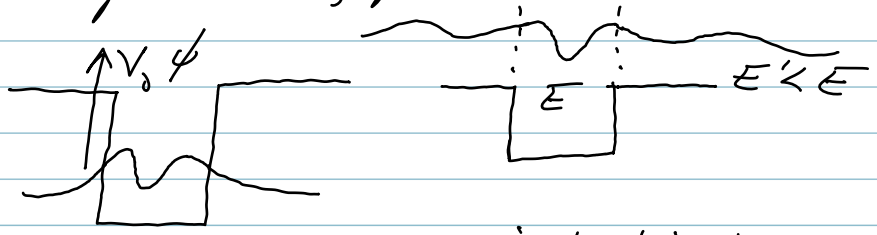
Start with atoms

We need to strip e^- so have a positively charged proton, p^+



normally bound

with high voltage applied

With p^+ in E-field

$$F = qE = ma$$

$$\Rightarrow \boxed{a = \frac{eE}{m}}$$

accel. of proton

At Fermilab, get p^+ to 800 keV.

Acceleration of particles

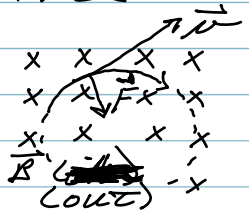
Like a car transmission!

- multiple accelerators
- each one increases particle energy to a range appropriate to the next one

synchrotron

Magnetic fields

- bend p^+ path roughly into a circle



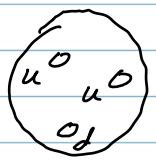
Electric field

- "push" particle along path an accelerate

Example: Fermilab Tevatron
(proton-antiproton collider)

③ Proton Collisions

A proton is a composite object



3 quarks
(2 up, 1 down)

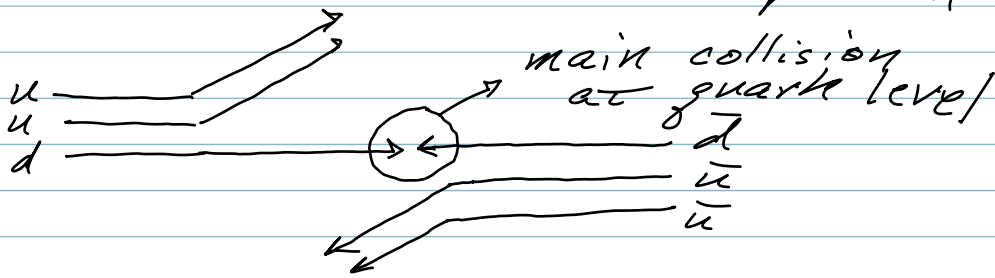
"up" quarks: $Q_u = +2/3$
"down" quarks: $Q_d = -1/3$

Proton charge Q_p

$$= \sum_i q_i$$

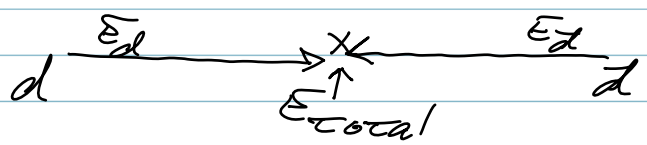
where sum is over quark charges, q_i

At high energy, proton-anti-proton



Particle Creation

Consider 2 particles colliding:



with energies $\mathcal{E}_d$ and $\mathcal{E}_d$.

- In center-of-momentum frame of system $\mathcal{E}_d = \mathcal{E}_d$ $(\vec{p}_d = -\vec{p}_d)$

$$\mathcal{E}_{total} = \mathcal{E}_d + \mathcal{E}_d = \underline{2\mathcal{E}_d}$$

This energy is now available to make virtual particles non-virtual, i.e.

$$\mathcal{E} = mc^2 \Rightarrow \underline{m_x = 2\mathcal{E}_d/c^2}$$

where m_x is the mass of some particle X

Otherwise,

Note! Virtual particle X can exist

$$m_x \Delta\tau \geq \hbar/2 \Rightarrow \underline{\Delta\tau \sim \frac{\hbar}{2m_x}}$$

$\Delta\tau$ = How long allowed to briefly violate momentum conservation.

(5)

Particle Natural Width

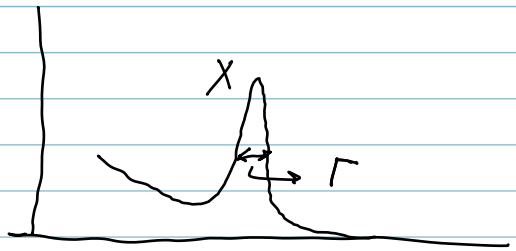
Produced particles generally have finite lifetime

- there's an uncertainty in their mass

$$\frac{\Gamma}{2}\Delta\tau \leq \hbar/2$$

$$\Gamma \simeq \hbar/\Delta\tau$$

We see this as a real "width" of distribution of masses



Not measurement error