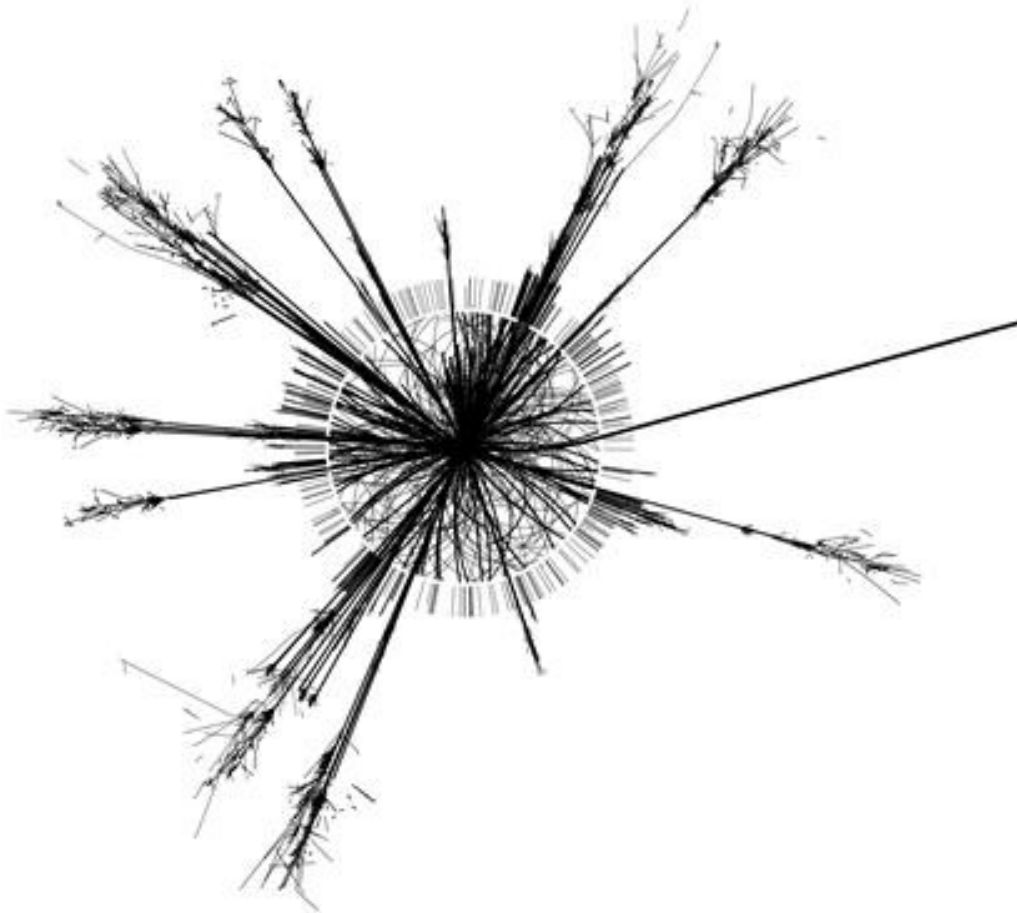


# From Atoms to Extra Dimensions



The Standard Model of Particle Physics

The Problematic Standard Model

New Experiments and the LHC

The Higgs Boson

Beyond the Standard Model

Eram Rizvi



Over 100 years of discovery and experimentation

Discovery of electron - Thompson 1897

Birth of quantum physics - Planck 1900

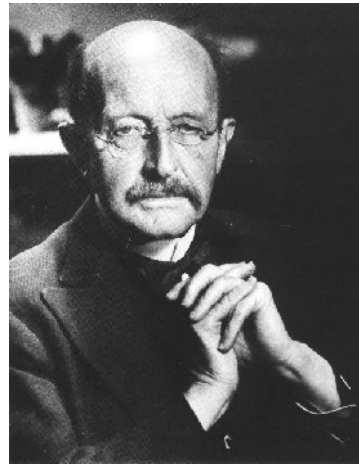
Relativity - Einstein 1905

Atomic structure - Rutherford 1911

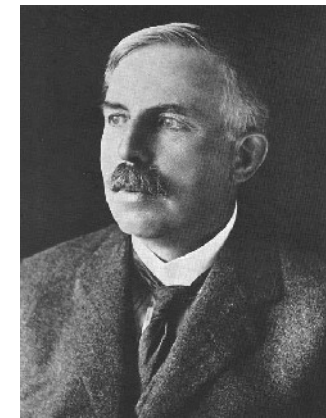
...and much more!



Thompson

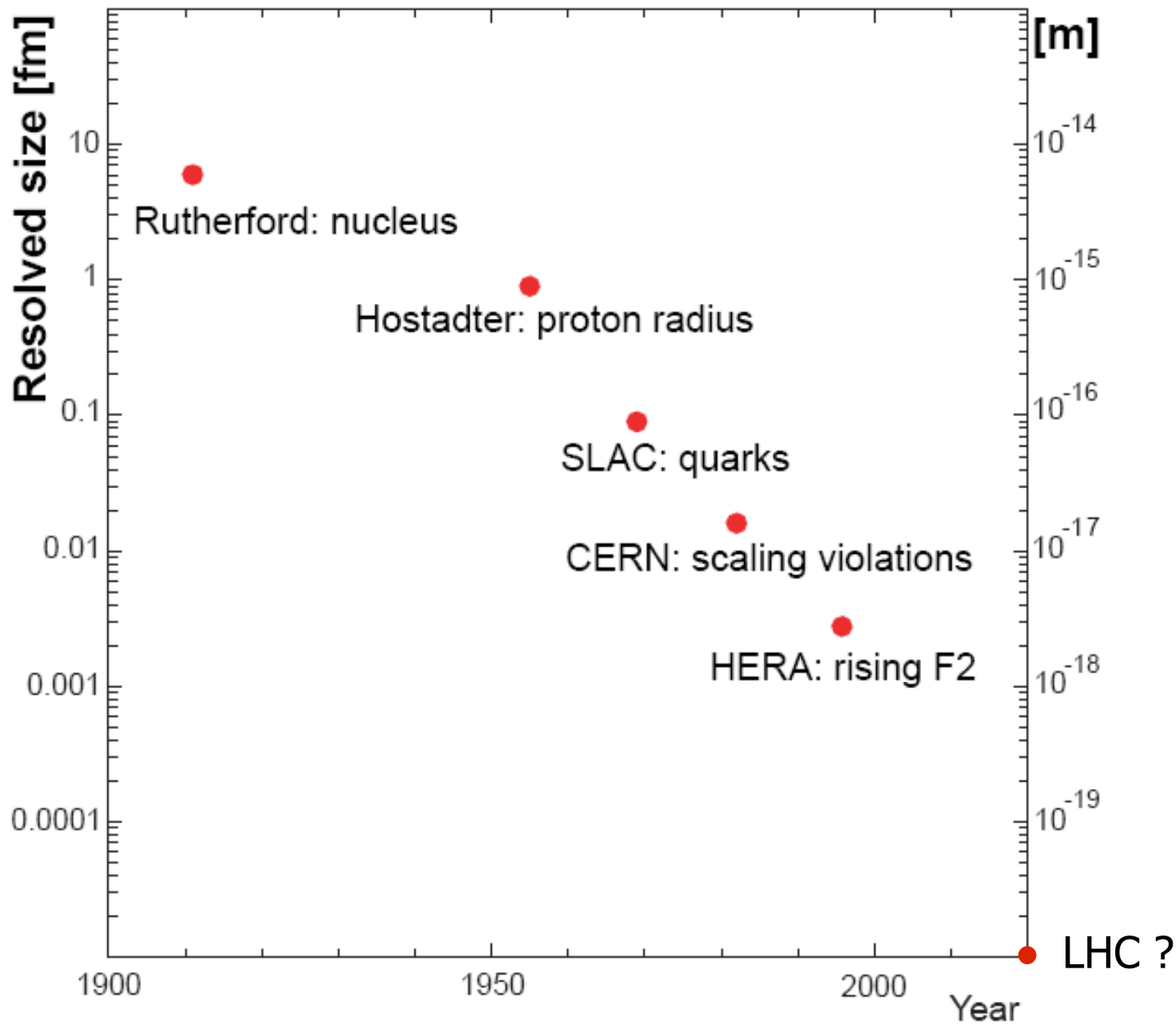


Planck



Rutherford













... what have we learnt ?



# The Standard Model

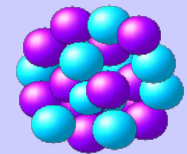


Worlds most successful theory to date - Describes fundamental constituents of matter

						quarks: strong, weak, electromagnetic
						charged leptons: weak, electromagnetic
						neutrinos: weak

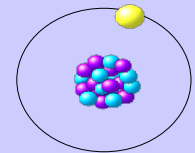
gluons 

Strong: holds atomic nucleus together



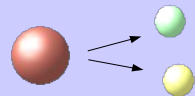
photons 

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

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

$$\text{Potential} = V + V'$$

$V$  gives rise to stationary stable, time independent states

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

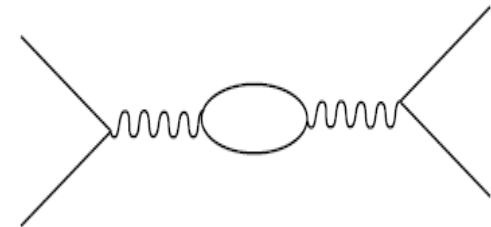
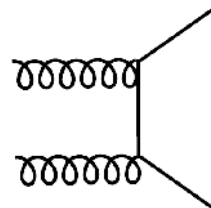
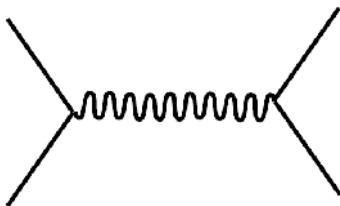
$$\sigma = \frac{2\pi}{\hbar} |V'_{fi}|^2 \rho(E_f)$$

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

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

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

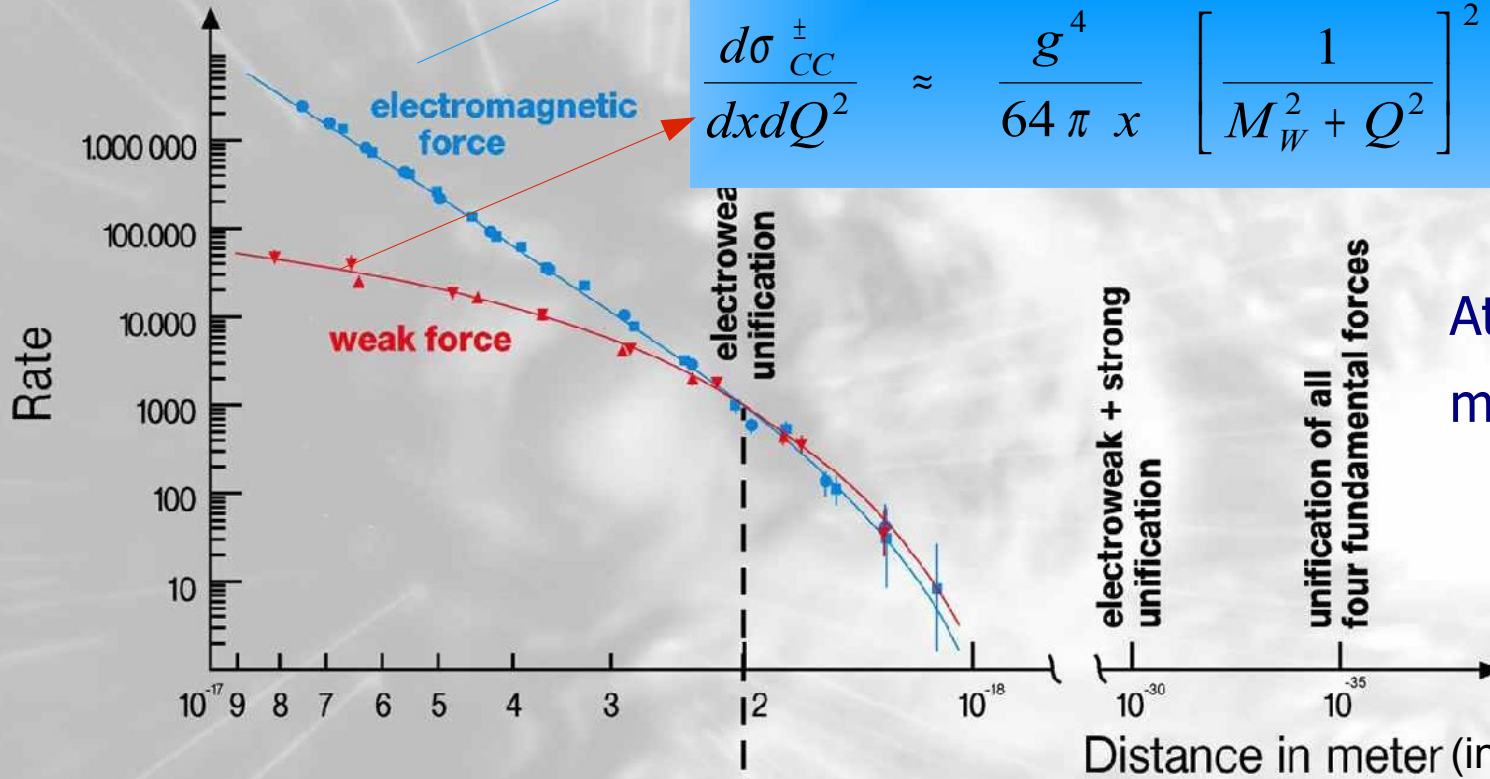
Series expansion in powers of couplings  $\alpha$  between particles for each force



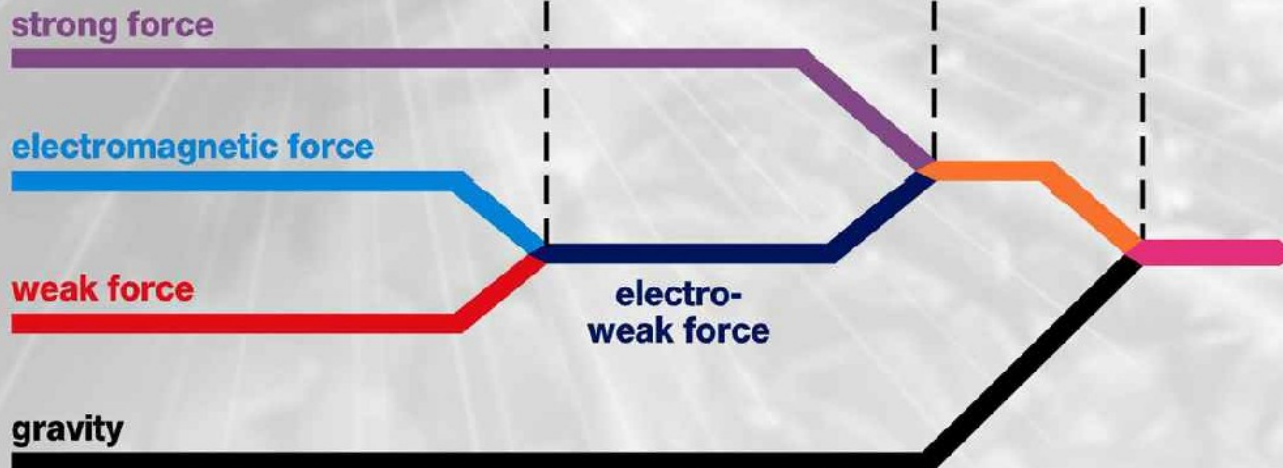
# Electro-Weak Unification

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

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



At high energy:  
masses are small  
→ forces are equal



Aim to unify all forces



Quantum mechanics predicts the gyromagnetic ratio of the electron  $(g-2)/2=0$   
(ratio of magnetic dipole moment to it's spin)

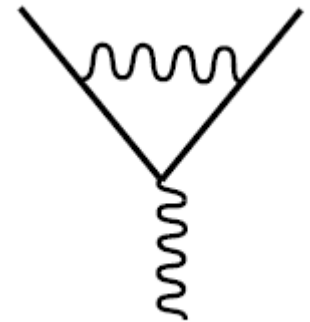
Experiment measures  $0.001159652140 \pm 0.00000000000028$

Non-zero due to quantum corrections

Electron emits and reabsorbs additional photons

$$\frac{g_{theory} - 2}{2} = 0.001159652140(28)$$

$$\frac{g_{exp} - 2}{2} = 0.001159652187(4)$$



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 precision

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 complete Standard Model Lagrangian

$$\begin{aligned}
 & -\frac{1}{2}\partial_\mu g_\alpha^a \partial_\nu g_\alpha^a - g_\alpha f^{abc} \partial_\mu g_\alpha^b \partial_\nu g_\alpha^c - \frac{1}{2}g_\alpha^2 f^{abc} f^{ade} g_\alpha^b g_\alpha^c g_\alpha^d g_\alpha^e + \\
 & \frac{1}{2}ig_\alpha^2 (g_\alpha^i \gamma^\mu g_\alpha^j) g_\alpha^k + G^a \partial^\mu G^a + g_\alpha f^{abc} \partial_\mu G^a G^b g_\alpha^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_W^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
 & \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_W^2} M \phi^0 \phi^0 - \partial_\mu [\frac{2M^2}{g^2} + \\
 & \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - ig_{C_{\alpha h}} [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\mu^0 (W_\nu^+ W_\mu^- - W_\mu^- \partial_\nu W_\nu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+) - ig_{S_{\alpha h}} [\partial_\nu \\
 & W_\nu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \epsilon \\
 & \frac{1}{2}g^2 W_\nu^+ W_\nu^- W_\nu^+ W_\nu^- \\
 & g^2 s_W^2 (A_\mu W_\nu^+ A_\nu W_\nu^- - \\
 & W_\nu^+ W_\nu^-) - 2A_\mu Z_\mu^0 \\
 & g M W_\nu^+ W_\nu^- H - \frac{1}{2}g_\alpha^2 \\
 & W_\nu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] \\
 & \phi^+ \partial_\mu H] + \frac{1}{2}g \frac{1}{c_W} (Z_\mu^0 (H \epsilon \\
 & ig_{S_{\alpha h}} M A_\mu (W_\nu^+ \phi^- - 1 \\
 & ig_{S_{\alpha h}} A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \\
 & \frac{1}{2}g^2 \frac{1}{c_W} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_W^2}{c_W} Z_\mu^0 F \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_W A_\mu H (1 \\
 & g^1 s_W^2 A_\mu A_\mu \phi^+ \phi^- - \epsilon^\lambda (\gamma \epsilon \\
 & m_h^2) d_J^\lambda + ig_{S_{\alpha h}} A_\mu [- (\epsilon^\lambda \gamma_\nu \\
 & \gamma^5) \nu^\lambda] + (\epsilon^\lambda \gamma^\mu (4s_W^2 \\
 & (d_J^\lambda \gamma^\mu (1 - \frac{2}{3}s_W^2 - \gamma^5) d \\
 & \gamma^5) C_{\lambda h} d_J^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^- [ \\
 & \frac{ig}{2\sqrt{2}} \frac{m_h^2}{M} [-\phi^+ (\partial^\lambda (1 - \gamma^5) \\
 & i\phi^0 (\epsilon^\lambda \gamma^5 \epsilon^\lambda)] + \frac{ig}{2M\sqrt{2}} d \\
 & \gamma^5) d_J^\lambda] + \frac{ig}{2M\sqrt{2}} \phi^- [m_h^2 ( \\
 & ig_{C_{\alpha h}} W_\mu^+ (\partial_\mu X^0 X^- - \partial_\mu X^+ X^0) + ig_{S_{\alpha h}} W_\mu^+ (\partial_\mu Y X^- - \partial_\mu X^+ Y) + \\
 & ig_{C_{\alpha h}} W_\mu^- (\partial_\mu X^- X^0 - \partial_\mu X^0 X^+) + ig_{S_{\alpha h}} W_\mu^- (\partial_\mu X^- Y - \partial_\mu Y X^+) + \\
 & ig_{C_{\alpha h}} Z_\mu^0 (\partial_\mu X^+ X^- - \partial_\mu X^- X^0) + ig_{S_{\alpha h}} A_\mu (\partial_\mu X^+ X^- - \partial_\mu X^- X^0) - \\
 & \frac{1}{2}g M [X^+ X^+ H + X^- X^- H + \frac{1}{c_W} X^0 X^0 H] + \frac{1-2c_W^2}{2c_W} ig M [X^+ X^0 \phi^+ - \\
 & X^- X^0 \phi^-] + \frac{1}{2c_W} ig M [X^0 X^- \phi^+ - X^0 X^+ \phi^-] + ig M s_W [X^0 X^- \phi^+ - \\
 & X^0 X^+ \phi^-] + \frac{1}{2}ig M [X^+ X^+ \phi^0 - X^- X^- \phi^0]
 \end{aligned}$$





## 22 Parameters of the SM to be measured

6 quark masses

3 charged leptons masses (better than 105 params of generic SUSY)

3 coupling constants

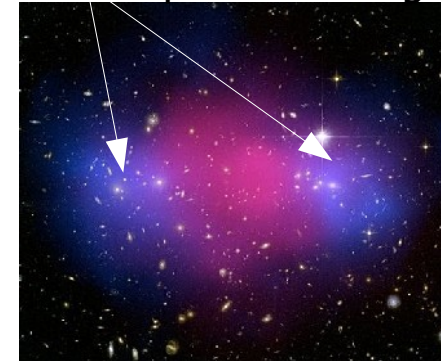
4 quark mixing parameters

4 neutrino mixing parameters

1 weak boson mass (1 predicted from other EW params)

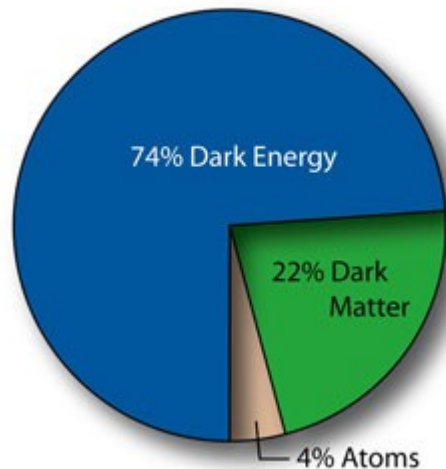
1 Higgs mass

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



Why is gravity  $\sim 10^{33}$  weaker than EW interactions?

Why is Higgs mass (100-1000 GeV) so much smaller than Planck energy ( $10^{19}$  GeV)?

combine constants of relativity  
quantum mechanics & gravity  
to give something with units of energy

$$E_{\text{planck}} = \sqrt{\frac{\hbar c}{G}} = 10^{19} \text{ GeV}$$

This is the energy where we think all three theories are relevant  
Far beyond any collider we could dream to build!

Large value of  $E_{\text{Planck}}$  leads to fine tuning problem:

quantum corrections to Higgs mass grow quadratically upto  $10^{19}$  GeV

physical Higgs mass = bare mass + "quantum corrections"  $m_H^2 = m_0^2 + \Delta m_H^2$

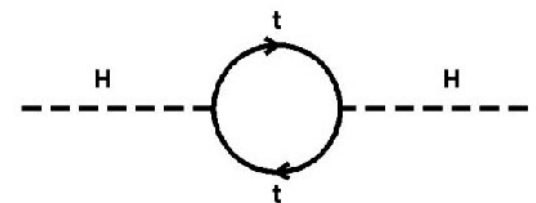
quantum corrections arise due to Higgs momentarily existing as another particle/anti-particle pair (consistent with Heisenberg Uncertainty Principle)

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

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

If SM valid upto  $E_{\text{Planck}}$  (i.e. no new physics from 1000 GeV -  $10^{19}$  GeV)

then **incredible** fine tuning required between bare mass and the corrections to maintain  $\sim 100$  GeV Higgs mass



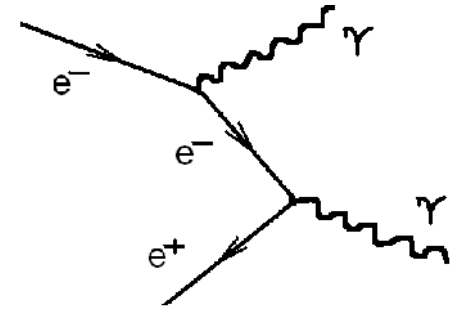


Standard Model is lacking:

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

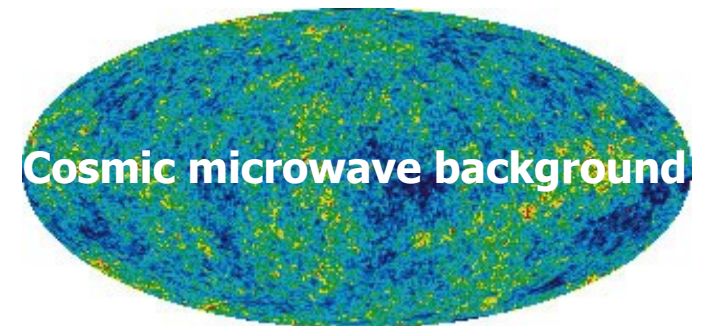
⇒ soon after big bang all matter will have annihilated to photons

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...



(Actually SM can account for only  $1000^{\text{th}}$  of this asymmetry)

What are the current collider experiments doing?

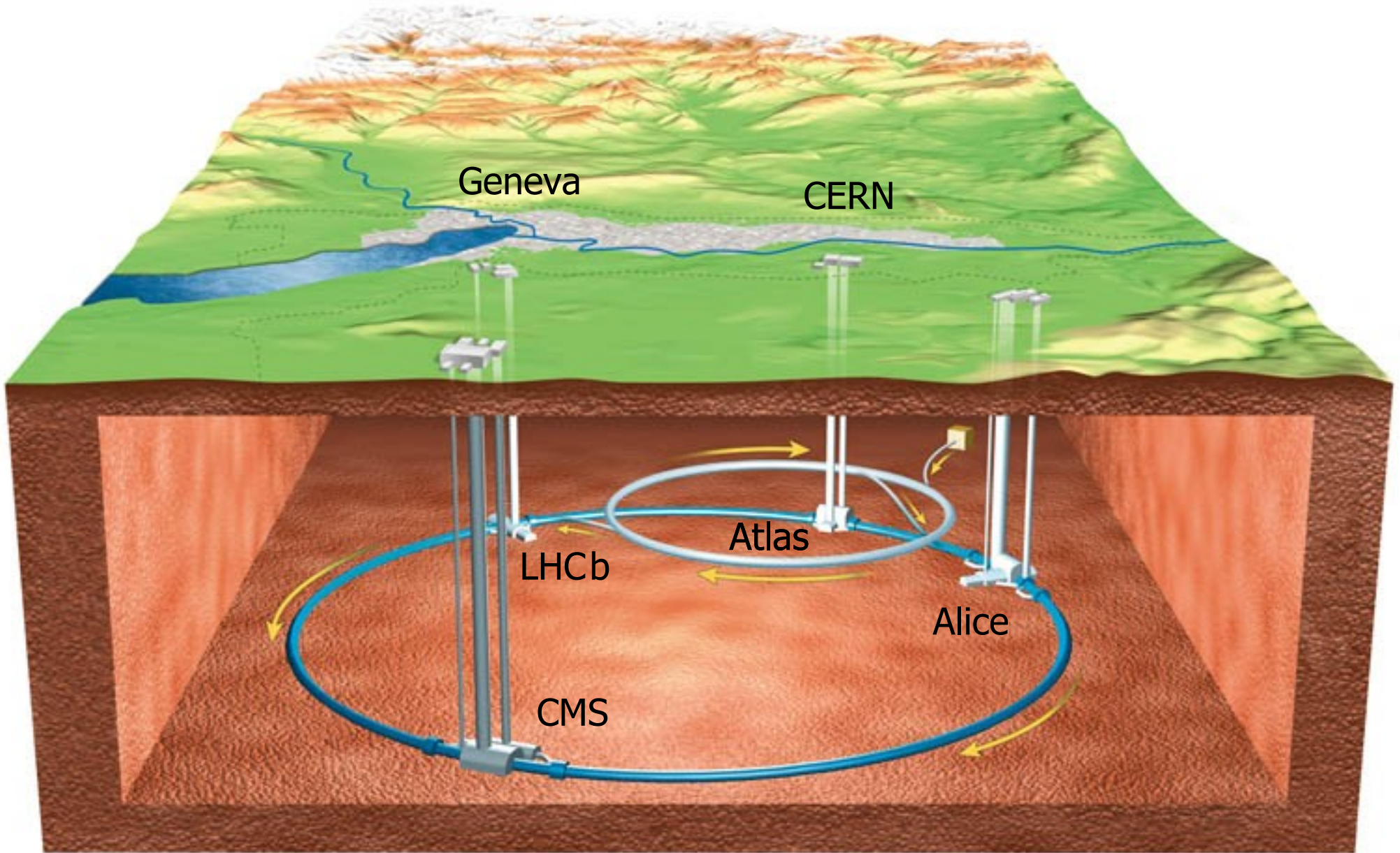
# The Large Hadron Collider



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



# The Large Hadron Collider





LHC will collide protons at 7 TeV (7000 GeV)

27 km circumference ring

1200 superconducting dipole magnets  $\sim 9$  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  $\sim 15 \mu\text{m}$  ( human hair  $\sim 20 \mu\text{m}$  )

20 interactions every bunch crossing

Particles from one collision still travelling when next collision occurs!

One of the largest scientific / technological projects ever undertaken

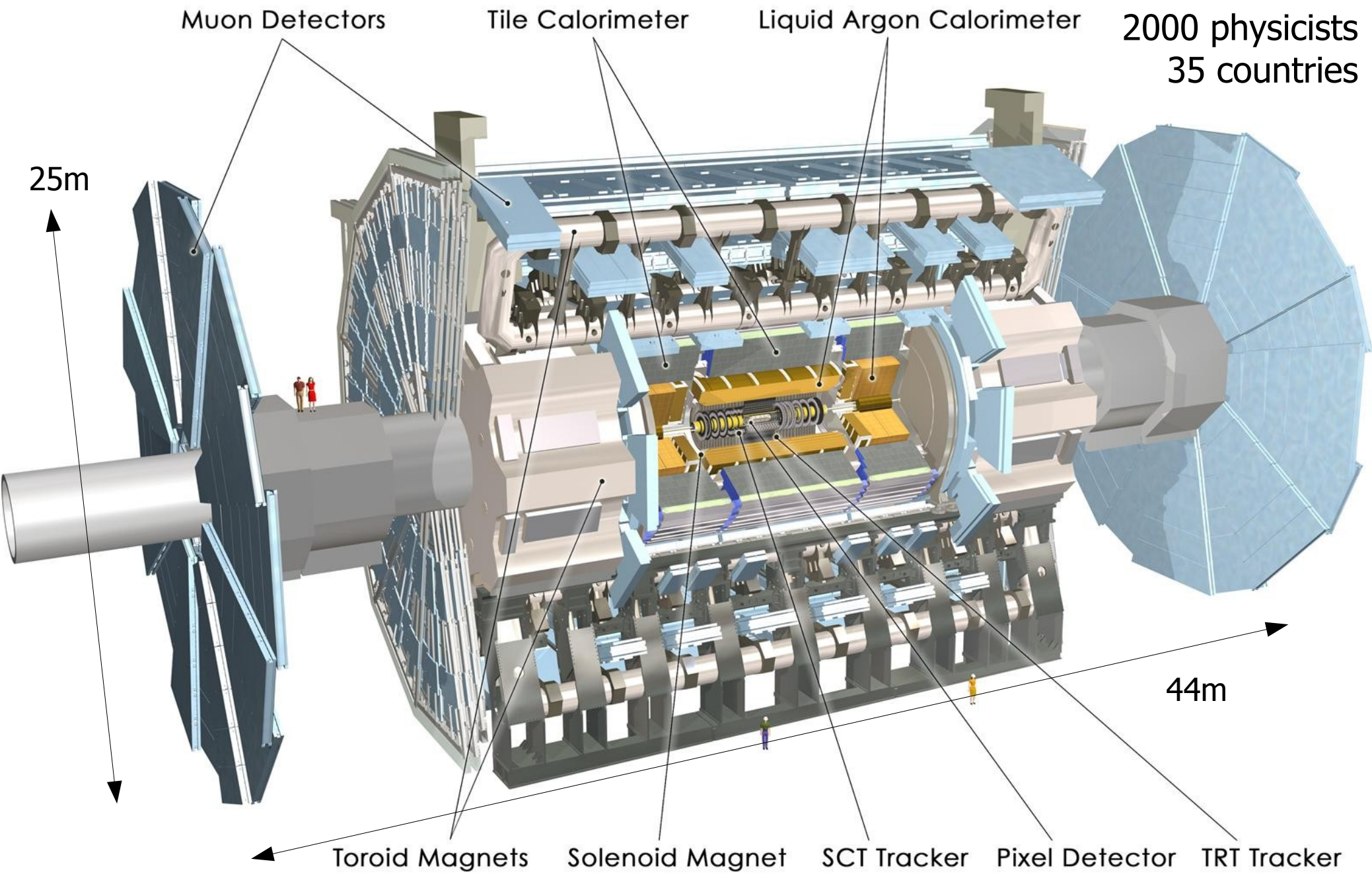
>  $100 \times 10^6$  electronic channels

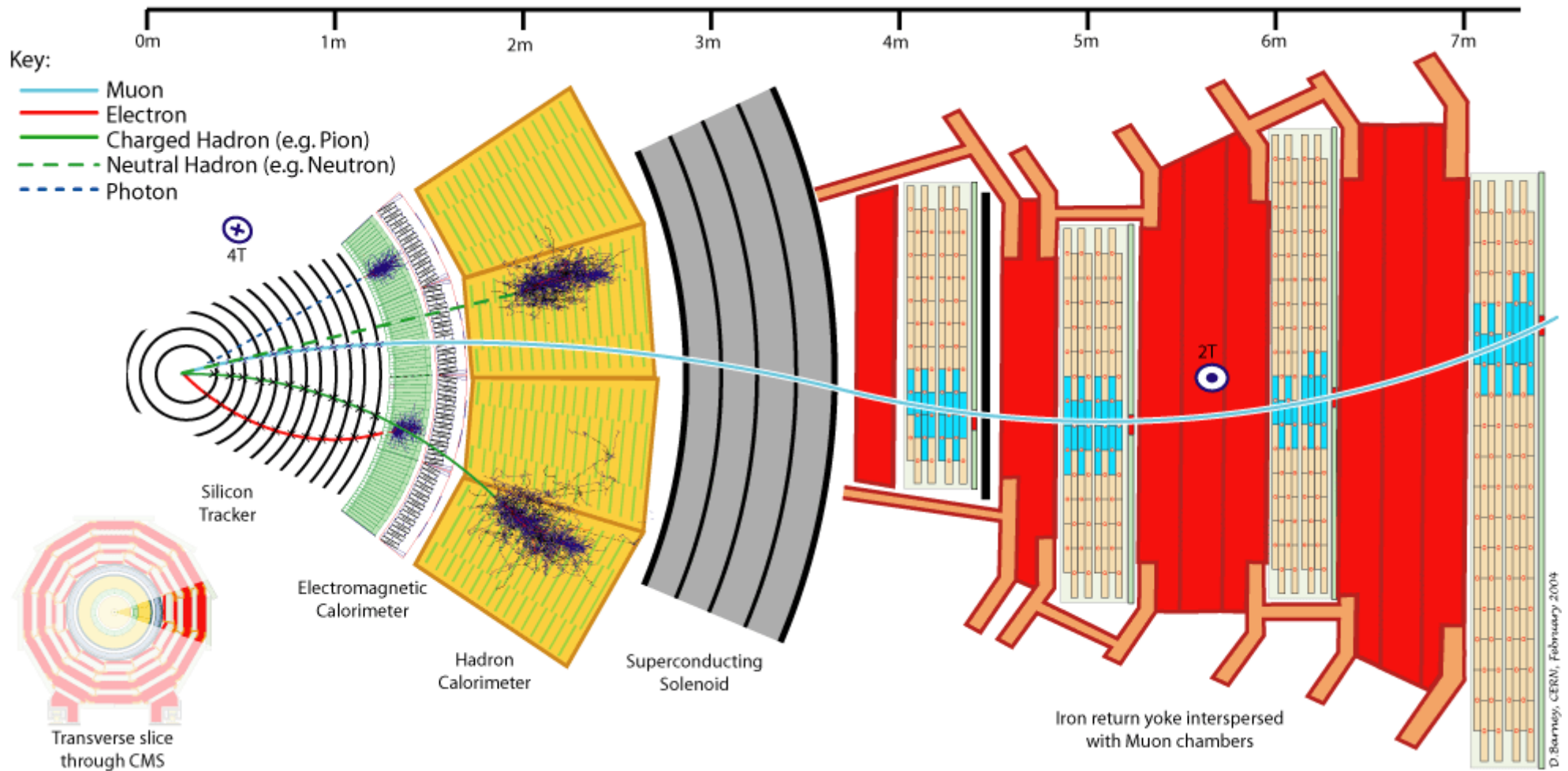
$\sim 10^9$  proton-proton interactions per second

$\sim 1$  Higgs  $\rightarrow \gamma\gamma$  per hour

**10 x 10<sup>6</sup> Gigabytes of data per year  
(equivalent to 1/2 million HD movies per year)**

# The Atlas Experiment

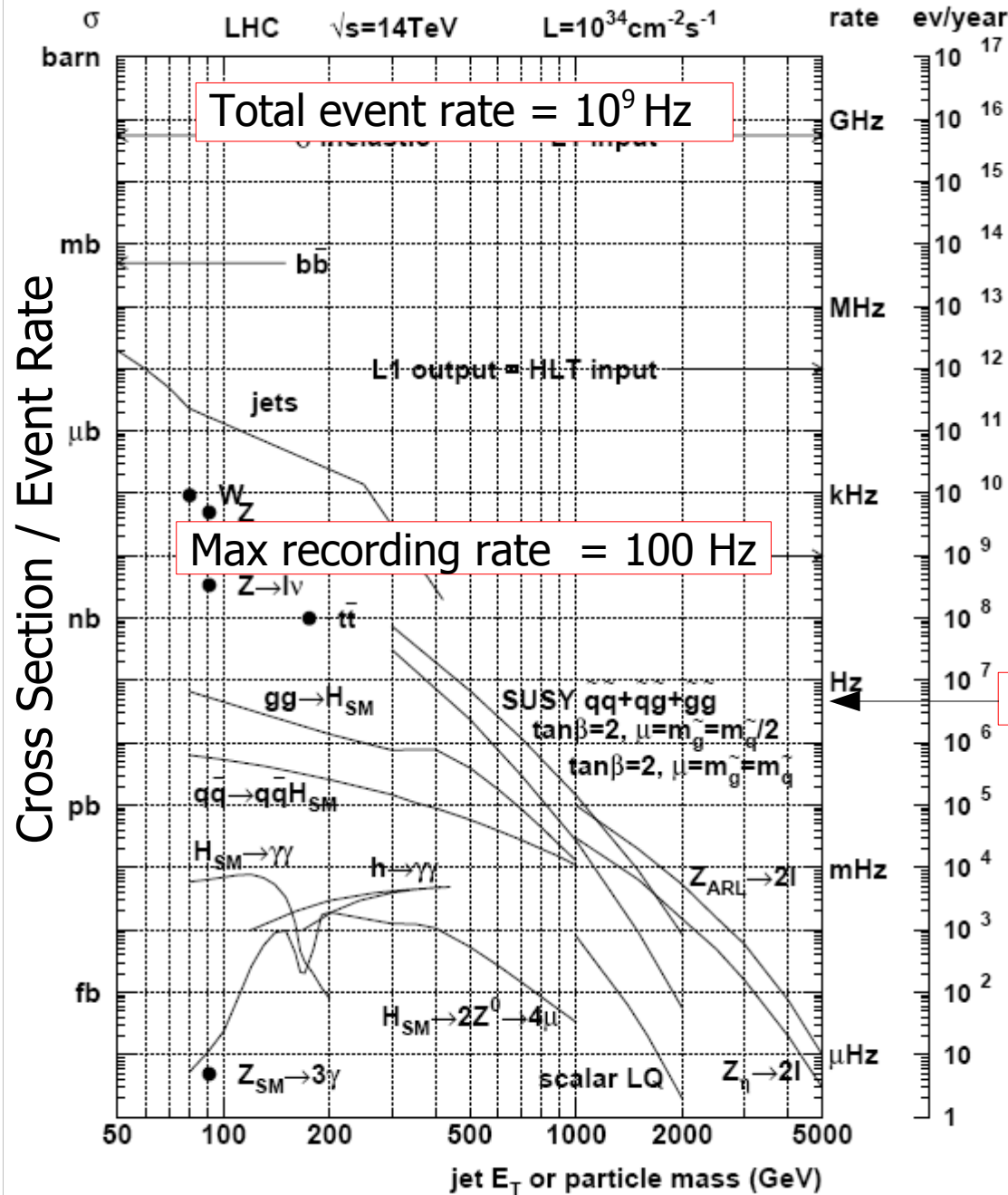




3600 physicists  
38 countries



# The Large Hadron Collider



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  $2 \mu\text{s}$

Rate of 100 GeV Higgs production

What are we looking for?

Almost all the visible mass of universe is due to massless QCD effects  
Energy associated with quark and gluon interactions  $\rightarrow$  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  $\sim 80$ - $90$  GeV (proton  $\sim 1$  GeV)

Higgs properties are well known except its mass!

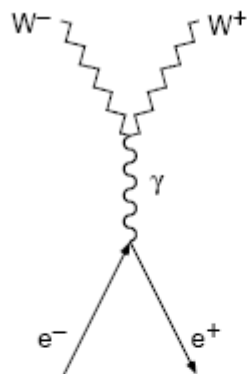
Direct searches:  $m_H > 114$  GeV

Examine energy dependence of scattering processes

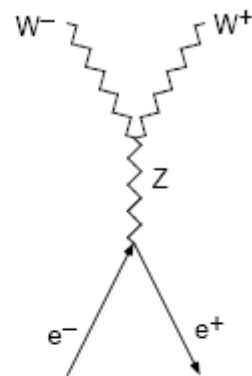
Process (a) and (b) are well behaved as energy increases

Process (c) becomes larger than total  $e^+e^-$  cross section! (unitarity is violated)

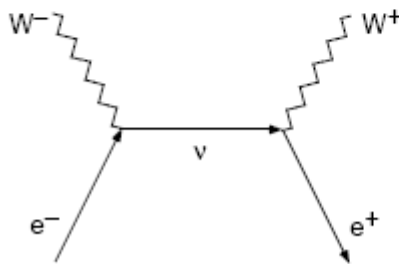
Higgs-like particle is needed to cancel  $e^+e^- \rightarrow W^+W^-$  scattering divergences



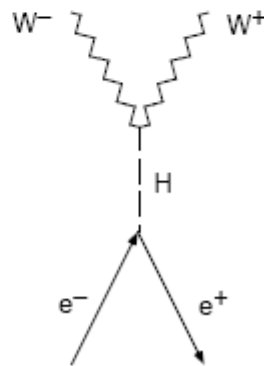
(a)



(b)



(c)



(d)

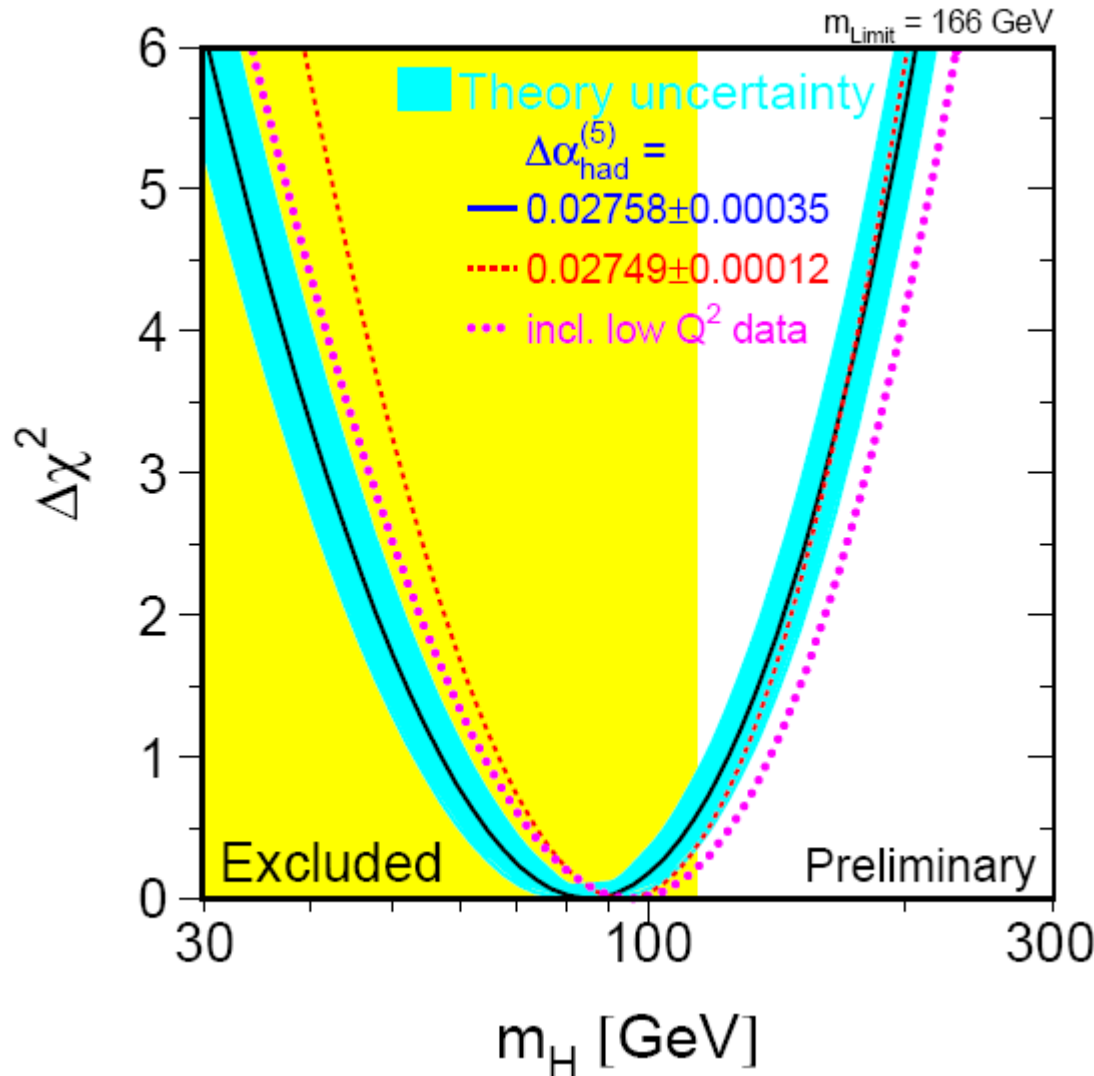
Requires Standard Model Higgs to be  $< \sim 1\text{TeV}$

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

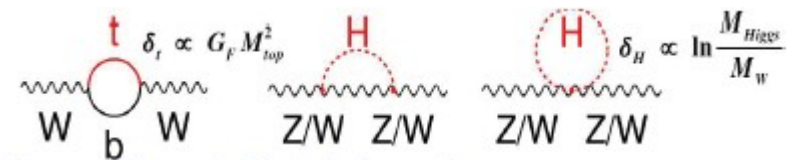
**win-win situation!**

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:  $\chi^2$  test  
Indicates light Higgs !

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

95% prob of SM Higgs  $< 166$  GeV

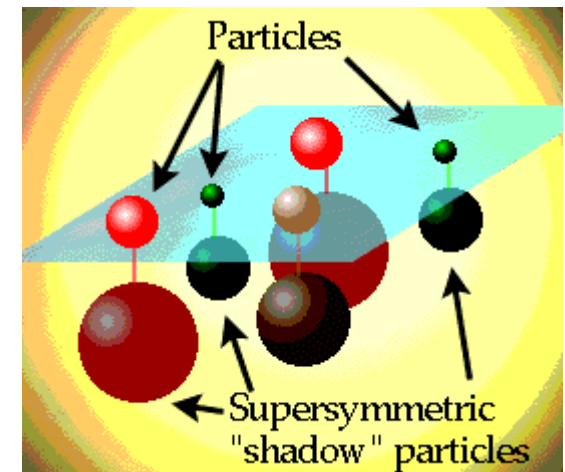
What are the alternatives to the Standard Model?

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 $\frac{1}{2}$ )	$\leftrightarrow$	squarks (spin 0)
leptons (spin $\frac{1}{2}$ )	$\leftrightarrow$	sleptons (spin 0)
photon (spin 1)	$\leftrightarrow$	photino (spin $\frac{1}{2}$ )
W,Z (spin 1)	$\leftrightarrow$	Wino, Zino (spin $\frac{1}{2}$ )
Higgs (spin 0)	$\leftrightarrow$	Higgsino (spin $\frac{1}{2}$ )



None of these has been observed

105 new parameters required by theory - So why bother??

- 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 10<sup>5</sup> 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:  $c$ ,  $\hbar$ ,  $G$

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

## Dark Matter Candidates

Astronomical observation show that  $\sim 25\%$  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

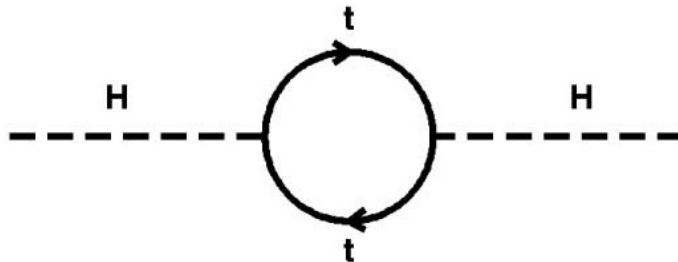
Cannot be neutrons - free neutrons decay

Cannot be neutrinos - mass too small

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

## Hierarchy Problem

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



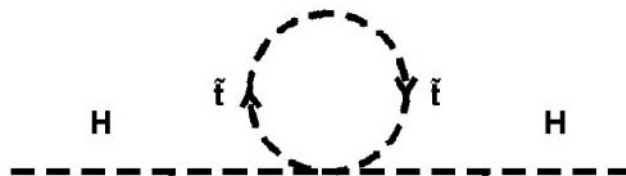
Higgs interacts with all spin  $\frac{1}{2}$  particle-antiparticle pairs in the vacuum

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  $\sim 1$  TeV Higgs mass

Seems unnatural

Only a problem for the Higgs (only SM particle with spin 0)

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

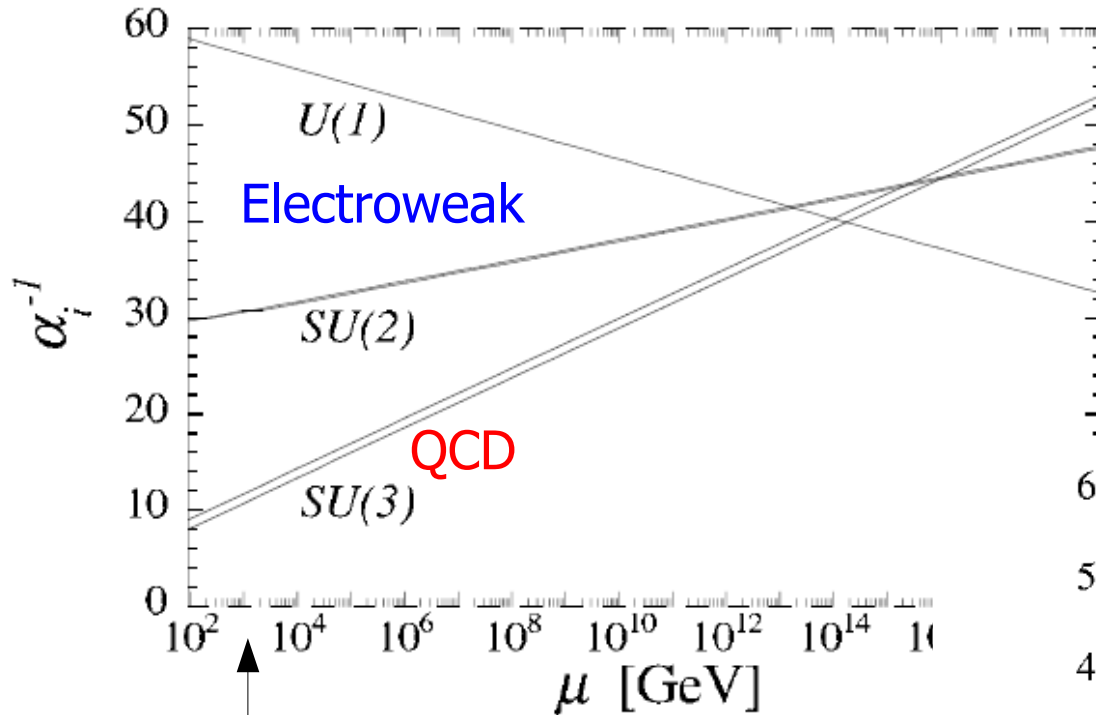


Higgs interaction with spin 0 sparticle cancels SM quantum corrections above

## GUT Unification

Another of SUSYs charms:

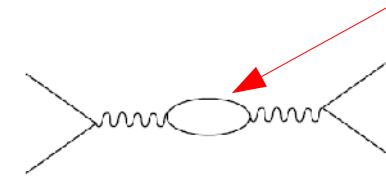
Coupling constants extrapolated to Planck scale do not intersect



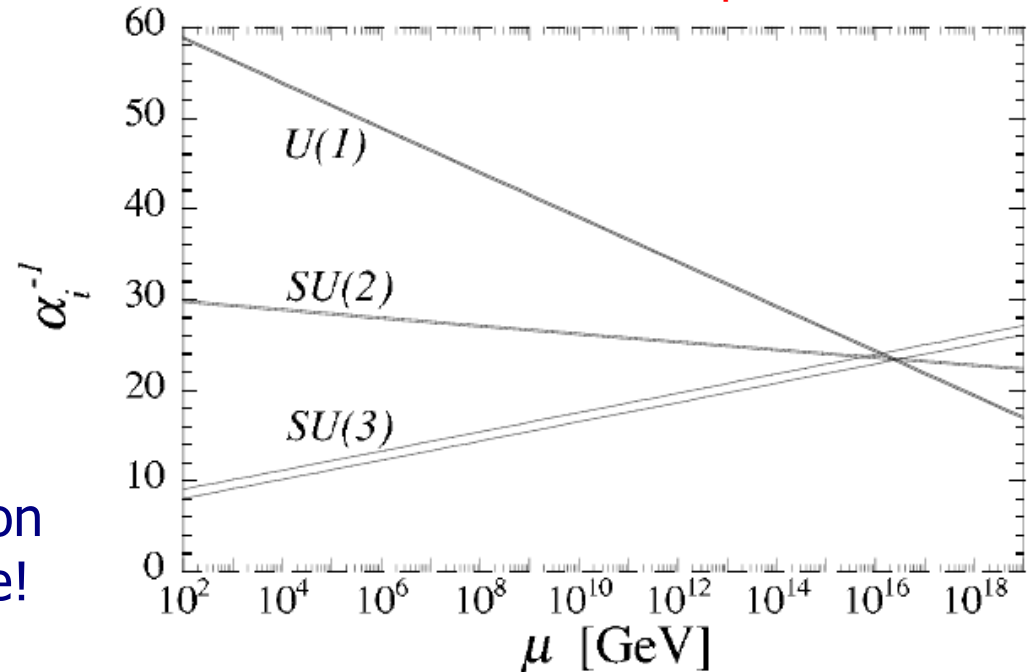
Current measurements

Incorporating SUSY into extrapolation brings unification below Planck scale!

16 orders of magnitude extrapolation!  
Involves including all particle loops



New SUSY particles = different loops  
= different extrapolation







## Quantum Gravity

Supersymmetry is a particular form of string theory  
Describes physics of Planck scale / quantum gravity  
Impossible to reach in any collider!

Some quantum gravity theories live in 10 or 11 dimensional space!  
predict gravitons propagate in extra dimensions  
(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 ( $\sim 0.1\text{mm}$ ) 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

$$T \approx \frac{(n+1)}{4\pi R} \quad \begin{array}{l} n = \text{number of extra dimensions} \\ R = \text{radius of compacted dimension} \end{array}$$

Why are the extra dims  $< 0.1\text{mm}$  ?

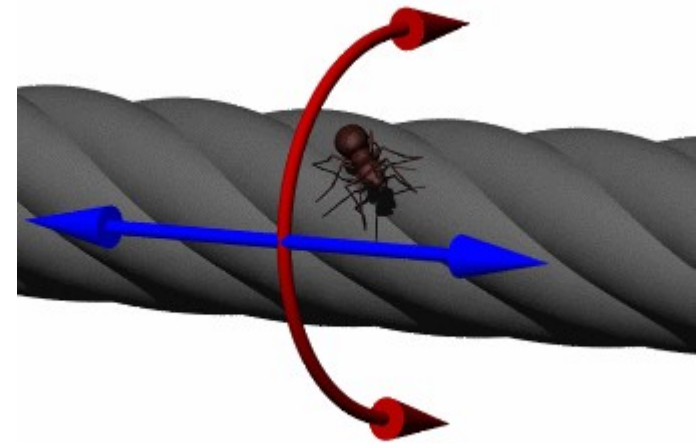
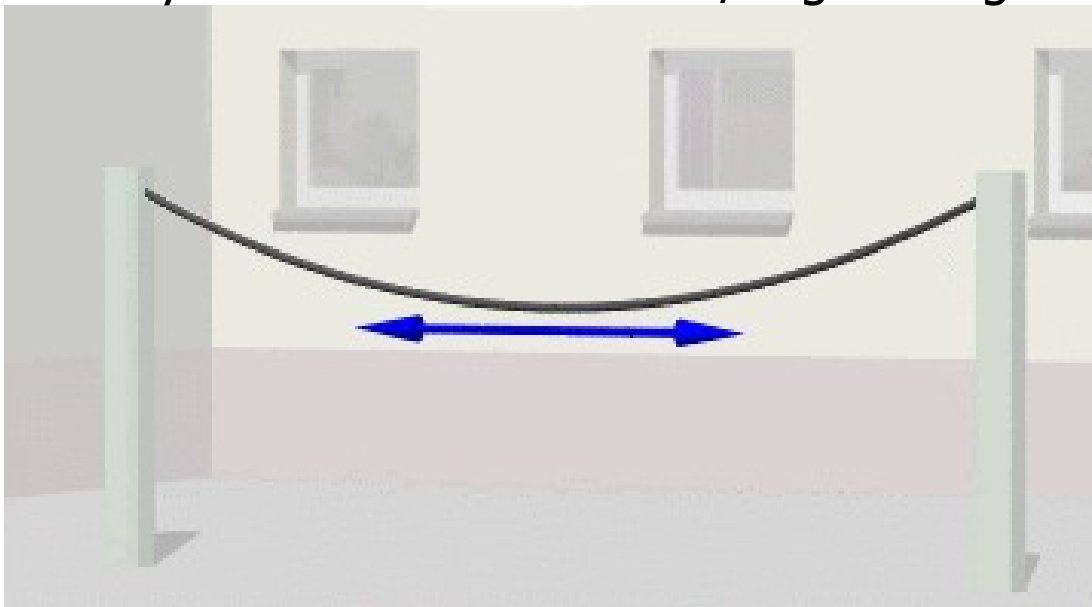
gravity has only been tested down to this scale!

current torsion balance experiments set limit on  $1/r^2$  dependence to  $< 0.16\text{mm}$

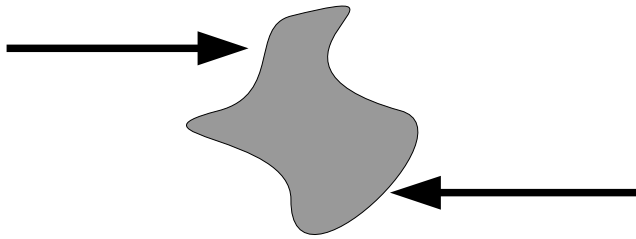
Where are the extra dimensions?

curled up (compactified) and finite

only visible at small scales / high energies

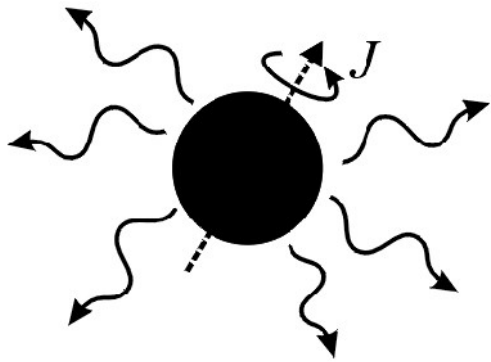


Relative strength of gravity explained by dilution of gravitons propagating in very large volume of bulk space - reduces Planck scale to reachable energies

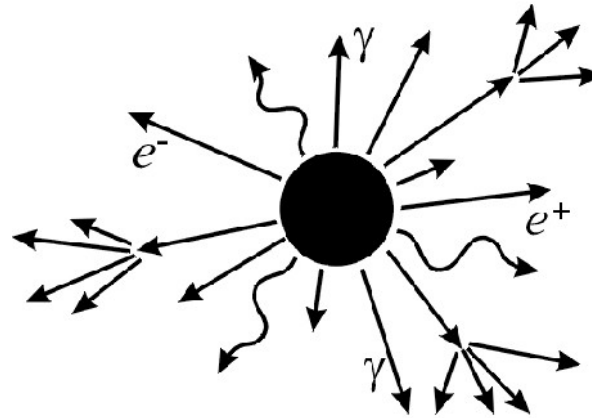


Collision produces complex state as horizon forms  
Not all energy is trapped behind horizon

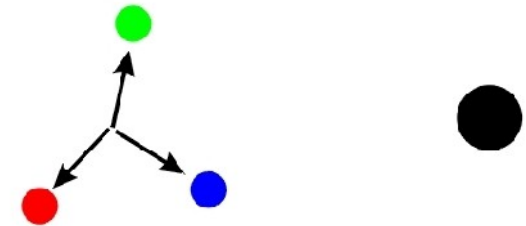
Extremely short lifetime  $\sim 10^{-25}s$



Balding  
Energy lost as BH settles into 'hairless' state

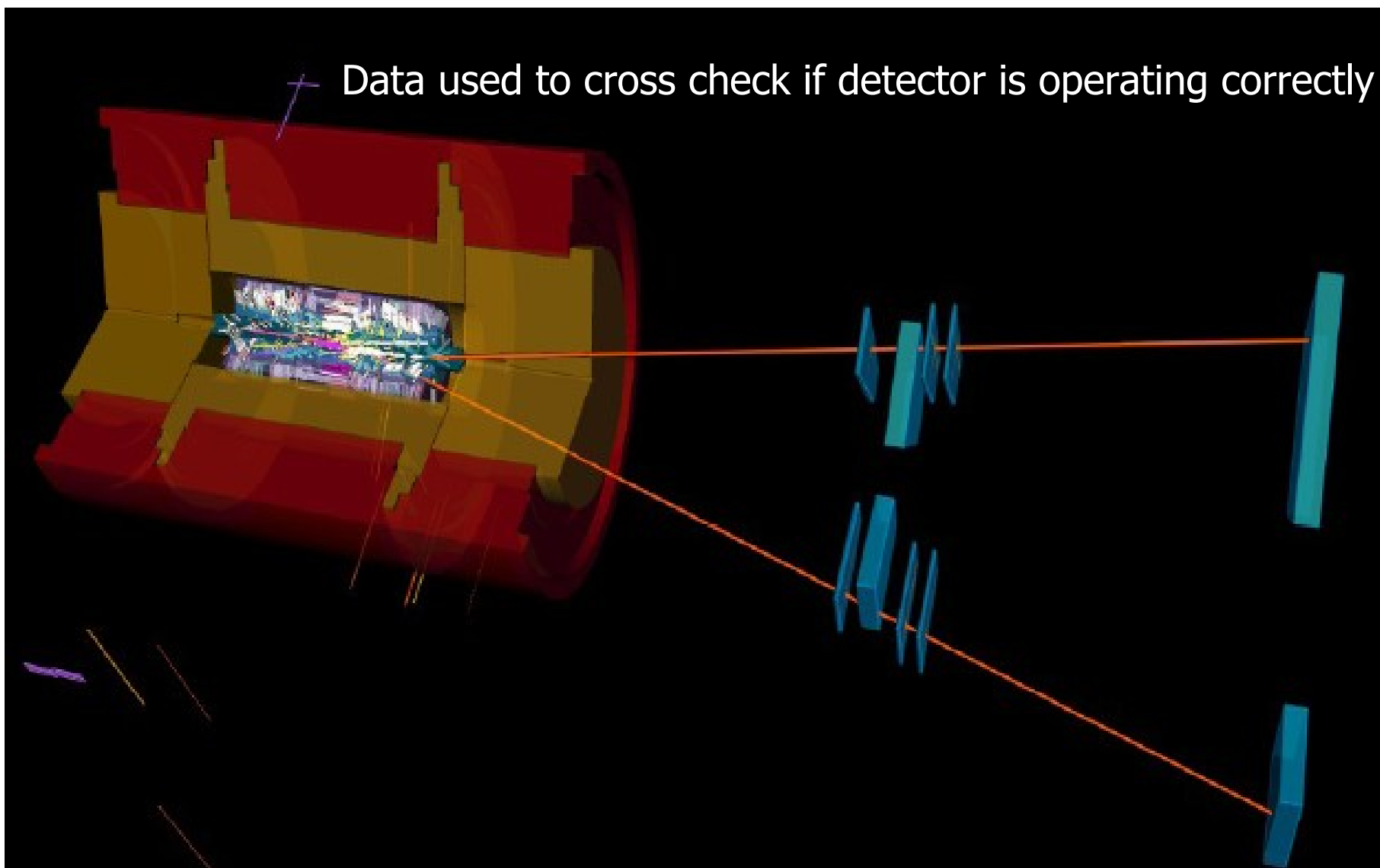


Evaporation  
Thermal Hawking radiation in form of SM particles & gravitons  
Greybody factors give emission probs for all quanta



Plank Phase  
For  $M_{BH} \sim M_D$  unknown quantum gravity effects dominates. BH left as stable remnant or final burst of particles  
**????**

## Atlas Experiment sees collision data



Long "physics run" of data taking starts this Spring for  $\sim 1$  year!

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 not thought of yet

Lots of work to be done in next few years!

The LHC started operation November 2009

Shutdown over winter

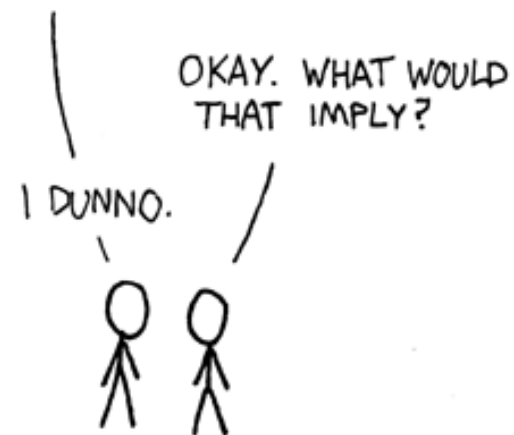
First collisions at low energy planned for tonight!

Data taking will start in earnest April 2010



## STRING THEORY SUMMARIZED:

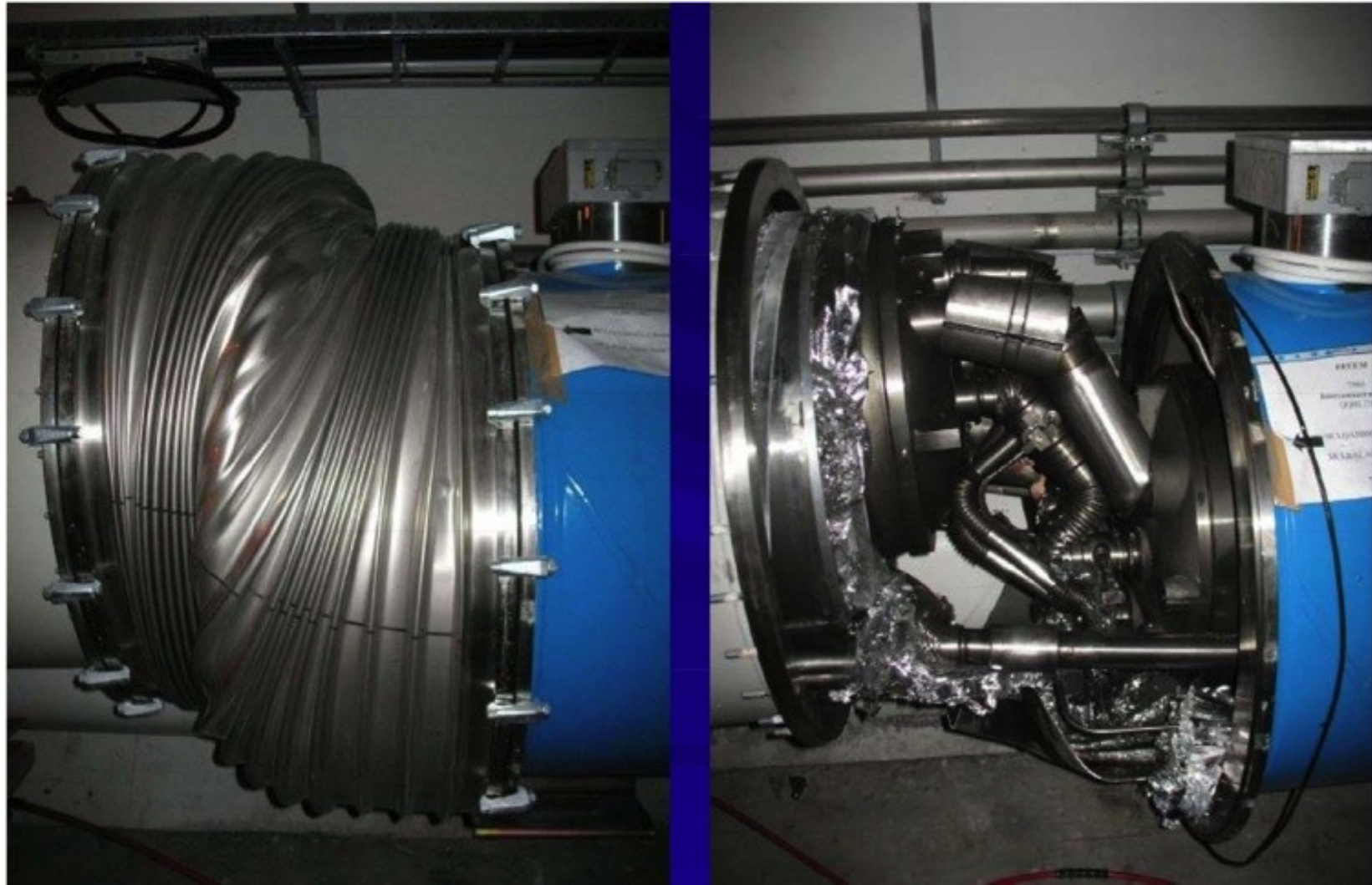
I JUST HAD AN AWESOME IDEA.  
SUPPOSE ALL MATTER AND ENERGY  
IS MADE OF TINY, VIBRATING "STRINGS."



© xkcd.com



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





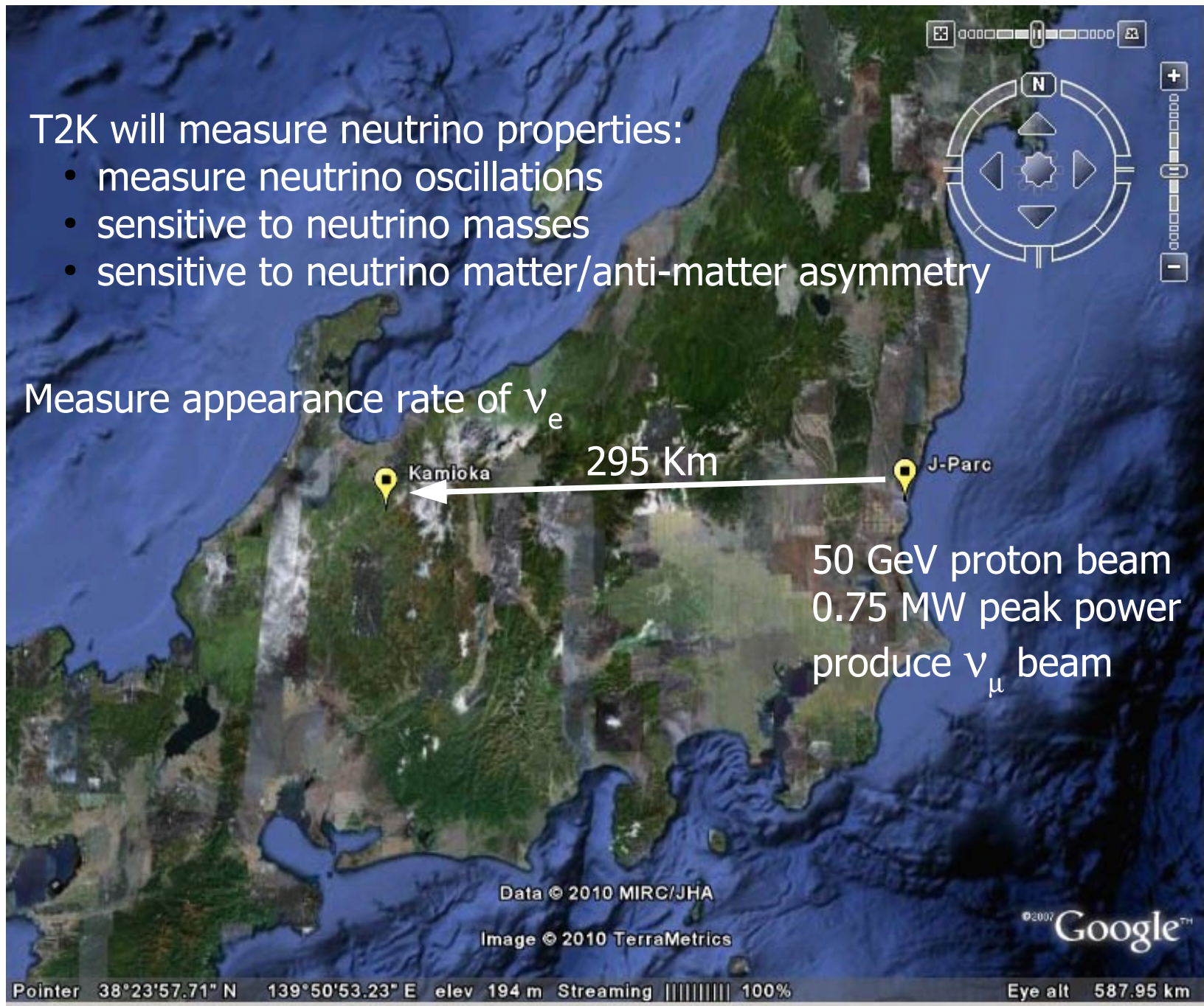
T2K will measure neutrino properties:

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

Measure appearance rate of  $\nu_e$

Kamioka ← 295 Km → J-Parc

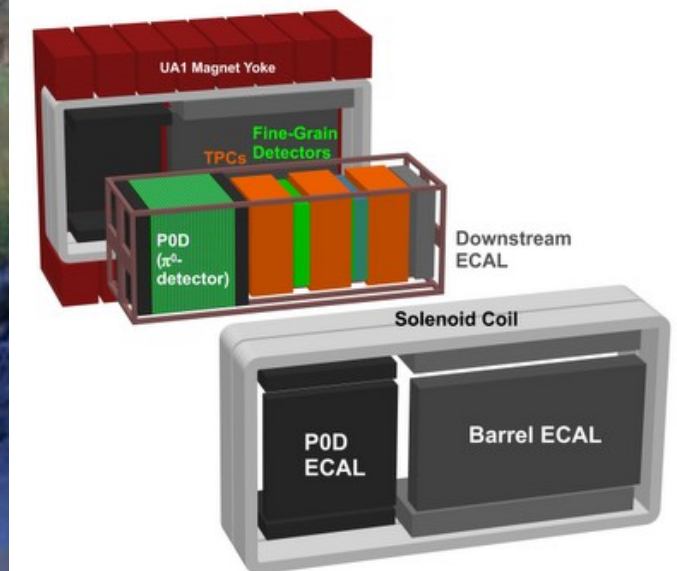
50 GeV proton beam  
0.75 MW peak power  
produce  $\nu_\mu$  beam



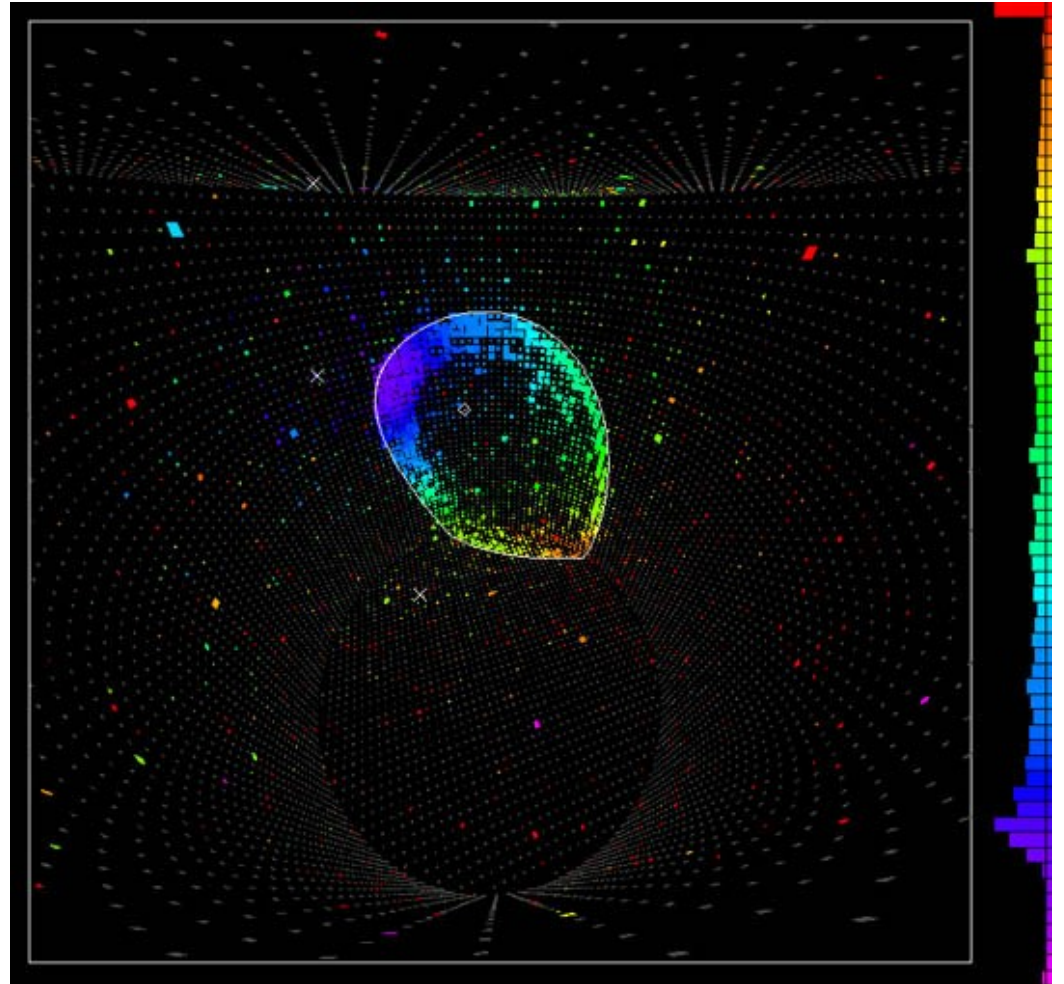
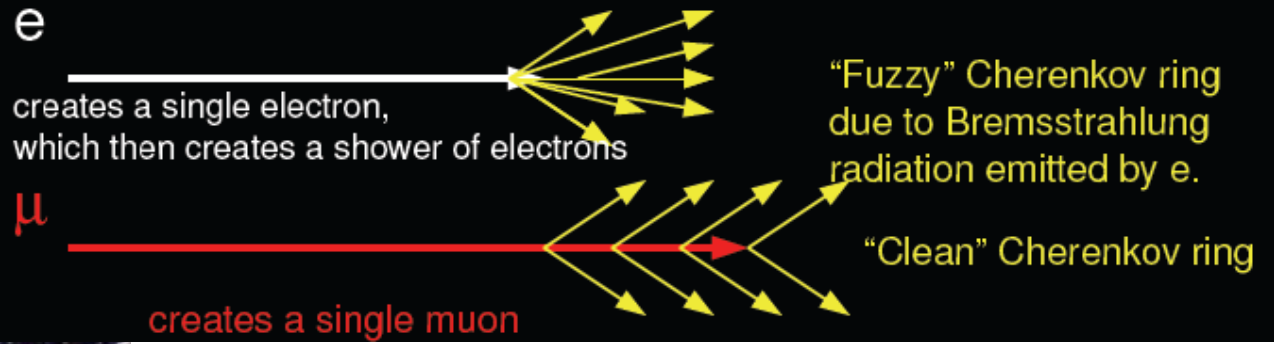
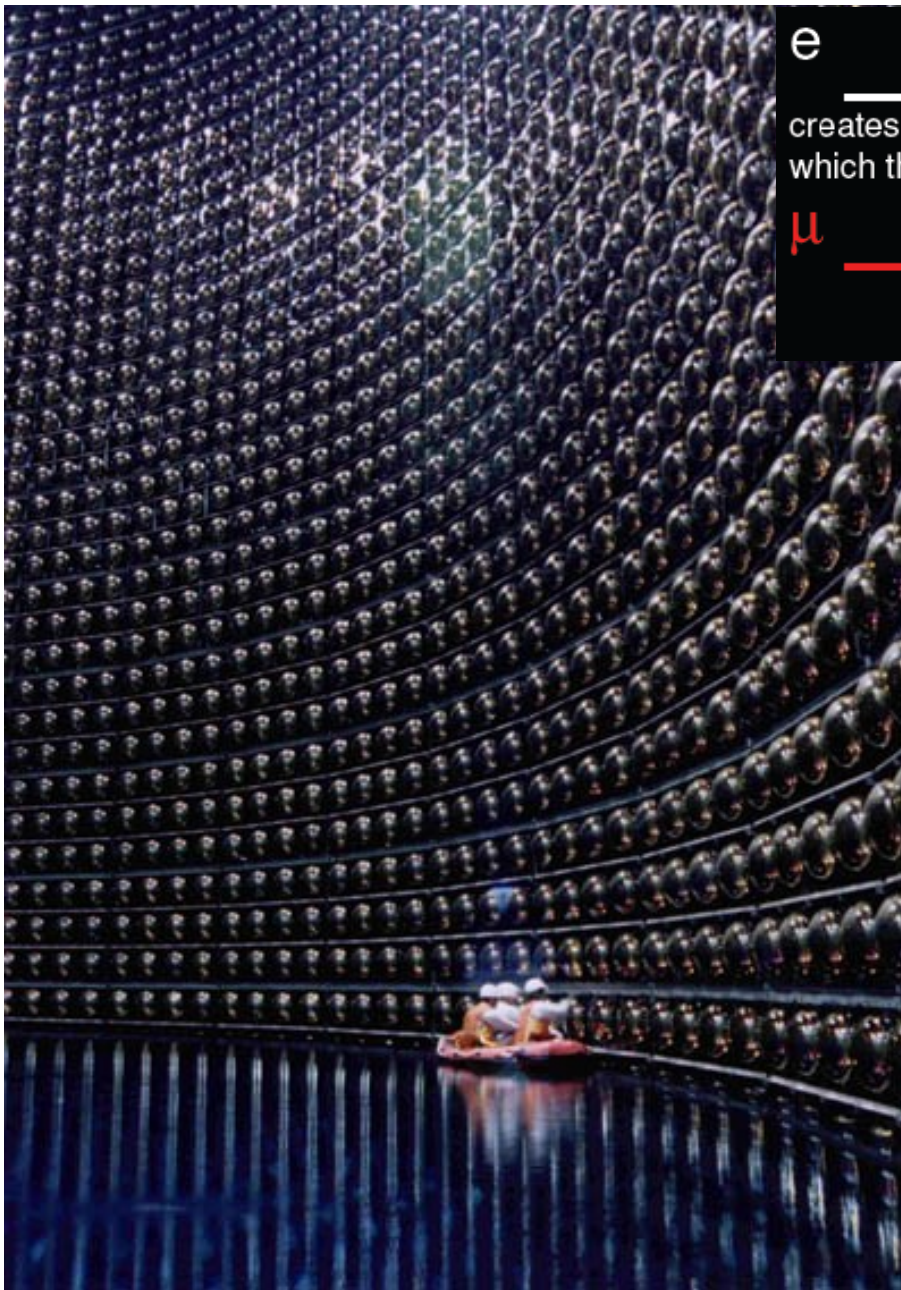
# The T2K Experiment



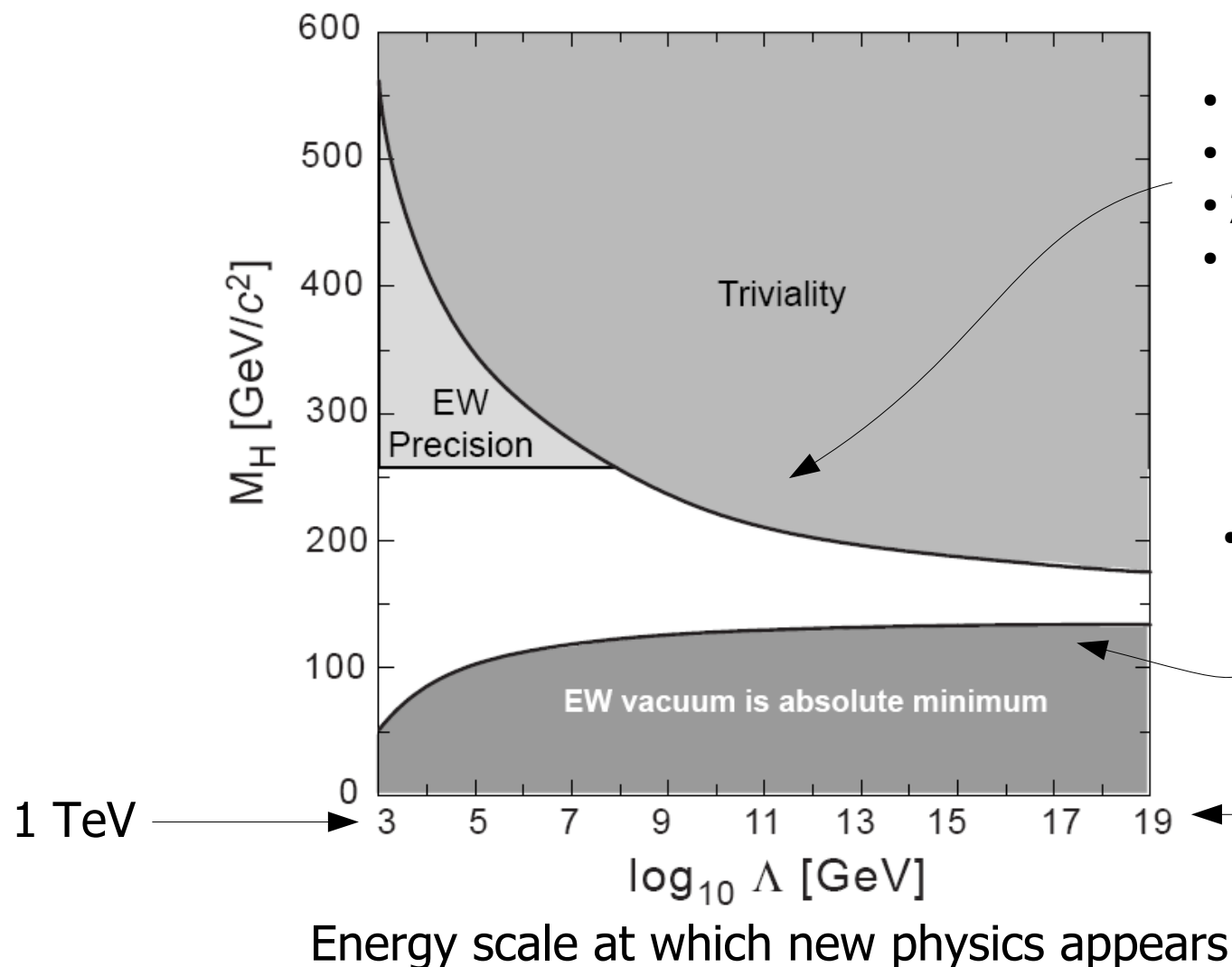
Super Kamiokande  
50,000 tons pure water  
11,200 photomultipliers  
Buried 1000 m deep in mine



# The T2K Experiment



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



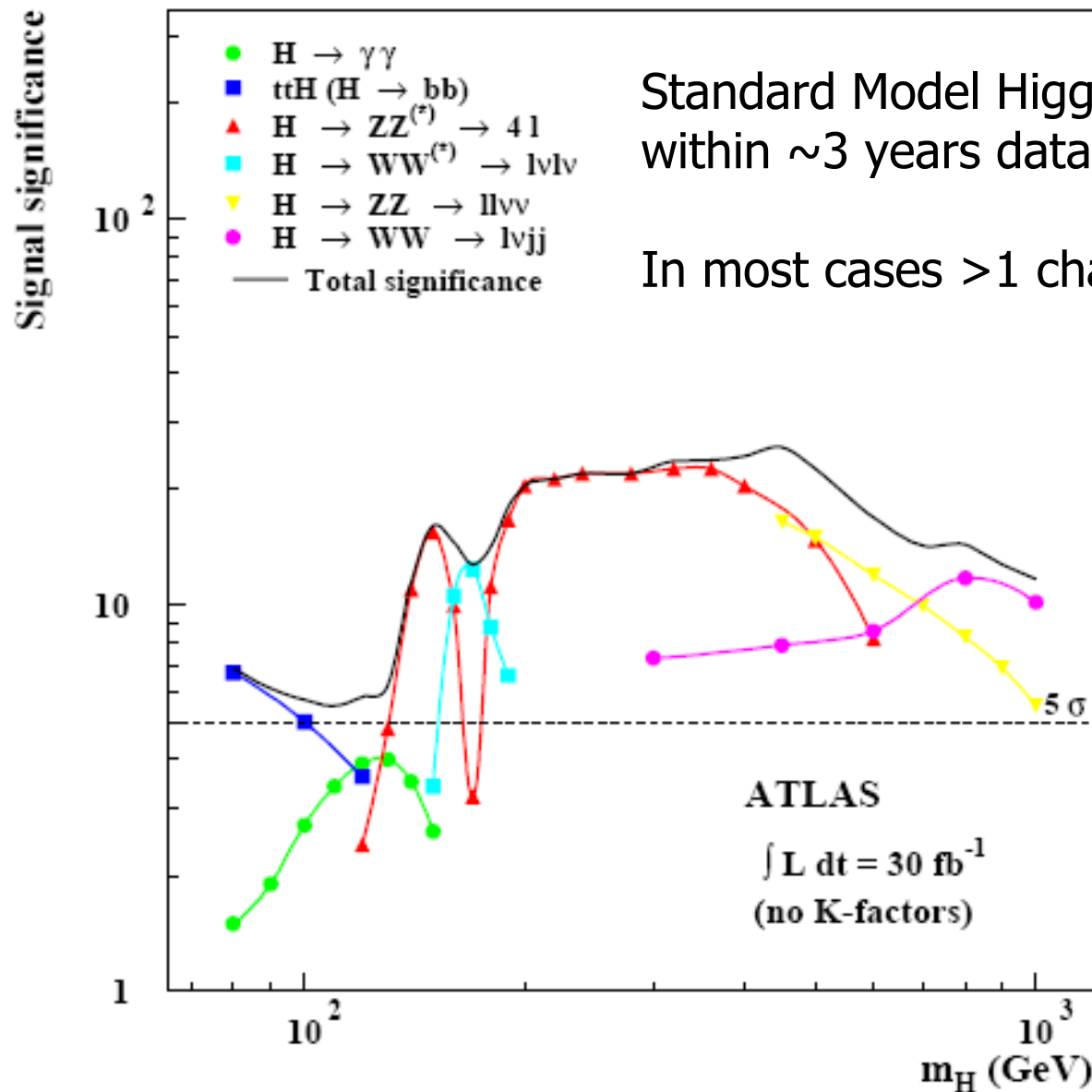
- Higgs self coupling =  $\lambda(Q)$
- $Q$  is energy at which you test
- $\lambda(Q)$  increases with  $Q$
- Requiring  $\lambda(Q)$  finite for  $Q < \Lambda$  fixes upper limit on  $M_H$

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

←  $10^{19}$  GeV !!!

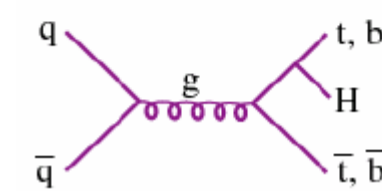
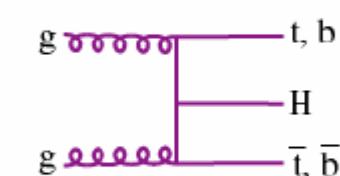
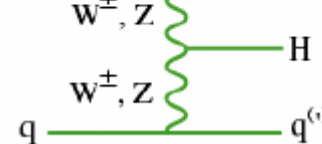
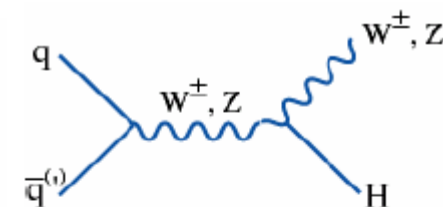
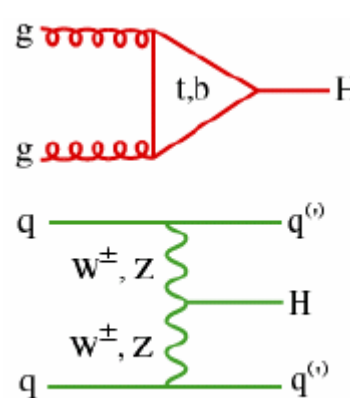
$\Lambda$  must be  $< 10^{19}$  GeV  
 scale at which gravity effects become important

## Likelihood of NOT being a statistical fluctuation vs Higgs mass



Standard Model Higgs discovered over full mass range within  $\sim 3$  years data taking

In most cases  $>1$  channel for discovery





Neutrinos only interact via weak force  $\Rightarrow$  very inert  
 involved in weak beta decays powering solar fusion  
 Solar neutrino flux is large  $\sim 10^6$  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:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

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

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

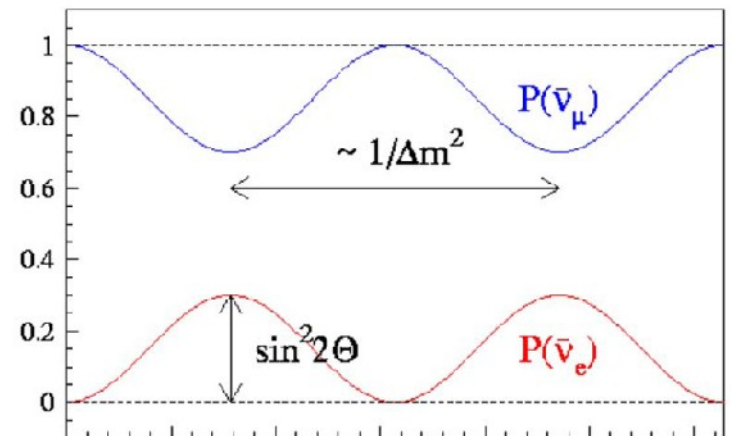
$L$  = distance

$E$  = neutrino energy

T2K will measure oscillation parameters

flavour eigenstates      mass eigenstates

Probability





Full 3x3 representation

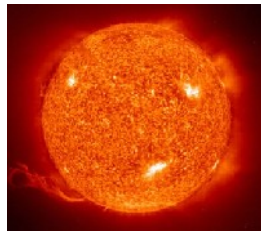
states of definite flavour

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} \delta \neq 0 \\ \Rightarrow \text{CP violation!} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

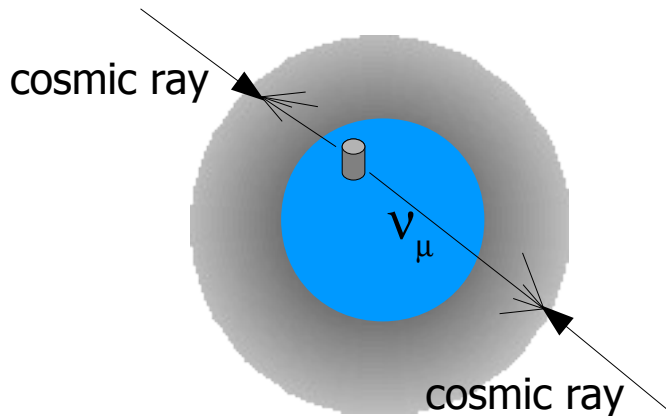
states of definite mass

So far experiments measured solar and atmospheric neutrino anomalies

Measure  $\nu_\mu$  from down-coming and up-going neutrinos produced in atmosphere

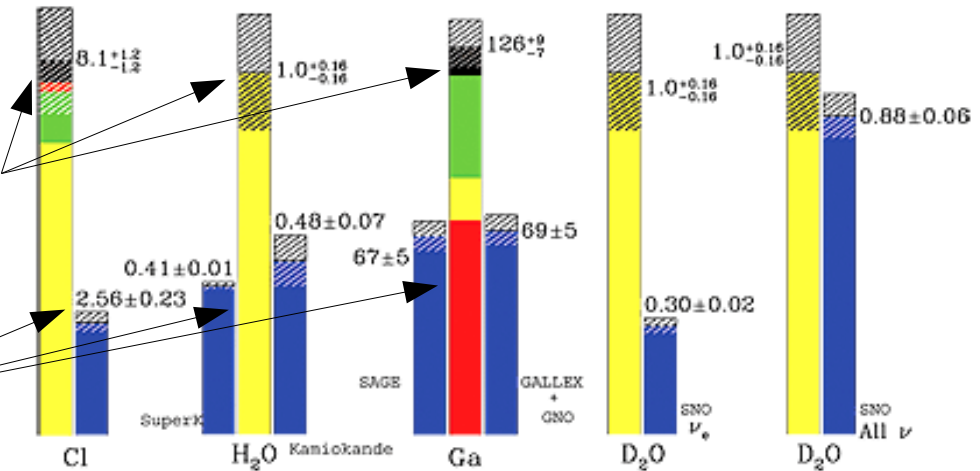


Sun produces calculable rate of  $\nu_e$   
measure  $\sim 30\%$  less than expected



calculated rate

measured rates



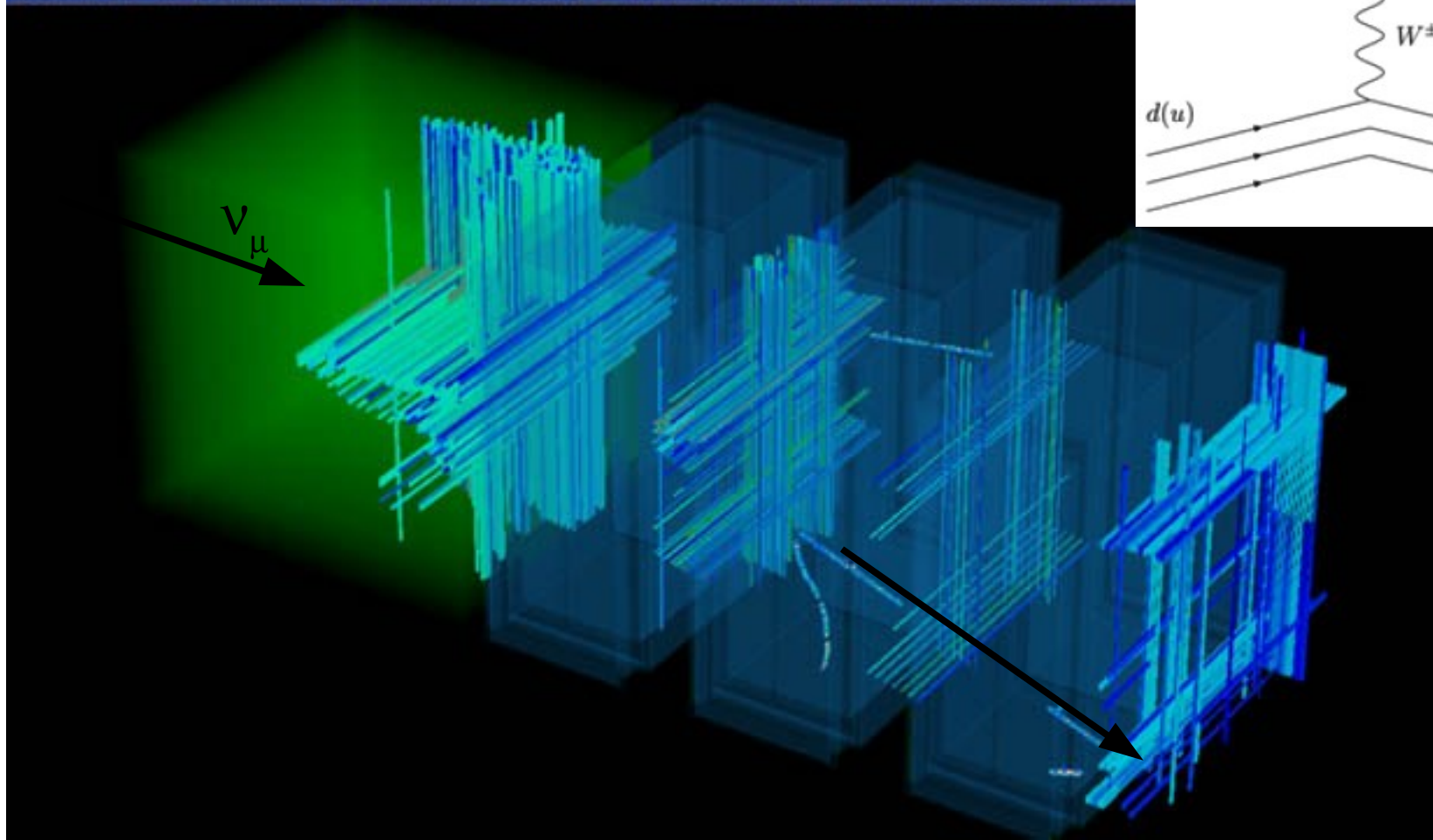
Experiments sensitive to different neutrino flavours

sensitive to all flavours!



## First neutrino interaction in ND280 off axis detector December 19, 2009

Event number : 491 | Partition : INVALID | Run number : 1539 | Spill : INVALID | SubRun number : 0 | Time : Sat 2009-12-19 07:40



Follow us on twitter

<http://twitter.com/neutrinosQMUL>



Neutrino oscillations prove neutrinos have mass  
Experiments (e.g. T2K) can only measure mass differences  
Search for rare process sensitive to neutrino mass:

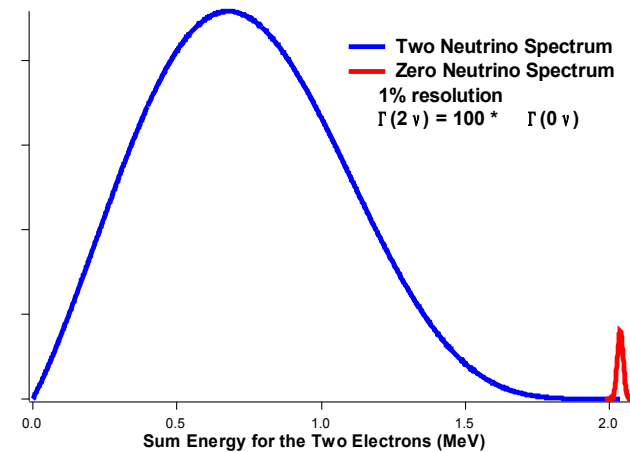
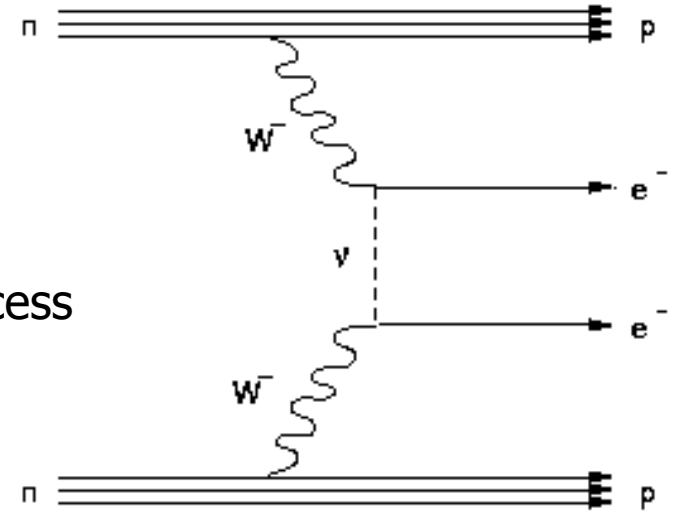
## Neutrinoless Double Beta decay

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

neutrinoless mode ( $0\nu\beta\beta$ ) 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

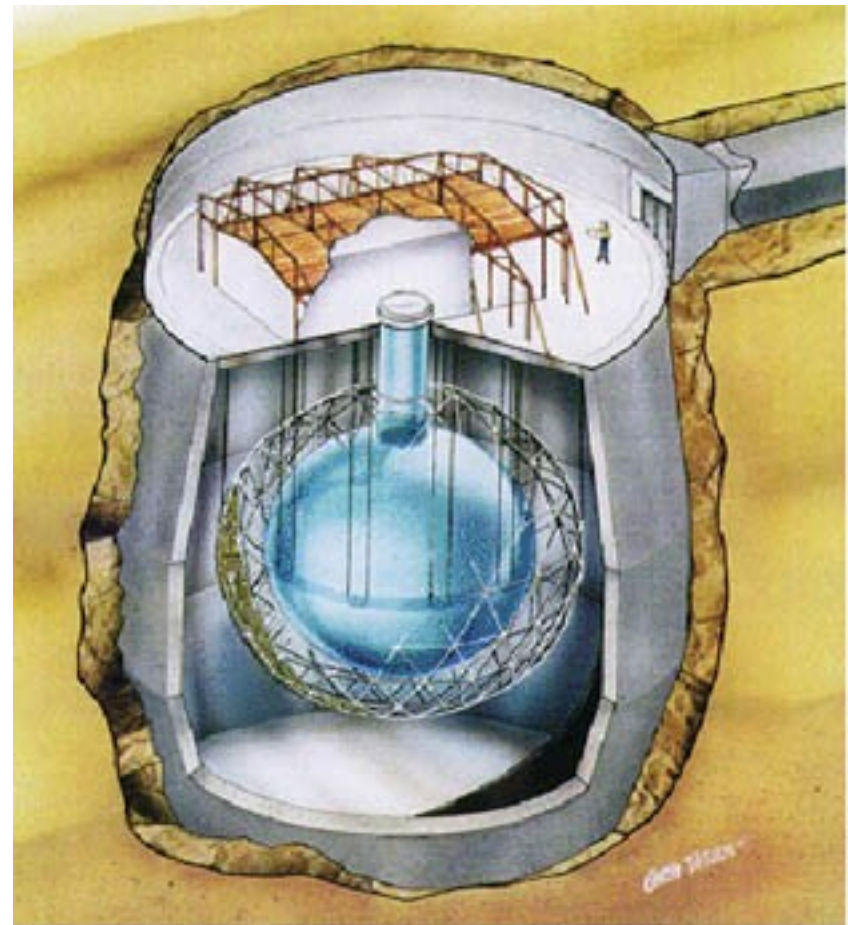
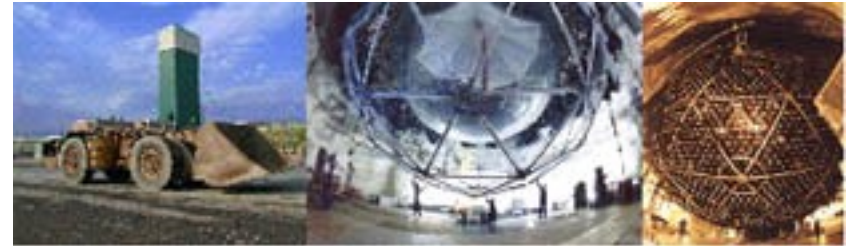


# The SNO+ Experiment

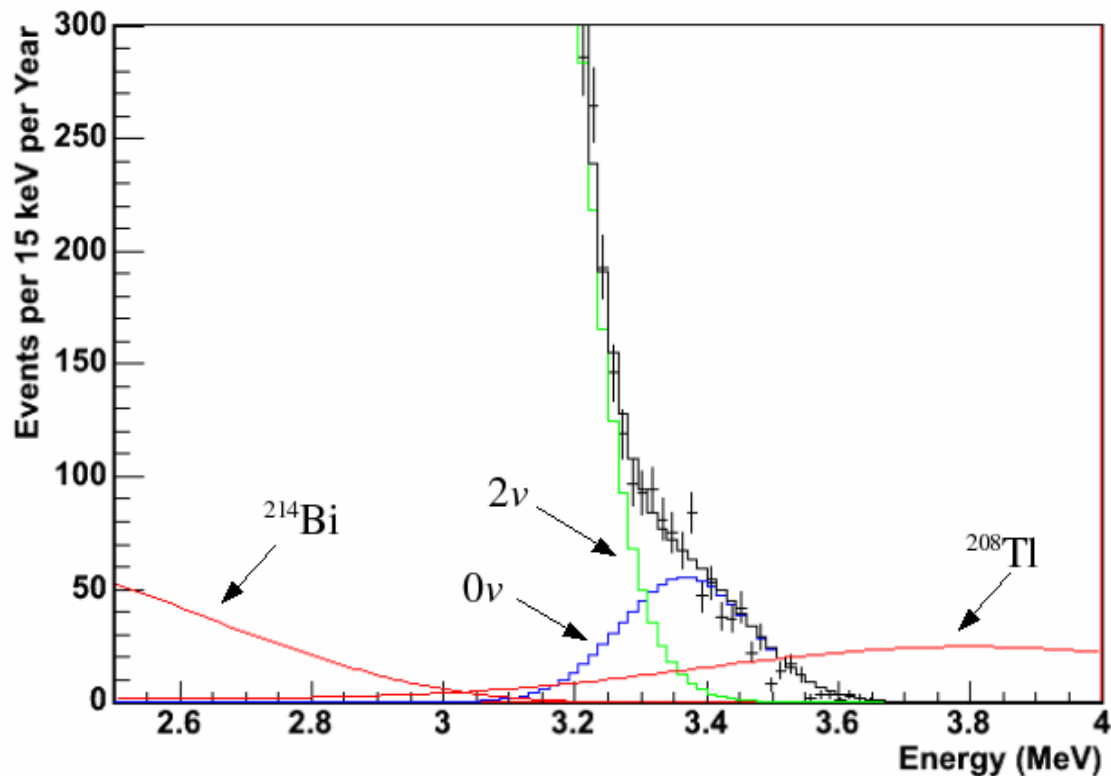


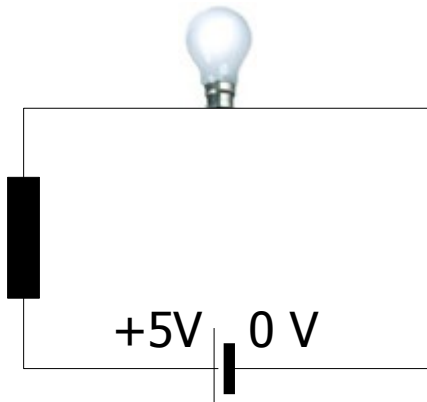
~2km underground in a Canadian Nickel mine  
12m diameter acrylic vessel with liquid scintillator  
Scintillation events observed by ~9500 PMTs  
7kilotonnes ultrapure H<sub>2</sub>O as a shield

Search for  $0\nu\beta\beta$  decay of  $^{150}\text{Nd}$  dissolved in scintillator (endpoint 3.3MeV)

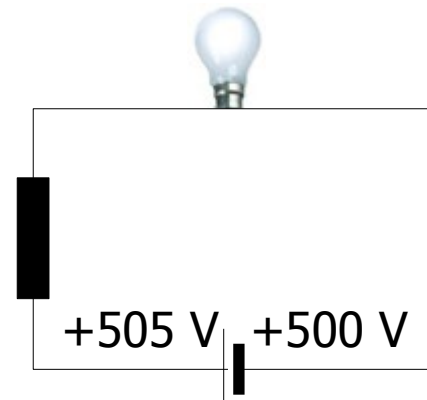


The Simulated Spectrum of Double Beta Decay Events





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  $\alpha$  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?  $\alpha \rightarrow \alpha(x,t)$



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