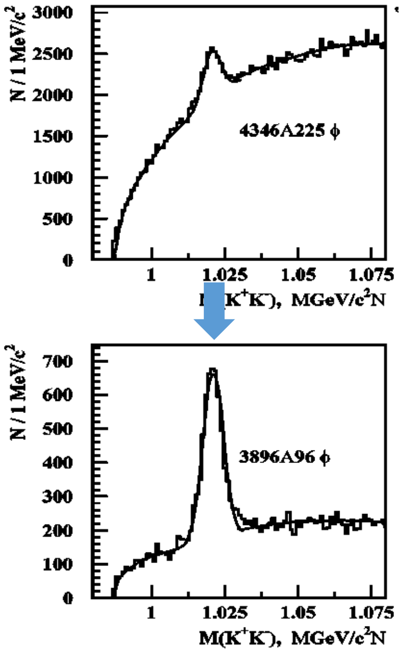
Charged hadron identification

- Charged hadrons (π, K, p) are all effectively stable, and have similar interactions → track + hadronic shower
- However, identifying them can be crucial, in particular for the study of hadronic decays: e.g. $\phi \rightarrow K^+ K^-$
- Making all two-track combinations in an event & calculating invariant mass → large *combinatoric* background (most tracks are pions, from other sources) – identifying the two tracks as kaons improves the S/B
- Flavour physics can help understand matter-antimatter asymmetry: CP violation differentiates matter from antimatter, e.g:

  $$\mathcal{B}(B^0 \rightarrow K^+ \pi^-) > \mathcal{B}(\overline{B}^0 \rightarrow K^- \pi^+)$$

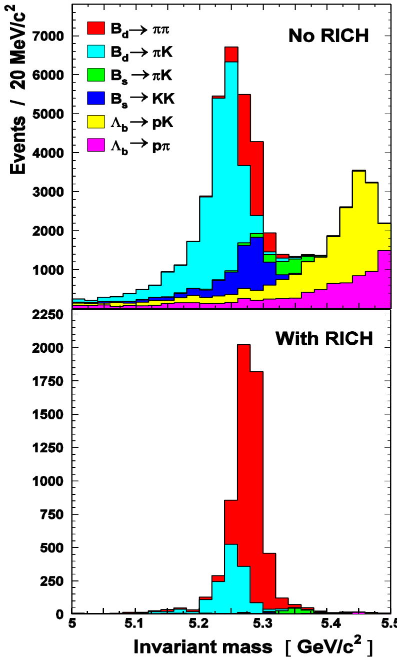
- Separating different two-body B decays requires charged hadron identification

ϕ without kaon ID



ϕ with kaon ID

2-body B decays



LHCb simulation

Separating charged hadrons

- Since the interactions of charged hadrons are similar, the most direct way to distinguish them is to determine their (rest) *mass*
- Their momentum is measured by the tracking system, so this is equivalent to determining their *velocity*, since $p = \gamma m v$, so $m = p/\gamma v = p/\gamma\beta c$
- Four main processes are used, that depend on the velocity of a particle:

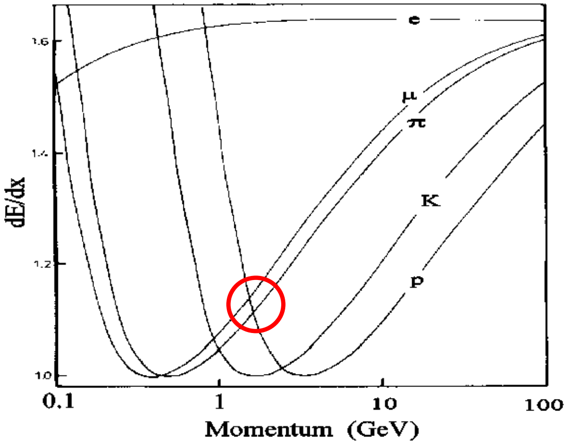
1) Interaction with matter: remember that the main source of energy loss is via **Ionization** (*dE/dx*), that depends on velocity
2) Most direct method: measure the **Time Of Flight** (TOF) of the particles over a fixed distance
3) If the velocity of the particle changes compared to the local speed of light it will radiate photons, detected as **Transition Radiation**
4) If a particle travels at *greater* than the local speed of light, it will radiate **Cherenkov Radiation**

1) *dE*/*dx*

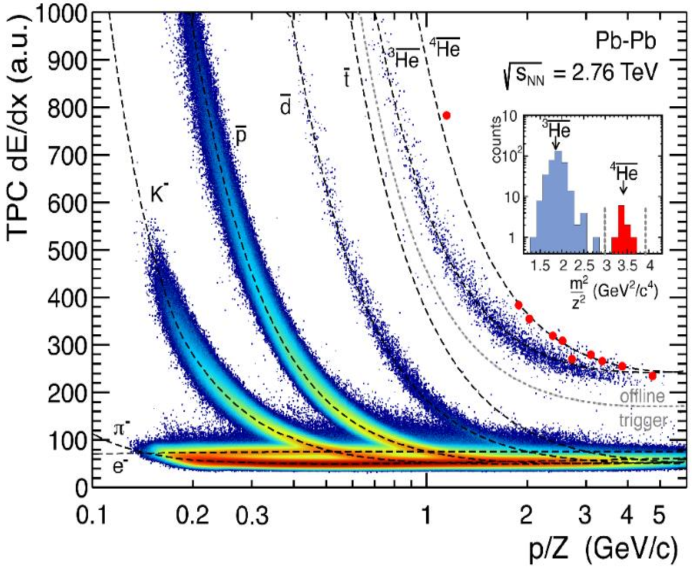
- Energy loss via ionization described by the Bethe-Bloch formula shown earlier, with universal velocity dependence
- This can be used to identify particles, particularly at low momentum where *dE*/*dx* varies rapidly
- *Advantage:* uses existing detectors needed for tracking (but requires the accurate measurement of the charge)

  Disadvantage: separation poor at high momentum, and curves cross-over for different particle types
- *Note:* these techniques all provide signals for charged *leptons* (e, μ) as well as π, K, p But $m_\mu \approx m_\pi$, so they are not well separated — dedicated detectors do a better job

dE/*dx* plotted vs *p* instead of $\beta\gamma$



ALICE TPC



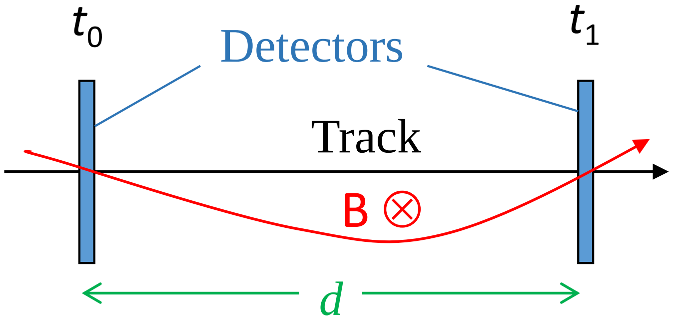
2) Time Of Flight

- Simple concept: measure the time difference between two detector planes

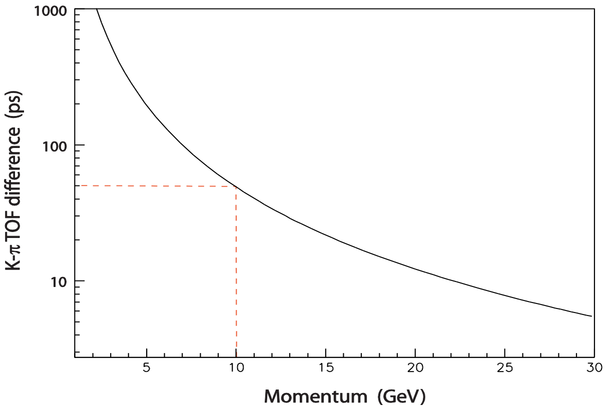
$\beta = d / c\, \Delta t$ $$m^2 = \frac{p^2}{c^2}\left(\frac{c^2 t^2}{d^2} - 1\right)$$

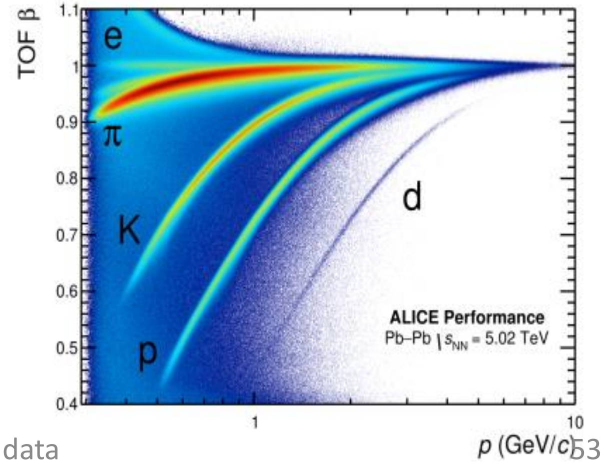
- At high energy, particle speeds are relativistic, closely approaching to *c*
- At 10 GeV, the time for a K to travel 12 m is 40.05 ns, whereas for a π it would be 40.00 ns, so the difference is only 50 ps
- Modern detectors & readout electronics have resolution σ_t ~ 10 ns, fast enough for the LHC (bunch crossings 25 ns apart) but need σ_t < 1 ns to do useful TOF
- TOF gives good ID at low momentum *Very* precise timing required for p > 5 GeV

Traditional approach: scintillator hodoscope
ALICE has a Multi-gap RPC with $\sigma_t \approx$ 60 ps



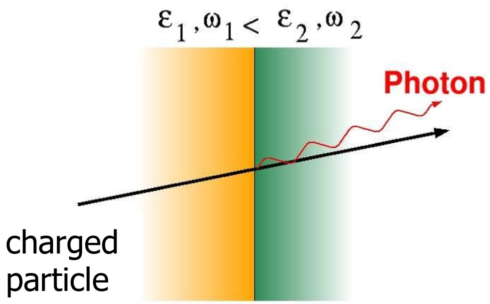
TOF difference for *d* = 12 m



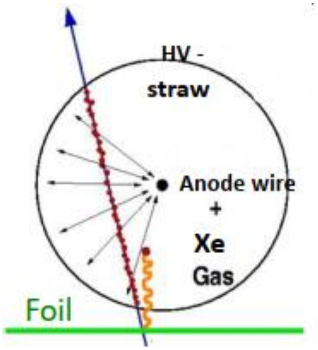


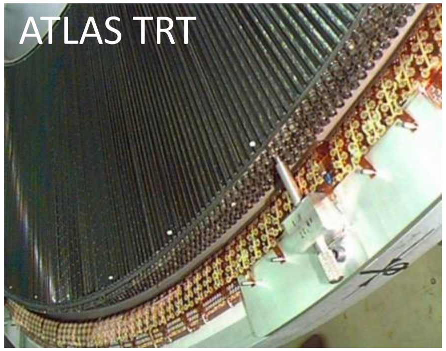
3) Transition radiation

- Local speed of light in a medium with refractive index n is $c_m = c/n$
  If its relative velocity $\boldsymbol{v}/c_m$ changes, a particle will radiate photons:
  1. Change of direction $\boldsymbol{v}$ (in magnetic field) → *Synchrotron* radiation
  2. Change of $|v|$ (passing through matter) → *Bremsstrahlung* radiation
  3. Change of refractive index n of medium → *Transition* radiation



- Transition radiation is emitted whenever a relativistic charged particle traverses the border between two media with different dielectric constants ($n \sim \sqrt{\varepsilon}$)
- The energy emitted is proportional to the boost γ of the particle
  → particularly useful for electron ID or for hadrons at high energy
- ATLAS **Transition Radiation Tracker** also acts as a central tracker:
  ~ 300,000 straw tubes

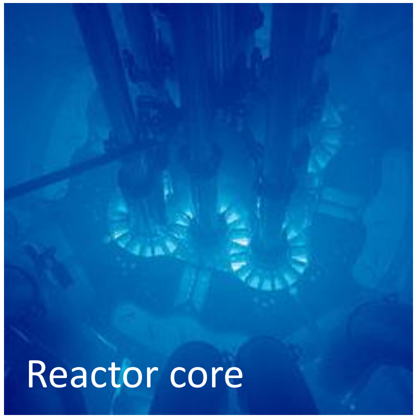




4) Cherenkov radiation

Nobel prize 1958
(P. Cherenkov)

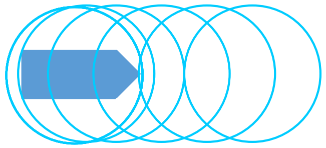
- From Relativity, nothing can go faster than the speed of light *c* (in vacuum)
- However, due to the refractive index *n* of a material, a particle *can* go faster than the *local* speed of light in the medium $c_m = c/n$
- This is analogous to the bow wave of a boat travelling over water or the sonic boom of an airplane travelling faster than the speed of sound
- The light is produced equally distributed over photon energies → when transformed to a wavelength distribution implies it is peaks at low wavelengths – it is responsible for the blue light seen in nuclear reactors



Reactor core

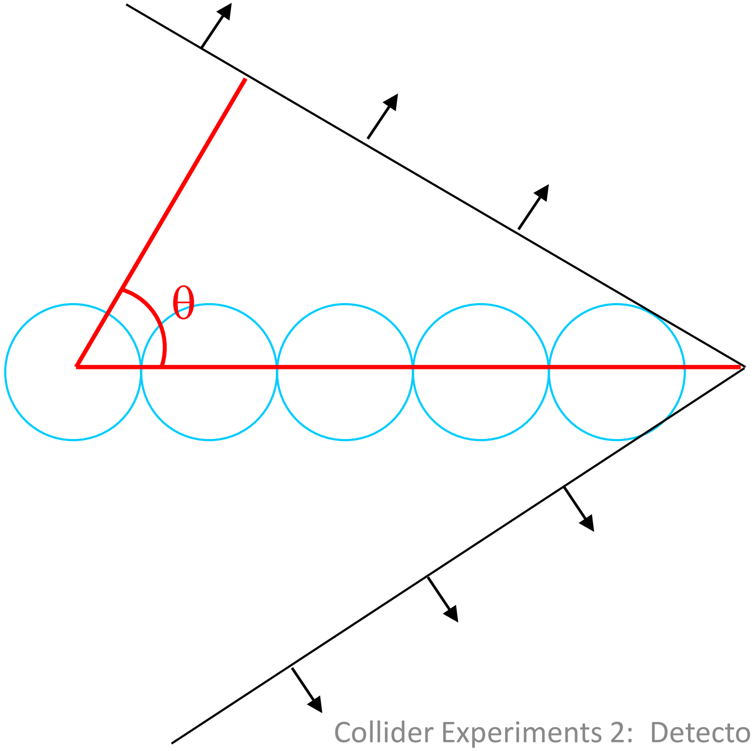
Propagating waves

- A stationary boat bobs up and down on a lake, producing waves
- Now the boat starts to move, but slower than the waves:
  no coherent wave-front is formed



Propagating waves

- A stationary boat bobs up and down on a lake, producing waves
- Now the boat starts to move, but slower than the waves: no coherent wave-front is formed
- Next the boat moves faster than the waves: a **coherent** wave-front is formed
- Finally the boat moves even faster: the *angle* of the wave-front changes



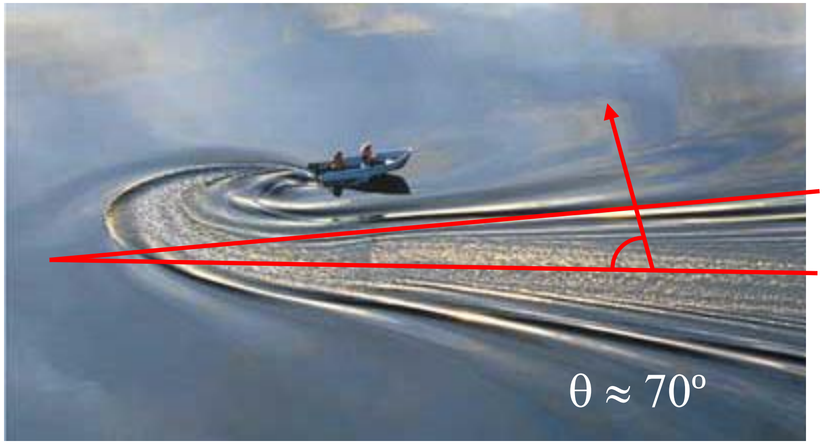
$$\cos\theta = \frac{v_{\text{wave}}}{v_{\text{boat}}}$$

Speed calculation

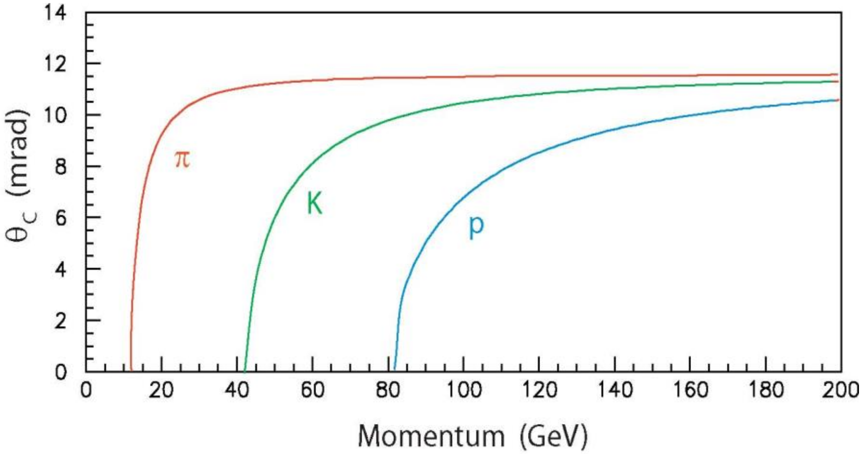
- Using this construction, you can determine (roughly) the boat speed:
  $\theta \approx 70^{\circ}$, v_{wave} = 2 m/s on water
  → $v_{\text{boat}} = v_{\text{wave}} / \cos\theta \approx 6$ m/s
- Cherenkov light is produced when charged particle ($v_{\text{boat}} = \beta c$) goes faster than the speed of light ($v_{\text{wave}} = c/n$)

→ $\cos\theta_C = 1 / \beta n$ θ_C = "Cherenkov angle"

- There is a *threshold* for light production at $\beta = 1/n$
- Produced in three dimensions, so the wavefront forms a *cone* of light around the particle direction
- Measuring the opening angle of cone → particle velocity can be determined

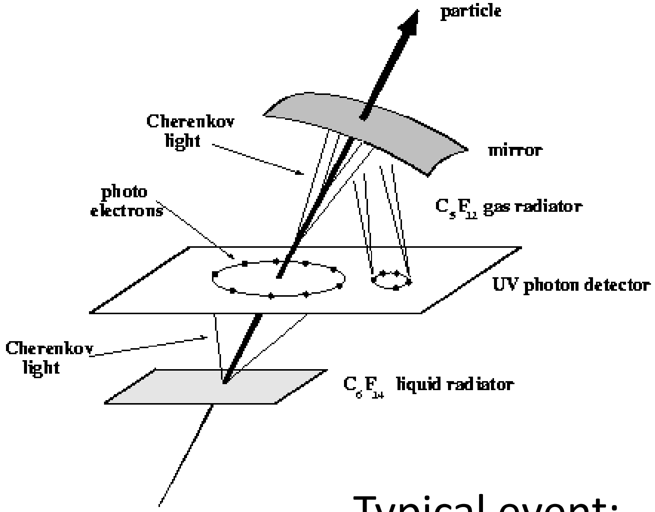


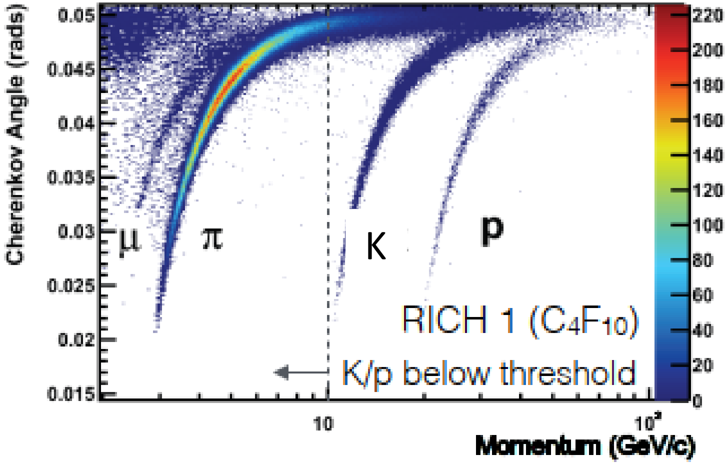
For Ne gas (n = 1.000067)



RICH detectors

- In a **Ring-Imaging Cherenkov** (RICH) detector the Cherenkov light is focussed onto a photodetector plane, usually with a spherical mirror, producing a ring image of single photons
- The LHCb RICH system combines the use of different gaseous radiator materials: fluorocarbons C_4F_{10} and CF_4 to cover different momentum ranges





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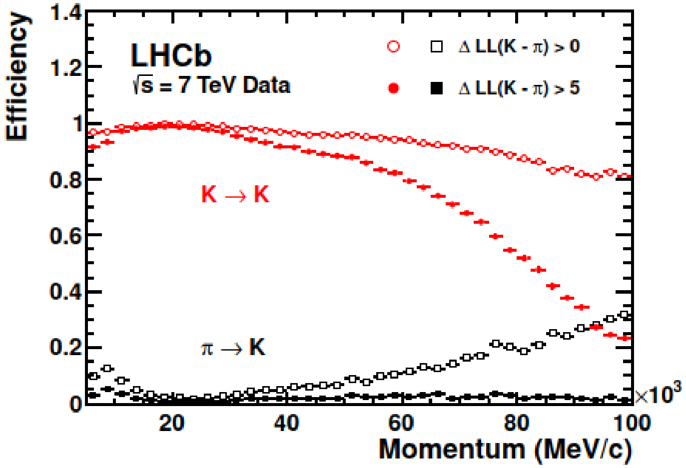
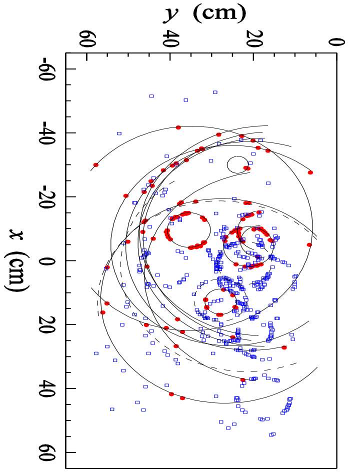
Kaon selection



Typical event:

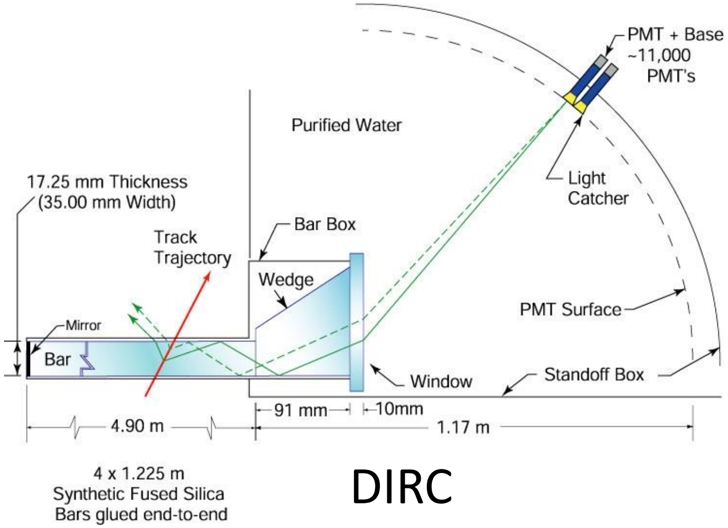
complex pattern recognition!



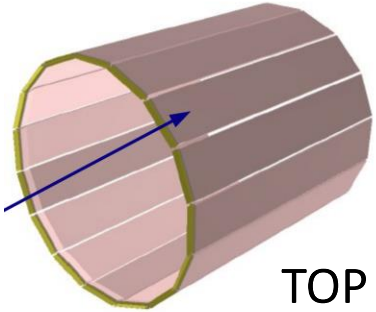
Compact Cherenkov detectors

- Alternative geometries have been developed for Cherenkov detectors using a solid radiator: silica **quartz** (SiO_2) – in the form of polished bars or **aerogel**, the lightest solid in the world
- Result in a much more compact detector, suitable for the low momentum particles at a B Factory

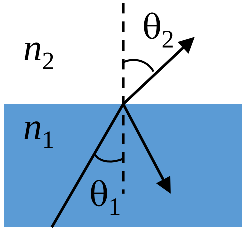
  Originally developed for the **DIRC** of BaBar (SLAC) similar technique now used for the **TOP** of Belle (KEK)

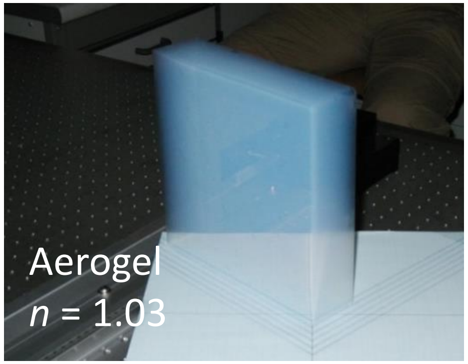


DIRC



TOP





Aerogel
$n = 1.03$

Quartz
$n = 1.45$

Law of refraction:

$n_1 \sin \theta_1 = n_2 \sin \theta_2$

$n_1 = 1.45$ (quartz)

$n_2 \approx 1.0$ (air)

→ *total internal reflection*

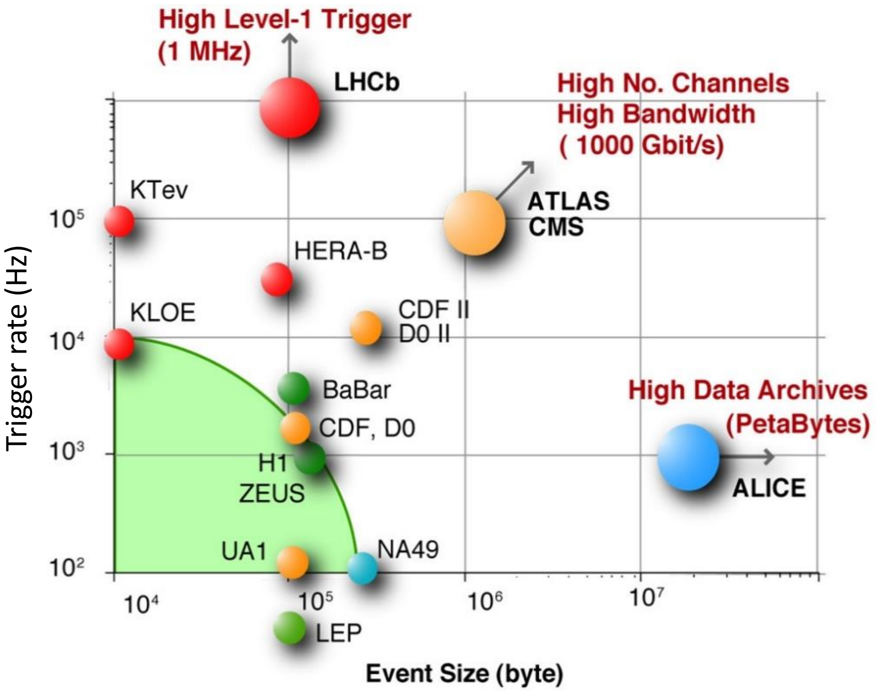
if $\theta_1 > \sin^{-1}(1/1.45) \approx 44^{\circ}$

4. Data taking

- The data produced as digital signals from the sub-detectors’ readout electronics has to be collected and “built” into complete events: *data acquisition,* typically ~ 1 MB/event
- Stored for later “offline” analysis using computers: can only record ~ 1000 events/s to storage, compared to interaction rate at LHC: ~ 10^9 events/s

$\Rightarrow$ Must reject ~ 10^7 events for each one stored, implemented using a **trigger** system

- 1 MB × 1 kHz × 10^7 s = 10^{10} MB / year i.e. 10 petabytes (PB) of data – would take ~ ten *million* CDs

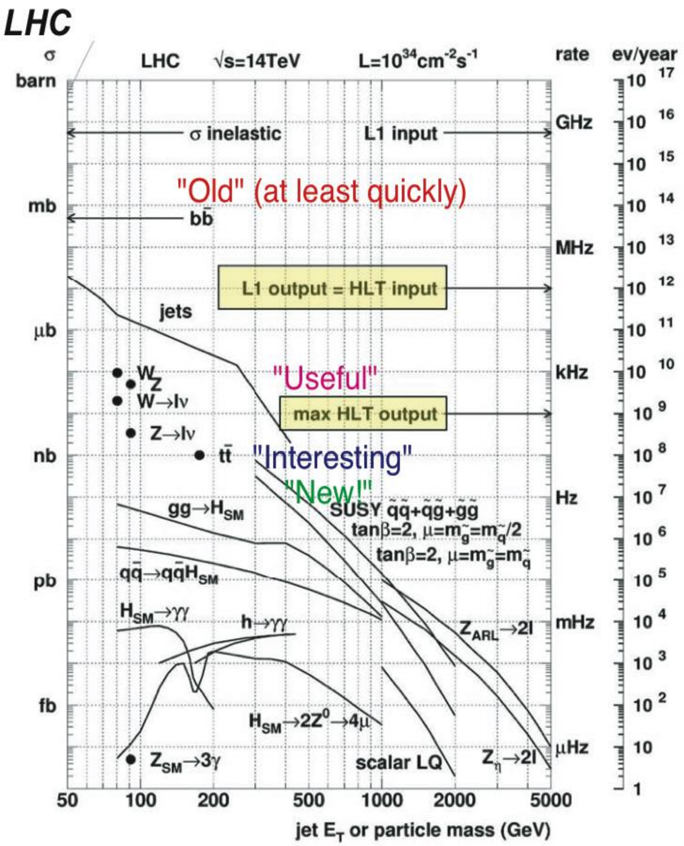


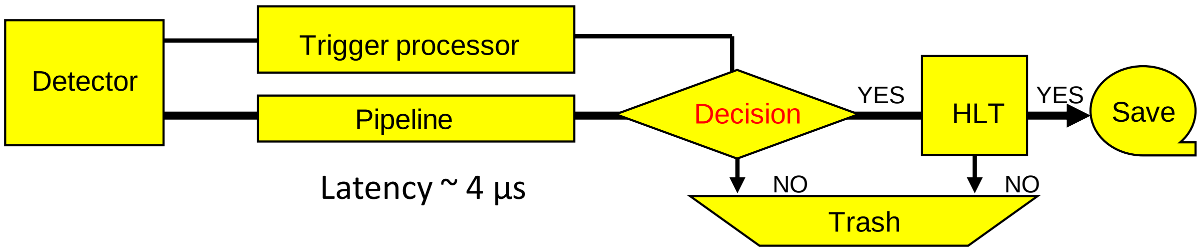
The boundaries of trigger rate and data volume are being pushed by the LHC experiments

(Details are beyond the scope of these lectures…)

Triggering

- Most interesting physics occurs at low rates compared to the 1 GHz input rate at the LHC (10 Hz top quark production, < Hz for searches)
- Want to keep most of the interesting events while rejecting others, in allowed bandwidth Selection is usually done in stages:
  - **Level 1:** 1 GHz → 100 kHz
  - **High Level Trigger:** 100 kHz → 1 kHz
- Trigger decision takes few μs >> 25 ns bunch crossing rate → store massive amount of data in *pipelines* while special trigger processors perform calculations using part of the data




Detector

Trigger processor

Pipeline

Latency ~ 4 μs

Decision

YES

HLT

YES

Save

NO

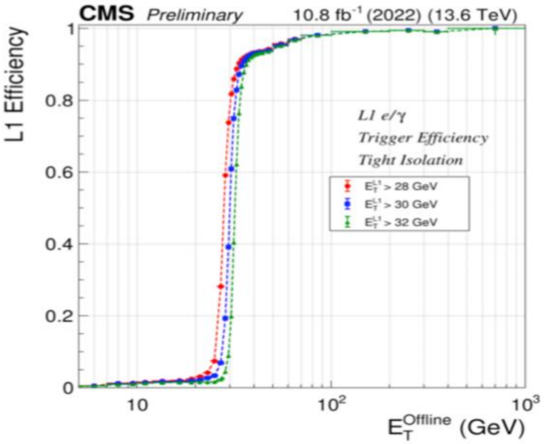
NO

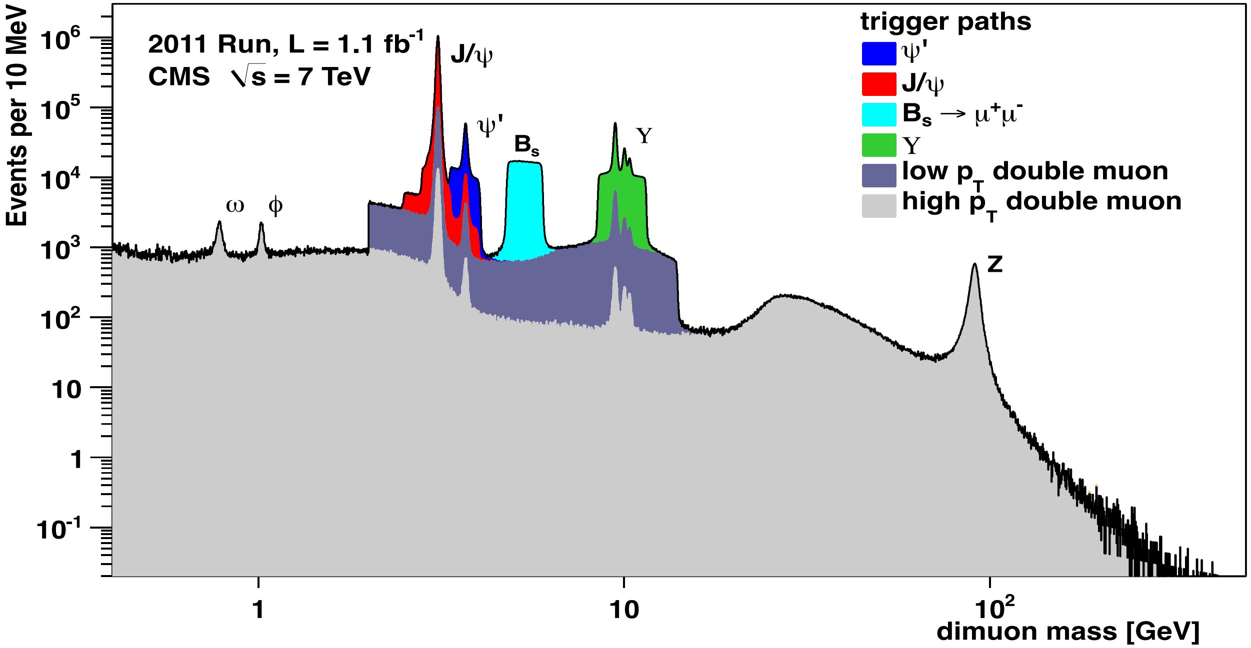
Trash

Events rejected by the trigger are lost forever → need to take care!

Trigger thresholds

- Trigger thresholds are set on the electronic signals from detectors (e.g. ADC counts)
- Have to be calibrated in terms of efficiency versus the physics quantity of interest
- A “menu” of many triggers run in parallel compromise between efficiency and bandwidth

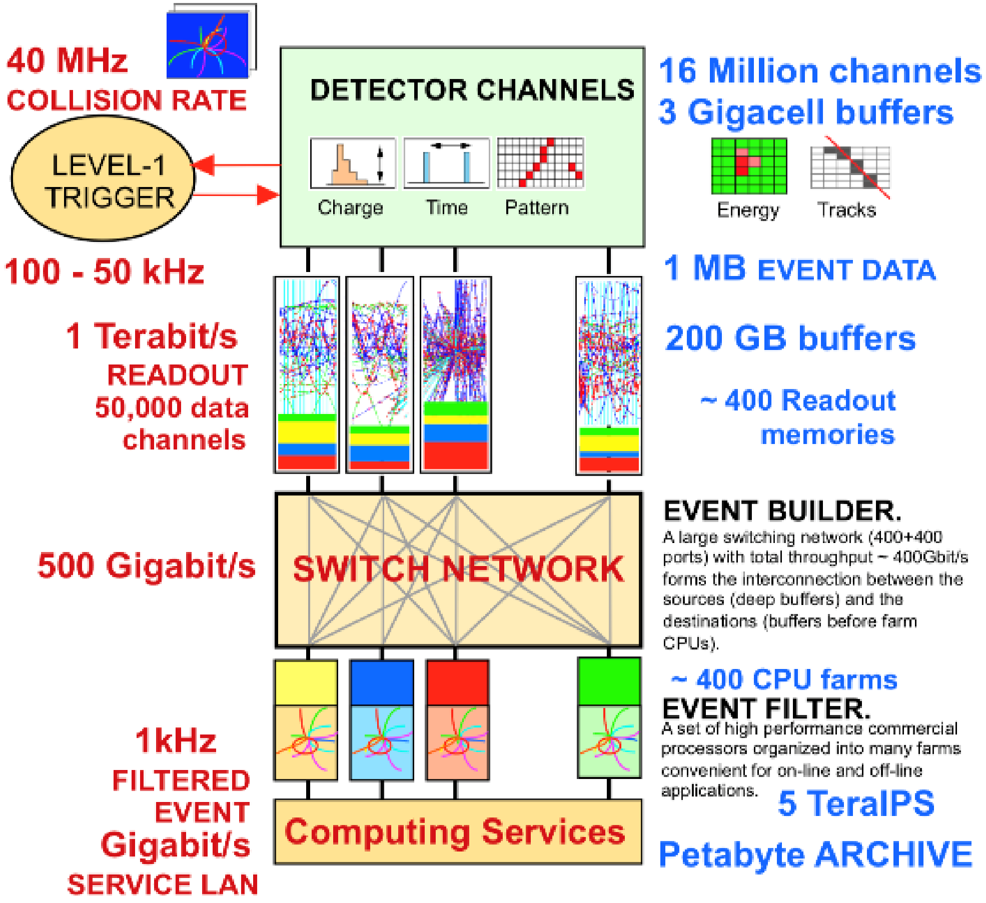




Example of dimuon triggers

Data acquisition

- First trigger level typically looks for signatures like high p_T leptons (e, μ)
- Data then read out to Higher Level Triggers for more complex selections running on a dedicated CPU farm (with ~ 1000 processors)



40 MHz
COLLISION RATE

LEVEL-1 TRIGGER

100 - 50 kHz

1 Terabit/s
READOUT
50,000 data channels

500 Gigabit/s

1kHz
FILTERED EVENT

Gigabit/s
SERVICE LAN

DETECTOR CHANNELS

16 Million channels
3 Gigacell buffers

1 MB EVENT DATA

200 GB buffers

~ 400 Readout memories

SWITCH NETWORK

EVENT BUILDER. A large switching network (400+400 ports) with total throughput ~ 400Gbit/s forms the interconnection between the sources (deep buffers) and the destinations (buffers before farm CPUs).

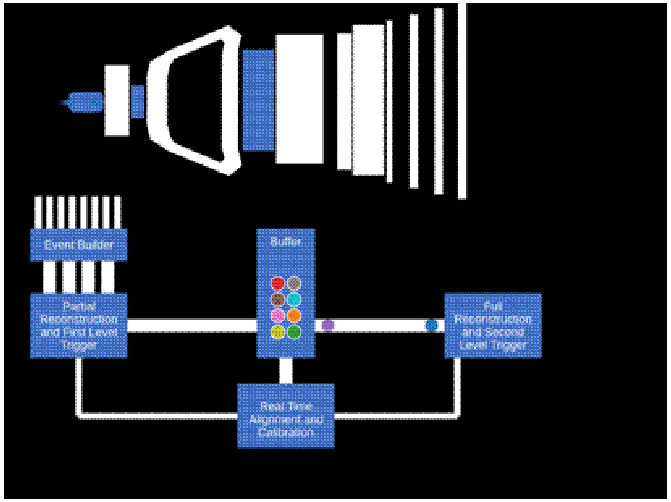
~ 400 CPU farms

EVENT FILTER. A set of high performance commercial processors organized into many farms convenient for on-line and off-line applications.

5 TeraIPS

Computing Services

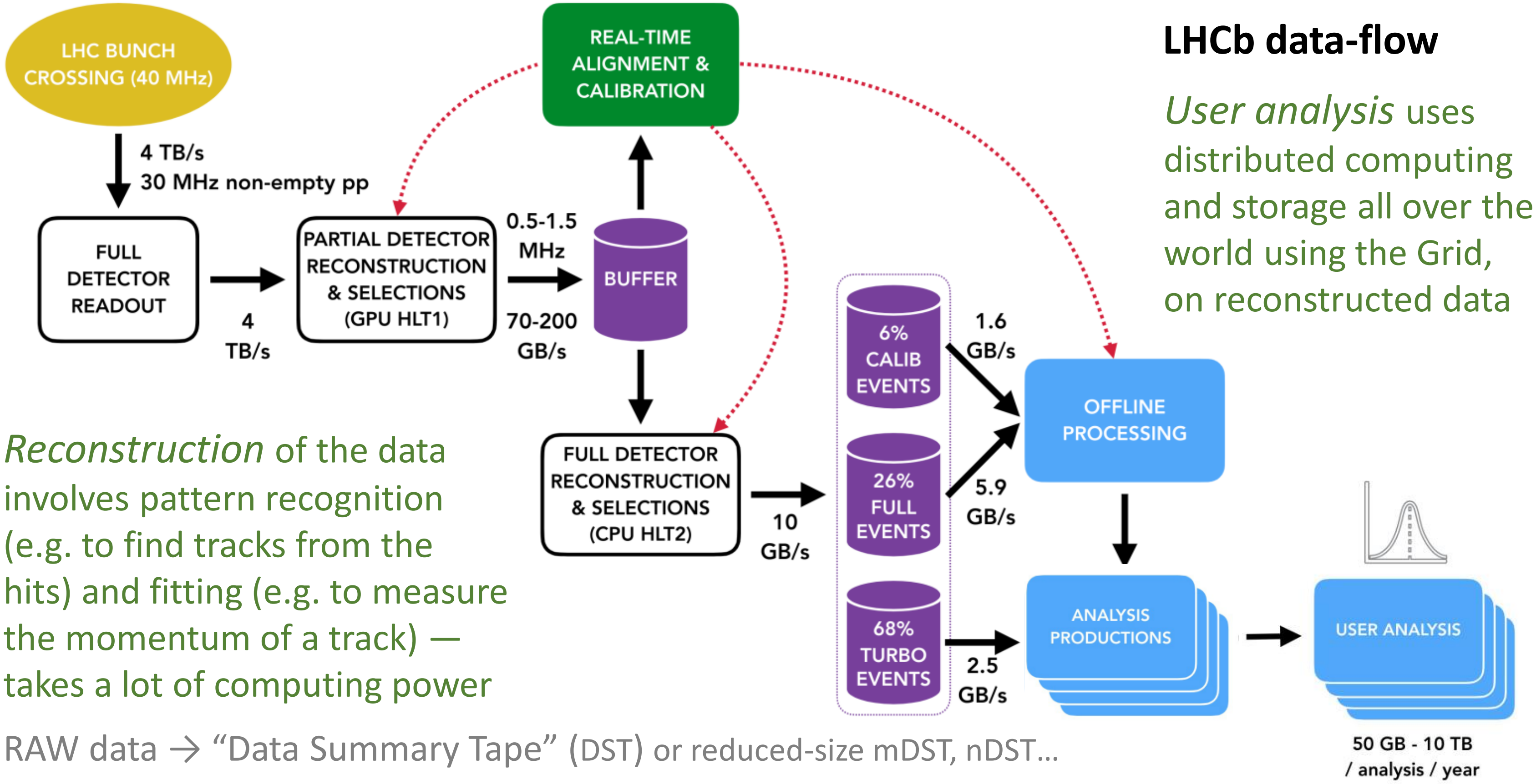
Petabyte ARCHIVE



LHCb's “Real Time Analysis”

“Triggerless” readout

- LHCb is now running *without* a hardware trigger → readout *full* detector at 40 MHz – all triggering is done in software (HLT) in GPU and CPU farms
- Possible due to the relatively small event size, but is a trend for the future
  Requires analysis done in real-time to provide the alignment and calibration



LHCb data-flow

User analysis uses distributed computing and storage all over the world using the Grid, on reconstructed data

LHC BUNCH CROSSING (40 MHz)

4 TB/s
30 MHz non-empty pp

FULL DETECTOR READOUT

4 TB/s

PARTIAL DETECTOR RECONSTRUCTION & SELECTIONS (GPU HLT1)

0.5-1.5 MHz

70-200 GB/s

BUFFER

REAL-TIME ALIGNMENT & CALIBRATION

FULL DETECTOR RECONSTRUCTION & SELECTIONS (CPU HLT2)

10 GB/s

6% CALIB EVENTS

26% FULL EVENTS

68% TURBO EVENTS

1.6 GB/s

5.9 GB/s

2.5 GB/s

OFFLINE PROCESSING

ANALYSIS PRODUCTIONS

USER ANALYSIS

50 GB - 10 TB / analysis / year

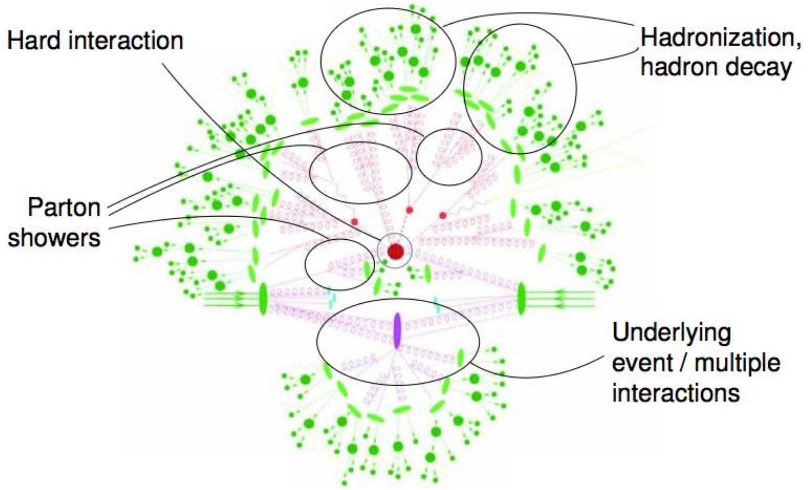
Reconstruction of the data involves pattern recognition (e.g. to find tracks from the hits) and fitting (e.g. to measure the momentum of a track) — takes a lot of computing power

RAW data → “Data Summary Tape” (DST) or reduced-size mDST, nDST…

Simulation

- Simulated data are widely used to help design physics analyses, estimate efficiencies, emulate the trigger, compare results to theoretical expectations etc.
  Treated in analysis like real events

Simulating a complete LHC event



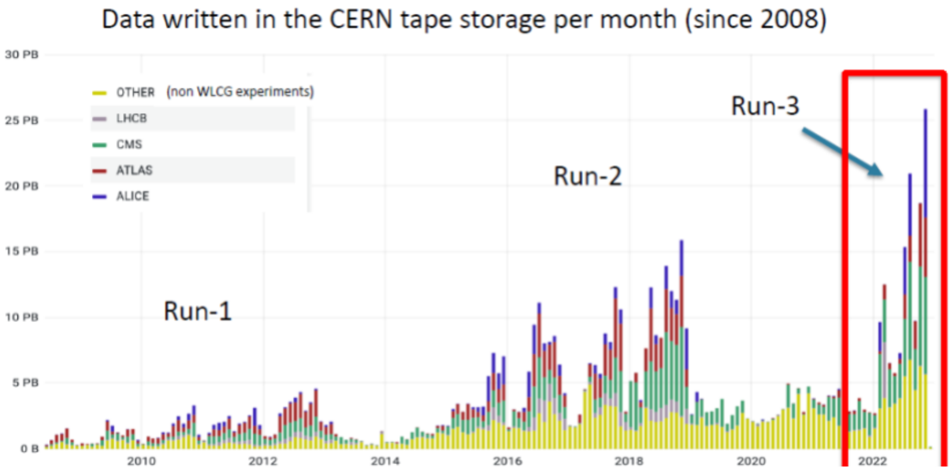
- Theoretical expressions are used for the underlying physics, with models for those features such as hadronization that cannot be calculated from first principles, and the *Monte Carlo* method (using random numbers) for evaluating integrals

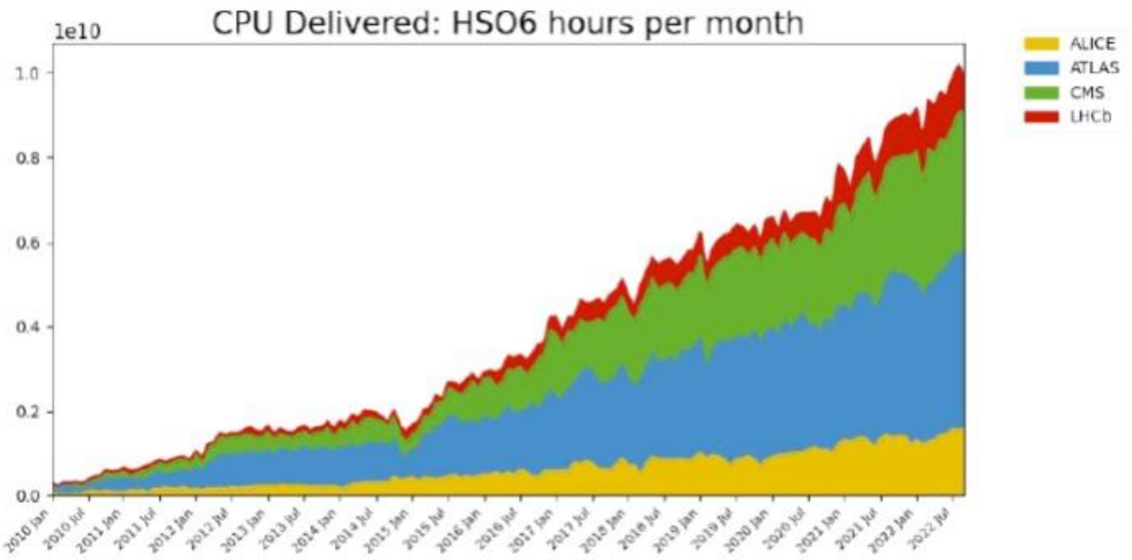
- General-purpose event generators (HERWIG, PYTHIA, SHERPA): include $1 \rightarrow 2$, $2 \rightarrow 2$, and $2 \rightarrow 3$ processes, hadronization and the underlying event
  Matrix Element generators (ALPGEN, MADGRAPH, MC@NLO) include expressions for multi-particle final states

- **Fast Simulation:** the detector response uses parameterized resolution
  Full Simulation: passage of particles through detector simulated in detail using the GEANT software package

Computing

- Distributed computing is used for offline analysis
- **World Wide Web** was invented at CERN, to help with data-intensive work
- Lots of data transferred to computer centres around the world (**WLCG**)

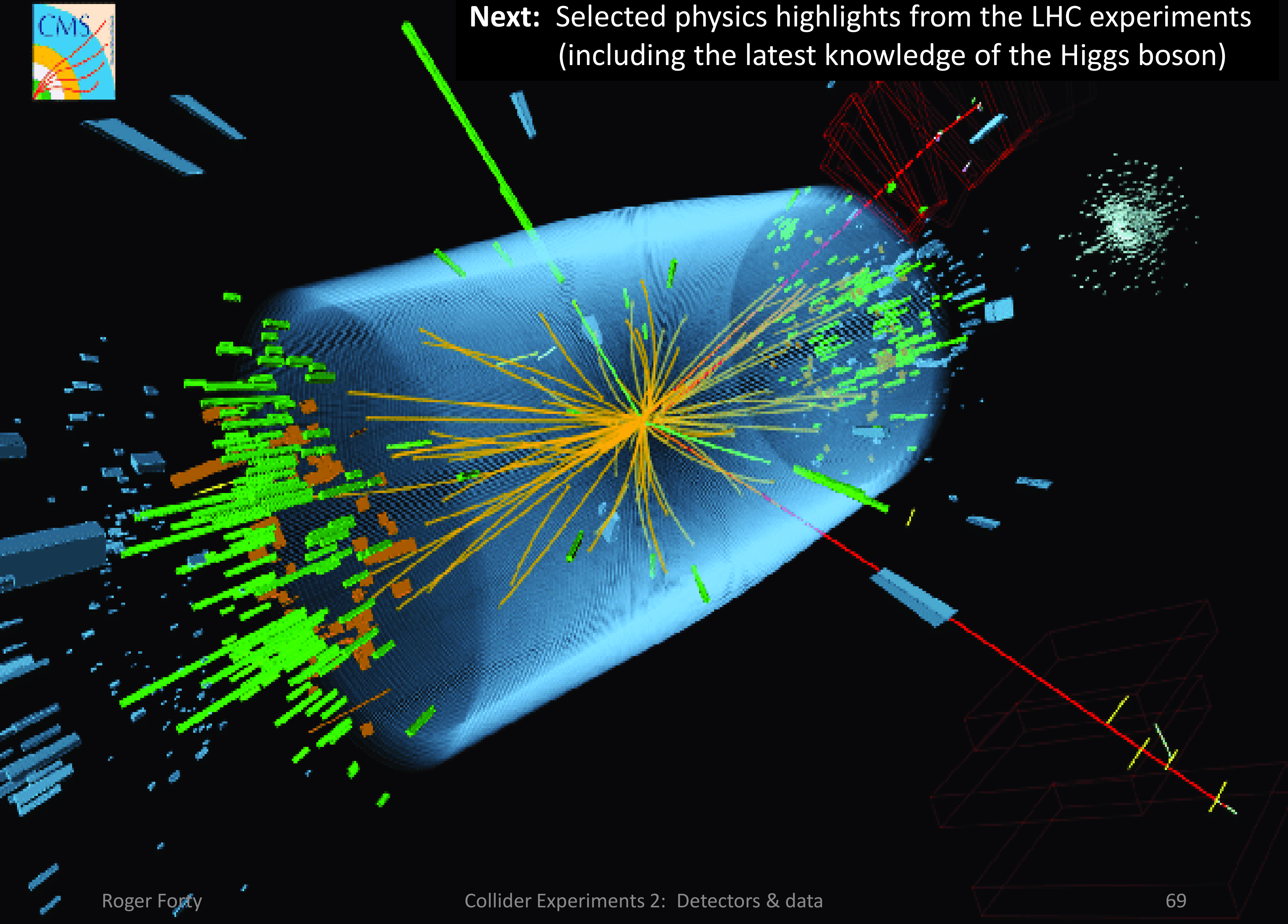

Data written in the CERN tape storage per month (since 2008)


CPU Delivered: HS06 hours per month

Summary (Lecture 2)

- Detector techniques used in the LHC experiments have been reviewed
  The overall layout of detectors depends on the choice of magnetic field
- **Tracking** detectors detect the ionization deposited by charged particles
  traditionally used gas-based detectors, more recently mostly silicon
  Along with the magnetic field, determines charge and momentum
- **Calorimeters** are important to measure the energy of particles
  Both charged and neutral particles can be detected
- **Particle identification** essential to reconstruct what happened in events:
  e.g. using muon detectors, energy loss and missing-energy signatures
  Separating charged hadrons requires specialized detectors like RICHes
- Modern experiments produce a mountain of **data**, like a multi-megapixel camera taking millions of photos a second

  Triggering selects events of interest, data acquisition builds the full events and sends them to storage, and offline computing is used to analyze them



Next: Selected physics highlights from the LHC experiments
(including the latest knowledge of the Higgs boson)