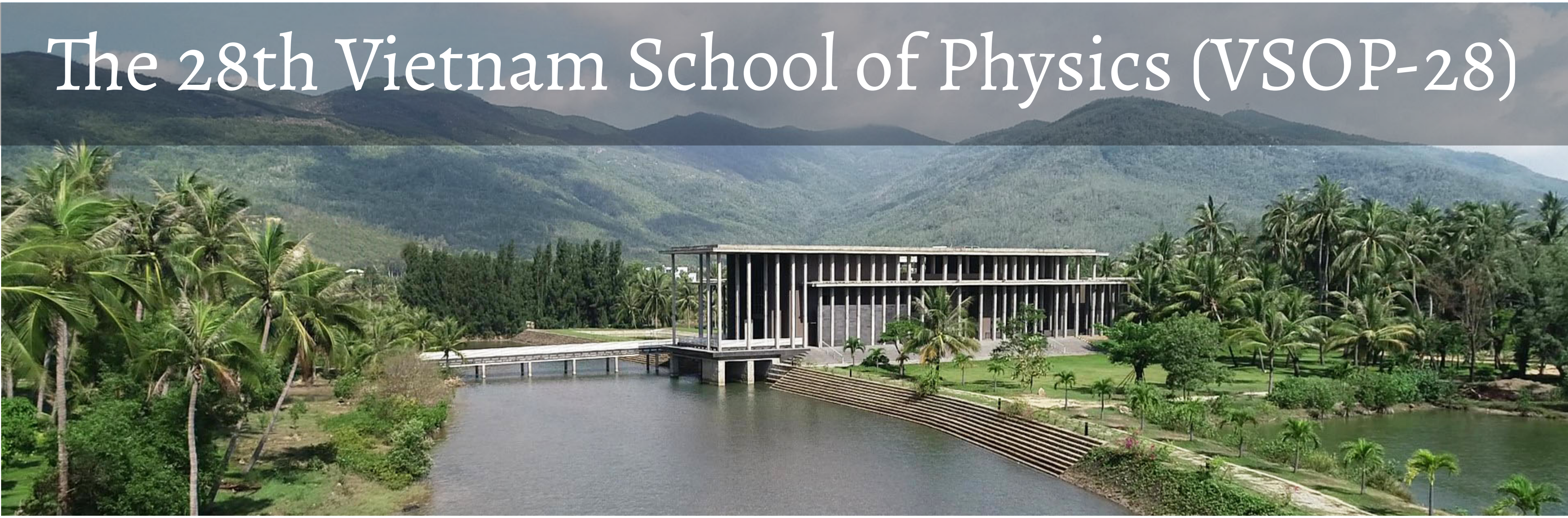


The 28th Vietnam School of Physics (VSOP-28)

Experimental methods for physics at the LHC

Sourabh Dube

IISER PUNE

July 24, 2022 to
August 5, 2022

Particle Physics

What are the fundamental constituents of our universe?

How do these fundamental constituents interact with each other?

Particle Physics

What are the fundamental constituents of our universe?

How do these fundamental constituents interact with each other?

Experimentally, how do we do it at the LHC?

Outline

Lecture 1: Colliders and LHC

Lecture 2 & 3: Detectors, subdetectors, object reconstruction

Lecture 4: Analysing the collision data

Lecture 5 & 6: Some discrete items of interest

Outline

Linear/Circular, LHC, Luminosity

Lecture 1: Colliders and LHC

Typical detector, basic principles of particle detection

Lecture 2 & 3: Detectors, subdetectors, object reconstruction

Electrons, photons, quarks, gauge bosons

Lecture 4: Analysing the collision data

Performing a data analysis to answer a physics question

Lecture 5 & 6: Some discrete items of interest

Backgrounds, fakes, substructure

Disclaimer

I will show material stolen shamelessly from many people and sources over the years… (that is how understanding builds)
I will try to give sources as much as possible, but if not, then big thank you to so many people over the years for their content.

I may focus more on CMS (and a little bit of ATLAS) because of my experience.

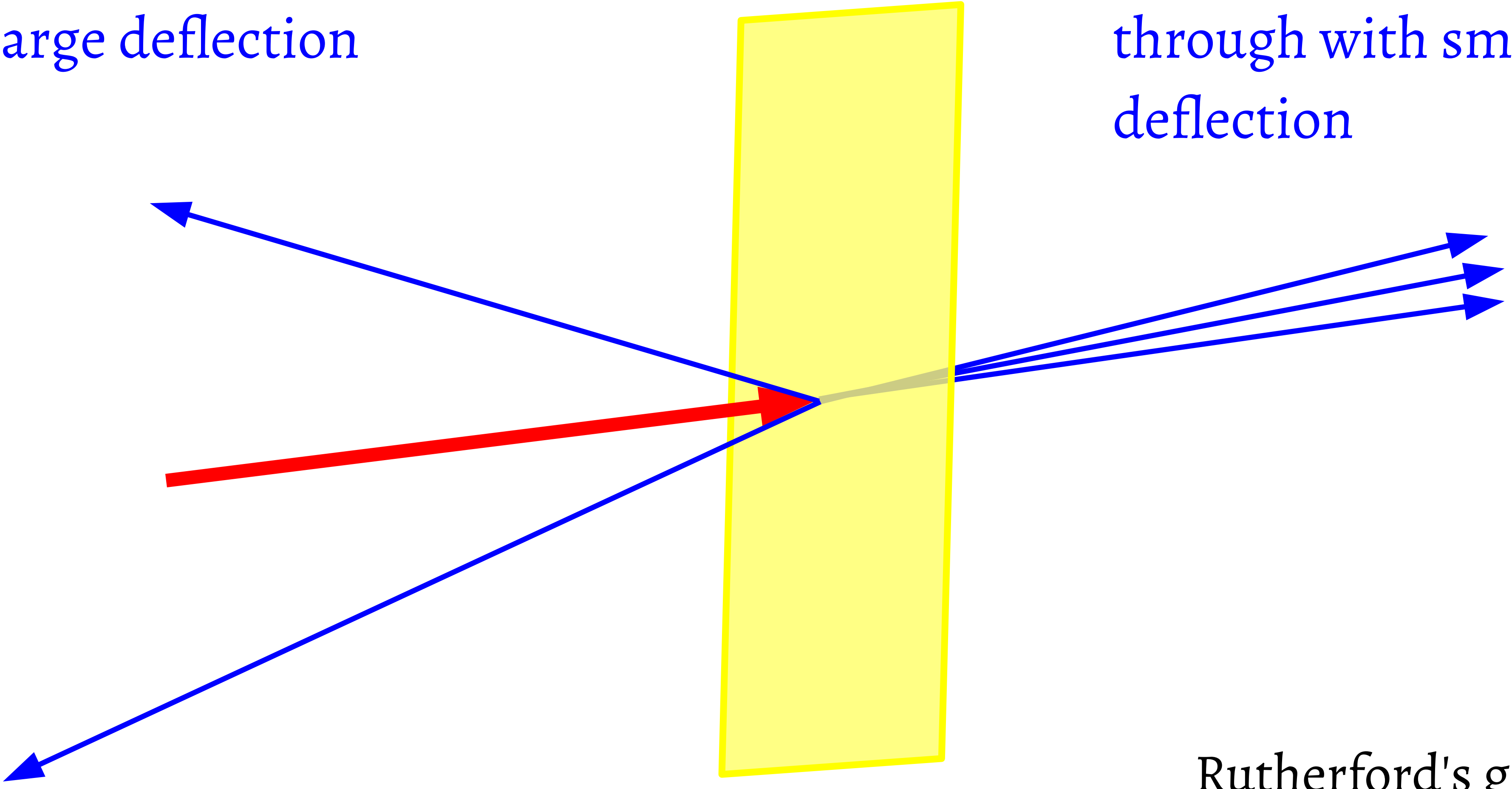
We have much to cover … so I will try to focus on concepts and ideas (rather than facts that you can look up).

Ask lots of questions! If I don't know, I promise to try to find answers.

I will try to give short exercises, and some paper-reading. We can talk about those over lunch/dinner. The more papers you look at, the more you know!

Lecture 1: Colliders

Why collide?

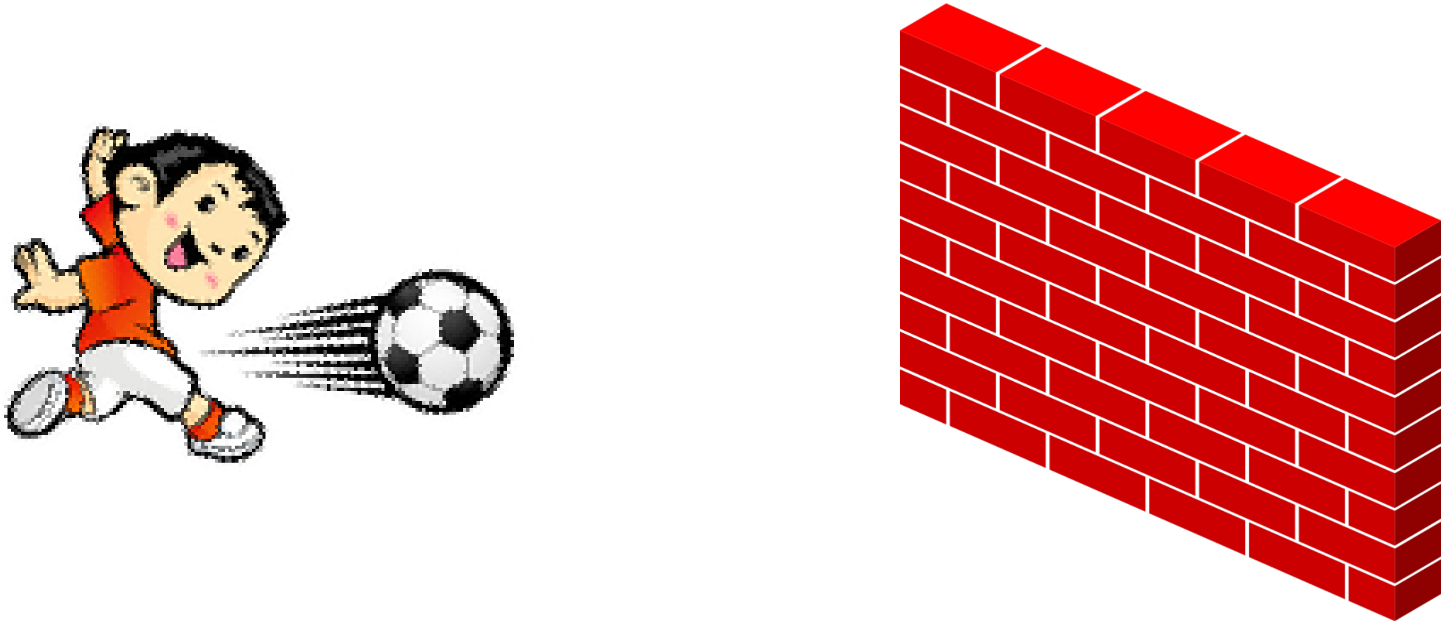


Some α-Particles have large deflection

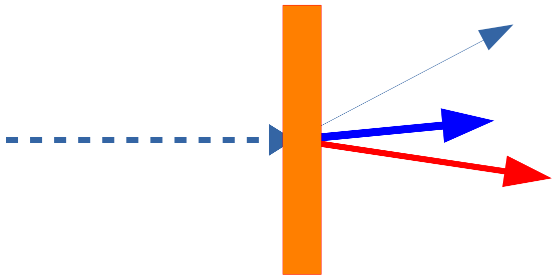
Most α-Particles go through with small deflection

Rutherford's gold foil experiment

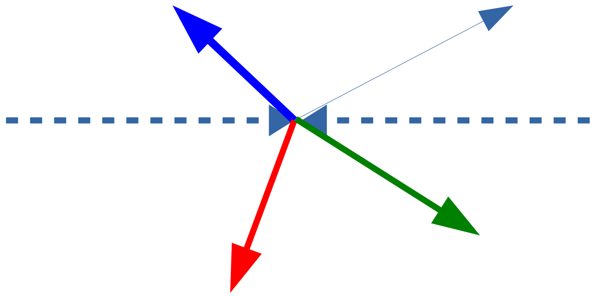
Why collide?



Accelerators/Colliders



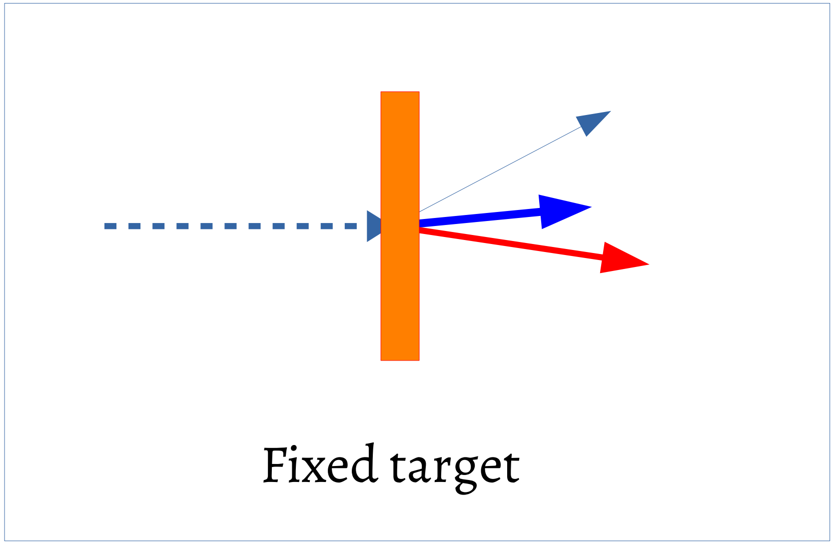
Fixed target



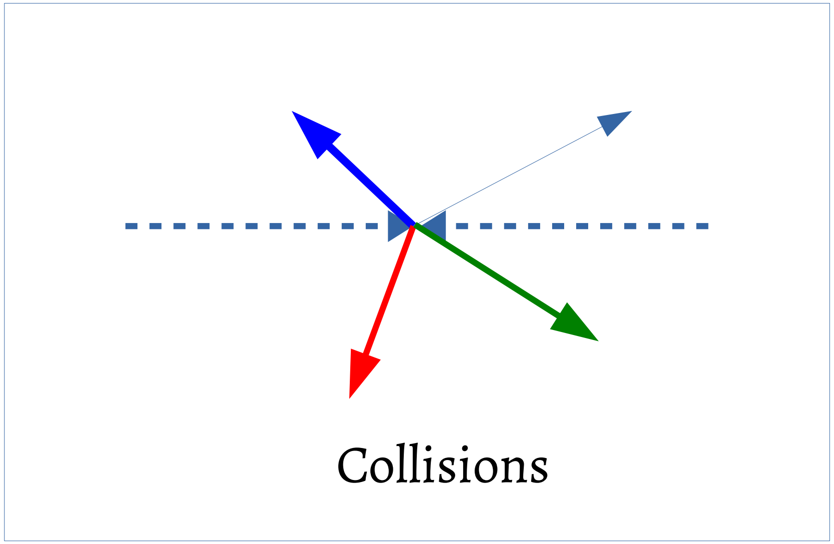
Collisions

- 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)

Some numbers

We have the de Broglie relation

$\lambda = h/p = hc/E$

And

$hc = 1.24\ \mathrm{eV.\mu m}$

Typical energy of α particle is 5 MeV

So we can probe ~ 250 fm

(Atom is 10^{-10} m, so certainly we could see inside it.)

Some numbers

We have the de Broglie relation

$\lambda = h/p = hc/E$

And

$hc = 1.24$ eV.μm

Typical energy of α particle is 5 MeV

So we can probe ~ 250 fm

(Atom is 10^{-10} m, so certainly we could see inside it.)

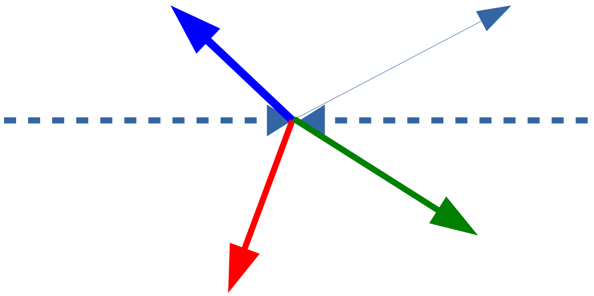
Proton is ~ 1 fm, thus we need energy of ~ 1.24 GeV to “peek inside” a proton.

Higher energy probes smaller distance scales.

Some numbers

We also have

$E = mc^2$

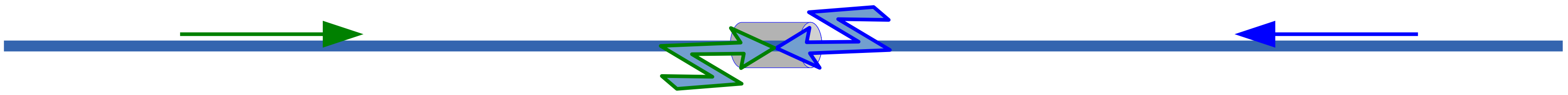


Collisions

A Higgs boson has a mass of 125 GeV, to produce it we would need collisions at COM energy of at least 125 GeV

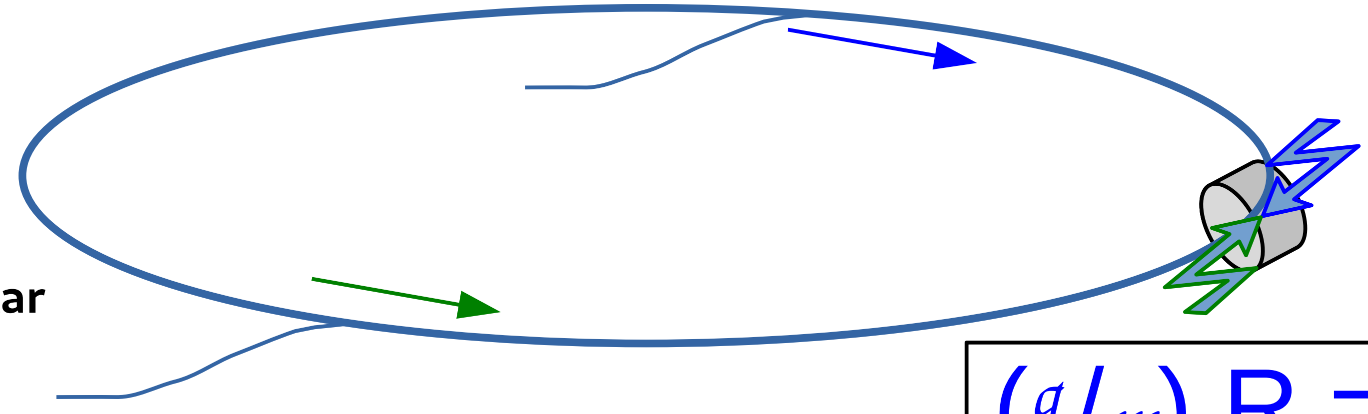
Higher energy allows us to produce higher mass particles.

Colliders



Linear

Good for light particles such as electrons



Circular

Use magnets to bend beams

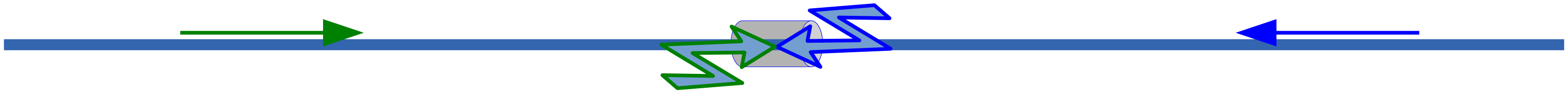
$$\boxed{(q/m)\,\mathrm{R} = v/\mathrm{B}}$$

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.

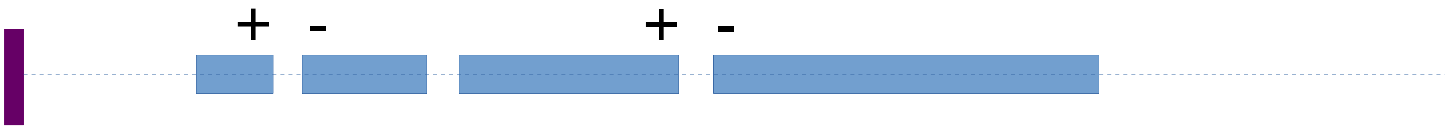
Linear Accelerators



Linear

Good for light particles such as electrons

A succession of kicks

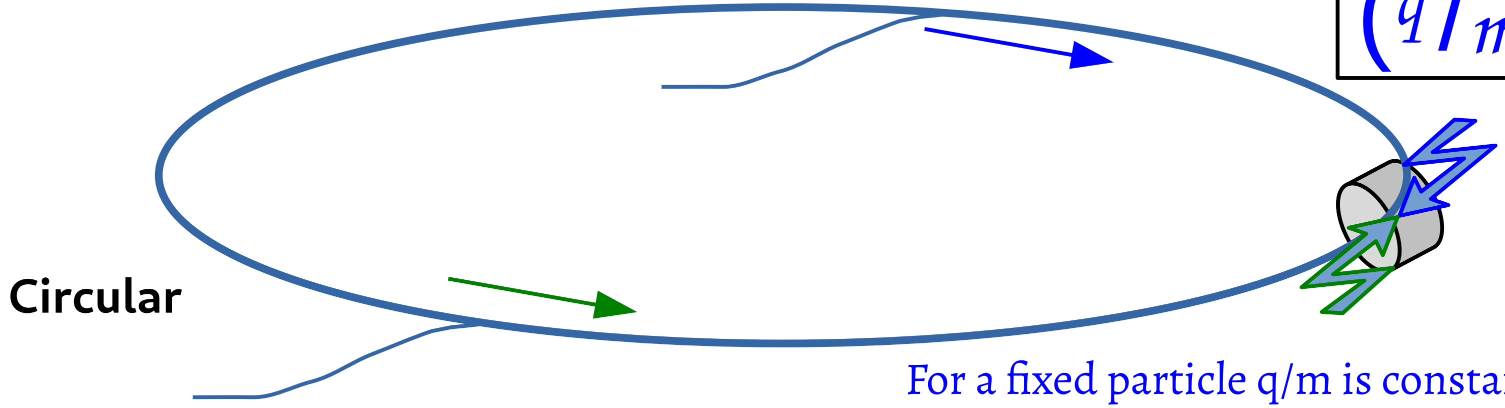


Choose successive lengths such that as velocity increases, it takes same time to traverse paths (use same RF source for all kicks)

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

Synchrotrons

$$\boxed{\left({}^{q}/_{m}\right) R = {}^{v}/B}$$



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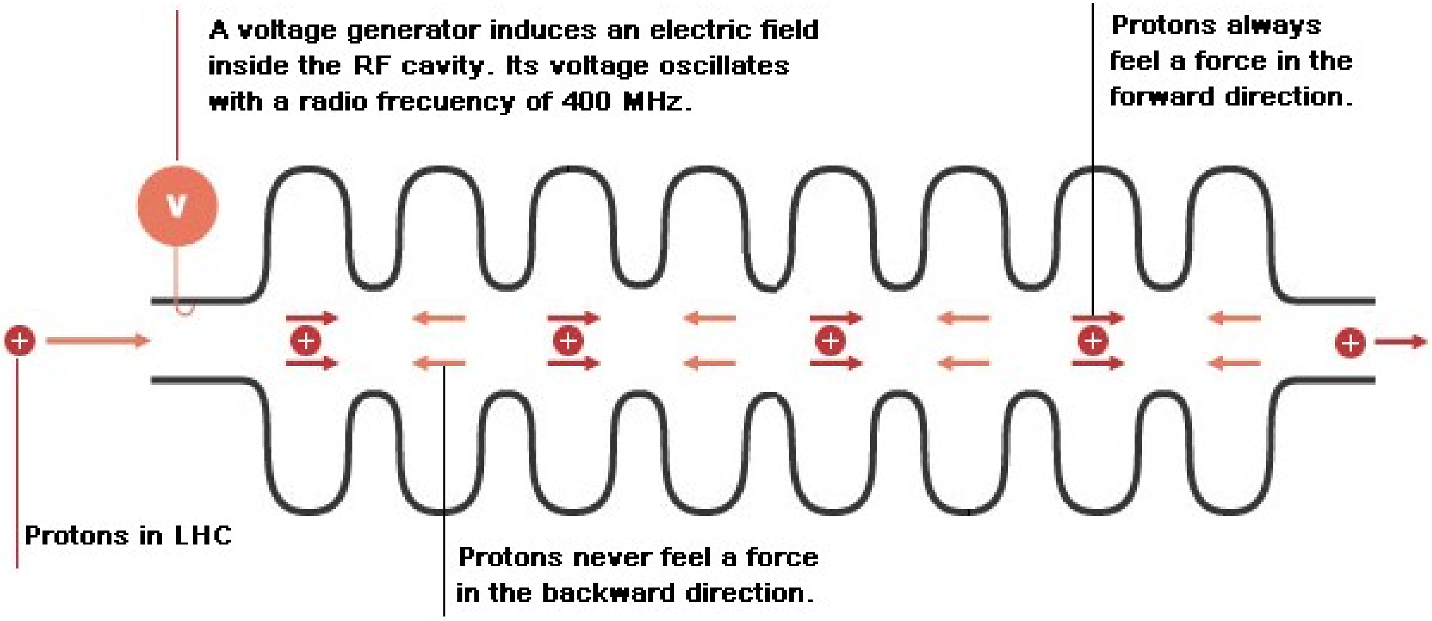


A voltage generator induces an electric field inside the RF cavity. Its voltage oscillates with a radio frecuency of 400 MHz.

Protons always feel a force in the forward direction.

Protons never feel a force in the backward direction.

eg. Large Hadron Collider, 26km circumference, accelerating protons to 13.6 TeV

Linear vs Circular?

Linear vs Circular?

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

Collider parameters

LINK

Hadron

	HERA (DESY)	TEVATRON* (Fermilab)	RHIC Brookhaven	LHC (CERN)		
Physics start date	1992	1987	2001	2009	2015	2026 (HL-LHC)
Physics end date	2007	2011	—	—		
Particles collided	ep	$p\bar{p}$	pp (polarized)	pp		
Maximum beam energy (TeV)	e: 0.030 p: 0.92	0.980	0.255 55% polarization	4.0	6.5	7.0
Max. delivered integrated luminosity per exp. (fb^{-1})	0.8	12	0.38 at 100 GeV 1.3 at 250/255 GeV	23.3 at 4.0 TeV 6.1 at 3.5 TeV	160	250/y

e^+e^-

	CESR (Cornell)	CESR-C (Cornell)	LEP (CERN)	SLC (SLAC)
Physics start date	1979	2002	1989	1989
Physics end date	2002	2008	2000	1998
Maximum beam energy (GeV)	6	6	100 - 104.6	50
Delivered integrated luminosity per experiment (fb^{-1})	41.5	2.0	0.221 at Z peak 0.501 at 65 – 100 GeV 0.275 at >100 GeV	0.022

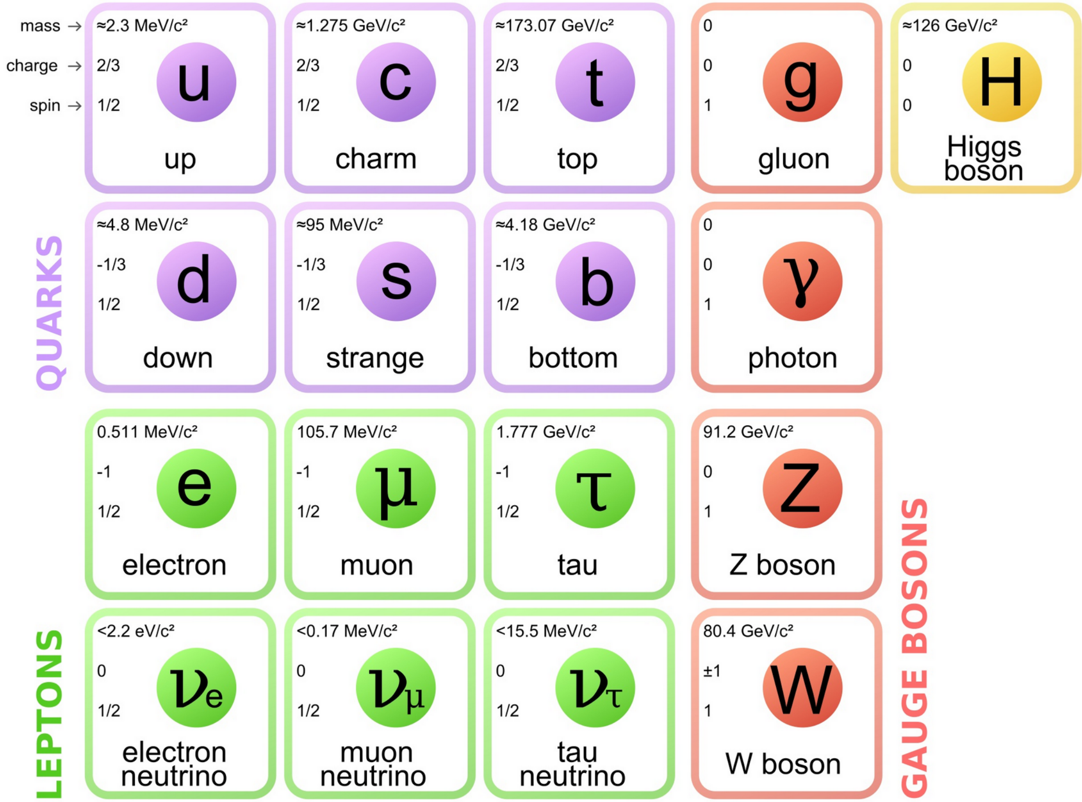
Heavy Ions

	RHIC (Brookhaven)		LHC (CERN)			
Physics start date	2000	2012 / 2018 / 2018 / 2012 / 2004 2014 / 2002 / 2015 / 2015	2010	2012	2017	≥ 2021 (high lum.)*
Physics end date	—		—			
Particles collided	Au Au	U U / Zr Zr / Ru Ru / Cu Au Cu Cu / h Au d Au / p Au / p Al	Pb Pb	p Pb	Xe Xe	Pb Pb
Max. beam energy (TeV/n)	0.1	0.1	2.51	p:6.5 Pb:2.56	2.72	2.76
$\sqrt{s_{NN}}$ (TeV)	0.2	0.2	5.02	8.16	5.44	5.5
Max. delivered int. nucleon-pair lumin. per exp. (pb^{-1})	2639 (at 100 GeV/n)	21 / 36 / 36.9 / 167 / 60 43 / 169 / 124 / 63 (all at 100 GeV/n)	77.8	194	0.05	≈ 121/y

Timeline of discoveries:

1897 : Electron – Cathode ray
1932 : Positron – Cloud chamber
1937 : Muon – Cloud chamber
1956 : Electron neutrino – Scintillator
1962 : Muon neutrino
1968 : u, d, s quarks – SLAC
1974 : c quark - SLAC
1975 : Tau – SLAC, LBNL
1977 : b quark – Fermilab
1979 : gluons - DESY
1983 : W and Z – UA1, UA2 (CERN)
1995 : t quark - Fermilab
2000 : Tau neutrino – DONUT collaboration

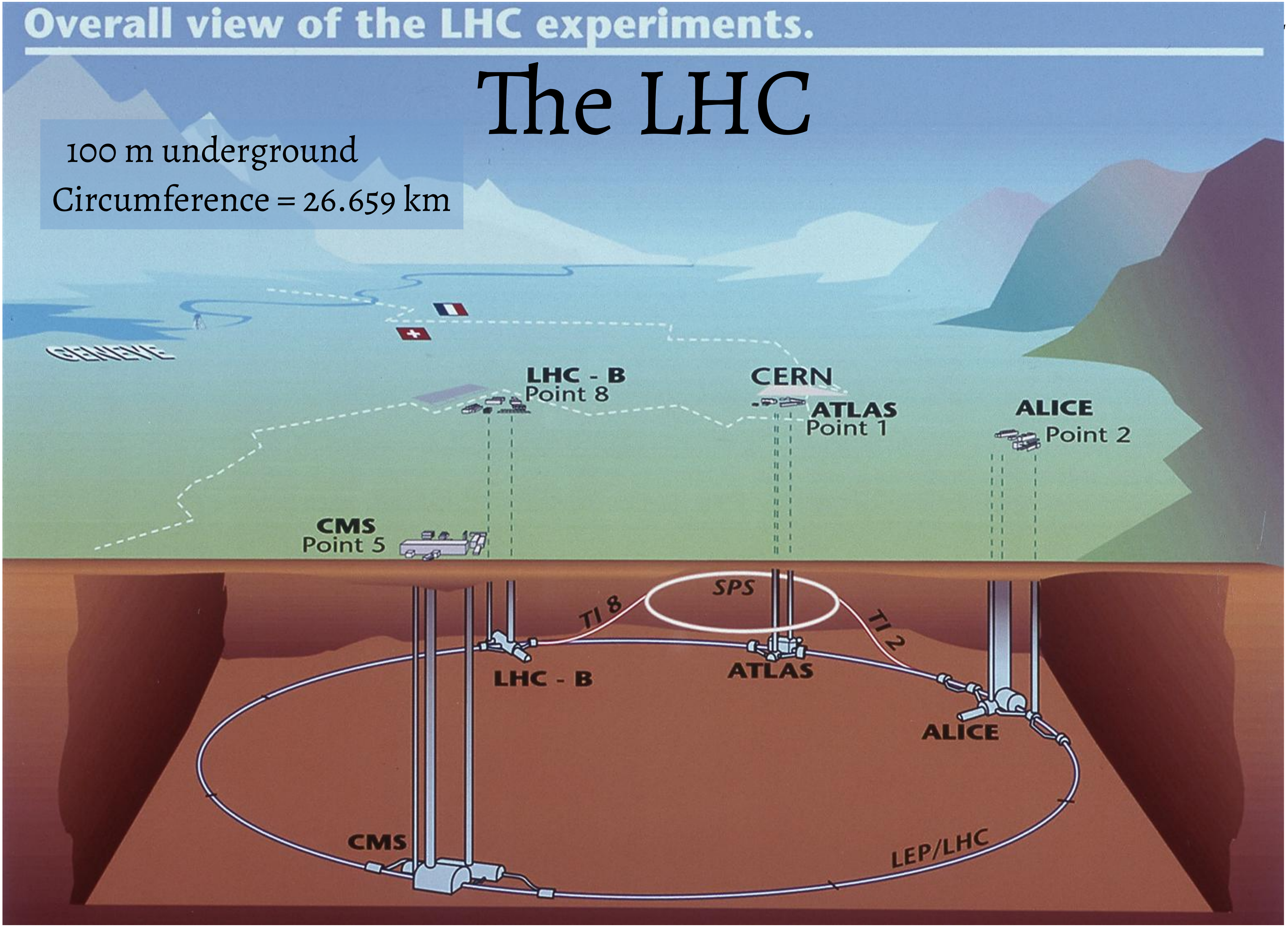
2012 : Higgs boson – LHC (CERN)



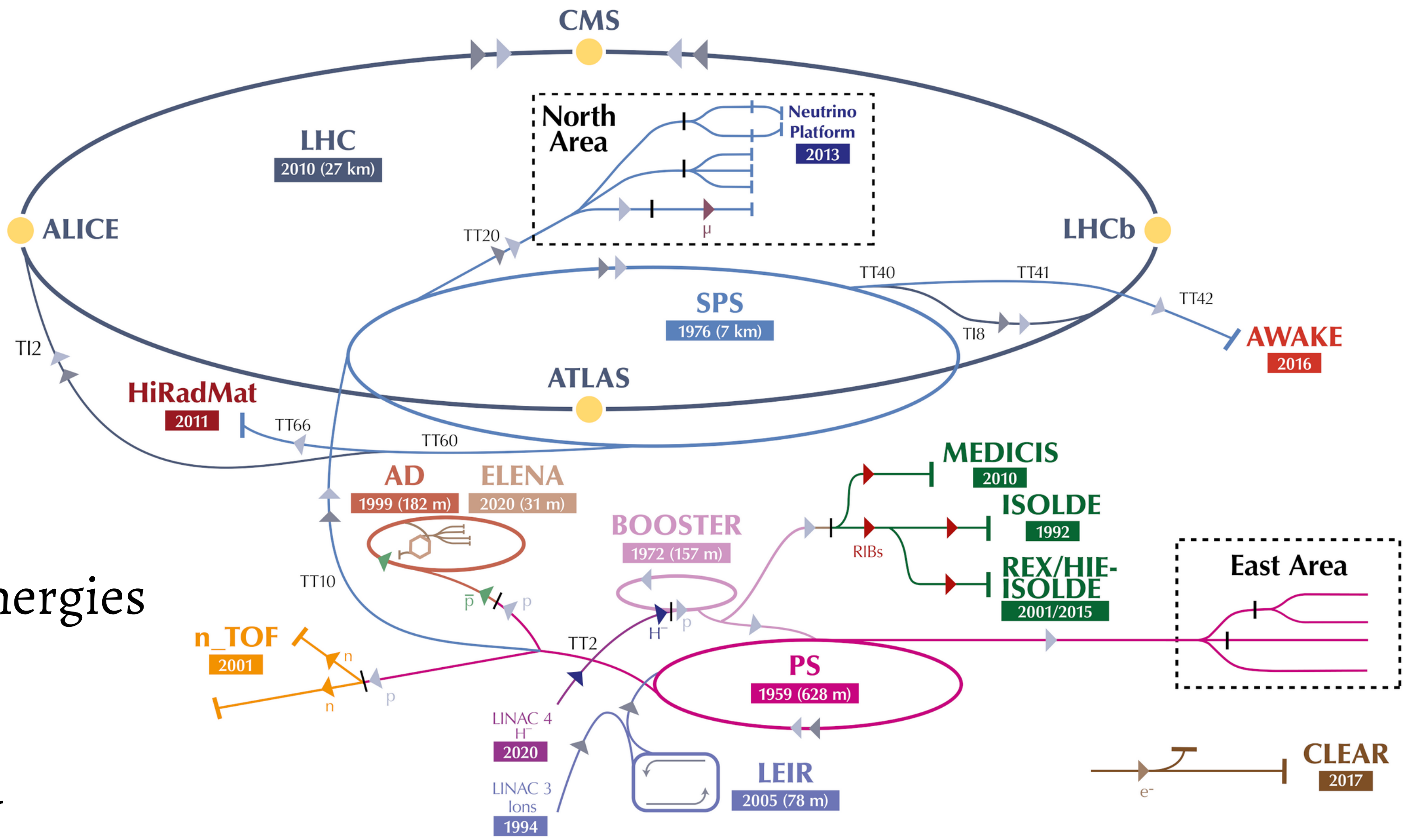
The LHC

100 m underground

Circumference = 26.659 km



LHC complex



LHC operating energies

2010+2011	7 TeV
2012	8 TeV
2015-2018	13 TeV
2022-....	13.6 TeV

LINAC	→	BOOSTER	→	PS	→	SPS	→	LHC
50 MeV		1.4 GeV		26 GeV		400 GeV		7 TeV

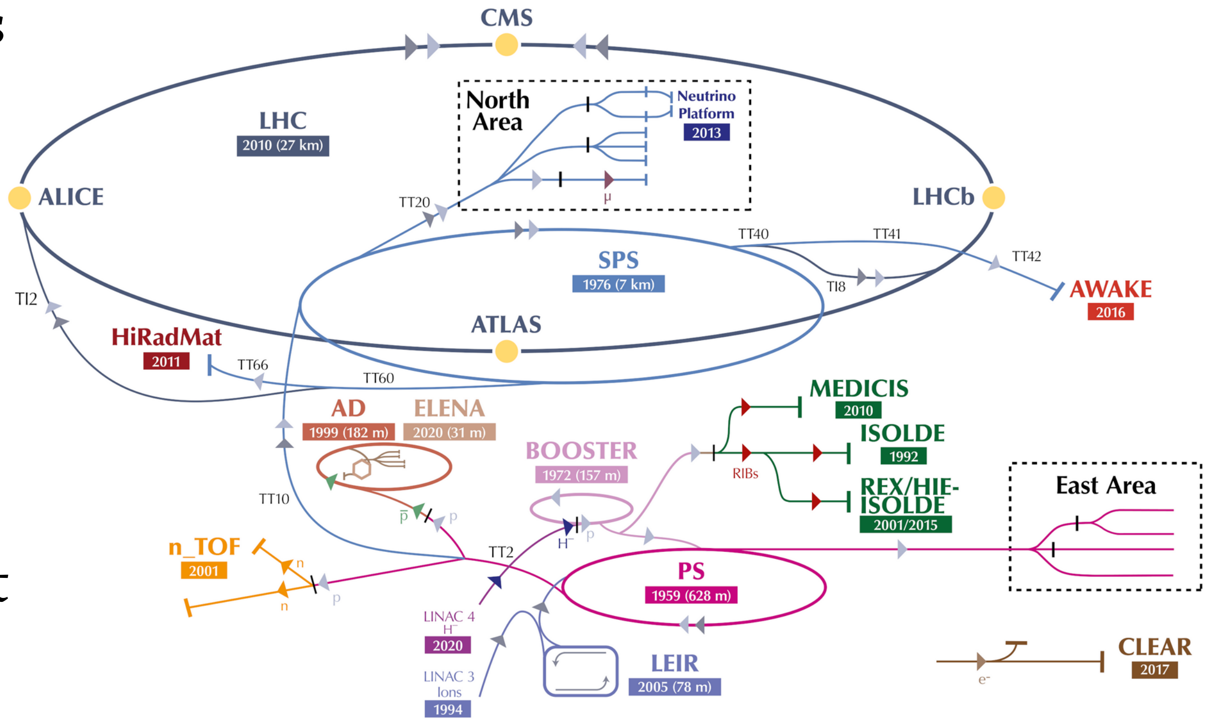
LHC complex

Beam consists of proton bunches

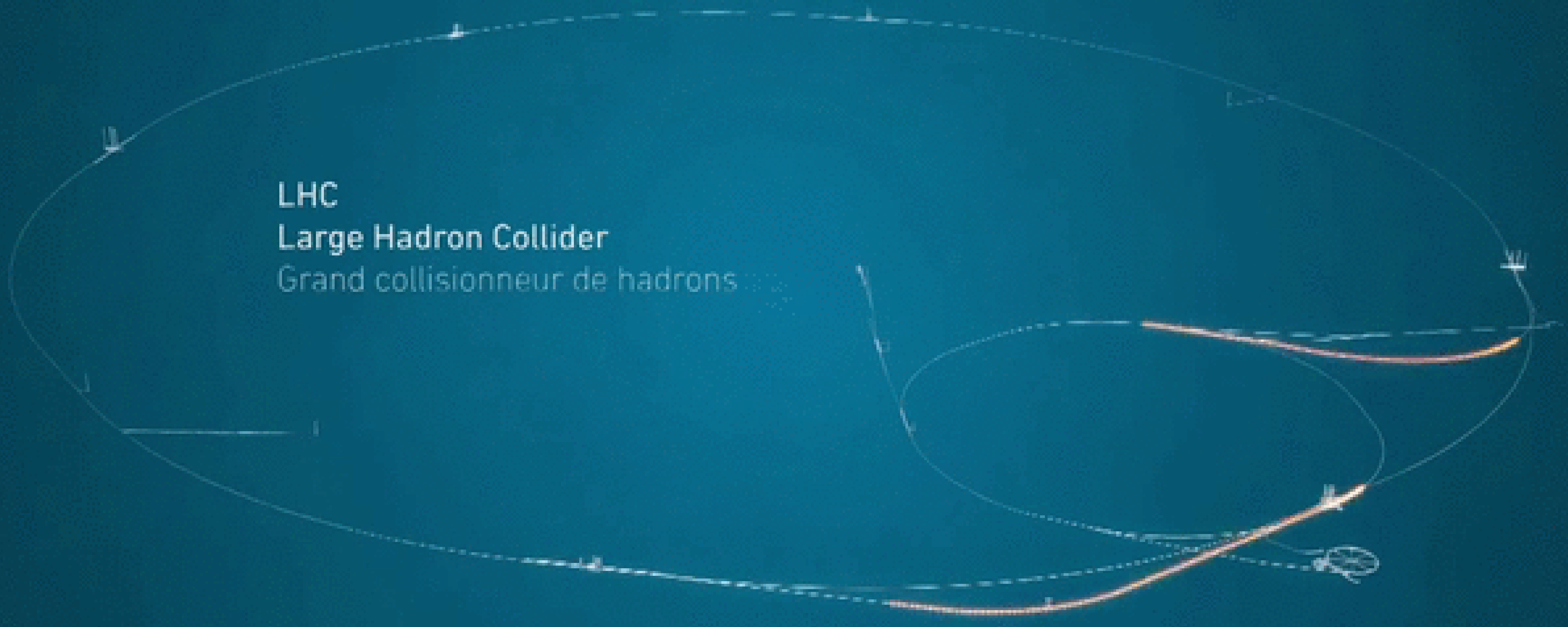
Each bunch has 10^{11} protons

There are ~2000 bunches in the beam, separated by 7.5m (25ns)

These bunches cross each other at specific points at 40 MHz
(these specific points are the detectors, where collisions happen each time a bunch crosses)

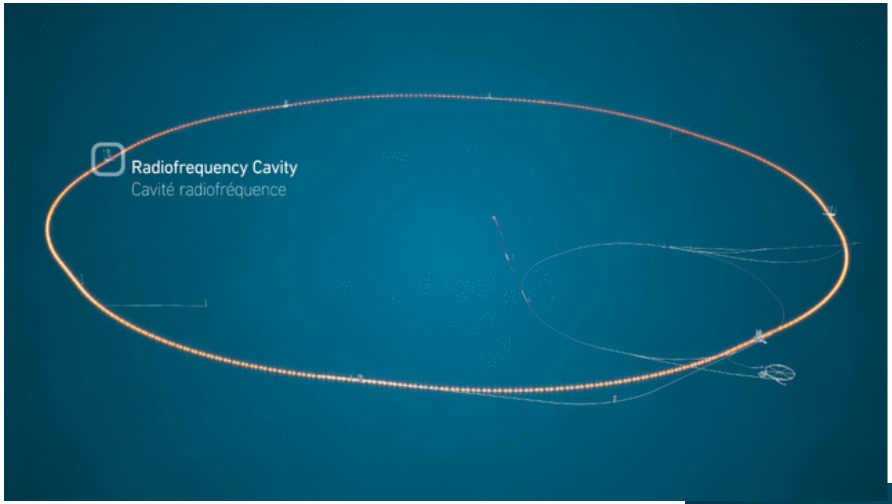


Thus, a collision = a bunch crossing

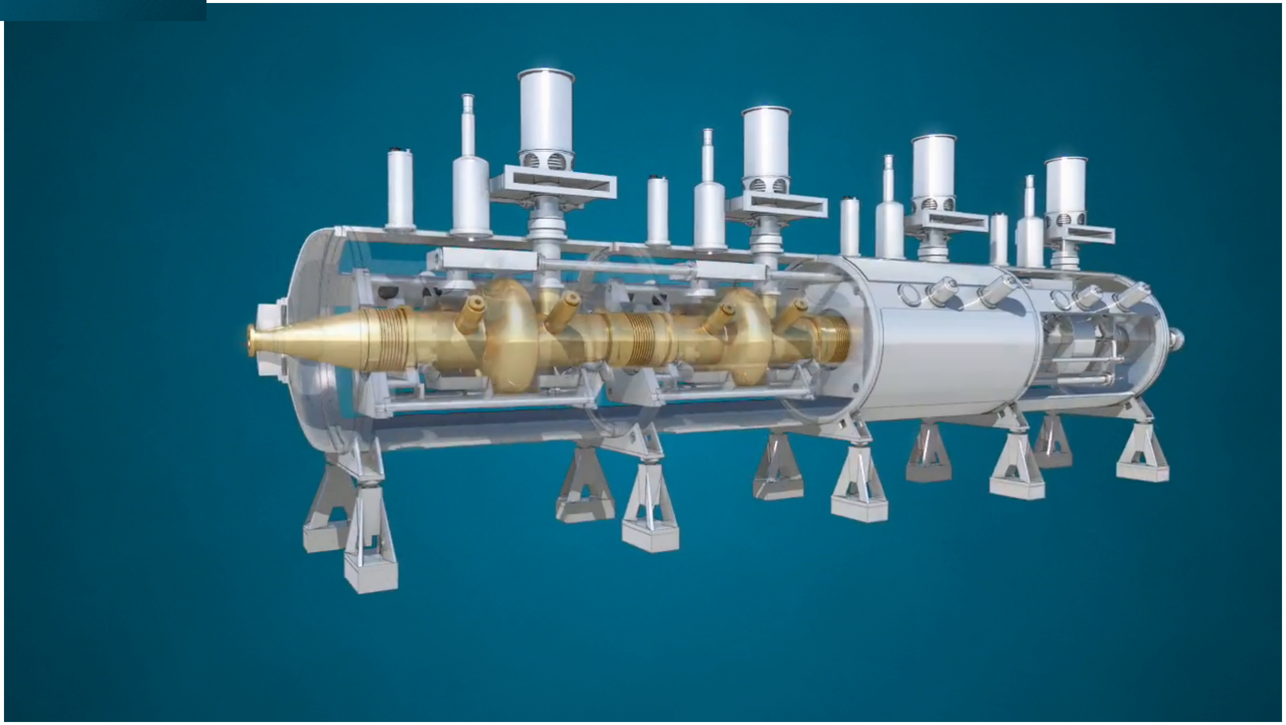


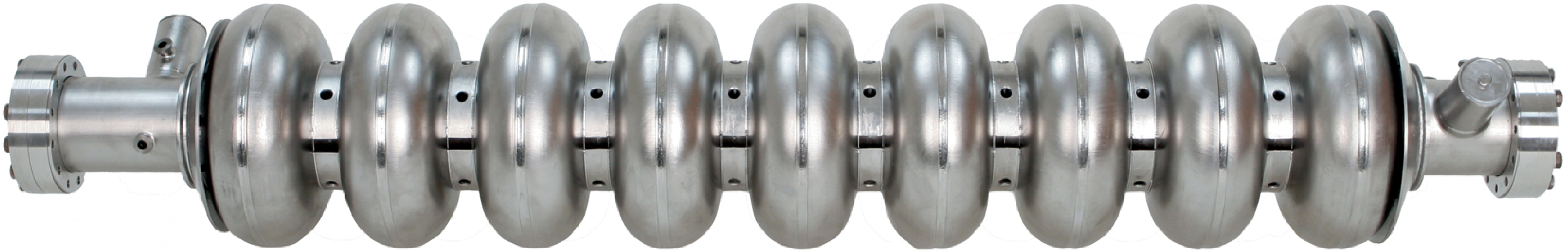
LHC
Large Hadron Collider
Grand collisionneur de hadrons

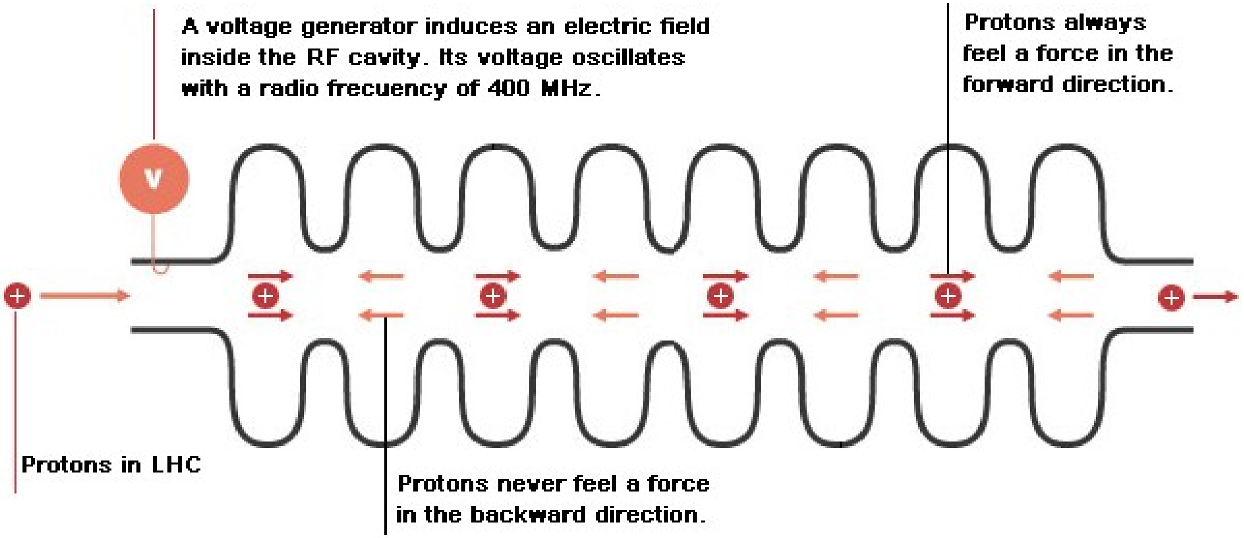
Acceleration



Primarily through RF cavities







A voltage generator induces an electric field inside the RF cavity. Its voltage oscillates with a radio frecuency of 400 MHz.

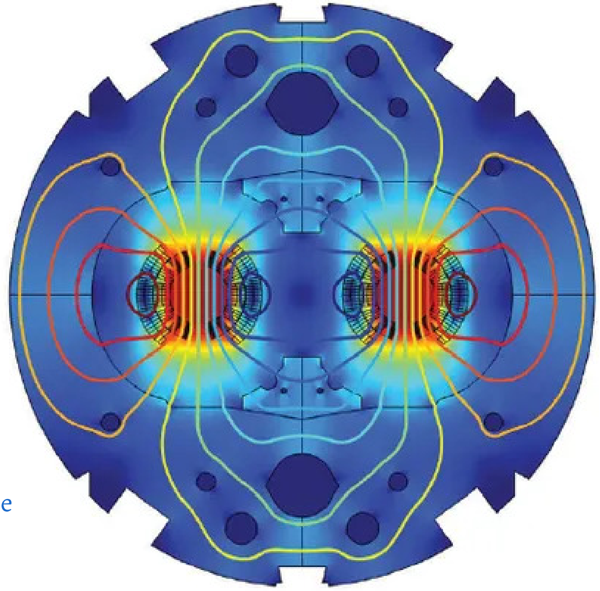
Protons always feel a force in the forward direction.

Protons in LHC

Protons never feel a force in the backward direction.

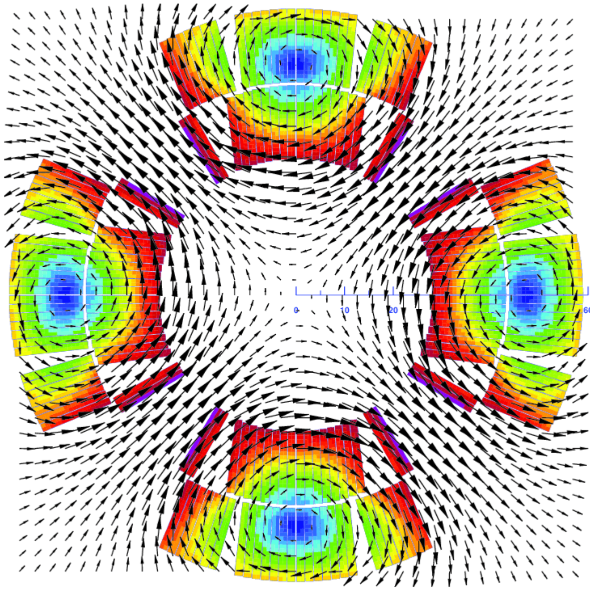
Magnets

Dipoles used for bending

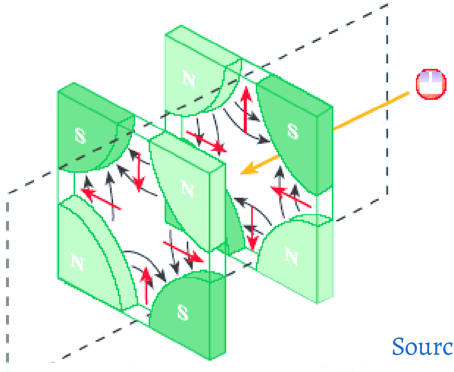


Source

Quadrupoles and higher poles for focusing



Sonnemann, Florian. (2022). Resistive Transition and Protection of LHC Superconducting Cables and Magnets.



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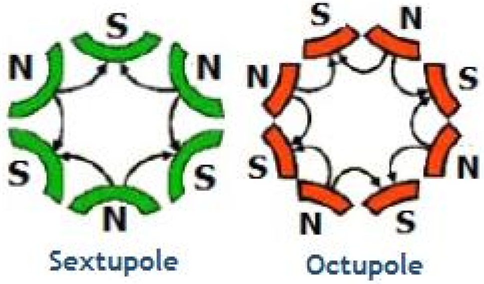
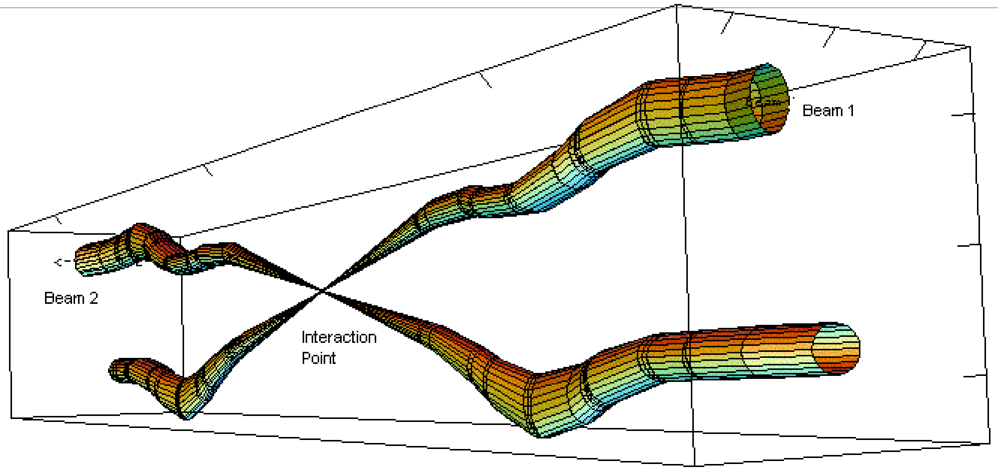




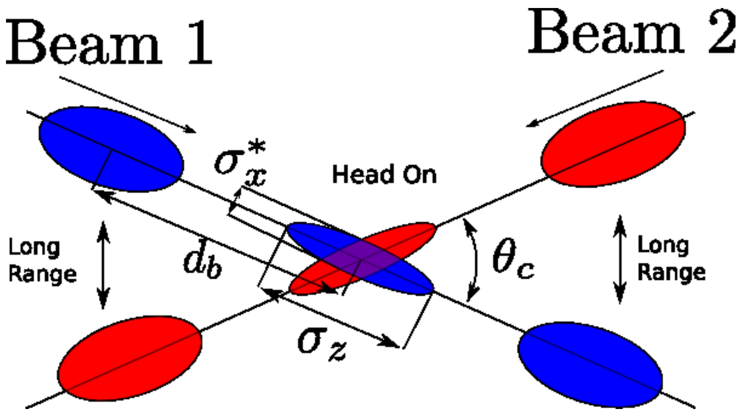
Relative beam sizes around IP1 (Atlas) in collision

Luminosity instantaneous (L_{inst}) and integrated ($\mathcal{L}$)

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

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.

LHC peak L_{inst} ~ 2x10^{34} $cm^{-2}s^{-1}$



De Maria, Riccardo & Brüning, Oliver & Leonid, Rivkin. (2008). LHC Interaction region upgrade.

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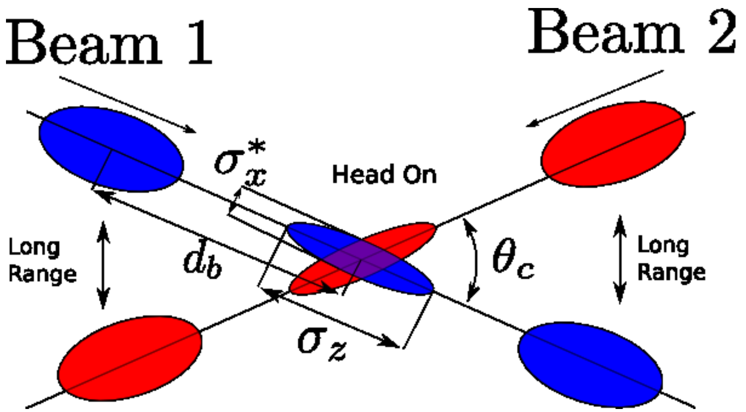
$$\mathcal{L} = \int L_{\text{inst}}\, dt$$

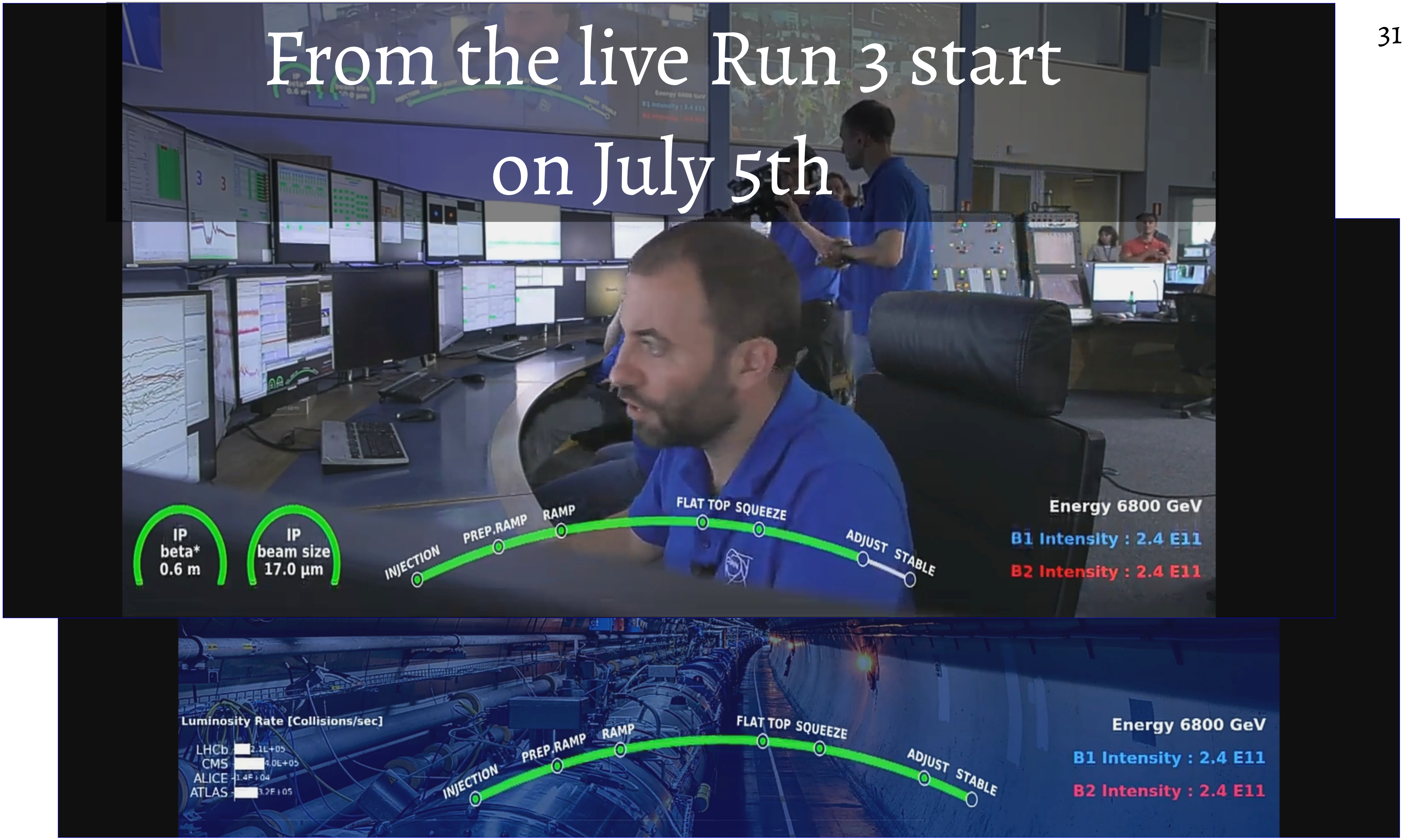
Integrated luminosity



De Maria, Riccardo & Brüning, Oliver & Leonid, Rivkin. (2008). LHC Interaction region upgrade.

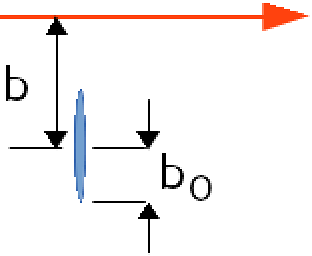
Effectively, the integrated luminosity is a measure of the total number of collisions…. more on that in just a bit….

From the live Run 3 start on July 5th



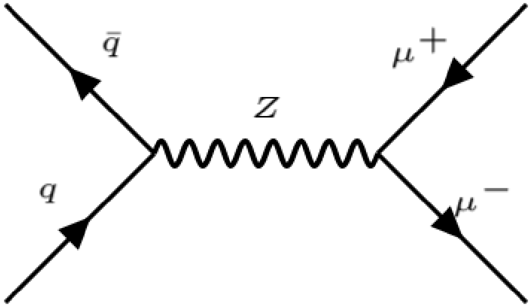
Youtube link

Quick aside: 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

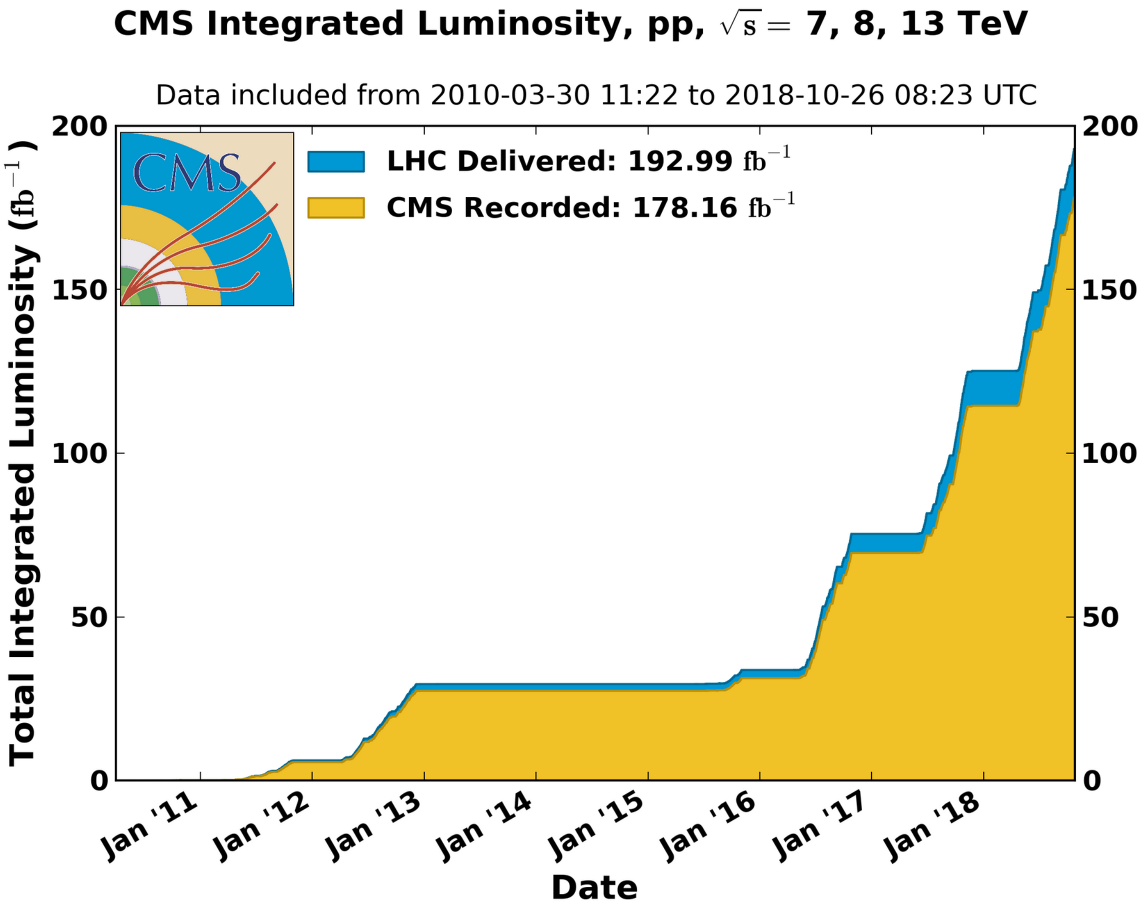
Integrated Luminosity

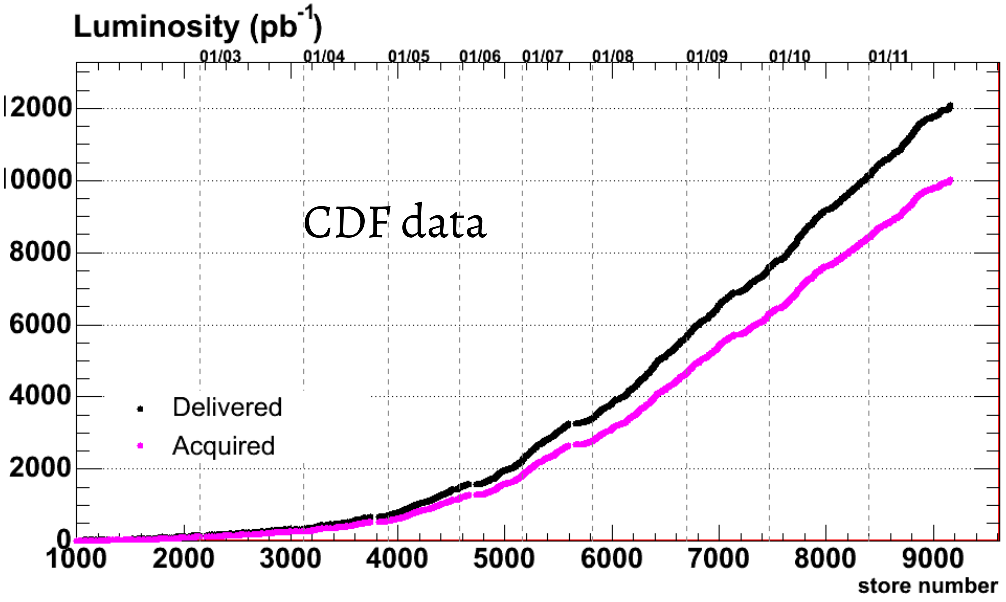
$\mathcal{L}$ has dimensions of inverse area.

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}

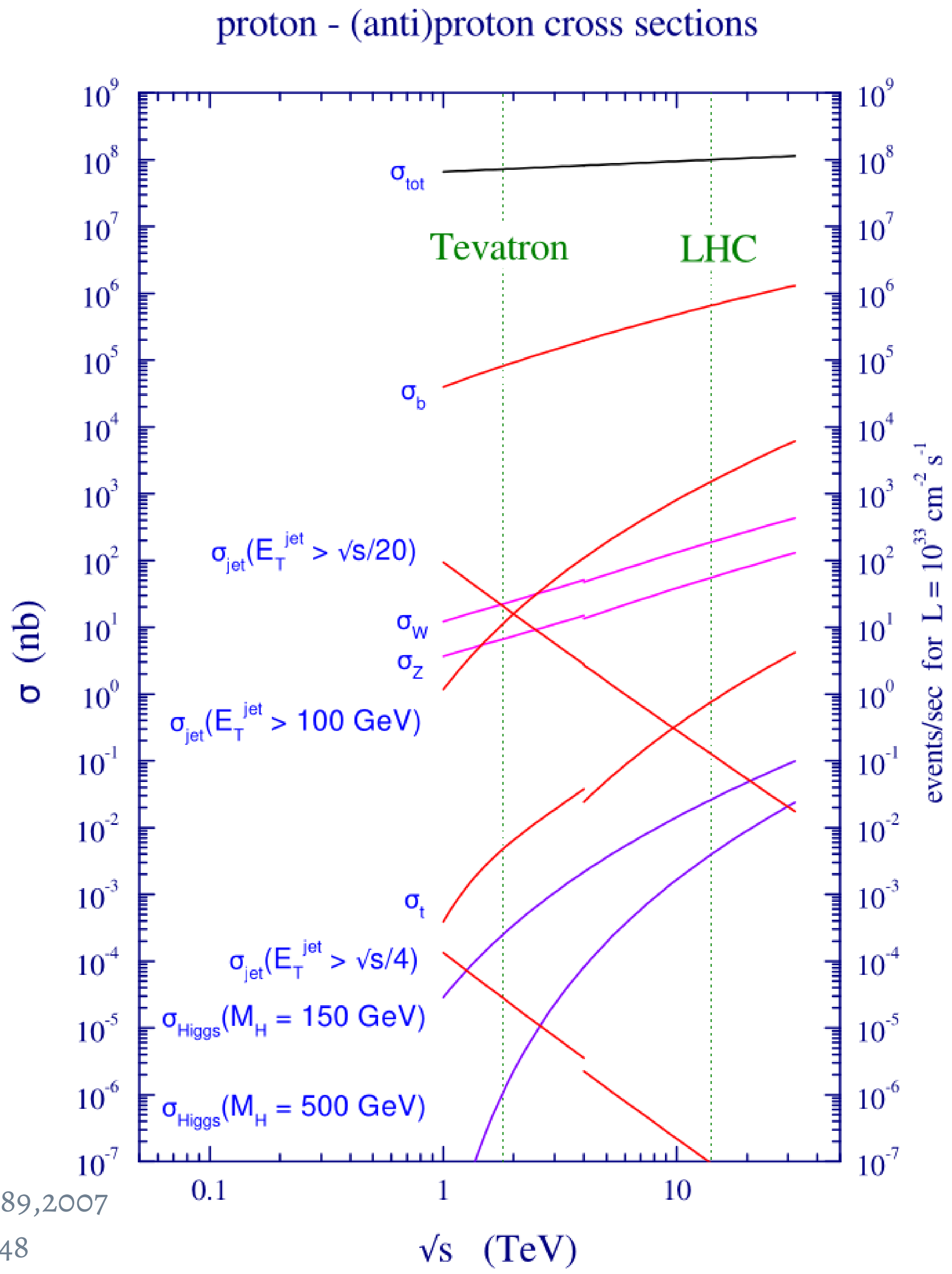




Event Counts

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

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

Next?

So we can now collide protons and produce a lot of data.

How do we observe and study the collisions?

Particle detection

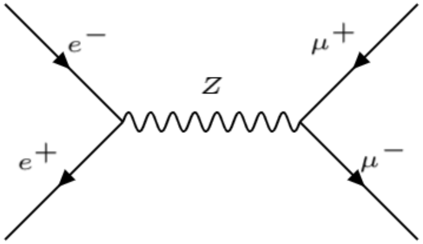
Particles can only be detected, if they interact with something.

Conversely, the primary interactions of particles can be used to detect them.
(eg. photons through EM interactions, hadrons through strong and EM interactions)

Before we get into material interactions, we have to cover two quick things
– right picture of proton collisions
– hadronization

Electron-positron collisions

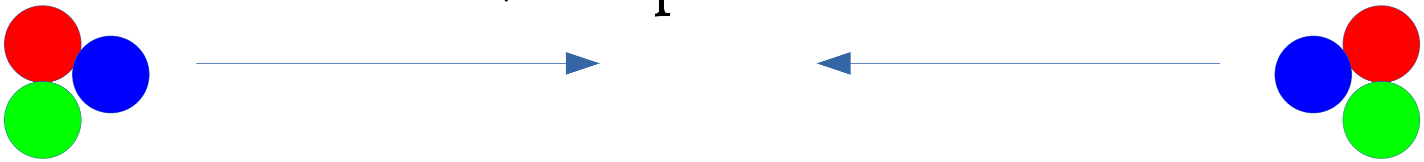
4-vector (E,p) of electron/positron known well



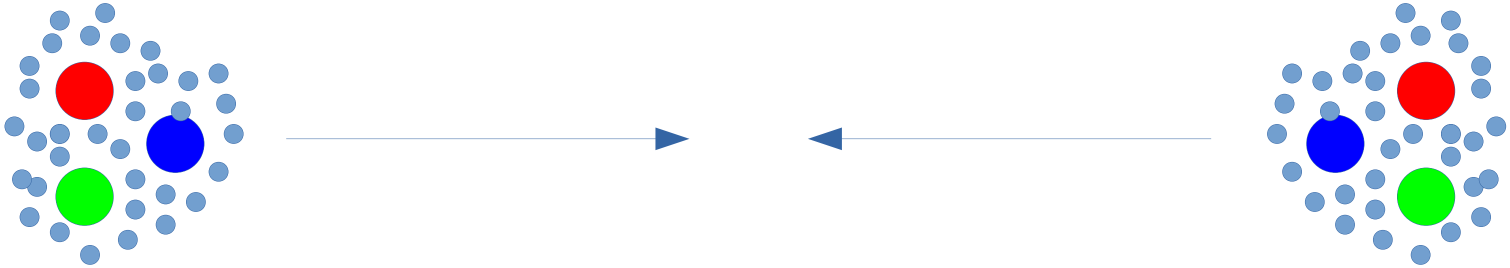
Need 4-vector of incoming particle to calculate cross section

Proton-proton collisions

Naive picture.

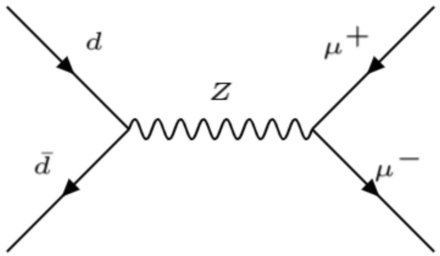


Actually,



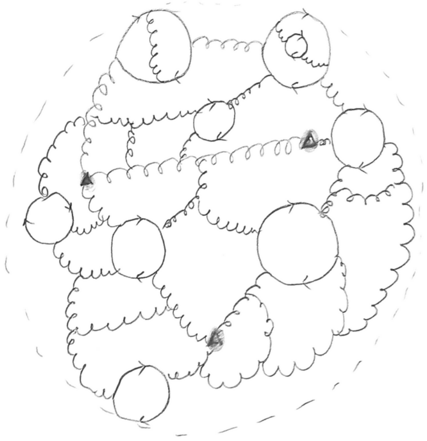
Messy… very messy.

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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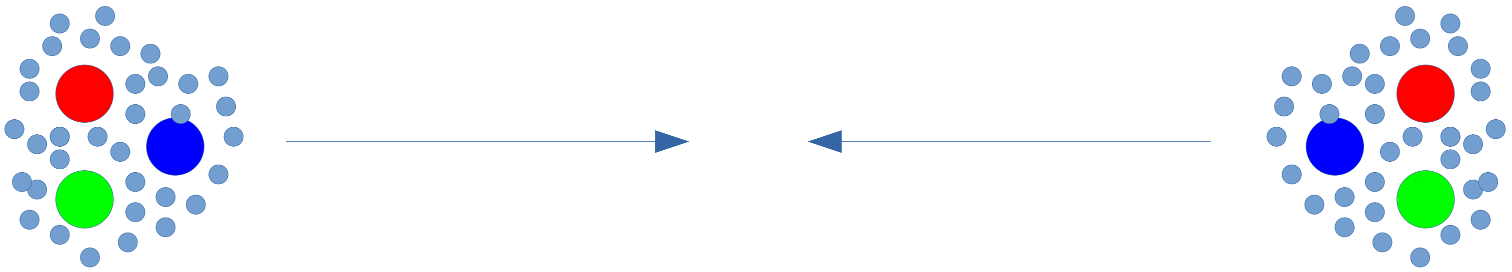
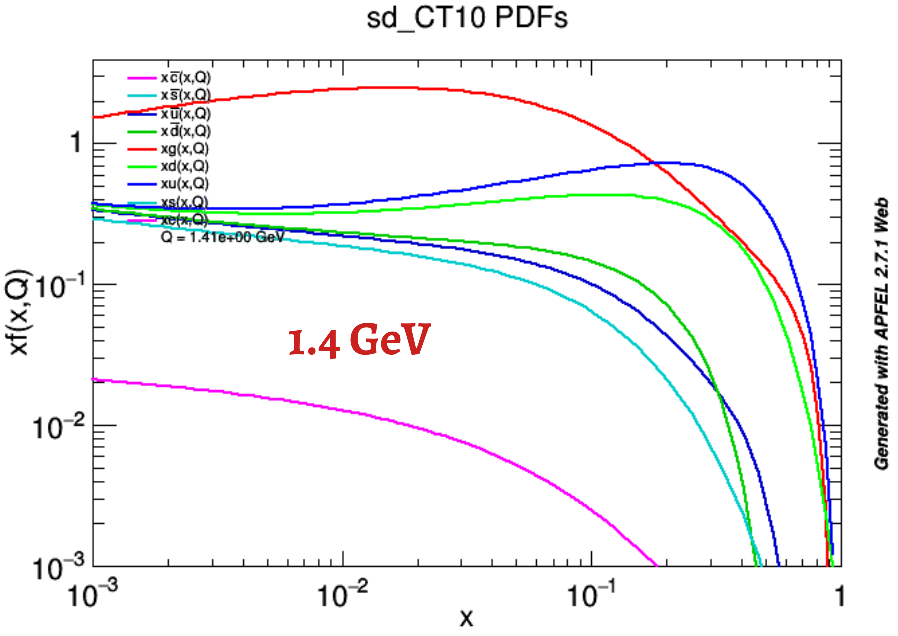
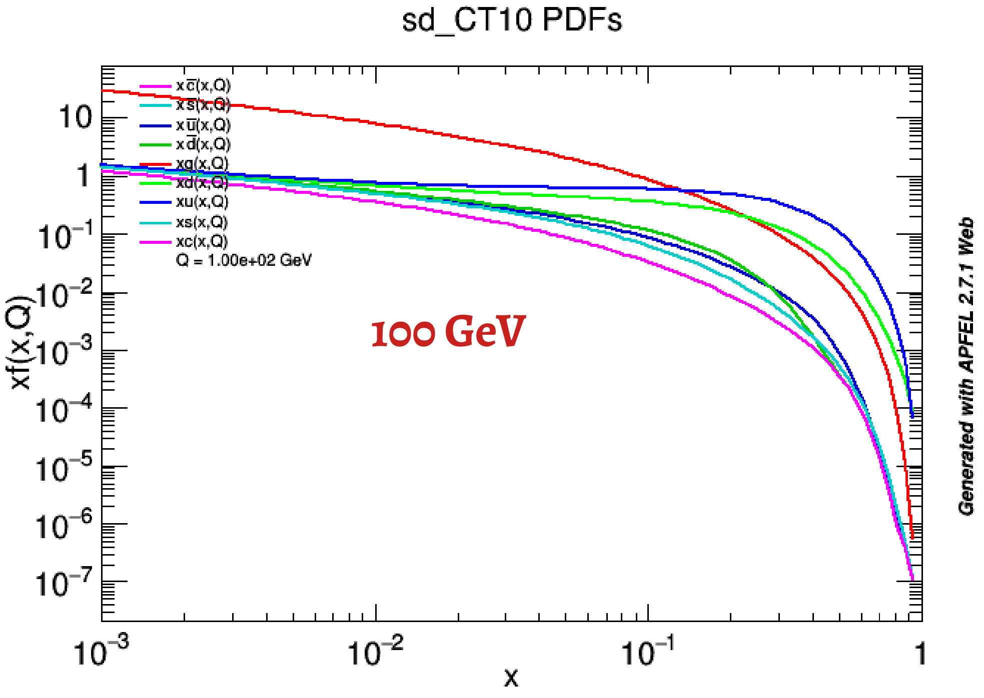


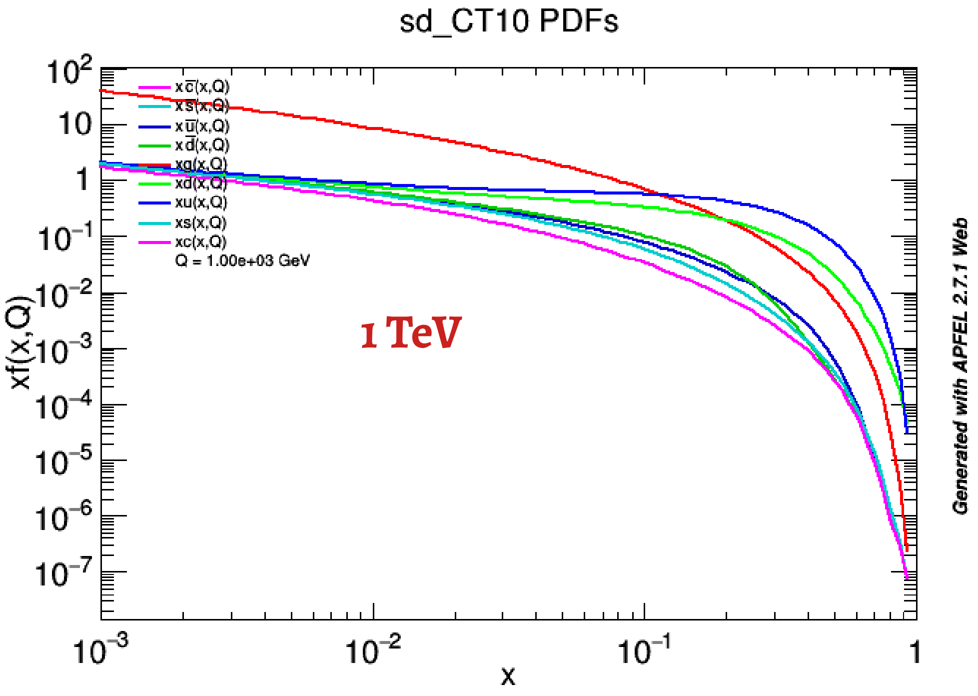
Messy… very messy.

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)

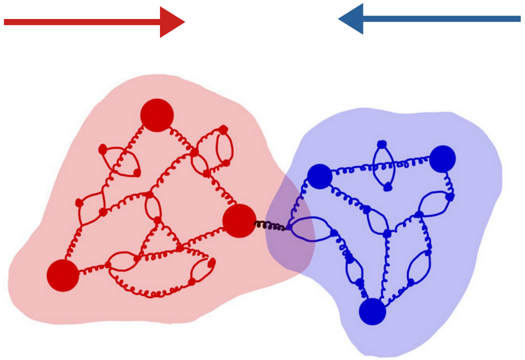
PDFs







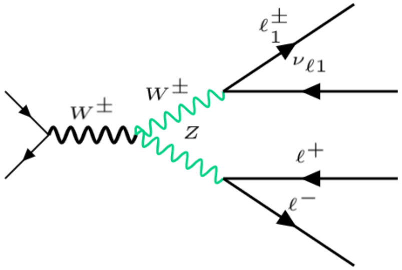
Used the CT10 PDF, and APFEL for visualization
https://apfel.mi.infn.it/home

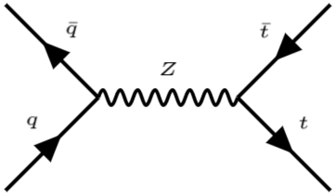


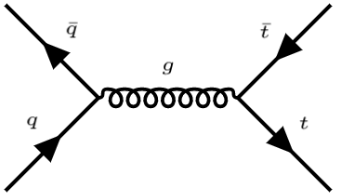
Typically, the interactions or processes that interest us, start from quarks or gluons.

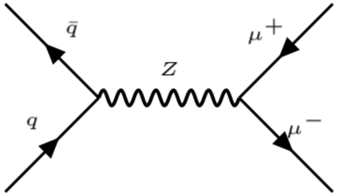
These incoming quarks/gluons will carry a fraction of the total energy/momentum of the proton…

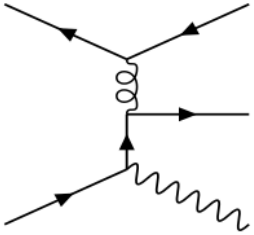
Effectively our collisions/processes occur at a range of energies

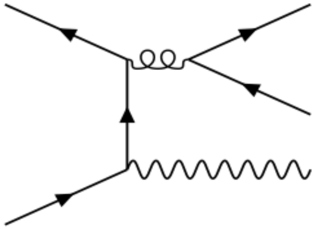












Hadronization

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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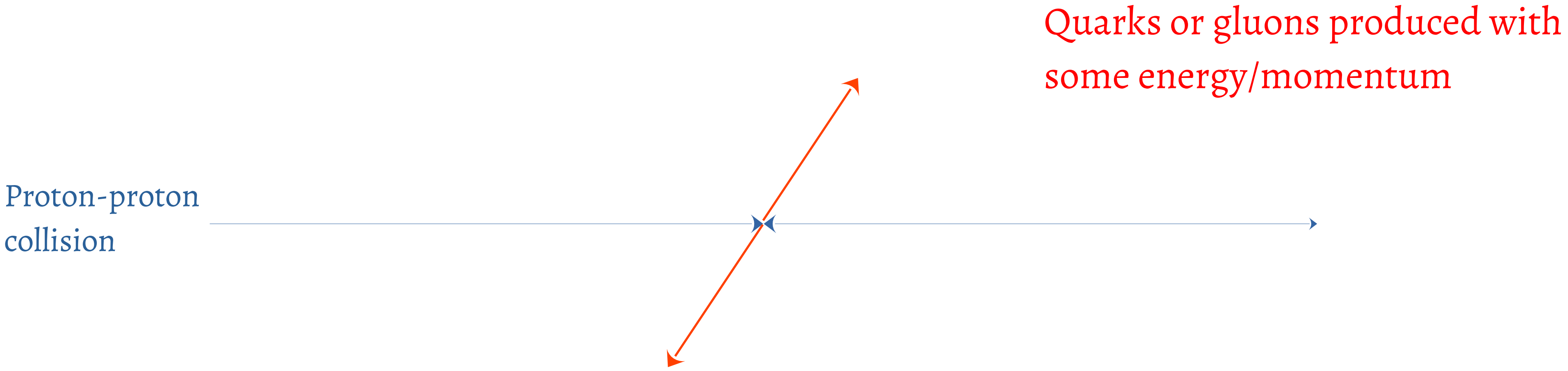

Quarks or gluons produced with some energy/momentum

Proton-proton collision

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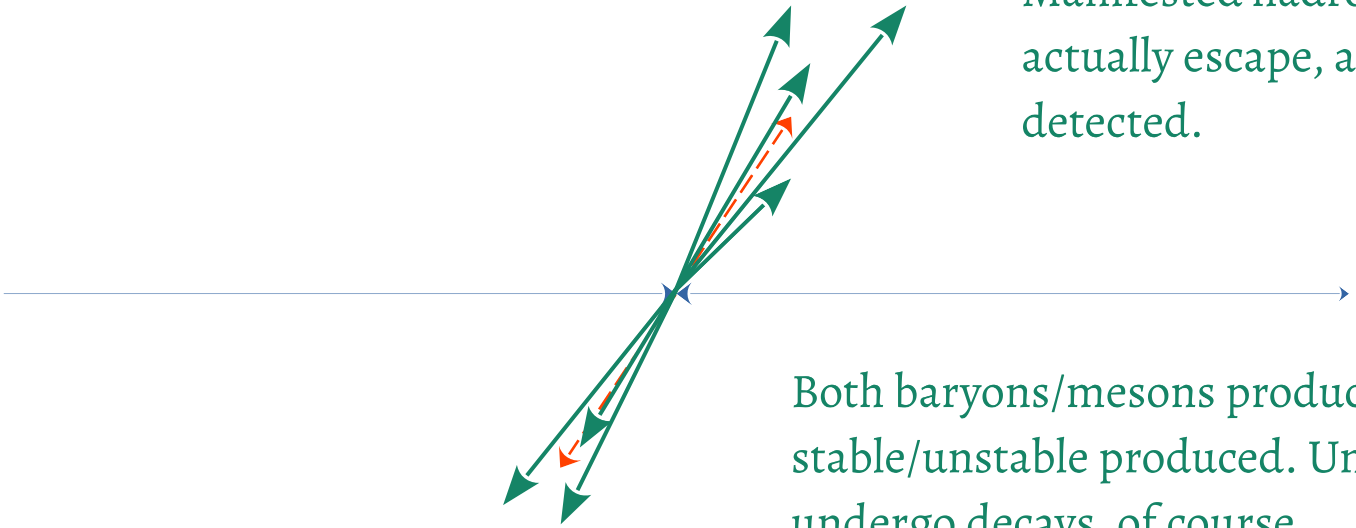

Proton-proton collision

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

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

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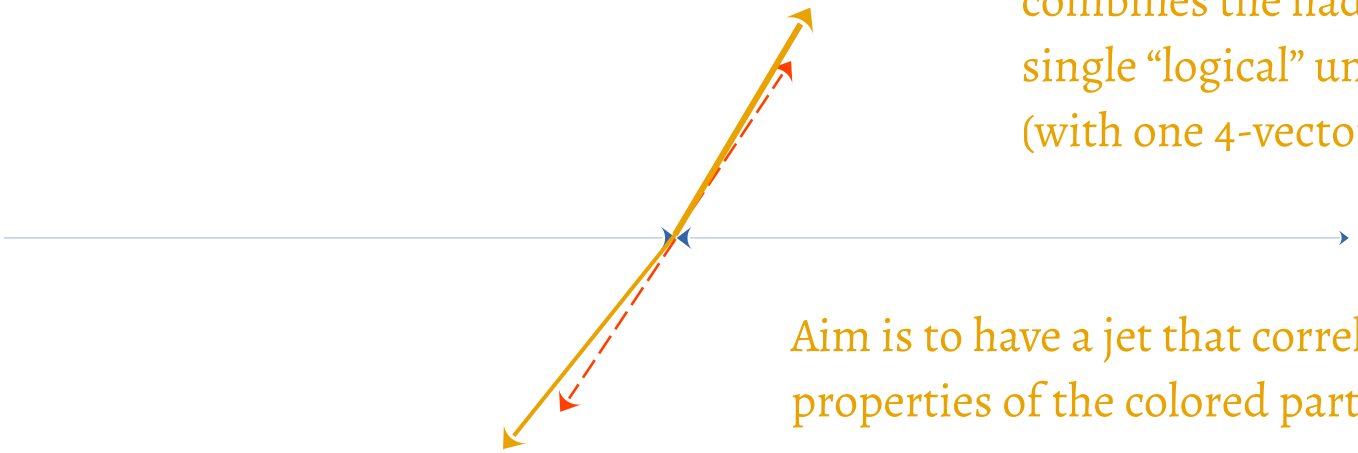

A jet clustering algorithm combines the hadrons into a single "logical" unit, called a jet (with one 4-vector)

Proton-proton collision

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

More on jet clustering algorithms later…