Jewels in the Crown of the LHC

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Weizmann Institute

Plan of lecture

- Prologue: CERN, LHC, ATLAS/CMS
- The first jewel: An elementary spin-0 particle
- A second jewel: Why the weak interaction is short range
- A third jewel: How the τ-lepton, t-quark, and b-quark gain their masses
- Epilogue: New questions, More Jewels, My own work

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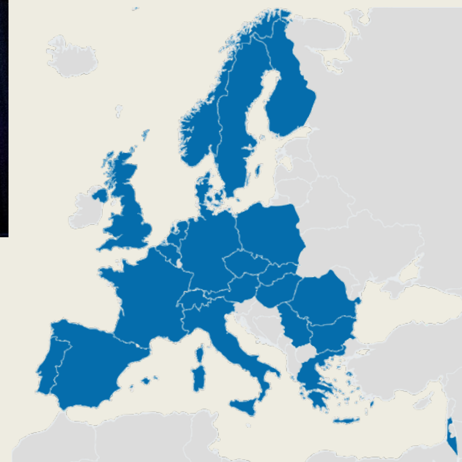
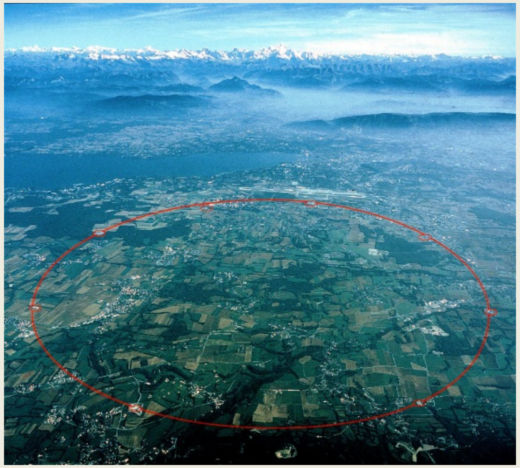
CERN



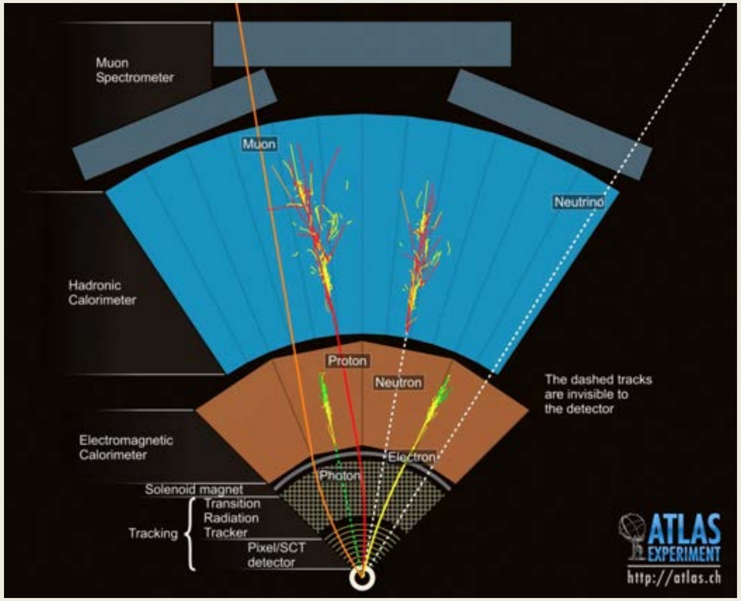
- Established in 1954 with the mission to
  - Provide a unique range of particle accelerator facilities that enable research at the forefront of human knowledge
  - Perform world-class research in fundamental physics
  - Unite people from all over the world to push the frontiers of science and technology for the benefit of all

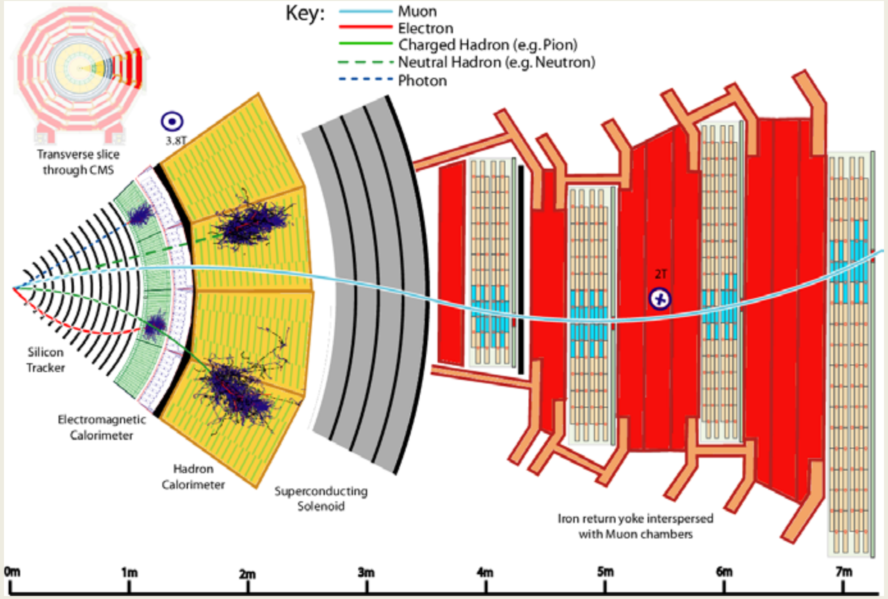


The LHC

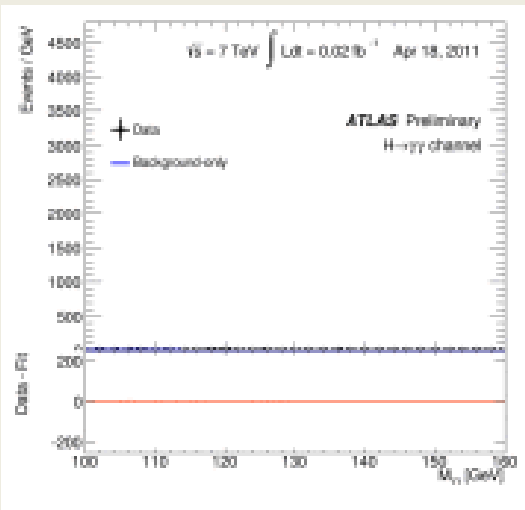
- Started on 2008
- A 27-kilometer ring
- Two high-energy proton beams travel at close to the speed of light before they are made to collide
- Superconducting magnets kept at -271.3^{o}
- 4×10^{7} collisions/second (10^{7}sec/year, 25 years)
- Four particle detectors: ATLAS, CMS, LHCb, ALICE

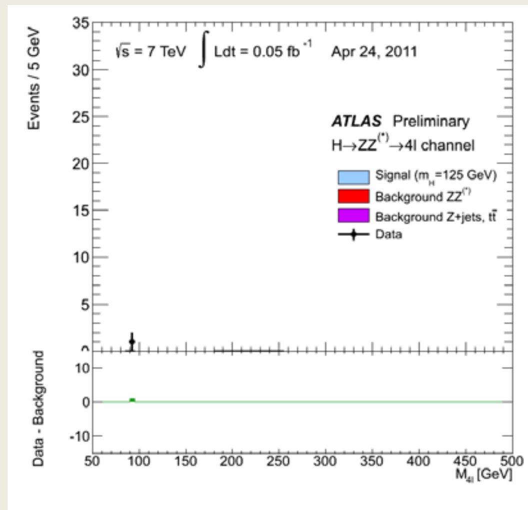
Multi-Messenger

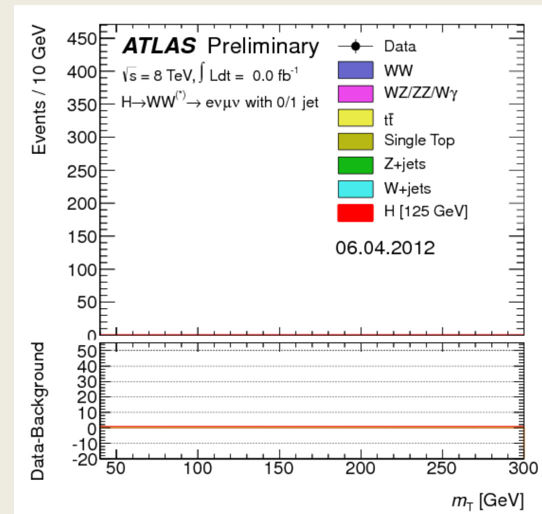




The Higgs Discovery







The first jewel

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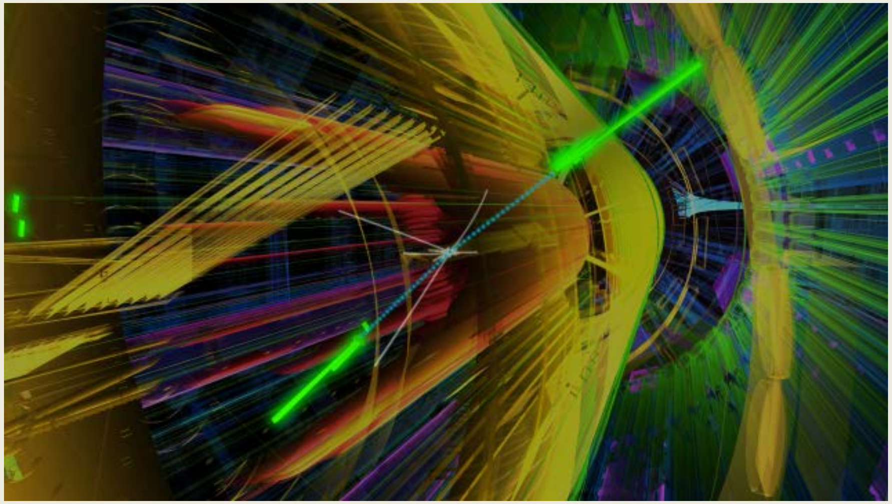
The first jewel

The discovery of an elementary spin-0 particle

- The first and only particle of this type to have been discovered
- The relevant processes:
  - $h \to \gamma\gamma$
  - $h \to ZZ^* \to 4\ell$



Elementary Particles Pre-2012

Matter Particles

particle	spin	color	charge
e, μ, τ	½	(1)	-1
ν_1, ν_2, ν_3	½	(1)	0
u, c, t	½	(3)	$+2/3$
d, s, b	½	(3)	$-1/3$

- All structures in the Universe are made of three of these twelve:
  - u, d, e
  - $p \sim uud,\ n \sim ddu$

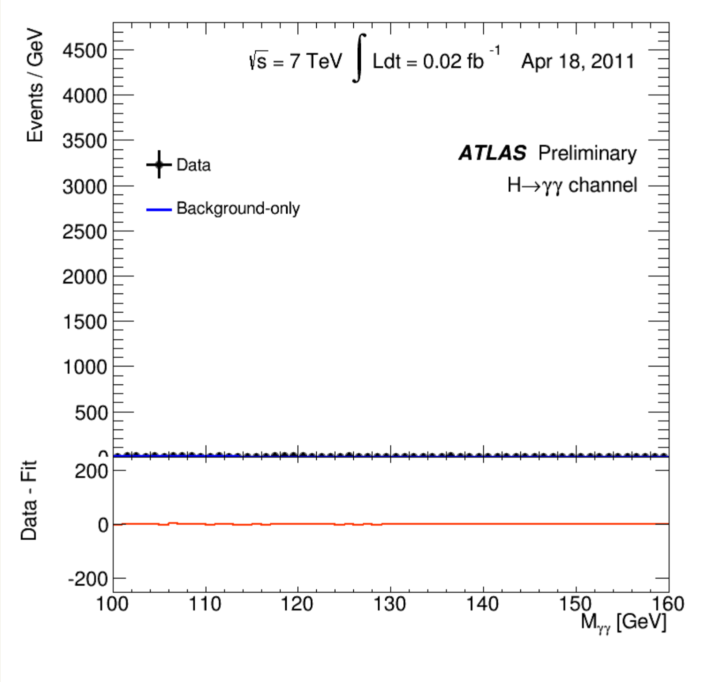
Force Carriers

particle	spin	color	charge
A^0	1	(1)	0
G	1	(8)	0
$W^{\pm}$	1	(1)	± 1
Z^0	1	(1)	0

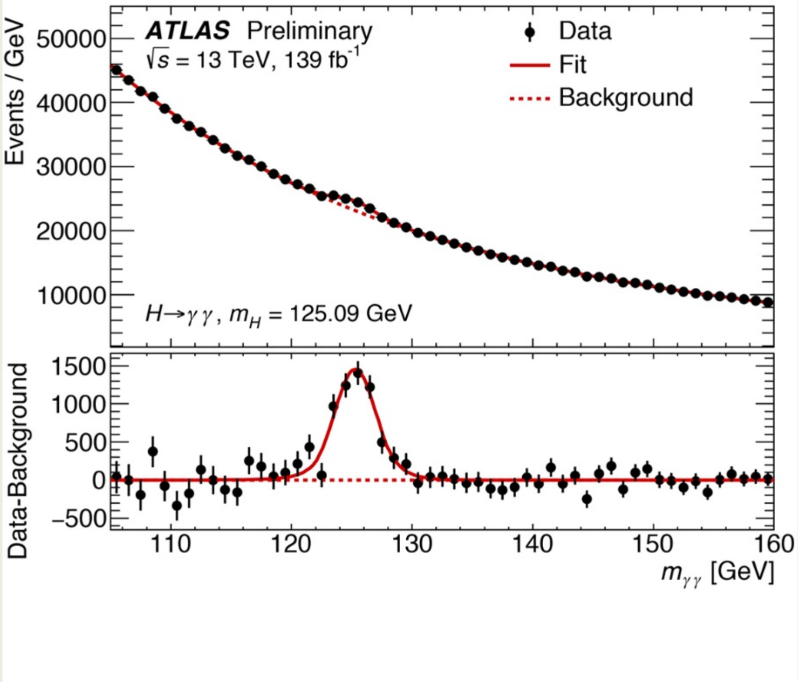
- The photon A^0 carries the EM force
- The gluon G carries the strong force
- The W- and Z-bosons carry the weak force

Discovery of $h \to \gamma\gamma$

2012



2019



Zero or Two?

- $h \rightarrow \gamma\gamma$

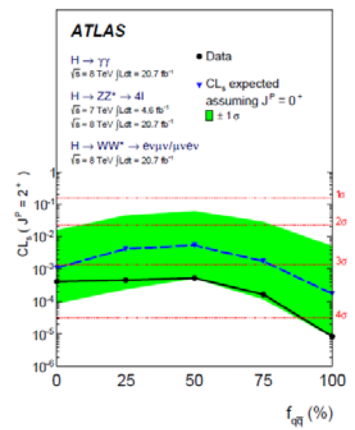
Landau-Yang theorem: A spin-1 particle cannot decay into two photons

  - $J = 0$ or 2, that is the question

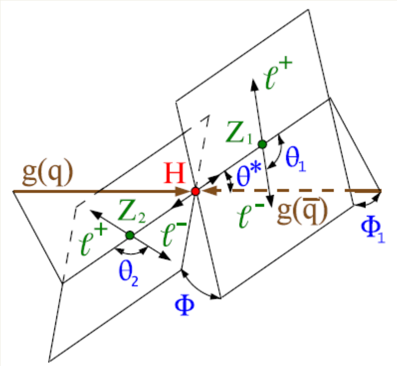
- $h \rightarrow ZZ^* \rightarrow 4\ell$

The spin of the parent particle affects the angular distribution of the daughter particles

  - $J^P = 0^+$, that is the answer



1307.1432



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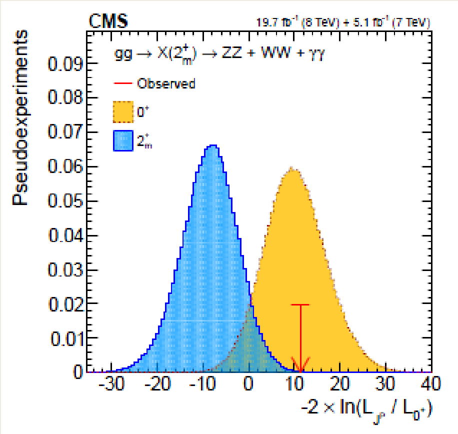
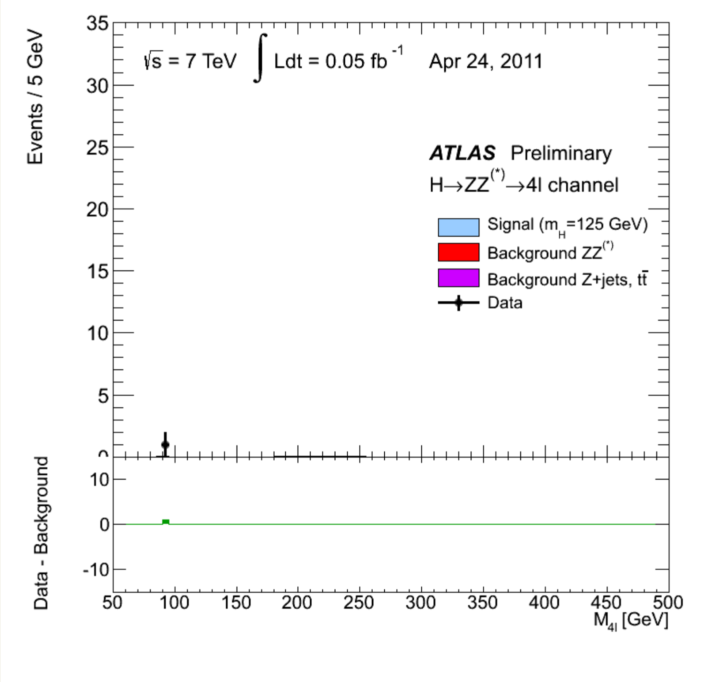


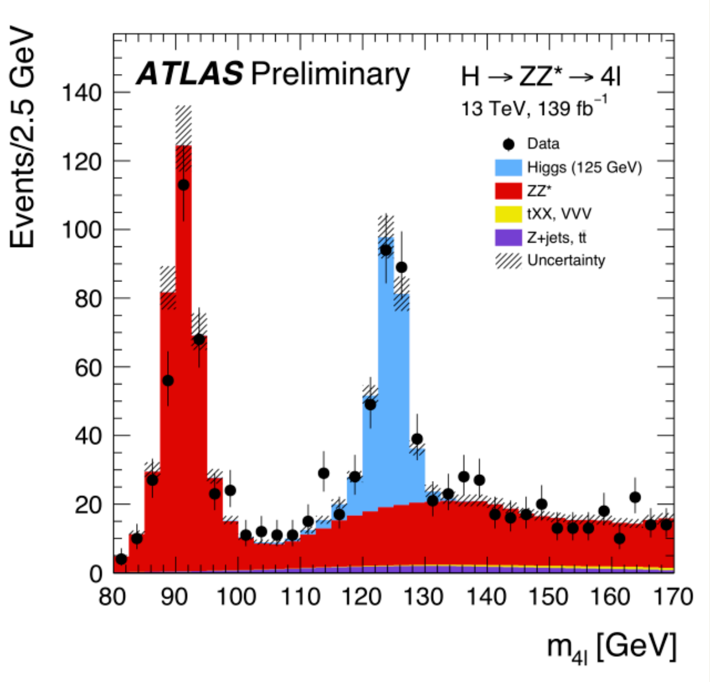
1411.3441

Discovery of $h \to ZZ^*$

2012



2019



Elementary or Composite?

If h is a composite spin-0 particle:

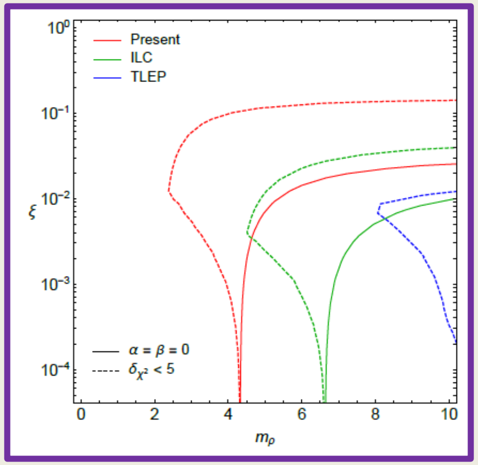
- A whole series of new composite particles, in particular spin-1 particles
- whose mass scale is (roughly) inversely proportional to the distance scale which characterizes its internal structure

- Three ways to experimentally test the question

Elementary or Composite?

- Virtual effects of the heavy spin-1 particles would modify various properties of the W- and Z-bosons (LEP)
- Direct searches for the new spin-1 particles (LHC)
- Properties of h would differ if it were elementary or composite (LHC)

$$L_{\text{compositness}} \leq O(10^{-19}\ \text{meters})$$



m_ρ: mass of spin-1 resonances

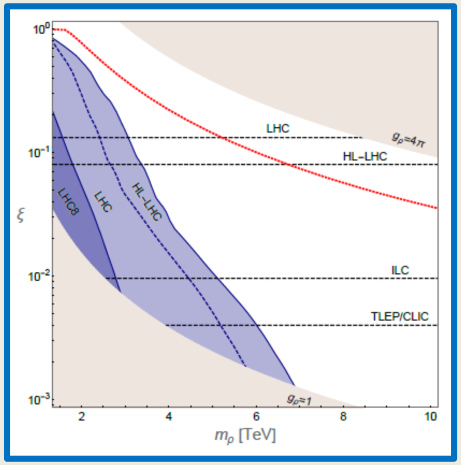
g_ρ: coupling to SM particles

$\xi = g_\rho^2 v^2 / m_\rho^2$

Thamm et al, 1502.01701

$\xi = -0.041^{+0.090}_{-0.094}$

Liu et al, 1809.09126



The first jewel - summary

ATLAS and CMS have discovered an elementary* spin-0 particle h

* At least down to a scale of $O(10^{-4})$ the size of the proton

- All other known elementary particles have either spin-½ (matter particles) or spin-1 (force carriers)
- The ways h is produced and the ways it decays call for its identification with the only particle that was predicted by the Standard Model and had not been observed until the 2012 discovery – the Higgs Boson

The SM spectrum

particle	spin	color	Q_{EM}	mass [v]
$W^{\pm}$	1	(1)	± 1	$g/2$
Z^0	1	(1)	0	$\sqrt{g^2+g'^2}/2$
A^0	1	(1)	0	0
G	1	(8)	0	0
h	0	(1)	0	$\sqrt{2\lambda}$
e, μ, τ	½	(1)	-1	$y_{e,\mu,\tau}/\sqrt{2}$
ν_e, ν_μ, ν_τ	½	(1)	0	0
u, c, t	½	(3)	$+2/3$	$y_{u,c,t}/\sqrt{2}$
d, s, b	½	(3)	$-1/3$	$y_{d,s,b}/\sqrt{2}$

A second jewel

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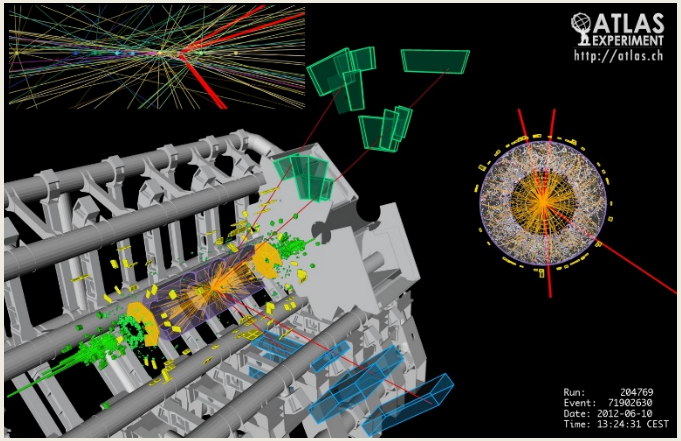
A second jewel

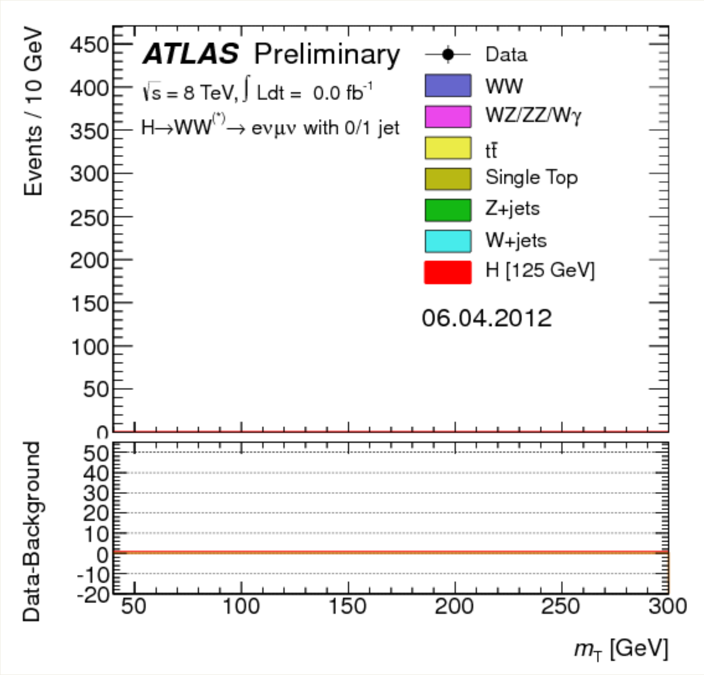
The discovery of the mechanism that makes the weak interactions short-ranged

- The short range of the weak interactions is in contrast to the other (electromagnetic and strong) interactions mediated by spin-1 particles
- The relevant processes:
  - $h \to ZZ^*, WW^*$ ($h \to V f \bar{f}$)
  - $WW \to h,\ ZZ \to h$ (VBF)



Discovery of $h \to WW^*$

2012



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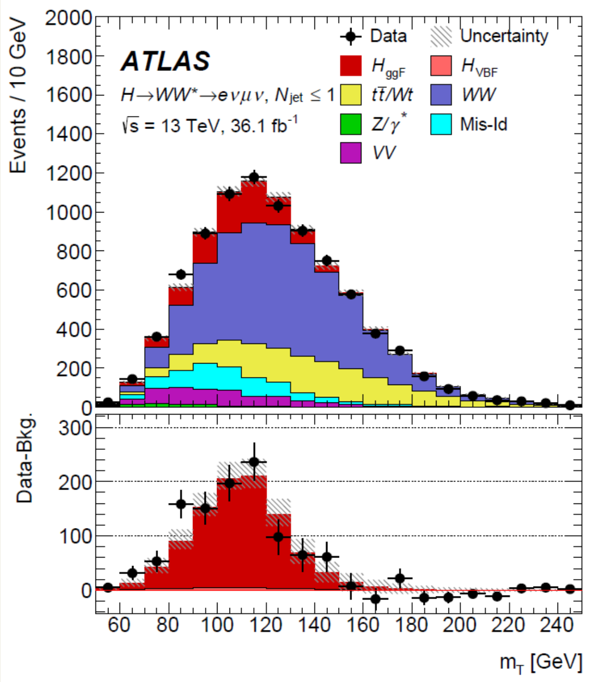


The range of interactions

- EM interactions are mediated by the massless photon $\Longrightarrow$ Long range
- Strong interactions are mediated by the massless gluon $\Longrightarrow$ Long range*

  * (Color confinement renders the long range effects unobservable)
- Weak interactions are mediated by the massive W- and Z-bosons $[m_V = O(100\, m_p)]$

  $\Longrightarrow$ At $d > 10^{-18}$ meters, the weak force is exponentially suppressed

Interactions with spin-1 mediators

- QFT's can predict the existence of int's with spin-1 mediators, and many of their features, by assuming that Nature has certain symmetries
- Numerous predictions stemming from these symmetries successfully tested
- The symmetries predict massless mediators:
  - EM - √
  - Strong - √
  - Weak - ???

A possible solution

- If the symmetry is respected by the QFT but not by the ground state (GS) of the Universe (spontaneous symmetry breaking):
  - The theory loses nothing of its predictive power
  - The predictions are, however, different from the case of symmetric ground state
  - In particular, the force carriers gain masses

A specific scenario

- One way in which the symmetry can be broken in the GS:
  - The field related to the Higgs boson h – the Higgs (BEH) field – does not vanish in the GS
  - The weak force carriers are slowed down by their interaction with the Higgs field
  - Moving at speeds lower than c is equivalent to $m_V \neq 0$

$\Longrightarrow$ the weak interactions are short range

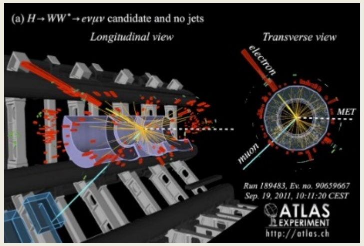
Consequences

Higgs field $= 0$	**Higgs field $\neq 0$**
• $m_Z \neq 0$ • $h \to ZZ^*$ - forbidden • $ZZ \to h$ - forbidden • Similarly for W	• $m_Z = 0$ • $h \to ZZ^*$ - allowed • $ZZ \to h$ - allowed • Similarly for W

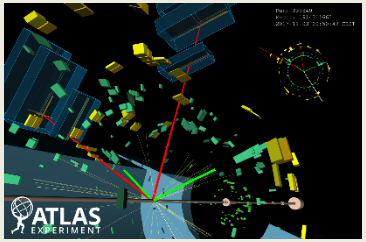
"The theory loses nothing of its predictive power":
The strength of the interaction of the Z-boson with the Higgs *field*, measured by m_Z, is closely related to the strength of interaction of the Z-boson with the Higgs *particle*, measured by $\Gamma(h \to ZZ^*)$ and by $\sigma(ZZ \to h)$

$\mu_{VV}^{i}\ (V = W, Z)$

- The Standard definition
  - $\mu_{VV^*}^{i} \equiv \dfrac{[\text{rate}(i \to h \to VV^*)]_{\text{experiment}}}{[\text{rate}(i \to h \to VV^*)]_{\text{SM}}}$
- My (broader) definition
  - $\mu_{VV^*}^{i} \equiv \dfrac{[\text{rate}(i \to h \to VV^*)]_{\text{experiment}}}{[\text{rate}(i \to h \to VV^*)]_{v_h}}$
- $[\text{rate}(i \to h \to VV^*)]_{v_h}$:
  - The rate that is predicted if the field v that gives f its mass is the field of the particle h



ATLAS/CMS



- $\mu_{WW^*} = 1.19 \pm 0.12$ [PDG 2022]
  - Within present experimental accuracy, $\Gamma(h \to WW^*)$ has the value that corresponds to the strength of interaction that would give the W-boson its mass, and would limit the effects of W-mediated weak interaction to short range
- $\mu_{ZZ^*} = 1.01 \pm 0.07$ [PDG 2022]
  - Within present experimental accuracy, $\Gamma(h \to ZZ^*)$ has the value that corresponds to the strength of interaction that would give the Z-boson its mass, and would limit the effects of Z-mediated weak interaction to short range
- $\mu^{\mathrm{VBF}} = 0.99 \pm 0.25$ [PDG 2022]
  - The rate of $\sigma(VV \to h)$ corresponds to the same strength of interactions

The second jewel - summary

- **ATLAS and CMS have established that the force carriers of the weak interaction gain their masses via their interaction with the everywhere-present Higgs field**
- The strength of these interactions is measured to be of the right size to limit the effects of the weak interactions to distances shorter than 10^{-18} meters

A third jewel

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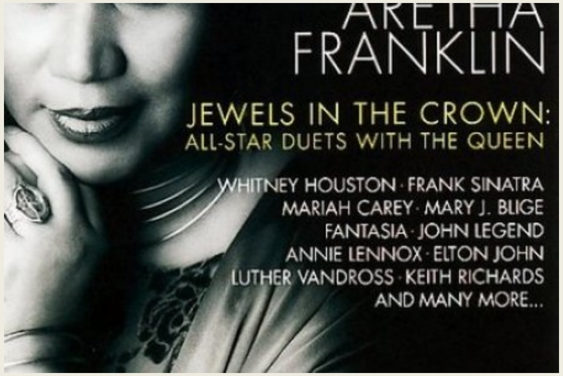
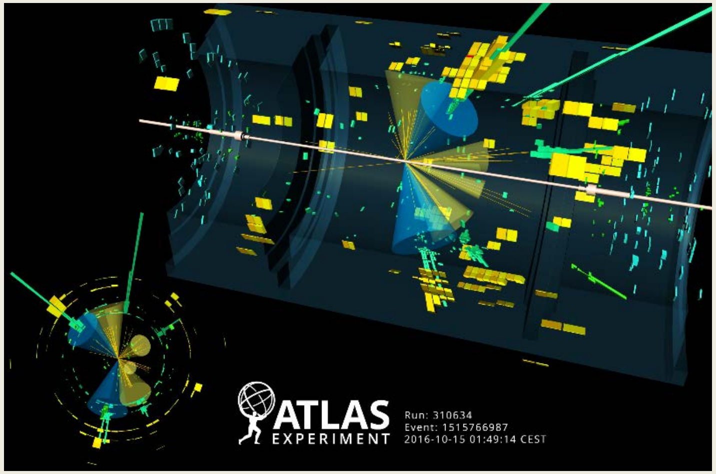


A third jewel

- **The discovery of the mechanism by which the τ-lepton and the t- and b-quarks gain their masses**

- The relevant processes:
  - $h \to \tau^+\tau^-$
  - $h \to b\bar{b}$
  - $pp \to ht\bar{t}$



Masses of matter particles

- Reminder – the matter particles f:
  - Up-type quarks: t, c, u
  - Down-type quarks: b, s, d
  - Charged leptons: τ, μ, e
  - Neutrinos: ν_3, ν_2, ν_1
- The symmetry that predicted $m_{W,Z} = 0$ predicts also $m_f = 0$
- Experiments established $m_f \neq 0$ (except, perhaps, the lightest ν)
- ???

A possible solution

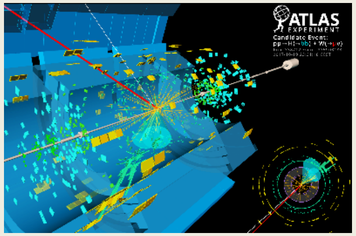
- The symmetry is spontaneously broken in the GS of the Universe
- Opens the door to $m_f \neq 0$
- But by what mechanism?
- Another open question that was (partially) answered by ATLAS and CMS

A specific scenario

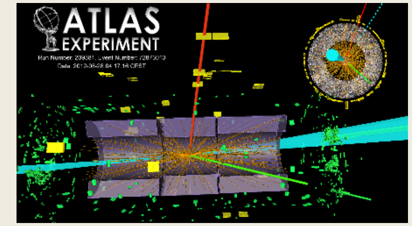
- The Higgs field, which slows down the W- and Z-bosons, can also slow down the matter particles
- But for this to happen, a new type of interaction has to exist: an interaction mediated by a spin-0 mediator, the Higgs boson itself
- "Yukawa interaction" – never observed before*

Consequences

- Discovery of $h \to f\bar{f}$ would mean a discovery of a new type of interaction, the Yukawa interaction
- "The theory loses nothing of its predictive power": The strength of the interaction of a matter particle f with the Higgs *field*, measured by m_f, is closely related to the strength of interaction of f with the Higgs *particle*, measured by $\Gamma(h \to f\bar{f})$ and, for the top, by $\sigma(pp \to ht\bar{t})$



ATLAS/CMS

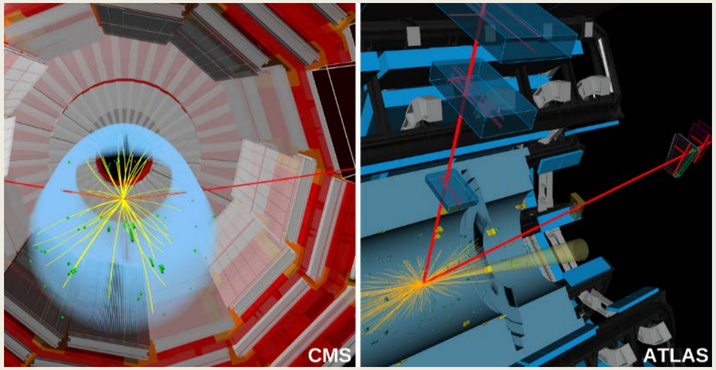


- $\mu_{\tau^+\tau^-} = 1.15^{+0.16}_{-0.15}$ [PDG 2022]
  - Within present experimental accuracy, $\Gamma(h \to \tau^+\tau^-)$ has the value that corresponds to the strength of interaction that would give the τ-lepton its mass
- $\mu_{b\bar{b}} = 0.98 \pm 0.12$ [PDG 2022]
  - Within present experimental accuracy, $\Gamma(h \to b\bar{b})$ has the value that corresponds to the strength of interaction that would give the b-quark its mass
- $\mu_{ht\bar{t}} = 1.10 \pm 0.18$ [PDG 2022]
  - Within present experimental accuracy, $\sigma(pp \to ht\bar{t})$ has the value that corresponds to the strength of interaction that would give the t-quark its mass

The third jewel - summary

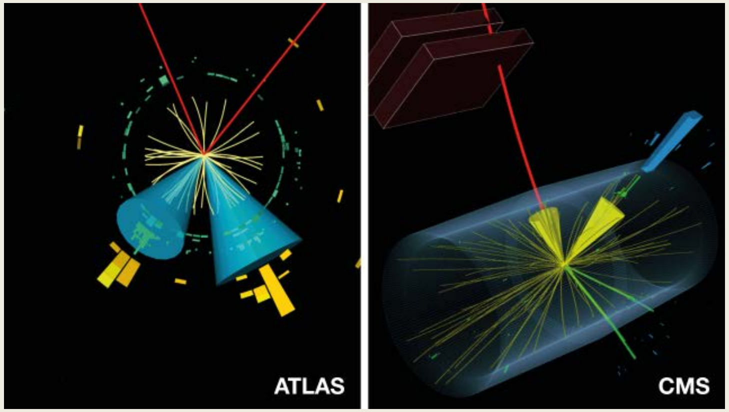
- **ATLAS and CMS have discovered that the third generation particles – the tau lepton, the bottom quark and the top quark – gain their masses via their interaction with the everywhere-present Higgs field**
- This is also the discovery of a new, and very special type of interaction: the Yukawa interaction, mediated by a spin-0 force carrier, the Higgs boson

The latest jewel



- **The discovery of the mechanism by which the μ-lepton (a second generation particle) gains its mass**
- The relevant process: $h \to \mu^+\mu^-$
- $\mu_{\mu^+\mu^-} = 1.19 \pm 0.34$ [PDG 2022]
  - Within present experimental accuracy, $\Gamma(h \to \mu^+\mu^-)$ has the value that corresponds to the strength of interaction that would give the μ-lepton its mass
  - For comparison, if the μ-lepton derived its mass from $d = 6$ terms, we would find $\mu_{\mu^+\mu^-} = 9$

On the way
to yet another jewel



- **The discovery of the mechanism by which the c-quark (a second generation particle) gains its mass**
- The relevant process: $h \to c\bar{c}$
- $1.2 < \mu_{c\bar{c}} < 26$ (at 95% CL) [CMS, arXiv:2205.05550]
- $\mu_{c\bar{c}}/\mu_{b\bar{b}} < 20$ (at 95% CL) [ATLAS, arXiv:2201.11428]
  - $y_c = 0$ excluded
  - $y_c < y_b$ established
  - If the c-quark derives its mass from $d = 6$ terms $\Longrightarrow \mu_{c\bar{c}} = 9$

The SM interactions

interaction	fermions	force carrier	coupling	flavor
EM	u, d, ℓ	A^0	eQ	universal
Strong	u, d	G	g_s	universal
NC weak	all	Z^0	$g(T_3 - s_W^2 Q)/c_W$	universal
CC weak	$\bar{u}d/\bar{\nu}\ell$	$W^\pm$	$gV/g\mathbf{1}$	FC/universal
Yukawa	u, d, ℓ	h	y_f	Diagonal

Epilogue

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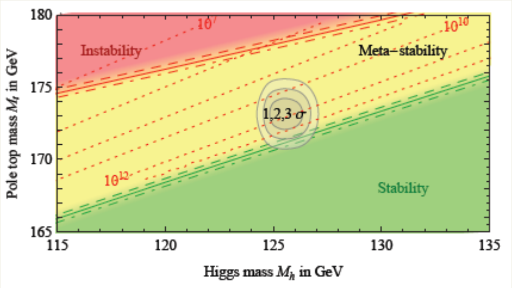
New Questions

– The value of m_h implies that our Universe is likely to be in an unstable state. In the (far) future, a transition should happen to an entirely different Universe

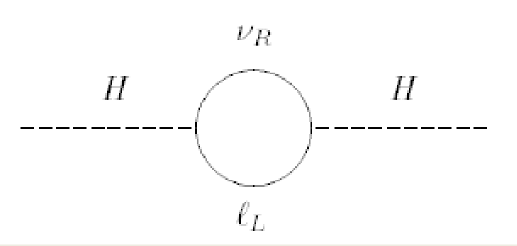
- Is the fundamental structure of the entire Universe only a temporary one?

Degrassi et al, 1205.6497



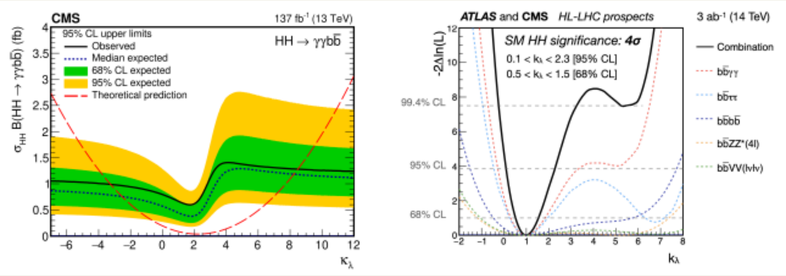
– The lightness of m_h, compared to m_{Planck}, or to Λ_{seesaw}, requires, within QFT, extreme fine-tuning

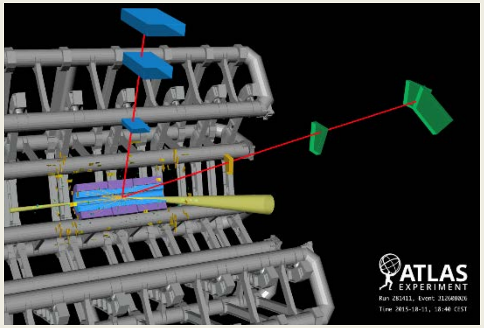
- Is Nature in fact unnatural?



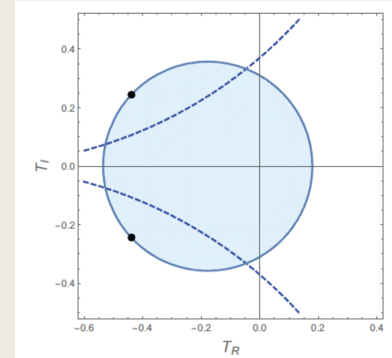
More Jewels

- What happened at the electroweak phase transition ($t_{\text{universe}} \sim 10^{-11}$seconds!)?
  - Strongly 1st-order or smooth crossover?
  - $\Gamma(h \to \text{invisible}), \Gamma(h \to gg), \Gamma(h \to \gamma\gamma)$ …
  - $\sigma(e^+e^- \to hZ)$
- What is the Higgs boson self coupling (λ_{hhh})?
  - The shape of the Higgs potential





My Own Work



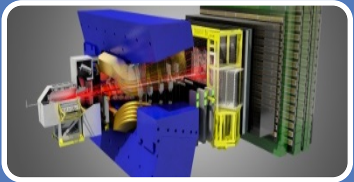
- $\mu_{\mu^+\mu^-} < 1.7$: A complex Yukawa coupling of the muon cannot be the dominant CP-violating source of the baryon asymmetry
- Yet, it could account for $O(16\%)$ of Y_B
- $\mu_{\tau^+\tau^-} = 0.91 \pm 0.13$: A complex Yukawa coupling of the tau can be the dominant CP-violating source of the baryon asymmetry
- The top and bottom Yukawa couplings cannot:
  - $Y_B^{(t)} \leq 0.02 Y_B^{\text{obs}}$, $Y_B^{(b)} \leq 0.04 Y_B^{\text{obs}}$
- PRL 124 (2020) 18; JHEP 05 (2020) 056; JHEP 07 (2021) 060
- E. Fuchs, M. Losada, YN, Y. Viernik,



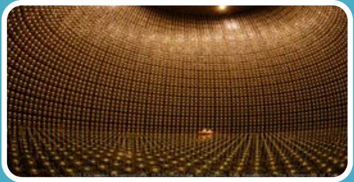
Conclusions

The LHC experiments have already several jewels – major discoveries – in their crown

There are additional jewels – major discoveries – guaranteed to be added to it



There are numerous other significant results from the LHC experiments



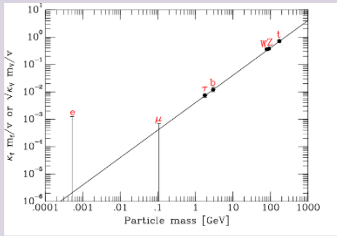
Major progress is expected also in other HEP experiments (neutrinos, flavor, EDMs…)

SM: $Y_F = (\sqrt{2}/v) M_F$

Proportionality	• ${}^{y_i}/_{y_j} = {}^{m_i}/_{m_j} \quad (y_i \equiv Y_{ii})$
Factor of proportionality	• ${}^{y_i}/_{m_i} = {}^{\sqrt{2}}/_{v}$
Diagonality	• $Y_{ij} = 0$ for $i \neq j$
CP conserving	• $Im({}^{y_i}/_{m_i}) = 0$

Experimental tests

Proportionality + Factor



Diagonality

- $\mathrm{BR}_{\mu\tau} < 1.5 \times 10^{-3}$
- $\mathrm{BR}_{e\tau} < 2.2 \times 10^{-3}$
- $\mathrm{BR}_{e\mu} < 6.1 \times 10^{-5}$
- $\mathrm{BR}_{t\to ch} < 1.1 \times 10^{-3}$
- $\mathrm{BR}_{t\to uh} < 1.2 \times 10^{-3}$

CP conserving

- $f_{CP}^{\tau} = -0.02 \pm 0.32$
- $f_{CP}^{t} = +0.00 \pm 0.33$

Experimental Higgs Physics

- $\mu_{\text{combined}} = 1.13 \pm 0.06$
- $\mu_{WW^*} = 1.19 \pm 0.12$
- $\mu_{ZZ^*} = 1.01 \pm 0.07$
- $\mu_{\gamma\gamma} = 1.10 \pm 0.07$
- $\mu_{b\bar{b}} = 0.98 \pm 0.12$
- $\mu_{c\bar{c}} = 37 \pm 19$
- $\mu_{\tau^+\tau^-} = 1.15 \pm 0.15$
- $\mu_{\mu^+\mu^-} = 1.19 \pm 0.34$
- $\mu_{t\bar{t}h} = 1.10 \pm 0.18$
- $\mu_{Z\gamma} < 3.6$
- $\mu_{\text{ggF}} = 1.07 \pm 0.08$
- $\mu_{\text{VBF}} = 1.21 \pm 0.24$

- $\text{BR}_{e^+e^-} < 3.6 \times 10^{-4}$
- $\text{BR}_{\mu\tau} < 1.5 \times 10^{-3}$
- $\text{BR}_{e\tau} < 2.2 \times 10^{-3}$
- $\text{BR}_{e\mu} < 6.1 \times 10^{-5}$
- $\text{BR}_{t\to ch} < 1.1 \times 10^{-3}$
- $\text{BR}_{t\to uh} < 1.2 \times 10^{-3}$
- $\text{BR}_{\text{invisible}} < 0.19$

What is the scale of new physics?