From Atoms to Extra Dimensions

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The Standard Model of Particle Physics

Forces of Nature

Problems of The Standard Model

Particle Accelerators & Experiments

The Large Hadron Collider

The Higgs Boson and Extra Dimensions

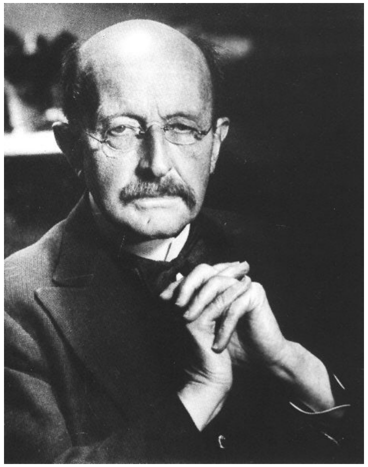
St Columba's College

8th March 2010

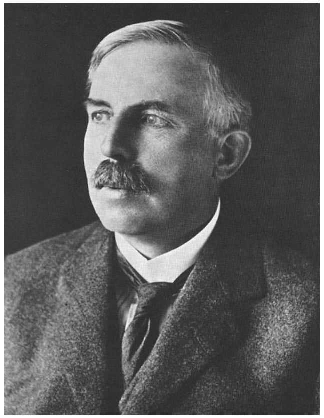
Over 100 years of discovery and experimentation

- Discovery of electron - Thompson, 1897
- Birth of quantum physics - Planck, 1900
- Relativity - Einstein, 1905
- Nuclear scattering experiment - Rutherford, 1911

Thompson



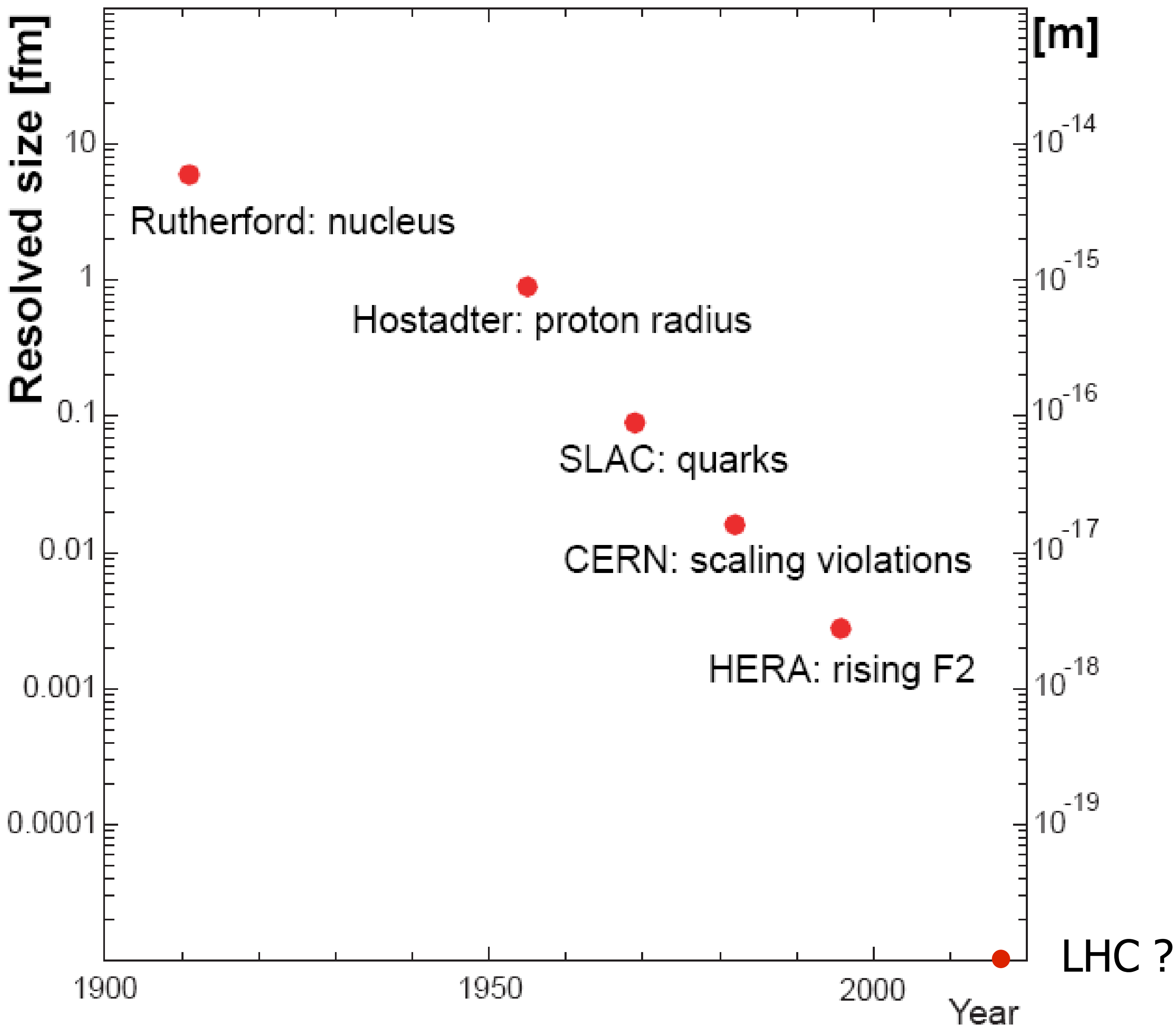
Planck



Rutherford

... what have we learnt ?

Introduction



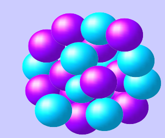
Worlds most successful theory to date - Describes fundamental constituents of matter

u d s c b t — quarks: strong, weak, electromagnetic

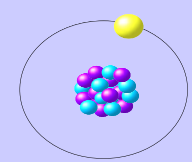
e μ τ — charged leptons: weak, electromagnetic

ν_e ν_μ ν_τ — neutrinos: weak

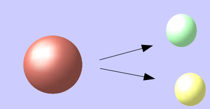
gluons — Strong: holds atomic nucleus together



photons — Electromagnetic: binds atom together



W & Z bosons — Weak: radioactive decay processes



No description of Gravity at sub-atomic level

Electromagnetic & Weak parts of Standard Model are known extremely precisely

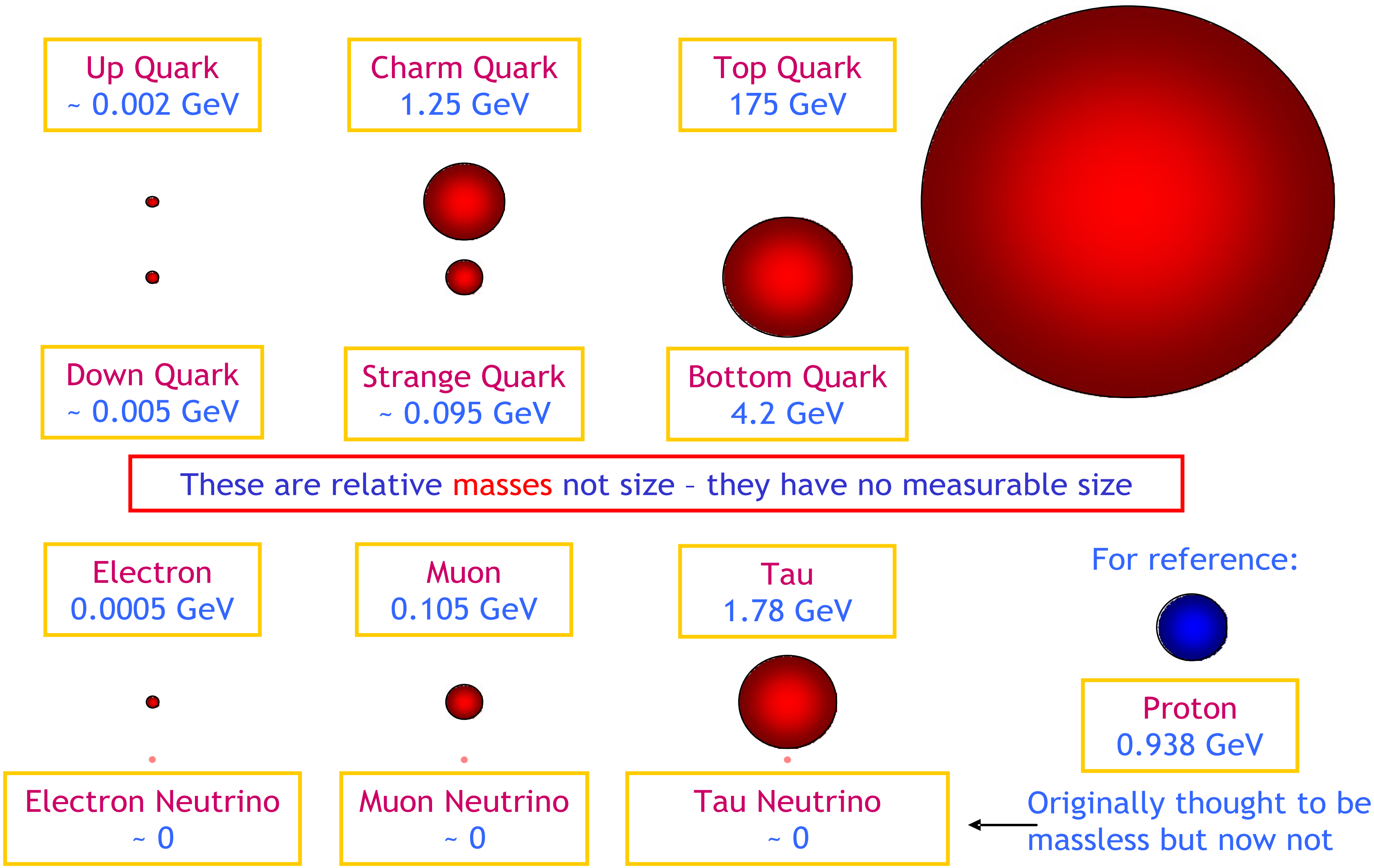
Theory of strong interactions is less well known

The Standard Model

1 eV = Energy of electron accelerated through 1 Volt

1 MeV = 10^6 eV 1 GeV = 10^9 eV 1 TeV = 10^{12} eV

Through $E=mc^2$ we can freely convert energy ↔ mass (exchange rate = c^2 !!!)

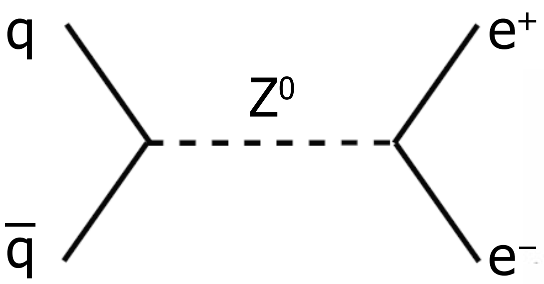


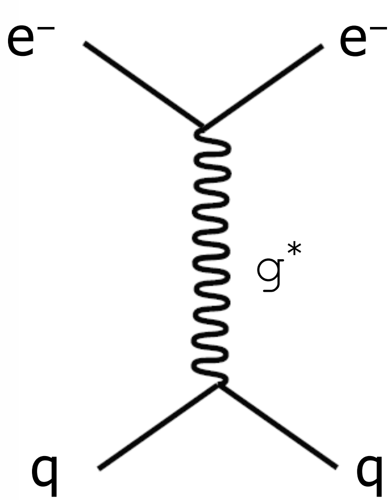
The Standard Model

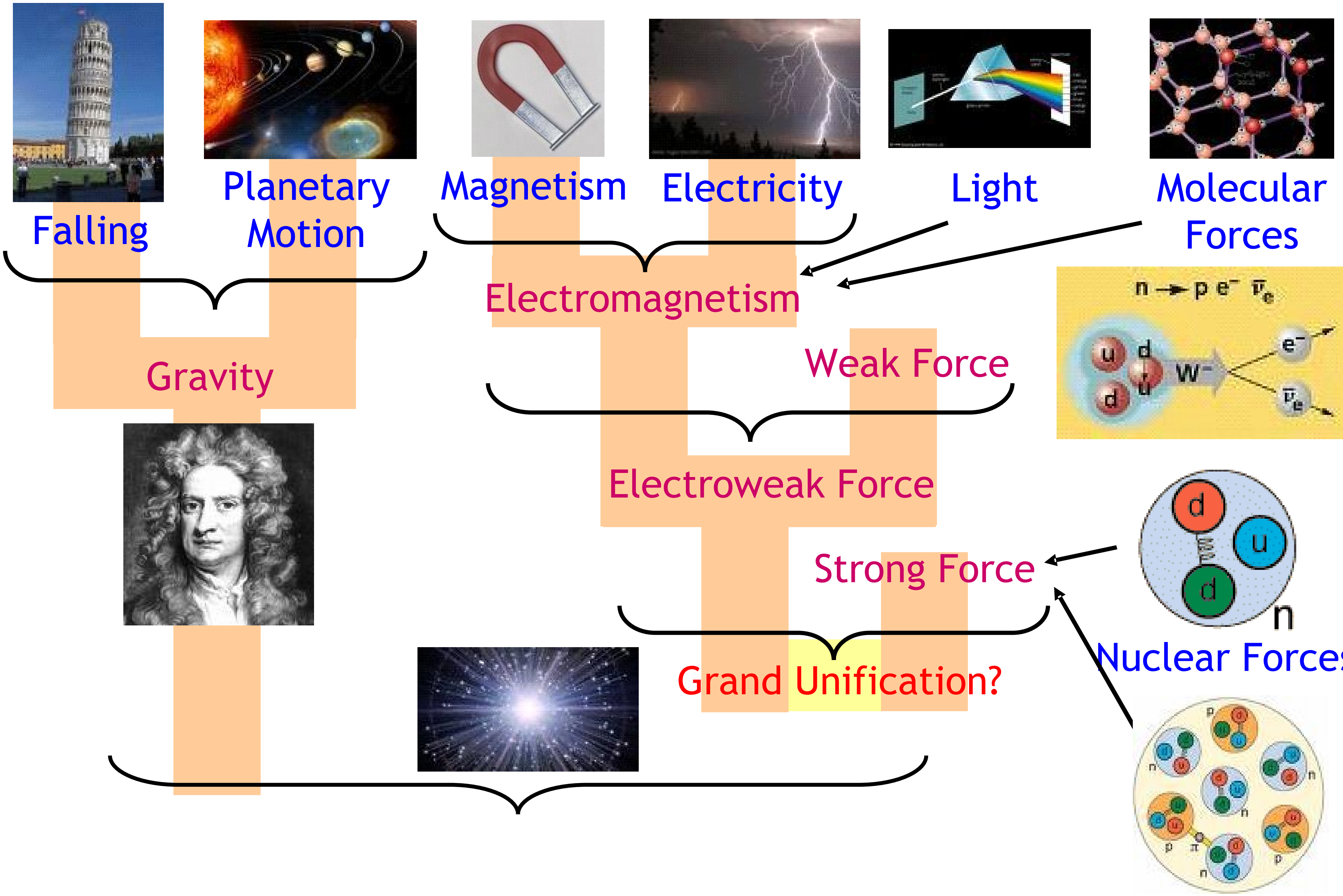
How does exchaning particles transmit a force?

if skaters exchange a ball they will move apart

acts like a repulsive force (if we don't see the ball!)






Falling
Planetary Motion
Magnetism
Electricity
Light
Molecular Forces
Electromagnetism
Gravity
Weak Force
Electroweak Force
Strong Force
Nuclear Forces
Grand Unification?
n → p e⁻ ν̄e
u
d
d
W⁻
e⁻
ν̄e
d
u
d
n

Strong Force
Strength: 1
Range: 10^{-15} m
Exchange: Gluon

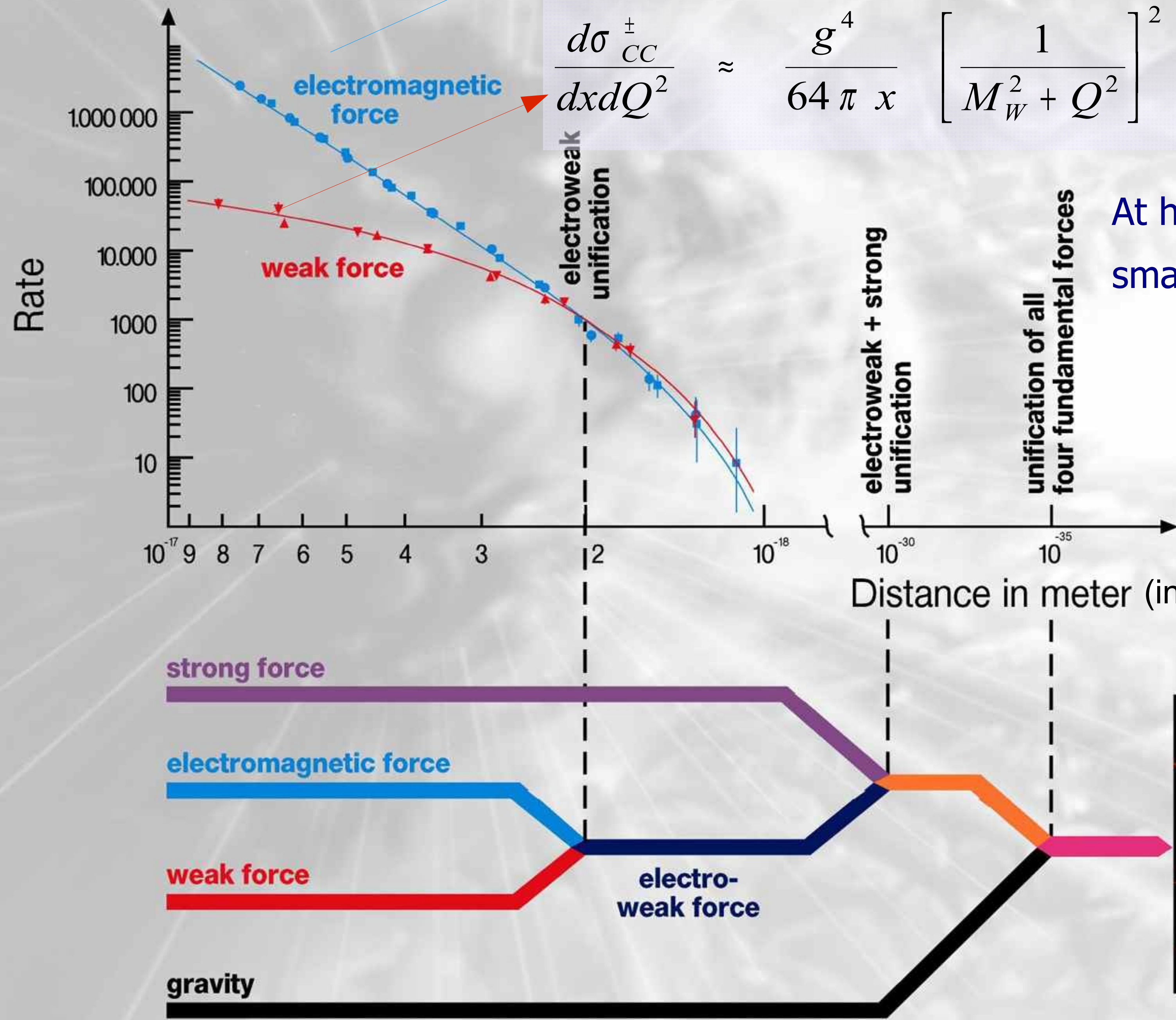
Electromagnetic Force
Strength: 0.01
Range: Infinite
Exchange: Photon

Weak Force
Strength: 10^{-6}
Range: 10^{-18}m
Exchange: $W^{\pm}$ Z^{0}

Gravity
Strength: 6×10^{-39}
Range: Infinite
Exchange: Graviton?

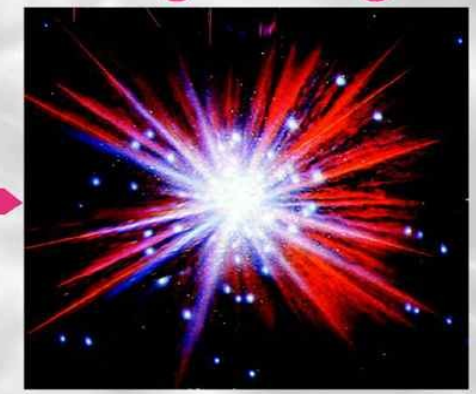
$$\frac{d\sigma^{\pm}_{NC}}{dx\,dQ^2} \approx \frac{e^4}{8\pi x}\left[\frac{1}{Q^2}\right]^2\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3\right]$$

$$\frac{d\sigma^{\pm}_{CC}}{dx\,dQ^2} \approx \frac{g^4}{64\pi x}\left[\frac{1}{M_W^2+Q^2}\right]^2\left[Y_+\tilde{W}_2^{\pm} \mp Y_- x\tilde{W}_3^{\pm}\right]$$

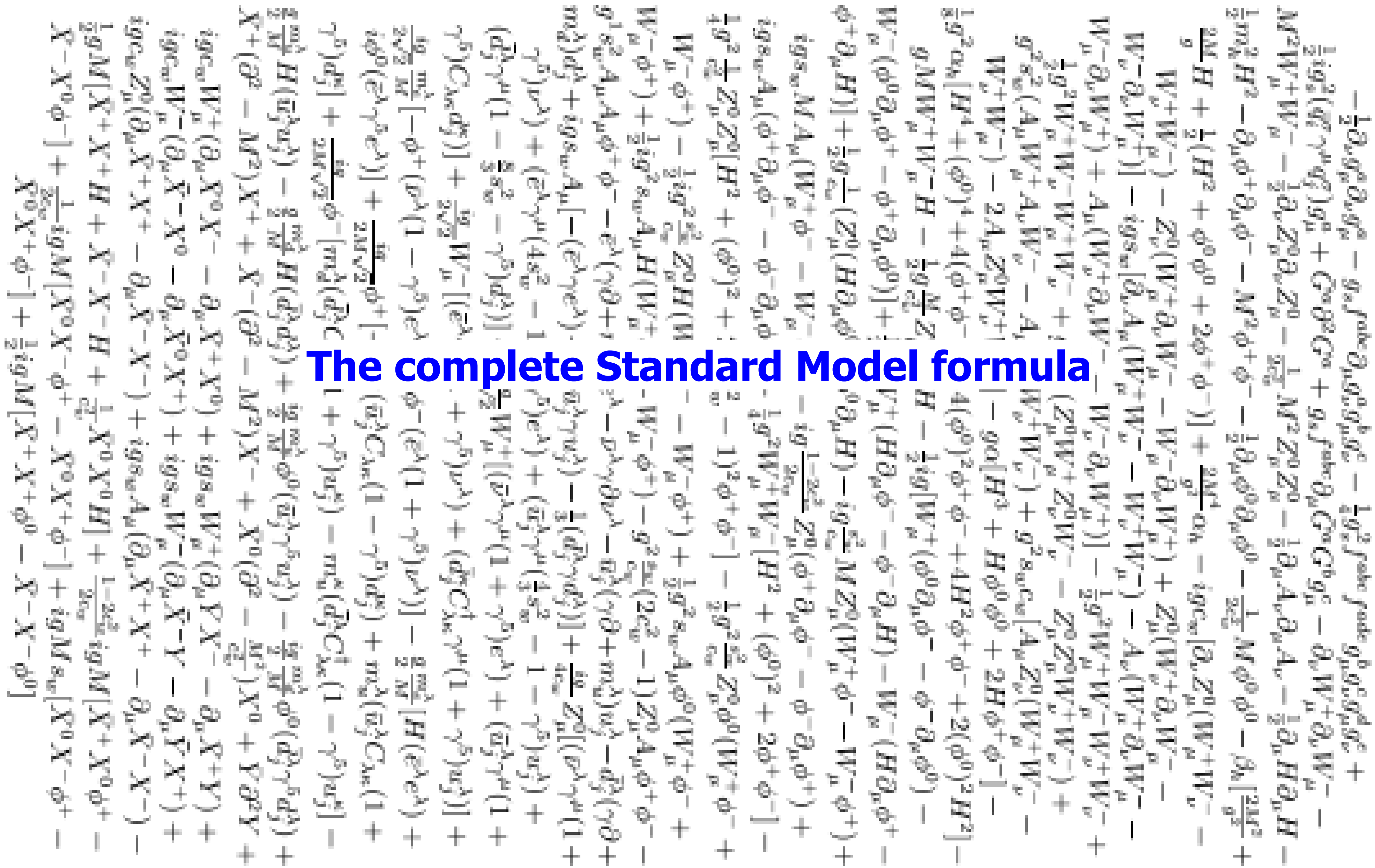


At high energy, masses small – forces are equal

big bang



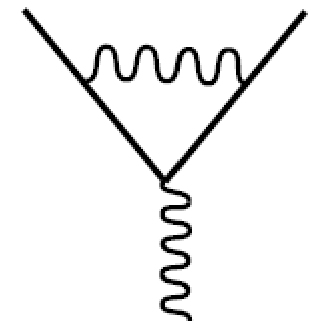
Aim to unify all forces



The complete Standard Model formula

Quantum mechanics predicts the gyromagnetic ratio of the electron g=2
(ratio of magnetic dipole moment to it's spin)
Experiment measures $g_{exp} = 2.0023193043738 \pm 0.0000000000082$

Discrepancy of g-2 due to radiative corrections
Electron emits and reabsorbs additional photons
Corresponds to higher terms in perturbative series expansion



$$\frac{g_{theory} - 2}{2} = 1159652140(\pm 28) \times 10^{-12}$$

$$\frac{g_{exp} - 2}{2} = 1159652186.9(\pm 4.1) \times 10^{-12}$$

Phenomenal agreement between theory and experiment! 4 parts in 10^8
QED (quantum electrodynamics) is humanity's most successful theory
Demonstrates understanding of our universe to unprecedented precsion

Equivalent to measuring distance from me to centre of moon
and asking if we should measure from top of head or my waist!

... but all is not well...

Standard Model is lacking:

- why 3 generations of particles?
- why do particles have the masses they do?
- no consideration of gravity on quantum level
- where is all the antimatter in the universe?

Too many free parameters - need to be determined from experiment:
(Compare to Newtonian gravity - one free parameter: G)

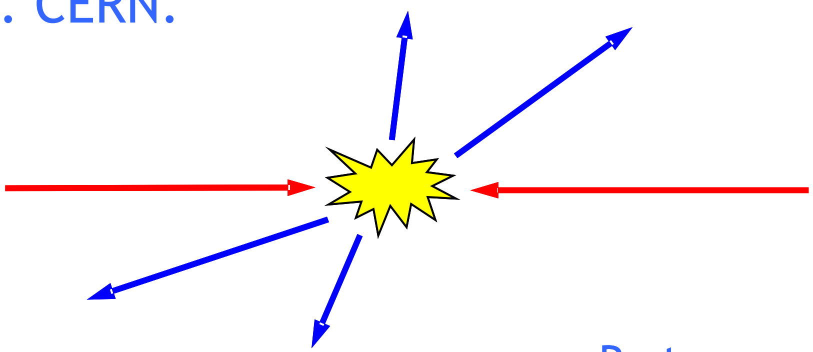
- 12 particle masses: 6 quarks, 3 charged leptons, 3 neutrinos
- 3 boson masses ($W^{\pm}$, Z^0, H^0)
- 3 coupling constants: EM, Strong, Weak
- 4 quark mixing parameters
- 4 neutrino mixing parameters

What are the current collider experiments doing?

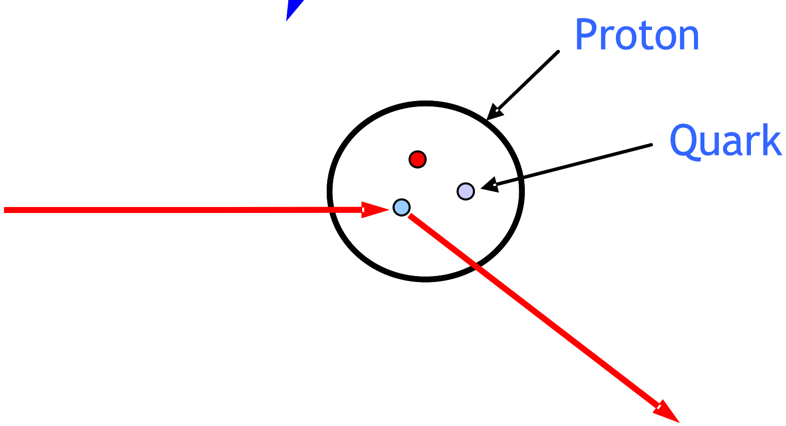
Particle Physics Experiments

Use large Particle Accelerators e.g. CERN.

Either annihilate two particles and use the total energy to create new particles using $E=mc^2$.



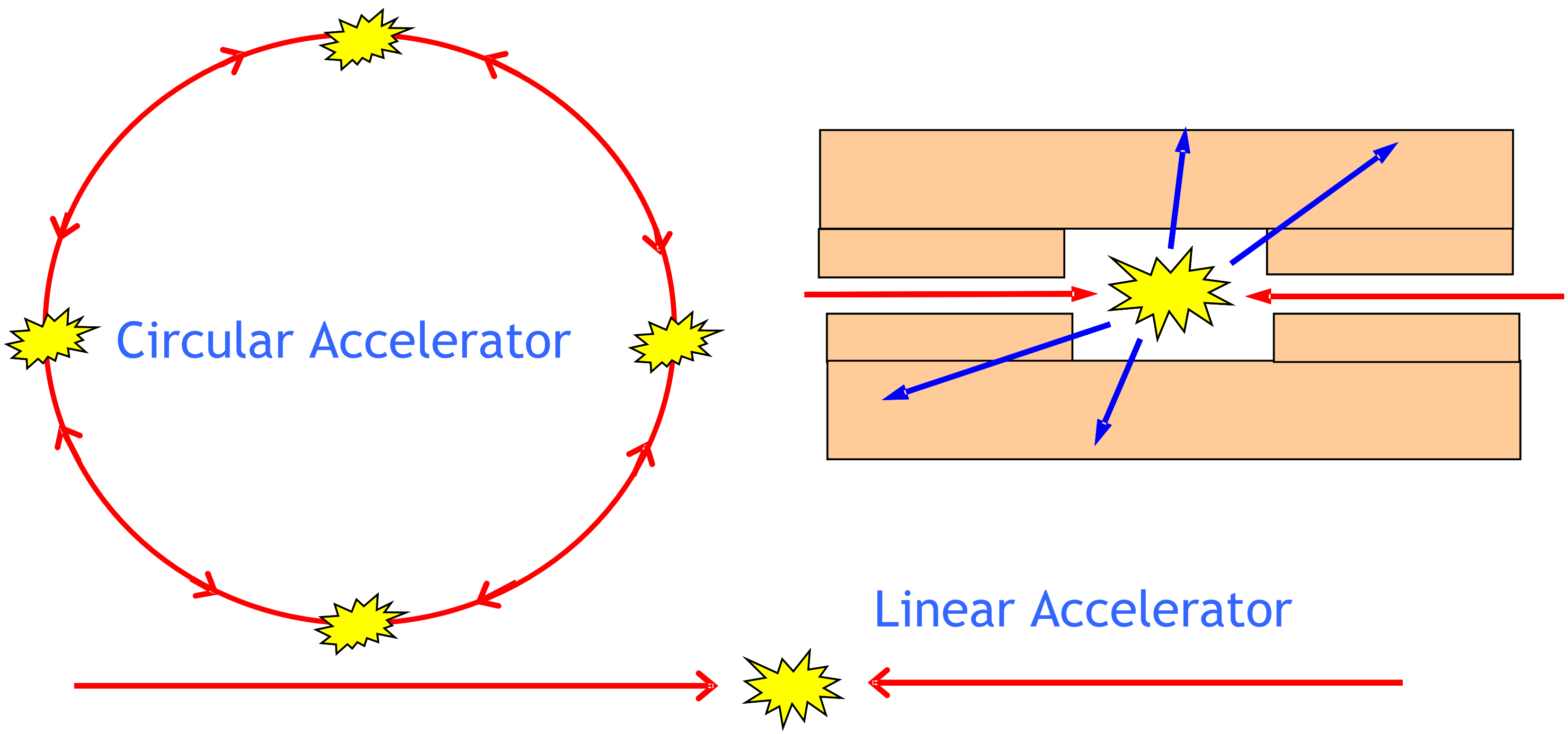
Or scatter one particle off something inside the other to see what it's made of.



The more energy you start with, the heavier the new particles you can make or the further you can see inside.
(Compare firing a bullet to throwing a bullet at something)

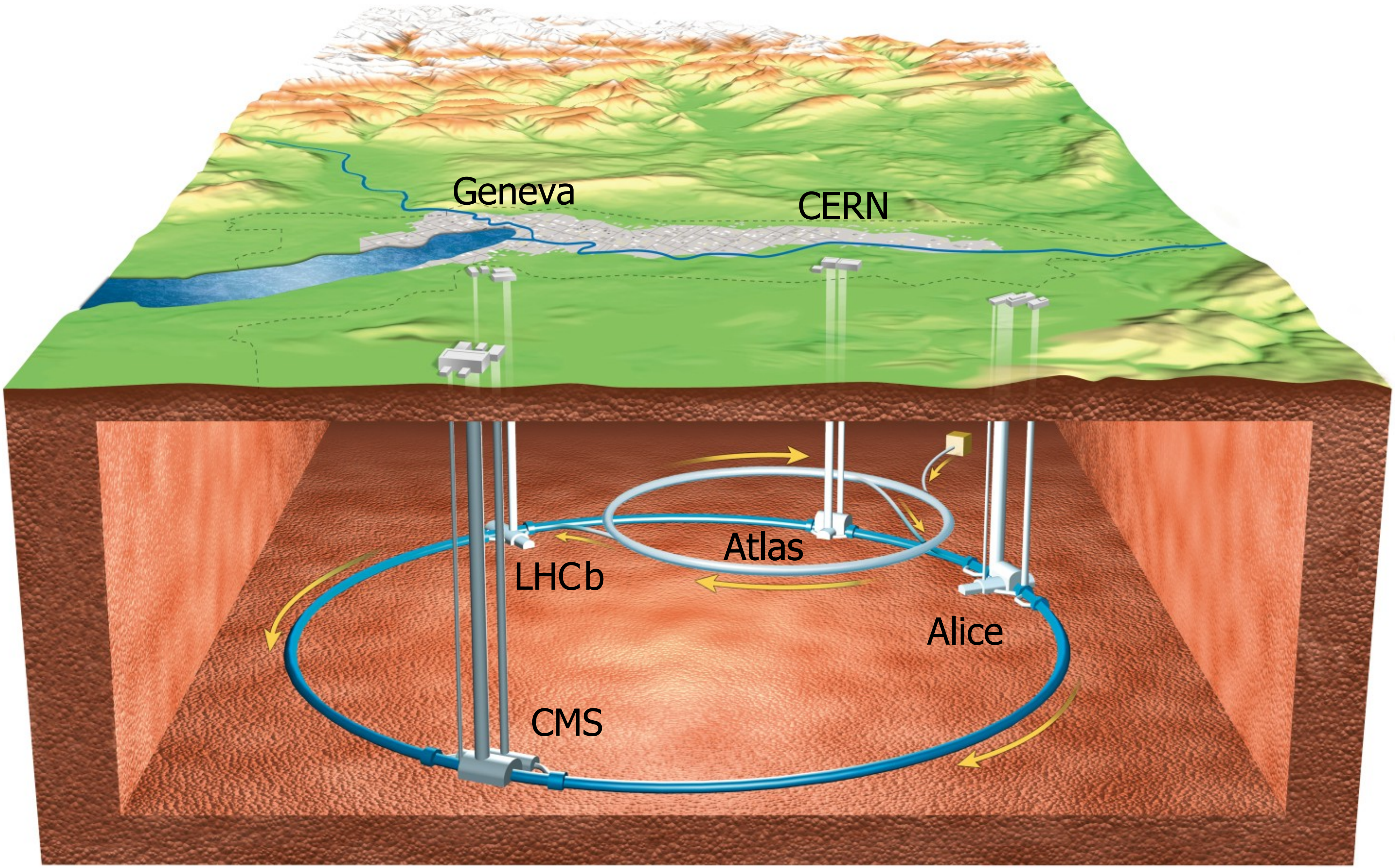
Particle Physics Experiments

Two beams of particle are accelerated in opposite directions and collide at interaction regions where the detectors are:

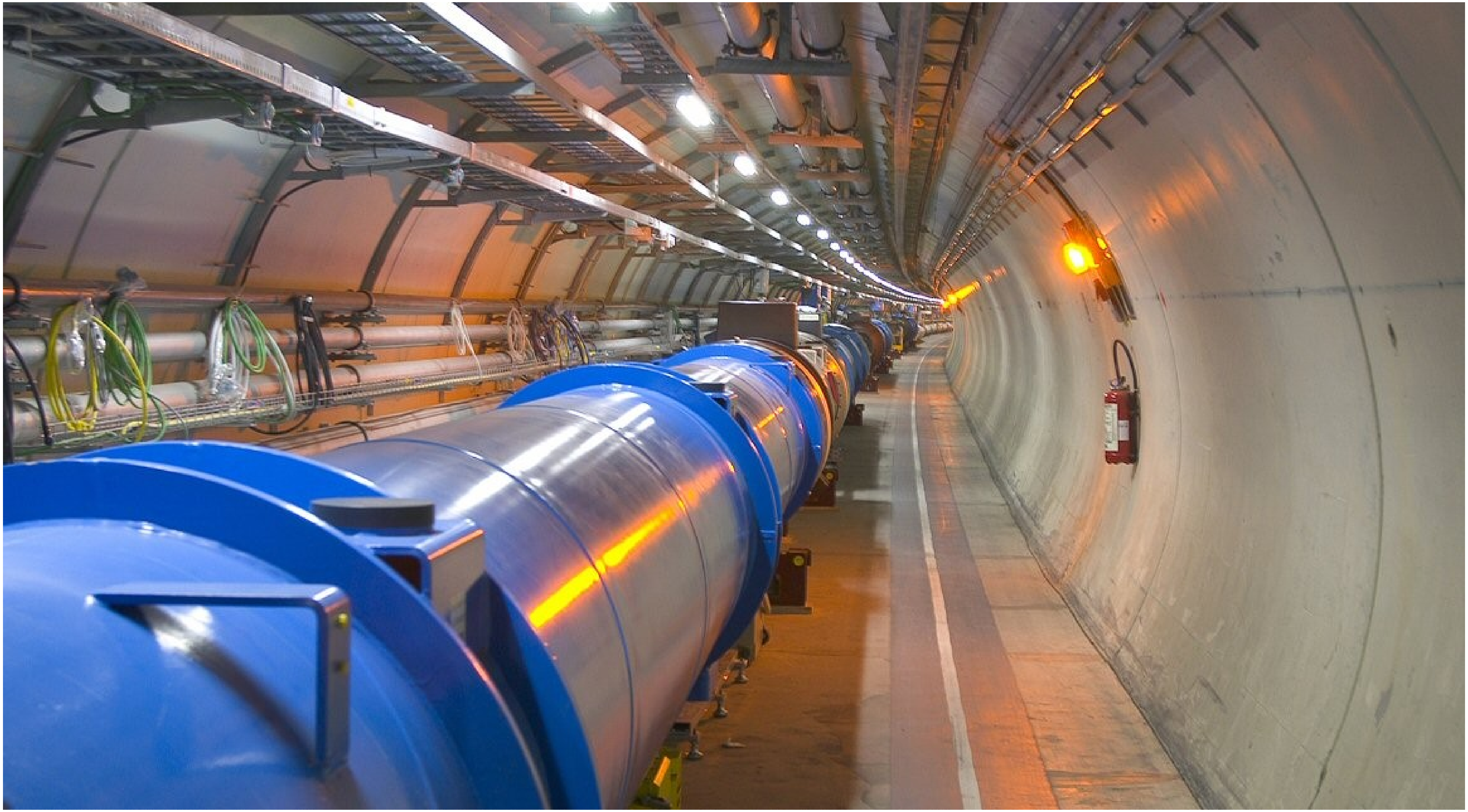


Particle Physics is a global enterprise: experiments in all continents (incl. antarctica!)
I will concentrate on LHC and the ATLAS experiment

The Large Hadron Collider

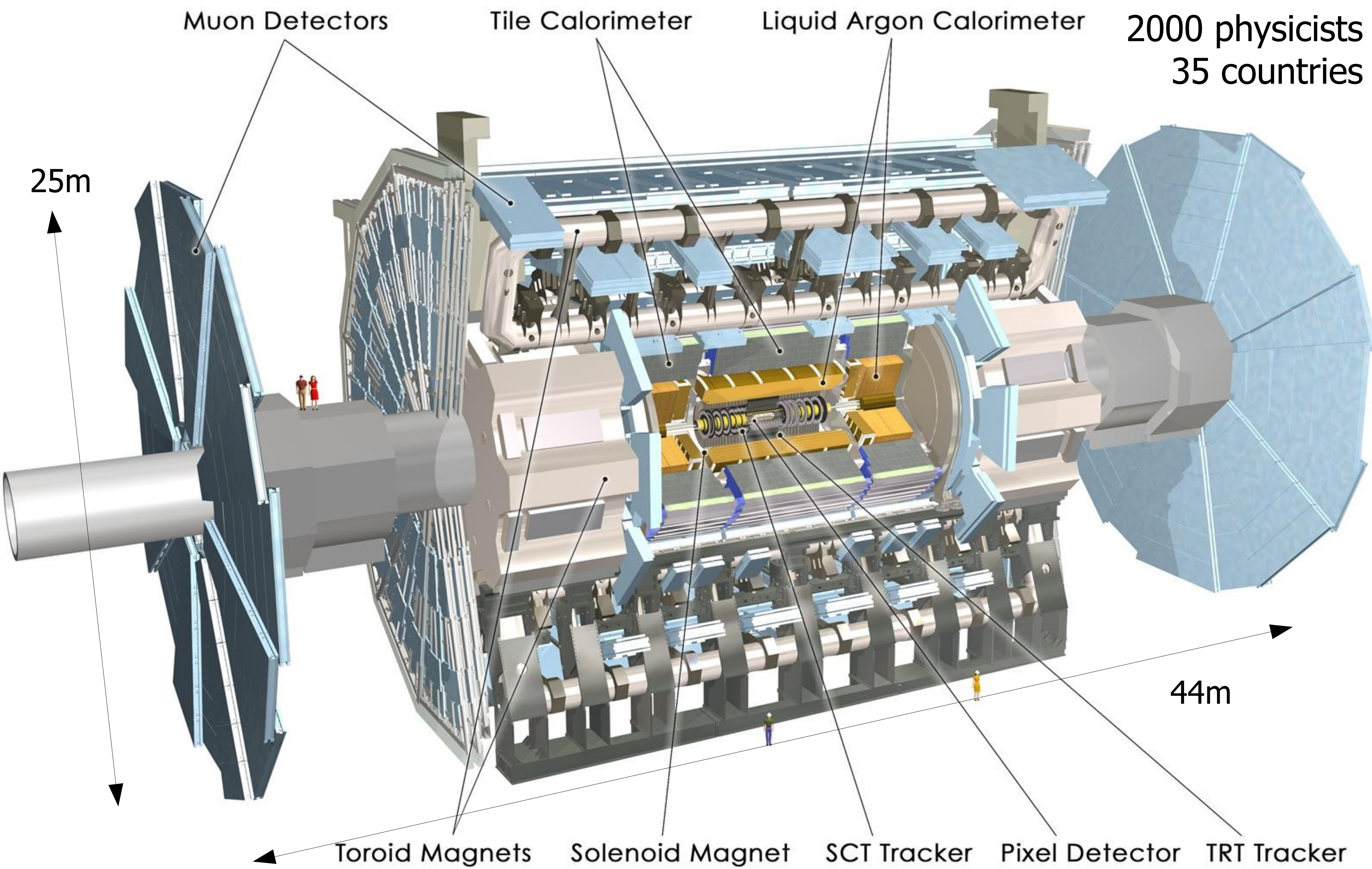


The Large Hadron Collider



The Atlas Experiment

2000 physicists
35 countries



The Large Hadron Collider

LHC will collide protons at 7 TeV (7000 GeV)

27 km circumference ring

1200 superconducting dipole magnets ~ 9 T field

3000 tons of magnets supercooled to 1.9K

Each beam has energy equivalent to 100 kph Eurostar train

Proton bunches collide in bunches every 25 ns

Beams have transverse size ~15 μm (human hair ~20 μm)

20 interactions every bunch crossing

Particles from one collision still travelling when next collision occurs!

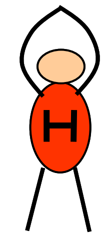
One of the largest scientific / technological projects ever undertaken

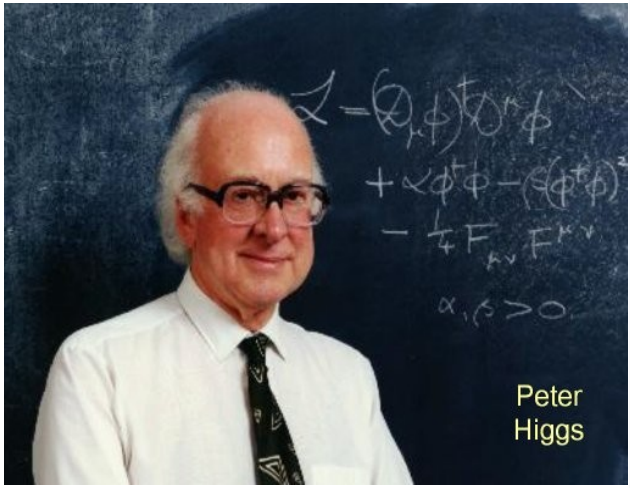
> 10^8 electronic channels
8×10^8 proton-proton interactions/second
2×10^{-4} Higgs per second
10 Petabytes of data a year
(10 Million GBytes = 14 Million CDs)

The Higgs Boson

Higgs particle postulated to explain masses of fundamental particles

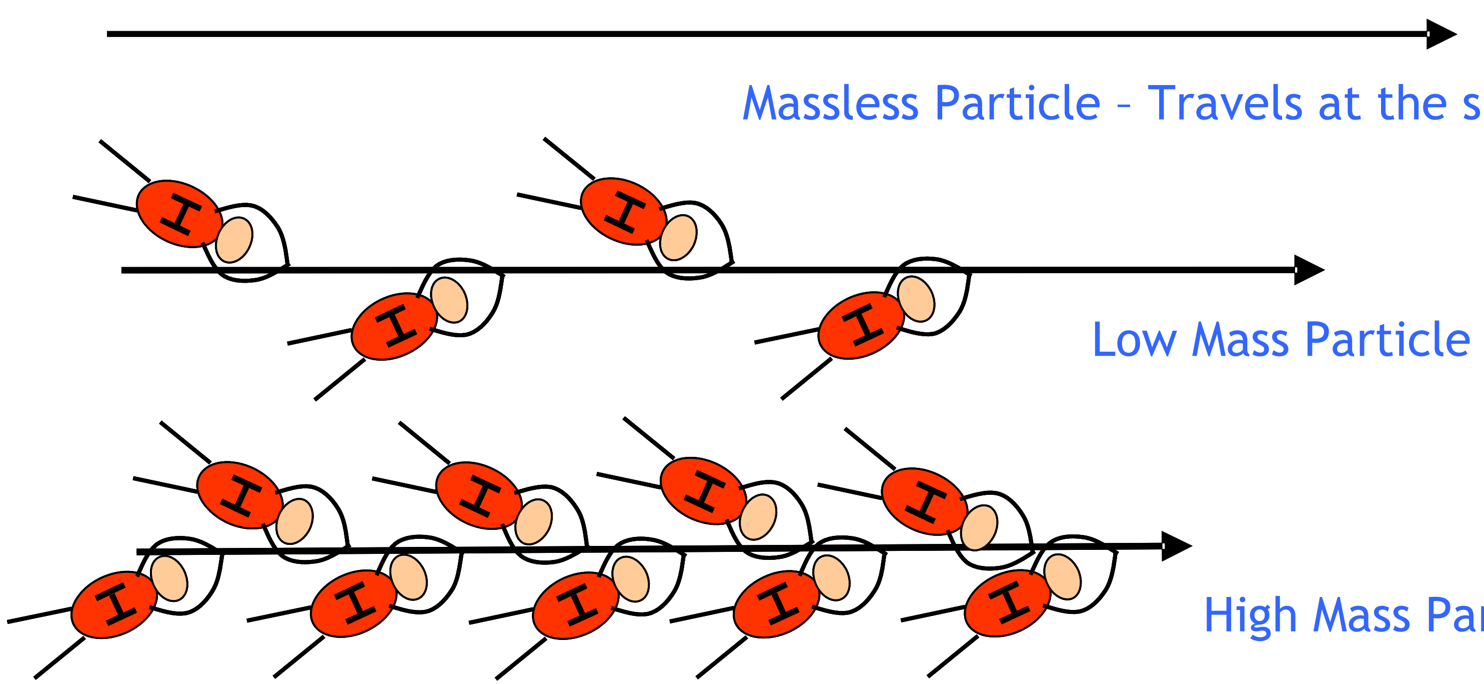
Theory predicts force carrier particles to be massless
But $W^{\pm}$& Z^0 boson have large masses ~80-90 GeV





Higgs properties are well known except its mass!

Direct searches: m_H>114 GeV



Massless Particle – Travels at the speed of light

Low Mass Particle – Travels slower

High Mass Particle – Travels slower still

Superymmetry

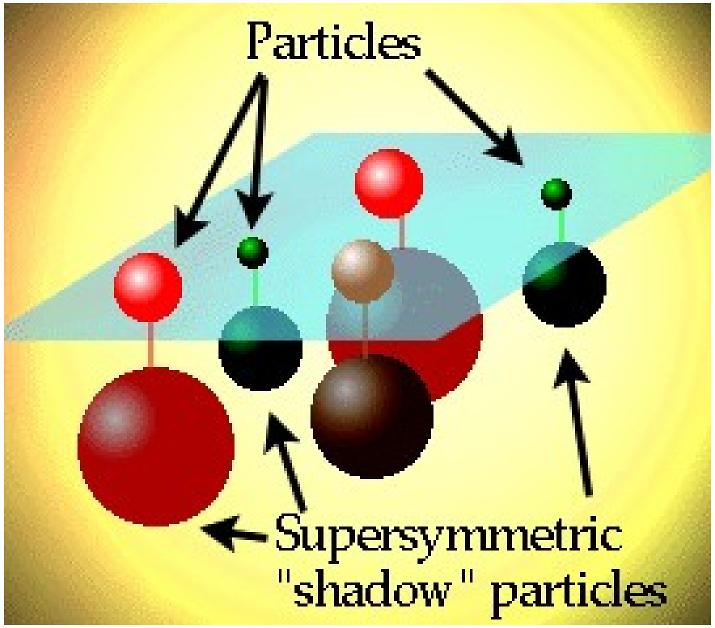
What are the alternatives to the Standard Model?

Best bet is Supersymmetry (SUSY)

Theoretically elegant - extends symmetry ideas of the Standard Model
Invokes a symmetry between fermions and bosons
(integer and half integer spin particles)

Immediately double number of particles
Each SM particle has a superpartner sparticle

quarks (spin ½) ↔ squarks (spin 0)
leptons (spin ½) ↔ sleptons (spin 0)
photon (spin 1) ↔ photino (spin ½)
W,Z (spin 1) ↔ Wino, Zino (spin ½)
Higgs (spin 0) ↔ Higgsino (spin ½)



None of these has been observed
105 new parameters required by theory - So why bother??

Quantum Gravity

Supersymmetry is a particular form of string theory
String theory aims to describe physics of Planck scale - domain of quantum gravity
Impossible to reach in any collider!

Some quantum gravity theories line in 10 or 11 dimesional space!
predict gravitons propagate in extra dimensions size of Planck length
(graviton = postulated force carrier of gravity)
Explains why gravity is 10^{23} times weaker than Weak force - gravity is diluted

But: If extra dimensions large (~0.1mm) quantum gravity could be seen at TeV scale
Gravity has never been tested at such short distances!
LHC could open the possibility of creating mini-black holes & gravitons
laboratory for testing quantum gravity!!!

Mini black holes will evaporate via Hawking radiation
experimentally look for particle decays with Black Body spectrum at Hawking Temp

$$T \approx \frac{(n+1)}{4\pi R}$$

n = number of <u>extra</u> dimensions
R = radius of compacted dimension

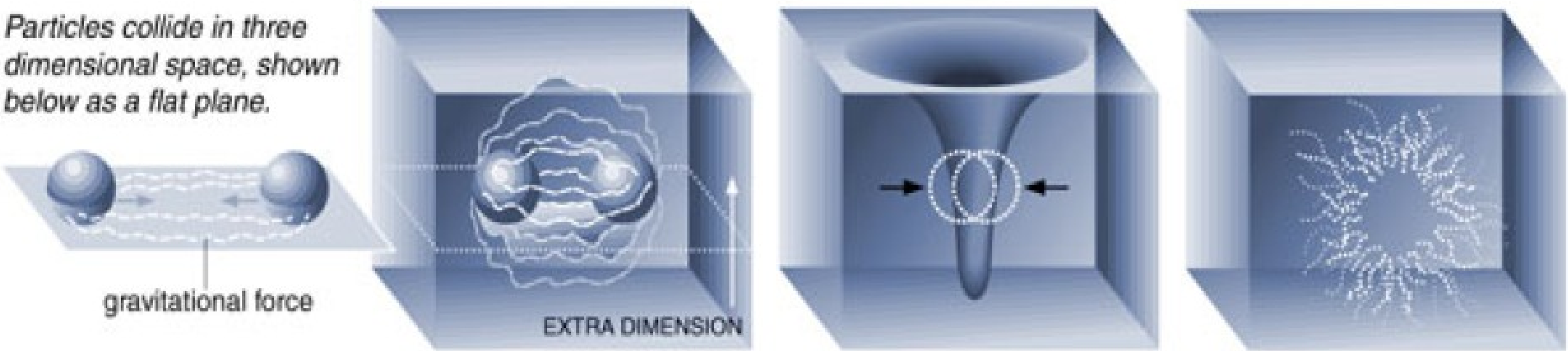
Micro Black Holes

Black Holes on Demand

NYT, 9/11/01

The New York Times ON THE WEB

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:



As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

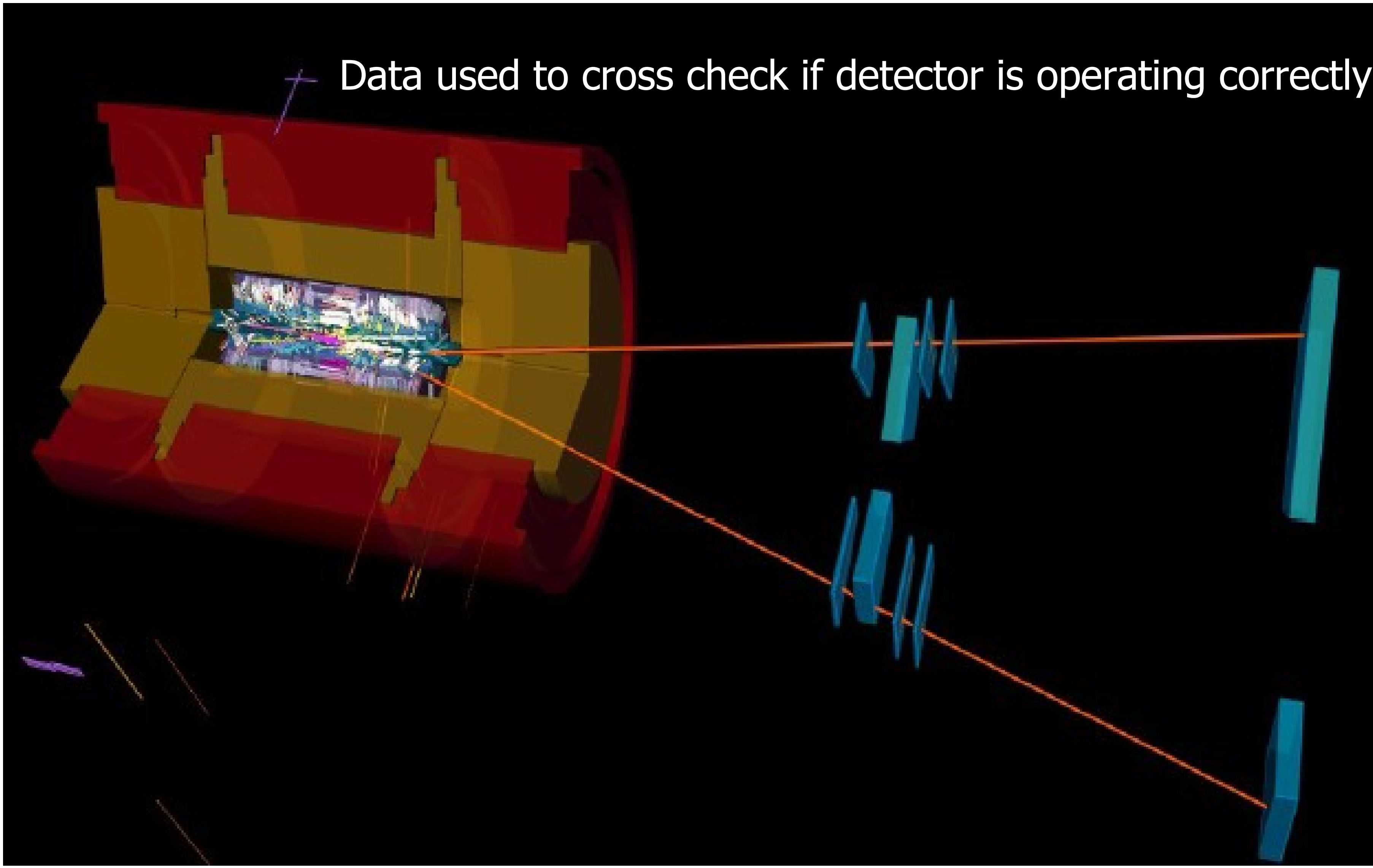
When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

LHC Starts Collisions!

Atlas Experiment sees collision data



Long “physics run” of data taking starts this Spring for ~ 1 year!

Summary

We're living in exciting times

Discovery potential of the LHC is huge

Higgs discovery
mini black holes
extra dimensions
supersymmetry
new phases of matter
quantum gravity
secret of dark matter
... something we haven't thought of yet

Lots of work to be done in next few years!

The LHC started operation November 2009

Data taking will start in earnest Feb 2010

In just a few years you could be working with us!

Mail Online

Are we all going to die next Wednesday?

Big Bang Day: Wednesday 10th September 2008!

The LHC turned on and the earth did not get eaten by a black hole!
Has taken over 2 decades to finally get to this point
Beam operators injected protons into one ring only
- complete circuit of the ring
- no acceleration to high energy
- means ~1000 magnets working, cryogenics OK, diagnostic systems ok
- vacuum inside beam pipe is ok...

Great success !

In following days CERN attempted to accelerate protons up to 5 TeV

On Friday 19th September an accident caused a “magnet quench”

To steer the beams powerful supercooled magnets are required
Cooled by liquid Helium to just above absolute zero
Magnets become superconducting - no electrical resistance!
Currents ~ 10,000 A

One electrical connection between magnets gained small resistance $\sim 10 \times 10^{-9}\ \Omega$
power = I^2R = 10 watts
enough to heat helium above critical temperature - no more cooling
magnets become resistive and dissipate power
    protection systems operated ok - magnets not damaged

sudden increase in pressure due to helium boiling
ruptured helium container and safety valves failed
    designed to withstand 8 tonnes of force from helium pressure
    400m section under investigation

This is what a few nano-ohms resistance in a superconducting magnet can do...