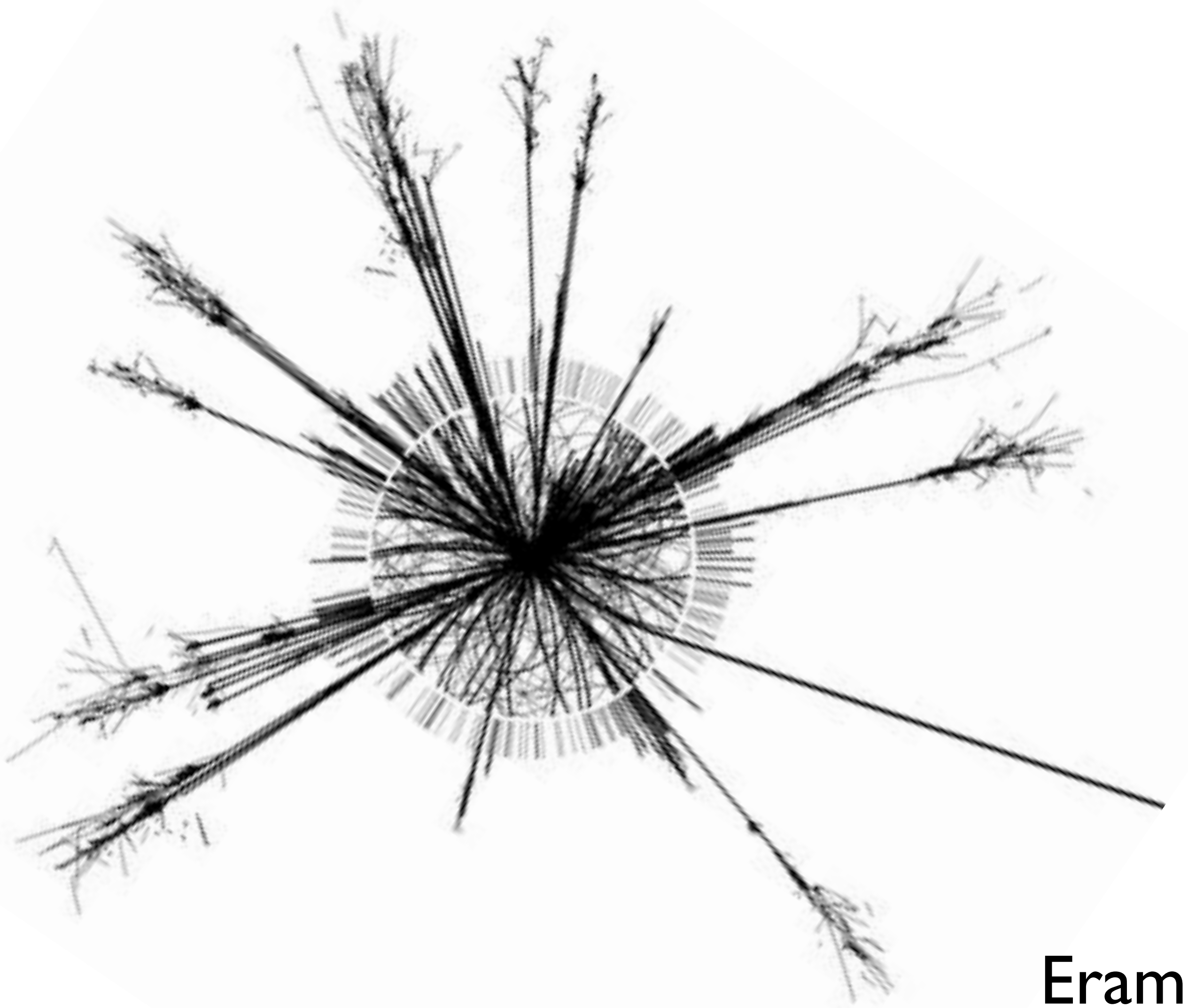
The Higgs and Beyond



- The Standard Model
- The Higgs Boson
- Hunting for the Higgs Boson
- What next?

Eram Rizvi

Queen Mary University of London

PsiStar - QMUL - London

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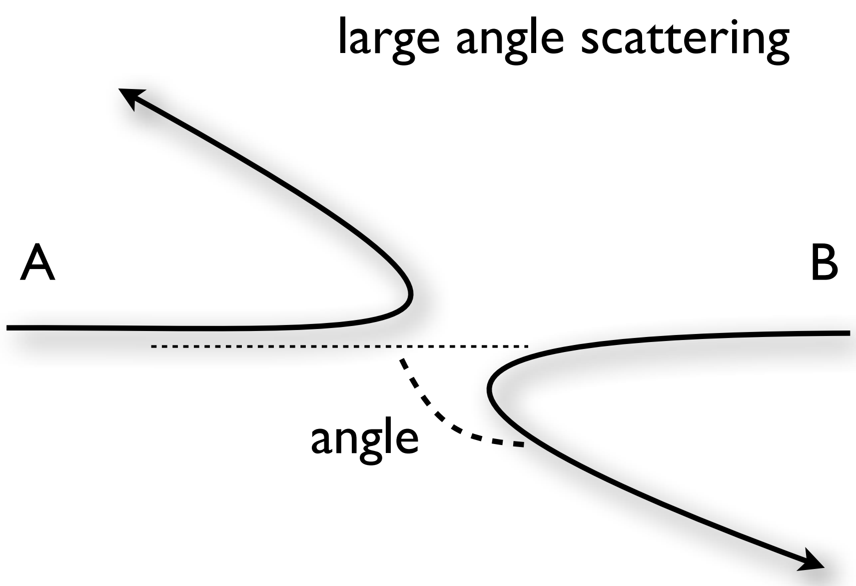
The Standard Model

	Quarks						Leptons		
electric charge	+2/3			-1/3			-1	0	
Fermions	u	u	u	d	d	d	e	ν_e	I
	c	c	c	s	s	s	μ	ν_μ	II
	t	t	t	b	b	b	τ	ν_τ	III

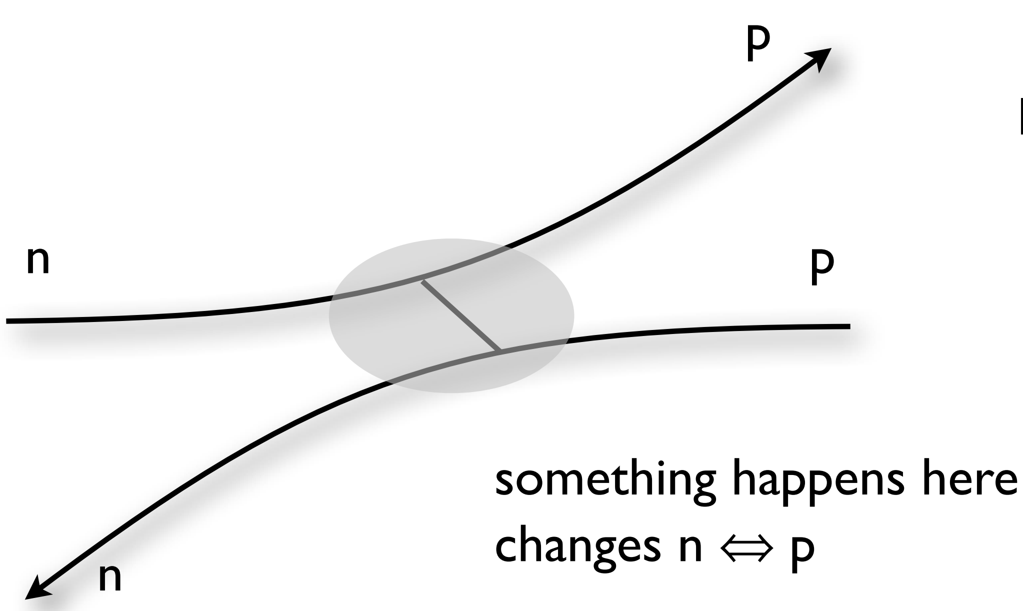
Bosons		
g g g g g g g g	8 gluons
W Z γ	3 electroweak bosons
H	1 Higgs boson

Our new baby is just 4 months old

The Exchange Model



Momentum is transferred between particles A and B

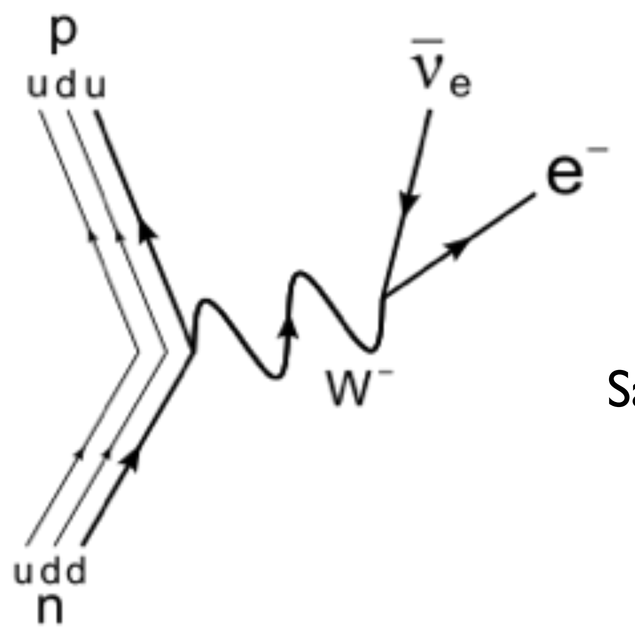


In some cases particles can even exchange identity!

The interaction must:
- exchange momentum
- exchange electric charge?

The Exchange Model

Weak force is responsible for β decay
quarks emit heavy W particle which decays



An exchange particle is forbidden
violates energy-momentum conservation

Particle cannot emit anything in its own rest-frame

Saved by the Heisenberg Uncertainty Principle:

$$\Delta E \Delta t > h$$

Small energy ΔE can be 'borrowed' for a time $\Delta t = h \,/\, \Delta E$!

This process is an interaction - it is the expression of a force of nature
Newton: force = rate of change of momentum (F=ma)

What can we predict about the exchange particle?

ΔE is 'used' to produce the particle with mass - what is it?
Weak force acts in β decay - has a range of 10^{-3} fm
Assume it travels at light speed c - how long does it live for?
$c\Delta t = 10^{-3}$ fm & $\Delta E = mc^2$

$$mc^2 \approx \frac{hc}{c\Delta t}$$

So m = 100,000 MeV/c^2
100 times proton mass!

But we don't understand why W,Z are heavy and photon is massless! ....

Feynman Diagrams

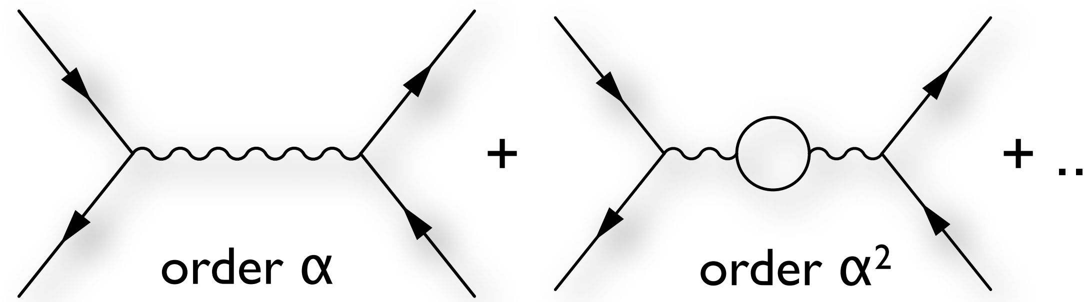
Transition due to the exchange of a gauge boson
Exchanges momentum & quantum numbers
Strength of the interaction is parameterised by <u>couplings</u> α
One α for each fundamental force

Simplest interaction is single boson exchange

More complicated loop diagrams also contribute

Draw all possible Feynman diagrams for your experiment:

M_{fi} = sum of transitions of initial state ψ_i to final state ψ_f

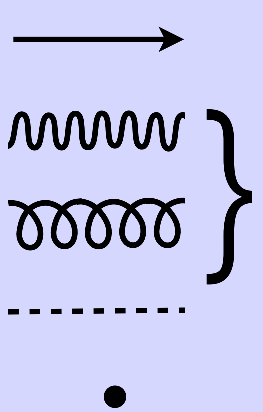


Potentially infinite series of diagrams for 2 → 2 scattering process

For each diagram calculate the transition amplitude
Add all transition amplitudes
Square the result to get the reaction rate

If perturbation is small i.e. α < 1
then contributions from extra loop diagrams is suppressed

Feynman Rules: start from left side



Write a free particle wave function for each particle
$$\psi = Ae^{i(kx-\omega t)}$$

Multiply by an exchanged boson write $\frac{1}{q^2 - m^2}$
for particle of momentum q and mass m

For each vertex multiply by coupling $\sqrt{\alpha}$ = e

Sum over all allowed particle states i.e. all quark flavours / colours / spins

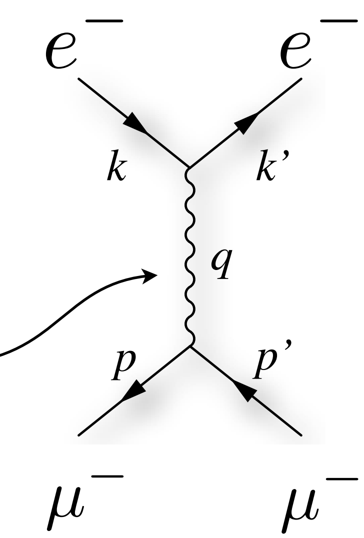
The propagator - transfers momentum
further a boson is from it's mass m
the more suppressed the interaction

reaction rate / probability $\propto |M_{fi}|^2$

Feynman Diagrams

in case you don’t believe me...

$$|M_{fi}|^2 = \frac{e^4}{q^4}\frac{1}{4}\sum_{spin}\{[\bar{u}(k')\gamma^{\mu}u(k)]\,[\bar{u}(k')\gamma^{\nu}u(k)]^*\}\{[\bar{u}(p')\gamma_{\mu}u(p)]\,\{[\bar{u}(p')\gamma_{\nu}u(p)]^*\}$$



note the photon propagator

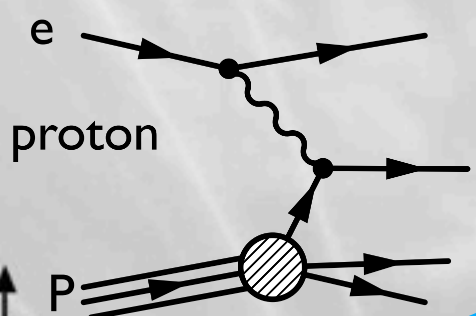
k, k' = incoming , outgoing electron momentum
p, p' = incoming , outgoing muon momentum
q = momentum transfer
e = strength of electromagnetic interaction (electric charge)

electron charge

For electromagnetism α_{EM} = 1/137 ~ e^2
Small enough for perturbation theory to work

For strong interaction α_S ~ 0.1
Perturbation theory works but need to calc more diagrams for precision - difficult!
For QCD it took 10 years to calculate second order diagrams!

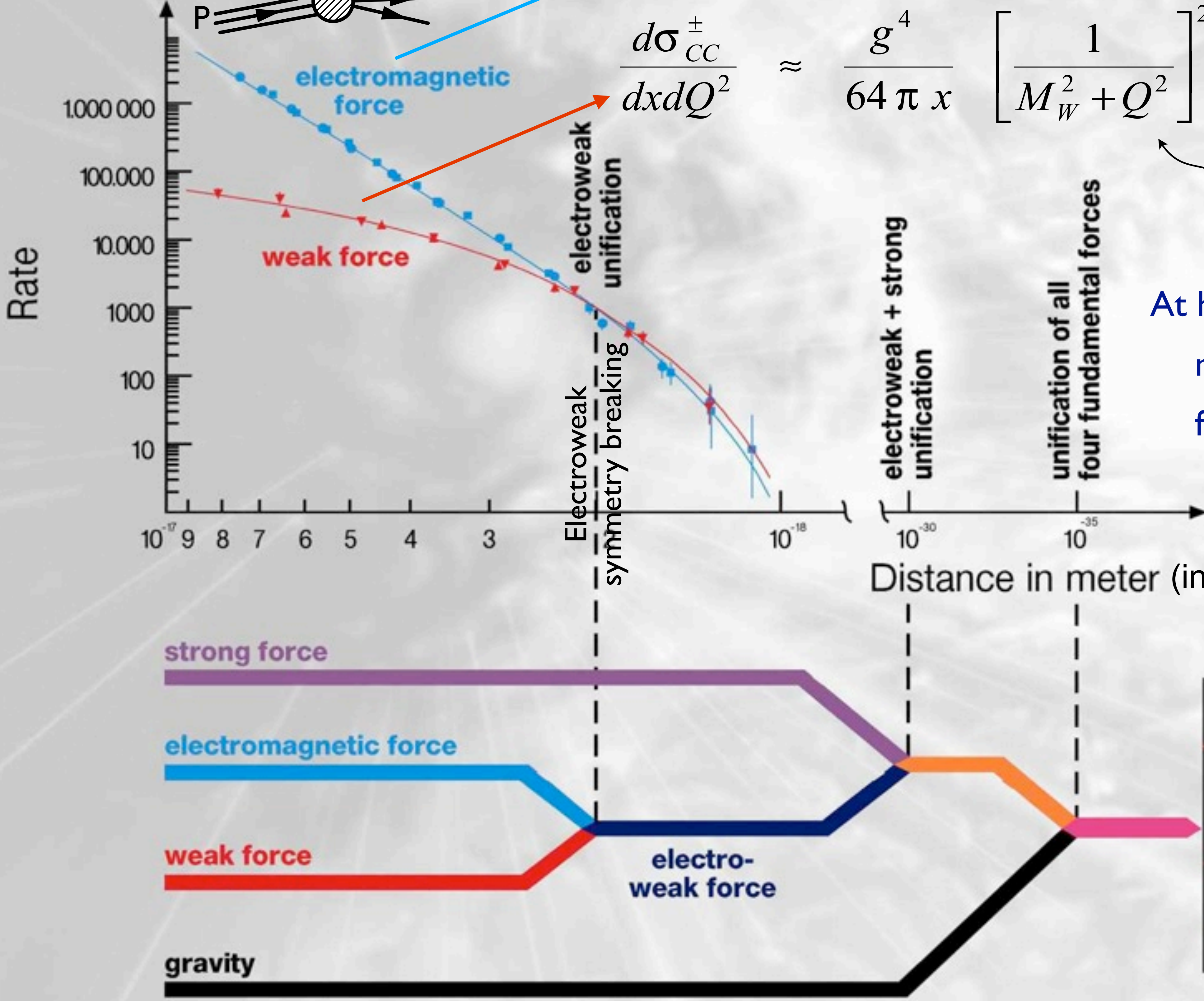
electron - proton scattering



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

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

propagator term



At high energy /momentum(Q):

masses M_W & M_Z are small

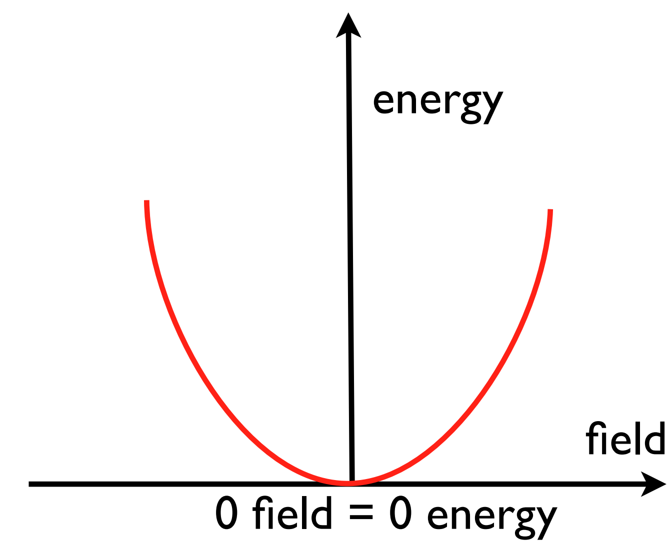
forces are ~ equal

big bang

Aim to unify all forces

Englert-Brout-Higgs-Guralnik-Hagen-Kibble Mechanism

Higgs boson <u>required</u> 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



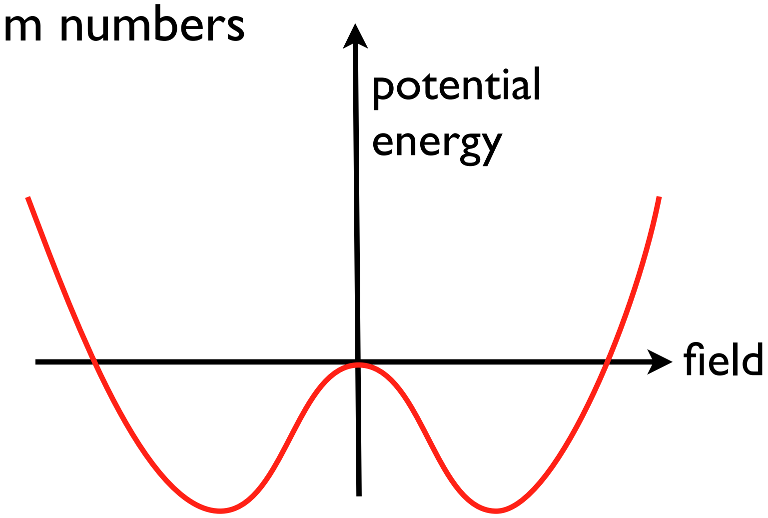
Usually fields have zero energy when field is zero: energy $\propto$ field^2

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

Higgs particle is a particle of the vacuum:
Has zero for all quantum numbers

- no charge
- no colour
- no spin

It just has mass!



At the Big Bang: field = zero
As universe cooled Higgs field 'collapsed' to min. energy

Higgs field has minimum energy when field is non-zero

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

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

Englert-Brout-Higgs-Guralnik-Hagen-Kibble Mechanism

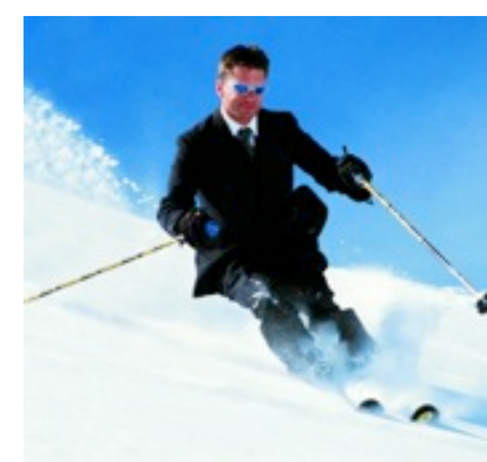
Empty space filled with Higgs field

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

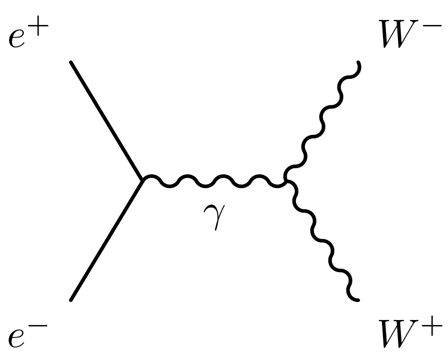


The Higgs Boson

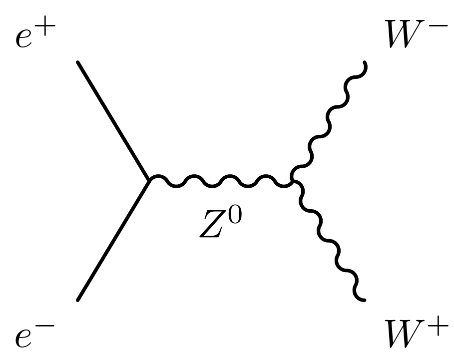
Higgs also saves the SM from some embarrassing predictions
Examine energy dependence of scattering process $e^+e^- \rightarrow W^+W^-$

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

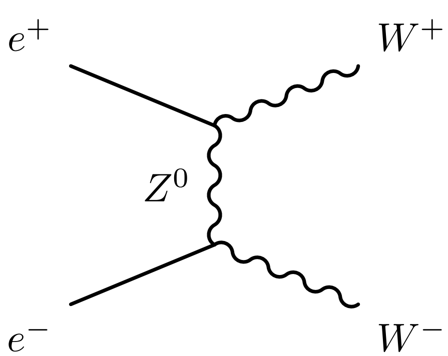
Higgs-like particle is needed to cancel $e^+e^- \rightarrow W^+W^-$ theoretical inconsistency



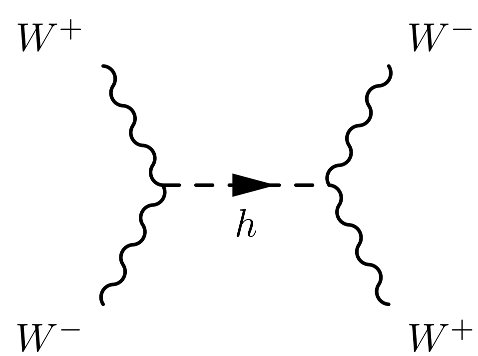
(a)



(b)



(c)



(d)

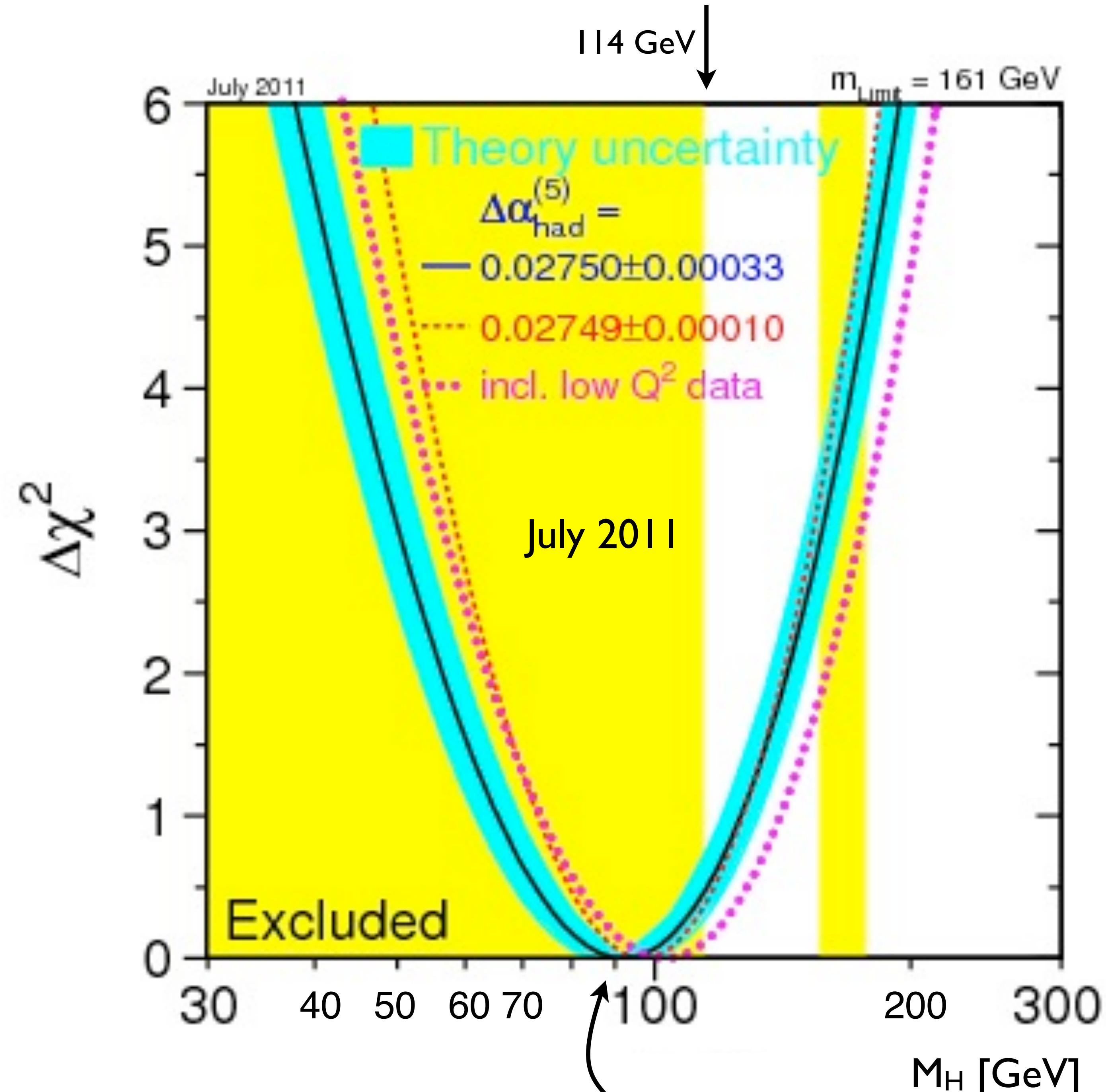
Requires Standard Model Higgs to be <~1TeV

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!

Indirect sensitivity to Higgs mass:



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

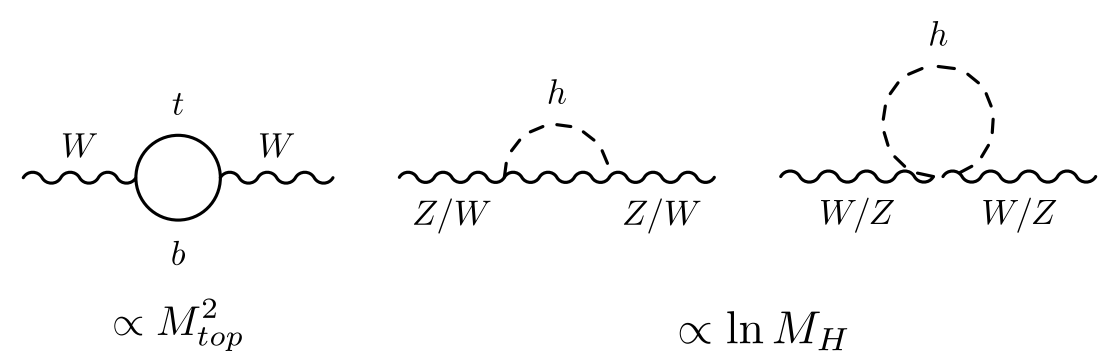
χ^2 tests the statistical compatibility of data & theory

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

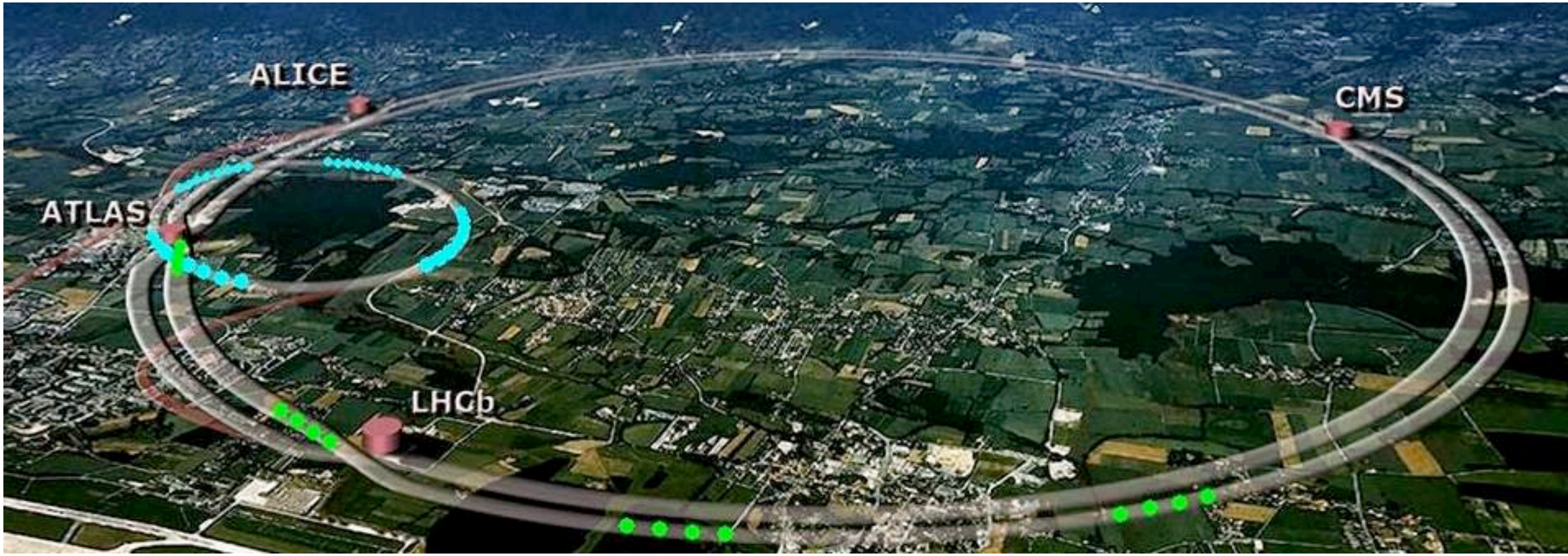
Loop corrections to Z/W scattering reactions :



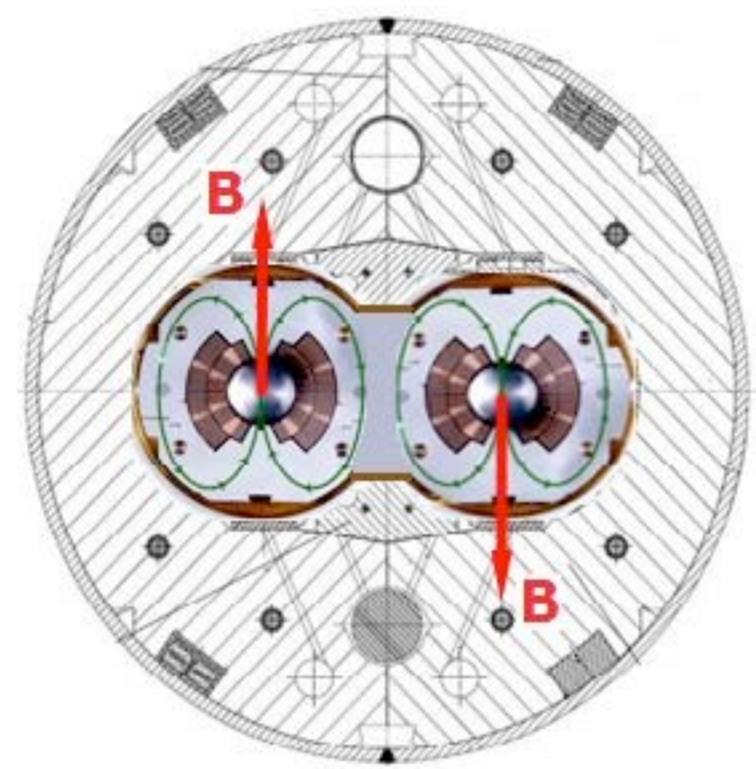
Measurements at energy E < M_H are logarithmically (i.e. weakly) sensitive to M_H
Confront data & theory: χ^2 test

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

The Large Hadron Collider

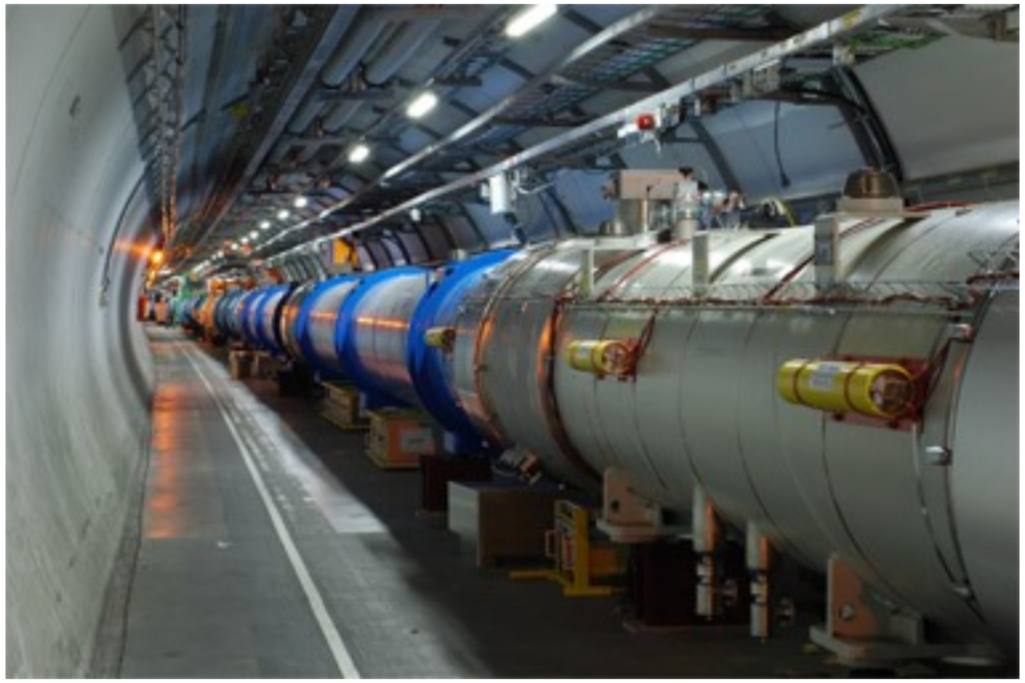


- 27 km circumference tunnel in France / Switzerland - near Geneva
- Highest energy accelerator in the world
- Protons accelerated to 7,000 GeV = 99.9999991% speed of light
- High vacuum
- Super cold superconducting magnets to achieve strong magnetic fields
- 17,000 A current in magnets
- Four experiments:
  - Atlas
  - CMS
  - LHCb
  - Alice



The LHC

Operating temperature: -271°C One of the coldest places in universe
High energy collisions equivalent to temperatures 100,000 times hotter than sun's core
High vacuum needed to avoid unwanted collisions with air molecules - less dense than solar system
1200 dipole magnets to bend the protons
Protons circulate 11,000 times per second
Generates up to 600 million collisions per second
LHC costs for material, construction, personnel (excluding experiments) = € 3, 000 , 000 , 000



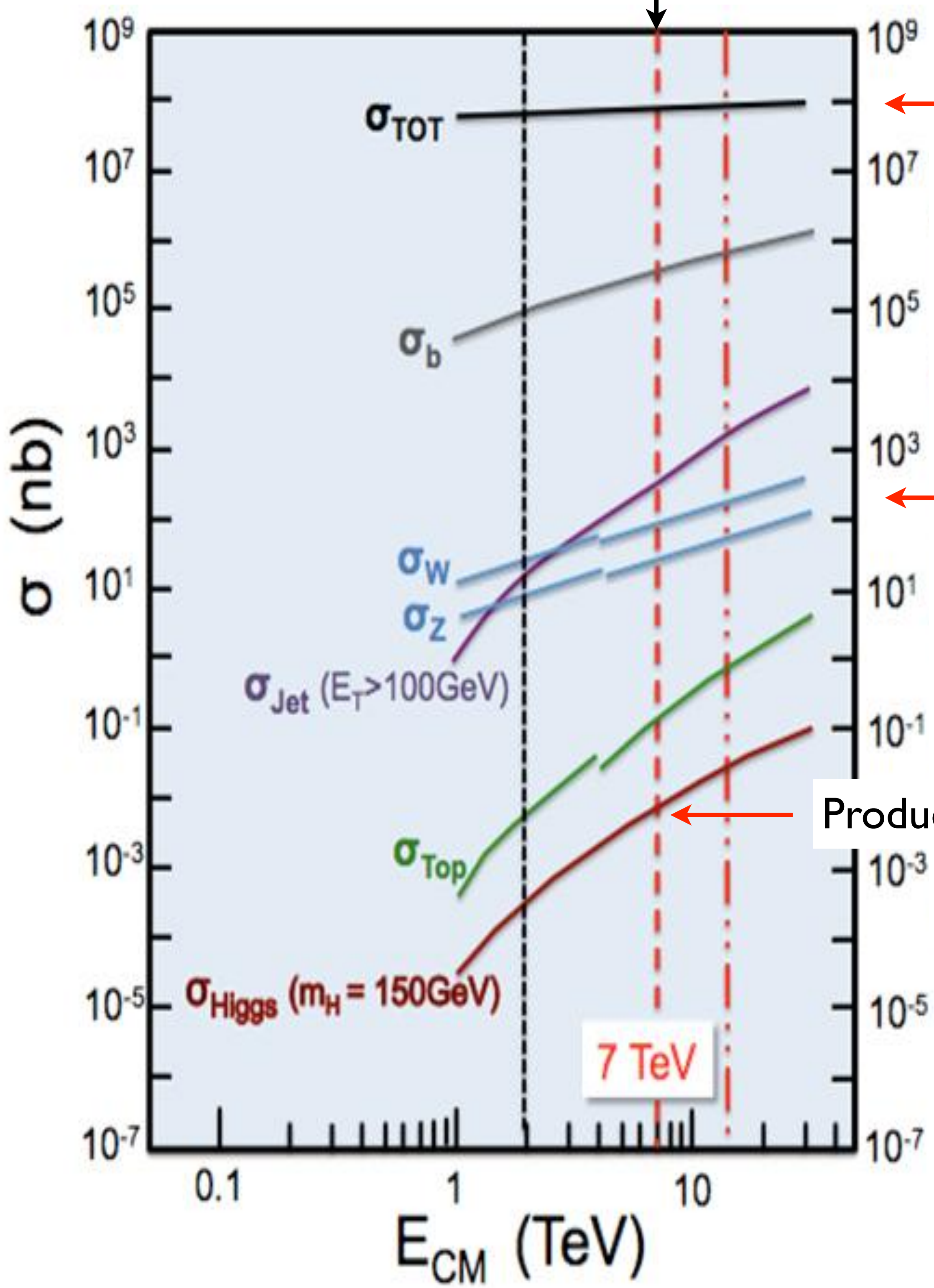
The LHC breaks record for 'luminosity'

Higgs Hunting

σ = reaction rate

current LHC operating energy

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



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

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

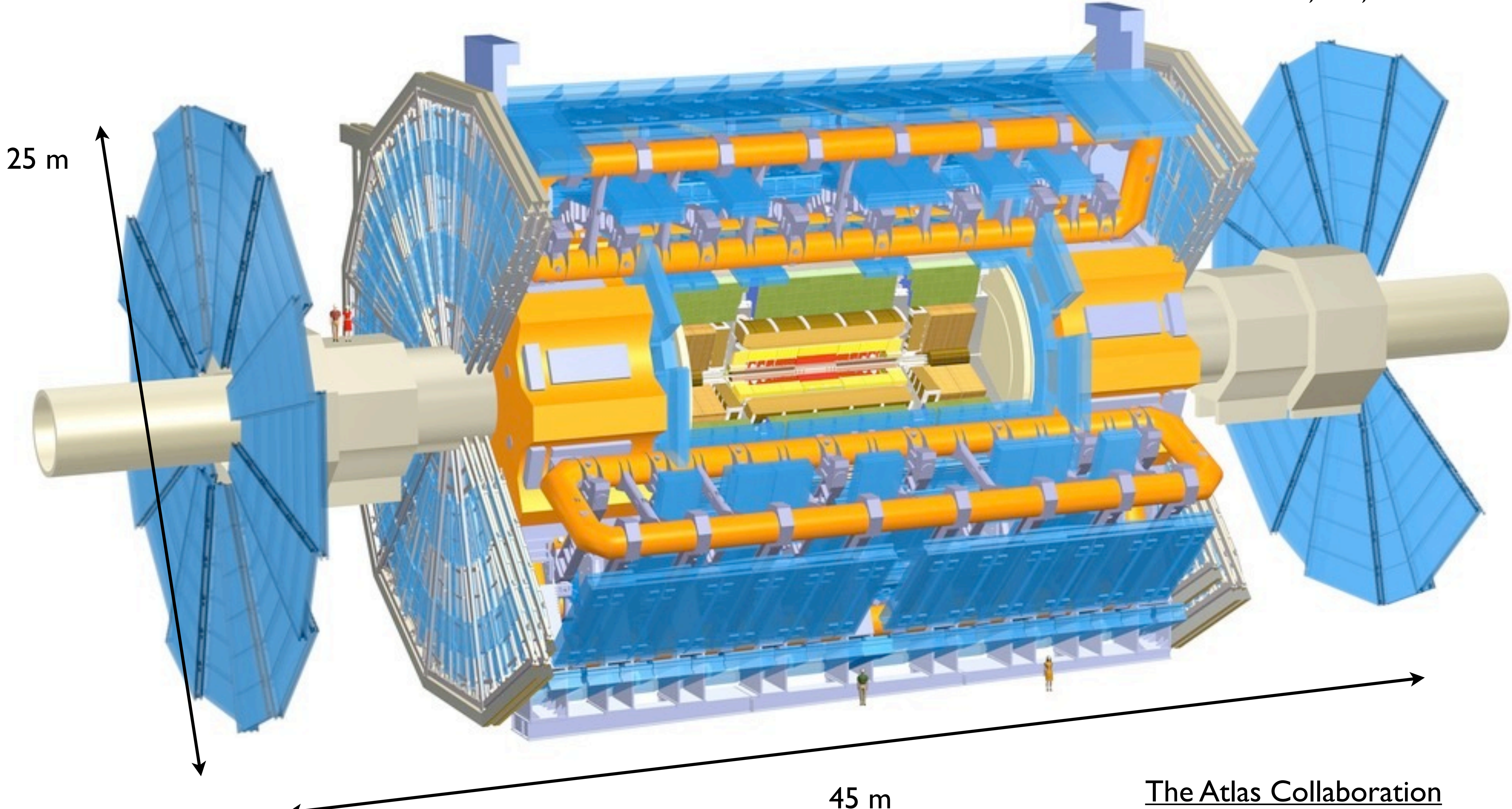
Maximum recording rate of ATLAS experiment: 200 events/second

Production rate of 125 GeV Higgs: 0.01 events/second

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

The ATLAS experiment at the LHC

<u>The Atlas Experiment</u>
7000 tonnes
Mass of the Eiffel Tower
Half the size of Notre Dame
data rate: 20,000,000 Gb/s



<u>The Atlas Collaboration</u>
3500 physicists
174 universities
38 countries

Particle Signatures

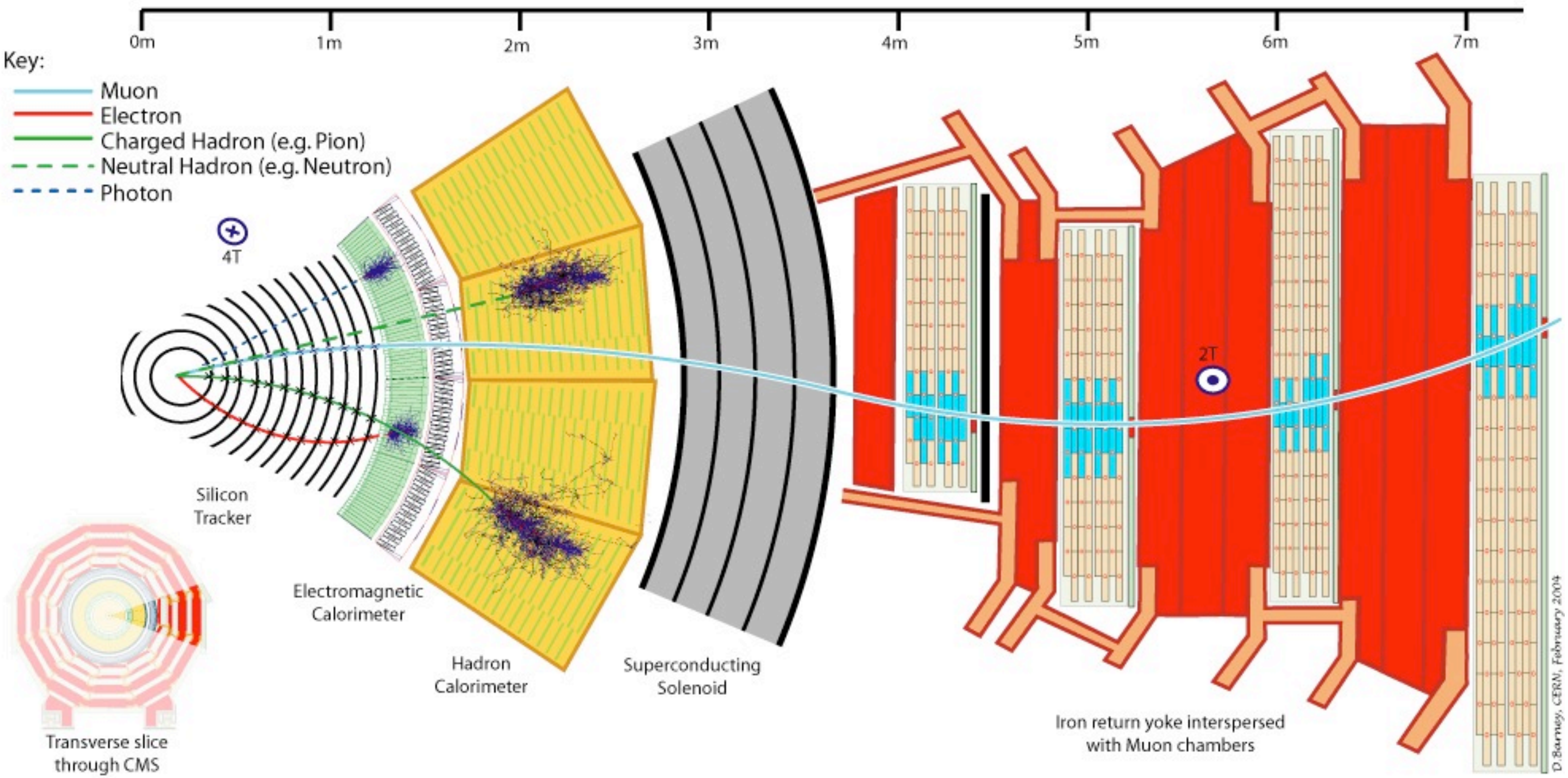
Measuring cross-section of a process requires recognising event properties:

Electromagnetic energy with a charged track	e+ or e-
Electromagnetic energy without track	photon
collimated 'jet' of particles	gluon/quark induced jet
penetrating charged track	μ+ or μ-
missing transverse energy	ν
missing longitudinal energy	beam remnants
displaced secondary vertex	in-flight decay of 'long lived' particle

Look at the event topology...

Particle Signatures

Large experiments needed to measure outgoing particles from collisions
Experiment consists of layered detectors each sensitive to different types of particle
Look for signatures of particle types



Higgs Hunting

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

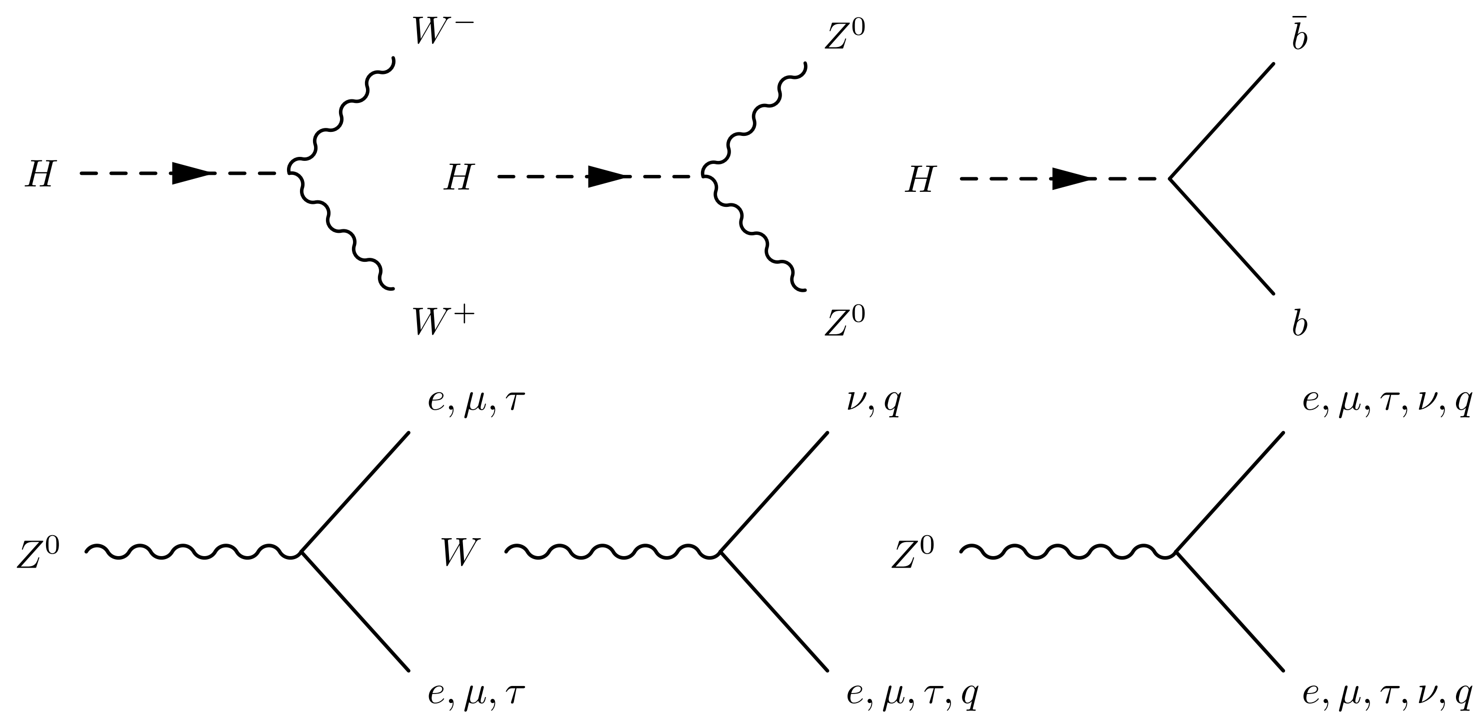
H→ττ

Rare, good at low mass, low background

H→ bb

Useful but difficult to identify b quarks

Many possible Higgs decay modes/channels:



W/Z can further decay to many combinations of fermions

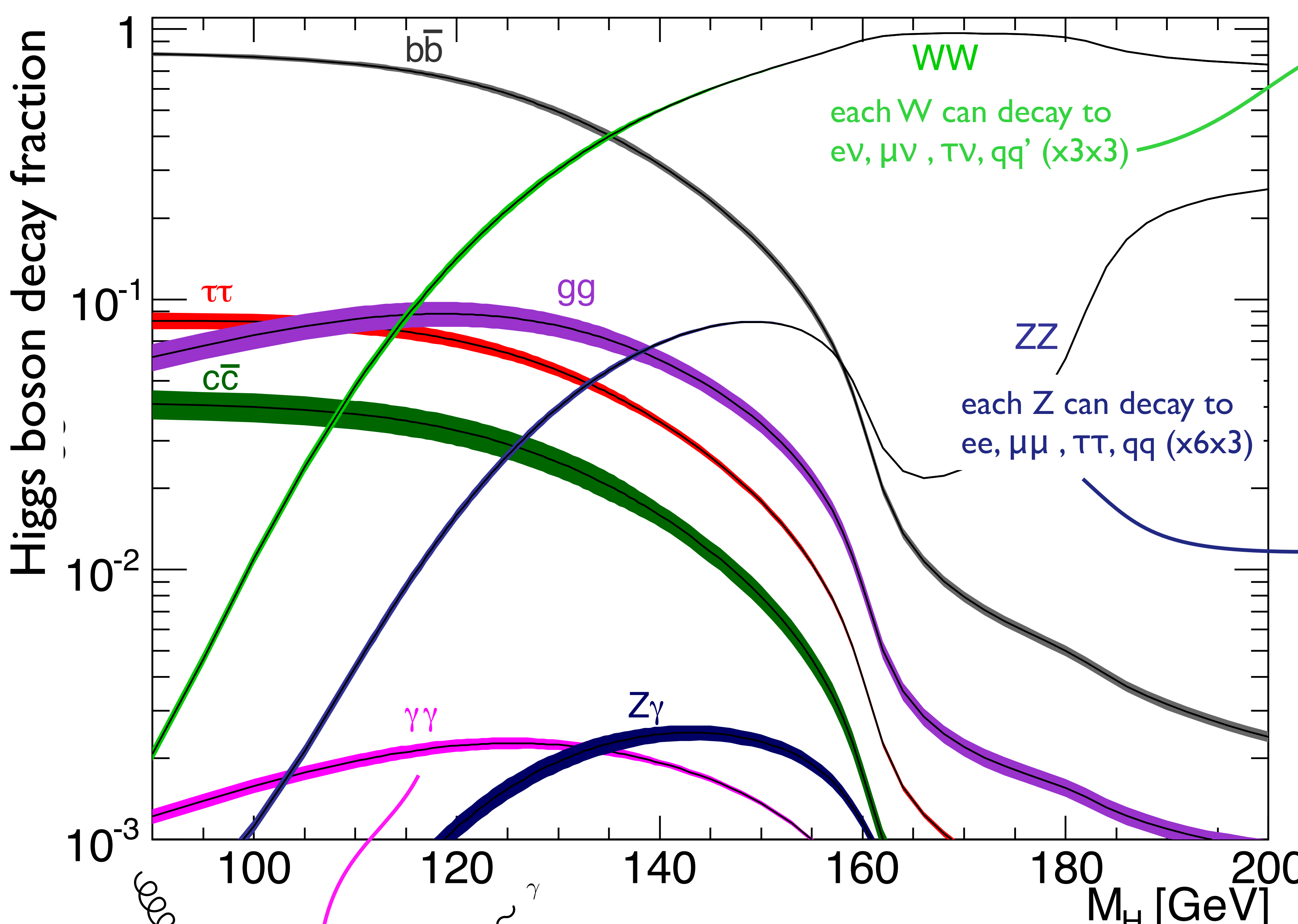
Each mode has different:

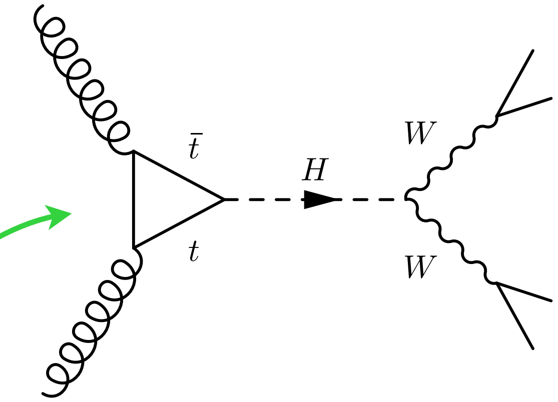
- sensitivity depending on mass range
- production rate
- contributions from background processes

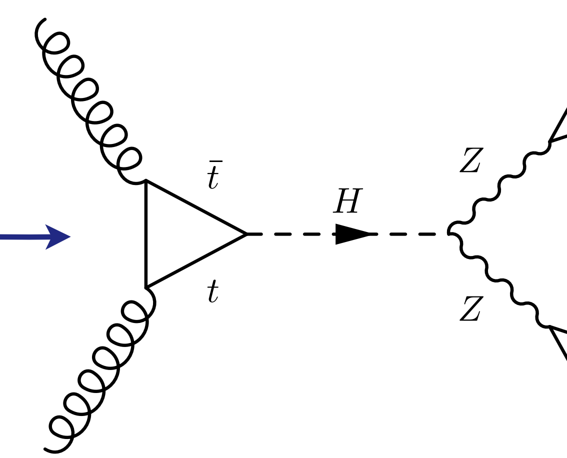
All modes need to be studied together!

Decay modes of the Higgs vs mass

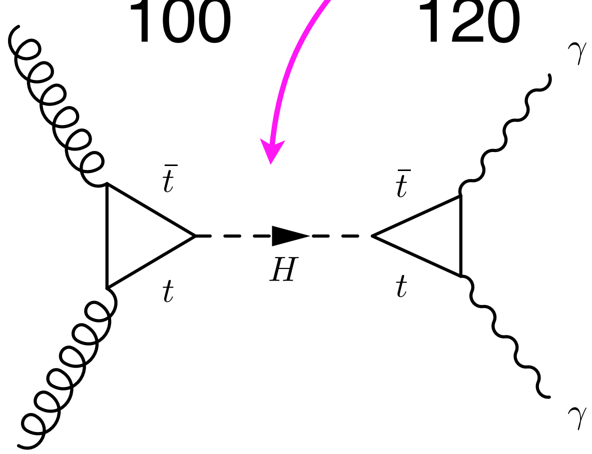
For $m_H > 2m_W$ then WW production dominates

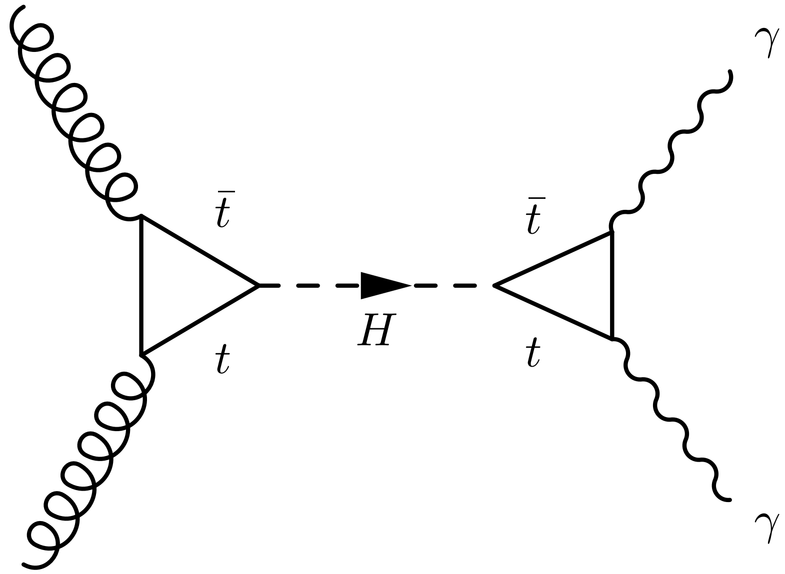






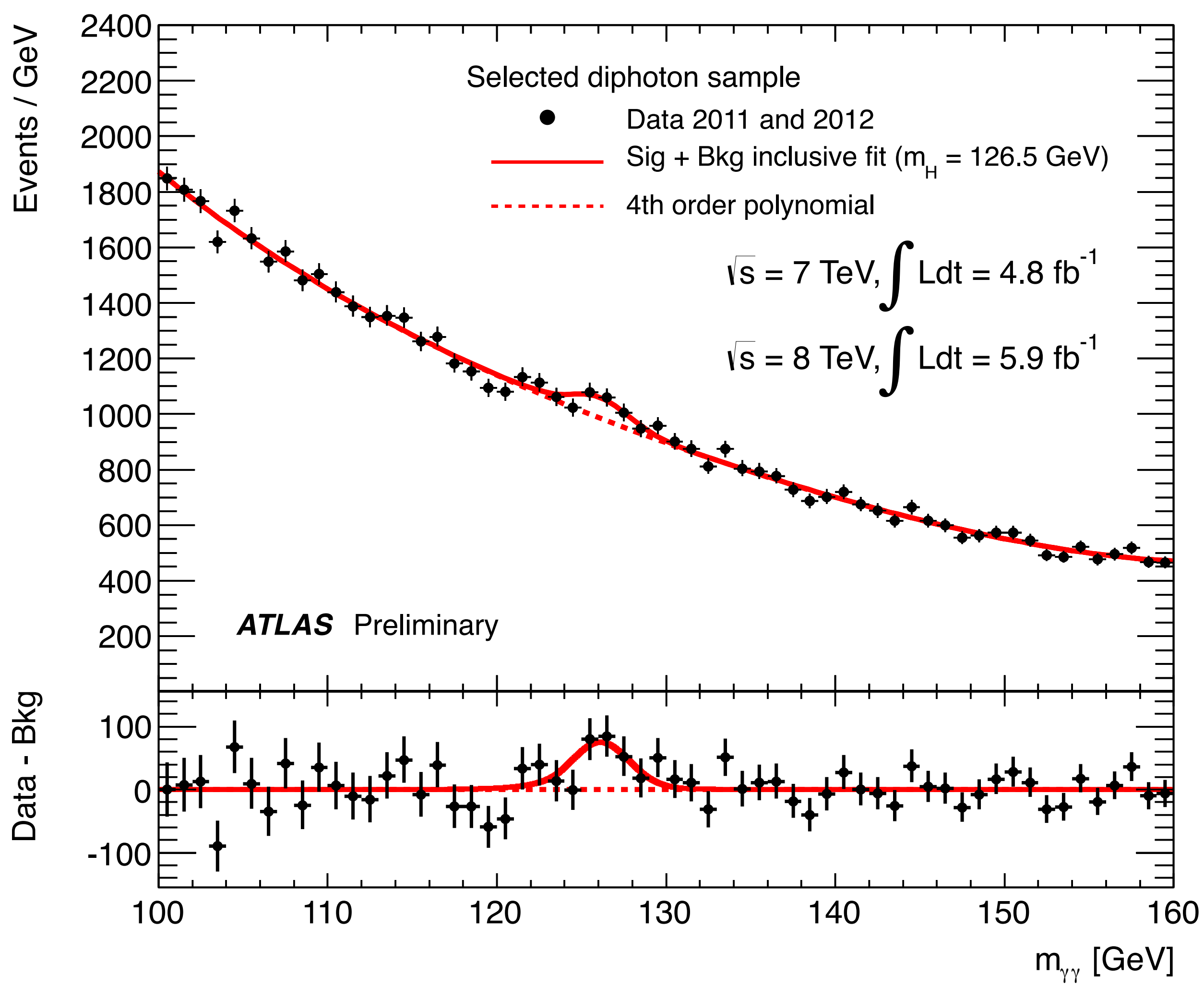
For $m_H > 2m_Z$ then ZZ production increases

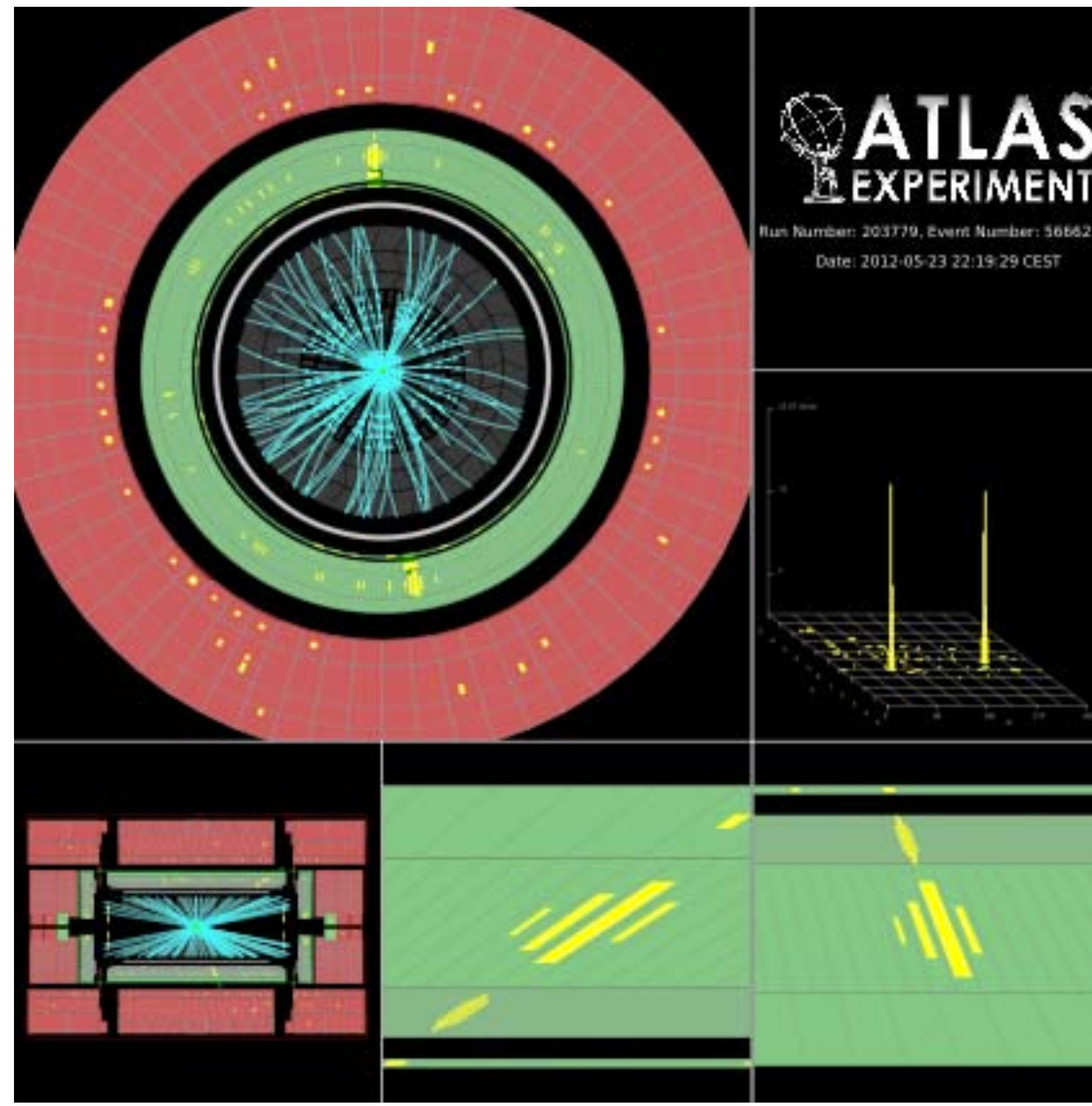


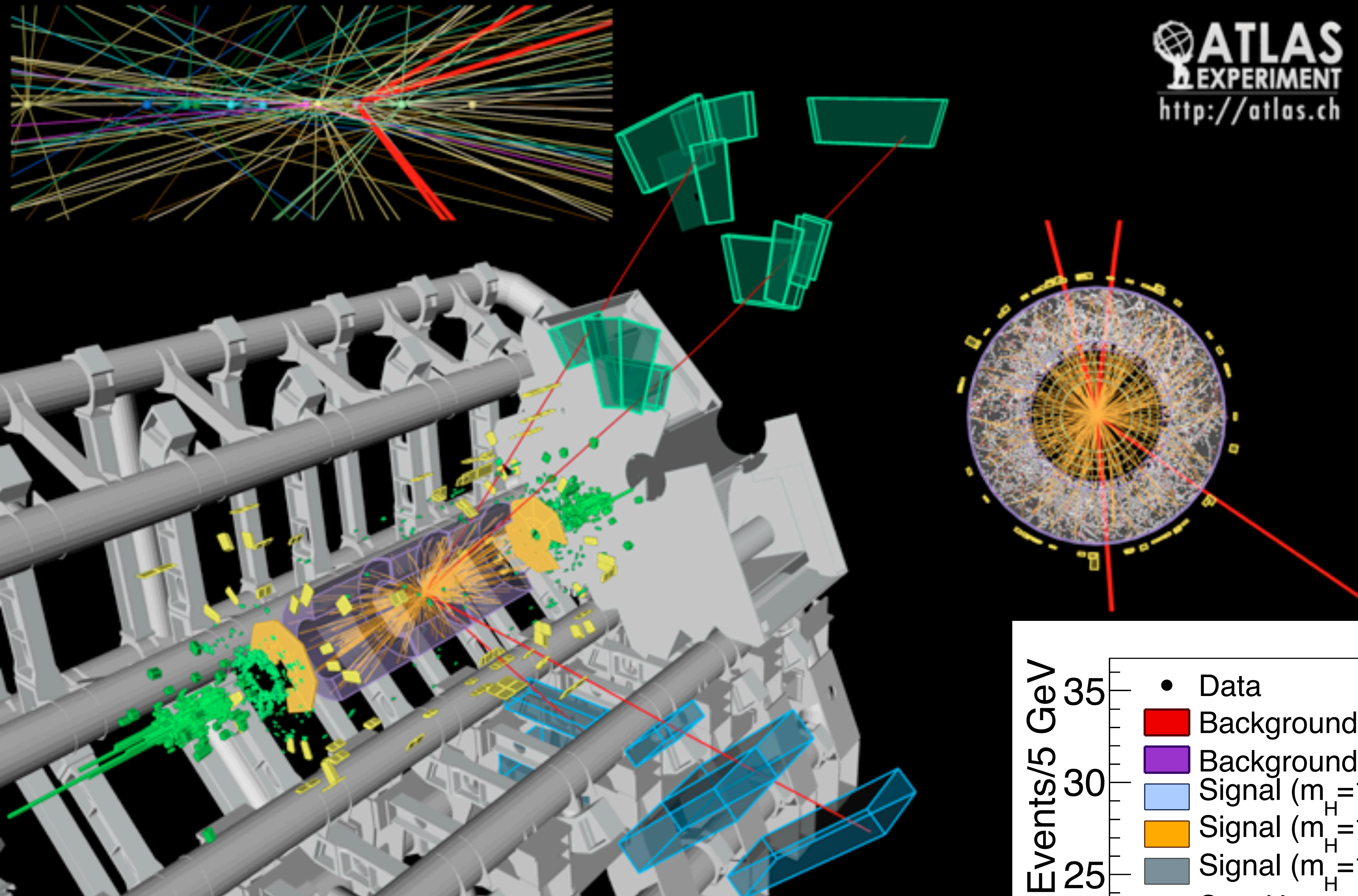


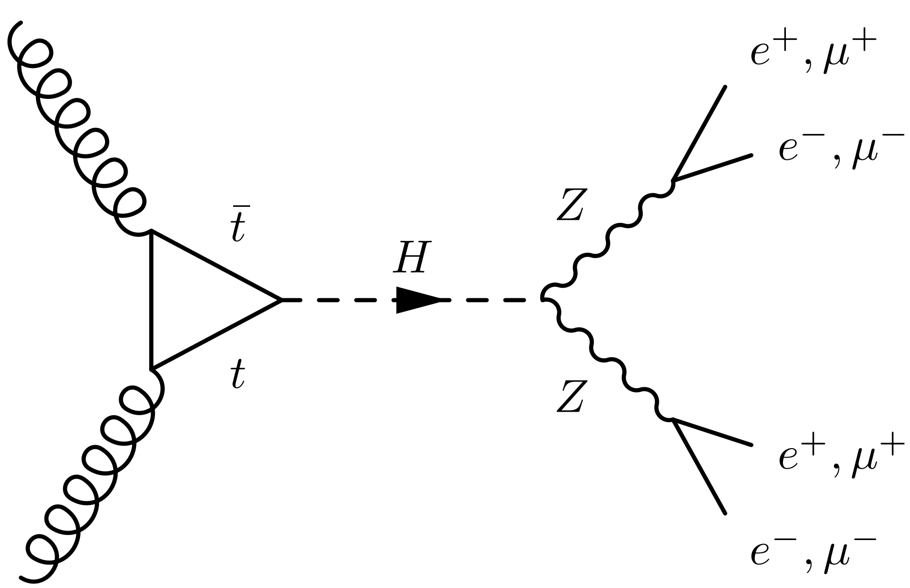
Experiment designs were optimised for this measurement 20 years ago!

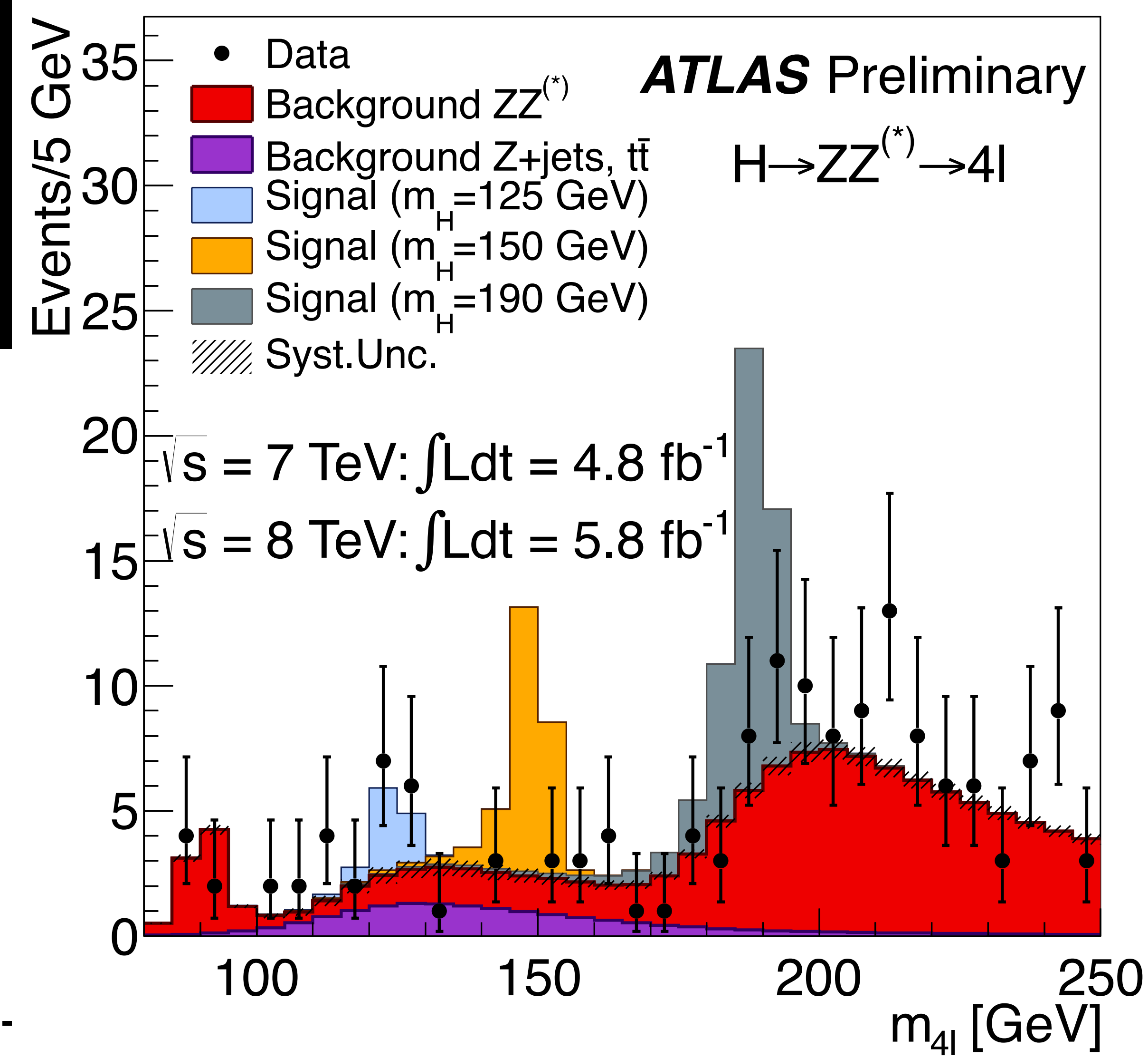
QM built & operate the trigger that collects this data (and more)

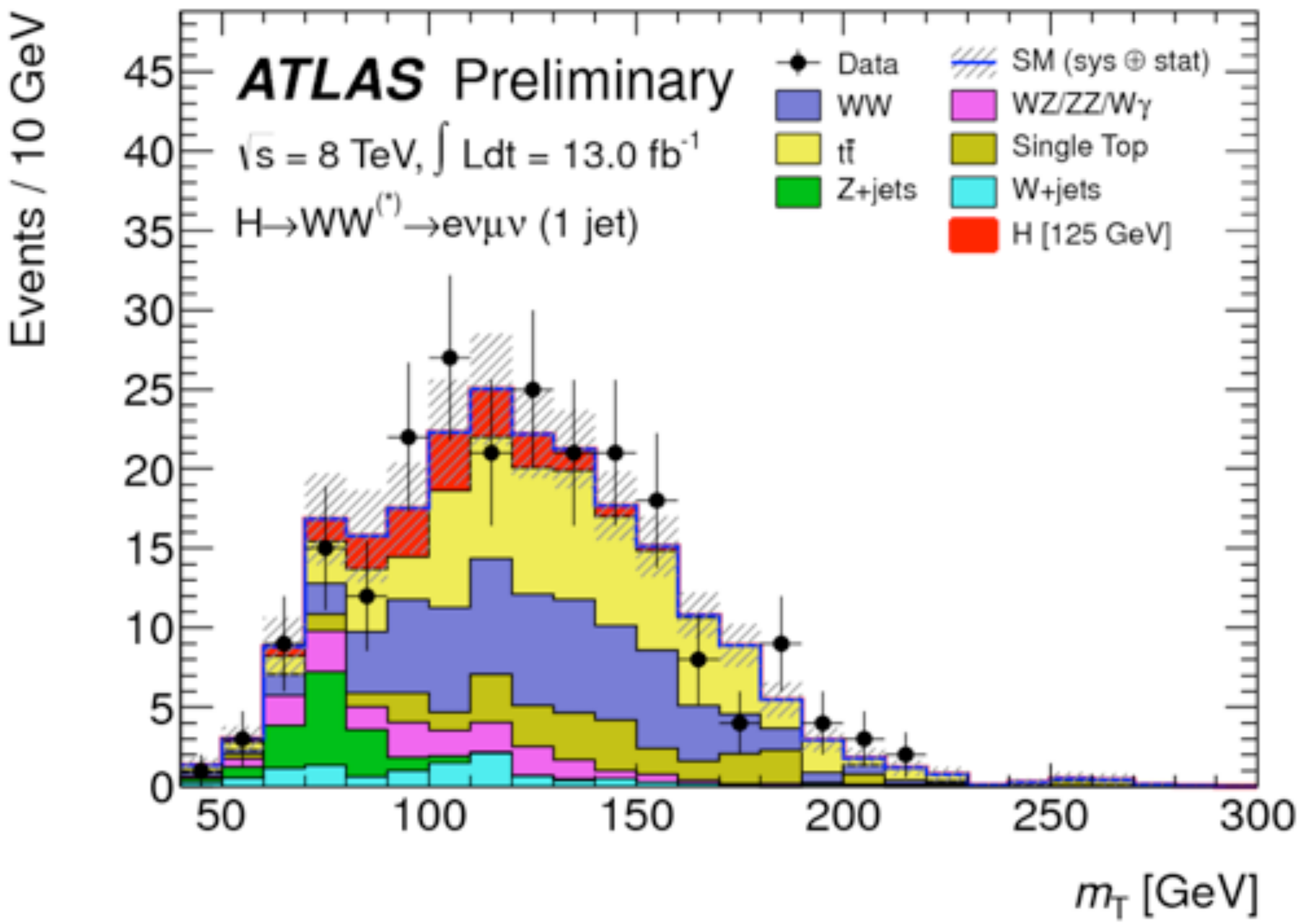


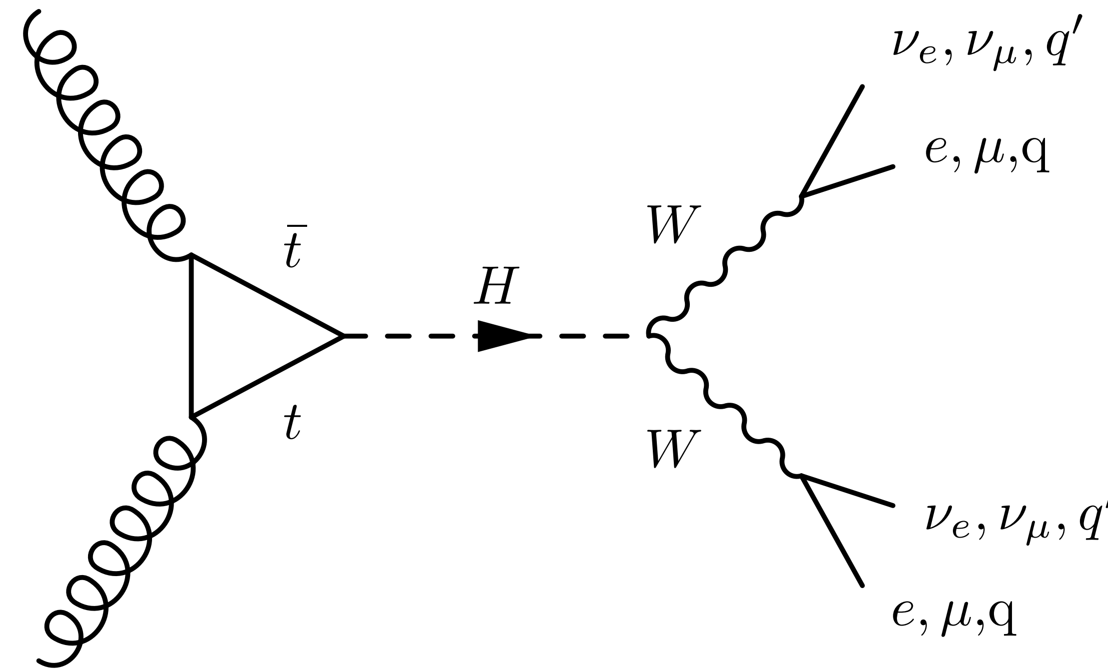



ATLAS EXPERIMENT
http://atlas.ch


$\bar{t}$
t
H
Z
Z
e^+, μ^+
e^-, μ^-
e^+, μ^+
e^-, μ^-

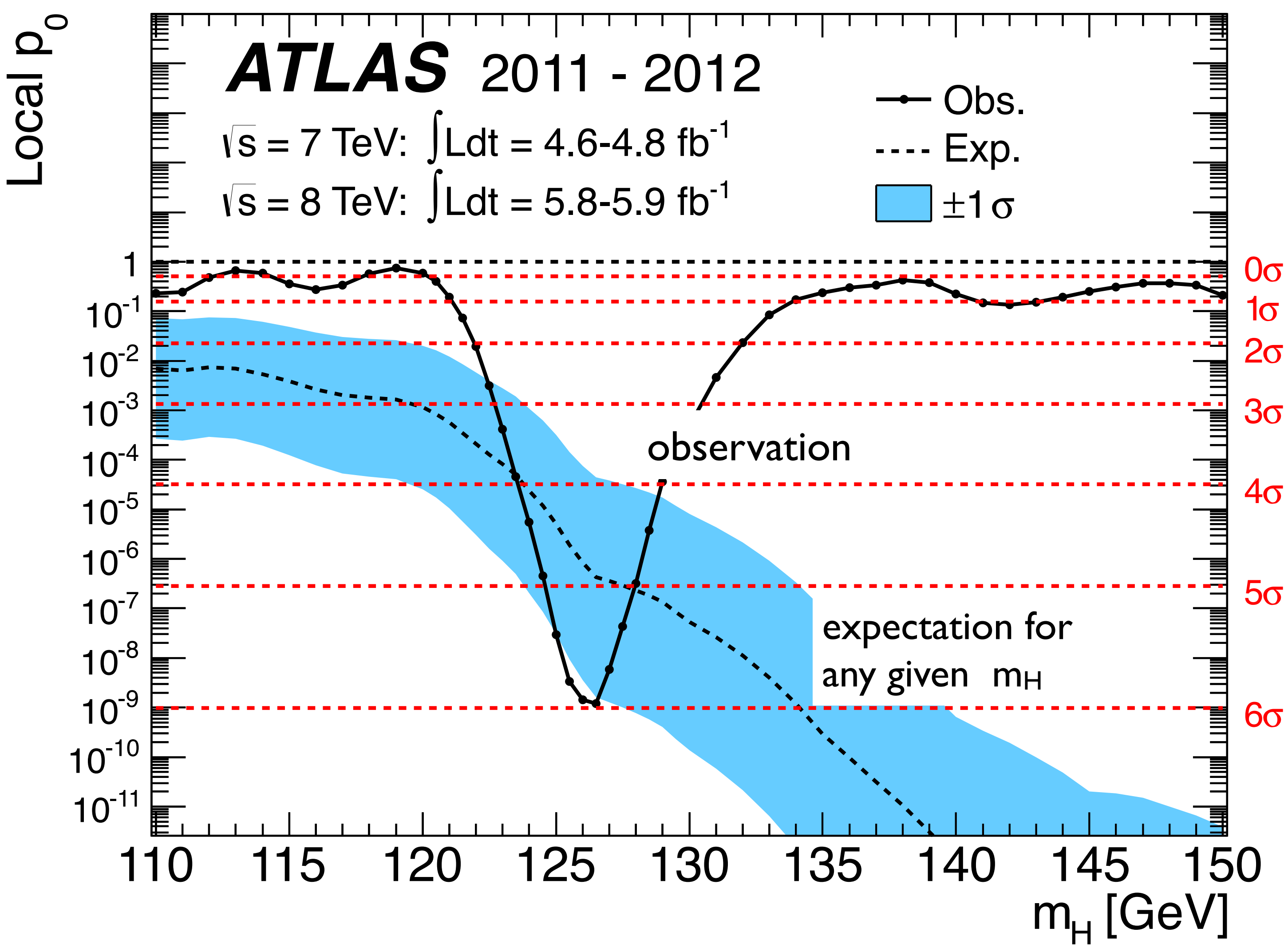

Data
Background ZZ(*)
Background Z+jets, $t\bar{t}$
Signal (m_H=125 GeV)
Signal (m_H=150 GeV)
Signal (m_H=190 GeV)
Syst.Unc.
ATLAS Preliminary
H→ZZ(*)→4l
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 5.8 fb^{-1}
Events/5 GeV
m_{4l} [GeV]
0
5
10
15
20
25
30
35
100
150
200
250

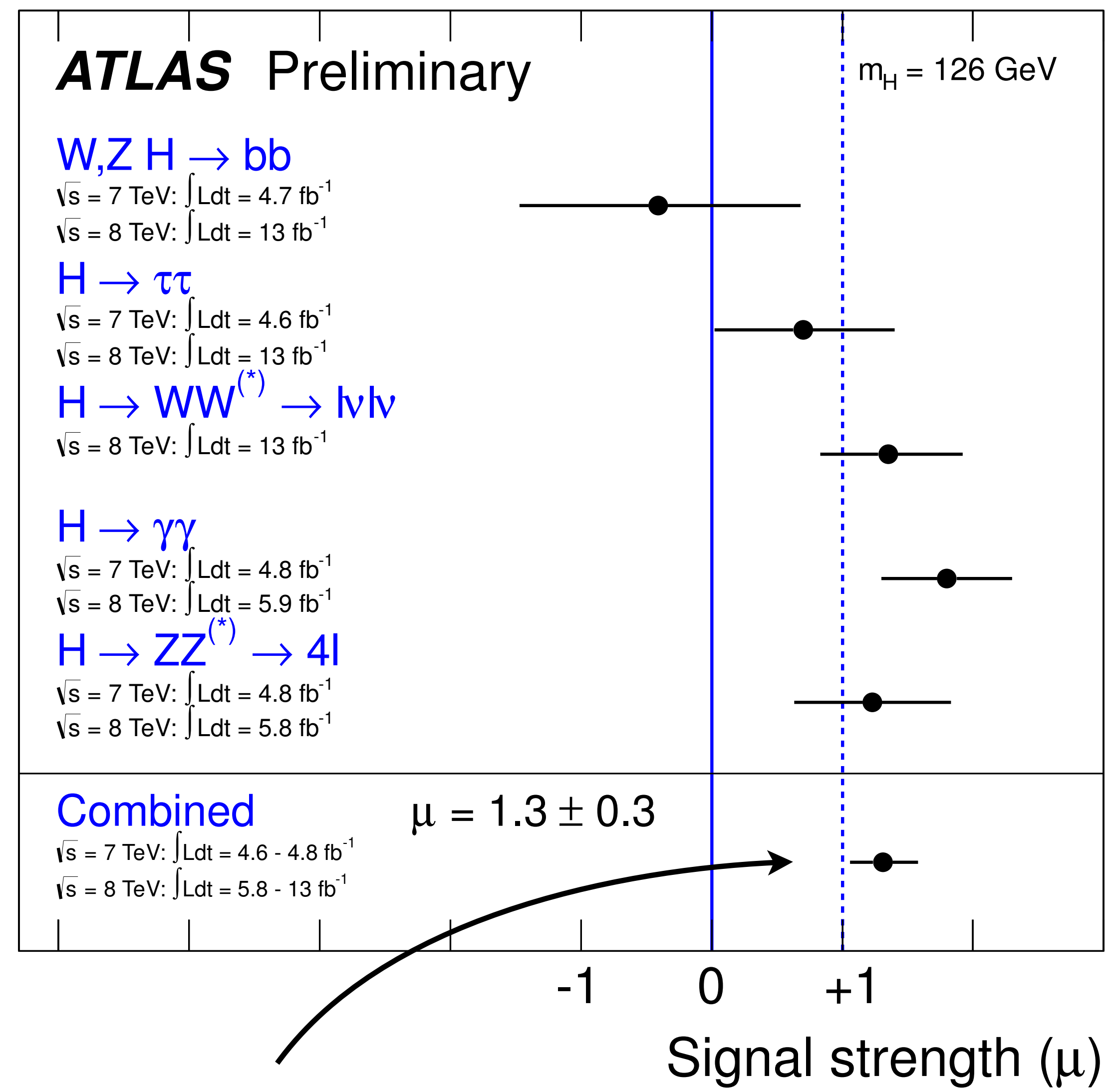

ATLAS Preliminary
√s = 8 TeV, ∫ Ldt = 13.0 fb-1
H→WW(*)→eνμν (1 jet)
Data
WW
tt̄
Z+jets
SM (sys ⊕ stat)
WZ/ZZ/Wγ
Single Top
W+jets
H [125 GeV]
Events / 10 GeV
mT [GeV]


t̄
t
H
W
W
νe, νμ, q′
e, μ,q
νe, νμ, q′
e, μ,q

Probability of "no Higgs" hypothesis fluctuating to mimic Higgs signal

Is the Higgs being produced at the expected rate?



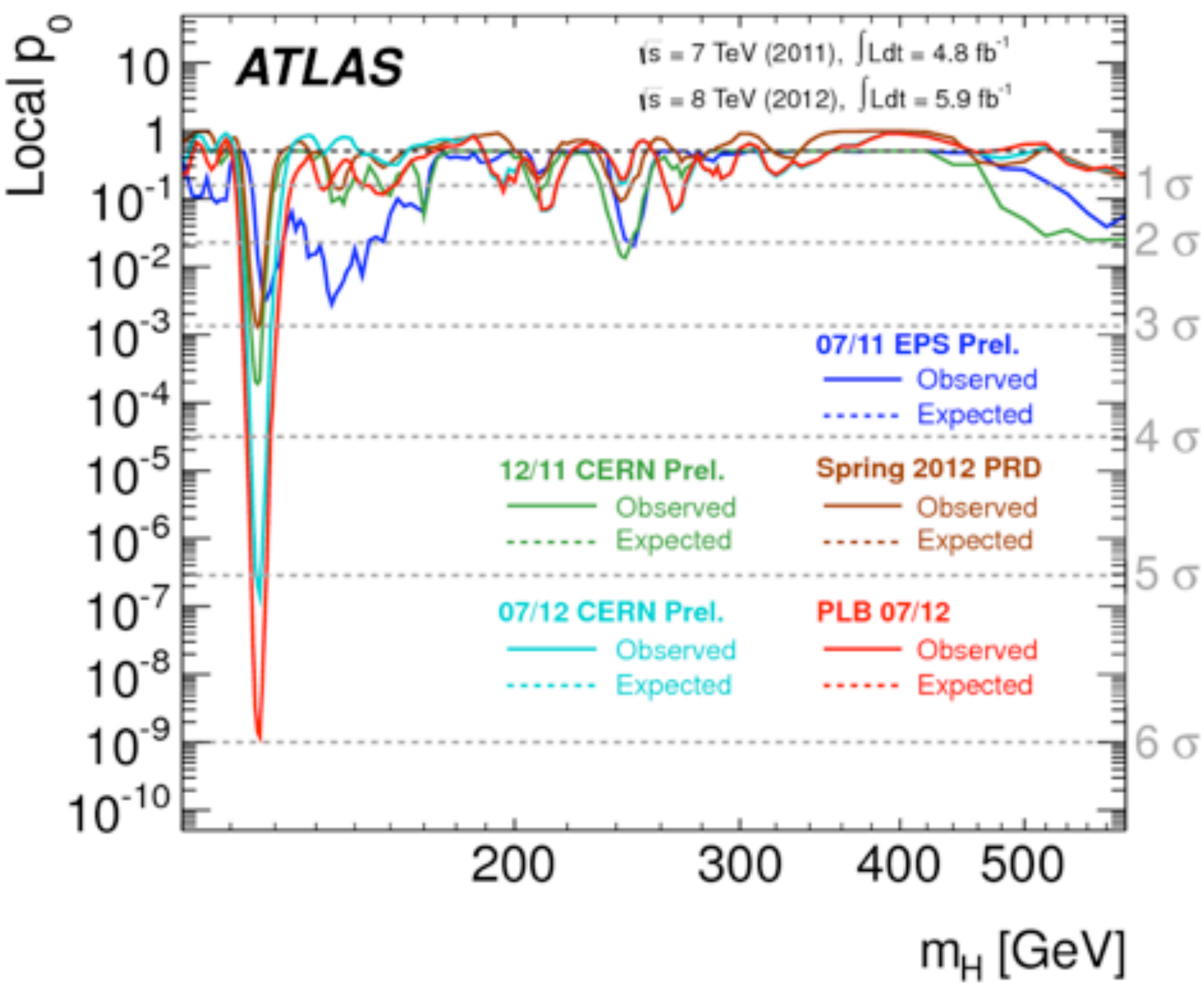


The new particle is being produced at about the Standard Model rate

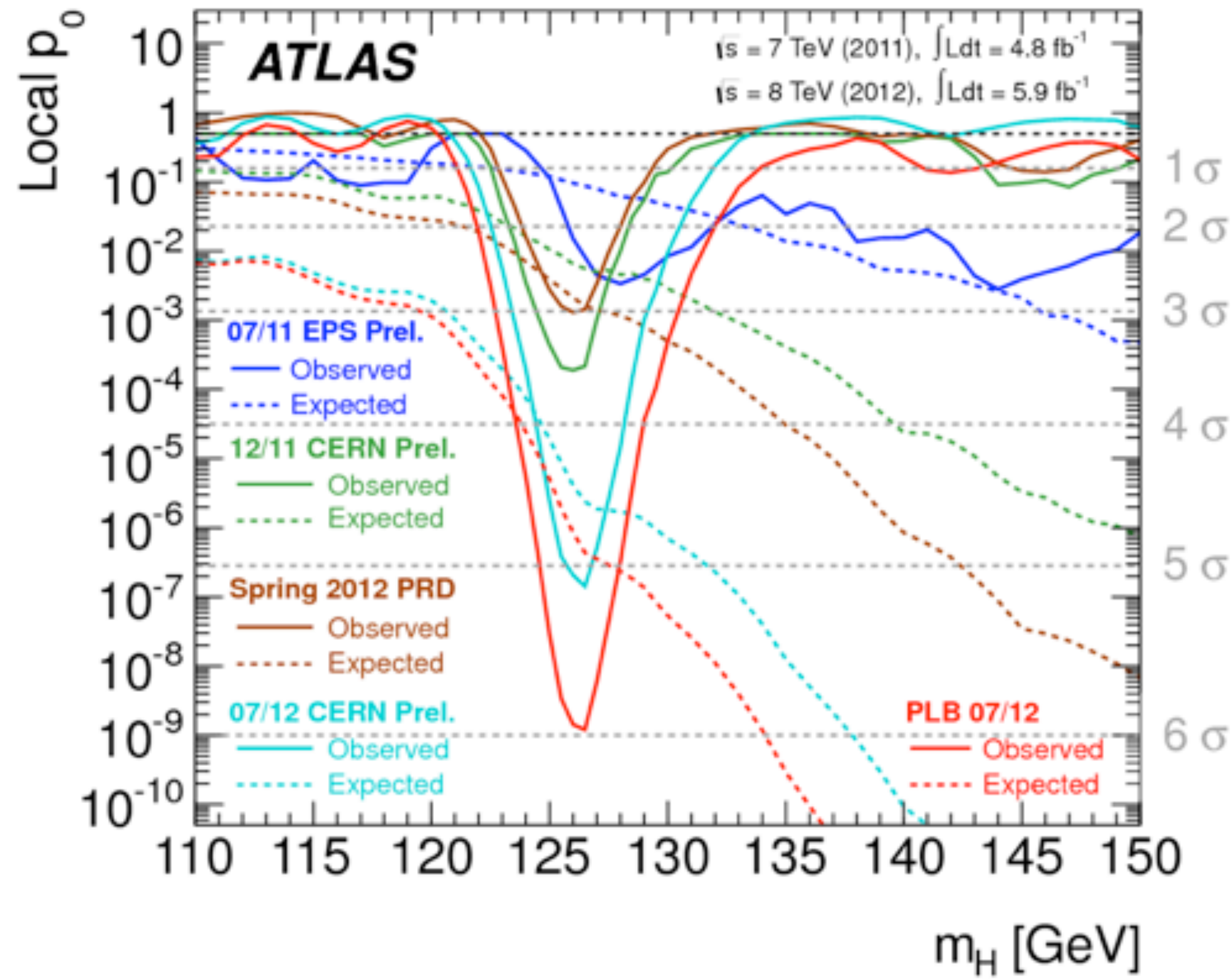
Have we found it ?
Cannot say yet - we need to measure its couplings to all particles, decay width, parity
(but in all likelihood this is it!)

Higgs Hunting

Signal evolution with time

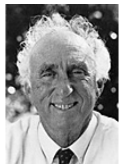


Wide mass range



Zoom of interesting region

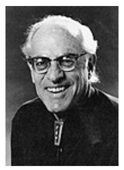
The Standard Model


Perl


Gross


Rubbia

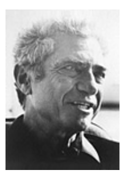

van der Meer


Reines


Lederman


Gell-man

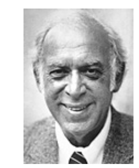

Cronin


Steinberger


Feynman

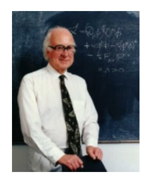

Glashow

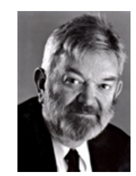

Taylor

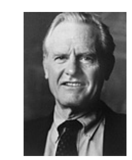

Friedman


Hofstadter


Schwinger


Higgs

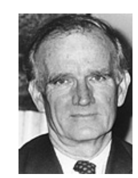

Veltman


Kendall


Politzer


Ting


Alvarez


Fitch


Schwarz


Richter


Weinberg

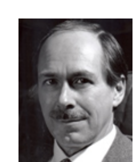

Yang

29 Nobel prizes awarded for the Standard Model


Wilczek


Salam


Lee


t'Hooft

1 more yet to come?

The Problematic Standard Model

$$
\begin{gathered}
-\frac{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 - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\frac{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 - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \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 - \beta_h[\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 - 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)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\frac{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^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_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^-] - \\
\frac{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 - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{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)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s_w^2 A_\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_w A_\mu[-(\bar{e}^\lambda\gamma e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma d^\lambda_j)] + \frac{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(\frac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + \\
(\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{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)] + \frac{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)] + \\
\frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + \\
i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+ \\
\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \\
\frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + \\
igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + \\
igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + \\
igc_w Z^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \\
\frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \\
\bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \\
\bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]
\end{gathered}
$$

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

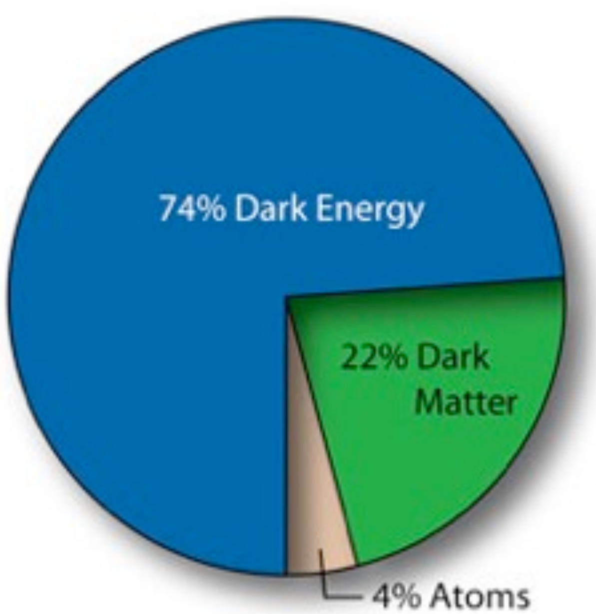
The Problematic Standard Model

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

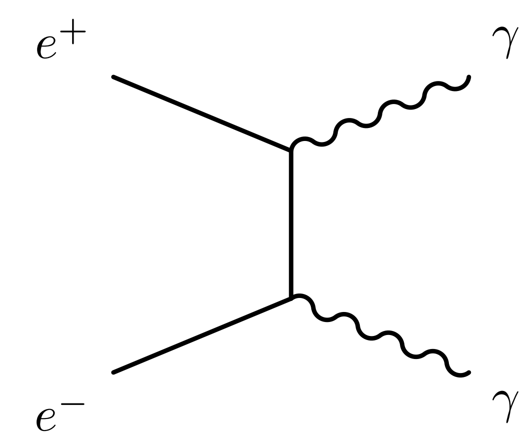
We know quantum gravity effects must play a role at the Planck scale i.e. energy ~ 10^{19} GeV

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

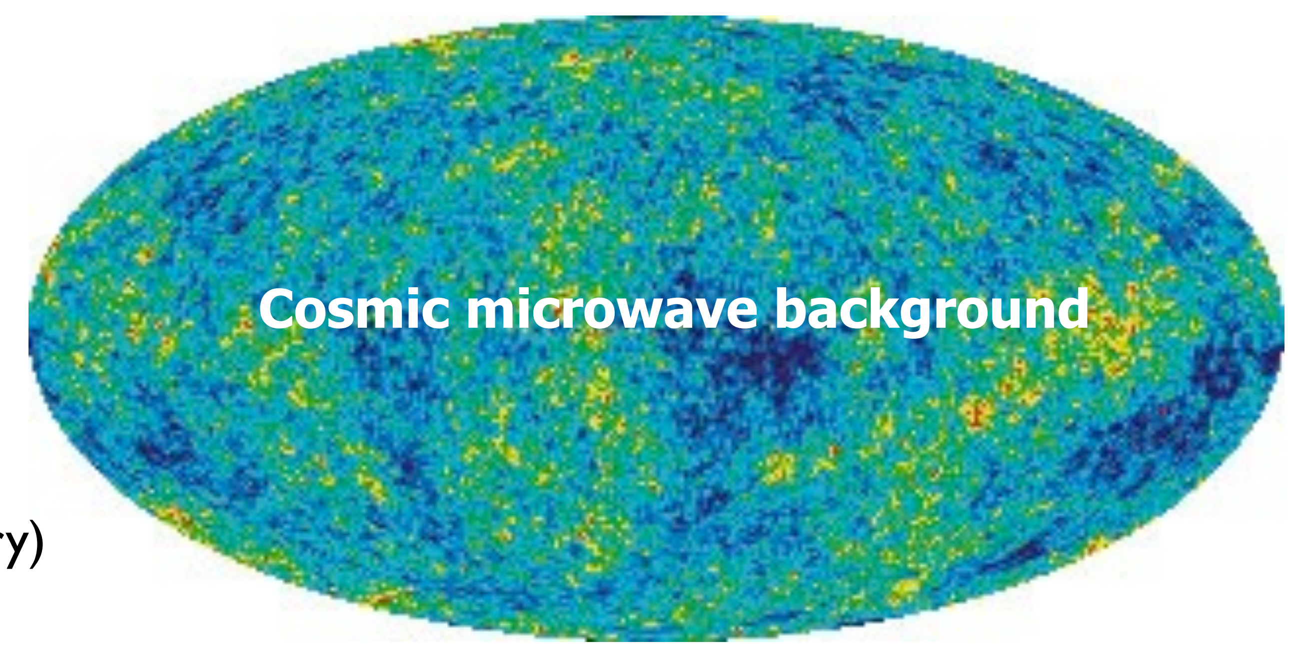
- In the Big Bang: for every quark, one anti-quark is also produced
- As universe cools expect all particles and anti-particles to annihilate
- ⇒ soon after big bang all matter will have annihilated to photons

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 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:
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:

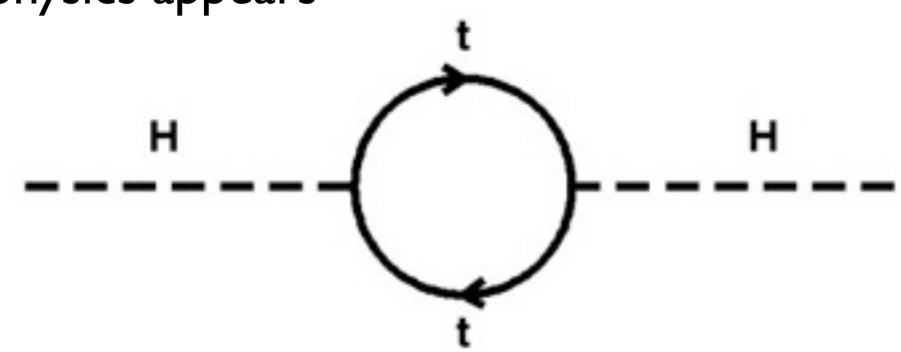
top quark loop: $\Delta m_H^2 = -a\Lambda^2$

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 ~ $(10^{19}\text{ GeV})^2$ and m_H^2 ~ $(100\text{ GeV})^2$

$$m_H^2 = m_0^2 + (-a+b+c)\Lambda^2$$

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

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

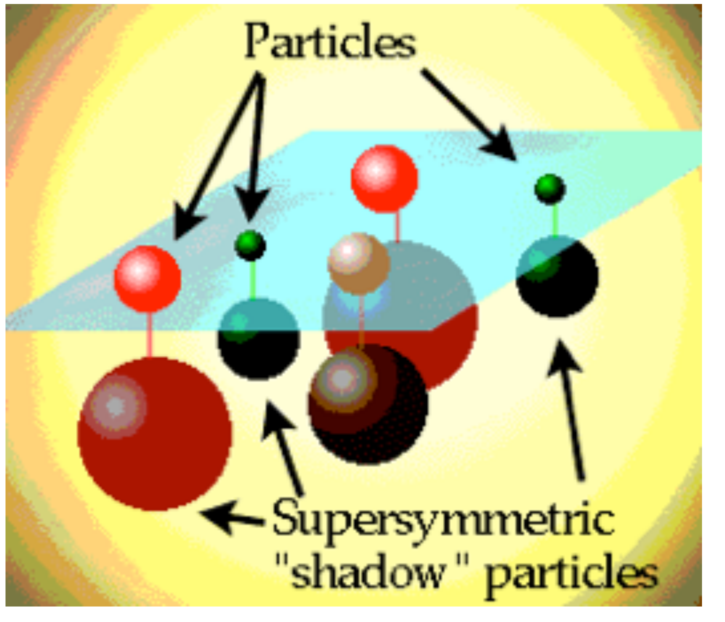
What are the alternatives to the Standard Model?

"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



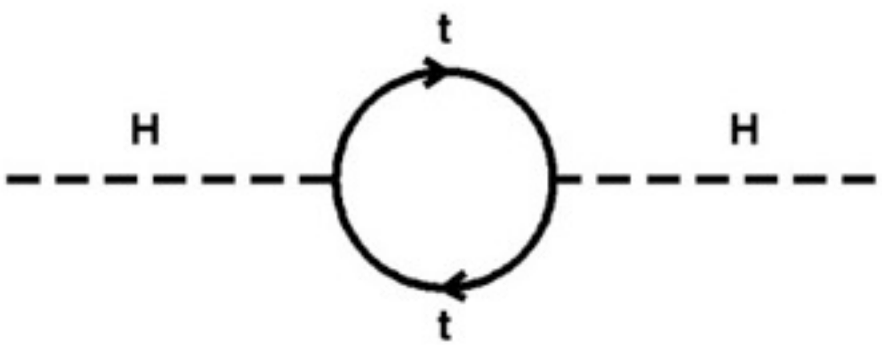
quarks (spin ½)	↔	squarks (spin 0)
leptons (spin ½)	↔	sleptons (spin 0)
photon (spin 1)	↔	photino (spin ½)
W,Z (spin 1)	↔	Wino, Zino (spin ½)
Higgs (spin 0)	↔	Higgsino (spin ½)

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)

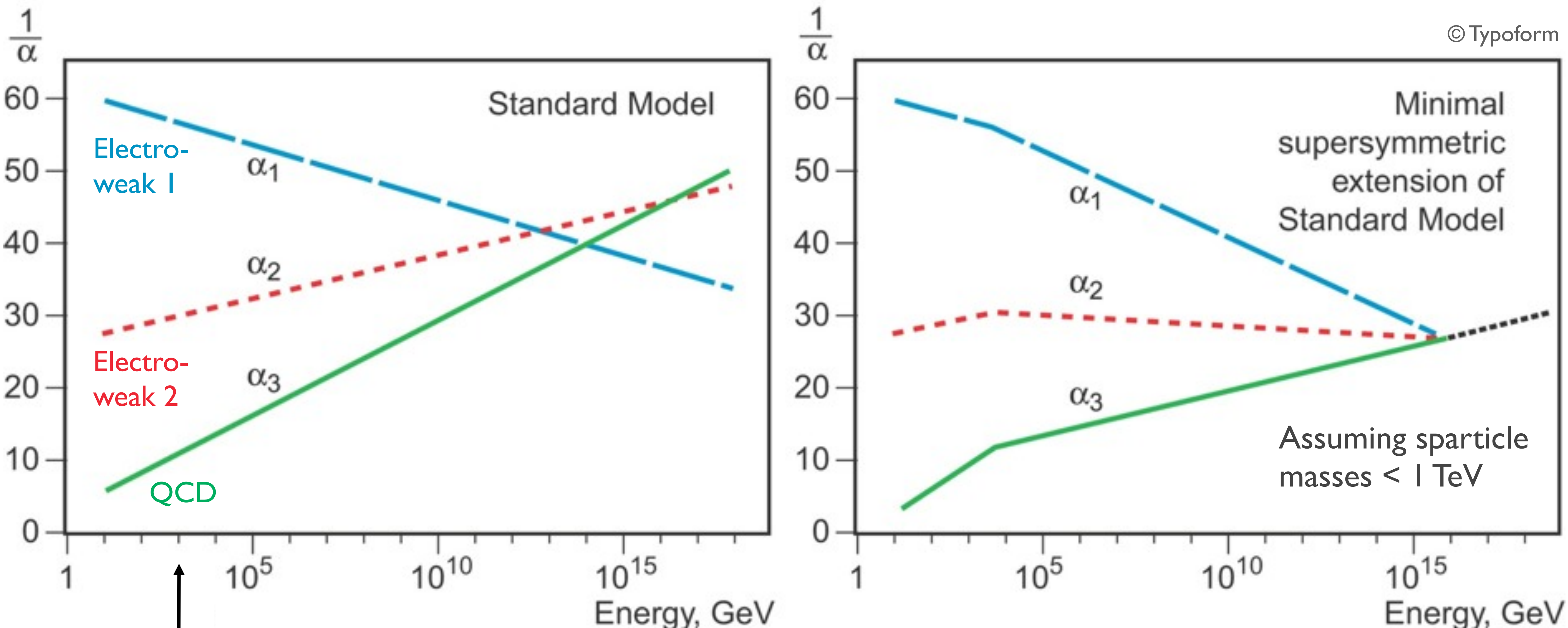
New SUSY sparticles (e.g. stop squark) contribute and cancel identically

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

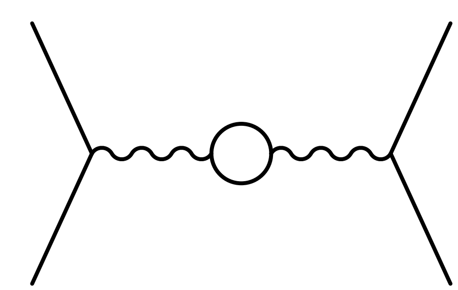


Current measurements at 1000 GeV

16 orders of magnitude extrapolation!
Involves including all particle loops

New SUSY particles = different loops
= different extrapolation

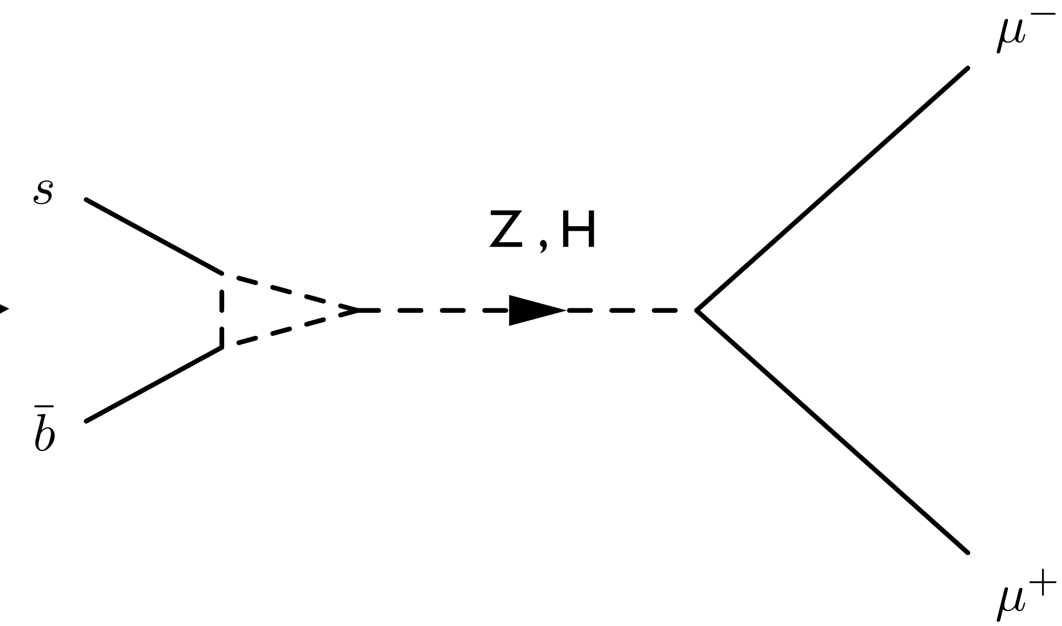
Incorporating SUSY into extrapolation
brings unification below Planck scale!



Supersymmetry "died" on Monday!

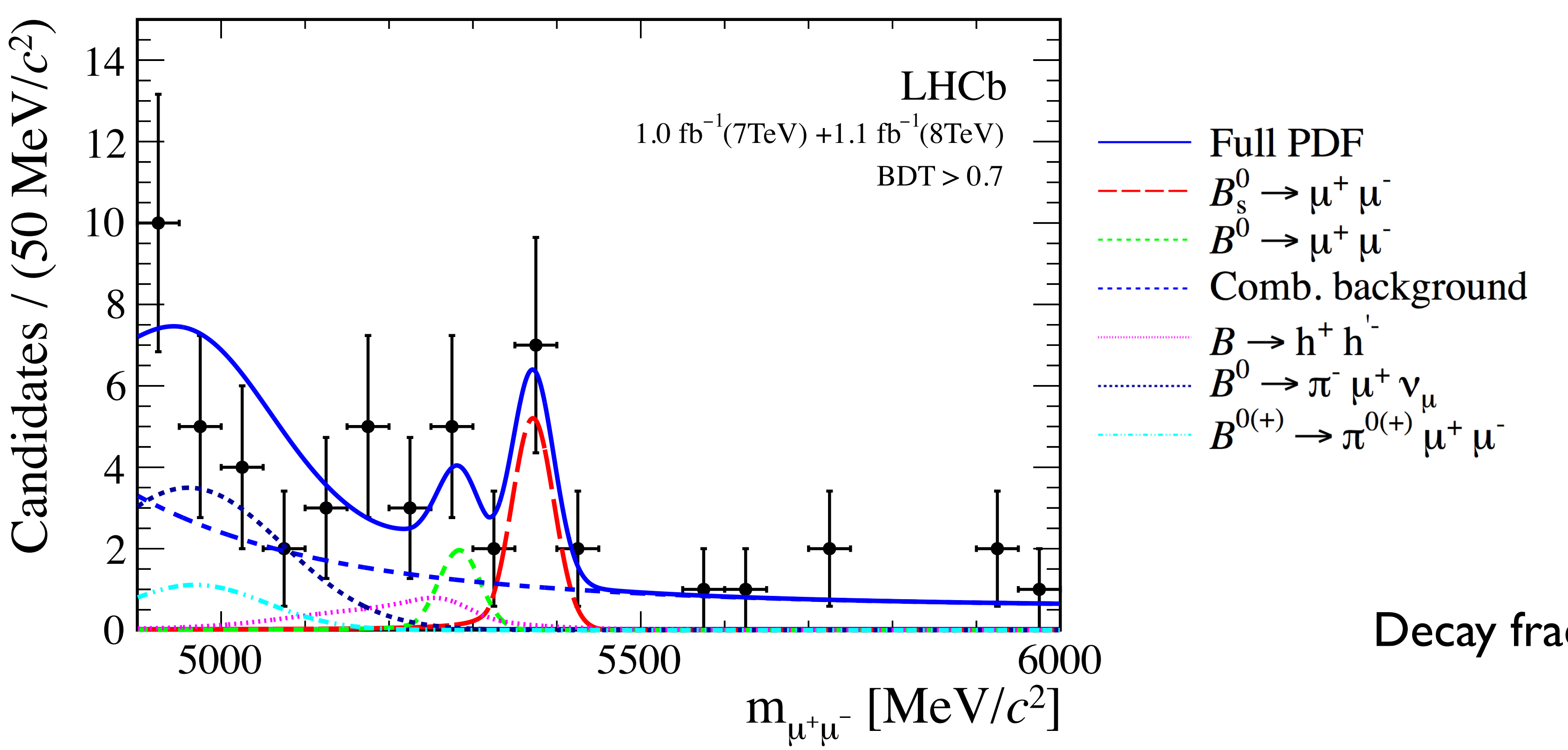
Experiments search for new physics (NP):
look for influence of new heavy particles via quantum loops
Choose a process heavily suppressed by Standard Model
(low contamination from SM background)

New physics quantum loop effects visible if
NP loops are similar size to SM loops



Measure the decay rate of the B_s^0 meson
Decay to $\mu^+\mu^-$ is very suppressed in SM - SM predicts fraction of decays is ~10^{-9} !!

New heavy particles can enter the loops and alter decay rate



On Monday LHCb experiment announced worlds first measurement of this very rare decay rate

Agrees with SM :(

Supersymmetry has few places left to hide!

Decay fraction $(B_s^0 \to \mu^+\mu^-) = 3.2^{+1.5}_{-1.2} \times 10^{-9}$

SM predicts: $(3.54 \pm 0.30) \times 10^{-9}$

There is plenty more work to be done!
Many exciting projects underway:

- T2K
- SNO+
- Super-LHC
- LHeC

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PHD PROGRAMME

View | Edit

The Particle Physics Research Centre at Queen Mary is an active research group collaborating in several international experiments in Europe, the United States and Japan. We are involved in a broad range of analyses from the study of the QCD structure of the proton at the smallest distance scales, to the understanding of the matter/anti-matter asymmetry of the universe. Two of the experiments are in the final analysis phase (H1 and Babar) whilst the ATLAS and T2K experiments have now commenced their physics programmes. In addition the group is involved in the development of a global computing Grid needed to provide computing resources for the next generation of experiments.

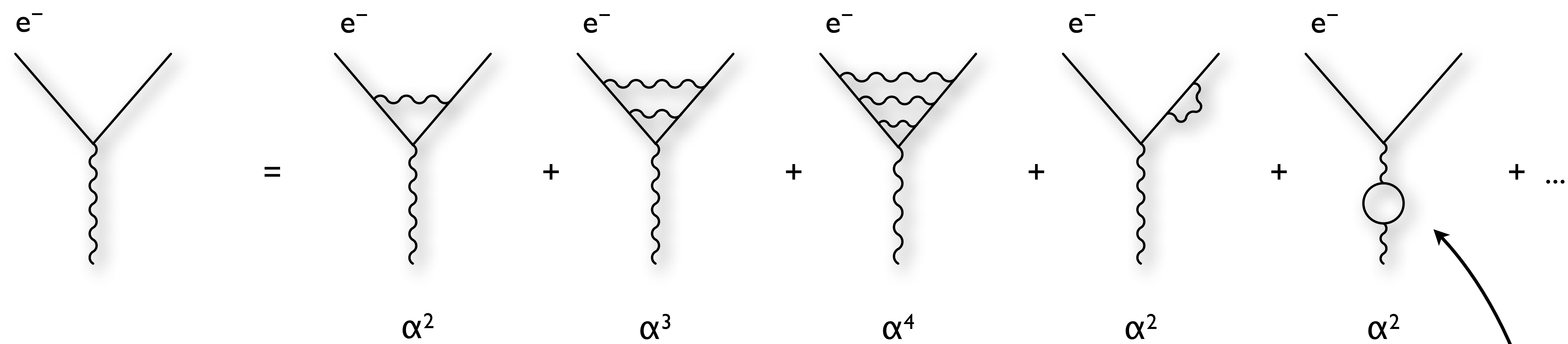
Details on the application procedure, eligibility criteria, and funding opportunities including **application deadlines** may be found on the applications page on the side bar.

Backup

The Higgs Boson

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

e.g. photon converts into <u>all</u> 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
Precision measurements are weakly sensitive to existence of new particles modifying "loop corrections"
Particle masses also affected by such quantum fluctuations
Particles have <u>fixed</u> 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

The Higgs Boson

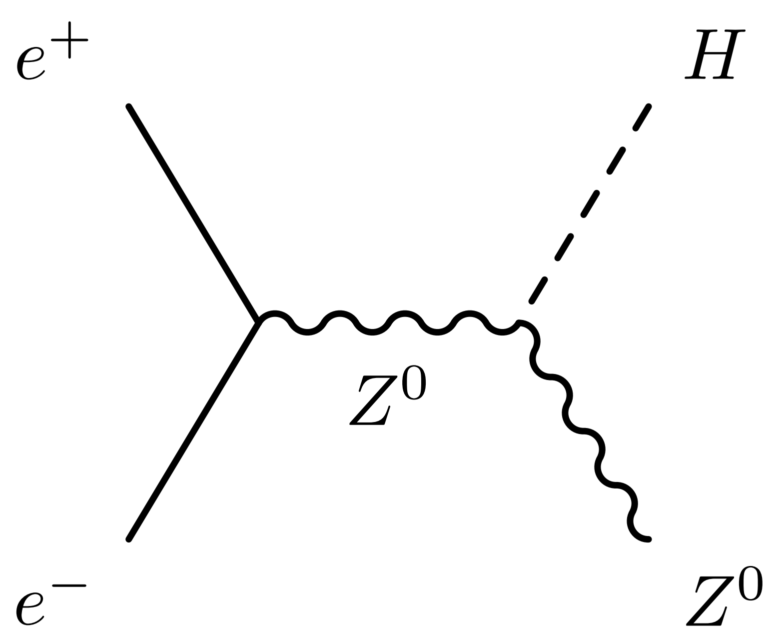
Almost all the visible mass of universe is due to massless QCD effects
Energy associated with quark and gluon interactions $\rightarrow$ proton & neutron mass

Higgs particle postulated to explain masses of fundamental particles

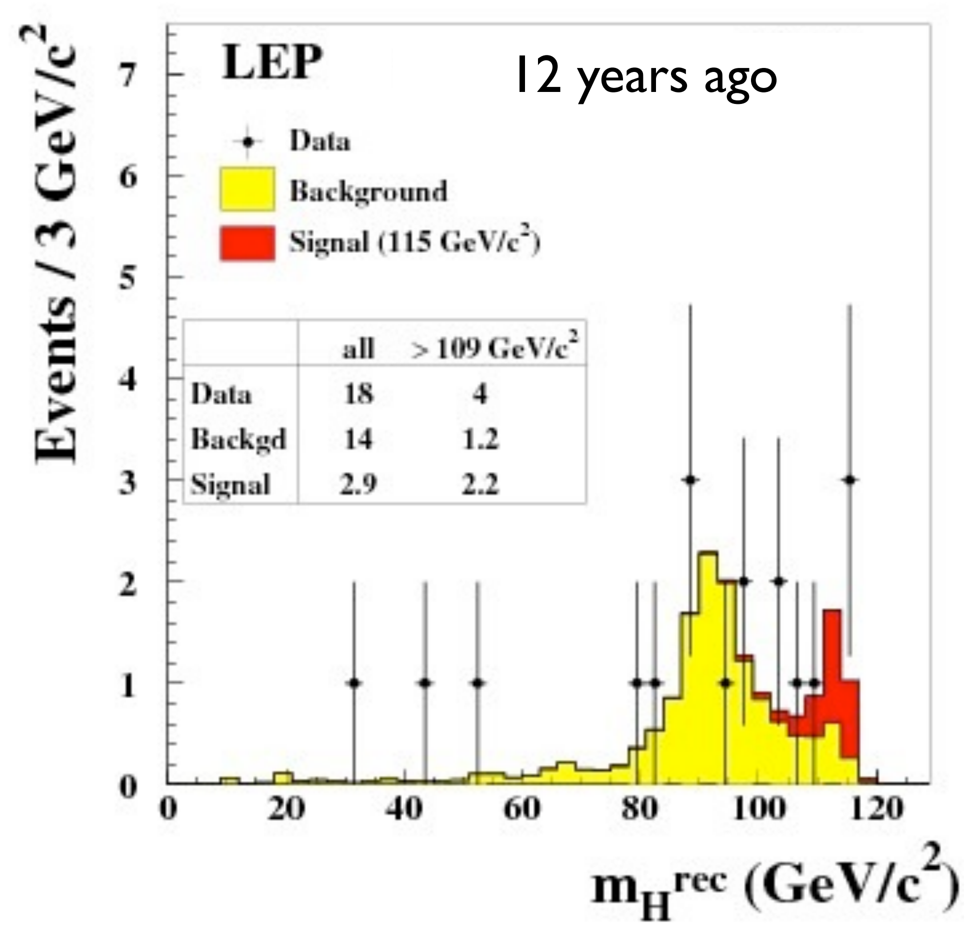
Gauge theory predicts force carrier particles to be massless e.g. photon & gluon
But $W^{\pm}$ & Z^0 boson have large masses ~80-90 GeV (proton~1 GeV)
Higgs mechanism explains why $W^{\pm}$ & Z^0 bosons are not massless

Higgs properties are well known except its mass!

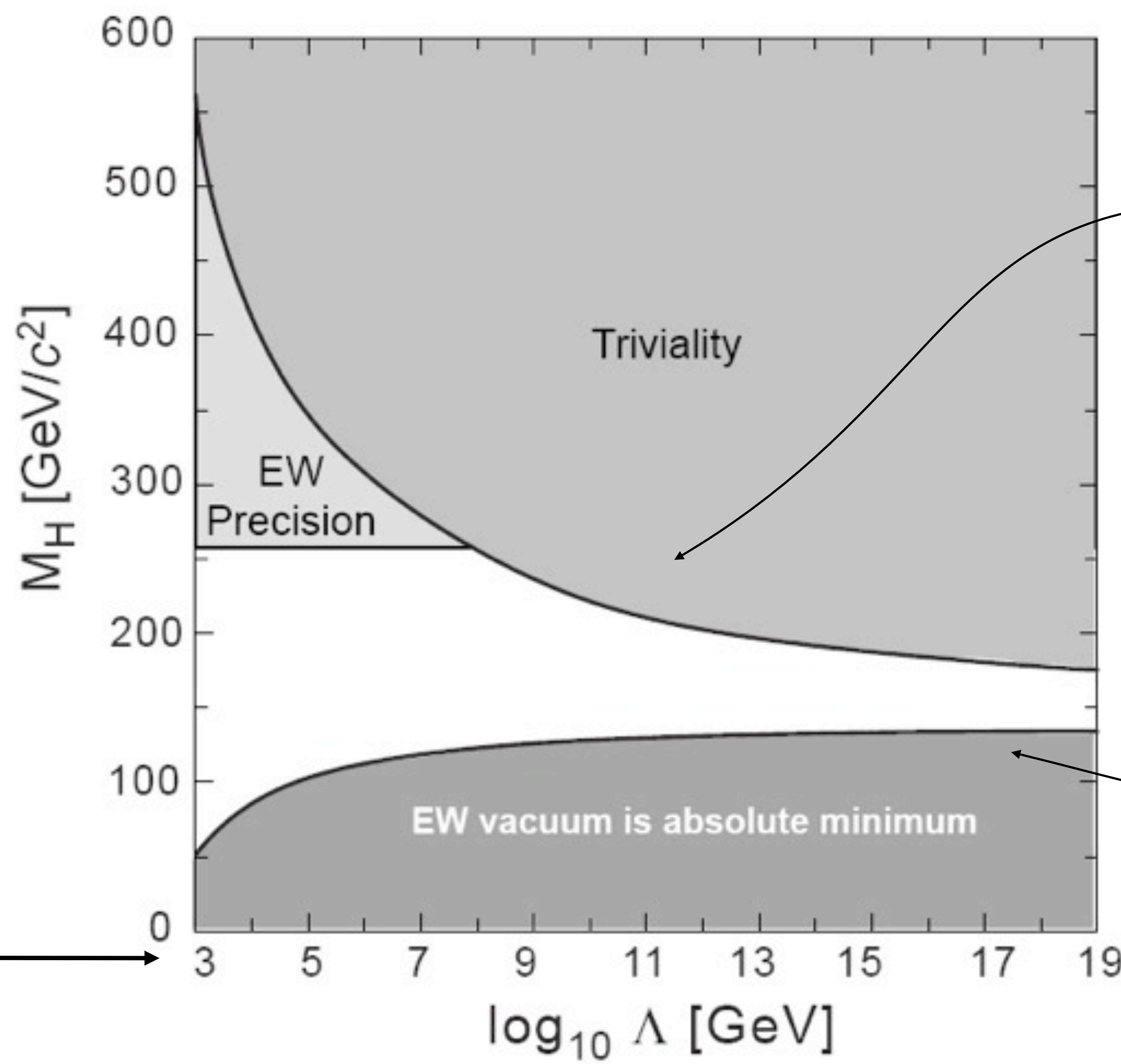
Direct searches at the LEP e^+e^- collider
No Higgs found within energy range of LEP $\Rightarrow$ mass m_H>114 GeV



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



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

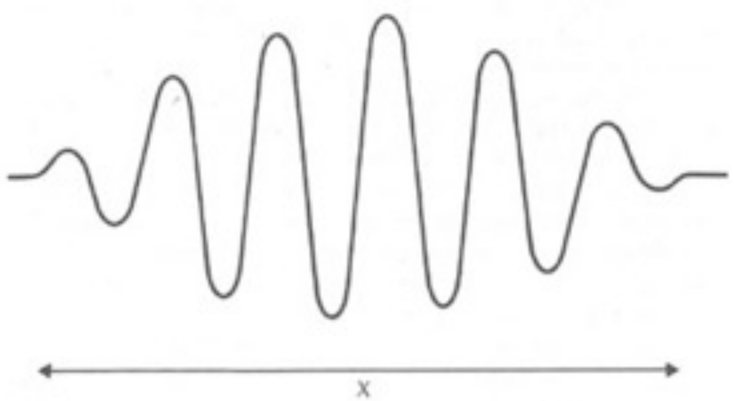
1000 GeV →

← 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

Recap



a wave packet corresponding to a particle located somewhere in the region X

$$\psi = Ae^{i(kx-\omega t)}$$

- A quantum mechanical particle is associated with a wave function ψ
- The wave function encapsulates all information about the particle
- The wave function squared is proportional to probability of finding the particle at a particular place, time, energy, momentum etc..

kinetic energy + potential energy = total energy

$$\frac{-\hbar^2}{2m}\nabla^2\psi + V(x,y,z)\psi = i\hbar\frac{\partial}{\partial t}\psi$$

Schrödinger equation describes the particle ψ behaves under influence of an energy field *V(x,y,z)*
x,y,z,t are co-ordinates in space and time
V(x,y,z) could be e.g. another particle's electric field

$$\frac{\partial}{\partial t}$$

The equation involves "derivative" operators:
⇒ mathematical operators acting on wave function
They calculate slopes - or how the wave function changes per meter, or per second

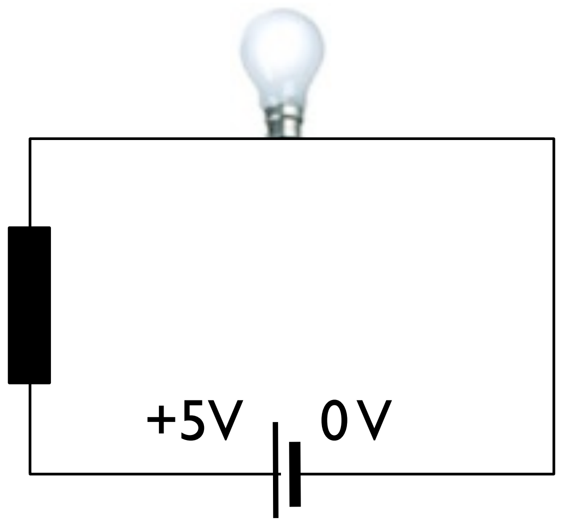
$$\nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}$$

operators act on something, just like + or ÷ or √
In this case they act on the wave function ψ

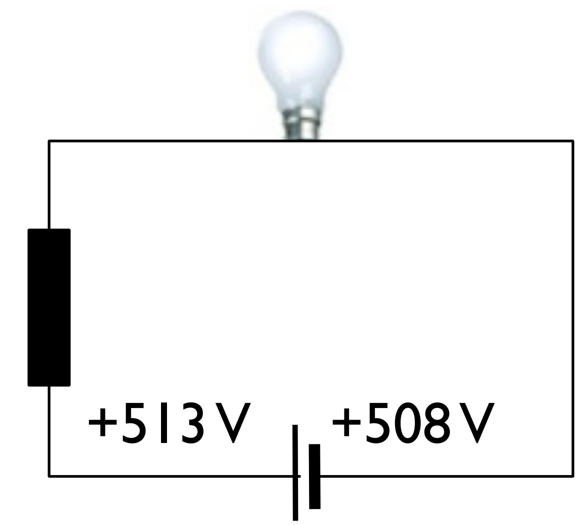
Symmetry:
A transformation which leaves an experiment unchanged
Each quantum symmetry is related to a conservation law

Translation in time	Energy conservation
Translation in space	Momentum conservation
Rotations	Angular Momentum conservation
Gauge Transformation	Charge conservation

Gauge Theory



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

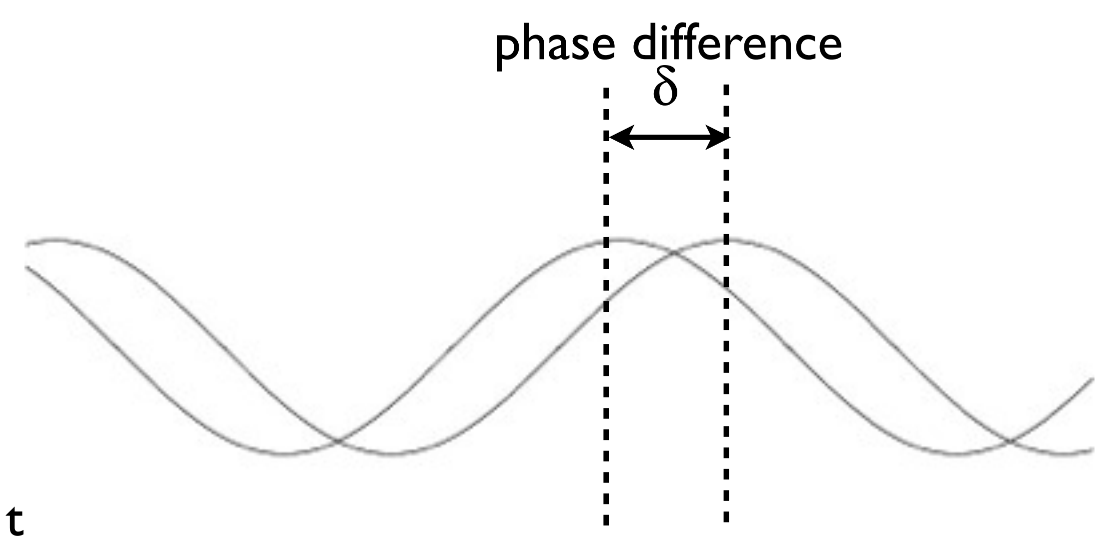


Both circuits behave identically
Circuit is only sensitive to potential differences
Change the ground potential of the earth and see no difference!
Leads to concept of charge conservation

In electromagnetism we are insensitive to phase δ of EM radiation
All experiments can only measure phase <u>differences</u>
Could globally change the phase at all points in universe
Yields no observable change

$\Rightarrow$ global gauge transformation

(In electromagnetism this is the gauge symmetry expressed by the U(1) group)



What happens if we demand <u>local</u> phase transformations? $\delta \rightarrow \delta(x,t)$
i.e. δ is no longer a single number, it depends on position x and time t

$$\frac{-\hbar^2}{2m}\nabla^2\psi + V(x,y,z)\psi = i\hbar\frac{\partial}{\partial t}\psi$$

δ(x,t) spoils the spatial & time derivatives

Wave functions of all particles get an extra piece from the change in δ
This spoils the Schrödinger equation
(actually, relativistic versions are the Klein-Gordon and Dirac equations)

(see lecture 2)

$$\psi = Ae^{-i(kx-\omega t)} \rightarrow \psi = Ae^{-i\delta(x,t)}e^{-i(kx-\omega t)}$$

... and since energy (E) and momentum (p) measurements are represented by operators in quantum mechanics

$$i\hbar\frac{\partial}{\partial t}\psi = E\psi \qquad \frac{\hbar}{i}\frac{\partial}{\partial x}\psi = p_x\psi$$

The derivatives cause nuisance terms to appear in equations arising from $\delta(x,t)$

But we still want physics to work the way it did before the gauge transformation!
We want the Schrödinger equation to still work!

So - add an additional term to the equation to cancel out those nuisance terms
After adding these to the equation we ask ourselves: what do the new equation pieces look like?

The alterations required to accommodate these changes introduce a new quantum field
This field has a 'spin' = 1
This field interacts with charged particles
This field no charge itself
The field particle has zero mass
- it is the photon!

Our consideration of local symmetry leads us to predict the photon

Gauge Theory

This can be applied to other quantum interactions:

local gauge invariance introduces new fields

oscillations in the fields <u>are</u> the probability wave functions of particles

Interaction	Gauge particle	Gauge group	Symbol	Felt by
Electromagnetism	photon	U(1)	wavy line	$q, W^{\pm}, e^{\pm}, \mu^{\pm}, \tau^{\pm}$
Strong force	gluons	SU(3)	curly line	q , gluons
Weak force	$W^{\pm}$ and Z^0	$SU(2)_L$	dashed line	$q, W^{\pm}, Z^0, e^{\pm}, \mu^{\pm}, \tau^{\pm}$, all ν

These are not simply abstract mathematical manipulations - the particles exist!

Weak bosons (spin 1 particles) discovered in 1983 at CERN's UA1 experiment

Energy of electrons from the decay of the W^- particle: $W \rightarrow e\nu_e$

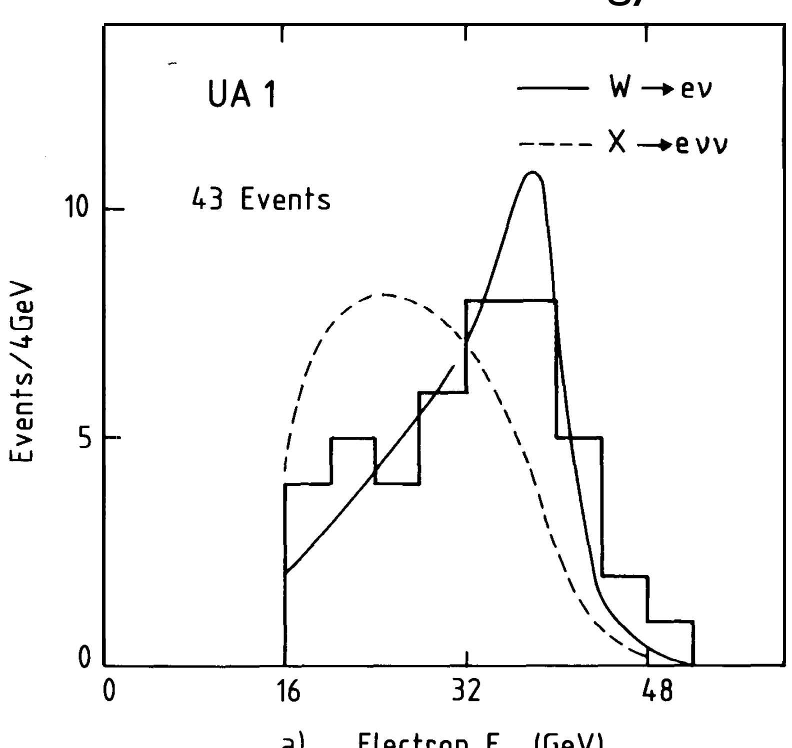
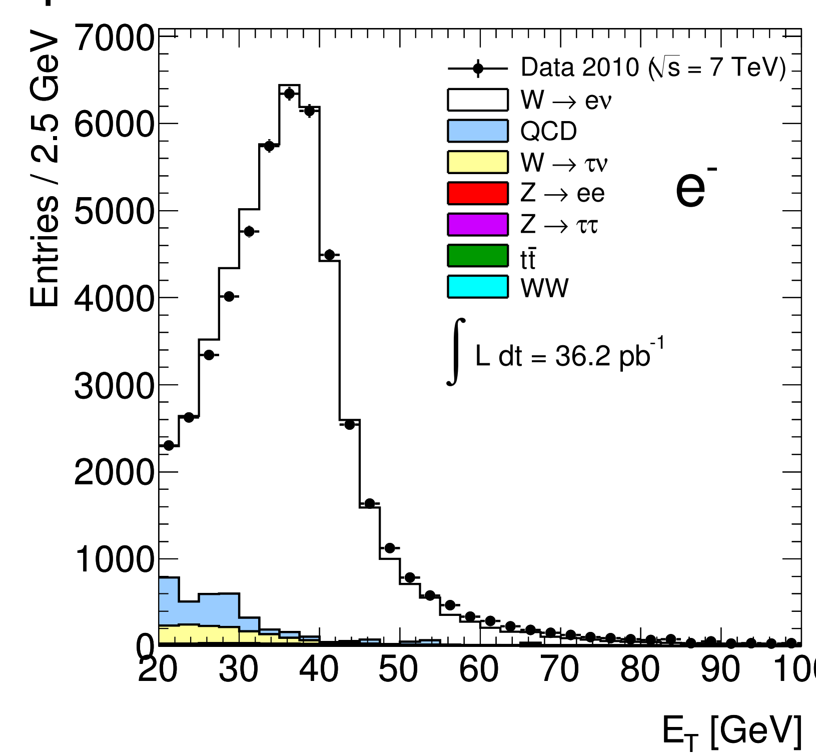


Fig. 19a. The electron transverse energy distribution. The two curves show the results of a lit of the enhanced transverse mass distribution to the hypotheses W→e+ν and X→e+ν+ν. The first hypothesis is clearly preferred.

1983 to 2010 →



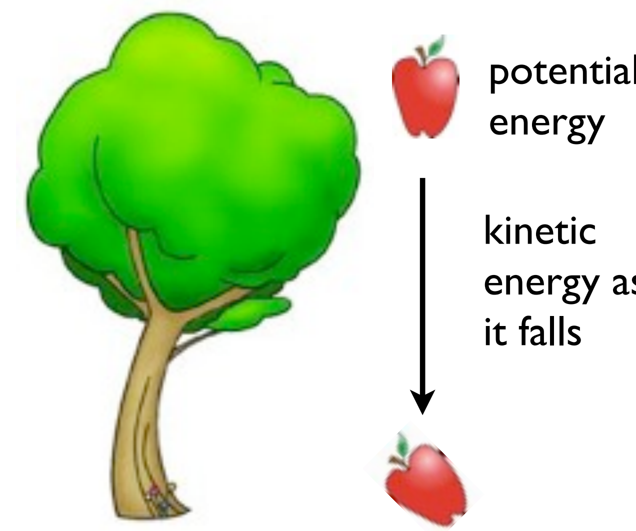
(In 2011 LHC has 40x more data than in 2010)

Perturbation Theory

So far theory predicted new particle's existence
How do we calculate particle reaction rates?
e.g. reaction rate of electron - positron scattering??

$$\frac{-\hbar^2}{2m}\nabla^2\psi + V(x,y,z)\psi = i\hbar\frac{\partial}{\partial t}\psi$$

In Schrödinger equation a particle interacts with a potential energy field V
Potential energy is energy an object has by virtue of position
Apple in a tree → it has potential energy in Earth's gravitational field
Apple falls → it releases potential energy into kinetic energy
Total energy is constant!



In quantum mechanics the potential causes a transition from initial state to final state wave functions $\psi_i \rightarrow \psi_f$

Potential = V + V'

V gives rise to stable, time independent quantum states ψ_f and ψ_i

V' is a weak additional perturbation leading to transitions between states

$$P = |M_{fi}|^2 = |\int \psi_f V' \psi_i \; dv|^2$$

P = probability of transition from initial to final state

M_{fi} is known as the matrix element for the scattering process

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

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

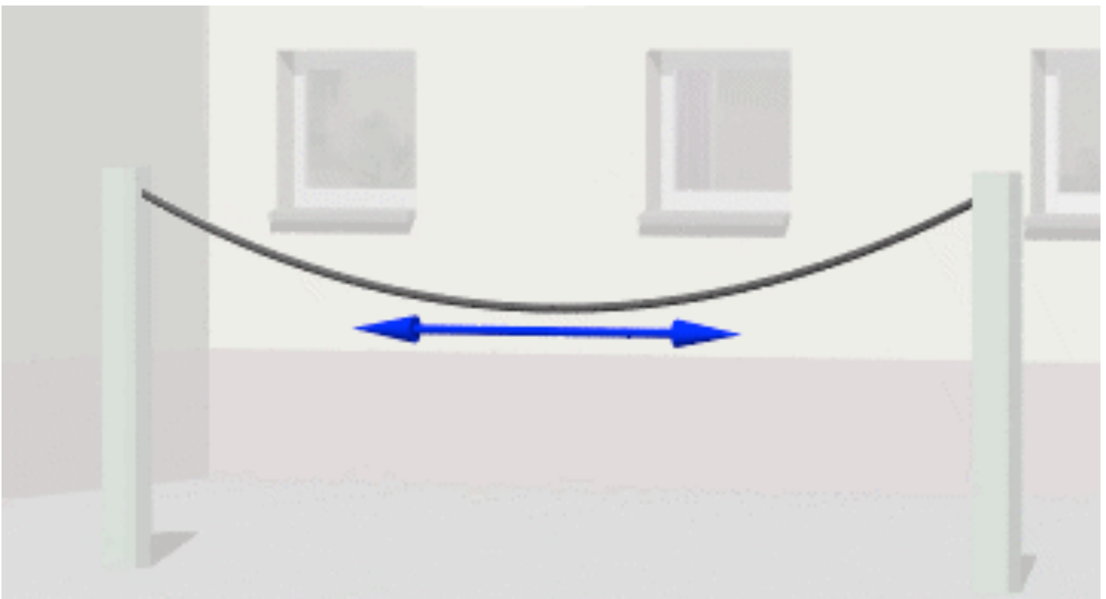
Why are the extra dims < 1 mm ?

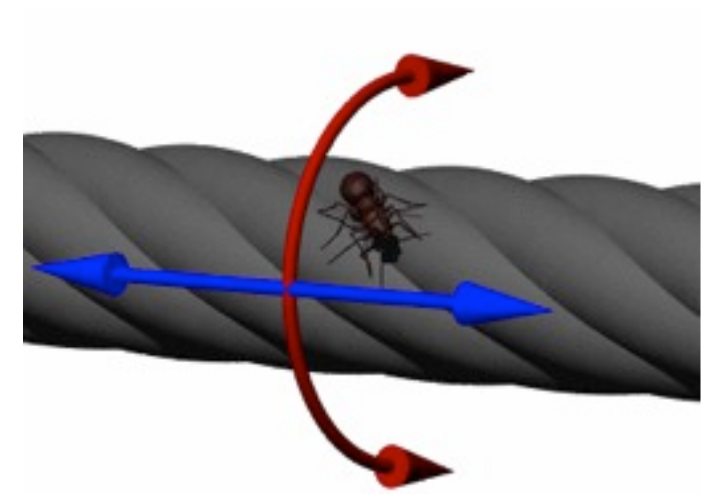
gravity has only been tested down to this scale!

Where are the extra dimensions?

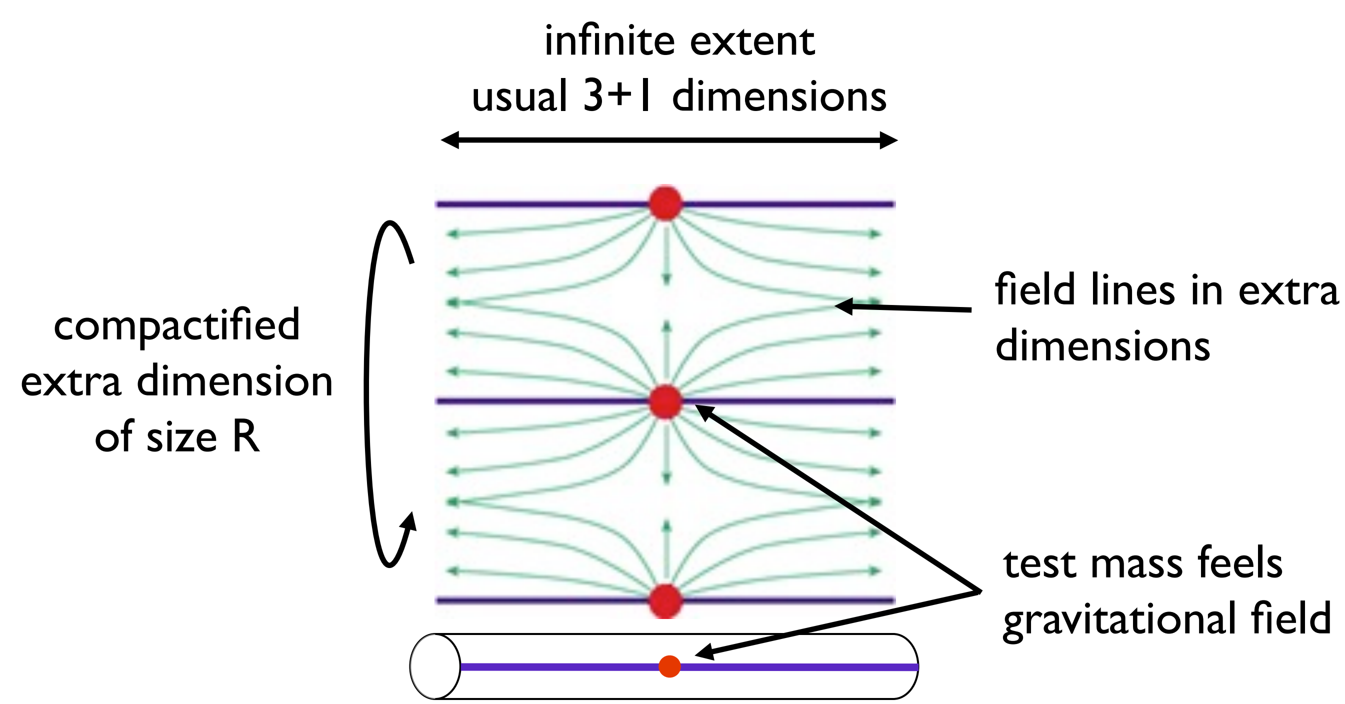
curled up (compactified) and finite

only visible at small scales / high energies



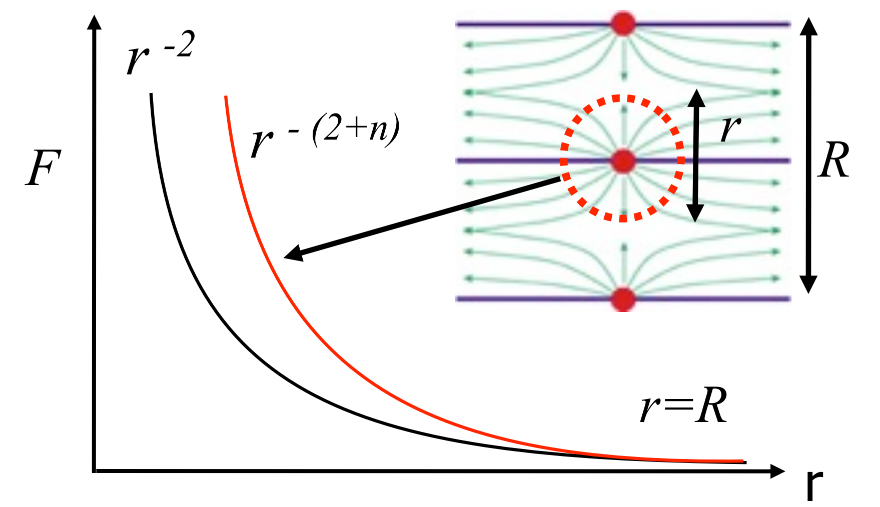


Relative strength of gravity explained by dilution of gravitons propagating in very large volume of bulk space



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

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

<u>units</u>

$c \rightarrow m\ s^{-1}$
$G \rightarrow m^3\ Kg^{-1}\ s^{-2}$
$\hbar \rightarrow Kg\ m^{-2}\ s^{-1}$

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

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!

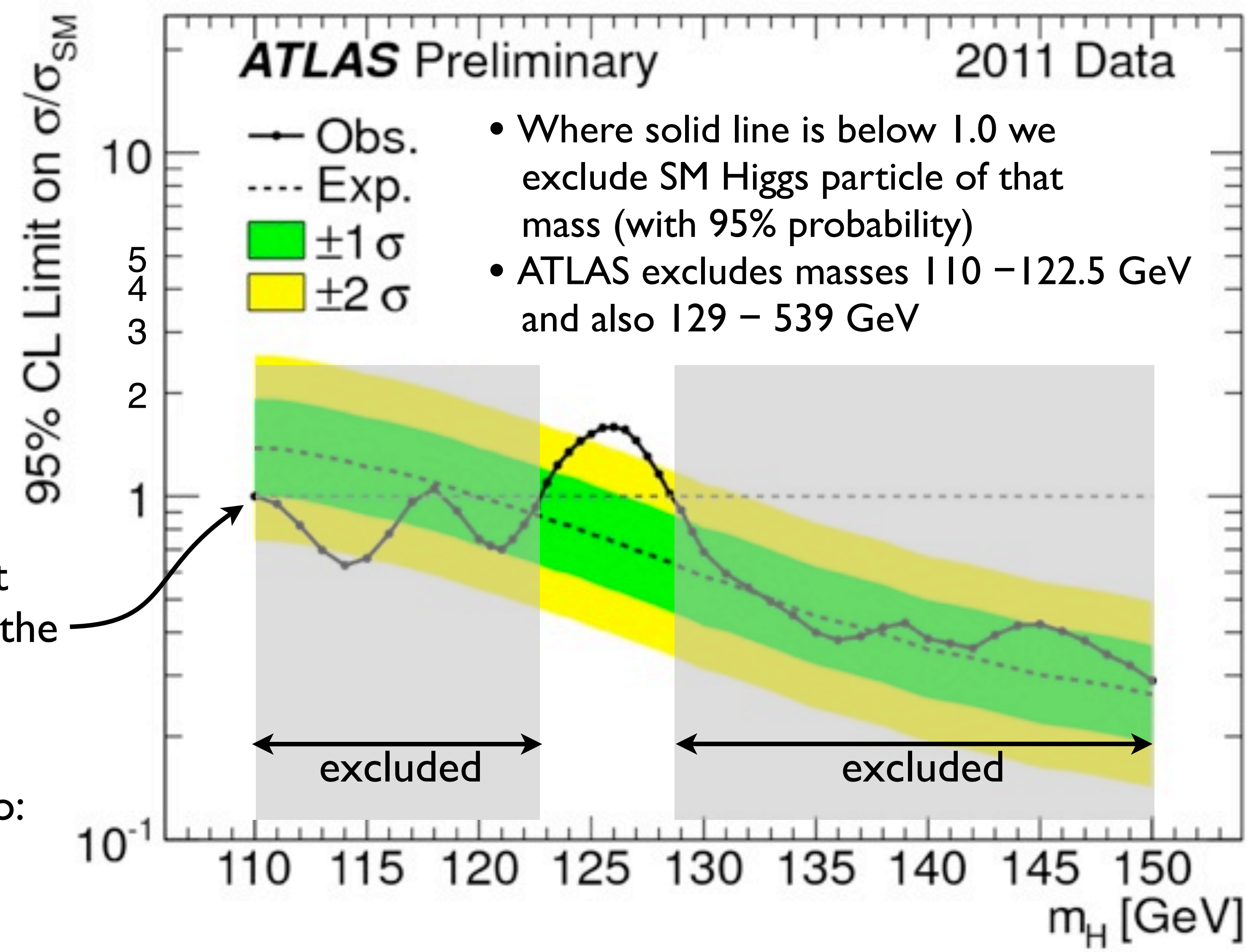
Higgs Hunting

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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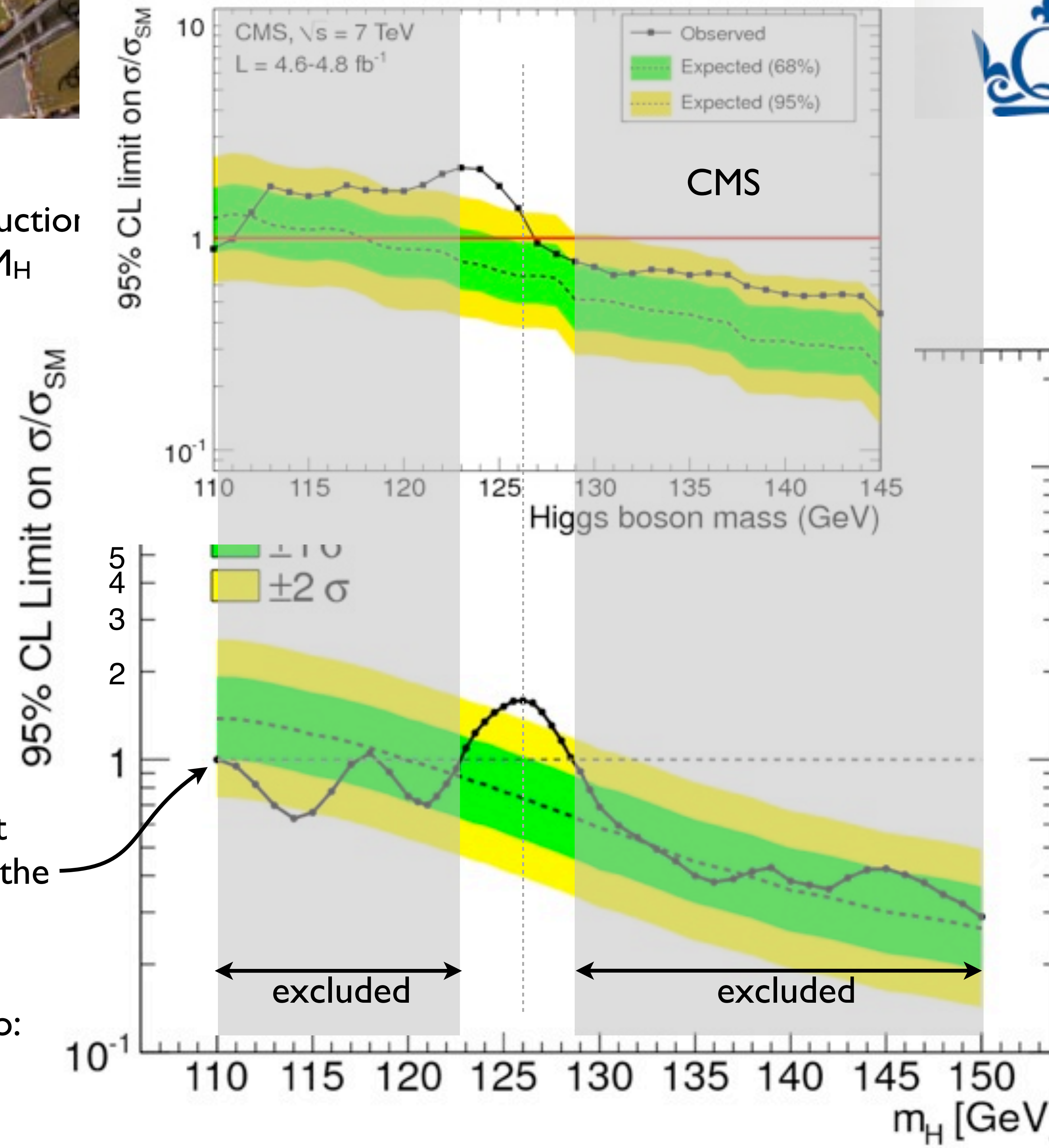

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In case you wanted to see the full version of this graph!