Introduction to Nuclear and Particle Physics

PHY357

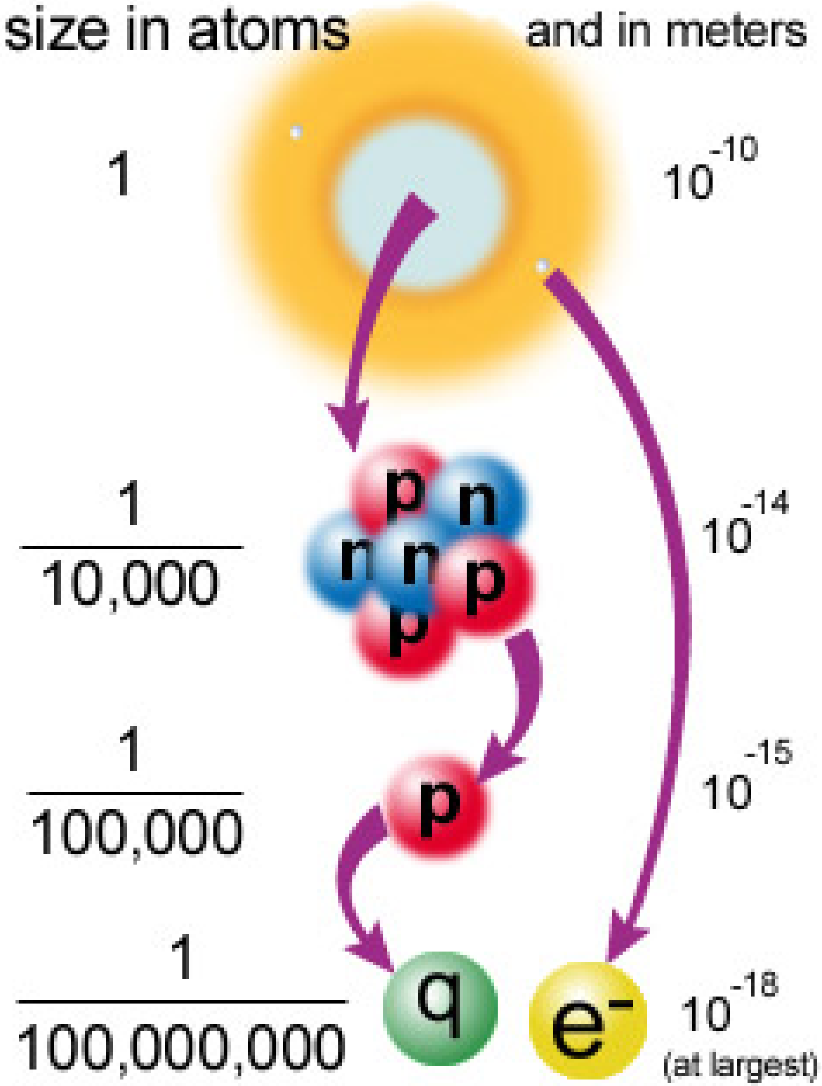
Better name is probably Introduction to Subatomic physics:

Emphasis is on particle physics; nuclear physics is simply particle physics at relatively low energy.

Course web page http://www.physics.utoronto.ca/~krieger/phys357.html

- **Course outline**
- **Announcements**
- **Reference materials**
- **Grading Scheme**
- **Dates for Assignments and Tests**
- **Office Hours**
- **Policies Assignments**
- **Policies on Email**

The Subatomic World



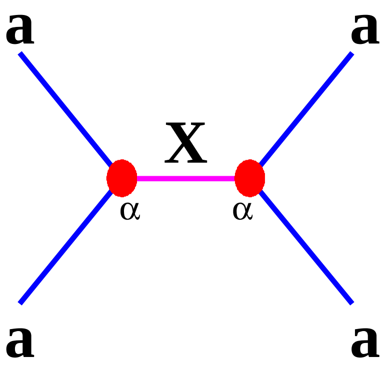
Experimental investigation of smaller and smaller distance scales require higher and higher energies

“fundamental” particles are point-like at the highest experimentally achievable energy scale

The Standard Model

Describes the FUNDAMENTAL PARTICLES and their INTERACTIONS

All known FORCES are mediated by PARTICLE EXCHANGE



Effective strength of an interaction depends on

- **the (dimensionless) coupling strength at the vertex**
- **the mass of the exchanged particle M_X**

Force	Effective Strength	Physical Process
Strong	10^{0}	Nuclear binding
Electromagnetic	10^{-2}	Electron-nucleus binding
Weak	10^{-5}	Radioactive β decay

Fundamental Interactions

Structure of the Standard Model:

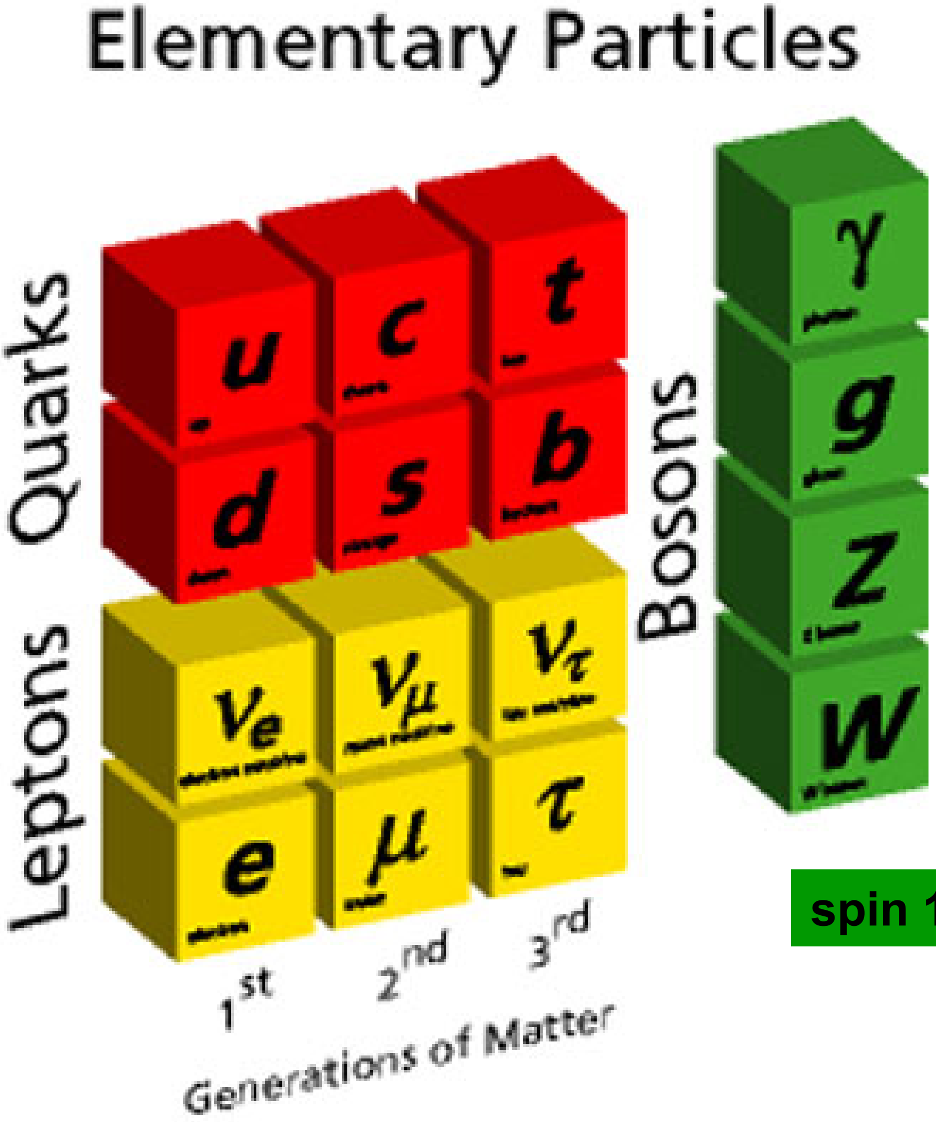
- **Electromagnetic Interaction (QED)**
- **Weak Interaction**
- **Strong Interaction (QCD)**

Electroweak Theory

QED = Quantum Electrodynamics

QCD = Quantum Chromodynamics

These models are defined by their particle content of the theory and by the allowed interactions of these particles (i.e. what are the allowed vertices)



spin 1/2

spin 1/2

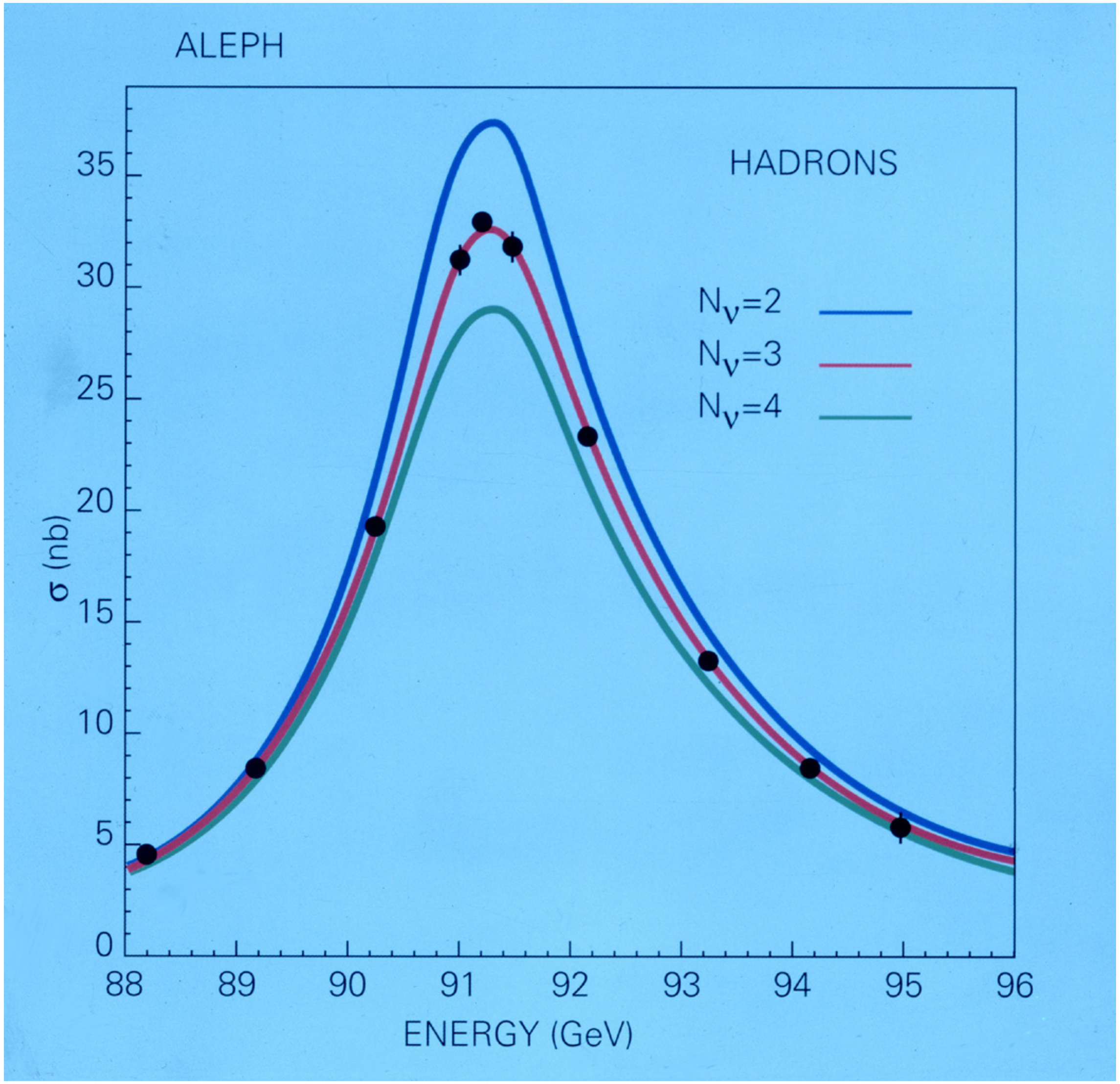
electromagnetic force

strong force

weak force

spin 1

Number of Light Fermion Generations



Need to account for the three colour states of each quark when calculating the SM rate for this process.

The Standard Model of Particle Physics

Fermions
(spin ½)
Matter particles

$$\begin{pmatrix} \mathbf{e} \\ \nu_{\mathbf{e}} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mu \\ \nu_{\mu} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \tau \\ \nu_{\tau} \end{pmatrix}_{\mathbf{L}}$$

charged leptons
neutral leptons

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix}_{\mathbf{L}}$$

quarks

Bosons
(spin 1)
Force carriers

$$\gamma$$

$$\mathbf{W}^{\pm}, \mathbf{Z}^{0}$$

$$\mathbf{g}$$

Standard Model predicts the existence of one fundamental scalar (spin-0) particle known as the *Higgs Boson*.

This is the only particle of the SM that has yet to be experimentally observed.

The Standard Model of Particle Physics

Fermions
(spin ½)
Matter particles

$$\begin{pmatrix} \mathbf{e} \\ \nu_{\mathbf{e}} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mu \\ \nu_{\mu} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \tau \\ \nu_{\tau} \end{pmatrix}_{\mathbf{L}}$$

Q = -1

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix}_{\mathbf{L}}$$

Q = +2/3

Q = -1/3

Bosons
(spin 1)
Force carriers

γ

$\mathbf{W}^{\pm}, \mathbf{Z}^{0}$

$\mathbf{g}$

Particles with electromagnetic interactions

The Standard Model of Particle Physics

Fermions
(spin ½)
Matter particles

$$\begin{pmatrix} \mathbf{e} \\ \nu_{\mathbf{e}} \end{pmatrix}_{\mathbf{L}} \qquad \begin{pmatrix} \mu \\ \nu_{\mu} \end{pmatrix}_{\mathbf{L}} \qquad \begin{pmatrix} \tau \\ \nu_{\tau} \end{pmatrix}_{\mathbf{L}}$$

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix}_{\mathbf{L}} \qquad \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix}_{\mathbf{L}} \qquad \begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix}_{\mathbf{L}}$$

Bosons
(spin 1)
Force carriers

$$\gamma$$

$$\boxed{\mathbf{W}^{\pm}, \mathbf{Z}^{0}}$$

$$\mathbf{g}$$

Particles with weak interactions

The Standard Model of Particle Physics

Fermions
(spin ½)
Matter particles

$$\begin{pmatrix} \mathbf{e} \\ \nu_{\mathbf{e}} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mu \\ \nu_{\mu} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \tau \\ \nu_{\tau} \end{pmatrix}_{\mathbf{L}}$$

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix}_{\mathbf{L}}$$

Bosons
(spin 1)
Force carriers

$$\gamma$$

$$\mathbf{W}^{\pm}, \mathbf{Z}^{0}$$

$$\mathbf{g}$$

Particles with strong interactions

The Standard Model of Particle Physics

Fermions

(spin ½)

Matter particles

$$\begin{pmatrix} \mathbf{e} \\ \nu_{\mathbf{e}} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mu \\ \nu_{\mu} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \tau \\ \nu_{\tau} \end{pmatrix}_{\mathbf{L}}$$

First observation 2001

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix}_{\mathbf{L}}$$

First observation 1995

Bosons

(spin 1)

Force carriers

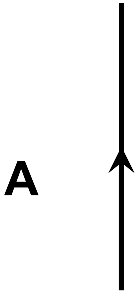
$$\gamma$$

$$\mathbf{W}^{\pm}, \mathbf{Z}^{0}$$

$$\mathbf{g}$$

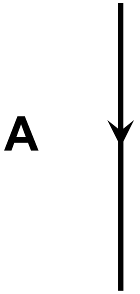
Feynman Diagrams for Fundamental Processes

Used to represent all fundamental interactions



Stable particle (A) in free space (moving or at rest)

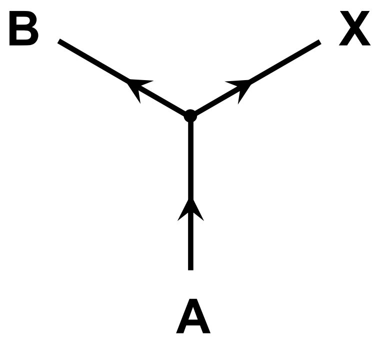
particle traveling backwards in time =
anti-particle traveling forwards in time



Stable anti-particle ($\bar{A}$) in free space (moving or at rest)

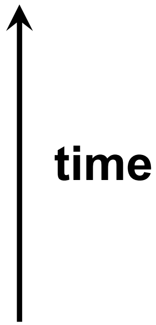
NB **here time runs upwards – The choice is merely a convention and has no other meaning. Often you will see it left to right.**

Feynman Diagrams for Fundamental Processes



Particle decay **$A \rightarrow B\ X$**

(assumes $M_A > M_B + M_X$)



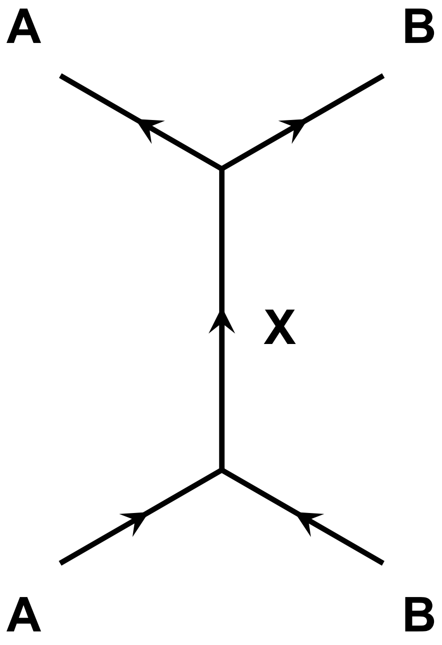
Read this as: at some point in time there is a particle A, and at a later point it decays into particles B and X

or X couples A to B

or X and B and A couple together

Note that there is no spatial component to these diagrams (the diverging lines do not imply that the particles are flying apart)

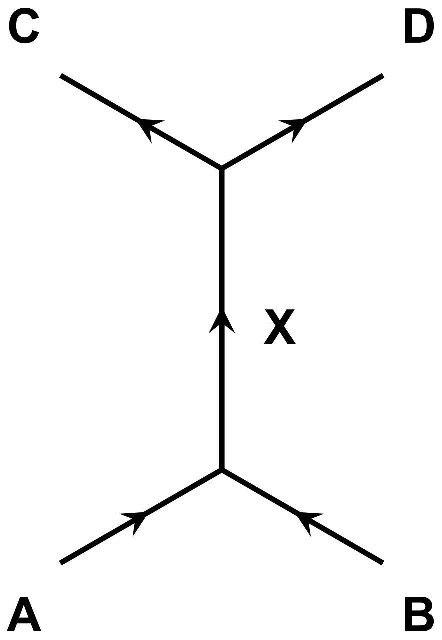
Feynman Diagrams for Scattering



Combine two vertex primitives to make lowest order scattering diagram

A + B → A + B

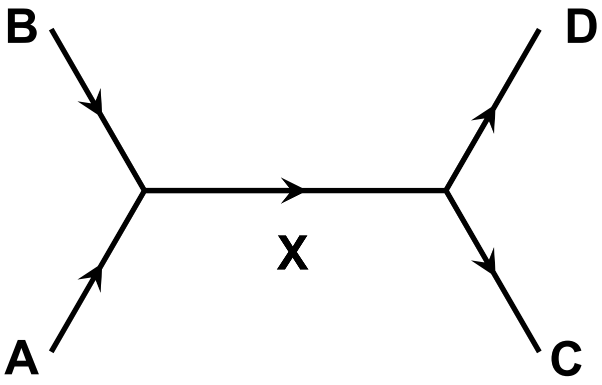
Feynman Diagrams for Scattering



if for example, X also couples C to D

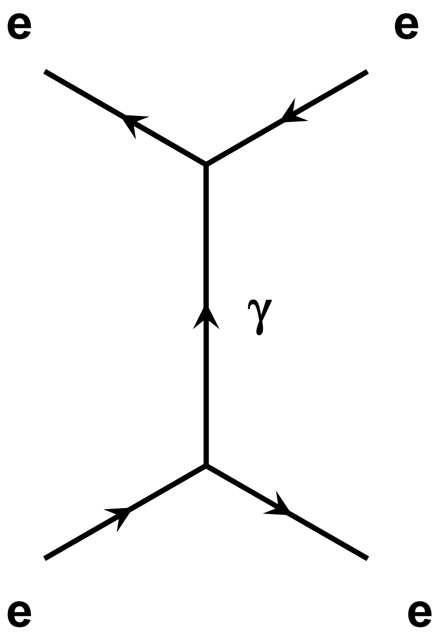
A + B → C + D

Feynman Diagrams for Scattering



$A + \bar{C} \rightarrow \bar{B} + D$

Feynman Diagrams for Scattering

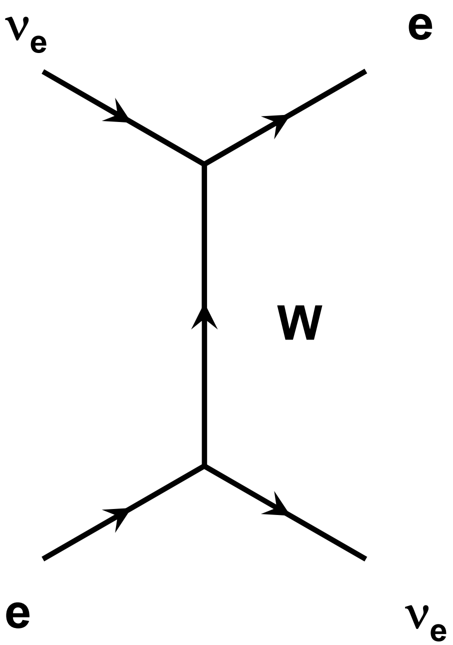


$e^+ e^- \rightarrow e^+ e^-$

(Bhabha scattering)

Electromagnetic interaction

Feynman Diagrams for Scattering

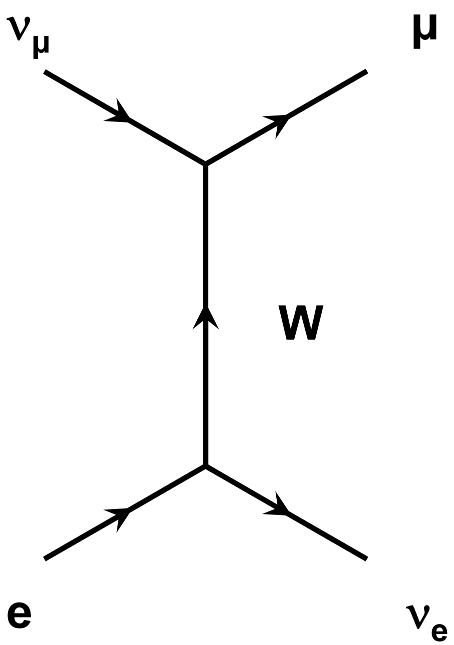


e $\bar{\nu}_e$ → e $\bar{\nu}_e$

(electron-neutrino scattering)

weak interaction

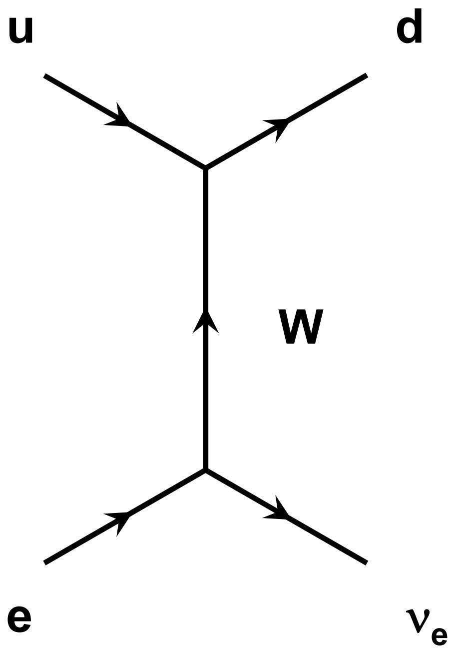
Feynman Diagrams for Scattering



$e\ \bar{\nu}_e \rightarrow \mu\ \bar{\nu}_\mu$

weak interaction

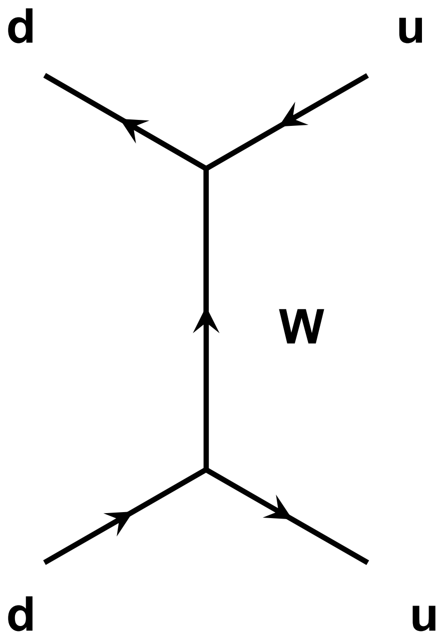
Feynman Diagrams for Scattering



$e\,\bar{\nu}_e \rightarrow \bar{u}\,d$

weak interaction

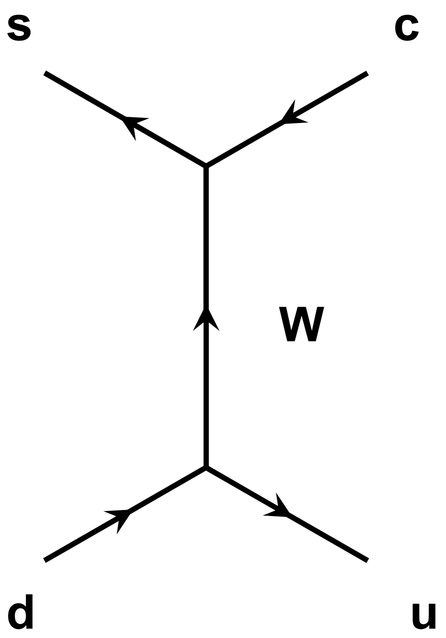
Feynman Diagrams for Scattering



$\bar{u}\, d \rightarrow \bar{u}\, d$

weak interaction

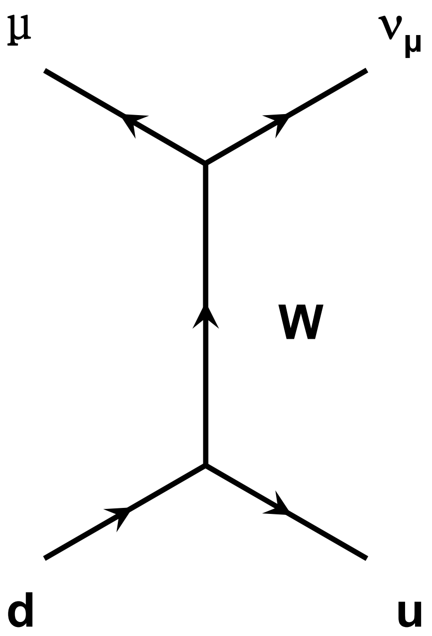
Feynman Diagrams for Scattering



$\bar{u}\, d \rightarrow \bar{c}\, s$

weak interaction

Feynman Diagrams for Scattering

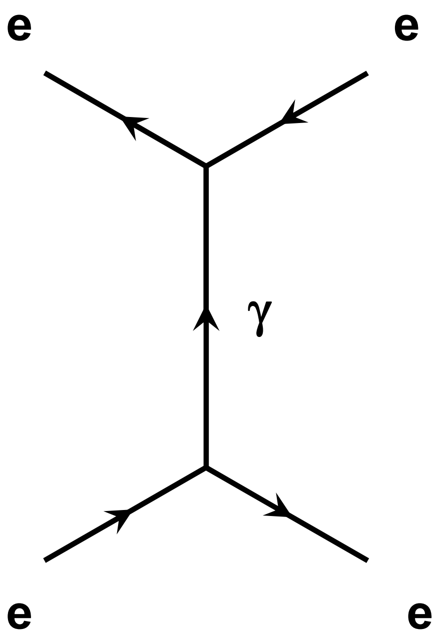


$\bar{u}\, d \to \mu\, \bar{\nu}_\mu$

weak interaction

Feynman Diagrams for Scattering

Often there is more than one diagram contributing to a single process

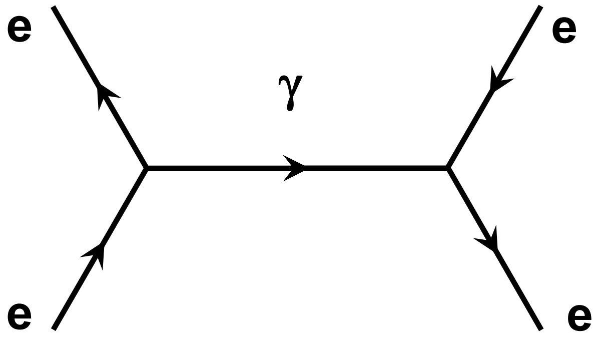


$e^+ e^- \rightarrow e^+ e^-$ (Bhabha scattering)

annihilation diagram

(s-channel)

Feynman Diagrams for Scattering

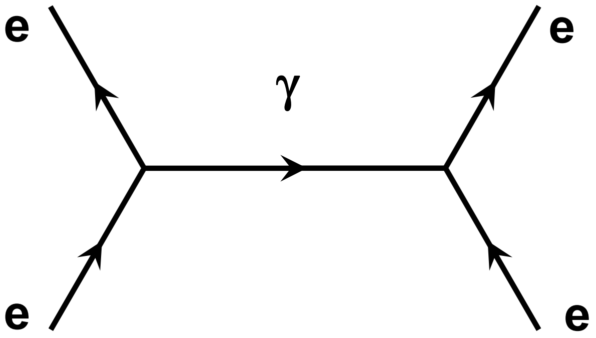


e^+ e^- → e^+ e^- (Bhabha scattering)

photon exchange diagram

(t-channel)

Feynman Diagrams for Scattering



$e^- e^- \rightarrow e^- e^-$ (Moller scattering)

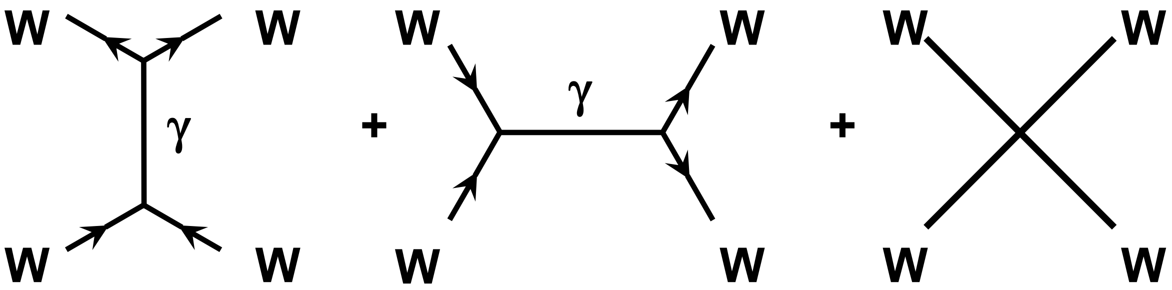
photon exchange diagram

(there is no annihilation diagram)

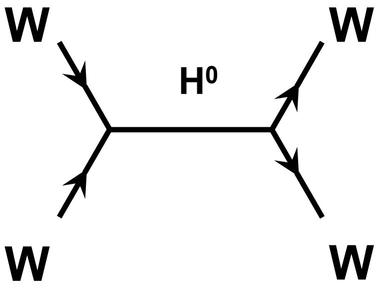
The Higgs Boson

Quantum Electrodynamics can be made to yield finite values for all calculations

Electroweak Theory give infinite result for processes such as $W^+W^- \rightarrow W^+W^-$



Amplitude for this process is finite if the Higgs boson is included



Higgs Boson makes $W^{\pm}$ and Z^0 massive and is also responsible generating the masses of fundamental particles. It is a quantum field permeating the Universe

A Physical Analogy

In vacuum, a photon has velocity = c and mass = 0

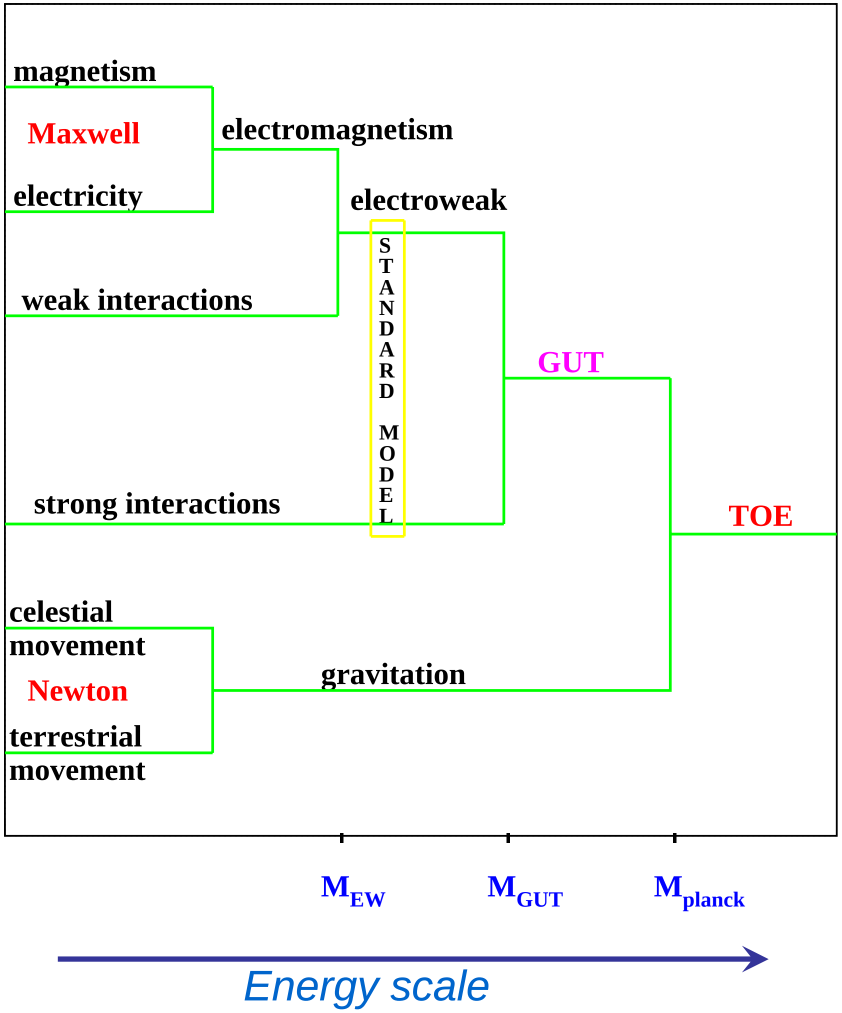
In glass a photon has velocity < c which is equivalent to mass > 0

This is due to the photon interactions with the electromagnetic field in condensed matter

By analogy, we can understand the masses of particles as arising due to interactions with Higgs field (in vacuum).

This Higgs field is an important part of inflationary theories

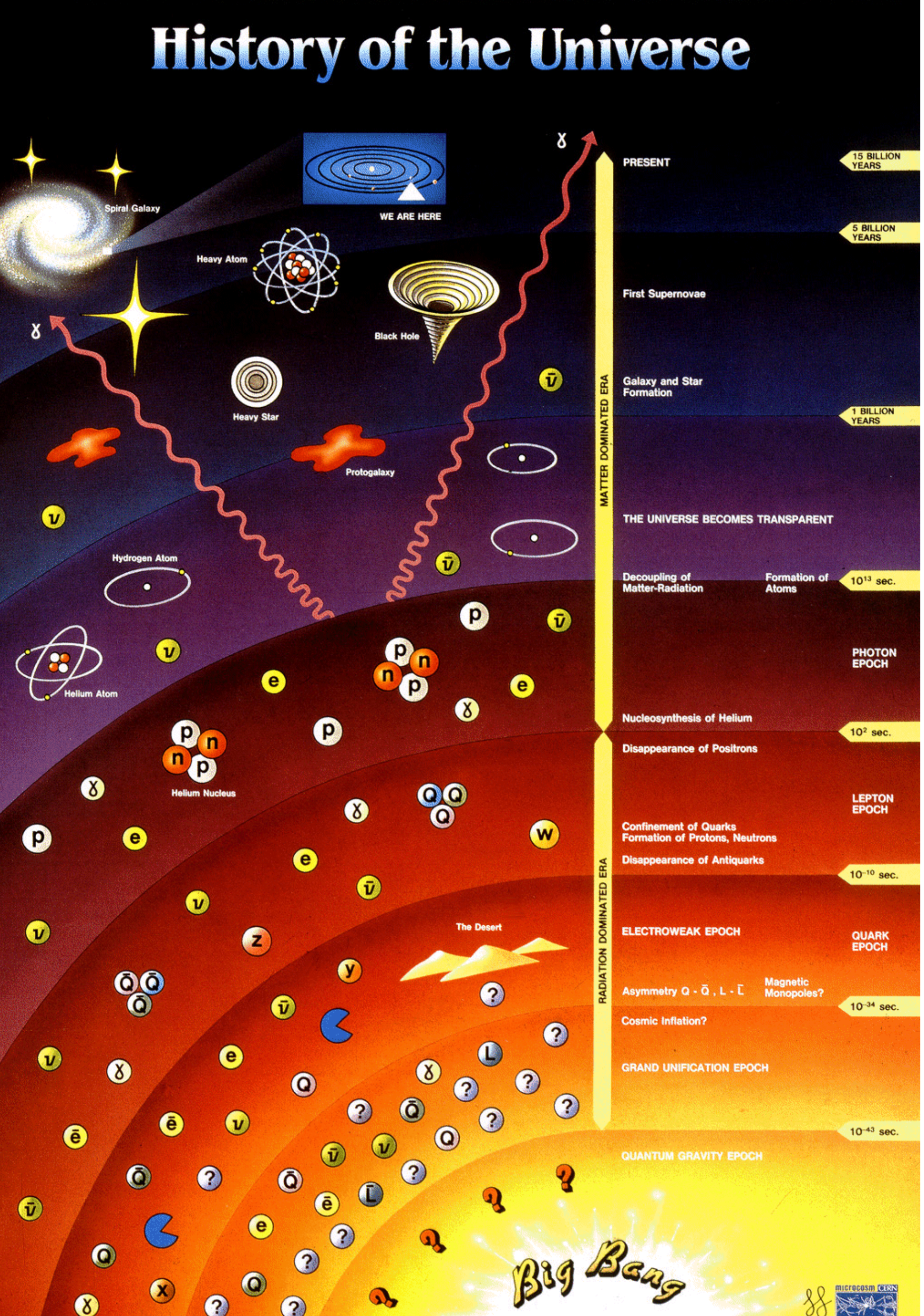
Force Unifications



Standard Model does NOT account for gravitational interactions

Planck Scale (or Planck Mass)

is defined as the energy scale at which gravitational interactions become of the same strength as SM interactions



YOU ARE HERE !

last-scattering

Responsible for

Cosmic Microwave Background

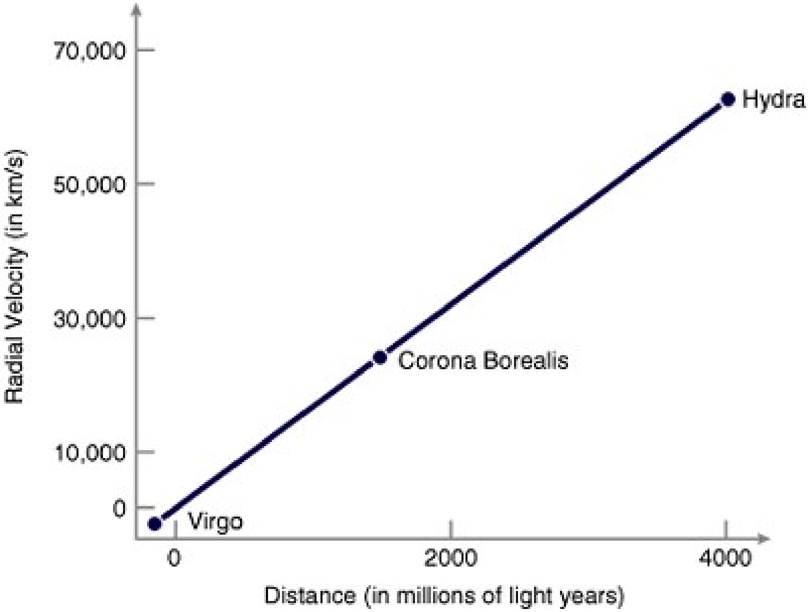
Grand Unification era

Expansion of the Universe

BIG BANG model came from the observation that the UNIVERSE IS EXPANDING

For distant galaxies velocity (w.r.t us) $\propto$ distance $v = H_0 \times$ distance

Hubble constant



Whether the Universe continue to expand or begins at some point to contract depends upon the density of matter and energy in the Universe

e.g. is there enough matter and energy in the Universe for the gravitational attraction to stop (and possible reverse) the Universe's expansion ?

The Fate of the Universe

If ρ_0, the density of matter and energy in the Universe, is greater than some critical density, ρ_c, the expansion of the Universe will eventually cease and reverse, so that it ultimately contracts (THE BIG CRUNCH)

If ρ_0, the density of matter and energy in the Universe, is LESS than then critical density, ρ_c, the expansion of the Universe will continue forever (THE BIG FREEZE)

Usually measure the density in units of ρ_c

$$\Omega_0 = \frac{\rho_0}{\rho_C} = \frac{8\pi G}{3} \frac{\rho_0}{H_0^2}$$

$\Omega_0 > 1$ spherical space-time: contraction

$\Omega_0 = 1$ flat space time: expansion (asymptotic)

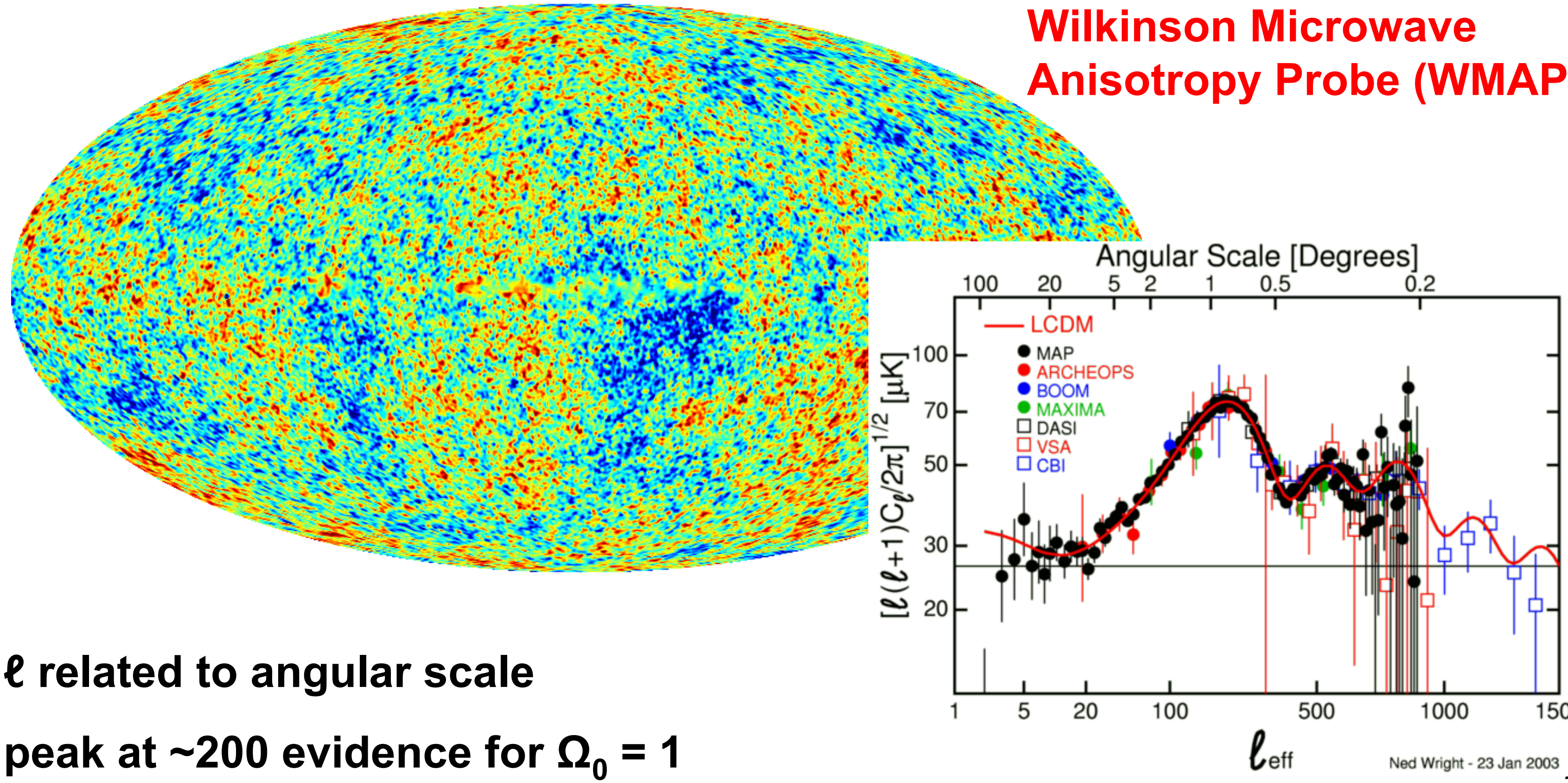
$\Omega_0 < 1$ hyperbolic space-time: expansion

Measuring Ω_0

Amazingly, we can measure the total matter/energy density in the Universe !!!

Use temperature fluctuations in the cosmic microwave background (CMB)

Wilkinson Microwave Anisotropy Probe (WMAP)



ℓ related to angular scale

peak at ~200 evidence for $\Omega_0 = 1$

Density of Standard Model Matter

Referred to as Baryonic Matter (eg. made of protons and neutrons)

Density is Ω_B

If Universe is made of ONLY quarks and leptons $\Omega_B = \Omega_0 = 1$

Ω_B measured from abundance of elements produced in nucleosynthesis

Deuterium, Helium, Lithium

$$\Omega_B = 0.05$$

$$\Omega_B \neq \Omega_0$$

Most of the Universe is NOT Standard Model matter.

Instead it is some form of

DARK MATTER

Density of All Matter Ω_M

Can measure the density of ALL matter by looking at gravitational effects

- **Rotation curves of galaxies**
- **Motion of galactic clusters**

This provides evidence for DARK MATTER since

$$\Omega_M = 0.4 \pm 0.1$$

Even with Dark Matter we cannot account for $\Omega_0 = 1$

Universe must ~ 60% DARK ENERGY

Dark Energy Ω_Λ

If the expansion of the Universe is slowed by gravitational attraction, expect that in the remote past galaxies were moving apart more rapidly than now.

Observations of distant supernovae show the opposite. Past galaxies are moving apart more slowly !

Expansion of the Universe is accelerating !

$$\Omega_\Lambda = 0.85 \pm 0.2$$

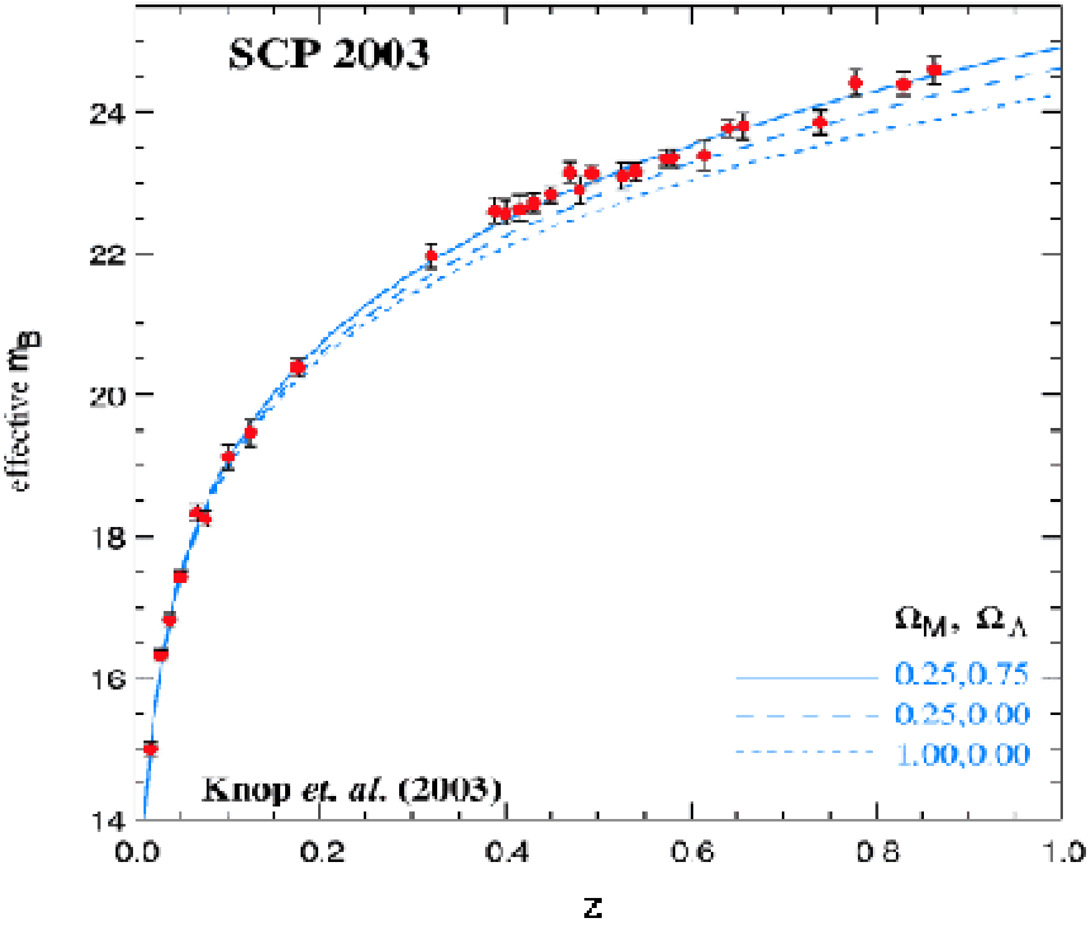
$$(0.4 \pm 0.1) + (0.85 \pm 0.2) = 1.25 \pm 0.22$$

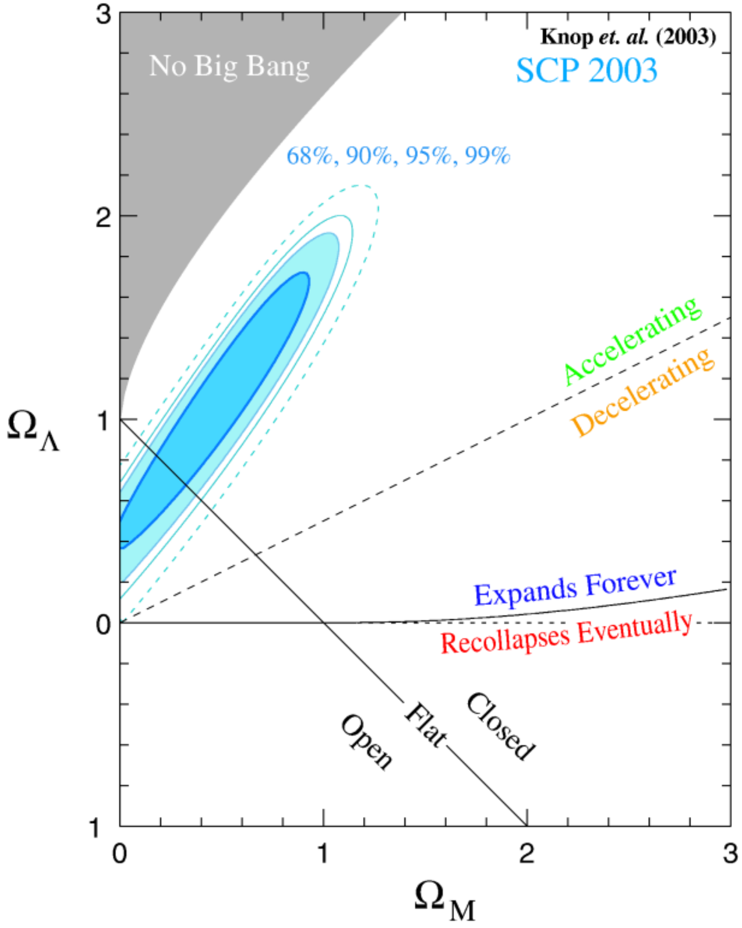
$$\Omega_M + \Omega_\Lambda = 1$$

Driven by some quantum field permeating the universe

Supernova Cosmology Project

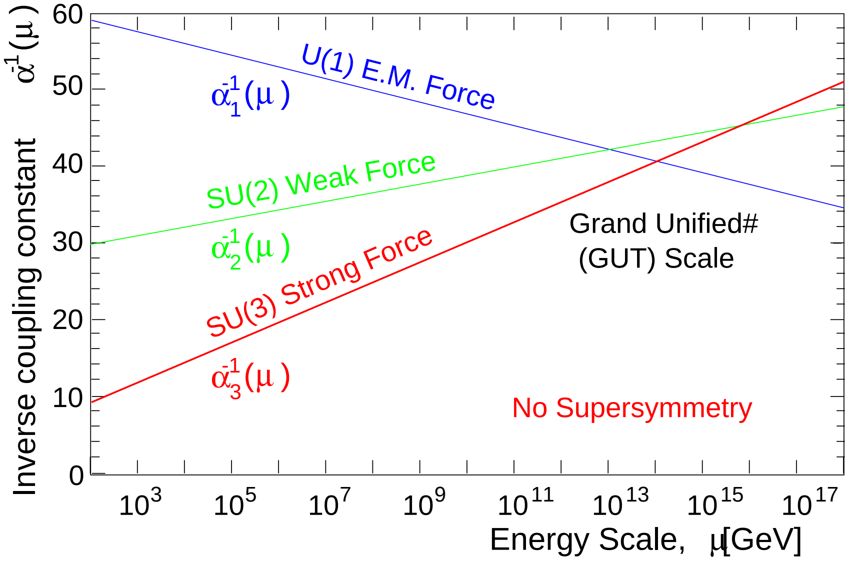
http://www-supernova.LBL.gov

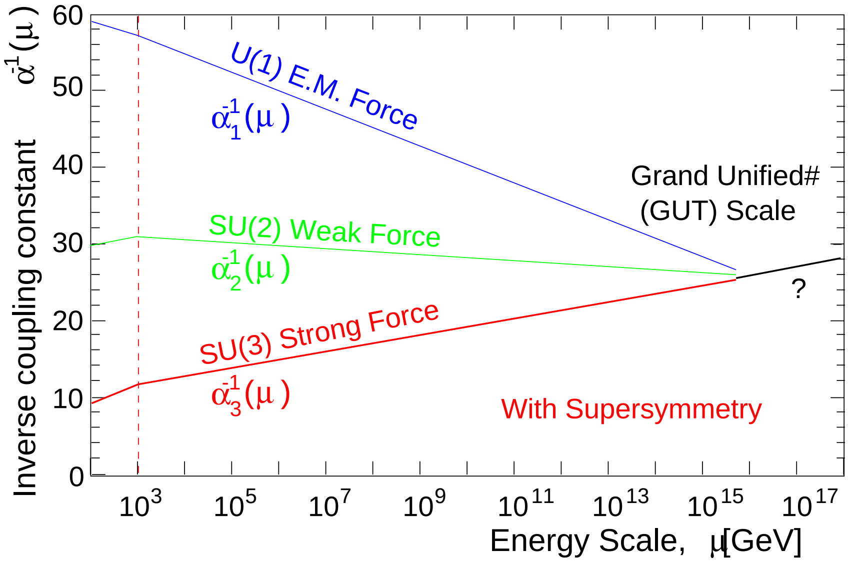




Supersymmetry (SUSY)

With only the particle content of the SM, unification of the forces does not appear to take place: forces never have the same strengths





The Higgs mass runs away to the Planck scale (technical issue for SM)

Both of these problems can be addressed by an extension to the SM called SUPERSYMMETRY (also known as SUSY)

Supersymmetry

Each SM boson (fermion) has a fermionic (bosonic) supersymmetric partner with IDENTICAL MASS and Standard Model COUPLINGS

leptons **sleptons**

$$\begin{pmatrix} \mathbf{e} \\ \nu_{\mathbf{e}} \end{pmatrix} \begin{pmatrix} \mu \\ \nu_{\mu} \end{pmatrix} \begin{pmatrix} \tau \\ \nu_{\tau} \end{pmatrix} \leftrightarrow \begin{pmatrix} \tilde{\mathbf{e}} \\ \tilde{\nu}_{\mathbf{e}} \end{pmatrix} \begin{pmatrix} \tilde{\mu} \\ \tilde{\nu}_{\mu} \end{pmatrix} \begin{pmatrix} \tilde{\tau} \\ \tilde{\nu}_{\tau} \end{pmatrix}$$

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix} \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix} \begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix} \leftrightarrow \begin{pmatrix} \tilde{\mathbf{u}} \\ \tilde{\mathbf{d}} \end{pmatrix} \begin{pmatrix} \tilde{\mathbf{c}} \\ \tilde{\mathbf{s}} \end{pmatrix} \begin{pmatrix} \tilde{\mathbf{t}} \\ \tilde{\mathbf{b}} \end{pmatrix}$$

quarks **squarks**

Spin 1/2 **Spin 0**

$W^{\pm}$	$\tilde{W}^{\pm}$	
Z^{0}	$\tilde{Z}^{0}$	**gauginos**
γ	$\tilde{\gamma}$	
h^{0}	$\tilde{h}^{0}$	
H^{0}	$\tilde{H}^{0}$	**higgsinos**
A^{0}	$\tilde{A}^{0}$	
$H^{\pm}$	$\tilde{H}^{\pm}$	
g	$\tilde{g}$	**gluinos**
Spin 1	**Spin 1/2**	

Supersymmetry is a Broken Symmetry

Supersymmetry requires a doubling of the particle spectrum. Is this cost excessive ?

It has been successful before (anti-matter) BUT

$$M_{e^+} = M_{e^-} \qquad M_e \neq M_{\tilde{e}}$$

We do NOT see supersymmetric matter made of snucleons and selectrons

Supersymmetry is a BROKEN SYMMETRY

For supersymmetry is to solve the problems mentioned require that

$$\boxed{\mathbf{M_{SUSY} \leq 1\ TeV}}$$

This is often referred to as WEAK-SCALE SUPERSYMMETRY

SUSY and Dark Matter

A conserved quantum number (R-parity) distinguishes SM from SUSY particles: this has two important phenomenological consequences:

- **SUSY particles must be produced in pairs**
- **A SUSY particle must decay into SUSY particle + SM particle(s)**

SUSY → SUSY + SM

The the lightest SUSY particles is cannot decay ! It is STABLE, but does not interact with ordinary matter (it is like a neutrino in that respect but is very massive).

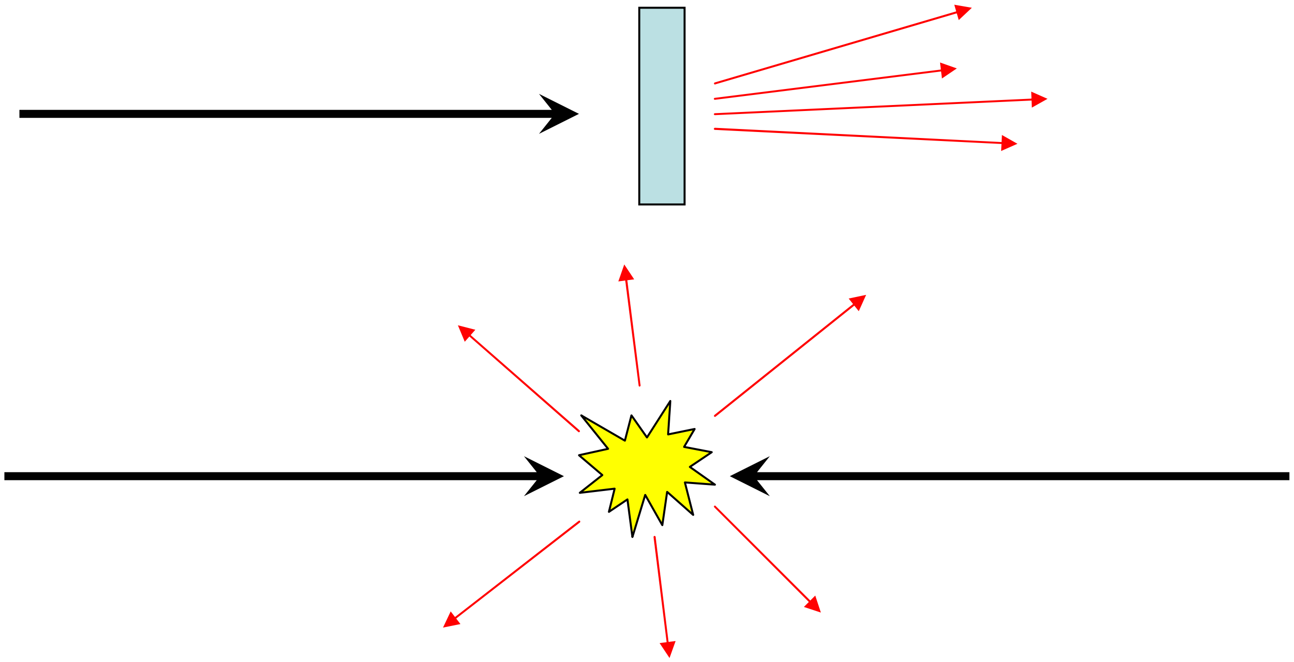
Lightest SUSY particle has properties making it a good Dark Matter candidate (so called Cold Dark Matter or CDM: non-relativistic)

WIMP = Weakly Interacting Massive Particle

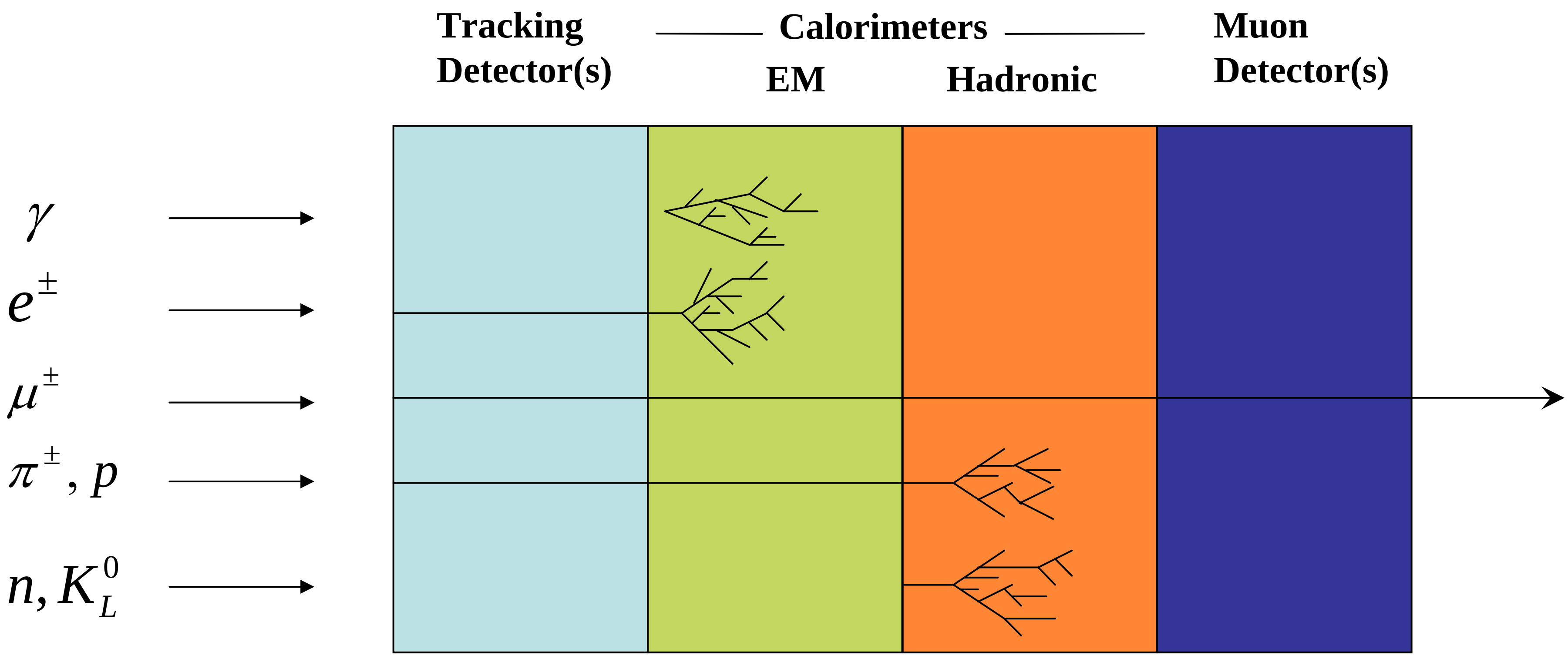
Hope to produce SUSY particles at the Large Hadron Collider (and the Higgs Boson as well) starting in 2007.

Scattering Experiments

- **Particles off a target (Rutherford scattering)**
- **Particles of particles (colliding beam)**
- **Will see that colliding beams is kinematically superior – more energy available to produce new particles in final state (no need to have momentum in final state.**



Particle Detectors



Tracking Detector(s)

Calorimeters

EM

Hadronic

Muon Detector(s)

γ

$e^{\pm}$

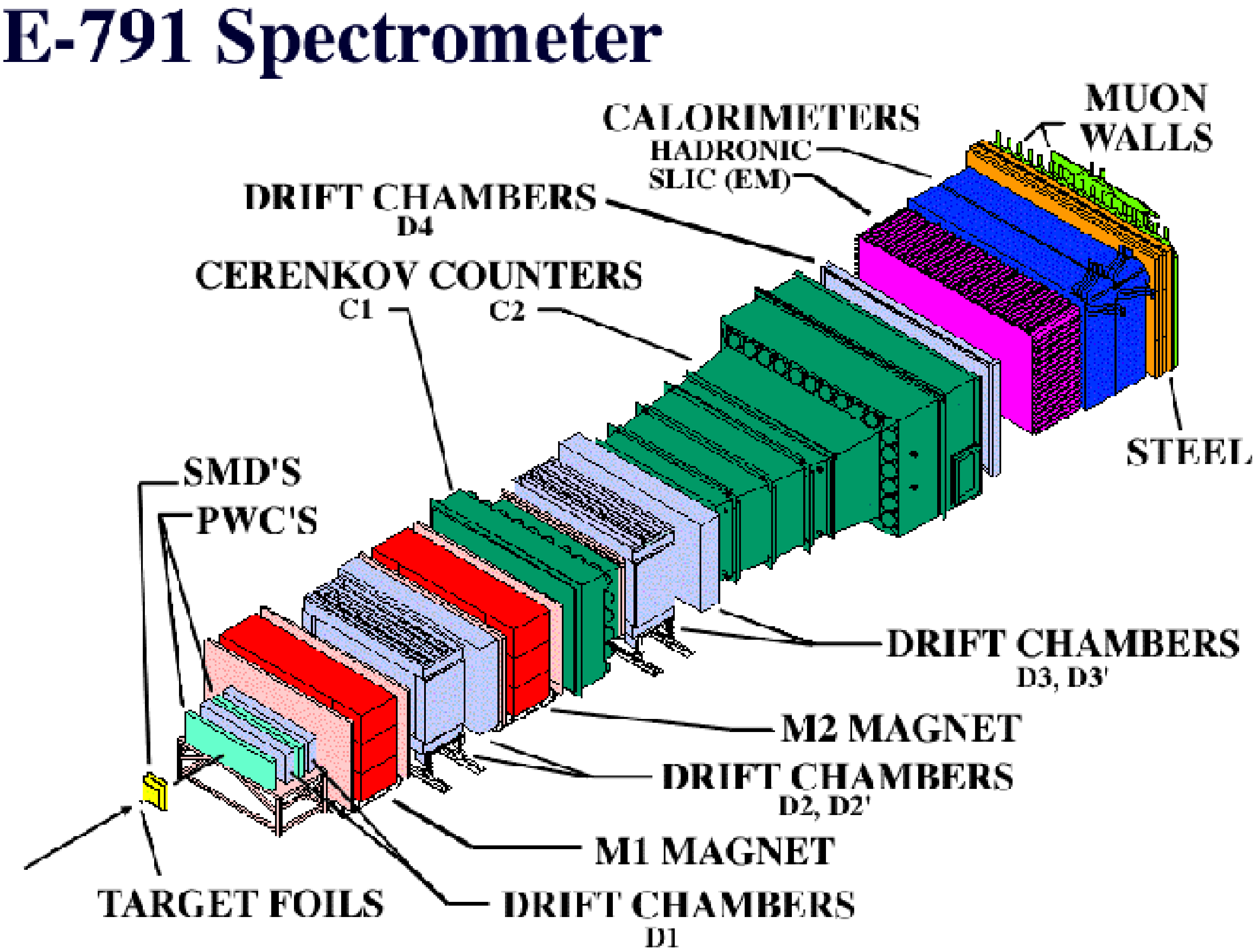
$\mu^{\pm}$

$\pi^{\pm}, p$

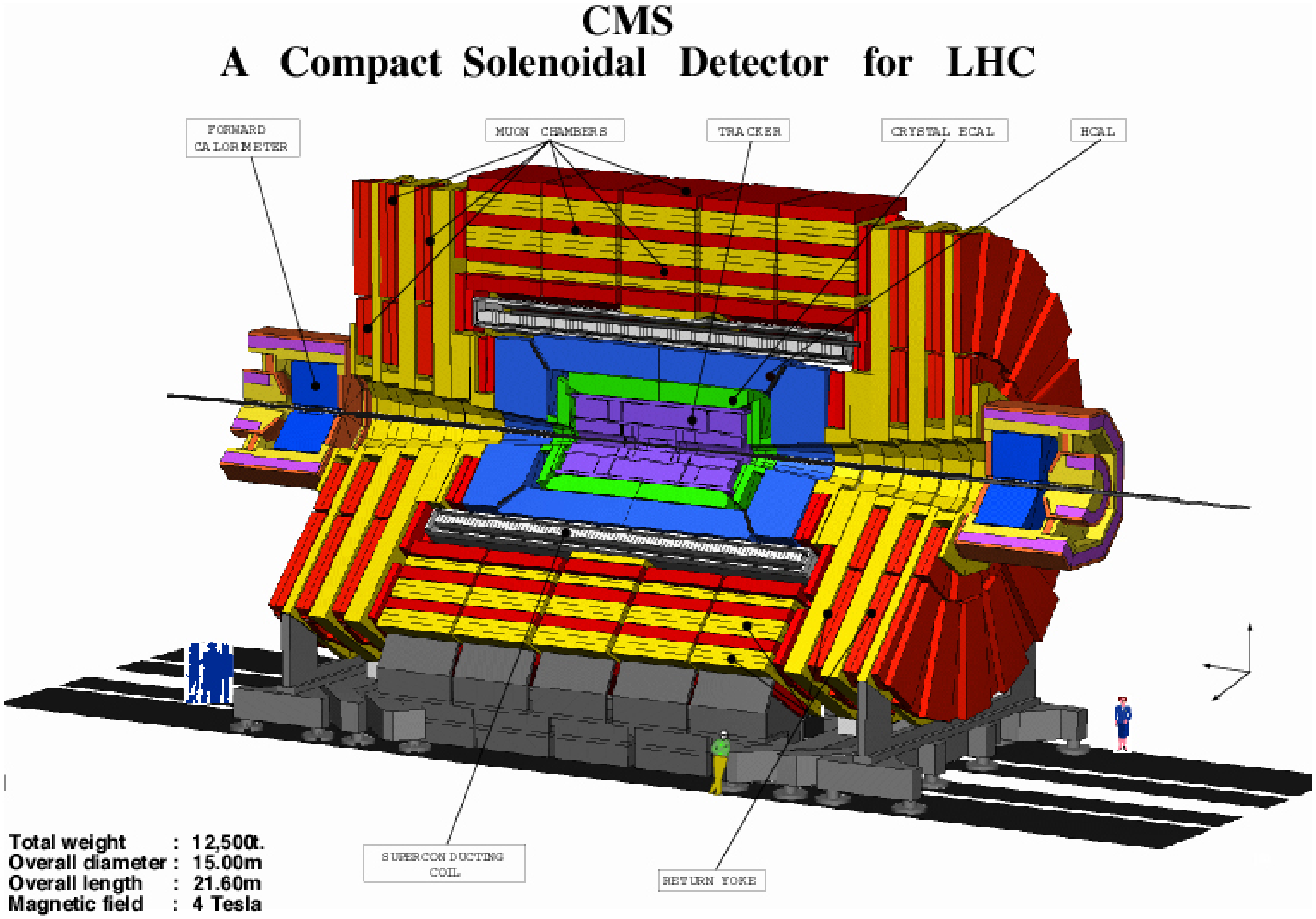
n, K_L^0

Neutrinos pass through the detector unobserved. The same would be true for any neutral, weakly interacting particle (if such particles exist)

Detector for Fixed Target Experiment



A Collider Detector



Radial “layering” of detector technologies

Require cylindrical symmetry and ~ full solid angle coverage (hermiticity)

Collider Experiments

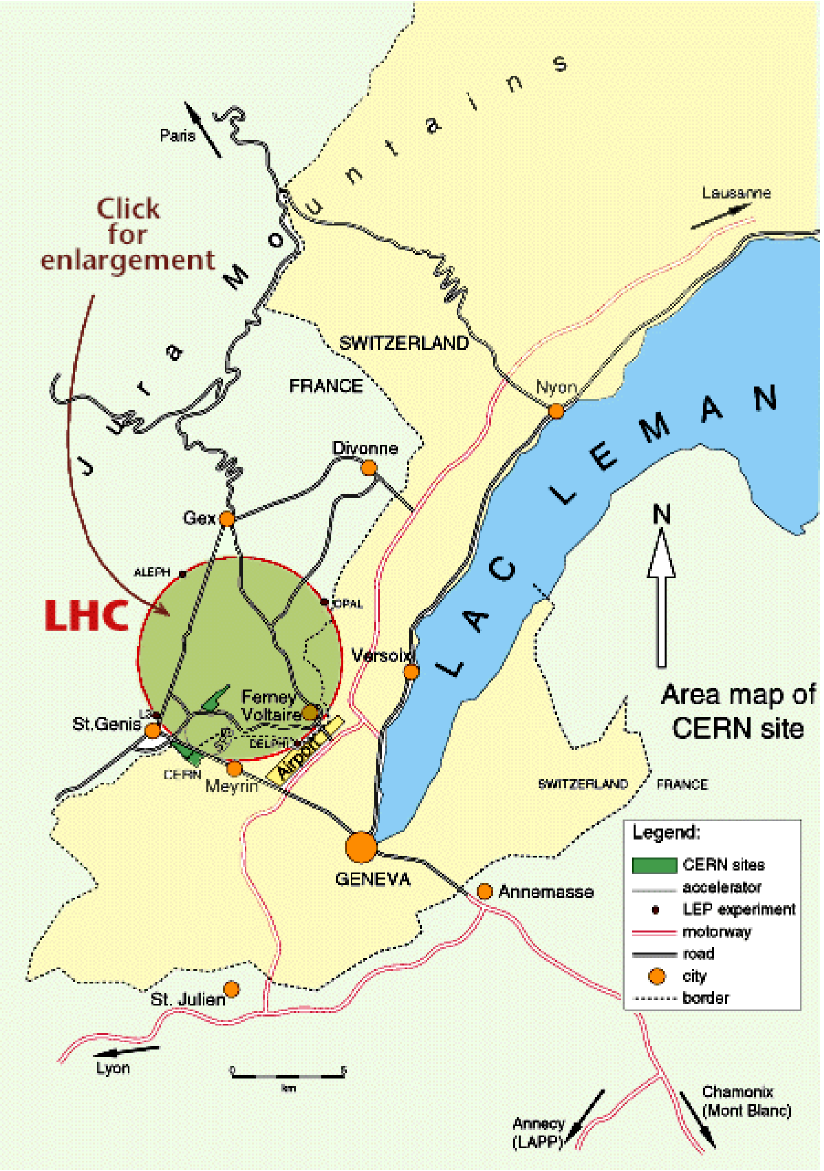
Linear Collider: have to accelerate particles in one shot

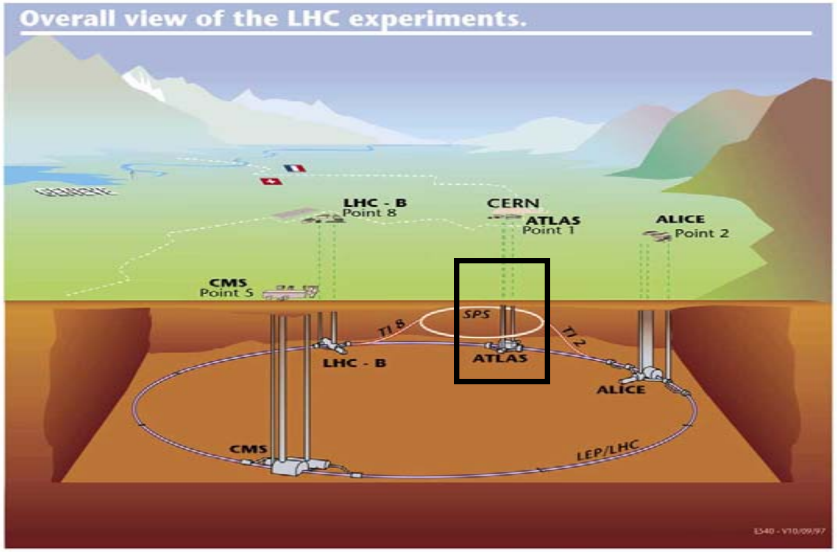
Circular Colliders: particles can travel in circles, slowly being accelerated up to the required energy over many circuits, then brought into collision.

World's largest collider is being built at CERN, in Geneva

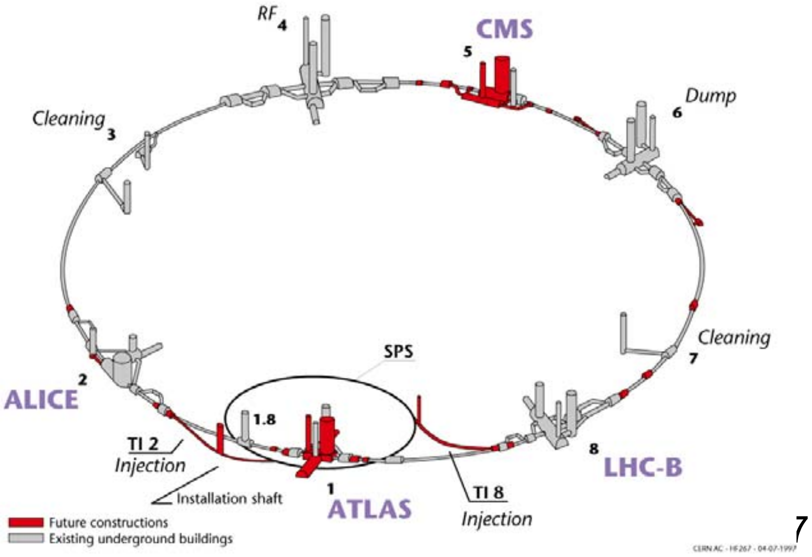
Lake Geneva

The Large Hadron Collider at CERN

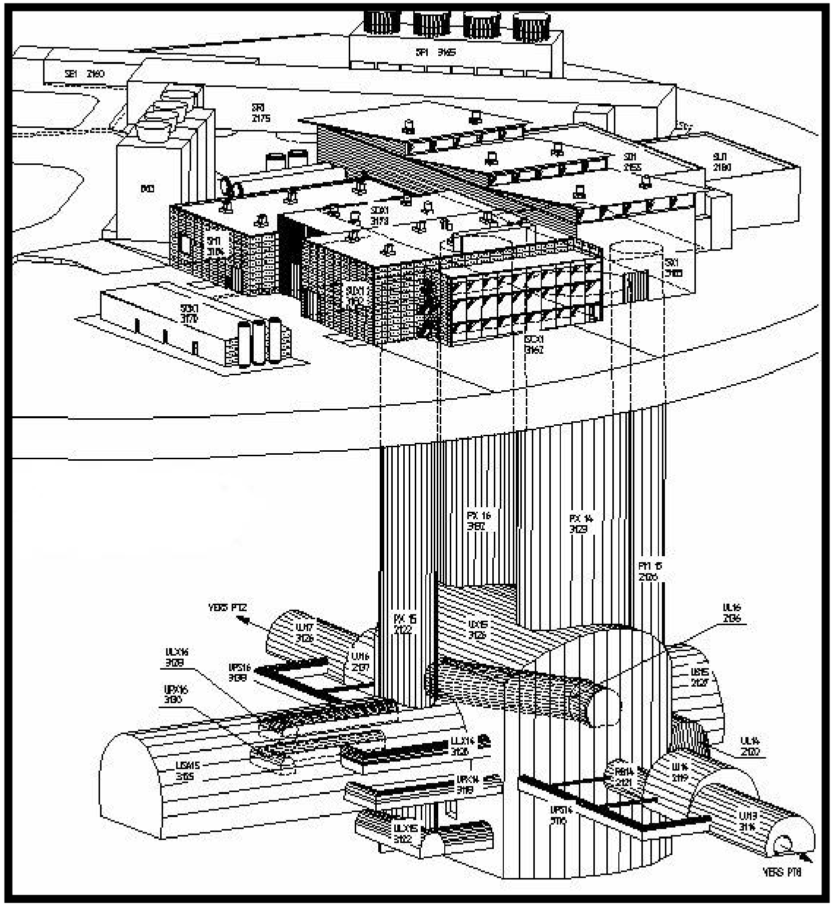


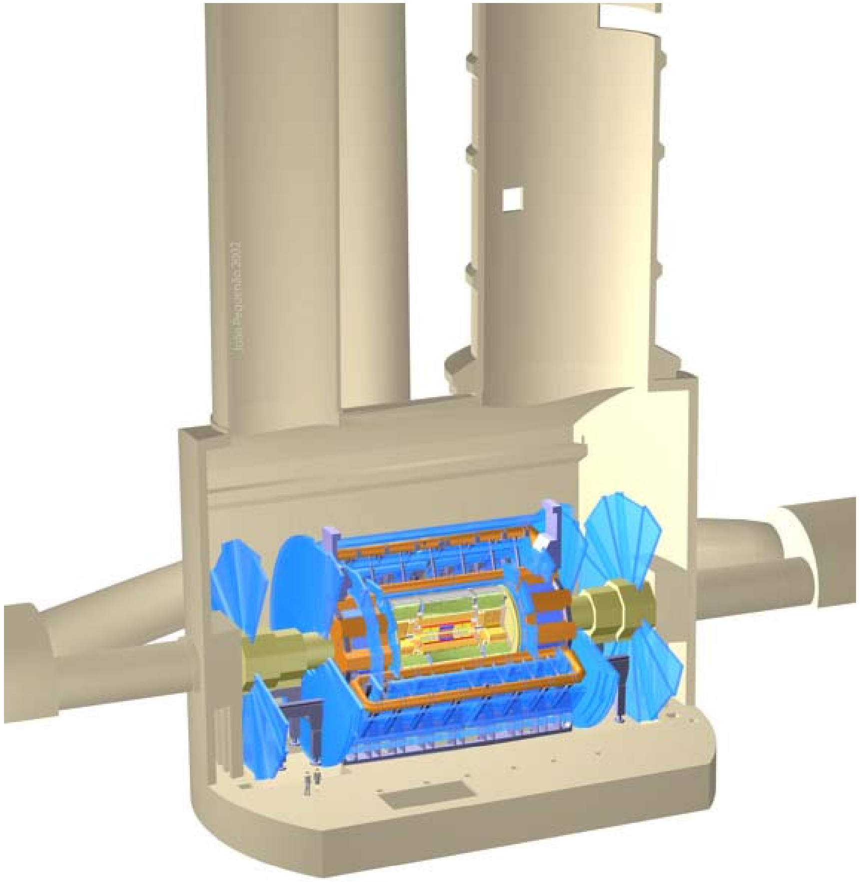

Overall view of the LHC experiments.

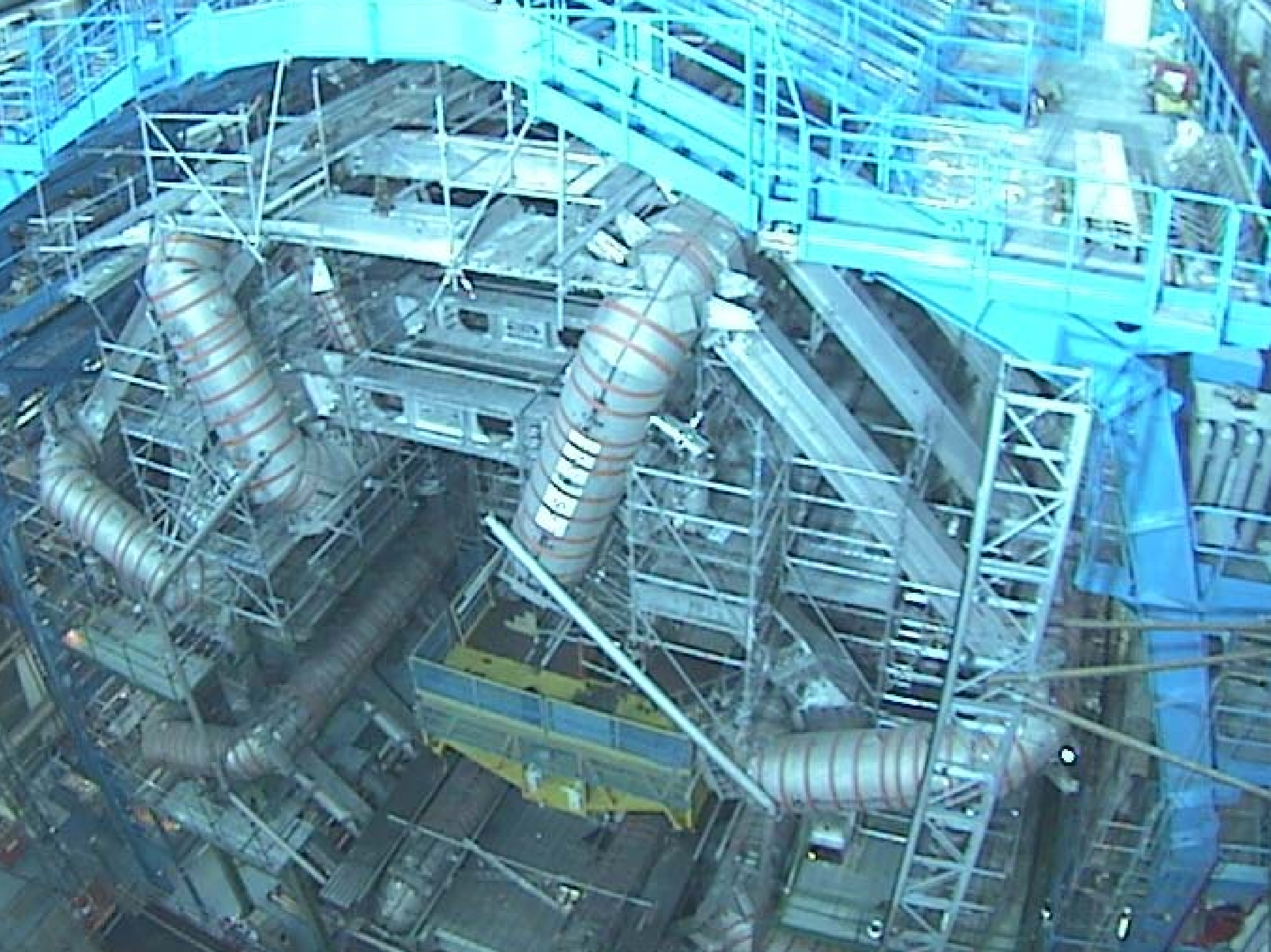
Layout of the LEP tunnel including future LHC infrastructures.



The ATLAS Cavern







Hadron Colliders vs Electron Positron Colliders

Bending a charged particle in a magnetic field costs energy

(synchrotron radiation)

$$\Delta \mathrm{E} = \frac{4\pi}{3} \cdot \frac{e^2 \beta^2 \gamma^4}{\rho} \propto \frac{1}{m^4} \; or \; \mathrm{E}^4$$

For fixed radius machine (i.e. in the LEP tunnel at CERN with ρ = 6.28km) synchrotron radiation loss for protons less than that for electrons by the amount

$$\left(\frac{m_e}{m_p} \right)^4 \approx 10^{-13}$$

Cannot build electron synchrotrons of arbitrarily high energy. Need either:

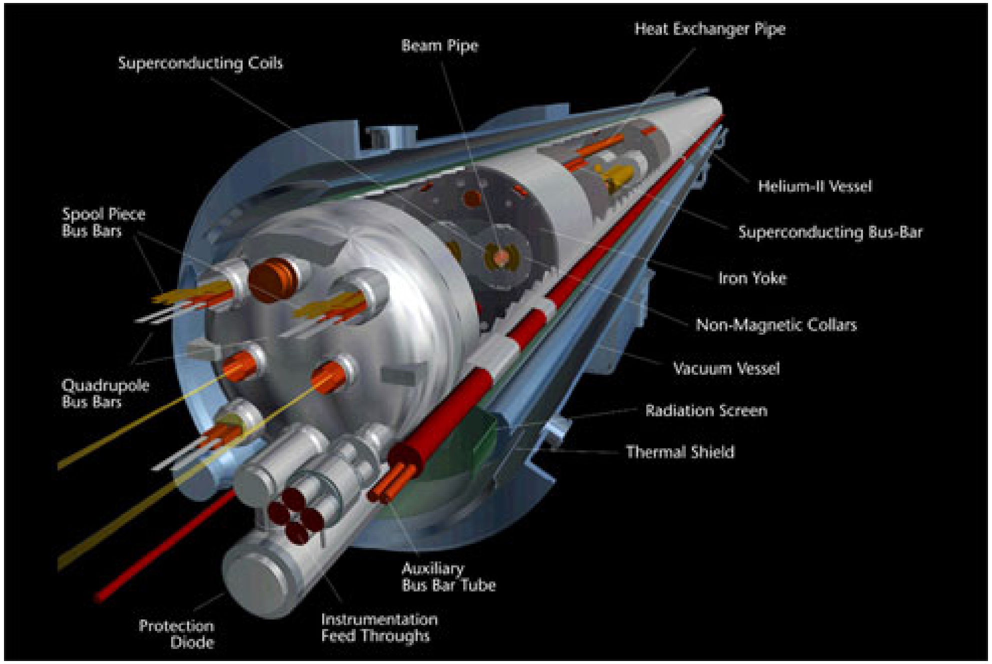
- ☺ **hadron collider**
- 😐 **linear electron-positron collider (next ?)**

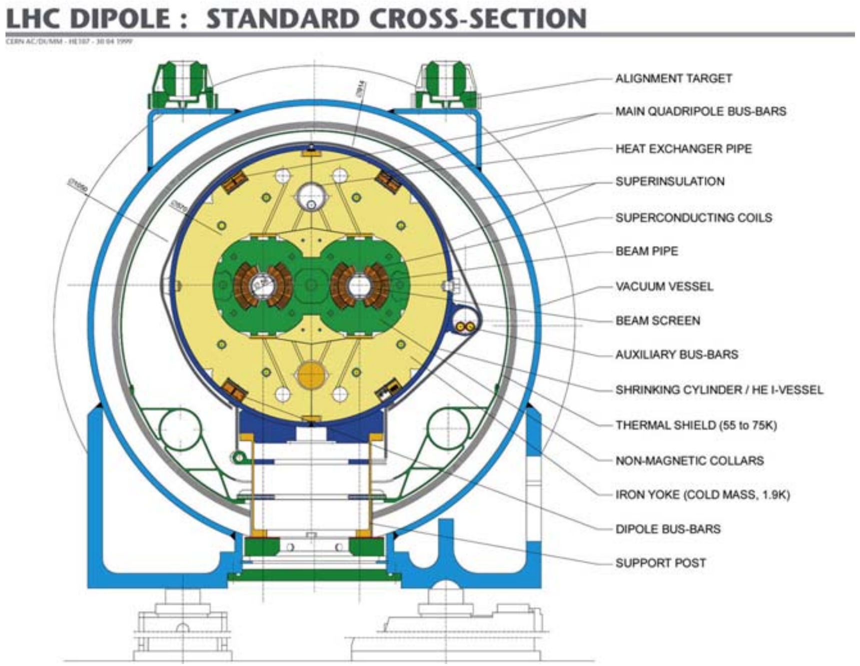
Circular Colliders

In order to keep the particles in a circular orbit, need to bend them with magnetic fields.

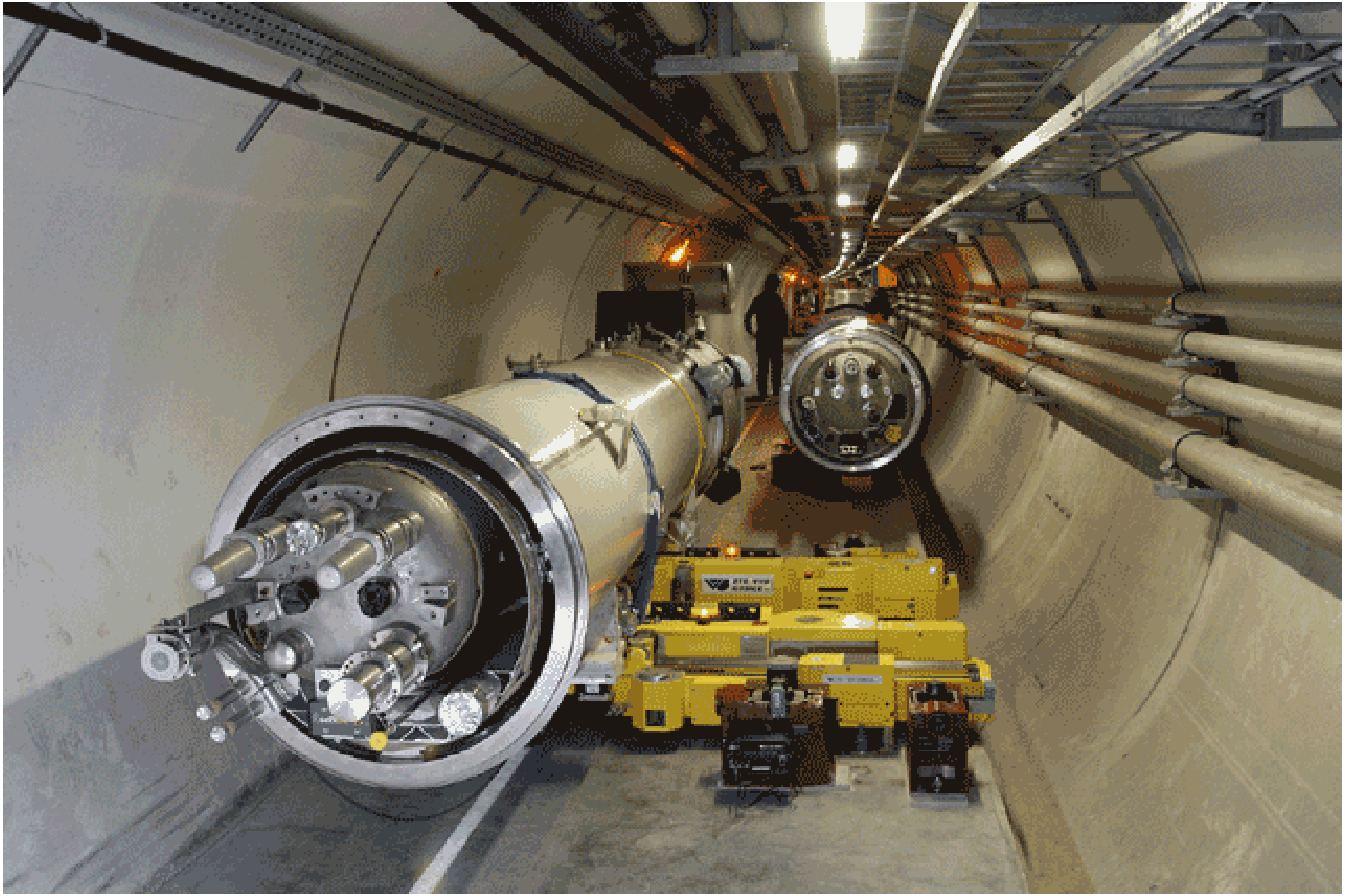
7000 GeV protons beams of LHC require VERY strong magentic fields

Relationship between beam momentum and field required for fixed bending radius:





LHC Dipole (Bending) Magnet in LHC Tunnel



The LHC pp Collider at CERN

14 TeV pp collider to be installed in the existing 27km ring

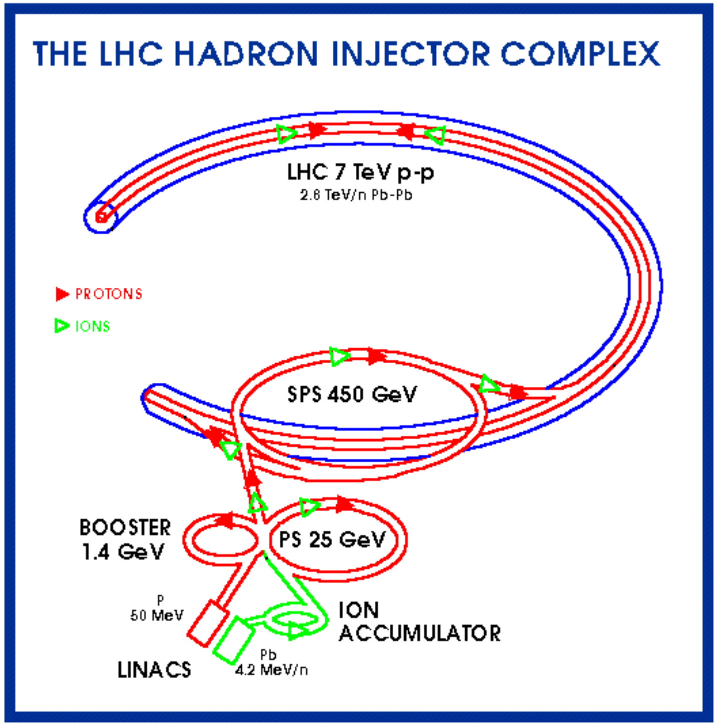
First collisions scheduled for 2007

Two general purpose detectors:

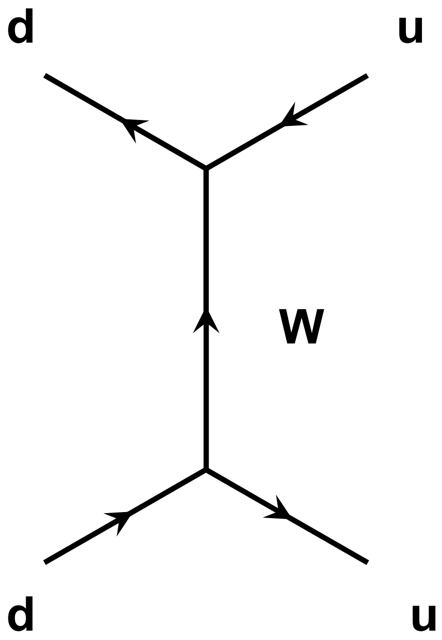
ATLAS 🍁 **and CMS**

Main objectives: Discover the new TeV scale physics

- ➢ **Discovery or exclusion of the SM Higgs**
- ➢ **Discovery or exclusion of Weak-Scale SUSY**



Feynman Diagrams for Quark-Quark Scattering

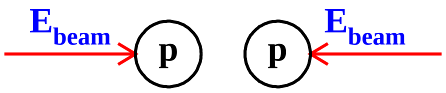


$\bar{u}\,d \rightarrow \bar{u}\,d$

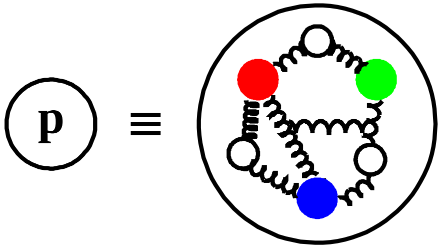
If free quarks do not exist, how do we look at such a process experimentally ?

Collisions at Hadron Colliders

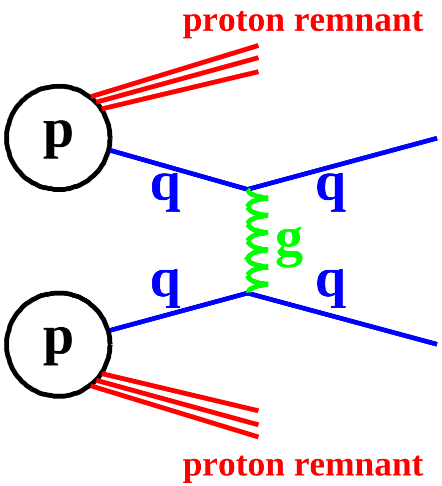
Hadron colliders can achieve higher centre-of-mass energies than electron-positron machines, but E_{CM} of constituent collision $\neq 2 \times \mathbf{E_{beam}}$

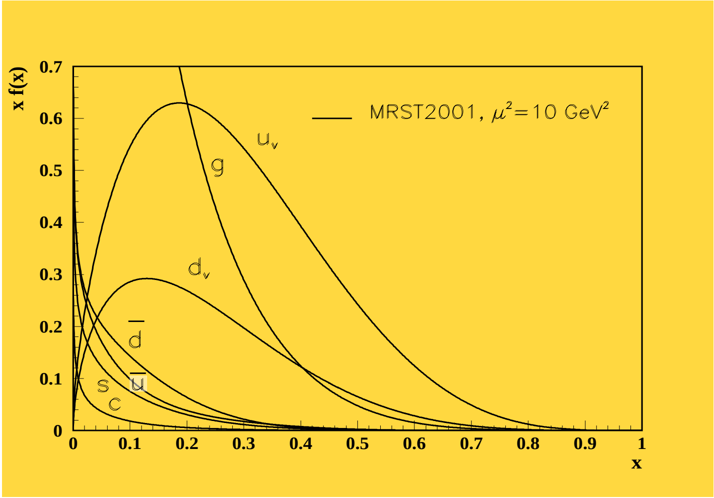


p-p "collision"



3 valence quarks
+ sea quarks
+ gluons

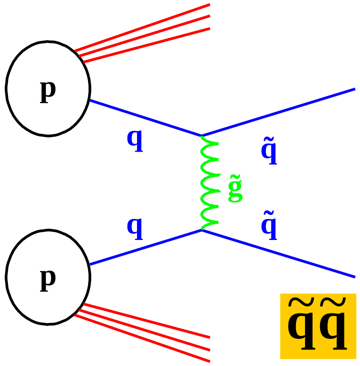


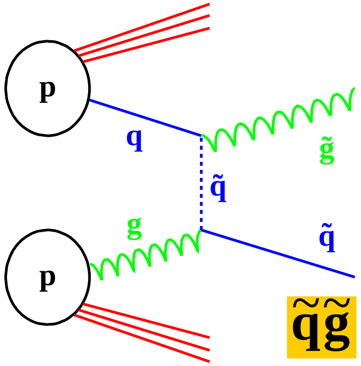


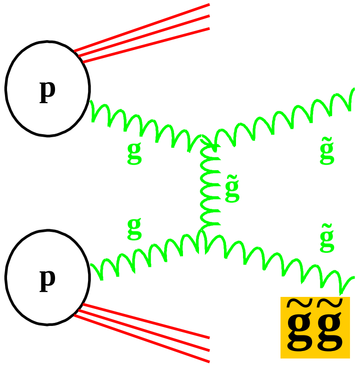
$qq', q\bar{q}', qg, gg$ collisions at a range of energies $0 < E_{CM}^{effective} < 2E_{beam}$

Messy experimental environment for precision measurements, but great for discovery of new physics

Supersymmetric Particle Production at LHC







Highest cross-section are for strongly interacting SUSY particles (squarks, gluinos)

Each production/decay sequence ends decay to the lightest supersymmetric particle (LSP)

missing E > 2· M_{LSP} (at least ~ 100-200 GeV)

Experimentally, detect this as an energy imbalance in the detector, since missing massive particles carry away undetectable energy in the form of mass and momentum