The Higgs boson: A personal view

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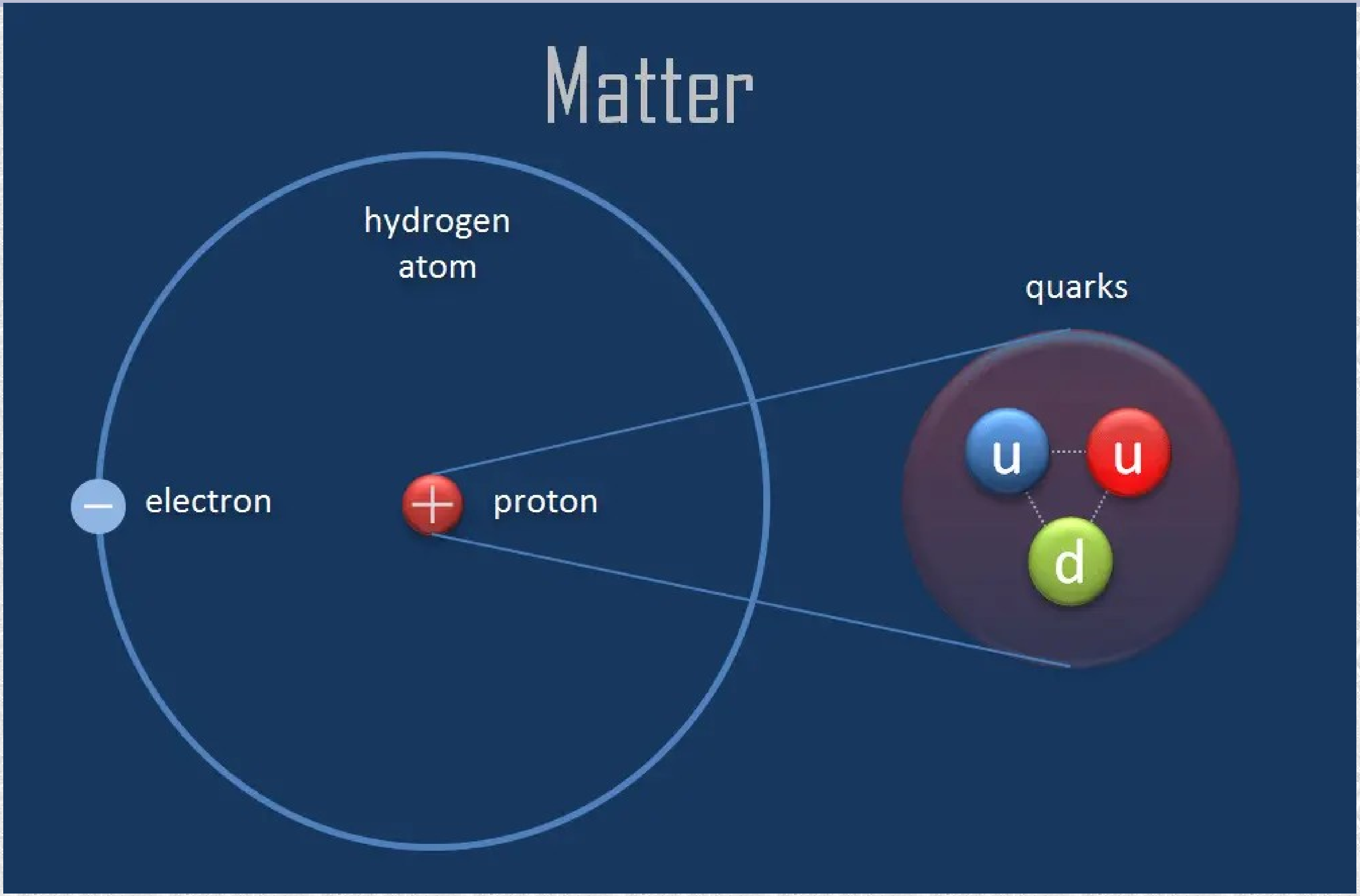
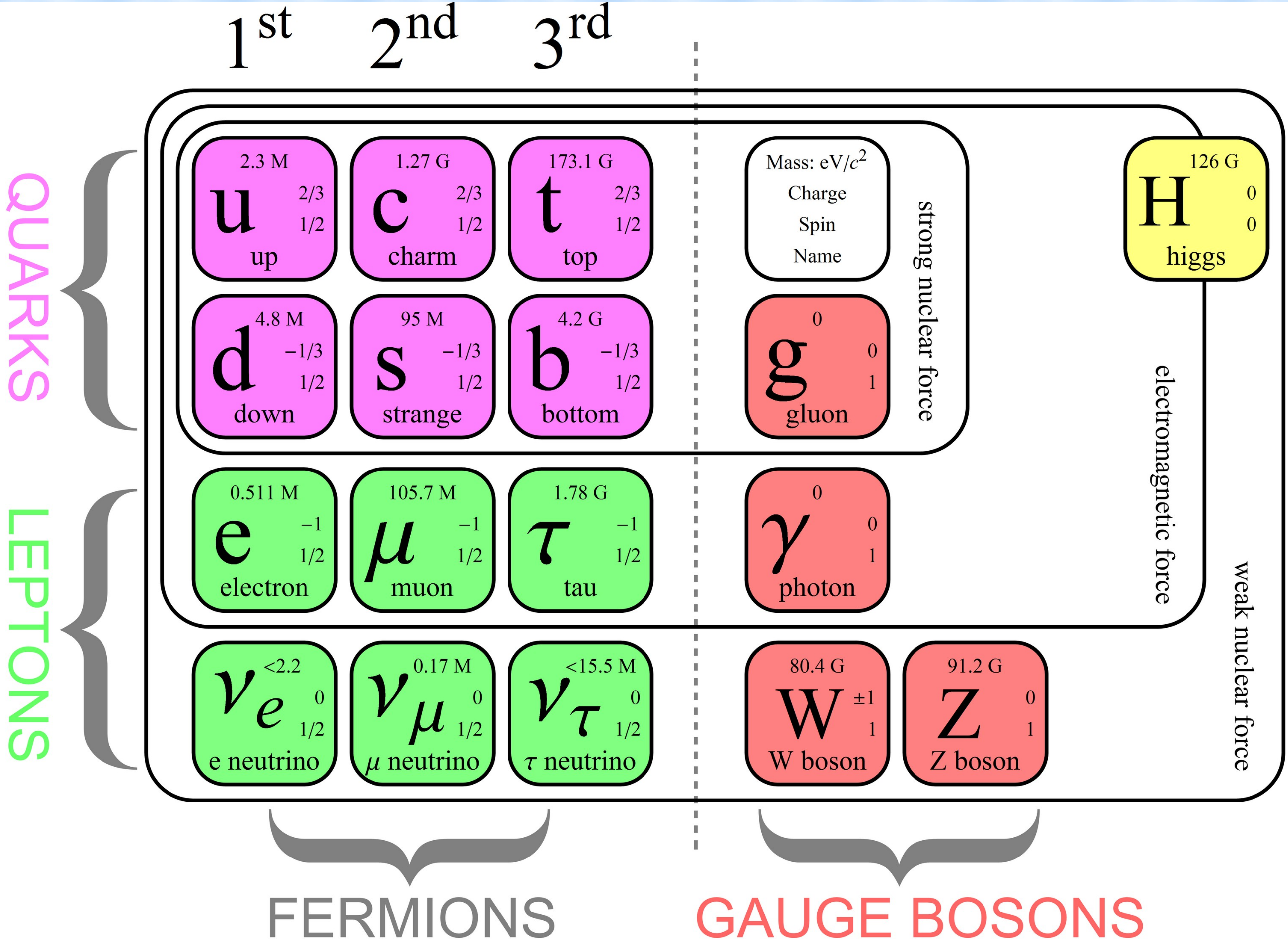
How did we find the Higgs?
What do we know of it?
What does it mean?

Particle physics: small science



- I hope this slide is familiar?


1st 2nd 3rd
QUARKS
LEPTONS
2.3 M u 2/3 1/2 up
1.27 G c 2/3 1/2 charm
173.1 G t 2/3 1/2 top
4.8 M d −1/3 1/2 down
95 M s −1/3 1/2 strange
4.2 G b −1/3 1/2 bottom
0.511 M e −1 1/2 electron
105.7 M μ −1 1/2 muon
1.78 G τ −1 1/2 tau
<2.2 νe 0 1/2 e neutrino
0.17 M νμ 0 1/2 μ neutrino
<15.5 M ντ 0 1/2 τ neutrino
Mass: eV/c2
Charge
Spin
Name
0 g 0 1 gluon
0 γ 0 1 photon
80.4 G W ±1 1 W boson
91.2 G Z 0 1 Z boson
126 G H 0 0 higgs
strong nuclear force
electromagnetic force
weak nuclear force
FERMIONS
GAUGE BOSONS

Some open questions

- Matter-antimatter asymmetry
  - Where did the antimatter go after the big bang?
- Gravity
  - There is no gravity in the Standard Model
- Neutrino Mass
  - Neutrinos have mass – but how? We do not know
- Dark matter
  - Most matter in the Universe is something unknown
- Dark energy
  - An unknown force accelerates the Universe expansion
- Mass
  - Why do particle have the masses they do?

Mass: Higgs idea

- Back in 1960’s maths said fundamental particles should be massless
  - True for the photon and the gluon
  - But W/Z bosons (forces) are massive ‘Gauge Bosons’
  - So are the quarks and leptons (matter)
- But it is not easy to add mass
  - It violates 'gauge symmetry'
  - That’s a 4th year undergraduate course
- In 1964 Peter Higgs, (who died last year), had an idea.....

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W

1964

- Peter Higgs wrote
  - "Broken Symmetries and the masses of Gauge bosons"
- Theory said the W/Z bosons should be massless
- They were not even discovered – but that proved them heavy
- So he gave a mechanism to allow it

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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1964

- Just two pages

massive vector bosons. There are two $I=\frac{1}{2}$ vector doublets, degenerate in mass between $Y=\pm 1$ but with an electromagnetic mass splitting between $I_3=\pm\frac{1}{2}$, and the $I_3=\pm 1$ 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]

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[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 $Y=\pm 1$, $I=\frac{1}{2}$ 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).

[9] In the theory of superconductivity the scalar fields are associated with fermion pairs; the doubly charged excitation responsible for the quantization of magnetic flux is then the surviving member of a U(1) doublet.

SPLITTING OF THE 70-PLET OF SU(6)

Mirza A. Baqi Bég
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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.

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W.

1964

- Just two pages
- Peter admits his theory ignores quantum mechanics
  - But its OK; Brout and Englert have the QM version

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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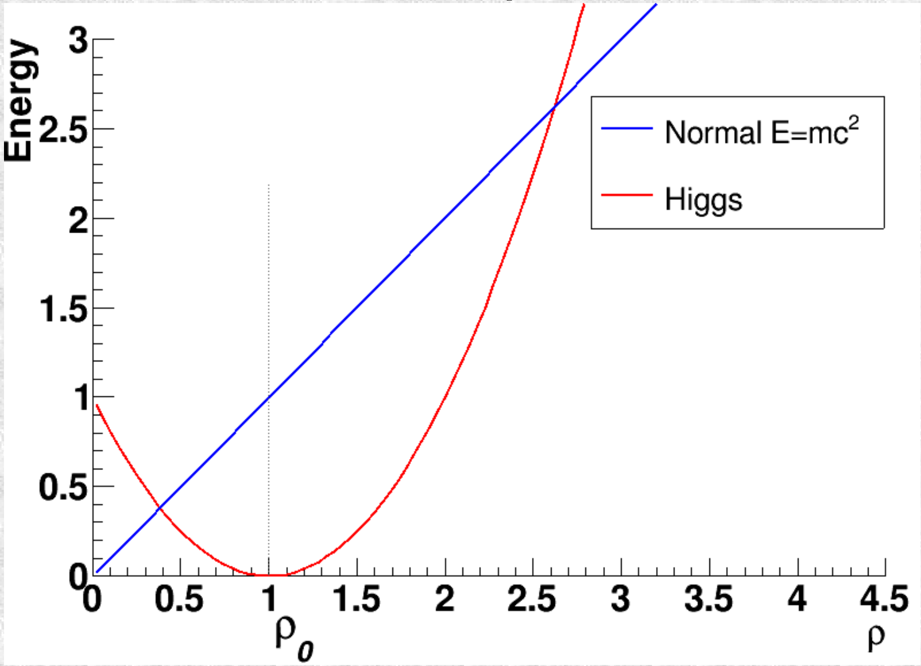
What does Higgs actually say?

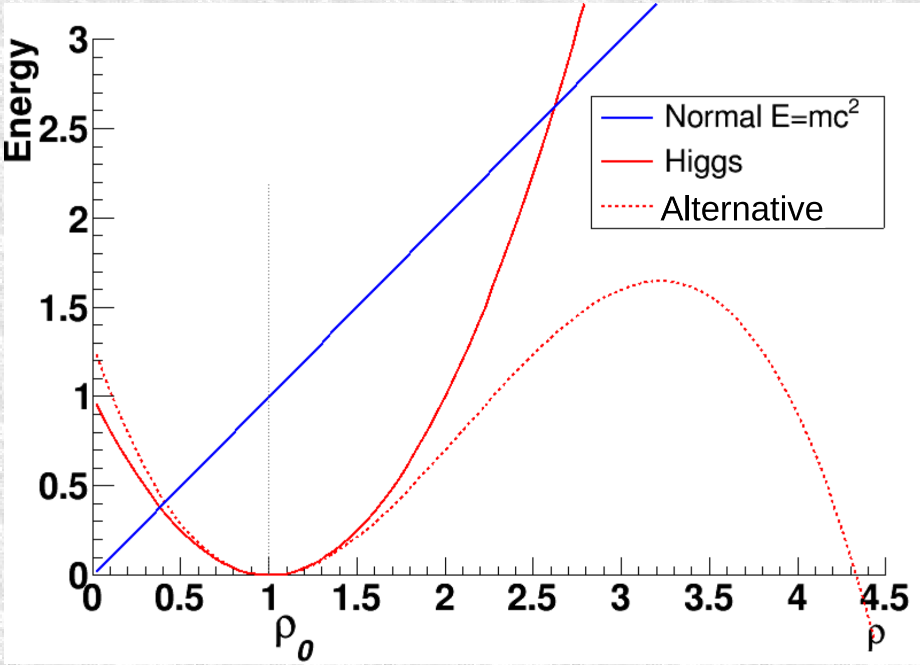
- That 1964 paper proposed a new field φ with a potential V(φ²)
  - φ is the QM amplitude of the Higgs field
- The density, ρ, of the field is φ² so V(φ²)=V(ρ)
- The paper supposes a ρ_0 where $\frac{dV(\rho_0)}{d\rho}=0, \frac{d^2V(\rho_0)}{d^2\rho}>0$

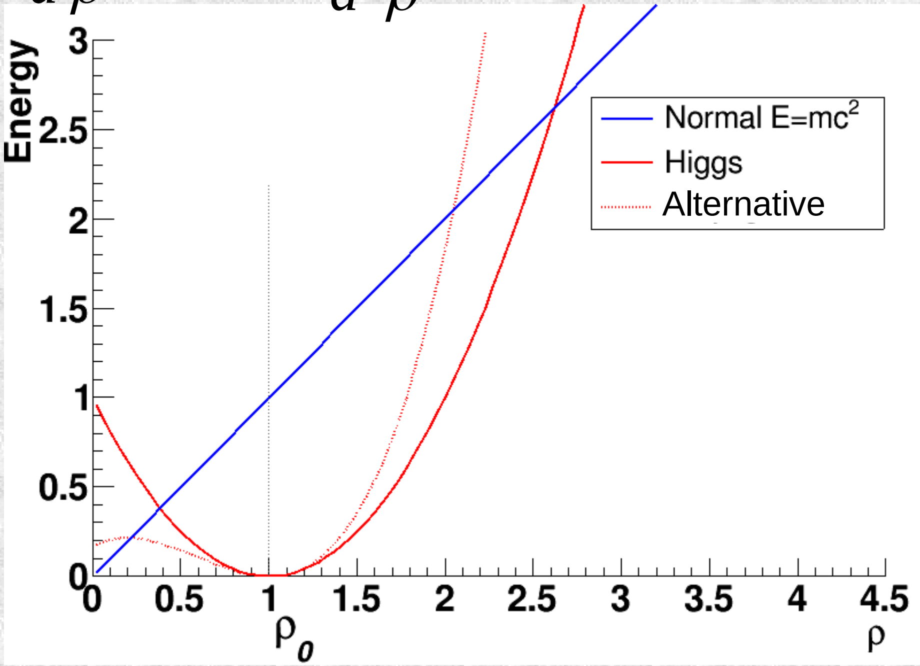
  and writes "then spontaneous breaking of symmetry occurs"
- Nowadays we write:
  - $V=-a_1\varphi^2+a_2\varphi^4$
  - and measure a_1 and a_2
- Compare with Einstein
  - Weird!



But are there alternatives?

- The SM uses $V=-a_1\varphi^2+a_2\varphi^4$
- But we could have $V=-b_1\varphi^2+b_2\varphi^4-b_3\varphi^6$ (left)
  - Chose b's so it looks similar near $\rho=\varphi^2=1$, but bends down
- Or $V=+c_1\varphi^2-c_2\varphi^4+c_3\varphi^6$ (right)
  - Again similar but with a little dip near zero
- Either of these meet Peter's $\frac{dV(\rho_0)}{d\rho}=0, \frac{d^2V(\rho_0)}{d^2\rho}>0$





Enough equations: analogy

- Think of a fish tank:

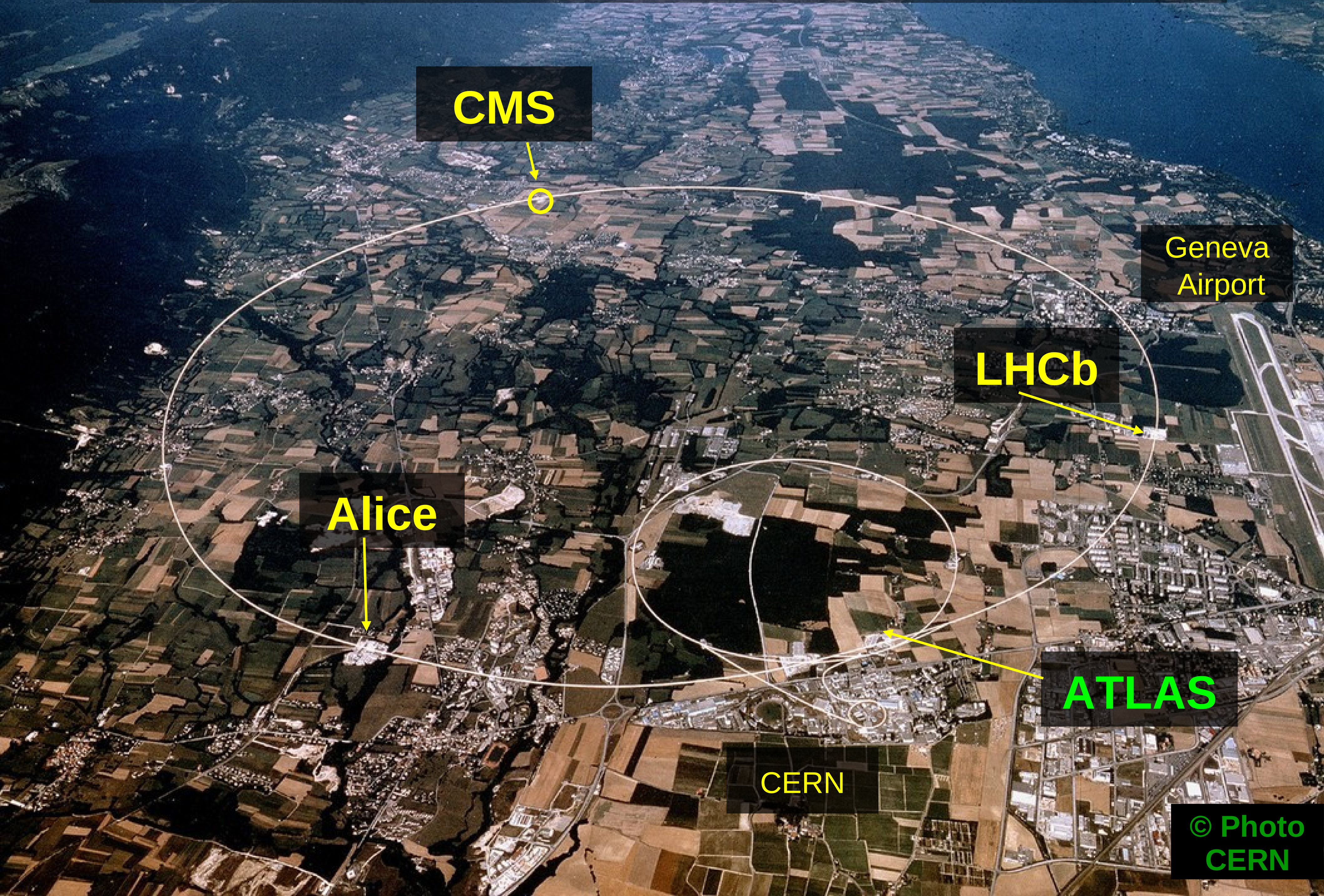
Empty the tank

- The fish will call this an empty tank
- but it still has water in it

Higgs theory

- In a way the same applies to us?
- Empty space is actually full of stuff – the Higgs field
  - Everywhere, all the time
    - It slows you down moving through it
    - And we feel that drag as mass
  - If we could get outside then we would be massless
    - But we cannot.
- How do we know if its true?
  - If we kick the 'water' (or Higgs field) we should make it ripple
  - The ripple is called the Higgs boson
- But how do we kick the Higgs field?
  - Build the LHC!

A huge accelerator: CERN's LHC

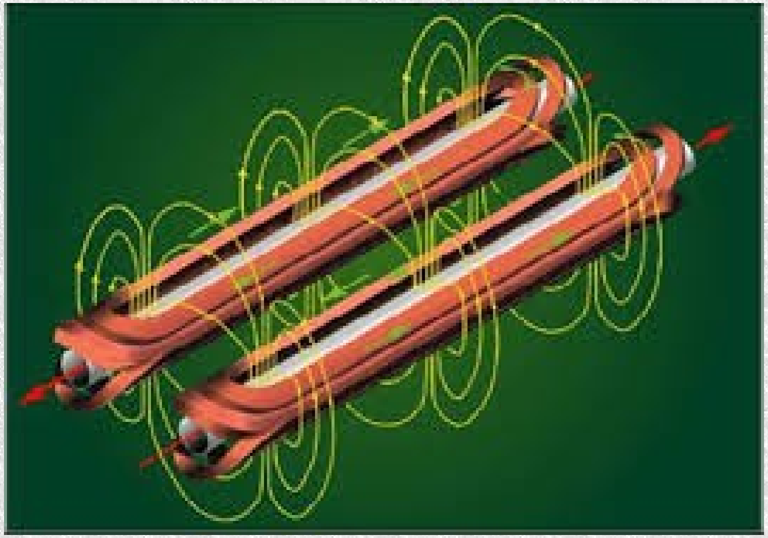


LHC operation

- LHC accelerates protons to 6.8 TeV (6800 GeV)
  - Tevatron (previous accelerator) got to 1000 GeV
  - 1eV is the energy an electron gets from a 1V battery
  - 1 GeV is the energy required to make a proton ($E=mc^2$)
  - Speed is 0.99999998c
- They circle the 27km tunnel 11,000 times / second
- The pass the accelerating cavities a million time in only 100 seconds
  - Increasing their energy is not really the problem
- Making the bending them is the tough job
  - Consider the lateral acceleration…. 10^{17}G
  - 8.3Tesla magnets

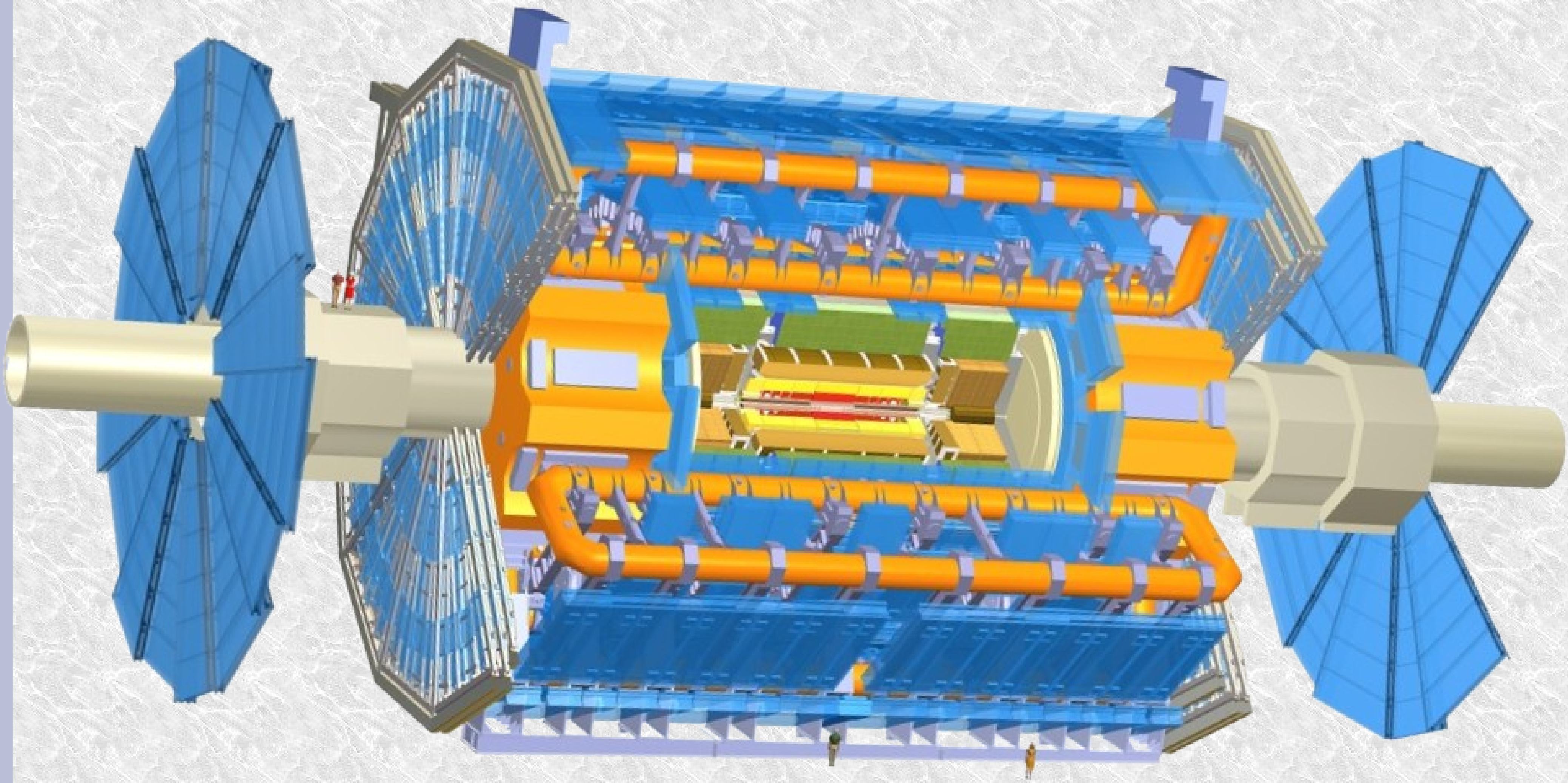
LHC magnets

- 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
- I^2R loses mandate superconductor
- Each magnet 15m long
  - 1232 of them in tunnel

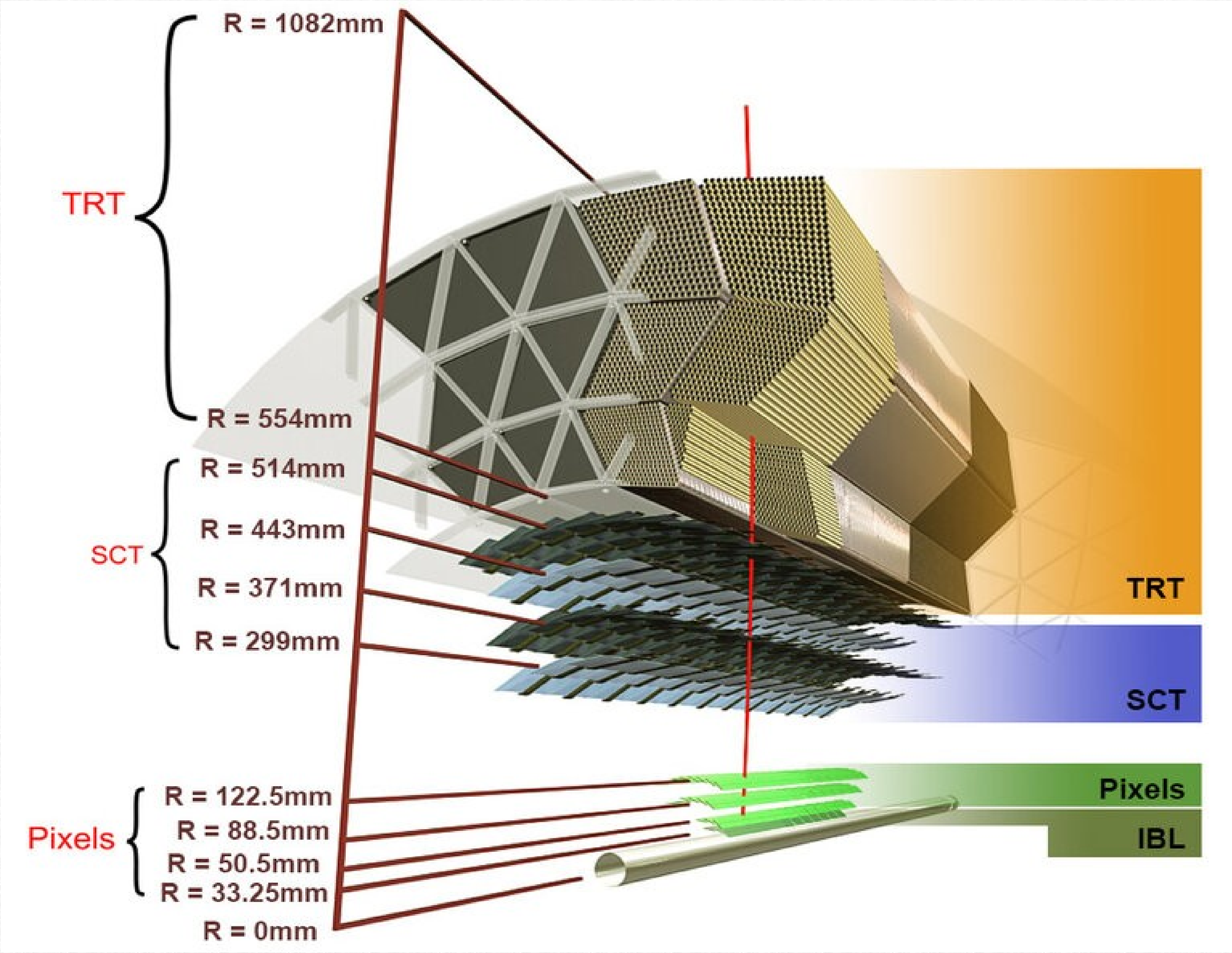


ATLAS detector

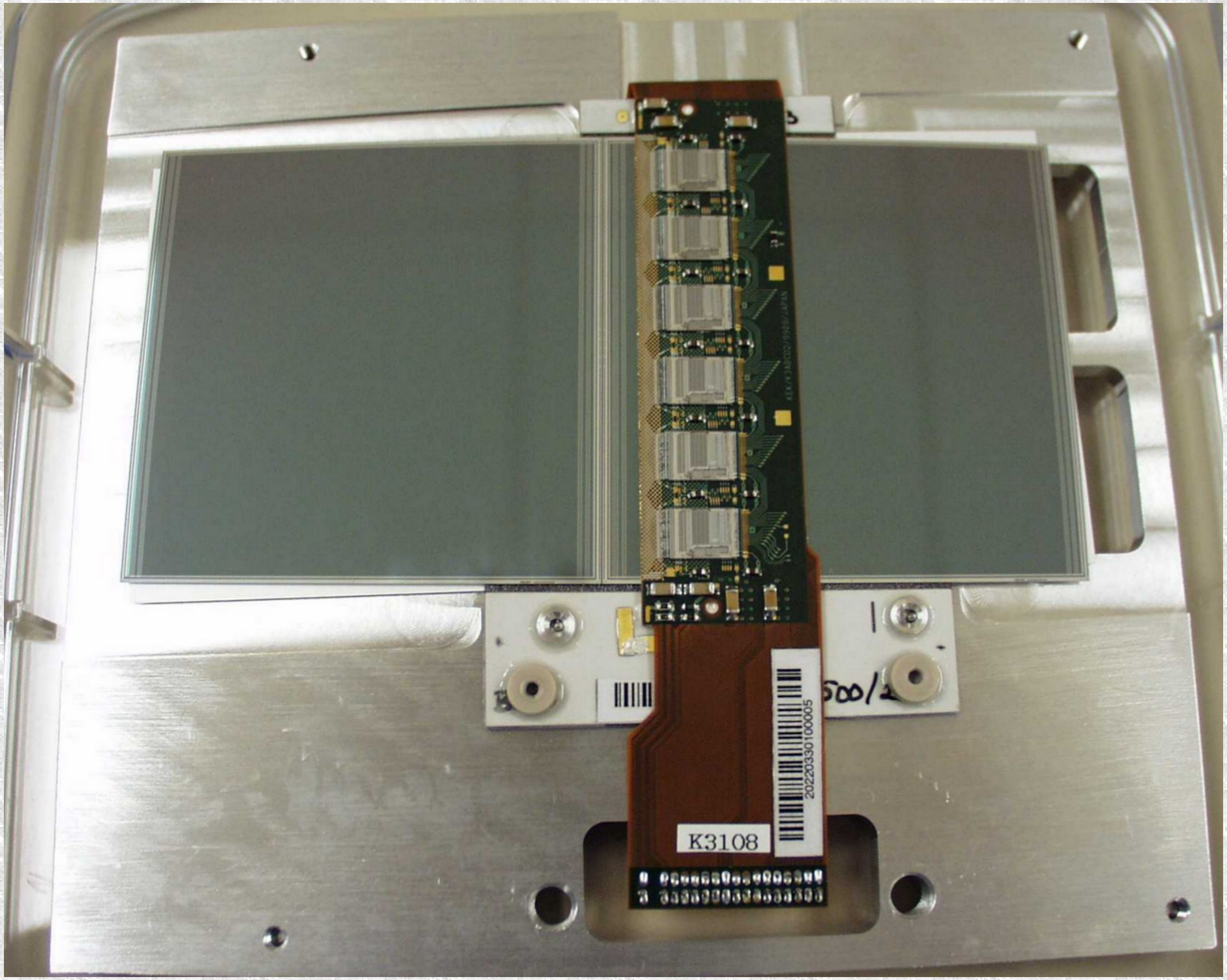
ATLAS cut-away



ATLAS current tracker

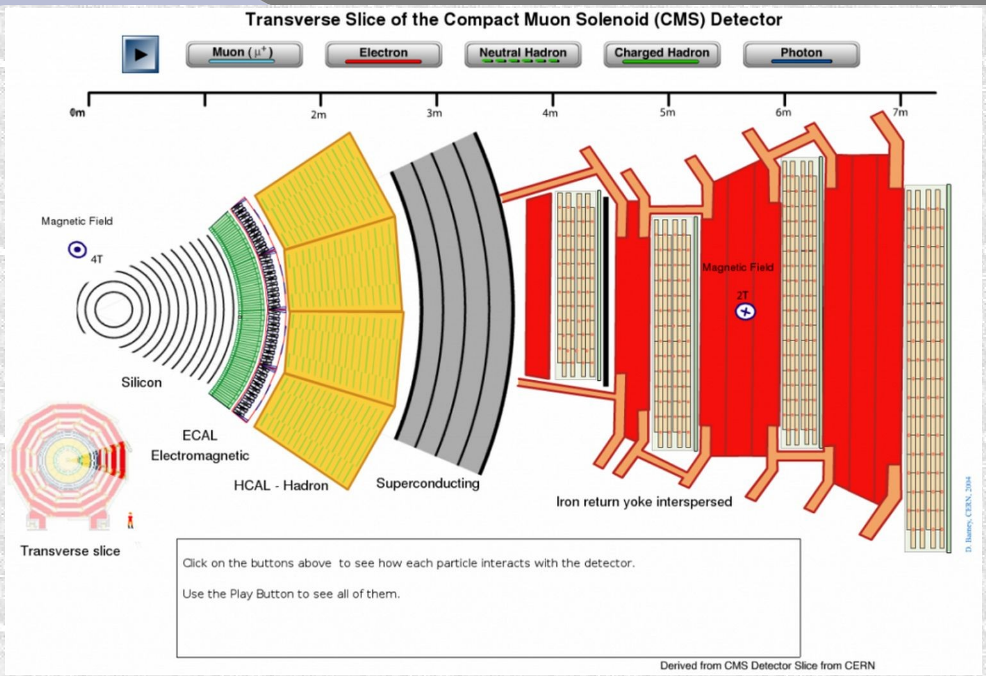


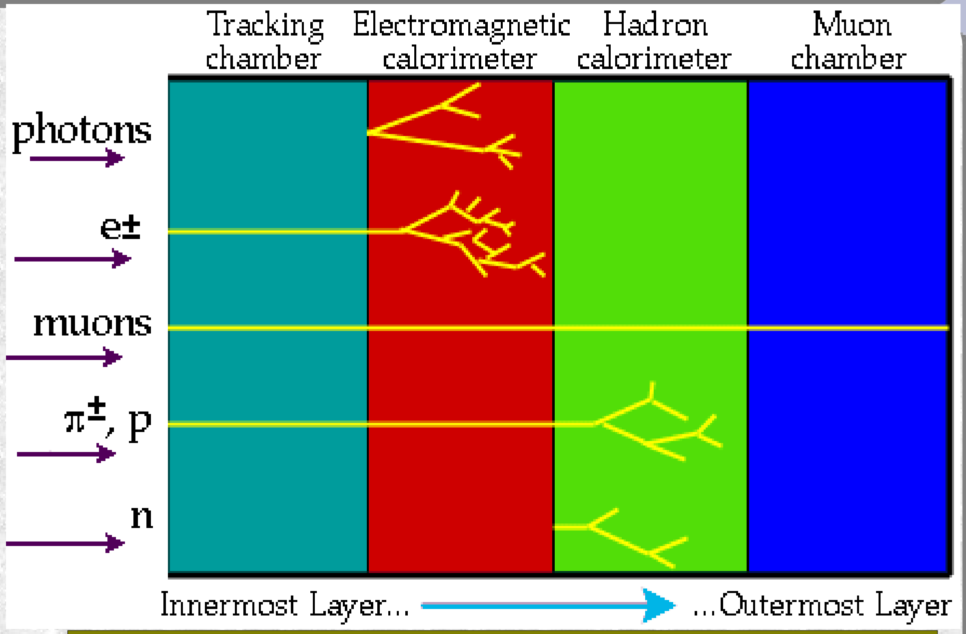
A RAL built silicon detector



- 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



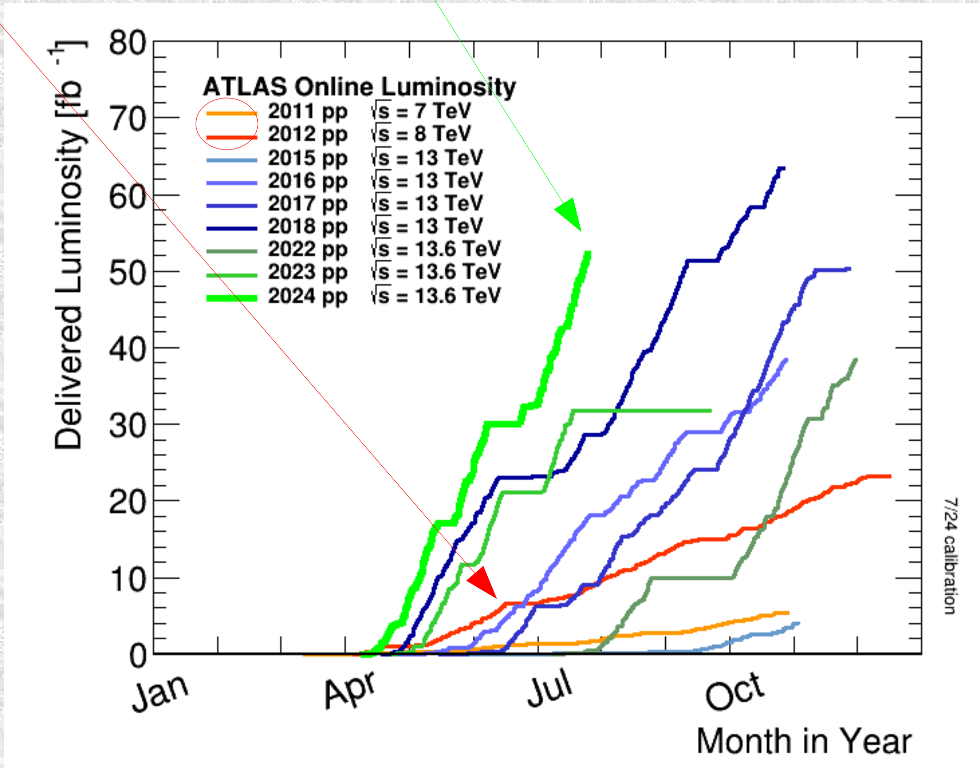


Look at me! I'm a neutrino

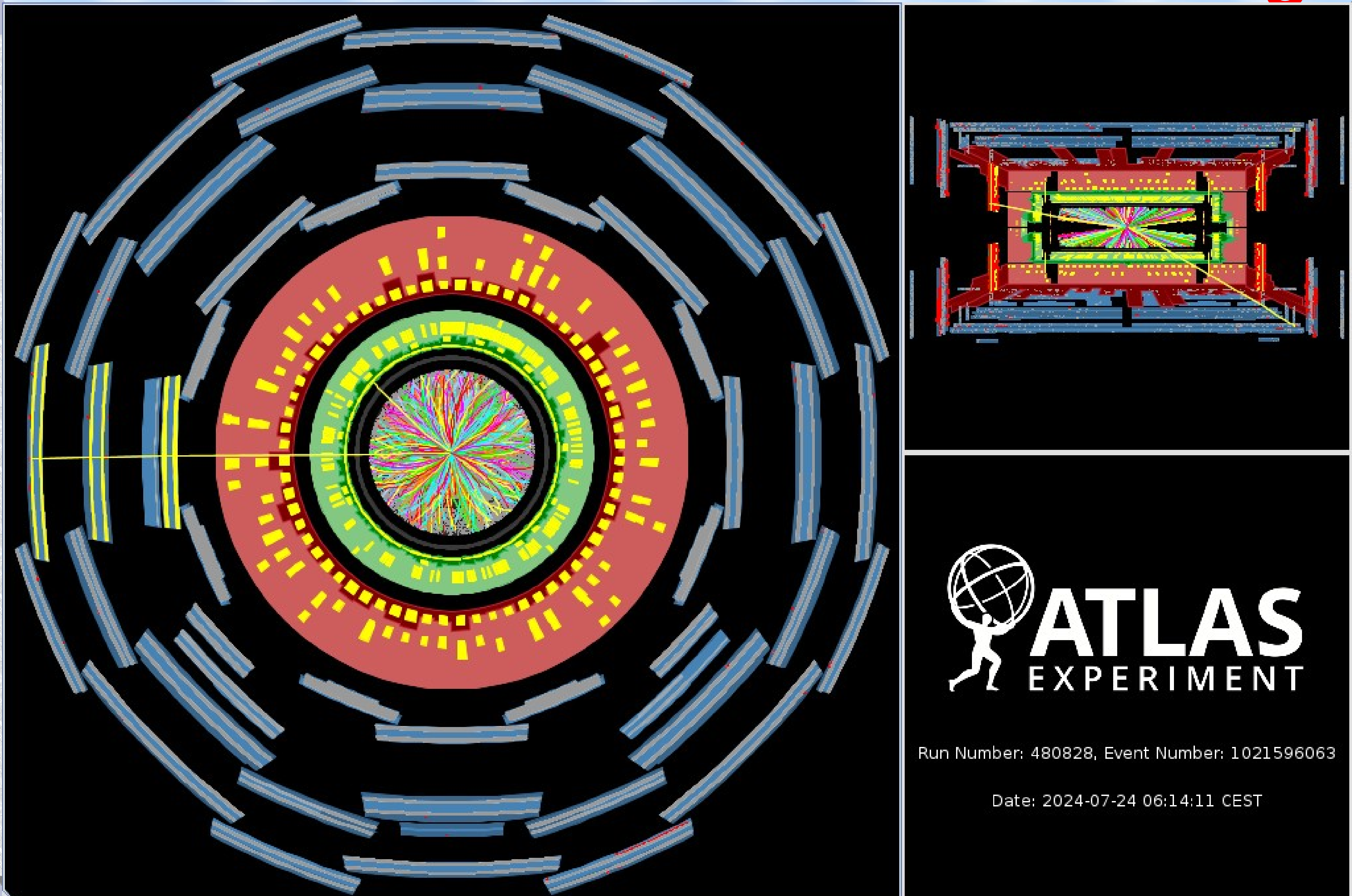
- Reconstruct long-lived particles in the detector
  - Basically only a few types: photons(γ), e^-, μ^-, p^+, π^+, n, ν
  - Can identify type by interaction pattern in the detector
  - Measure the momentum by bending them in a magnetic field
- Electrons, muons and photons especially useful
  - There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

LHC status

- LHC started back in 2010
- But the energy and collision rate keep increasing
- Higgs discovery mid 2012
- Run 3 is 2022-2025
  - 2024 is giving us a record-breaking dataset
    - Best delivery for July
    - and at 13.6 TeV
      - highest ever energy
- We are getting a huge dataset
  - 30B W bosons
  - 10B Z bosons
  - 250M $t\bar{t}$
  - 100M Higgs
- Enabling 1300 papers so far
  - From my expt ‘ATLAS’
- On many subjects

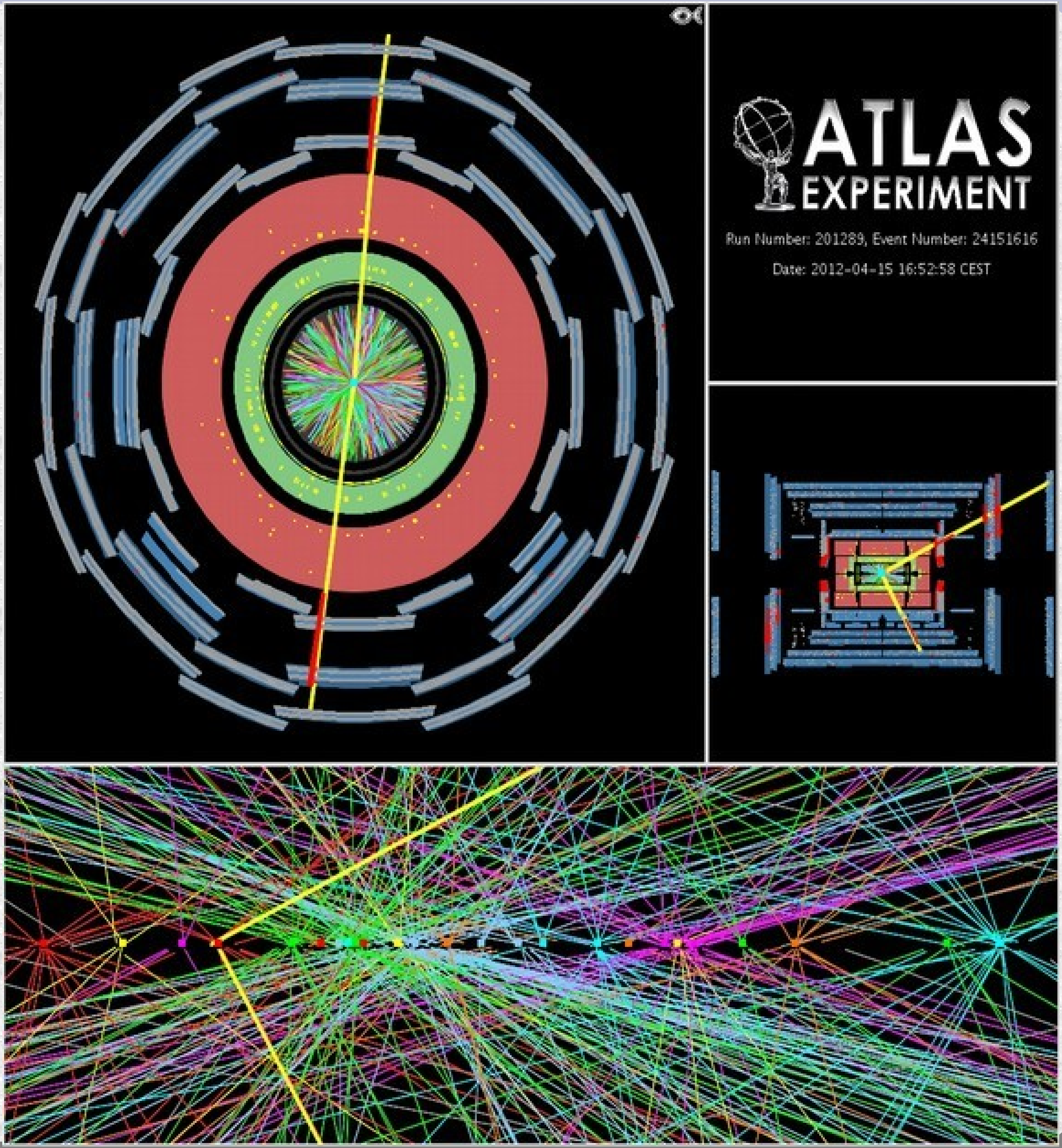


An ‘event’ recorded this morning

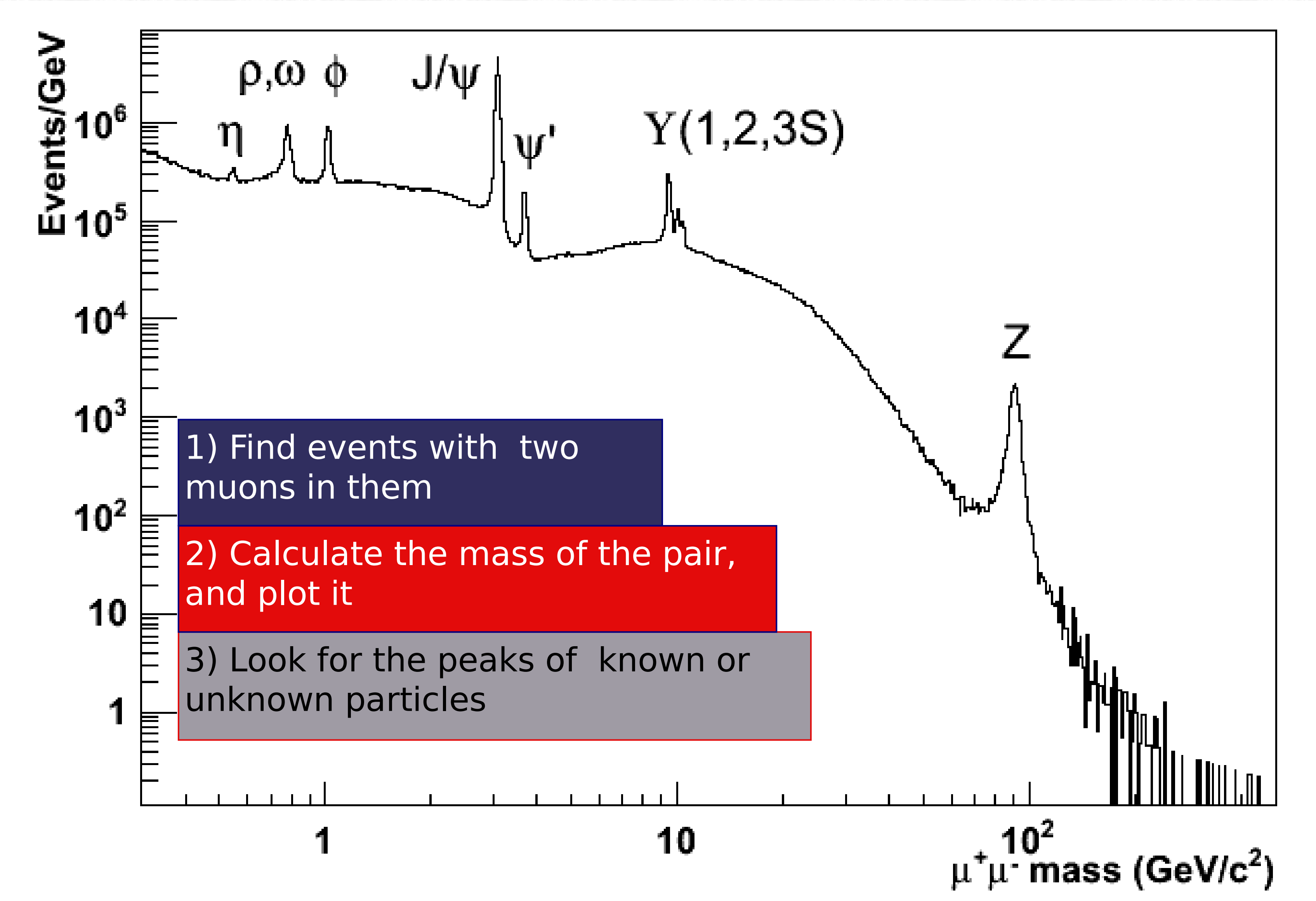


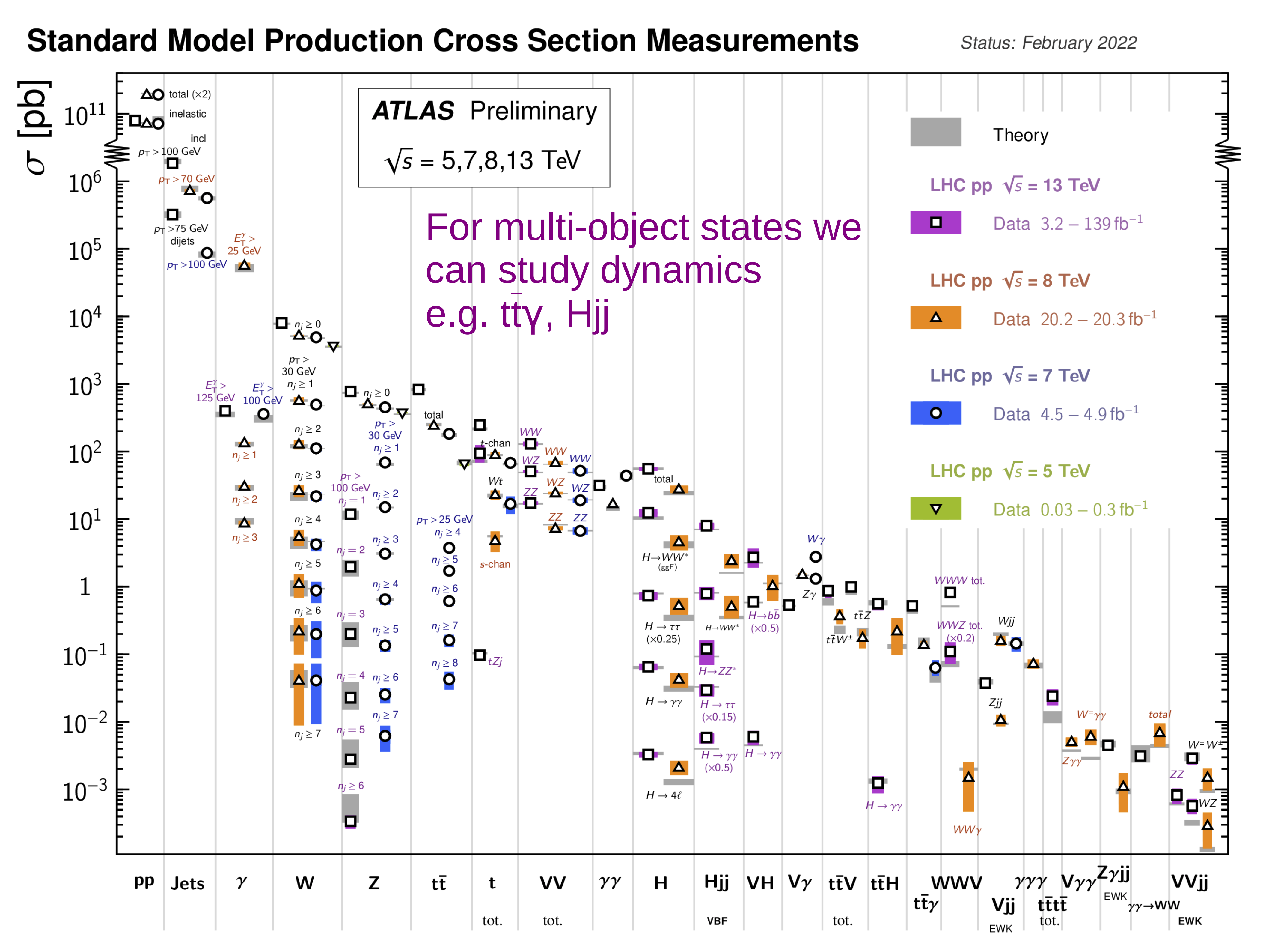
Here is an event with 2 muons

- Most particles are stopped at the green calorimeter
- Muons get right to the outside
  - Two are seen here
  - They are heavy copies of electrons
- They both come from the same collision
  - Are they connected?



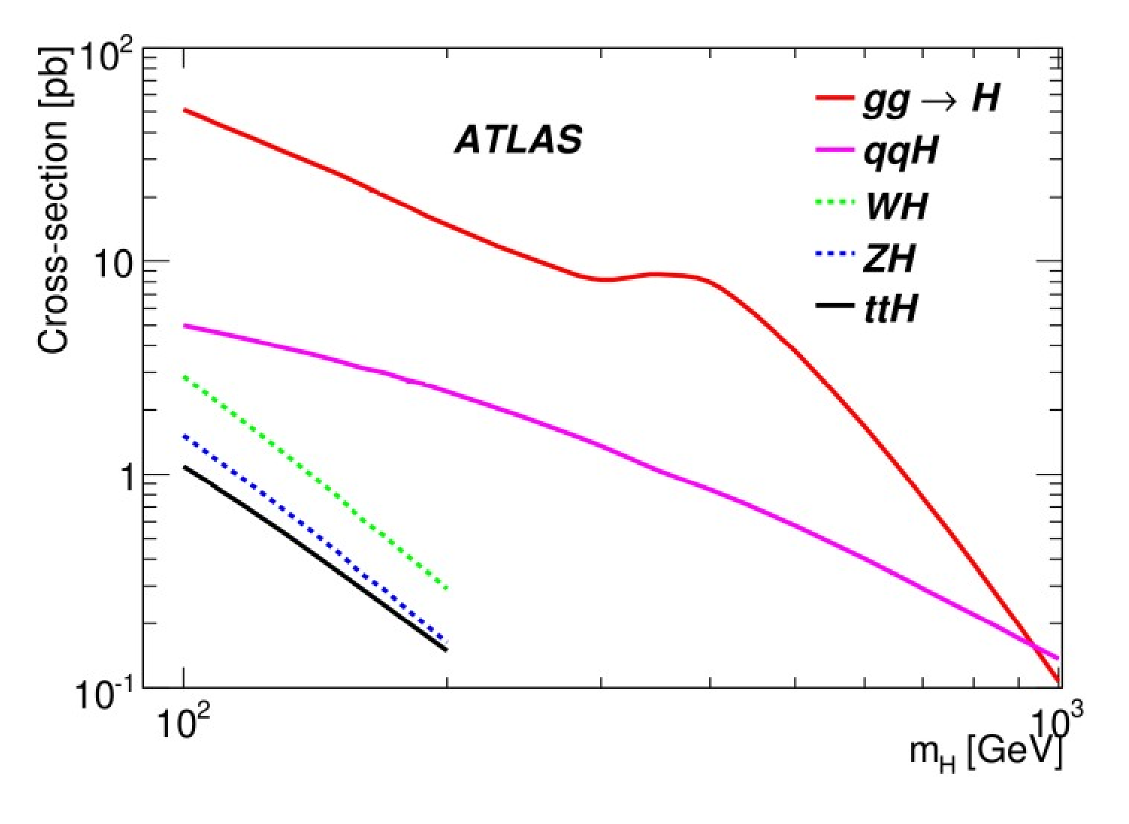
Hunting for mass bumps

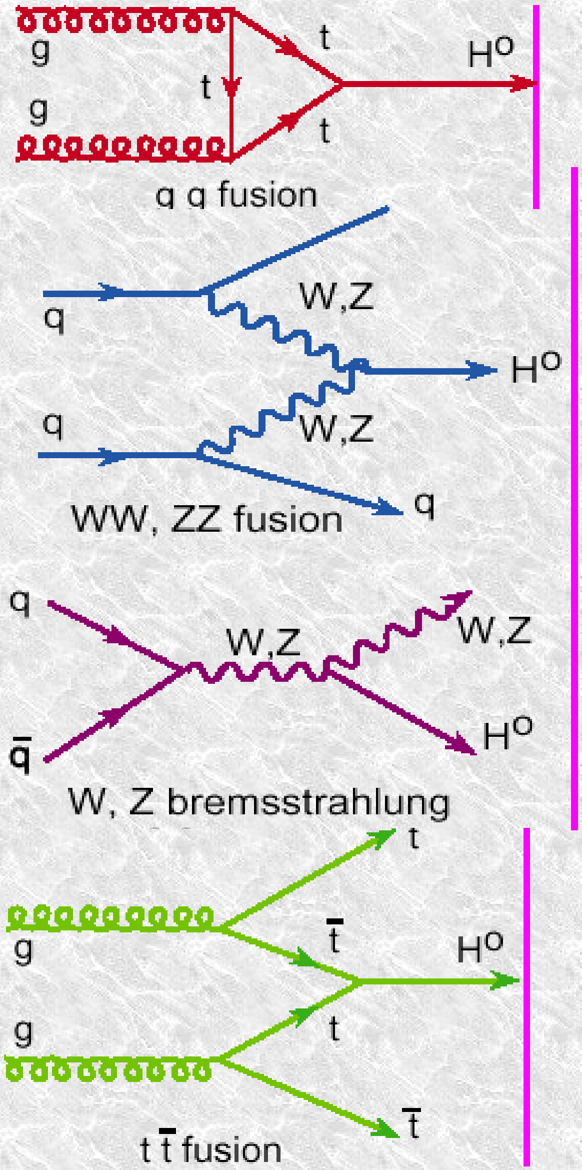



Standard Model Production Cross Section Measurements
Status: February 2022
ATLAS Preliminary
√s = 5,7,8,13 TeV
For multi-object states we can study dynamics
e.g. tt̄γ, Hjj
σ [pb]
Theory
LHC pp √s = 13 TeV
Data 3.2 – 139 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 5 TeV
Data 0.03 – 0.3 fb⁻¹
pp
Jets
γ
W
Z
tt̄
t
tot.
VV
tot.
γγ
H
Hjj
VBF
VH
Vγ
tt̄V
tot.
tt̄H
tt̄γ
WWV
Vjj
EWK
γγγ
tt̄tt̄
tot.
Vγγ
Zγjj
EWK
γγ→WW
VVjj
EWK
total (×2)
inelastic
incl
total
t-chan
s-chan
Wt
tZj
H→WW*
H → ττ
(×0.25)
H → γγ
H → 4ℓ
H→ZZ*
H→bb̄
(×0.5)
Wγ
Zγ
tt̄Z
tt̄W±
WWW tot.
WWZ tot.
(×0.2)
WWγ
Wjj
Zjj
W±γγ
Zγγ
W±W±
ZZ
WZ

How can LHC make a Higgs?

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

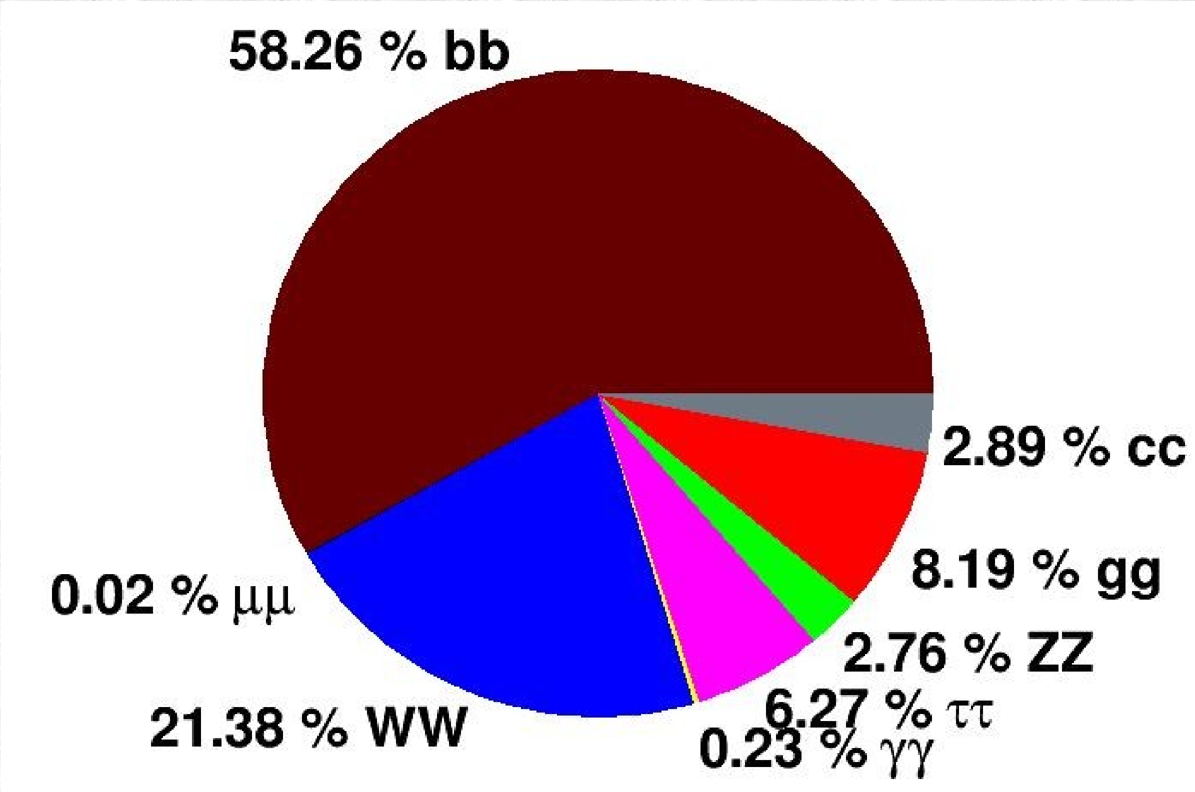




What does a Higgs do? It decays!

- Couples to mass so decays mostly to heaviest thing it can make a pair of
- But other decays are also possible

Higgs BRs



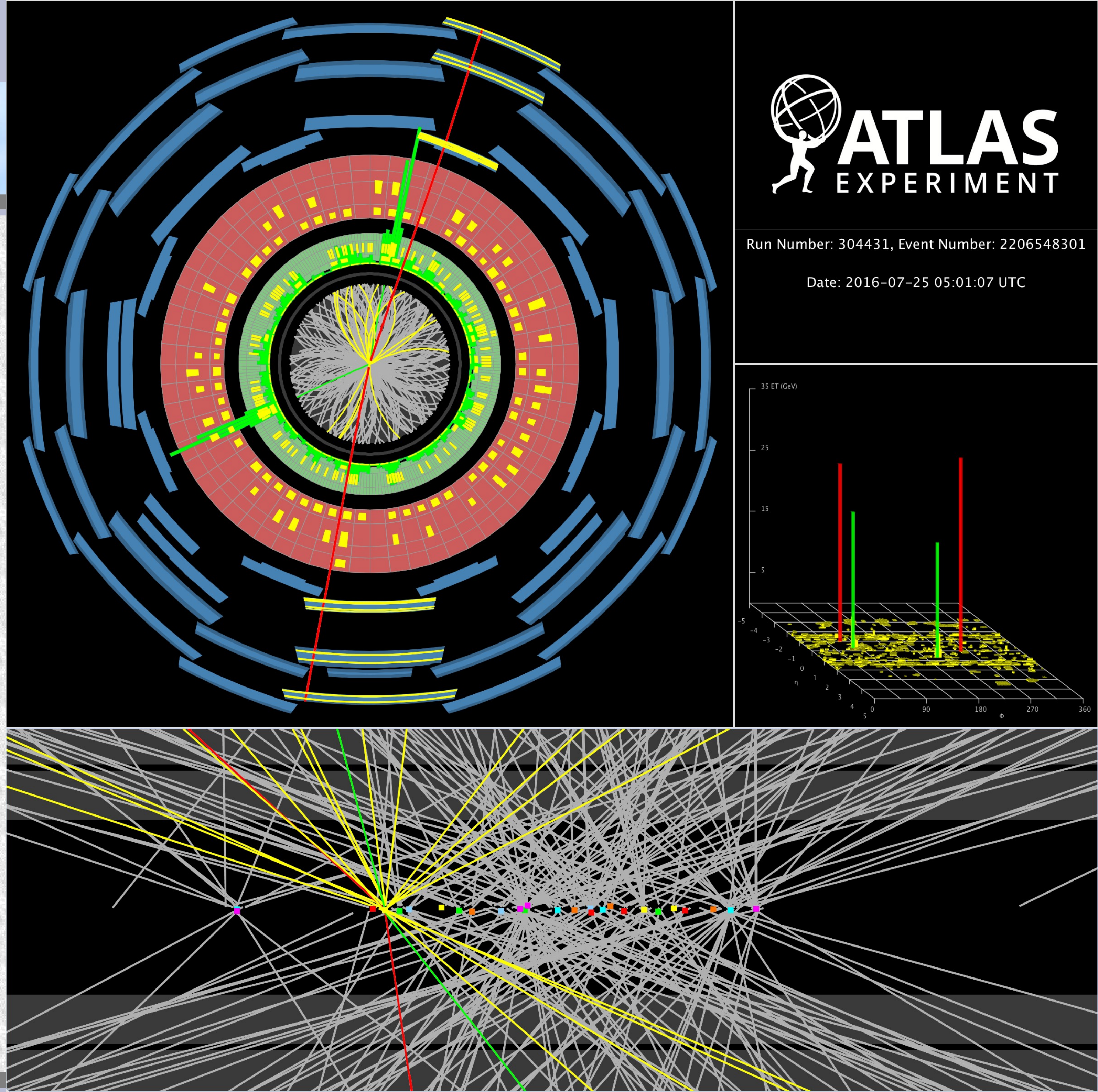
- They each have different challenges to observe

So...the hunt was on….

- By 2012 LHC had collided some 10^{15} pp pairs
  - that's a lot of haystacks to search through
- But $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow llll$ give distinctive signatures and sharp mass peaks
  - Focus on those rare (0.2% & 0.02%) decay modes
- On Friday 29th of June 2012 ~10 of us met
  - ATLAS and CMS both had 5σ peaks at 125 GeV
  - Interesting, we thought. More data needed we said.
  - We had a nervous weekend.
    - Fabiola Gianotti, ATLAS spokesperson, had emergency dental surgery on Sunday morning
- A seminar had been arranged: Wed., 4th of July
  - What to say?

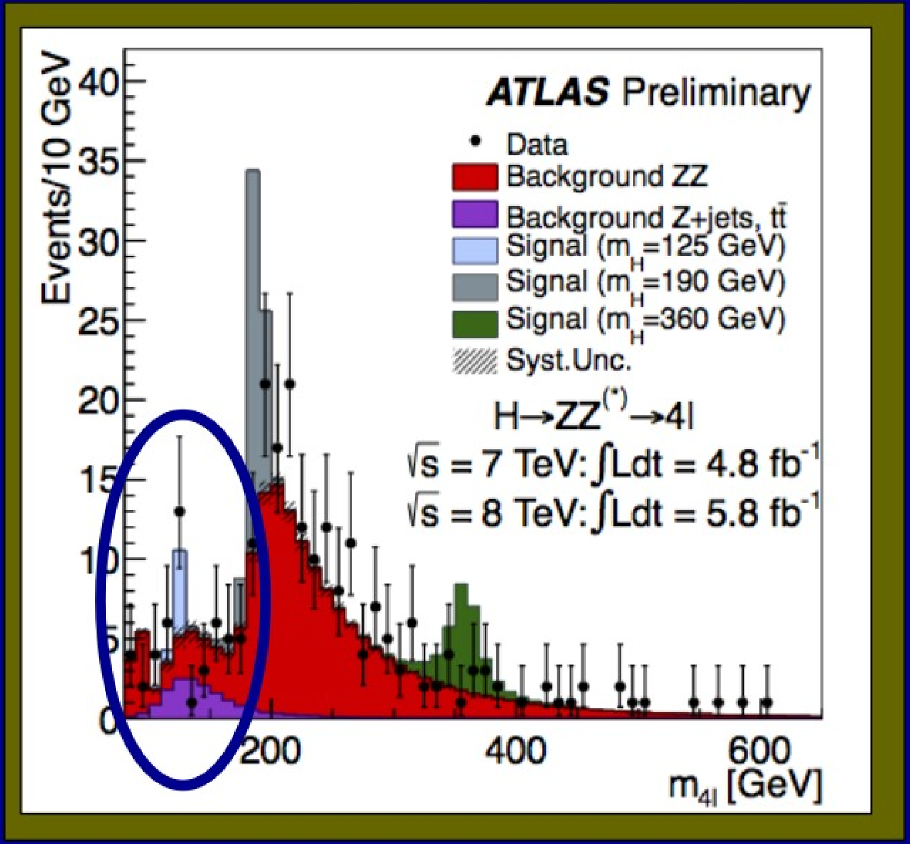
Science and Technology Facilities Council

H→ZZ →llll



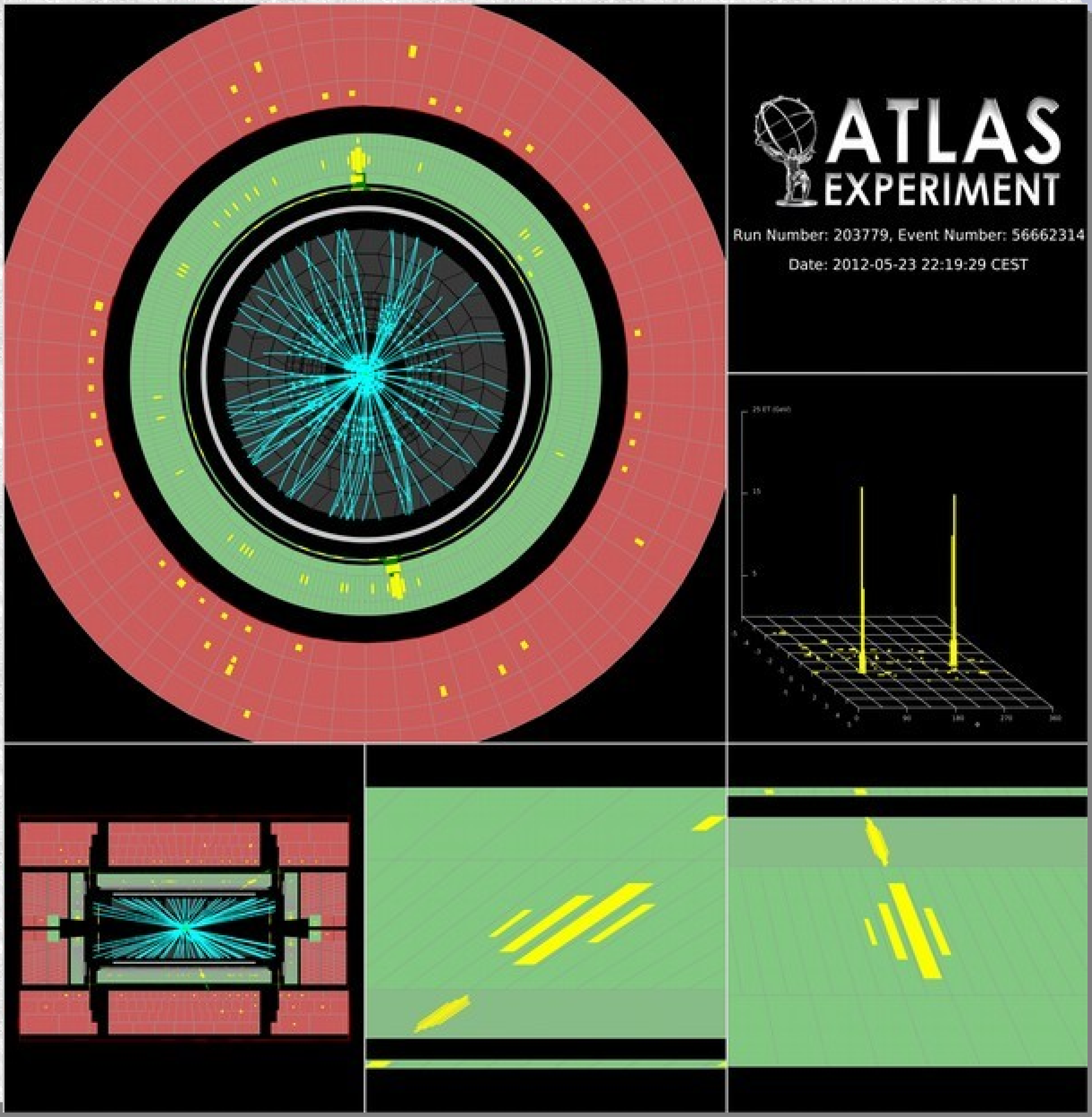
H to ZZ: Fabiola's 2012 slide

H→ 4l mass spectrum after all selections: 2011+2012 data

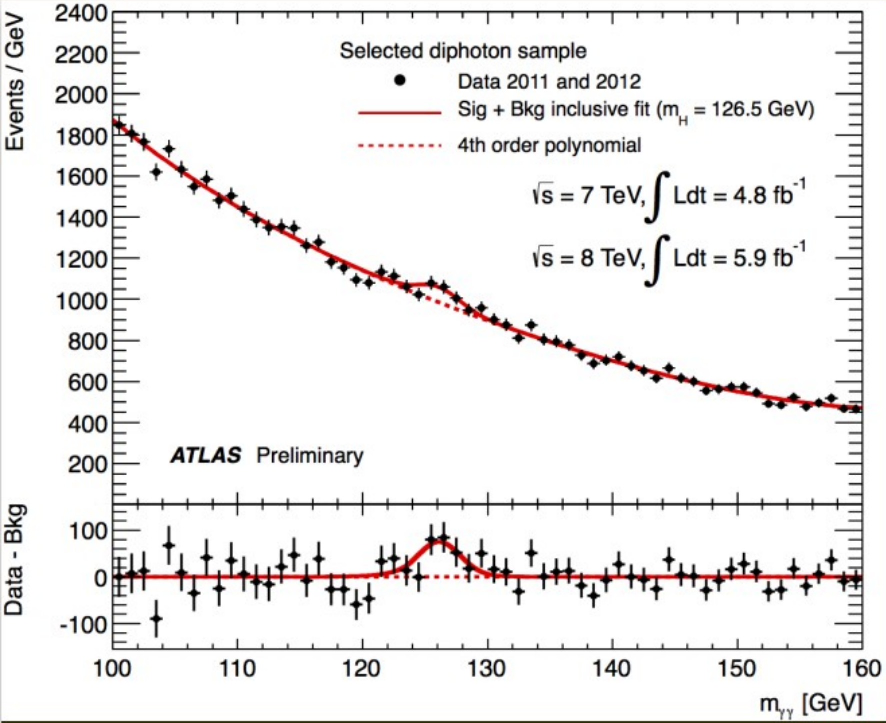


H→γ γ

- Not a common decay
  - But 10x ZZ
  - 2 per 1000 Higgs
  - Measure photon energy/direction
    - Extract γγ 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 to γγ: Fabiola's 2012 slide:



Total after selections: 59059 events

$m_{\gamma\gamma}$ spectrum fit, <u>for each category</u>, with Crystal Ball + Gaussian for signal plus background model optimised (with MC) to minimize biases

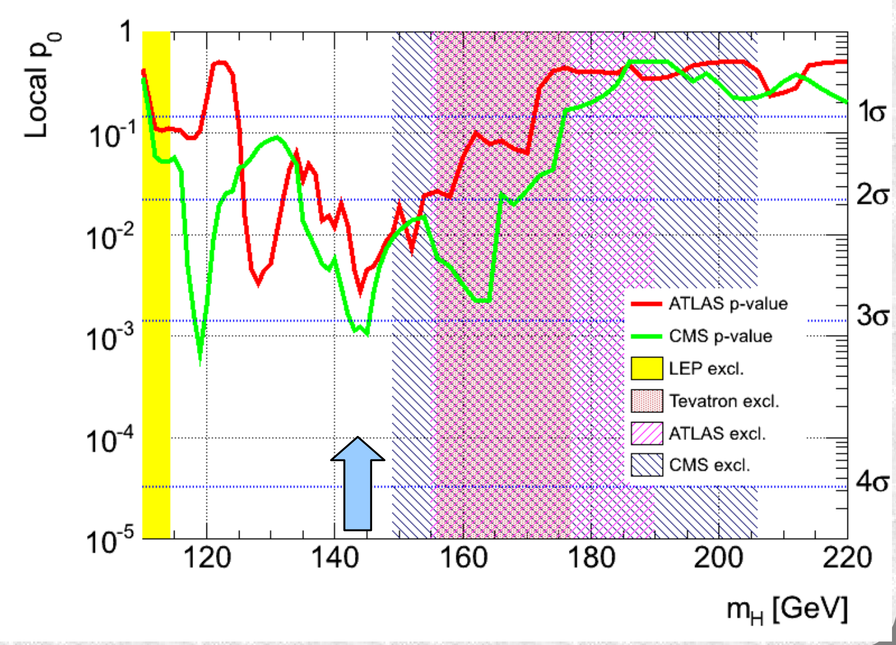
Max deviation of background model from expected background distribution taken as systematic uncertainty

Main systematic uncertainties

Signal yield	
Theory	~ 20%
Photon efficiency	~ 10%
Background model	~ 10%
Categories migration	
Higgs p_T modeling	up to ~ 10%
Conv/unconv γ	up to ~ 6%
Jet E-scale	up to 20% (2j/VBF)
Underlying event	up to 30% (2j/VBF)
H→ γγ mass resolution	~ 14%
Photon E-scale	~ 0.6%

What to say?

- The LEP accelerator in year 2000 had a 2σ bump about right for a Higgs, mass 115GeV
  - We called for its closure to be delayed a year to check
  - But it was closed..good call.
- In 2011 I summarised ATLAS and CMS Higgs searches at a summer conference in Grenoble
  - The plot shows the evidence for a Higgs v mass then
  - Both ATLAS and CMS had ~3 sigma suggesting m_H=143
  - We didn't claim anything
    - fortunately
- What should we say now?



CERN director's 1-slide talk

Global Effort → Global Success

Results today only possible due to extraordinary performance of accelerators – experiments – Grid computing

Observation of a new particle consistent with a Higgs Boson (but which one…?)

Historic Milestone but only the beginning

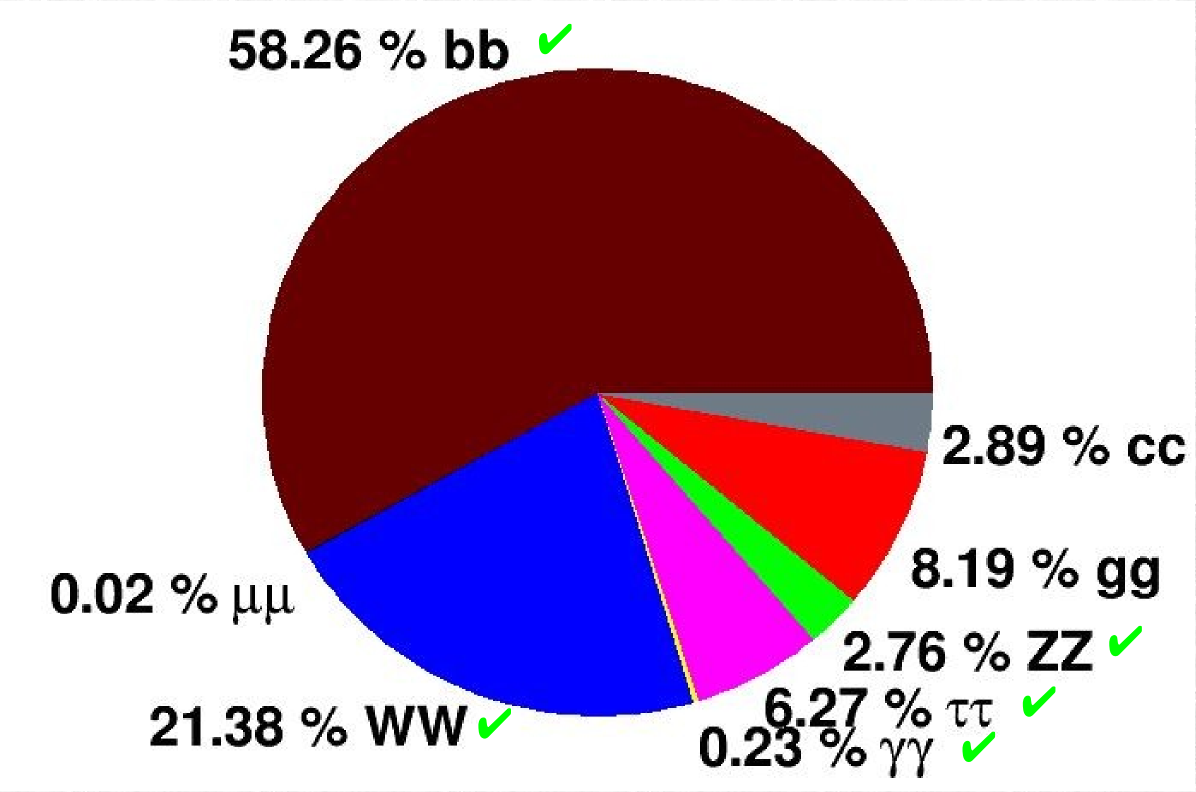
Global Implications for the future

R-D Heuer

CERN

Since 2012?

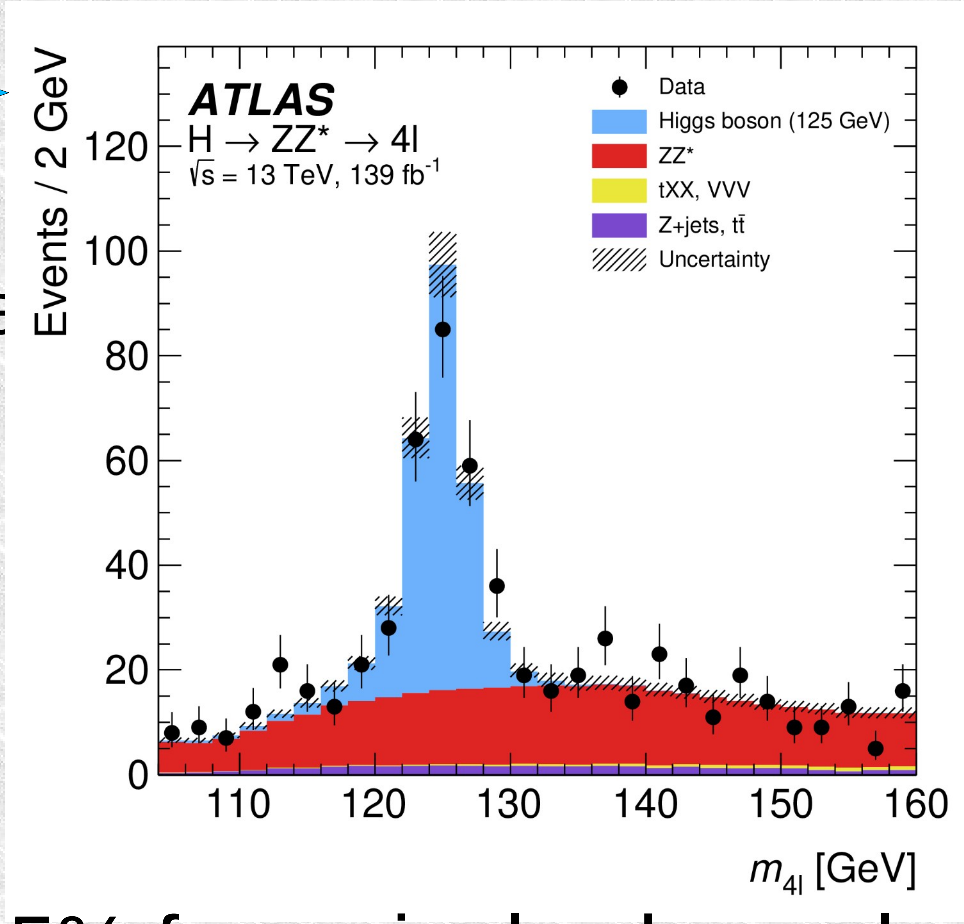
- Higgs observed again
  - In each year's data separately
  - Five decay channels are confirmed at 5σ

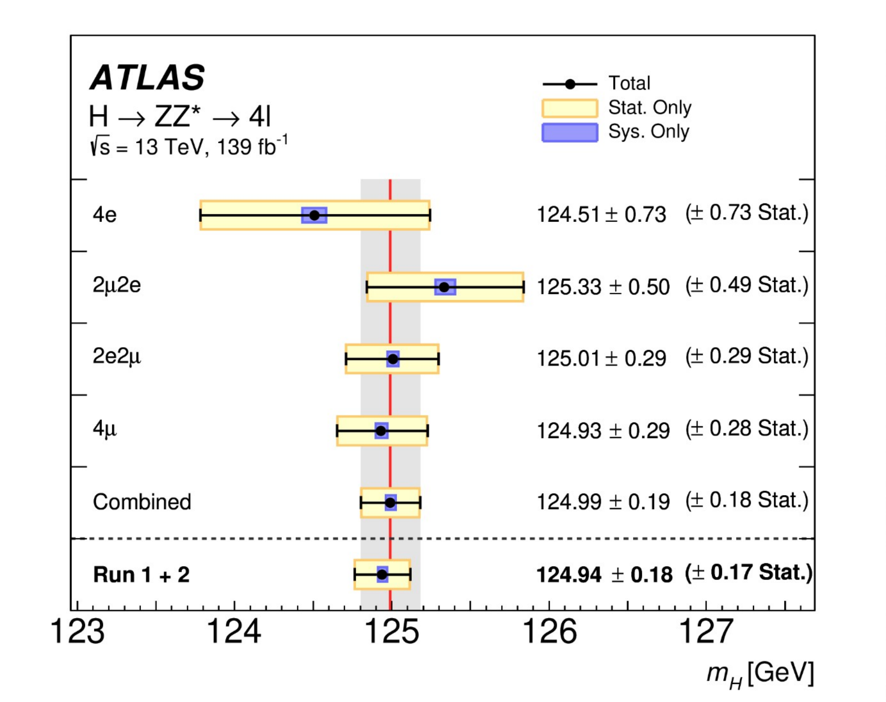


  - And five production modes: ggH, VBF, WH, ZH, ttH

H to ZZ & mass HIGG-2020-07

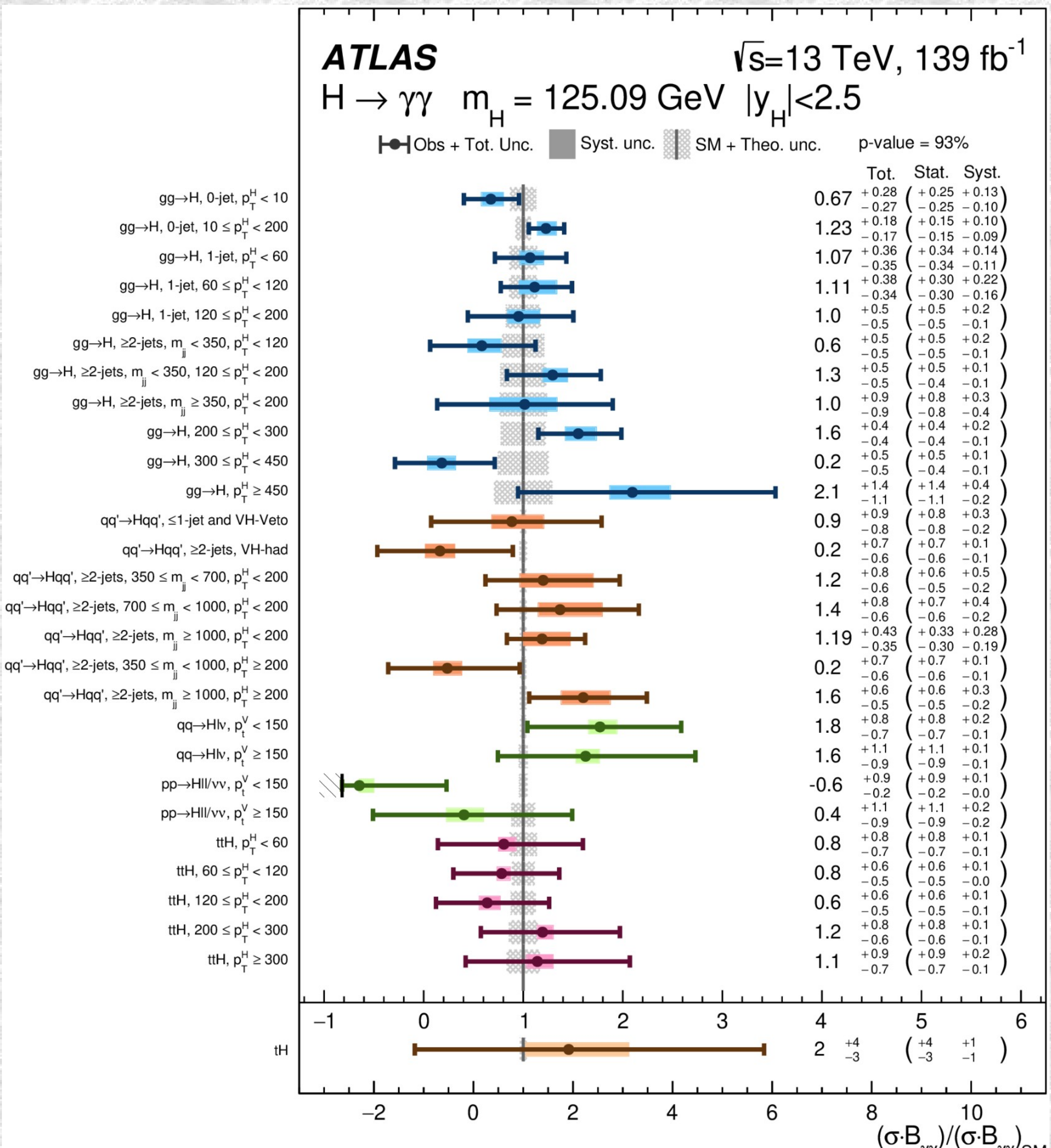
- Clean ZZ mode used for much
  - Fig is from mass paper
- M_H=124.94±0.19GeV
  - Stat dominated
  - 28 MeV unc. from μ p_T scale
    - (Run 2)

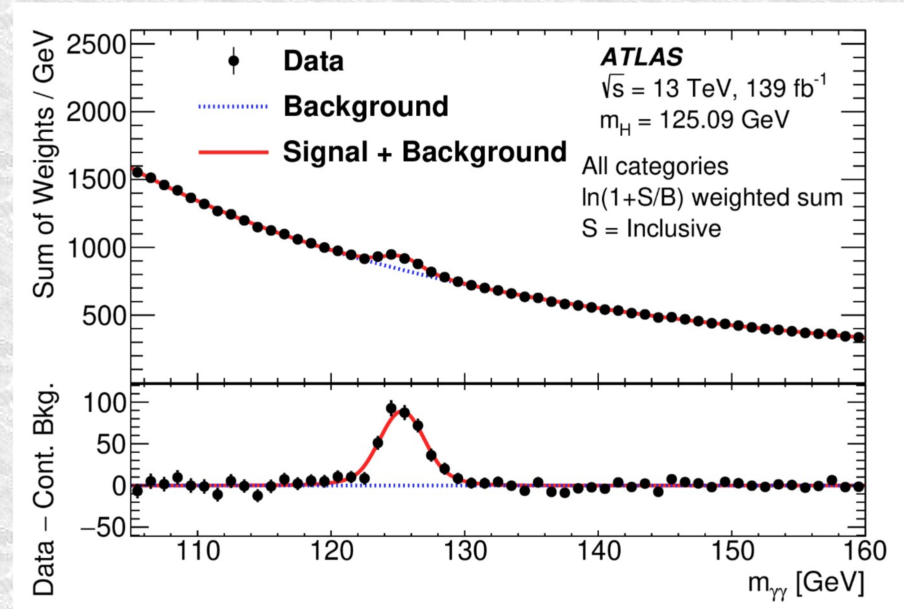




- 0.15% from single channel
  - More to come (H→γγ)

H to $\gamma\gamma$ HIGG-2020-16



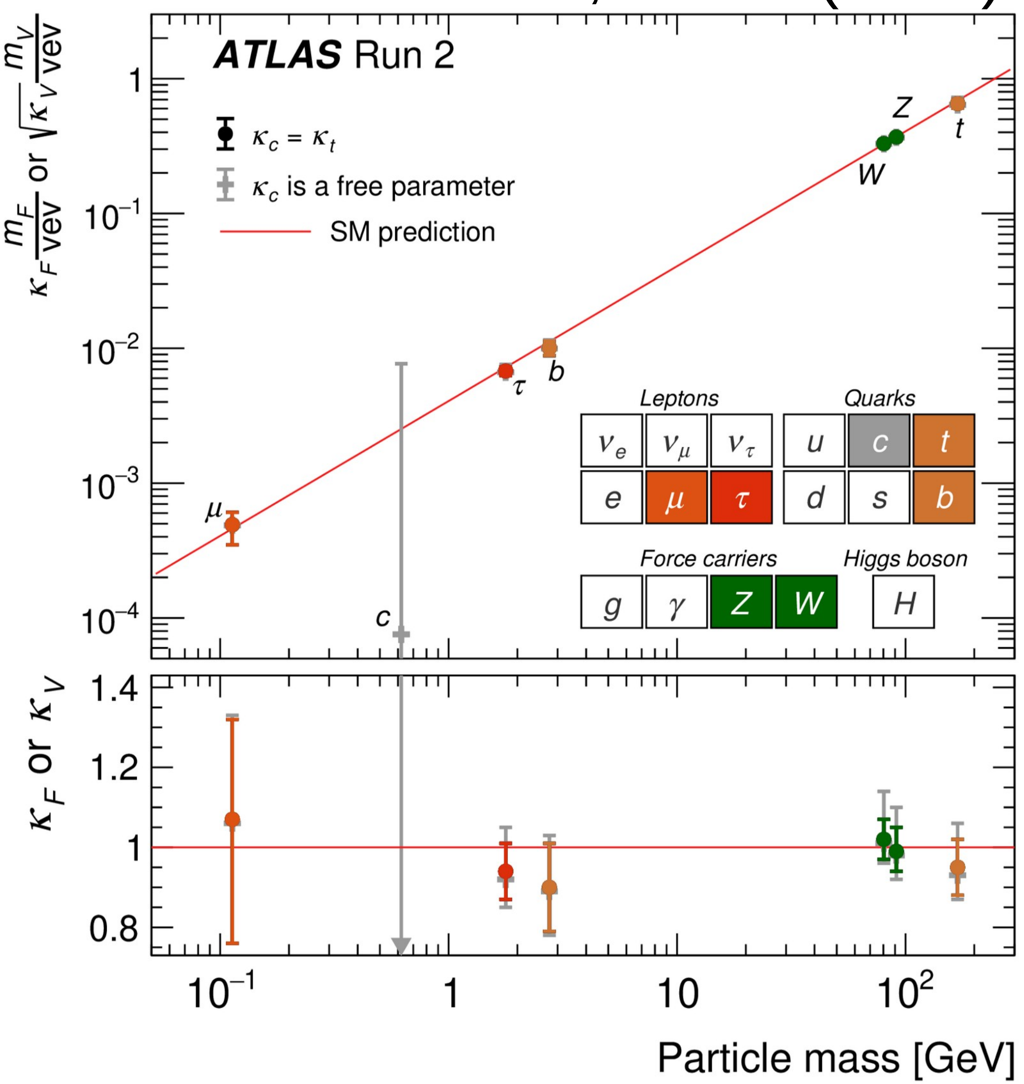


- Thousands of events
  - Allows probing many production modes
  - ggF, VBF, VH, ttH
- Overall $\mu=1.04^{+0.10}_{-0.09}$

Interactions with all particles?

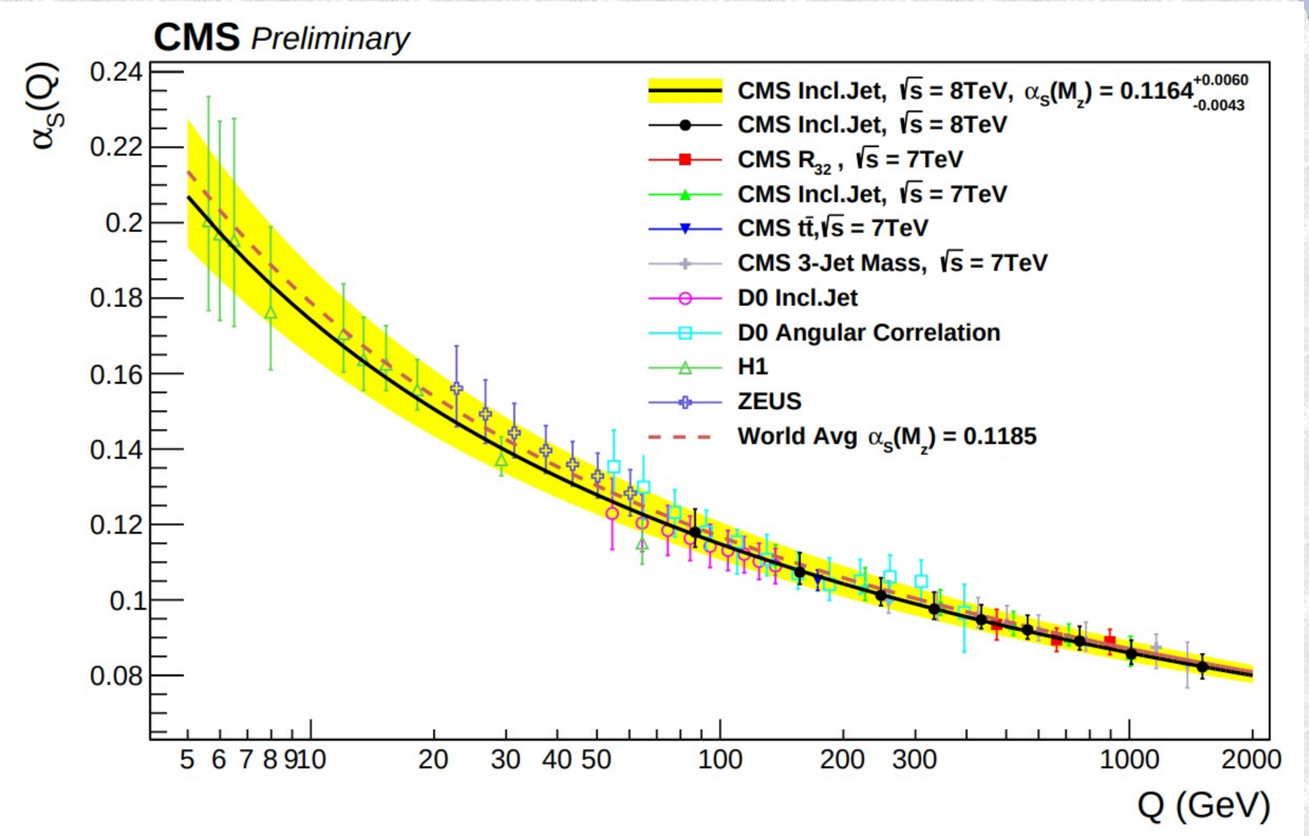
- Interaction should scale with mass
- Confirmed for vector bosons and all 3rd generation fermions
  - Except ν_τ!
- We have 3σ evidence Higgs decays to muon pairs too
  - 2nd generation fermions
- But WHY these masses? No idea….

Nature 607, 52–59 (2022)



A digression – running couplings

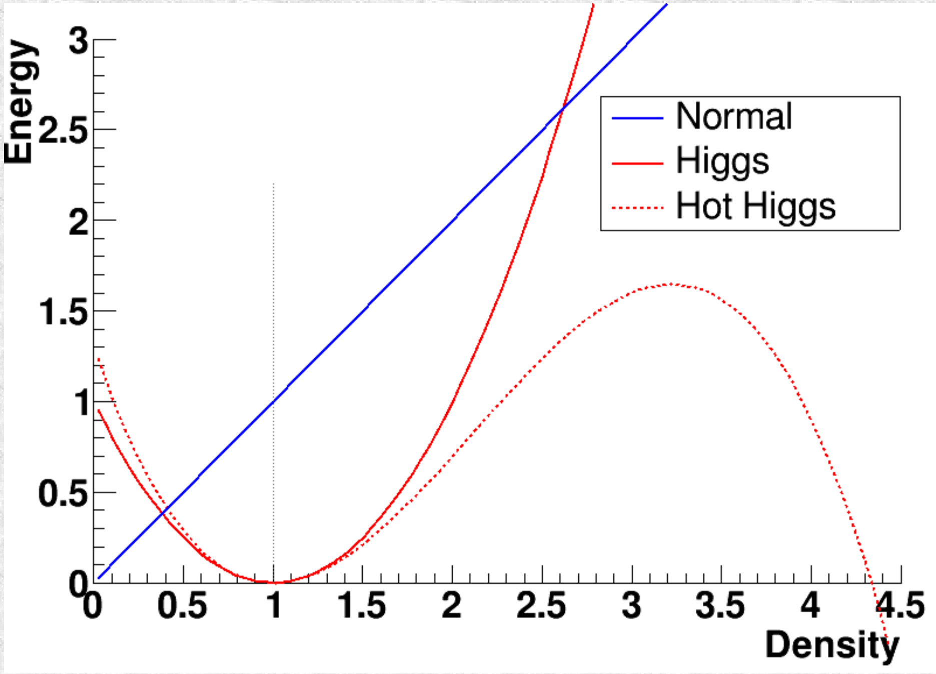
- In QM ‘constants’ actually vary with energy
- The plot show the ‘running’ of the strength of the strong force



- Assorted measuresements at energies from 5 to 1000 GeV show the strong force gets weaker with rising energy
  - in a predictable way

The Higgs potential also ‘runs’

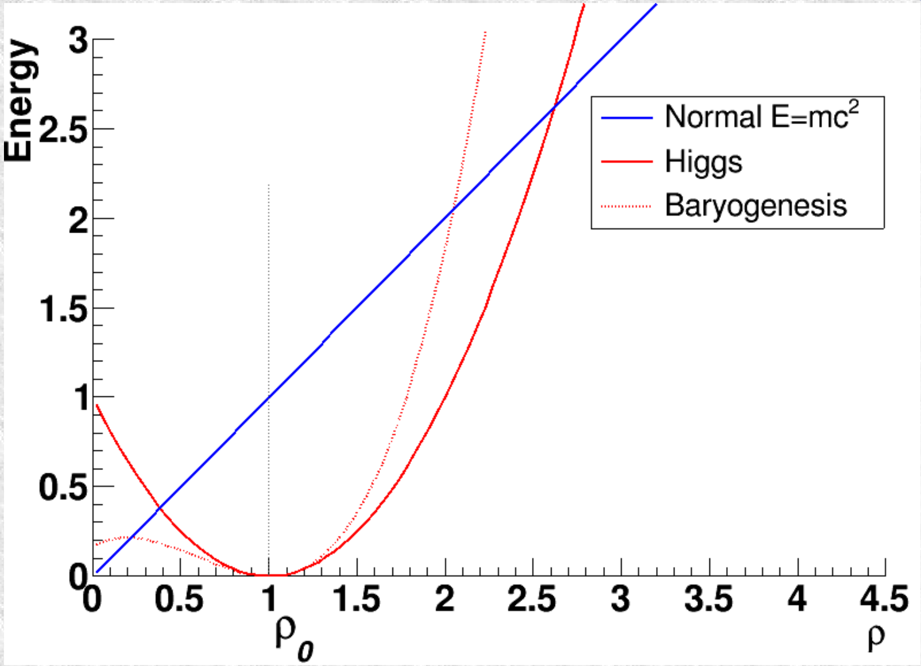
- Here is the Higgs potential at low and high energy or temperature
- In fact one of the ‘alternatives’ I showed you is actually a hot Higgs field
- At high temperature and density, the potential drops...and keeps dropping forever
- If the Higgs field was to get into that state it would keep increasing in density, releasing energy as it did so…..



How bad?

- 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 way more than the universe lifetime
- Furthermore this is a result of interactions with the known particles
  - Who knows how dark matter will change this prediction?

But it could be good!

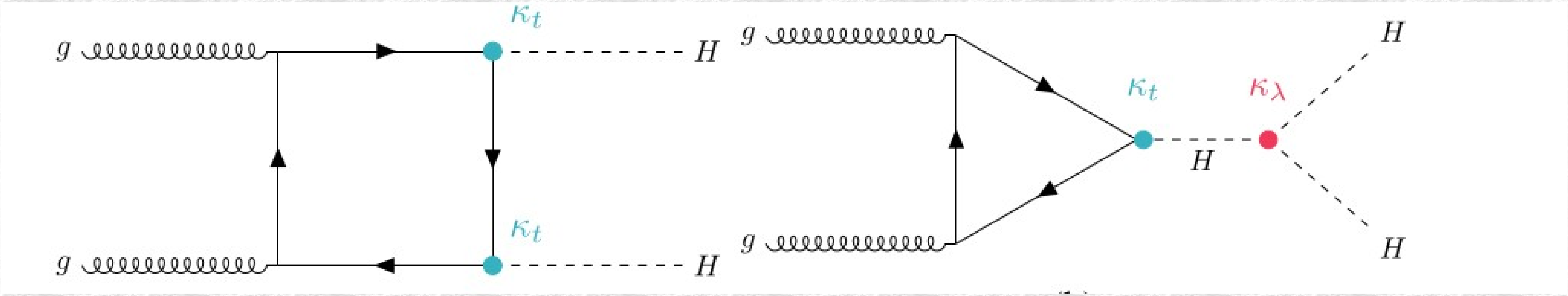


- Remember: the Higgs potential was MADE UP
- I show right an alternative
  - Our measurements are all near the minimum
  - so we don't know
- With this potential the Universe would stick at ρ=0
  - until somewhere it got kicked into the true minimum
  - The expanding bubble would have happened early in the Universe's history
  - and provides part of the conditions necessary to create a matter/antimatter asymmetry
- So perhaps the Higgs fields explains why we are here?

What do we know of the field?

- The Higgs mechanism needs the field filling space
  - Unlike light, you turn it off and it is still there
  - ~2 Higgs bosons / fm^3
- The density of the field is cosmologically ridiculous
  - The mass of Mt Everest in a pint glass!
  - So why does all that not collapse the Universe??
    - We don't have a quantum theory of gravity
- So do we really expect you to believe its there?
- We should measure the self-coupling of the Higgs
  - This is what generates the field.
  - We will learn something from studying events with two Higgs bosons at once
    - Major goal for LHC now

Di-Higgs production



- Left shows two Higgs bosons produced independently
- Right is one Higgs splitting in two
  - That's what we want to study
- But you need to reconstruct both bosons in these rare events
- Today we don’t even have proof of HH production

Phase II?

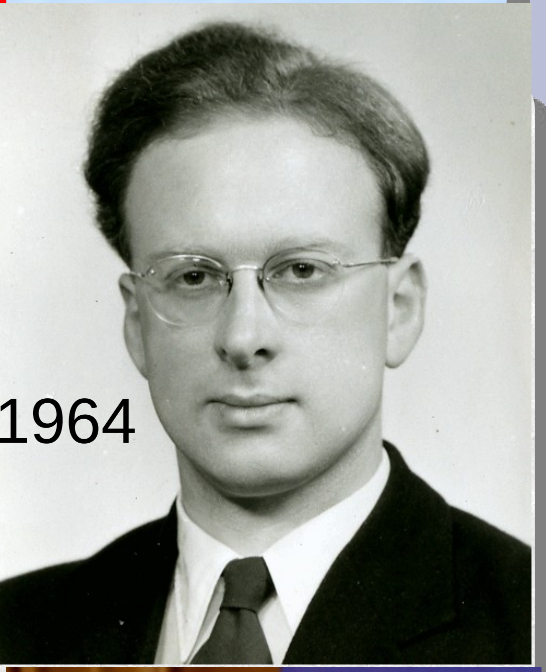
- LHC was designed to produce 300fb^{-1} of data
  - With 280fb^{-1} delivered so far it is likely to exceed that
- Run 3 finishes in 2025, and with it the LHC programme
- But LHC Phase II is to start in 2029
  - Aiming to deliver 3000fb^{-1}
  - Studying the Higgs self-coupling is one of the major goals
- But both machine and detectors need major rebuilds to do it.

Upgrade Example: Inner tracker

- Tracker rebuild to handle radiation & tracks density
- ITk features
  - All silicon (fast) layout
    - 5 pixel, 4 strip
  - Higher granularity
    - Reduced occupancy
  - Improved radiation handling
  - Extended angular coverage
- Shown: a support for the with silicon detectors
- But RAL (and others) need to make them…..

What comes next?

- We have found a Higgs boson
- This confirms a 'Higgs Field' filling space
- This is something radically new
  - It is not like matter, not like a force
    - Newton, 1704, described world as these
  - It is a Higgs field, something new.
- Now we need to understand it
- LHC is producing large amounts of high energy data for that
- And there are lots of possibilities for other discoveries too


1964

2012

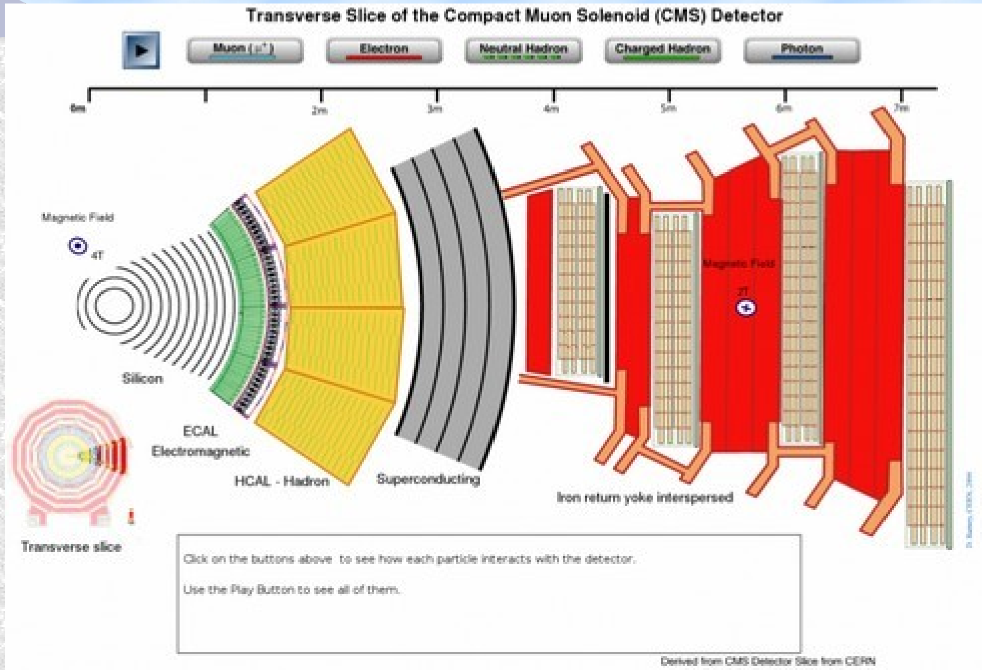
The complete theory:

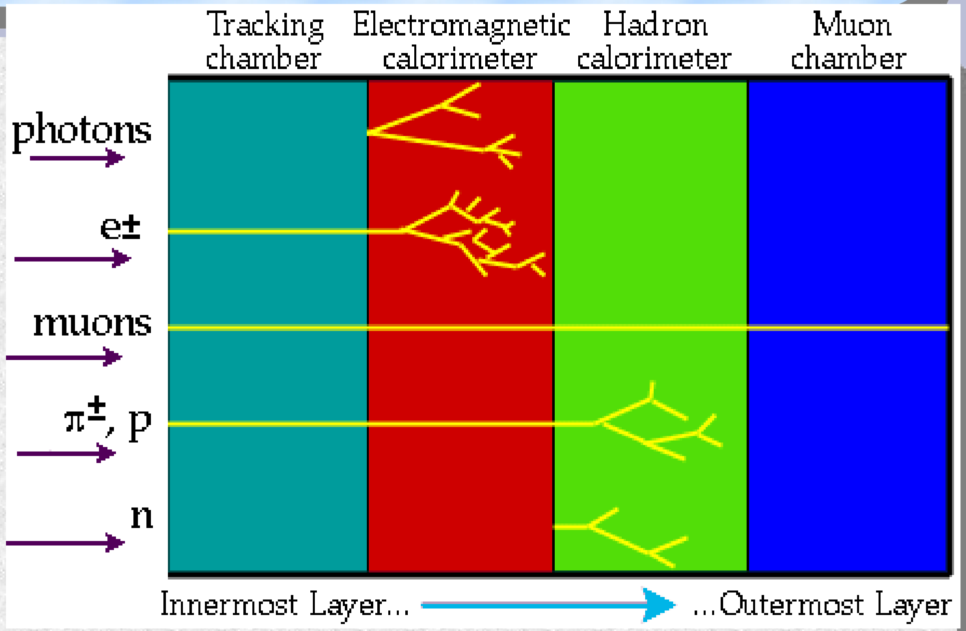
- We have maths that describes particles and forces

$$
\begin{aligned}
\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f\bar{\Psi}_f\gamma^\mu\Psi_f A_\mu) + \\
+\frac{g}{\sqrt{2}}\sum_i (\bar{a}^i_L\gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L\gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w}\sum_f \bar{\Psi}_f\gamma^\mu (I^3_f - 2s^2_w Q_f - I^3_f\gamma_5)\Psi_f Z_\mu + \\
-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2}|\partial_\mu W^+_\nu - \partial_\nu W^+_\mu + \\
-ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 + \\
-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 + \\
-\frac{1}{2}M^2_\eta\eta^2 - \frac{gM^2_\eta}{8M_W}\eta^3 - \frac{g'^2 M^2_\eta}{32 M_W}\eta^4 + |M_W W^+_\mu + \frac{g}{2}\eta W^+_\mu|^2 + \\
+\frac{1}{2}|\partial_\mu\eta + iM_Z Z_\mu + \frac{ig}{2c_w}\eta Z_\mu|^2 - \sum_f \frac{g}{2}\frac{m_f}{M_W}\bar{\Psi}_f\Psi_f\eta
\end{aligned}
$$

- But we cannot discuss that here

Particle identification





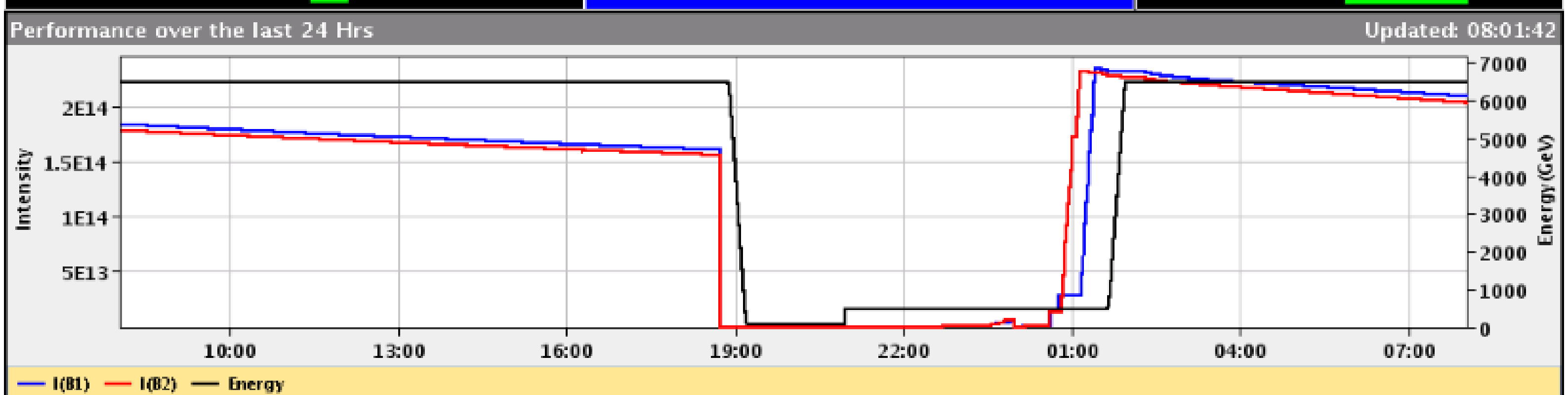
Look at me! I'm a neutrino

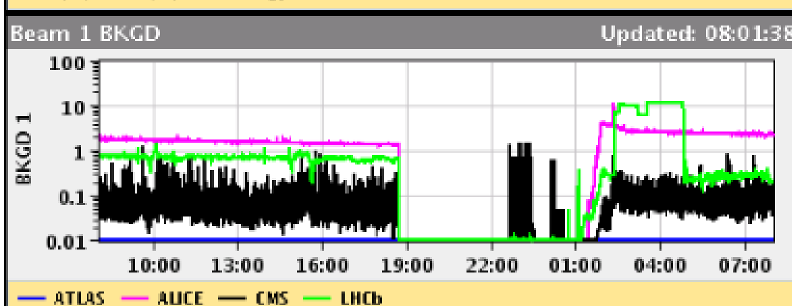
- Reconstruct long-lived particles in the detector
  - Basically only a few types: photons(γ), e^-, μ^-, p^+, π^+, n, ν
  - Can identify type by interaction pattern in the detector
  - Measure the momentum by bending in magnetic field
- Electrons, muons and photons especially useful
  - There are none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

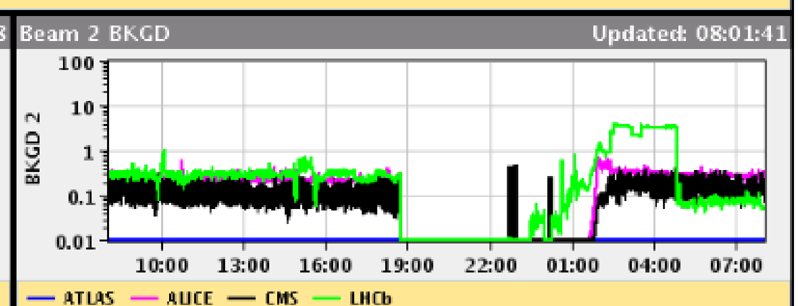
LHC running

28-Oct-2015 08:01:42	Fill #: 4540	Energy: 6500 GeV	I(B1): 2.09e+14	I(B2): 2.03e+14
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi [(ub.s)^-1]	3590.800	5.041	3352.136	352.695
BRAN Luminosity [(ub.s)^-1]	3663.8	4.1	3086.0	163.7
Fill Luminosity (nb)^-1	75712.930	100.385	71707.406	4831.953
Beam 1 BKGD	0.000	2.246	0.098	0.190
Beam 2 BKGD	0.000	0.271	0.132	0.049

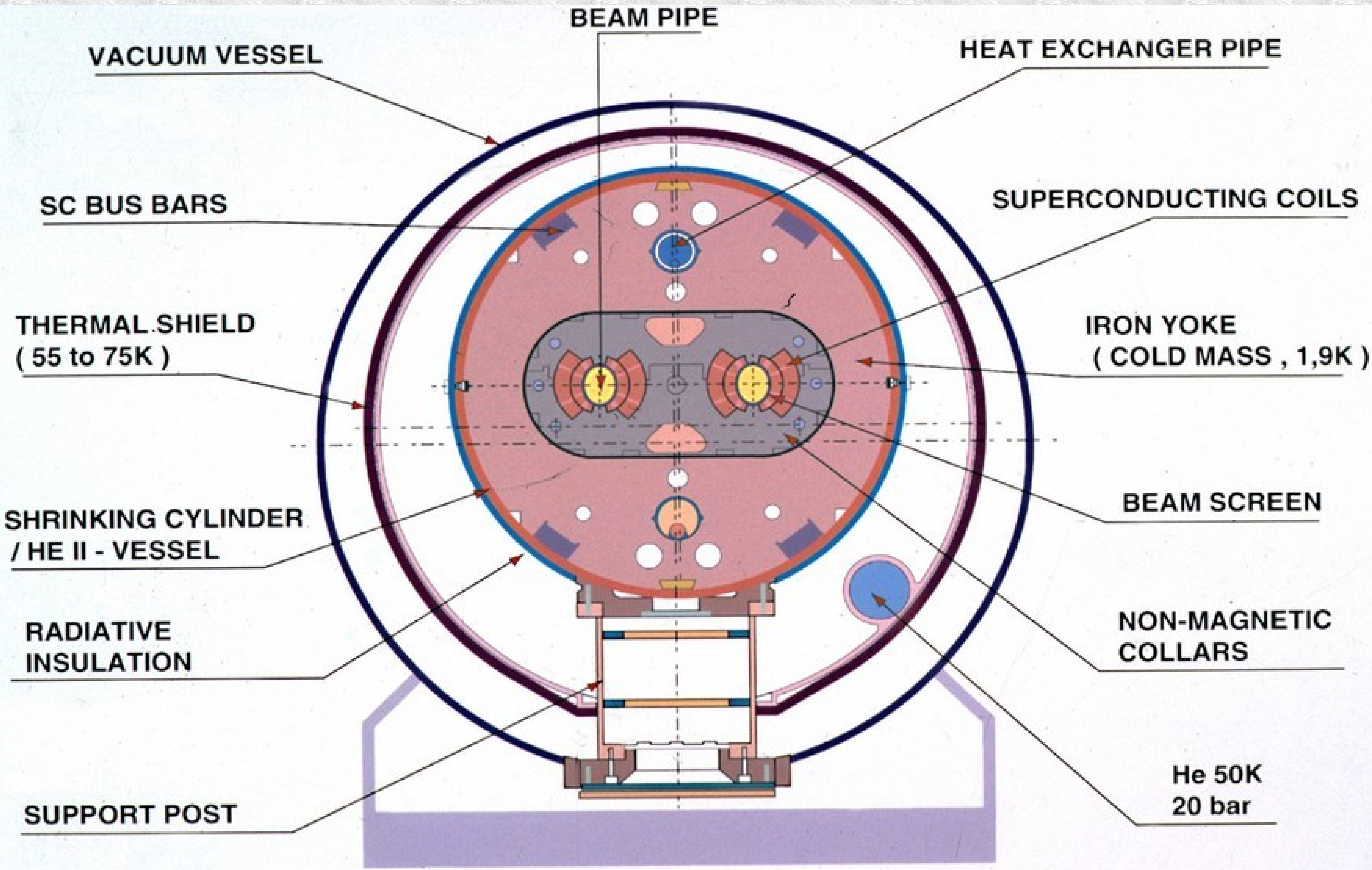
LHCb VELO Position IN Gap: -0.0 mm | STABLE BEAMS | TOTEM: STANDBY







LHC magnets



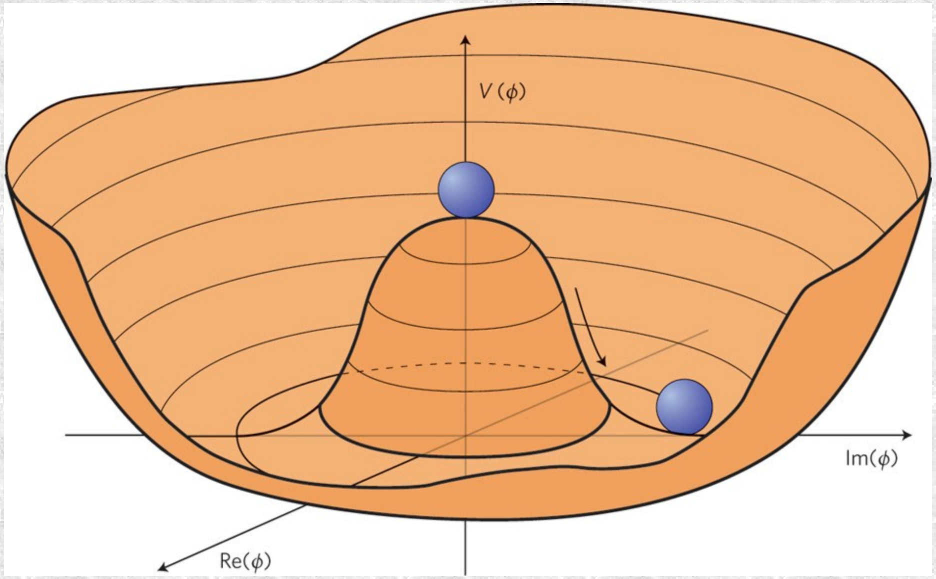
Cross Section of LHC Dipole

The 4 big detectors

- LHC has 4 points where the beams cross
- ATLAS
  - Designed to see what happens at the highest energy
  - 'General Purpose' – ready for anything
    - e.g. Higgs, Supersymmetry, dark matter, black holes
- CMS
  – Similar to ATLAS. 2 experiments check each other
- LHCb
  - Studies b quarks, for matter-antimatter differences
  - LHC energy & luminosity means lots of particles
- ALICE
  - Studies the quark gluon plasma
  - A soup of free quarks when two lead nuclei collide
  - LHC switches to Pb+Pb for last few weeks of year

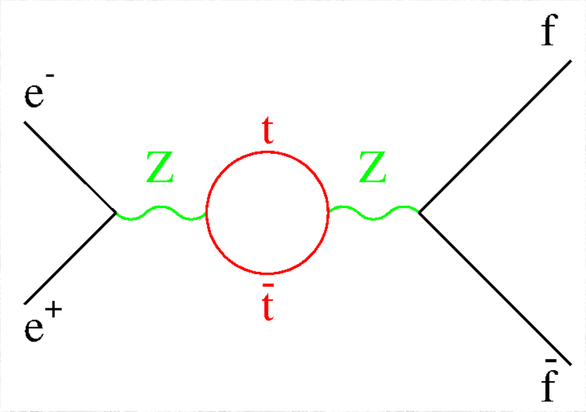
The Higgs self-interaction

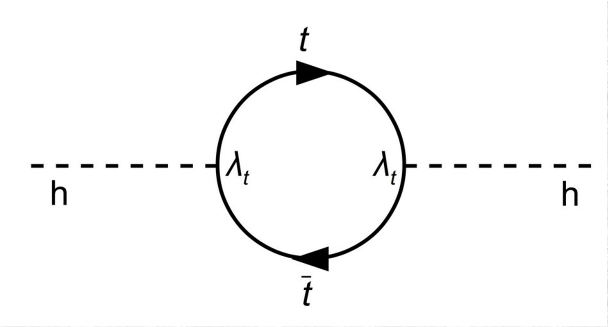
- The Brout-Englert-Higgs theory replaces a mass term ($m\varphi^2$) by a two-term piece ($-m\varphi^2+\varphi^4$)
- Φ is the field density
- The field-energy, or action, has a minimum away from zero
- It is this that means the Universe sits in a high Higgs density state



A tale of two top loops

- Z and Higgs bosons are neutral and interact with top quarks
  - They can split (Uncertainty) into a tt pair and reform again
  - This changes measured properties
- Precise measurements of Z bosons at LEP (etc.) in 1990s predicted m_t=173±12 GeV
  - C/f 173±1 GeV from measurement
- Conclusion: Loops are real and work as we expect

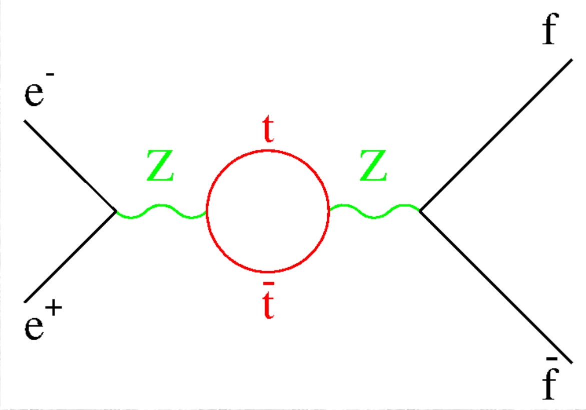


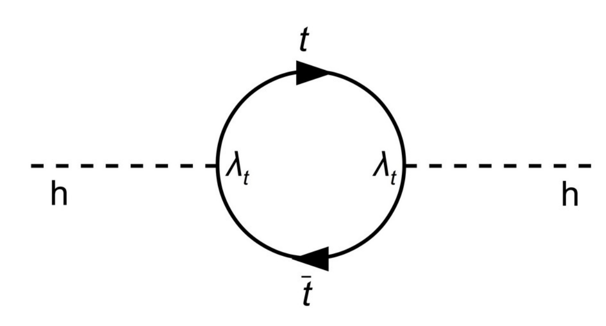


A tale of two top loops

- Higgs boson properties are also changed by top loop
  - But maths is different because H is spin 0, Z spin 1
- Effect is to correct measured mass to be

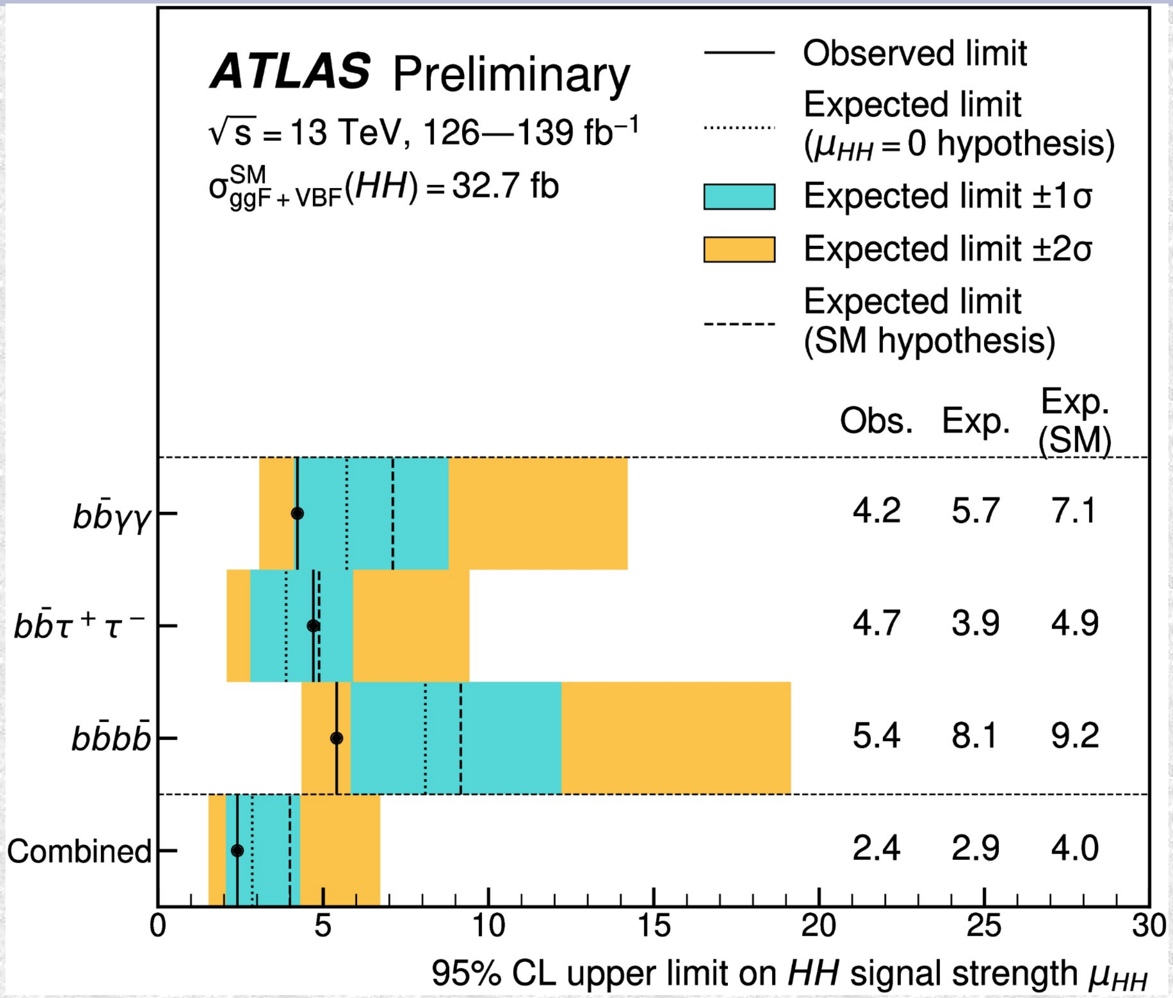
  $M^2_{H,meas} = M^2_{H,bare} + p^2_{max}/c^2$
- p_{max} is the highest momentum allowed before theory changes
  - e.g. scale of Gravity? ~ 10^{18} GeV
- So the fact we see 125GeV says our theory stops around 125GeV!





Combined HH

ATLAS-CONF-2022-050



- Limit on HH production at 2.4 x SM strength
  - c/f 2.9 expected (no HH) or 4.0 (SM)