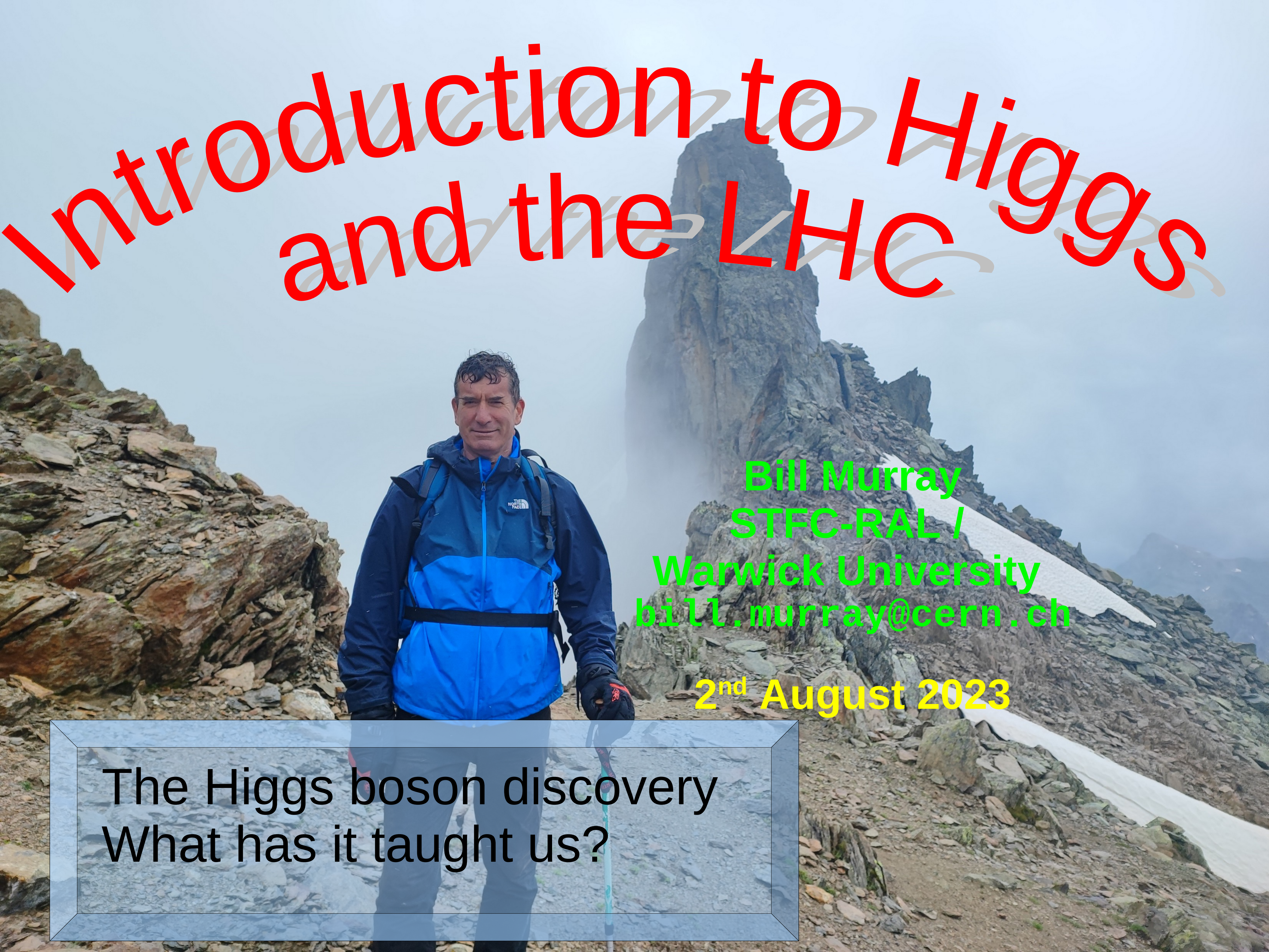

Introduction to Higgs and the LHC

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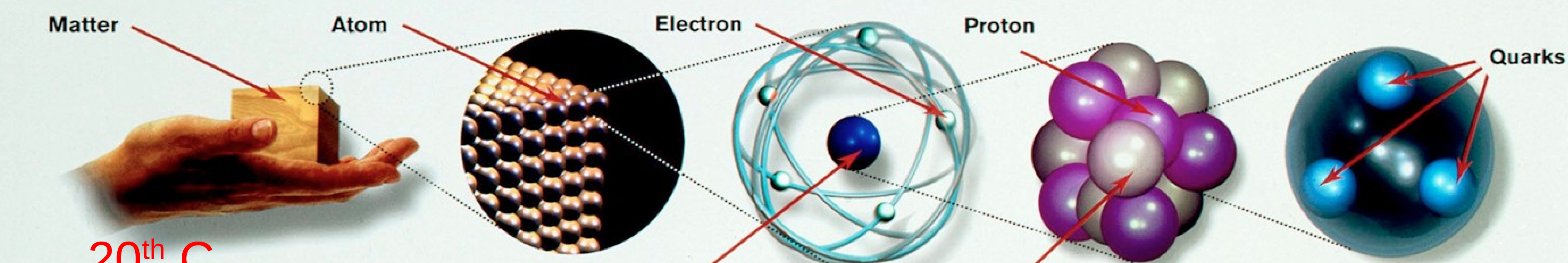
2nd August 2023

The Higgs boson discovery
What has it taught us?



20th C The Standard Model

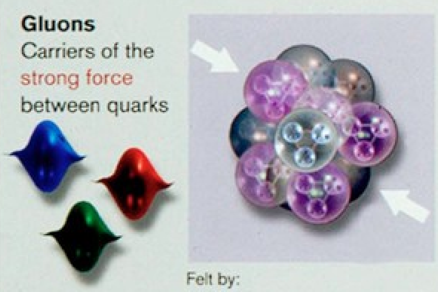
Matter particles
All ordinary particles belong to this group

These particles existed just after the Big Bang. Now they are found only in cosmic rays and accelerators

	LEPTONS		QUARKS	
FIRST FAMILY	**Electron** Responsible for electricity and chemical reactions; it has a charge of -1	**Electron neutrino** Particle with no electric charge, and possibly no mass; billions fly through your body every second	**Up** Has an electric charge of plus two-thirds; protons contain two, neutrons contain one	**Down** Has an electric charge of minus one-third; protons contain one, neutrons contain two
SECOND FAMILY	**Muon** A heavier relative of the electron; it lives for two-millionths of a second	**Muon neutrino** Created along with muons when some particles decay	**Charm** A heavier relative of the up; found in 1974	**Strange** A heavier relative of the down; found in 1964
THIRD FAMILY	**Tau** Heavier still; it is extremely unstable. It was discovered in 1975	**Tau neutrino** not yet discovered but believed to exist — Found 2001	**Top** Heavier still	**Bottom** Heavier still; measuring bottom quarks is an important test of electroweak theory

Force particles
These particles transmit the four fundamental forces of nature although gravitons have so far not been discovered

Gluons
Carriers of the strong force between quarks



Felt by: quarks

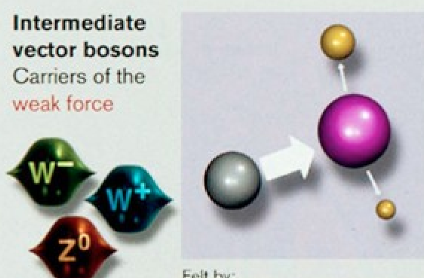
The explosive release of nuclear energy is the result of the strong force

Photons
Particles that make up light; they carry the electromagnetic force

Felt by: quarks and charged leptons

Electricity, magnetism and chemistry are all the results of electro-magnetic force

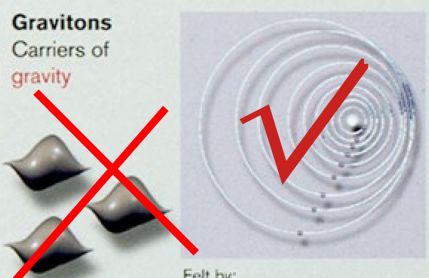
Intermediate vector bosons
Carriers of the weak force



Felt by: quarks and leptons

Some forms of radio-activity are the result of the weak force

Gravitons
Carriers of gravity



Felt by: all particles with mass

All the weight we experience is the result of the gravitational force

GRAPHICS: PETER CROWTHER

The Standard Model

But where was the Higgs?

- From 1973 to 2012 physicists used the model in the initial diagram
  - But it contained a contradiction
- All the particles were supposed to be massless
  - But the quarks and charged leptons have mass
  - Strikingly, the W/Z bosons have mass while γ and gluons are massless
    - Hints W/Z might be part of the solution?
- Peter Higgs (et al.) had proposed a new field and new particle in 1964
  - What did he suggest?

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W

1964

- Peter Higgs wrote
  - "Broken Symmetries and the masses of Gauge bosons"
- But theory said the W/Z bosons should be massless
  - Like the photon
- They were not even discovered – but assumed to be heavy

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson[3] has drawn attention: that the scalar zero-mass excitations of a superconducting neutral Fermi gas become longitudinal plasmon modes of finite mass when the gas is charged.

The simplest theory which exhibits this behavior is a gauge-invariant version of a model used by Goldstone[2] himself: Two real[4] scalar fields φ_1, φ_2 and a real vector field A_μ interact through the Lagrangian density

$$L = -\tfrac{1}{2}(\nabla\varphi_1)^2 - \tfrac{1}{2}(\nabla\varphi_2)^2 - V(\varphi_1^2+\varphi_2^2) - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad (1)$$

where

$$\nabla_\mu\varphi_1 = \partial_\mu\varphi_1 - eA_\mu\varphi_2,$$

$$\nabla_\mu\varphi_2 = \partial_\mu\varphi_2 + eA_\mu\varphi_1,$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu,$$

e is a dimensionless coupling constant, and the metric is taken as $-+++$. L is invariant under simultaneous gauge transformations of the first kind on $\varphi_1 \pm i\varphi_2$ and of the second kind on A_μ. Let us suppose that $V'(\varphi_0^2)=0$, $V''(\varphi_0^2)>0$; then spontaneous breakdown of U(1) symmetry occurs. Consider the equations [derived from (1) by treating $\Delta\varphi_1$, $\Delta\varphi_2$, and A_μ as small quantities] governing the propagation of small oscillations about the "vacuum" solution $\varphi_1(x)=0$, $\varphi_2(x)=\varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \quad (2a)$$

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \quad (2b)$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A^\mu\}. \quad (2c)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

$$B_\mu = A_\mu - (e\varphi_0)^{-1}\partial_\mu(\Delta\varphi_1),$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu = F_{\mu\nu}, \quad (3)$$

into the form

$$\partial_\mu B^\mu = 0, \quad \partial_\nu G^{\mu\nu} + e^2\varphi_0^2 B^\mu = 0. \quad (4)$$

Equation (4) describes vector waves whose quanta have (bare) mass $e\varphi_0$. In the absence of the gauge field coupling ($e=0$) the situation is quite different: Equations (2a) and (2c) describe zero-mass scalar and vector bosons, respectively. In passing, we note that the right-hand side of (2c) is just the linear approximation to the conserved current: It is linear in the vector potential, gauge invariance being maintained by the presence of the gradient term.[5]

When one considers theoretical models in which spontaneous breakdown of symmetry under a semisimple group occurs, one encounters a variety of possible situations corresponding to the various distinct irreducible representations to which the scalar fields may belong; the gauge field always belongs to the adjoint representation.[6] The model of the most immediate interest is that in which the scalar fields form an octet under SU(3): Here one finds the possibility of two nonvanishing vacuum expectation values, which may be chosen to be the two $Y=0$, $I_3=0$ members of the octet.[7] There are two massive scalar bosons with just these quantum numbers; the remaining six components of the scalar octet combine with the corresponding components of the gauge-field octet to describe

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- Just two pages

massive vector bosons. There are two $I=\frac{1}{2}$ vector doublets, degenerate in mass between $Y=\pm1$ but with an electromagnetic mass splitting between $I_3=\pm\frac{1}{2}$, and the $I_3=\pm1$ components of a $Y=0$, $I=1$ triplet whose mass is entirely electromagnetic. The two $Y=0$, $I=0$ gauge fields remain massless: This is associated with the residual unbroken symmetry under the Abelian group generated by Y and I_3. It may be expected that when a further mechanism (presumably related to the weak interactions) is introduced in order to break Y conservation, one of these gauge fields will acquire mass, leaving the photon as the only massless vector particle. A detailed discussion of these questions will be presented elsewhere.

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields.[9]

[1] P. W. Higgs, to be published.
[2] J. Goldstone, Nuovo Cimento 19, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).
[3] P. W. Anderson, Phys. Rev. 130, 439 (1963).
[4] In the present note the model is discussed mainly in classical terms; nothing is proved about the quantized theory. It should be understood, therefore, that the conclusions which are presented concerning the masses of particles are conjectures based on the quantization of linearized classical field equations. However, essentially the same conclusions have been reached independently by F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964): These authors discuss the same model quantum mechanically in lowest order perturbation theory about the self-consistent vacuum.
[5] In the theory of superconductivity such a term arises from collective excitations of the Fermi gas.
[6] See, for example, S. L. Glashow and M. Gell-Mann, Ann. Phys. (N.Y.) 15, 437 (1961).
[7] These are just the parameters which, if the scalar octet interacts with baryons and mesons, lead to the Gell-Mann–Okubo and electromagnetic mass splittings: See S. Coleman and S. L. Glashow, Phys. Rev. 134, B671 (1964).
[8] Tentative proposals that incomplete SU(3) octets of scalar particles exist have been made by a number of people. Such a rôle, as an isolated $Y=\pm1$, $I=\frac{1}{2}$ state, was proposed for the κ meson (725 MeV) by Y. Nambu and J. J. Sakurai, Phys. Rev. Letters 11, 42 (1963). More recently the possibility that the σ meson (385 MeV) may be the $Y=I=0$ member of an incomplete octet has been considered by L. M. Brown, Phys. Rev. Letters 13, 42 (1964).
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SPLITTING OF THE 70-PLET OF SU(6)

Mirza A. Baqi Bég
The Rockefeller Institute, New York, New York

and

Virendra Singh*
Institute for Advanced Study, Princeton, New Jersey
(Received 18 September 1964)

1. In a previous note,[1] hereafter called I, we proposed an expression for the mass operator responsible for lifting the degeneracies of spin-unitary spin supermultiplets [Eq. (31)-I]. The purpose of the present note is to apply this expression to the 70-dimensional representation of SU(6).

The importance of the 70-dimensional representation has already been underlined by Pais.[2] Since

$$\underline{35}\otimes\underline{56}=\underline{56}\oplus\underline{70}\oplus\underline{700}\oplus\underline{1134}, \qquad (1)$$

it follows that $\underline{70}$ is the natural candidate for accommodating the higher meson-baryon resonances. Furthermore, since the SU(3)⊗SU(2) content is

$$\underline{70}=(\underline{1},\underline{2})+(\underline{8},\underline{2})+(\underline{10},\underline{2})+(\underline{8},\underline{4}), \qquad (2)$$

we may assume that partial occupancy of the $\underline{70}$ representation has already been established through the so-called γ octet[2] $(\frac{3}{2})^-$. Recent experiments appear to indicate that some $(\frac{1}{2})^-$ states may also be at hand.[3] With six masses at one's disposal, our formulas can predict the masses of all the other occupants of $\underline{70}$ and also provide a consistency check on the input. Our discussion of the $\underline{70}$ representation thus appears to be of immediate physical interest.

W.

1964

- Just two pages
- One sentence says:
  - ‘it may be expected ...presumably..one of these gauge fields will acquire mass’
  - This is the Higgs boson
- Peter admits his theory ignores quantum mechanics
  - But its OK; Brout and Englert have the QM version

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massive vector bosons. There are two $I=\frac{1}{2}$ vector doublets, degenerate in mass between $Y=\pm1$ but with an electromagnetic mass splitting between $I_3=\pm\frac{1}{2}$, and the $I_3=\pm1$ components of a $Y=0$, $I=1$ triplet whose mass is entirely electromagnetic. The two $Y=0$, $I=0$ gauge fields remain massless: This is associated with the residual unbroken symmetry under the Abelian group generated by Y and I_3. It may be expected that when a further mechanism (presumably related to the weak interactions) is introduced in order to break Y conservation, one of these gauge fields will acquire mass, leaving the photon as the only massless vector particle. A detailed discussion of these questions will be presented elsewhere.

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What is the Higgs field like?

- Think of a fish tank:

Empty the tank

- The fish will call this an empty tank

- but it still has water in it

What does the model say?

- The Higgs field is like the water the fish are in
  - Without it everything would be different
  - But we cannot get out
- It explain the mass of the W & Z bosons
  - The carriers of the weak nuclear force
- It also allows the maths to include masses for the fermions, the matter particles
  - They are proportional to their interaction with the Higgs boson.
    - Sort-of how much they bounce around as they travel
  - It does not predict these masses, we invent a ‘coupling constant’ for each one to get measured value

What does the model predict?

- Massive W and Z bosons,
  - and the ratio of their masses is predicted
- A mass-less photon (and gluon)
- A massive spin-less Higgs boson
  - Interacting with all particles in proportion to their mass
  - But its mass unknown
- Vacuum filled with a ‘sea’ of weak charge
  - The ‘Higgs field’

What we knew pre-LHC

- Massive W and Z bosons,
  - and the ratio of their masses is predicted
- A mass-less photon (and gluon)
- A massive spin-less Higgs boson
  - Interacting with all particles in proportion to their mass
  - But its mass unknown

LHC designed to test this

- Vacuum filled with a ‘sea’ of weak charge
  - The ‘Higgs field’
  - Caused by very odd interactions of Higgses??

So how do we test this?

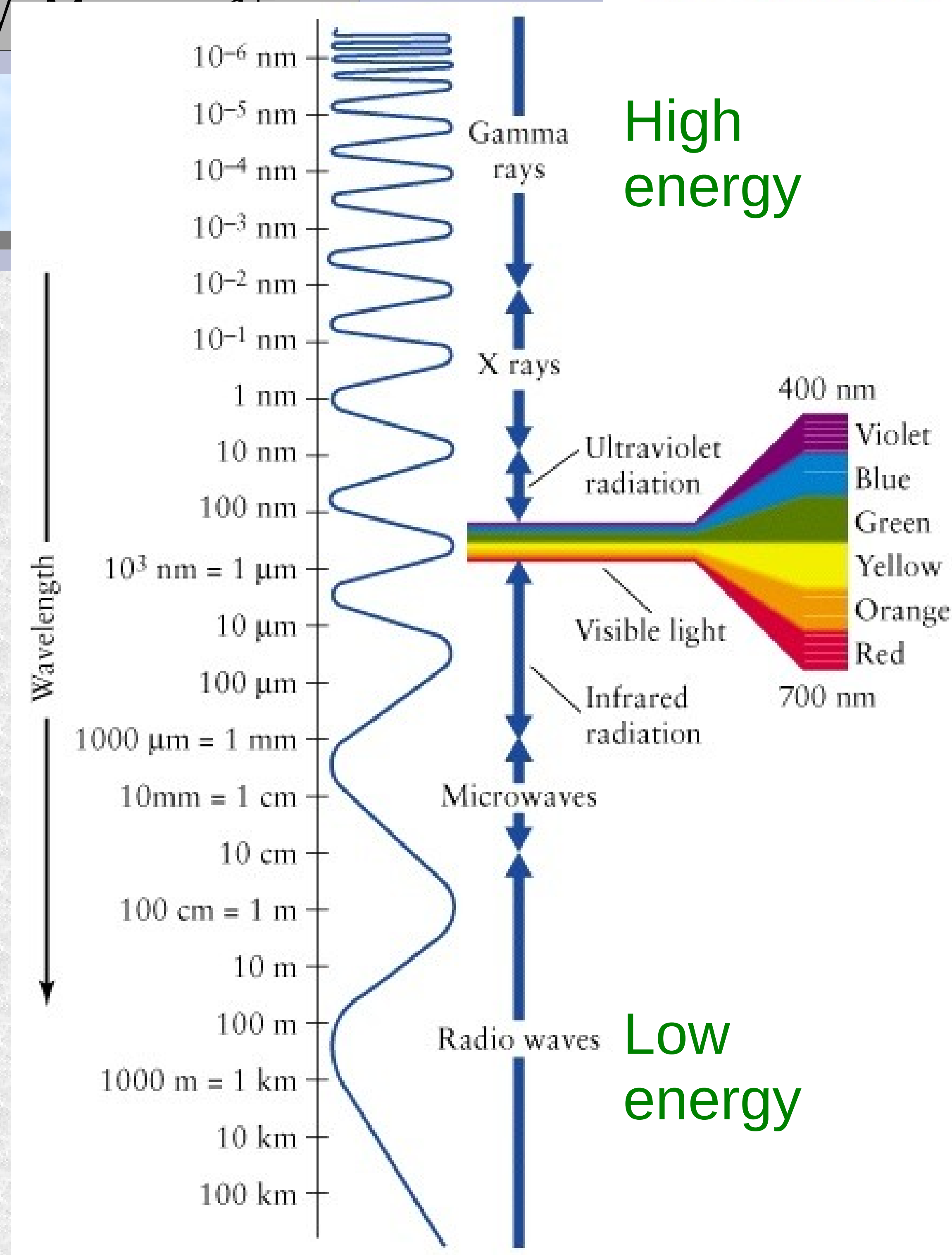
How long is a light wave?

Light reveals the world around us by bouncing off it

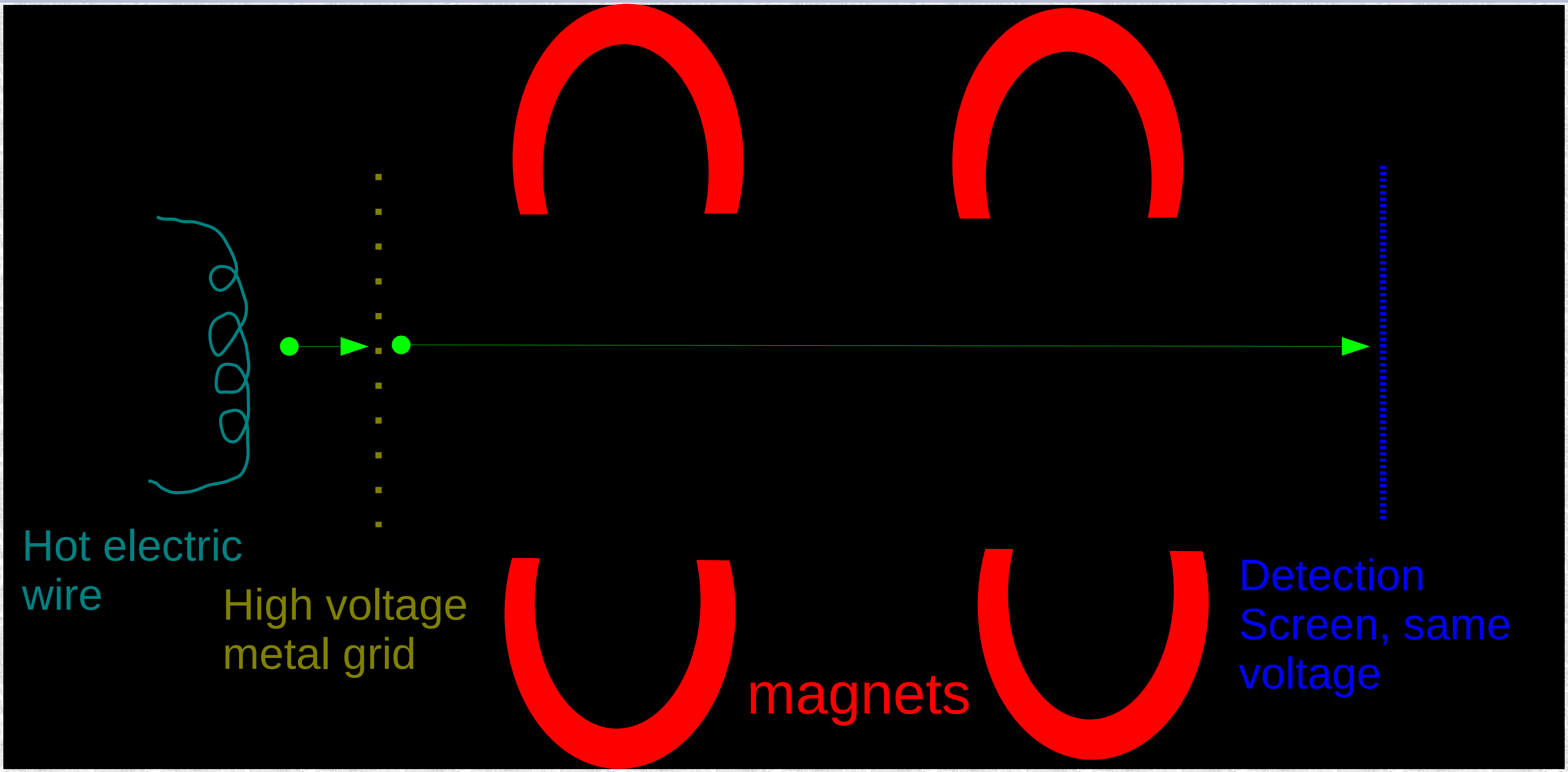
But struggles to show details shorter than its wavelength.

The shorter the wave-length, the more energy the light caries

Or use something else small – a high energy particle



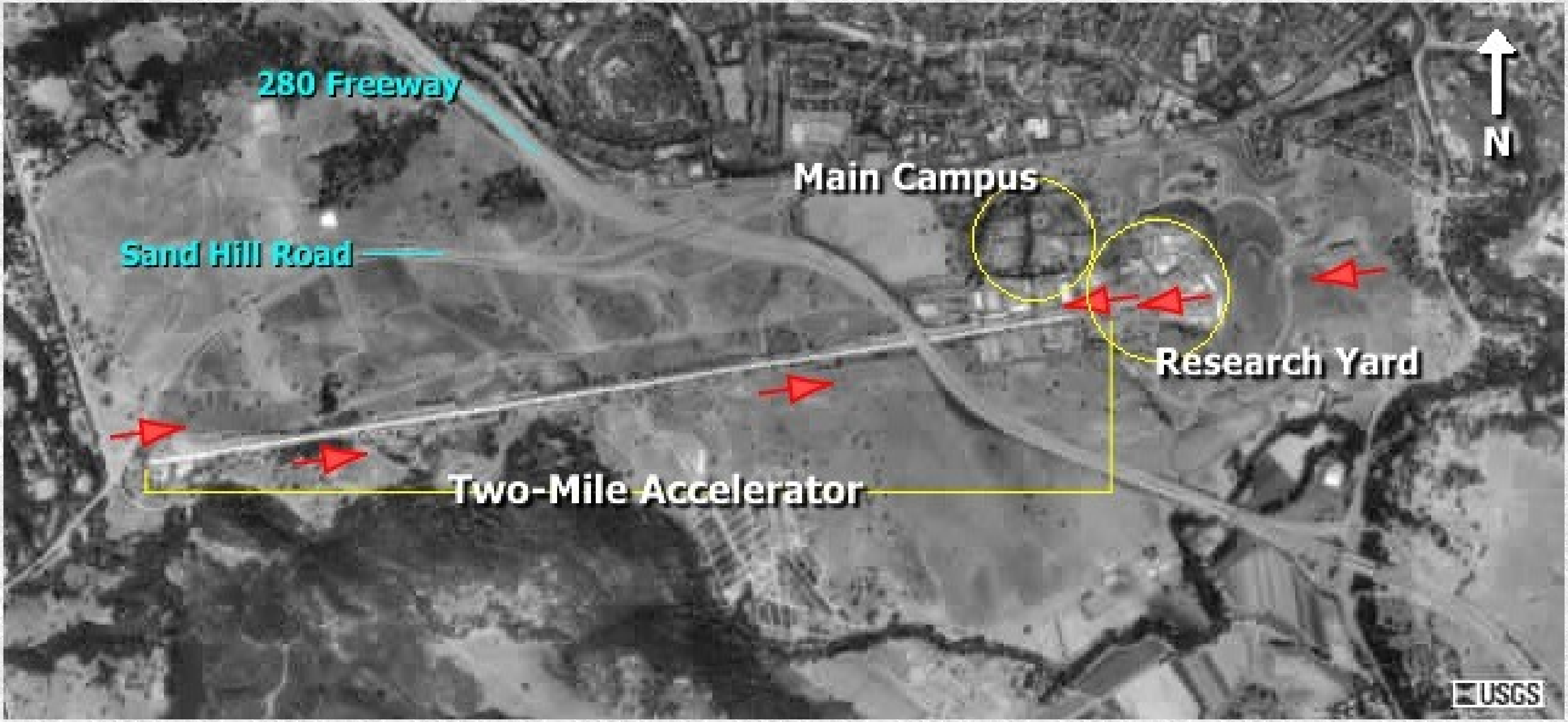
Basics of an electron accelerator



Electrons 'boil off' hot wire like water boiling
Negative electrons head for positive grid
Some go through holes in the grid - their momentum keeps them going
Steer them with magnets as they go

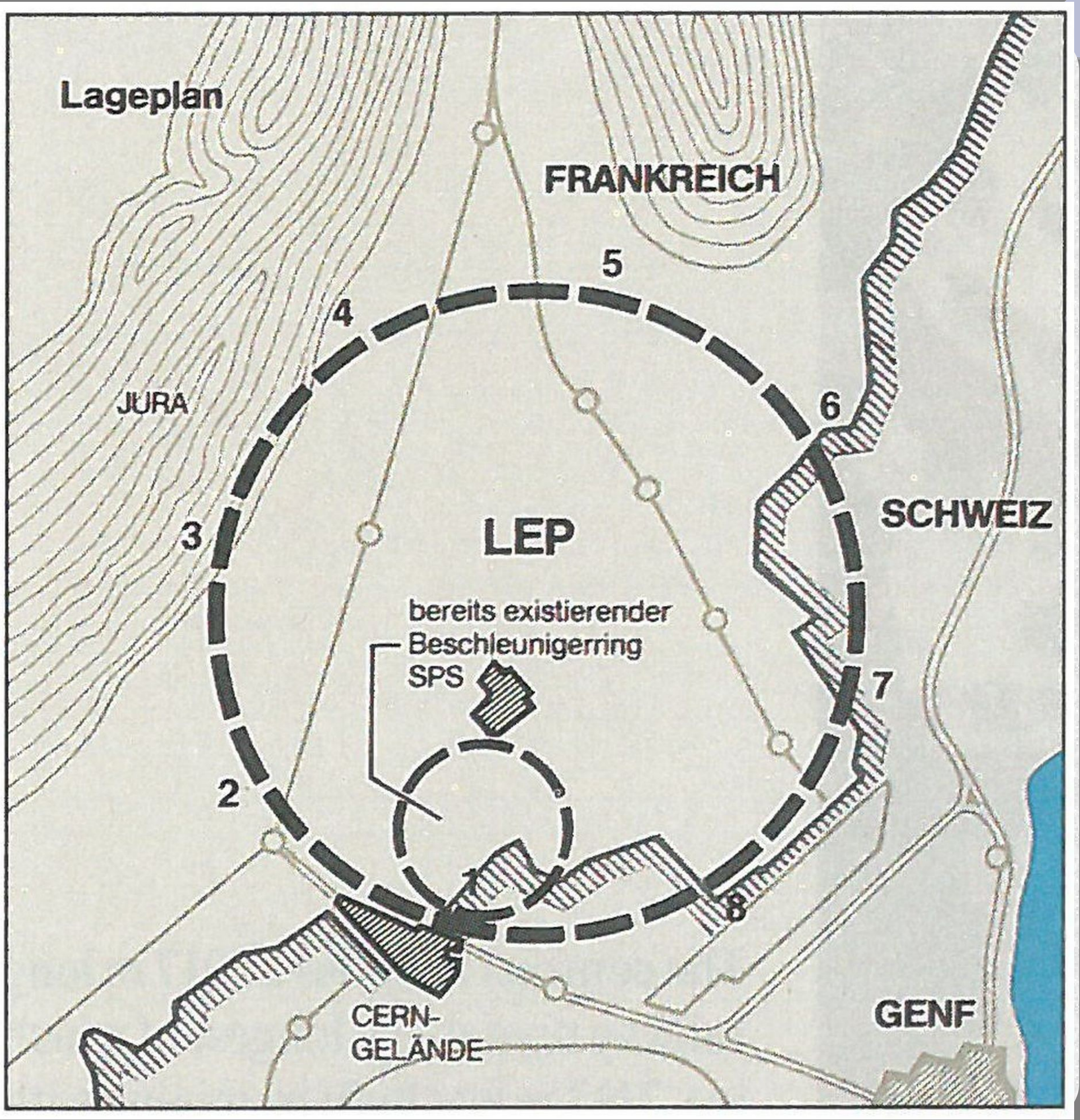
Stanford Linear Accelerator

- Two miles long - a row of accelerating cavities
  - each kicks the electrons as they pass through
  - Getting to 50 GeV (~50 times proton mass/energy)
    - More energy would need longer accelerator



1980s Big experimental searches

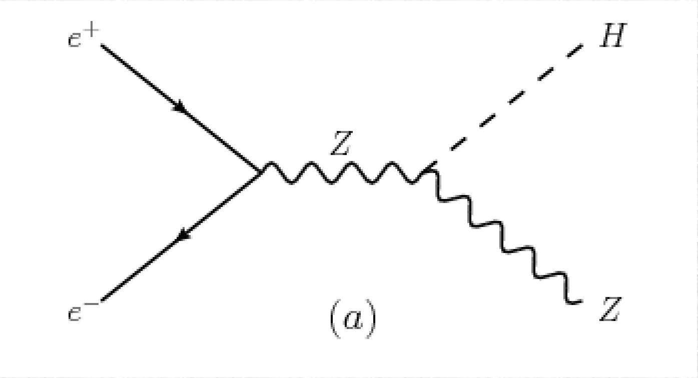
- Plan a 27 km tunnel, below the French-Swiss border
- Circular, so re-use accelerating cavities
- An e^+e^- collider
  - matter-antimatter
- The LEP accelerator ran from 1989 to 2000
  - Energy 90-208 GeV
    - 1 GeV≈1 proton
- My Ph.D: $e^+e^- \rightarrow e^+e^-$
- Now the LHC tunnel



LEP Higgs search

- LEP energy varied up to E_{com}=208 GeV
  - Searching for $e^+e^- \rightarrow ZH$
  - Needs enough energy to make both
  - The Z mass is 91 GeV/c^2
  - So limited to (close to)

$$m_H \leq E_{CoM} - m_Z$$



Higgsstrahlung

- Able to make the Higgs is mass below 115 GeV
  - Would it be enough?
- Not quite: LEP closed in 2000 having shown

  m_H>114.4 GeV

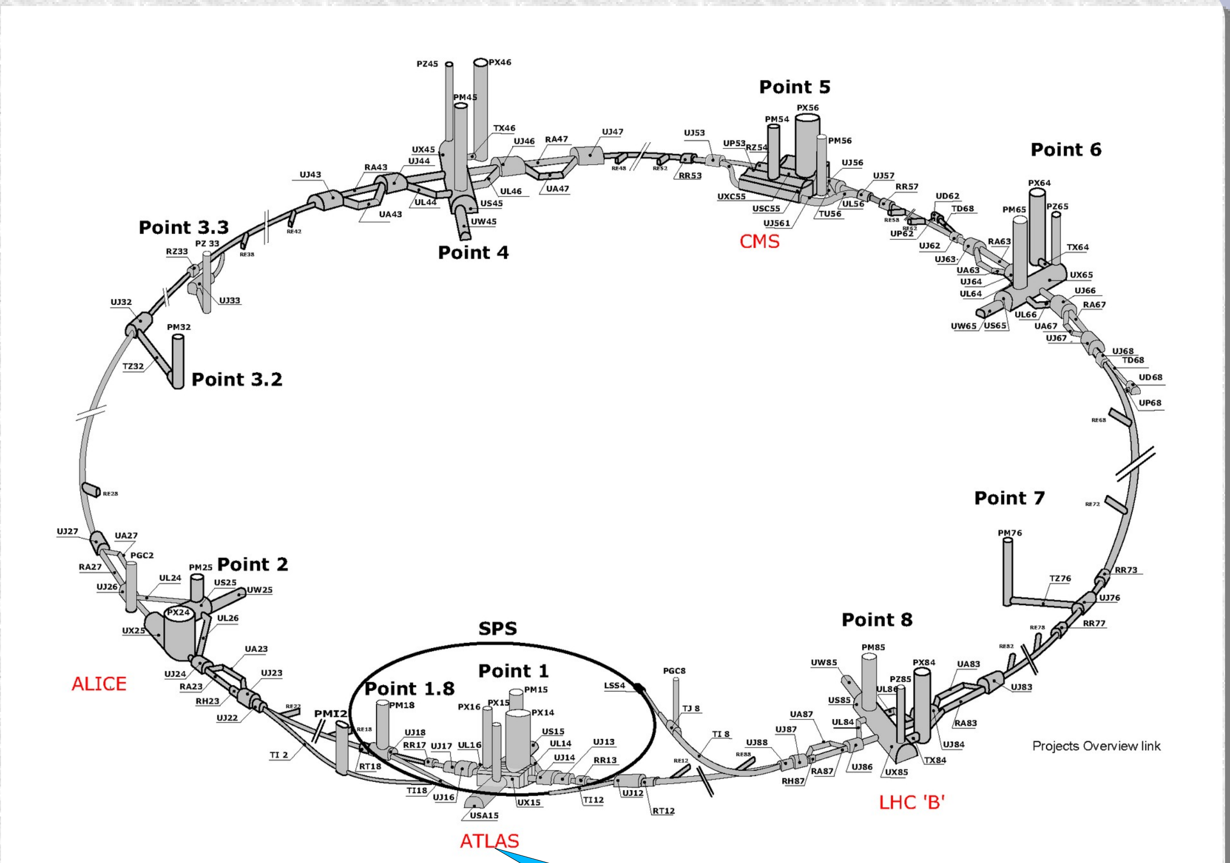
Meanwhile, Fermilab in the US

- The Tevatron,
  - 6km $p\bar{p}$ ring,
- Found the top quark 1995
- Searched for Higgs from 2000-2011
  - but only hints

- The energy was 2 TeV
  - Well below the LHC
- And the data collection rate about 50 times less
- It just didn’t make enough of them

The LHC

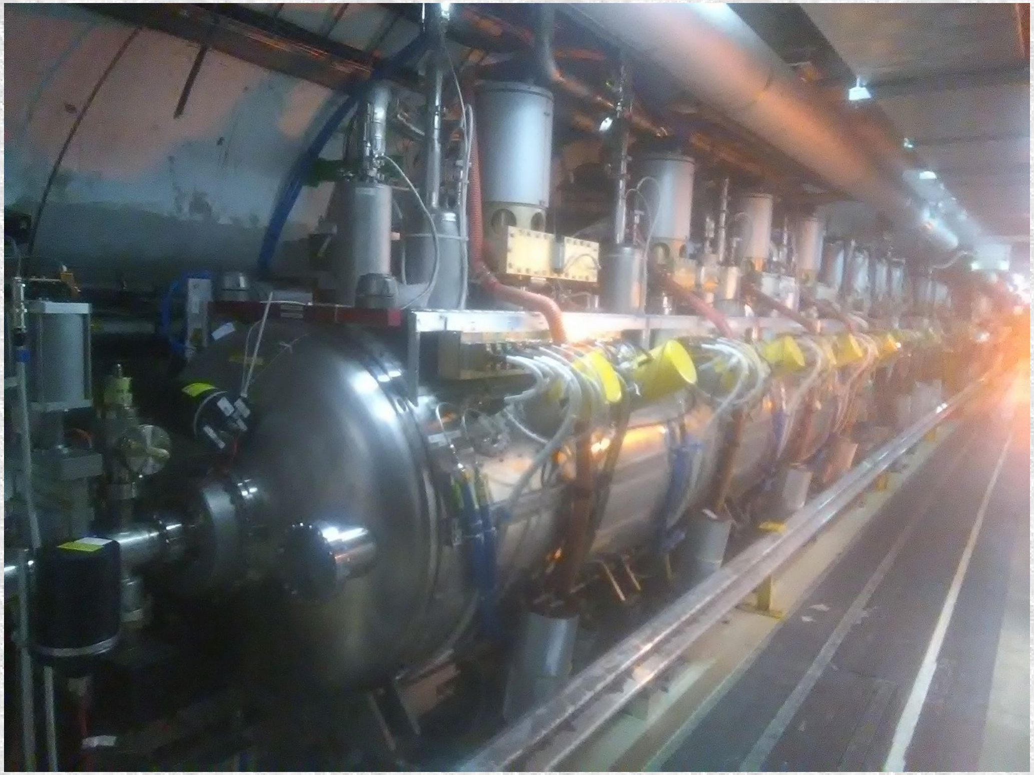
- The 27km LEP tunnel reused for a pp collider
  - Protons easy to get
- Designed for:
  - 7+7=14TeV collisions
  - 40MHz bunch crossing
  - 23 pp collisions/BX
- To give 300fb^{-1}
- 4 sites for experiments



My experiment

LHC: record energy!

- Target collision energy for LHC was 2x7,000 GeV
  - 1 GeV is the energy required to make a proton
- Proton energy implies a time dilation of 7500
  - They can get to Alpha Centauri in 5 hrs – their time
- Speed is 0.99999998c
  - They circle the 27km tunnel 11,000 times / sec
  - 1M passes in 100s
- Right: LHC HV cavities
  - 8/beam, give 2MV each pass.
  - Energy is ‘easy’ in a ring



The real challenge?

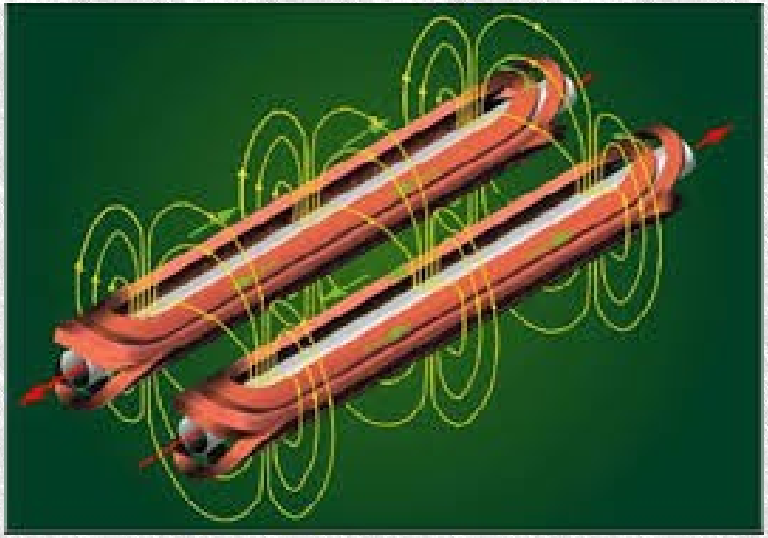
- Making the protons bend is the tough job
  - Circular motion means constantly reversing direction
  - 22000 times a second, to nearly the speed of light
- The centripetal force is huge

$$a=v^2/r$$

  - The bigger the radius, the smaller the acceleration
  - $a=10^{17}G$ (allowing for relativity)
- How do we bend them so hard?
  - A charged particle moving in a magnetic field feels a transverse force
  - Given the tunnel circumference you can work out how strong the field must be: 8.3Tesla

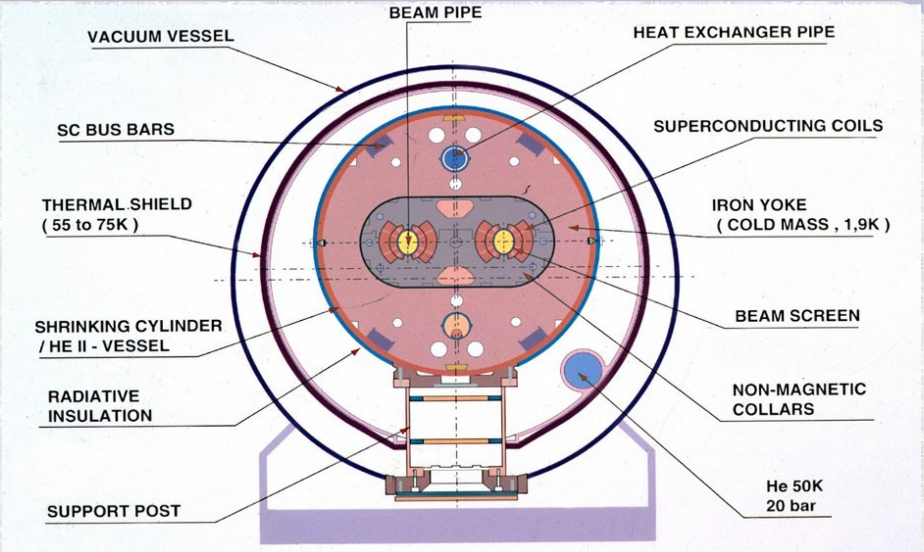
LHC magnets

- Required field is 8.3Tesla
  - c/f Earth's field, 0.00003T at equator
  - A fridge magnet is ~0.01T
  - Record for permanent magnets (rare earth) is 5 Tesla
  - So use electromagnets
- A current in a wire generates a field.
  - But at a few cm distance ~1MA is needed for 8T
- Actually provided by 12000 amps
  - With 80 turns
- Each magnet 15m long
  - 1232 of them in tunnel



LHC magnet cooling

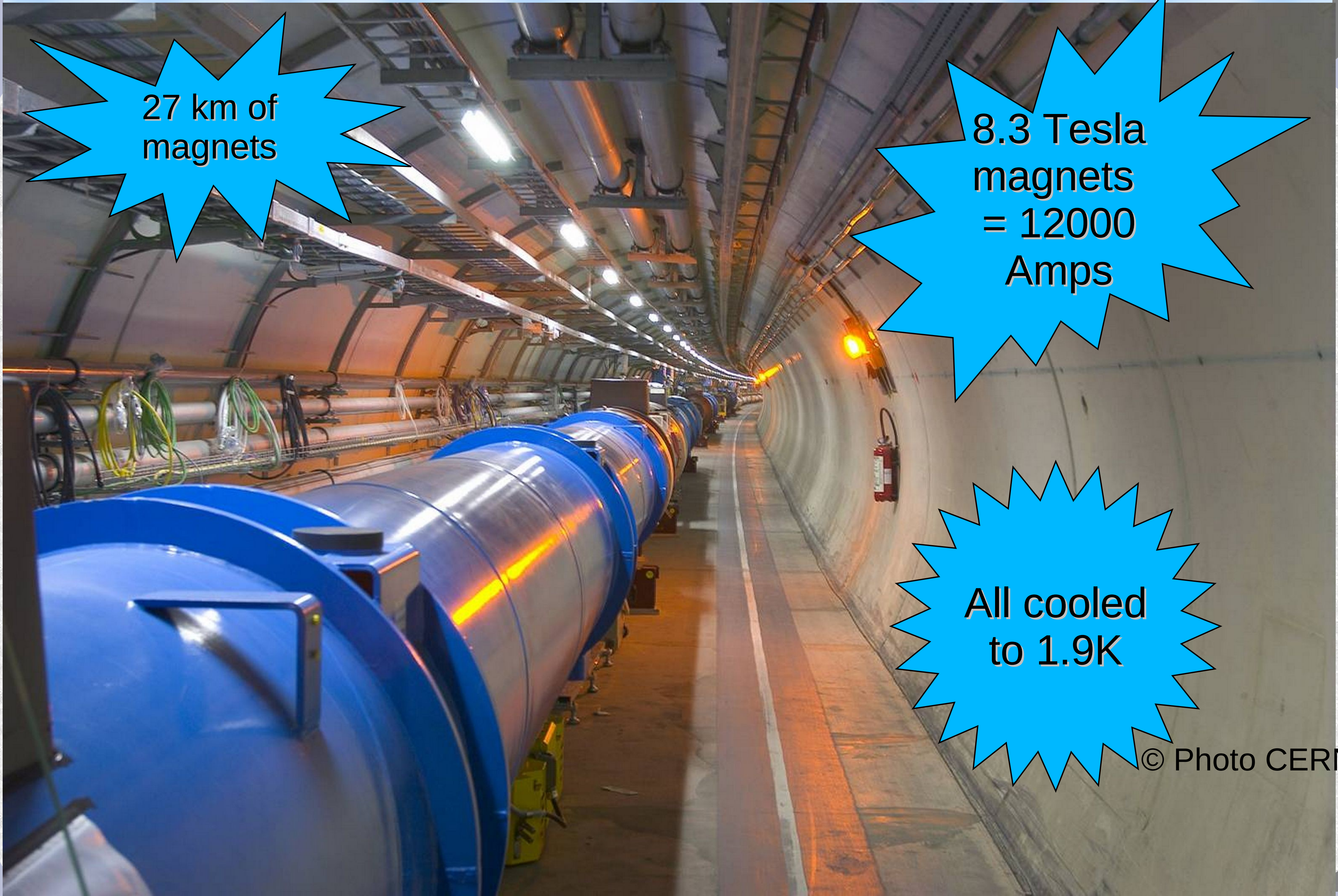
- Power lost in resistor is I^2R
- A 1Ω resistor would have 12000^2=144MW power in it
  - And we have to make 20 km of these magnets
- Superconductivity is the answer – 0 resistance



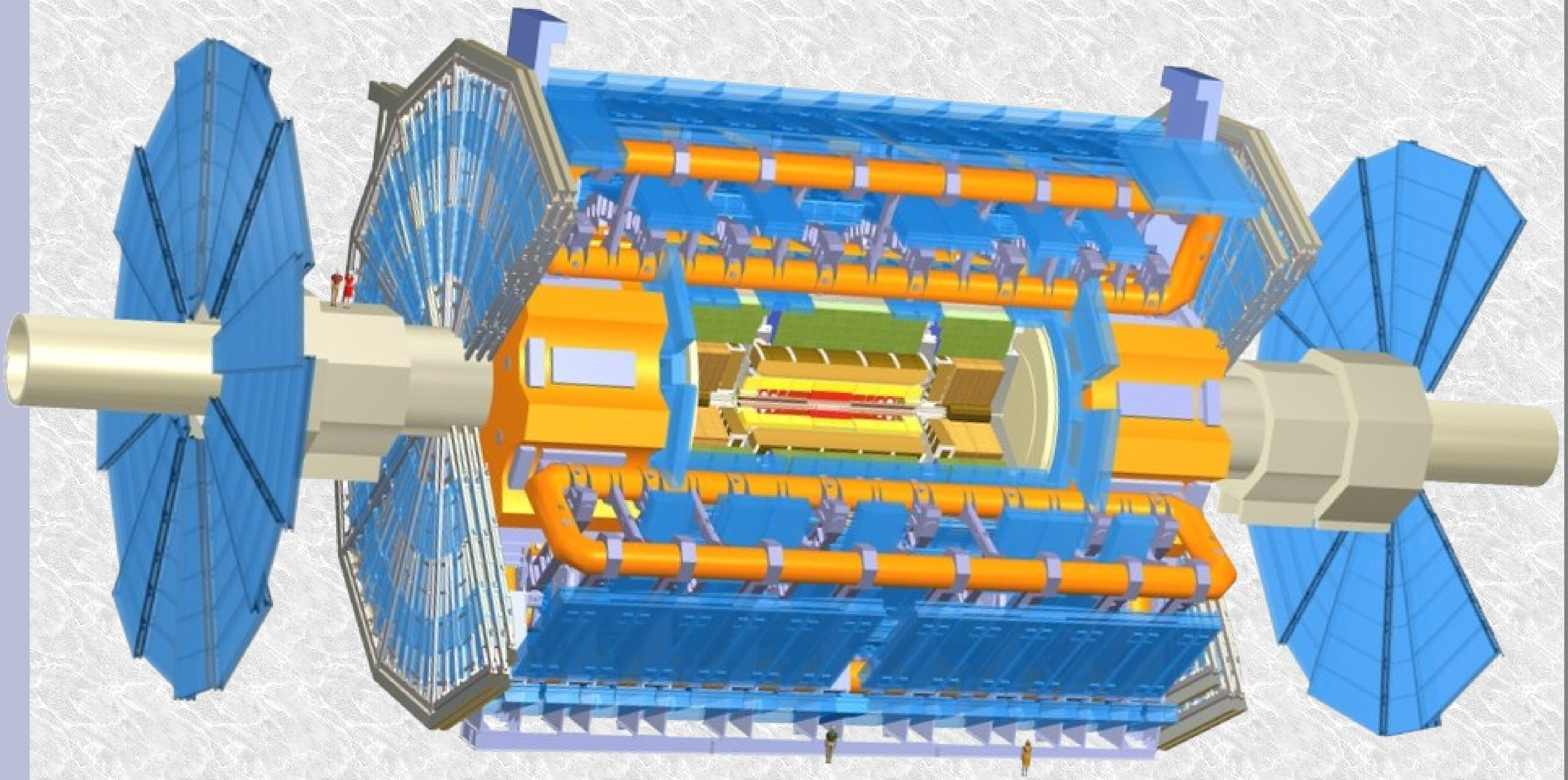
Cross Section of LHC Dipole

  - Niobium-Titanium superconducts at low temperature
  - LHC cools it to 1.9K or -271°C
  - The only magnet power bill is for the cooling
- Cooling provided with liquid Helium
  - It's the only thing not a solid at these temperatures

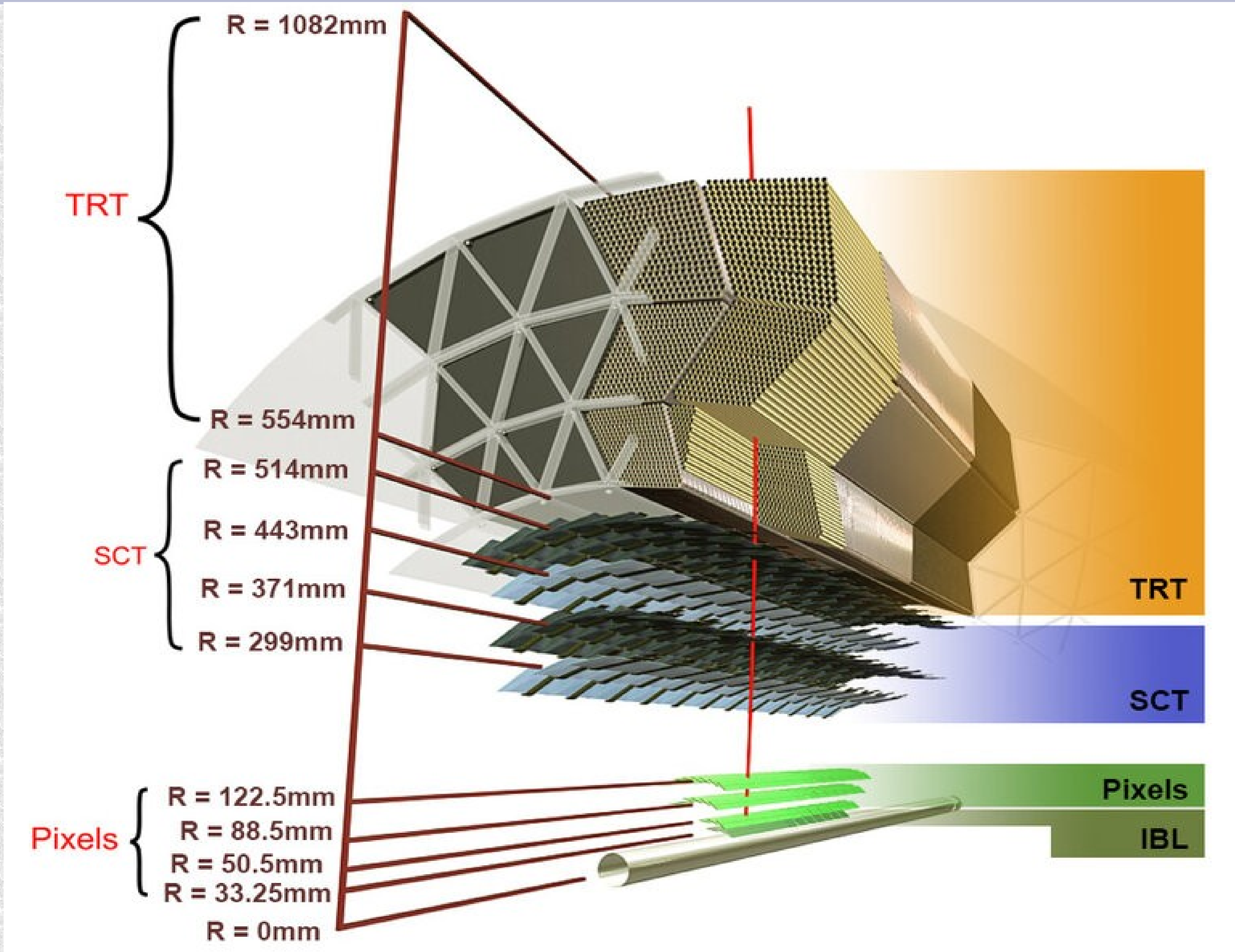
The LHC


27 km of magnets
8.3 Tesla magnets = 12000 Amps
All cooled to 1.9K

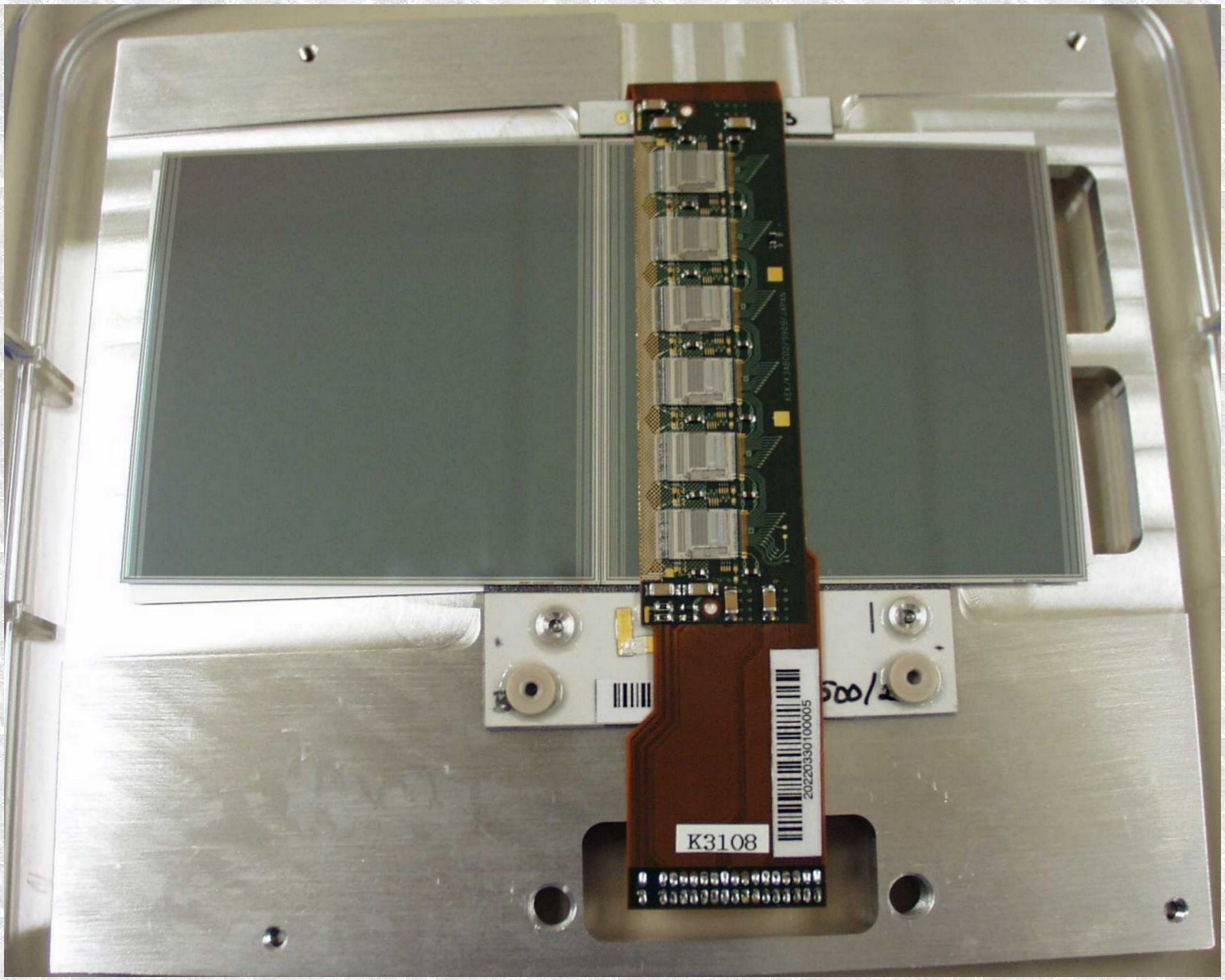
ATLAS cut-away



ATLAS current tracker

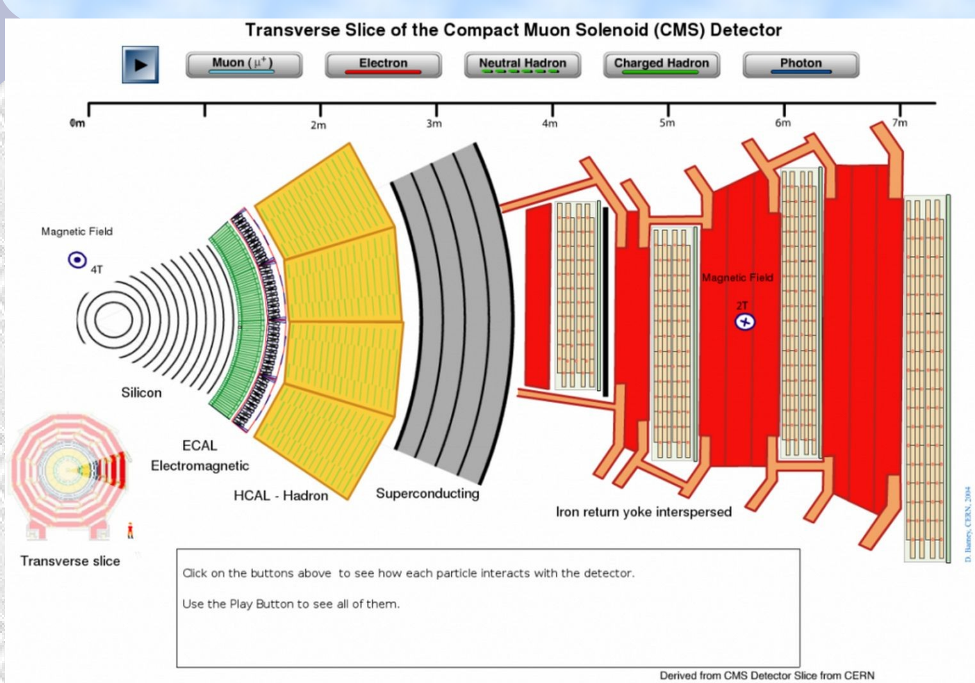


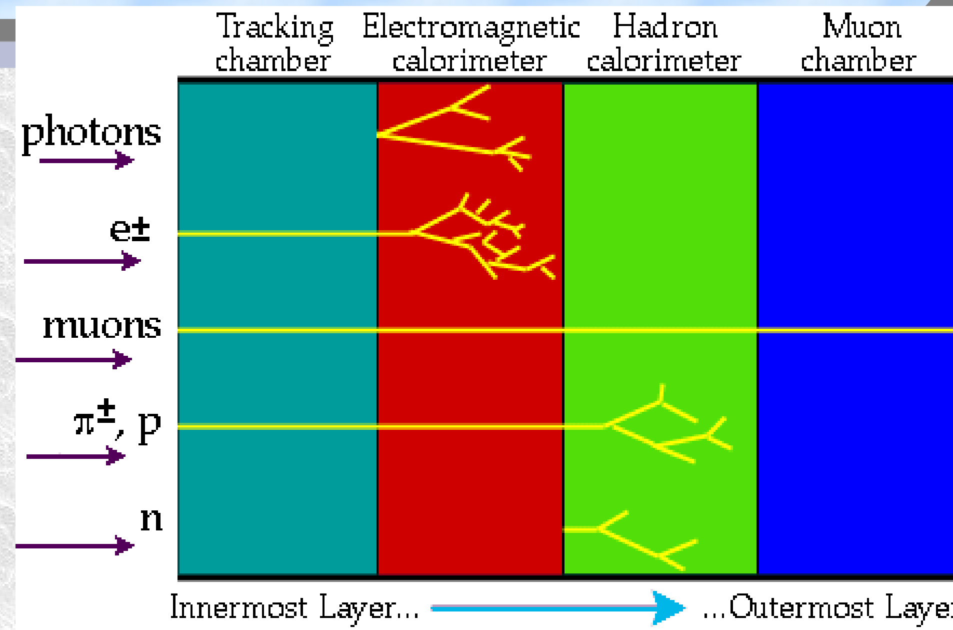
A RAL built silicon detector



- 12cm by 6cm
- 1536 readout strips
- 12 chips (front/back) read at 40MHz
- 1DVD per second data
- Built to a few μm
- Reports `hits' by particles to 20μm precision
- 700 used to tile a barrel around collision point

Particle identification





Look at me! I'm a neutrino

- Reconstruct long-lived particles in the detector
  - Basically only a few types: photons(γ), e^-, μ^-, p^+, π^+, n, ν
  - Can identify type by interaction pattern in the detector
  - Measure the momentum by bending them in a magnetic field
- Electrons, muons and photons especially useful
  - There are none in a proton so their presence is suggestive

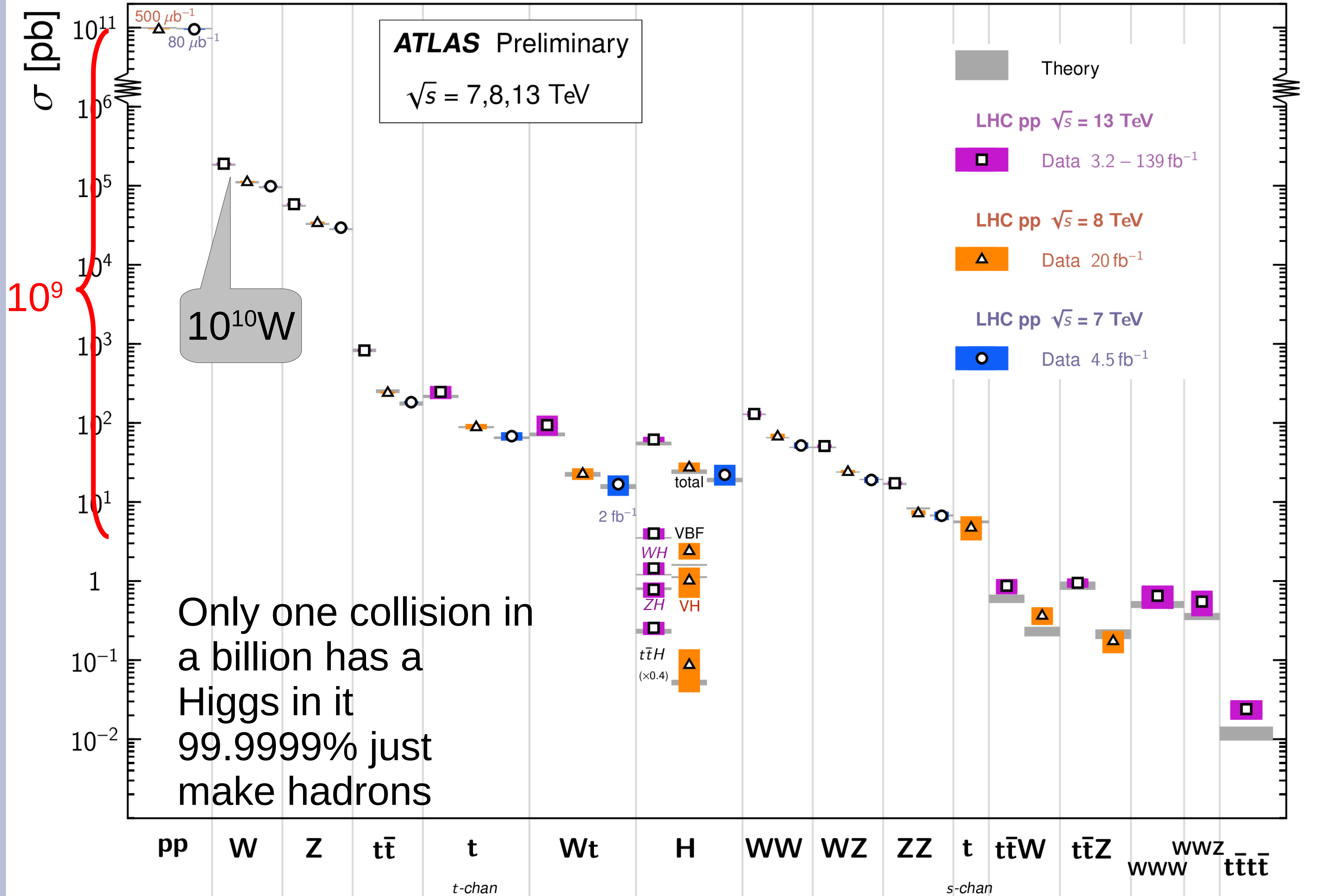
The LHC timeline

- LHC started in 2008
  - And promptly had a major electrical fault
- Run 1 was 2010 – 2012
  - At half design energy, to protect magnets
  - Generating 25fb^{-1} of data
  - Enough to discover the Higgs
- Shutdown 1: 2013-14: Improve thousands of connections
- Run 2: 2015-18: Ran at 13 TeV (almost design)
  - With 139fb^{-1} data
  - Made 10x the Higgs bosons of Run 1 for study
- Run 3: 2021-24: Lots more data, 13.6 TeV
- Phase 2: 2027? - 203?: 3000fb^{-1}, 14 TeV

So, now LHC is running

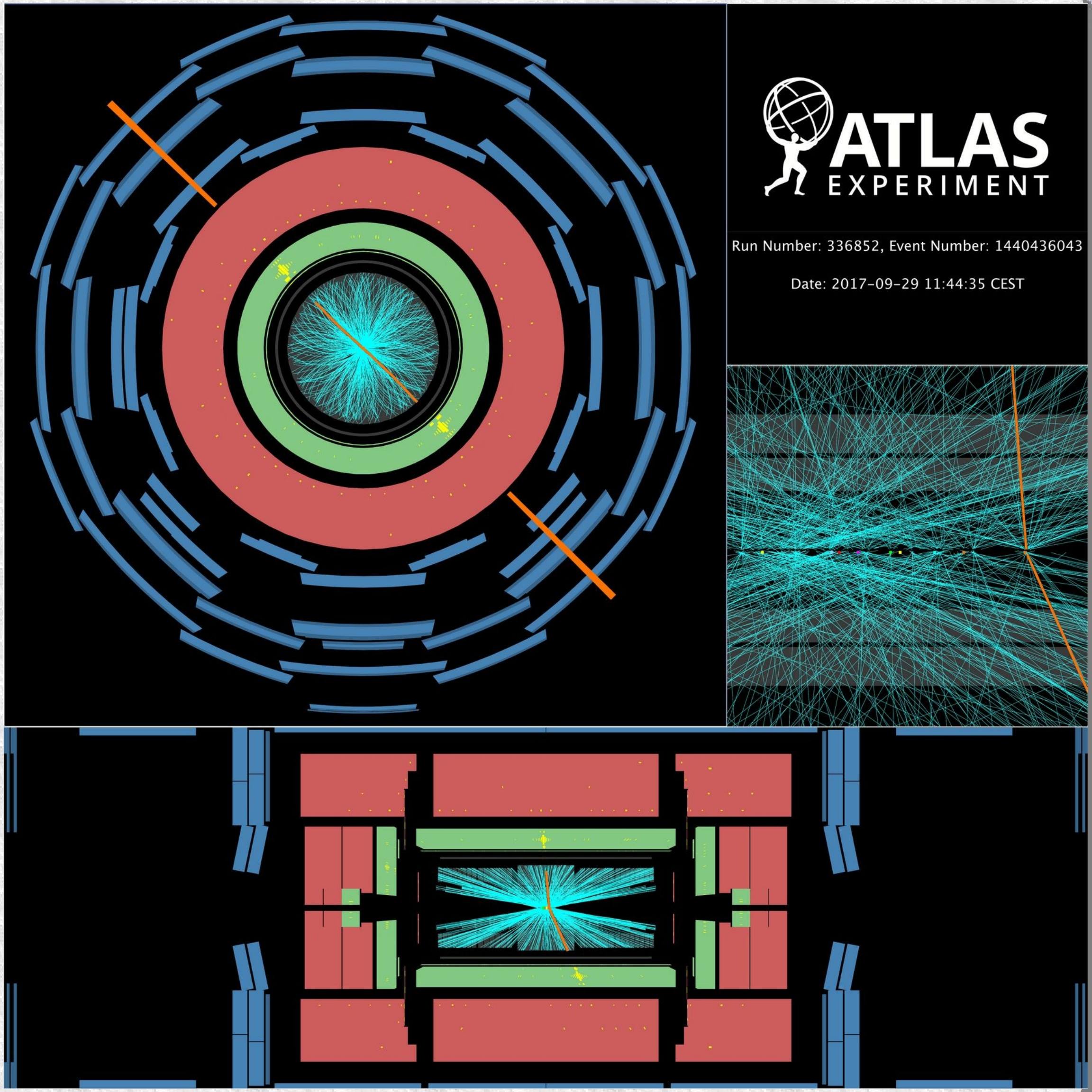
- What do we see?

Standard Model Total Production Cross Section Measurements



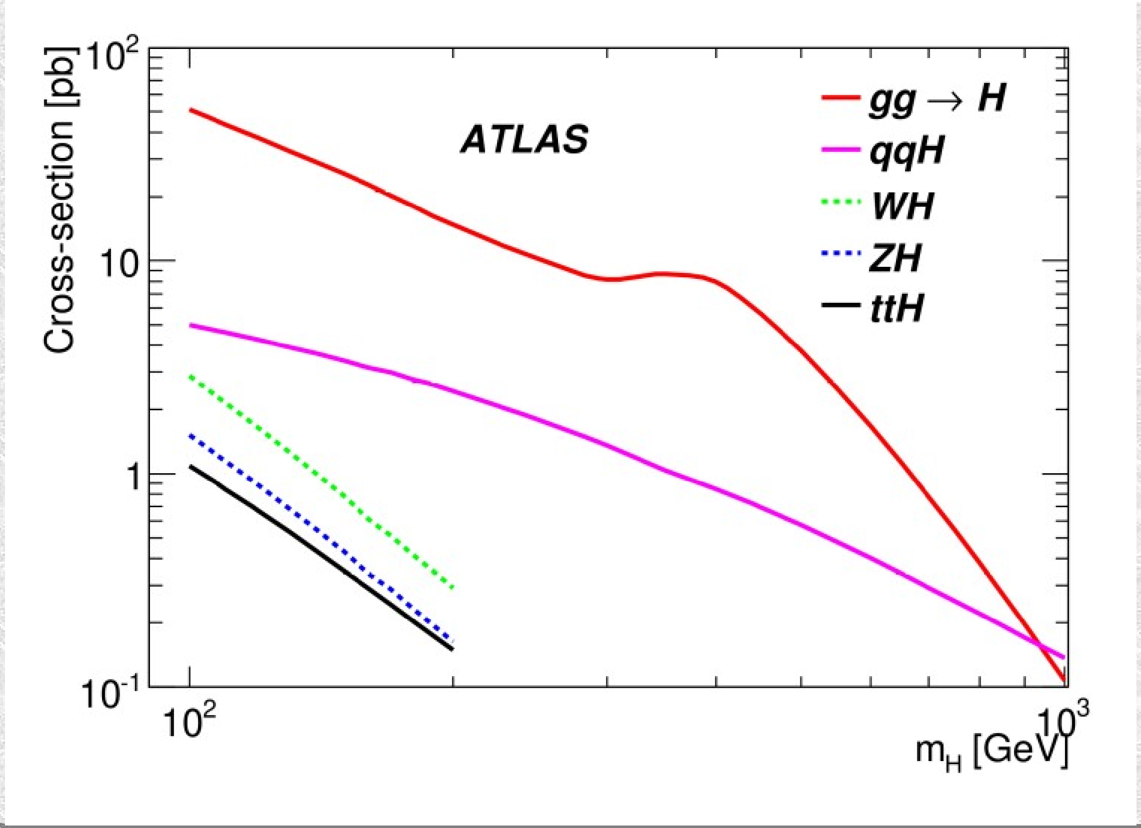
pp collision with e^+e^- pair

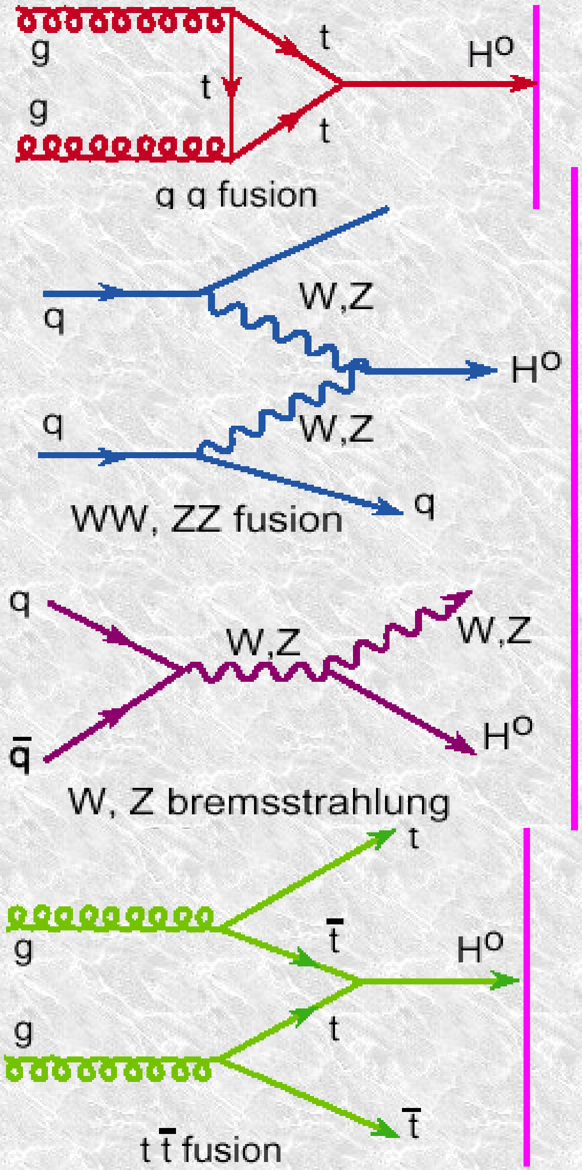
- pp bunches collide at 40 MHz
  - ~62 pp collisions each time
- End view shows lots of particles (blue)
  - But two electrons give yellow energy deposits
- Side view we can see separate pp collisions
- Electrons, photons and muons stand out at LHC
  - Many measurements rely on them



Higgs production

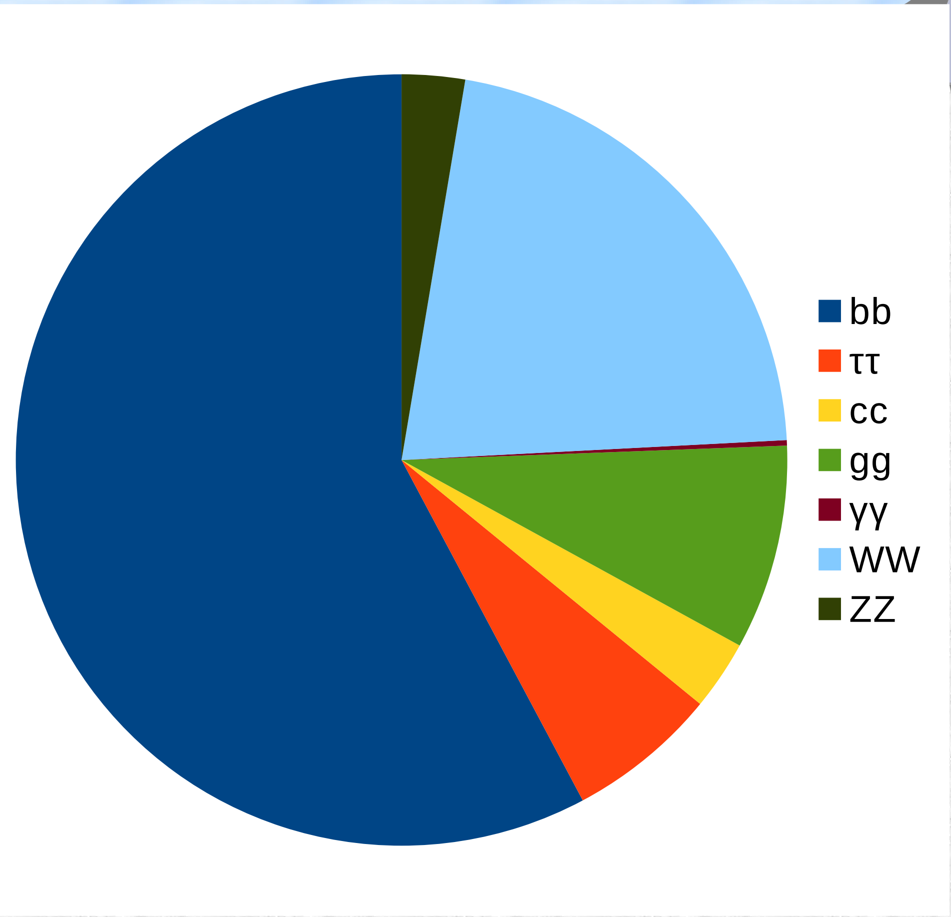
- Higgs interacts with mass
  - Quarks in proton are light
  - So typically make W,Z or t
    - Higgs produced from them





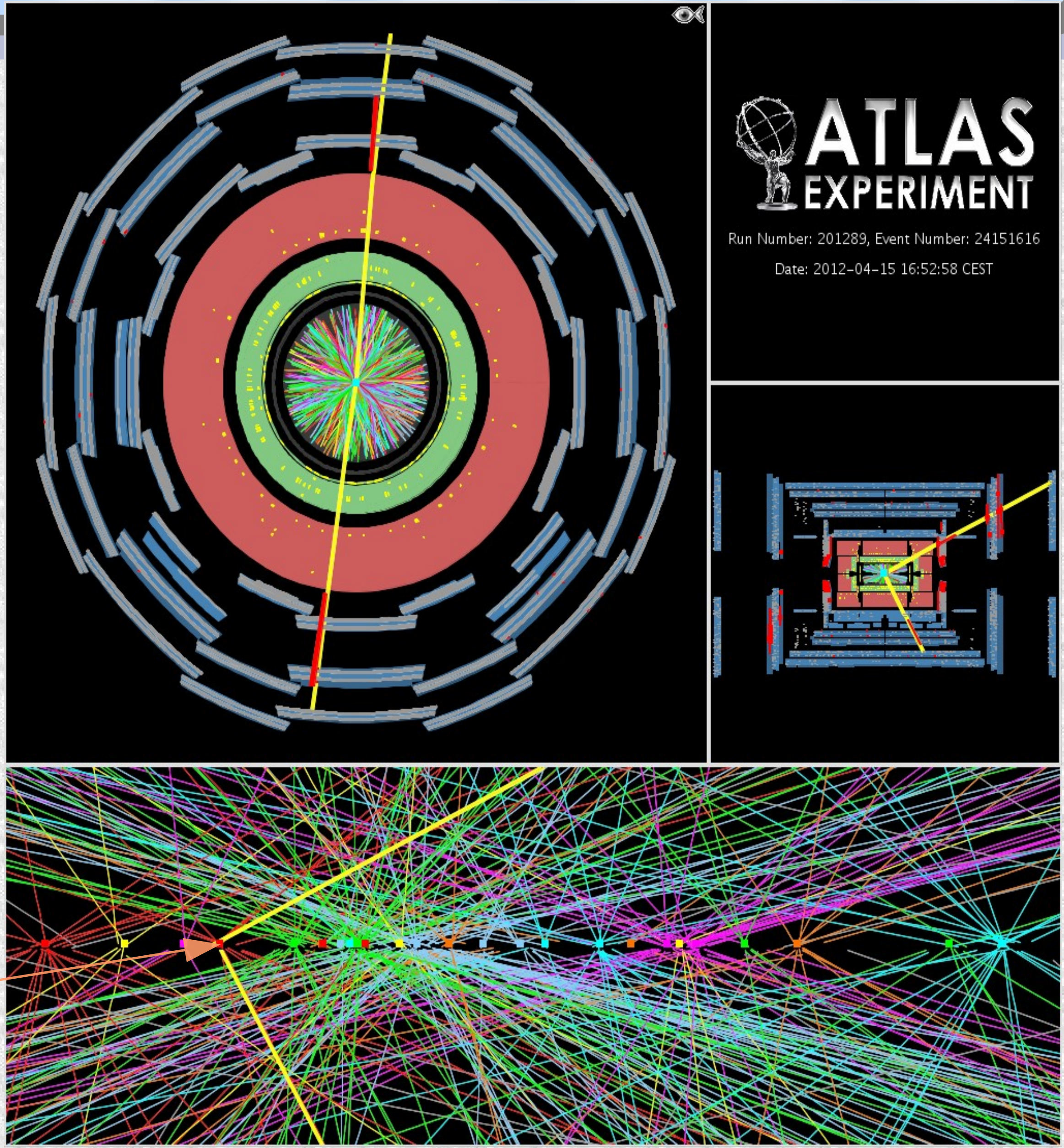
Higgs decay modes used

- $H \to bb$
  - Common but not distinctive
- $H \to WW$
  - $WW \to$ quarks difficult
  - $WW \to l\nu l\nu$: Good but miss ν
- $H \to gg$: no way!
- $H \to \tau\tau$
  - Tau’s are complicated
- $H \to ZZ$
  - Many Z decay modes..but..
  - $ZZ \to llll$: ($l=e/\mu$) Golden mode – 0.02%
- $H \to \gamma\gamma$
  - Rare, but distinctive – 0.2%

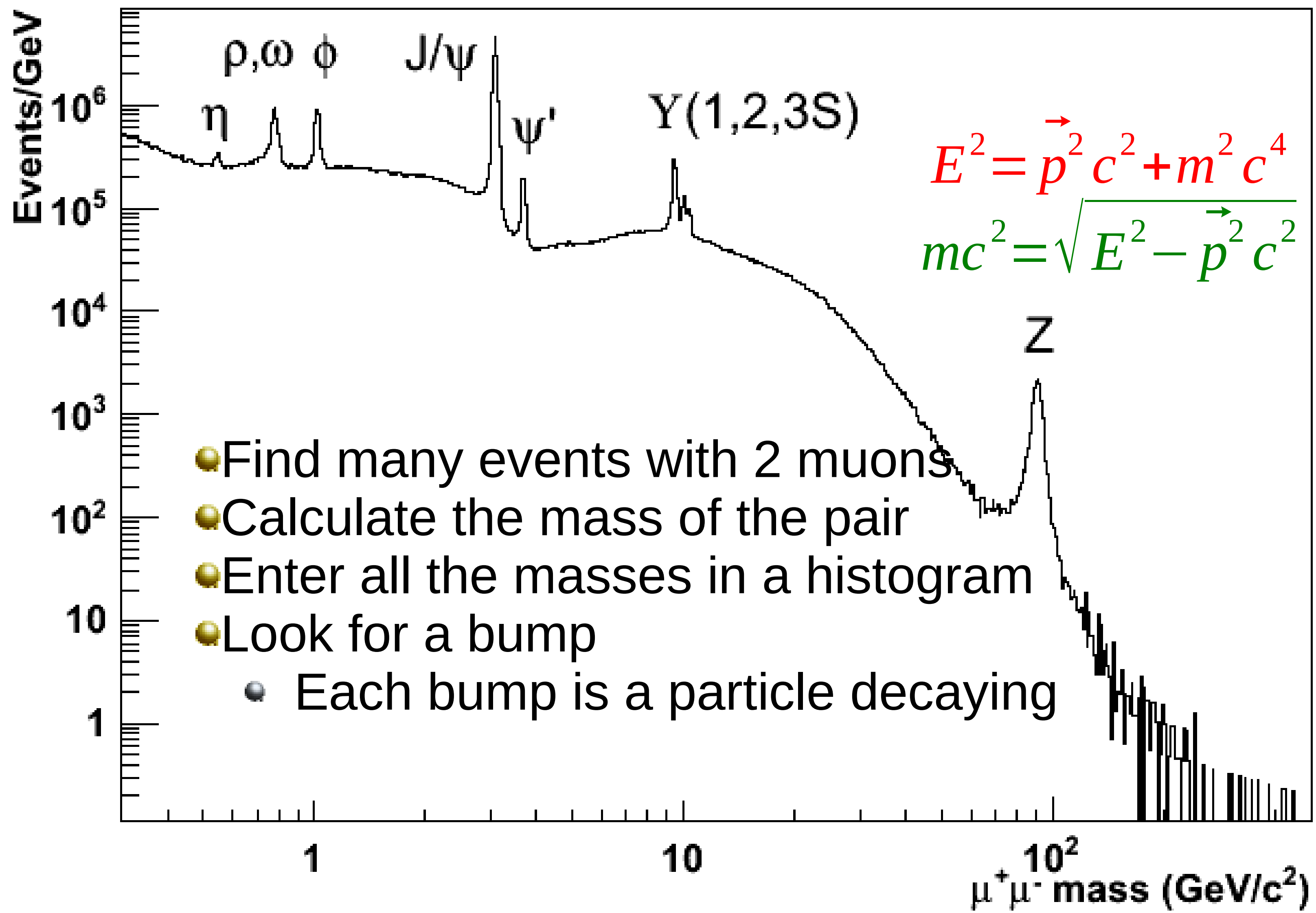


Here is an event with 2 muons

- Most particles are stopped at the green calorimeter
- The two muons get right to the outside
  - Muons are very penetrating
  - They are heavy copies of electrons
- They both come from the same collision
  - Are they related?



Hunting for mass bumps



$$E^2 = \vec{p}^{\,2} c^2 + m^2 c^4$$

$$mc^2 = \sqrt{E^2 - \vec{p}^{\,2} c^2}$$

- Find many events with 2 muons
- Calculate the mass of the pair
- Enter all the masses in a histogram
- Look for a bump
  - Each bump is a particle decaying

The Higgs discovery

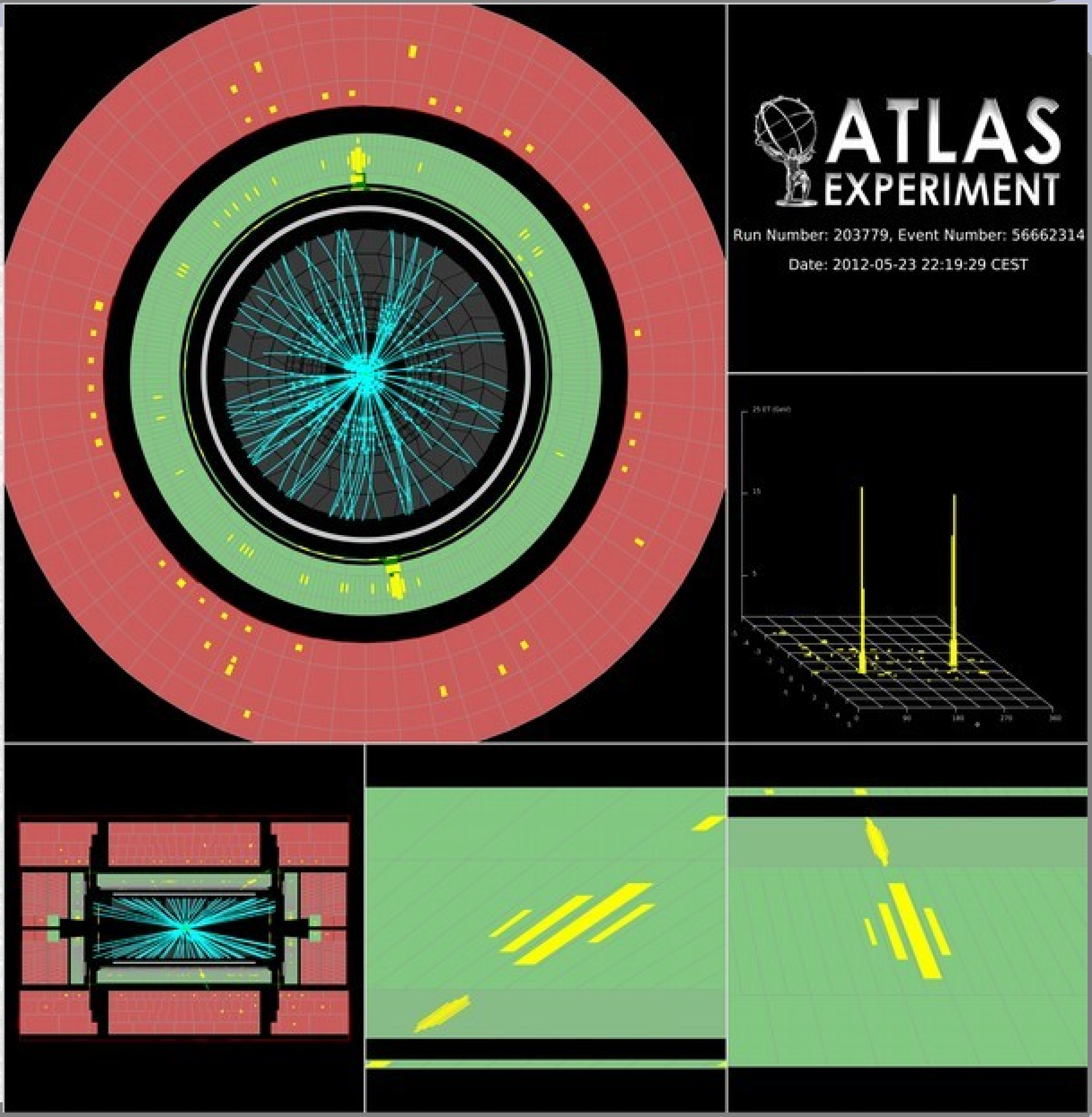
- 2011: I was convening the ATLAS Higgs group
  - In December we had 3σ evidence (~1 in 300)
    - Very interesting, but not regarded as proof
- January 2012: LHC annual planning meeting
  - 5fb^{-1} more data would settle the question
  - LHC agreed to try to deliver by mid-summer
- 1st week July 2012: International HEP conference: ICHEP
  - The experiments planned to release results at it
- Friday 29th June: secret CERN meeting
  - A dozen of us looked at the ATLAS and CMS results
  - Both have a 5σ bump at 125 GeV (1 in 2M chance)
  - But were we convinced to tell the world 'We have it'?
- Monday 2nd July
  - After a busy weekend we decided we had to announce

4th July 2012: The CERN meeting

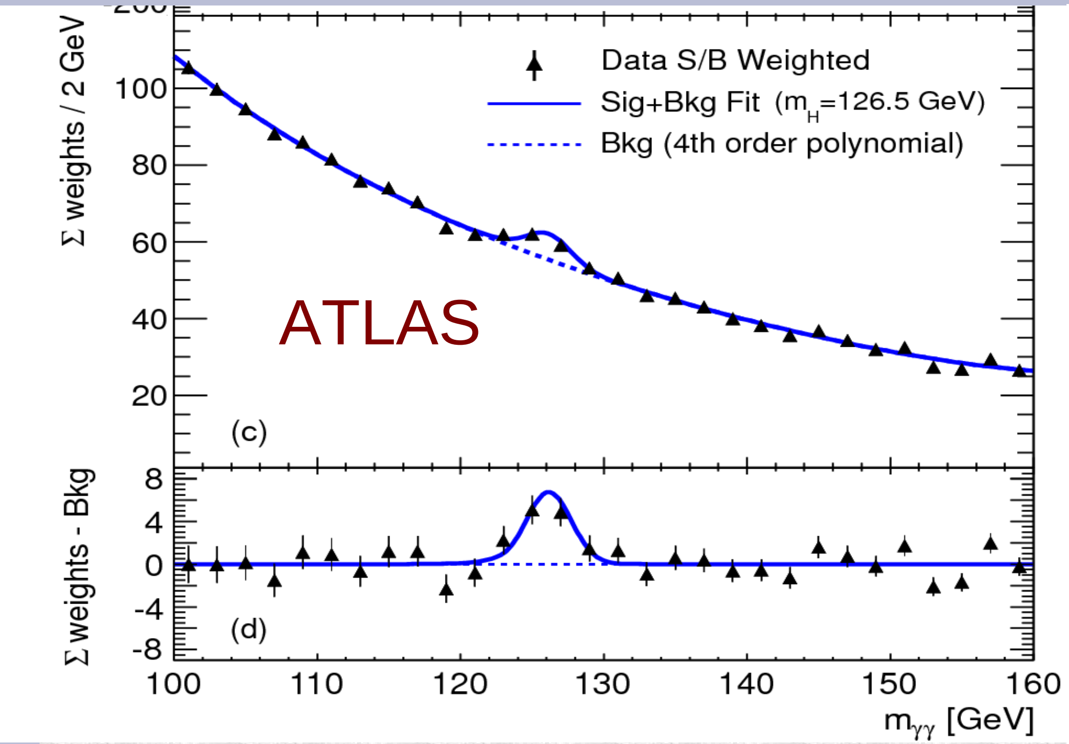
- Major event at CERN
  - Higgs and Englert were there
  - As well as hundreds of journalists
  - Auditorium queue started night before
- The discovery was made via llll and γγ
  - They give well-defined mass peaks
  - On small or moderate backgrounds
  - You can look at the plots and SEE something is there
  - Though the main analysis uses statistical
- $H \rightarrow WW \rightarrow l\nu l\nu$ followed within weeks
  - Higher rate but with two invisible neutrinos

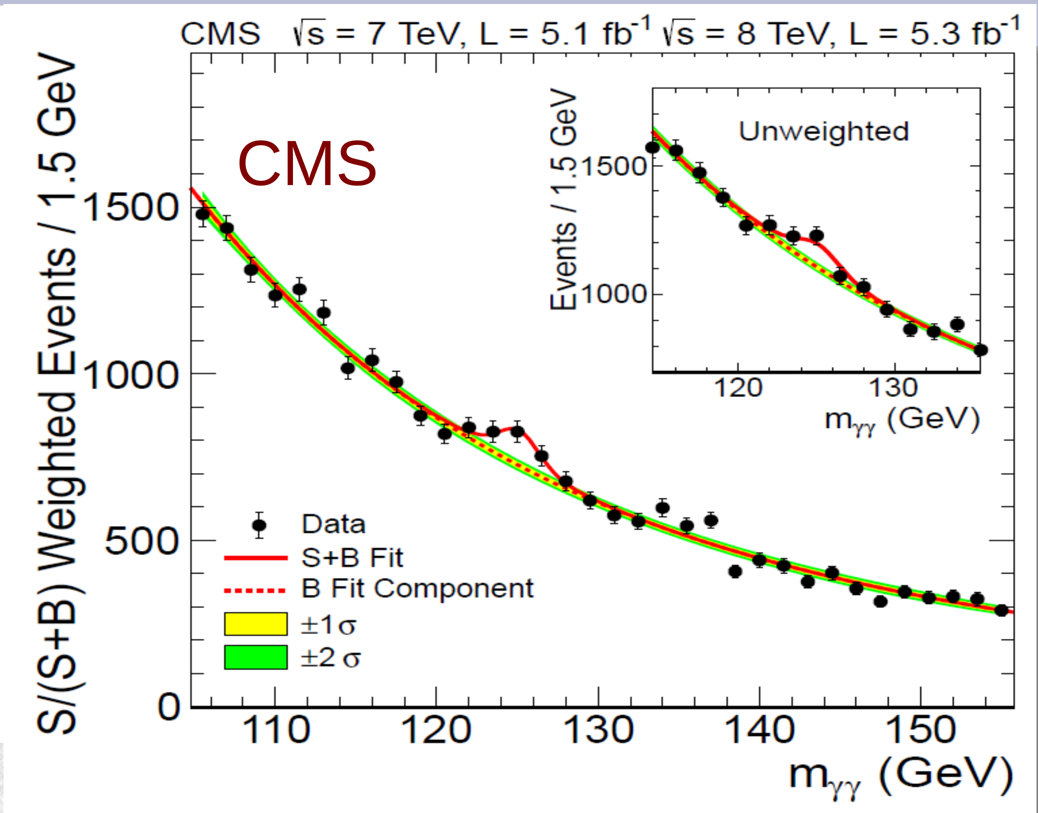
H → γγ

- Not common decay
  - 2 per 1000 Higgs
  - But can be measured well
    - Extract mass
- Photon is neutral, so no track
- But a cluster of energy in 'ECAL'
- But photons are light – lots of light comes out of collisions



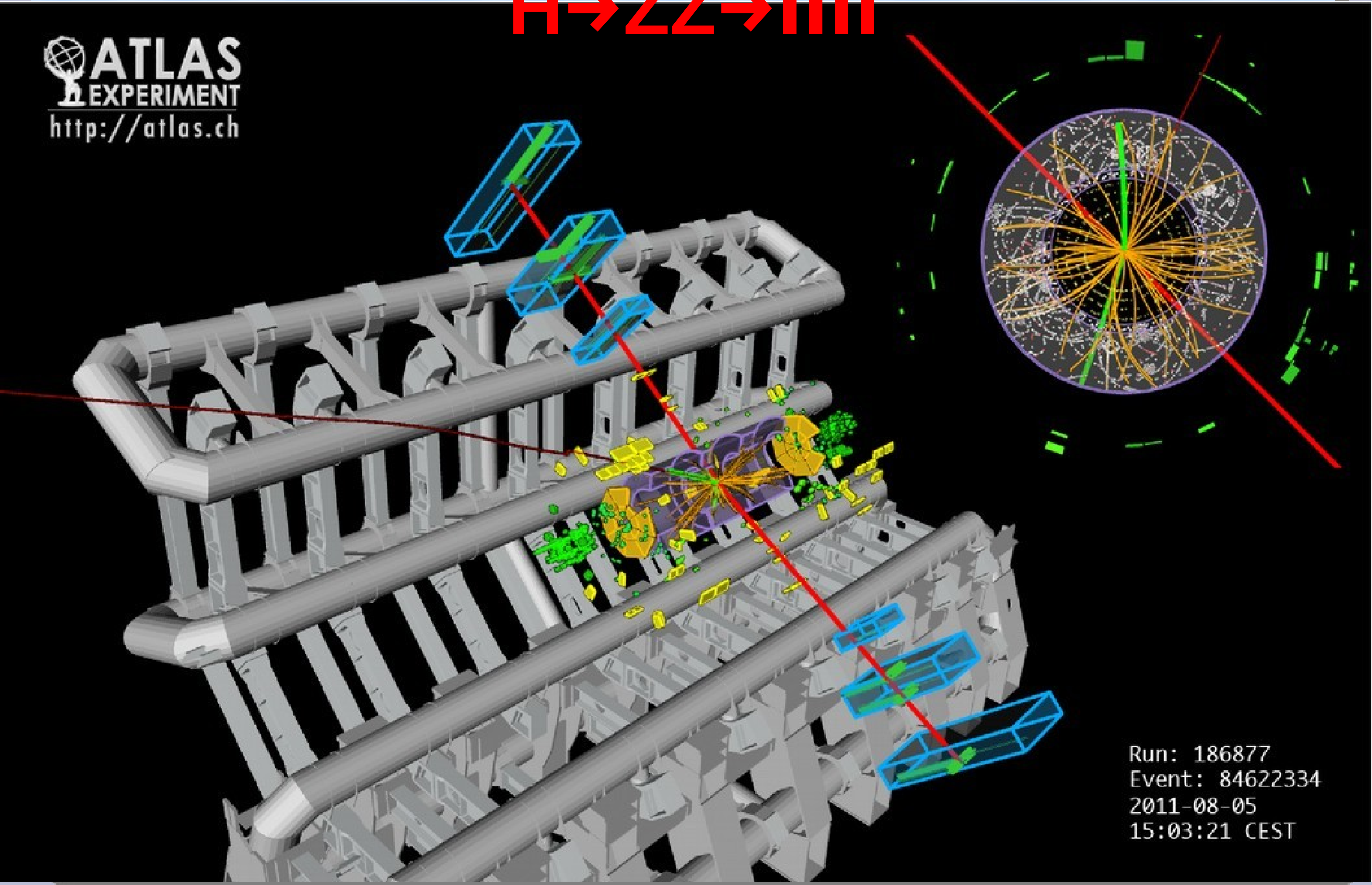
H → γγ @ discovery



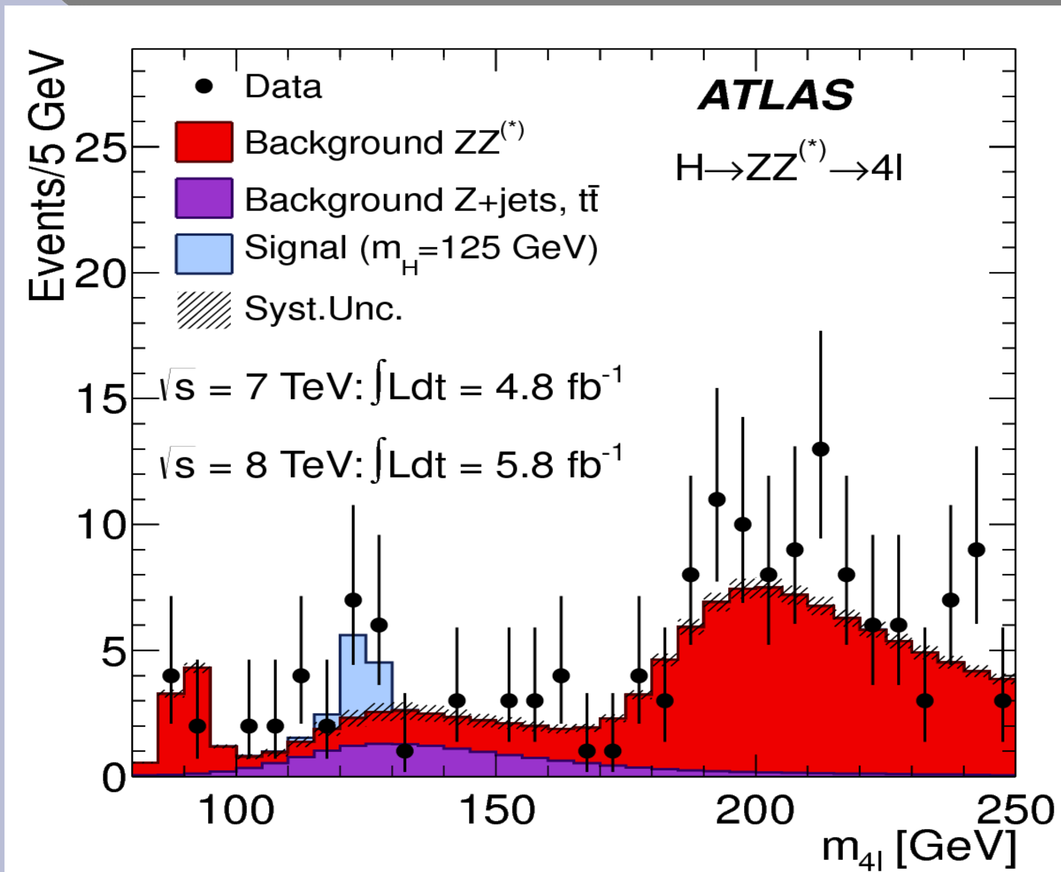


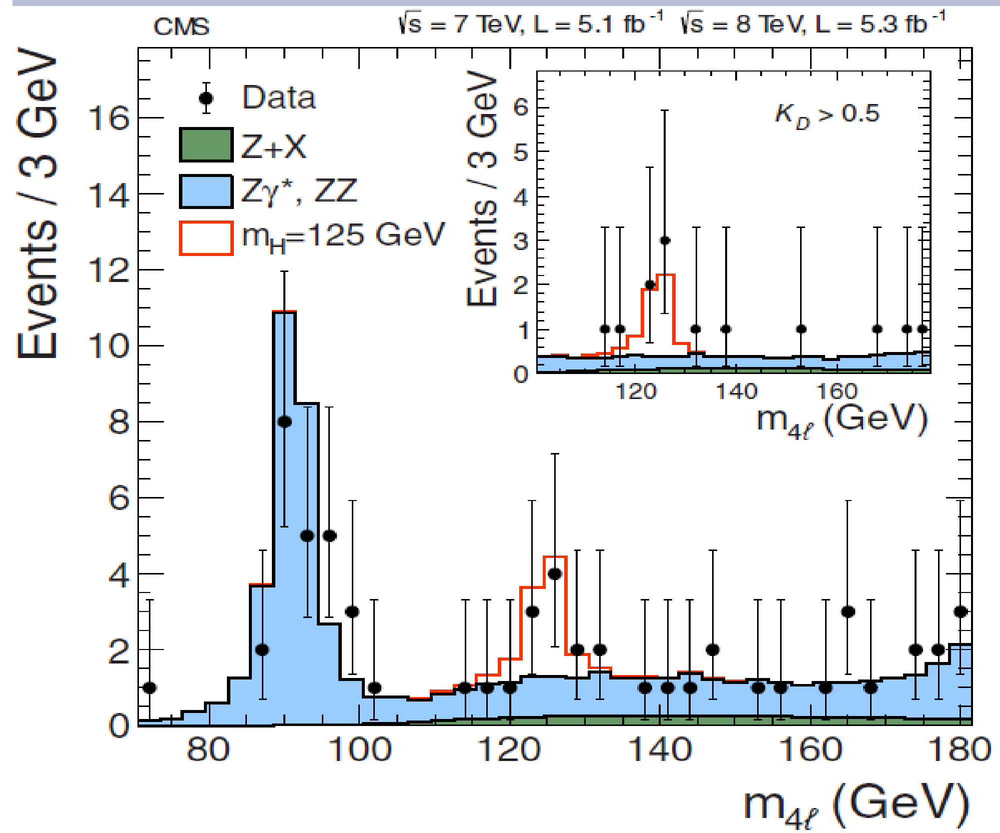
- Both experiments see significant peaks around 125
  - Events are 'Weighted', giving more importance to those which seem likely to have a Higgs in them

H→ZZ→llll


ATLAS
EXPERIMENT
http://atlas.ch
Run: 186877
Event: 84622334
2011-08-05
15:03:21 CEST

$l^+l^-l^+l^-$ Mass distribution

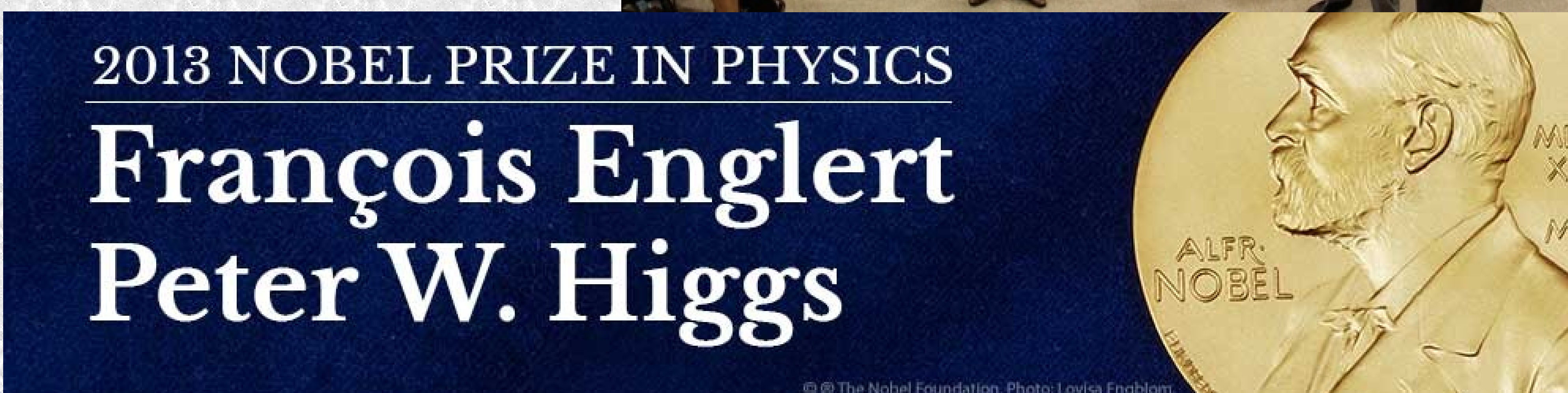




- Only a handful of Higgs bosons
  - But in an even smaller background
- Again, a peak at 125 GeV in both experiments

Discovery!

- Announced in 2012
- Fabiola Gianotti (my expt, ATLAS) and Joe Incandela (CMS)

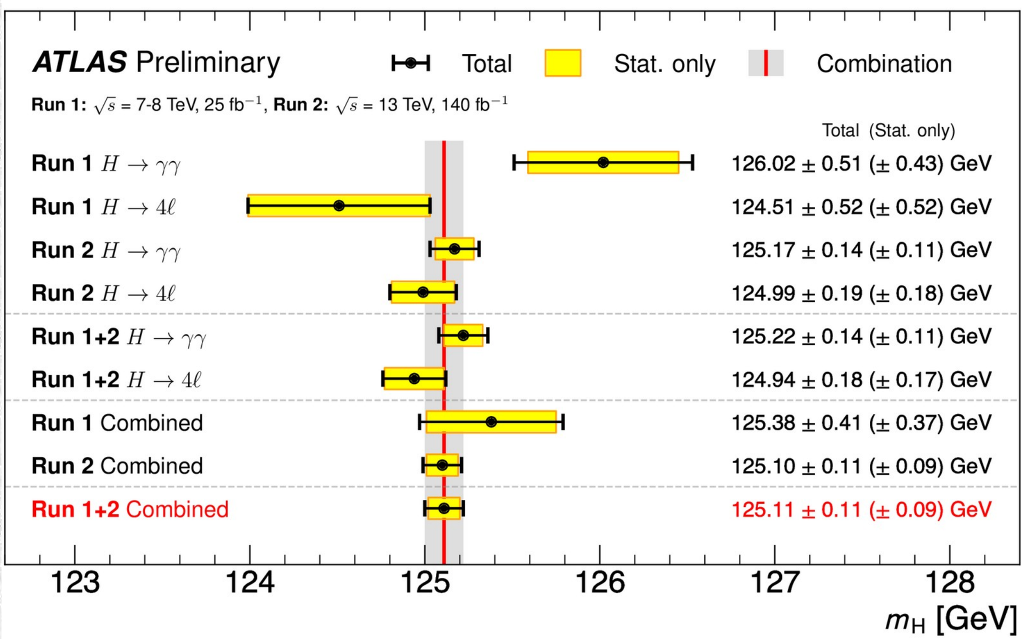


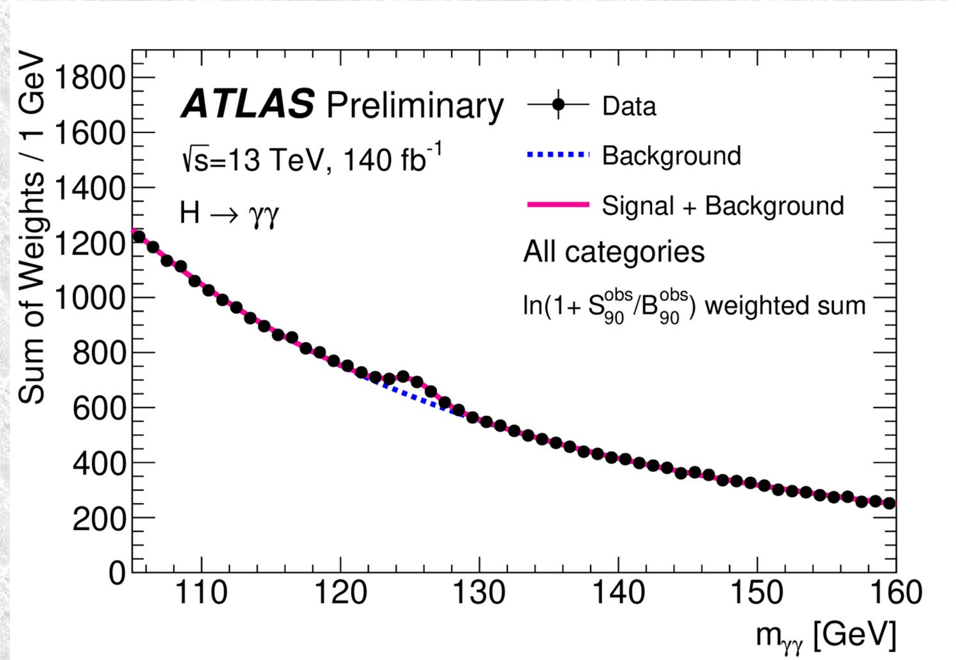
So..what next?

- We had found a particle
  - It pretty clearly decayed to pairs of photons and Zs
  - And fairly soon we had evidence for decay to Ws
- But was it the Higgs?
- Needed to measure:
  - Its mass – in the SM this is the only unknown
  - Its spin – should be spinless
  - Its width...should be narrow.
  - Does it interact with matter in proportion to their mass?
  - Production properties: momentum distribution etc.
  - Pair production – to check self-interaction

The Higgs mass

- Measured in γγ and llll in ATLAS and CMS
  - ATLAS currently have best result:

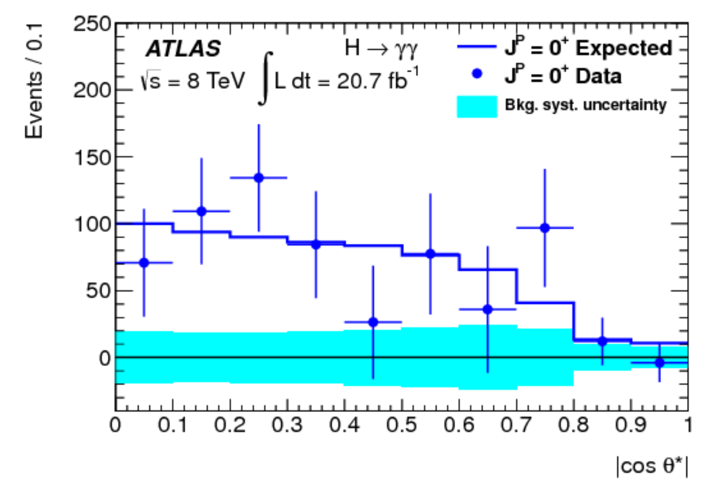




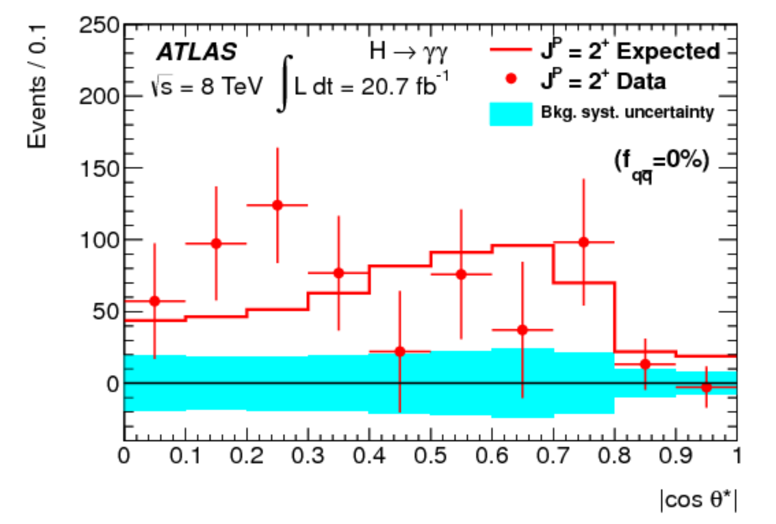
  - A lot of work understanding photon energy measurement
  - Precision better than 0.1%!

Spin

- Look at angles distributions of the decay products
- Many studies were made in 2012-2014
  - Exclude spin 0, parity minus
  - Exclude spin 1 completely
  - Spin 2: a dozen models tested, all excluded
  - Spin 3 or higher are ruled out by theory principles



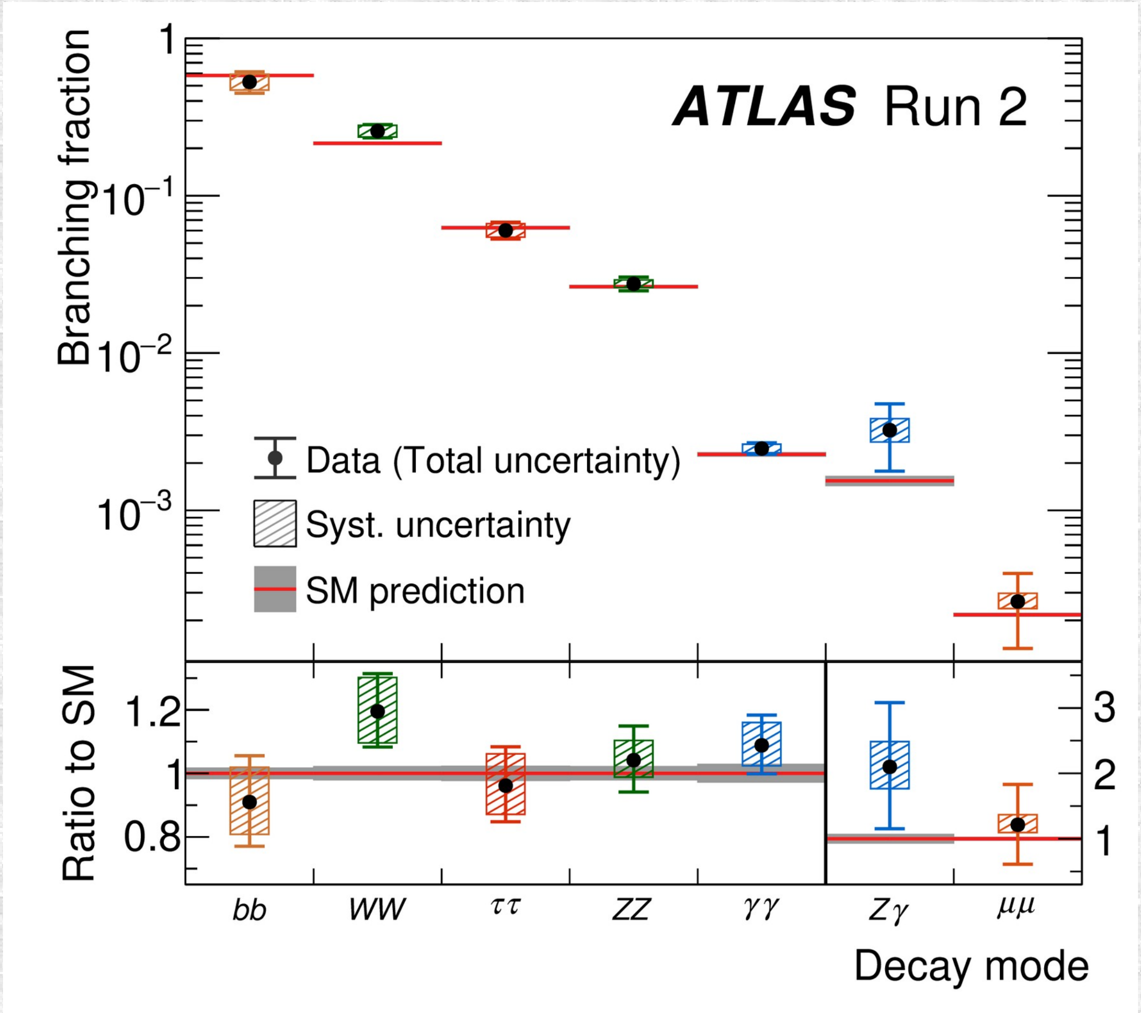
Example gamma gamma plots



- Spin 0 seems to fit..but not quite a proof

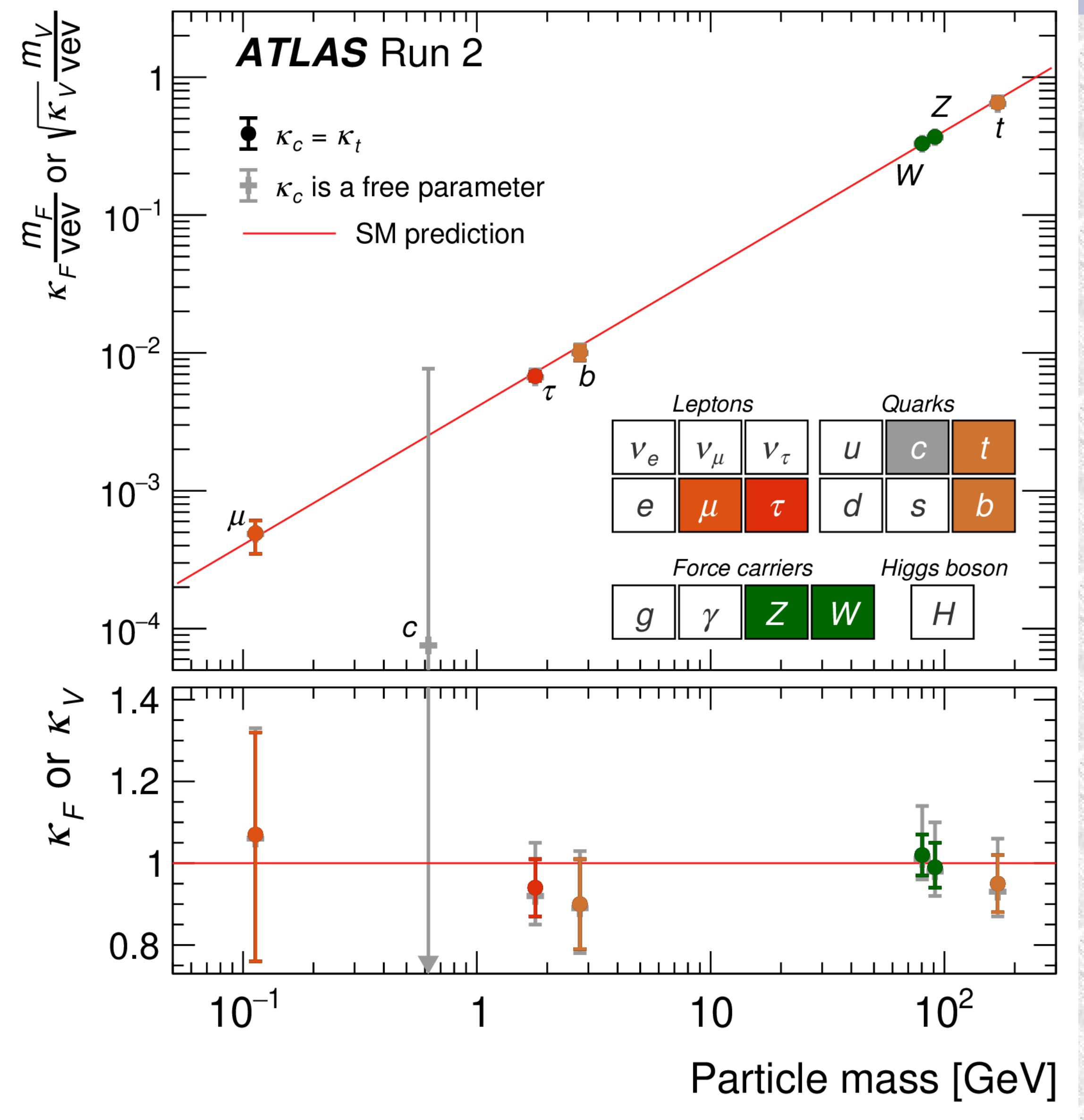
Production and decay

- By now we see (@5σ) four production modes:
  - Gluon fusion
  - VBF
  - WH+ZH
  - $t\bar{t}H$
- And 5 decay modes
  - W^+W^-
  - ZZ
  - γγ
  - $\tau^+\tau^-$
  - $b\bar{b}$
  - +hints of Zγ and μμ
- All looks like SM!



Do interactions scale with mass?

- Yes!
- The 5 strongest have all been seen
- Note the W/Z couplings measured to 6%
  - We are getting precise!
- Some evidence for H → μμ
  - Important, as 2nd generation particle



The Higgs is special

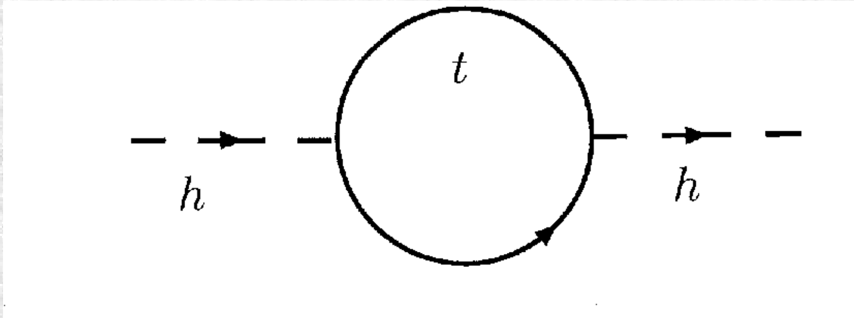
- The Higgs is the only fundamental scalar known
  - There are huge fine-tuning problems (next)
- The π^0 looked like a fundamental scalar
  - Until we discovered quarks
- Brout-Englert-Higgs theory replaces a mass term ($m\varphi^2$) by a two-term piece ($-m\varphi^2+\varphi^4$)
  - But it is adapted from Ginzburg-Landau superconductivity

$$F = F_n + \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4 + \frac{1}{2m}|(-i\hbar\nabla - 2e\mathbf{A})\psi|^2 + \frac{|\mathbf{B}|^2}{2\mu_0}$$

  - Which is a phenomenological description of the cooper pair
- These examples hint the Higgs may be composite

Naturalness: curse of the scalar

- Consider this diagram:
  - H → tt → H
  - Quantum effect, allowed by uncertainty principle



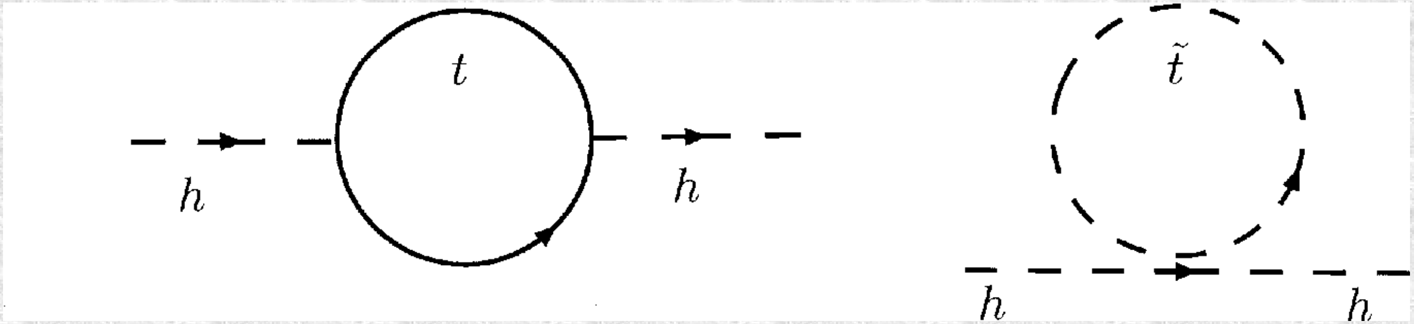
- We do not know it has happened: you only see a Higgs
  - Measuring Higgs properties averages over such diagrams.
  - e.g.The Higgs mass is corrected by $\Sigma_{diagrams}$
- But the momentum circulating in the loop is arbtirary
  - Integrate over all posible momenta
  - Need a maximum, **Λ**. Typical m_{planck}: once gravity matters or maths has gone wrong
- $m_{obs}^2 = m_{bare}^2 + O(m_t/170\ \mathbf{\Lambda})^2$
- But m_{planck}~10^{18} GeV – and does not know m_t

Naturalness

- The SM is incredibly fine tuned
- We measure m_H=125.09GeV/c^2
- Did it really start as -10^{18}?
  - It would need to be 'just right'
  - The loop involves m_t and the upper scale of the theory
    - Nothing to do with m_H
  - How can they cancel so exactly?
- This is so big because the Higgs is spin 0
  - Similar, smaller effects have been found in the Z
    - And effect of $Z \rightarrow ZH \rightarrow Z$ was used to predict m_H.
  - They work...so why don't they work for H?

Naturalness

- This *suggests* something is missing
  - and it cannot be far in mass from the top quark
- Supersymmetry makes a good example
  - It predicts a new particle cancelling the top loop (stop)
    - And a dark matter candidate



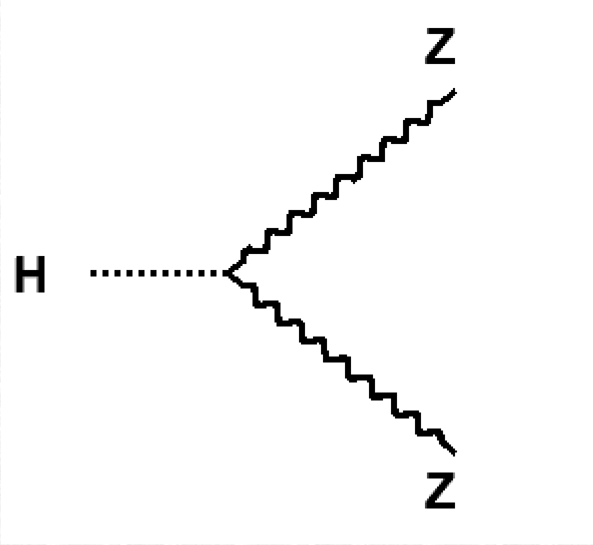
- Many other theories
  - But all need something with mass O(m_H)
  - And it must interact with the H, so we can study it.
- This gives a high motivation to LHC searches

What about the Higgs field?

- The Higgs mechanism needs the field filling space
- This is neither matter nor particle: something new
- Actually reminiscent of the 'luminoferous ether'
  - But a fully relativistic version
  - Unlike light, you turn it off and it is still there
  - ~2 Higgs bosons / fm^3
- The density of the field is cosmologically ridiculous
  - It is 120 orders of magnitude larger than dark energy
  - Remember: we don't have a quantum theory of gravity
- So do we really expect you to believe its there?
  - Well, there was the $H \rightarrow ZZ$ decay...

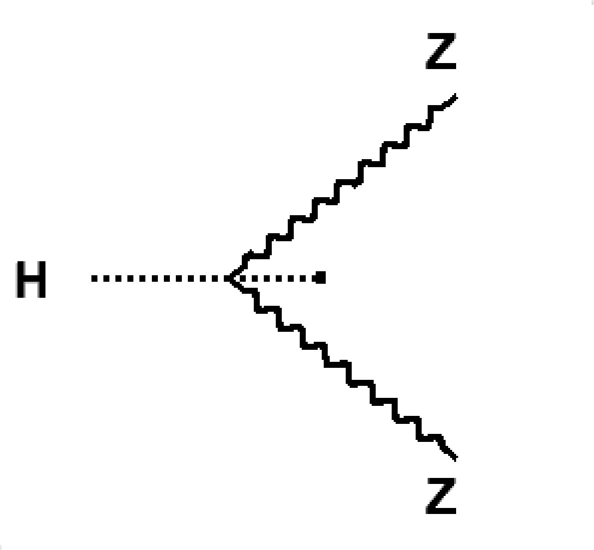
H to ZZ and H to γγ

- The measured $H\rightarrow ZZ$ rate is about $10\text{x}H\rightarrow\gamma\gamma$
  - After allowing for $Z\rightarrow ll$ Br
  - But the Z is massive, so harder to make
  - So HZZ must be a powerful interaction
- We know the Z interacts with weak charge
  - Just like the photon does with EM charge
- HZZ strength shows the H must be weak charged
  - But Z is neutral (Charge and weak charge)
  - So in $H\rightarrow ZZ$ where does the charge go?



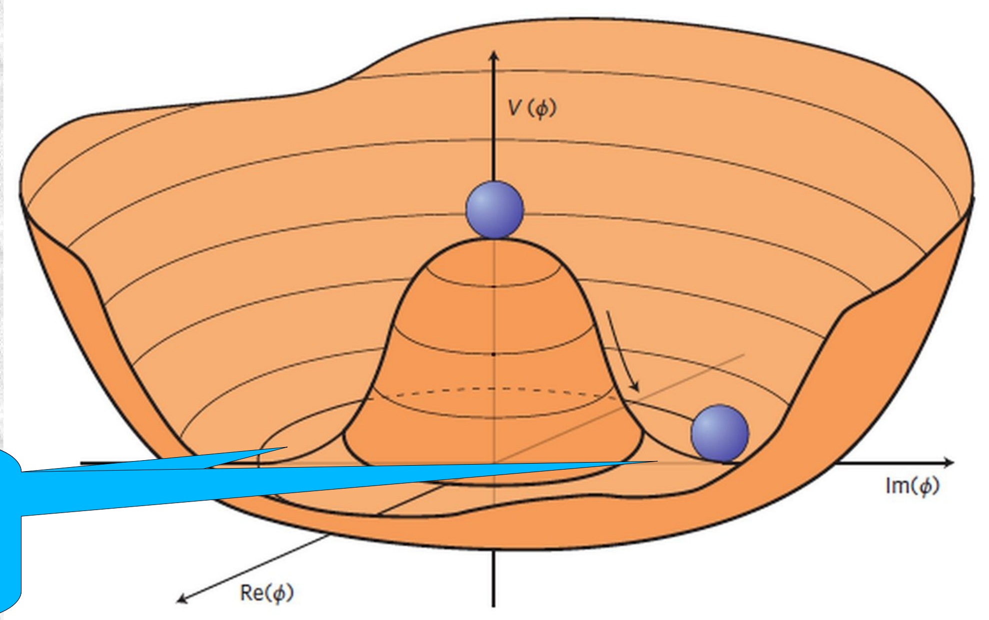
H to ZZ and H to γγ

- The measured H→ZZ rate is about 10xH→γγ
  - After allowing for Z→ll Br
  - But the Z is massive, so harder to make
  - So HZZ must be a powerful interaction
- We know the Z interacts with weak charge
  - Just like the photon does with EM charge
- HZZ strength shows the H must be weak charged
  - But Z is neutral (Charge and weak charge)
  - So in H→ZZ where does the charge go?
- It is really a 4-point coupling
  - One leg 'grounded' in the vacuum
- The ZZ decay needs vacuum help
  - Absorbing a (weak) charge!
- This is evidence the BEH field exists



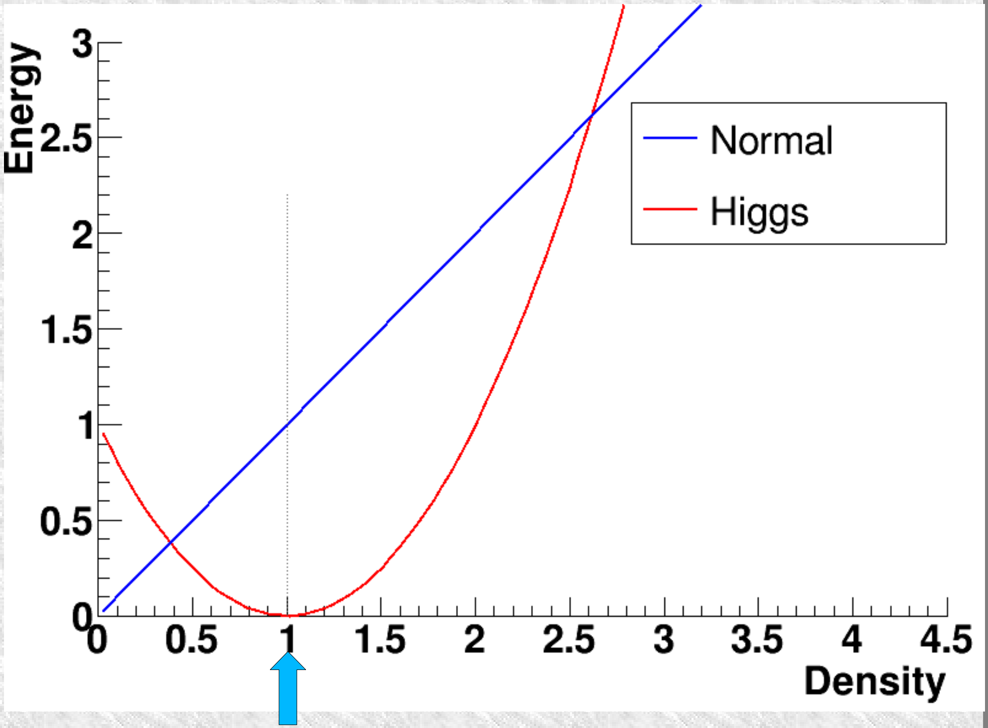
The Higgs field

- The key property of the Higgs is the field
- This is not like an electromagnetic field
  - Switch off the source and the EM field is gone
  - The Higgs field is always there – there is a ‘standard density’ of Higgs bosons per volume
- Higgs interaction strength with W/Z measures the curvature of this plot
  - In the region around minimum
- That came out right in the plot I just showed you
  - To about 6%

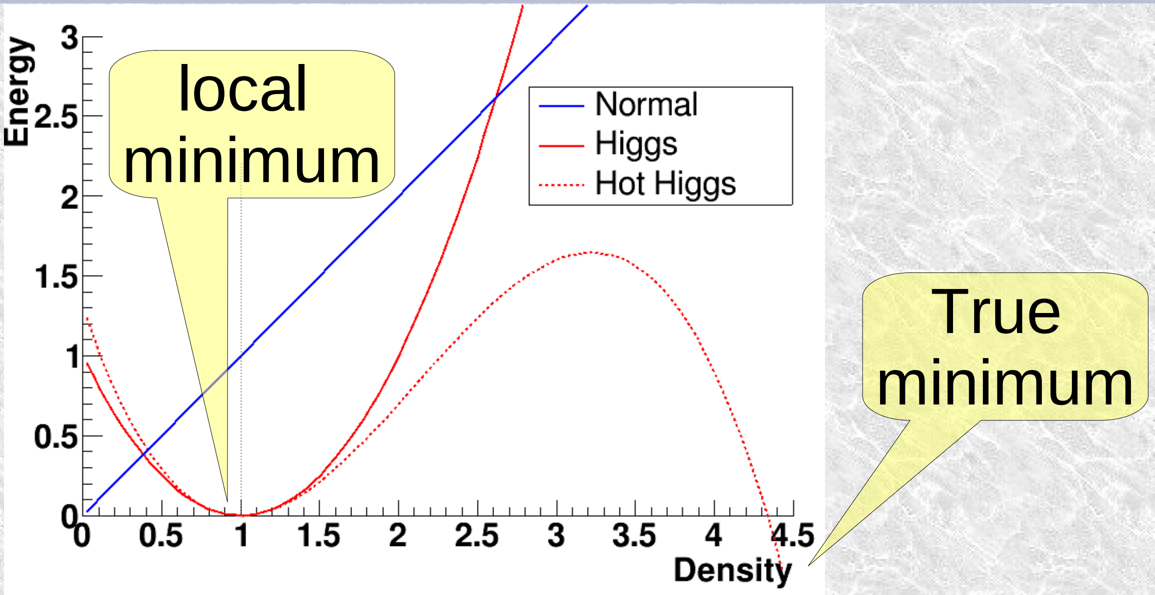


The Higgs field II

- Look at the same curve on different axes:
- Ordinary matter obeys $E=mc^2$; energy rises with density
- Higgs obeys the red curve
  - The minimum energy is at a standard density (“1”)
- Higgs have no quantum numbers so we can create or destroy Higgses to move to lowest point
- We have only measured this curve near 1
  - Elsewhere we have to trust theory...or not.
- So what?



We are all doomed



- The equations describing the Higgs field depend on temperature
- Heat it up and it becomes unstable
  - Will drop into its true minimum
- It's now in a meta-stable state
  - When it falls, it will heat the neighbouring field..which will fall too.

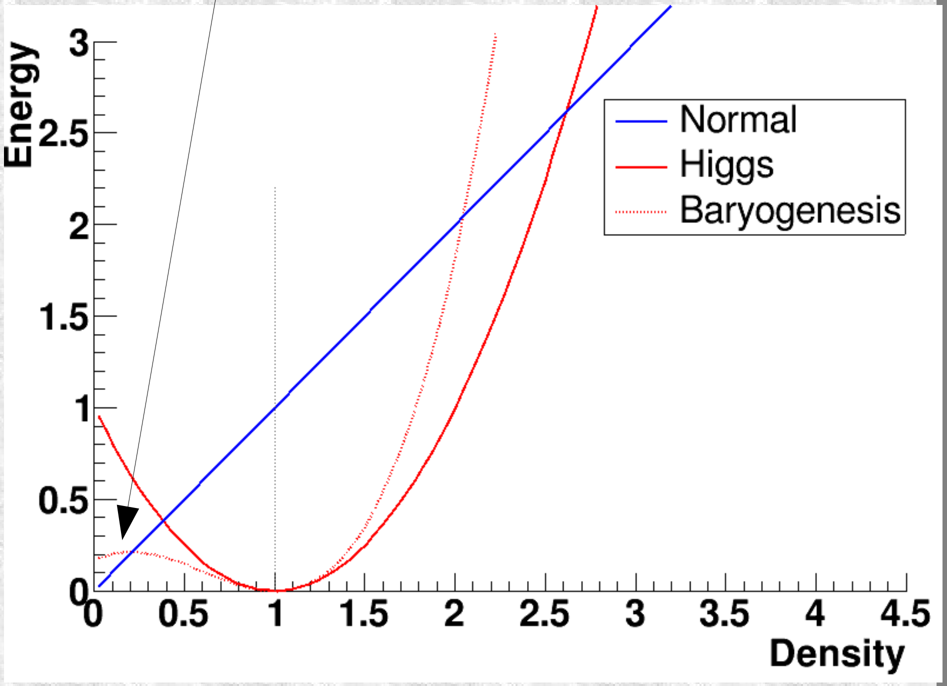
Doom postponed/cancelled

- If that happens anywhere in the Universe a ball of super-dense state will expand at the speed of light.
  - And destroy all it touches
- But: the expected lifetime is >>>> the universe
- Also, it seems likely the Big Bang would have set it off
- So probably our equations miss something?

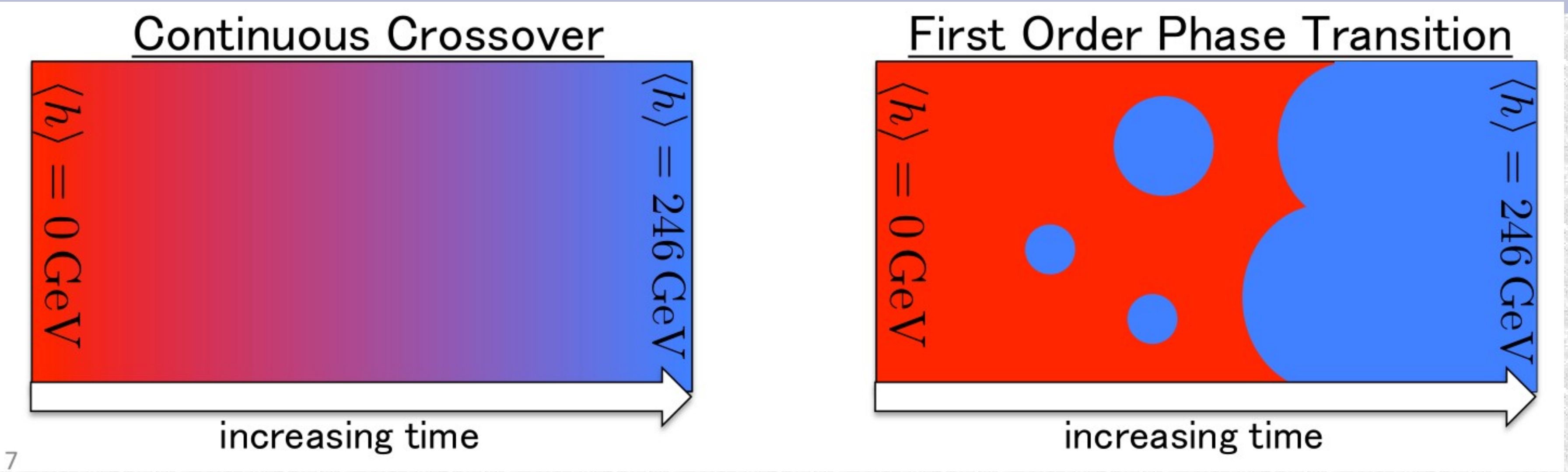
Wanted:
Quantum gravity
Dark Matter
Dark energy
Matter-antimatter asym
Neutrino mass type

The beginning of the Universe?

- The assumption is the Universe started empty
  - With the Higgs density at zero
- Then rapidly slid down to the density we see
- But what if the curve is really the dotted one?
  - Looks just the same where we can measure it
  - But the early Universe would have sat in a false minimum until bumped out
  - Rather like the doom-bubble
- Called a 'first order phase transition', like water boiling



Why do we care?



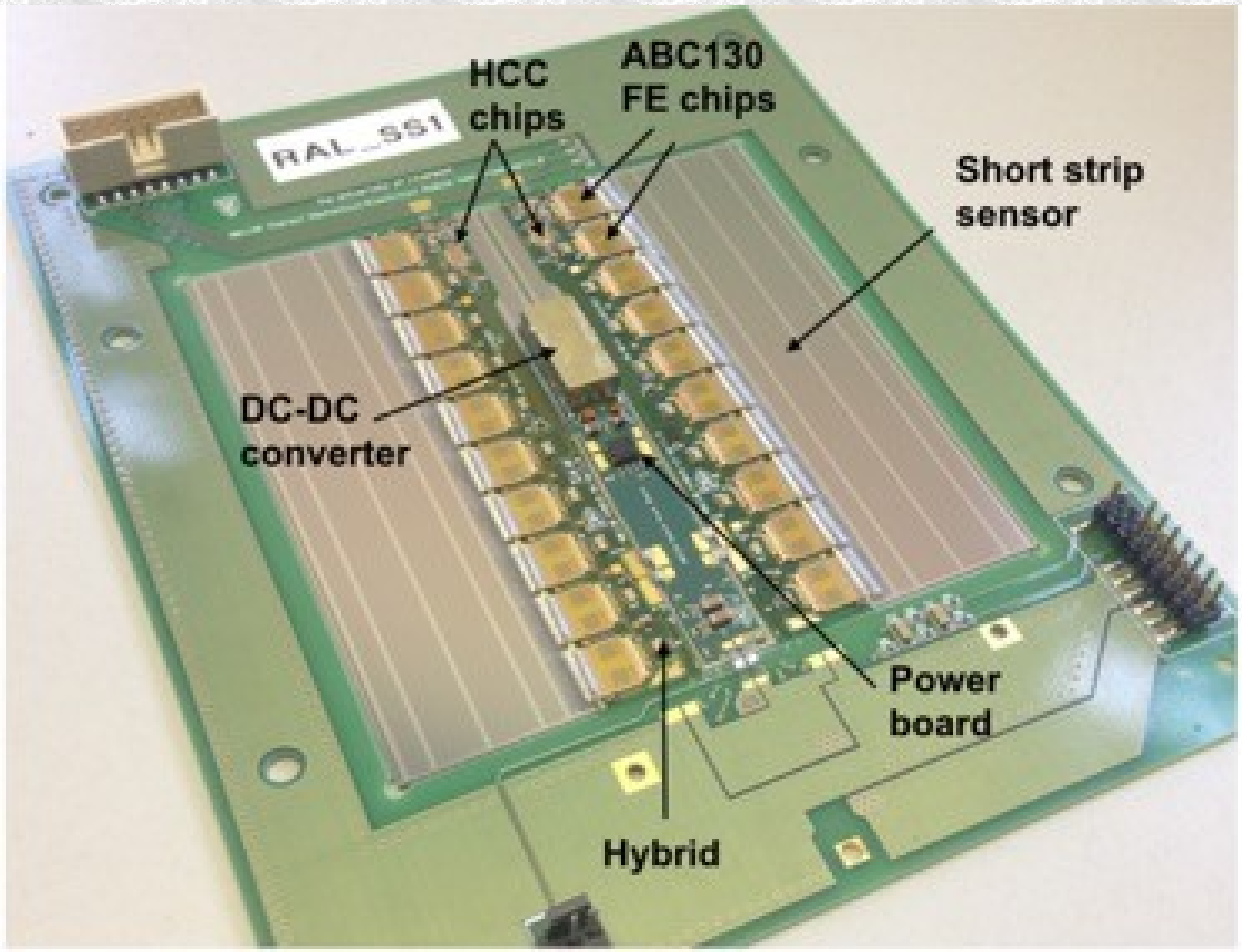
- If these bubbles formed, the consequences could include:
  - Create the observed matter/antimatter asymmetry?
  - Or maybe create lots of small black holes
    - Which some people speculate might be dark matter
  - Will create gravitational waves
    - Potentially observable with gravity wave detectors

Check: Higgs self-interaction

- Need to produce 2 Higgs bosons
  - The LHC can do it...but can we see it?
- This is 1000x rarer than making one Higgs
  - And we still need to recognize them
- The best Higgs modes: $\gamma\gamma$ and $ZZ\rightarrow llll$ have BR of 0.002 and 0.0002 respectively
  - If we want $HH\rightarrow(\gamma\gamma)(\gamma\gamma)$ we expect one by 2035!!
    - Not enough to measure
  - So we need to try to use more abundant modes
    - $HH\rightarrow\gamma\gamma bb$, $HH\rightarrow bbbb$, $HH\rightarrow\tau\tau bb$ will all be used
- This is a major motivator for Phase 2
  - 10 times more data
  - With upgrades to LHC and detectors

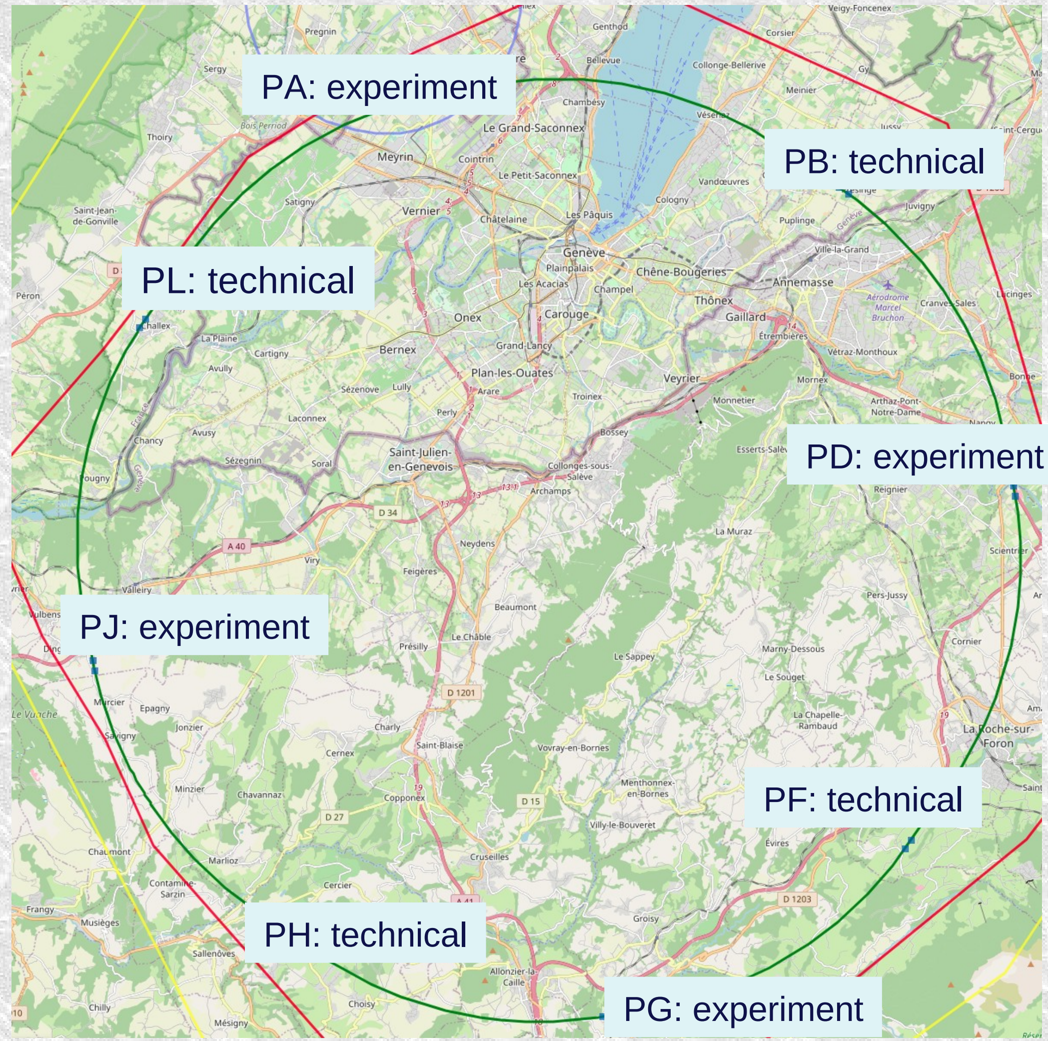
New trackers for upgraded LHC

- The original spec was for 23 pp collisions at once
- HL-LHC may have 200
  - Building new tracker to cope



How to study it better?

- LHC found the Higgs, and Phase-II will learn more
- Fcc is a proposed 100km circumference ring
  - Being seriously designed
  - ee → ZH for clean precise measurements
  - pp at 100TeV will make many Higgs boson pairs
    - Study that potential properly.
- There is a lot more to discover about the Higgs
  - And beyond it!



Conclusions

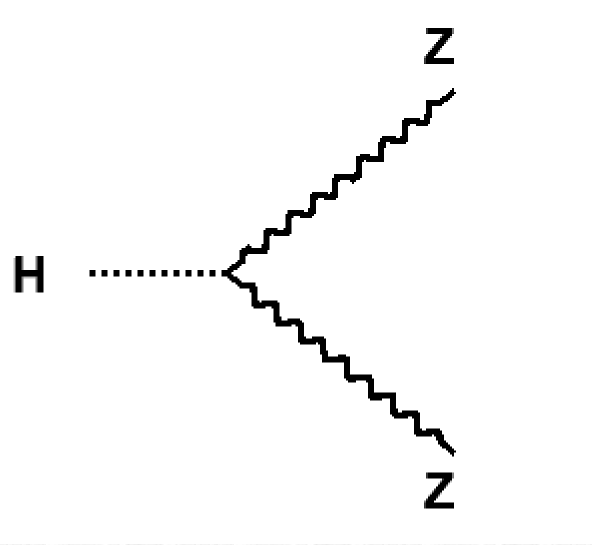
- Maths has guided us to the Higgs boson
  - The Brout-Englert-Higgs field is real
  - The boson fits the model from 1964
- We are advancing rapidly:
  - Many production and decay modes seen
- We continue to probe deeper
  - Much more to come from LHC
  - Possible future accelerators now being designed
- We should expect surprises
  - The Higgs boson warns us of the end of the Universe
  - And may explain the matter-antimatter asymmetry that allows us to be here

What about the Higgs field?

- The Higgs mechanism needs the field filling space
- This is neither matter nor particle: something new
- Actually reminiscent of the 'luminoferous ether'
  - But a fully relativistic version
  - Unlike light, you turn it off and it is still there
  - ~2 Higgs bosons / fm^3
- The density of the field is cosmologically ridiculous
  - It is 120 orders of magnitude larger than dark energy
  - Remember: we don't have a quantum theory of gravity
- So do we really expect you to believe its there?
  - Well, there was the $H \rightarrow ZZ$ decay...

H to ZZ and H to γγ

- The measured H→ZZ rate is about 10xH→γγ
  - After allowing for Z→ll Br
  - But the Z is massive, so harder to make
  - So HZZ must be a powerful interaction
- We know the Z interacts with weak charge
  - Just like the photon does with EM charge
- HZZ strength shows the H must be weak charged
  - But Z is neutral (Charge and weak charge)
  - So in H→ZZ where does the charge go?



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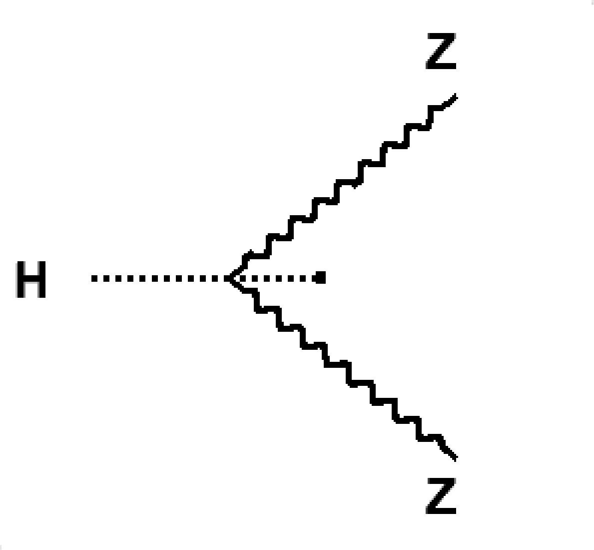
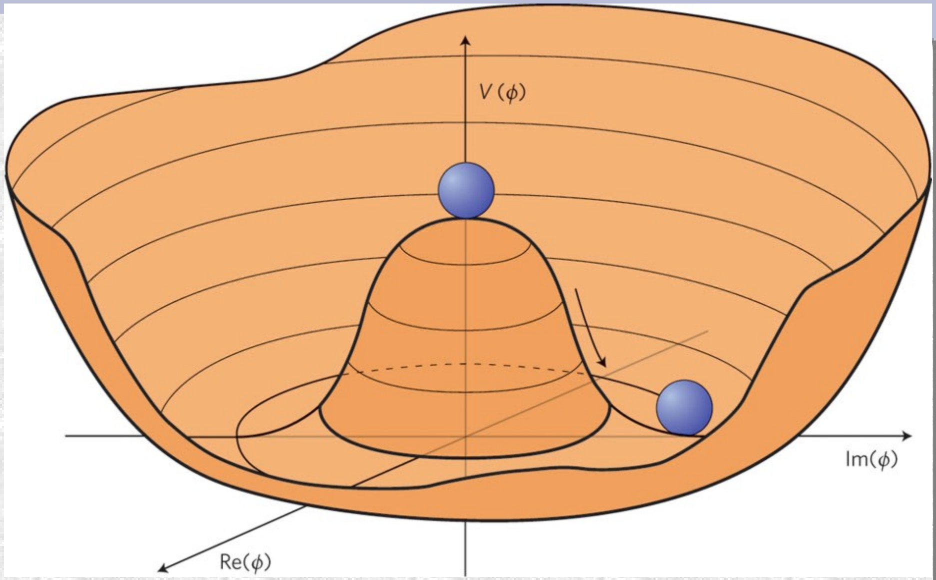
  - So in H→ZZ where does the charge go?
- It is really a 4-point coupling
  - One leg 'grounded' in the vacuum
- The ZZ decay needs vacuum help
  - Absorbing a (weak) charge!
- This is evidence the BEH field exists



The Higgs self-interaction

- The Brout-Englert-Higgs theory replaces a mass term ($m\varphi^2$) by a two-term piece ($-m\varphi^2+\varphi^4$)
- Φ is the field density
- The field-energy, or action, has a minimum away from zero
- It is this that means the Universe sits in a high Higgs density state



Measure Higgs self-interaction?

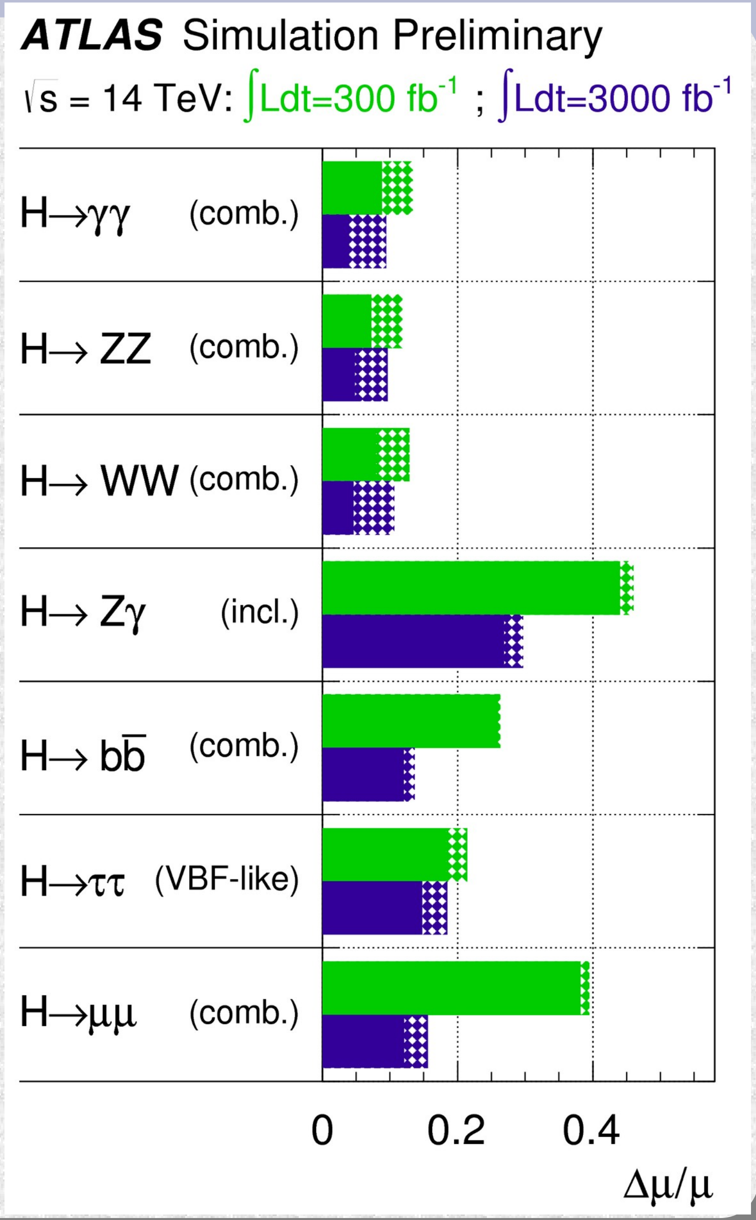
- Need to produce 2 Higgs bosons
  - The LHC is the only machine on earth with a chance
- They are much rarer than making one Higgs
  - And we still need to recognise them
- The best Higgs modes: γγ and ZZ→llll have BR of 0.002 and 0.0002 respectively
  - If we want HH→(γγ)(γγ) we can make one by 2035!!
    - Not enough to measure
  - So we need to try to use more abundant modes
  - e.g. HH→ γγbb has 300 expected events
    - Tough due to backgrounds, but maybe
- This is one of the major goals for the LHC by 2035
  - We do need to study this new aspect of the Universe

HL-LHC

- There are many physics motivations for HL-LHC
- Three seem to dominate to me
  - Extended searches for new particles to higher energies
  - Extended searches for new particles produced more rarely
  - Accurate precision measurements
    - Exemplified by Higgs couplings

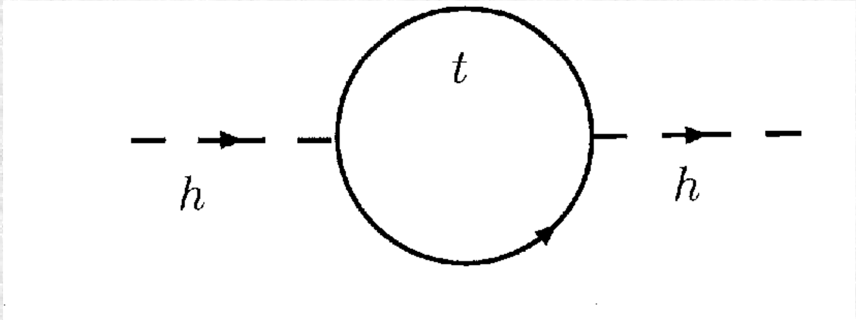
HL-LHC Higgs couplings

- The projected precision with which Higgs boson couplings can be measured by ATLAS with 300 or 3000 fb^{-1}
- The solid bars excluded theory errors – hashed included them
  - Hard to predict their size
- But 7 decays can be studied to 10-30%, and productions too
  - Sensitive to new physics



Naturalness: curse of the scalar

- Consider this diagram:
  - H→tt→H
  - Quantum effect, allowed by uncertainy



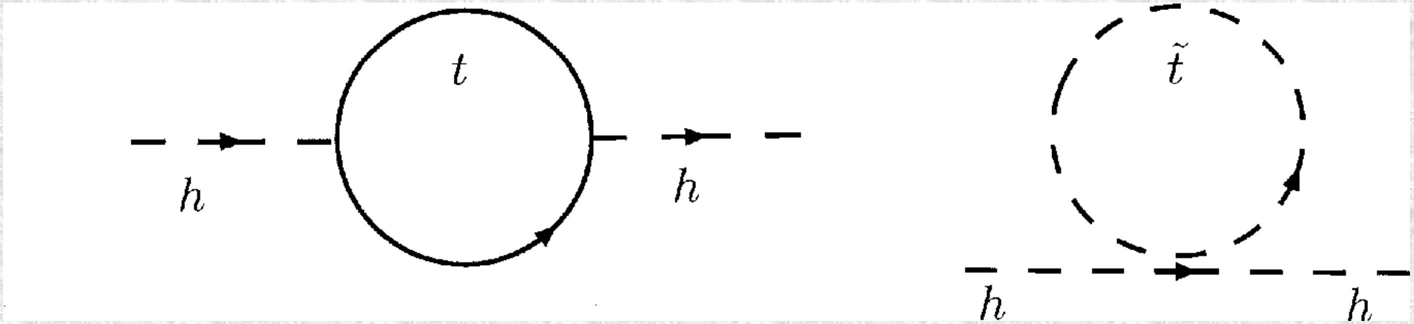
- We do not know it has happened: you only see a Higgs
  - Measuring Higgs properties averages over such diagrams.
  - e.g.The Higgs mass is corrected by $\Sigma_{diagrams}$
- But the momentum circulating in the loop is arbtirary
  - Integrate over all posible momenta
  - Need a maximum, Λ. Typical m_{planck}: once gravity matters or maths has gone wrong
- $m_{h,meas}^2 = m_{h,theory}^2 + O(mt/170\ \Lambda)^2$
- But m_{planck}~10^{18} GeV

Naturalness

- The SM is incredibly fine tuned
- We measure m_H=125.09GeV/c^2
- Did it really start as -10^{18}?
  - It would need to be 'just right'
  - The loop involves m_t and the upper scale of the theory
    - Nothing to do with m_H
  - How can they cancel so exactly?
- This comes because the Higgs is spin 0
- Other spin 0 things exist:
  - π^0
  - Cooper pair
- But they are made of smaller pieces: $q\bar{q}$, ee

Naturalness

- This *suggests* something is missing
  - and it cannot be far in mass from the top quark
- Supersymmetry makes a good example
  - It predicts a new particle cancelling the top loop (stop)
    - And a dark matter candidate



- Many other theories
  - But all need something with mass $O(m_H)$
    - Because the loop is real and happeing
- This gives a high motivation to LHC searches

What comes next?

- We have found a Higgs boson
- This confirms a 'Higgs Field' filling spac
  - Unlike light, you turn it off and it persists
  - But it is much denser than lead...
- This is not like matter, not like a force
    - Breaking Newton's 1730, description
  - It is a Higgs field, something new.
- Now we need to understand it
- LHC is working excellently
  - At 13TeV and higher collision rate
  - We will measure at least 7 decay modes
  - And perhaps di-Higgs production.
  - Great hopes of finding something else too
    - Maybe the $\gamma\gamma$ is it?

The complete theory:

- We have maths that describes particles and forces

$$\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) +$$

$$+ \frac{g}{\sqrt{2}} \sum_i (\bar{a}^i_L \gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L \gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I^3_f - 2s^2_w Q_f - I^3_f \gamma_5)\Psi_f Z_\mu +$$

$$- \frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2} |\partial_\mu W^+_\nu - \partial_\nu W^+_\mu +$$

$$- ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 +$$

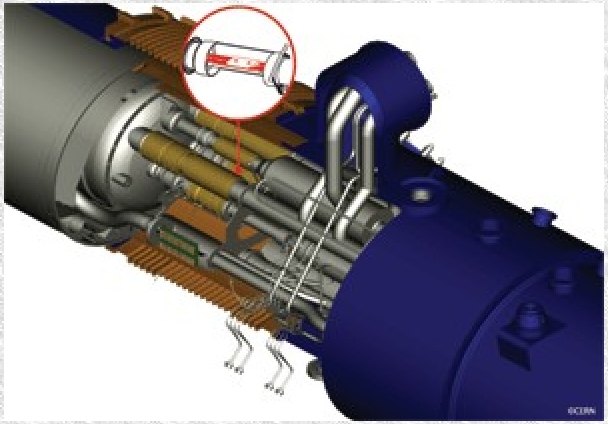
$$- \frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 +$$

$$- \frac{1}{2} M^2_\eta \eta^2 - \frac{g M^2_\eta}{8 M_W} \eta^3 - \frac{g'^2 M^2_\eta}{32 M_W} \eta^4 + |M_W W^+_\mu + \frac{g}{2} \eta W^+_\mu|^2 +$$

$$+ \frac{1}{2} |\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta$$

- But we cannot discuss that here

The 'incident'



- Interconnect between two dipoles had resistive joint
  - Tens of nΩ?
- At 9KA, I^2R gives watts of heat
  - Wire went normal conducting..and vaporized
- Punched hole from helium vessel to insulation vacuum, then to beam pipes
  - Helium poured down the beam tubes
  - Vacuum seals every 200m tried to block it
  - 3 were forced open..pushed with their quadrupoles
- Took a year to clean, fix and install new safety systems

Danger of Stored Power

The beam power is 350MJ

This British aircraft-carrier at 12 knots

Steered through a very small hole

Danger of Stored Power

The beam power is 350MJ

This British aircraft-carrier at 12 knots

Steered through a very small hole

The magnetic energy in the fields is 11000MJ

Danger of Stored Power

The bea
This Brit
knots
Steered
hole

The mag
fields i

This American aircraft carrier at 32 knots