The Higgs?

Bill Murray
bill.murray@stfc.ac.uk
14th September 2012

- What is a Higgs boson?
- How do we look for it?
- Did we find it?
- What are the implications?
The 'Standard Model' describes the interactions of subatomic particles.

- **3 pairs of quarks**
  - $(u,d),(c,s),(t,b)$

- **3 pairs of leptons**
  - $(e, \nu_e), (\mu, \nu_\mu), (\tau, \nu_\tau)$

- **3 forces**
  - Electromagnetism, $(\gamma)$
  - Weak nuclear force, $(W,Z)$
  - Strong nuclear force $(g)$

But what is this dotted Higgs boson for?

Don't forget: No gravity, dark matter etc....
Unifying principle: symmetry

Symmetry guided 20\textsuperscript{th} Century physics

In 1918 E. Noether proved that each symmetry has a conservation law:
- Mirror reflection $\rightarrow$ Parity
  - This leads to electron 'exclusion principle' and chemistry
- Start time $\rightarrow$ Energy conservation
- Position $\rightarrow$ Momentum conservation

Internal Symmetries
- Quantum Mechanics says particles have associated waves
- The wave height tells you the probability of finding the particle
- The phase of the wave (crest or trough?) is irrelevant
- This is a symmetry $\Rightarrow$ Electric charge conservation
Deeper Symmetries:

Some symmetries are so complete we don't see them
– e.g. The phase of quantum mechanical waves
– Internally important, externally irrelevant
– A global change of all phase everywhere changes nothing

'Gauge' symmetries are one we change locally
– Change *this* electron's phase but not *that* one over there
– The implications of this change spread out at the speed of light
– But more than that....they ARE light

If the QM phase of an electron is locally changeable
  You have to add the photon to the theory to keep it consistent.
Just requiring a symmetry has predicted a particle!
Gauge Symmetries

\[ SU(3) \times SU(2) \times U(1) \]

This is the symmetry set of the Standard Model.
The symmetries define the structure of the model.
Forces from Symmetry

<table>
<thead>
<tr>
<th>Force</th>
<th>Force</th>
<th>Particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>U(1)</td>
<td>Electromagnetism</td>
<td>Photon, $\gamma$</td>
</tr>
<tr>
<td>SU(3)</td>
<td>Strong Nuclear force</td>
<td>Gluon, $g$</td>
</tr>
<tr>
<td>SU(2)</td>
<td>Weak Nuclear force</td>
<td>W and Z particles</td>
</tr>
</tbody>
</table>

Each force has a symmetry generating it.
The symmetry requires force particles.
The problem is, the symmetry also insists the force carriers are massless.....

Not true for W, Z!

Are we really on the right lines here at all?
Spontaneous Symmetry Breaking? ⚫

Propose a symmetric potential giving a non-symmetric result. A very neat solution!

Introduce a new field with this property

Matter Particles:
Interact with Higgs field slows them down → generates mass

Force Particles:
W,Z particles gain mass
Photons/gluons don't notice SU(2); stay massless
The Higgs model

- Mass is an interaction with a field filling the vacuum
  - We cannot escape from it
- The W and Z bosons are intimately linked to it
  - The W mass can be predicted from other forces and masses
  - Allows a test of the model
- The mass for the quarks and leptons can be described
  - But each quark or lepton mass is added 'by hand'
  - It makes no predictions here – and is easily changed
- But to make it work there must be a new particle
  - The Higgs boson
  - Everything about this is predicted – except its mass
    - It is spinless
    - It decays almost immediately
    - To things with a probability proportional to $m^2$
    - Its rate of production is predicted
The W mass

- Green band is SM prediction
  - Its width comes from the (unknown) Higgs mass
  - 115 to 600 GeV shown
- Yellow+black band is the measured mass
- They match incredibly
  - Many theories failed this test
The W mass

- Green band is SM prediction
  - Its width comes from the (unknown) Higgs mass
  - 115 to 600 GeV shown
- Yellow+black band is the measured mass
- They match incredibly
  - Many theories failed this test
The W mass

- Green band is SM prediction
  - Its width comes from the (unknown) Higgs mass
  - 115 to 600 GeV shown

- Yellow+black band is the measured mass

- They match incredibly
  - Many theories failed this test
  - But only works at the right edge of the band
    • A light Higgs, near 115GeV

- Nb. This calculation assumes no unknowns
  - Could be badly wrong
History of the search

- 1964 Brout & Englert, Higgs, Gouralnik, Hagen & Kibble,
  Not taken too seriously until...
- 1967 Used in the formulation of the 'Standard Model'
  Proven to be self-consistent in 1971
- 1973 Experimental acceptance of the 'Standard Model'
- 1983 Discovery of W and Z bosons
  Closely linked to the Higgs boson
- 1993 LEP studies Z's and rules out $m_H < 53$ GeV
  And indirectly excludes $m_H > 300$ GeV
- 2000 LEP limits reach 114.4 GeV
  Hint of production at 115?
- 2011 LHC excludes 130-550 GeV, Tevatron 156-175
  Some indications for a particle at 125?
- 4th July 2012 New particle found at 126 GeV
  Consistent with the Higgs
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.
The Standard Model 1970

Only 8 (of 17) particles were known
  - One column was added to the theory in 1973
  - But the forces/Higgs not touched
The W/Z linked to Higgs sector
  - Not found until 1983/4
This was really a bold extrapolation
  - But by 1984 14 of the pieces were known
  - The last ($\nu_\tau$) arrived in 2003
  - Leaving only the Higgs unseen
The LHC in a slide

- The LHC collides protons at 4000GeV
  - Two head on makes 8000GeV
  - Will get to 2x7000GeV in 2015
- The energy to make a proton is ~1GeV
  - Many particles can be created in the collision
- A proton is a bag of quarks
  - In most collisions the bag breaks,
  - They 'hadronise' and appear as a jet of known particles
- Occasionally other things appear
  - Maybe one in 10,000,000,000 makes a Higgs
  - But few of those can be recognised
- So bunches collide at 20MHz
  - With 30 protons smashed each time
ATLAS and CMS

Two massive detectors studying highest energies

3 stage of identification
- Tracking charged particle for 1m or so
- Then massive absorbers stop the particles & measure energy
- Second set of 'trackers' looks for the penetrating muons

Note the people
New particles (e.g. Higgs) decay extremely fast
- Reconstruct what happened from decay products
- Can identify type by interaction pattern in the detector

Electrons, muons and photons are very useful
- There are none in a proton so their presence is suggestive
- We can measure their energy very well
How do we look for things?

Masses of pairs of muons show lots of structure:

- Sort through the LHC data
- Find events with two muons
- Measure their momenta
- Assume they come from the breakup of some particle
- Calculate its mass
- Put entry in the histogram
- Repeat for next event

Each peak is a (known) particle decaying to 2 muons
Hunting the Higgs Boson
pre-LHC knowledge

There was a minimum Higgs mass
- $m_H > 114.4$ GeV
- Set by LEP, an electron-positron collider at CERN
  - In the same tunnel as LHC but much lower energy

A region was excluded by the Tevatron
- Proton-antiproton collider in Fermilab, USA
- from 155-173 GeV ruled out
- They also have 'evidence for' at 110-140 GeV

The W mass suggested below about 160 GeV
- But it assumes there is nothing else to find
- That cannot really be true
Rates?

- LHC backgrounds!

Every event at a lepton collider is physics; every event at a hadron collider is background

$10^{10}$

Sam Ting
Huge event rates needed

- The rate of jets as a function of their $p_T$
- 20-2000GeV tested
- Rate falls off by thirteen orders of magnitude
- We need to understand the common process extremely well
W/Z/top measurements

**ATLAS** Preliminary

LHC pp $\sqrt{s} = 7$ TeV
- Theory
- Data 2010 (L = 35 pb$^{-1}$)
- Data 2011 (L = 1.0 - 4.7 fb$^{-1}$)

LHC pp $\sqrt{s} = 8$ TeV
- Theory
- Data 2012 (L = 5.8 fb$^{-1}$)

$\sigma_{\text{total}}$ [pb]
Higgs production

- The three most common modes
  - Others also exits: $t\bar{t}H$, $tH$ ...
- Gluon fusion has highest rate
  - Note: a 'loop' process with a virtual top quark
- Vector boson fusion and associated have extra activity
  - Can be used to tag process
  - Improves the purity
Higgs decay fractions

- $H \to ZZ$
  - $ZZ \to llll$: Golden mode
  - $ZZ \to ll\nu\nu$: Good high mass
  - $ZZ \to llbb$: Also high-mass
- $H \to WW$
  - $WW \to ll\nu\nu$: Most sensitive
  - $WW \to llqq$: highest rate
- $H \to \gamma\gamma$
  - Rare, best for low mass
- $H \to \tau\tau$
  - Need VBF, low mass
- $H \to bb$
  - $t\bar{t}H$, WH, ZH useful but hard
Rates by channel at 125GeV

- Data to June 2012
- From 10s to 100000 events per channel
  - Easy!
- But total pp events: \(8 \times 10^{14}\)
- 20 Higgs to \(\ell\ell\ell\ell\) events
- Needs incredible background rejection
  - The green channels end up the most sensitive
LHC started at 7TeV in 2010
- But really a development year
2011 was first year of large data production
5fb$^{-1}$ allowed SM Higgs sensitivity
Luminosity in 2011 rose smoothly
- 5.5fb$^{-1}$ delivered
Compare with Tevatron
- US pp collider. 1TeV+1TeV
- 12fb$^{-1}$ in 10 years
Great effort by LHC team!
The LHC energy was increased from 7TeV to 8TeV
- Brings a 30% increase in Higgs bosons/collision
- Also increases the collision rate as beams shrink naturally

The LHC beams were squeezed harder
- 40% reduction in size – 40% higher chance of colliding
- Overall factor two increase in rate.

LHC has delivered 14fb⁻¹
- 6fb⁻¹ was used for discovery
- Running until Christmas
  - 20fb⁻¹+ assumed
  - Will allow study

LHC Online Luminosity

ATLAS Online Luminosity $\sqrt{s} = 8$ TeV
- LHC Delivered
- ATLAS Recorded

Total Delivered: 14.66 fb⁻¹
Total Recorded: 13.73 fb⁻¹
In 2011 9 collisions per bunch crossing.

Changed to 20 in 2012.

That is how LHC increased the data rate....

So learn to cope.
Pileup in 2012

- An interesting event
  - $Z \rightarrow \mu\mu$ here
- Has multiple overlayed interactions
  - 25 seen here
- The tracker can distinguish them by position
- The calorimeter finds it harder
  - Make checking momentum balance hard
So what do 2012 data say?

- Papers submitted 31\textsuperscript{st} July by CMS and ATLAS
  - Both claiming observation of a new particle
- Focus on region 115-129GeV left from 2011
- ATLAS used only 3 strongest channels:
  - $\gamma\gamma$
  - $ZZ$
  - $WW$
- CMS used these, but also two more
  - $\tau\tau$
  - $bb$

![Sensitivity graph showing 95% CL limit on $\sigma/\sigma_{SM}$ as a function of Higgs boson mass.](chart.png)
Rare decay,
- 2 per mille
- $110 < m_H < 150$

Drove ECAL design
- Resolution in CMS
- Pointing in ATLAS

To measure mass need to know vertex position
- Pileup hurts!

Good jet rejection also essential
H \rightarrow yy mass resolution

- Best check is Z \rightarrow ee
  - But Z has a natural width, broadens distn.
  - Higgs will be narrower
    - Need to trust MC

**Best category**

- ATLAS and CMS similar
Both experiments measure sample composition
- yy, yj or jj?
- Use less-well identified data samples to measure it
- Samples are dominated by real di-photon.
- We did reject 99.99% of jets!
In principle look at the $m(\gamma\gamma)$ spectrum for a bump
But signal/background and resolution depend upon other variables
Both experiments split into several categories, fit at once
  ATLAS uses $p_{Tt}$, barrel/forward, converted/unconverted
  CMS uses MVA to select categories
One or two 2-jet categories sensitive to VBF added too
  Gives more power
  But also useful to understand physics of production
But..too many plots to take in
  20 in ATLAS' case
  So experiments weight categories and add them up.
Both experiments see significant peaks around 125

Weighted sum clearer
Background Compatibility

- Peak around 126 in both years, both experiments
- Probability around $10^{-5}$ in each case
- Definitely looking interesting
The golden mode

Good energy measurement like $\gamma \gamma$

But know production point

Very low backgrounds

Dominated by $ZZ \to \ell\ell\ell\ell$

But signal rate low

$Z \to ee$ or $\mu\mu$ br only 3%

Need to maximise efficiency
How is analysis done?

- Find events with 4 leptons (e/μ) in them
- Request a pair is in region of the Z mass
- The second is allowed to be much lower in mass
  - Because two normal Z's weigh more than the Higgs signal
  - One of them is force to be off-shell, lighter

Major background:
- ZZ → llll (where Z's are not to do with the Higgs)
  - 'irreducible'
- Zbb
- tt → WbWb → νlνb

The b quark can decay to a lepton + a charm quark
- Require isolation – b's decay products should be visible
- Require leptons from primary – b's travel a mm or so
**Selection methods**

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum lepton $p_T$</td>
<td>7 GeV (e) / 6 GeV (μ)</td>
<td>7 GeV (e) / 5 GeV (μ)</td>
</tr>
<tr>
<td>Mass $Z_1$</td>
<td>50 - 106</td>
<td>40 - 120</td>
</tr>
<tr>
<td>Mass, $Z_2$</td>
<td>17.5 - 115</td>
<td>12 - 120</td>
</tr>
</tbody>
</table>

- CMS cuts always a little looser, more efficient
  - ATLAS efficiency: 36%, 21%, 18% in $\mu\mu\mu\mu$, $ee\mu\mu$, $eeee$
  - CMS efficiency 40%, 27%, 18% in $\mu\mu\mu\mu$, $ee\mu\mu$, $eeee$
  - 10% higher efficiency in CMS

- Backgrounds similar despite different cuts:
  - ATLAS background expected (120-130): 4.9
  - CMS background (121.5 -130.5): 3.8
  - 10% less background in CMS per GeV

- CMS also uses 'matrix element'
  - Uses leptons angles & Z masses to separate sig. from back.
Request two isolated leptons making Z mass
Find two more, no isolation or impact parameter cuts
ATLAS $m_{34}$ (left) and CMS $m_{1234}$ (right) measure fakes
Extrapolate fake rate to isolated region
“Matrix element likelihood analysis”
- Uses predicted distributions of 5 angles and 2 Z masses of the H → ZZ → llll system to see how like s or b each event is
- Background modelled as ZZ* / Zγ*
- Several events are 125 GeV are seen to have very high 'MELA' values, $K_D$
Background shapes decently seen in both
- Note peaks at 90 and >180 (1 real Z, 2 real Z's)
- Small peak at 125 GeV seen in both experiments
  - These events are mostly signal!
ATLAS expects about 2.8 sigma at 126 GeV.
CMS sensitivity nearly 4 sigma at 126 GeV.

Diference largely from use of 4-lepton matrix-element.
H → WW → lνlν
The most sensitive channel for $130 < m_H < 200$
- Still one of the 3 most important at 125GeV
- But poor mass information due to 2 undetected neutrinos

Good trigger, reasonable rate
- Largest background is non-resonant $WW$
  - Also top when looking at $WW+1$ jet
- Backgrounds measured from control regions

Request two leptons
- 15,25 GeV (ATLAS) 10,20GeV (CMS)
  - ATLAS only uses $e-\mu$ pairs in 2012 ($ee/\mu\mu$ have more bkgd.)

Require missing $E_T$ ($E_t^{rel}$) and $p_T(ll)$ for $WW$

Select signal area with $\Delta \phi$ and $m_{ll}$ selections
- CMS using cut-based and multivariate
- ATLAS prefers cut-based.

Many backgrounds need estimation from data - tricky
Backgrounds are (almost) all found in control regions

- ATLAS same-sign (left) check W+jets
- ATLAS WW control (right) from high $m_T$ events

Integrals must match data/MC by construction.
But scale factors are near 1.
Modelling of shapes from simulation

- Tricky business, different simulation programs are compared

Distinct excess in both experiments

- In the region signal is expected
- But not well localised
- 2.8σ in ATLAS, 1.6σ in CMS
Both set bad limits
2.8sigma excess in ATLAS, 1.6sigma in CMS
Two neutrinos means mass not well measured
  So broad excess seen
CMS $H \rightarrow \tau\tau$

- Best fermion decay mode
- Using many combinations:
  - $e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$ decays
  - 0jet/1jet * high/low $p_T$, + VBF
- VBF is most sensitive
  - No sign of a signal here
  - Actually close to 95% exclusion
**H → ττ limits**

- Limits at 1.2xSM at 125GeV
- Almost excludes a signal
  - But doesn't
  - Anyway, break data into enough subsets and one will look odd.
- But it is interesting
  - More data and ATLAS results keenly anticipated
The most common Higgs decay mode – but hard
ATLAS has not released 2012 results yet
CMS uses 6 channels:
- $WH, W \rightarrow l\nu (e,\mu)$
- $ZH, Z \rightarrow ll (e,\mu)$
- $ZH, Z \rightarrow \nu\nu$
- $ttH$ - 2011 only
Also divided into
- medium $p_T$
- high $p_T$ ( $> 100$ to $> 170$)
Backgrounds are from
- $W/Z$ plus $b$ jets
- $tt$
- $W/Z$ plus $Z$
Boosted Decision Trees select signal
Estimating the mass is difficult
- B jets break into many pieces
- But work goes on to improve it

BDT (pattern recognition algorithm) output for \( \nu \nu bb \) search is shown to left
- No evidence for a signal
The expected limit is $1.6 \times \text{SM}$ strength. 
- 2.1x is observed
Small excess of $0.7\sigma$
- $1.6\sigma$ would have been expected for a Higgs
So this is not very conclusive today
- The improvement in sensitivity is remarkable, passing $H \rightarrow \gamma\gamma$ at low mass
Both experiments exclude nearly all mass range at high confidence.
Probabilities $10^{-7}$ to $10^{-9}$

5σ and 5.9σ

...we got it
But what did we get?
2D fits of rate and mass reduce model dependence

- **ATLAS**: $m_H = 126 \pm 0.4 \pm 0.4$
- **CMS**: $m_H = 125.3 \pm 0.4 \pm 0.5$

These channels all have consistent solutions...1 particle
The Combined Results

For a signal at 126 (or 125.3):
- ATLAS just over a sigma above SM rate, $1.4 \pm 0.3$ @126
- CMS just under a sigma below, $0.87 \pm 0.23$@125.3GeV

This is consistent with a SM Higgs
Channel results

- Allmost all channels favour a signal
- More powerful ones (WW, ZZ, γγ) all do.
- Is there too much γγ? Not really ... so far.

\[ \mu = 0.87 \pm 0.23 \]

\[ m_H = 125.5 \text{ GeV} \]
WE want to test whether what we have is the Higgs boson
Like the EW fits done at LEP
We need 'pseudo observables' that encapsulate results and allow fits:
The LHC cannot measure the total width
There are always impossible decays like $H \rightarrow \text{gluons}$
So some assumption is needed
Many couplings accessible:
- $ZZ$, $WW$, $\gamma\gamma$, $bb$, $tt$, $gg$, $\tau\tau$, $\mu\mu$?, invisible?
- Note $gg/\gamma\gamma$ are effective coupling through loops
Too many to fit all at once
Simplify by grouping the couplings
- e.g. Bosons and fermions
$\kappa_V \kappa_F$ couplings

Top right:
- $W/Z$ scaled via $\kappa_V$
- Fermions by $\kappa_F$
- Assume no invisible decay
- Sign of fermion coupling tested in photon decay loop
  - We will have some sensitivity to sign with more data
- Measuring single top+Higgs would help this

Bottom right tests $W \nu Z$
- Custodial symmetry
  - $1.07^{+0.35}_{-0.27}$

$\lambda_{WZ}$
- $-2 \ln \Lambda(\lambda_{WZ})$
- $\lambda_{WZ}$
- $-2 \ln \Lambda(\kappa_V \kappa_F) < 2.3$
- $-2 \ln \Lambda(\kappa_V \kappa_F) < 6.0$

$\int s = 7$ TeV, $\int L dt = 4.8$ fb$^{-1}$
$\int s = 8$ TeV, $\int L dt = 5.8-5.9$ fb$^{-1}$

ATLAS Preliminary
- SM
- Best fit
Another possibility is to **ASSUME** a SM Higgs
- But allow the loops to have unknown particles
  - $ggF, \, H \rightarrow yy$
- Top assumes no invisible decay
  - $(1,1)$ is the SM strength compatible with this
- Bottom tests for invisible branching ratio
  - Cannot all be invisible as we see it!

We test many other possibilities ... all look like SM
So what do we know?

<table>
<thead>
<tr>
<th>Property</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs Mass</td>
<td>Measured – agrees with SM rough prediction</td>
</tr>
<tr>
<td>Spin</td>
<td>Should be 0. We know it is integer, and not 1</td>
</tr>
<tr>
<td>Parity (mirror symmetric?)</td>
<td>Should be symmetric. Unknown</td>
</tr>
<tr>
<td>Charge</td>
<td>Zero, as it should be</td>
</tr>
<tr>
<td>Lifetime</td>
<td>Unknown, but narrow resonance and no obvious flight, OK.</td>
</tr>
<tr>
<td>Interaction with W,Z</td>
<td>Rates in WW,ZZ look as expected.</td>
</tr>
<tr>
<td>Interaction with matter</td>
<td>ATLAS information weak here</td>
</tr>
<tr>
<td>(quarks/leptons)</td>
<td>CMS bb+ττ combination 2σ low. No LHC proof this exists</td>
</tr>
<tr>
<td></td>
<td>But Tevatron has around 3σ evidence - twice expected</td>
</tr>
<tr>
<td>Interaction with gluons</td>
<td>Total rates suggest this as expected</td>
</tr>
<tr>
<td>Interaction with photons</td>
<td>1.6±0.4 (CMS) and 1.8±0.5 (ATLAS)</td>
</tr>
<tr>
<td></td>
<td>This is ~2σ high</td>
</tr>
</tbody>
</table>

It is consistent with the SM Higgs

With reasonable statistical fluctuations
What does 125-126 tell us?

In SM $m_H = 94^{+29}_{-24}$ GeV

So observed mass fits SM with no additions
What does $m_H = 126$ tell us?

- The Higgs self-interaction changes with energy
  - Penalty to make more decreases as $E$ rises
- If $m_H$ is small 'penalty' can become gain
  - Then unlimited are made
  - Vacuum collapses

$$V(\phi) = -\frac{\lambda}{2}|\phi|^2 + \frac{g}{4!}|\phi|^4$$

- 125 GeV is at the divide
  - Universe may be meta-stable
  - Suggests unknown 'fix'
What does 125-126 tell us?

But *why* is $m_H$ so low?

The Higgs potential:

$$V(\phi) = -\frac{\lambda}{2} |\phi|^2 + \frac{g}{4!} |\phi|^4$$

Suffers from loop correction like the top loop

The mass gets quantum corrections from the highest scale in the theory
- Tends to be moved to $\sim$ this scale
- The only we know is $10^{16}\text{GeV}$ (gravity)

This 'heirarchy problem' motivates supersymmetry
- Corrections from superparticles cancel the particles and $m_H$ is allowed (forced!) to be light
- SUSY enthusiasts encouraged!!
How many neutrinos?

- LEP proved 3 light neutrinos hence 3 generations?
- Now we know neutrinos have mass maybe $2m_\nu > m_Z$?
  - Could be a heavy neutrino
- But Higgs production is mostly through gluon fusion
  - Virtual top in a loop
  - A new heavier quark would increase the rate a lot
  - Whatever mass the quark had
- Much harder to believe in a 4\textsuperscript{th} generation today.
Dark Matter?

- If this is a Higgs, in many models it couples strongly to dark matter
- 5-50GeV dark matter will be severely tested by fact Higgs decays as expected
- Not yet, but the blue area will be constrained
  - SUSY prediction OK!

Xenon plot from ArXiv: 1005.0380v3
SUSY prediction from: JHEP 0812:024, 2008
What about the Higgs field?

A unique prediction of the Higgs mechanism is the field filling space
- Unlike light, you turn it off and it is still there
- More like water filling the sea

The density of this field is ruled out by big-bang cosmology
- It is 120 orders of magnitude larger than dark energy – and the opposite sign

So do we really expect you to believe its there?

This really means we don't have a QM theory of gravity
Evidence: H to ZZ

As a photon only couples to charged particles a Z only interacts with those with weak force charge

The Z is neutral
  - Charge and weak charge

ZZH vertex shows the H must be weak charged
  - But in $H \rightarrow ZZ$ where does the charge go?
Evidence: H to ZZ

- As a photon only couples to charged particles a Z only interacts with those with weak force charge
- The Z is neutral
  - Charge and weak charge
- ZZH vertex shows the H must be weak charged
  - But in H→ZZ where does the charge go?
- It is really a 4-point coupling
  - One leg 'grounded' in the vacuum
- The ZZ decay is telling is the vacuum is really important
  - An active participant in interactions
  - With a (weak) charge!
- The apparent 3 point couplings come from $-\lambda[(v+h)/\sqrt{2}]^4$ – but v is the VeV
- There IS a field
Quid nunc for Higgs?

- The mass is just great
- LHC targets 5 modes
  - ZZ
  - WW
  - $\gamma\gamma$
  - $bb$
  - $\tau\tau$
- More coming
  - $Z\gamma$
  - $\mu\mu$
  - $XX$
- Lepton collider
  - $gg$
  - $cc$
Next Steps for Higgs studies

Proton Colliders
- LHC: $11\text{fb}^{-1} \rightarrow 25\text{fb}^{-1}$
- Run 2021 with $300\text{fb}^{-1}$ at 14TeV delivered
  - 30 times what we have seen so far!
- HL-LHC calls for $3000\text{fb}^{-1}$ LHC running to 2030
  - Natural extension of LHC, 30% rise in $\sqrt{s}$ sensitivity
- HE-LHC – 33TeV proton beam with 20T magnets in the LHC tunnel (or even stronger)
- VLHC – a larger proton ring up to 80 km is considered

Electron colliders
- ILC – 250-500GeV, up to 1TeV later, linear collider
- CLIC – 250-3000GeV linear collider
- LEP-3 – 240GeV $e^+e^-$ ring in LHC tunnel – (tunnel is in use!)
- Several ideas for 60-100km ring $e^+e^-$ machines

All this was debated in European Strategy meeting
- Krakow, 10-12\textsuperscript{th} September
How will we do?

- The following GUESSES assume SM rates
- They also assume a lot of work

<table>
<thead>
<tr>
<th>Production Mechanism</th>
<th>Gluon fusion</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>5σ</td>
<td>1σ</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WW</td>
<td>3σ</td>
<td>1σ</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>γγ</td>
<td>4σ</td>
<td>2σ</td>
<td>0.5σ</td>
<td>0</td>
</tr>
<tr>
<td>bb</td>
<td>0</td>
<td>0</td>
<td>2σ</td>
<td>0.3σ</td>
</tr>
<tr>
<td>ττ</td>
<td>0</td>
<td>2.5σ</td>
<td>0.5σ</td>
<td>0</td>
</tr>
</tbody>
</table>

If true we see 5 decays and 3 production mechanisms
Pretty good for the discovery year!
Weights of channels

Assume results Gaussian – not true
Plot $\chi^2$ contribution you EXPECT from each channel
- Tevatron contributes most in $bb$
- But (combined) is 3rd by 2013
But nearly all the evidence is from LHC

July 2012

July 2013?
Spin/parity

- We know integer spin, not 1
  - To reasonable confidence
- We can establish from ZZ/WW/yy
  - $\sim 3\sigma 0^+ \nu 0^-$
  - $\sim 3\sigma 2^+ \nu 0^+$
- But there are caveats:
  - Spin 2 assumes the production/ helicity structure
    - Why make those?
  - There are some very hard to separate
  - The bosonic decay projects out 0+ from a mixed state
    - We are not sensitive to mixed (CP violating) systems
- So..we WILL learn something
  - But theorists are not expecting surprises here
  - The rates match too well the 0$^+$ model...
Today we have two big discrepancies:

- The CMS $\tau\tau$ search almost rules out SM Higgs
  - ATLAS results keenly awaited
  - Fermiophobic already excluded...but some half-way house?
- $H \rightarrow \gamma\gamma$ excess
  - At about $2\sigma$ level
  - In an interesting place

My prejudice:
- Adding 'new physics' to the SM very likely to affect loops
- Like $H \rightarrow \gamma\gamma$

We will know a lot more when 2012 data is fully analysed
Whither LHC?

25fb\(^{-1}\) by end of year
300fb\(^{-1}\) by end of 2021
- With Energy 13+ TeV
- ~50 times the Higgs events reported on so far....
CMS projections

Comparison of current errors and 300fb\(^{-1}\)

These plots always involve assumptions about systematic errors.

But 10-20% errors expected.
CMS coupling expectations

- **5D fit here**
- Photons (loop)
- Vector bosons
- Gluons (loop)
- Quarks
- Leptons

- No invisible modes allowed
- Solves the absolute coupling issues

---

**CMS Projection**

Expected uncertainties on Higgs boson couplings

- $10 \text{ fb}^{-1}$ at $\sqrt{s} = 7 \text{ and } 8 \text{ TeV}$
- $300 \text{ fb}^{-1}$ at $\sqrt{s} = 14 \text{ TeV}$
- $300 \text{ fb}^{-1}$ at $\sqrt{s} = 14 \text{ TeV}$ w/o theory unc.

- $C_\gamma$
- $C_v$
- $C_g$
- $C_q$
- $C_l$
HL-LHC and ATLAS

- LHC runs to 2022
- 300 fb\(^{-1}\) at 14 TeV expected
  - SLHC is proposed thereafter - 3000 fb\(^{-1}\)
- \(t\bar{t}H, H \rightarrow \gamma\gamma\) and \(H \rightarrow \mu\mu\) are two interesting studies

But in general Higgs couplings must gain from factor 10 more data!
Interesting to compare ATLAS and CMS expectations

- Pretty close for ZZ and γγ
- Factor 3 apart for ττ at 300fb⁻¹ (different channels, systematics)

Being conservative is dangerous too!
Self coupling

- Needs observation of Higgs pairs
  - Thats a tall order!
- But it is not enough
  - Need to prove triple Higgs involved
  - negative interference :(
  - $bb\gamma\gamma$ allows $3\sigma$ HH observation
  - ATLAS+CMS, more channels, may give $3\sigma$ coupling measurement
250 GeV gives maximum for ZH

Need a very large energy before the vector boson fusion channels overtake that
HIGGS FACTORIES $e^+e^-$

**Linear Colliders**
- **ILC**
  - 250 GeV
  - 500 GeV
  - 250 GeV + Klystron based
- **CLIC**
  - 500 GeV
  - > 500 GeV

**Circular Colliders**
- **CERN**
  - LEP3 at LHC tunnel
  - DLEP – New tunnel, 53 km
  - TLEP – New tunnel, 80 km
  - 250 GeV- 40, 60 km tunnel
- **Super TRISTAN**
  - 400
  - 500

W.Murray STFC/RAL 88
HIGGS FACTORIES e+e- R&D & main issues

**Linear Colliders**
- **ILC**
  - Almost ready SC rf technology, need of opt for low energy, TDR by end ‘12, XFEL as test facility

**CLIC**
- Low E: X-band Klystron technology
- Demonstrated High gradient cavities
- Sinergy with XFELs
- ≥ 500, CDR, need >10 years R&D
- CTF3 test facility

**Circular Colliders**
- **CERN**
  - Low E - Tunnel ready (not available), technology ok, SCrf cavities ok
  - Long tunnel, high costs, environment impact

**Super TRISTAN**
- Technology assessed, tunnel & site ???

**e+ e-**

W. Murray STFC/RAL 89
Linear Colliders

- ILC
  - 500 GeV: 7B$ (2007), 31 km next costing end ‘12
- CLIC
  - 500 GeV: 8B$ (2012), 13 km next costing end ’12
  - > 500 GeV staging up to 3 TeV Costing to be defined

Circular Colliders

- LEP3: 1.5B$
- DLEP, TLEP (40, 80 km), 3-4B$
- TRISTAN
  - 2.7, 3.5B$ (40, 60 km), 250 GeV
  - 4B$ - 60 km 400 GeV
  - 5B$ - 60 km 500 GeV
Use LHC tunnel and detectors

$L \sim 10^{34}$

Need of booster + collider ring: two rings in LHC tunnel, lightweight magnets

Energy loss per turn: 7 GeV (3.5 @ LEP2)

Rf voltage: 12 GV, 1.3GHz (3.6 @ LEP2, 350 MHz)

Synchrotron radiation: 100 MW (7.2 mA) total

Integration and cohabitation with LHC, HL-LHC, HE-LHC
LEP 3 scheduling

Possible schedules

<table>
<thead>
<tr>
<th>LEP2</th>
<th>LS3</th>
<th>LS4</th>
<th>LS6</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>LEP3</td>
<td>HL-LHC</td>
<td>HE-LHC</td>
</tr>
</tbody>
</table>

0-Jan-00 31-Dec-09 1-Jan-20 1-Jan-30 2-Jan-40

Rough cost estimate

<table>
<thead>
<tr>
<th>Item</th>
<th>LEP3</th>
</tr>
</thead>
<tbody>
<tr>
<td>tunnel</td>
<td>-</td>
</tr>
<tr>
<td>RF</td>
<td>600</td>
</tr>
<tr>
<td>magnets</td>
<td>50</td>
</tr>
<tr>
<td>beam pipe</td>
<td>80</td>
</tr>
<tr>
<td>accelerator ring</td>
<td>200</td>
</tr>
<tr>
<td>injector</td>
<td>100</td>
</tr>
<tr>
<td>others</td>
<td>100</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>1130</strong></td>
</tr>
</tbody>
</table>
This takes into account modifications required to take care of the beamstrahlung effect pointed out by I. Telnov and K. Yokoya

-- energy aperture has been increased to ±4%
-- but energy spread at IP does not increase significantly

NB: This allows multibunch operations at lower than maximum energy
LEP3 offers:

$10^{34}$/cm$^2$/s Average Luminosity in 2 experiments i.e. 2x500fb-1
2x20'000 ZH events per year.

Challenges:
-- low vertical emittance must be maintained while fitting in the existing tunnel
-- beam-beam interaction is somewhat extreme (but nothing like LC!)
-- Most components are ‘off-the-shelf’
   except RF power source operating in CW mode
-- first use of a large system of ILC cavities (8% of ILC@250 GeV)

By-products
-- By multibunching one would be able to reach luminosities of
  $O(\sim 5 \times 10^{35})$/cm$^2$/s at the Z pole (Tera-Z)
  $O(\sim 5 \times 10^{34})$/cm$^2$/s at the W pair threshold (Mega W)
  $\Delta M_W < 1$ MeV, $\Delta M_Z, \Gamma_Z < 1$ MeV, $\sin^2\theta_{W_{\text{eff}}} < 0.0001$ (to be studied)
  beam transverse polarization easier than LEP
  because of low transverse emittance (in collision?)
ZH through Z only

The total cross-section can be seen with very low Higgs decay mode dependence
True of any lepton collider
Table 2: The precision (or 95% C.L. sensitivity for the invisible decay) on the Higgs boson cross sections and couplings obtained from studies of the Higgsstrahlung process, with five years of running at the ILC, at LEP3 with CMS and ATLAS, and at LEP3 with CMS, ATLAS and two additional detectors. The numbers for the ILC were obtained with $m_H = 120\,\text{GeV}/c^2$, $\sqrt{s} = 250\,\text{GeV}$, and leading-order cross sections, while those for LEP3 were conservatively obtained with $m_H = 125\,\text{GeV}/c^2$, $\sqrt{s} = 240\,\text{GeV}$, and next-to-next-to-leading-order cross section. The Hcc and HWW couplings will be added in a forthcoming update of this note.

<table>
<thead>
<tr>
<th></th>
<th>ILC</th>
<th>LEP3 (2)</th>
<th>LEP3 (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{HZ}$</td>
<td>3%</td>
<td>2.7%</td>
<td>1.9%</td>
</tr>
<tr>
<td>$\sigma_{HZ} \times \text{BR}(H \rightarrow bb)$</td>
<td>1%</td>
<td>1.2%</td>
<td>0.8%</td>
</tr>
<tr>
<td>$\sigma_{HZ} \times \text{BR}(H \rightarrow \tau^+\tau^-)$</td>
<td>6%</td>
<td>3.2%</td>
<td>2.2%</td>
</tr>
<tr>
<td>$\sigma_{HZ} \times \text{BR}(H \rightarrow \text{invisible})$</td>
<td>?</td>
<td>1%</td>
<td>0.7%</td>
</tr>
<tr>
<td>$g_{HZZ}$</td>
<td>1.5%</td>
<td>1.3%</td>
<td>1%</td>
</tr>
<tr>
<td>$g_{Hbb}$</td>
<td>1.6%</td>
<td>1.5%</td>
<td>1%</td>
</tr>
<tr>
<td>$g_{Htt}$</td>
<td>3%</td>
<td>2.1%</td>
<td>1.5%</td>
</tr>
<tr>
<td>$g_{Hcc}$</td>
<td>4%</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>$g_{HWW}$</td>
<td>4%</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

ILC aims for 250fb$^{-1}$ in 5 years
LEP 3 offers multiple collision points
A possible way to go

**80km tunnel** around Geneva could be fit avoiding Jura, Vuache and Salève...

Then as a first step a « TLEP » 350 GeV $e^+e^-$ ring
-- still significantly cheaper than the LC of the same energy
-- reaching 175 GeV/beam (top threshold) with $6 \times 10^{33} \text{ /cm}^2\text{/s}$ luminosity.

The top threshold is interesting for precision measurements of top mass, (rare) top decays and precise constraint on $\alpha S$

This machine would have luminosity at ZH threshold of $> (2?) 10^{34} \text{ /cm}^2\text{/s}$

And the tunnel could house a future Hadron collider
$(80/27) \times (20T/8T) \times 14 \text{ TeV} \simeq 100 \text{ TeV ECM}$
Beyond LHC: new tunnels?

1) 42 TeV c.o.m. with 8.3 T (present LHC dipoles)
2) 80 TeV c.o.m. with 16 T (high field based on Nb3Sn)
3) 100 TeV c.o.m. with 20 T (very high field based on HTS)

Figure 9. Two possible location, upon geological study, of the 80 km ring for a Super HE-LHC (option at left is strongly preferred)
~ 2 B CHF (only the tunnel)
Higgs self coupling

- LHC will have some chance to impact on this
  - In my opinion we will do better than we can prove
  - But this is guesswork
- LEP 3 can do nothing here
- ILC needs ~1TeV to make a measurement maybe a factor 2 better than LHC
  - ~20% errors?
  - How well do we need to know this?
Recommendations

Should a new particle such as a Higgs boson with a mass below approximately 1 TeV be confirmed at LHC, Japan should take the leadership role in an early realization of an e+e- linear collider. Committee on Future Projects, which includes the High Energy Physics Committee members as its core, should be able to swiftly and flexibly update the strategies for these key, large-scale projects according to newly obtained knowledge from LHC and other sources.

In the light of the 'new boson' a 250GeV 'stage 1' is strongly favoured.
Summary

After 48 years we have found something remarkably like the SM Higgs boson:
- 'A Higgs boson'; Rolf Heuer, CERN-DG
- A new form of stuff, not matter or force...

We need to establish what we have and what clues it has about the next level of understanding
- We will know more by Christmas for sure

The detectors ATLAS+CMS perform superbly

In 2012 LHC is working remarkably well
- We will have twice the discovery data soon
- By 2021, 300fb⁻¹ at 14TeV will allow precise studies

Many possible options for closer studies
CMS huge exclusion – close to LEP limit (which?)
ATLAS only have 1fb⁻¹ result public
Candidate masses: $m_1 \text{ v } m_2$

- CMS plot showed few events with $m_{Z_1} > 90$ GeV
  - Had sparked theoretical papers!
  - ATLAS version is reassuring
SUSY Higgs

The new boson might be one of the 5 Higgses of SUSY
- \( h, H, A, H^+, H^- \)

The most likely in the lightest, \( h \)
- This is bound to be below \( \sim 130 \text{GeV} \) in most scenarios
- The others could then be almost any higher mass
  - May or may not ever turn up at LHC
- The relatively large mass, \( 126 \text{GeV} \) suggests:
  - High SUSY mass scale
  - And/or light stop – near top mass
  - Interestingly, light stau/stop could increase \( h \rightarrow yy \) rate

Alternatively it could be the heaviest, \( H \)
- That would mean the others are all around \( 100 \text{GeV} \)
- If so \( H^+/H^- \) at least should be found this year
SLHC as Higgs factory

- Increasing luminosity, factor 10, to $10^{35}$ cm$^{-2}$s$^{-1}$
  - New proton linac & focus elements needed
  - Pileup increases by similar factor, 300 events/BX?
  - New trackers, calorimetry readout, TDAQ needed to cope

- Beams are rapidly 'burnt-off'
  - It may be helpful to limit luminosity early on
  - Extends beam lifetime, limits pileup

- Going from 300fb$^{-1}$ to 3000fb$^{-1}$ at 14 TeV
  - $H \to ZZ$ go from 300 to 3000
  - Improved measurements clear in $ZZ$, $\gamma\gamma$
  - $H \to \mu\mu$ and $Z\gamma$ can be measured
  - $WW$, $bb$, $\tau\tau$ will be improved – but systematics hard to know
  - Self-coupling in $HH \to b\bar{b}\gamma\gamma$ and $bb\tau\tau$ looks just possible
  - Again, estimates of systematics difficult
Bias in discovery rates

- Mock up experiment like $H \rightarrow yy$
- With a signal present
- Measure the fitted rate
  - At the correct mass
  - At any mass
- If you fit at the true mass you get the correct rate (on average)
- But if you report results at the biggest rate observed you can add a bias
  - Was 40% for LHC in 2011
  - Now down to 8% only
  - Not allowed for ATLAS/CMS
SLHC and ATLAS

- LHC runs to 2022
- 300fb\(^{-1}\) at 14TeV expected
  - SLHC is proposed thereafter - 3000fb\(^{-1}\)
- \(ttH, H \rightarrow \gamma\gamma\) and \(H \rightarrow \mu\mu\) are two interesting studies

But in general Higgs couplings must gain from factor 10 more data!
Interesting to compare ATLAS and CMS expectations
- Pretty close for ZZ and $\gamma\gamma$
- Factor 3 apart for $\tau\tau$ at $300\text{fb}^{-1}$
- We need to understand this!
SLHC as Higgs factory

- Increasing luminosity, factor 10, to $10^{35}\text{cm}^{-2}\text{s}^{-1}$
  - New proton linac & focus elements needed
  - Pileup increases by similar factor, 300 events/BX?
  - New trackers, calorimetry readout, TDAQ needed to cope

- Beams are rapidly 'burnt-off'
  - It may be helpful to limit luminosity early on
  - Extends beam lifetime, limits pileup

- Going from $300\text{fb}^{-1}$ to $3000\text{fb}^{-1}$ at 14 TeV
  - $H \rightarrow ZZ$ go from 300 to 3000
  - Improved measurements clear in $ZZ, \gamma\gamma$
    - $H \rightarrow \mu\mu$ and $Z\gamma$ can be measured
  - $WW, bb, \tau\tau$ will be improved – but systematics hard to know
  - Self-coupling in $HH \rightarrow b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ looks just possible
  - Again, estimates of systematics difficult
ILC

Well known proposal for high-energy linear ee collider.
- Much cleaner collisions than LHC
- But cost/GeV of RF cavities in high
- Power bill tends to be large too

Can make Higgs bosons
- 10,000 ZH/year

Sensitive to all, including invisible
- LHC can never be sure of total rate

Accurate measure:
- $c, \tau, b, W, Z, t$
- $hh$ coupling too
  - Just

Sensitive to light SUSY
LEP-3?

- LEP3 is an $e^+e^-$ storage ring, maybe in the LHC tunnel
  - $\sqrt{s}=240\text{GeV}$
  - 4 bunch mode gives $10^{34}\text{cm}^2\text{s}^{-1}$.
  - Dual-ring allows 'top-up mode' to maintain average luminosity.
  - $100\text{fb}^{-1}$ per year
  - 20,000 ZH events per year/experiment
  - 50MW/beam synchrotron loss

- Physics programme:
  - 1 'year' at 91GeV – $10^{11} Z^0$
  - 1 'year' at 160 GeV – sub -MeV statistical precision on $m_W$
  - 5 'years' at 240 GeV – 100,000 HZ/experiment
Higgs studies potential

<table>
<thead>
<tr>
<th></th>
<th>ILC</th>
<th>LEP3 (2)</th>
<th>LEP3 (4)</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{HZ}$</td>
<td>3%</td>
<td>2.7%</td>
<td>1.9%</td>
<td>–</td>
</tr>
<tr>
<td>$\sigma_{HZ} \times \text{BR}(H \rightarrow b\bar{b})$</td>
<td>1%</td>
<td>1.2%</td>
<td>0.8%</td>
<td>–</td>
</tr>
<tr>
<td>$\sigma_{HZ} \times \text{BR}(H \rightarrow \tau^+\tau^-)$</td>
<td>6%</td>
<td>3.1%</td>
<td>2.2%</td>
<td>–</td>
</tr>
<tr>
<td>$\sigma_{HZ} \times \text{BR}(H \rightarrow \text{invisible})$</td>
<td>?</td>
<td>1%</td>
<td>0.7%</td>
<td>–</td>
</tr>
<tr>
<td>$\gamma_{HZZ}$</td>
<td>1.5%</td>
<td>1.3%</td>
<td>1%</td>
<td>13%</td>
</tr>
<tr>
<td>$\gamma_{Hbb}$</td>
<td>1.6%</td>
<td>1.5%</td>
<td>1%</td>
<td>21%</td>
</tr>
<tr>
<td>$\gamma_{H\tau\tau}$</td>
<td>3%</td>
<td>2.0%</td>
<td>1.5%</td>
<td>13%</td>
</tr>
<tr>
<td>$\gamma_{Hcc}$</td>
<td>4%</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>$\gamma_{HWW}$</td>
<td>4%</td>
<td>?</td>
<td>?</td>
<td>11%</td>
</tr>
</tbody>
</table>

- The electron machine beats LHC for Higgs coupling
  - But $ttH$ is not doable at LEP-3
  - Higgs self-coupling is tough anywhere – but impossible LEP-3
The ideal schedule from LEP-3 side is to run in 2022
- LHC has delivered 300fb\(^{-1}\)
- ATLAS and CMS might be available
- CMS simulations indicate it can do the physics:
  - Z → ll, H → X shown

The problem is: SLHC would be cancelled!
- This is an interesting choice
- One which I believe deserves to be studied
- I THINK the LHC case would win. But we should look
Calculating $H \rightarrow \gamma\gamma$ mass

- Need $H$ decay position
  - CMS compare tracking vertices; match $p_T$ etc
  - ATLAS use pointing from calorimetry – vertex not needed

ATLAS somewhat more pileup robust
$m_H \ll 2m_Z$

The decay involves one $Z$ being far from 'mass-shell'.

The softest lepton is typically below 10 GeV $p_T$.

Need to push lepton momentum range.

**CMS Simulation, $\sqrt{s} = 8$ TeV**

$H \rightarrow ZZ^* \rightarrow 2e2\mu$

$m_H = 126$ GeV

- Before analysis selection
- After analysis selection
Charged Higgs at LHC

- Space for charged Higgs below $m_t$ getting squeezed
  - Next round will aim for $m_t$ exclusion $\tan \beta$ independent
- $m_{H^+} > m_t$ still largely unexplored