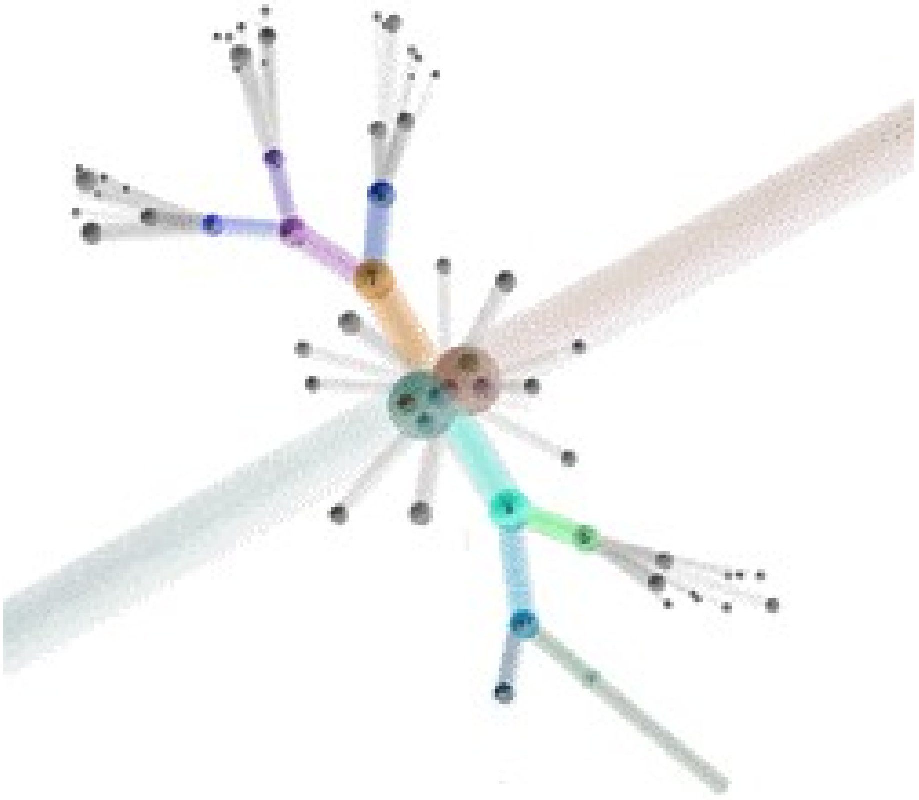
From Atoms to Extra Dimensions



- The Standard Model of Particle Physics
- The Problematic Standard Model
- New Experiments: T2K & the LHC
- The Higgs Boson
- Beyond the Standard Model

Queen Mary
University of London

HEP Seminar

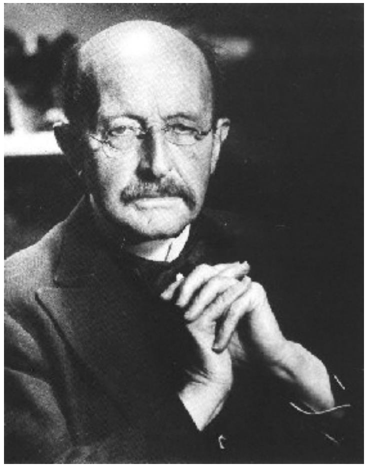
Introduction

Over 100 years of discovery and experimentation

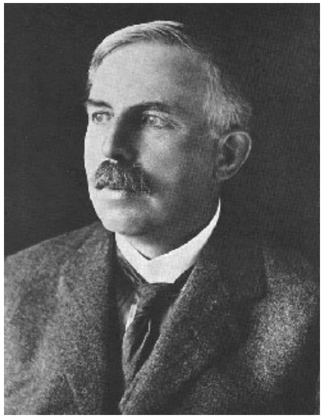
- Discovery of electron - Thompson 1897
- Birth of quantum physics - Planck 1900
- Relativity - Einstein 1905
- Atomic structure - Rutherford 1911

...and much more!

Thompson



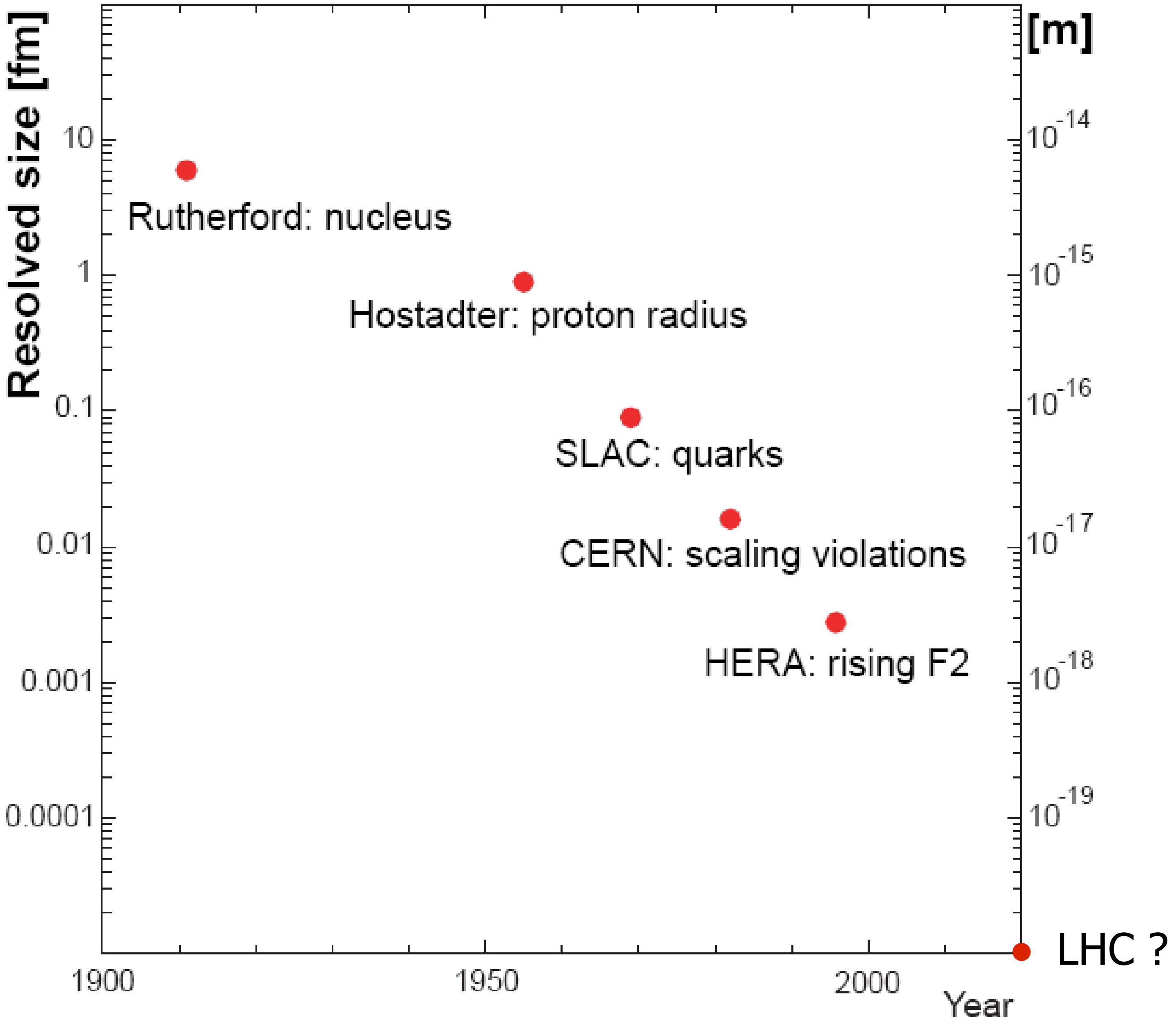
Planck

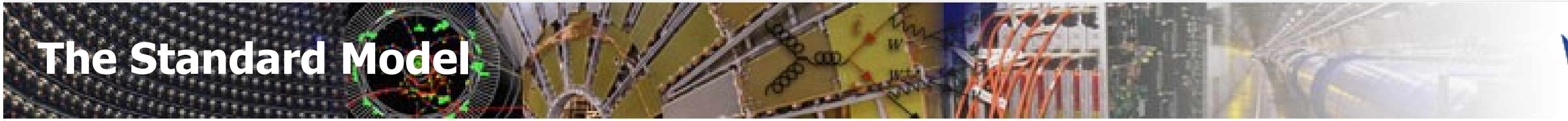


Rutherford

... what have we learnt ?

Introduction





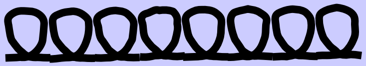
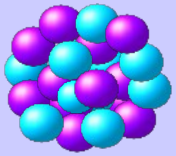
The Standard Model

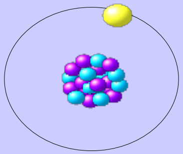
Worlds most successful theory to date - Describes fundamental constituents of matter

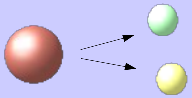
u d s c b t quarks: strong, weak, electromagnetic

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 and 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

Based on perturbation theory & relativistic quantum mechanics given us the language of Feynman diagrams to calc cross sections

Potential = V + V'

V gives rise to stationary stable, time independent states

V' is a weak additional potential leading to transitions between states $\psi_i \rightarrow \psi_f$

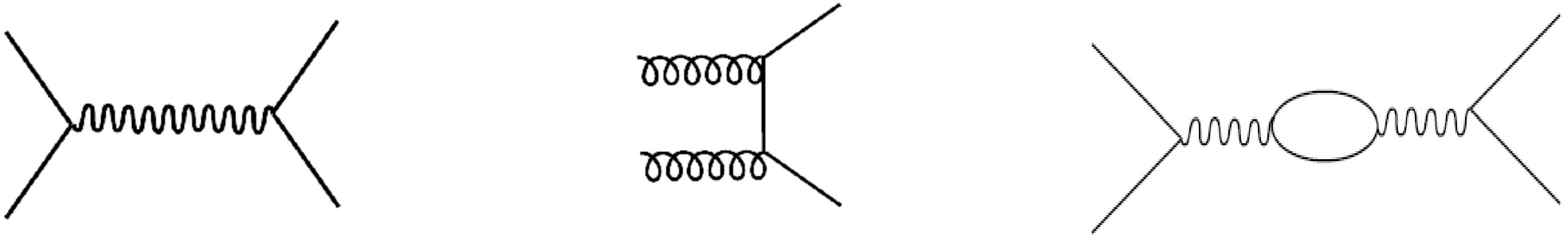
$$\sigma = \frac{2\pi}{\hbar} |V'_{fi}|^2 \rho(E_f)$$

$\rho(E_f)$ density of final states and flux factors

$V'_{fi} = \int \psi_f^* V_{fi} \psi_i \, dv$ is known as the matrix element for the scattering process

V' contains the standard model Lagrangian describes the dynamics of all interactions

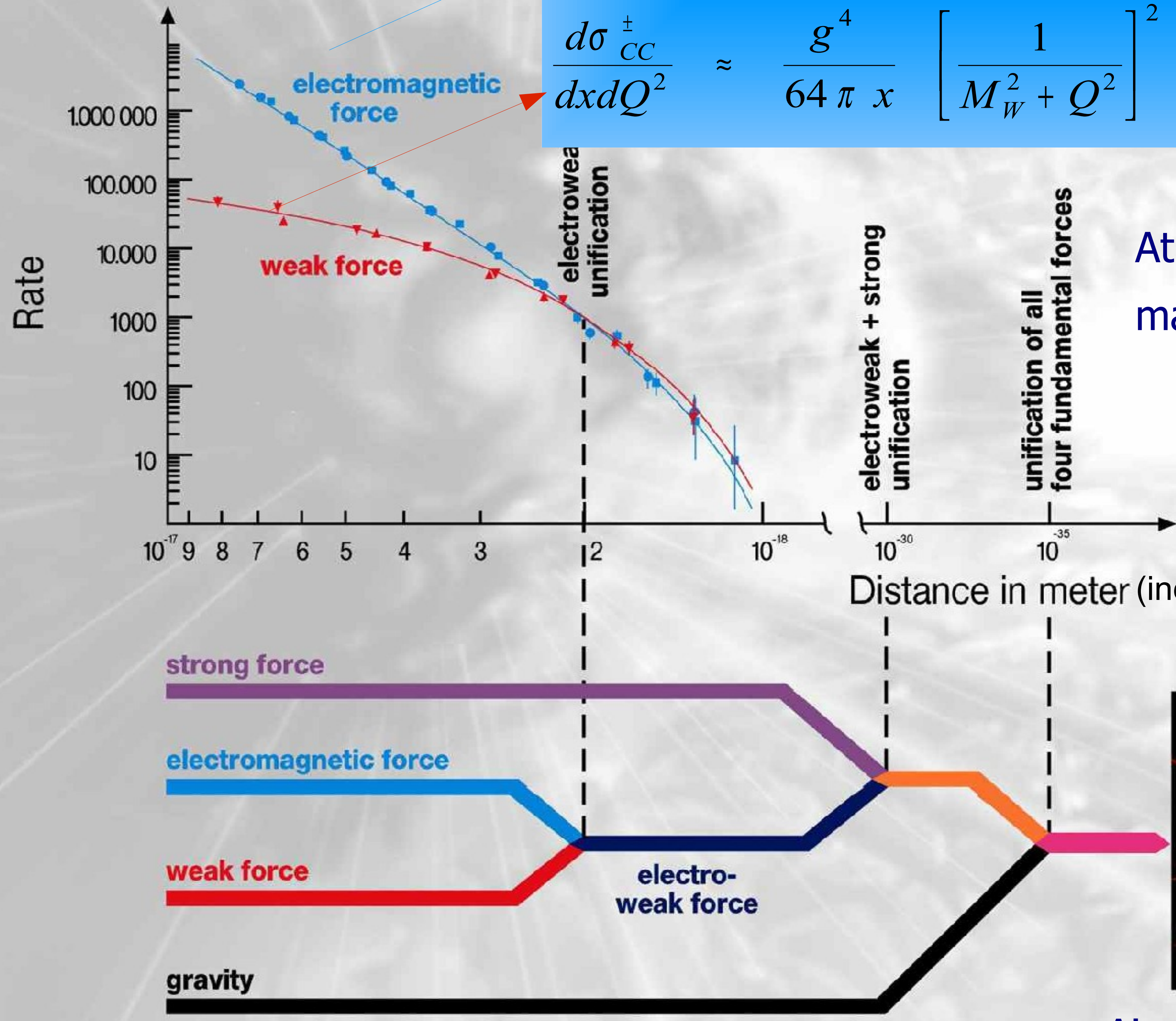
Series expansion in powers of couplings α between particles for each force



Electro-Weak Unification

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

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

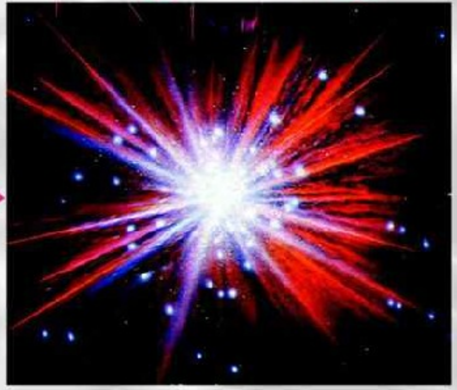


At high energy:

masses are small

→ forces are equal

big bang



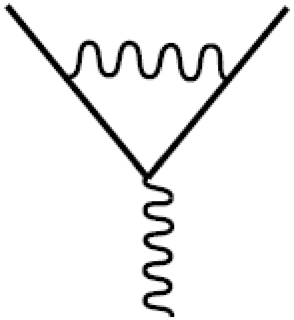
Aim to unify all forces

The Standard Model

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

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

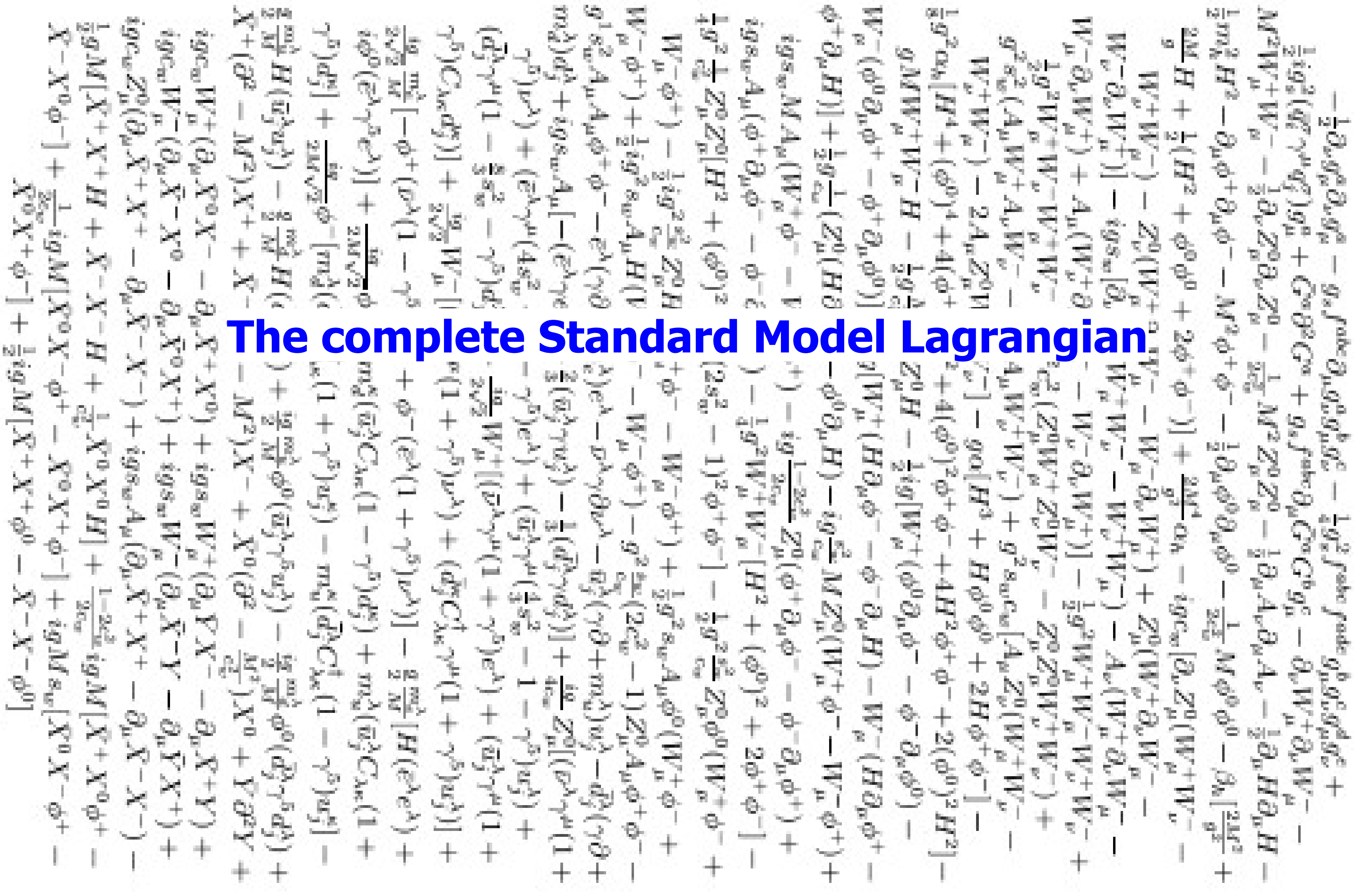
$$\frac{g_{exp} - 2}{2} = 1159652186.9(4.1) \times 10^{-12}$$

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 ...

The Standard Model



The complete Standard Model Lagrangian

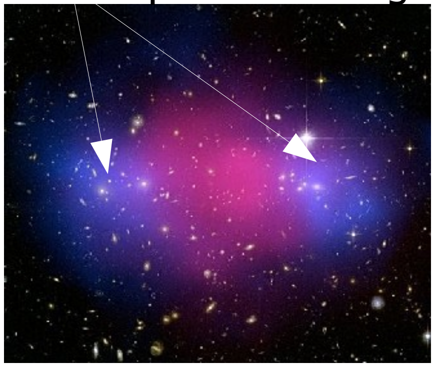
The Problematic Standard Model

22 Parameters of the SM to be measured

- 6 quark masses
- 3 charged leptons masses
- 3 coupling constants
- 4 quark mixing parameters
- 4 neutrino mixing parameters
- 1 weak boson mass (1 predicted from other EW params)
- 1 Higgs mass

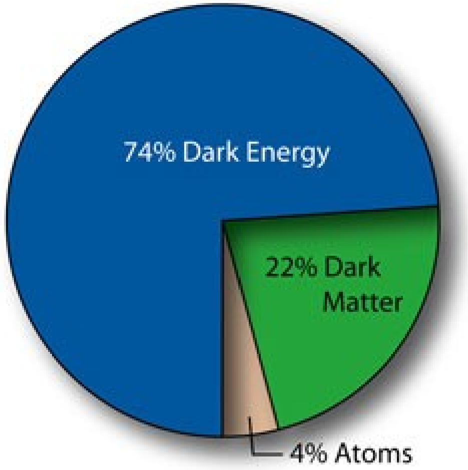
(better than 105 params of generic SUSY)

Two gas clouds collide
Clouds slow down
Dark matter passes through



We have no idea what 96% of the universe is!

- unknown form of dark energy
- unknown form of dark matter



No treatment of gravity in the Standard Model...
In a symmetric theory gauge bosons are massless
Higgs mechanism explains EW symmetry breaking
→ EW bosons acquire mass

...but there must be a deeper relationship
between Higgs / mass / gravity / dark energy

The Hierarchy Problem

Why is gravity ~10^{33} weaker than EW interactions?
Why is Higgs mass (~100 GeV) so much smaller than Planck mass (10^{19} GeV)?

Leads to fine tuning problem

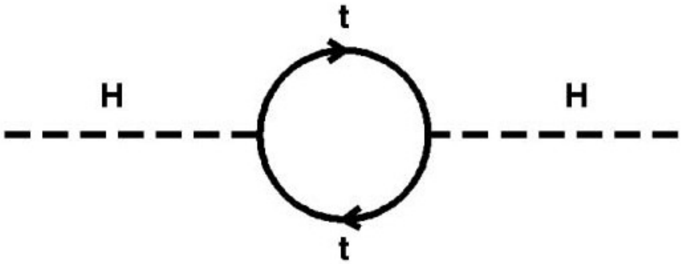
self energy corrections to Higgs mass are quadratically divergent upto 10^{19} GeV

physical mass = bare mass + "loops" $m_H^2 = m_0^2 + \Delta m_H^2$

since Higgs is scalar field we get:

for top: $\Delta m_H^2 = -\frac{6}{16\pi^2} g_t^2 \Lambda^2$ (g is Yukawa coupling $\propto$ mass)

for EW bosons: $\Delta m_H^2 = +\frac{1}{16\pi^2} g^2 \Lambda^2$



for Higgs: $\Delta m_H^2 = +\frac{1}{16\pi^2} \lambda^2 \Lambda^2$ (λ is Higgs self coupling)

$m_H^2 = m_0^2 + \frac{1}{16\pi^2}\left(-6g_t^2 + g^2 + \lambda^2\right)\Lambda^2 -$ …new physics…

For $\Lambda^2 : (10^{19}\text{GeV})^2$ and $m_H : (100\text{ GeV})^2$ then

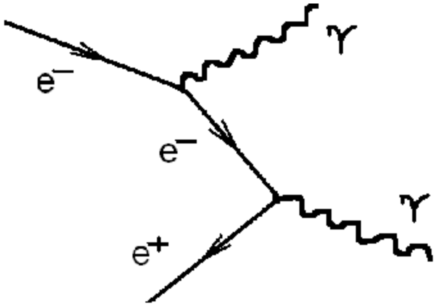
$m_H^2 = m_0^2 + \frac{1}{16\pi^2}\left(-6g_t^2 + g^2 + \lambda^2\right)\cdot 10^{38} \approx (100\text{ GeV})^2$

- if SM is valid to this scale (i.e. no new physics from 1 TeV - 10^{19} GeV) incredible fine tuning required between bare mass and the corrections to maintain ~ 100 GeV Higgs mass

The Problematic Standard Model

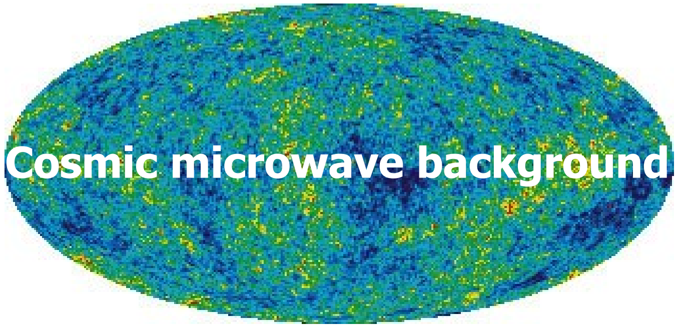
Standard Model is lacking:

- why 3 generations of particles?
- why do particles have the masses they do?
- no consideration of gravity on quantum level...



In the Standard Model matter and anti-matter produced in equal quantities

- In the Big Bang: for every quark, one anti-quark is also produced
- As universe cools expect all particles and anti-particles to annihilate
  - ⇒ soon after big bang all matter will have annihilated to photons
- We should not exist!
- For every proton/neutron/electron in universe there are 10^9 photons (CMB)
- Thus matter/anti-matter asymmetry must be $1{:}10^9$
- We cannot see where this asymmetry lies...


Cosmic microwave background

(Actually SM can account for only 1000th of this asymmetry)

What are the current collider experiments doing?

The T2K Experiment

Neutrinos only interact via weak force ⇒ very inert
- involved in weak beta decays powering solar fusion
- Solar neutrino flux is large ~ 10^6 through your thumbnail every second!

Neutrinos exhibit quantum mechanical property of flavour oscillation
- neutrinos are produced with definite flavour but propagate with definite mass
- flavours oscillate during propagation
- sensitive to neutrino masses (small, but currently unknown)

Simple case of two neutrino flavours: $\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$

flavour eigenstates

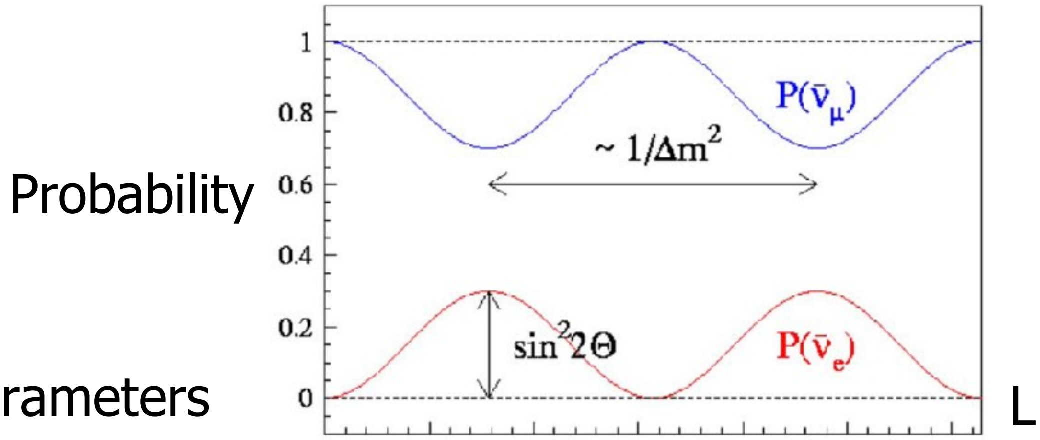
mass eigenstates

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta) \cdot \sin^2\left(1.27 \cdot \Delta m^2 \cdot \tfrac{L}{E}\right)$$

$$\Delta m^2 = \left| m_1^2 - m_2^2 \right|$$

$L =$ distance

$E =$ neutrino energy



T2K will measure oscillation parameters

The T2K Experiment

Full 3x3 representation

$\cos\theta_{13}$ $\sin\theta_{13}$

$\delta \neq 0$

$\Rightarrow$ CP violation!

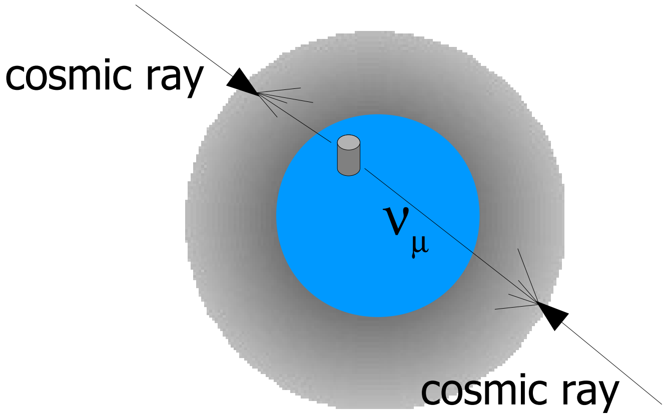
states of definite flavour

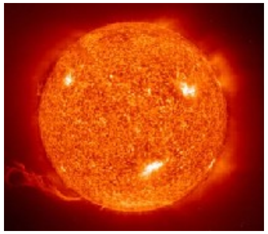
states of definite mass

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

So far experiments measured solar and atmospheric neutrino anomalies

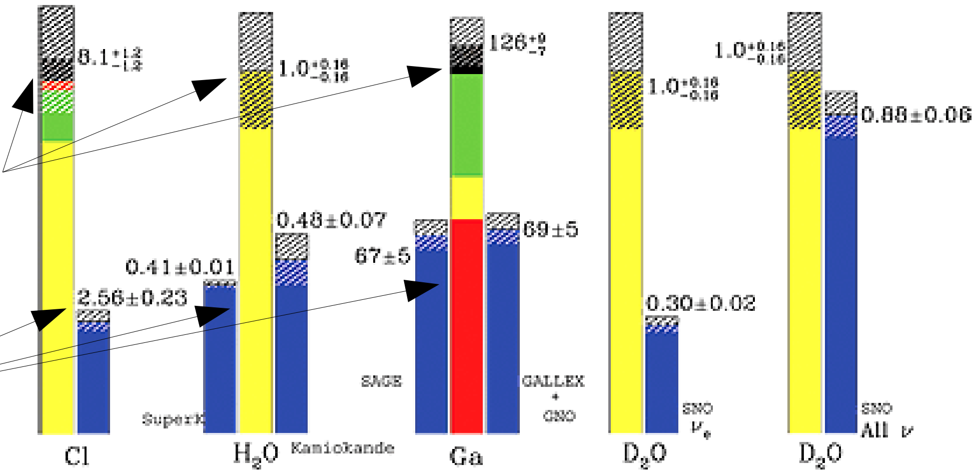
Measure ν_μ from down-coming and up-going neutrinos produced in atmophere





Sun produces calculable rate of ν_e

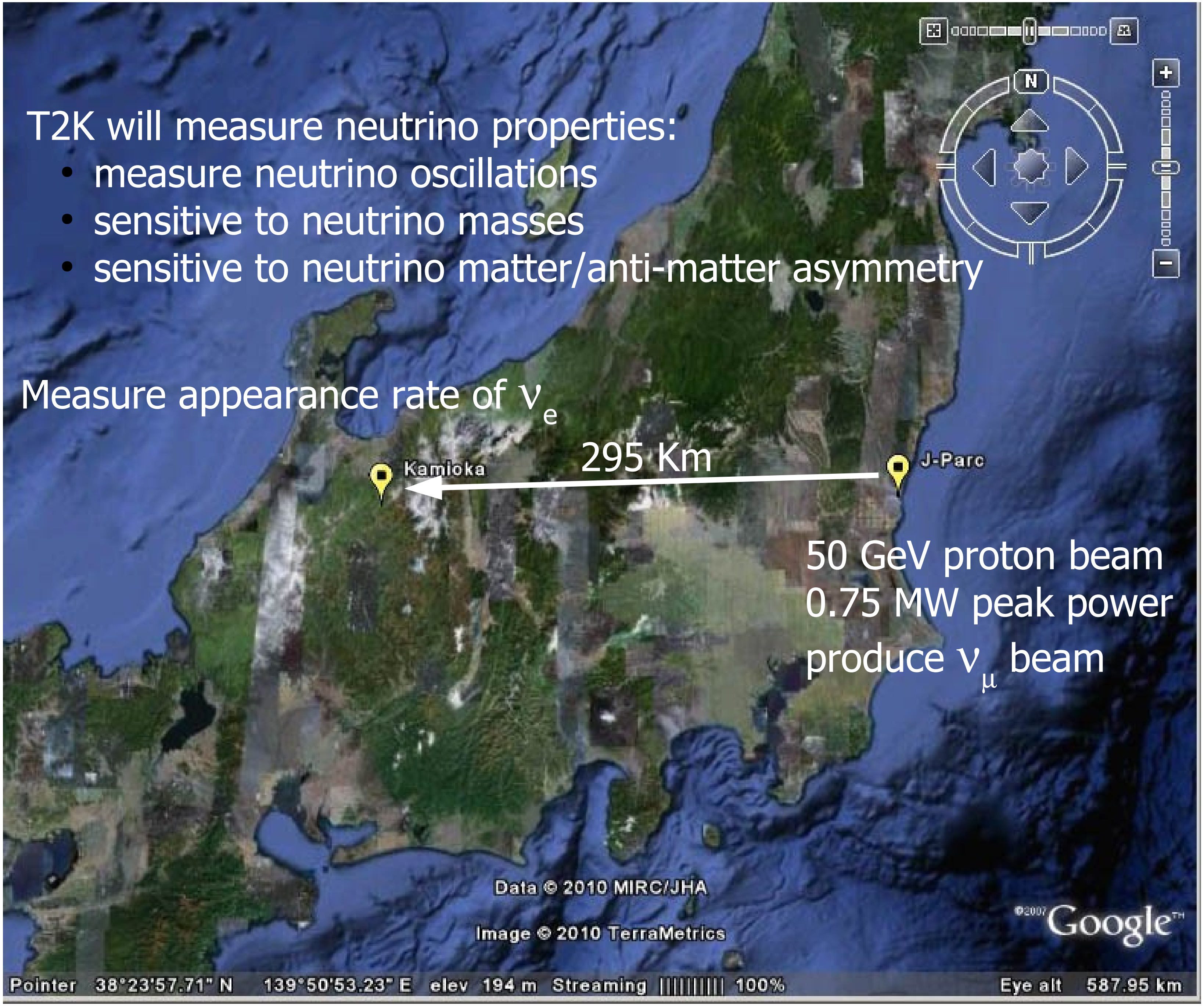
measure ~30% less than expected



Experiments sensitive to different neutrino flavours

sensitive to all flavours!

The T2K Experiment



T2K will measure neutrino properties:

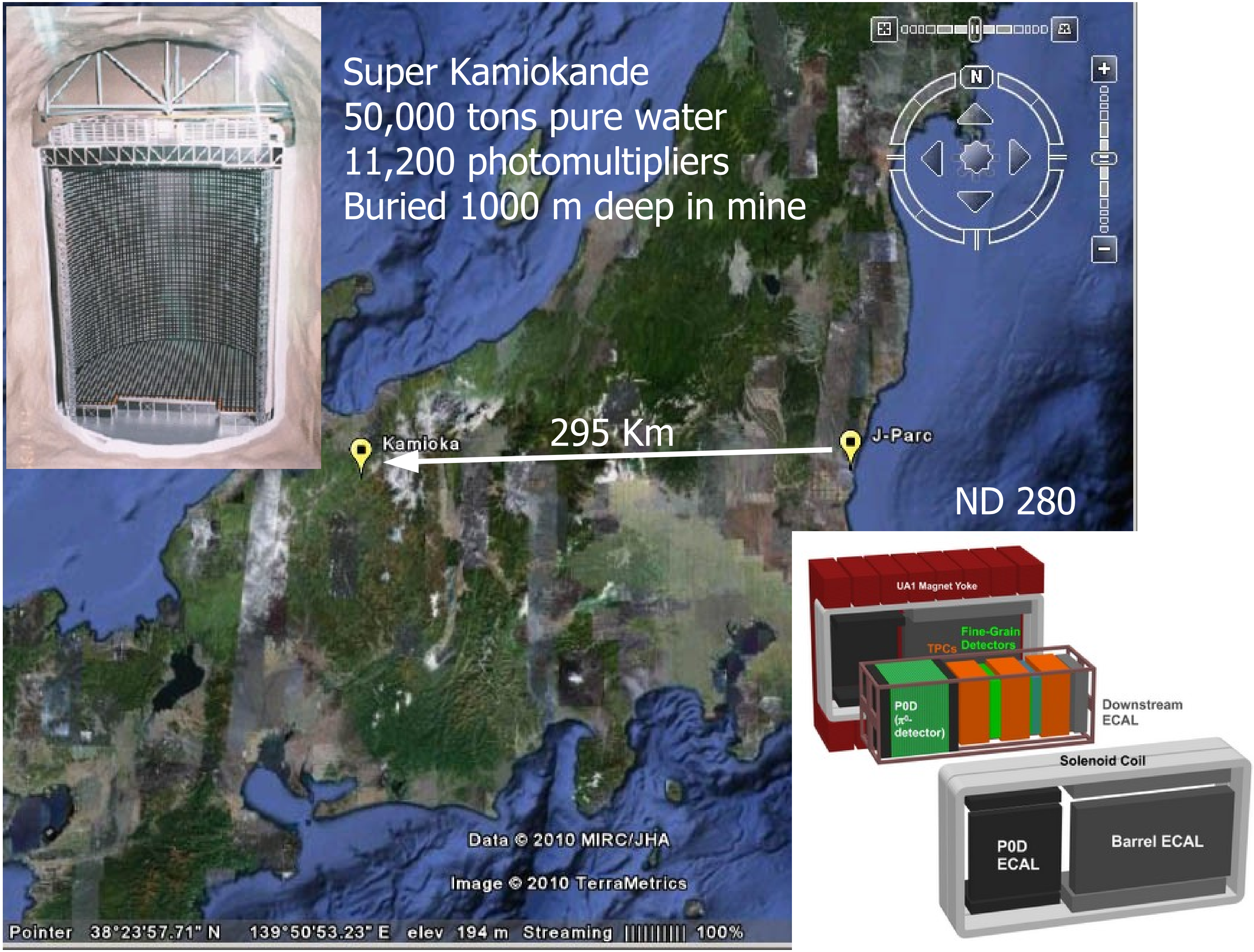
- measure neutrino oscillations
- sensitive to neutrino masses
- sensitive to neutrino matter/anti-matter asymmetry

Measure appearance rate of ν_e

295 Km

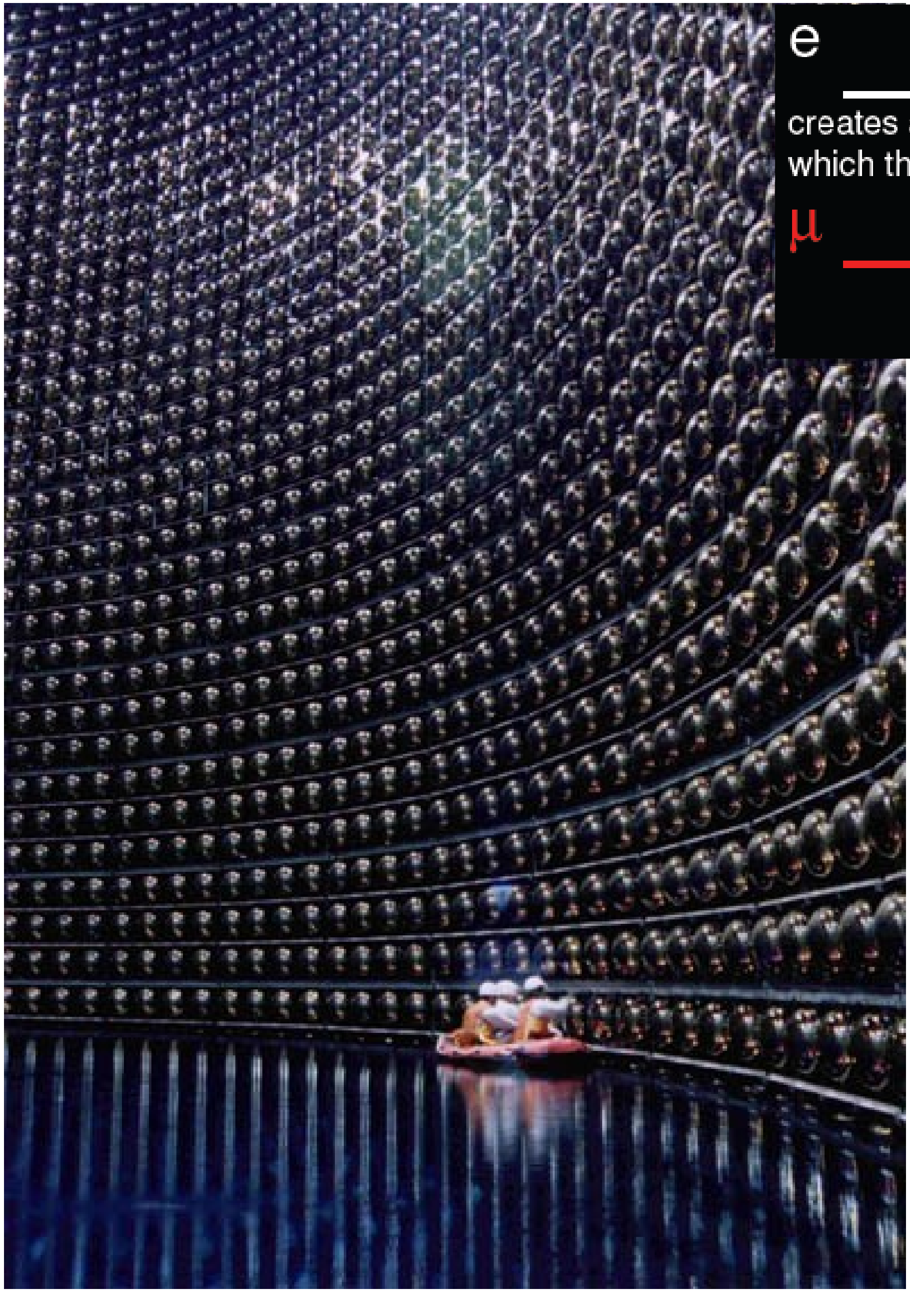
50 GeV proton beam
0.75 MW peak power
produce ν_μ beam

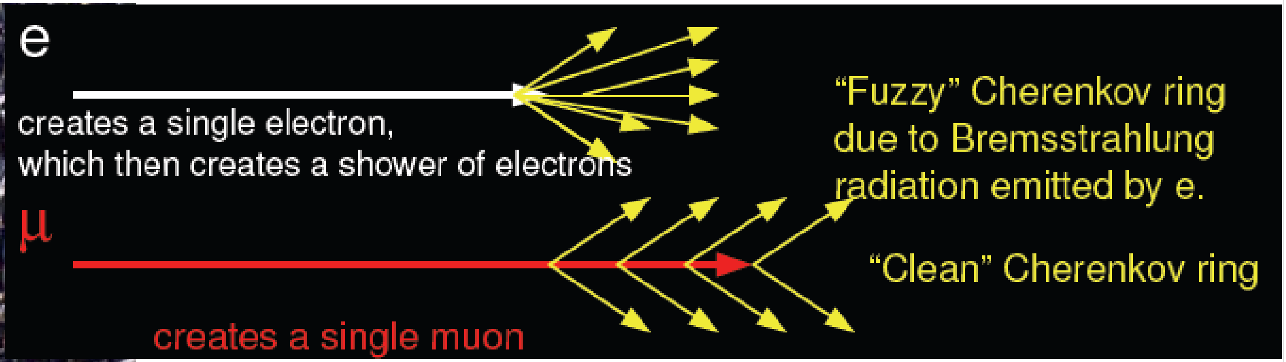
The T2K Experiment



Super Kamiokande
50,000 tons pure water
11,200 photomultipliers
Buried 1000 m deep in mine

The T2K Experiment




e

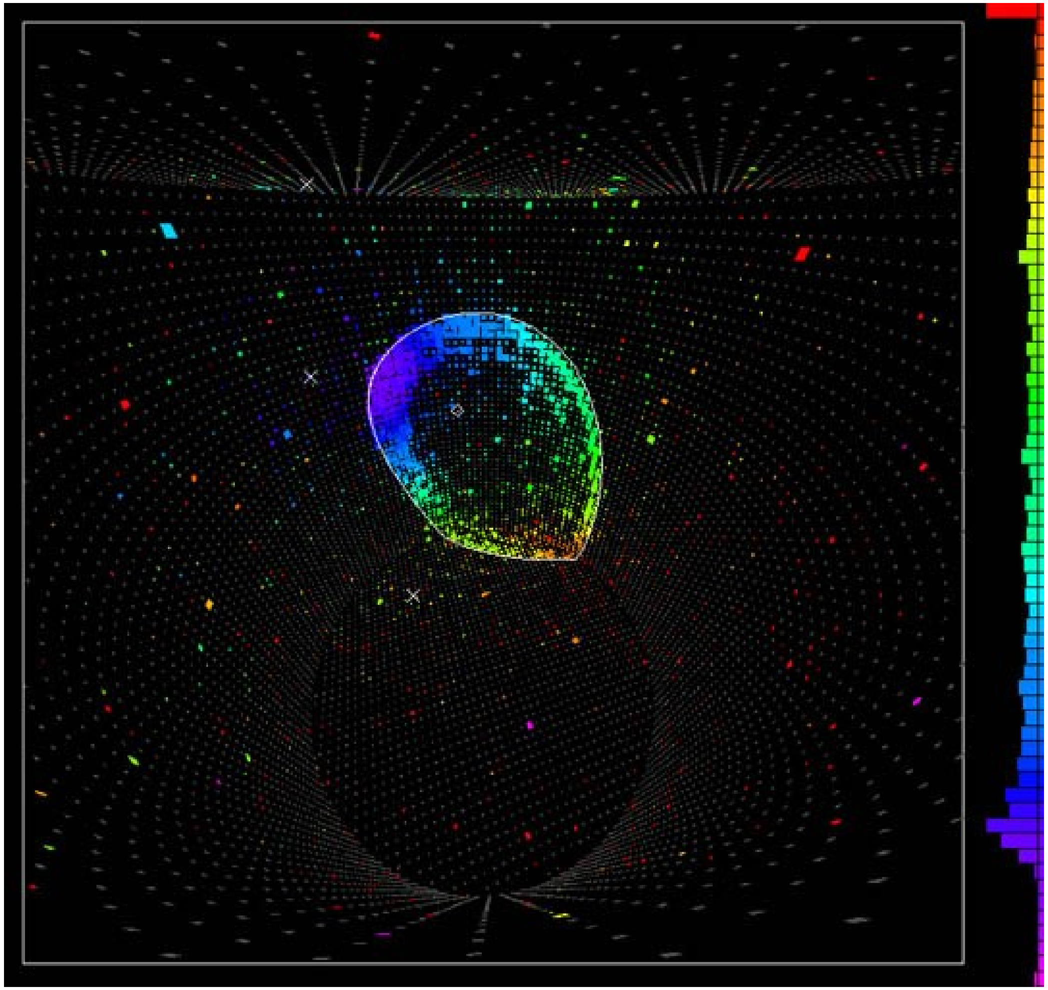
creates a single electron, which then creates a shower of electrons

"Fuzzy" Cherenkov ring due to Bremsstrahlung radiation emitted by e.

μ

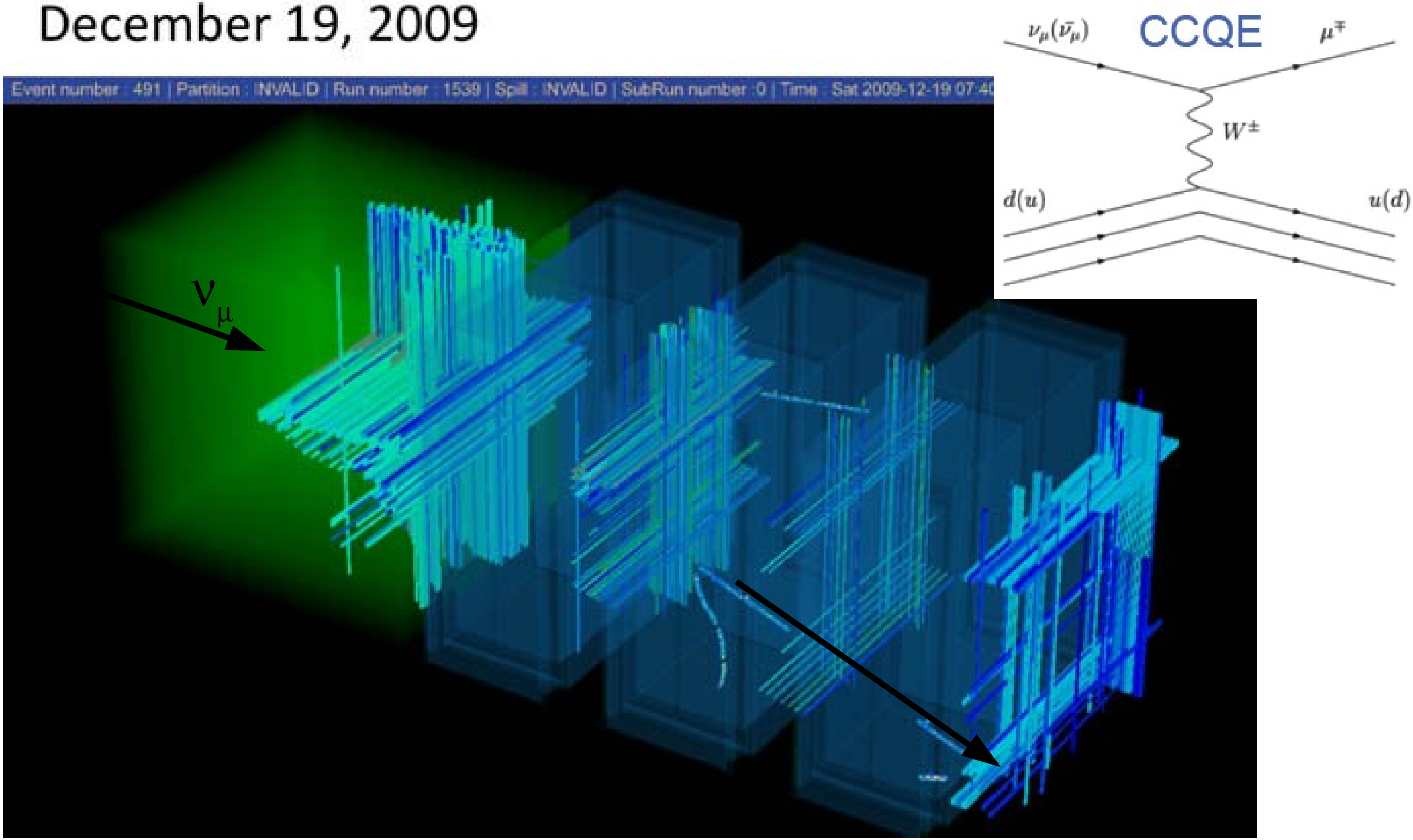
"Clean" Cherenkov ring

creates a single muon



First neutrino interaction in ND280 off axis detector

December 19, 2009



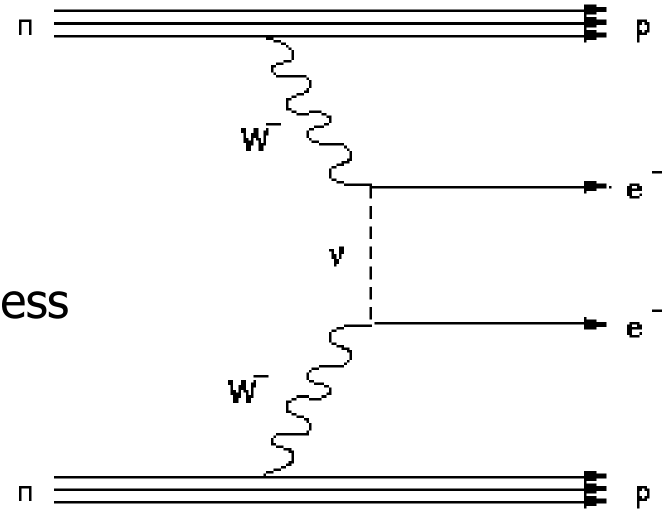
Follow us on twitter http://twitter.com/neutrinosQMUL

The SNO+ Experiment

Neutrino oscillations prove neutrinos have mass

Experiments (e.g. T2K) can only measure mass differences

Search for rare process sensitive to neutrino mass:



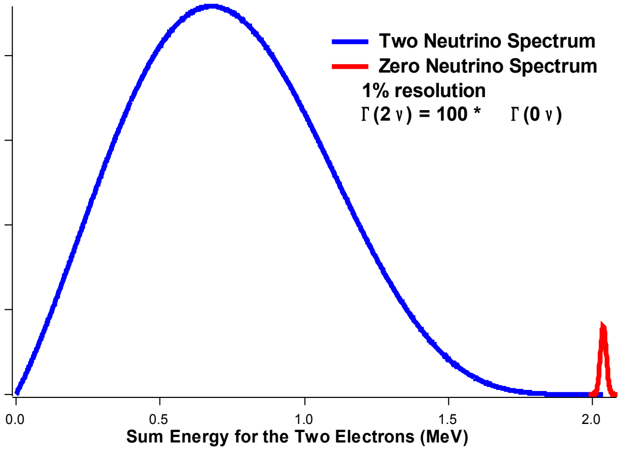
Neutrinoless Double Beta decay

2 neutrino double beta decay(2νββ) is a second order process allowed by the standard model

neutrinoless mode(0νββ) can only occur if neutrino is a Majorana particle that acts as its own antiparticle

Rate proportional to absolute neutrino mass

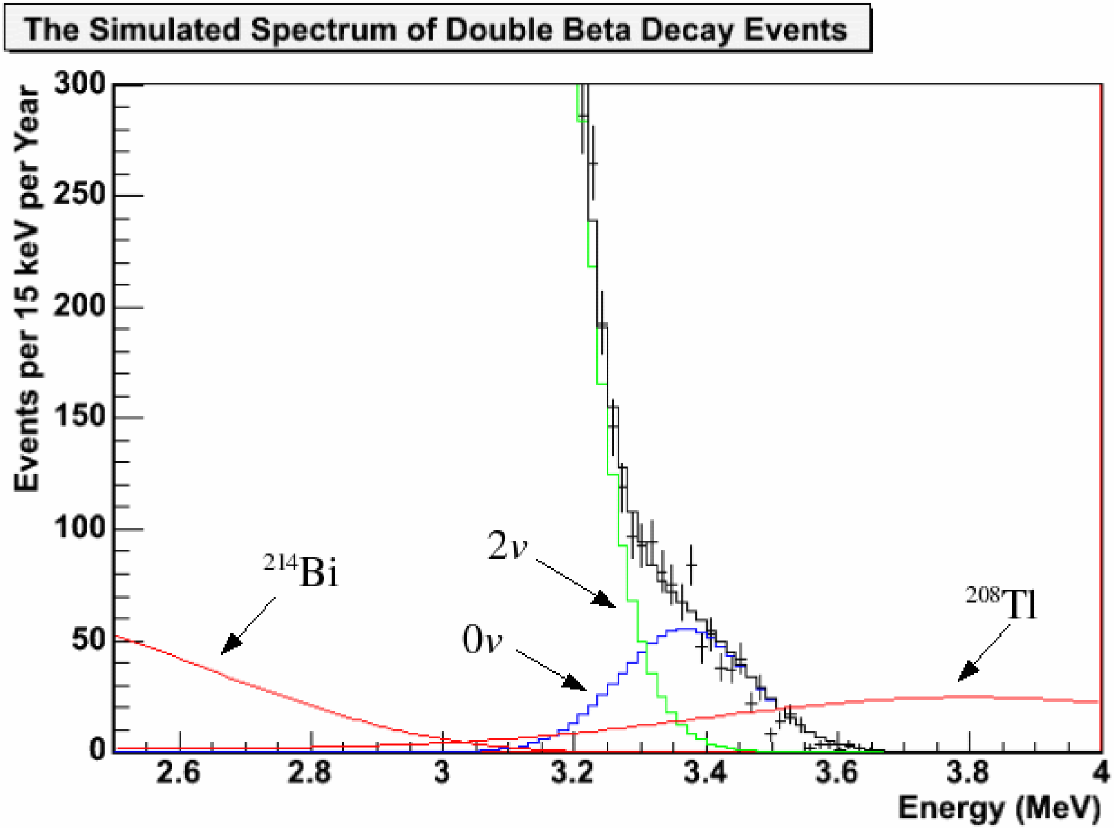
Look for a peak at the endpoint of the 2e$^-$ spectrum

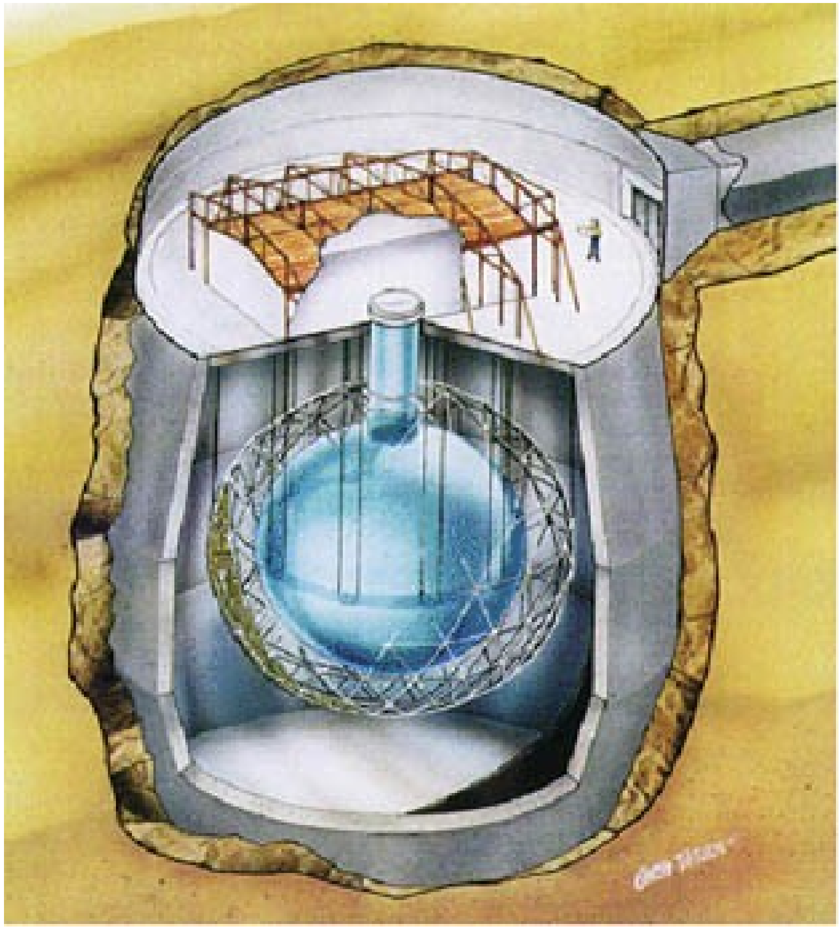


The SNO+ Experiment

~2km underground in a Canadian Nickel mine
12m diameter acrylic vessel with liquid scintillator
Scintillation events observed by ~9500 PMTs
7kilotonnes ultrapure H_2O as a shield

Search for 0νββ decay of ^{150}Nd dissolved in scintillator (endpoint 3.3MeV)

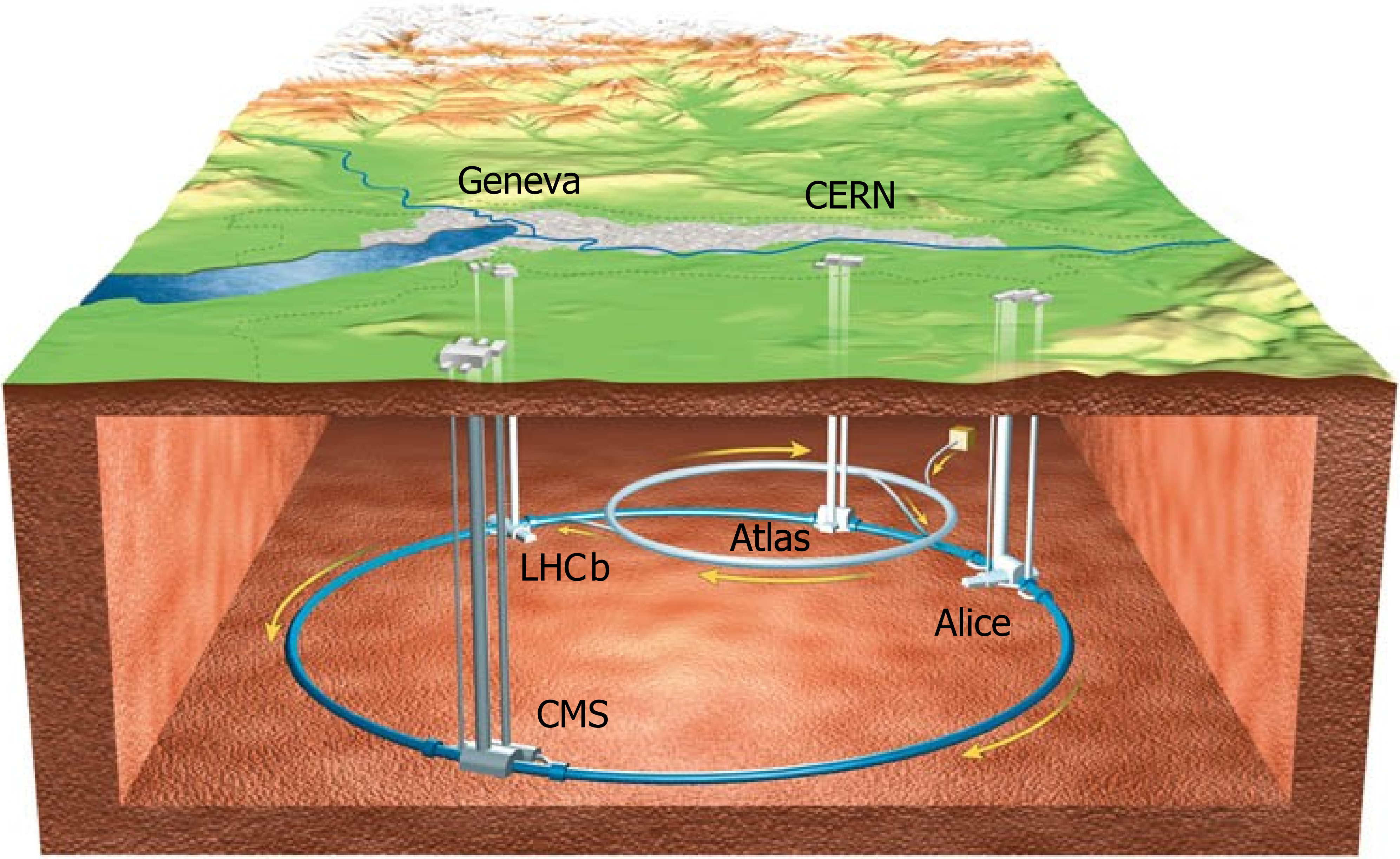




The Large Hadron Collider

Particle Physics is a global enterprise: experiments in all continents (incl. antarctica!)

The Large Hadron Collider



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!

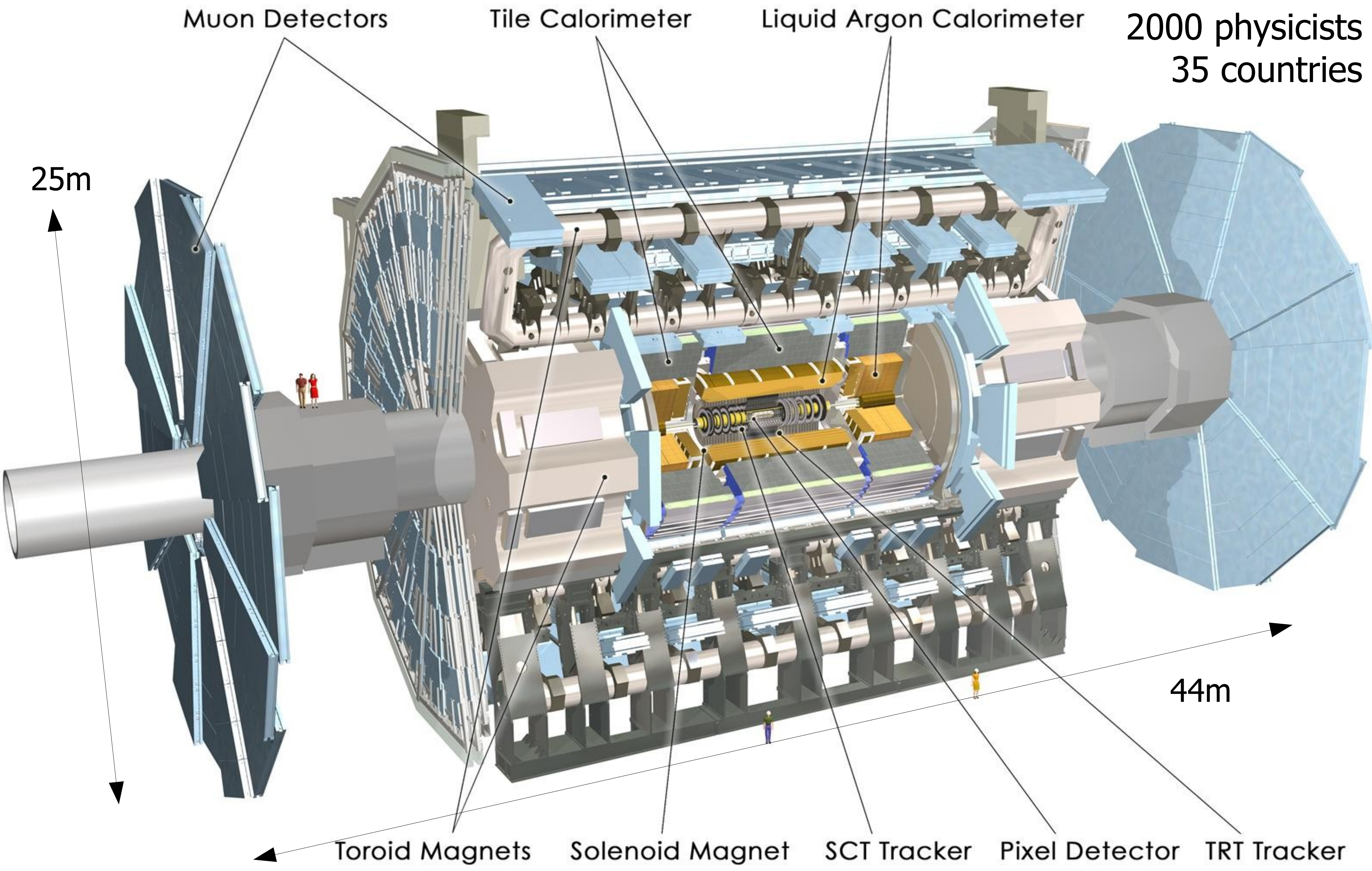
One of the largest scientific / technological projects ever undertaken

$> 100 \times 10^6$ electronic channels
$\sim 10^9$ proton-proton interactions per second
~ 1 Higgs $\rightarrow \gamma\gamma$ per hour

10×10^6 Gigabytes of data per year
(equivalent to ½ million HD movies per year)

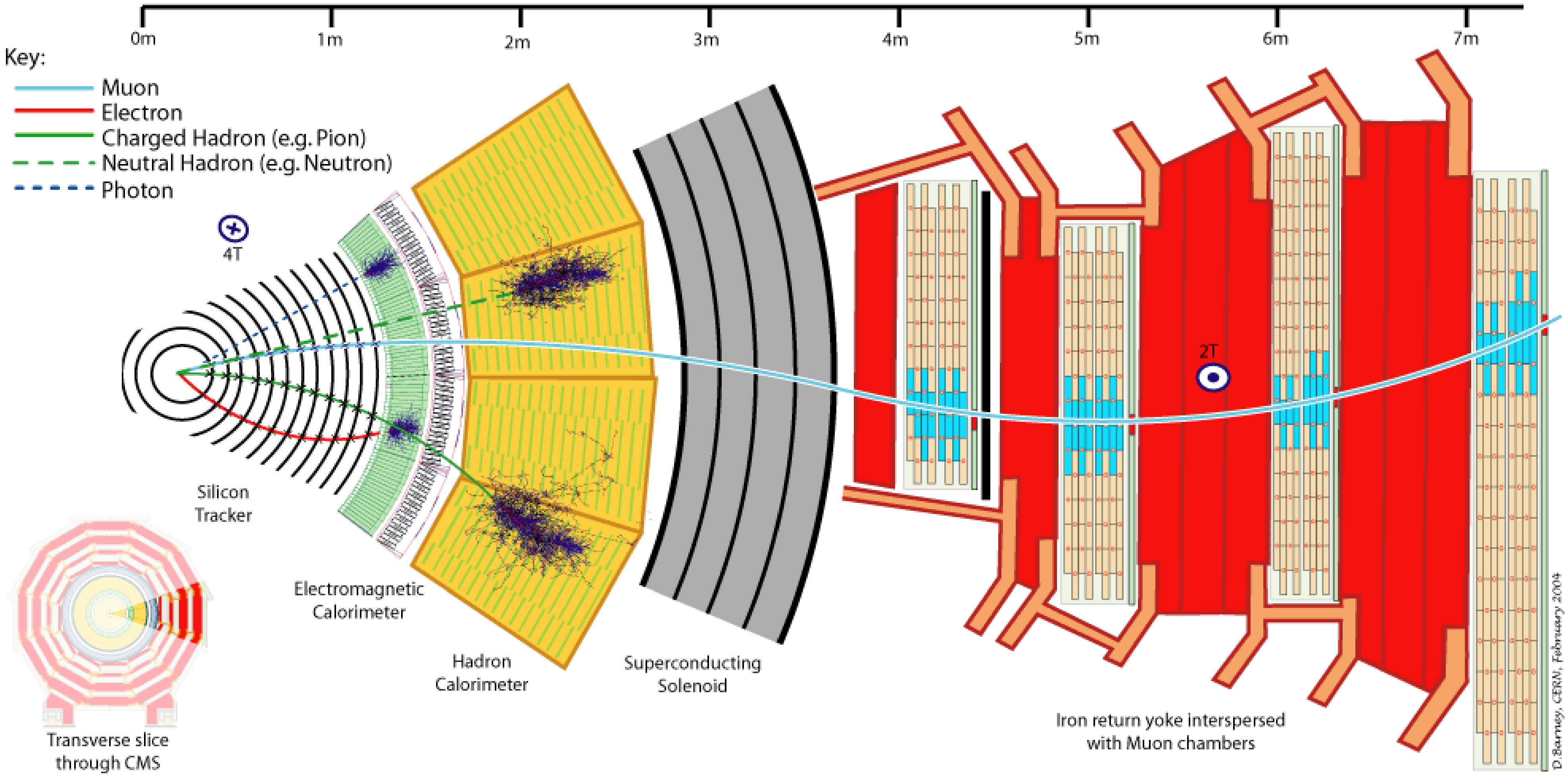

eGee
Enabling Grids
for E-sciencE
Scheduled = 6849
Running = 10359
09:26:06 UTC
GridPP
UK Computing for Particle Physics

The Atlas Experiment



2000 physicists
35 countries

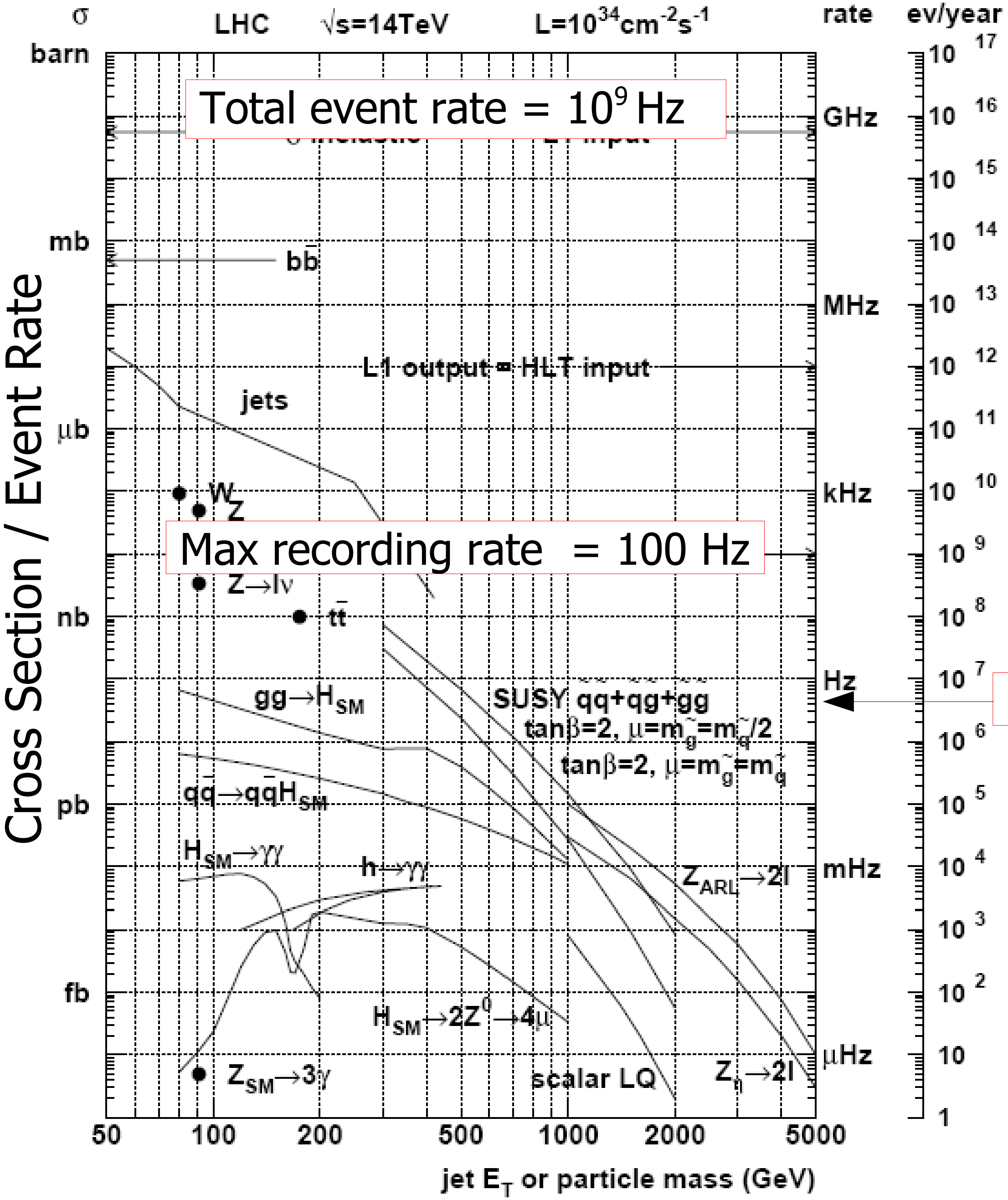
The CMS Experiment



3600 physicists
38 countries

The Large Hadron Collider

Cross Section / Event Rate



Total event rate = 10^9 Hz

Max recording rate = 100 Hz

Rate of 100 GeV Higgs production

Huge event rates

New physics swamped!

Need to filter events 1:10^7 online

Like trying to find a cheap plumber from entire human population in 2 μs

What are we looking for?

Higgs Boson

Almost all the visible mass of universe is due to massless QCD effects
Energy associated with quark and gluon interactions → proton & neutron mass

Higgs particle postulated to explain masses of fundamental particles

Gauge theory predicts force carrier particles to be massless e.g. photon & gluon
But $W^{\pm}$& Z^{0} boson have large masses ~80-90 GeV (proton~1 GeV)

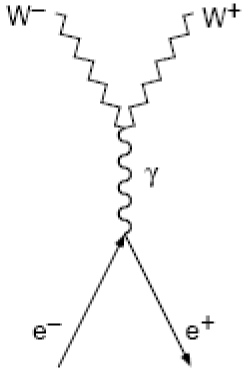
Higgs properties are well known except its mass!

Direct searches: m_H>114 GeV

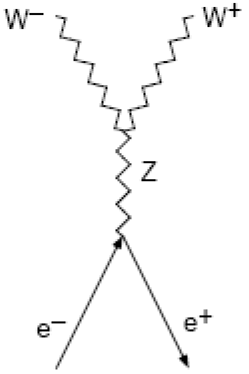
Higgs Boson

Examine energy dependence of scattering processes
Process (a) and (b) are well behaved as energy increases
Process (c) becomes larger than total e^+e^- cross section! (unitarity is violated)

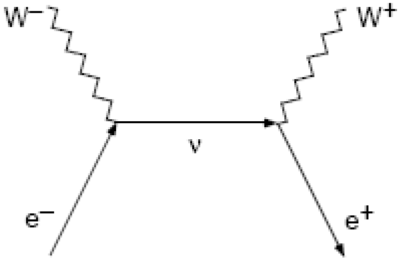
Higgs-like particle is <u>needed</u> to cancel $e^+e^- \rightarrow W^+W^-$ scattering divergences



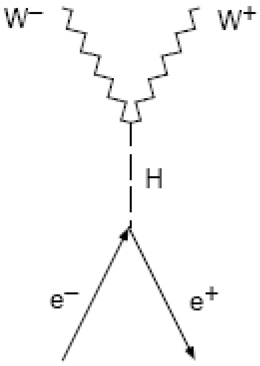
(a)



(b)



(c)



(d)

Requires Standard Model Higgs to be <~1TeV

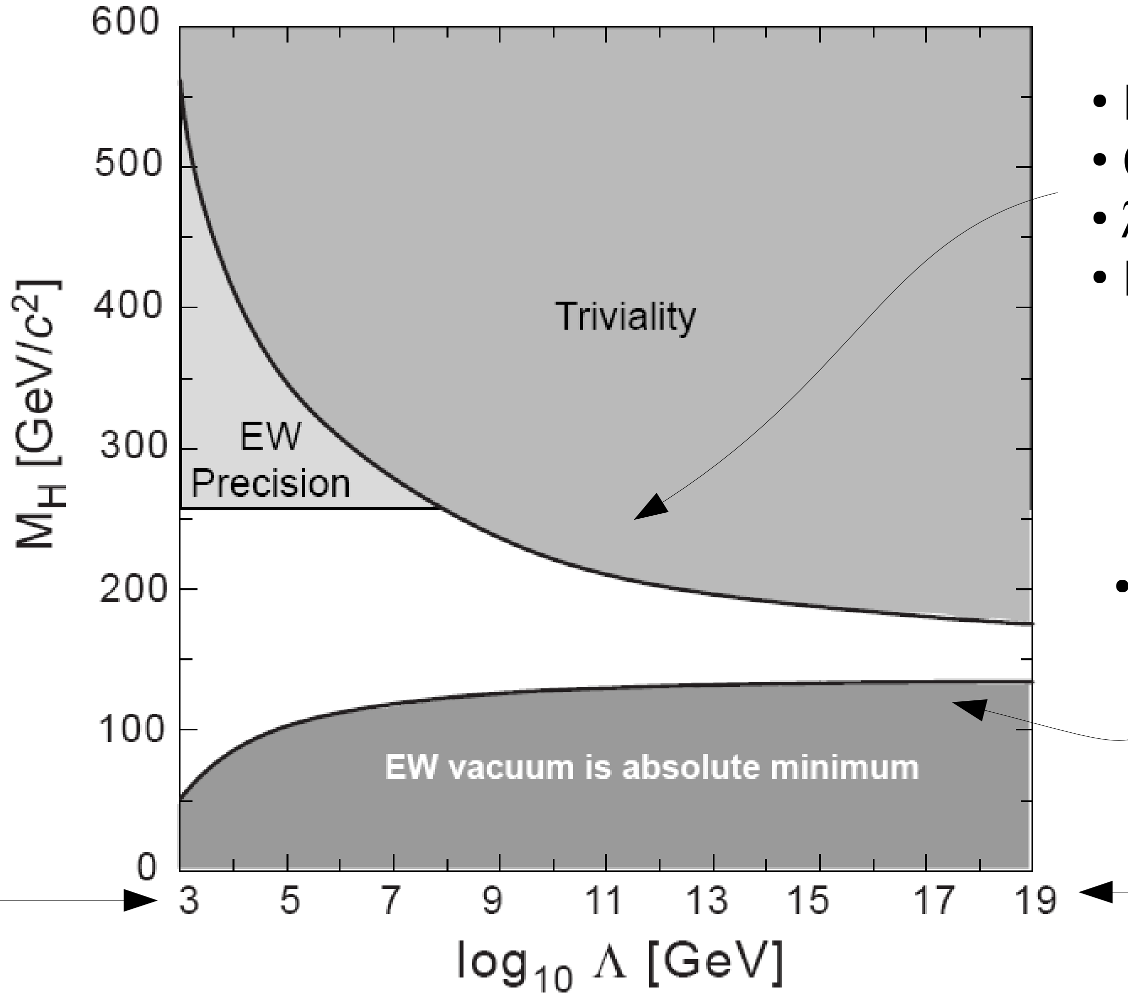
If Standard Model is correct we will find the Higgs at the LHC!

If Standard Model is wrong some new particle must do this job

win-win situation!

Higgs Boson

Even if Standard Model Higgs doesn't exist, a Higgs-like particle must!
Place bounds on mass of Higgs-like particle by requiring self consistency of theory



- Higgs self coupling = $\lambda(Q)$
- Q is energy at which you test
- $\lambda(Q)$ increases with Q
- Requiring $\lambda(Q)$ finite for $Q<\Lambda$ fixes upper limit on M_H

- Requiring $\lambda(Q) > 0$ for $Q<\Lambda$ fixes lower limit on M_H

1 TeV →

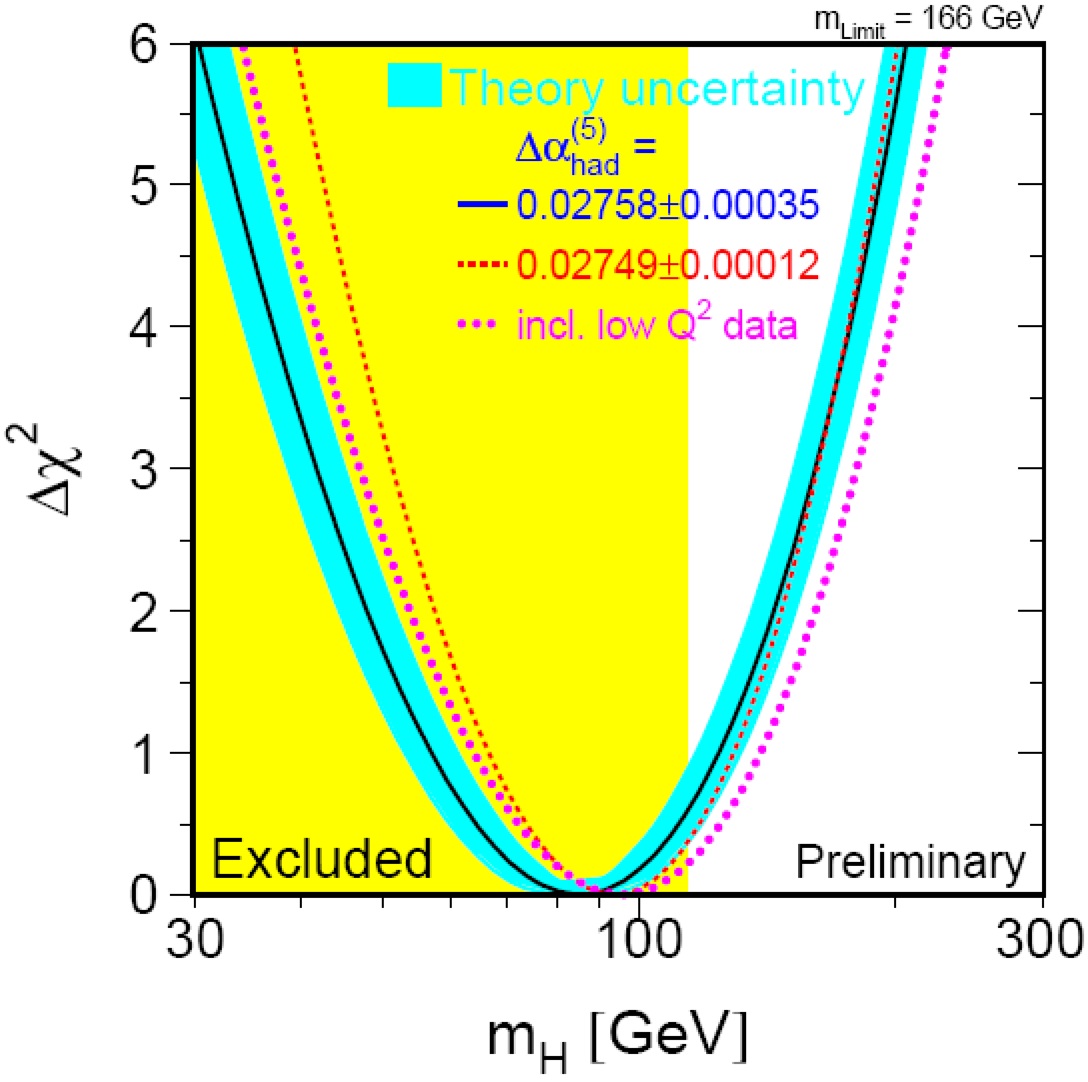
← 10^{19} GeV !!!

Energy scale at which new physics appears

Λ must be < 10^{19} GeV scale at which gravity effects become important

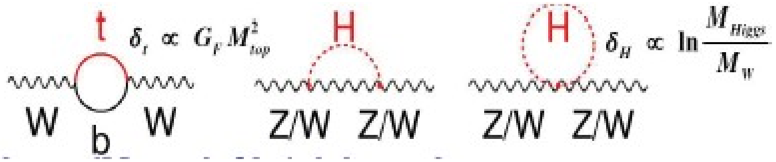
Higgs Boson

But we should have already seen it!



Precise measurements at low energy are sensitive to Higgs loops

Perturbations on a perturbation!



Measurements at E < m_H are

logarithmically sensitive to m_H

Confront data & theory: χ^2 test

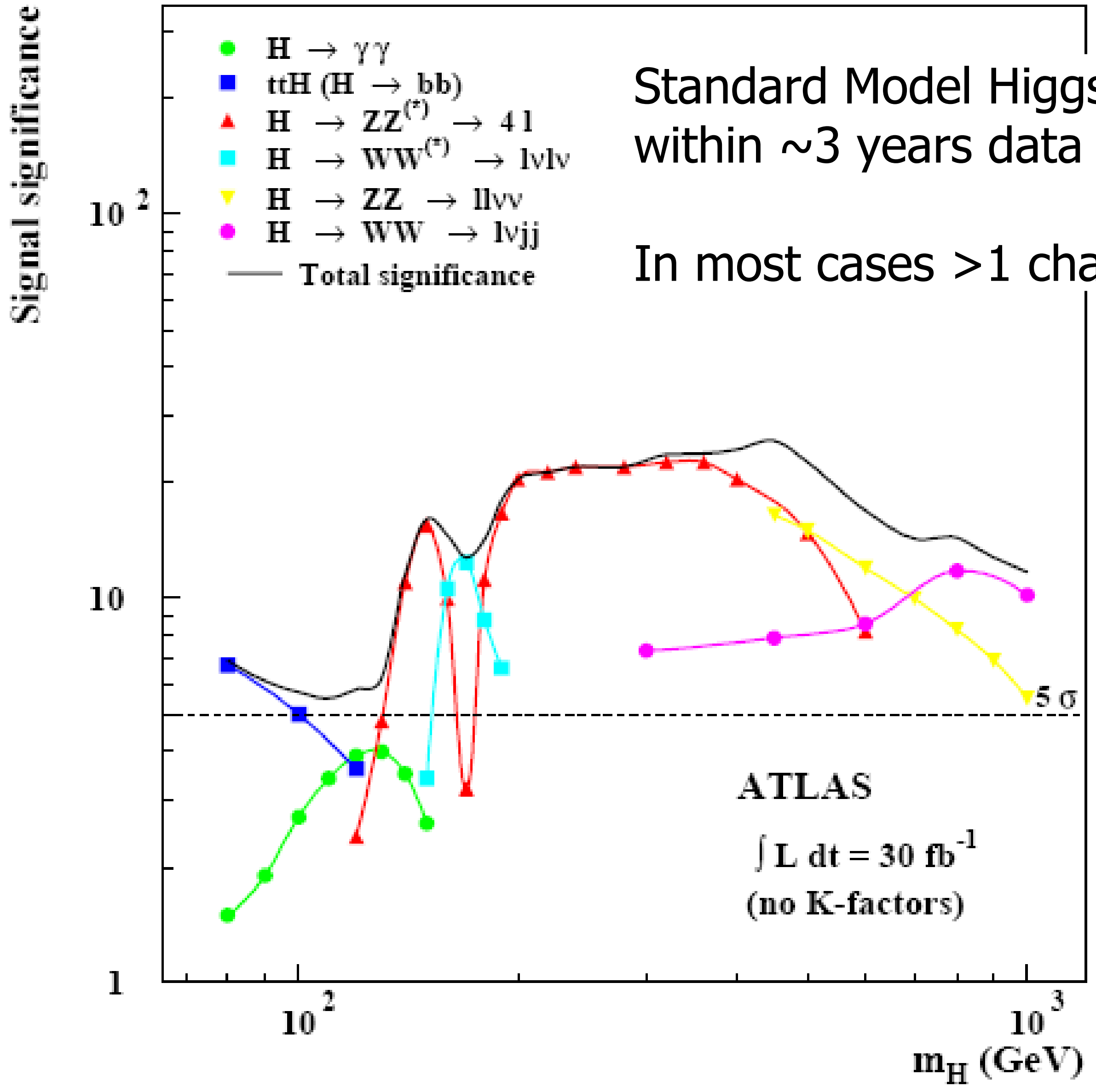
Indicates light Higgs !

68% prob of SM Higgs in range 85^{+39}_{-28} GeV

95% prob of SM Higgs < 166 GeV

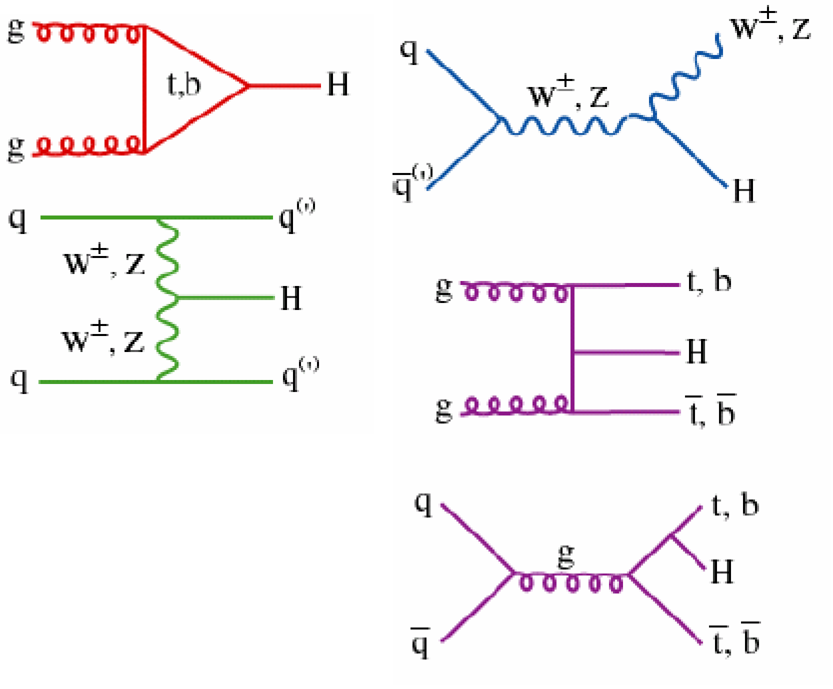
Higgs Boson

Likelihood of NOT being a statistical fluctuation vs Higgs mass



Standard Model Higgs discovered over full mass range within ~3 years data taking

In most cases >1 channel for discovery



Supersymmetry

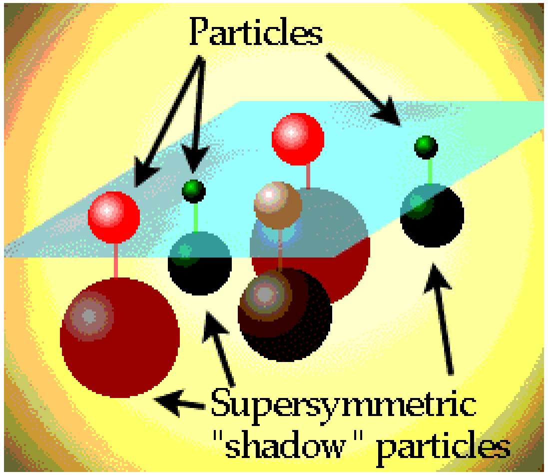
What are the alternatives to the Standard Model?

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??

Supersymmetry

- Naturally extends to quantum gravity
- Provides a candidate for dark matter
- SUSY solves hierarchy problem
- Brings about GUT unification of couplings
- Some general assumptions can reduce 105 parameters to 5

What are GUTs?

Grand unified theories: quantum gravity
Expect this to occur at energy scales when couplings reach strength of gravity
Construct a quantity with dimensions of energy or length from constants of relativity, quantum mechanics & gravity: c, ħ, G

$$E_{planck} = \sqrt{\frac{\hbar c}{G}} = 10^{19}\ \text{GeV} \qquad L_{planck} = \sqrt{\frac{G\hbar}{c^3}} = 10^{-35}\ \text{m}$$

Dark Matter Candidates

Astronomical observation show that ~25% of universe is dark matter
It should be cold (i.e. non-relativistic) and stable (does not decay)

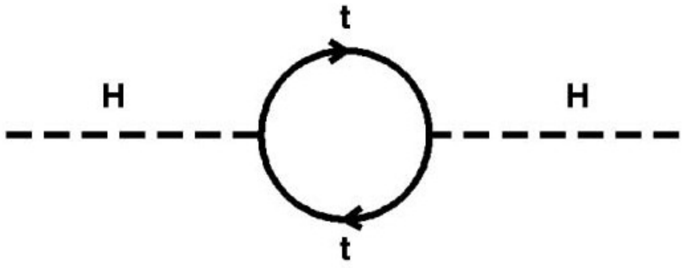
- Must be non-charged (or will interact with photons)
- Must be only weakly interacting
- Cannot be neutrons - free neutrons decay
- Cannot be neutrinos - mass too small

The lightest SUSY particle (LSP) is a prime dark matter candidate!

Supersymmetry

Hierarchy Problem

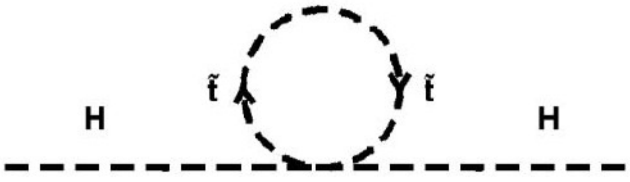
Why is Higgs mass (~1 TeV) so much smaller than the Planck scale (10^{19} GeV)?
Such calculations need to take account virtual fluctuations



Higgs interacts with all spin ½ particle-antiparticle pairs in the vacuum

Higgs mass quantum corrections are quadratically divergent upto 10^{19} GeV
If SM valid upto Planck scale then incredible fine-tuning of cancellations is needed to ensure ~1 TeV Higgs mass
<u>Seems</u> unnatural
Only a problem for the Higgs (only SM particle with spin 0)

New SUSY sparticles (e.g. stop squark) contribute and cancel identically

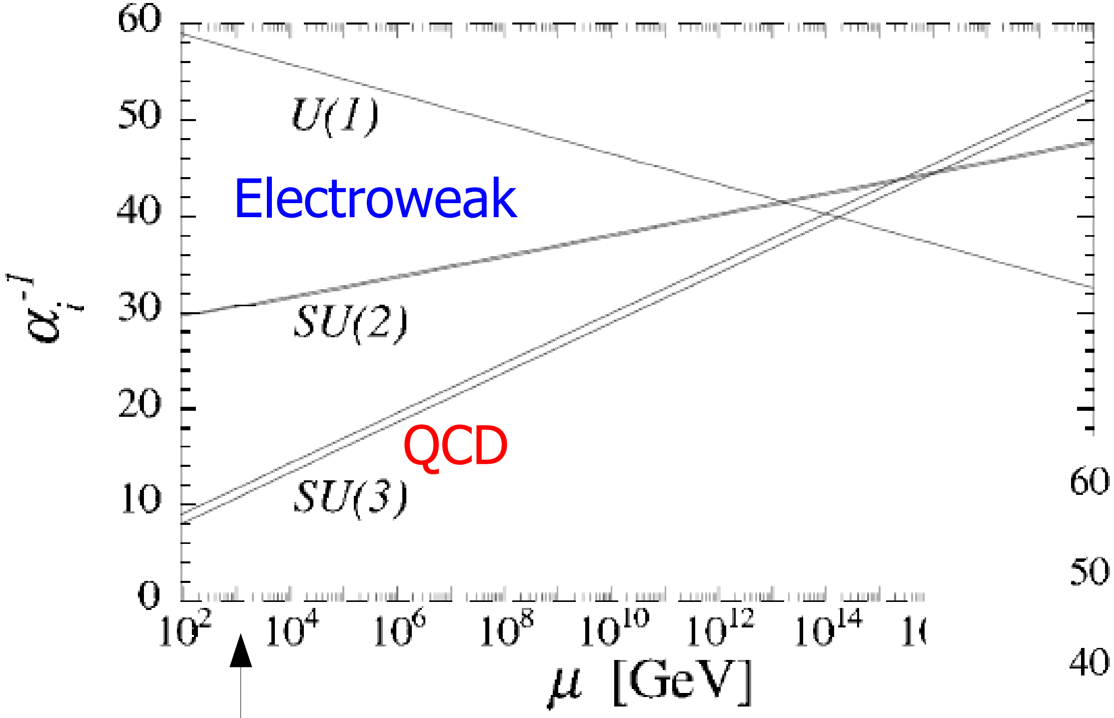


Higgs interaction with spin 0 sparticle cancels SM quantum corrections above

GUT Unification

Another of SUSYs charms:

Coupling constants extrapolated to Planck scale do not intersect

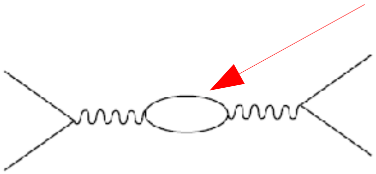


Electroweak

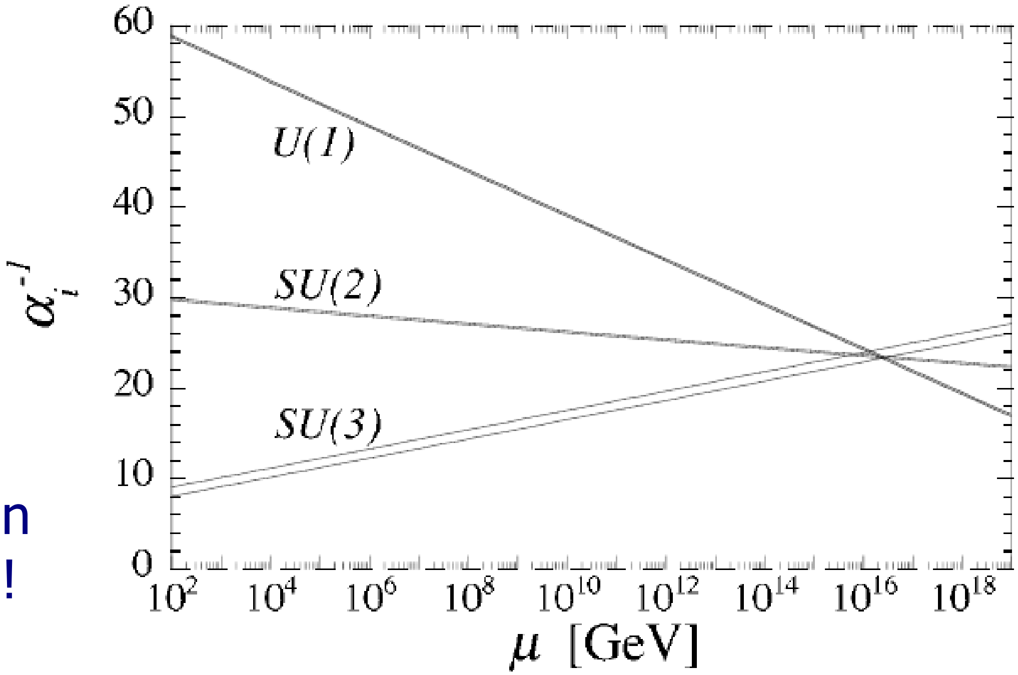
QCD

Current measurements

16 orders of magnitude extrapolation!
Involves including all particle loops



New SUSY particles = different loops
= different extrapolation



Incorporating SUSY into extrapolation
brings unification below Planck scale!

Supersymmetry

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

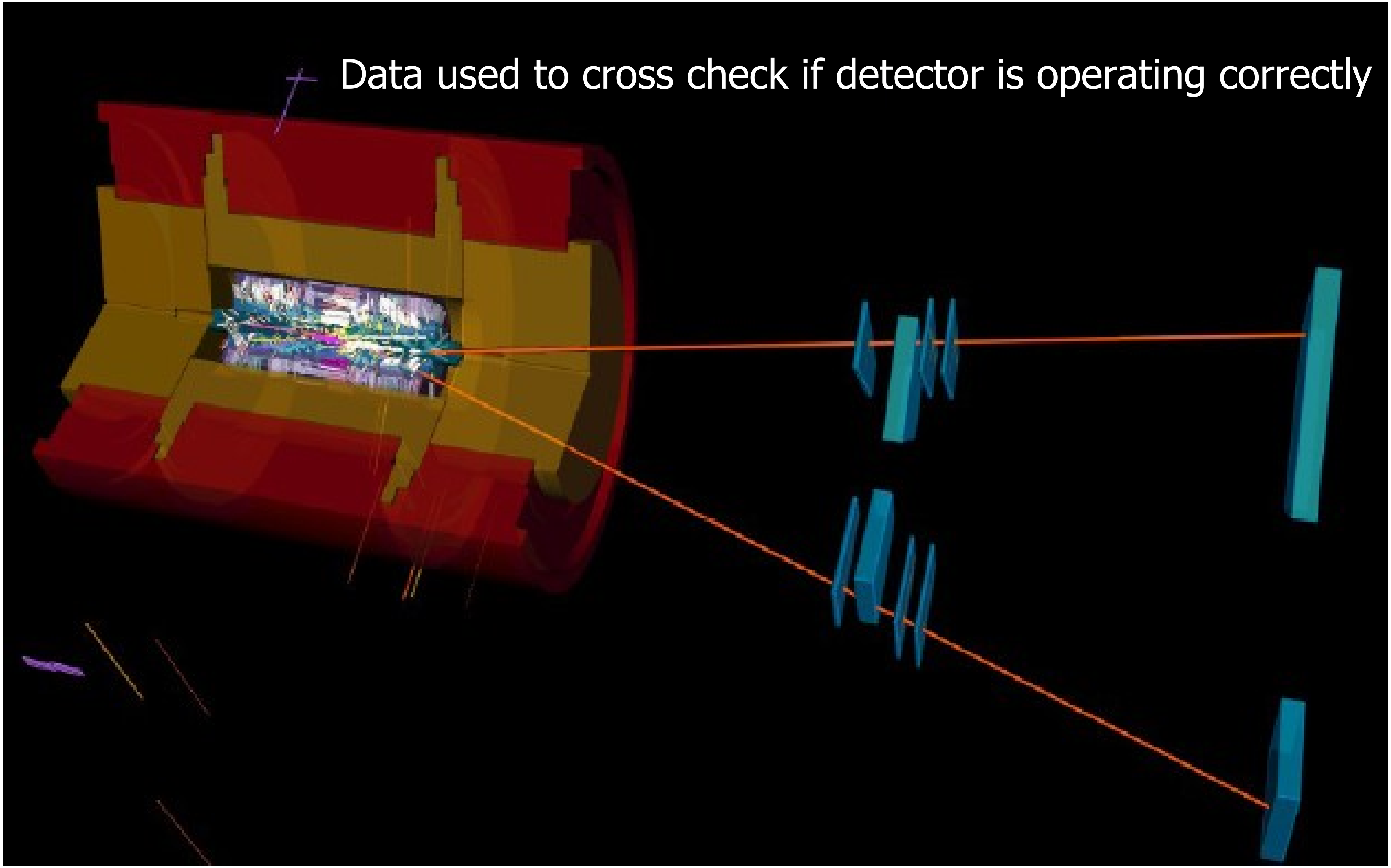
$$T \approx \frac{(n+1)}{4\pi R}$$

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

LHC Turns On

LHC Starts Collisions!

Atlas Experiment sees collision data



Data used to cross check if detector is operating correctly

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

Summary

We're living in exciting times

T2K may discover reasons for matter/anti-matter asymmetry in universe

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!

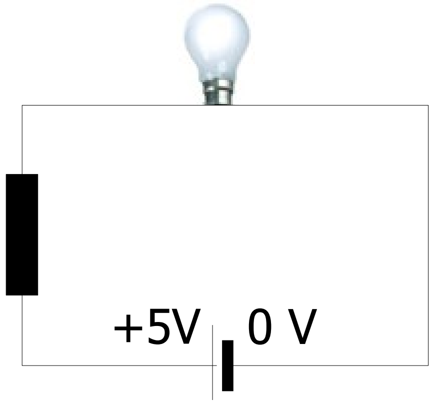
The LHC started operation November 2009

Data taking will start in earnest Feb 2010

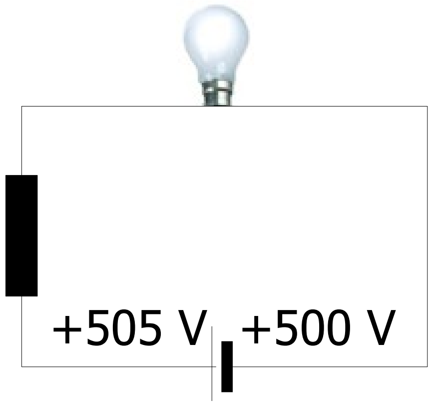
T2K commenced operation in Japan

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

Gauge Theories

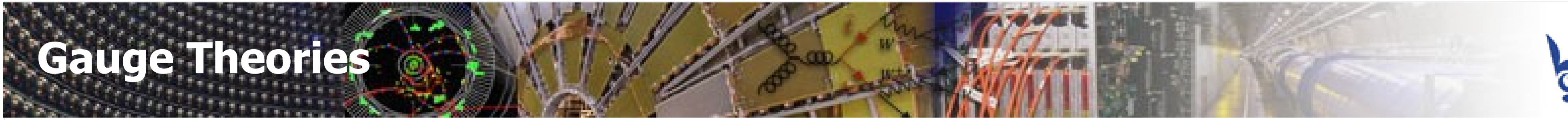


A gauge transformation is one in which a symmetry transformation leaves the physics unchanged



Both circuits behave identically
Circuit is only sensitive to potential differences
Change the ground potential of the earth and see no difference!
Leads to concept of charge conservation

In electromagnetism we are insensitive to phase α of EM radiation
Could globally change the phase at all points in universe: no difference
global gauge transformation
What happens if we demand local phase transformations? $\alpha \rightarrow \alpha(x,t)$



Gauge Theories

If we demand local phase invariance AND consistent physics then we must alter Maxwell's equations

The alterations required to accommodate these changes introduce a new field - interaction of charged particle with an EM field - the photon!

This can be applied to many situations:

local gauge invariance introduces new fields & particles:

Electromagnetism	photon
Quantum chromodynamics	gluons
Weak force	$W^{\pm}$ and Z^0

Intimately related to symmetries and conservation laws