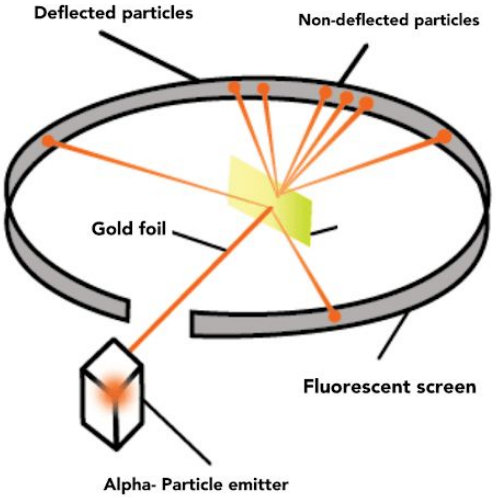
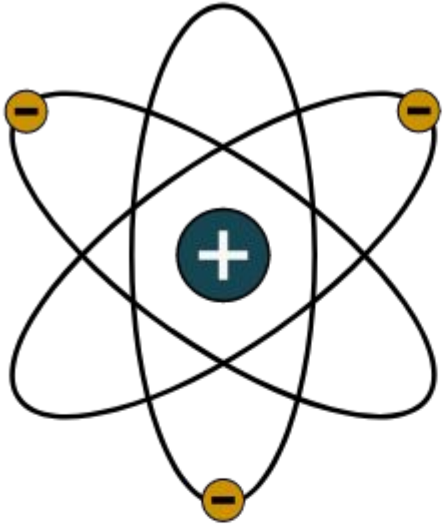
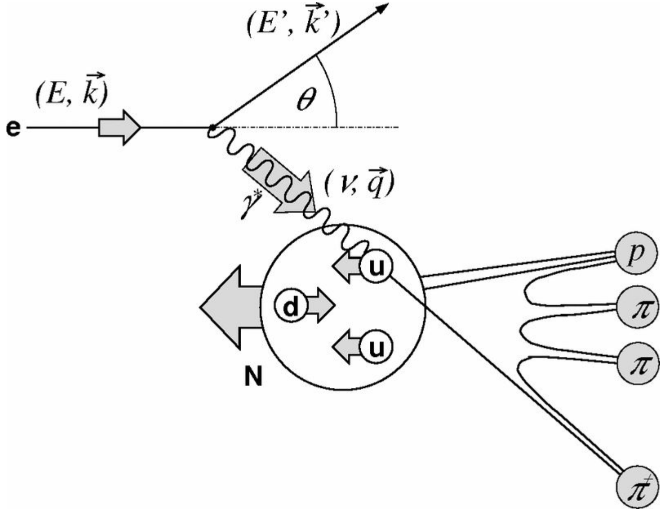
Collider Physics

Scattering experiments

- In 1911, Ernest Rutherford passed a beam of α particles through gold foil
  - Scattering pattern revealed existence of the atomic nucleus
- Scattering experiments still used to measure structure of nucleons
  - Increasing incident particle energy necessary to improve resolution







Studying new particles

- Heavy particles are unstable and quickly decay
- Several approaches available to study high energy particles
  - Astrophysical processes
  - Cosmic rays
  - Nuclear reactors
  - Particle accelerators
- Particle accelerators allow very high energy interactions
  - Can give access to new physics beyond the reach of other methods
  - Collision parameters can be precisely controlled
- A combination of approaches provides the best insights into nature, but we will focus entirely on accelerators in this class

Other applications

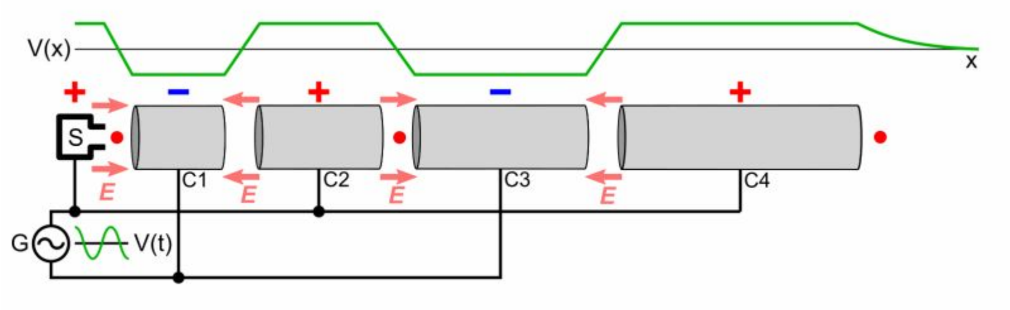
- Many practical applications of high-energy particles
- Fundamental research
  - Neutrino physics
  - High-energy light sources
  - Isotope embedding
- Medical applications
  - Imaging
  - Radiation therapy
- Industrial applications
  - Component sterilization
  - Semiconductor manufacturing
  - Material processing and welding
  - Food sterilization

Accelerating charged particles

- Electric fields provide linear acceleration and magnetic fields curve trajectory

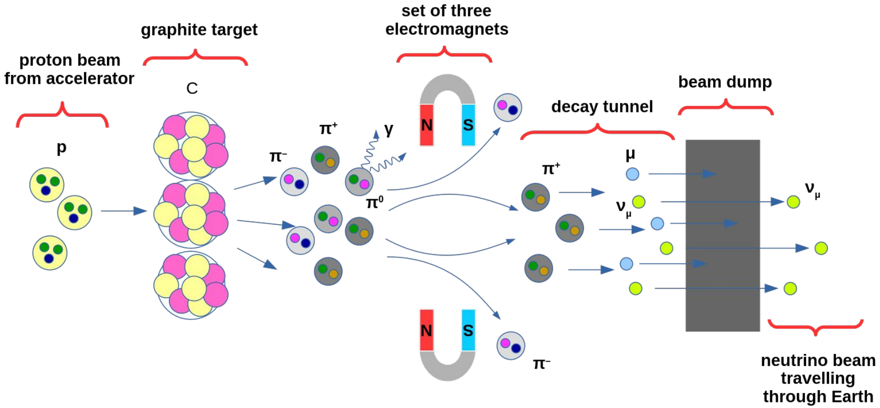
$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

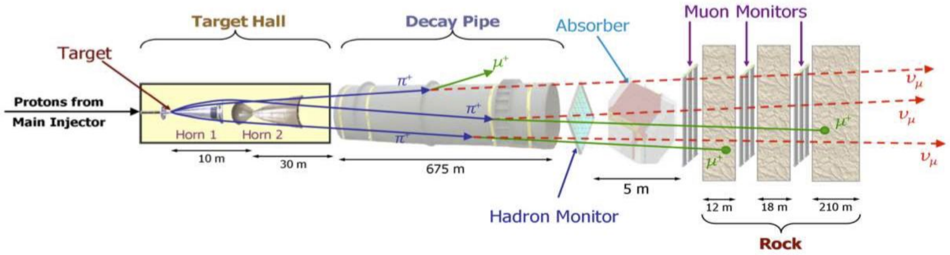
- First accelerators used static electric fields
  - Simple to create, but severely limited due to voltage requirements
- Electrodynamic accelerators oscillate electric field
  - Magnetic induction
  - Alternating voltages along a series of plates or radio frequency (RF) cavities



Neutral particle beams

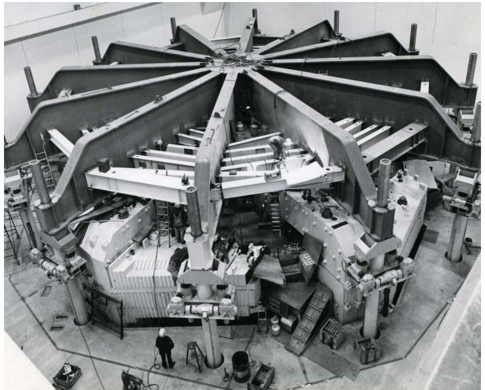
- Neutral particles cannot be directly accelerated using traditional methods
  - Novel techniques such as laser-induced acceleration are possible
- Beams of high-energy neutral particles (n, v, π^0, etc.) from fixed targets
  - Radiation therapy, neutrino experiments, etc.

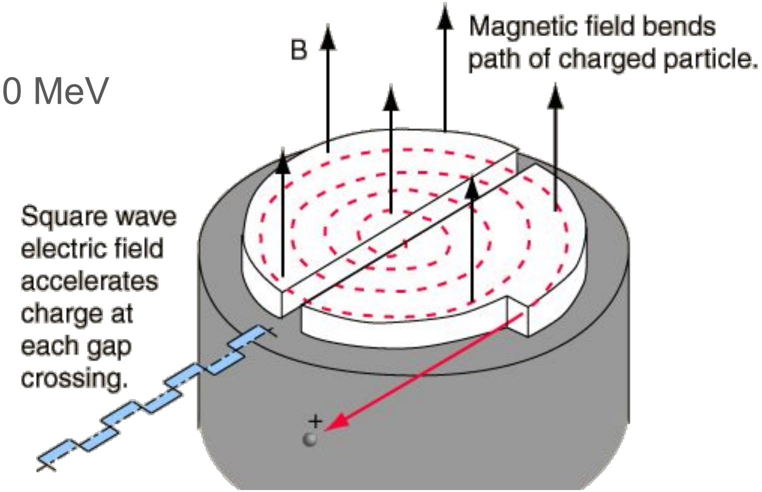




Cyclotron accelerators

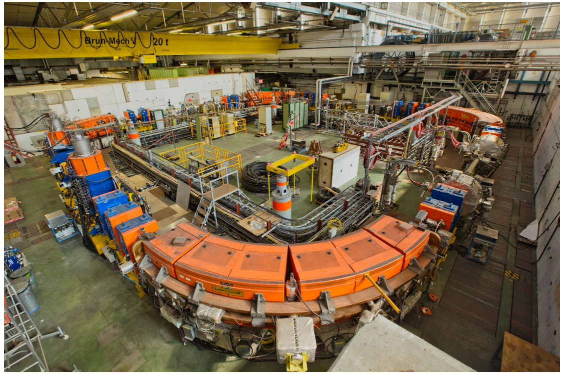
- First circular accelerator - invented in 1929 by Ernest Lawrence
  - First model was 5 inches in diameter and accelerated hydrogen to 80 keV
- External magnetic field applied to particles circulating in “dee”s
- Alternating (const frequency) electric field across gap adds energy to particles
- Particles spiral outwards as energy increases
  - Energy limitation due to material requirements
  - Most powerful examples achieve energies of 500-600 MeV





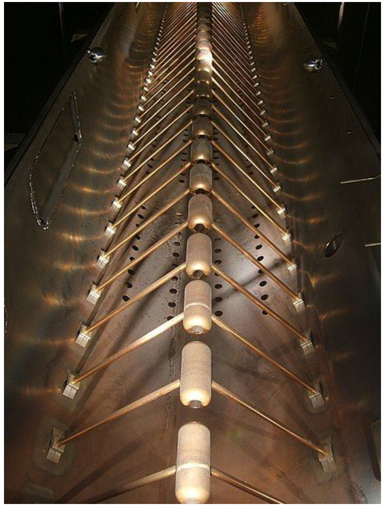
Synchrotron accelerators

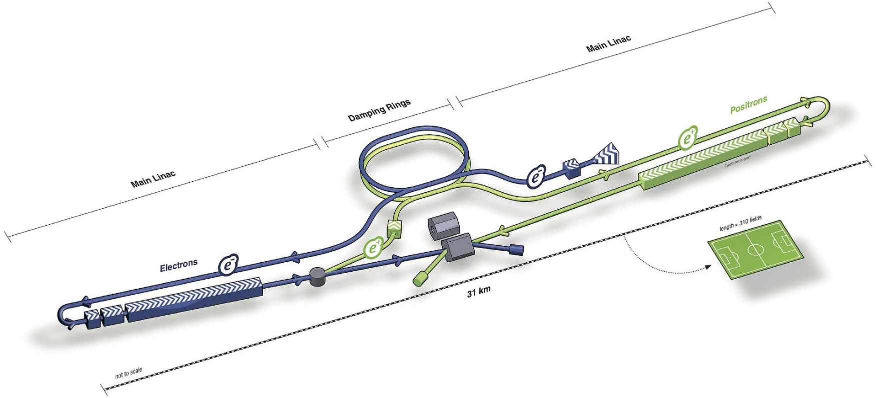
- A fixed-radius circular accelerator with a closed-loop path
  - Beams of particles circulate along the same trajectory repeatedly - reuse beam
- Series of RF cavities and magnets around the ring
  - RF cavities continue to accelerate beams during each circulation
- Magnets used to steer beams of particles
  - Dipole magnets used to deflect particles and keep them in the beamline
  - Quadrupole and sextupole magnets used to focus beams
- Minimal material requirements
  - Vacuum only needed in beam pipe
  - Material only needed along circumference
- Larger accelerator sizes needed for higher energy
  - Limited by strength of dipole magnets and synchrotron radiation



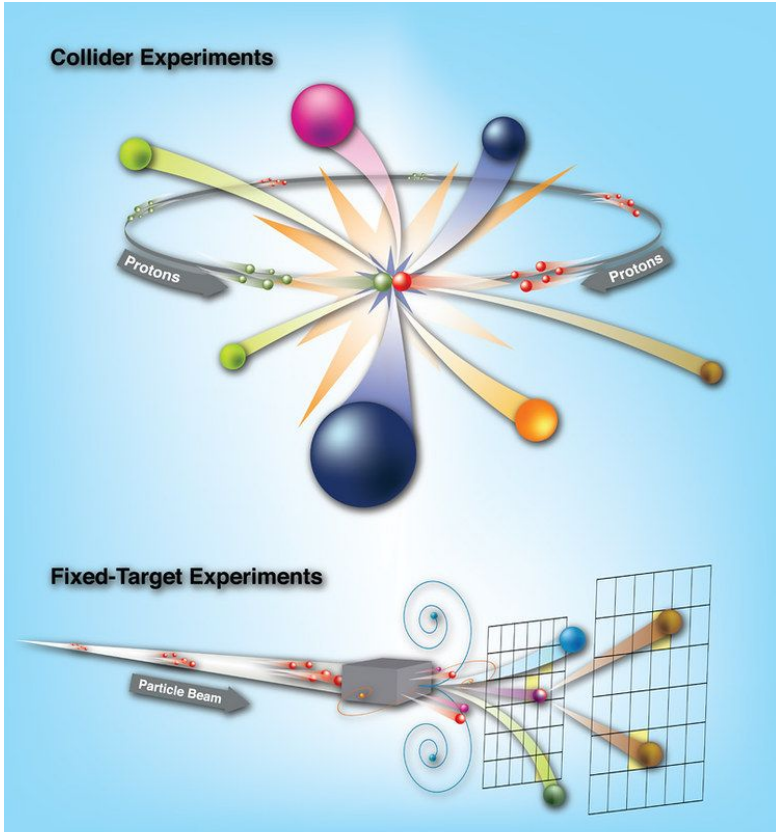
Linear accelerators

- Accelerate particles in a straight line using RF cavities
- Increasing cavity length along accelerator
- Each particle can only be used once
- Increasing energy requires longer accelerators
- Future technologies such as plasma-wakefield may allow energies to be increased significantly



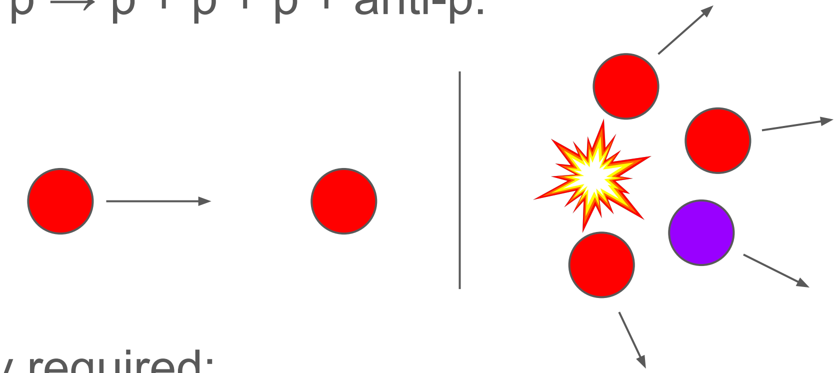


Fixed targets vs colliders



Fixed target experiments

- Accelerate a beam of particles at a stationary target
    - Simple design - only one set of beam dynamics to control
- Only a small fraction of incident beam energy is available for particle creation
- Let’s look at p + p → p + p + p + anti-p:



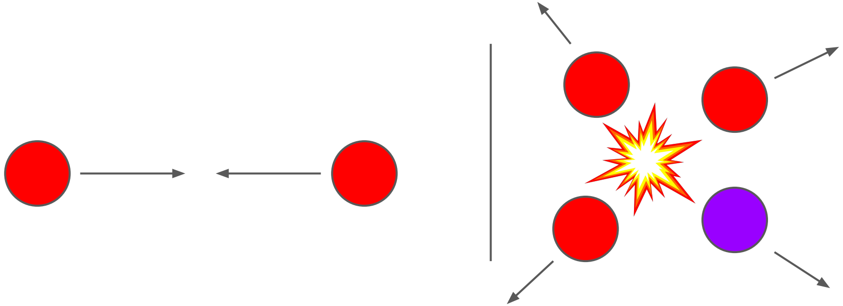
- Minimum energy required:

$$E_{min} = 7m_pc^2$$

- Large fraction of energy goes into outgoing kinetic energy

Collider experiments

- Accelerate two beams of particles towards each other
  - More complex design - two sets of beam dynamics to control
- Full incident beam energy is available for particle creation
- Let’s look at p + p → p + p + p + anti-p:

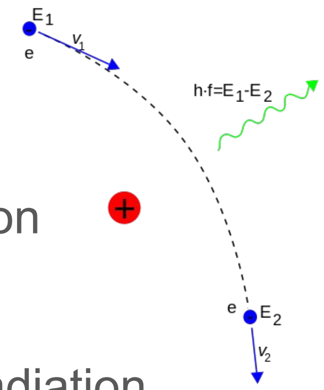


- Minimum energy required for each beam (final state particles at rest):

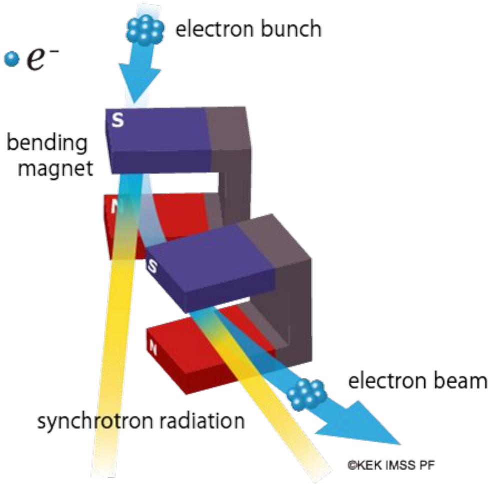
$$E_{min} = 2m_pc^2$$

- Any extra energy goes into outgoing kinetic energy

Synchrotron radiation



- Accelerating a charged particle produces electromagnetic radiation
    - Bremsstrahlung (German for “braking radiation”) for linear acceleration
    - Gyroscopic radiation for rotational acceleration
- Synchrotron radiation is the ultra-relativistic case of gyroscopic radiation
- Emitted primarily in plane of acceleration
- Can be used as dedicated high-energy light sources
- Rate of energy loss from particle beams:



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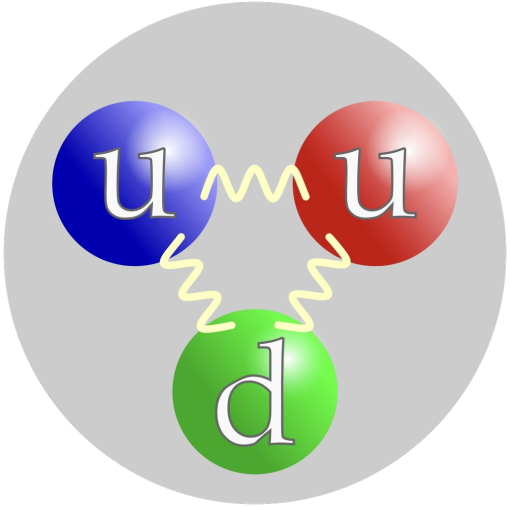
$$P = \frac{2}{3}\frac{e^2}{4\pi\varepsilon_0 m^2 c^3}\gamma^2\left(\frac{dp}{dt}\right)^2$$

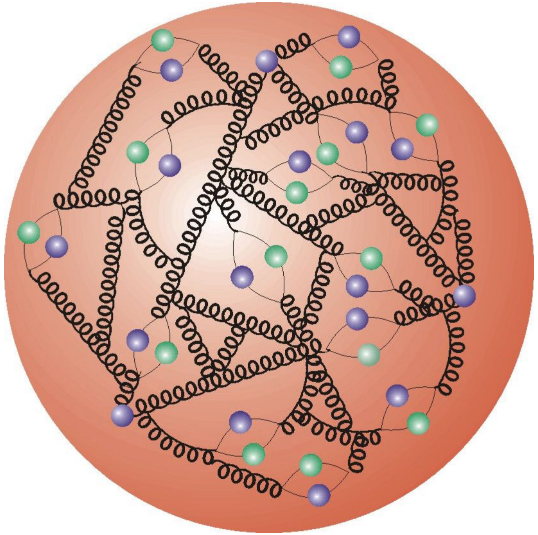
- Inversely proportional to m^2 - light particles lose energy much more quickly

Structure of the proton



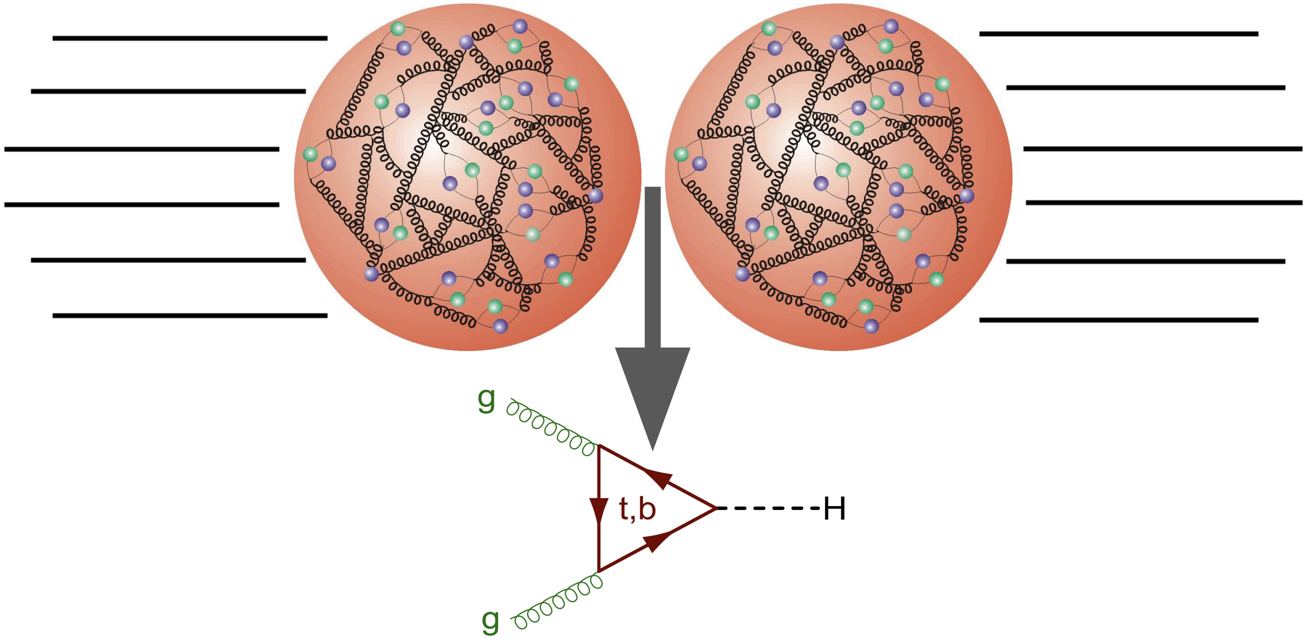
- 3 quarks (2 up and 1 down)
- Quarks bound together by gluons
- Useful illustration, but entirely incorrect

Structure of the proton



- 3 valence quarks (2 up and 1 down)
- Significant gluon activity
- Virtual (sea) quark/anti-quark pairs
- Quarks and gluons called “partons”
- Not entirely correct, but sufficient for today

Proton-proton collisions



- When protons collide, one parton from each interacts with the other
- Each parton carries an indeterminate fraction of the total proton energy

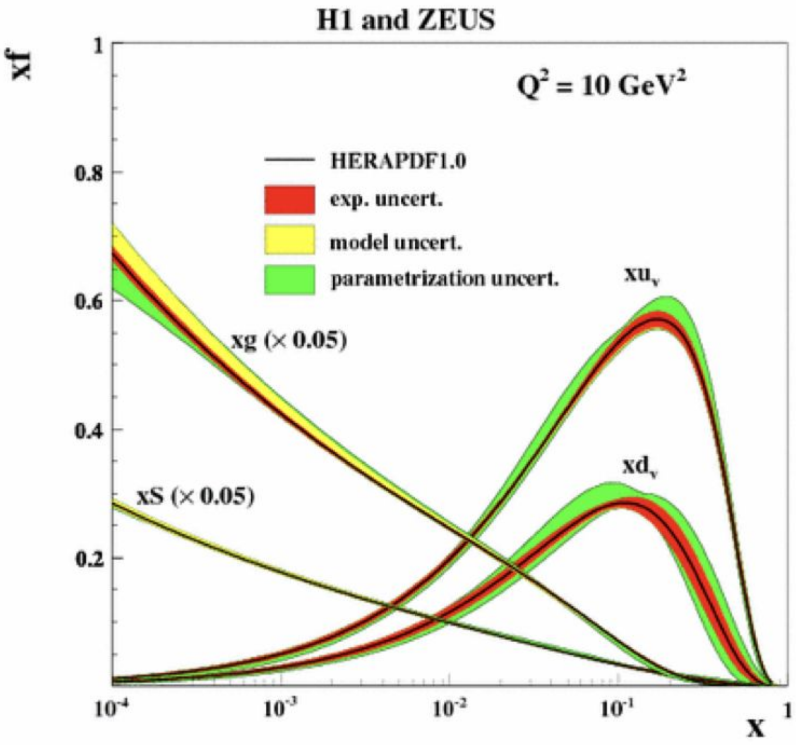
Parton distribution functions

- Deep Inelastic Scattering (DIS) experiments find probability distributio of parton energy fractions
- x is the fraction of the proton energy carried by a parton

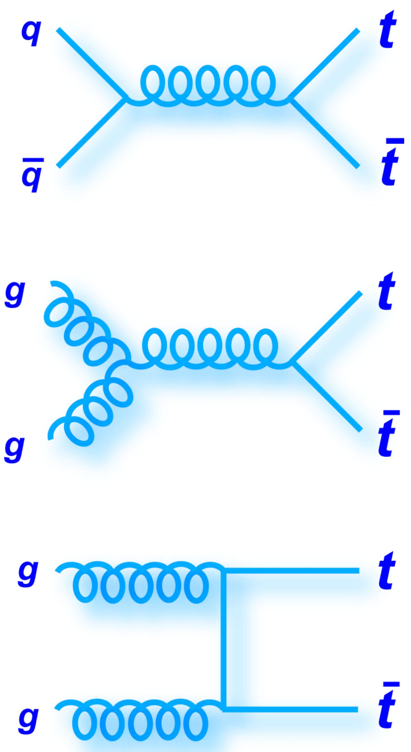
$$E_{parton} = x * E_{proton}$$

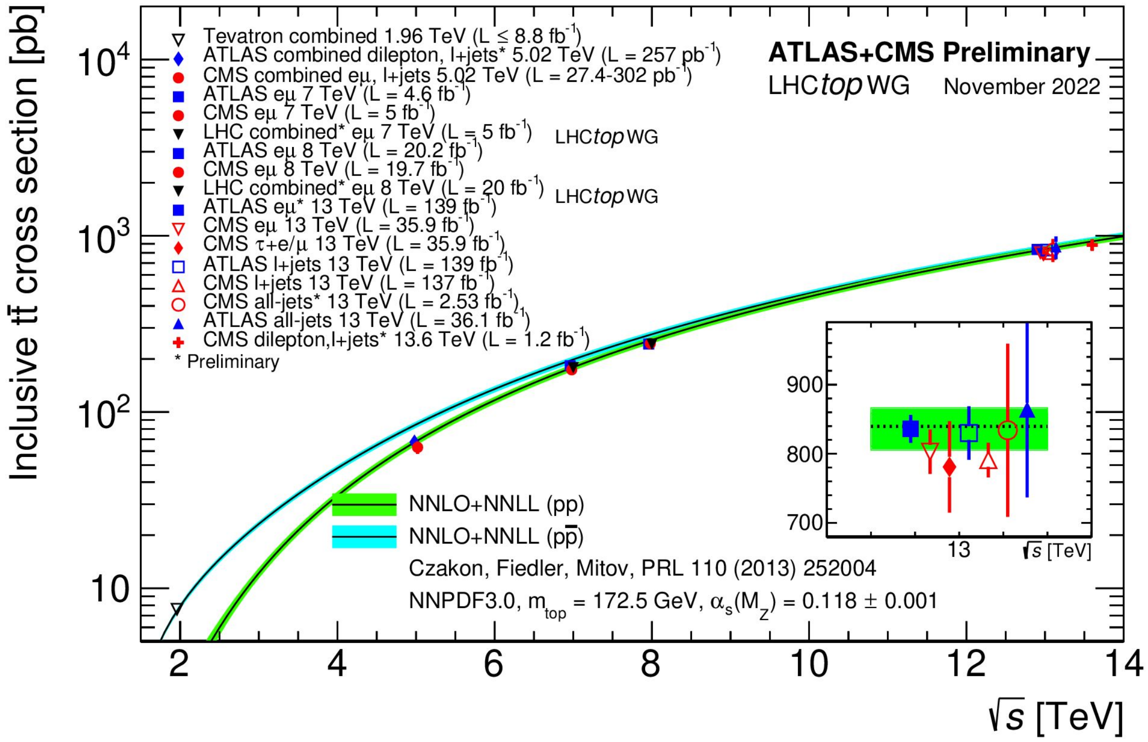
$$E_{total} = x_1 * x_2 * E_{COM}$$

- Peaks around ⅓ for valence quarks, falling distribution for sea quarks and gluons



Top quark pair production





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Particle types

- Any stable charged particles can be used in a particle accelerator
    - Protons, anti-protons, heavy ions, electrons/positrons, muons, etc.
- Choice of particle type depends on use-case and accelerator design
    - Hadrons are generally used in circular accelerators
    - Leptons are used in linear or circular accelerators depending on purpose
- Anti-protons are generally used in lower-energy colliders
    - High-x quark-quark interactions with net charge of 0
    - Difficult to produce high rate of anti-protons
    - Higher energies mean that low-x gluon-gluon interactions of pp collisions are more useful

Hadron vs Lepton colliders

Lepton colliders:

- Consistent collision energy
- Little hadronic radiation
- Large synchrotron energy loss
- Optimal for linacs
- Precision measurements

Hadron colliders:

- Indeterminate collision energy
- Significant hadronic radiation
- Small synchrotron energy loss
- Optimal for synchrotrons
- Optimal for discoveries

Luminosity

- The amount of data collected in a collider is measured using luminosity (L)
- Instantaneous luminosity:

$\mathscr{L}$ = (beam particles per unit area) x (target particles) x (frequency of collision)

- Integrated luminosity:

$\int\mathscr{L}dt$ = (average beam particles per unit area) x (average target particles)

- Units of inverse area (e.g., fb^{-1})
- Number of events:

$$N_{events} = \sigma \times \int\mathscr{L}dt$$