An Introduction to Modern Particle Physics

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Course Synopsis

★ Introduction : Particles and Forces
- what are the fundamental particles
- what is a force

★ The Electromagnetic Interaction
- QED and e^+e^- annihilation
- the Large Electron-Positron collider

★ The Crazy world of the Strong Interaction
- QCD, colour and gluons
- the quarks

★ The Weak interaction
- W bosons
- Neutrinos and Neutrino Oscillations
- The MINOS Experiment

★ The Standard Model (what we know) and beyond
- Electroweak Unification
- the Z boson
- the Higgs Boson
- Dark matter and supersymmetry
- Unanswered questions

Recap

The particle world is rather simple :

- There are 12 fundamental particles

Electron (e^-)	Muon (μ^-)	Tau (τ^-)
Electron Neutrino (ν_e)	Muon Neutrino (ν_μ)	Tau Neutrino (ν_τ)
Up Quark (u)	Charm Quark (c)	Top Quark (t)
Down Quark (d)	Strange Quark (d)	Bottom Quark (b)

- + Anti-matter equivalents of all particles

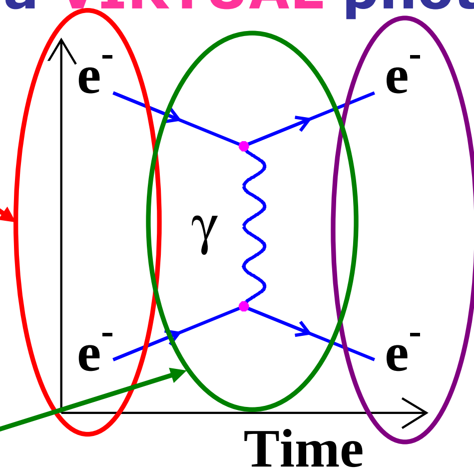
- and 4 fundamental forces

Strong	Weak
Electromagnetic	Gravity

Feynman Diagrams

★Particle interactions represented by **FEYNMAN** diagrams

e.g. two electrons "scattering" – repelling each other - by exchanging a **VIRTUAL** photon



ON THE LEFT

The initial state:
i.e. particles before the interaction,
here $e^- + e^-$

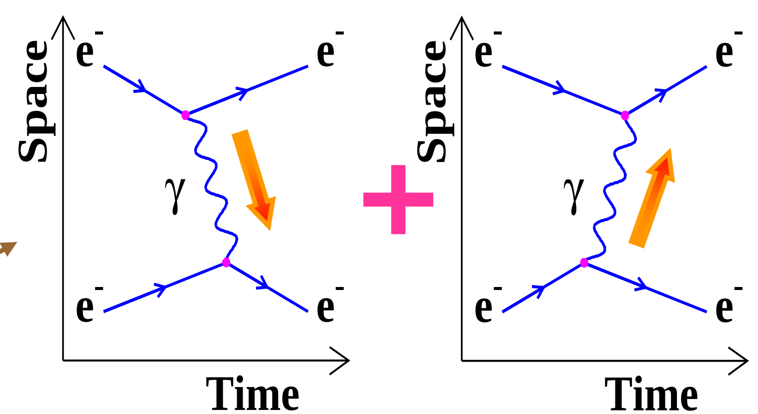
ON THE RIGHT

The final state:
i.e. particles after the interaction,
here $e^- + e^-$

IN THE MIDDLE

"Whatever happened in between."
Here one e^- emitted a photon and the other absorbed it, giving a transfer of momentum i.e. **FORCE**.

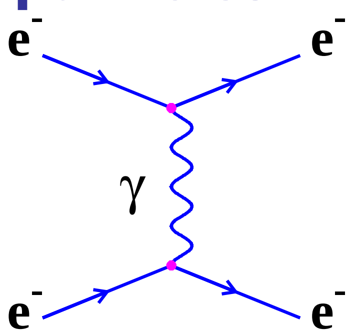
Recall we don't know which e^- emitted/absorbed the γ.
Feynman diagrams represent the sum over all time orderings

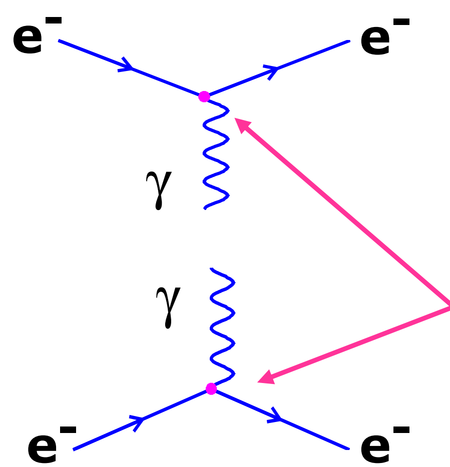


QED

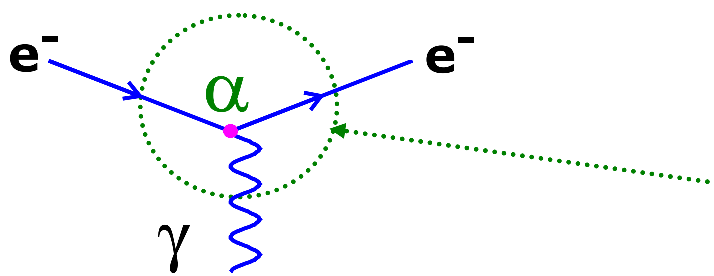
- Quantum electrodynamics **(QED)** is the theory of the interaction of **light** (photons) with electrons +
- We have seen how particles can attract/repel via the exchange of a force carrying Gauge boson
- Now need to discuss how the gauge bosons **COUPLE** to the particles

e.g.





The nature of the FORCE is determined by the interaction between the photon and the electron INTERACTION VERTEX

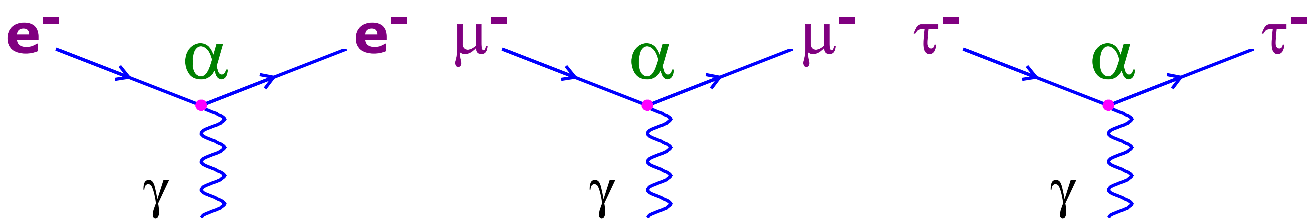


The basic strength of the interaction is given by the coupling constant α, related to the "probability of emitting a photon".

QED Vertices

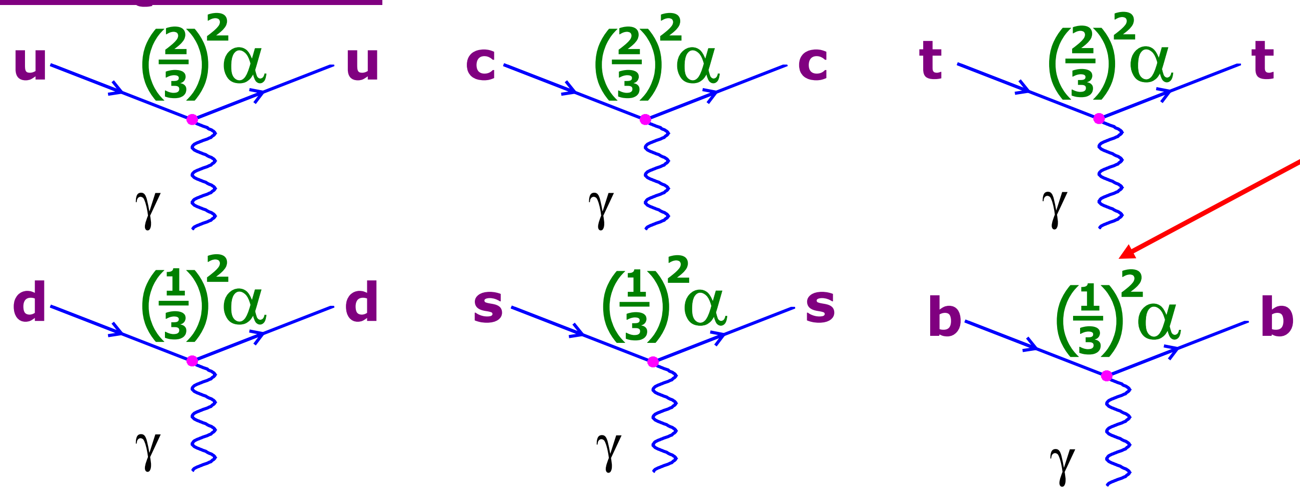
- **PHOTONS couple to ALL charged particles with the same intrinsic strength :**

CHARGED LEPTONS: (but not NEUTRINOS)



Same interaction strength – QED only cares about charge

ALL QUARKS:



Coupling slightly less for quarks due to fractional charge

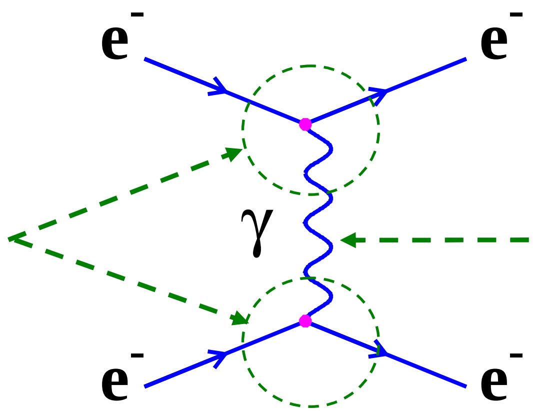
NOTE: the electromagnetic interaction does not change flavour : e.g. an electron emitting a photon does not turn into a muon

The Propagator

FOR COMPLETENESS……..

- ★ **In addition to coupling strength interaction probability depends on energy of intermediate photon**
  - **- "it is easier to emit a low energy/momentum VIRTUAL photon"**
- ★ **Mathematically called the propagator – fairly easy to derive from QM**

Coupling probability proportional to $Q^2\alpha$



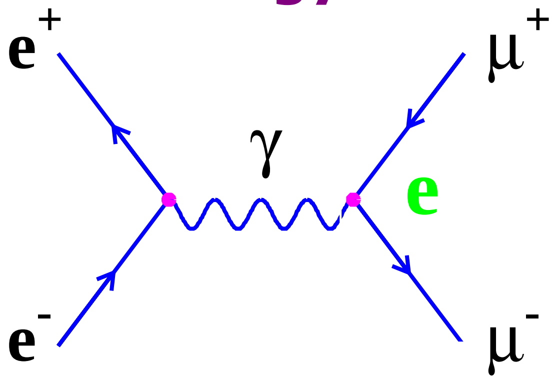
$$\frac{1}{(E^2 - p^2c^2 - m^2c^4)^2}$$

Annihilation

What happens when matter and anti-matter meet ?

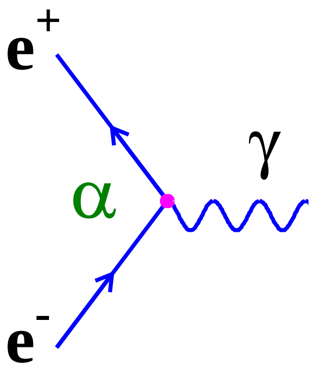
e.g. an electron, e^-, and a positron (anti-electron), e^+

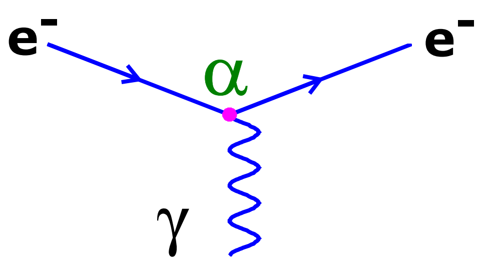
- ★ they can annihilate into "energy"
- ★ this "energy" is in the form of particle



★ In this example the photon has energy : $E_\gamma = E_{e+} + E_{e-}$

- ★ same basic interaction as scattering:





★ With the same intrinsic strength

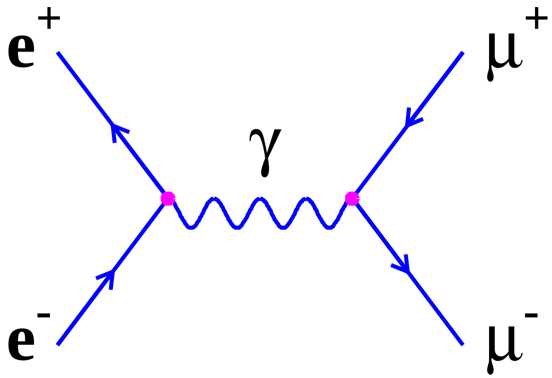
Electron-Positron Annihilation

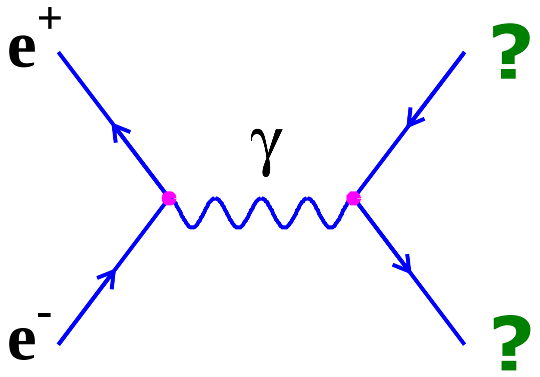
★ Electrons/positrons are relatively easy to accelerate to high energies

★ All of the energy of the collision is converted into the energy of the photon

★ That energy can then create a particle – anti-particle pair provided:

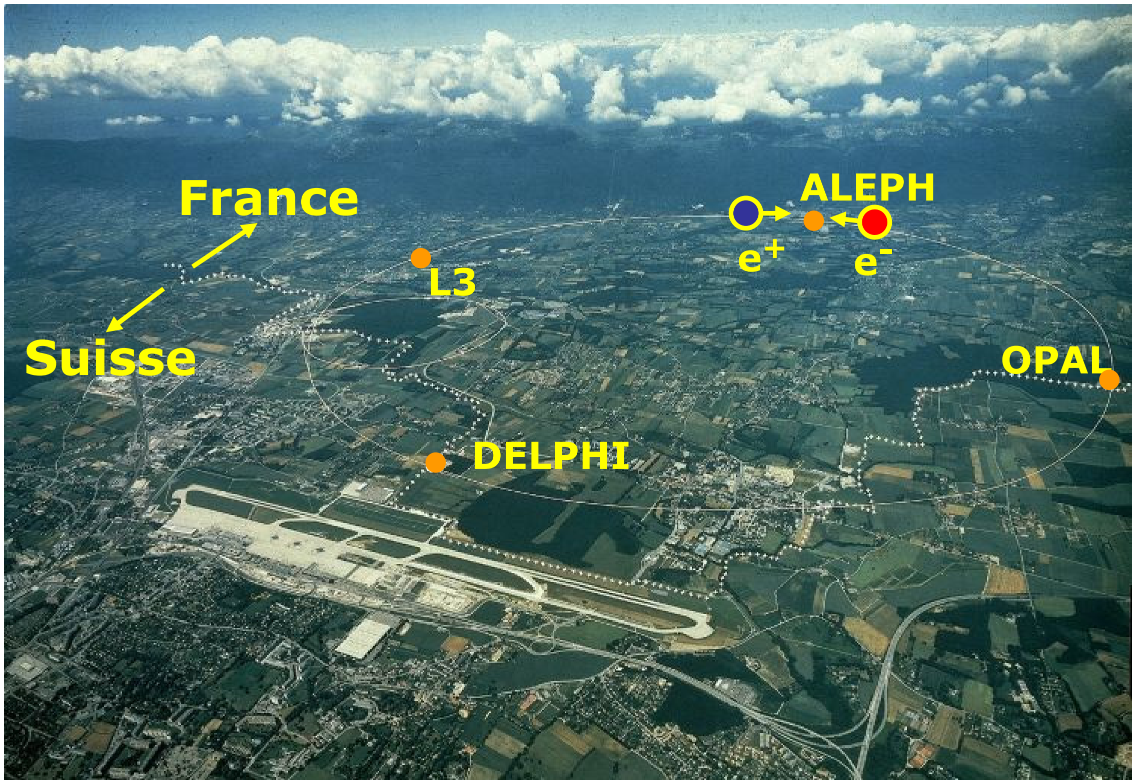
- **they are charged** (need to interact with a photon)
- **energy > 2 mc^2** (need sufficient energy to make the two new particles)





LEP : the Large Electron Positron Collider

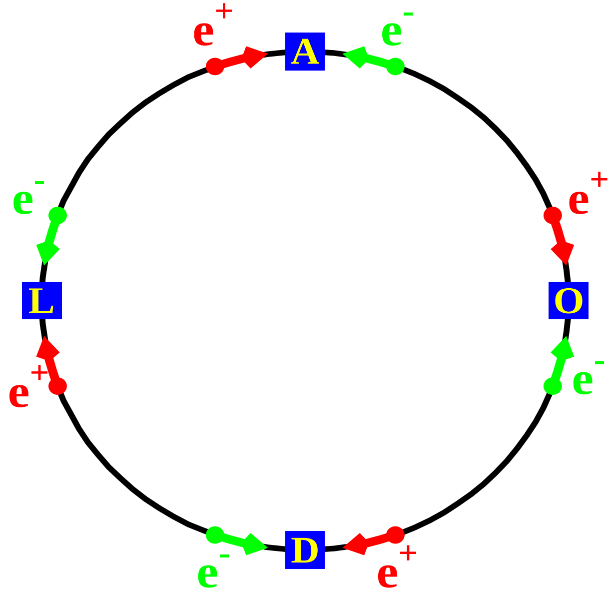
- The world's largest electron positron collider ran from 1989-2000 at CERN



- 26 km circumference
- Accelerated e^- and e^+ to 99.999999999 % c
- Built to study Z and W bosons (we'll come back to this)
- e^- and e^+ brought into collision at 4 places around the ring
- 4 large detectors:
  - ALEPH
  - DELPHI
  - L3
  - OPAL
- 1600 physicists

The LEP ring

- Approximately 100 m below the surface
- 4 bunches of counter-rotating e^+ and e^-

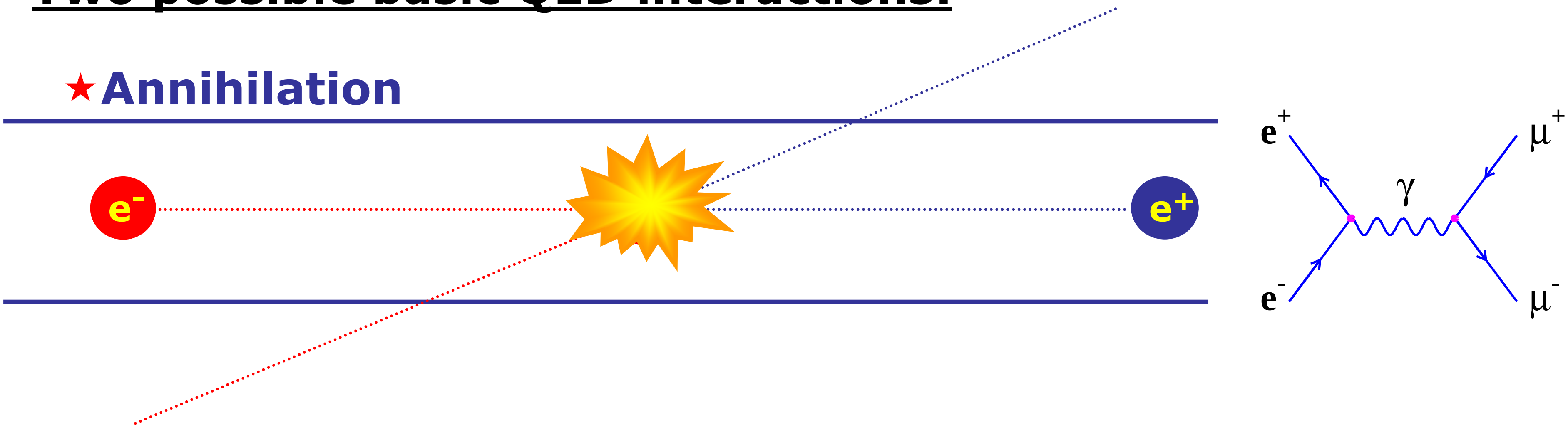


- e^+ and e^- accelerated using RF cavities, “steered” using super-conducting magnets
- e^+ and e^- collide at 4 interaction points

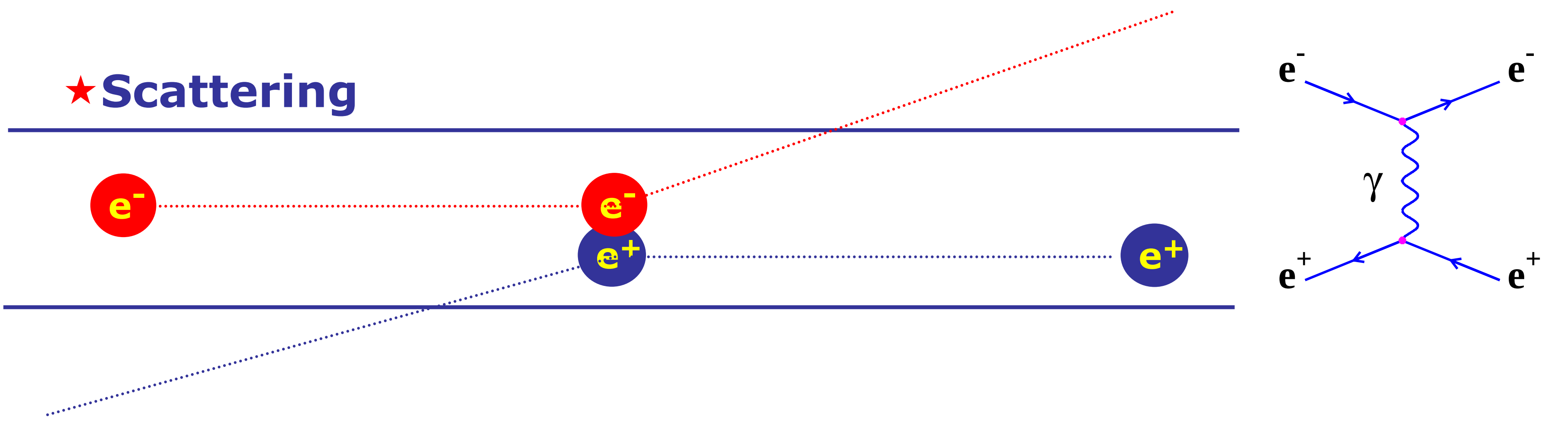
QED at e^+e^- Colliders

Two possible basic QED interactions:

★ **Annihilation**

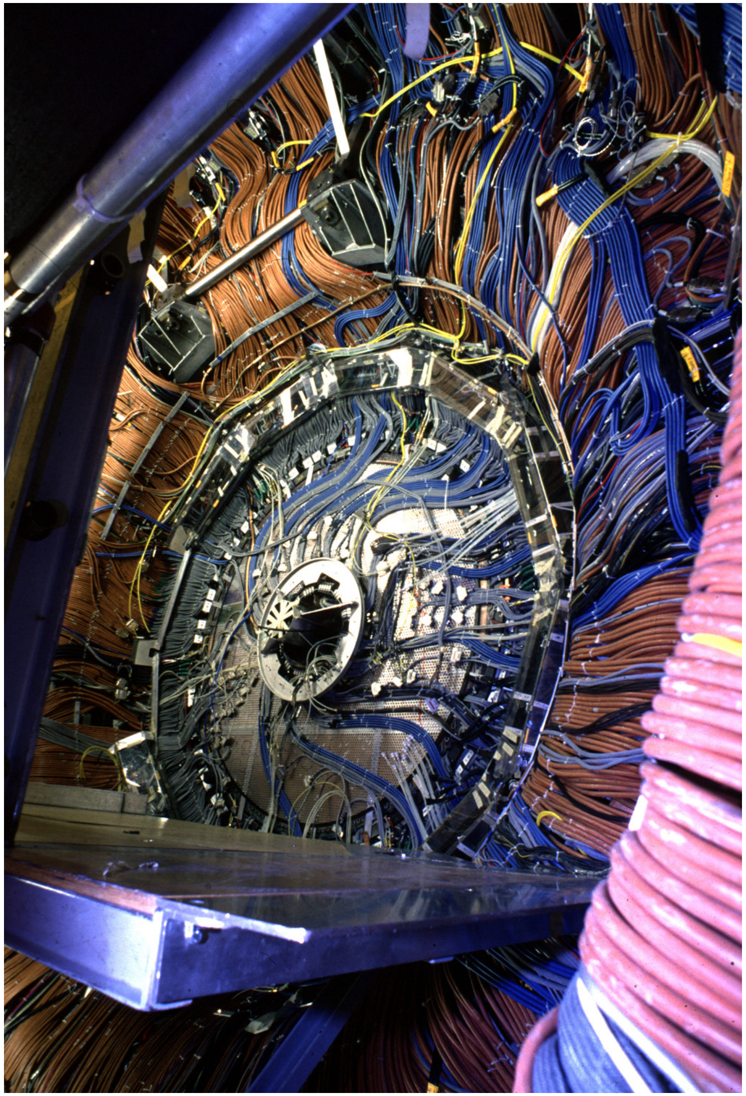


★ **Scattering**



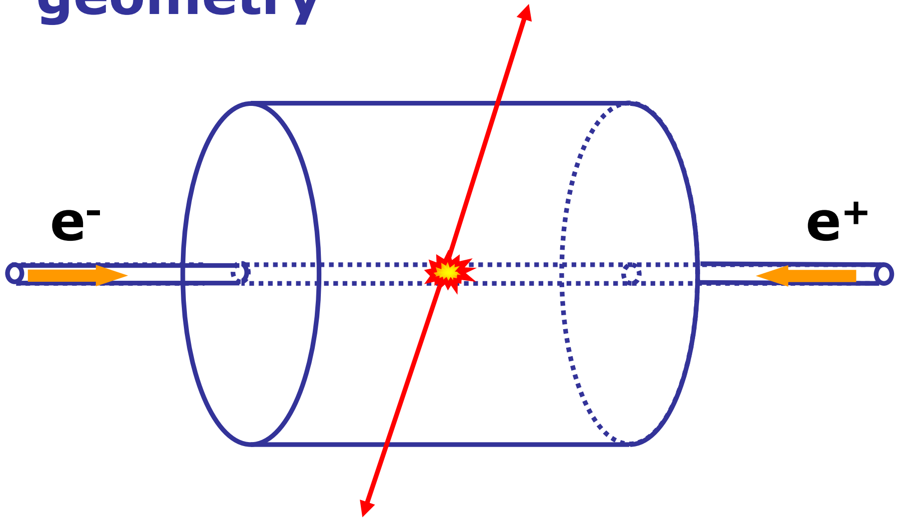
✸ **By observing and identifying the particles produced in the collisions obtain information on the underlying physics !**

Particle Detection



★ The particles produced interactions are observed and identified in large multi-purpose detectors

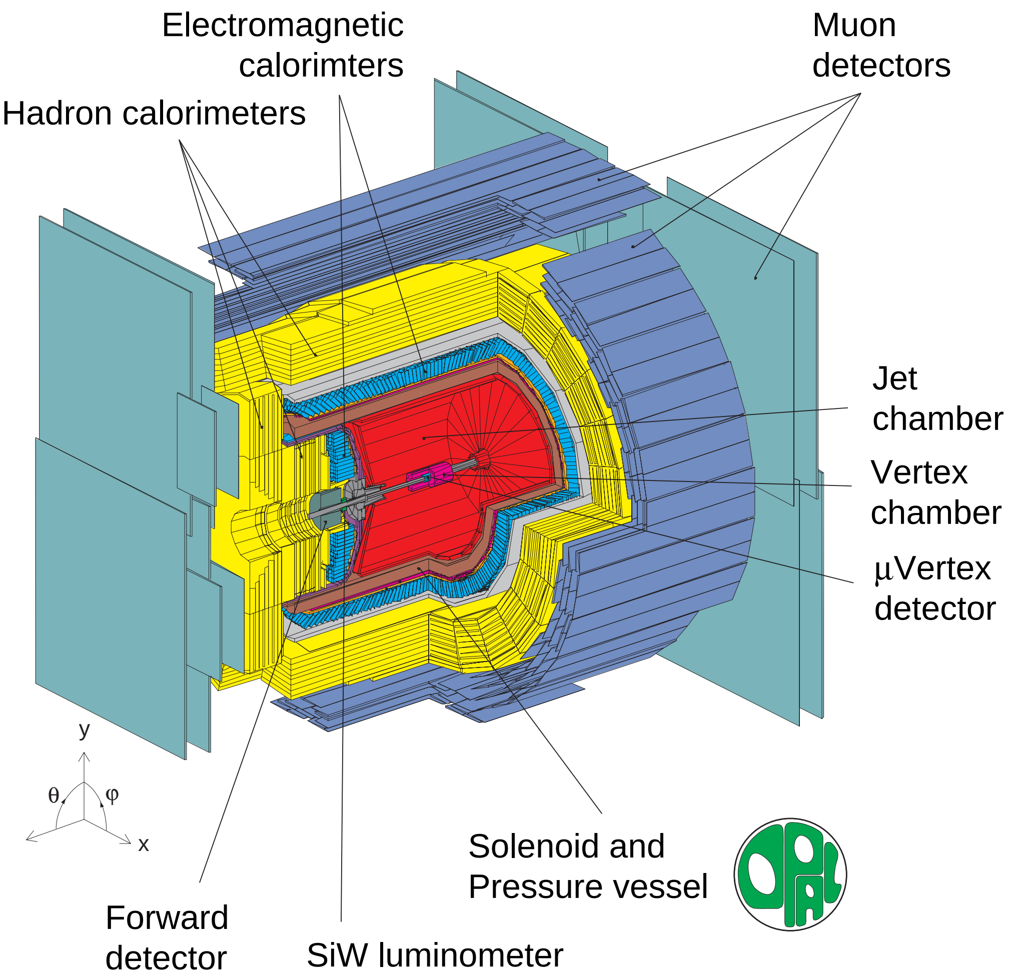
★ All have same basic geometry



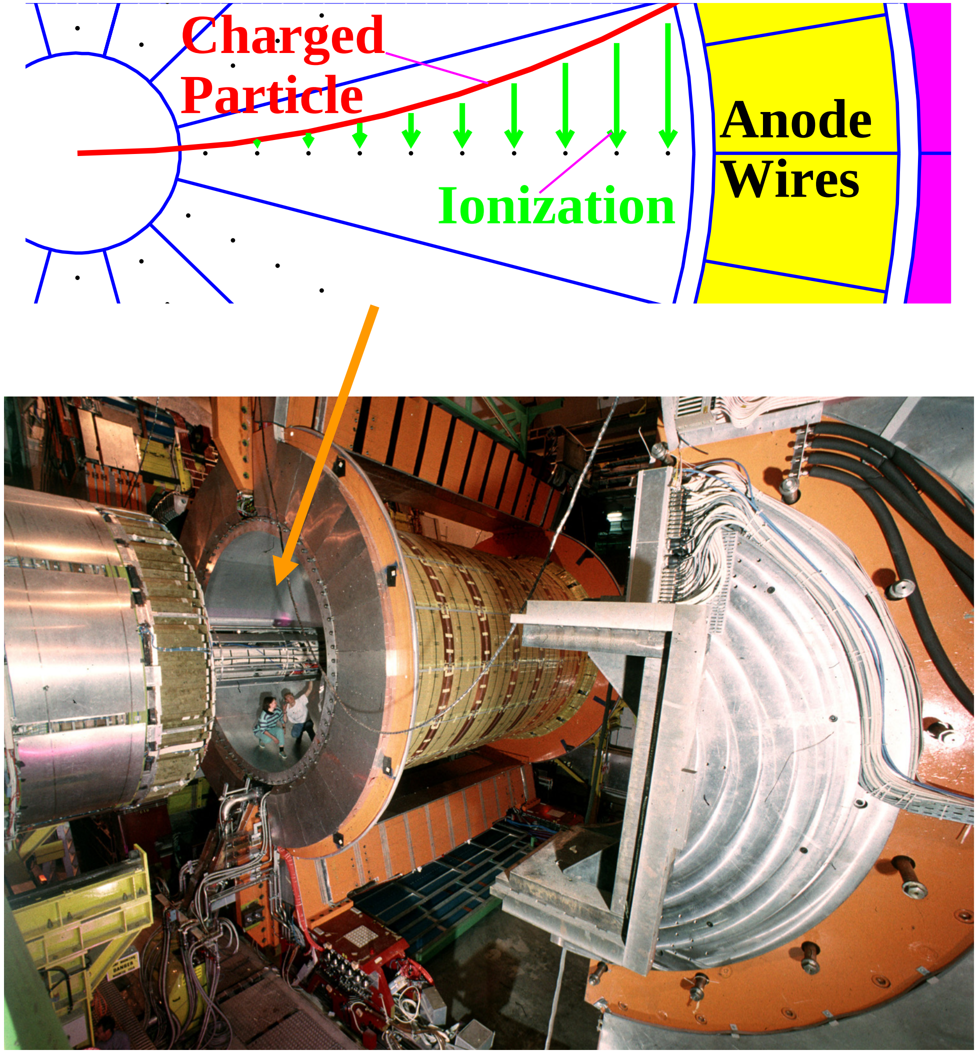
★ Need to detect particles as they cross the detector volume

The OPAL Experiment

- Many different layers of "sub-detectors"
- **4 main categories**
  - Tracking Chambers
    - charged particles
  - ECAL
    - electrons/photons
  - HCAL
    - hadrons
  - MUON chambers
    - muons

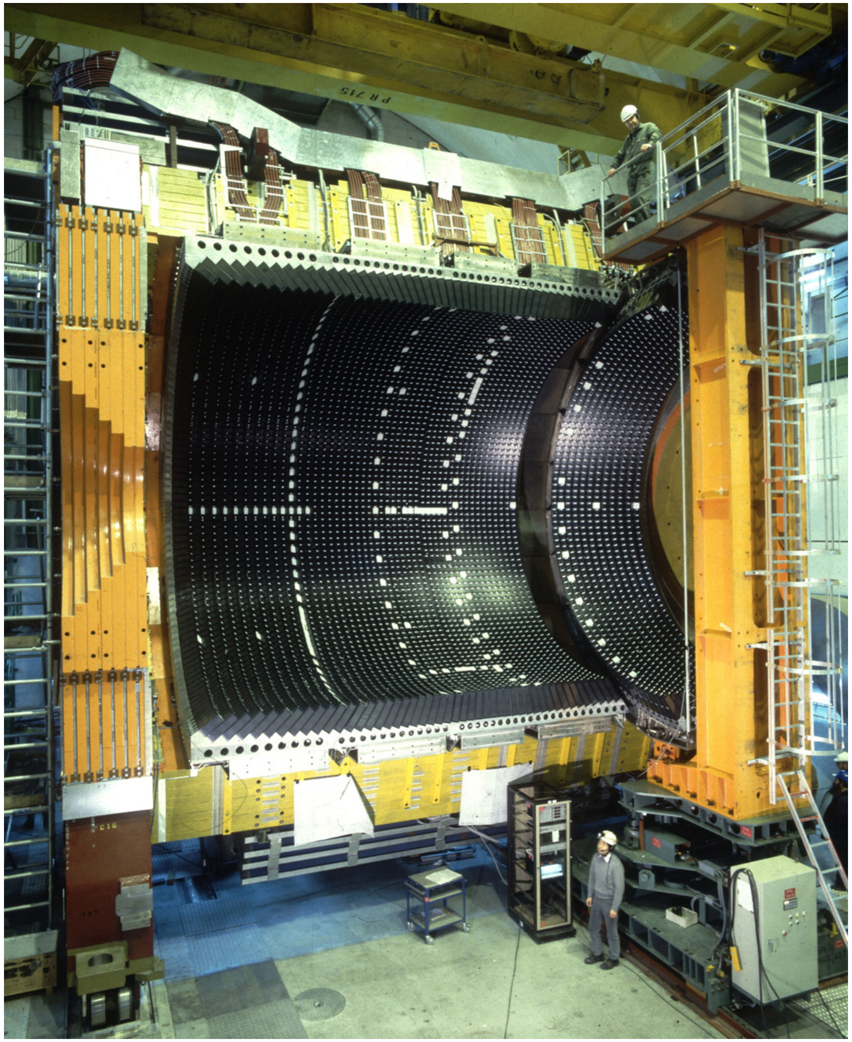


Tracking Chambers

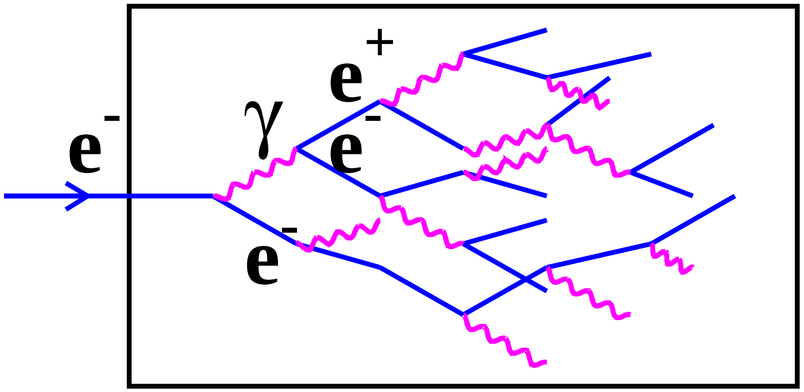


- Charged particles ionize gas
- +ve ions and liberated electrons drift in electric field
- Charge collected on sense wires and produces an electrical signal
- **NOTE:** track bends in the magnetic field – curvature ⇨ particle momentum

Electromagnetic Calorimeter (ECAL)

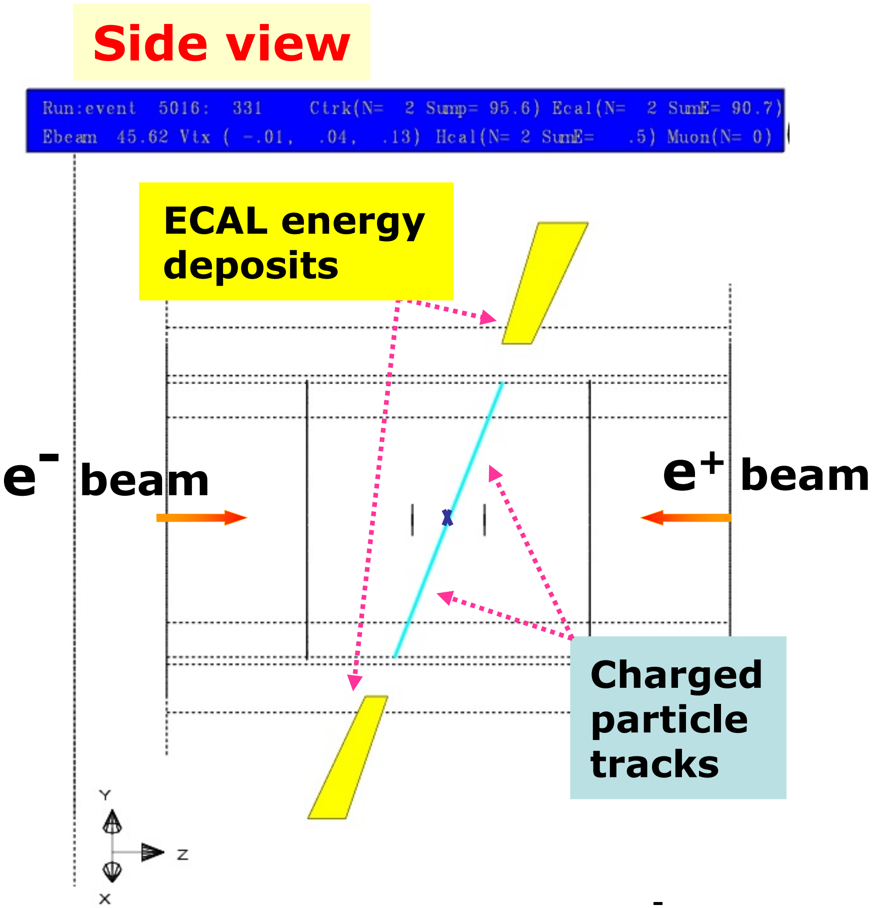


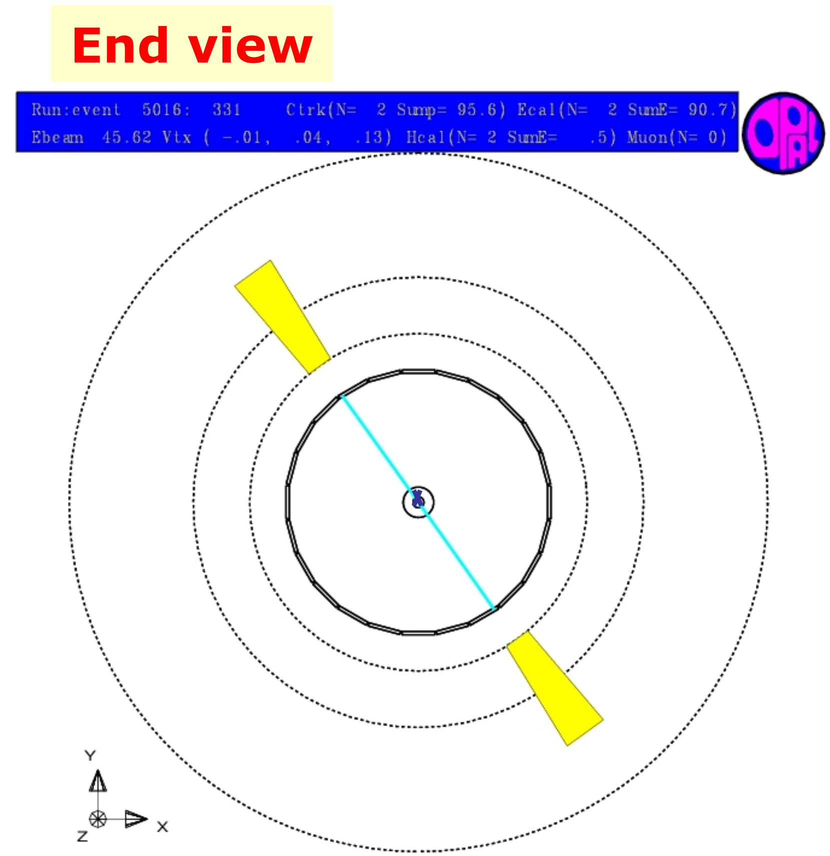
- **ECAL : 11705 Pb-Glass blocks (10x10x30 cm^3)**
- **When an $e^{\pm}/\gamma$ enters block it produces a $e^{\pm}/\gamma$ cascade**



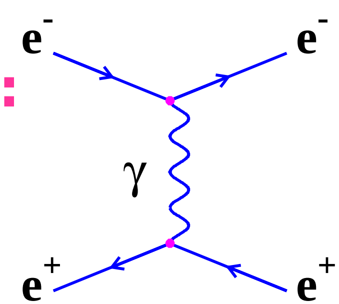
- **light detected using photo-multiplier tubes**

$e^+ e^- \rightarrow e^+ e^-$

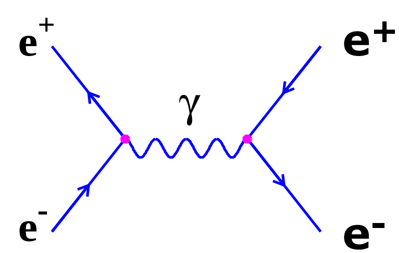




★This event could be:

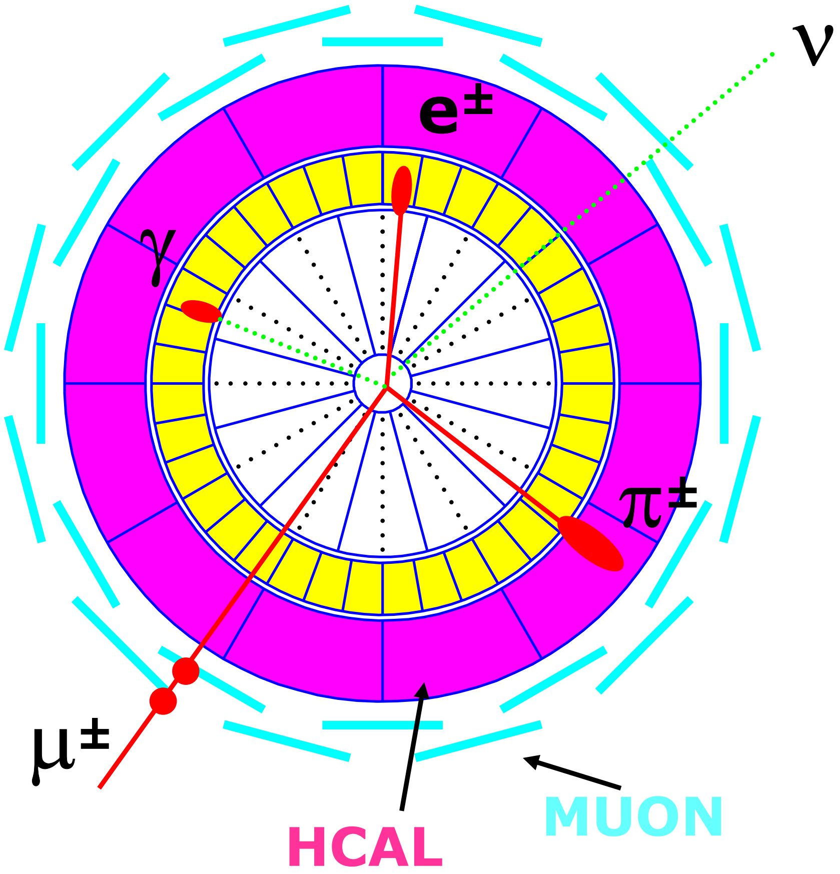


or



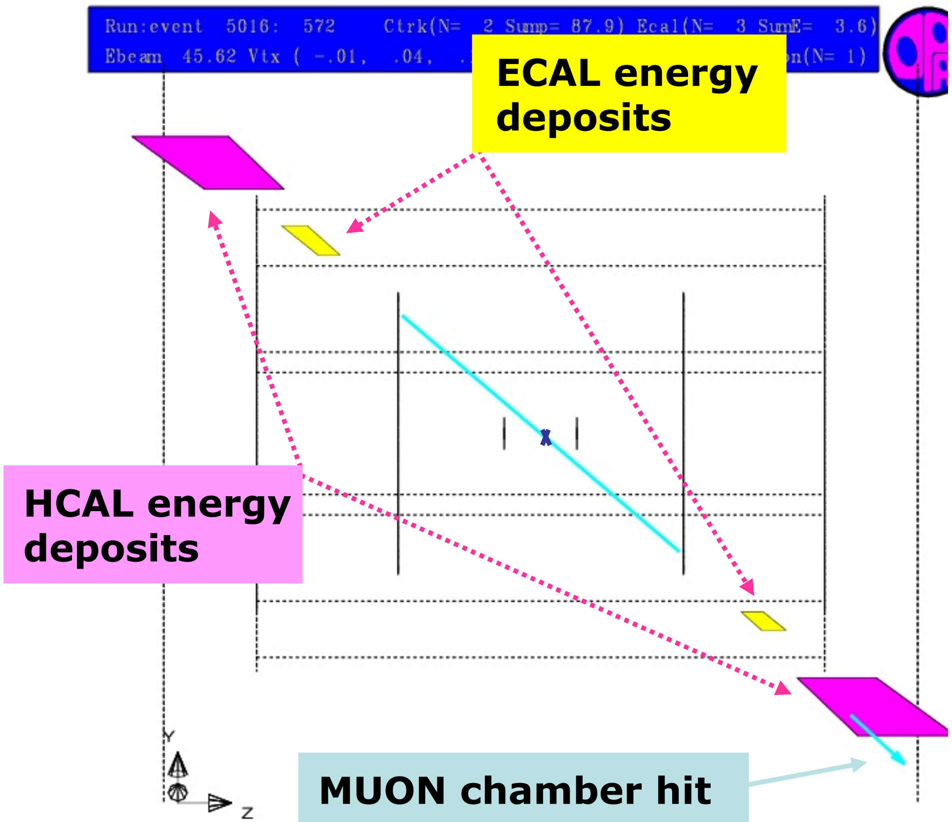
Particle Identification

- Different particles leave characteristic signals in the different "sub-detectors" – making particle identification possible

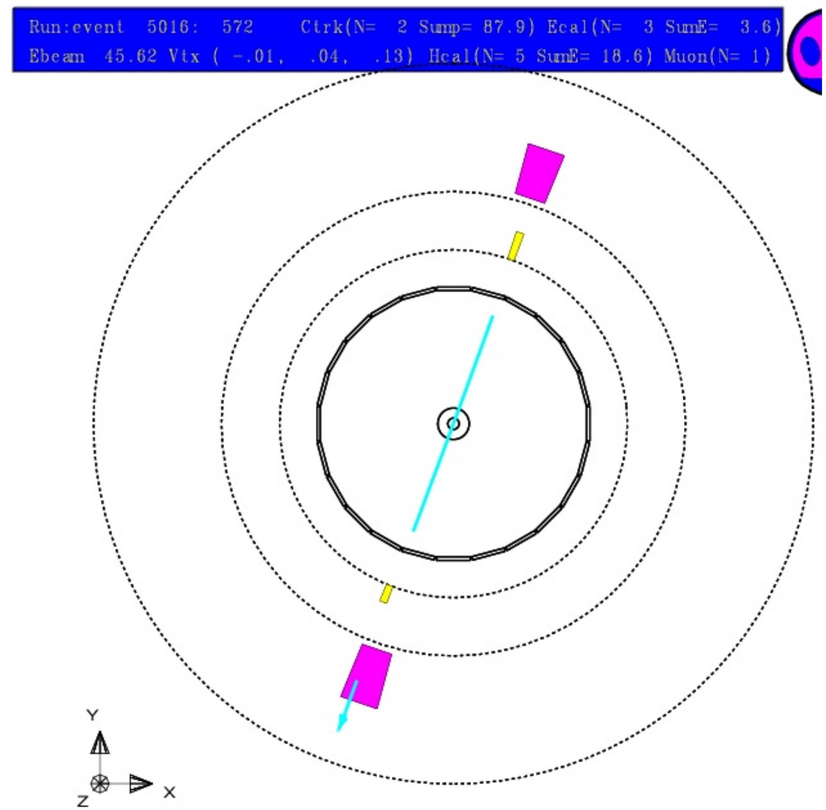


$e^+ e^- \rightarrow \mu^+ \mu^-$

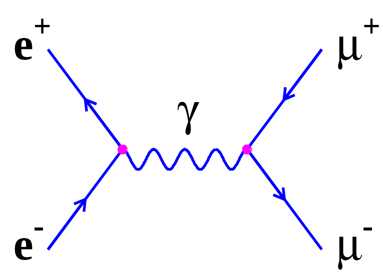
Side view



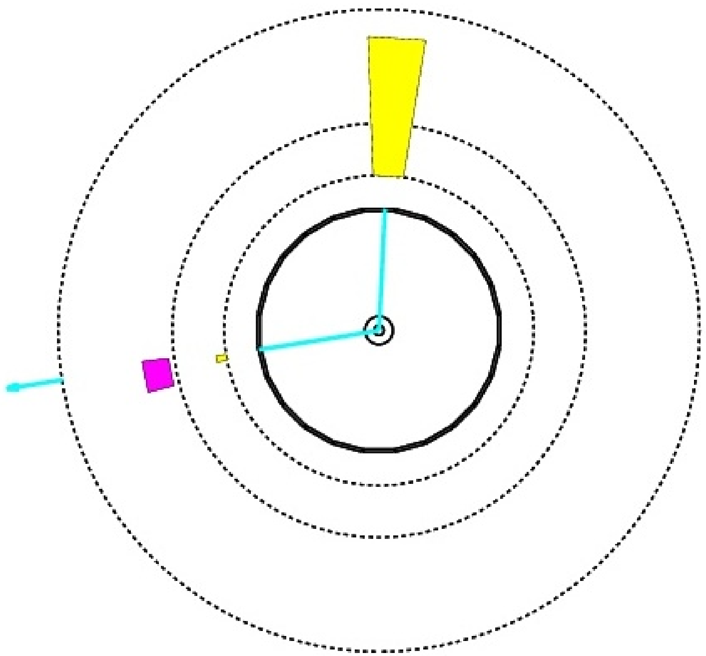
End view

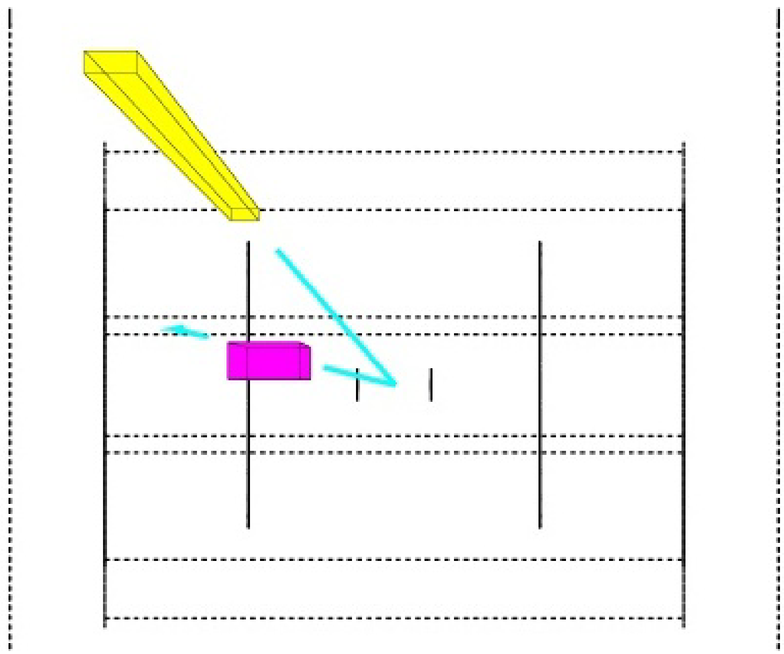


★ **This event could be:**

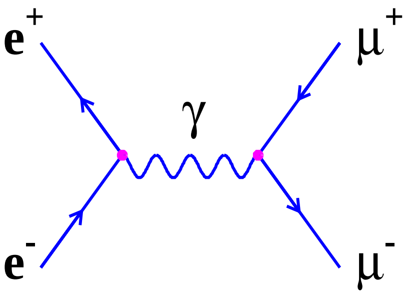


What about ?





- ★ a single electron and a single muon
- ★ **BUT** can't be simple $e^+ e^- \rightarrow e^+ \mu^-$ **!** **(WHY?)**
- ★ QED doesn't change flavour
  - produces particle/anti-particle pairs
- ★ Conservation of momentum implies some "invisible particle" also produced
- ★ **WAIT FOR DISCUSSION OF W-BOSONS**



Interaction Cross-Section

★ We have seen how we identify different type of particles – but what can we measure ?

★ The most basic quantity is the CROSS-SECTION for a particular interaction

★ Related to event rate

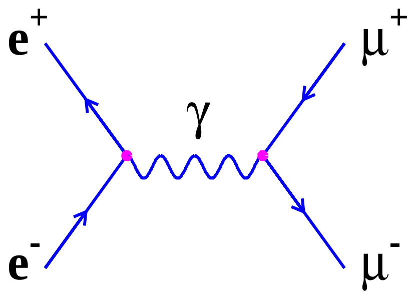
★ CROSS-SECTION ⟶ "how likely is a certain process to happen"

★ The cross-section, σ, for a process can be calculated using Quantum Mechanics

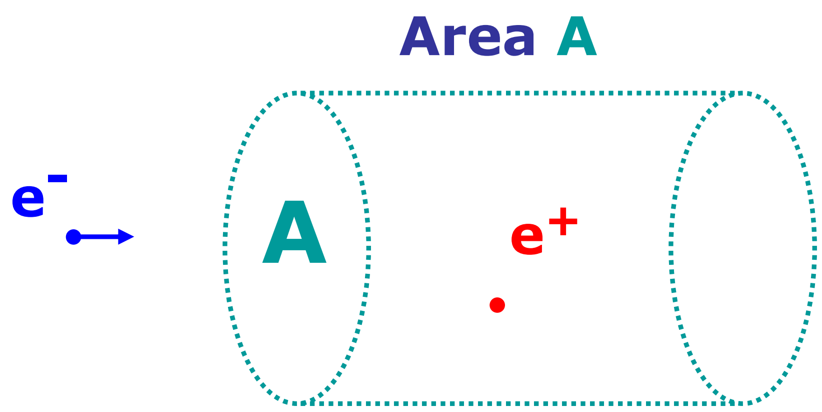
★ Here we will concentrate on the meaning

Example:

- Suppose we have a single e^- crossing a region of area, A, in which there is one e^+ - what is the probability that they will annihilate and a μ^- μ^+ will be produced via

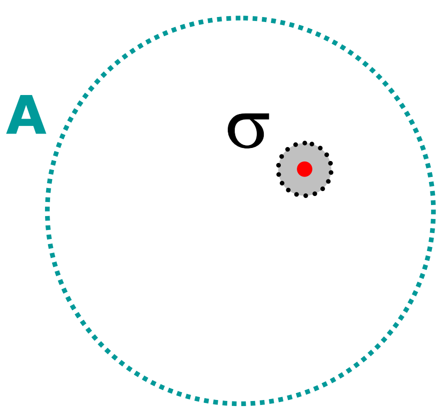


Geometrical picture of σ



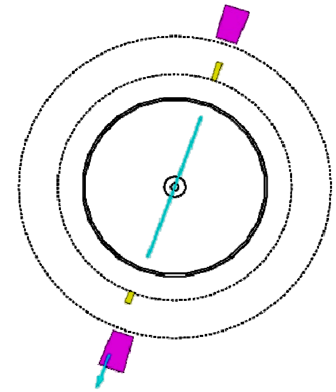
What is the probability the e^+e^- will have annihilated after the e^- passes through this region ?

- **Picture the situation end on.**
- **The probability of interaction is given by the cross-section/Area : σ/A**
- **The interaction cross-section can be considered as an "imaginary" area drawn around the e^+ such that if the e^- passes through this area they will annhiliate.**



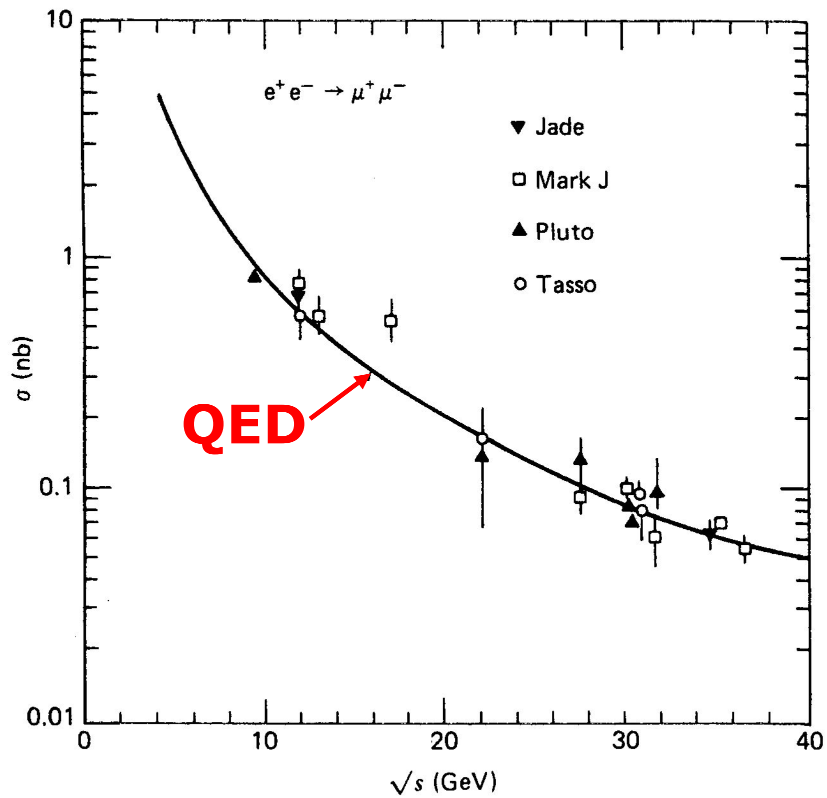
Probability of interaction $\boxed{\dfrac{\sigma}{A}}$

Tests of QED



e.g. measure cross-sections by counting number of $e^+e^- \rightarrow \mu^+\mu^-$ events

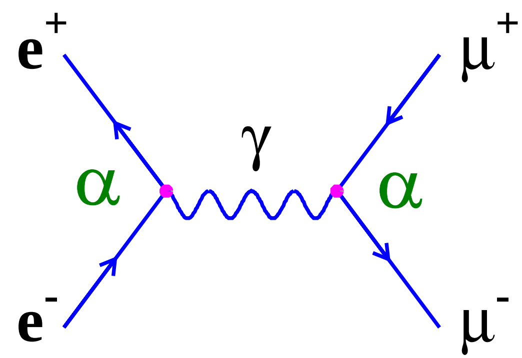
(computers do the work !)



Perfect agree with QED prediction !

$$\boxed{\sigma = \frac{\pi\alpha^2}{3E^2}}$$

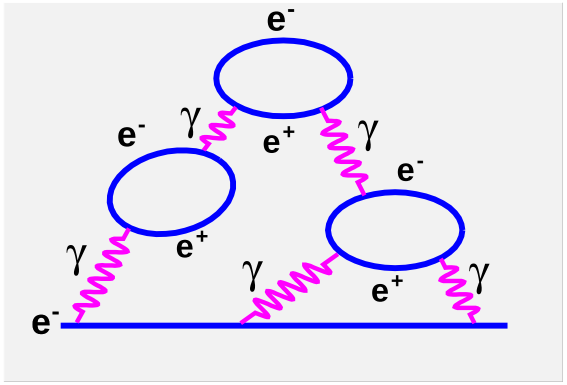
<u>NOTE:</u> cross-section proportional to α^2



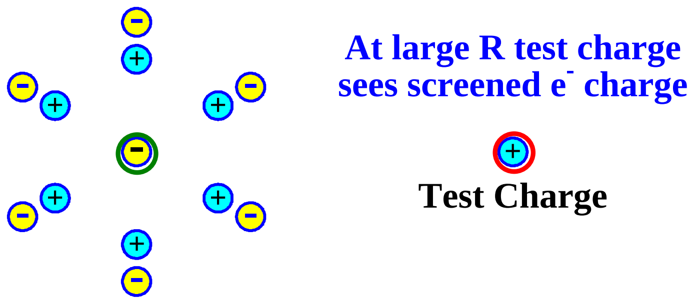
Running Coupling

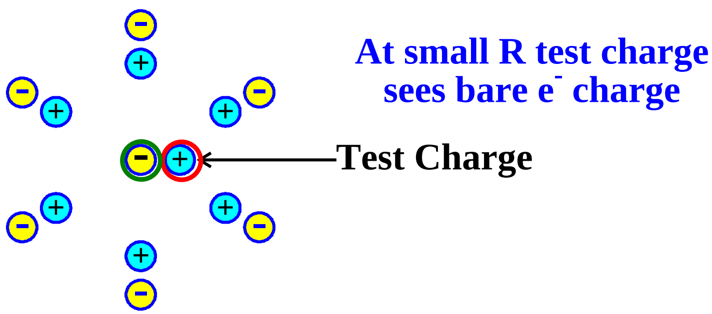
★ α specifies the strength of the interaction between an electron and a photon

★ **BUT** α isn't constant !



★ an electron travelling through the vacuum is surrounding by a cloud of virtual electron/positron pairs





★ As a result the strength of the electromagnetic interaction increases (slightly) with energy

★ At low energies:

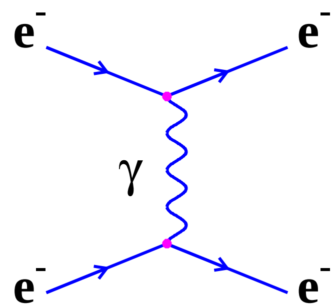
$\alpha = \mathbf{1/137}$

★ At LEP:

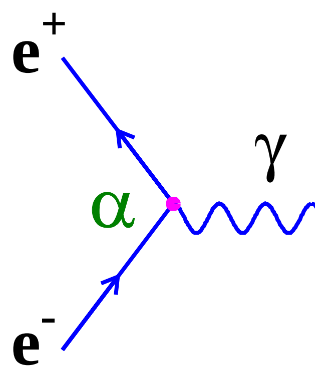
$\alpha = \mathbf{1/128}$

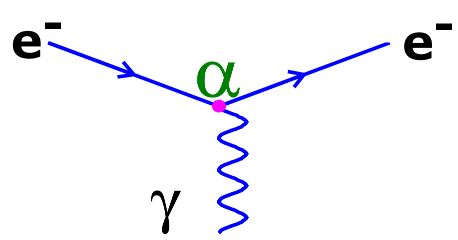
Summary

- The electromagnetic interaction is due to the exchange of a **VIRTUAL** photon:



- In **QED** the interaction between a charged particle and a photon is parameterised by the coupling strength, α



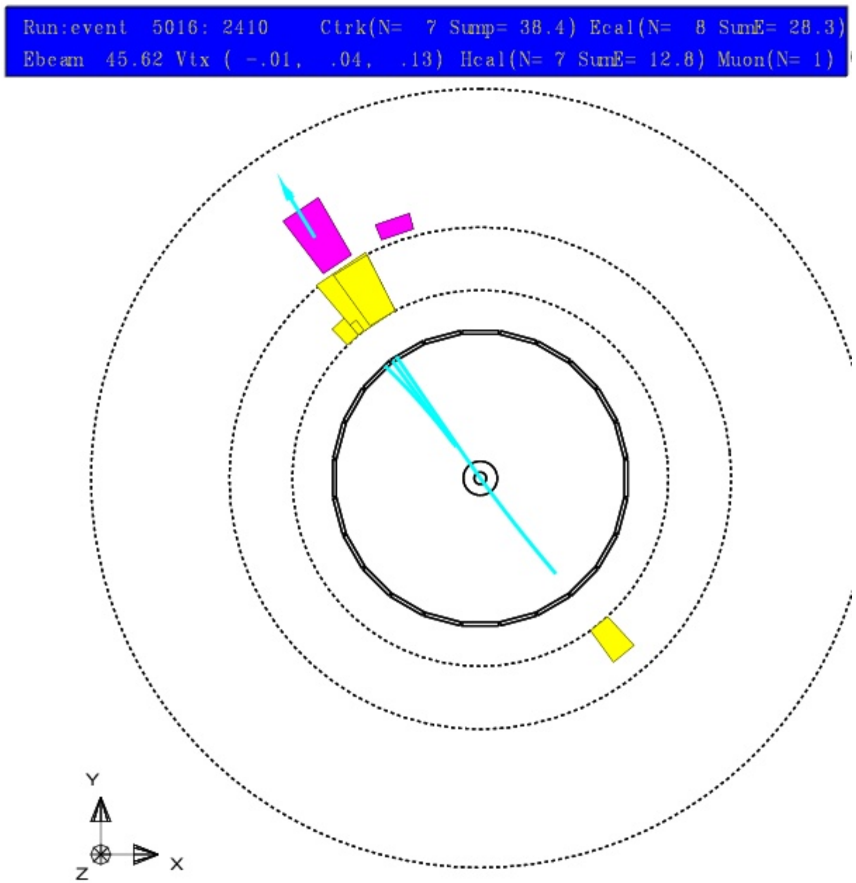


- α is not constant, it "runs", increasing with energy
- In many ways the theory of the strong interaction, **QCD**, is very similar to **QED**……

Rogues Gallery : I

What is this event ?

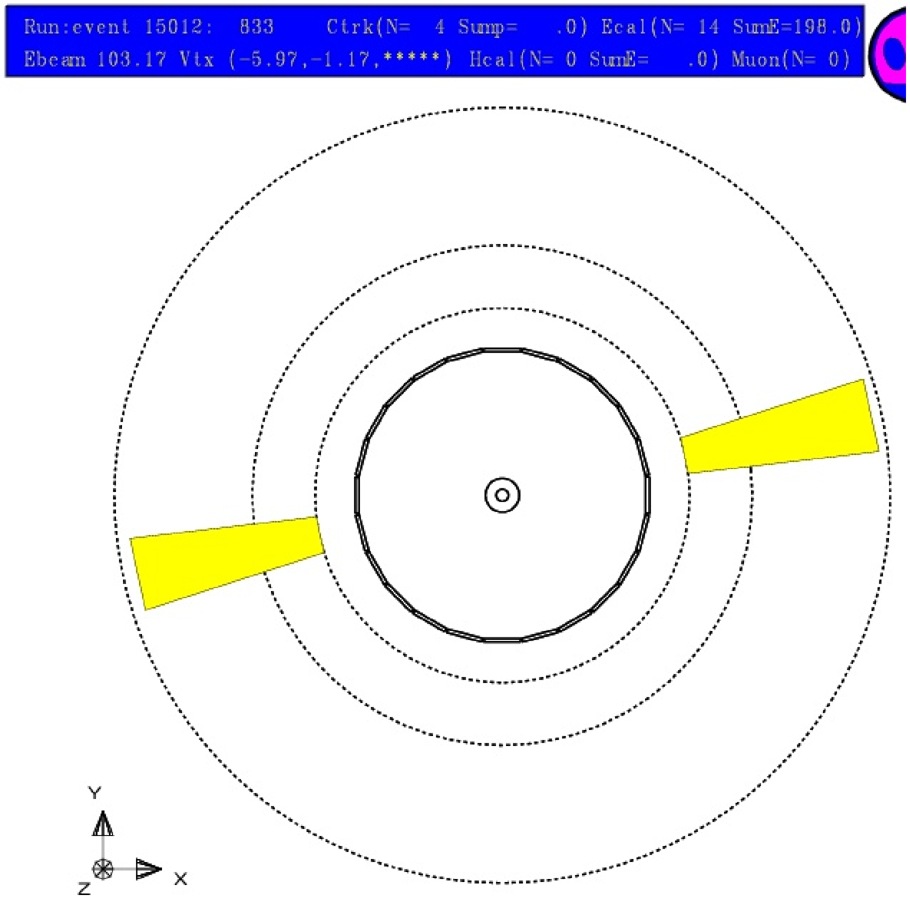
+Feynman Diagram ?



Rogues Gallery II

What is this event ?

+Feynman Diagram ?



Rogues Gallery : III

What is this event ?

+Feynman Diagram ?