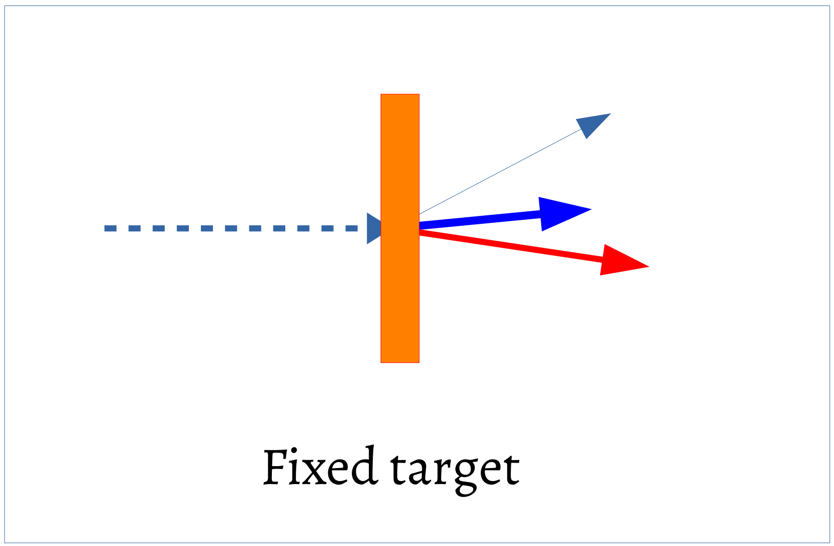
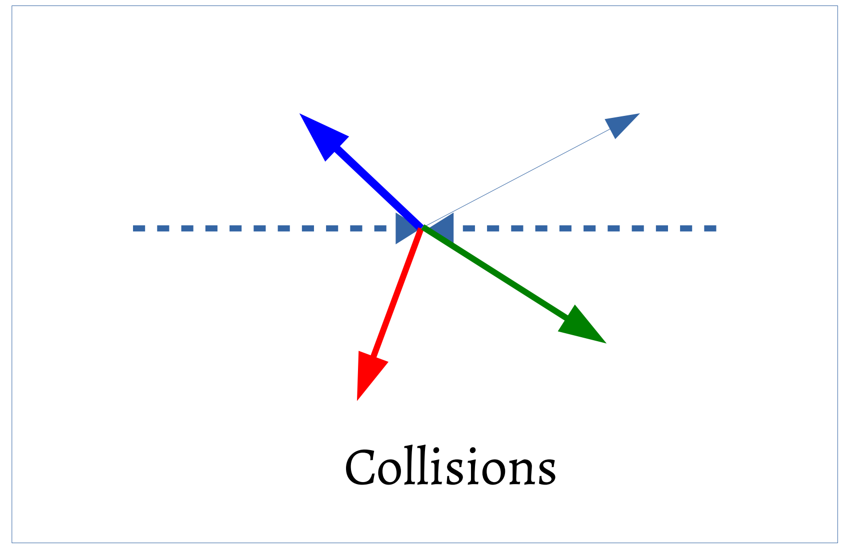
PH4154

Nuclear and Particle Physics

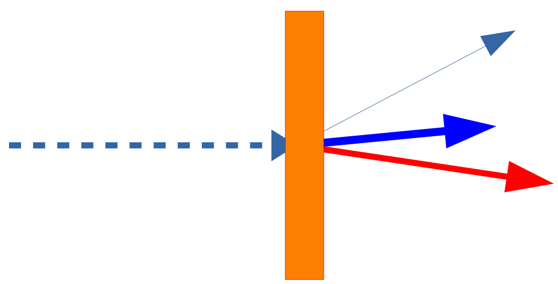
Accelerators/Colliders



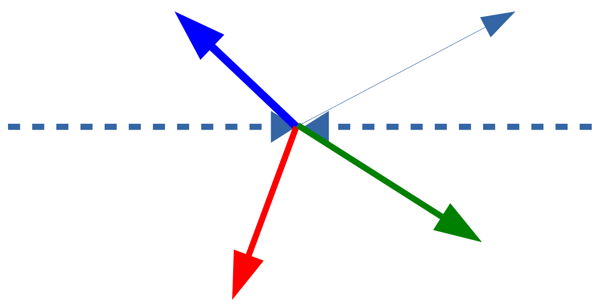


- What particles should I collide? At what energy?
- What particles will be ejected? How do I identify them? What are their properties and how do I measure them?

Accelerators/Colliders



Fixed target



Collisions

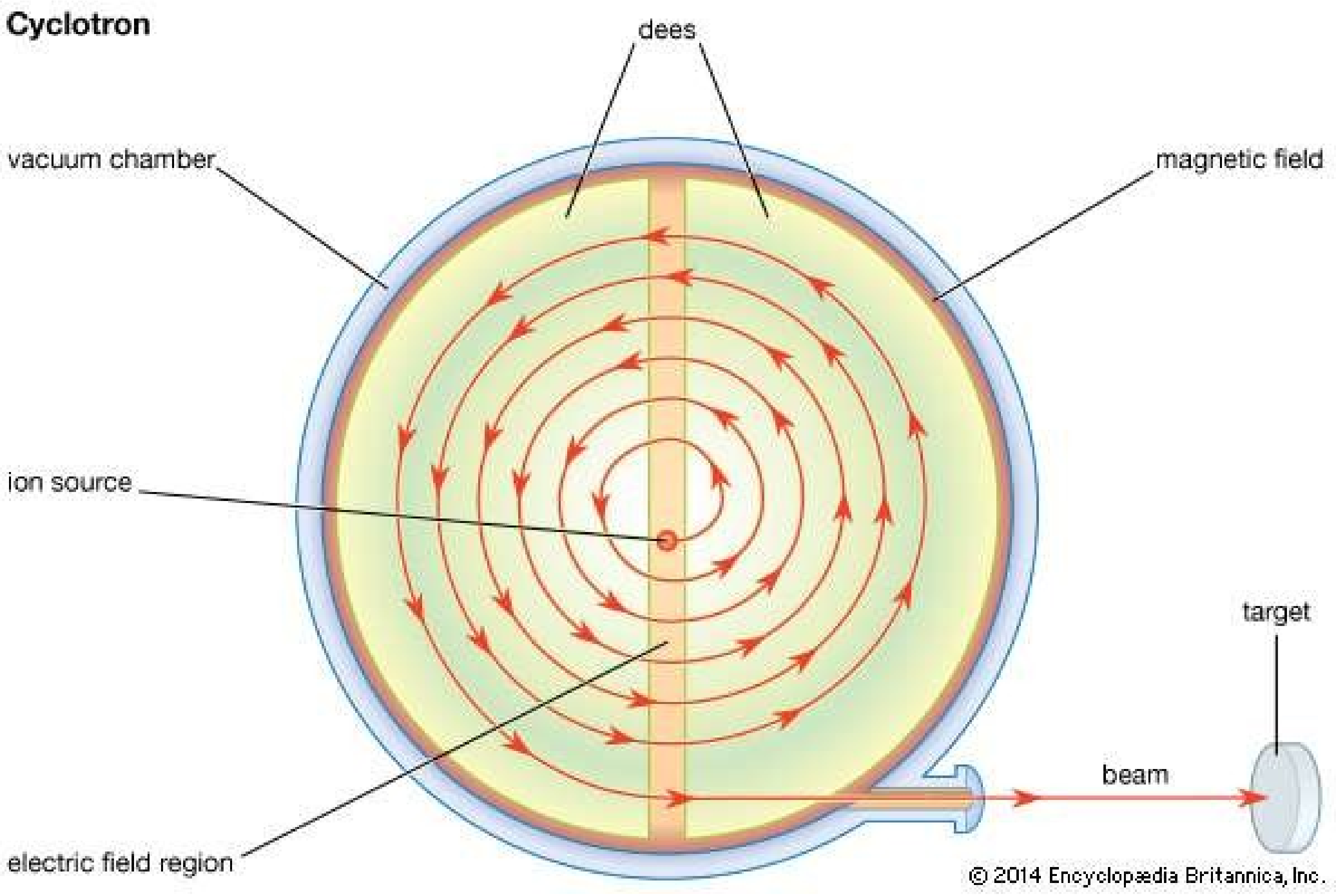
We can be adventurous.. but primary constraints are

1. Are these particles easily available?
2. Can I manipulate them readily?

Two particles fit the bill – electrons and protons.

Almost all experiments start from these (and if needed go on to produce other particles)

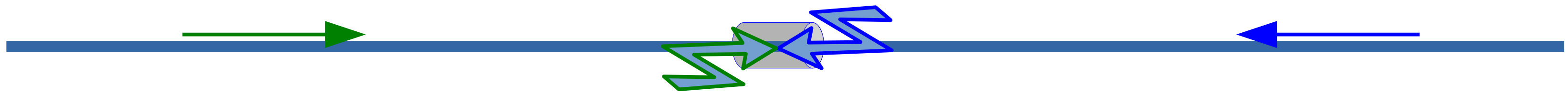
Cyclotron



Can't reach the high energies we need.

Accelerate using electric field, Bend using magnetic field

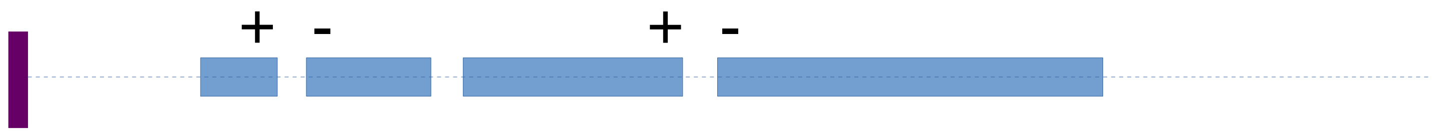
Linear Accelerators



Linear

Good for light particles such as electrons

A succession of kicks



Ion source

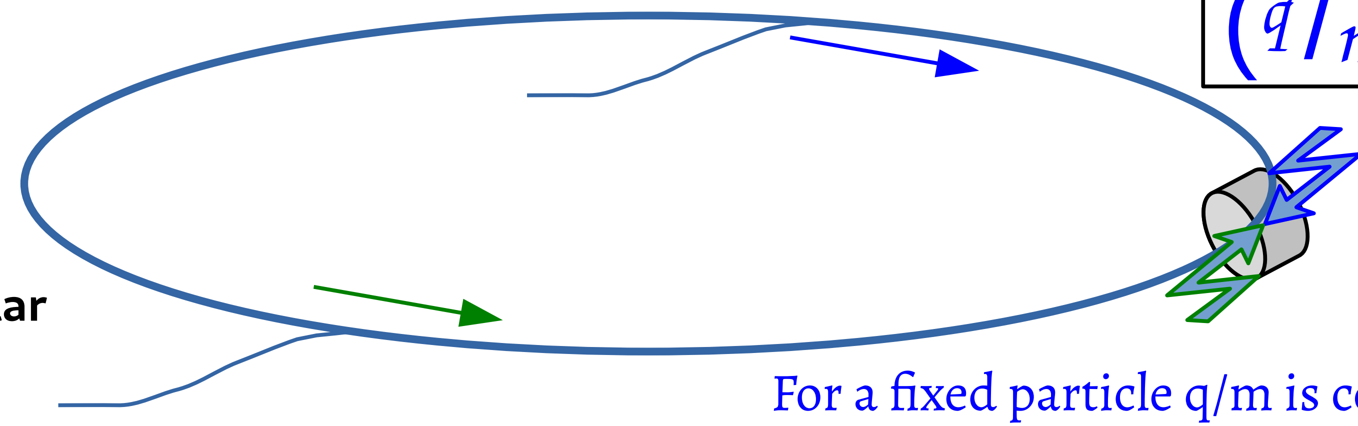
Choose successive lengths such that as velocity increases, it takes same time to traverse paths (use same RF source for all kicks)

eg. Stanford Linear Accelerator, 3.2km long, accelerating ele to 50 GeV

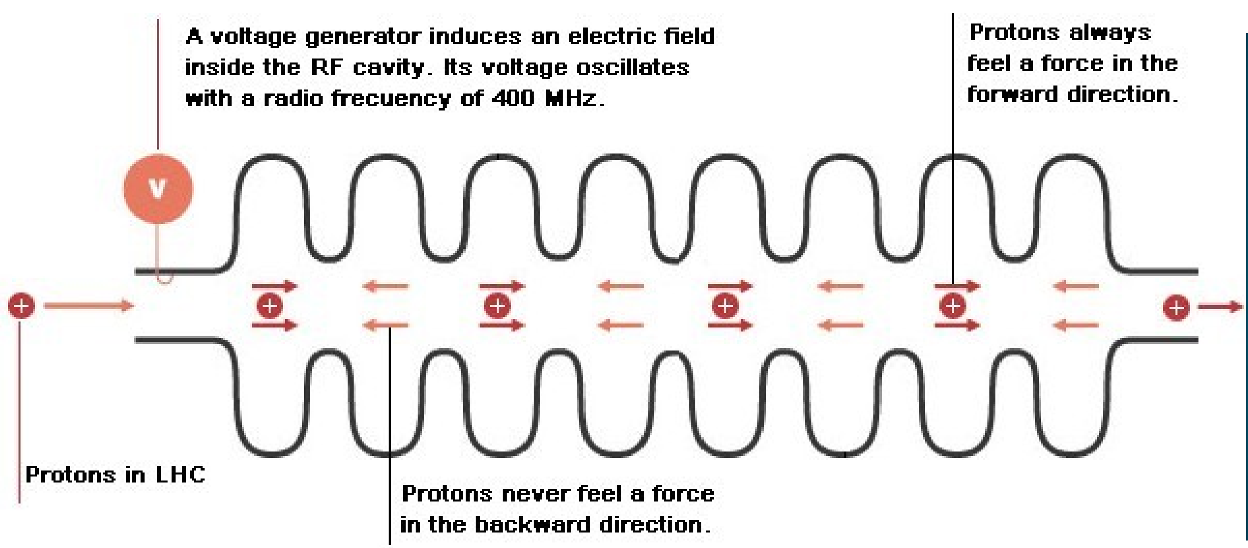
Synchrotrons

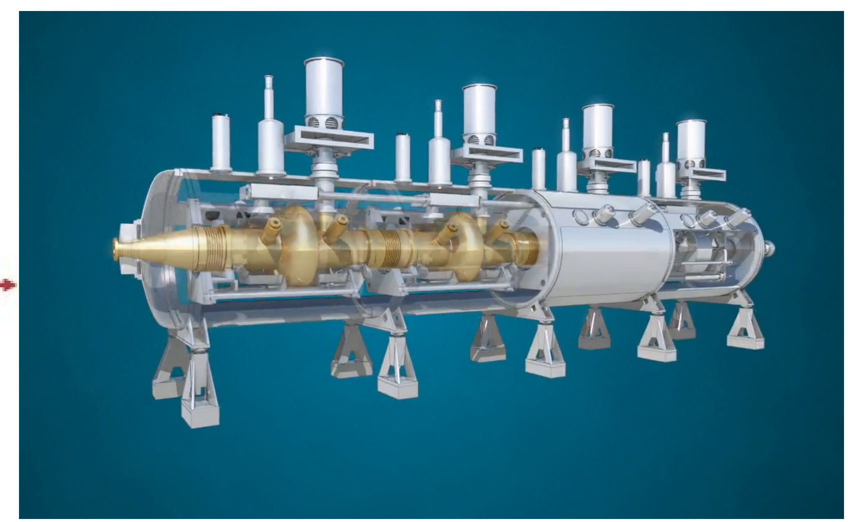
$$\left(\frac{q}{m}\right) R = \frac{v}{B}$$

Circular



For a fixed particle q/m is constant,
for a given collider radius R is constant.
So magnetic field B must increase with velocity v.





Linear vs. Circular colliders

Linear vs. Circular colliders

Charged particles radiate in circular motion. Circular colliders lose energy to bremsstrahlung. (Need bigger rings and/or heavier particles). Superconducting magnets for bending is harder (expensive, more maintenance)

Circular colliders can accelerate to higher energies (particles come around)
Can reuse particles (particles come around)
Can have multiple collision points/detectors

This is important.
Repeatability of a result.

Quantifying amount of data

Quantifying amount of data

$$L_{\text{inst}} = \frac{N_1 N_2}{4\pi\sigma_x\sigma_y} \times f_0 n_b \times \text{ Correction factors}$$

$$\mathcal{L} = \int L_{\text{inst}}\,\mathrm{dt}$$

N_i =number of particles in bunch, f_0 =beam revolution frequency, n_b =number of bunches, $\sigma_{x,y}$ =transverse beam size; depends on beam emittance, and beam squeezing parameters.

1232 Dipole Magnets, 858 Quadropoles, >6000 Correction Magnets

Total ~ 9300 magnets.

Number of protons in a bunch = 10^{11}

Number of bunches ~ 2000

Bunch spacing = 25 ns (7.5 m)

β^* = 30-60 cm

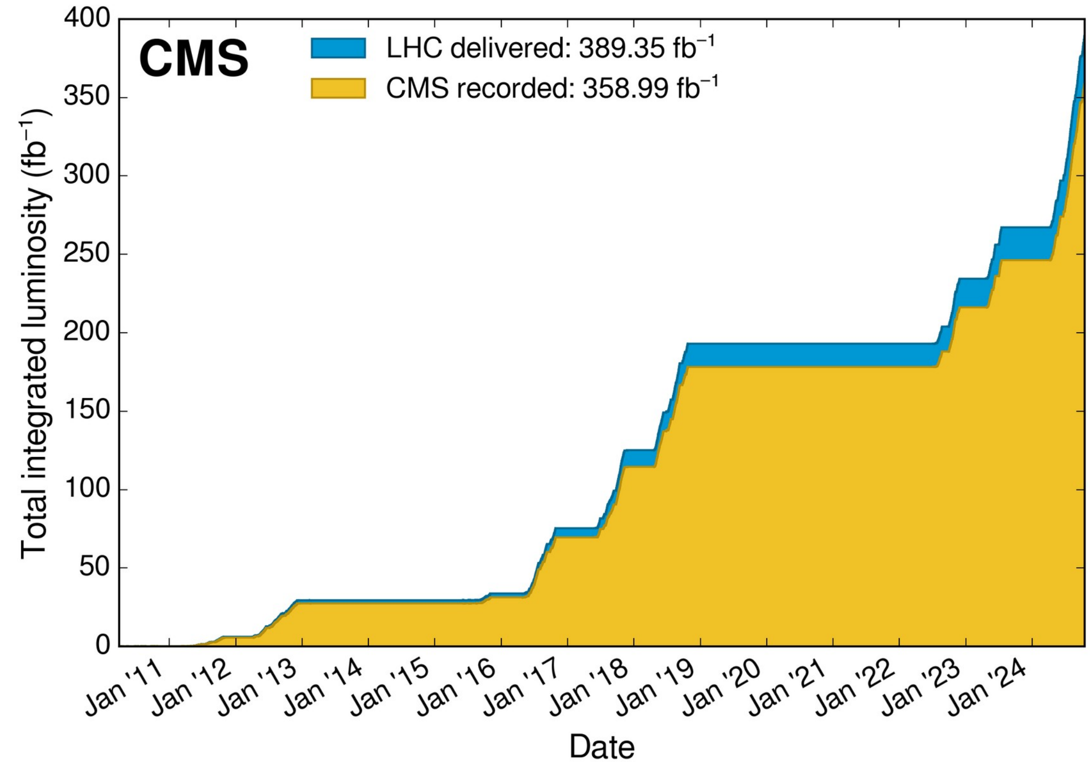
Integrated Luminosity

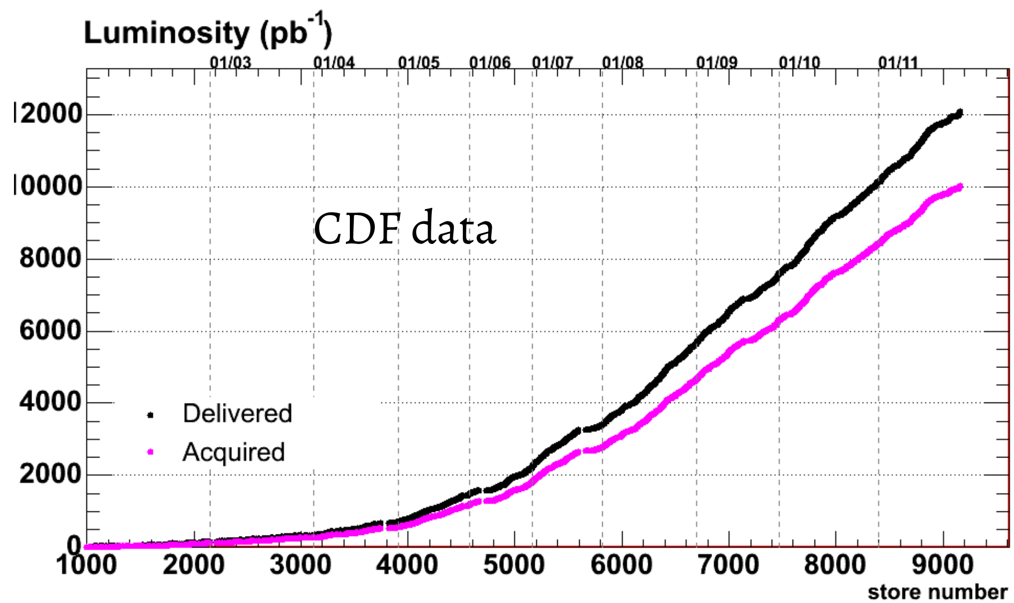
$\mathcal{L}$ has dimensions of inverse area.

1 barn = 10^{-28} m^2

Measured in inverse barns, inverse millibarns, inverse picobarns, inverse femtobarns

1 fb^{-1} = 10^3 pb^{-1}
1 pb^{-1} = 10^6 mb^{-1}

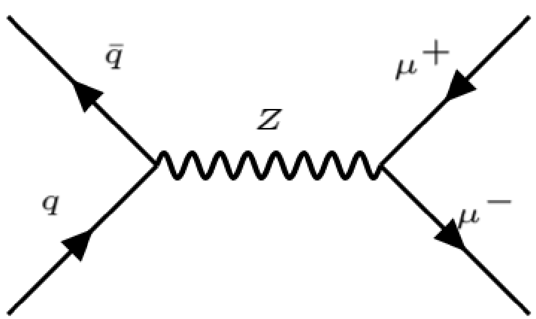




Cross section

From classical scattering, the "rate" at which an interaction will happen is proportional to the "area" of overlap between incident particle and target.

For us, the cross section (denoted by σ) quantifies the "rate" or "probability" of a certain interaction taking place.



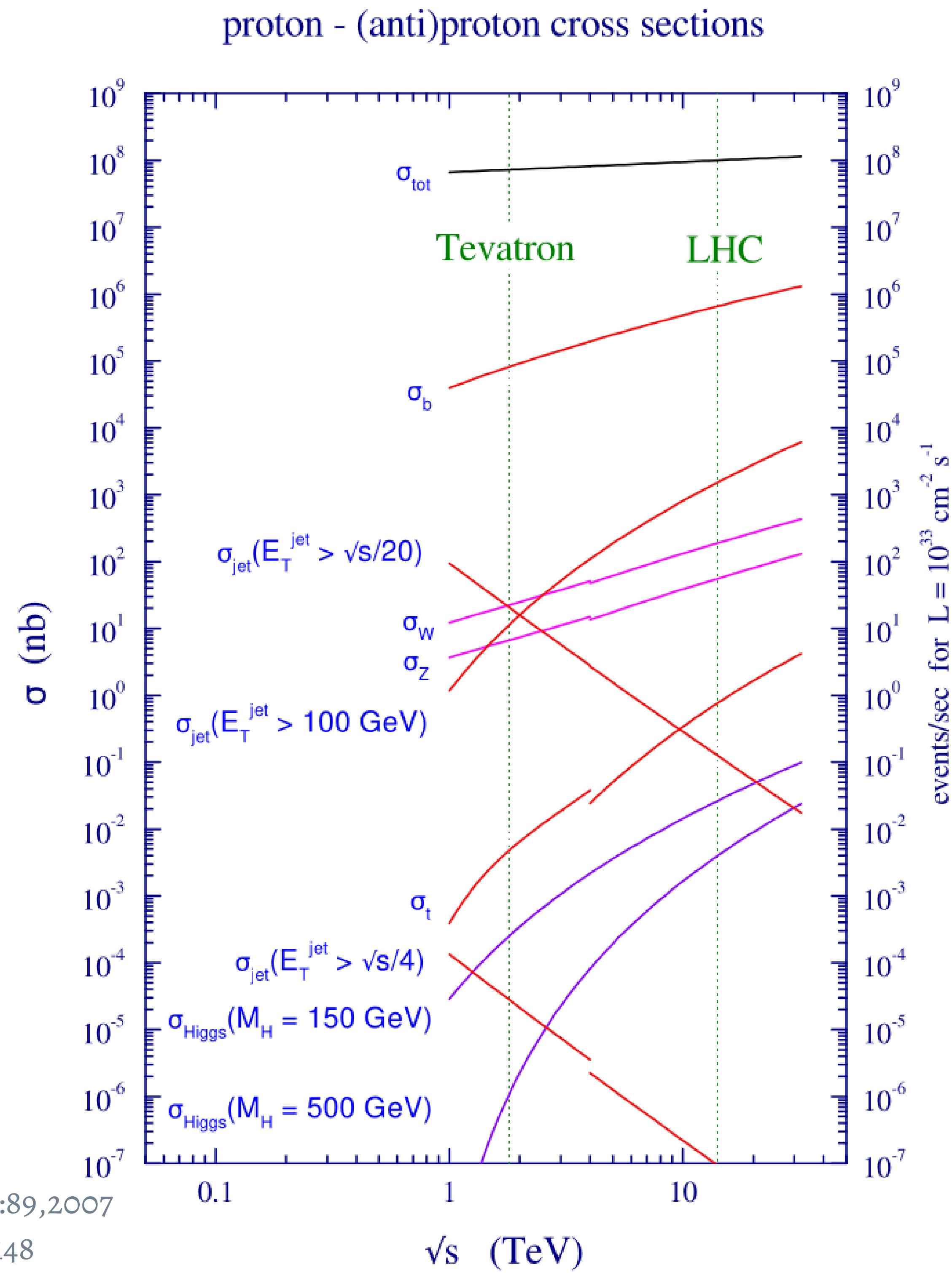
This rate depends on the incoming particle 4-vectors, the type of interaction [which particles are interacting]

Cross section is measured in dimensions of area, in units of barns: 1 barn = 10^{-28} m^2
Typical cross sections are in picobarns or femtobarns.
1 pb = 10^3 fb

Event Counts

$$N = \mathcal{L}\,\sigma$$

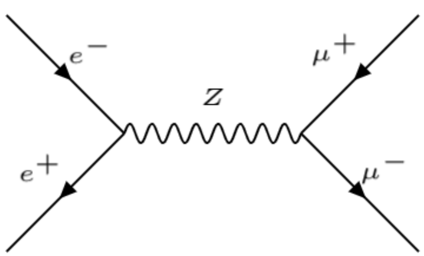
The number of produced events for a process is the integrated luminosity times the cross section of that process ("amount of data" times the "rate")



Rept.Prog.Phys.70:89,2007
arXiv:hep-ph/0611148

Electron-positron collisions

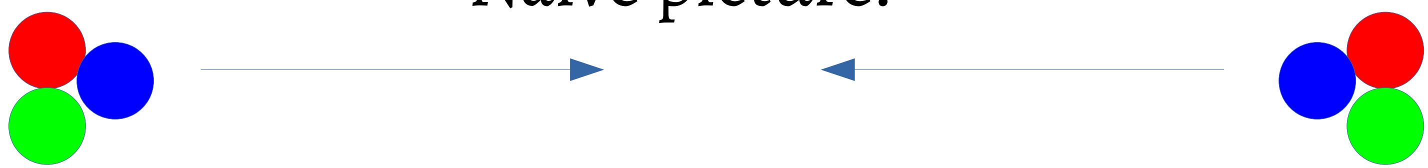
4-vector (E,p) of electron/positron known well



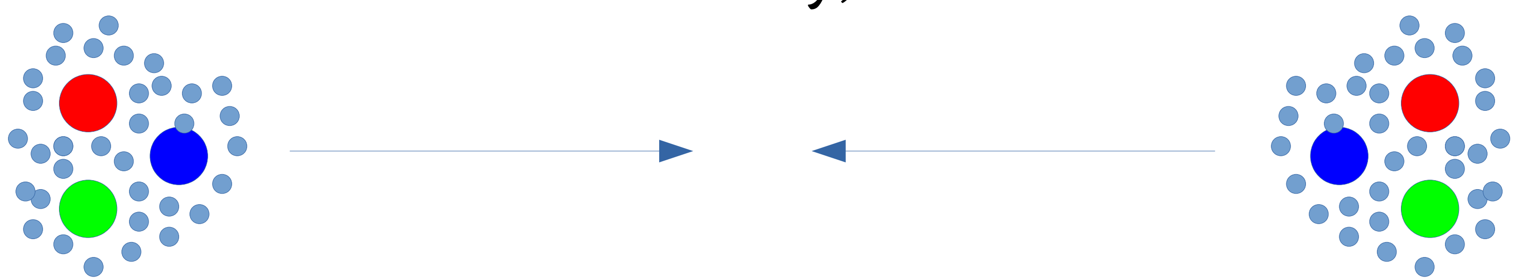
Need 4-vector of incoming particle to calculate cross section

Proton-proton collisions

Naive picture.

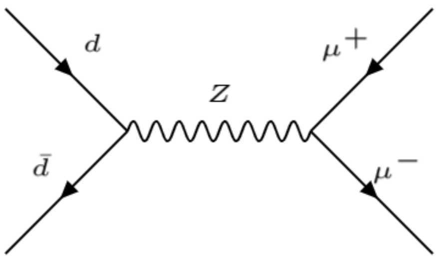


Actually,



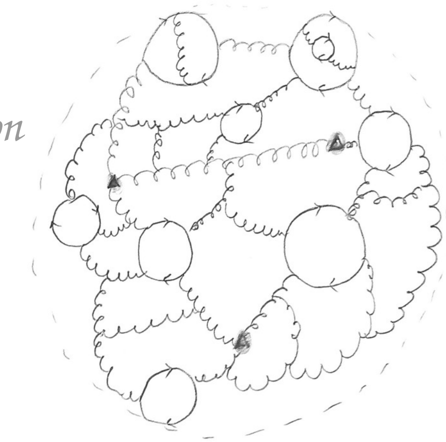
Messy… very messy.

Proton-proton collisions



Need 4-vector of incoming particle to calculate cross section

My sketch of the innards of a proton at high energy



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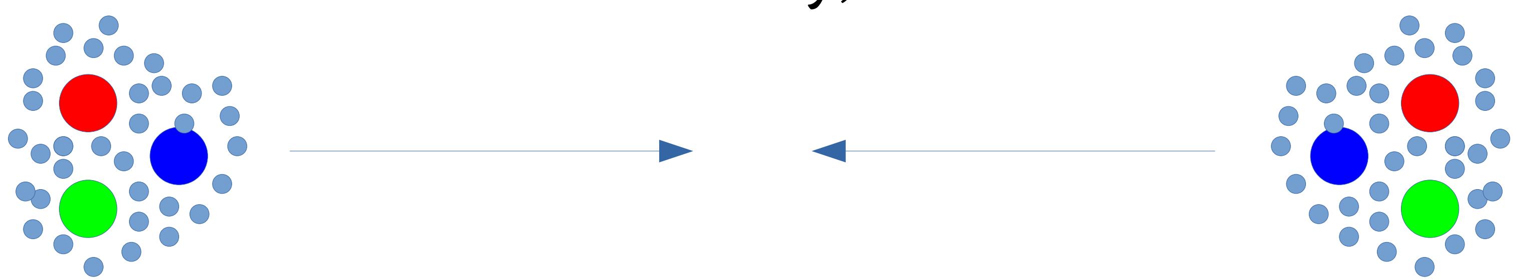
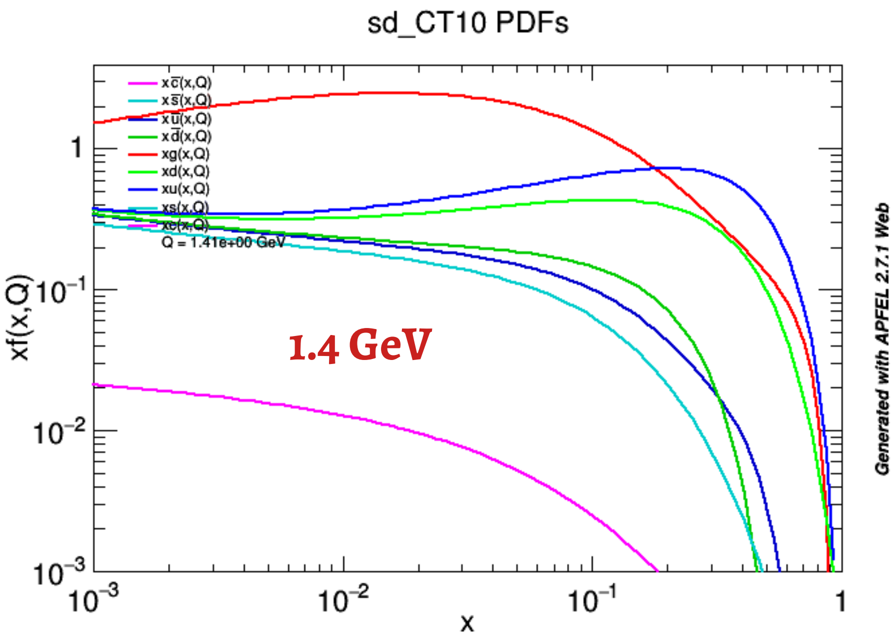
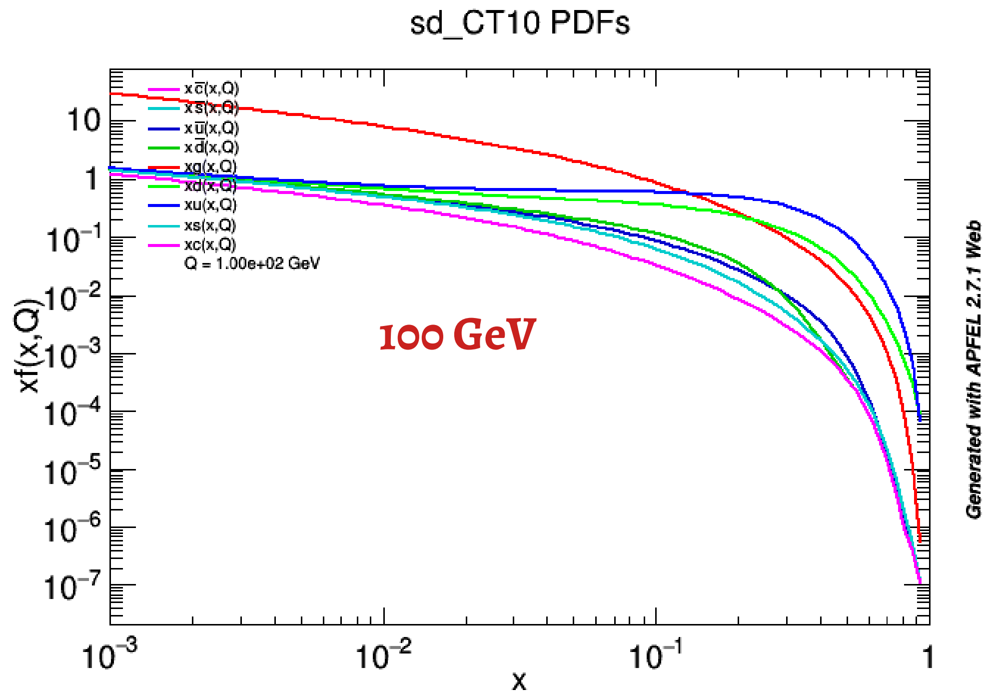


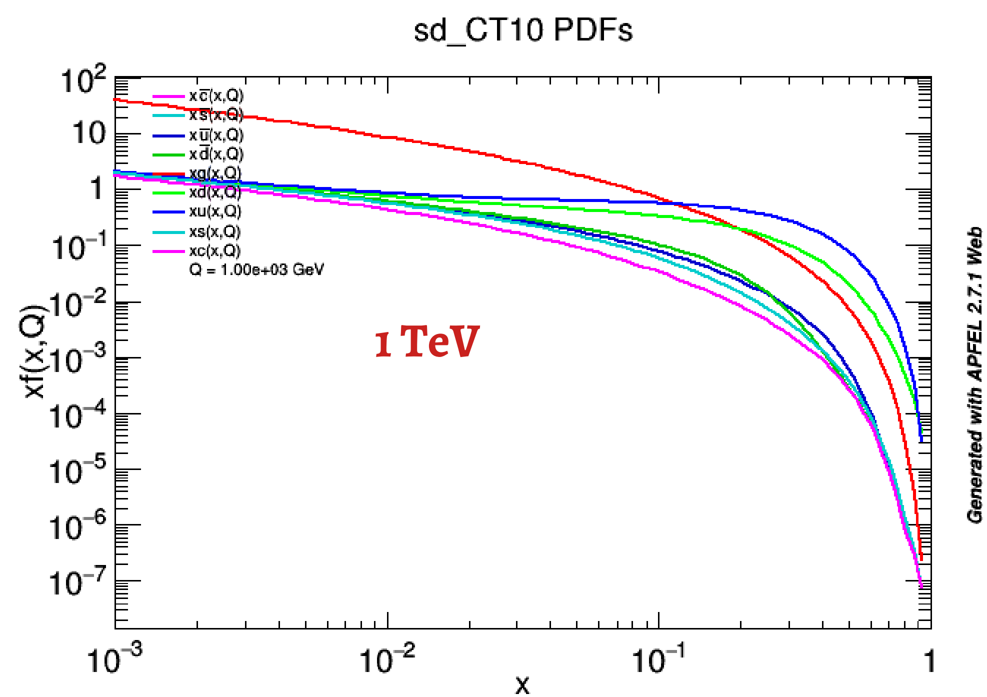
Messy… very messy.

When a pair of protons interact, it could easily be gluon from one and strange quark from another. This information is quantified in parton distribution functions (PDFs)

PDFs

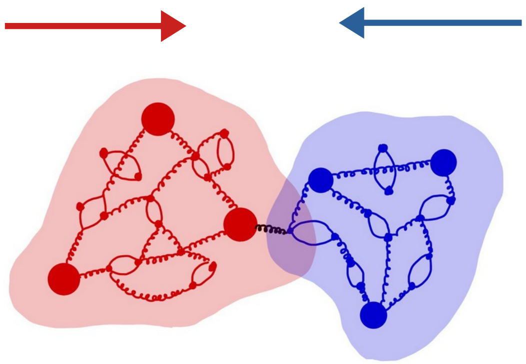






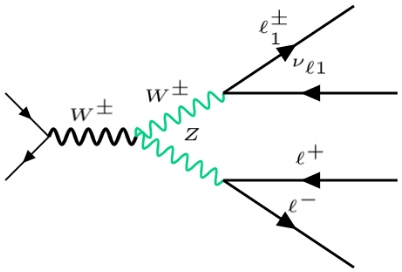
Used the CT10 PDF, and APFEL for visualization
https://apfel.mi.infn.it/home

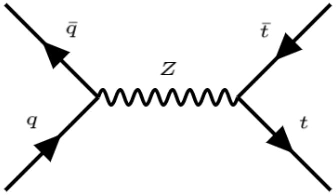
Typically, the interactions or processes that interest us, start from quarks or gluons.

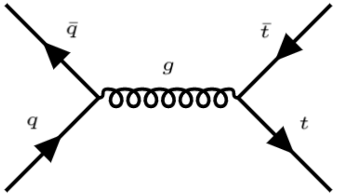


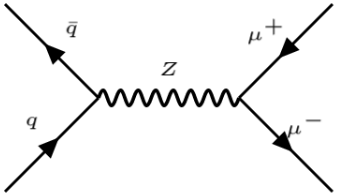
These incoming quarks/gluons will carry a fraction of the total energy/momentum of the proton…

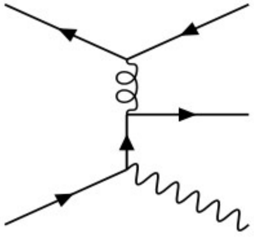
Effectively our collisions/processes occur at a range of energies

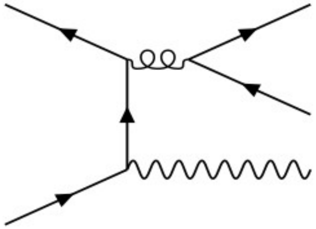












Hadronization

A colored particle (quark and gluon) that is produced, cannot exist/escape by itself. Part of the production energy/momentum is used to produce additional quark/antiquark pairs – which then form hadrons. It is the hadrons that exist/escape from the collision.

Proton-proton collision

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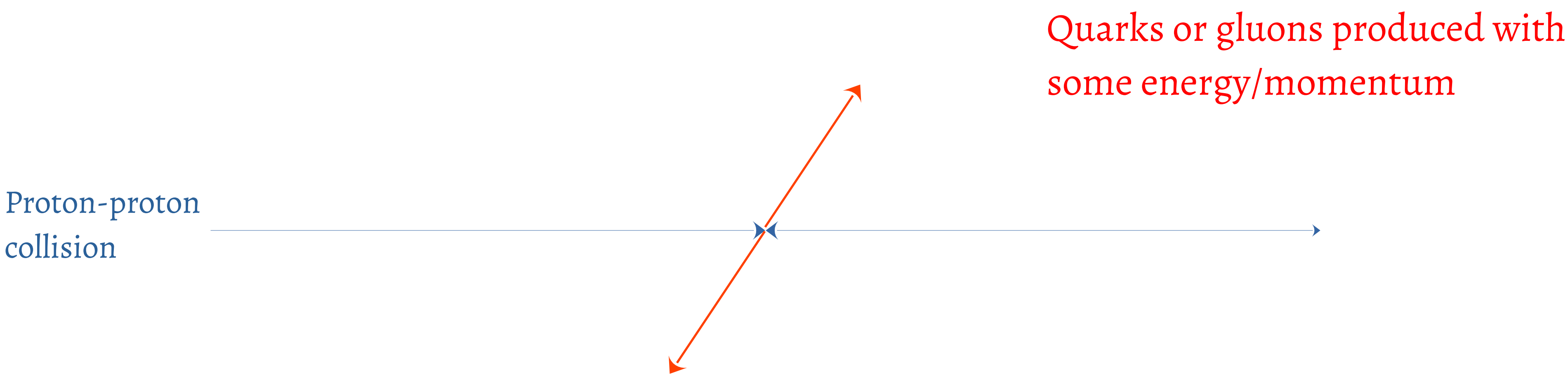

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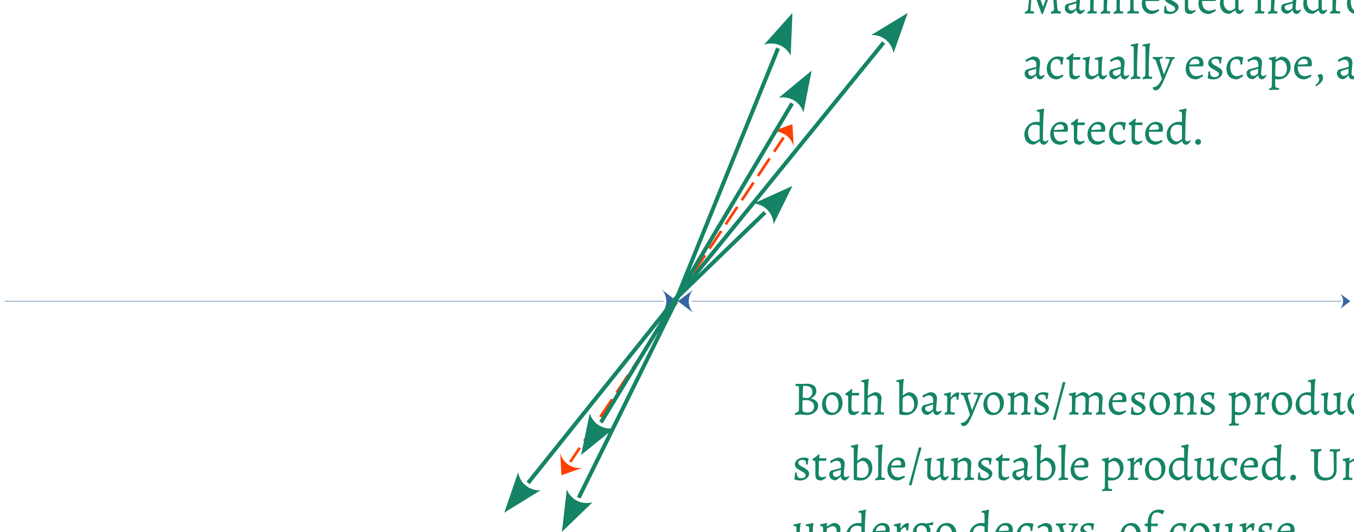
Manifested hadrons are what actually escape, and will be detected.

Proton-proton collision



Both baryons/mesons produced, both stable/unstable produced. Unstable hadrons undergo decays, of course.
(Different ways to hadronize 'same' initial state)

Hadronization

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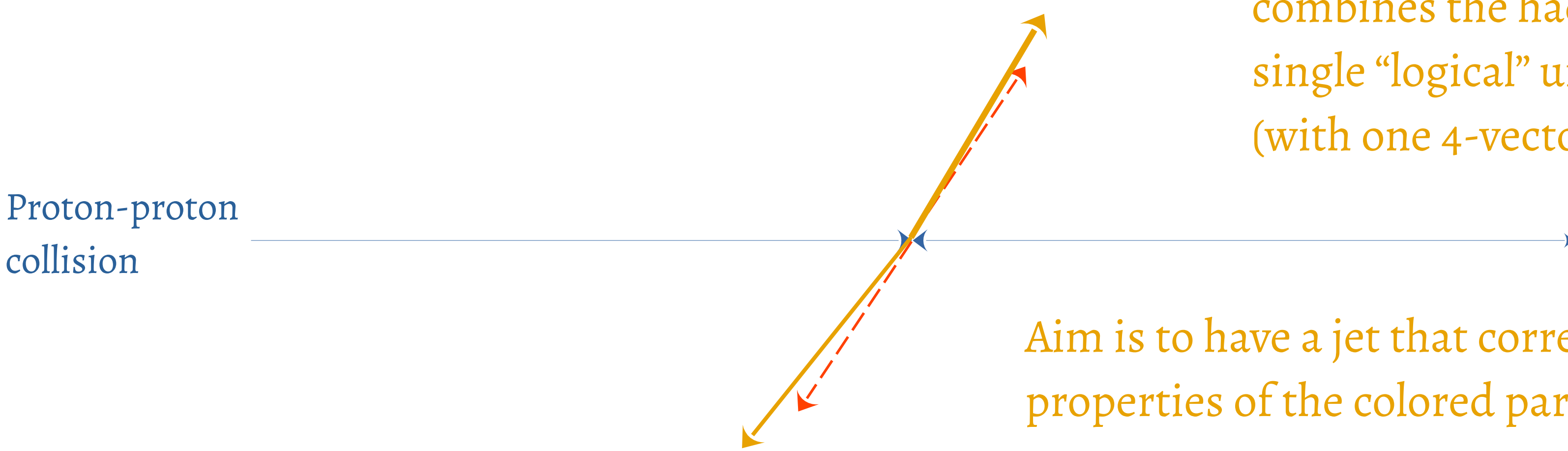
A jet clustering algorithm combines the hadrons into a single "logical" unit, called a jet (with one 4-vector)



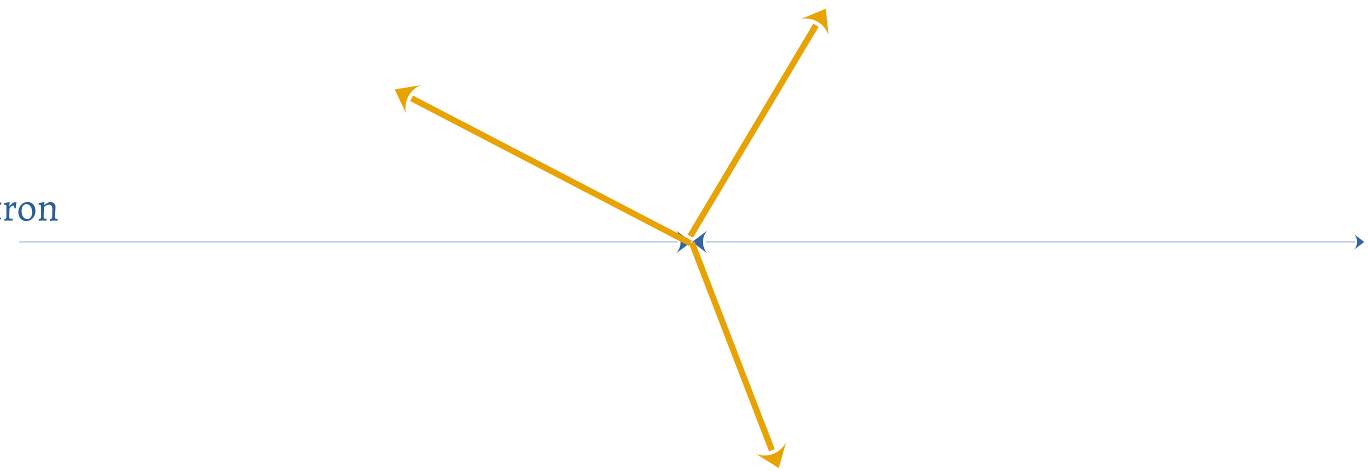
Aim is to have a jet that correlates with the initial properties of the colored particle.

One jet per colored particle is observed in the detector

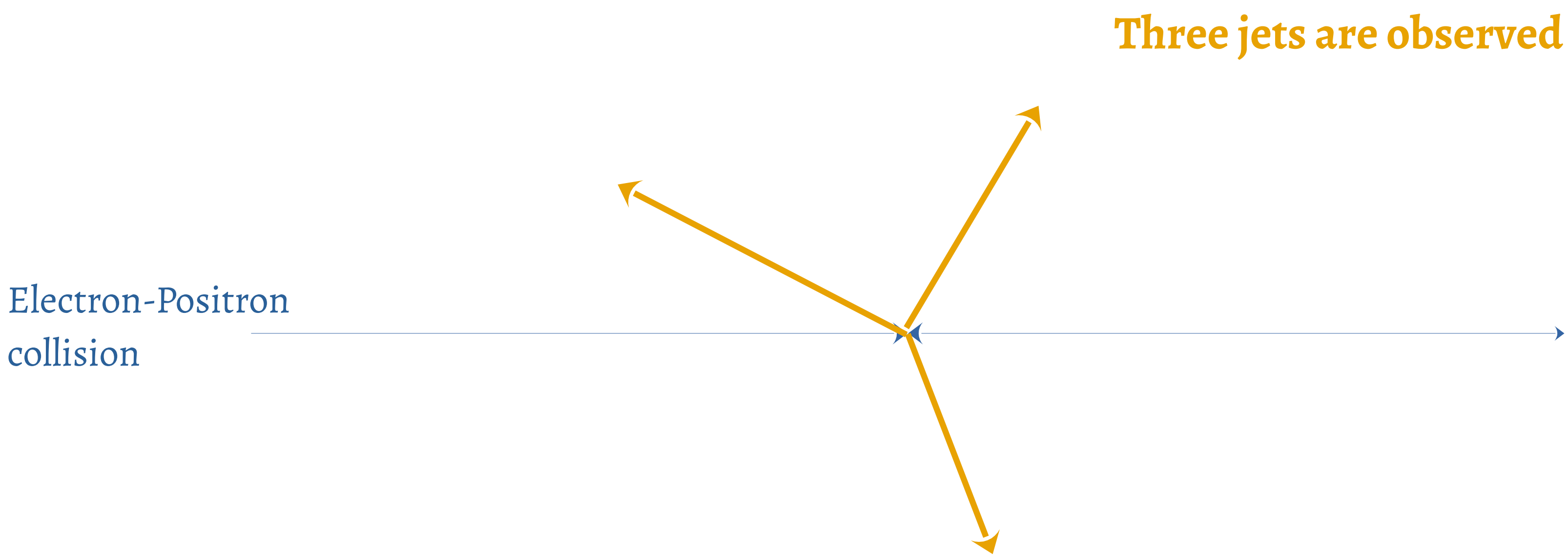
Discovery of gluons

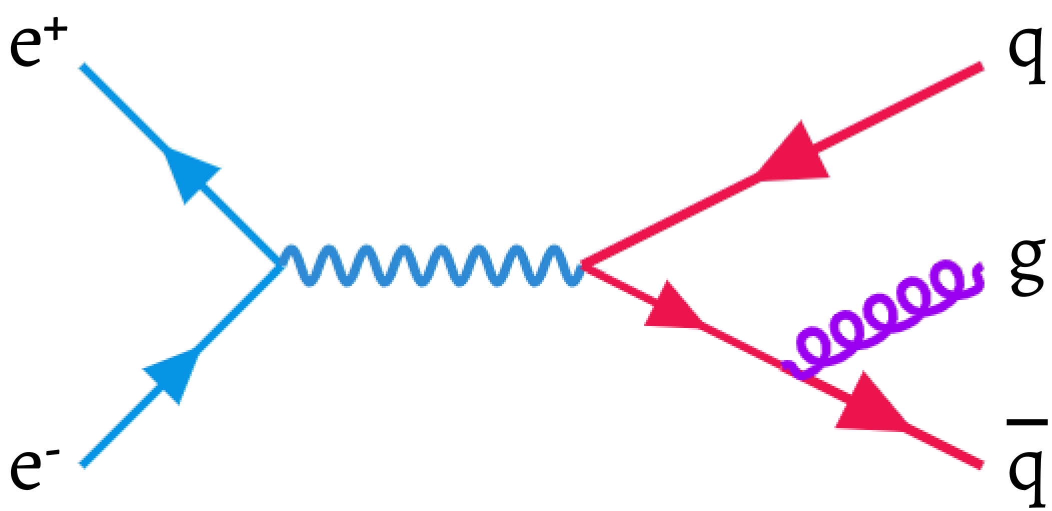
Three jets are observed

Electron-Positron collision

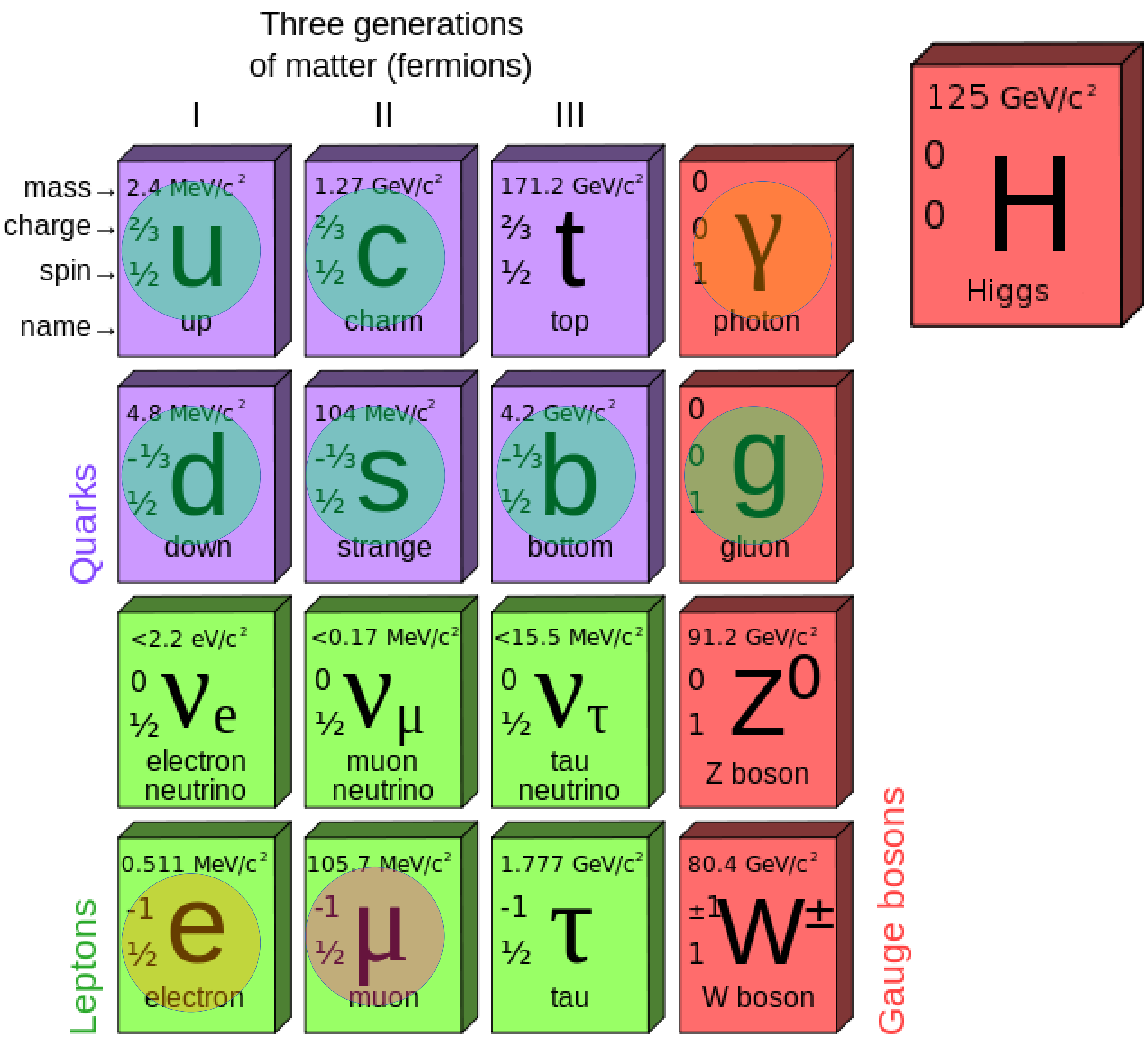


Discovery of gluons





List of particles

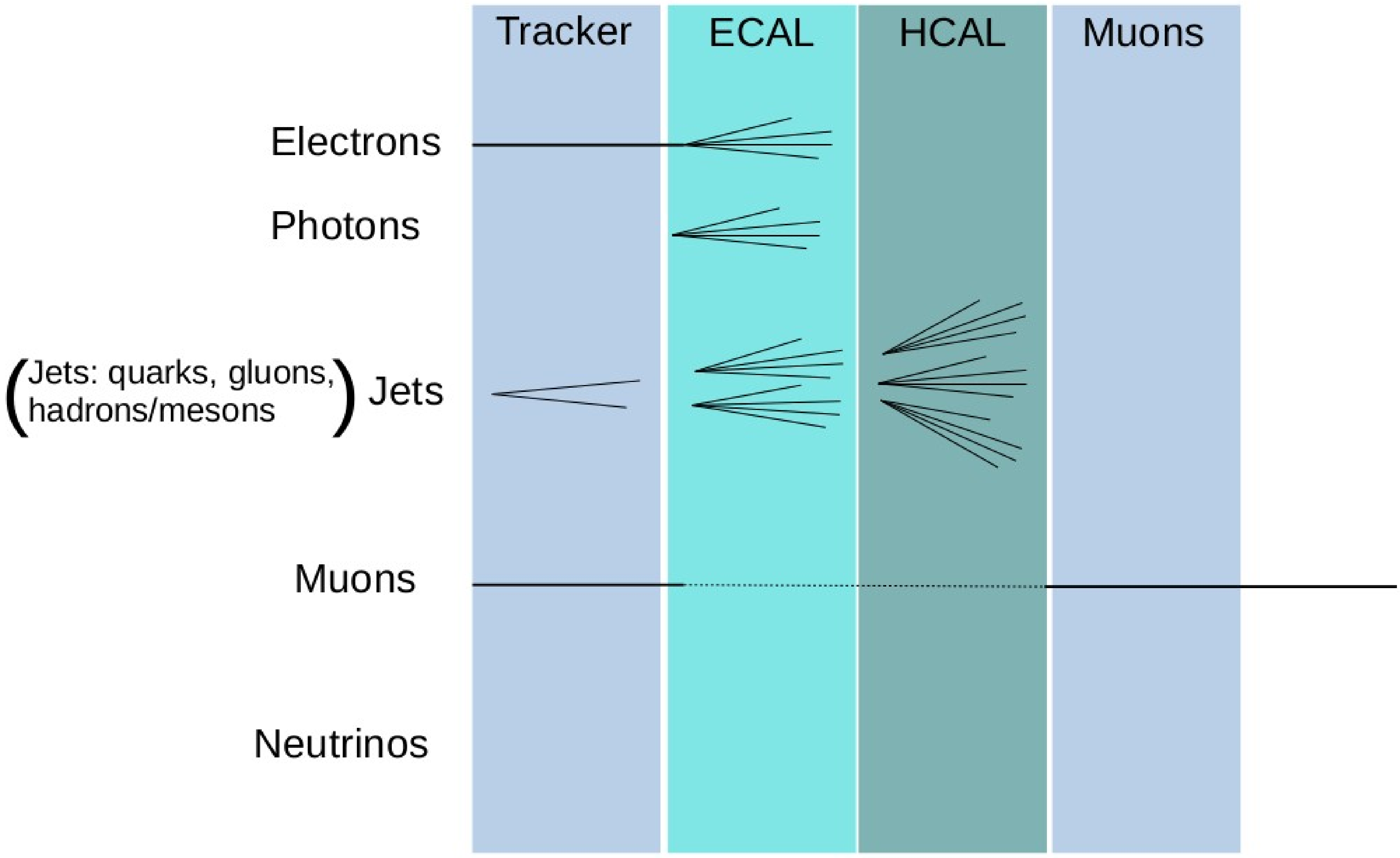


Stable

Stable in this context

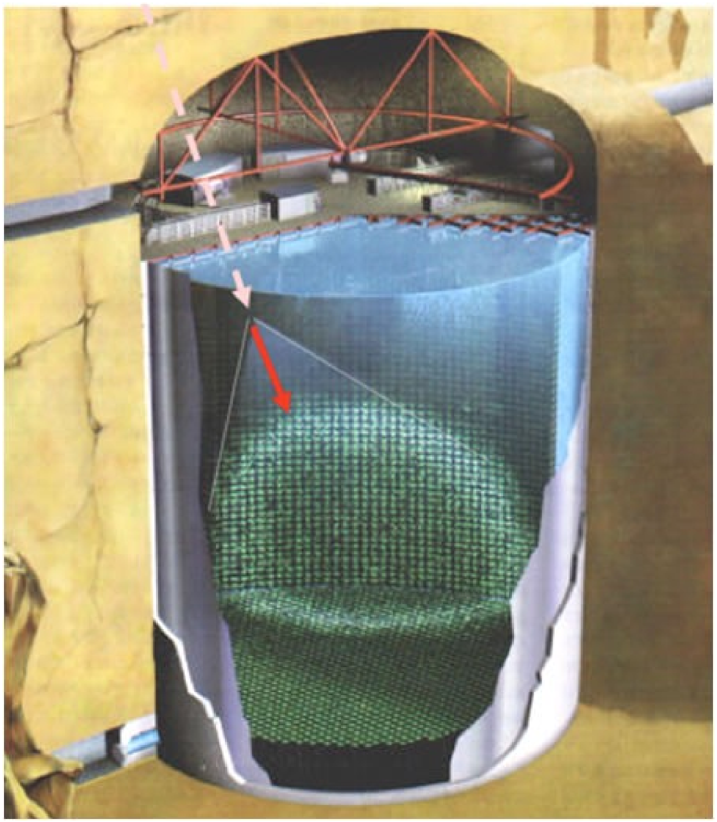
Hadronize

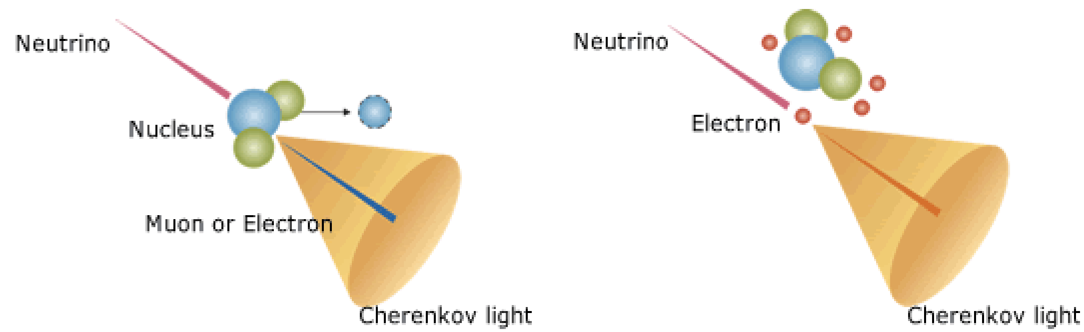
Design of Modern Multipurpose Detectors



Neutrinos at neutrino detectors

Consider the Super-K experiment
(Super-Kamioka Neutrino Detection Experiment)
Uses 50K tons of ultrapure water and detects Cherenkov light.

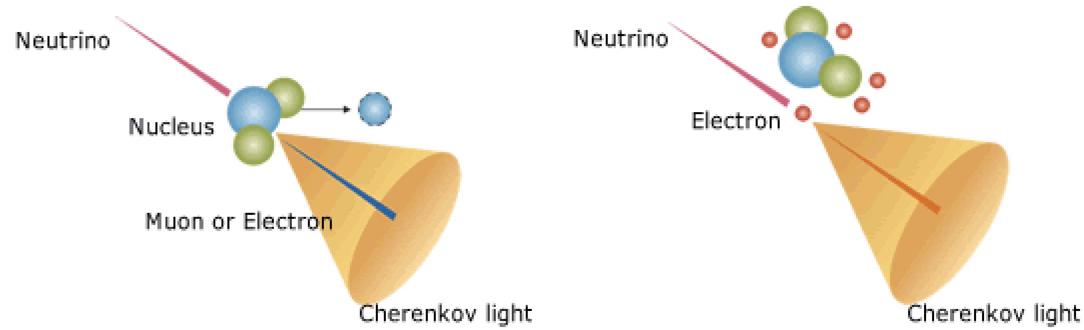




The generated charged particle emits the Cherenkov light.

Images: Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

Neutrinos at neutrino detectors



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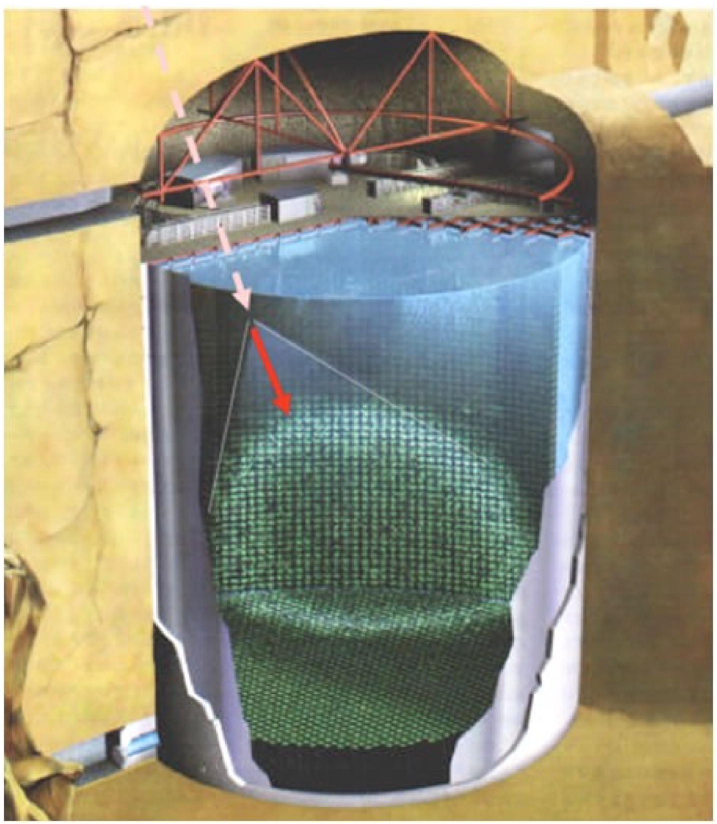

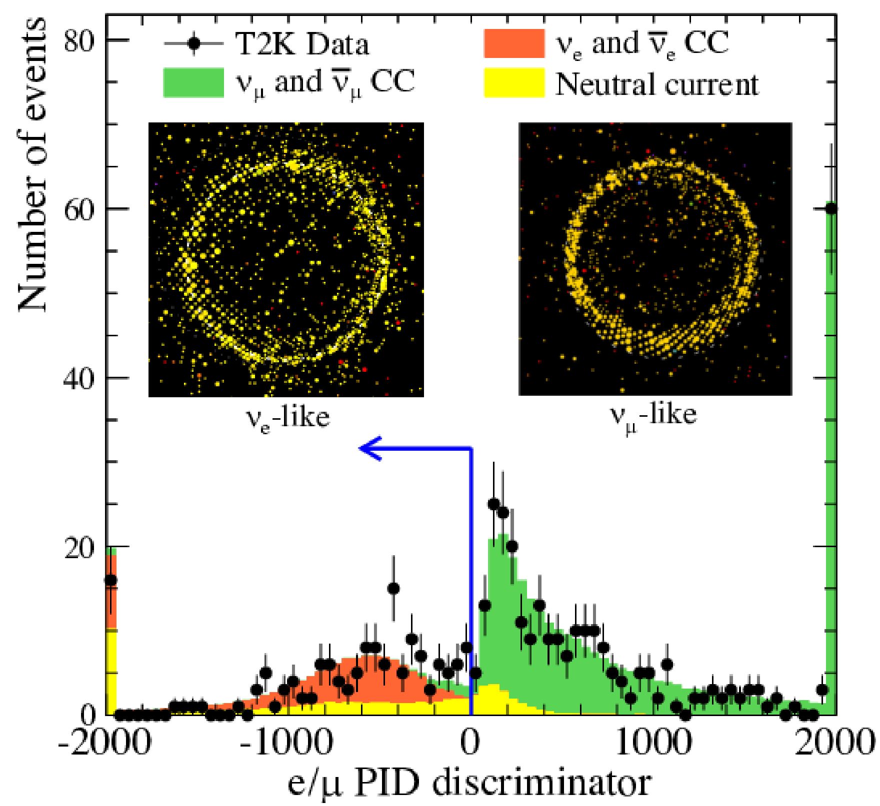

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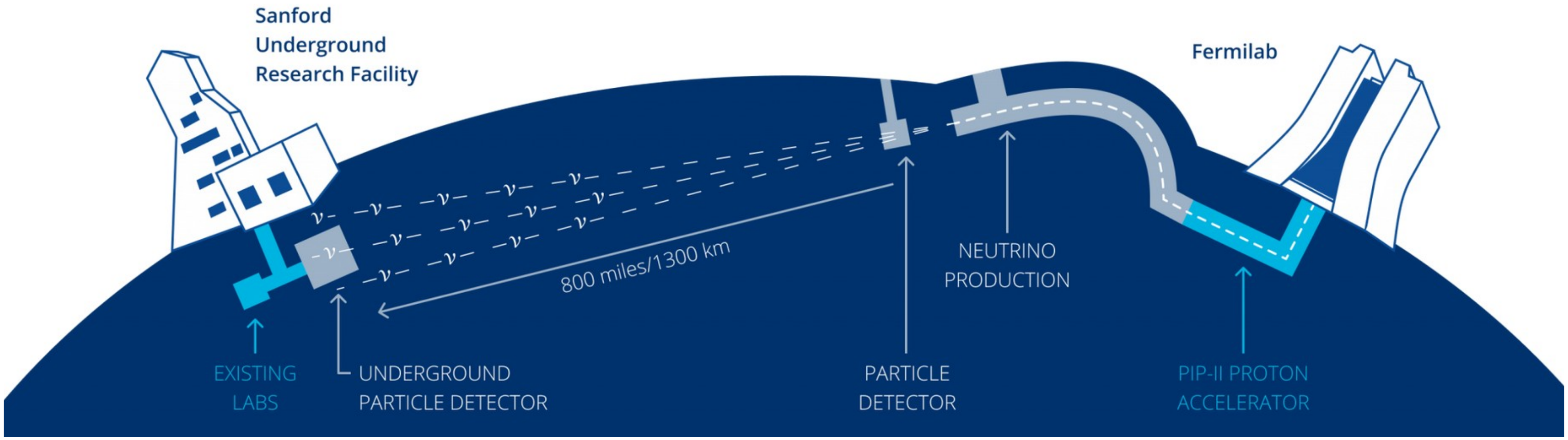
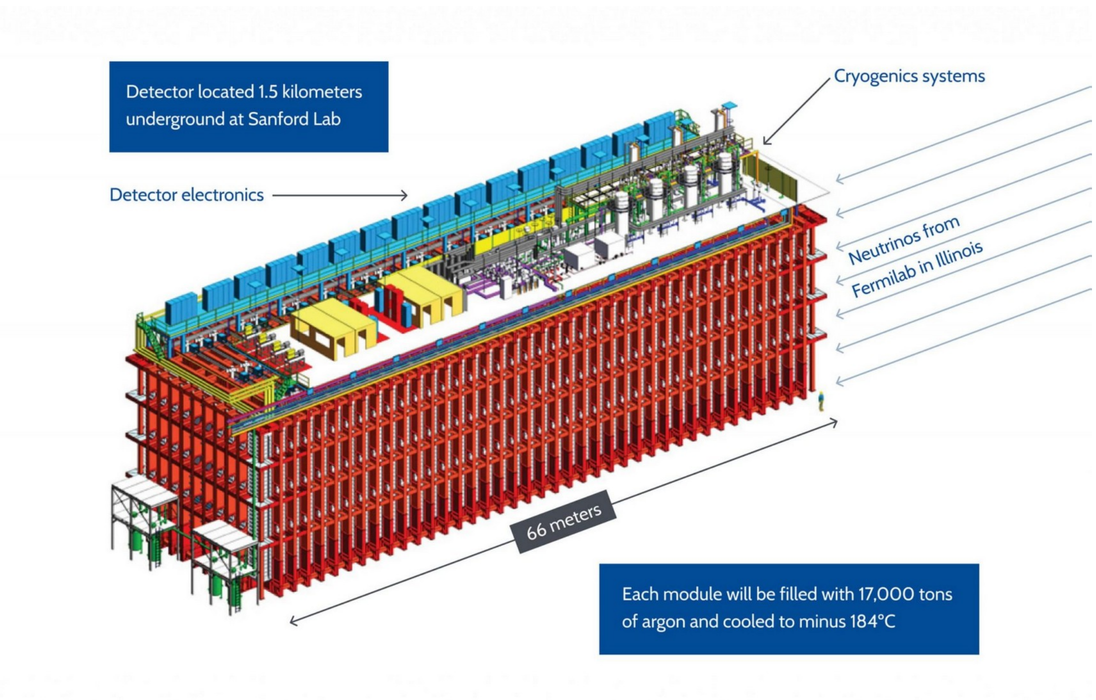
Nature 580, 339-344 (2020)

Neutrinos at neutrino detectors



Consider the DUNE experiment
(Deep Underground Neutrino Experiment)
70k tons of Liquid-Argon



https://lbnf-dune.fnal.gov/

Event yields

$$N = \mathscr{L}\,\sigma\,\mathcal{B}\,\varepsilon$$

N = Number of events

L = integrated luminosity, amount of data

σ = cross section, probability that particle is produced

B = branching fraction, probability that particle will decay to a given final state

ε = experimental efficiency (and other factors)