High Energy Physics and the ATLAS Detector

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.

La physique des hautes énergies et le détecteur de particules ATLAS.

ABSTRACT

La physique des hautes énergies étudie les constituants de base de la matière et la nature de leurs interactions. Ce sujet est fondamental et captive beaucoup de scientifiques. De hautes énergies sont requises pour sonder les petites dimensions associées au monde des particules élémentaires. Plusieurs de ces particules ont une masse importante; de hautes énergies sont donc aussi requises pour les créer et les étudier. De nos jours, la physique expérimentale des hautes énergies utilise en général des accélérateurs de particules géants ainsi que des détecteurs très sophistiqués. Le Modèle Standard de la physique des particules offre une description très précise des interactions entre les particules élémentaires aux plus petites dimensions et aux plus hautes énergies accessibles aujourd'hui. Mais plusieurs questions importantes demeurent sans réponses. De quoi est fait un électron? Quelle est l'origine de la masse? Quelle est la nature de la matière noire? N'y a-t-il que trois dimensions spatiales? Le grand collisionneur de hadrons (LHC pour Large Hadron Collider), qui bientôt débutera son opération au CERN, à Genève, produira des collisions proton-proton de 14 TeV d'énergie, ce qui permettra d'atteindre des régions nouvelles et inexplorées de la nature. Plusieurs physiciens et physiciennes du Canada contribuent à la construction et à la mise en opération d'ATLAS, un des deux principaux détecteurs de particules qui étudieront les collisions produites au LHC. Ce colloque présentera quelques uns des sujets de recherche les plus intéressants de la physique aux plus hautes énergies. Le détecteur ATLAS et les difficultés expérimentales de la physique au LHC seront également traités.

La physique des hautes énergies et le détecteur de particules ATLAS.

High Energy Physics and the ATLAS Detector

CUPC 2004, Victoria
6 Nov 2004

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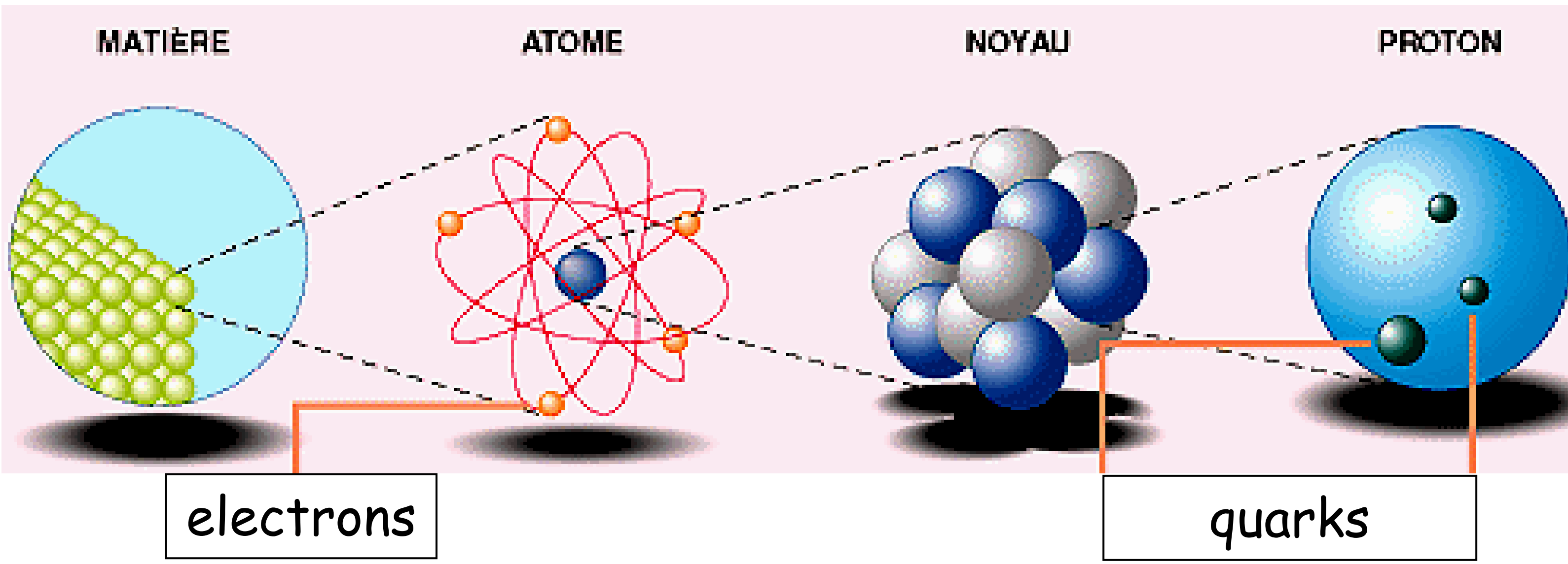
High Energy Physics

Motivation:

Understanding nature's fundamental constituents and forces

Normal Matter

$\approx 10^{-10}$ m $\approx 10^{-14}$ m $\approx 10^{-15}$ m



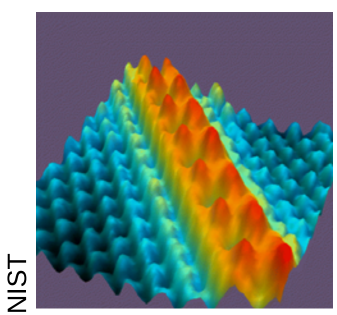
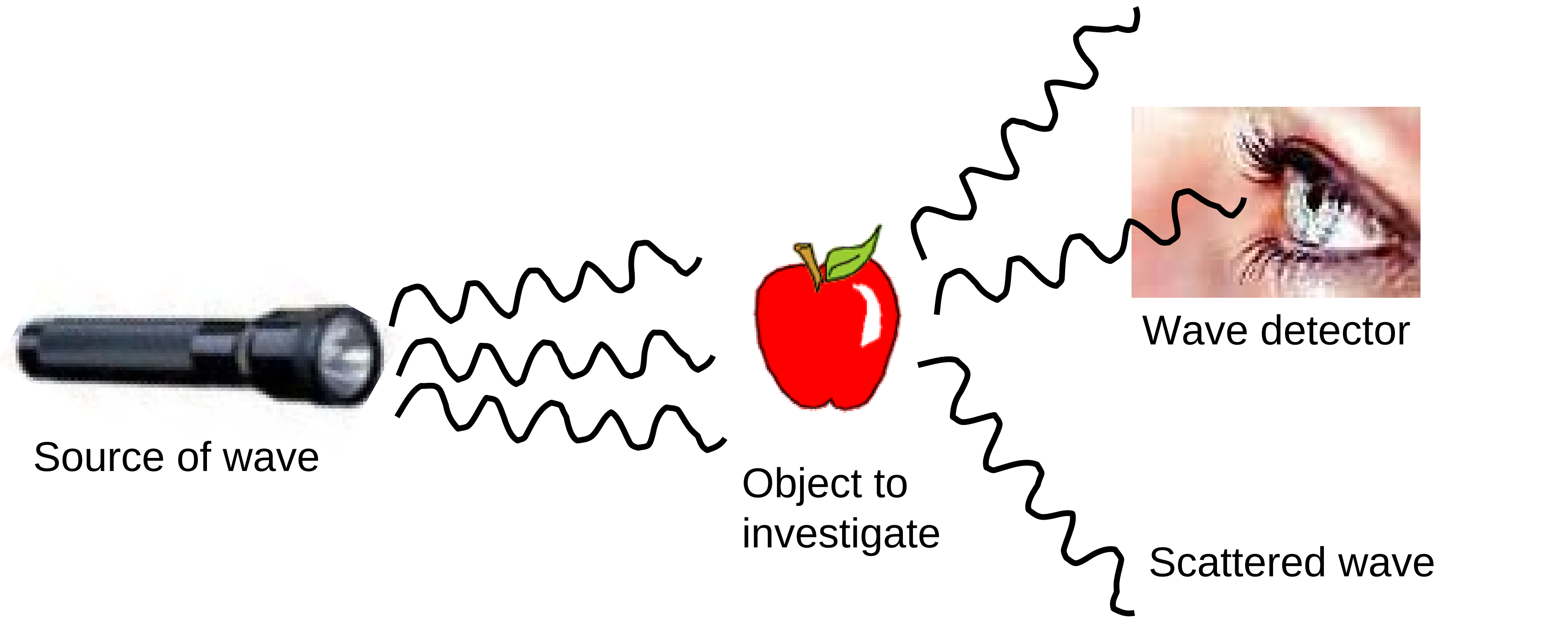


Image 7 nm × 7 nm from a scanning tunneling microscope showing a single zig-zag chain of Cs atoms (red) on the GaAs(110) surface (blue).

Scattering Experiment



The wave can resolve features about the size of its wavelength

Matter Waves

Einstein – de Broglie relations

particle aspect

$$\left\{ \begin{array}{l} p = \dfrac{h}{\lambda} \\ E = h\nu \end{array} \right\}$$

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

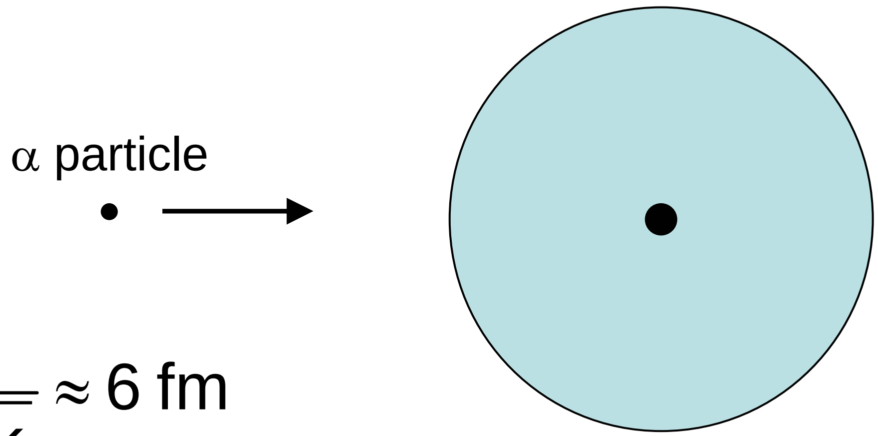
Rutherford Scattering

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

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

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

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



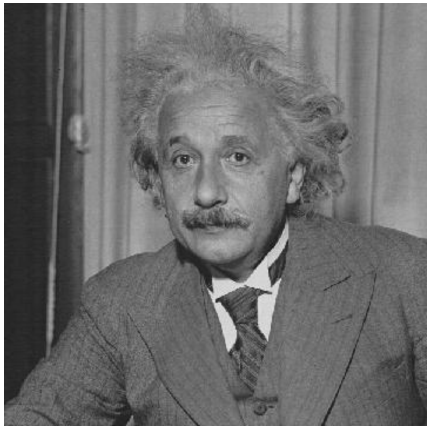
Atom and nucleus
(not to scale!)

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

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



Albert Einstein
1879-1955

⇨ **massless particles carry momentum!!**

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

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

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

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

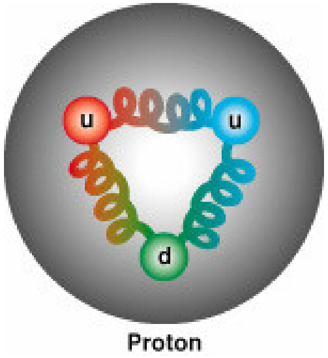
⇨ **relativistic particles**

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

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.

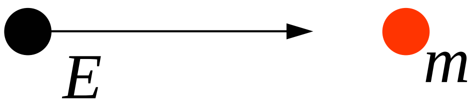
A Proton is found to have a size and an electric charge distribution.

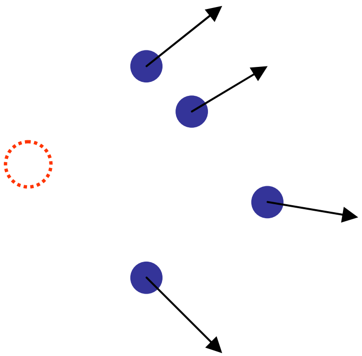
Probing deeper, with higher energy probes, it is found to be made mainly of three quarks!

Colliding Particles

“Fixed target”:

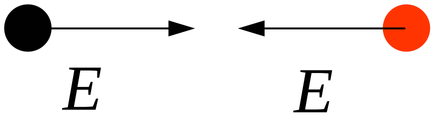
available energy $\simeq \sqrt{2mE}$

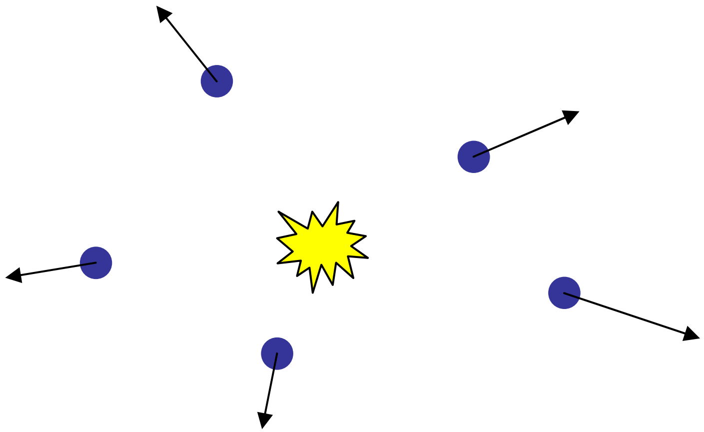




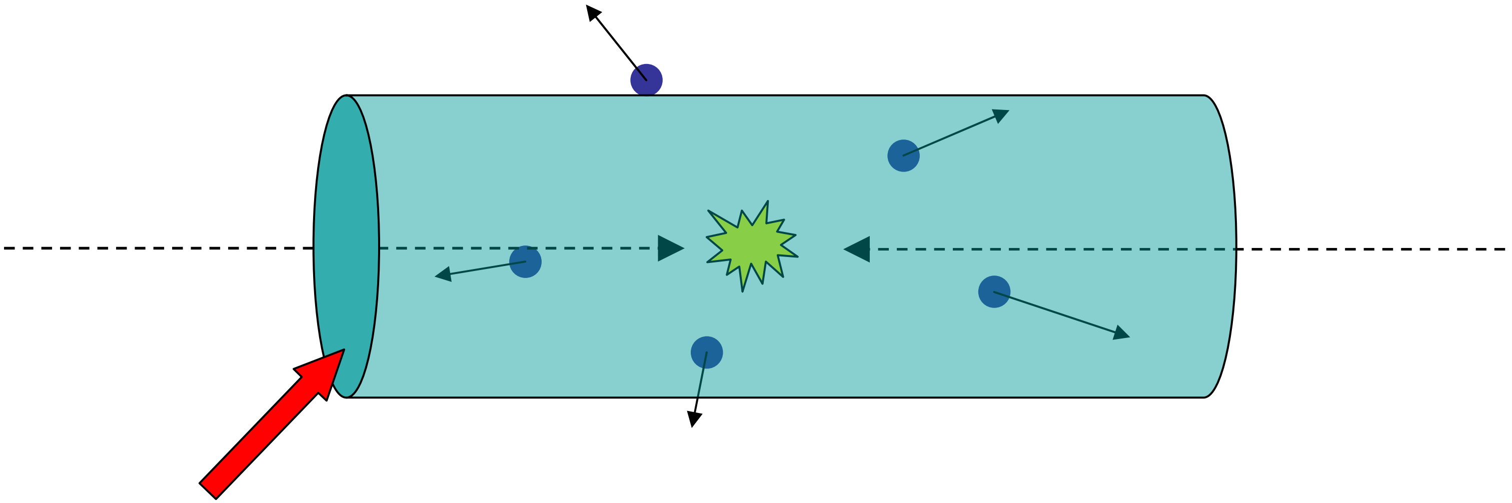
“Collider”:

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

- $p\bar{p}$: Spp̄S at CERN

1981-1990 with a maximum beam energy of 315 GeV

Probing nature down to $\approx 2 \times 10^{-17}$ 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 $\approx 6 \times 10^{-18}$ 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 $\approx 3 \times 10^{-18}$ m !!

top quark discovery!!!

Elementary Particles

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

Leptons spin = 1/2

Flavor	Mass GeV/c²	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/c²	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

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

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

Unified Electroweak spin = 1

Name	Mass GeV/c²	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/c²	Electric charge
g gluon	0	0

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

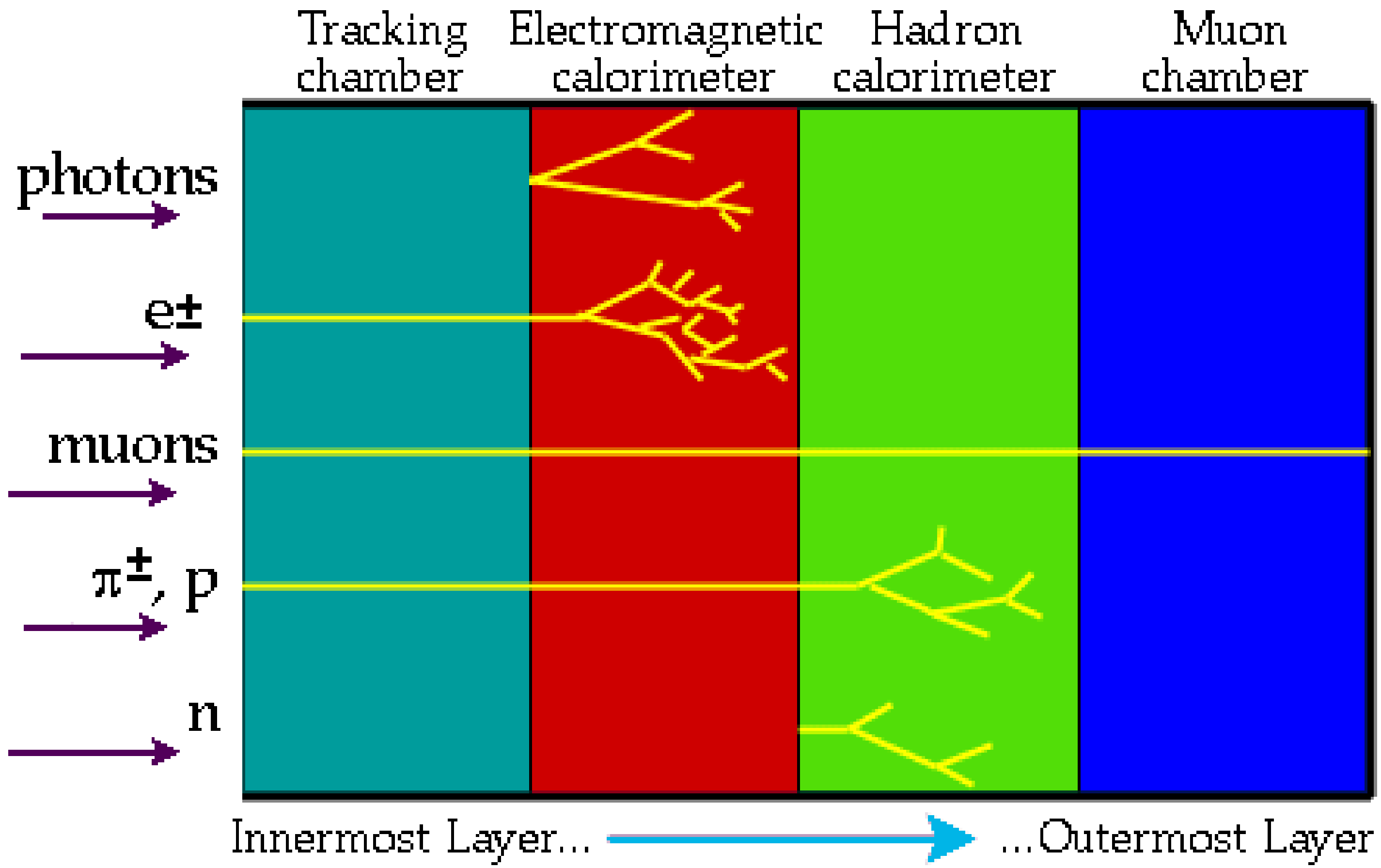
Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	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

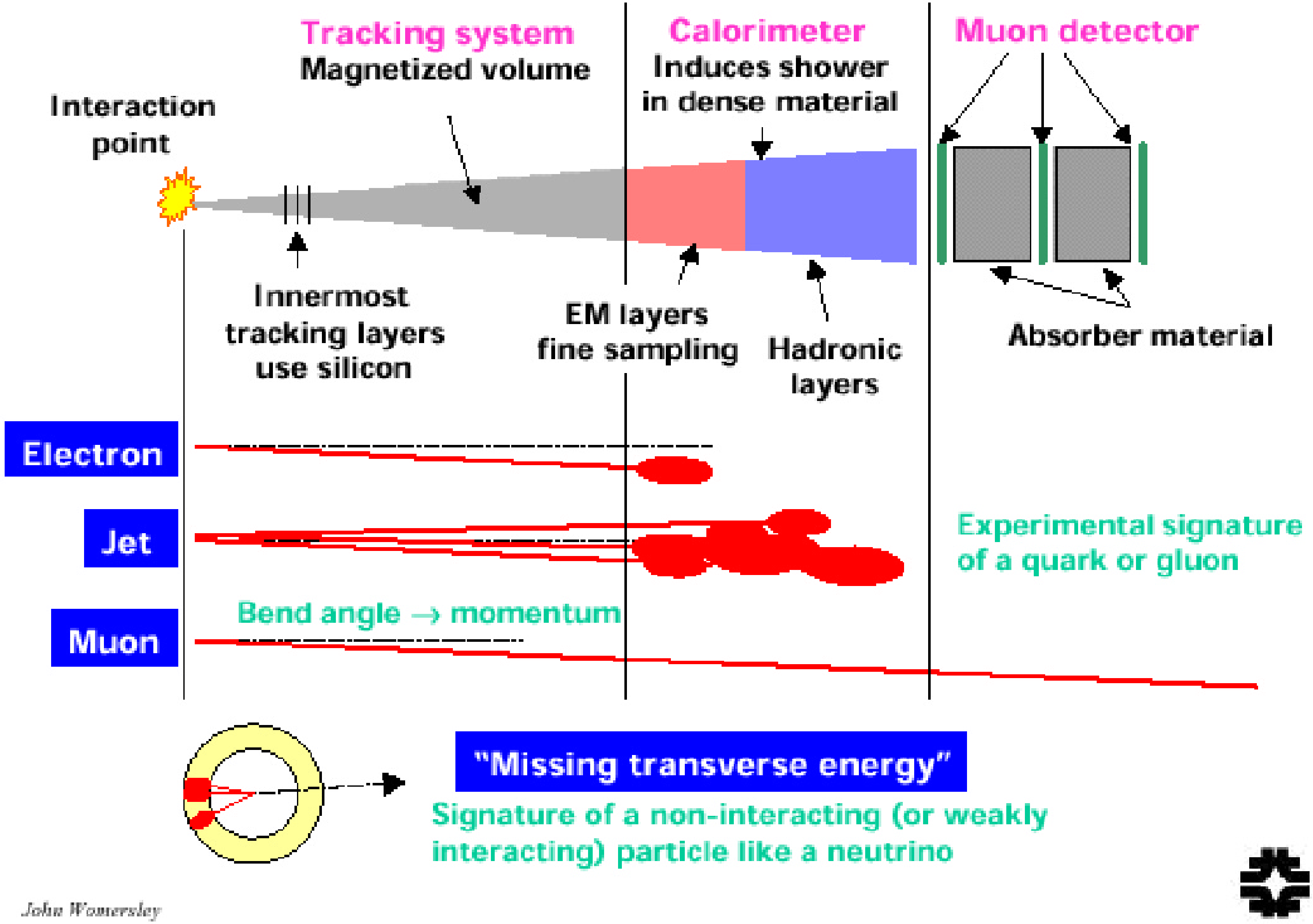
Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	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



The Standard Model Particles

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

bosons	$U(1)_Y$	B	$\not{EW}$ →	γ	electro-weak	radiation
	$SU(2)_L$	W_1 W_2 W_3		W^+ W^- Z^0		
	$SU(3)_C$	$g_{1\text{-}8}$		$g_{1\text{-}8}$	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	$\Leftrightarrow$	momentum
homogeneity of time	$\Leftrightarrow$	energy
isotropy of space	$\Leftrightarrow$	angular momentum
more abstract symmetry	$\Leftrightarrow$	some "charge"

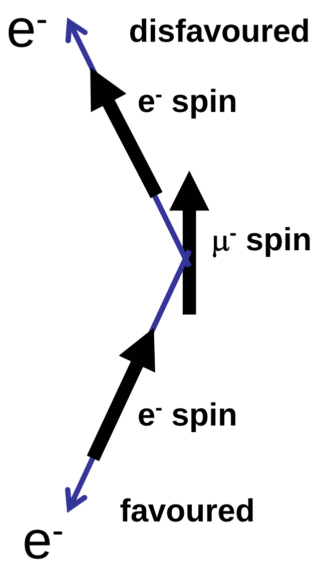
Local Symmetry and Fundamental Forces

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

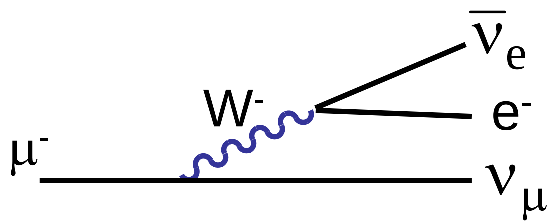
What about a quantum theory of gravity? See Dr Peet's talk!

Weak Interaction



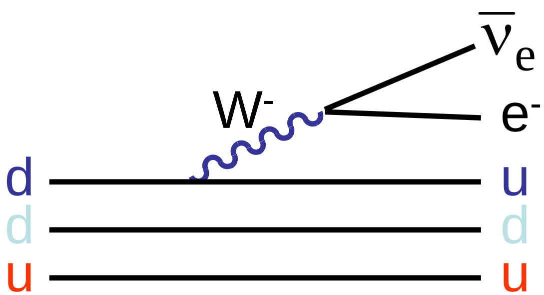
The weak interaction violates parity!!

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

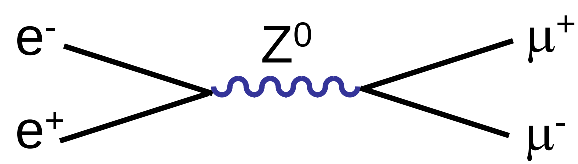


muon decay

The interaction is "weak" because it is mediated by massive vector bosons



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



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

This weak reaction controls the star burning rate!!

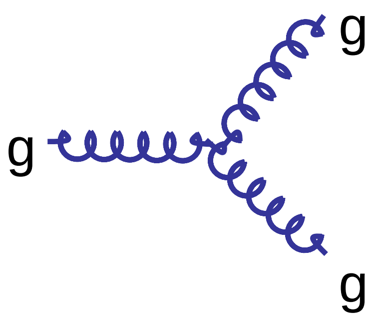
$$p + p \to d + e^+ + \nu_e$$

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!!!

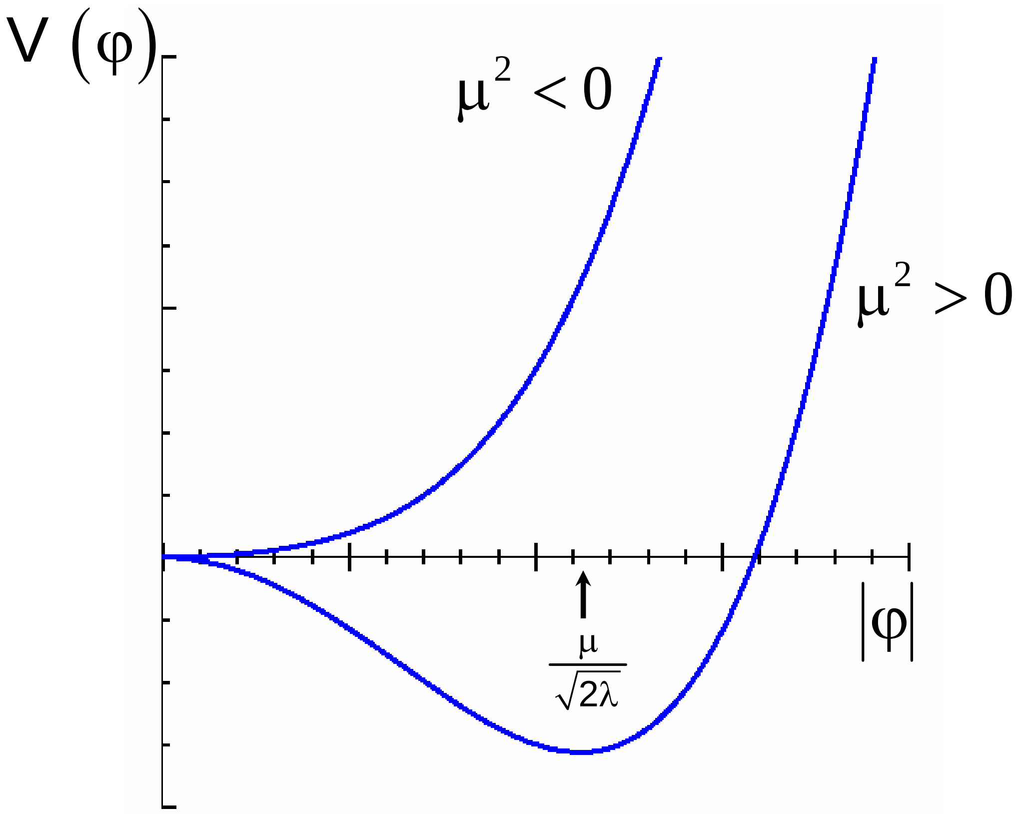
Big problem: We want to have a gauge principle to give us the interactions and we know that most particles have mass

The solution: The Higgs Mechanism

Higgs Mechanism

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.

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



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

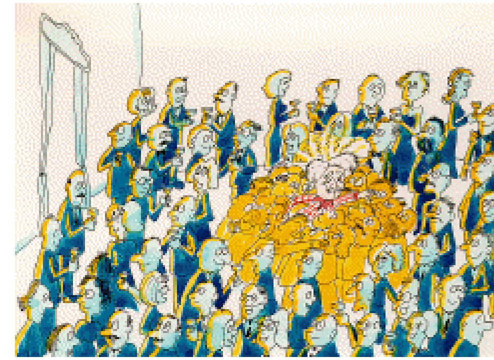
$$|\varphi|^2 = |\varphi_0|^2 = \frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2} > 0$$

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...

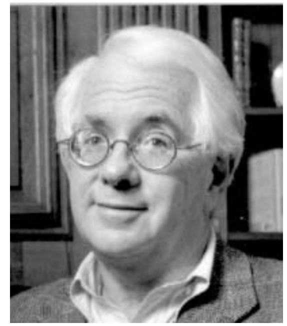
…if a rumor crosses the room...

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

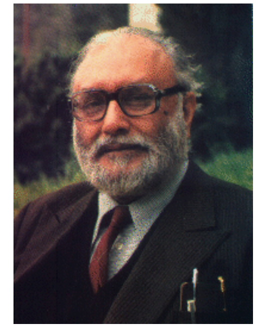
ATLAS educational web page, adapted from an idea from Dr D. J. Miller

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 (matter)

				charge
leptons	ν_e	ν_μ	ν_τ	0
	e	μ	τ	-1
quarks	u	c	t	$+2/3$
	d	s	b	$-1/3$

bosons (radiation)

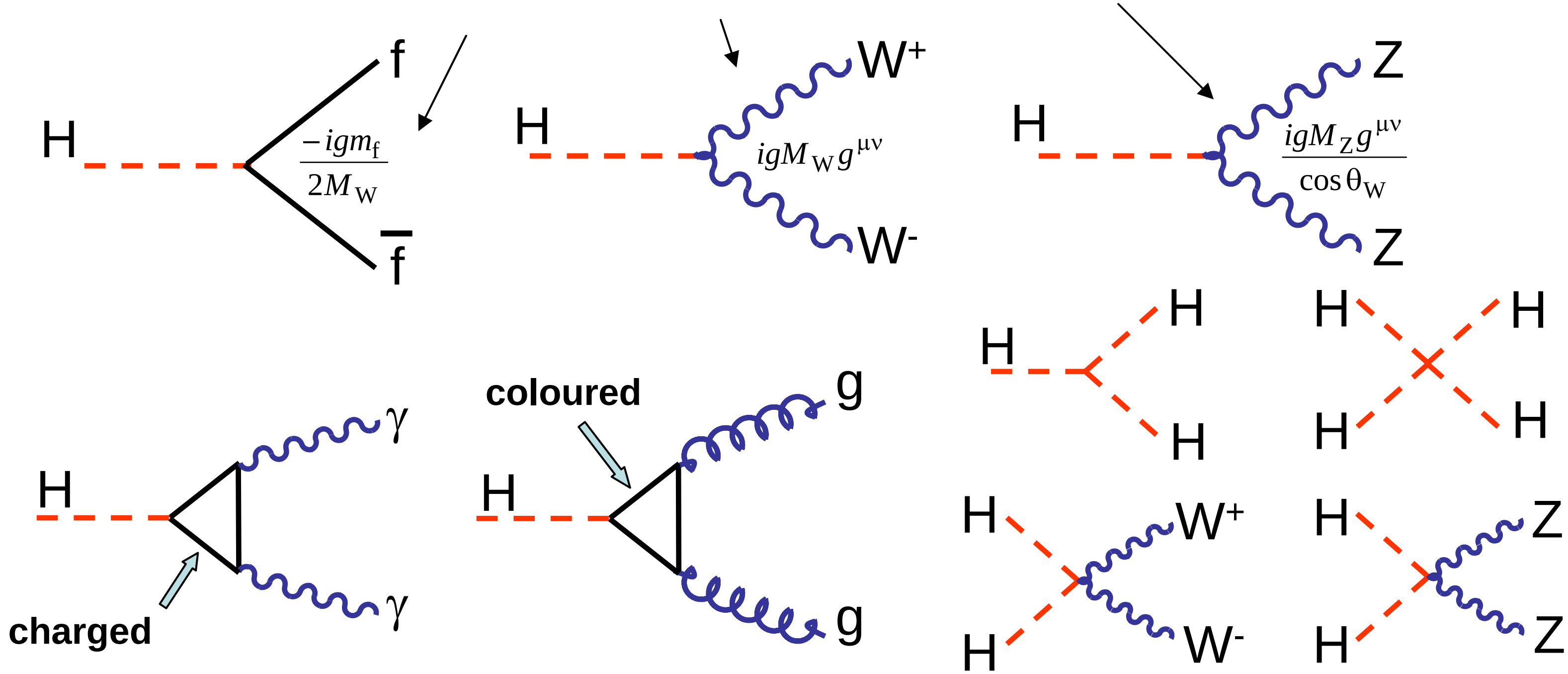
		$\not{EW}$ $\Rightarrow$	
$U(1)_Y$	B	γ	electro-weak
$SU(2)_L$	W_1	W^+	
	W_2	W^-	
	W_3	Z^0	
$SU(3)_C$	$g_{1\text{-}8}$	$g_{1\text{-}8}$	strong
Higgs doublet	$\varphi_1+i\varphi_2$, $\varphi_3+i\varphi_4$	H^0	

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

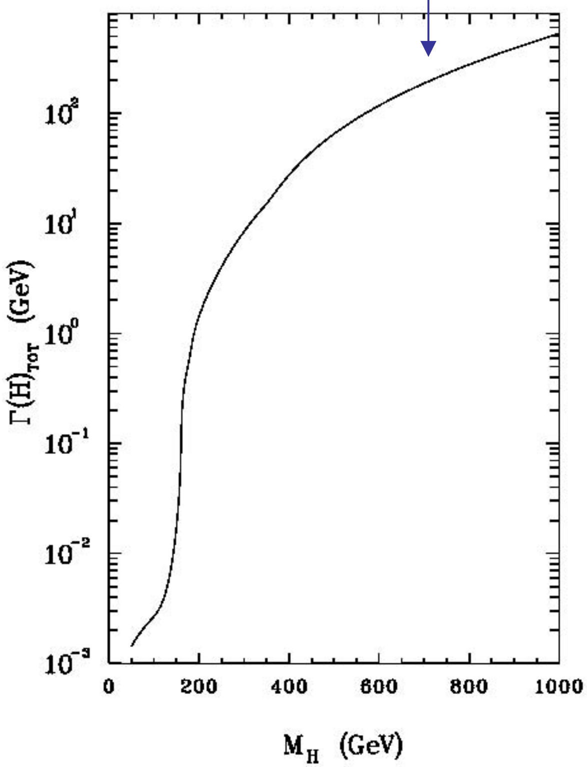
Higgs couplings proportional to mass $g^2 = 4\sqrt{2} G_F M_W^2$



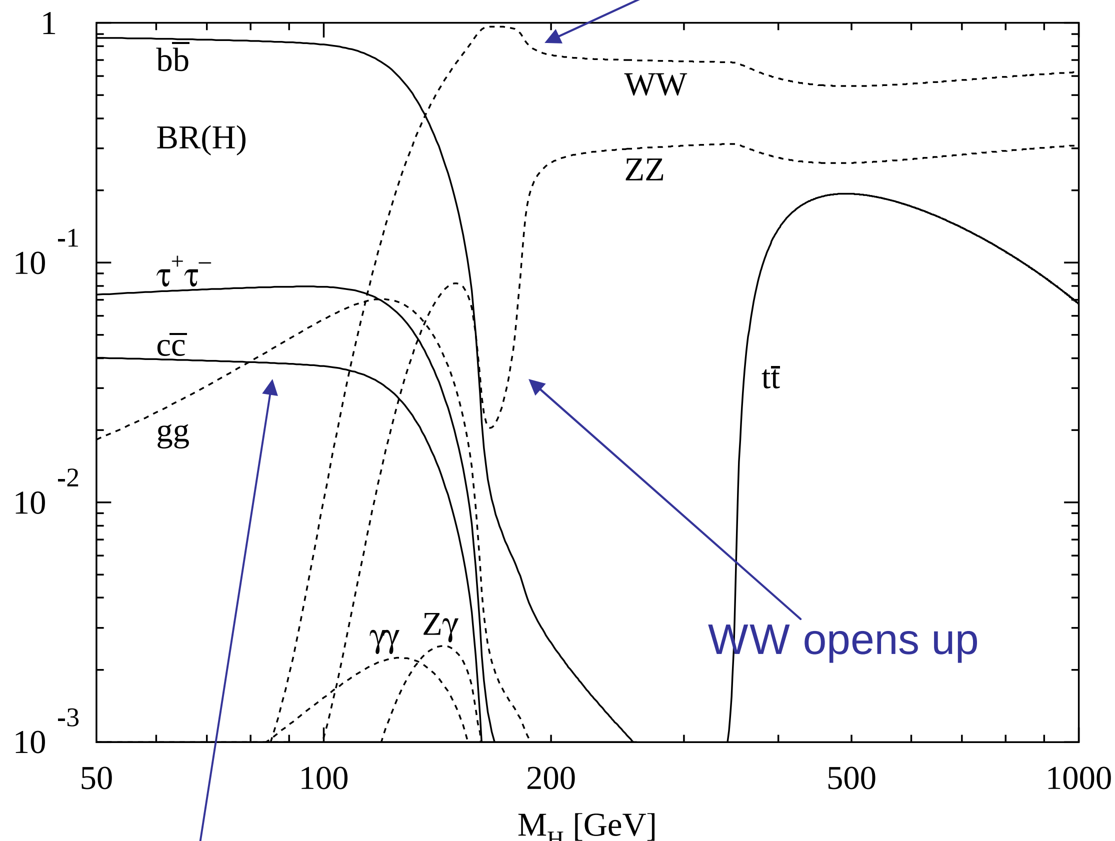
SM Higgs Decays

(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 $\approx 0.9 \times 10^{-18}$ m !!

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

2015- with a beam energy of 250 GeV

Probing nature down to $\approx 2 \times 10^{-18}$ 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

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

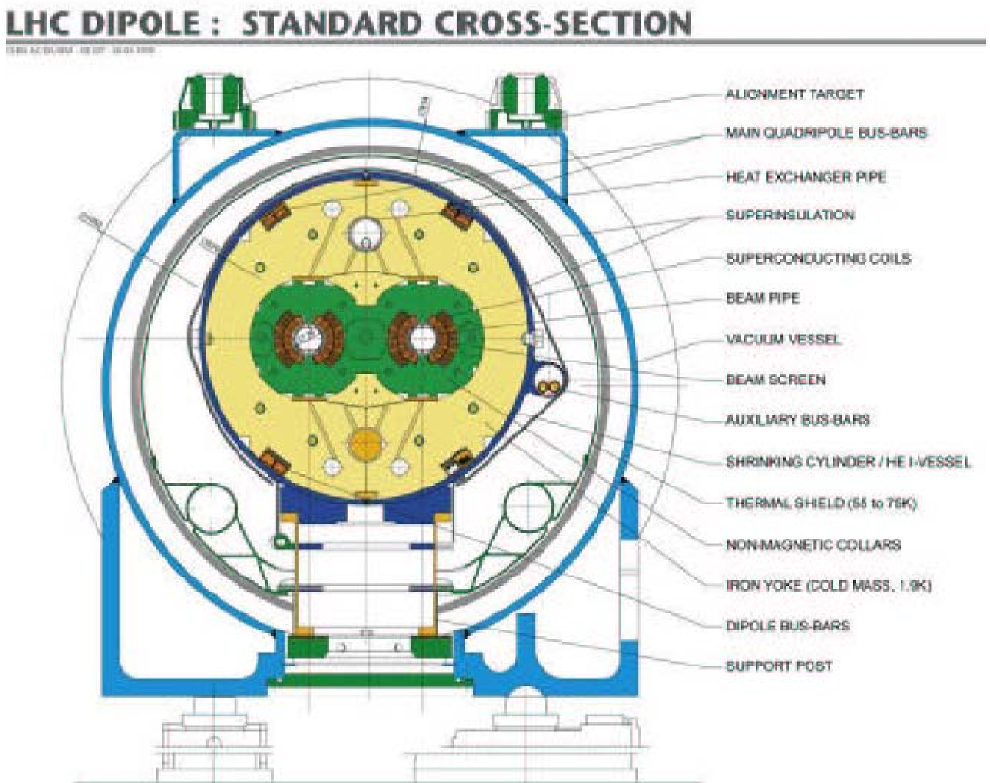
then the number of events is given by

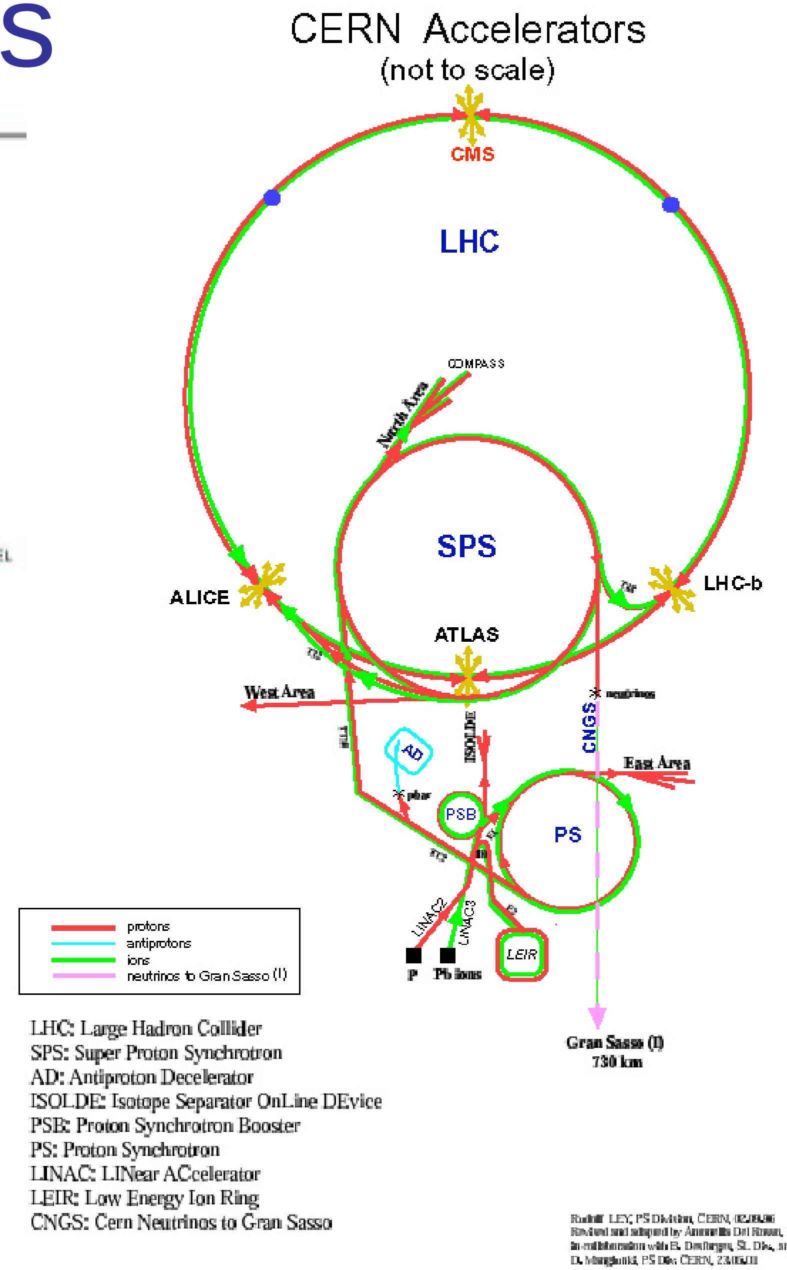
$$N = \mathcal{L}\,\sigma$$

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: 7 TeV on 7 TeV proton-proton

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

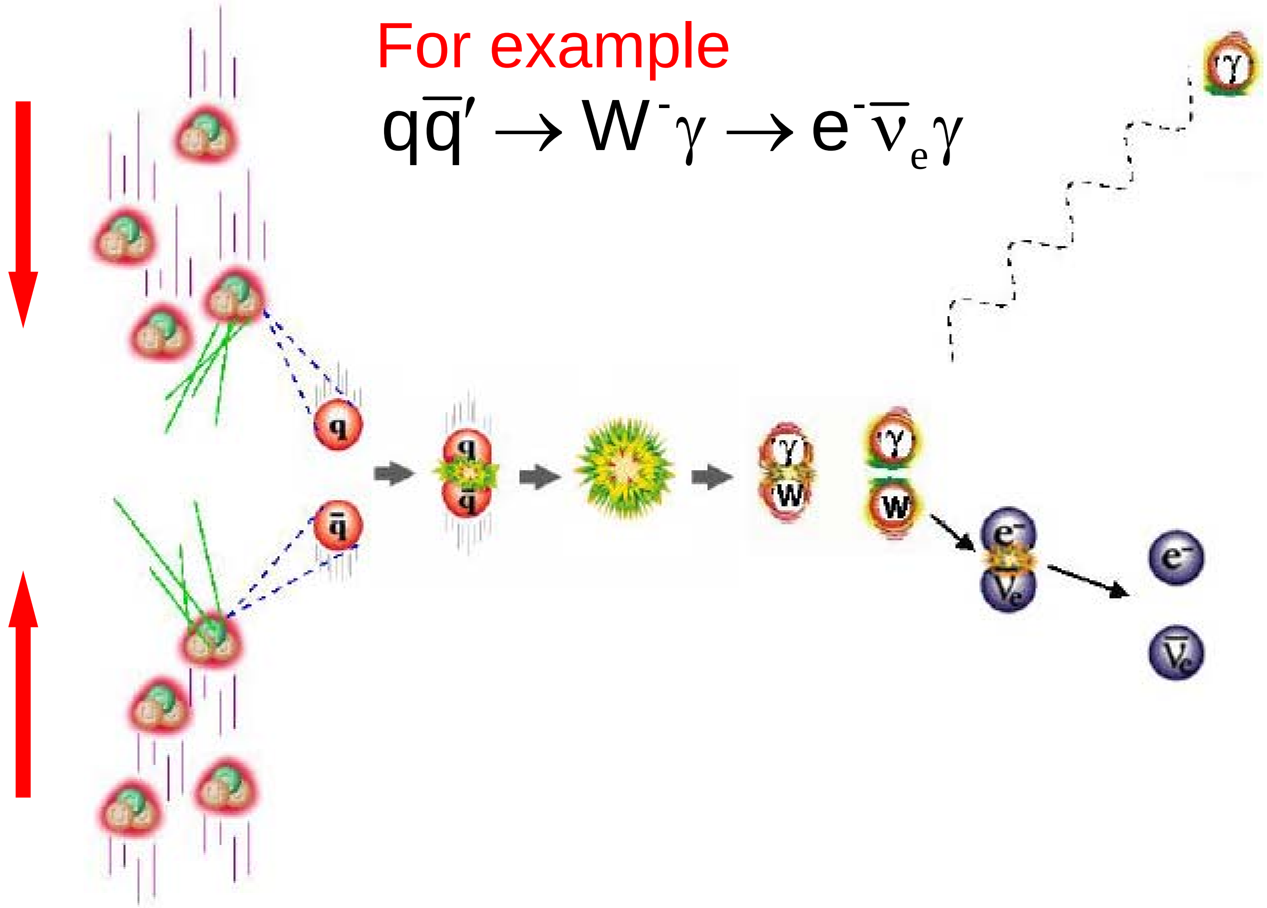
pp Collisions at the LHC

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

For example

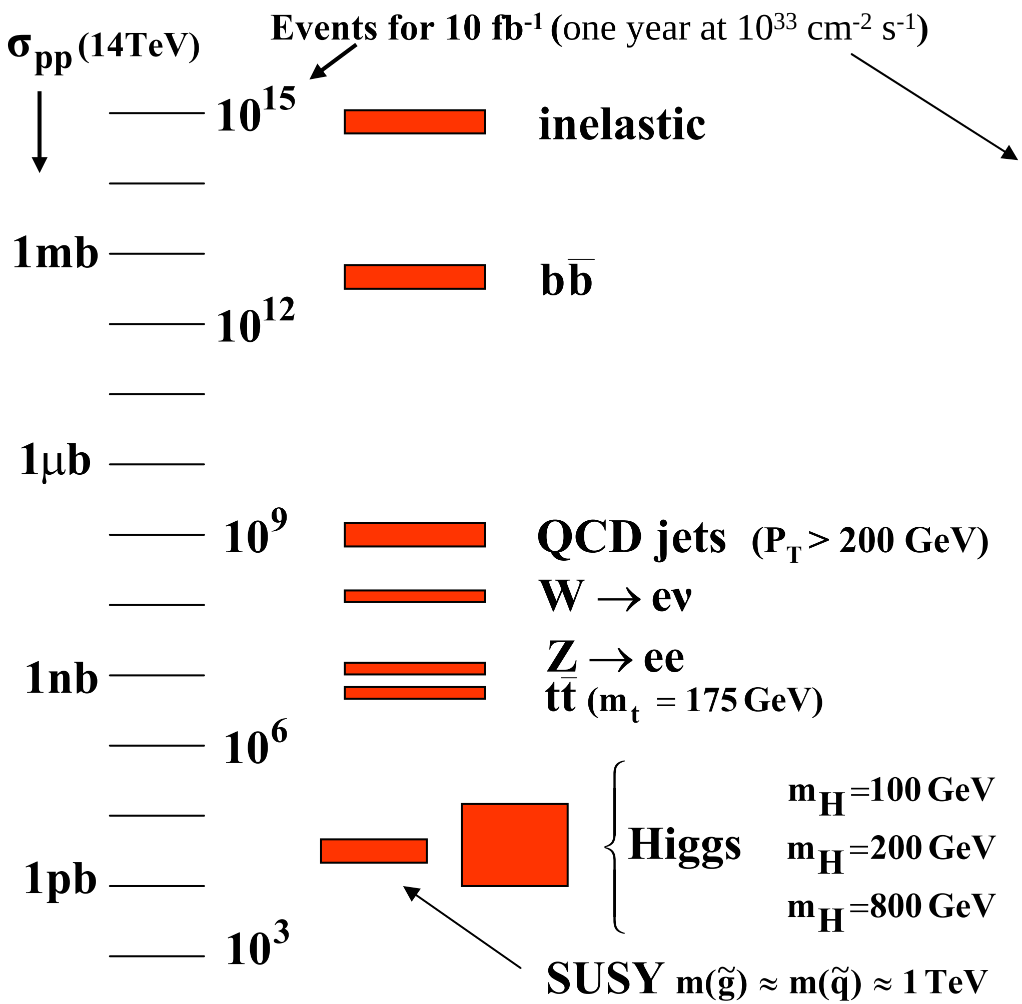
$q\bar{q}' \rightarrow W^{-}\gamma \rightarrow e^{-}\bar{\nu}_e\gamma$

7 TeV



7 TeV

LHC PP Cross Section



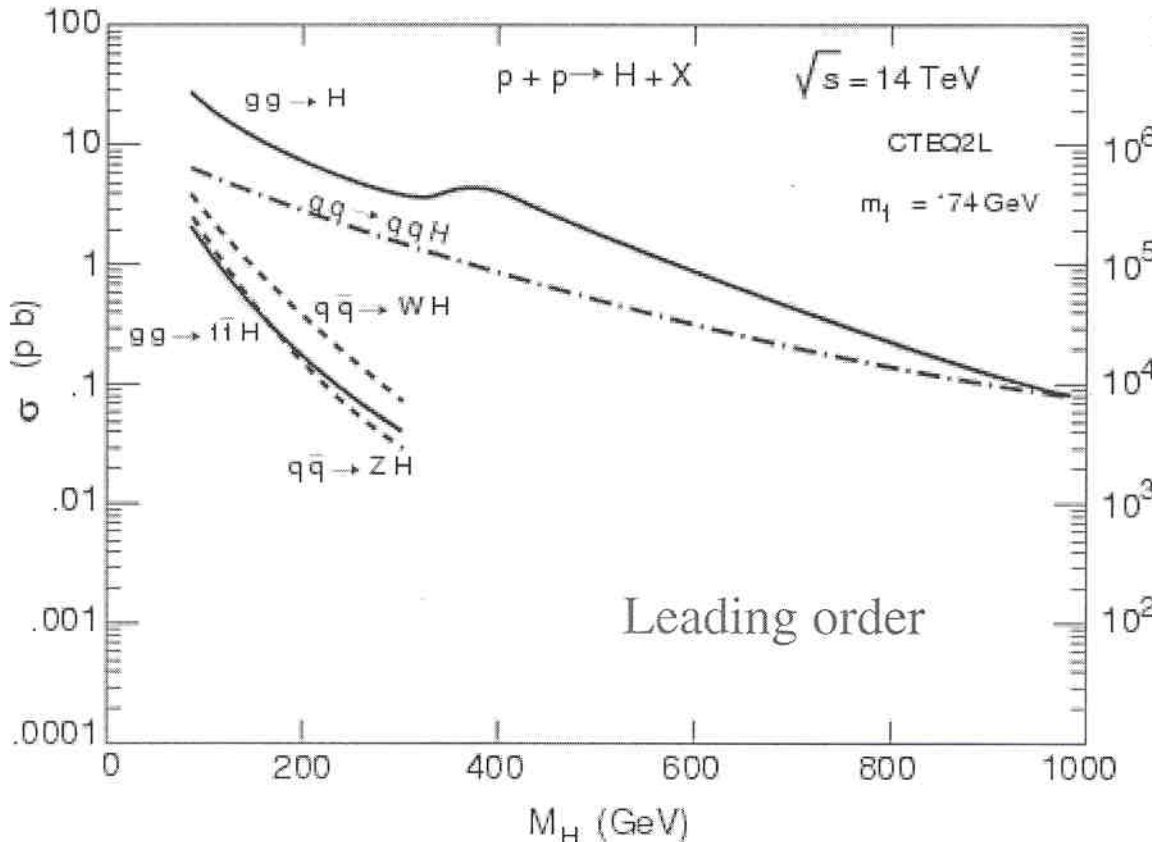
6.7 times the commissioning luminosity

83% of first year luminosity

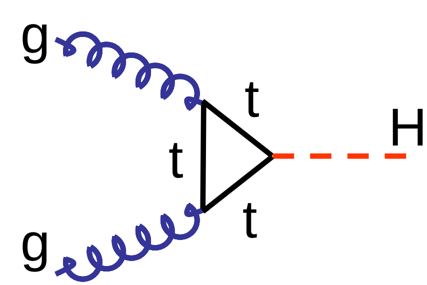
10% of nominal luminosity

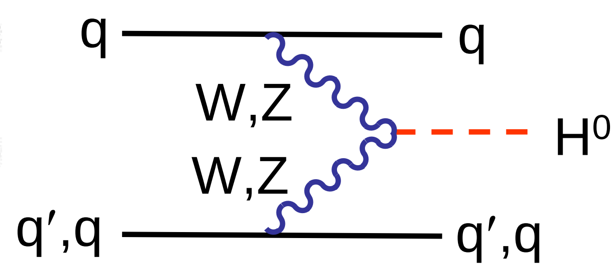
It is a challenge to “fish out” events that are more than 10 orders of magnitude rarer than the most common interactions

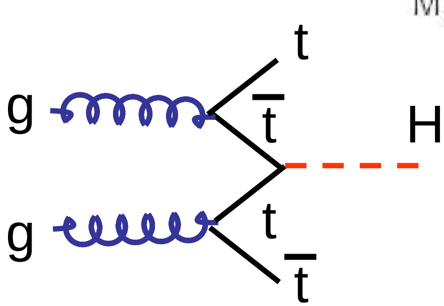
SM Higgs Production at the LHC

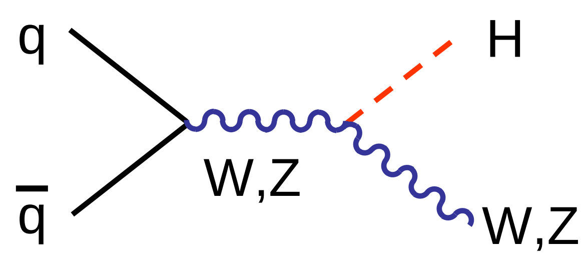


Events for
100 fb^{-1} (one year at 10^{34} cm^{-2} s^{-1})



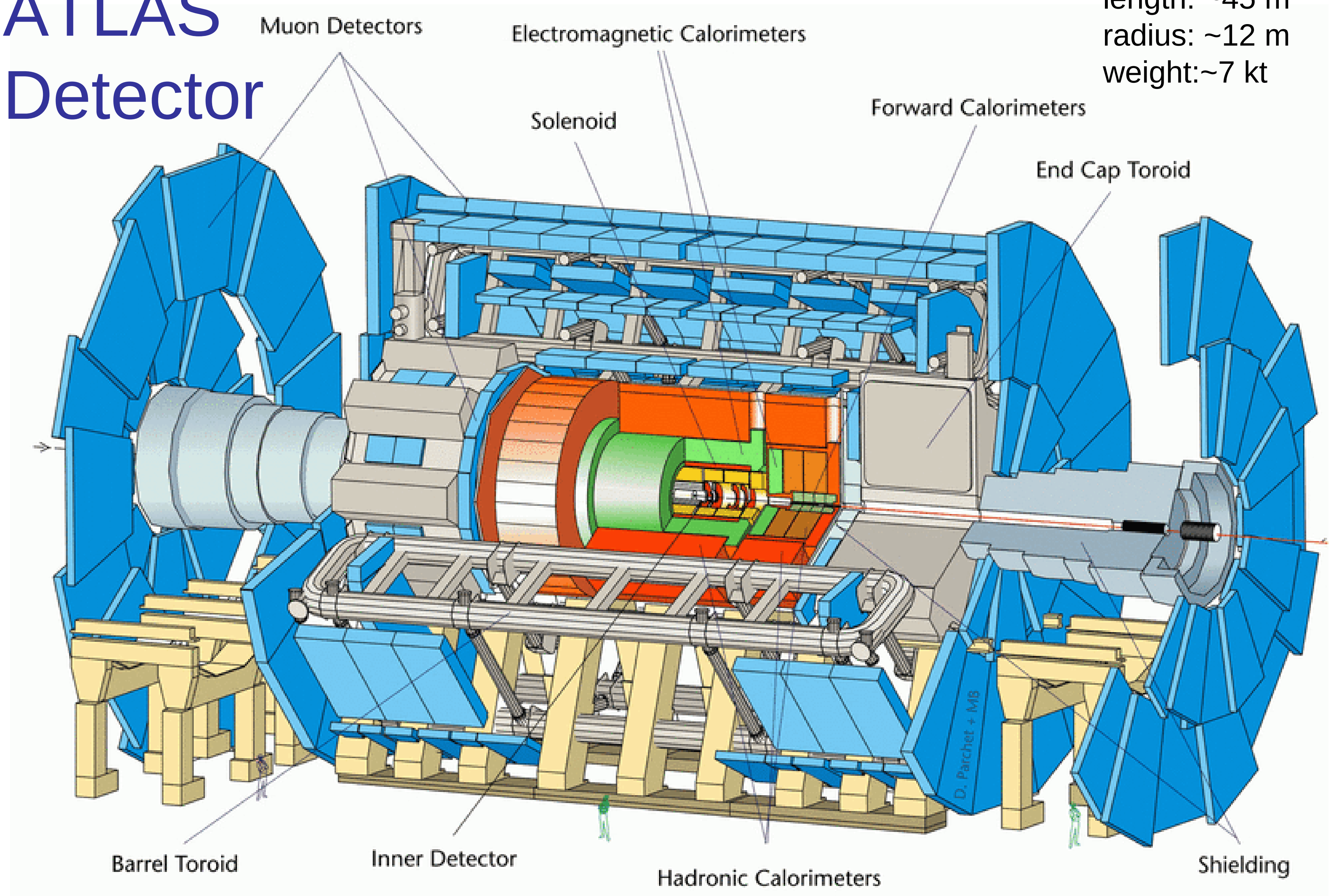




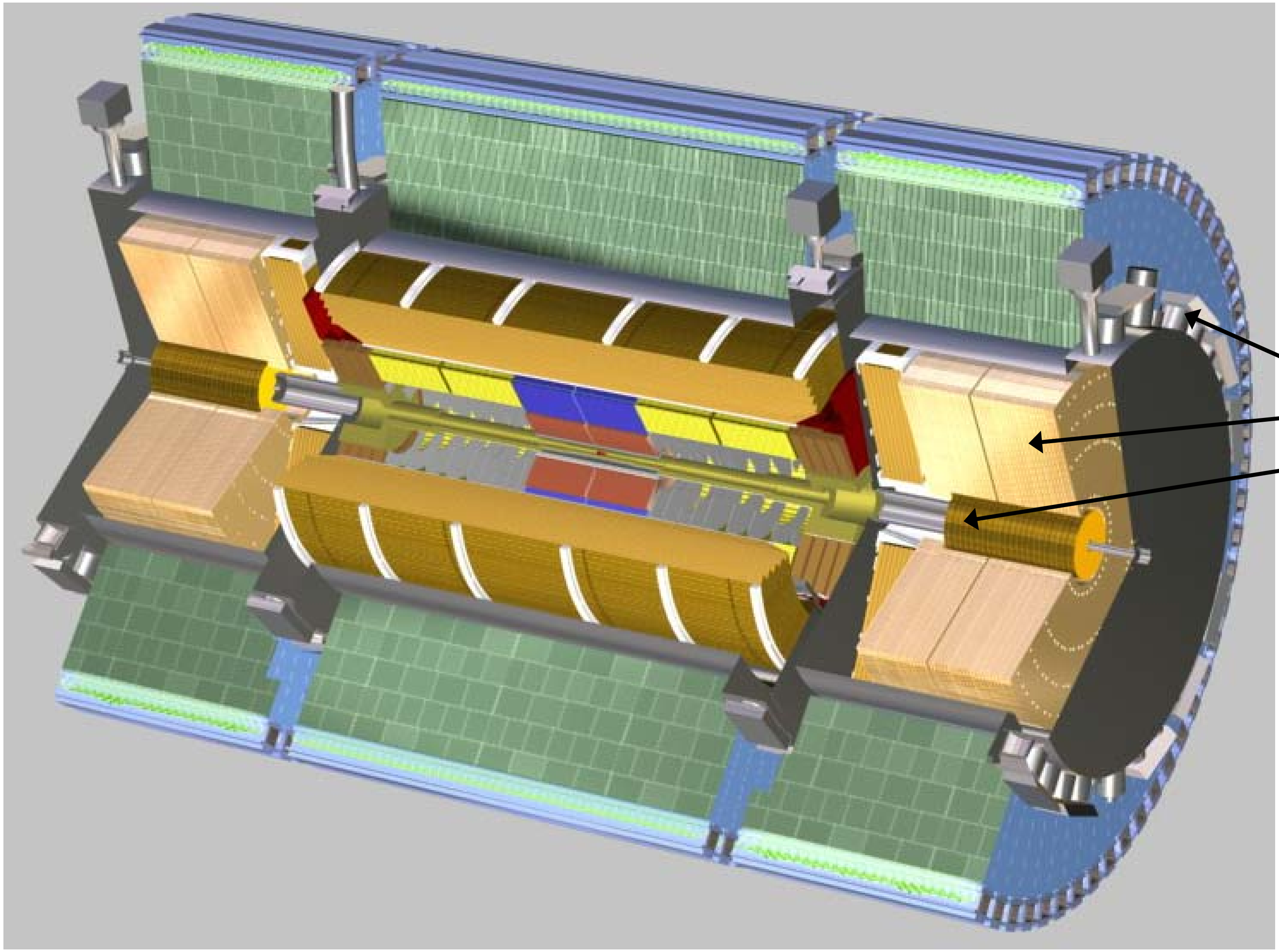


ATLAS Detector

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



ATLAS Calorimetry: energy measurement



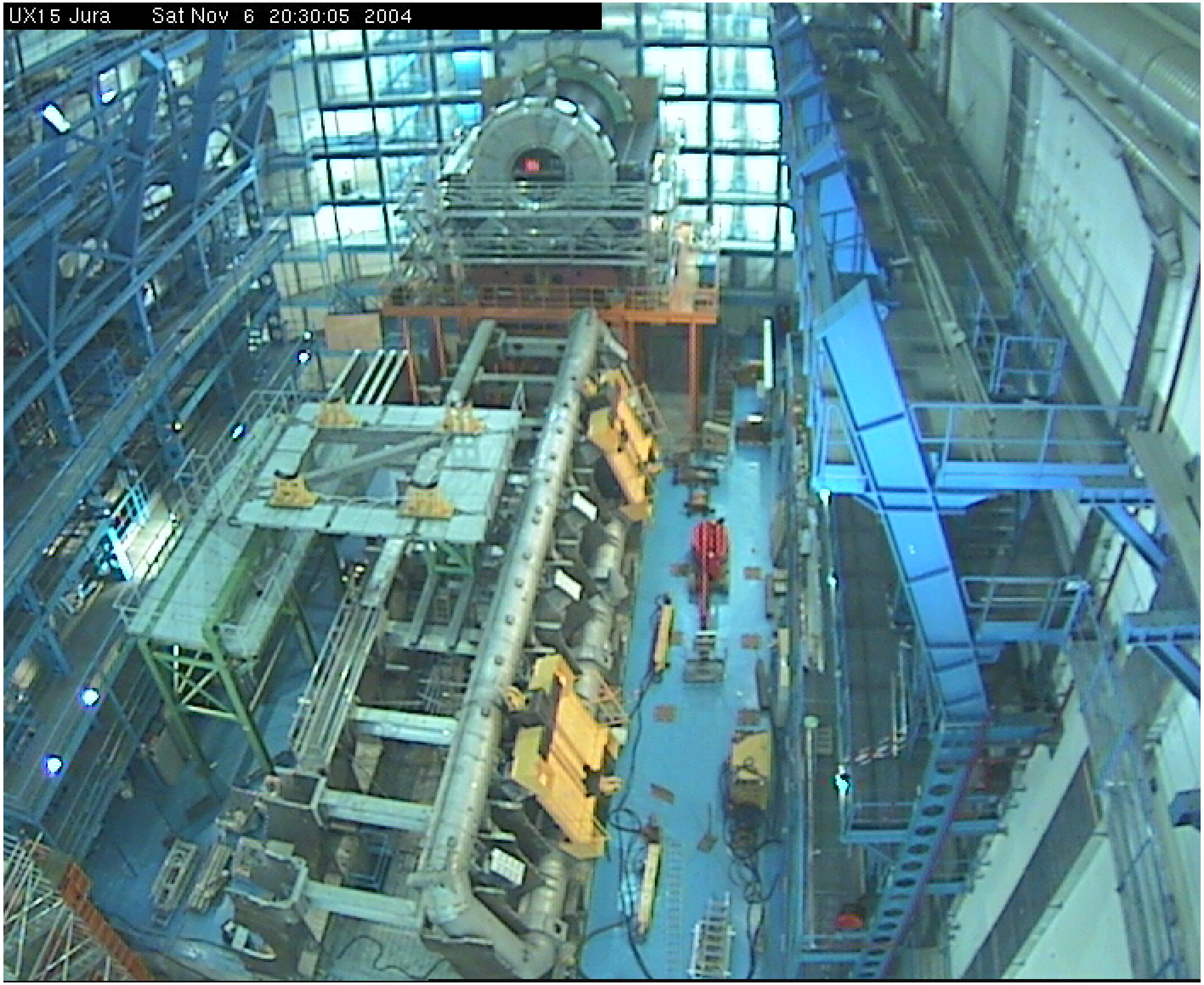
Built in Canada

ATLAS Installation Web Cam

http://atlas.web.cern.ch/Atlas/TCOORD/Activities/TcOffice/Scheduling/Installation/ATLASinstallation.html

Nov 6

20:30



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

3D rotations... } Lorentz
pure boosts..... } Lorentz } Poincare′
4D translations............. } Poincare′ } superPoincare′
SUSY translations............................ } 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_{SUSY}<~ 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 $M_{\text{SUSY}} \approx$ 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... } Lorentz } Poincare′ } superPoincare′
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

$$B^0, W^0 \to \gamma, Z^0$$
$$\tilde{W}^\pm, \tilde{H}^\pm \to \chi_{1,2}^\pm$$
$$\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0 \to \chi_{1,2,3,4}^0$$
$$\tilde{l}_L, \tilde{l}_R \to \tilde{l}_1, \tilde{l}_2$$
$$\tilde{q}_L, \tilde{q}_R \to \tilde{q}_1, \tilde{q}_2$$

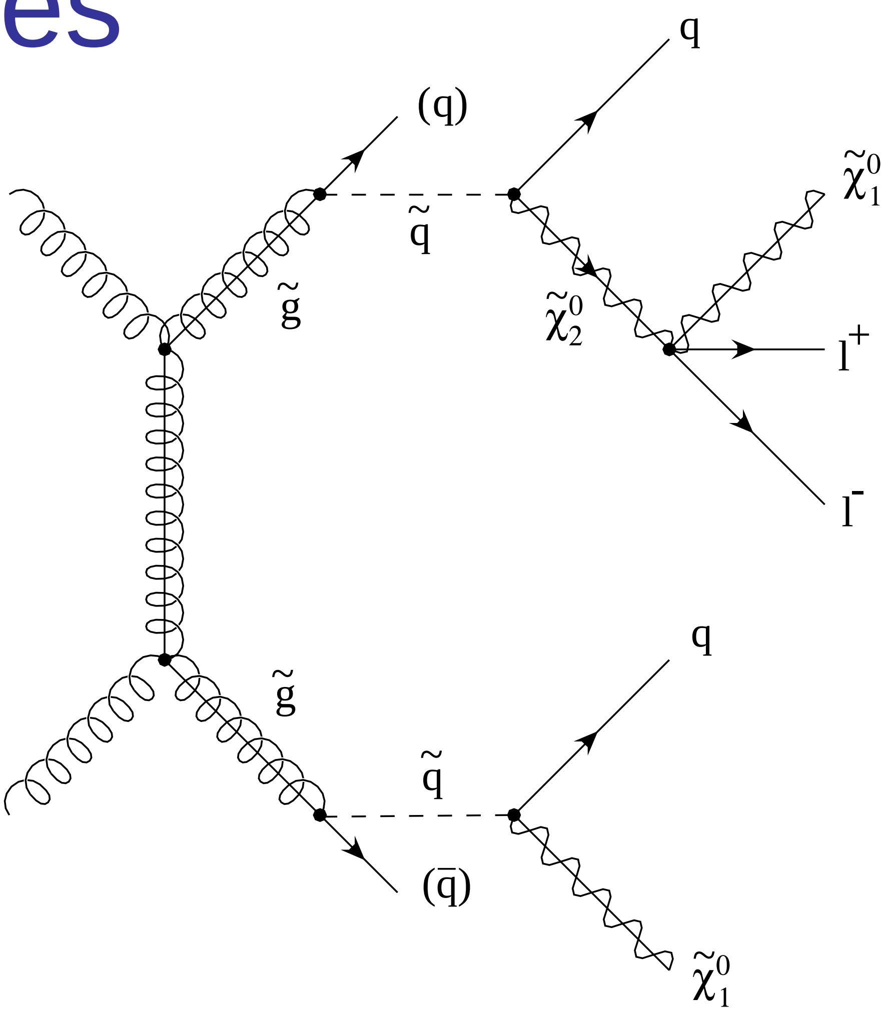
with off-diagonal elements proportional to fermion masses

SUSY Signatures

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

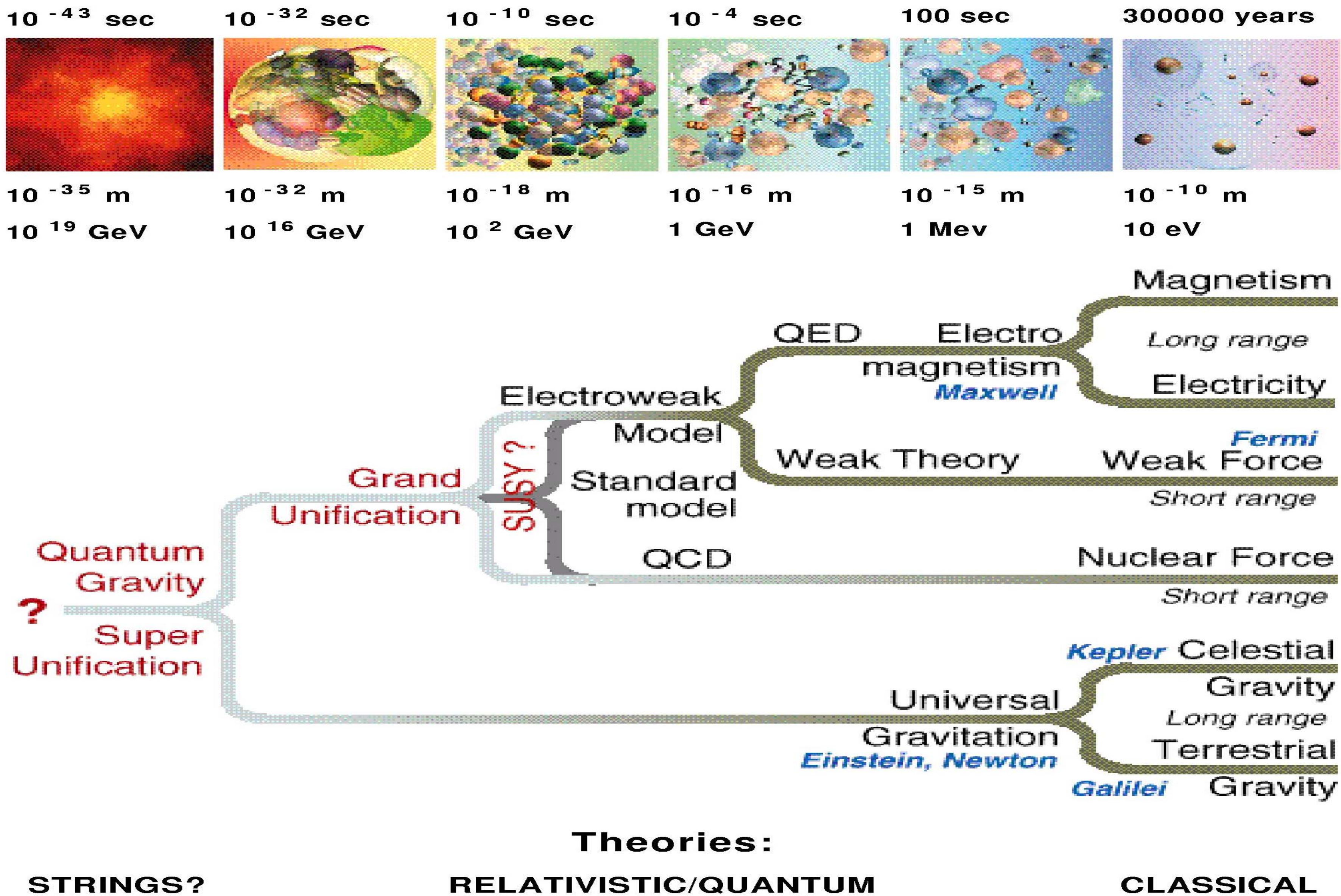
In most SUSY models, sparticles are produced in pair, so that there would always be 2 LSP escaping detection.

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



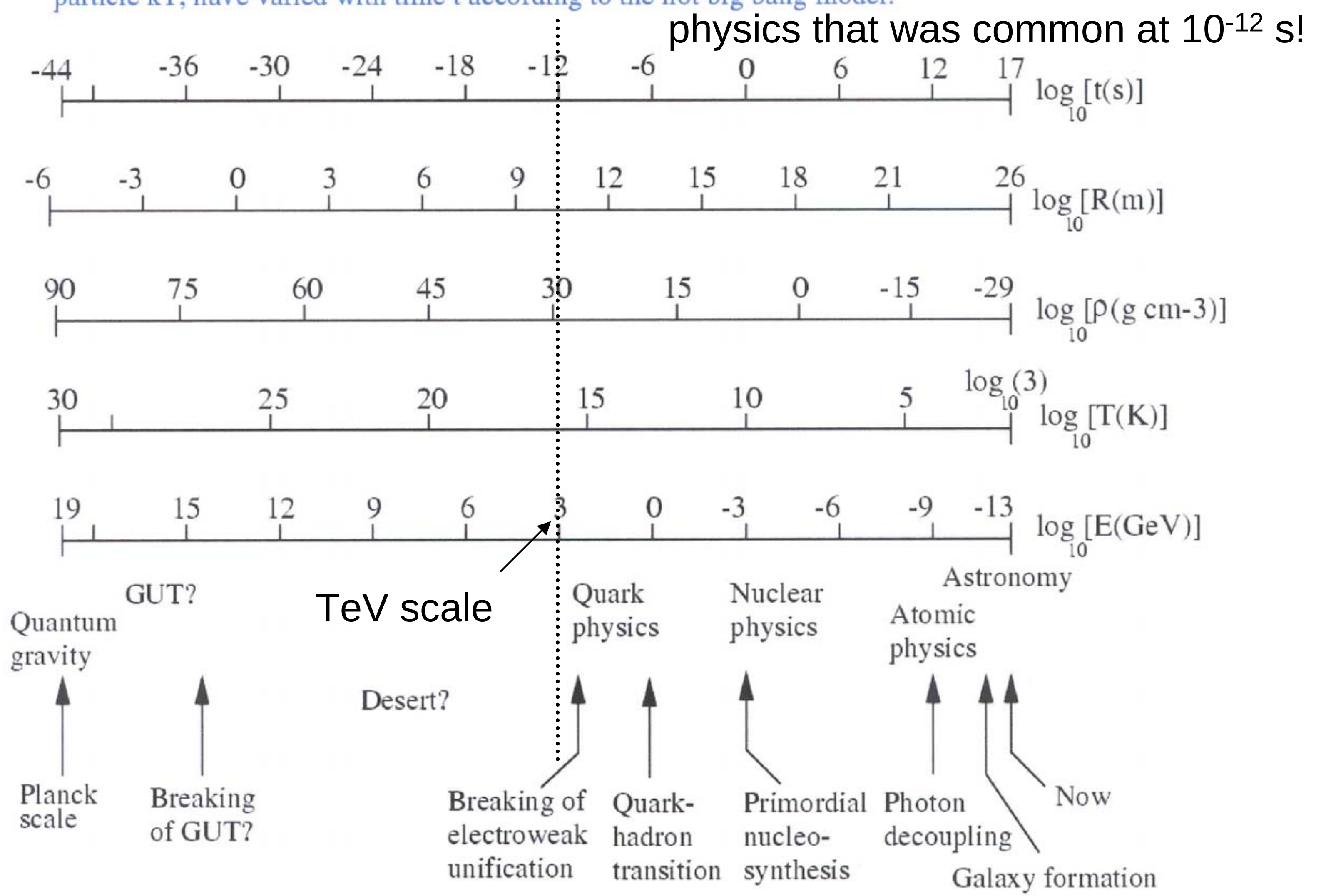
$$gg \rightarrow \tilde{g}\tilde{g} \rightarrow qqqq\ell^+\ell^-\chi_1^0\chi_1^0$$

Grand Unification?



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.



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 clooaboration with TRIUMF, Canada's national particle and nuclear physics laboratory

Many other activities including

- Computing, software, radiation studies

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

Alberta
Carleton
CRPP
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!