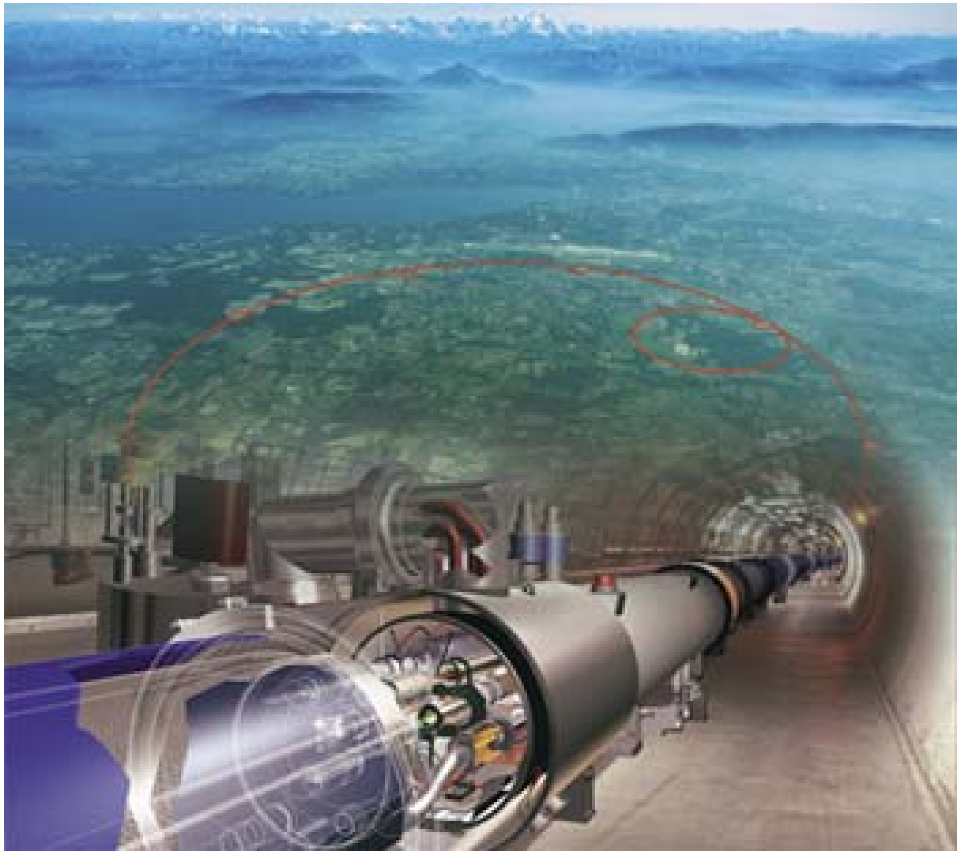
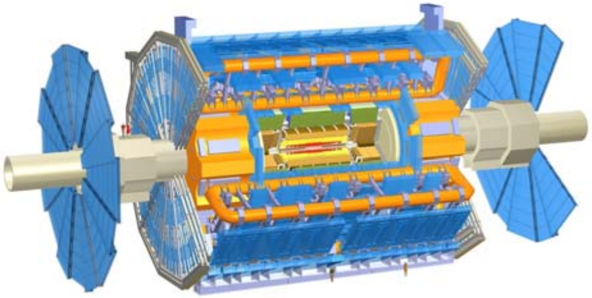
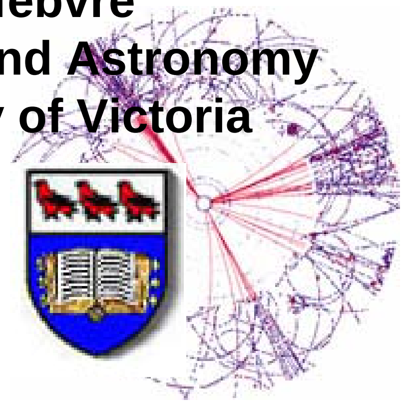
The ATLAS detector at the Large Hadron Collider: to boldly look where no one has looked before



UBC
14 July 2006



Michel Lefebvre
Physics and Astronomy
University of Victoria



The ATLAS detector at the Large Hadron Collider: to boldly look where no one has looked before

ABSTRACT

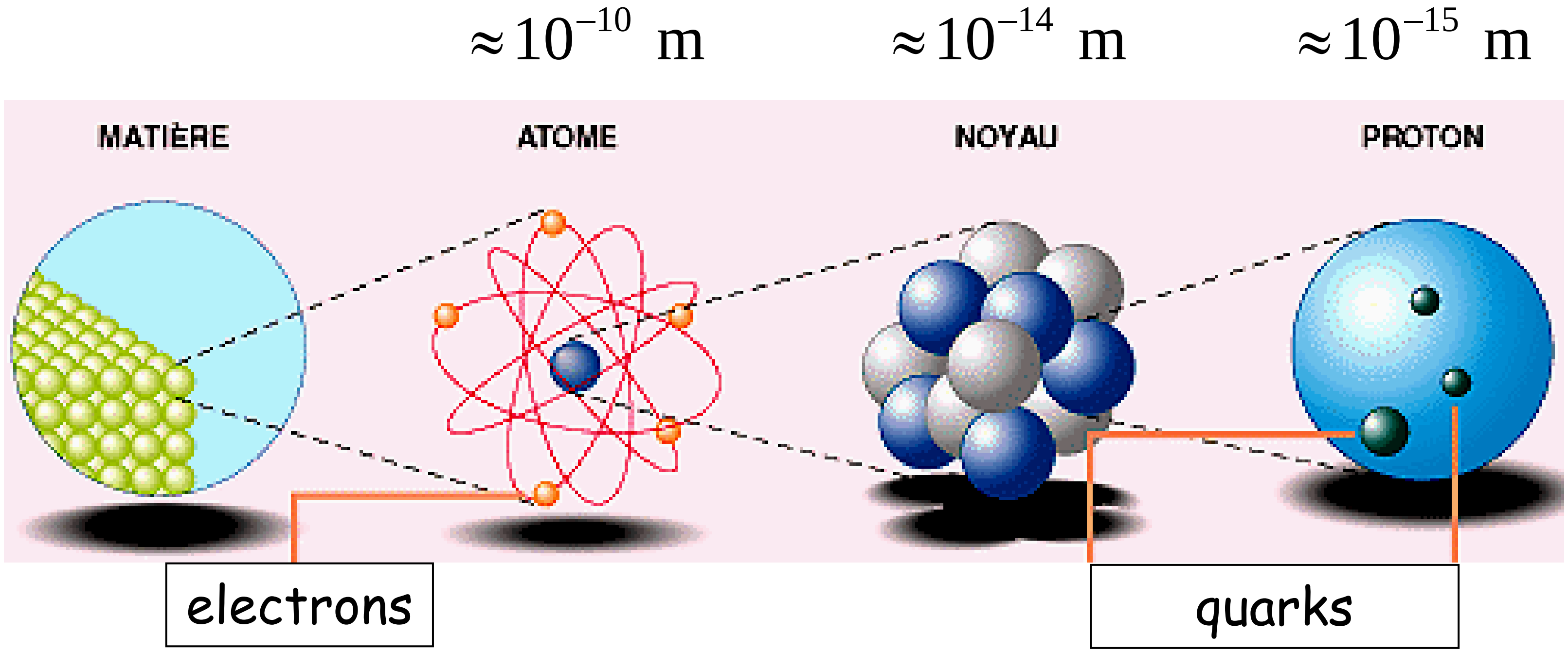
High Energy Physics deals with the study of the ultimate constituents of matter and the nature of the interactions between them. This study is fundamental and draws much interest. High energy is required to probe the very small distance scales associated with elementary particles. Since many of the fundamental particles have large masses, high energy is also required to create them for study. Modern High Energy Physics experiments typically require giant particle accelerators and sophisticated detectors. Although the Standard Model of particle physics offers a very successful description of the interactions of the fundamental constituents of matter at the smallest scales and highest energies accessible to current experiments, there remain many unanswered and important questions. What is an electron made of? What is the origin of mass? What is the nature of Dark Matter? Is nature only made of three spatial dimensions? The Large Hadron Collider (LHC), soon to start operation at CERN, Geneva, will produce 14 TeV energy proton-proton collisions, opening a new and unexplored window into the fabric of nature. Canadian physicists are contributing to the construction and operation of ATLAS, one of two multi-purpose particle detectors that will harvest the LHC collisions. This talk will present some of the most exciting quests of physics at the energy frontier. The ATLAS detector will also be presented, with an emphasis on the experimental challenges at the LHC.

High Energy Physics

Motivation:

Understanding nature’s fundamental constituents and forces

Normal Matter



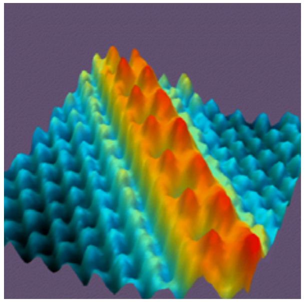
$\approx 10^{-10}$ m

$\approx 10^{-14}$ m

$\approx 10^{-15}$ m

electrons

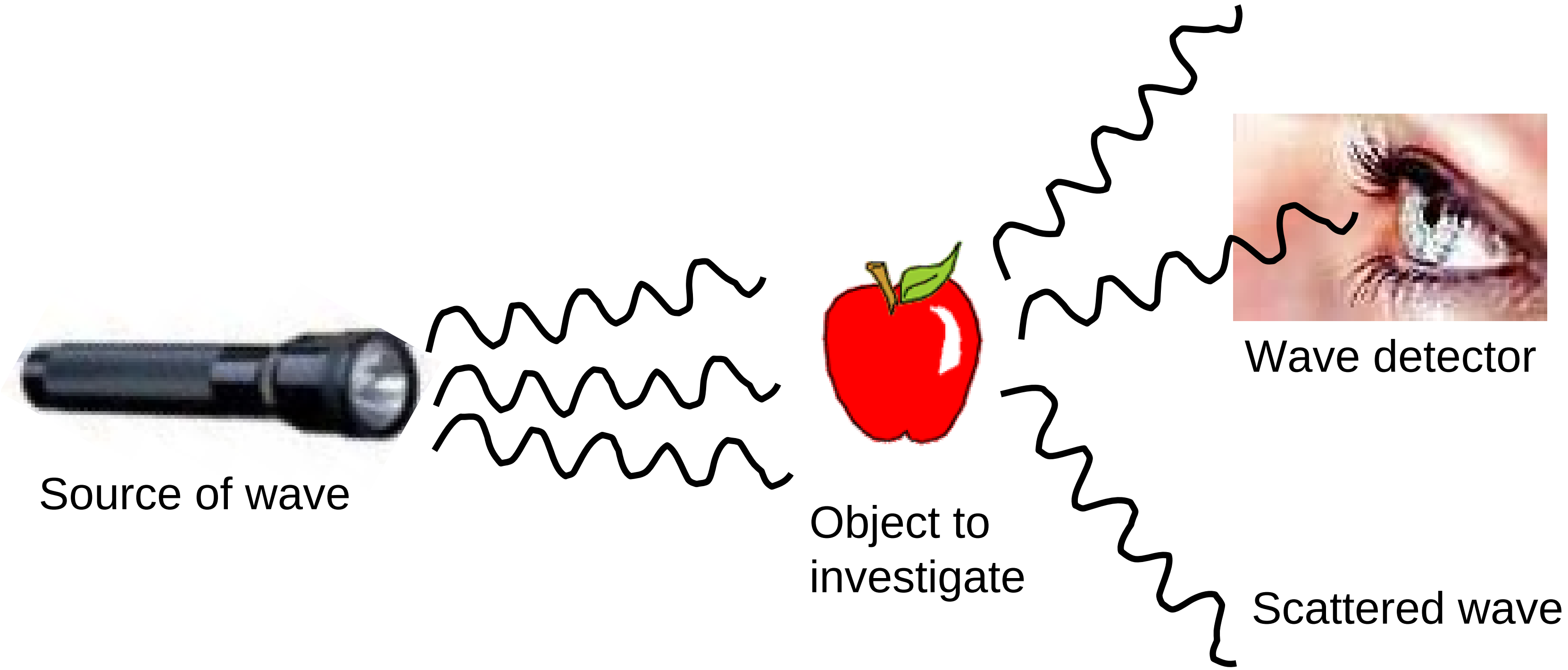
quarks



NIST

Image 7 nm × 7 nm from a scanning tunneling microscope showing a single zig-zag chain of Cs atoms (red) on the GaAs(110) surface (blue).

Scattering Experiment



The wave can resolve features about the size of its wavelength

Matter Waves

Einstein – de Broglie relations

$$\text{particle aspect}\left\{\begin{array}{lcl} p & = & \dfrac{h}{\lambda} \\[1em] E & = & h\nu \end{array}\right\}\text{wave aspect}$$

h is Planck's constant

Fundamentally, nature is made of particles. Their dynamics is governed by matter waves equations, like Schrödinger, Dirac and Maxwell equations

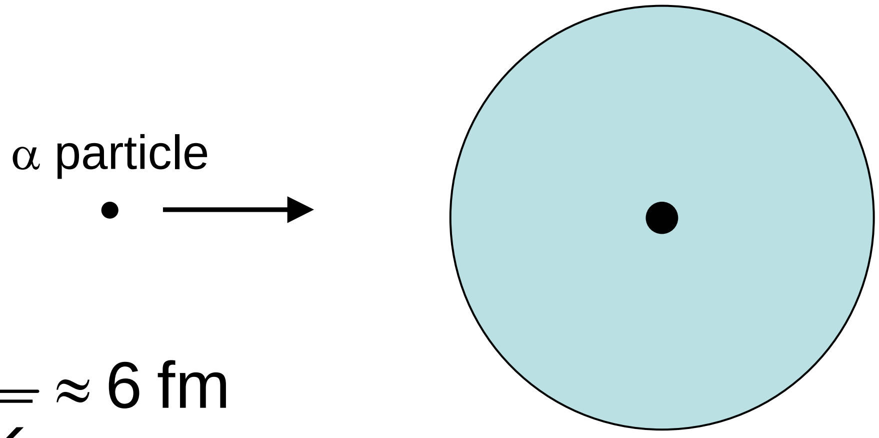
Rutherford Scattering

$$K \approx 5\,\mathrm{MeV}$$

$$m \approx 4\,\mathrm{GeV}/c^2$$

$$\hbar c \approx 197\,\mathrm{MeV\ fm}$$

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mK}} = \frac{2\pi\hbar c}{\sqrt{2mc^2K}} \approx 6\,\mathrm{fm}$$



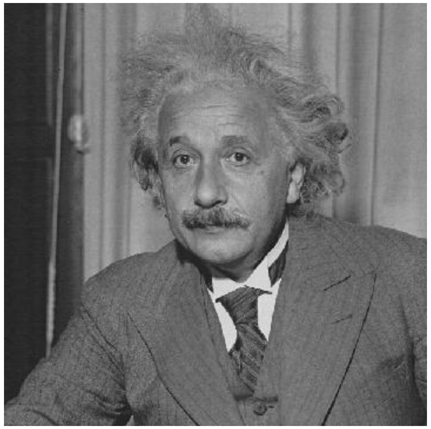
Atom and nucleus
(not to scale!)

Rutherford was able to discover that most of the atom’s mass was in its nucleus

The matter wave can resolve features about the size of its wavelength

Relativistic Dynamic

$$\left.\begin{aligned} E&=\gamma mc^2\\ p&=\gamma m\mathrm{v}\end{aligned}\right\}\Leftrightarrow\left\{\begin{aligned} E^2&=(pc)^2+\left(mc^2\right)^2\\ \frac{pc}{E}&=\frac{\mathrm{v}}{c}\end{aligned}\right.$$



Albert Einstein
1879-1955

⇨ **massless particles carry momentum!!**

$$m=0 \quad\rightarrow\quad E=pc \quad \text{and} \quad \mathrm{v}=c$$

$$\gamma\equiv\left[1-\left(\tfrac{\mathrm{v}}{c}\right)^2\right]^{-1/2}$$

⇨ **equivalence of mass and energy!!**

$$E=mc^2 \quad\rightarrow\quad m=E/c^2$$

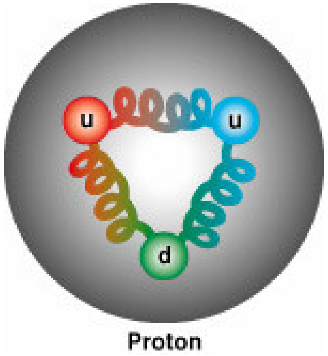
⇨ **relativistic particles**

$$E\gg mc^2 \quad\rightarrow\quad E=pc \quad \text{and} \quad \mathrm{v}=c$$

Natural units: $\hbar=c=1 \;\Rightarrow\; 197\ \mathrm{GeV}\cdot\mathrm{fm}\ =1$

Particle Accelerators

$\approx 10^{-15}$ m



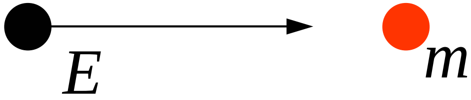
High energy particle accelerators have been used to probe the structure of the proton.

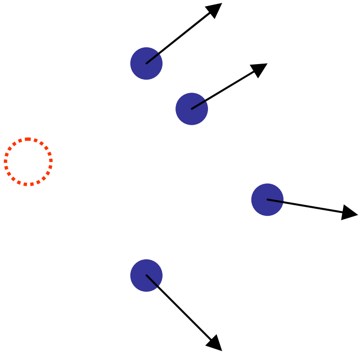
A Proton is found to have a size and an electric charge distribution.

Probing deeper, with higher energy probes, it is found to be made mainly of three quarks... and also of other quarks and gluons!

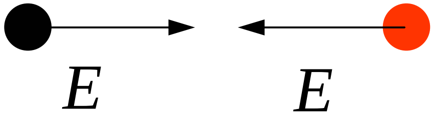
Colliding Particles

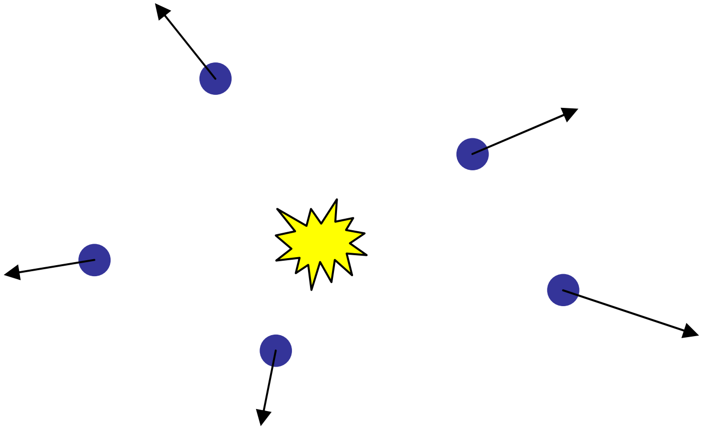
“Fixed target”:
available energy $\simeq \sqrt{2mE}$



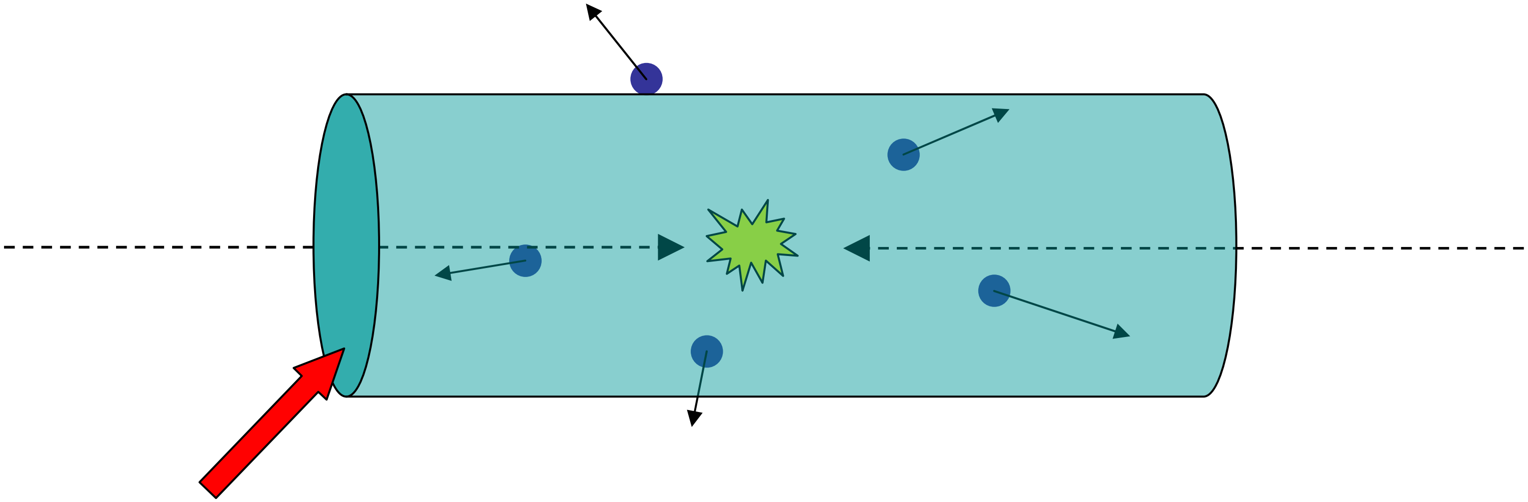


“Collider”:
available energy $\simeq 2E$





Detecting Particles



Particle detector: Ideally, identify, for each particle produced in each collision, its type (mass, electrical charge, spin, other quantum numbers), and its 4-vector (energy, p_x, p_y, p_z) at the interaction point.

In practice, a good detector will measure only a subset of all the available information for each event. Data analysis techniques are then required to best reconstruct each event.

A few Colliders

- $p\bar{p}$: Sp$\bar{p}$S at CERN

1981-1990 with a maximum beam energy of 315 GeV

Probing nature down to ≈ 2×10^{-17} m !!

W, Z particles discovery!!!

- e^+e^-: Large Electron Positron collider at CERN

1989-2000 with a maximum beam energy of 105 GeV

Probing nature down to ≈ 6×10^{-18} m !!

3 families of leptons!!!
Precision measurements

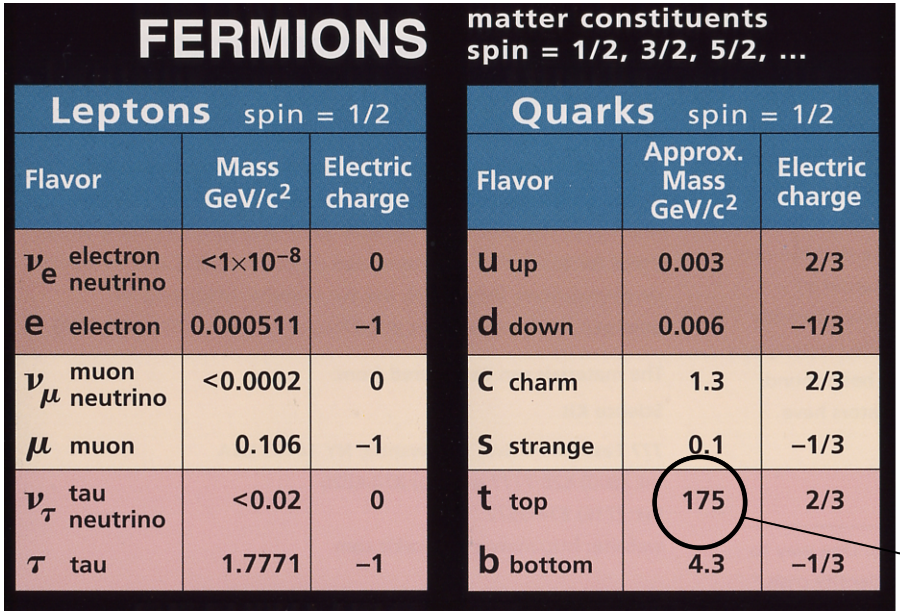
- $p\bar{p}$: Tevatron at Fermilab

1987- with a maximum beam energy of 980 GeV

Probing nature down to ≈ 3×10^{-18} m !!

top quark discovery!!!

Elementary Particles



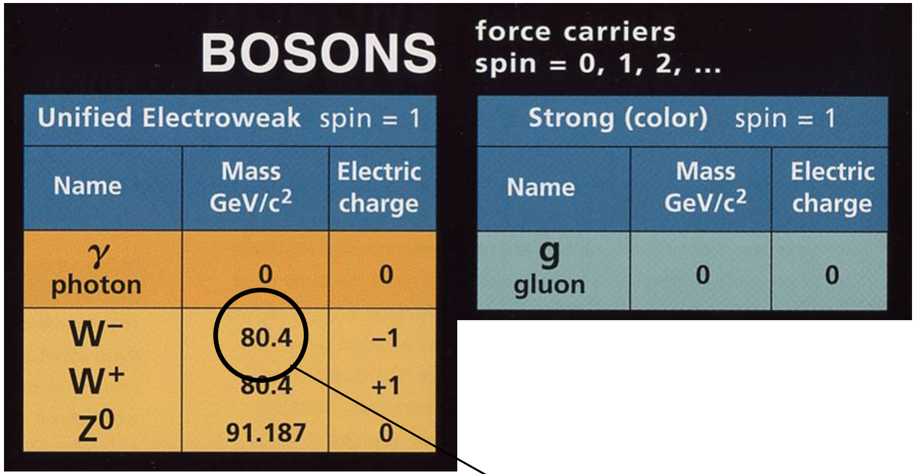
FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3



BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

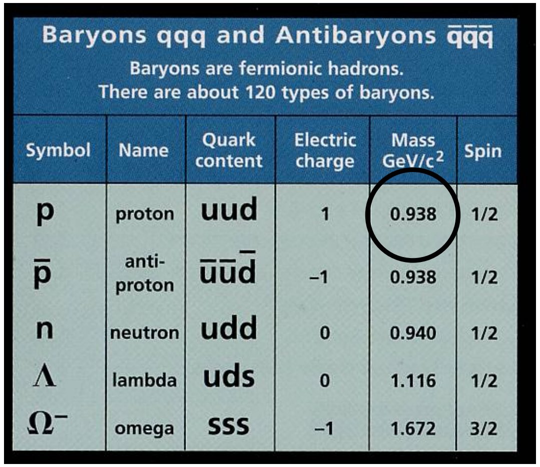
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

$M_t \approx$ M of $_{76}$Os

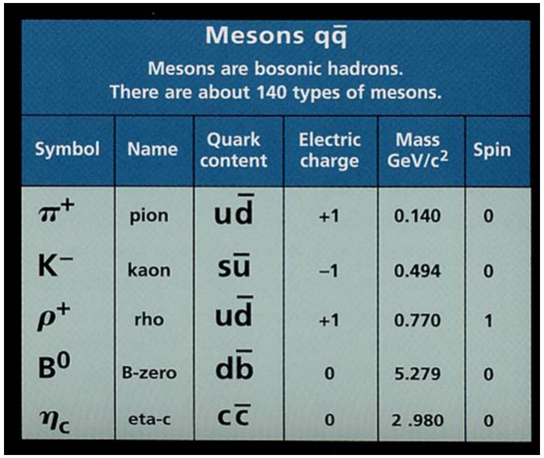
$M_W \approx$ M of $_{38}$Sr



Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

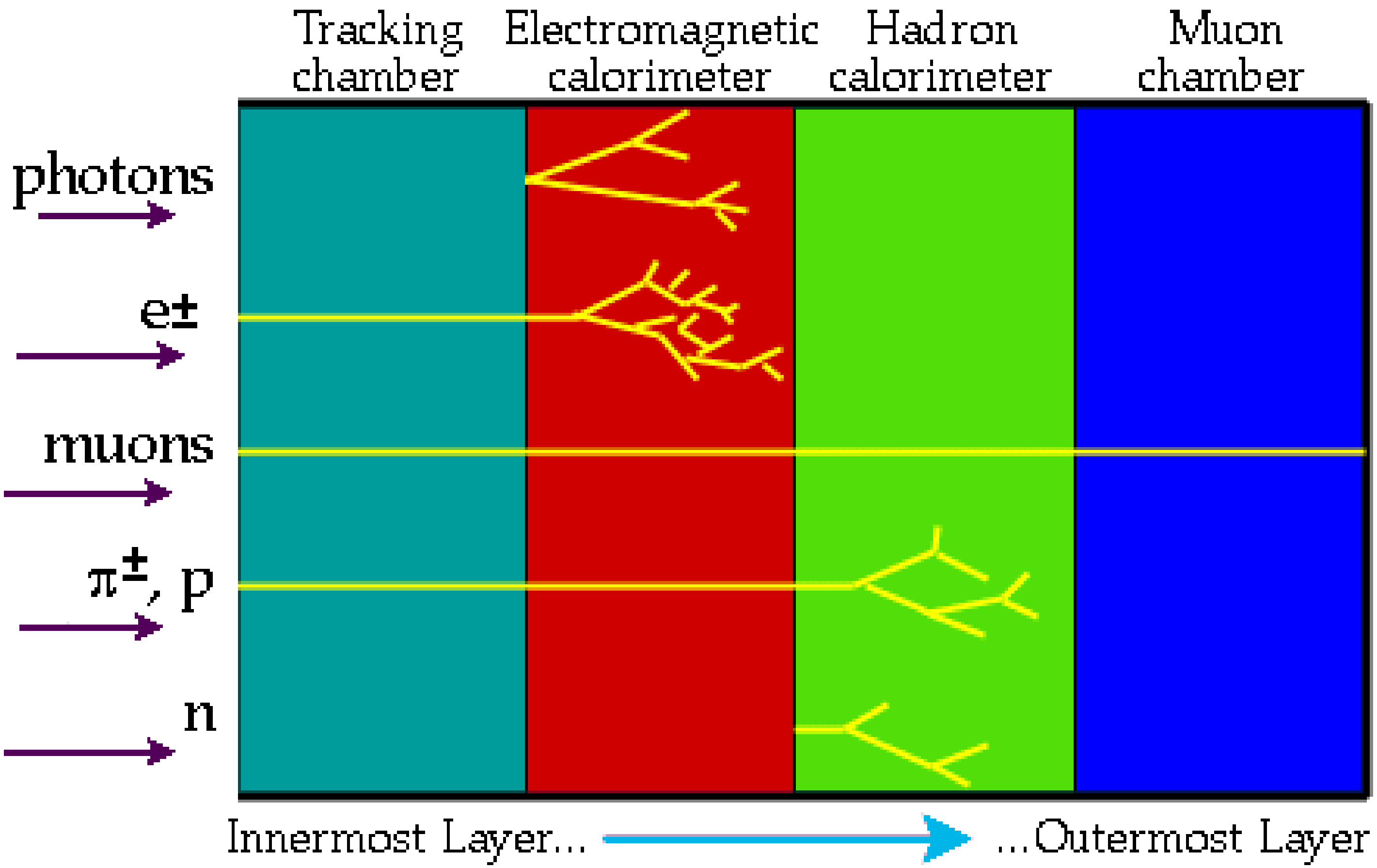


Mesons $q\bar{q}$

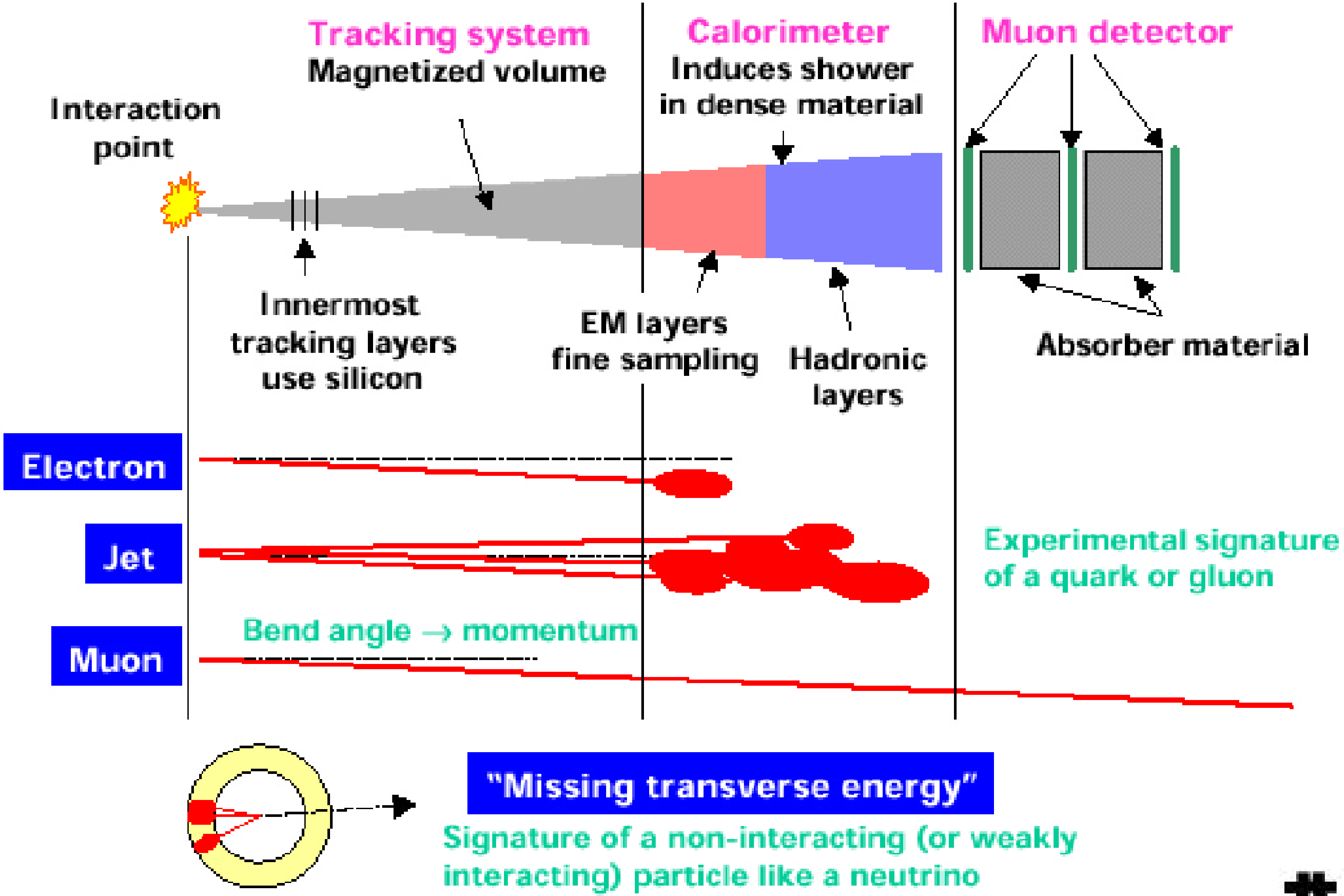
Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Typical Detector Components



Typical Detector



Tracking system
Magnetized volume

Calorimeter
Induces shower
in dense material

Muon detector

Interaction
point

Innermost
tracking layers
use silicon

EM layers
fine sampling

Hadronic
layers

Absorber material

Electron

Jet

Experimental signature
of a quark or gluon

Muon

Bend angle → momentum

"Missing transverse energy"

Signature of a non-interacting (or weakly interacting) particle like a neutrino

John Womersley

The Standard Model Particles

$$\text{fermions}\left\{\begin{array}{lcccc} \text{leptons} & \begin{pmatrix}\nu_e\\ e\end{pmatrix} & \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix} & \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix} & \begin{matrix}0\\ -1\end{matrix}\\ \text{quarks} & \begin{pmatrix}u\\ d\end{pmatrix} & \begin{pmatrix}c\\ s\end{pmatrix} & \begin{pmatrix}t\\ b\end{pmatrix} & \begin{matrix}+2/3\\ -1/3\end{matrix}\end{array}\right\}\text{matter}$$

bosons

U(1)$_Y$	B	$\xrightarrow{\cancel{EW}}$	γ W^+ W^- Z^0	electro-weak	radiation
SU(2)$_L$	W_1 W_2 W_3				
SU(3)$_C$	$g_{1\text{-}8}$		$g_{1\text{-}8}$	strong	
Higgs doublet	$\varphi_1+i\varphi_2$ $\varphi_3+i\varphi_4$		H^0		

Global Symmetry and Conservation Laws

Symmetry		Conservation of
homogeneity of space	⇔	momentum
homogeneity of time	⇔	energy
isotropy of space	⇔	angular momentum
more abstract symmetry	⇔	some “charge”

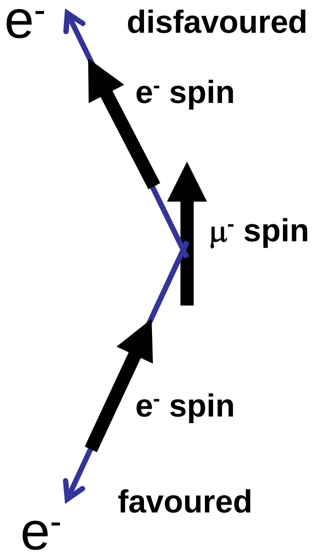
Local Symmetry and Fundamental Forces

To require the laws of nature to be invariant under a local symmetry is to invoke a Gauge Principle. All known fundamental interactions are formulated as Gauge Theories

- Electromagnetic
- Weak
- Strong
- Gravity

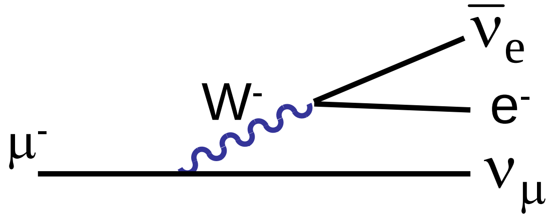
What about a quantum theory of gravity??

Weak Interaction



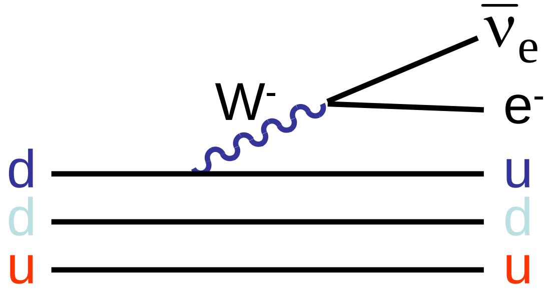
The weak interaction violates parity!!

This is very odd, and crucial to the understanding of the mystery of the origin of mass

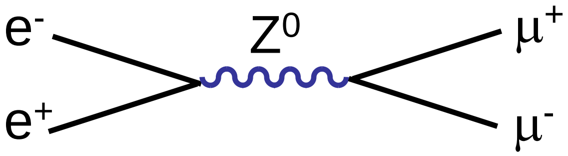


muon decay

The interaction is “weak” because it is mediated by massive vector bosons



$$n \rightarrow p + e^- + \bar{\nu}_e$$



$$e^+ + e^- \rightarrow Z^\circ \rightarrow \mu^+ + \mu^-$$

This weak reaction controls the star burning rate!!

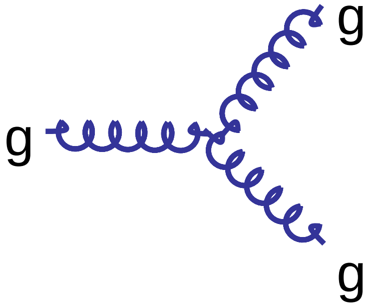
$$p + p \rightarrow d + e^+ + \nu_e$$

Strong Interaction

Each quark can have one of three different strong interaction charges, called colours.

Quantum ChromoDynamics (QCD)

The strong interaction is mediated by gluons between coloured objects. Photons do not carry (electric) charge, but gluons carry (strong) charge, so they can interact with each other!!



It is believed that this leads to confinement: only colour singlets can exist in nature. High energy quarks produced in collisions will result in jets of hadrons, typically many light mesons

Higgs Mechanism

It turns out that it is not possible to have the required gauge symmetries for the electromagnetic, weak and strong forces, AND to have ANY particle with a mass!!!

Big problem: We want to have a gauge principle to give us the interactions and we know that most particles have mass

The solution: The Higgs Mechanism

Higgs Mechanism

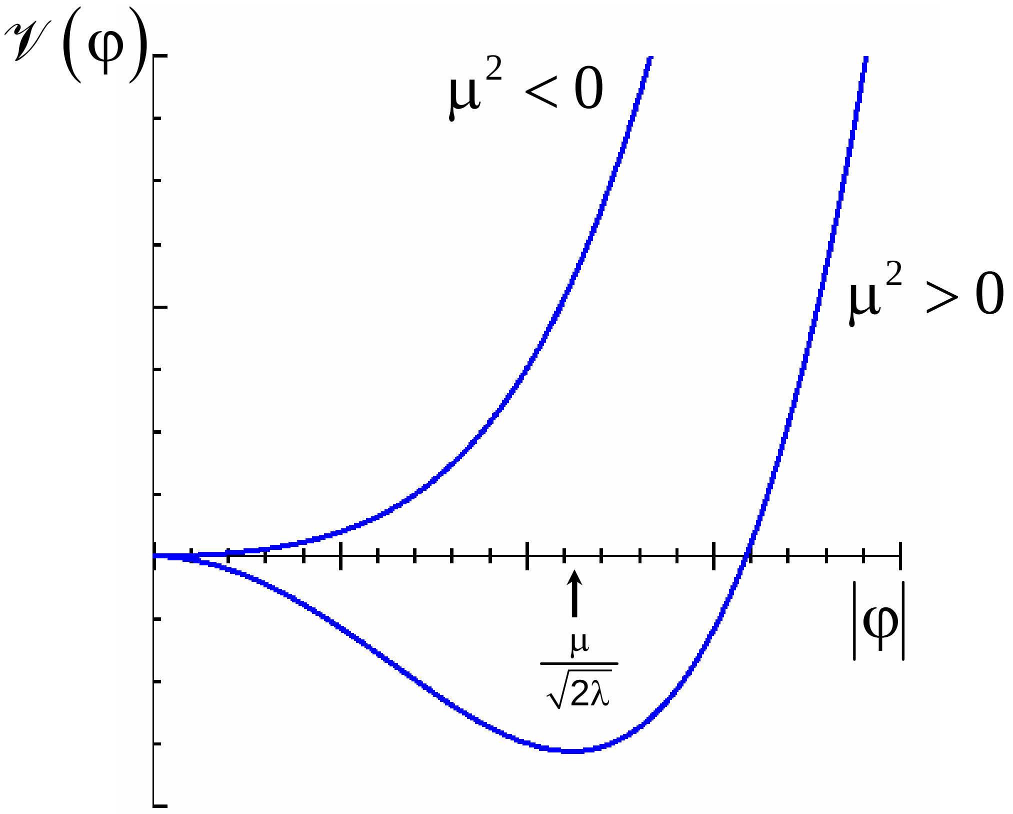
$$V(\varphi) = -\mu^2 \varphi^* \varphi + \lambda \left(\varphi^* \varphi\right)^2 \qquad \lambda > 0$$

A fundamental scalar Higgs field $\varphi(x)$ is postulated, with an energy density that has a minimum for a non-zero value of the field... Nature chooses one of the possible minima for its vacuum: spontaneous symmetry hiding.

$$V(\varphi)\Big|_{\mathrm{min}} = -\frac{\mu^2 v^2}{4} \Rightarrow$$

$$|\varphi|^2 = |\varphi_0|^2 = \frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2} > 0$$

From the measured value of the Fermi coupling constant G_F, we obtain v = 246 GeV



Higgs Mechanism

A room full of physicists chattering quietly is like space filled with the Higgs field...

… a well-known scientist walks in, creating a disturbance as he moves across the room and attracting a cluster of admirers with each step...

…this increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field...

…if a rumor crosses the room...

…it creates the same kind of clustering, but this time among the scientists themselves. In this analogy, these clusters are the Higgs particles

ATLAS educational web page, adapted from an idea from Dr D. J. Miller

The Standard Model
of Electroweak and Strong Interactions

Gauge invariance
$U(1)_Y \times SU(2)_L \times SU(3)_C$


Glashow
1932-


Salam
1926-1996


Weinberg
1933-

Spontaneous symmetry hiding in the electroweak sector

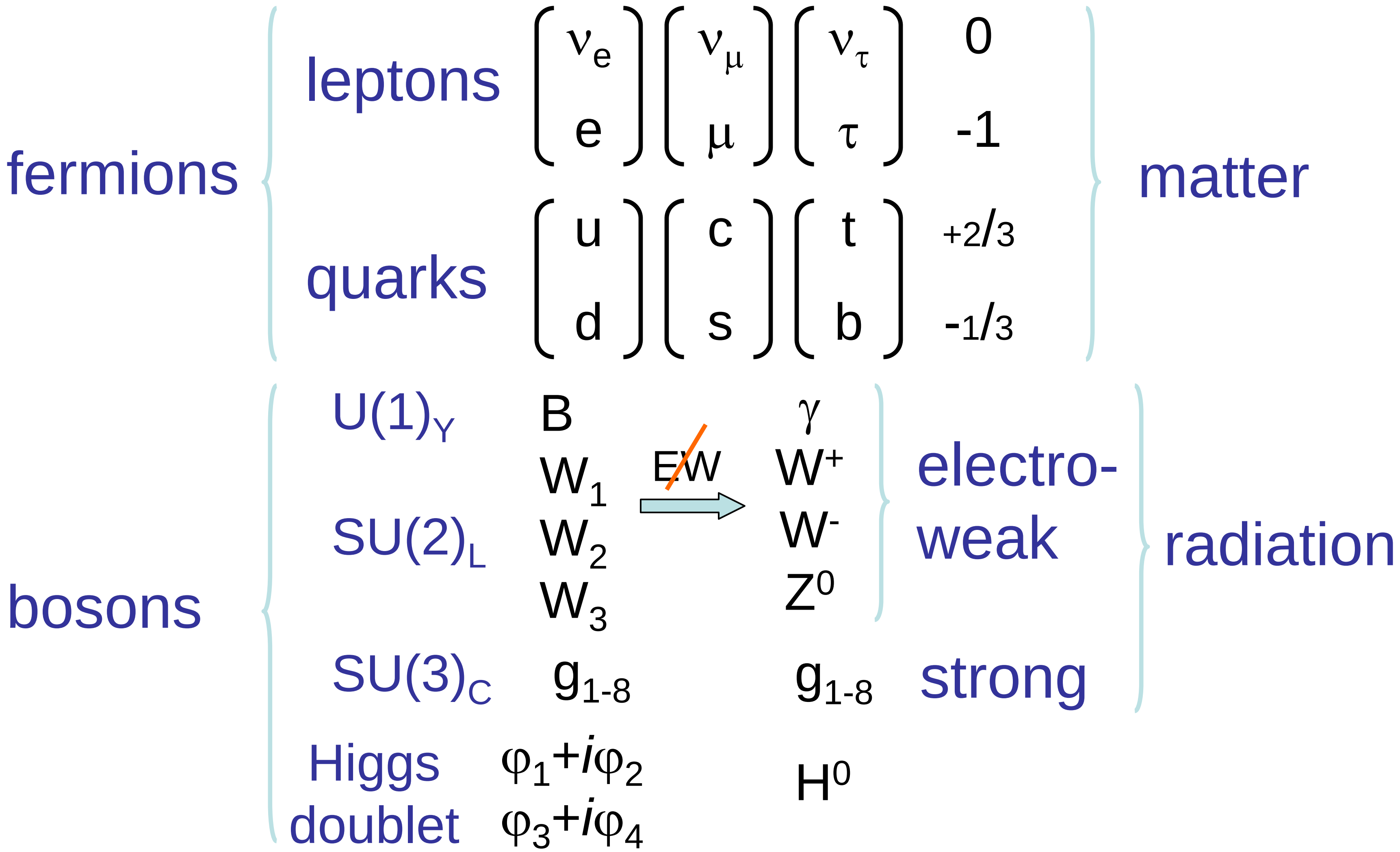
Higgs mechanism: $U(1)_Y \times SU(2)_L \rightarrow U(1)_Q$

Residual (non-hidden) symmetry: $U(1)_Q \times SU(3)_C$

massless photons

massless gluons

The Standard Model Particles



fermions

leptons $\begin{pmatrix}\nu_e\\ e\end{pmatrix}\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}\begin{matrix}0\\ -1\end{matrix}$

quarks $\begin{pmatrix}u\\ d\end{pmatrix}\begin{pmatrix}c\\ s\end{pmatrix}\begin{pmatrix}t\\ b\end{pmatrix}\begin{matrix}+2/3\\ -1/3\end{matrix}$

matter

bosons

$U(1)_Y$ B

$SU(2)_L$ W_1 W_2 W_3 $\xrightarrow{\cancel{\text{EW}}}$ γ W^+ W^- Z^0

electro-weak

$SU(3)_C$ g_{1-8} g_{1-8} strong

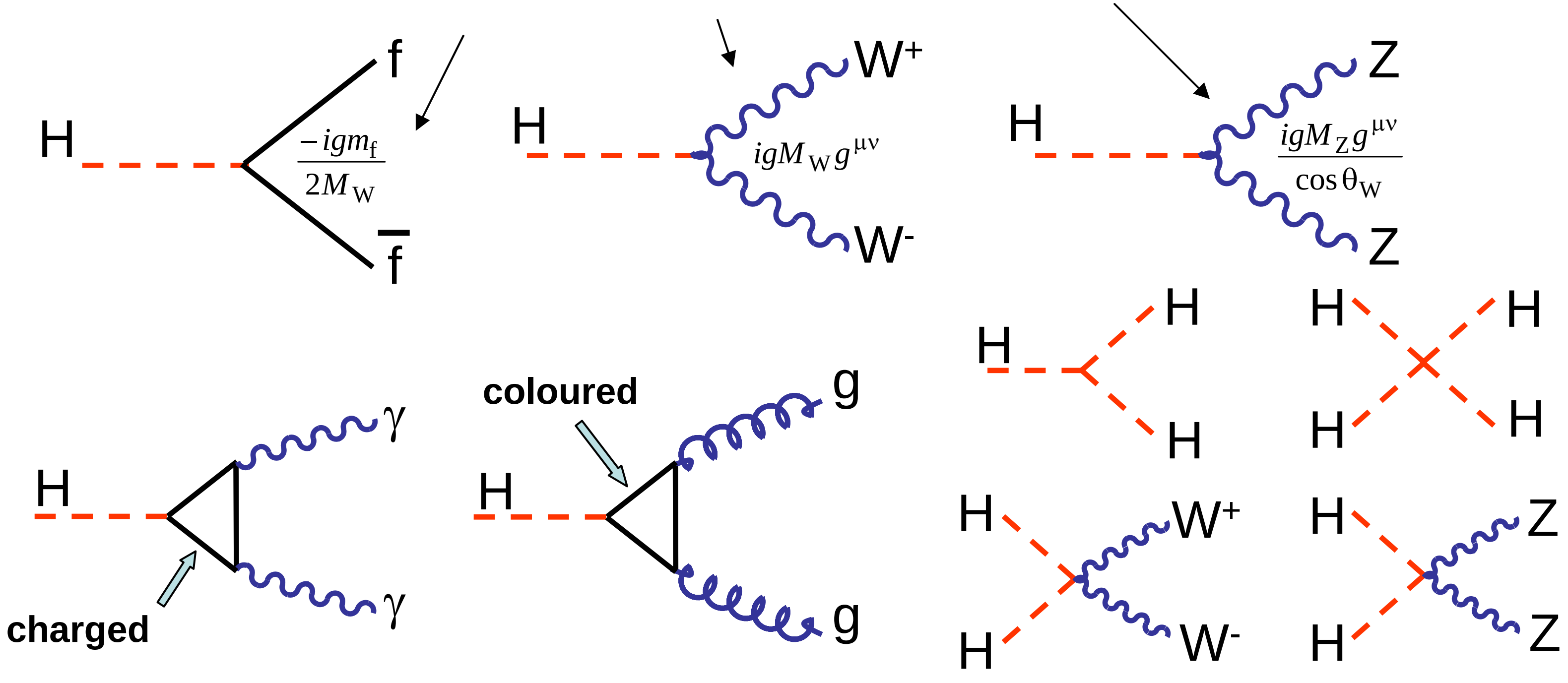
radiation

Higgs doublet $\varphi_1+i\varphi_2$ $\varphi_3+i\varphi_4$ H^0

SM Higgs Interactions

The Standard Model Higgs mechanism generates particle masses and predicts the existence of the Higgs Boson and its exact interaction with other particles... but ironically it does not predict its mass!!

(direct searches) **114 GeV < M_H < 219 GeV** (indirect searches) 95% CL

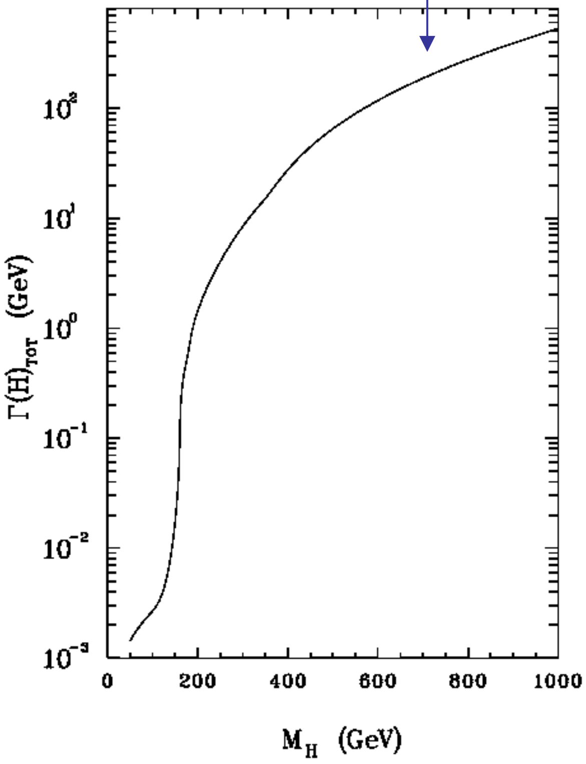


Higgs couplings proportional to mass $g^2 = 4\sqrt{2} G_F M_W^2$

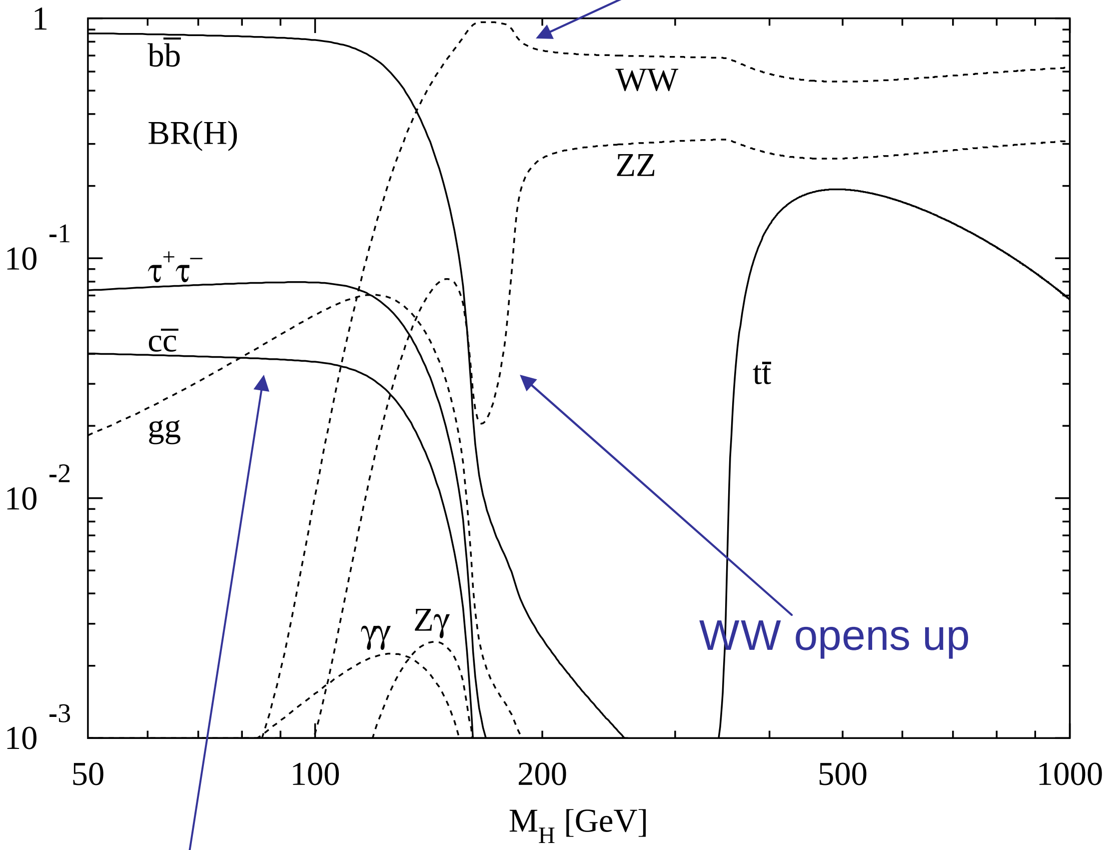
SM Higgs Decays

(direct searches) $114 \text{ GeV} < M_H < 219 \text{ GeV}$ (indirect searches) 95% CL

Fat!



ZZ opens up



WW opens up

due to c reduced running mass

New Colliders

- pp : Large Hadron Collider at CERN

2007- with a beam energy of 7 TeV

Probing nature down to ≈ 0.9×10^{-18} m !!

- e^+e^-: Linear Collider (site under discussion)

2015- with a beam energy of 250 GeV

Probing nature down to ≈ 2×10^{-18} m !!

Luminosity

Let

L: Machine luminosity (in cm^{-2}s^{-1})

σ: cross section for the relevant scattering process

R: event production rate

Then we have $R = L\sigma$ 1 barn = 10^{-28} m^2

Defining the integrated luminosity

$$\mathcal{L} = \int L \, \mathrm{d}t$$

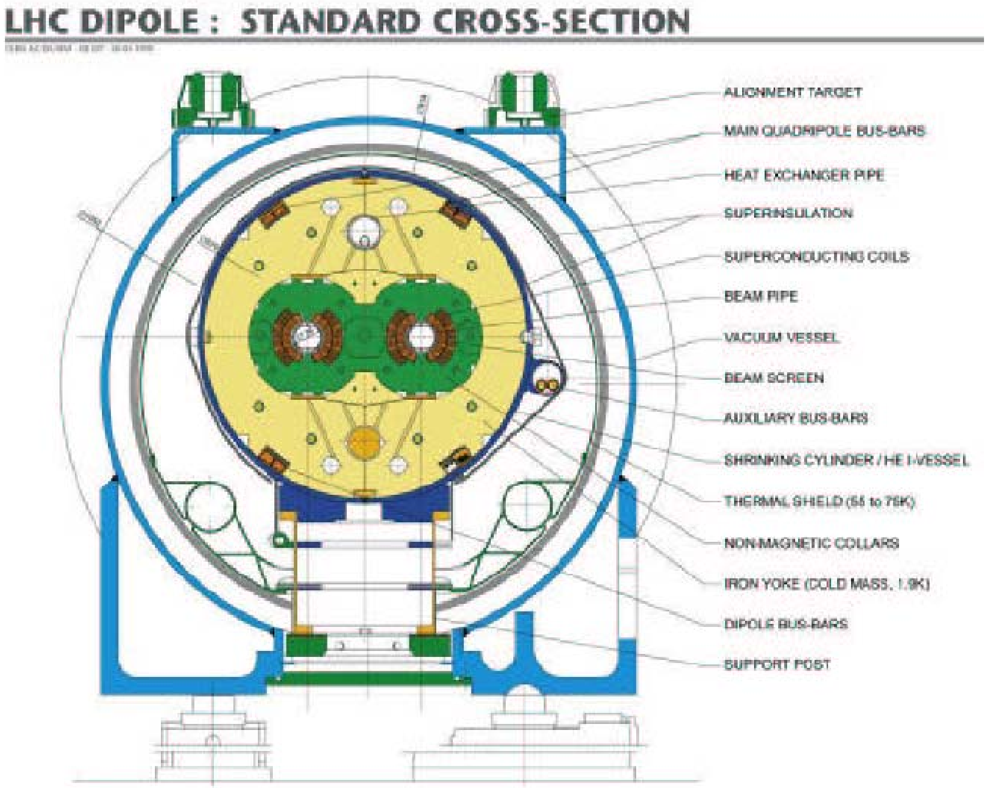
then the number of events is given by

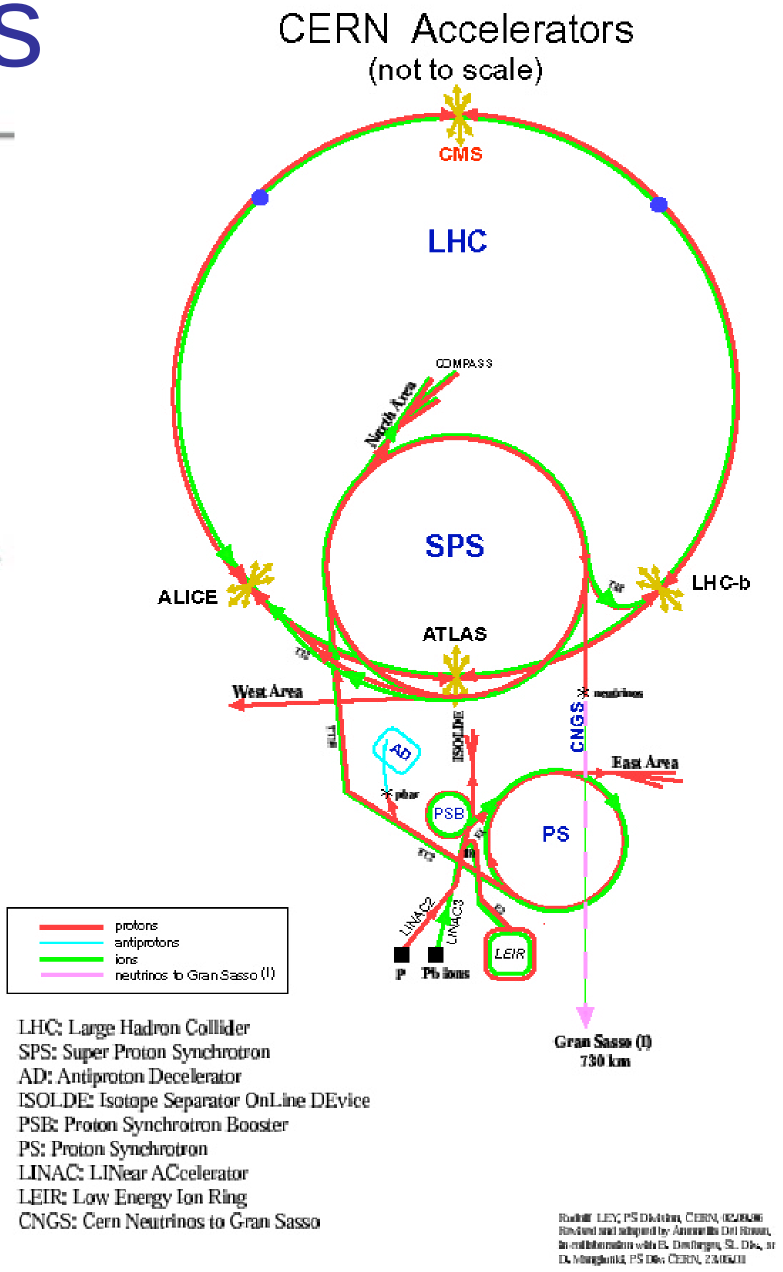
$$N = \mathcal{L}\,\sigma$$

Therefore if you want to make a measurement of a rare process (low cross section) with any significance, you need a large integrated luminosity. If you want to achieve this in a reasonable time, you need a large luminosity!

Aerial View of CERN

CERN Accelerators





LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Rudolf LEY, PS Division, CERN, 02.09.96
Revised and adapted by Antonella Del Rosso,
in collaboration with B. Desforges, SL Div., and
D. Manglunki, PS Div. CERN, 23.05.01

LHC: 7 TeV on 7 TeV proton-proton

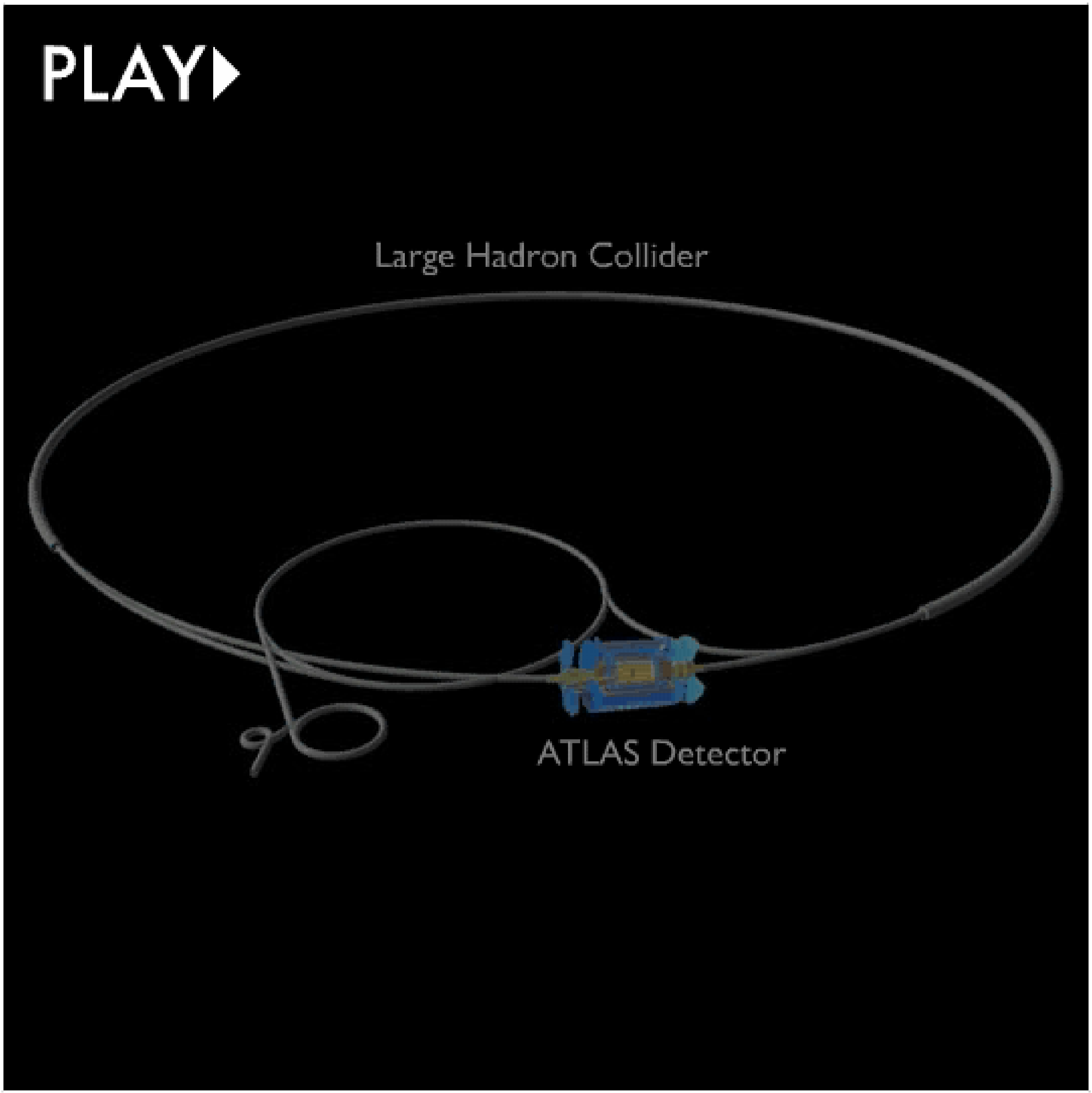
Design luminosity of 10^{34} cm^{-2}s^{-1}

LHC

7 TeV proton beams

Luminosity of 10^{34} cm^{-2}s^{-1}

Bunch crossing every 25 ns

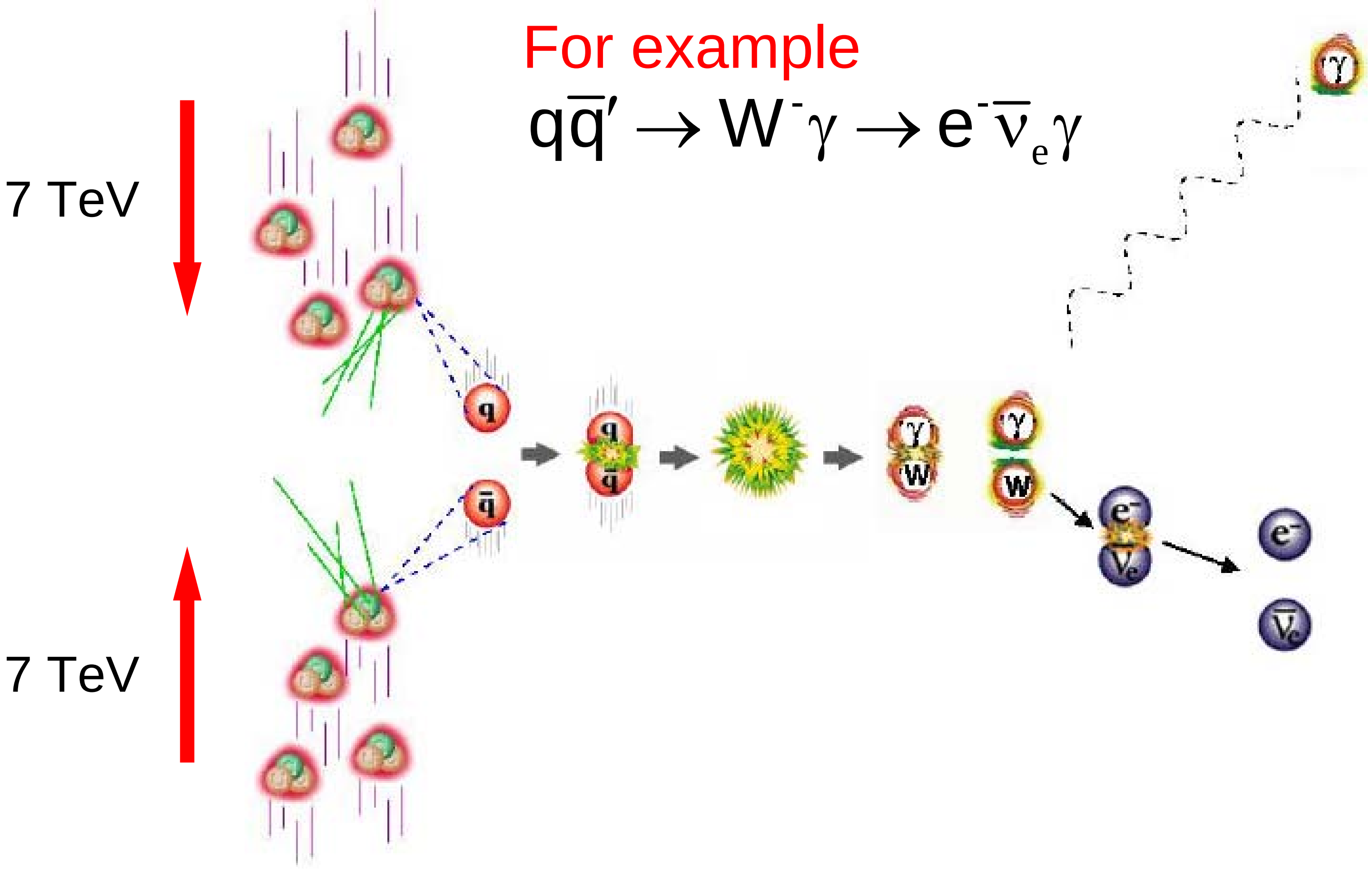


pp Collisions at the LHC

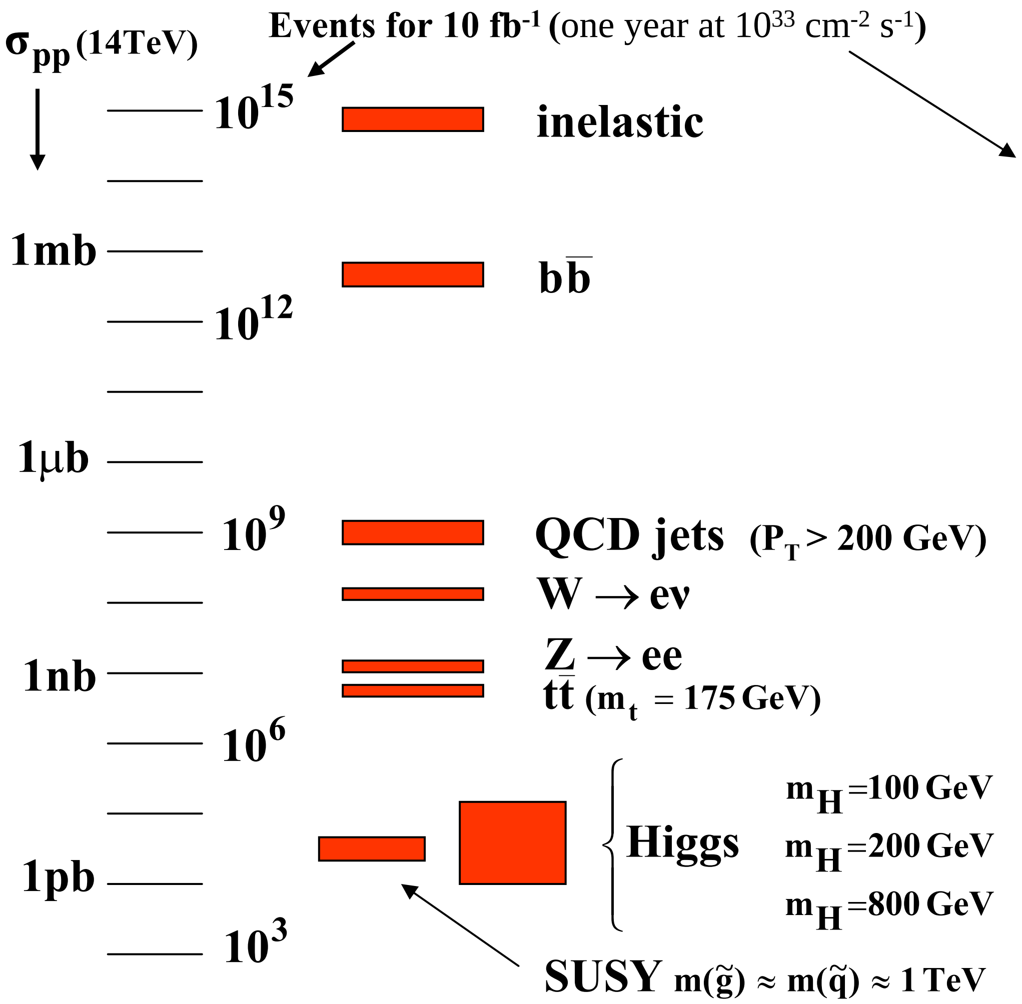
When protons collide at very high energy, what actually collides are constituents, quarks or gluons.

For example

$$q\bar{q}' \rightarrow W^{-}\gamma \rightarrow e^{-}\bar{\nu}_{e}\gamma$$



LHC PP Cross Section



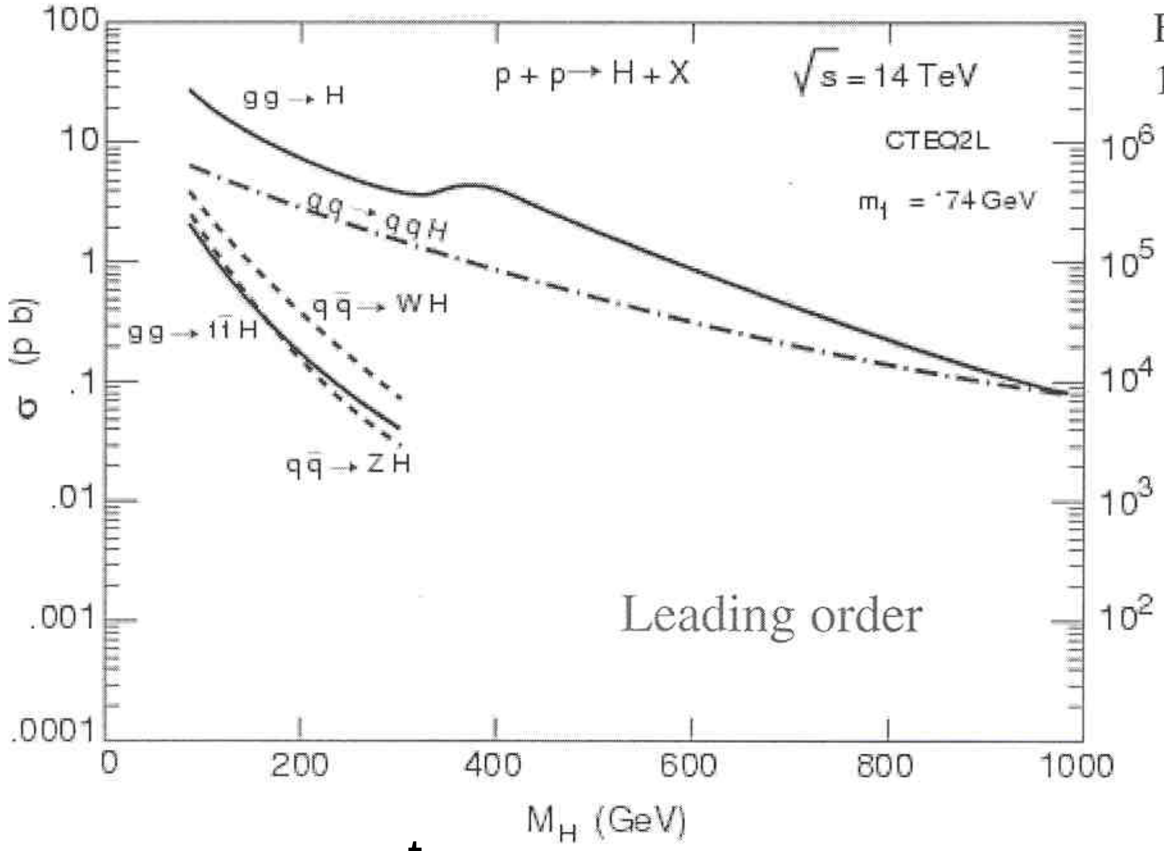
6.7 times the commissioning luminosity

83% of first year luminosity

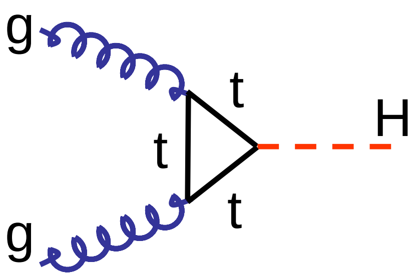
10% of nominal luminosity

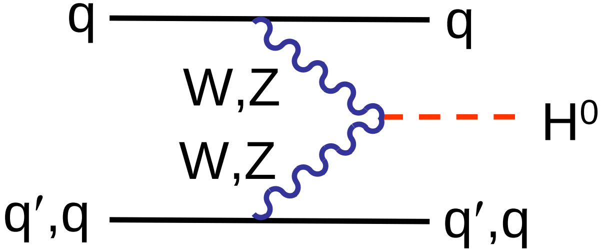
It is a challenge to “fish out” events that are more than 10 orders of magnitude rarer than the most common interactions

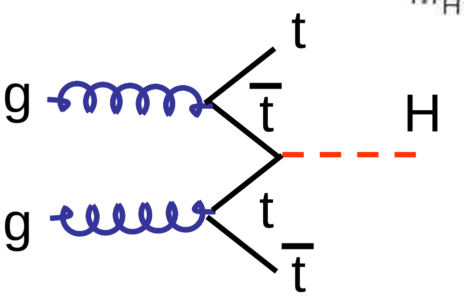
SM Higgs Production at the LHC

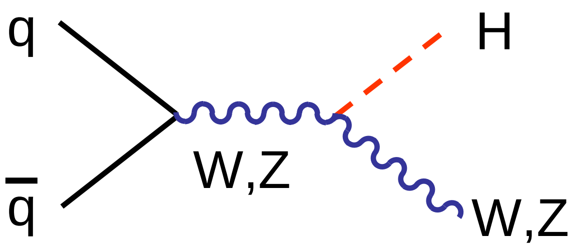


Events for
100 fb^{-1} (one year at 10^{34} cm^{-2} s^{-1})



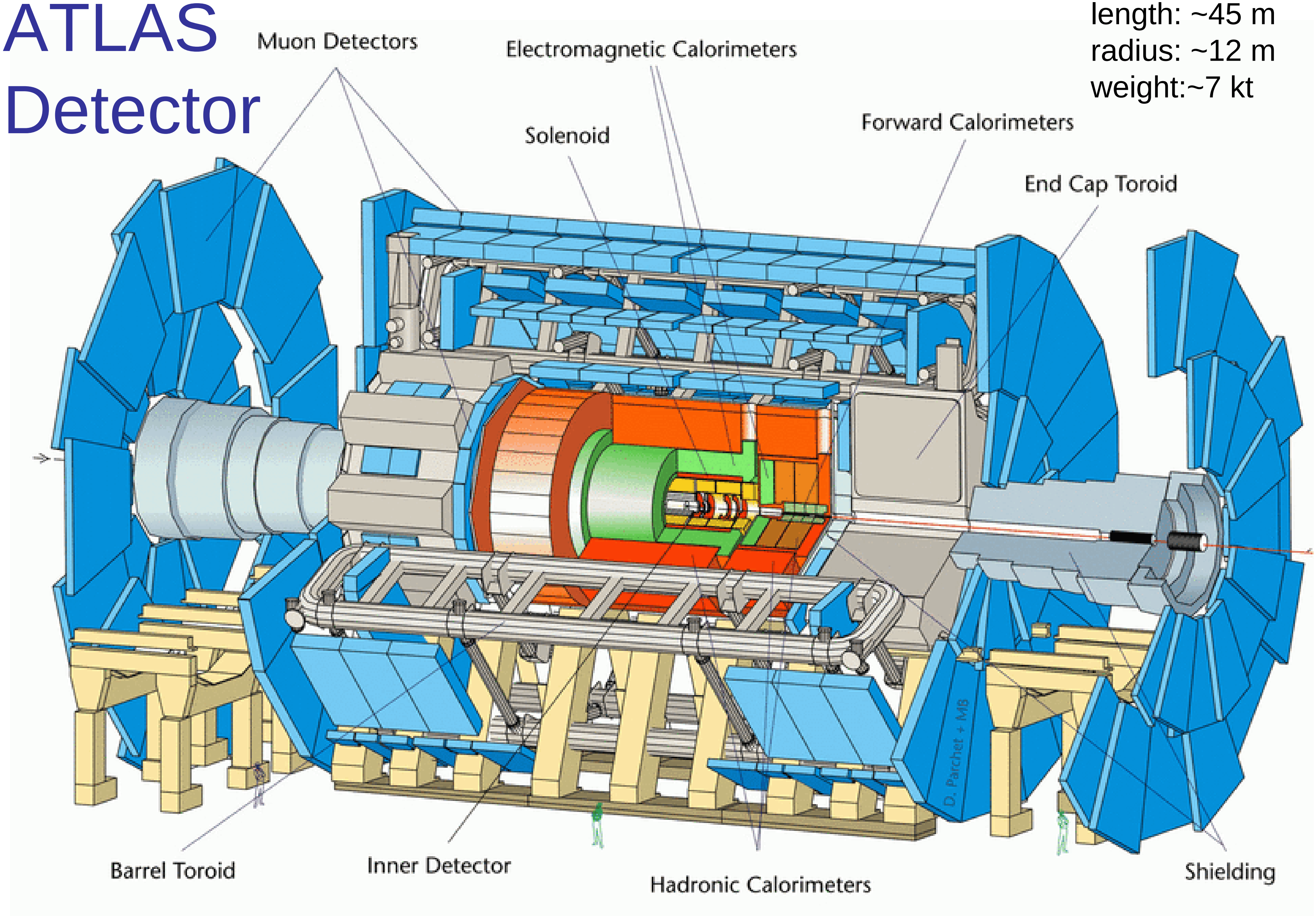




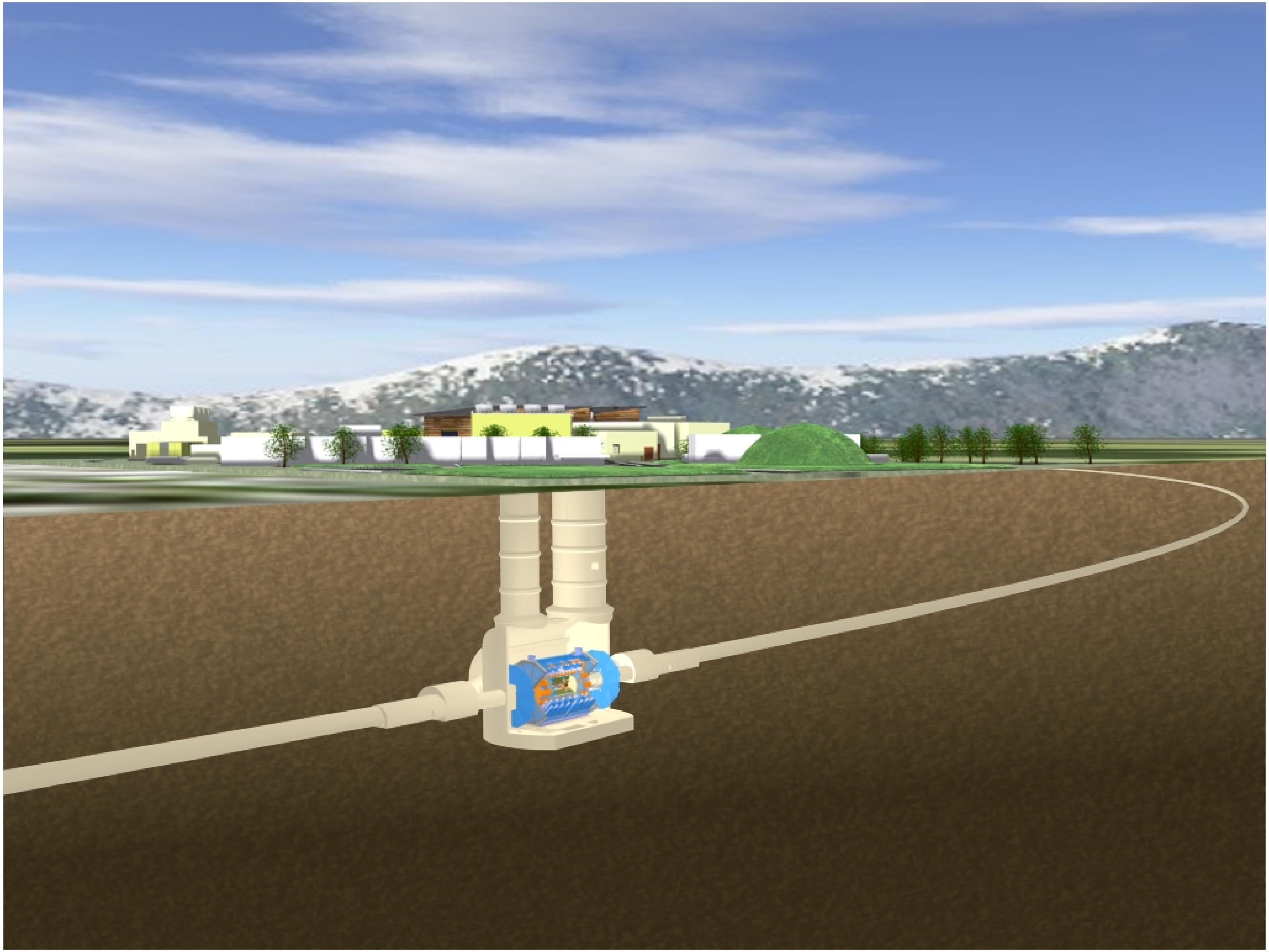


ATLAS Detector

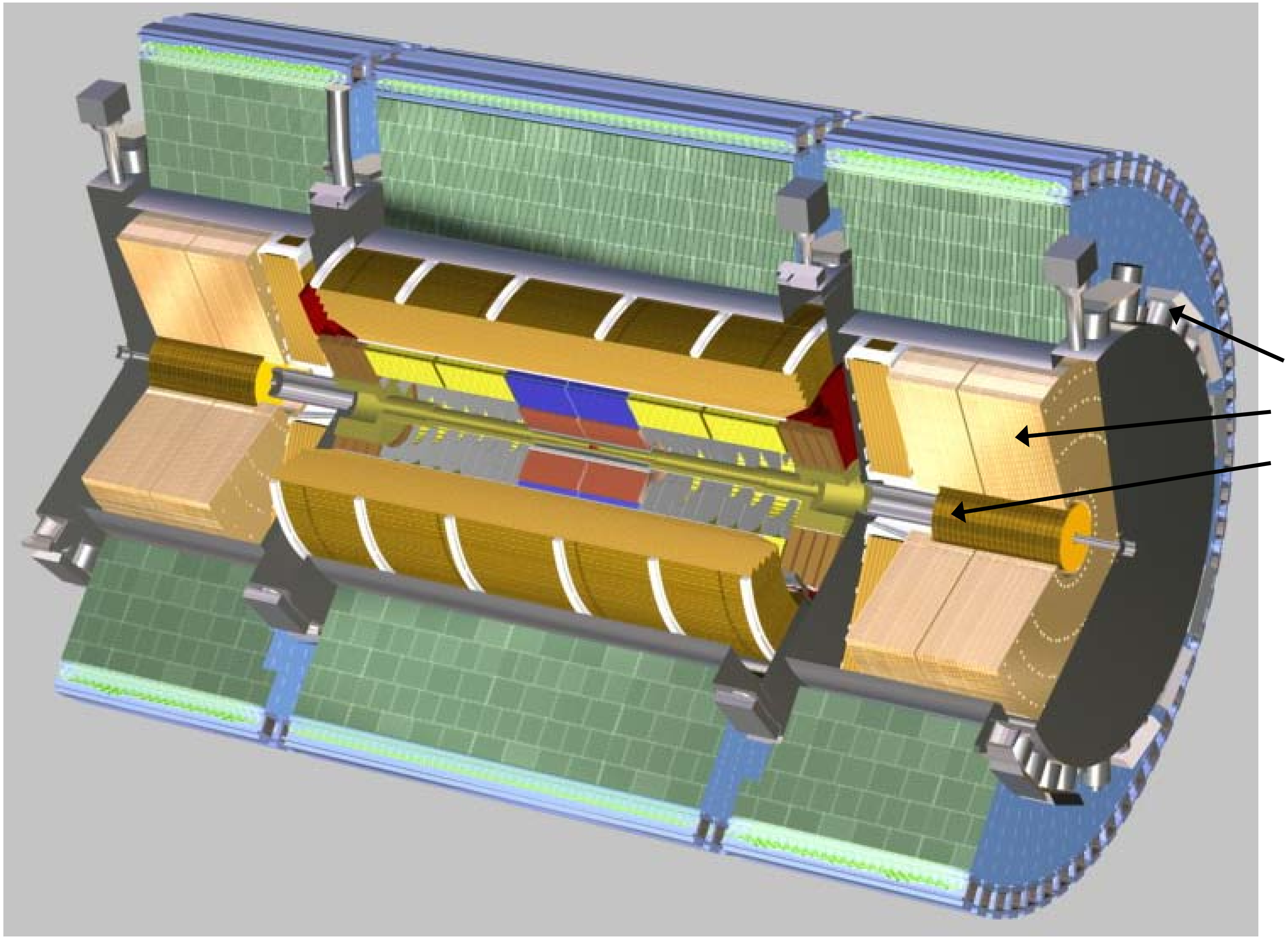
length: ~45 m
radius: ~12 m
weight:~7 kt



ATLAS Detector underground



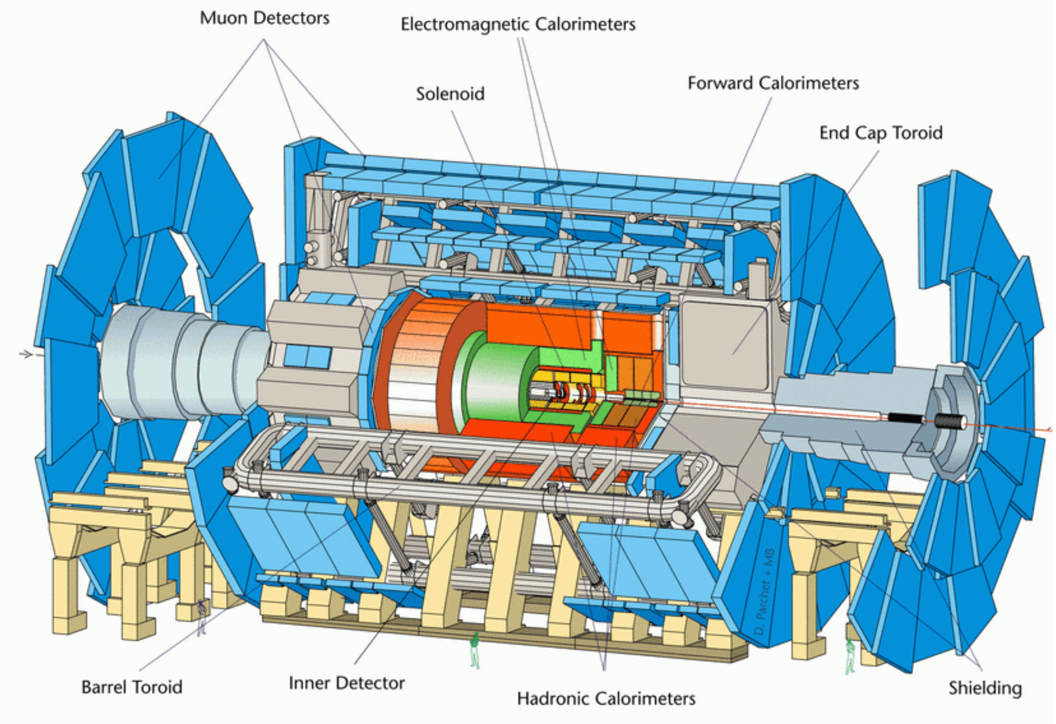
ATLAS Calorimetry: energy measurement



Built in Canada

ATLAS Installation

ATLAS detector components have been produced around the world. The detector is in its last phases of assembly.



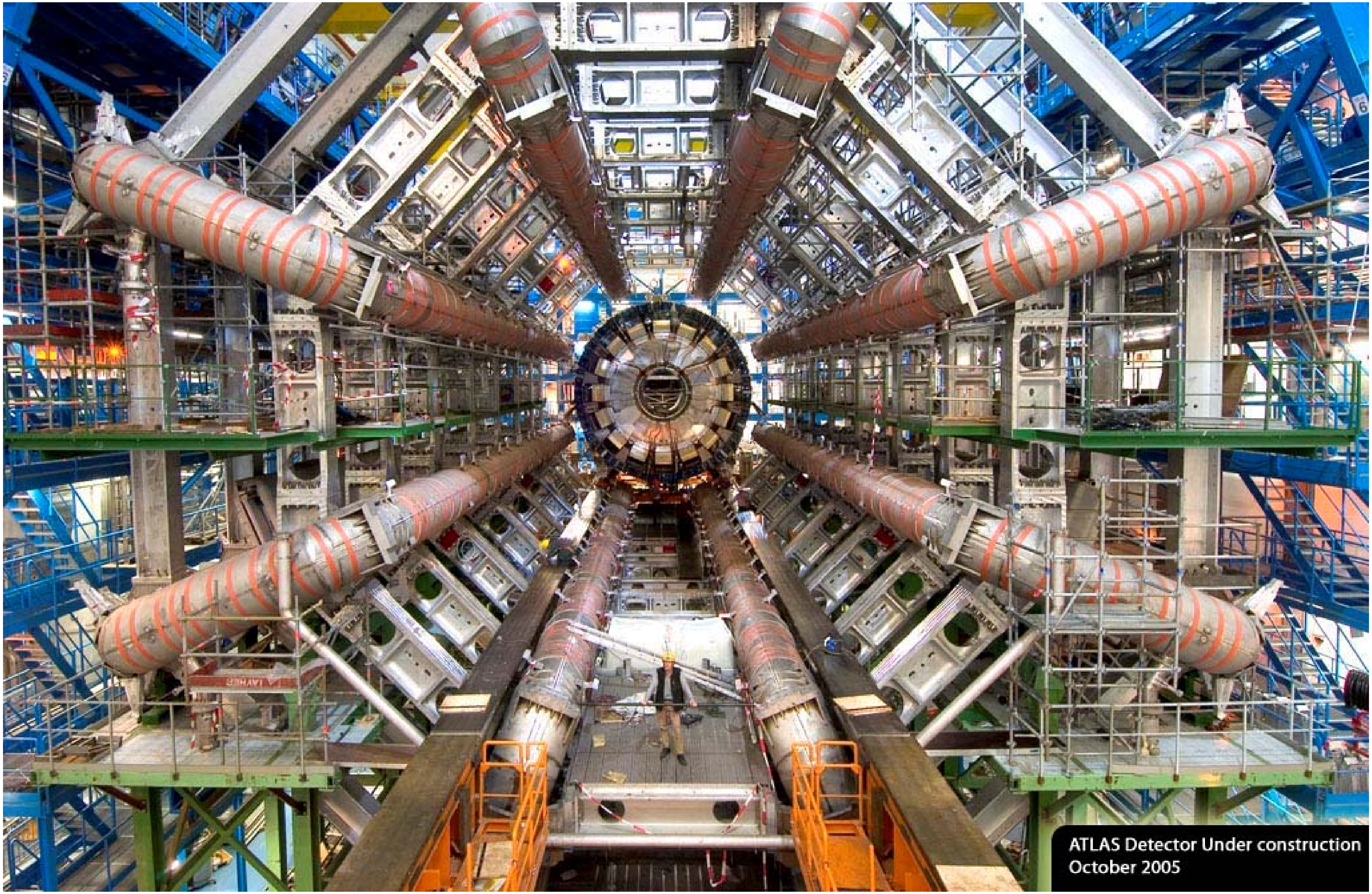
Whole Installation

Barrel Toroid Coils

Barrel Calorimeter

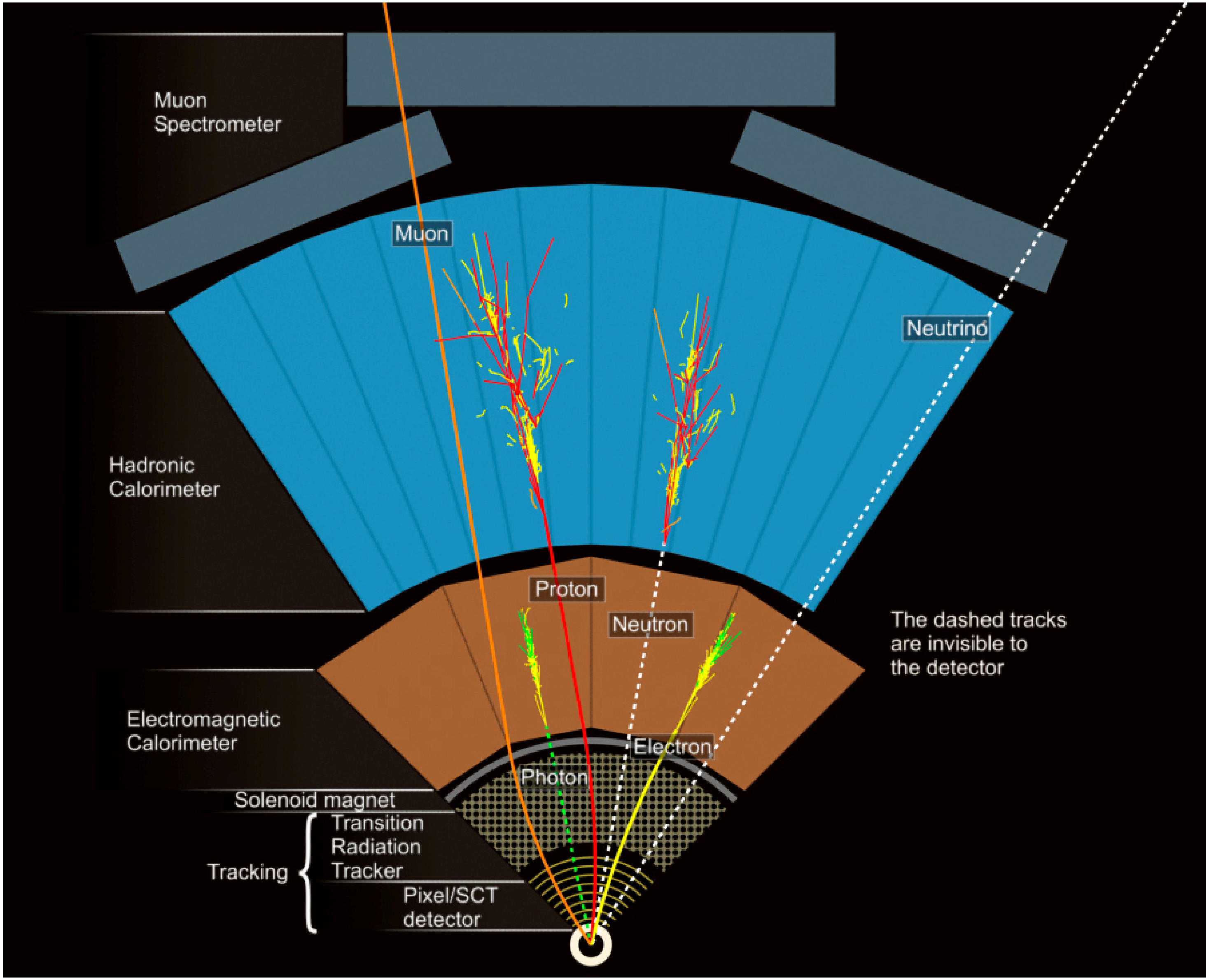
Endcap Calorimeter

ATLAS



ATLAS Detector Under construction
October 2005

ATLAS Detector in the transverse plane



ATLAS Detector Challenges

Particle bunch crossing: 25 ns

High radiation environment, in particular close to the beam pipe

Need to trigger efficiently on events of interest

Expect over 1 PByte (a million GByte) of data per year!

Over 2000 collaborators!

Beyond the Standard Model

The SM of particle physics is extremely successful at describing ALL experimental results so far. But we know the theory has technical problems. Possible solutions to these problems have been proposed, including

- SuperSymmetry
  - Should be able to find superparticles with masses less than about 1 TeV.
- Extra Spatial Dimensions
  - Leads to energy "leaking out" into other dimensions, escaping detection!

SuperSymmetry

$$\left.\begin{array}{l}\left.\begin{array}{l}\left.\begin{array}{l}\textbf{3D rotations...}\\ \textbf{pure boosts.....}\end{array}\right\}\textbf{Lorentz}\\ \textbf{4D translations.............}\end{array}\right\}\textbf{Poincare}'\\ \textbf{SUSY translations............................}\end{array}\right\}\textbf{superPoincare}'$$

Maximal extension of the Poincaré group

SUSY actions are invariant under superPoincaré

they are composed of an equal number of bosonic and fermionic degrees of freedom

SUSY mixes fermions and bosons

exact SUSY ⟹ there should exist fermions and bosons of the same mass
clearly NOT the case ⟹ SUSY IS BROKEN

A solution to the hierarchy problem

If the Higgs is to be light without unnatural fine tuning, then (softly broken) SUSY particles should have $M_{\mathrm{SUSY}} <\sim 1$ TeV. SUSY can be viable up to M_{PL} AND be natural!

GUT acceptable coupling constant evolution

The precision data at the Z mass (LEP and SLC) are inconsistent with GUT's using SM evolution, but are consistent with GUT's using SUSY evolution, if $M_{\mathrm{SUSY}} \approx 1$ TeV

A natural way to break EW symmetry

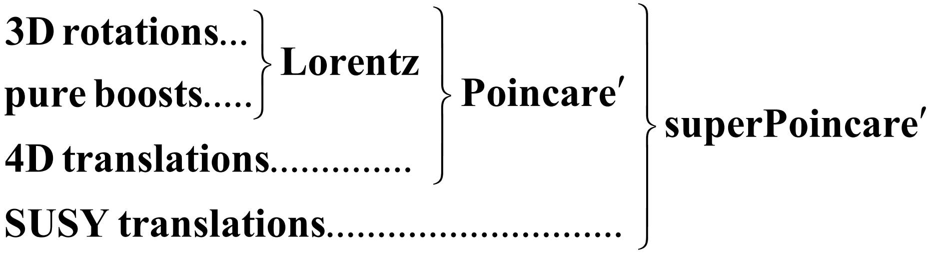
The large top Yukawa coupling can naturally drive the Higgs quadratic coupling negative in SUSY

Lightest SUSY particle is a cold dark matter candidate

Local SUSY is SUperGRAvity!

SuperSymmetry

Maximal extension of the Poincaré group


3D rotations...

pure boosts.....

Lorentz

4D translations.............

Poincare′

SUSY translations............................

superPoincare′

SUSY mixes fermions and bosons.

Exact SUSY predicts superpartners of all particles!!!

Is this crazy? Recall Dirac predicted that all fermions would have anti-fermions...

Lightest SUSY particle (LSP) is a cold dark matter candidate!!!

Minimal SUSY Higgs Sector

MSSM: SM + an extra Higgs doublet + SUSY partners

SUSY breaking

0	H_d^-	H_d^0	H_u^0	H_u^+						$\tilde{q}_R^d$	$\tilde{q}_L^d$	$\tilde{q}_R^u$	$\tilde{q}_L^u$	$\tilde{\nu}_L$	$\tilde{l}_R$	$\tilde{l}_L$
$\frac{1}{2}$	$\tilde{H}_d^-$	$\tilde{H}_d^0$	$\tilde{H}_u^0$	$\tilde{H}_u^+$	$\tilde{B}^0$	$\tilde{W}^0$	$\tilde{W}^-$	$\tilde{W}^+$	$\tilde{g}$	q_R^d	q_L^d	q_R^u	q_L^u	ν_L	l_R	l_L
1					B^0	W^0	W^-	W^+	g							

EW symmetry breaking

	CP odd	CP even														
0	A	H	h	H^-	H^+					$\tilde{q}_2^d$	$\tilde{q}_1^d$	$\tilde{q}_2^u$	$\tilde{q}_1^u$	$\tilde{\nu}_l$	$\tilde{l}_2$	$\tilde{l}_1$
$\frac{1}{2}$	χ_4^0	χ_3^0	χ_2^0	χ_1^0	χ_2^-	χ_1^-	χ_2^+	χ_1^+	$\tilde{g}$	q_R^d	q_L^d	q_R^u	q_L^u	ν_l	l_R	l_L
1					Z^0	γ	W^-	W^+	g							

⟶ **5 massive Higgs particles, with $M_h < 130$ GeV**

At tree level, all Higgs boson masses and couplings can be expressed in terms of two parameters only (in “constrained MSSM”)

$$m_A \quad \text{and} \quad \tan\beta = \frac{\text{vev } H_u}{\text{vev } H_d}$$

Note that we also have the following mixings

$$B^0, W^0 \rightarrow \gamma, Z^0$$

$$\tilde{W}^\pm, \tilde{H}^\pm \rightarrow \chi_{1,2}^\pm$$

$$\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0 \rightarrow \chi_{1,2,3,4}^0$$

$$\tilde{l}_L, \tilde{l}_R \rightarrow \tilde{l}_1, \tilde{l}_2$$

$$\tilde{q}_L, \tilde{q}_R \rightarrow \tilde{q}_1, \tilde{q}_2$$

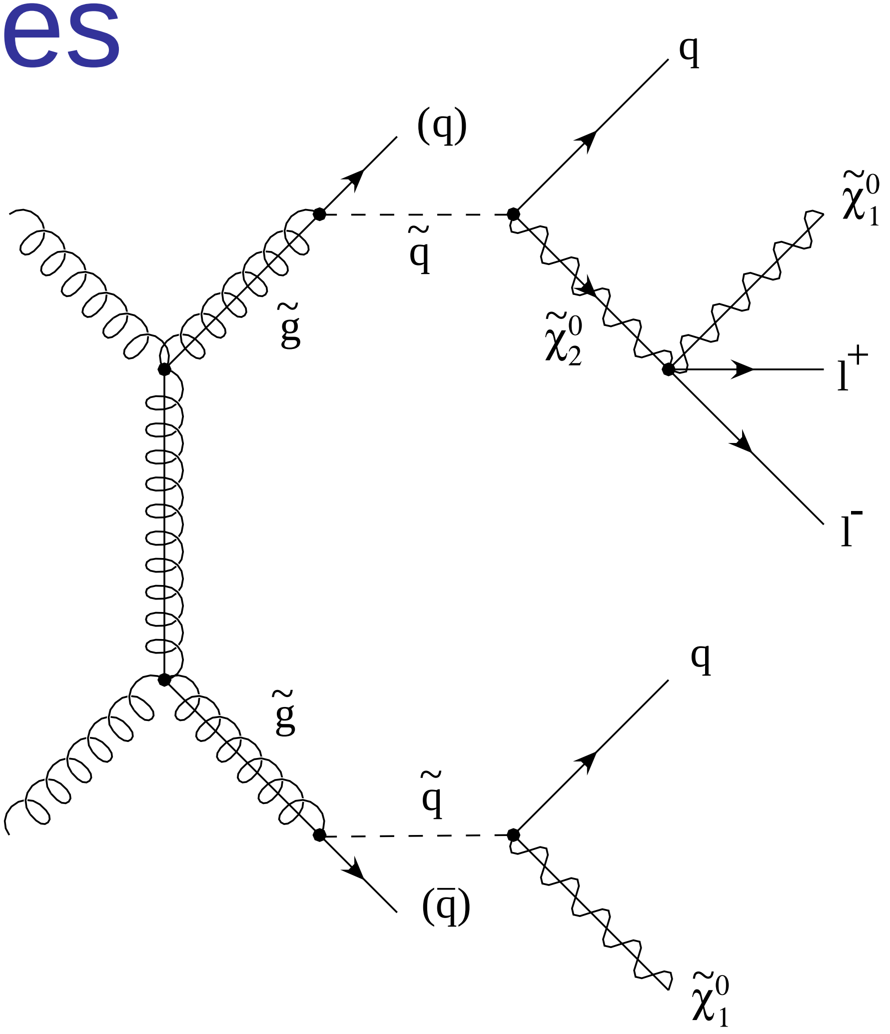
with off-diagonal elements proportional to fermion masses

SUSY Signatures

The production of SUSY particles often yield events with many hadron jets and significant missing energy.

In most SUSY models, sparticles are produced in pair, so that there would always be 2 LSP escaping detection.

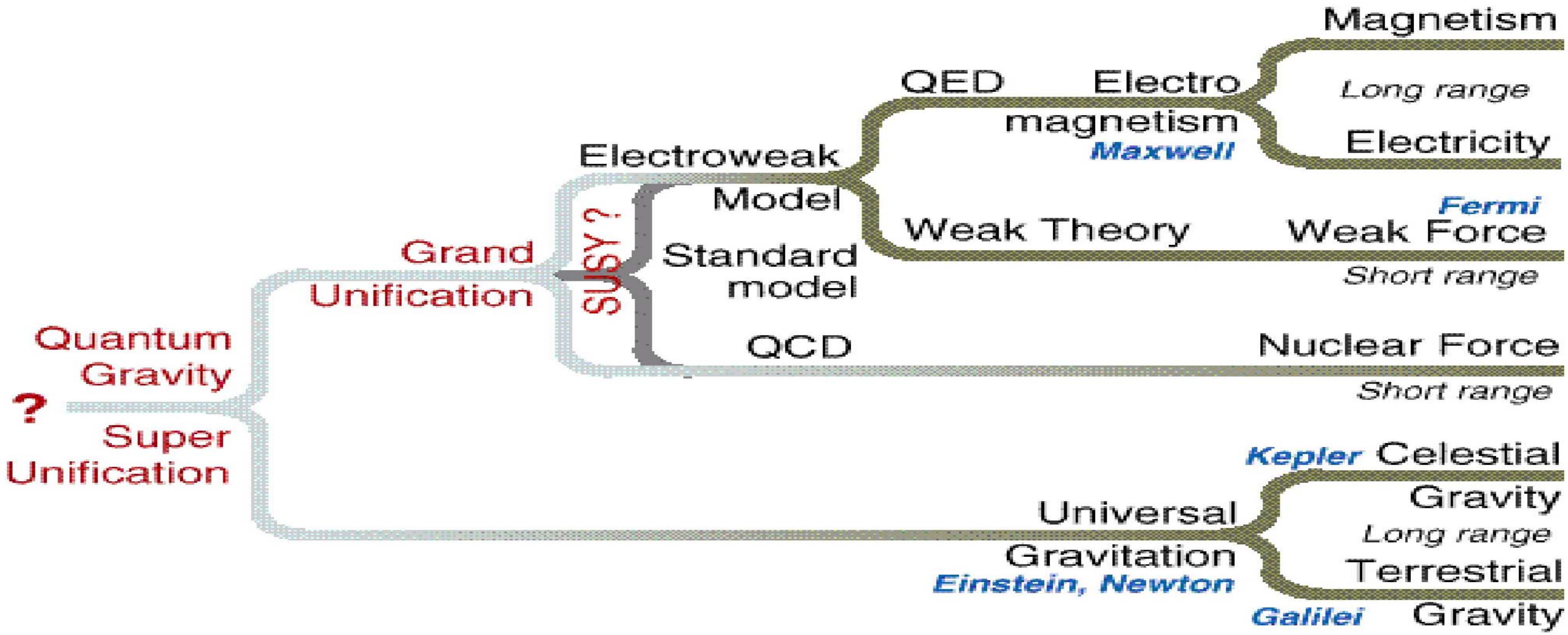
If SUSY particles exist at the electroweak scale (less than 1TeV), discovery should be easy at the LHC



$$gg \rightarrow \tilde{g}\tilde{g} \rightarrow qqqq\ell^+\ell^-\chi_1^0\chi_1^0$$

Grand Unification?

10^{-43} sec	10^{-32} sec	10^{-10} sec	10^{-4} sec	100 sec	300000 years
10^{-35} m	10^{-32} m	10^{-18} m	10^{-16} m	10^{-15} m	10^{-10} m
10^{19} GeV	10^{16} GeV	10^{2} GeV	1 GeV	1 Mev	10 eV



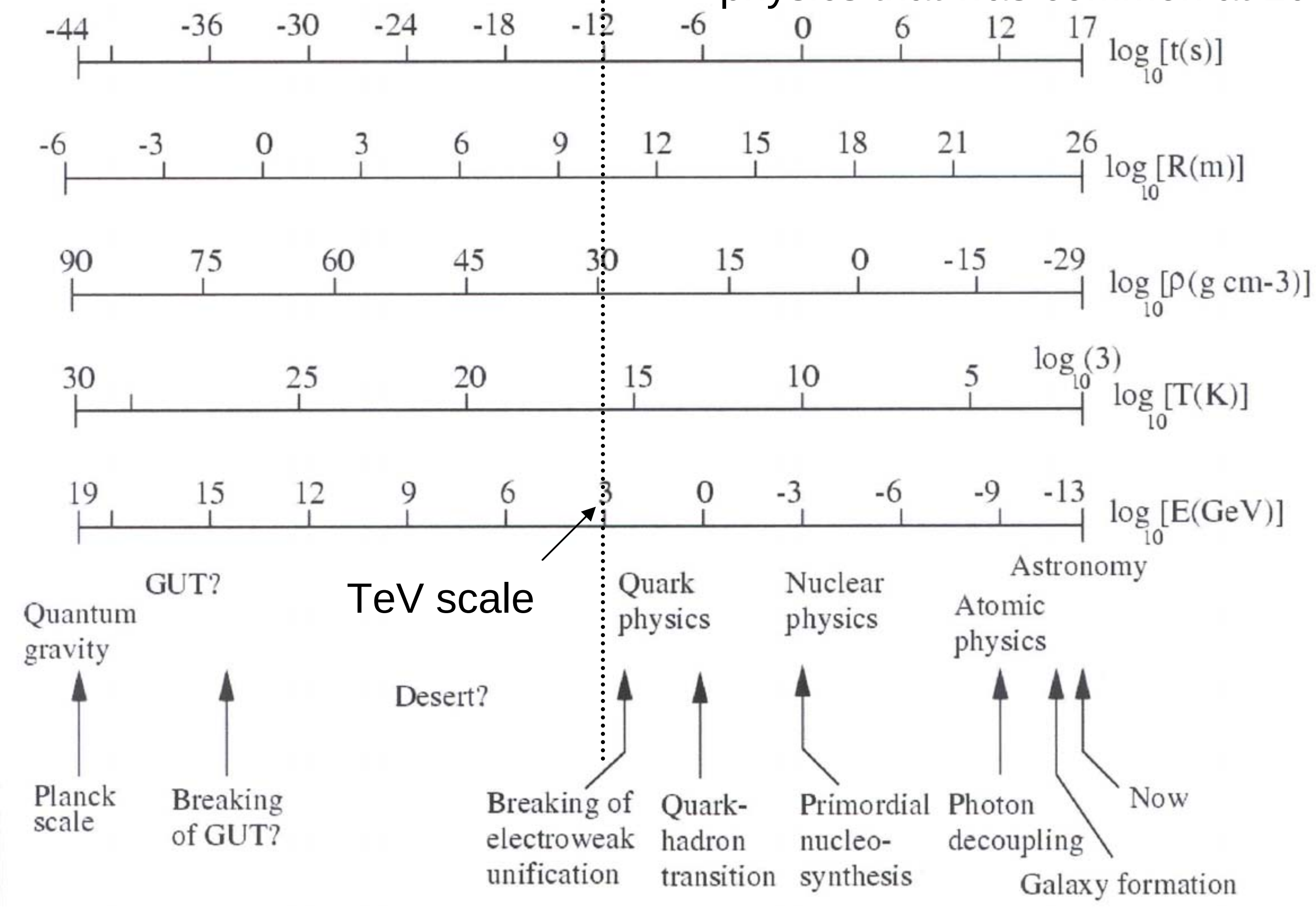
Theories:

STRINGS? **RELATIVISTIC/QUANTUM** **CLASSICAL**

Cosmic Connection

The "History" of the Universe from the Planck time to the present, showing how the size of the presently observable universe R, the average density ρ, the temperature T, and the energy per particle kT, have varied with time t according to the hot big bang model.

physics that was common at 10^{-12} s!



TeV scale

Canada and ATLAS

Activities focused on Liquid Argon Calorimetry

4 Major Projects Funded by Major Installation Grants

- Endcap Hadronic Calorimeter
- Forward Hadronic Calorimeter
- Frontend-Board Electronics
- Endcap Signal Cryogenics Feedthroughs

Work in close collaboration with TRIUMF, Canada’s national particle and nuclear physics laboratory

Many other activities including

- Computing, software, calibration, reconstruction

Currently involved in installation, commissioning and getting ready to use ATLAS for physics studies!!

Alberta
Carleton
McGill
Montréal
SFU
Toronto
TRIUMF
UBC
Victoria
York

Conclusions

ATLAS at the LHC is expecting first collision in 2007

Boldly look where no one has looked before, probing nature at the TeV scale

Many unanswered questions... and very likely many surprises!

You can be part of it!

Particle Physics at UVic

One of the strongest group in Canada!

http://particle.phys.uvic.ca/

- BaBar at SLAC
- ATLAS at CERN
- Linear Collider
- T2K- From Tokai To Kamioka, ν experiment
- Theory

We are recruiting graduate students!