HIggs Pairs and POtential

Arnaud Ferrari (UU)
on behalf of the HIPPO consortium

23 November 2021

Once upon a time in the Universe...

Only picoseconds after the Big Bang, the Universe experienced a phase transition into a state of lower energy, in which nearly all fundamental particles became massive by interacting with the *Higgs field*.

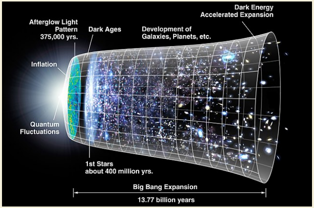

Image: NASA/WMAP Science Team

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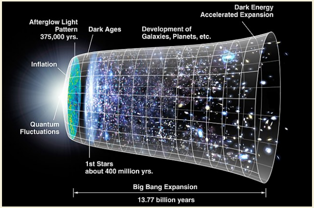
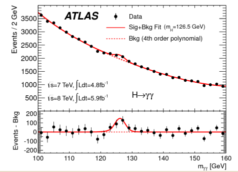
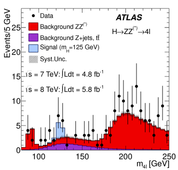


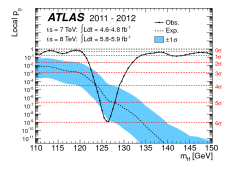
Image: NASA/WMAP Science Team

First came the Higgs-dependence Day...

4 July 2012: the ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC) announced the discovery of a spin-0 particle with a mass of about 125 GeV.







Images: ATLAS Collaboration, Phys. Lett. B 716 (2012) 1.

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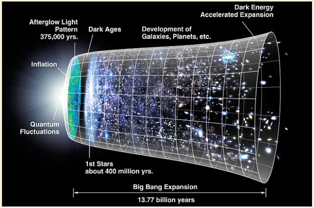

Image: NASA/WMAP Science Team

Then came the Nobel prize.

8 October 2013: the Nobel prize in physics was awarded to Englert and Higgs ”for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s LHC”.

The Higgs field/boson is the cornerstone of the Standard Model

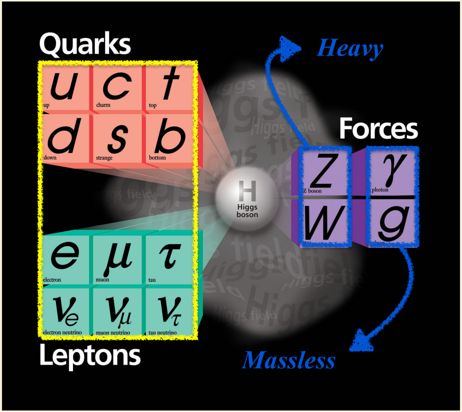

Image: Fermilab communications

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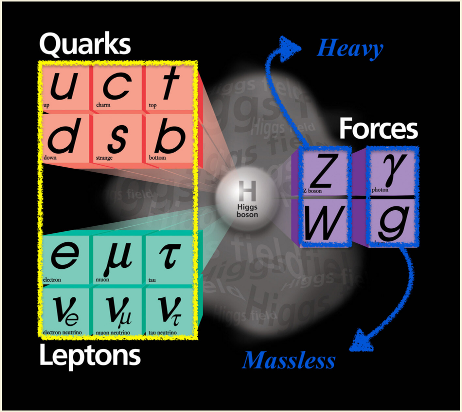


Image: Fermilab communications

And this all fits on a mug...

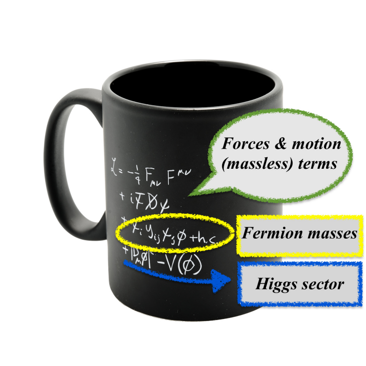


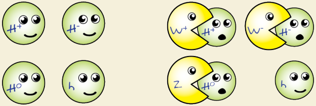
Image: https://visit.cern/shop

The Higgs sector in the Standard Model

In the mathematical framework of the Standard Model (SM), the Higgs field is a complex scalar doublet ϕ and the Higgs sector is described by:

$$\mathcal{L} = |D_\mu \phi|^2 - V(\phi).$$

The first term describes the coupling of ϕ to gauge bosons:



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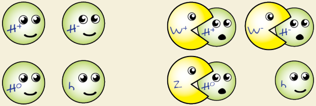
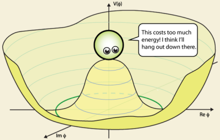


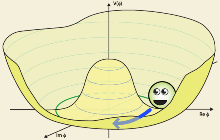
The second term, $V(\phi)$, is the Higgs potential. In its *minimal* form, it is:

$$V(\phi) = -\mu^2(\phi^\dagger \phi) + \lambda(\phi^\dagger \phi)^2.$$

If μ^2 and λ are both positive, the minimum of the Higgs potential lies at a vacuum expectation value $v \neq 0$.



Universe = a hot soup of massless stuff



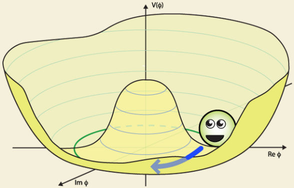
Universe = a cool place to live in

All Sketches from www.quantumdiaries.org

The ultimate probe of the Higgs sector

What's next?

After discovering the Higgs boson, one needs to fully measure the shape of the Higgs potential.

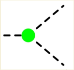


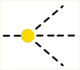
$< \phi_0 > = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \; v = \sqrt{\mu^2/\lambda}.$

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \overset{\phi \to v+H}{\supset} \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

mass term $\frac{1}{2} m_H^2 H^2$

self-interaction terms (never observed)

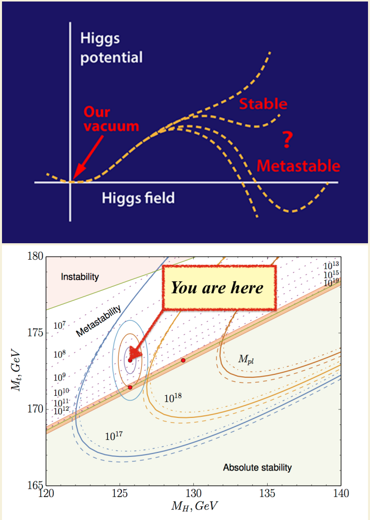




$\Longrightarrow$ In order to fully test the SM, one must observe the self-interaction term(s) and measure the Higgs boson self-coupling λ via Higgs boson pair production.

Why does it matter?

- The shape of the Higgs potential has other implications beyond the mass-generation mechanism.
- In particular, the vacuum state of the Universe depends on the Higgs potential.
- Whether the Universe exists in a true or metastable vacuum can be calculated from the Higgs boson and top-quark masses.
- In the absence of new physics that may affect the Higgs sector, there is a (borderline) possibility that our Universe is in a metastable state, i.e. a false vacuum.



Images: APS/Alan Stonebraker (top) and adapted from Phys. Rev. Lett. 115 (2015) 201802 (bottom).

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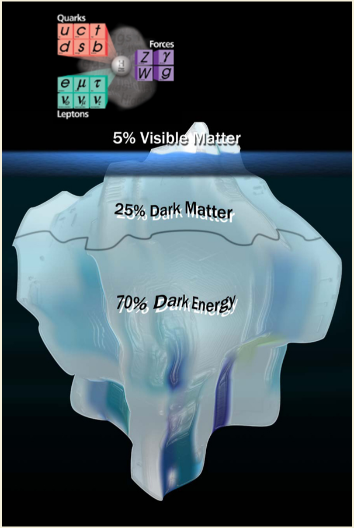
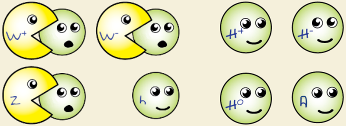


Sketches adapted from www.quantumdiaries.com

There are already many (indirect) hints of new physics beyond the SM! And its Higgs sector has serious short-comings:

- Why so many orders of magnitude across the fermion couplings to the Higgs field?
- m_H should be driven to a very large scale by quantum loop corrections, why such a remarkably precise cancellation against the bare mass?
- Why should the Higgs potential have a minimal form, and could there be an extended Higgs sector?



Higgs boson pair production at the LHC

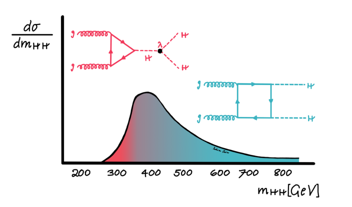
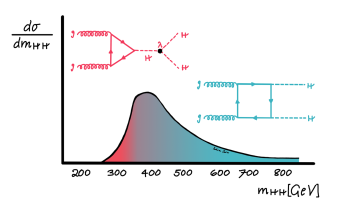


Image: ATLAS Collaboration

Non-resonant HH production in the SM:

Due to the destructive interference between the Higgs boson self-coupling and box diagrams, the production rate for Higgs boson pair production is very small in the SM, i.e. ~3 orders of magnitude smaller than for single Higgs boson production.

Higgs boson pair production at the LHC



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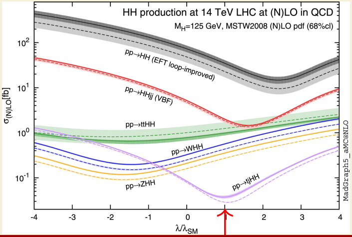
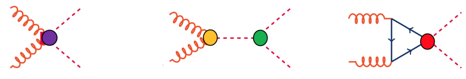
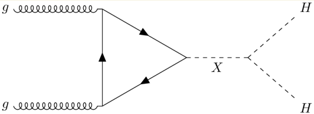
Non-resonant HH production in the SM:

Due to the destructive interference between the Higgs boson self-coupling and box diagrams, the production rate for Higgs boson pair production is very small in the SM, i.e. ∼3 orders of magnitude smaller than for single Higgs boson production.

Enhancements of the HH production rate can occur through variations of the Higgs boson coupling to top-quarks in the loops or to itself (λ, undetermined), through beyond-SM vertices or operators, or via e.g. a new resonance.







⟵ Image: Phys. Lett. B732 (2014) 142

HH search results from ATLAS

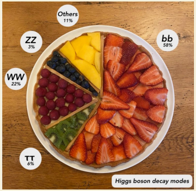


Image: @PhysicsCake (Twitter)

HH decays and search channels:

Upon production, the Higgs boson vanishes immediately, with a multitude of decay modes. In turn, this offers a (multitude)^2 of HH search channels, each with its own variety of experimental challenges and sensitivity reach.

Non-resonant HH search results in ATLAS based on LHC Run-2 data at 13 TeV

	bb	WW
bb	33% JHEP01(2019)030	
WW	25% JHEP04(2019)092	4.6% JHEP05(2019)124
$\tau\tau$	7.4% ATLAS-CONF-2021-030	2.5%
ZZ	3.1%	1.2%
$\gamma\gamma$	0.26% ATLAS-CONF-2021-016	0.10% EPJC78(2018)1007

27.5 – 36.1 fb^{-1}

139 fb^{-1}

$bbll$ ($l = e$ or μ)
($bbWW$, $bb\tau\tau$, $bbZZ$)
PLB801(2020)135145

Combination
($bbbb$, $bbWW$, $WWWW$, $bb\tau\tau$, $bb\gamma\gamma$ and $WW\gamma\gamma$)
PLB800(2020)135103

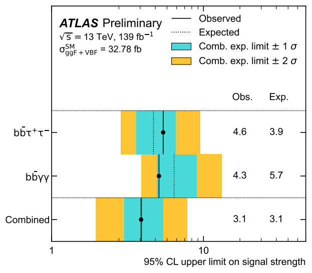
Combination
($bb\tau\tau$, $bb\gamma\gamma$)
ATLAS-CONF-2021-052

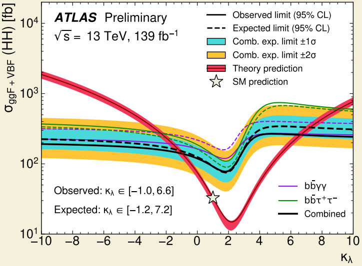
Table design by Petar Bokan

Latest HH search results from ATLAS

Recently, ATLAS published a statistical combination of two HH search results in the $bb\gamma\gamma$ and $bb\tau\tau$ channels:

- 95% confidence-level exclusion of $\sigma_{\mathrm{HH}}/\sigma_{\mathrm{HH}}^{\mathrm{SM}}$ above 3.1;
- 95% confidence-level constraint on the Higgs boson self-coupling: $\kappa_\lambda = \lambda/\lambda_{\mathrm{SM}} \in [-1.0; +6.6]$.



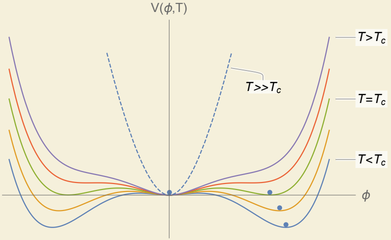


- A statistical combination of searches for **resonant** HH production was also presented, considering the *bbbb* channel as well.

Gravitational waves as a probe of the Higgs potential?

In the SM, the electroweak phase transition to the current ground state occurred in a smooth way (second-order) and cannot account for e.g. the matter-antimatter asymmetry in our Universe.

What about a more dramatic (first-order) electroweak phase transition?



Higgs potential vs temperature.
Image by Rikard Enberg

- At high T, the minimum is at $\phi = 0$ (symmetric vacuum, massless particles).
- When T decreases, a second minimum develops. At the critical temperature T_c the two minima have the same energy.
- Eventually, the minimum at $\phi \neq 0$ has the lowest energy – tunnelling is possible

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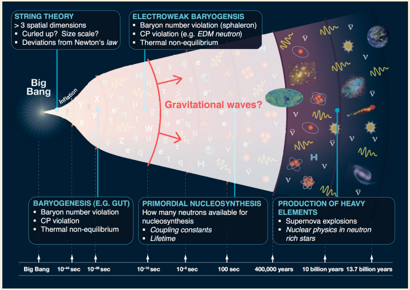

Image by David Weir

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- When T decreases, a second minimum develops. At the critical temperature T_c the two minima have the same energy.
- Eventually, the minimum at $\phi \neq 0$ has the lowest energy – tunnelling is possible
  $\Rightarrow$ First-order phase transition via bubble nucleation, with a huge amount of energy being released.
  $\Rightarrow$ Production of gravitational waves!

The HIPPO project

- HIPPO was formed by theorists and ATLAS members from four Swedish academic nodes to coherently tackle, experimentally and theoretically, the fundamental question of the Higgs boson self-coupling.
- The corresponding research topics are organised in four inter-connected work packages, which exploit the interplay between direct probes of the Higgs potential using HH production at colliders, and indirect probes of the electroweak phase transition in the early Universe using the predicted gravitational-wave background.
- The proposed project also fosters knowledge transfer and collaborative research, with itinerant workshops including outreach events.

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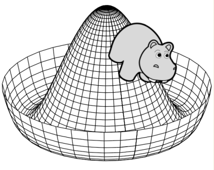
We don't have funding yet... but we are working hard on a KAW application.

Still, we have a cool logo and a HHilarious sense of HHumor!



Logo by Sara Strandberg

The HIPPO project – who are we?

Five KAW applicants:

- R. Enberg (UU, theory);
- A. Ferrari (UU, ATLAS experiment);
- J. Rathsman (LU, theory);
- J. Strandberg (KTH, ATLAS experiment);
- S. Strandberg (SU, ATLAS experiment).

Other faculty members and research staff:

C. Clément (SU), E. Lytken (LU), S. Moretti (UU), L. Panizzi (UU), R. Pasechnik (LU), J. Sjölin (SU) + a few post-docs and PhD students... we hope to recruit more!

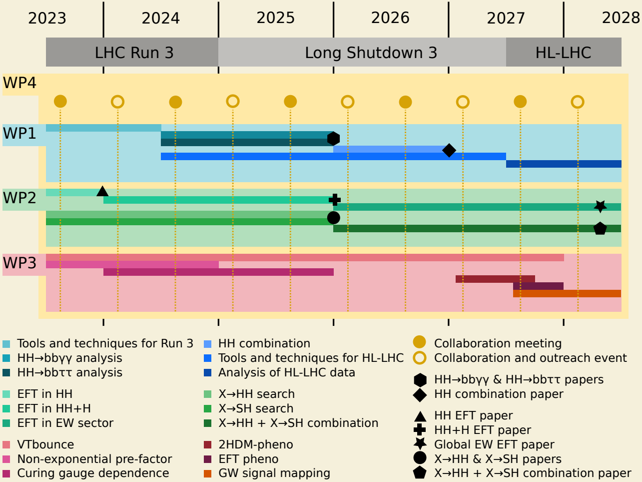
International collaborators:

- R. Gröber (HH expert, University of Padua, Italy);
- H. Haber (BSM Higgs physics expert, UC Santa Cruz, US);
- A. Morais (GW and cosmology expert, University of Aveiro, Portugal);
- D. Weir (GW expert and LISA experiment, University of Helsinki, Finland).

The HIPPO project – work packages

1. Establishing the Higgs boson self-coupling:
   - Exclude $\lambda = 0$ with ATLAS+CMS Run-2 statistical combination;
   - HH Run 3 ATLAS data-analyses ($bb\gamma\gamma$ and $bb\tau\tau$) and combinations;
   - Detector performance and novel analysis techniques.
2. Higgs boson pairs beyond the SM:
   - EFT interpretations of the ATLAS HH data-analyses (including combination with single-H measurements);
   - Searches for resonances decaying to HH and SH in ATLAS;
   - Theoretical interpretations based on simplified models (benchmarks: SUSY and Higgs compositeness).
3. Gravitational waves as probes of the Higgs potential:
   - Theoretical investigations of relations between details of the electroweak phase transition, the Higgs sector and the gravitational-wave spectrum.
   - Prospects for measurements with the LISA experiment.
   - Improved tool to compute the tunnelling probability.
4. Outreach and public events.

The HIPPO project – work packages



Summary

The HIPPO project aims at addressing, both experimentally and theoretically, the fundamental questions of the Higgs potential and the electroweak phase transition in the early Universe, with pairs of Higgs bosons and gravitational waves as probes.

We are at a historic junction, where the measurement of HH production in the terrestrial LHC experiments can shed light on the early Universe and its behaviour as a whole.

A funding application will be submitted to KAW in early 2022 in order to inject funding into the HIPPO project, for the recruitment of additional person-power at PhD and post-doctoral levels.