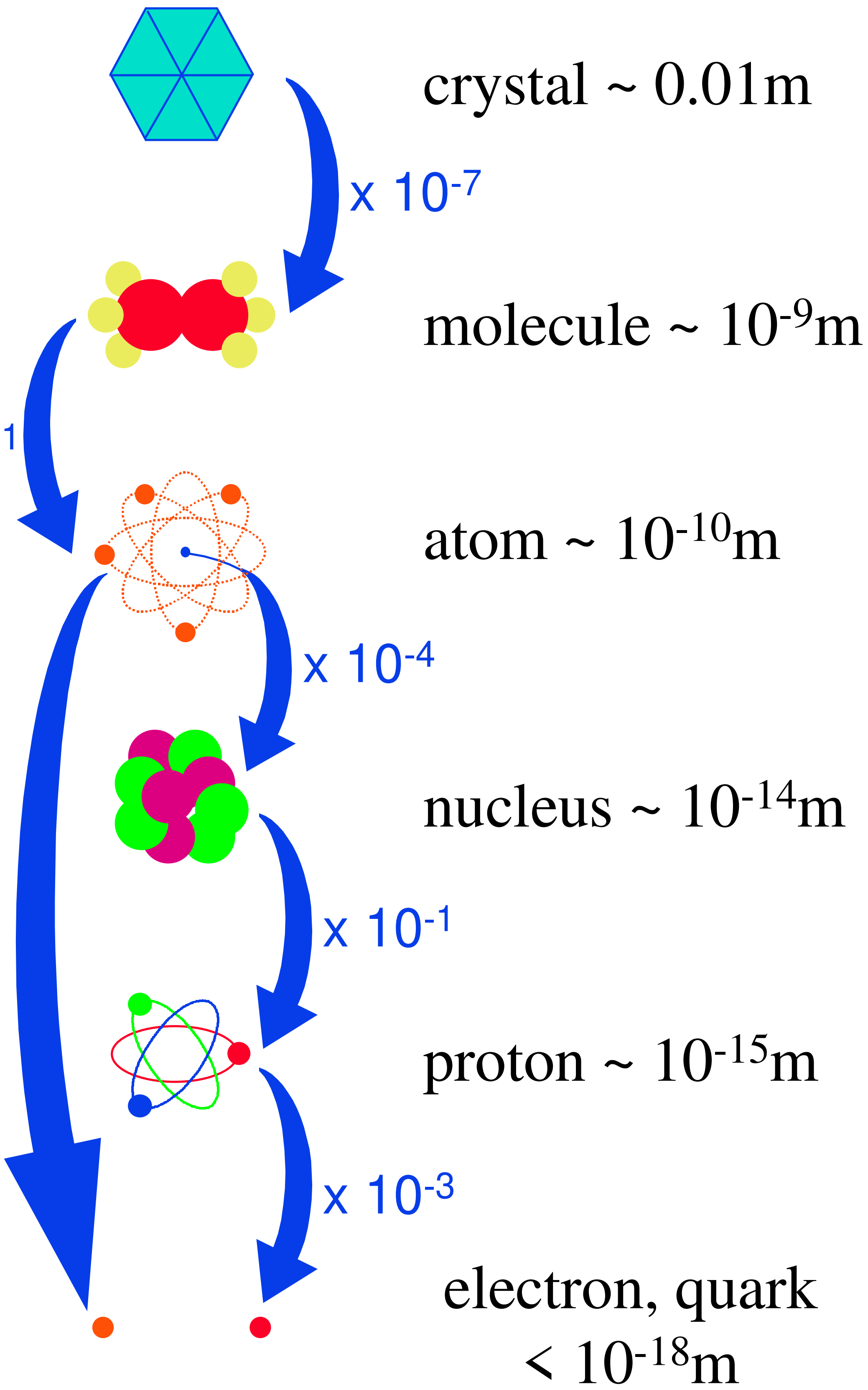
High Energy Physics

- What is HEP?
- Fundamental particles:
  - Electrons and Quarks.
- Forces and force carrying particles:
  - Electromagnetism and the photon
  - Gluons and the strong force
  - The W^+, W^-, Z^0 and the weak force
- LEPI and LEPII.
- Detectors.

High Energy Physics

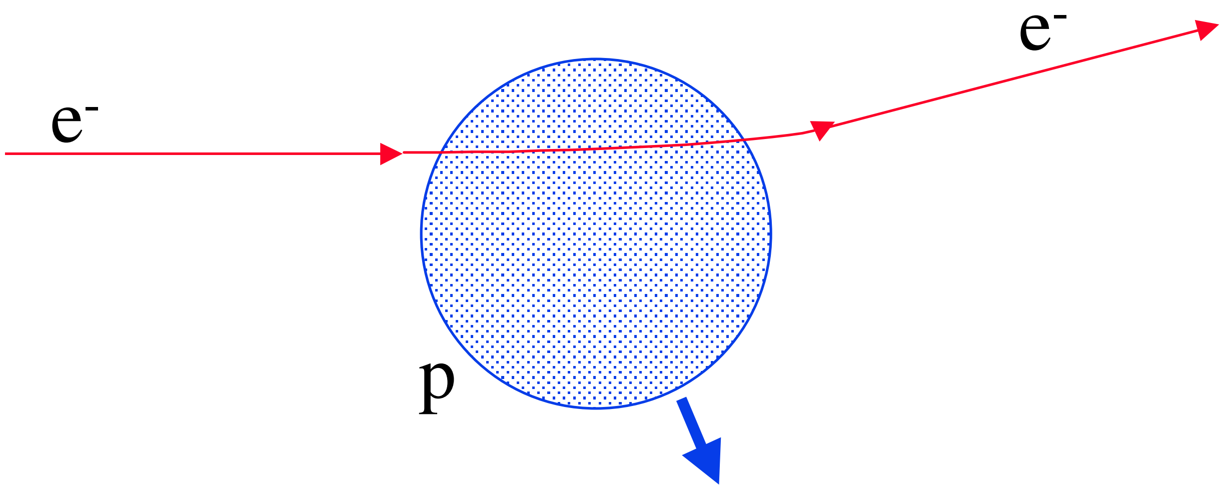
- High Energy Physics is search for answers to two questions:
  - What are fundamental constituents of matter?
  - What governs interactions between these constituents?
- Leucippus (c. 530 BC) first proposed matter composed of fundamental particles, “atoms”.
- First of what now believed to be fundamental particles identified by J.J. Thomson in 1897.

Fundamental Matter Particles

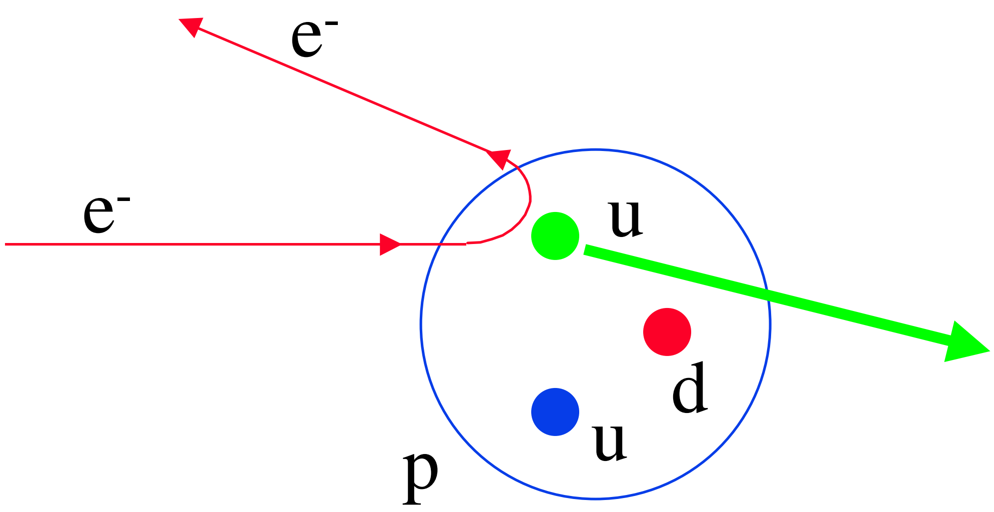


Evidence for Quarks: The Basic Idea

- Fire electrons at protons.
- If proton "charge cloud":

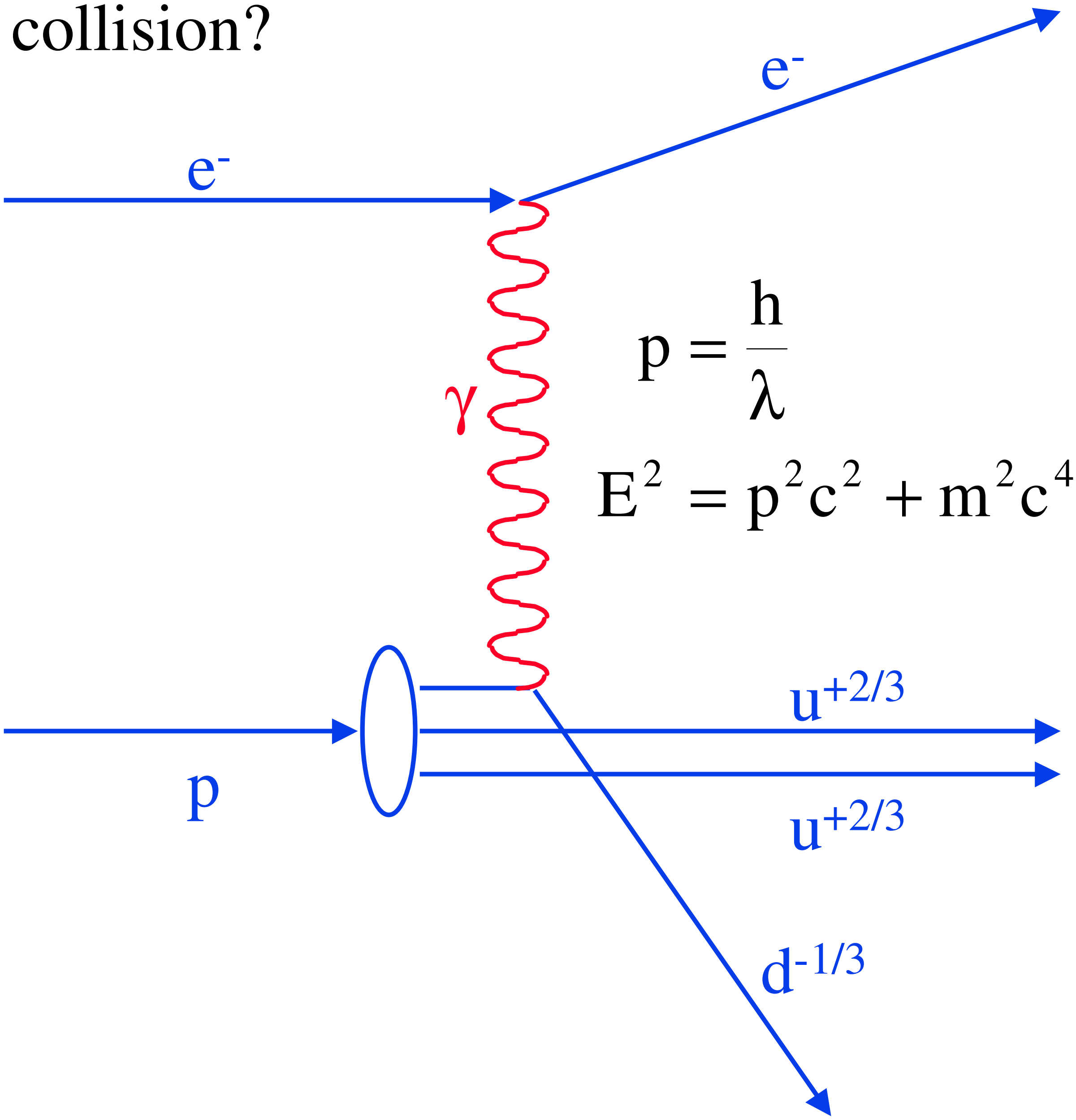


- If proton contains point charges, some of time see:



Evidence for Quarks: More Detail

- Look at protons using “electron microscope”.
- Resolution dependent on wavelength.
- What is happening in electron proton collision?



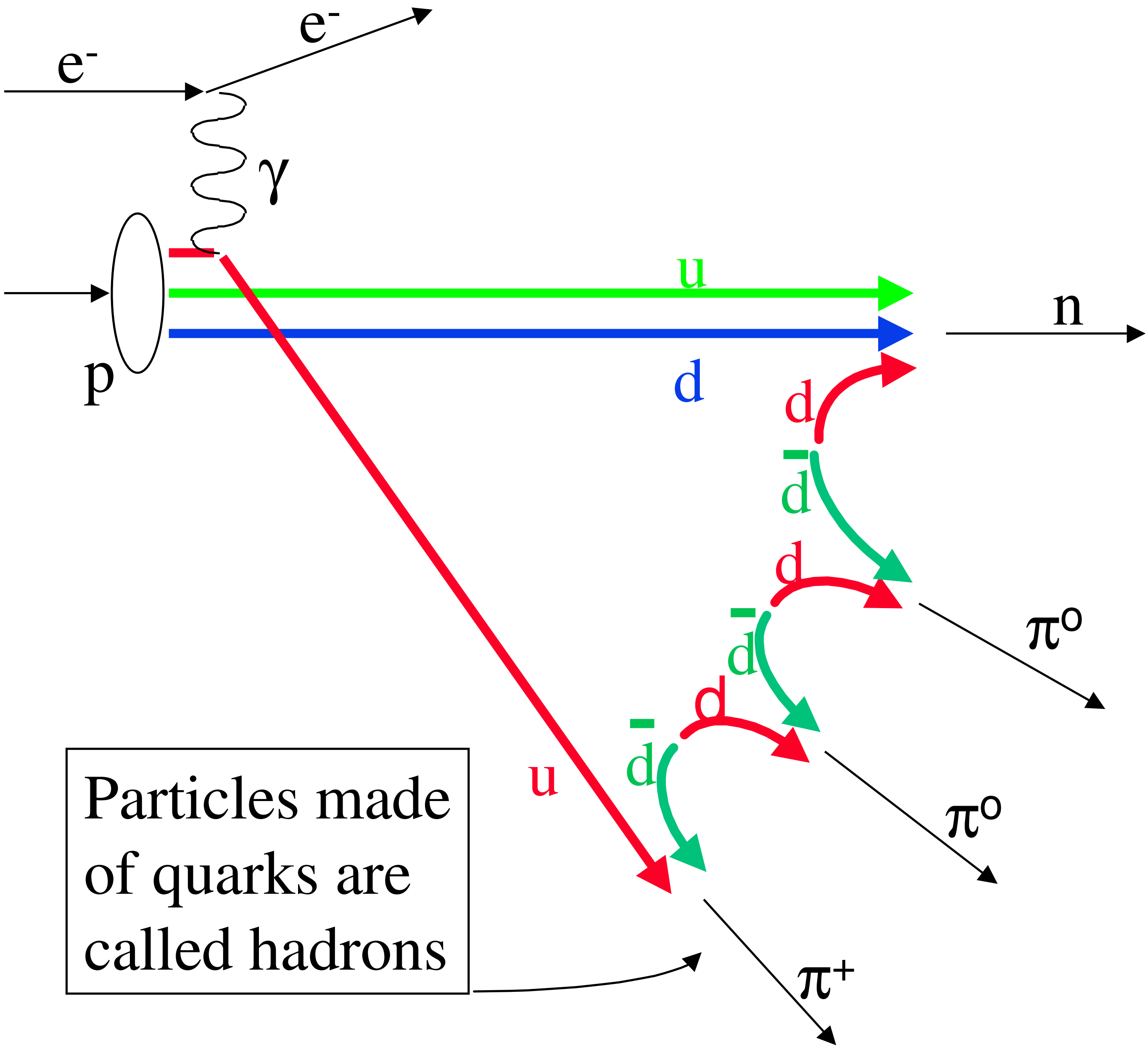
The Strong Force

- Why don't protons "blow-up"? (Like electric charges repel!)
- Held together by force stronger than electromagnetism - the strong force.
- Three types of strong charge, red, blue and green.
- Particles (like proton) stable if charges sum to white:
  - red + blue + green = white
  - red + $\overline{\text{red}}$ = white

cyan

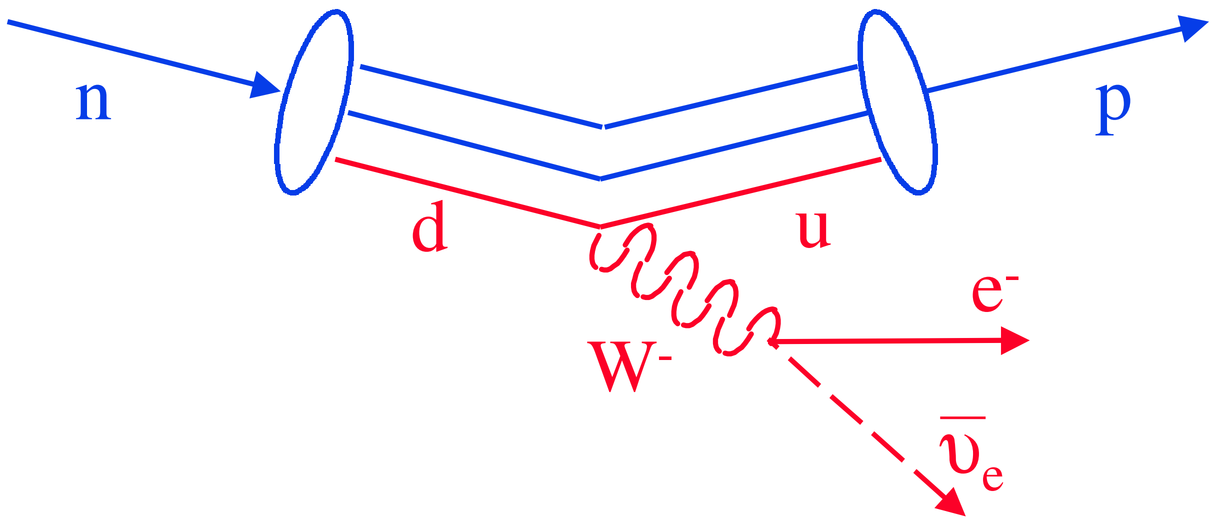
But we don’t see quarks...

- Strength of force between colour charges increases with separation.
- Never see “free” quarks!



Photons, Gluons and other Force Carrying Particles

- Electromagnetic force carried by photons, γ.
- Strong force carried by gluons, g.
- Need additional "weak" force to describe radioactivity, nuclear fusion...
- At high energy, strength of electromagnetism and "weak" forces same => electroweak force.
- Electroweak force carrying particles are γ, Z^o, W^+ and W^-.
- Neutron decays via weak force



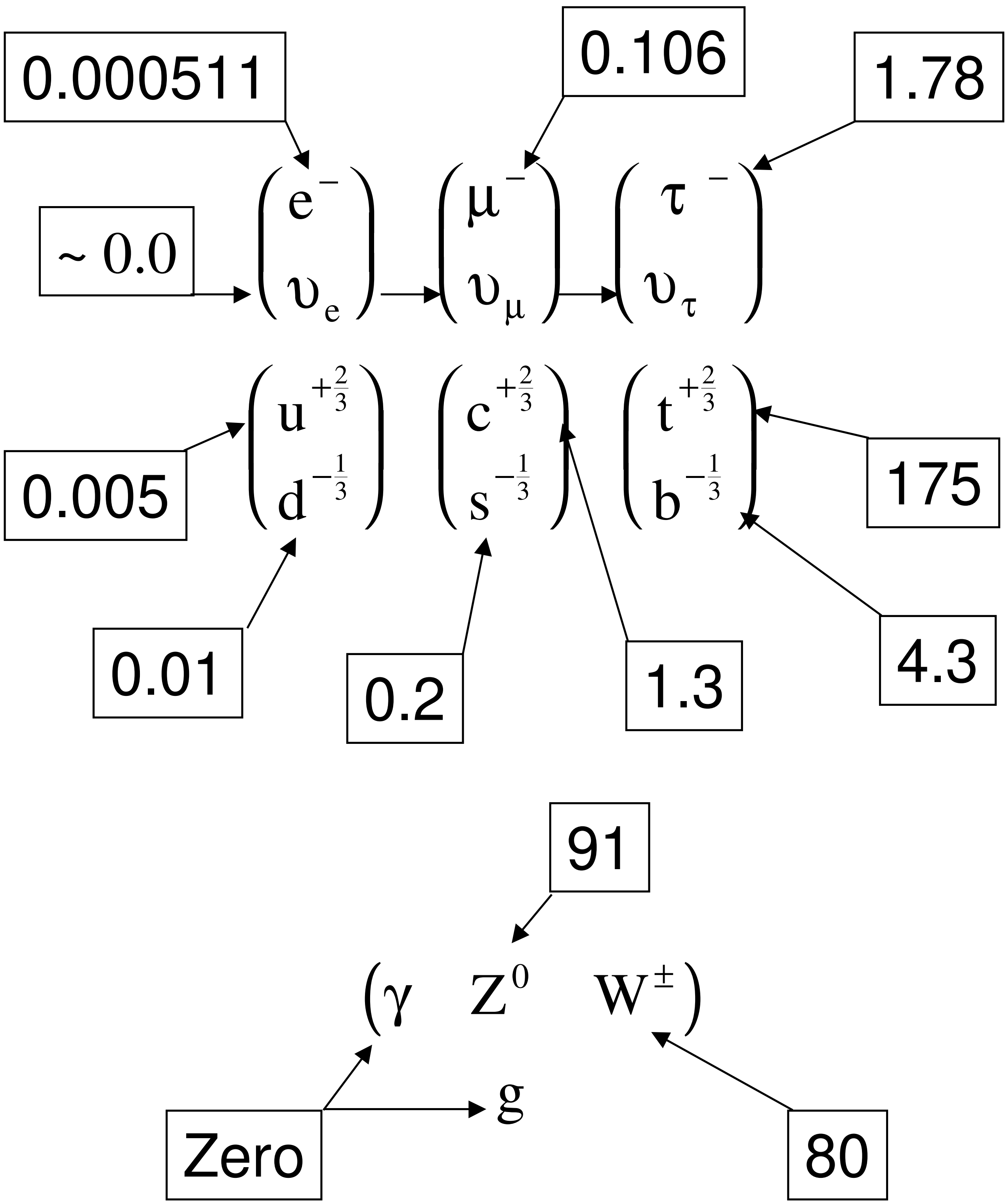
More Quarks and Leptons

- For daily life need:
  - u and d quarks.
  - Electron with its neutrino, υ_e.
  - Force carrying particles (bosons) g, γ, Z^o, W^+ and W^-.
- Experiment has shown that:
  - Matter particles all have anti-particle partners.
  - There are (more massive) "carbon copies" of u, d, e and υ_e!

$$\begin{pmatrix} e^- \\ \upsilon_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \upsilon_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \upsilon_\tau \end{pmatrix} \longleftarrow \text{leptons}$$

$$\begin{pmatrix} u^{+\frac{2}{3}} \\ d^{-\frac{1}{3}} \end{pmatrix} \begin{pmatrix} c^{+\frac{2}{3}} \\ s^{-\frac{1}{3}} \end{pmatrix} \begin{pmatrix} t^{+\frac{2}{3}} \\ b^{-\frac{1}{3}} \end{pmatrix} \longleftarrow \text{quarks}$$

Masses in Gev/c^2



Forces Affecting Quarks and Leptons

- EM (γ)

$$\begin{pmatrix} e^- \\ \upsilon_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \upsilon_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \upsilon_\tau \end{pmatrix}$$

$$\begin{pmatrix} u^{+\frac{2}{3}} \\ d^{-\frac{1}{3}} \end{pmatrix} \begin{pmatrix} c^{+\frac{2}{3}} \\ s^{-\frac{1}{3}} \end{pmatrix} \begin{pmatrix} t^{+\frac{2}{3}} \\ b^{-\frac{1}{3}} \end{pmatrix}$$

- Weak $\begin{pmatrix} Z^0 \\ W^\pm \end{pmatrix}$

$$\begin{pmatrix} e^- \\ \upsilon_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \upsilon_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \upsilon_\tau \end{pmatrix}$$

$$\begin{pmatrix} u^{+\frac{2}{3}} \\ d^{-\frac{1}{3}} \end{pmatrix} \begin{pmatrix} c^{+\frac{2}{3}} \\ s^{-\frac{1}{3}} \end{pmatrix} \begin{pmatrix} t^{+\frac{2}{3}} \\ b^{-\frac{1}{3}} \end{pmatrix}$$

- Strong (g)

$$\begin{pmatrix} e^- \\ \upsilon_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \upsilon_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \upsilon_\tau \end{pmatrix}$$

$$\begin{pmatrix} u^{+\frac{2}{3}} \\ d^{-\frac{1}{3}} \end{pmatrix} \begin{pmatrix} c^{+\frac{2}{3}} \\ s^{-\frac{1}{3}} \end{pmatrix} \begin{pmatrix} t^{+\frac{2}{3}} \\ b^{-\frac{1}{3}} \end{pmatrix}$$

LEPI

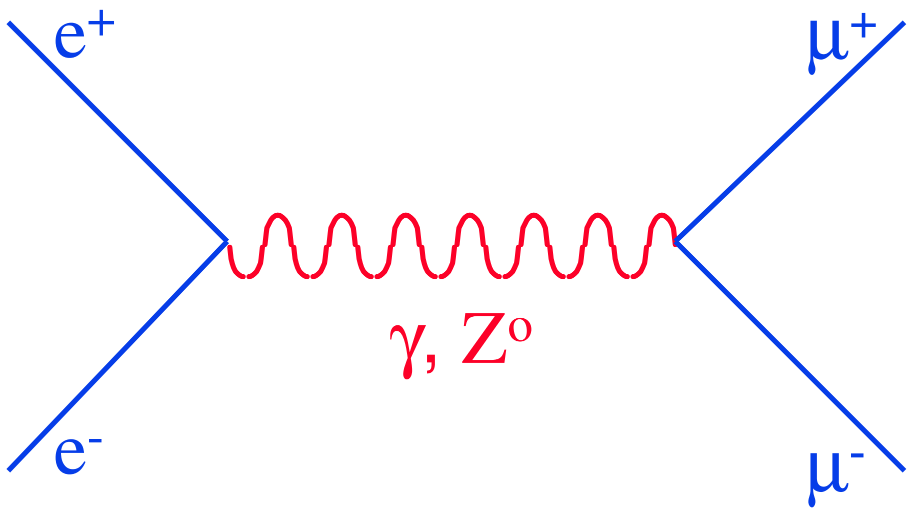
- Collide electrons (e^-) with positrons (e^+) at 45 GeV.
- Matter and anti-matter annihilate.
- Energy appears as force carrying particle.
- "Freezes out" into matter/anti-matter.
- Produce all energetically allowed matter particles.
- $2m_t c^2 > 2 \times 45$ GeV, so top quark not produced.

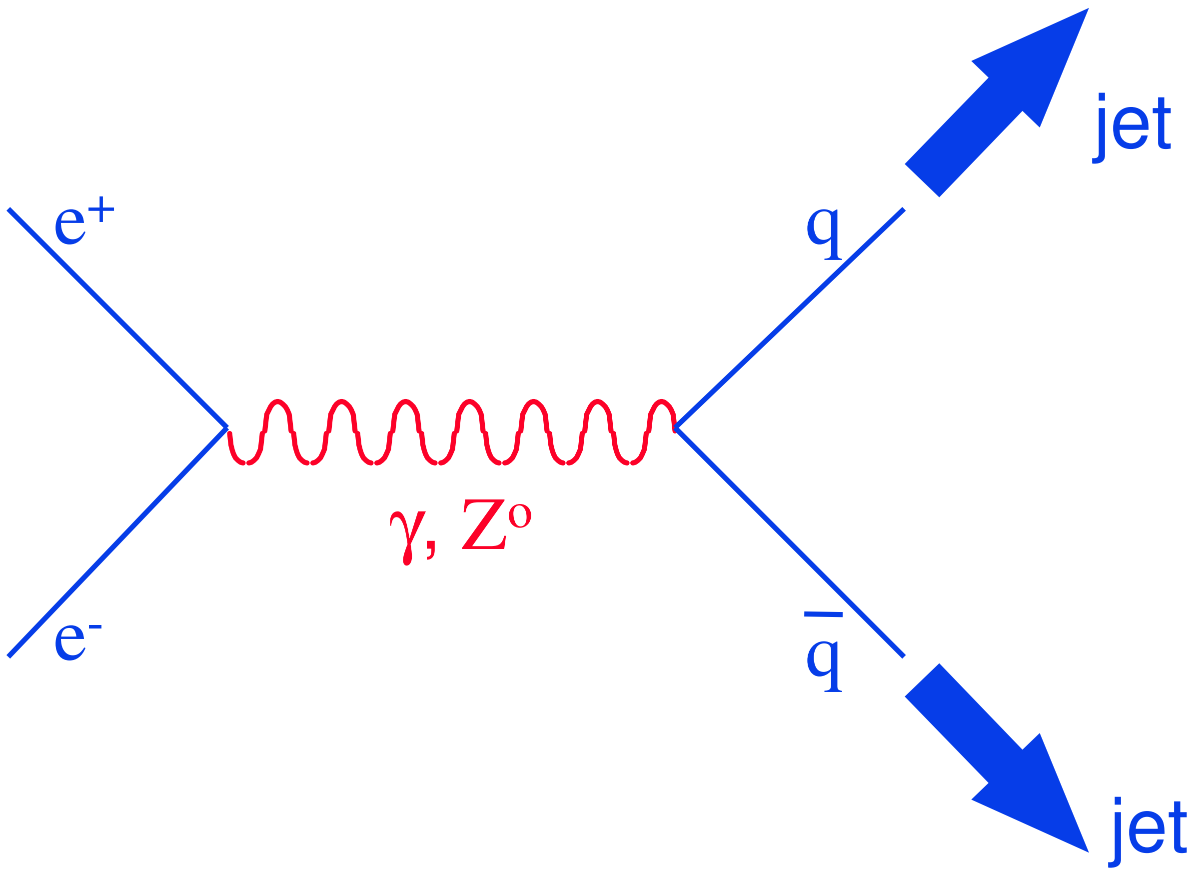
An Aside, Units

- $$45\,\text{GeV} = 45\times10^{9}\,\text{eV}$$
  $$= 45\times10^{9}\times1.6\times10^{-19}\,\text{J}$$
  $$= 7.2\times10^{-9}\,\text{J}$$
- Using $E = mc^2$ or $m = E/c^2$
  can write masses in units of energy divided by c^2, e.g. $m_p = 0.938\,\text{GeV}/c^2$
  $$\approx 1\,\text{GeV}/c^2$$
- Similarly, using $E^2 = p^2c^2 + m^2c^4$
  can write momenta in units of GeV/c.

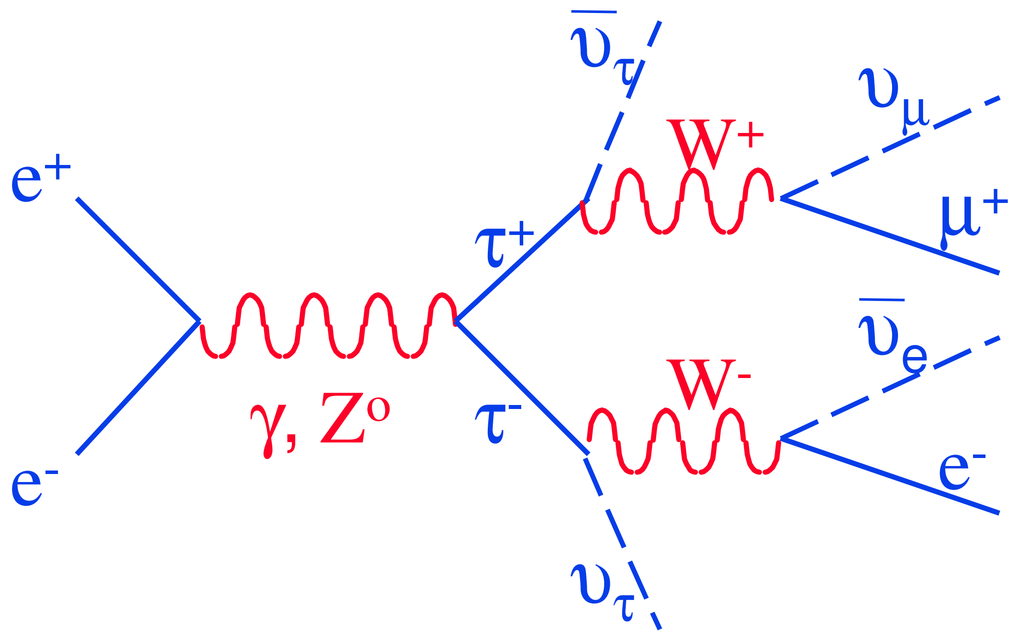
LEPI cont.

- Important Feynman diagrams at LEPI





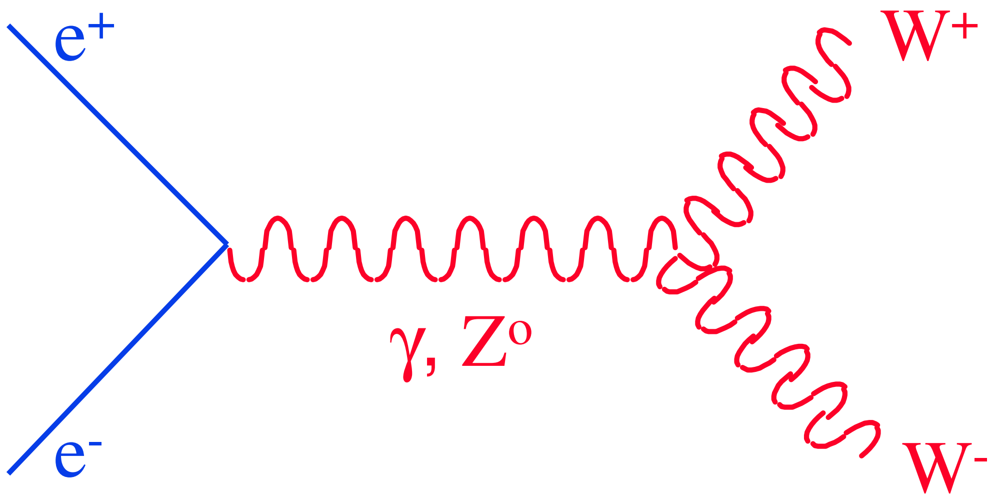
LEPI Feynman diags cont.



- More about possible τ decays in PC exercise.

LEPII

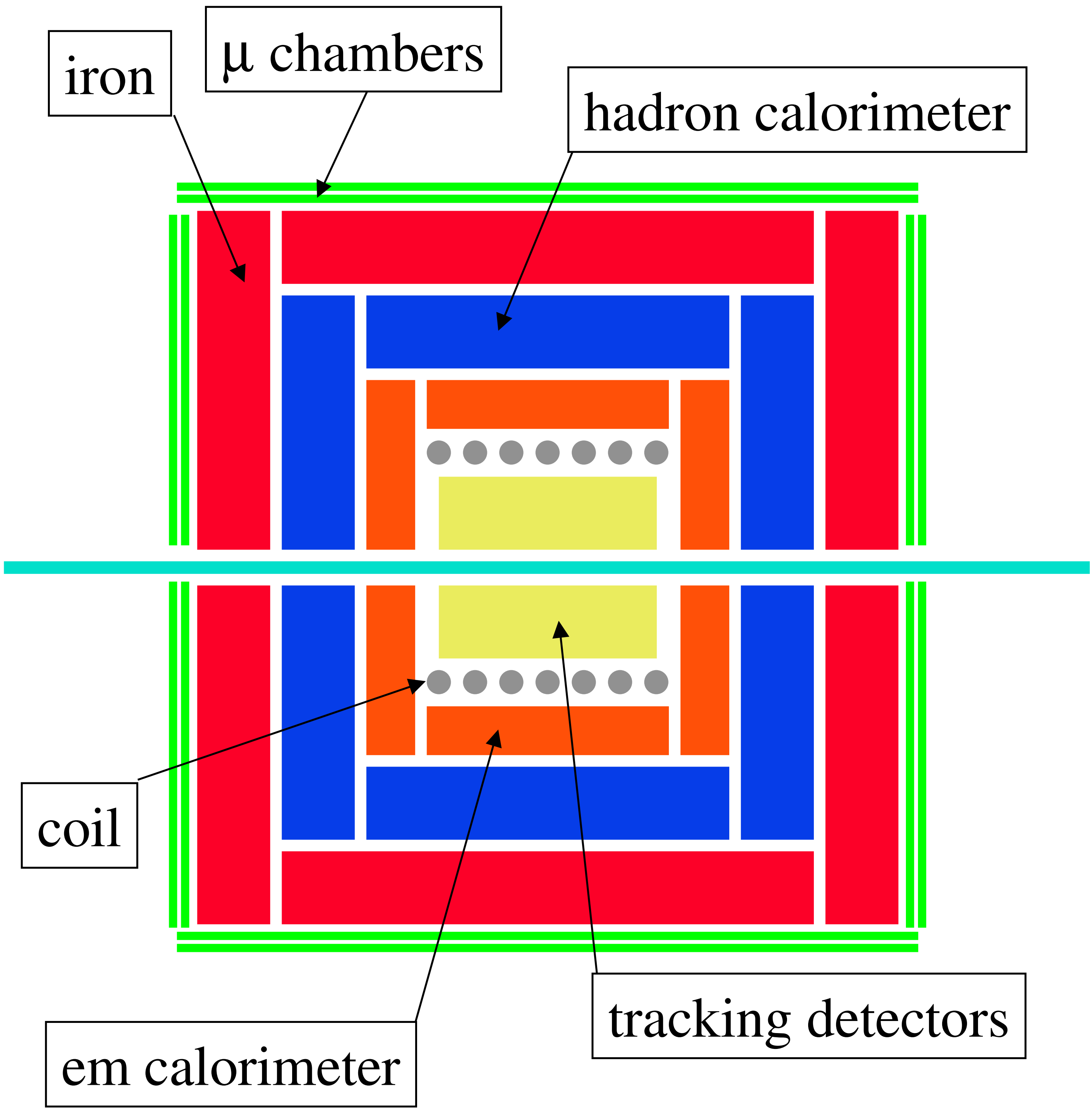
- Increase electron and positron beam energies to 81 GeV.
- Still below top threshold, but...
- Now see force particles interacting with other force particles!



- Observed for first time at LEPII

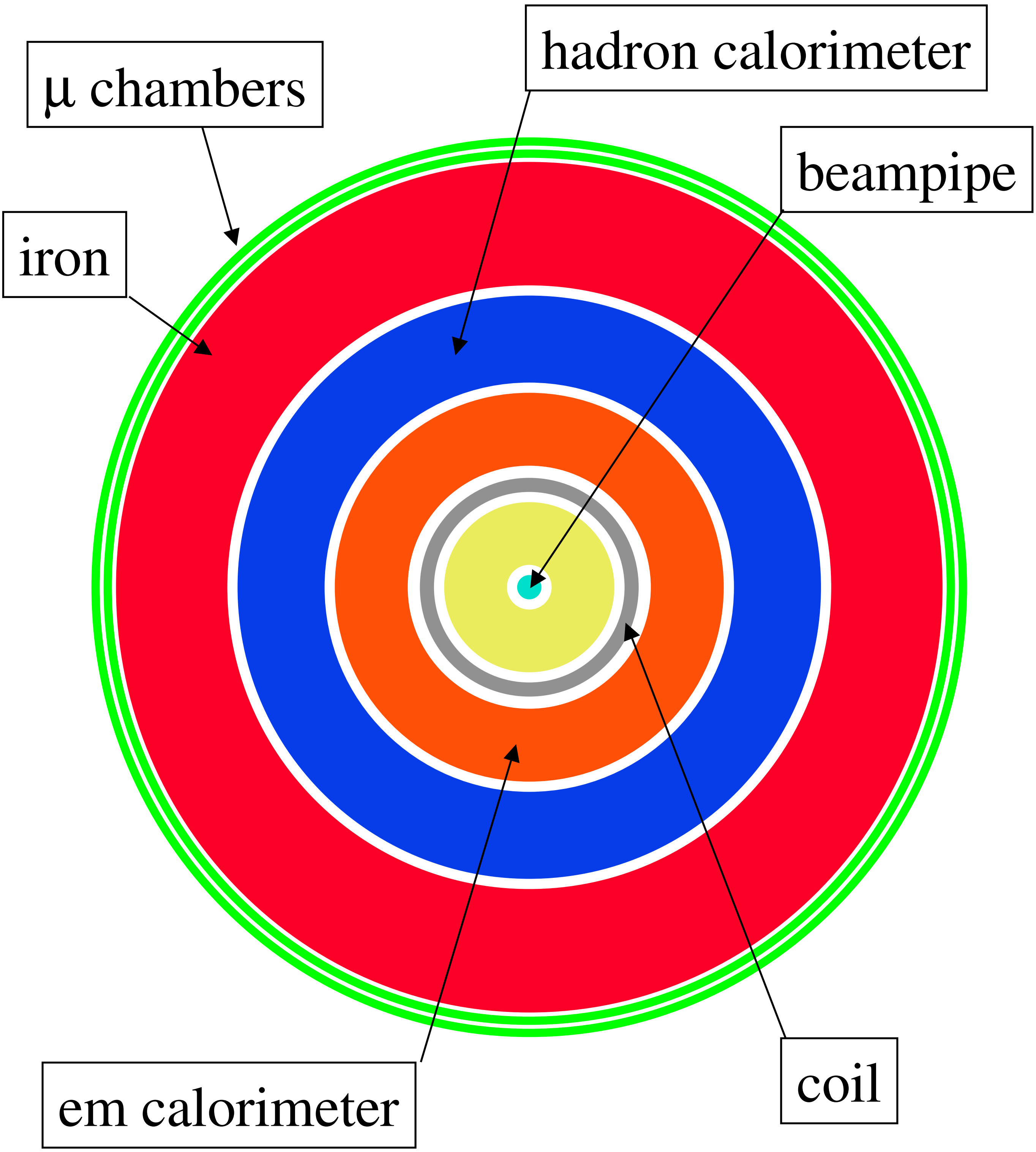
The Detectors

- Many Particle Physics detectors have similar design.



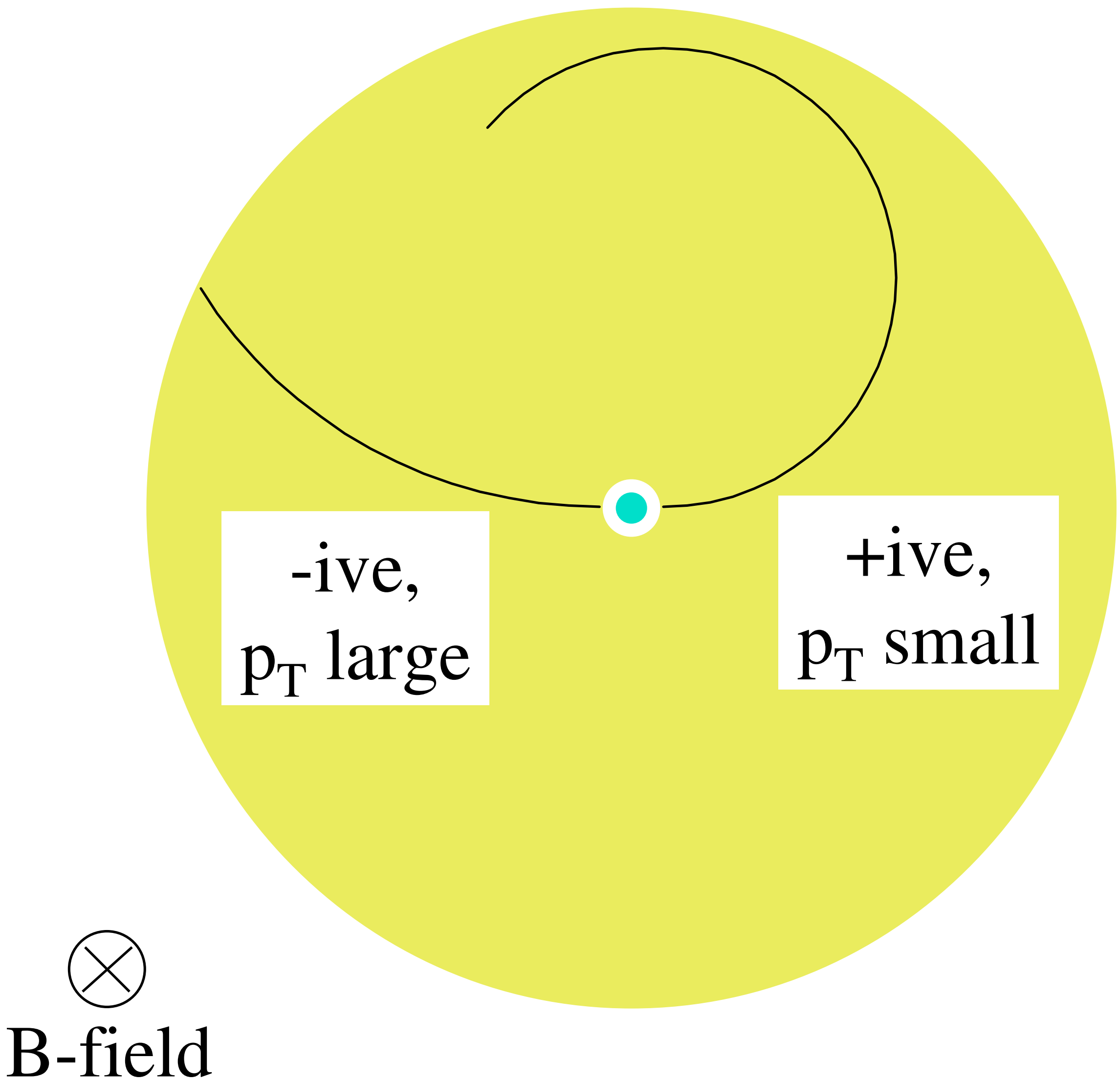
Detectors cont.

- End view



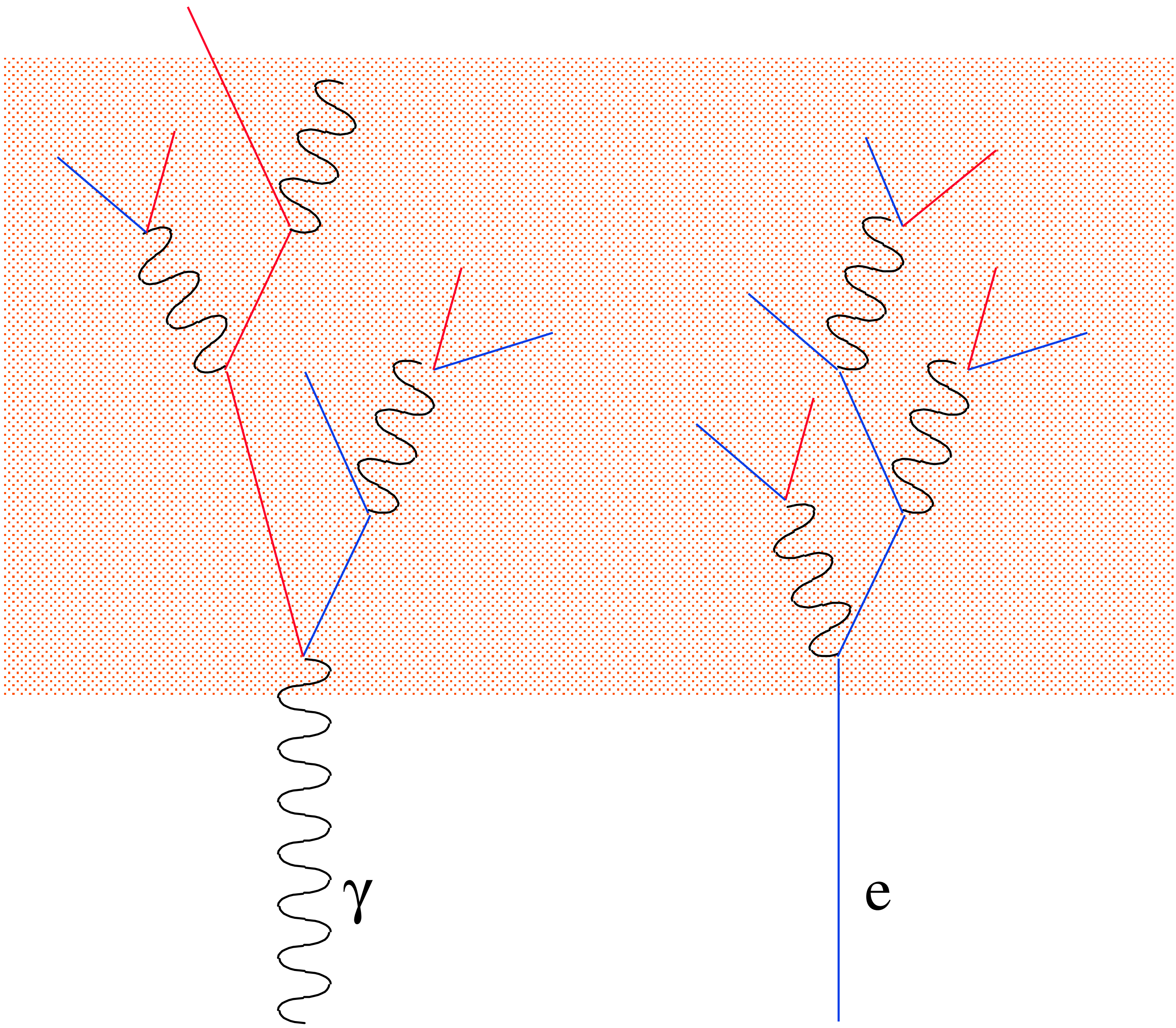
Tracking Detectors

- Measure path of charged particles.
- Lorentz force due to magnetic field parallel to beam makes path helical.
- Radius of curvature gives transverse momentum.



Electromagnetic Calorimeter

- Electrons and photons lose all their energy in an electromagnetic shower.



Hadronic Calorimeter

- Hadrons (particles made of quarks) lose their energy in Had shower.
- Strong interactions with nuclei.
- Typical length scale for EM shower $X_0 \sim 1$ cm.
- Typical length scale for Had shower $\lambda_I \sim 20$ cm, so Had Calo deeper than EM Calo.

Muons and Neutrinos

- Muons:
  - Visible in tracking detectors.
  - Lose little energy in EM and Had calorimeters.
  - Lose little energy in iron.
- Place muon detectors after iron.
- Only muons give signal here.
- Neutrinos lose essentially no energy in any part of detector.
- Detect via “missing momentum”.

Summary

- Fundamental particles:
  - Electrons
  - Quarks
- Forces:
  - Electromagnetic
  - Weak
  - Strong
- Conservation laws
  - Electric charge
  - Electron number
  - Baryon number
- Accelerators
- Detectors
- Now try and identify the products of some e^+e^- collisions observed at LEP!