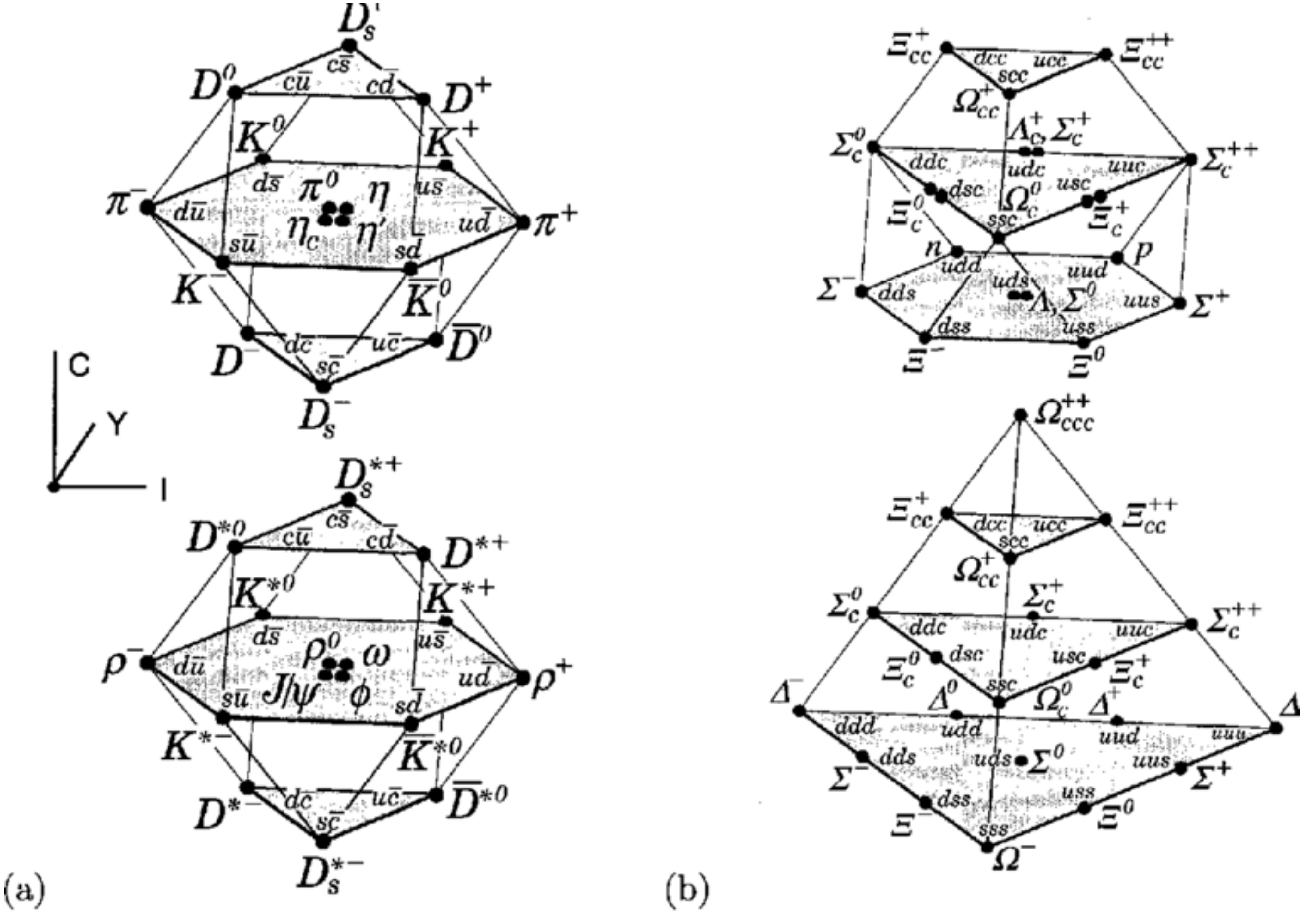
The Quark Model



PRS Question: Which of the following reactions not forbidden?

A) $\mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$
B) $\mathrm{p} + \mathrm{n} \rightarrow \mathrm{p} + \bar{\mathrm{p}} + \pi^{+}$
C) $\mu^{-} \rightarrow \nu_{\mu} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$
D) $\pi^{+} + \pi^{-} \rightarrow \mathrm{p} + \bar{\mathrm{n}}$
E) $\mathrm{p} \rightarrow \pi^{0} + \mathrm{e}^{+}$

$\mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$ violates energy conservation

$\mathrm{p} + \mathrm{n} \rightarrow \mathrm{p} + \bar{\mathrm{p}} + \pi^{+}$ violates baryon number

$\pi^{+} + \pi^{-} \rightarrow \mathrm{p} + \bar{\mathrm{n}}$ violates charge conservation

$\mathrm{p} \rightarrow \pi^{0} + \mathrm{e}^{+}$ violates baryon/lepton number

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- C) $\mu^{-} \rightarrow \nu_{\mu} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$
- ~~D) $\pi^{+} + \pi^{-} \rightarrow \mathrm{p} + \bar{\mathrm{n}}$~~
- ~~E) $\mathrm{p} \rightarrow \pi^{0} + \mathrm{e}^{+}$~~

There are 6 **flavors** of quarks

up charm top ← $q = +2/3$
down strange bottom ← $q = -1/3$

All have baryon number 1/3 and spin 1/2

All have antiparticles

Some common baryons

p: uud Λ^0=uds Δ^{++} = uuu
n: udd Ω^-=sss Σ^+ = uus

Some common mesons

$\pi^+=u\bar{d}$ $\pi^-=\bar{d}u$ $\pi^0=\bar{u}u$ or $\bar{d}d$
$K^+=\bar{u}s$ $K^0=\bar{d}s$ $\bar{K}^0=\bar{s}d$

The Strange Properties of Quarks

Quarks come in three colors: red, green, blue

Anti-quarks come in anti-colors: anti-red, anti-green, anti-blue

These are just degrees of freedom, not to be associated with the “usual” notion of color

Strong Force binds quarks together to form baryons (quark triplets) and mesons (quark-anti-quark pairs)

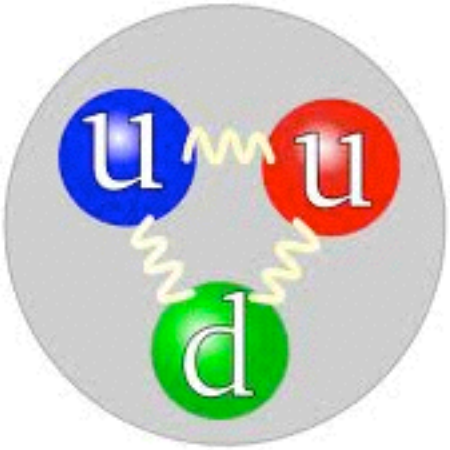
Confinement (no free color): sum of color has to be “white” or “black”

Consider the proton

One quark in the proton must be blue

One quark in the proton must be red

One quark in the proton must be green



The total color is of the proton is white

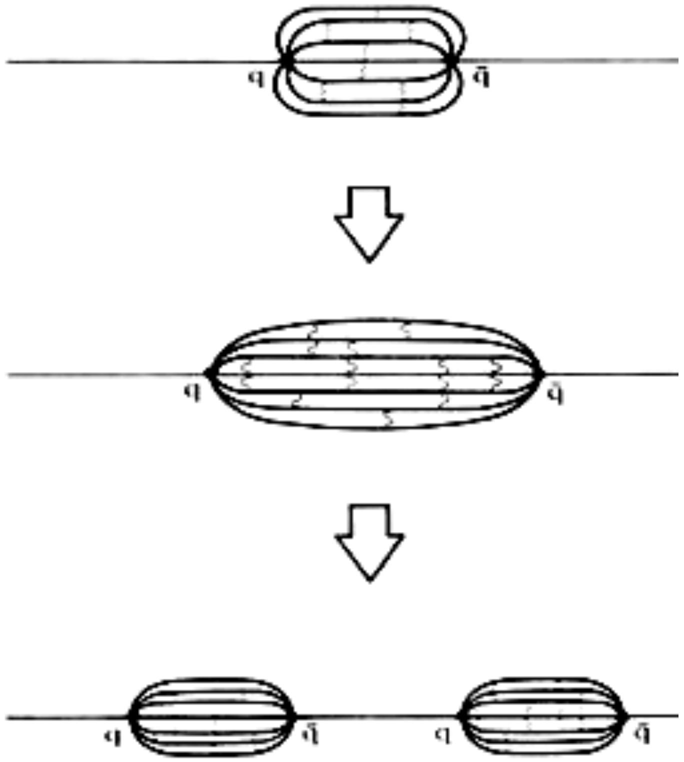
“Three quarks for Muster Mark!
Sure he has not got much of a bark
And sure any he has it's all beside the mark.”
-- James Joyce, Finnegans Wake

Consider the pion (a quark-anti-quark bound state)

If one quark is blue, then the other is anti-blue

If one quark is red, etc., etc.

What happens if you try to pull apart two quarks?



It requires so much energy, that you create another quark and antiquark to **keep the products**

Color is important as a **distinguishing property**.

What if you have three up quarks in a baryon?

By Pauli exclusion principle, such a state cannot exist. There are three fermions at least two of which have the same quantum numbers (if you account for the possible spins).

But the Δ^{++} is exactly that particle!

The reason it exists is because each quark has a different color. Since **color is a quantum number**, there is no problem with the Δ^{++} existing. In fact, it has been produced in the lab.

The Restricted Conservation Laws

Strangeness is conserved in **strong and electromagnetic interactions**, but **violated** in weak ones.

$\pi^- + \mathrm{p} \rightarrow \Lambda^0 + \pi^0$ doesn't occur because Λ has S=-1

$\pi^- + \mathrm{p} \rightarrow \Lambda^0 + \mathrm{K}^0$

does occur because K^0 has S=+1

The above are both **strong interactions.**

In weak interactions strangeness can be violated:

$$\Lambda^0 \rightarrow \mathrm{p} + \pi^-$$

$$\mathrm{K}^+ \rightarrow \pi^+ + \pi^0$$

Charm number and bottom number are **also** both conserved in strong (and electromagnetic) interactions.

They are violated in weak interactions.

As you may have guessed by now, strange, charm, and bottom number have to do with **how many quarks are in the hadrons.**

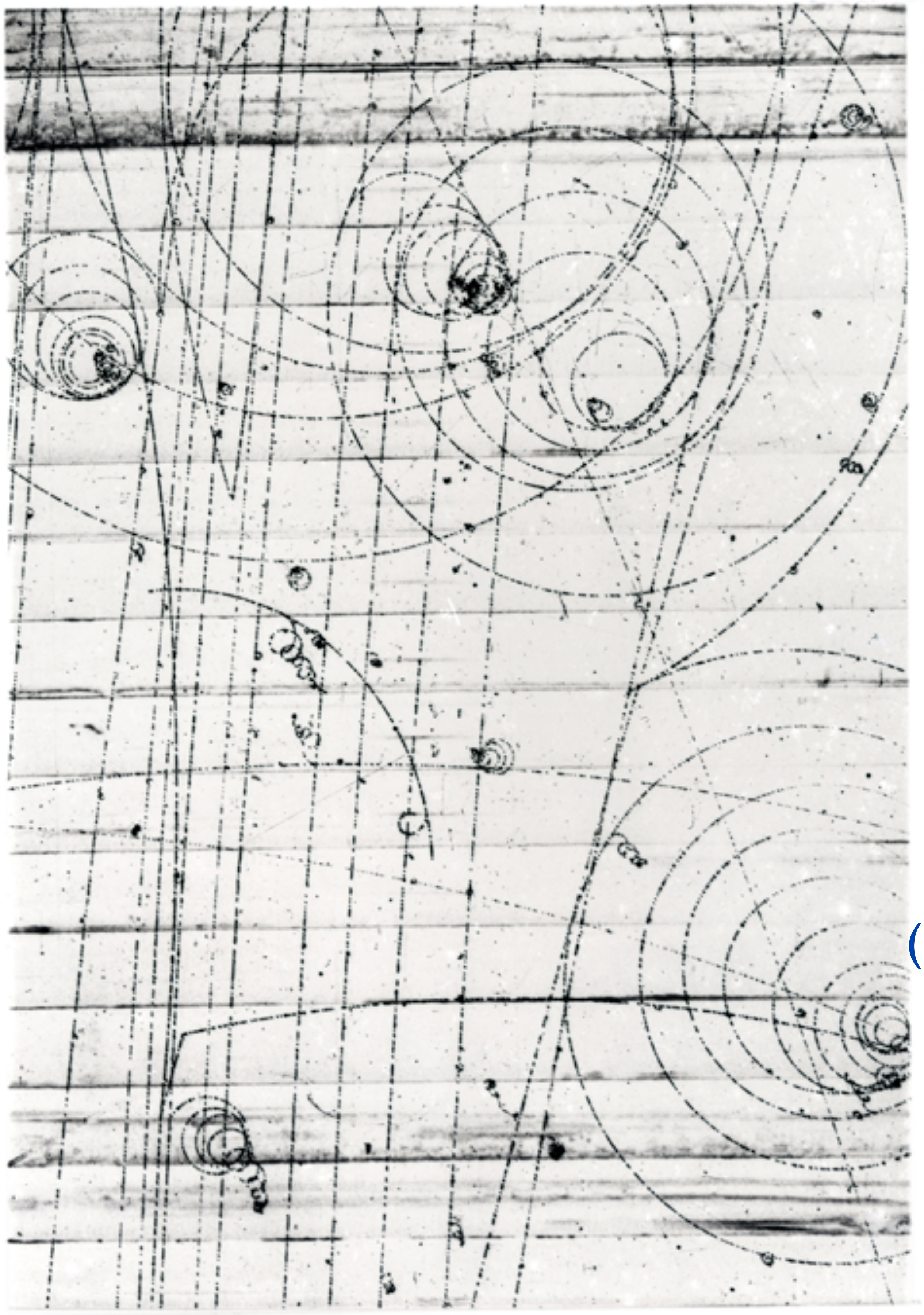
The strange quark has S=-1.

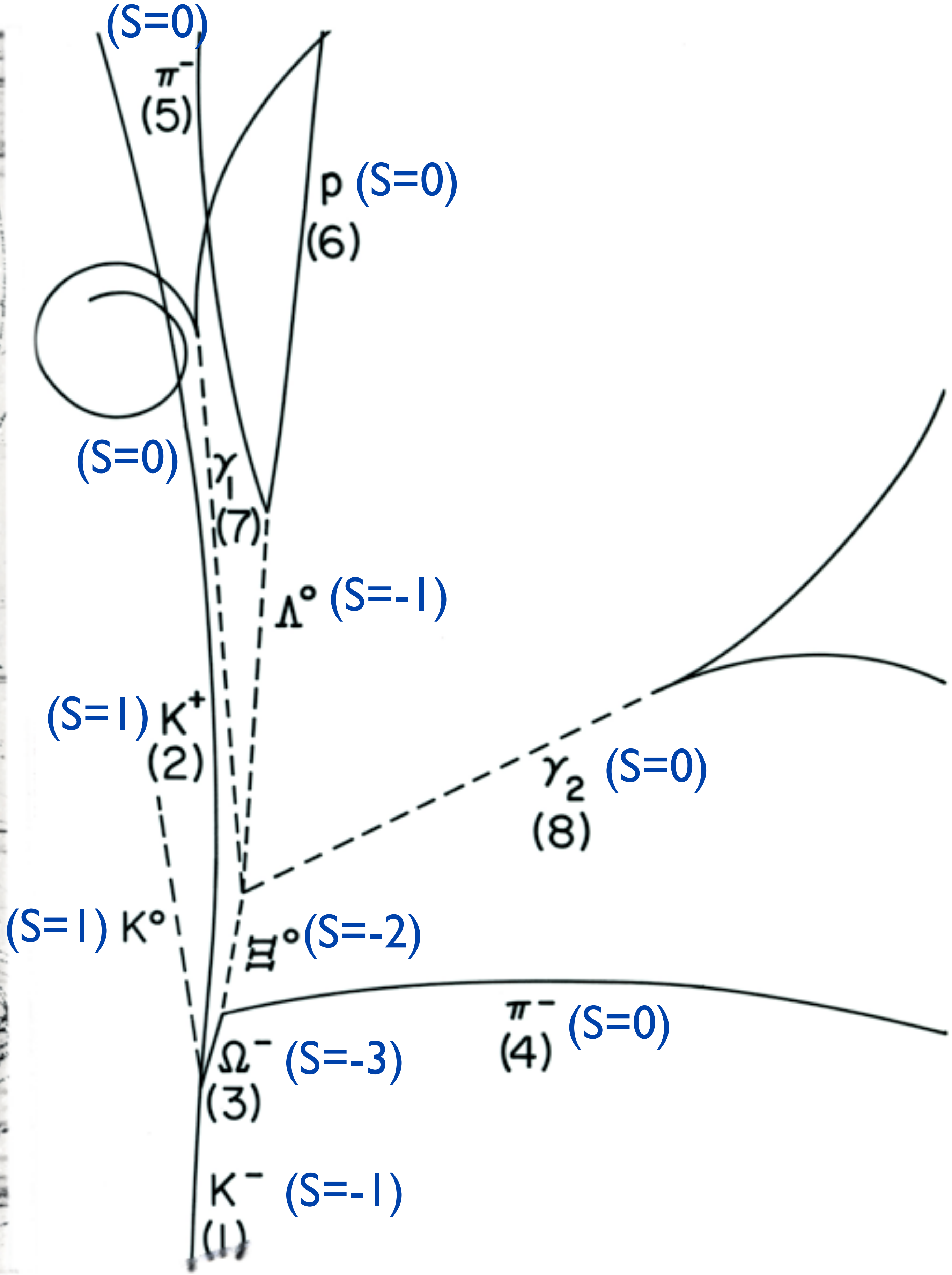
The charm quark has C=+1.

The bottom quark has B=-1.

The top quark has ...?

...T=+1, but the top quark can't form a bound state.



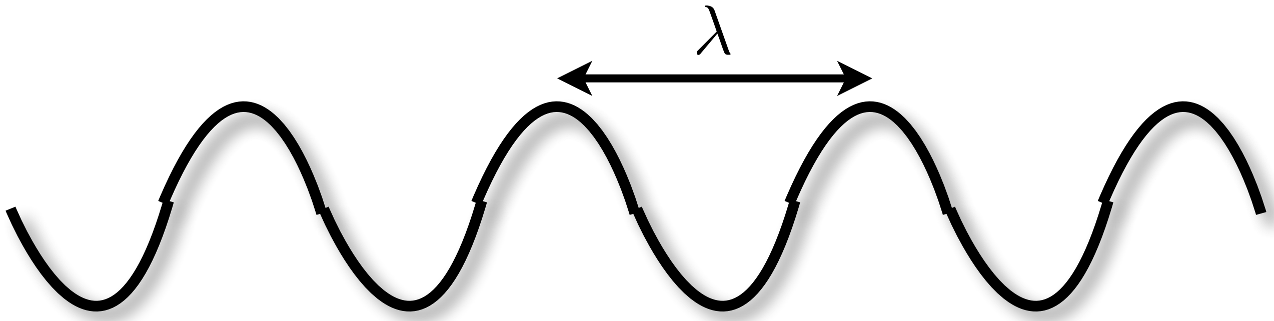

(S=0)
π^-
(5)
p (S=0)
(6)
(S=0)
γ_1
(7)
Λ° (S=-1)
(S=1) K^+
(2)
γ_2 (S=0)
(8)
(S=1) K°
Ξ°(S=-2)
π^- (S=0)
(4)
Ω^- (S=-3)
(3)
K^- (S=-1)
(1)

- Wave-particle duality: particles exhibit both particle- and wave-like behavior

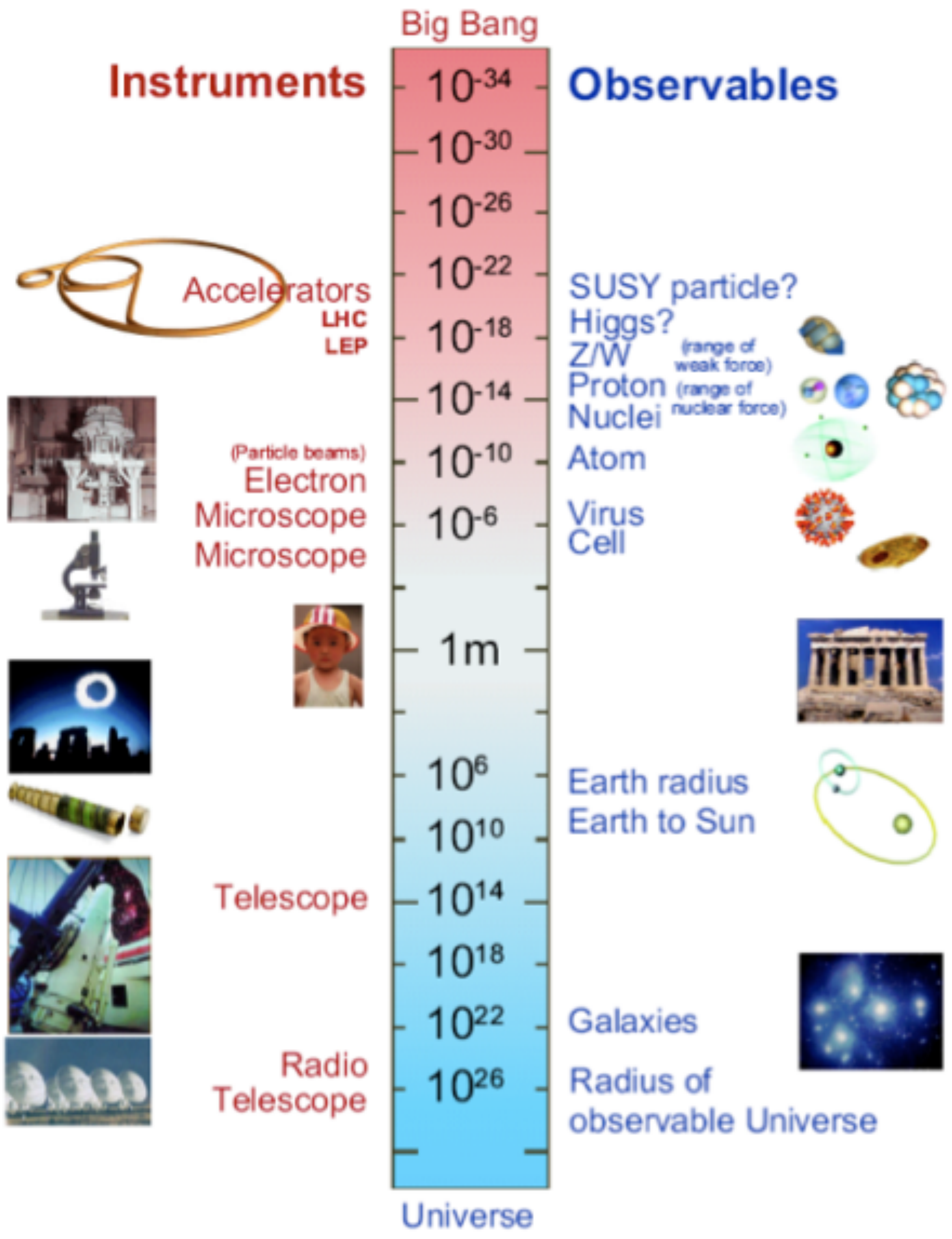
Planck's constant

particle momentum $$p = \frac{h}{\lambda}$$ wavelength

- If you want to probe short length scales, use high momenta particles!



- We collide high energy protons to study the smallest length scales (particles)

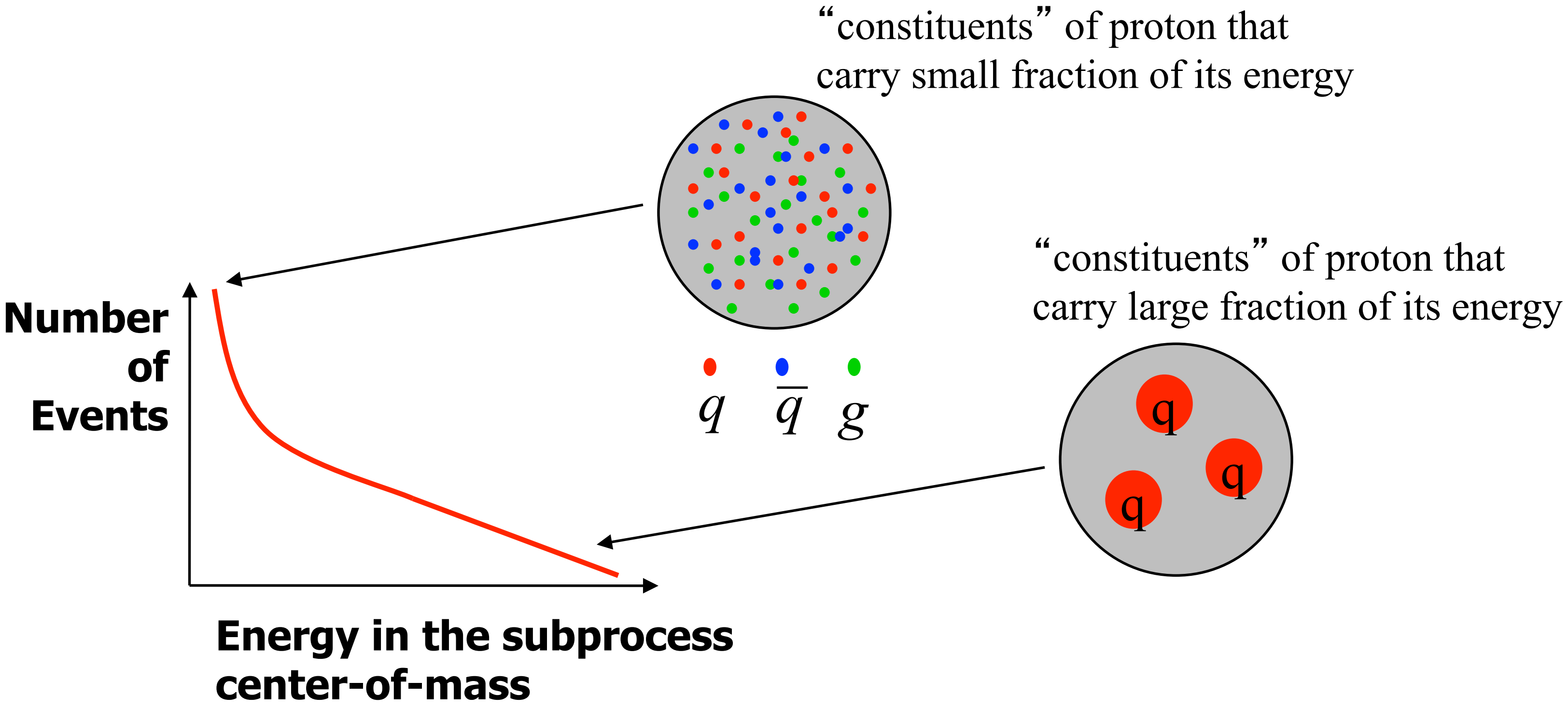


Easiest way to achieve high center-of-mass energy is colliding beams of protons or anti-protons

- heavy, so no synchrotron radiation
- stable, so can take time accelerating

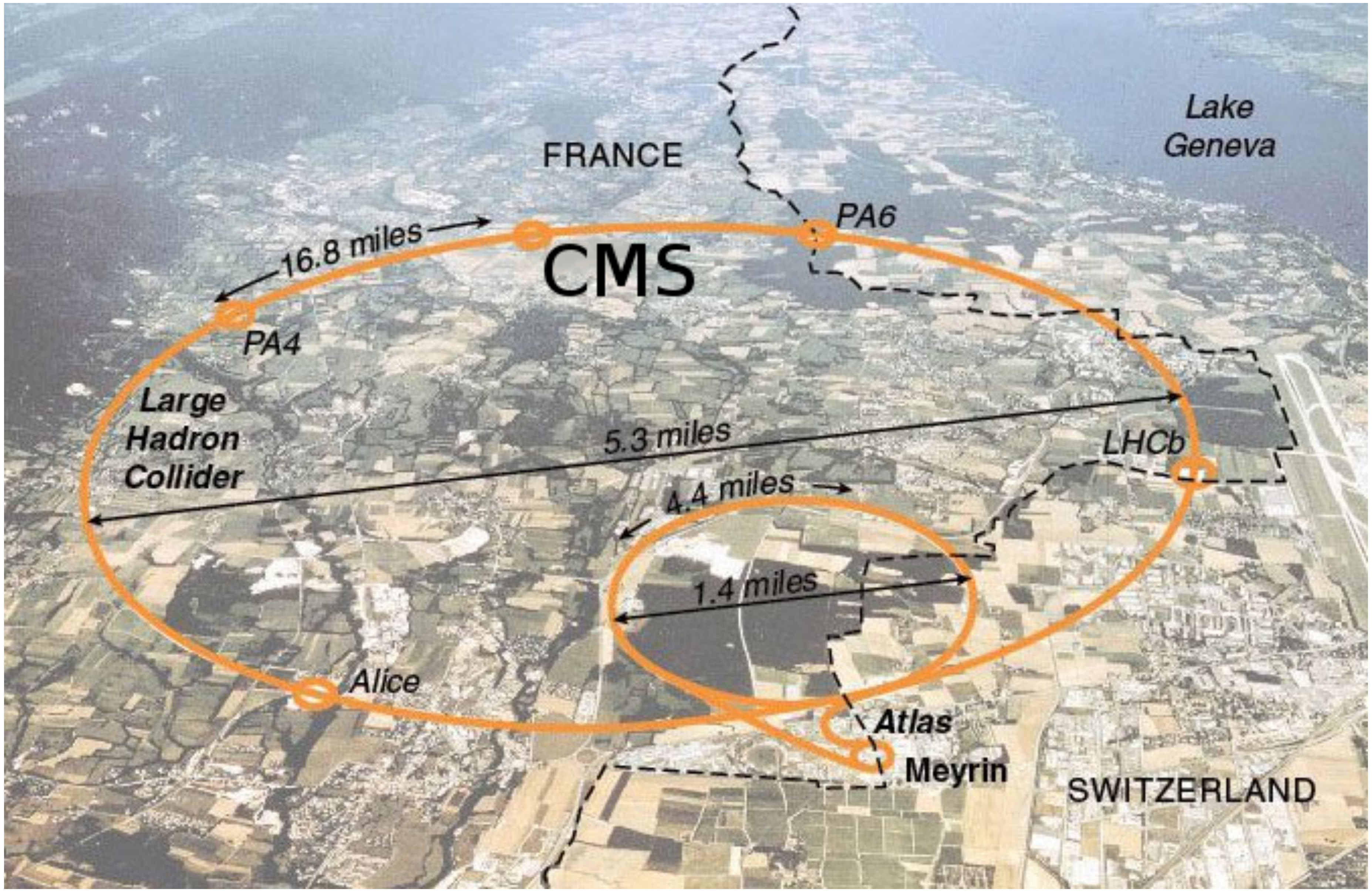
But: messy!

- hadron colliders are really quark/gluon colliders



The LHC is the world’s highest energy particle collider

two beams of protons are accelerated around the ring (**to 4 TeV of energy**) and collide with each other at various points around the ring



Why is colliding two particles together so effective?

- Suppose you collider a proton with E=8 TeV against another proton at rest.
  - Compare that to a colliding two protons each with E=4 TeV against each other.
- **Which process produces the more massive/energetic particles?**

Consider the reaction

$$\mathrm{p} + \bar{\mathrm{p}} \to \mathrm{X}$$

where X is an unknown particle you want to create.

In the center of mass frame, the X is produced at rest. This means that the energy required to produce the X is

$$K_\mathrm{p} + K_{\bar{\mathrm{p}}} + m_\mathrm{p}c^2 + m_{\bar{\mathrm{p}}}c^2 = m_\mathrm{X}c^2$$

Since the mass of the proton and antiproton are the same, and the momentum are equal (but opposite)

$$K_\mathrm{p} = m_\mathrm{X}c^2/2 - m_\mathrm{p}c^2 \ \to \ E_\mathrm{p} = m_\mathrm{X}c^2/2$$

is the minimum energy needed to produce the X.

What is happens if the antiproton is at rest?

We can use our old nuclear physics equation to help.

$$K_{\mathrm{Th}} = -Q \cdot \frac{\text{Sum of all masses}}{2 \times \text{ target mass}}$$

$$Q = \left(m_{\mathrm{p}} + m_{\bar{\mathrm{p}}} - m_{\mathrm{X}}\right) c^2$$

$$\text{Sum of all masses} = m_{\mathrm{p}} + m_{\bar{\mathrm{p}}} + m_{\mathrm{X}}$$

$$\text{target mass} = m_{\bar{\mathrm{p}}}$$

Therefore,

$$K_{\mathrm{Th}} = \frac{m_{\mathrm{X}}^2 - 4m_{\mathrm{p}}^2}{2m_{\mathrm{p}}} c^2 \;\rightarrow\; E_{\mathrm{Th}} = \frac{m_{\mathrm{X}}^2 - 2m_{\mathrm{p}}^2}{2m_{\mathrm{p}}} c^2$$

Now, suppose the mass of the X is much greater than the mass of the proton.

$$E_{\mathrm{Th}} \approx \frac{m_{\mathrm{X}}^2}{2m_{\mathrm{p}}}c^2 = (m_{\mathrm{X}}c^2/2)\frac{m_{\mathrm{X}}}{m_{\mathrm{p}}}$$

Compare this with two protons colliding with equal but opposite momenta:

$$E = m_{\mathrm{X}}c^2/2$$

Notice the extra factor?

Suppose M_X=1000 m_p.

- Two protons colliding head on would each need a total energy of 500 m_pc^2 to create the X.
  - That is approximately 469 GeV **each**.

- If the antiproton was at rest, the colliding proton would need 500000 m_pc^2 to create the X.
  - This is approximately 469 **TeV**.