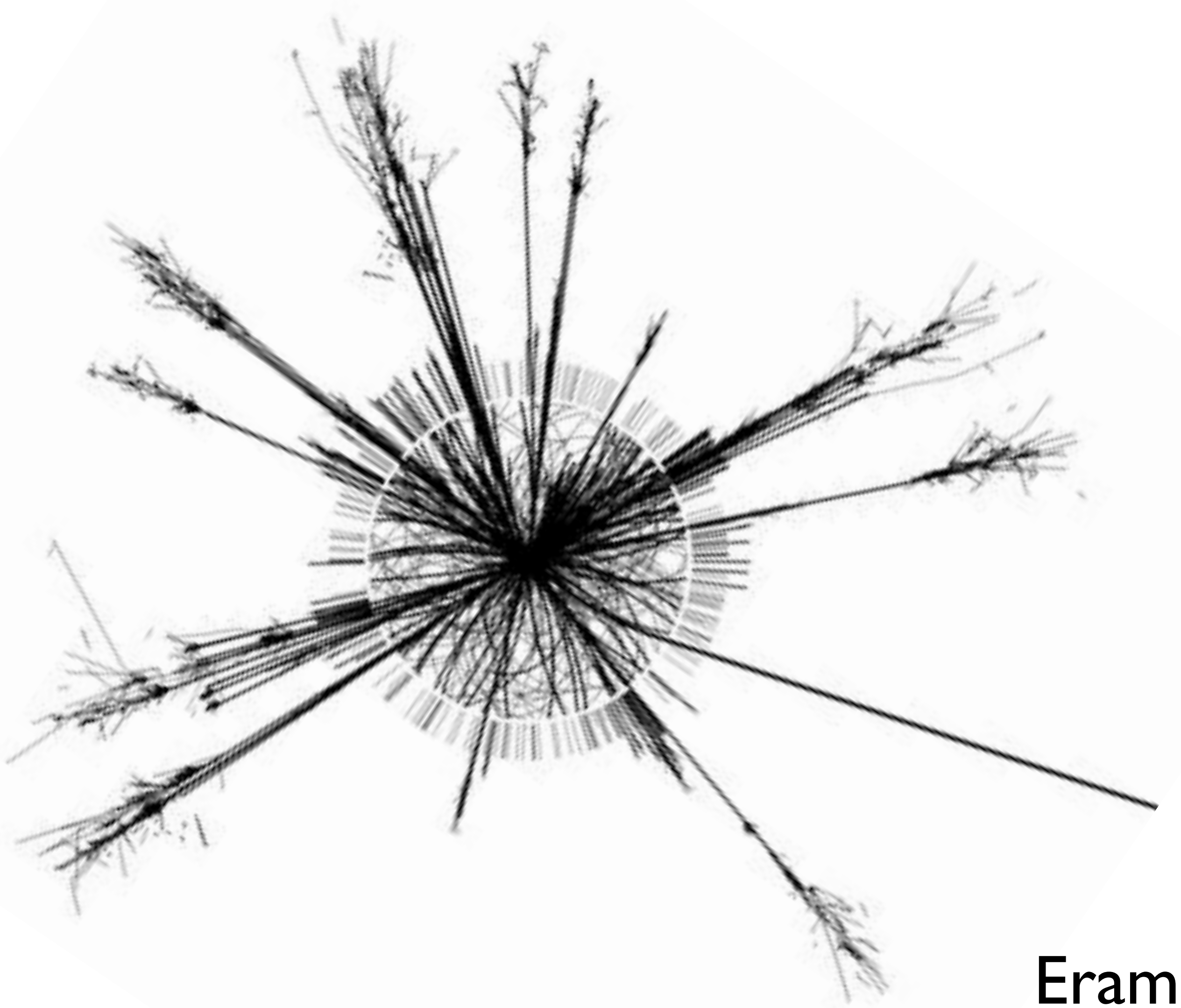
Beyond the Standard Model

Lecture 5



- The Higgs Boson
- Supersymmetry
- Large Extra Dimensions

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Outline - Subject to Change...

A Century of Particle Scattering 1911 - 2011
- scales and units
- overview of periodic table → atomic theory
- Rutherford scattering → birth of particle physics
- quantum mechanics - a quick overview
- particle physics and the Big Bang

A Particle Physicist's World - The Exchange Model
- quantum particles
- particle detectors
- the exchange model
- Feynman diagrams

The Standard Model of Particle Physics - I
- quantum numbers
- spin statistics
- symmetries and conservation principles
- the weak interaction
- particle accelerators

The Standard Model of Particle Physics - II
- perturbation theory & gauge theory
- QCD and QED successes of the SM
- solar neutrino problem

Beyond the Standard Model
- where the SM fails
- the Higgs boson
- the hierarchy problem
- supersymmetry

The Latest Results
- large extra dimensions
- new results from LHC, Tevatron & HERA
- the neutrino sector
- future experiments

The Problematic Standard Model

$$
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
&\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu\partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H\partial_\mu H - \\
&\tfrac{1}{2}m_h^2H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
&\tfrac{2M}{g}H + \tfrac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
&W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
&W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
&\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
&g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2s_wc_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3+H\phi^0\phi^0+2H\phi^+\phi^-] - \\
&\tfrac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] - \\
&gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
&W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
&\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
&igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
&igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] - \\
&\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^1 s_w^2A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial+m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial+m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial+ \\
&m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma e^\lambda)+\tfrac{2}{3}(\bar{u}^\lambda_j\gamma u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+ \\
&\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2-1-\gamma^5)u^\lambda_j) + \\
&(\bar{d}^\lambda_j\gamma^\mu(1-\tfrac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+ \\
&\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \\
&\tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + \\
&i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_jC_{\lambda\kappa}(1+ \\
&\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \\
&\tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \\
&\bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2-\tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + \\
&igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + \\
&igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + \\
&igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \\
&\tfrac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \\
&\bar{X}^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \\
&\bar{X}^0X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]
\end{aligned}
$$

The Standard Model works beautifully!
Describes all experimental data!

But it’s incomplete
Many things have to be inserted by hand
Leaves many questions unanswered

The Problematic Standard Model

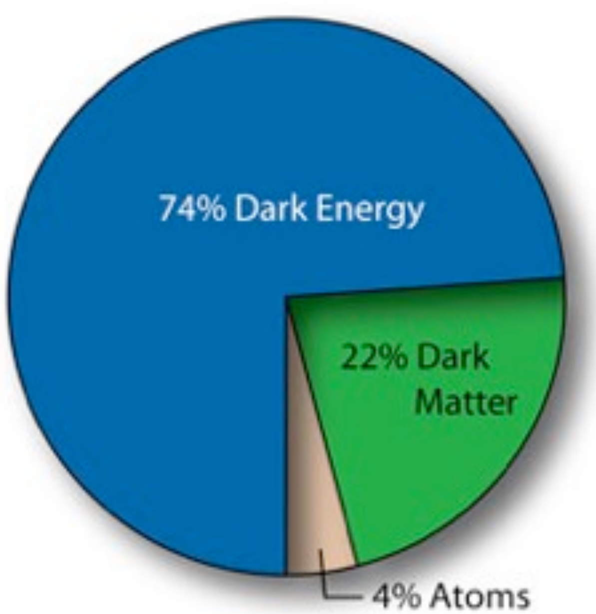
22 Parameters of the SM to be measured

- 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 supersymmetry)

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

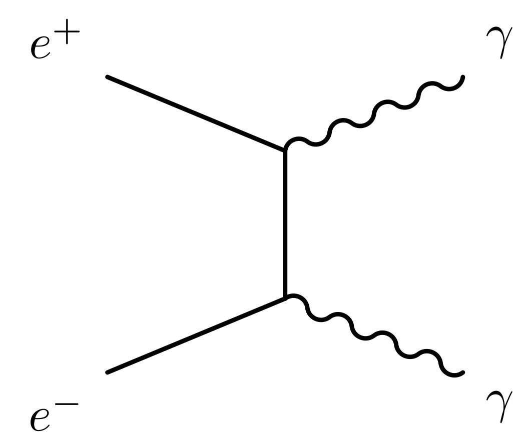
We know quantum gravity effects must play a role at the Planck scale i.e. energy ~ 10^{19} GeV

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...

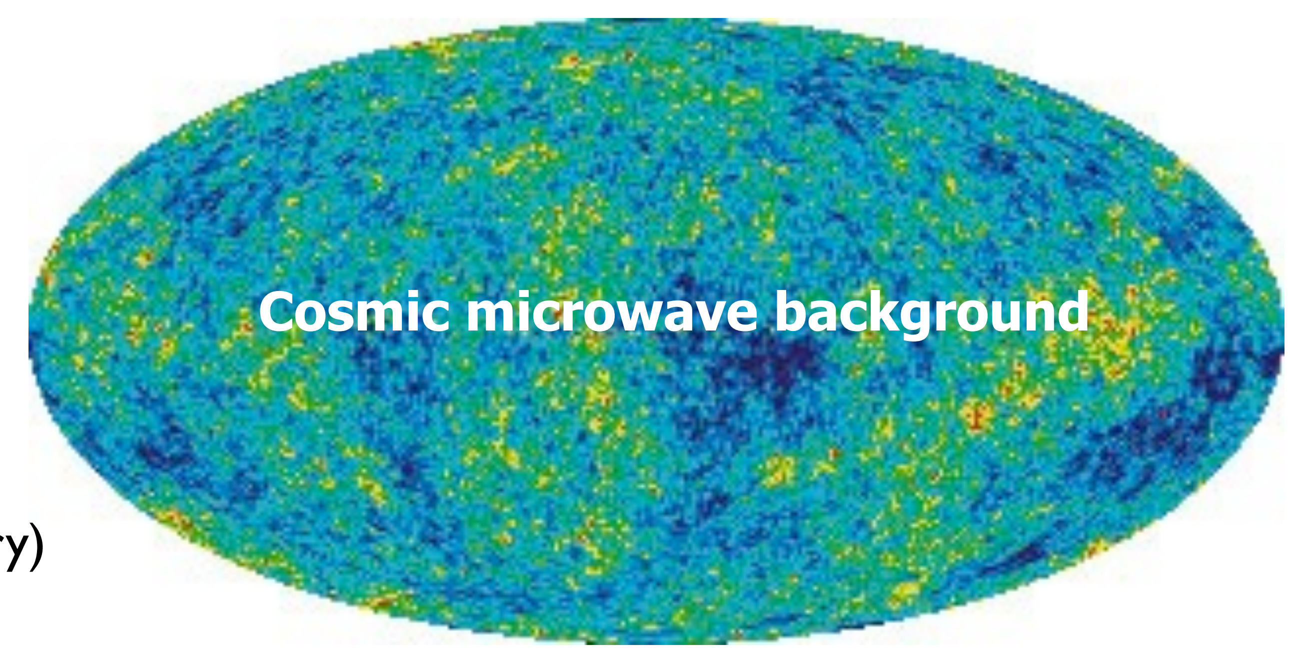
$e^+ e^-$ annihilation



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 - cosmic microwave background)
Thus matter/anti-matter asymmetry must be $1:10^9$
We cannot see where this asymmetry lies...



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

The Higgs Boson

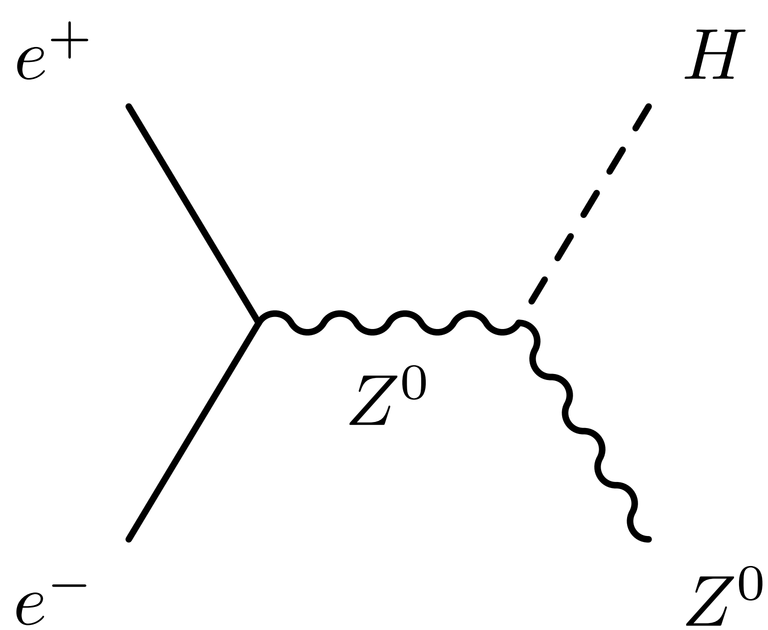
Almost all the visible mass of universe is due to massless QCD effects
Energy associated with quark and gluon interactions → proton & neutron mass

Higgs particle postulated to explain masses of fundamental particles

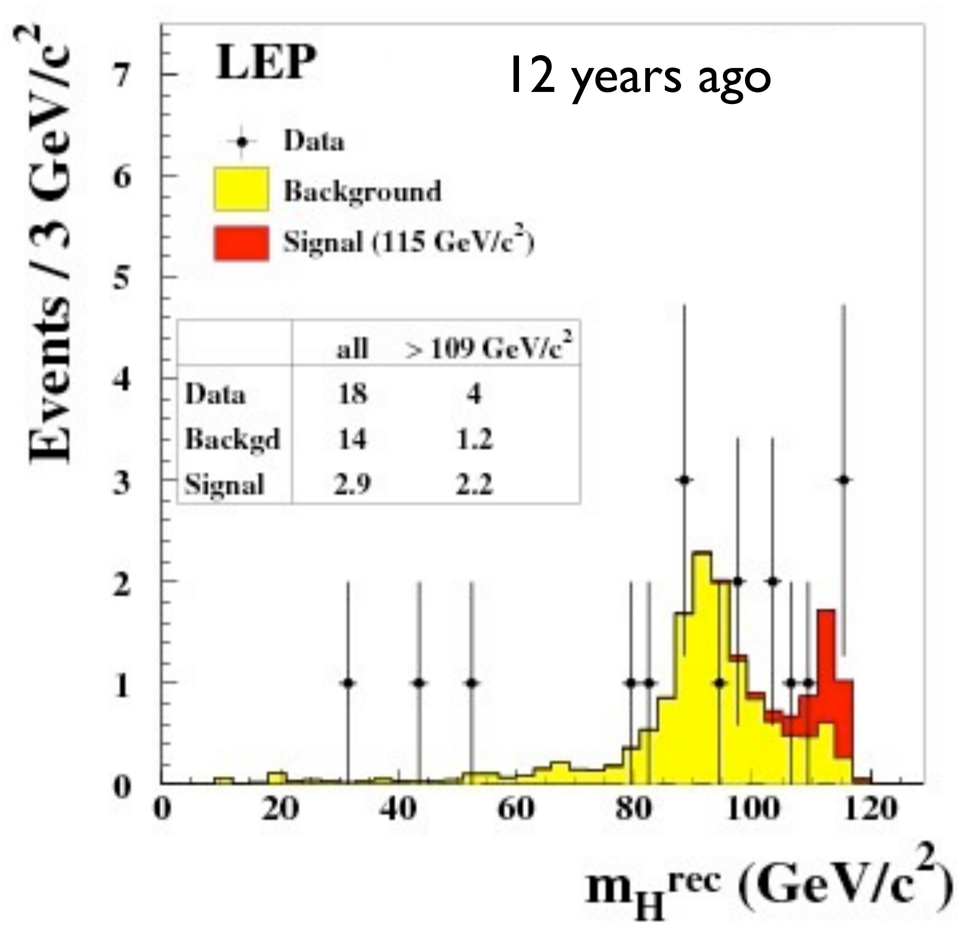
Gauge theory predicts force carrier particles to be massless e.g. photon & gluon
But $W^\pm$ & Z^0 boson have large masses ~80-90 GeV (proton~1 GeV)
Higgs mechanism explains why $W^\pm$ & Z^0 bosons are not massless

Higgs properties are well known except its mass!

Direct searches at the LEP e^+e^- collider
No Higgs found within energy range of LEP ⇒ mass m_H>114 GeV



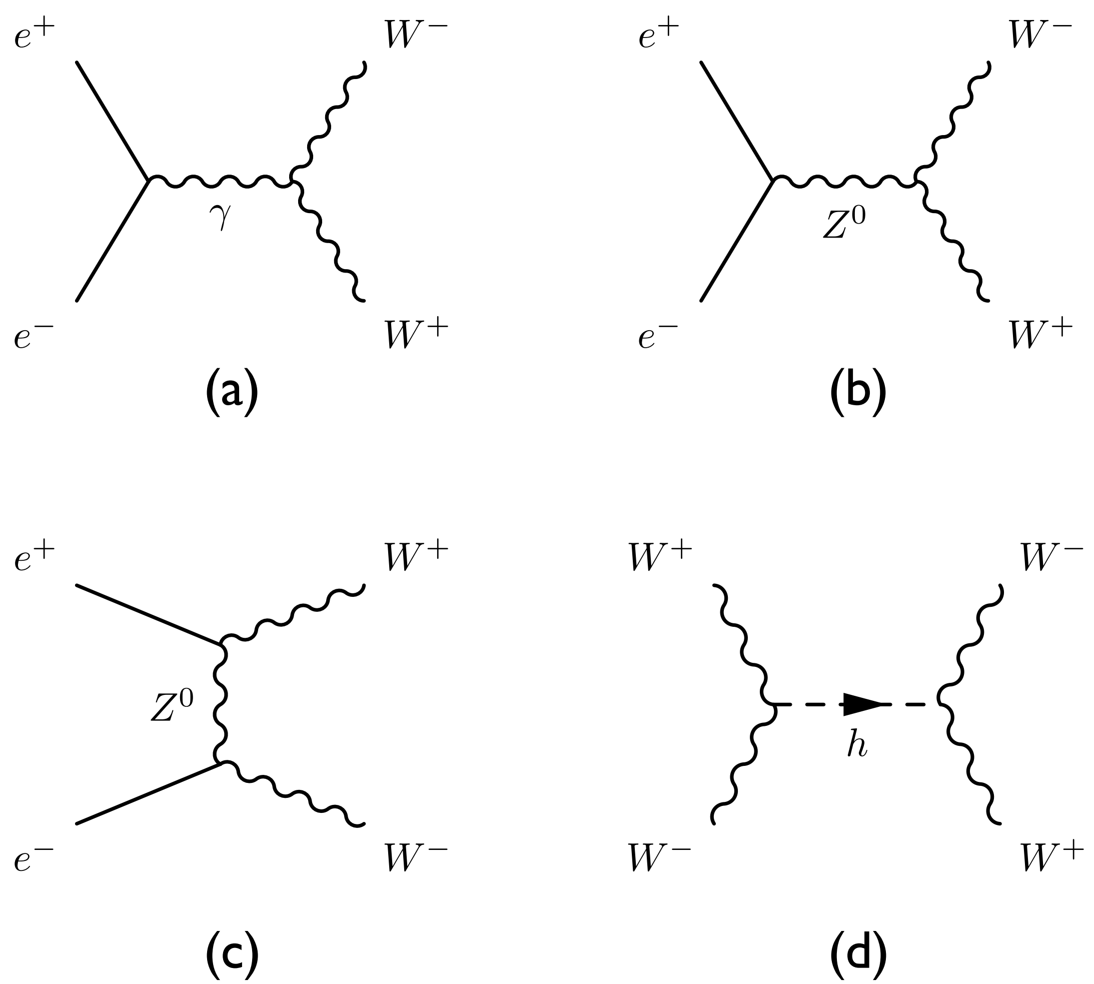
4 LEP experiments combined their data
points = data after many selection criteria
yellow = simulation of background contribution
red = simulation of potential Higgs contribution
Not statistically conclusive!
LEP was shutdown to start LHC construction



Higgs also saves the SM from some embarrassing predictions
Examine energy dependence of scattering process $e^+e^- \rightarrow W^+W^-$

Processes (a) (b) and (c) become larger than total e^+e^- reaction rate! (probability greater than 100%)

Higgs-like particle is needed to cancel $e^+e^- \rightarrow W^+W^-$ theoretical inconsistency



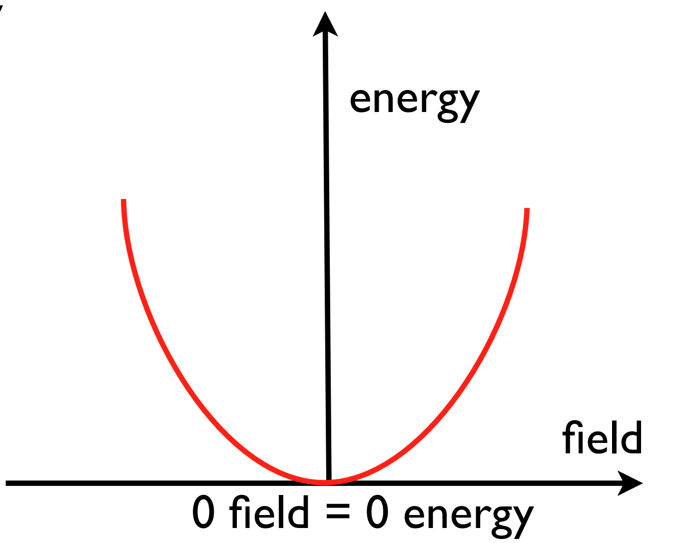
Requires Standard Model Higgs to be <~1TeV

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!

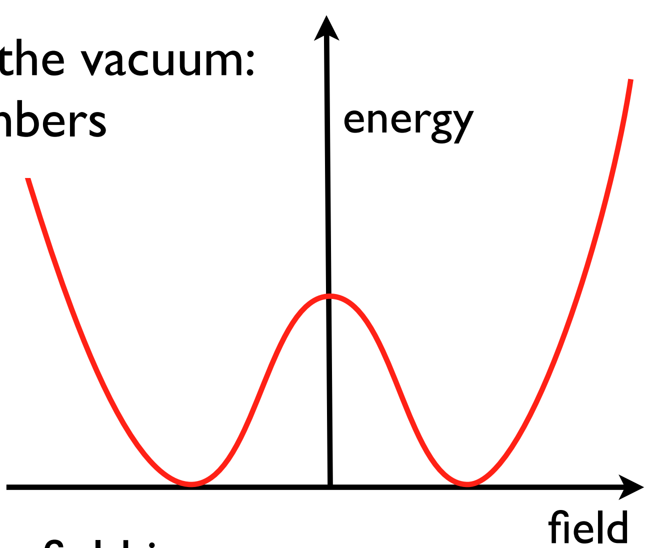
Higgs boson is required to explain why $W^{\pm}$ and Z^{0} bosons are very heavy
And why the photon is massless
In a symmetric theory all force particles should be massless



In quantum field theory all particles are described as oscillations in a field
Electrons are oscillations of the 'electron field' etc...
Oscillations are the particle wave functions

Usually fields have zero energy when field is zero
energy $\propto$ field^2

Higgs particle is a particle of the vacuum:
Has zero for all quantum numbers
- no charge
- no colour
- no spin
It just has mass!



In early universe at the Big Bang field was zero
As universe cooled Higgs field 'collapsed' to lowest energy

Higgs field has energy when field is zero
Higgs field has minimum energy when field is non-zero

In vacuum of empty space energy = 0
so Higgs field is non-zero
⇒ Higgs particles are everywhere!

Any particles interacting with Higgs field acquire mass - Higgs particles slow them down

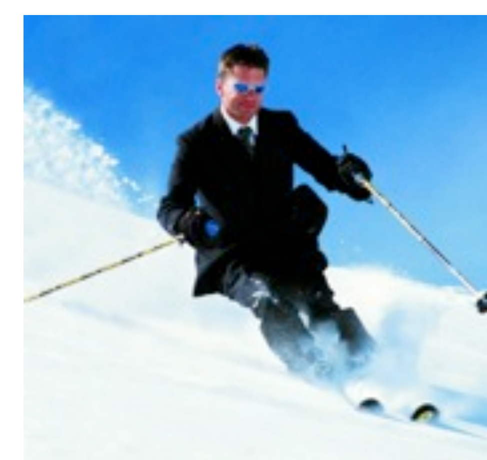
The Higgs Boson

Particle with strong Higgs interaction is slowed down
Imagine walking with boots on snow
Appear to have large mass

Particle with moderate Higgs interaction travels faster
Like walking with snow shoes
Has moderate mass

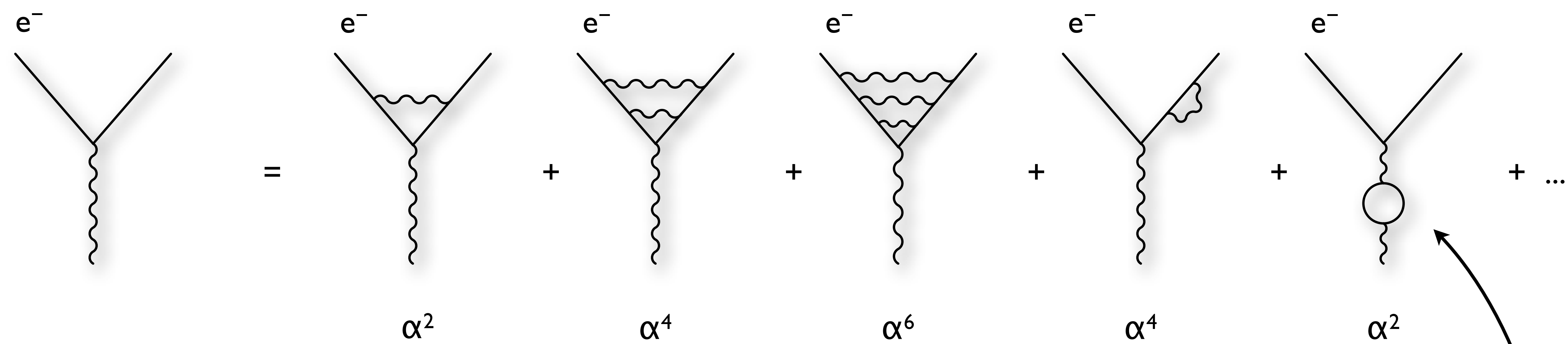
Higgs particle appears as a snow-flake

Particle with no Higgs interaction travels at speed of light
⇒ massless particle



Reminder from last week:
Quantum fluctuations affect all reaction rate measurements
Effects are subtle but measurable
Consider e⁻ scattering process:

e.g. photon converts into all possible fermion/anti-fermion pairs and back again:
$e^+e^-, \mu^+\mu^-, u\bar{u}, s\bar{s}...$



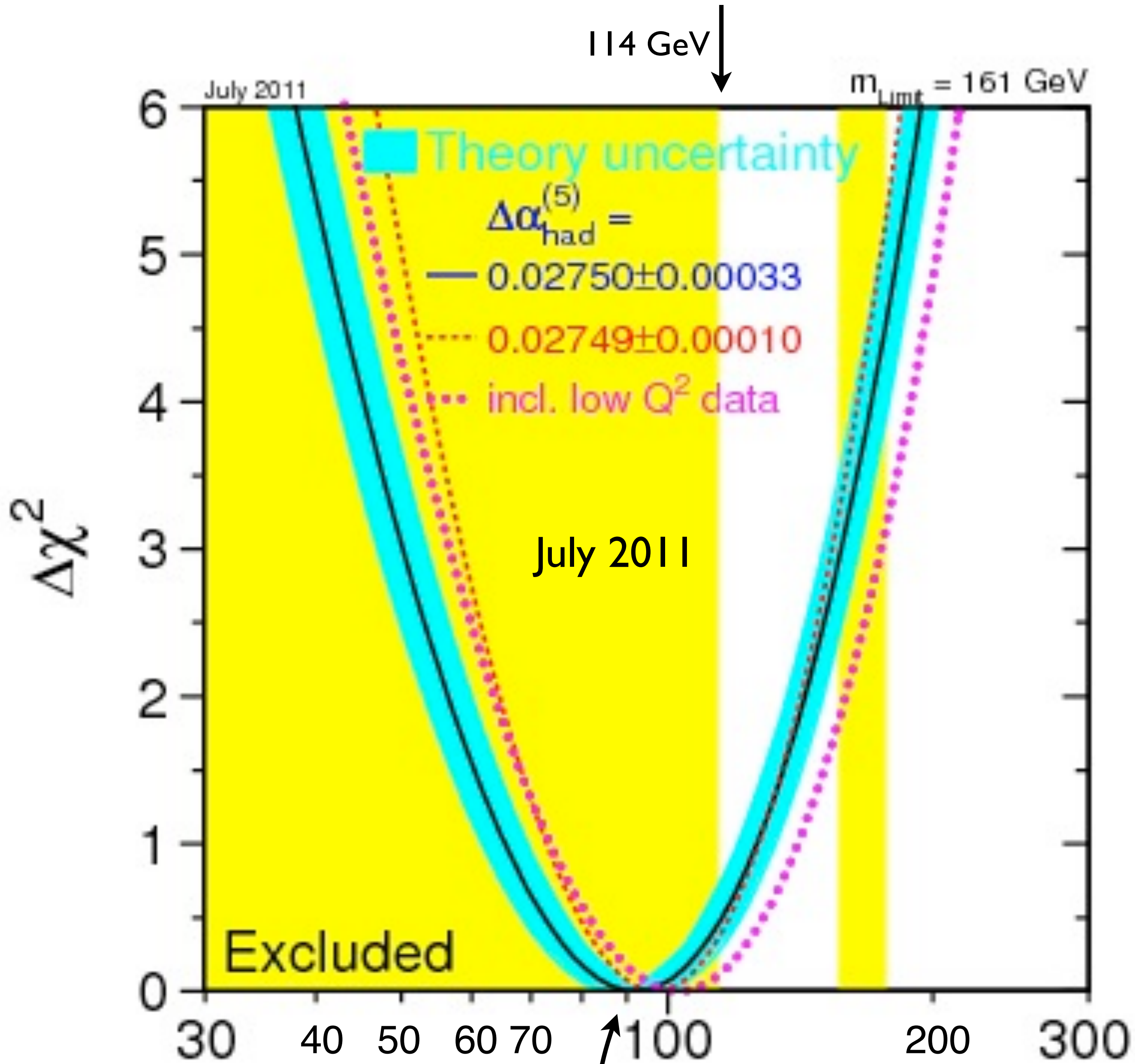
An infinite number of diagrams contribute to this scattering process
Result is finite due to cancellations

All these and more diagrams are required to calc g-2 of the electron with high precision (see lecture 4)
Precision measurements are weakly sensitive to existence of new particles modifying "loop corrections"
Particle masses also affected by such quantum fluctuations
Particles have fixed mass, but experimentally measured mass = "bare" mass + quantum fluctuations

$$m_H^2 = m_0^2 + \Delta m_H^2$$

quantum fluctuations affect a "bare" particle mass resulting in experimentally measurable mass

Indirect sensitivity to Higgs mass:



68% prob of SM Higgs in range 92^{+34}_{-26} GeV
95% prob of SM Higgs < 161 GeV

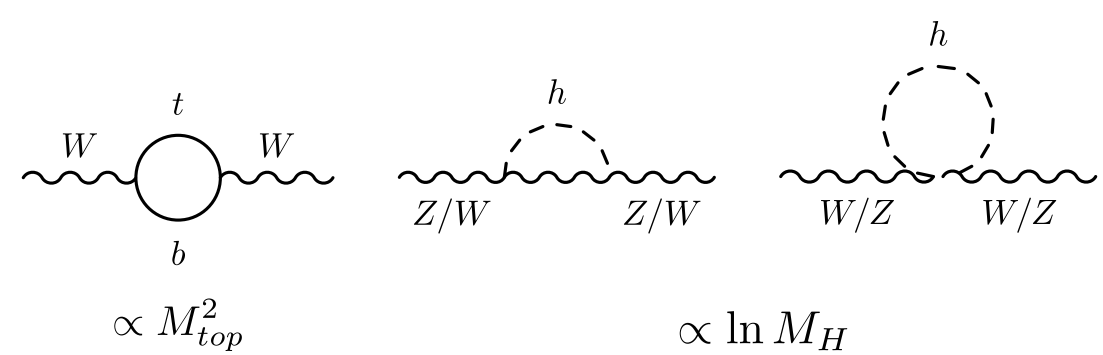
χ^2 is a statistical quantity

Compare data and theory with each other
→ extract theory parameters where χ^2 is smallest

(χ^2 is only valid within context of theory being tested)

Precise measurements at low energy are sensitive to Higgs loops

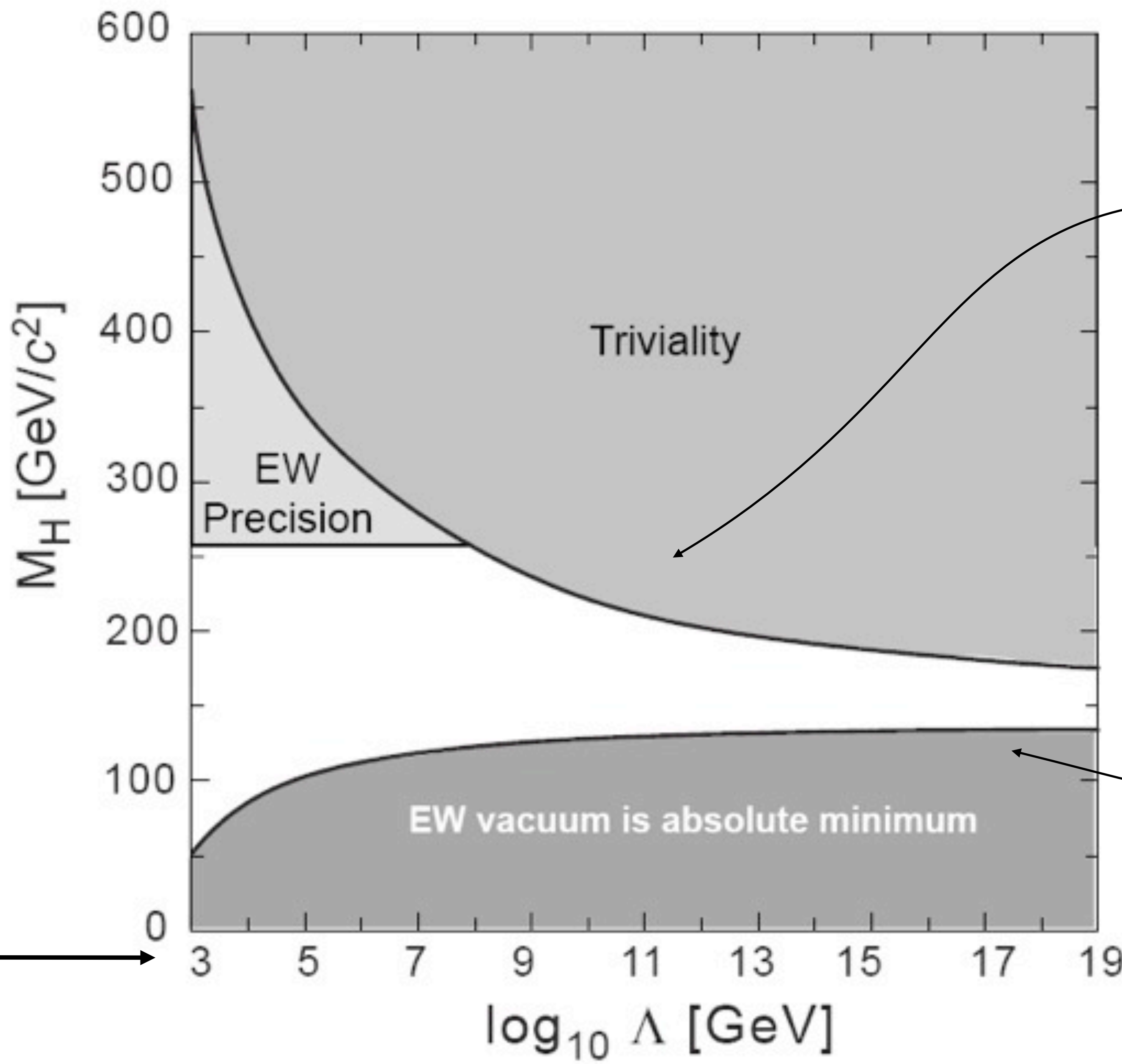
Loop corrections to Z/W scattering reactions :



Measurements at energy E < M_H are logarithmically (i.e. weakly) sensitive to M_H
Confront data & theory: χ^2 test

Indicates light SM Higgs !
But large margin of error...

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



Requiring Higgs self coupling is finite for E < Λ fixes upper limit on M_H

Requiring Higgs self coupling > 0 for E < Λ fixes lower limit on M_H

1000 GeV →

← 10^{19} GeV !!!

Λ is energy scale at which new physics appears

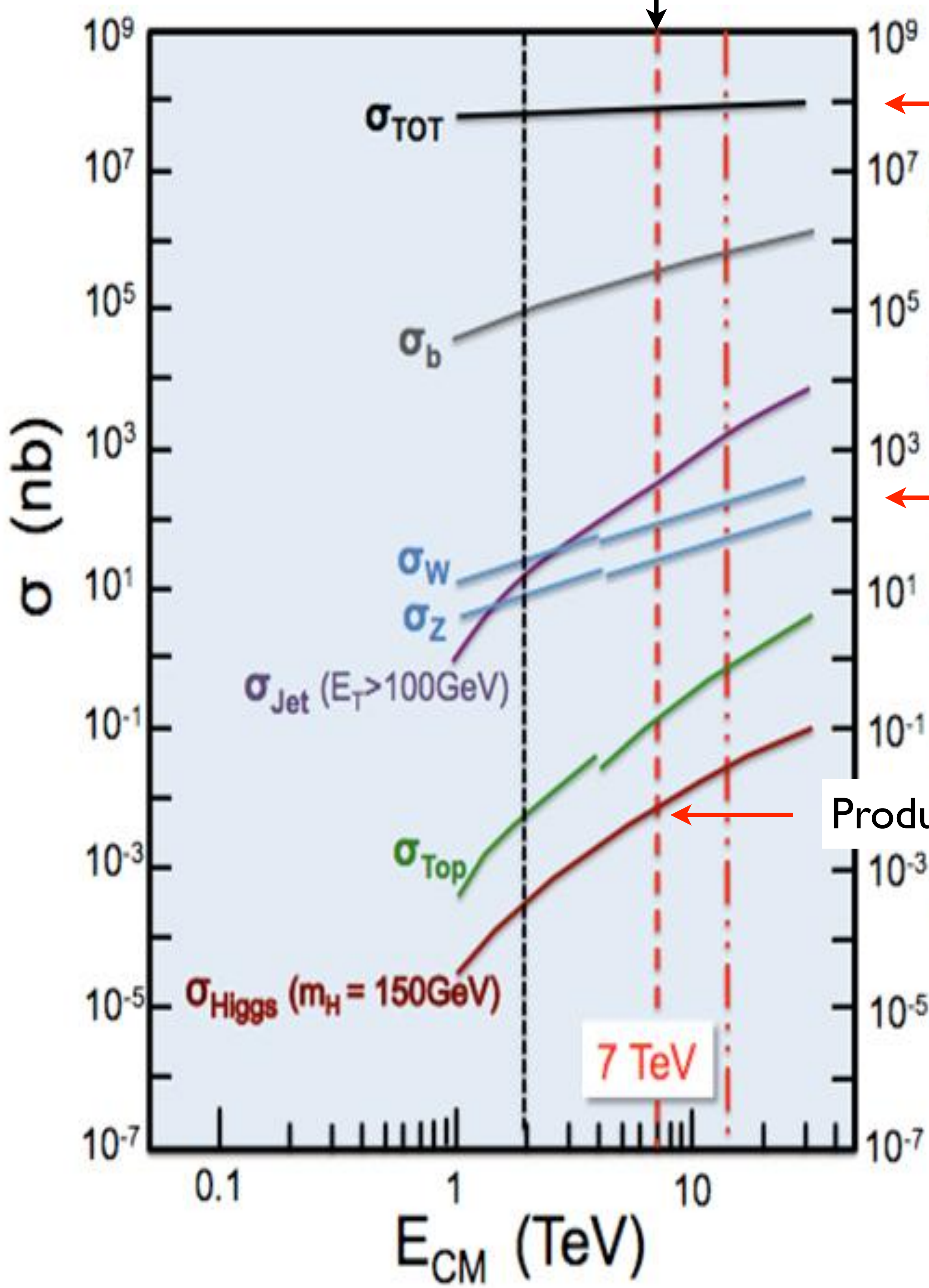
Λ must be < 10^{19} GeV
Scale at which gravity effects become important

The Higgs Boson

σ = reaction rate

current LHC operating energy

Number of events (i.e. collisions) per second



Total rate of data produced by LHC: 100,000 events/second

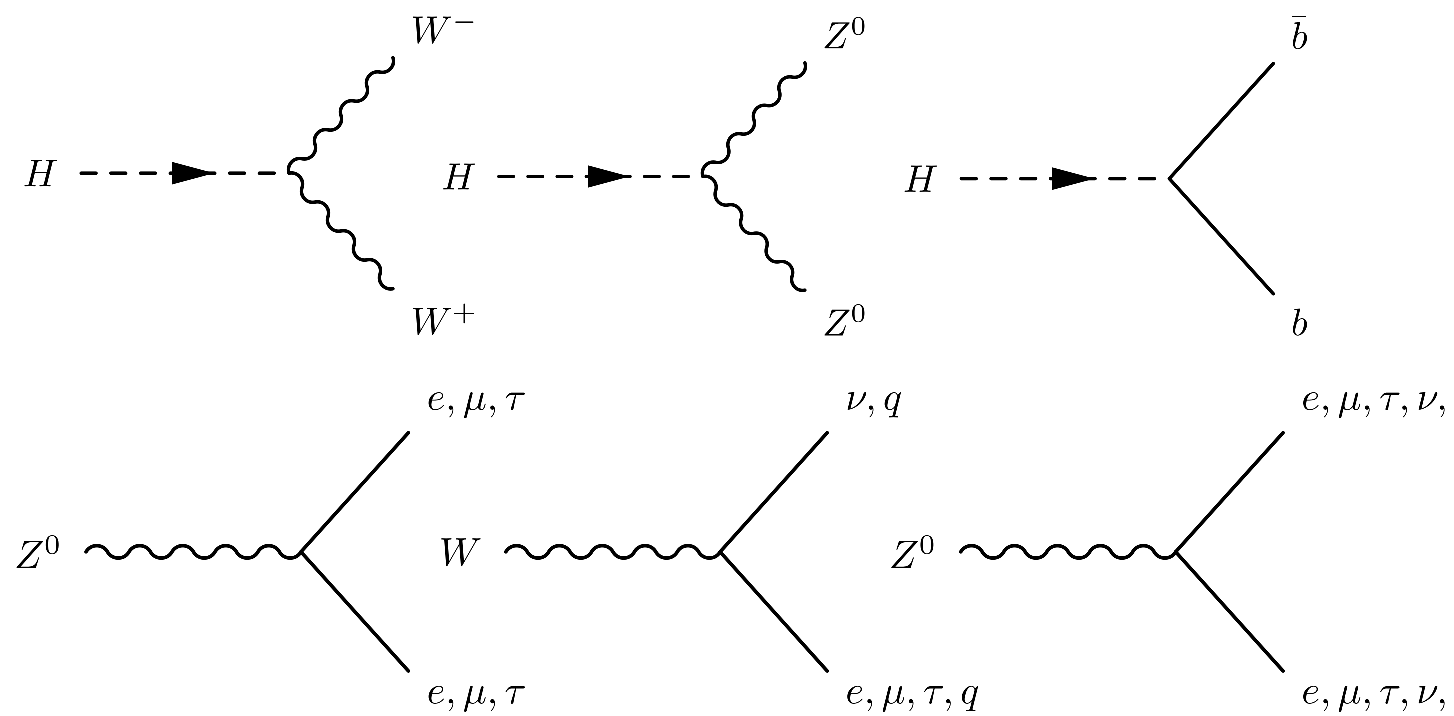
Huge event rates
New physics swamped!
Need to filter events 1:10^7 online

Maximum recording rate of ATLAS experiment: 200 events/second

Production rate of 150 GeV Higgs: 0.01 events/second

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

Many possible Higgs decay modes/channels:



W/Z can further decay to many combinations of fermions

H→ ZZ
ZZ → llll (4 lepton golden mode)
ZZ → llνν (good for high mass Higgs)
ZZ → llbb (good at high mass)

H→ WW
WW→ lνlν (most sensitive)
WW → lνqq (highest rate)

H→ γγ
Rare, best for low mass Higgs
high background

H→ττ
Rare, good at low mass, low background

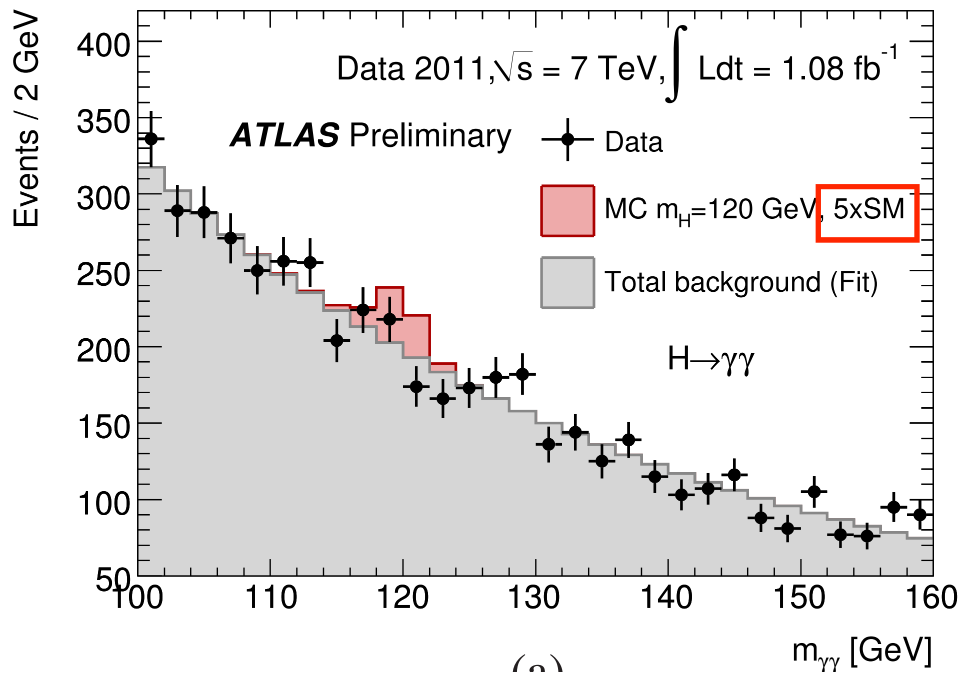
H→ bb
Useful but difficult to identify b quarks

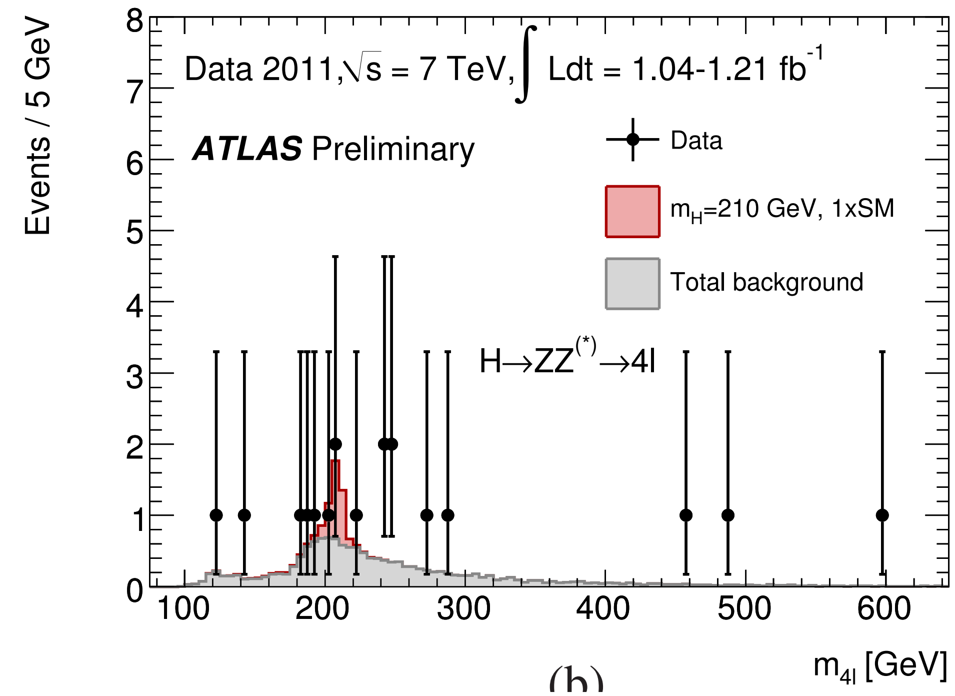
Each mode has different:
- sensitivity depending on mass range
- production rate
- contributions from background processes

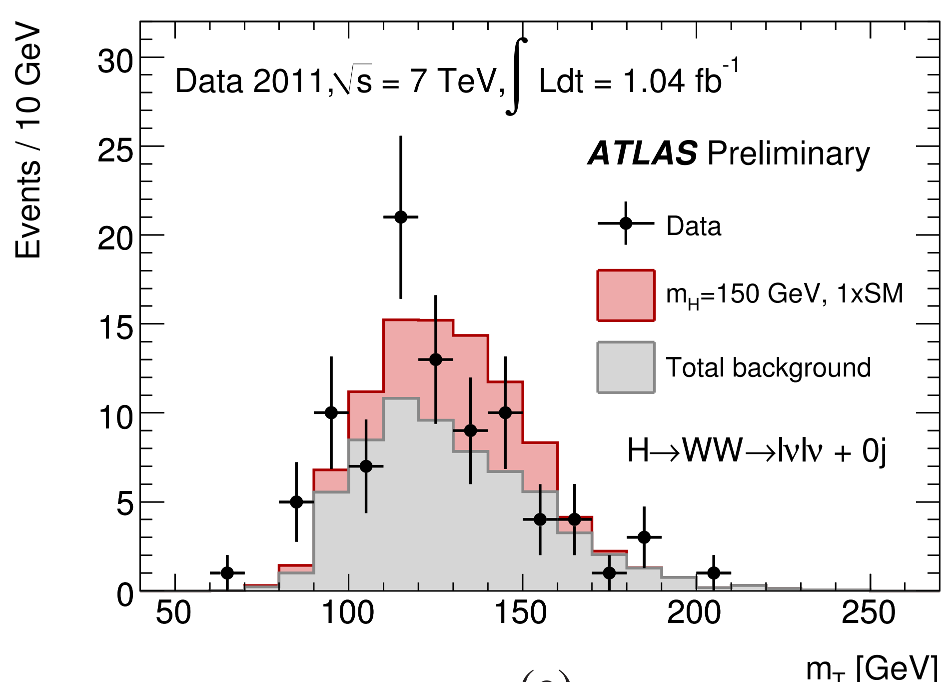
All modes need to be studied together!

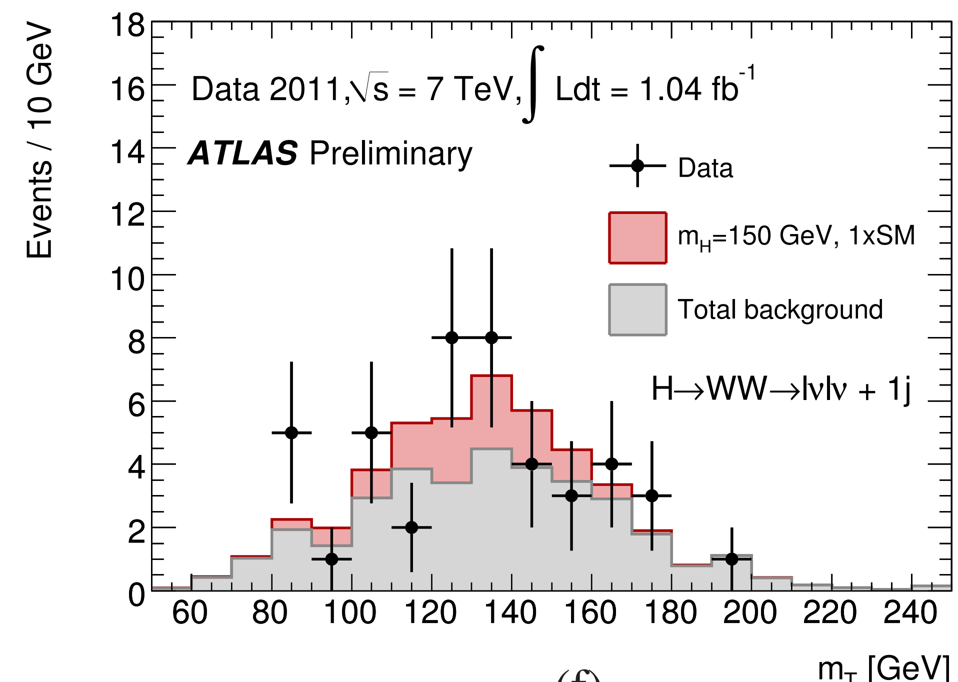
Four example channels demonstrating subtlety of finding the Higgs

- points = data
- grey histogram = background
- red histogram = simulated Higgs contribution for M_H = 120 / 150 / 210 GeV









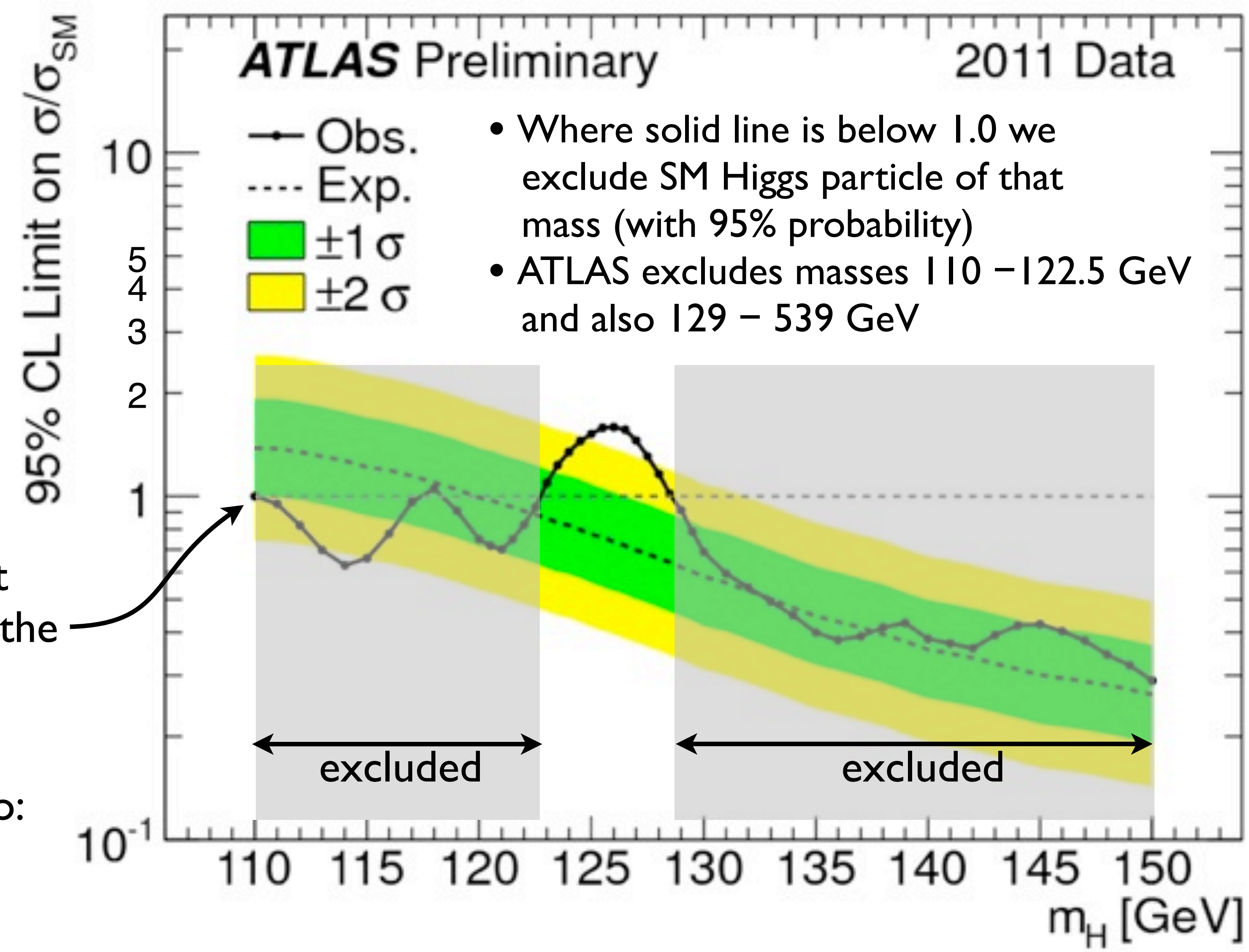
The Higgs Boson

Search all channels for Higgs decays
If not found then place upper limit on Higgs production rate versus M_H
SM predicts Higgs production rate for any given M_H

Solid black line = observation from data:
maximum allowed production rate
compared to SM prediction

Dashed black line = Simulation of experiment:
maximum allowed production rate
compared to prediction with no Higgs

For M_H = 110 GeV there is a 95% probability that Higgs production can be no more than 1.0 times the predicted SM rate



Any difference in solid / dashed lines is only due to:
- statistical fluctuations in the data
- Higgs

Quantify expected statistical fluctuations:
- 68% of fluctuations should lie within green band
- 95% of fluctuations should lie within yellow band

In region 122.5−129 GeV data show an excess
Excess is still consistent with fluctuation...
... but it's looking very interesting!

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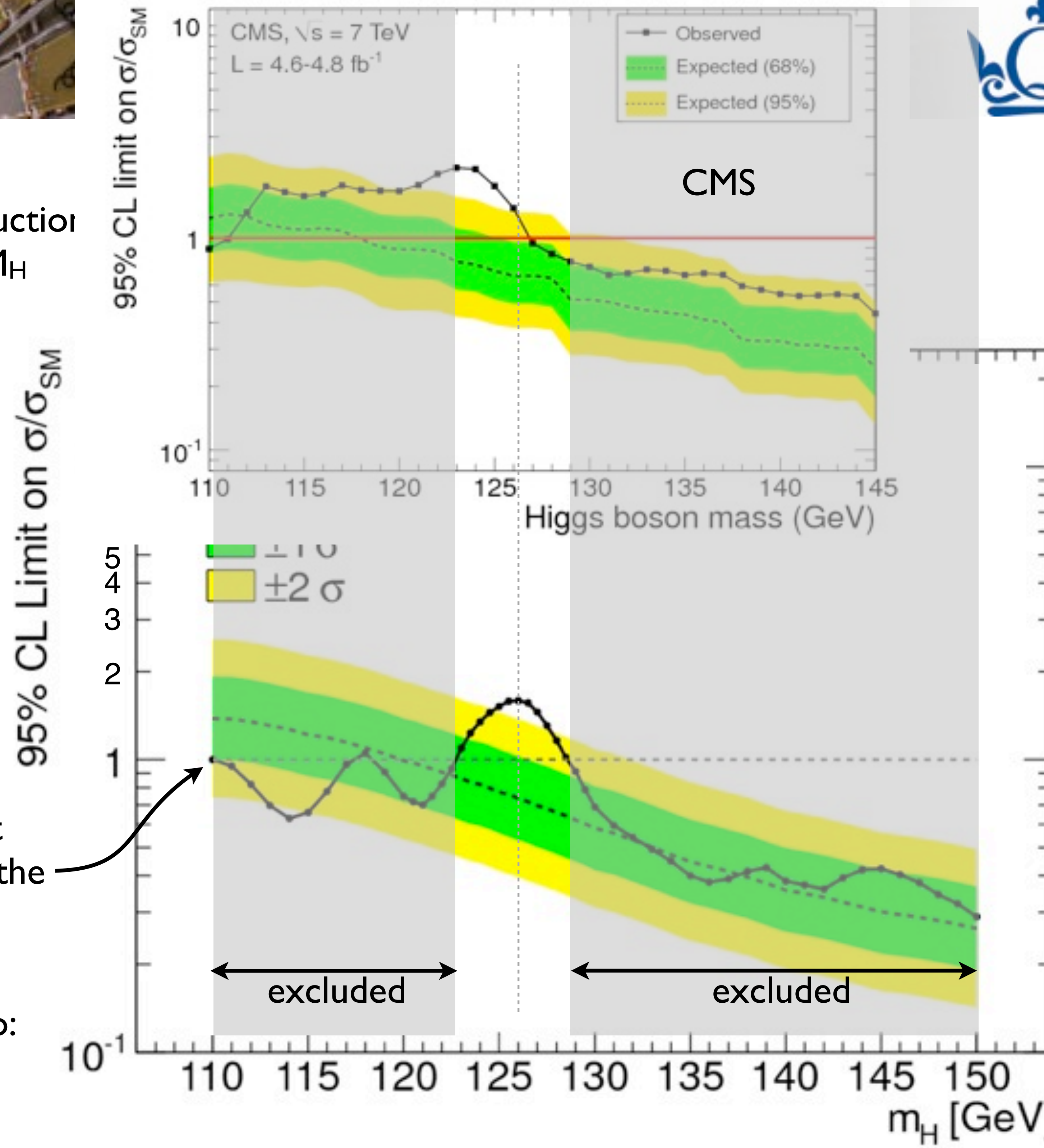

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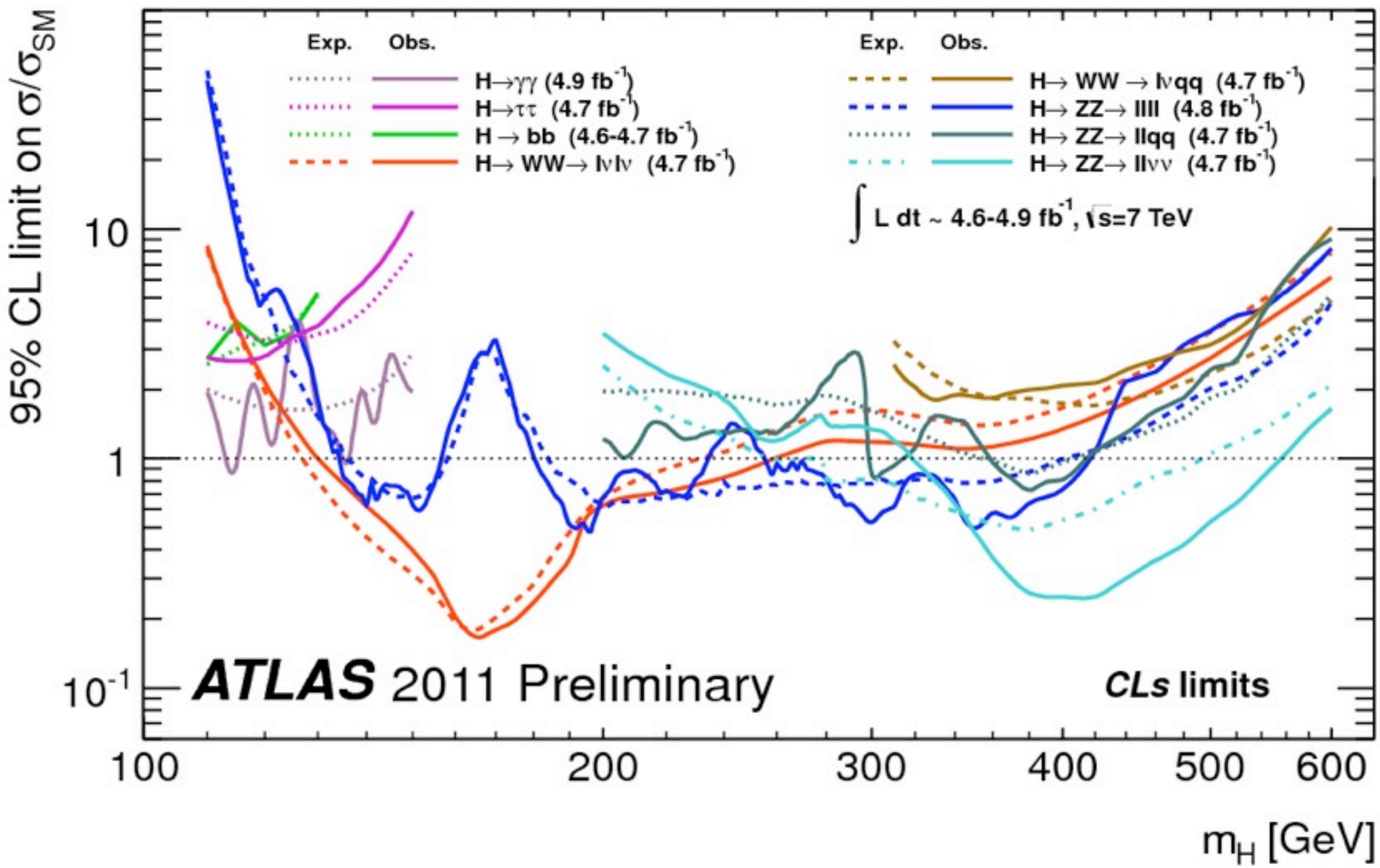
... but it's looking very interesting!

In case you wanted to see the full version of this graph!



The Heirarchy 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:
Corrections to Higgs mass rapidly diverge up to 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:

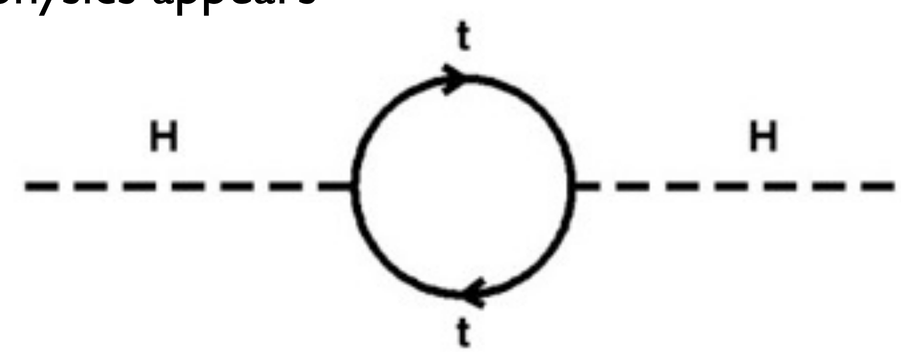
top quark loop: $\Delta m_H^2 = -a\Lambda^2$

W/Z boson loop: $\Delta m_H^2 = +b\Lambda^2$

Higgs loop: $\Delta m_H^2 = +c\Lambda^2$

Λ is the energy up to which the SM is valid
... or the energy at which new physics appears

a,b,c are couplings of particles to Higgs



top quark loop contributing to Higgs mass

If Λ^2 ~ (10^{19} GeV)^2 and m_H^2 ~ (100 GeV)^2

$$m_H^2 = m_0^2 + (-a + b + c)\Lambda^2$$
$$m_H^2 = m_0^2 + (-a + b + c) \cdot 10^{38} \approx 100^2$$

If SM is valid to energy scale Λ (i.e. no new physics from 10^3 GeV − 10^{19} GeV)
incredible fine tuning required between bare mass and the corrections
to maintain ~ 100 GeV Higgs mass

Supersymmetry

What are the alternatives to the Standard Model?

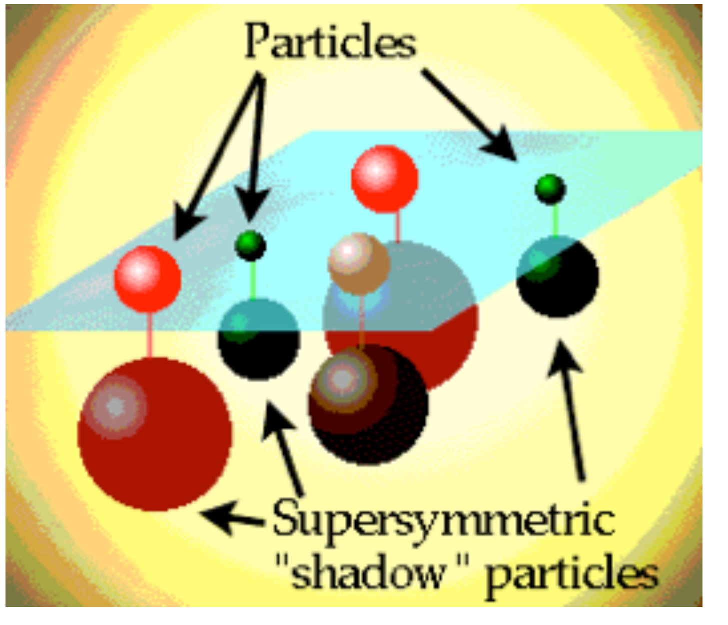
"The LHC opens a door to a new room, but we've got to have a good look around in that new room. The Higgs particle is a very important question but it's far from the only one."
Jon Butterworth

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)

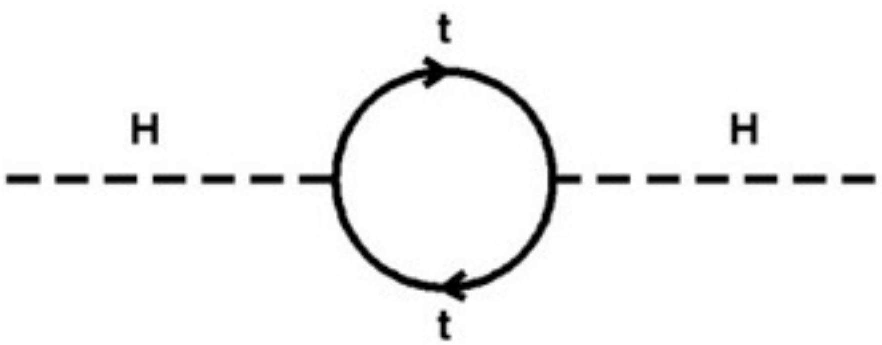
Immediately double number of particles
Each SM particle has a super-partner sparticle

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??

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 diverge up to 10^{19} GeV
If SM valid upto Planck scale then incredible fine-tuning of cancellations is needed to ensure ~1 TeV Higgs mass
Seems unnatural
Only a problem for the Higgs (only SM particle with spin 0)

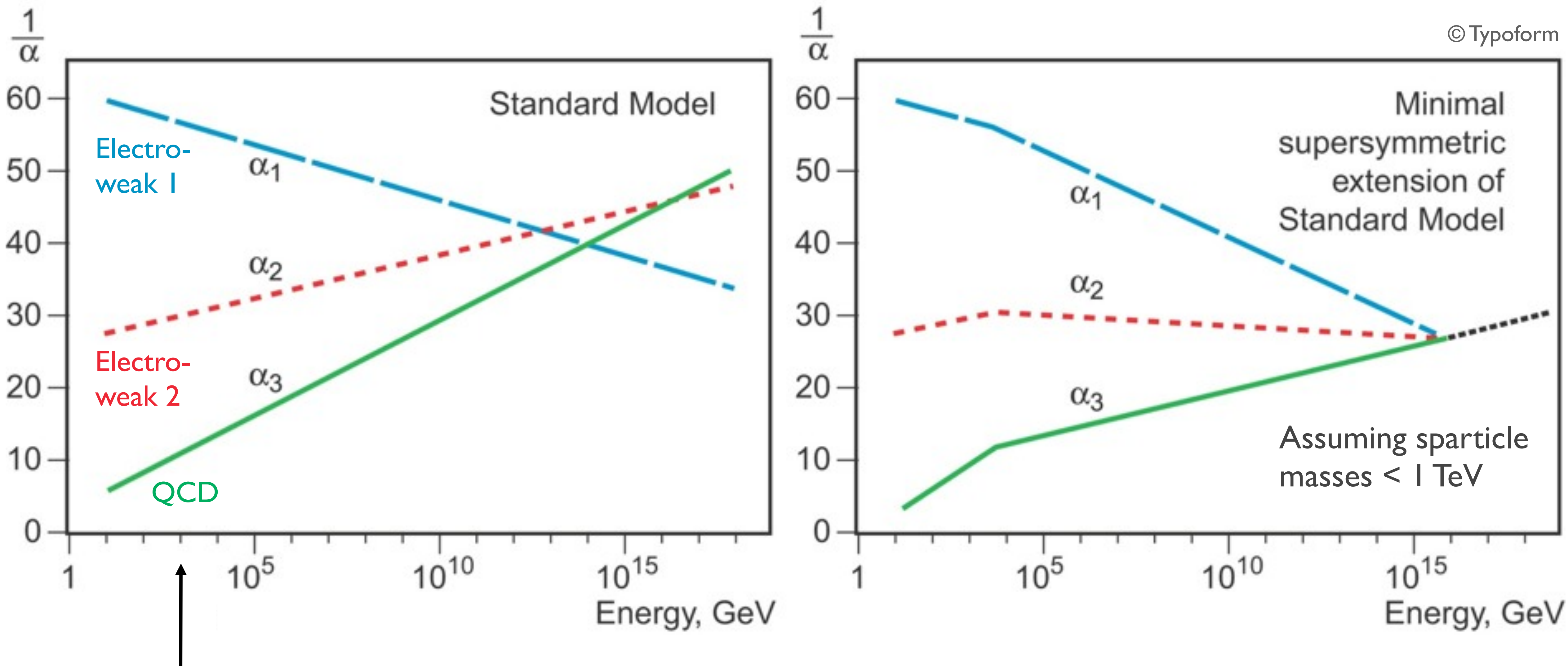
New SUSY sparticles (e.g. stop squark) contribute and cancel identically

Higgs interaction with spin 0 sparticle cancels SM quantum corrections above

GUT Unification

Another of SUSY's charms:

Coupling constants extrapolated to Planck scale do not intersect

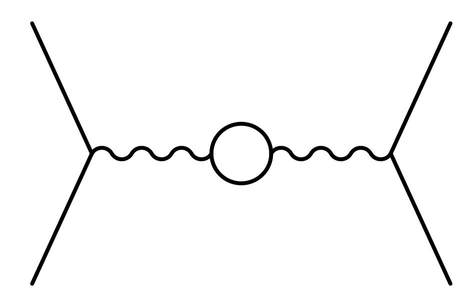


Current measurements at 1000 GeV

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

- 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

units
c → m s^{-1}
G → m^3 Kg^{-1} s^{-2}
ħ → Kg m^{-2} s^{-1}

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

Planck energy

$$L_{\text{Planck}} = \sqrt{\frac{\hbar G}{c^3}} = 10^{-35}\ \text{m}$$

Planck length

$$T_{\text{Planck}} = \sqrt{\frac{\hbar G}{c^5}} = 10^{-44}\ \text{s}$$

Planck time

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!

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 live in 10 or 11 dimensional 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!!!

Large Extra Dimensions

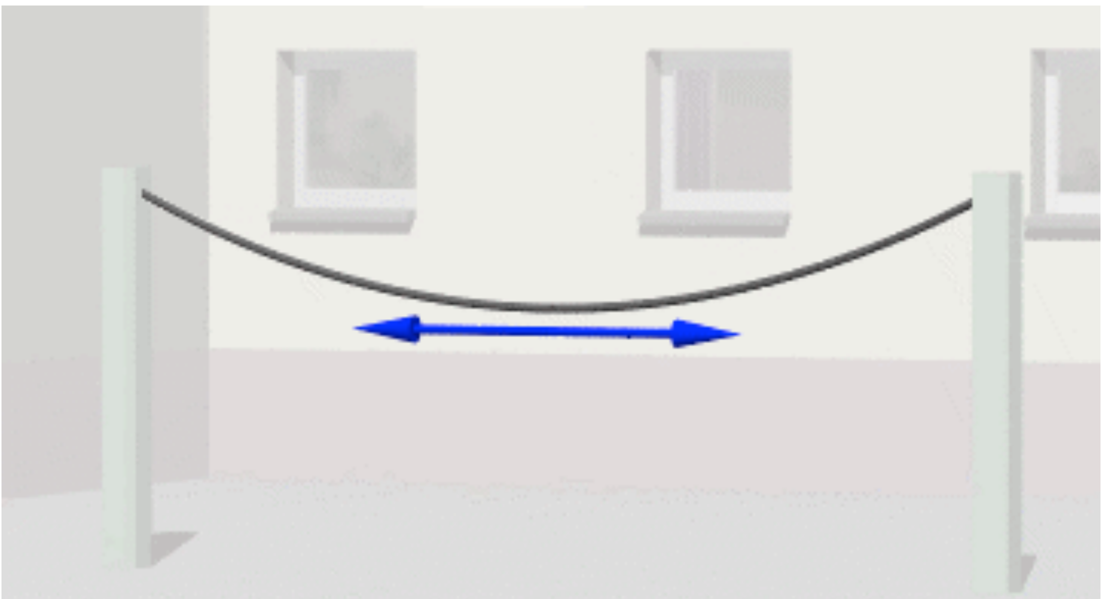
Why are the extra dims < 1 mm ?

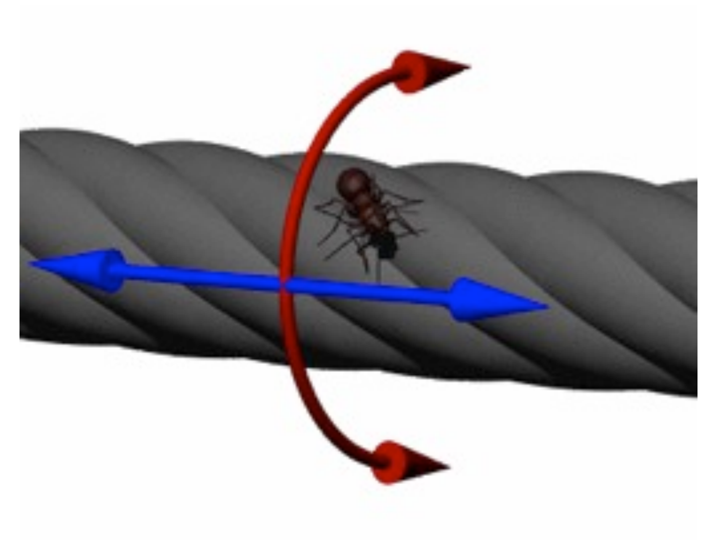
gravity has only been tested down to this scale!

Where are the extra dimensions?

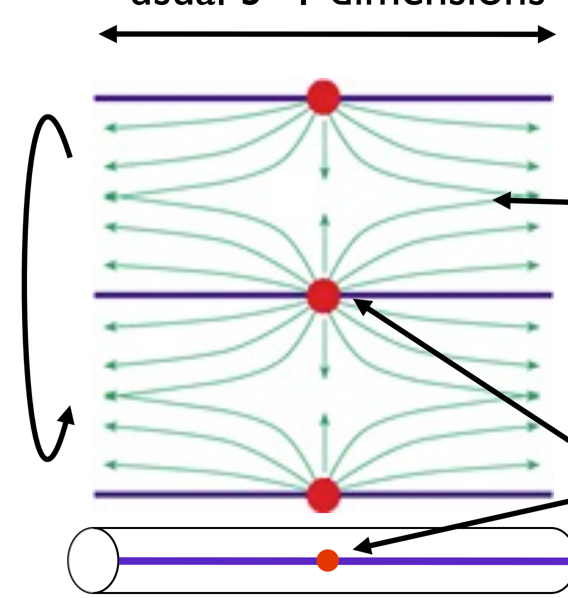
curled up (compactified) and finite

only visible at small scales / high energies





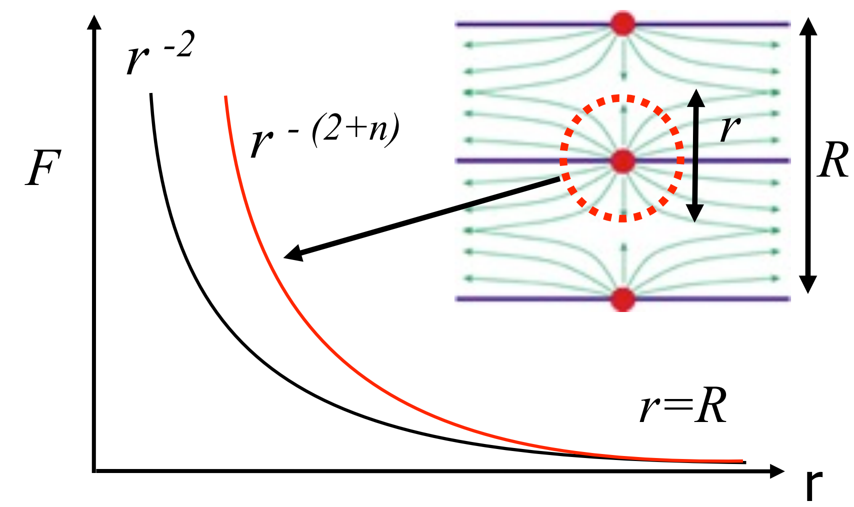
Relative strength of gravity explained by dilution of gravitons propagating in very large volume of bulk space



Large Extra Dimensions

With extra dimensions gravity becomes modified

Newton's law: $F = \frac{m_1 m_2}{r^2}$



With *n* extra spatial dimensions each of size *R*

$$F = G_D \frac{m_1 m_2}{r^{2+n}}$$

$$F = \left(\frac{G_D}{R^n}\right)\frac{m_1 m_2}{r^2} \quad \text{i.e} \quad G = \frac{G_D}{R^n}$$

dilution due to volume of extra dimensions

For $r \gg R$ we recover Newtonian gravity

Planck scale: $M_P^2 = \frac{\hbar c}{G}$

In extra dimensions full scale of gravity M_D is given by $M_D^{2+n} = \frac{\hbar c}{G_D} = \frac{M_P^2}{R^n}$

Thus M_D can be ~ 1 TeV when R^n is large

To be continued in final lecture...