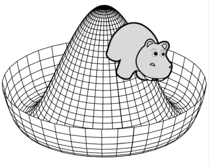
UPPSALA
UNIVERSITET



HIggs Pairs and POtential

Arnaud Ferrari

Uppsala, 6 December 2023

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*.

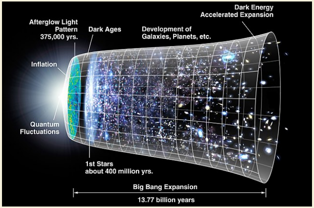


Image: NASA/WMAP Science Team

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*.

About 13.8 billion years later...

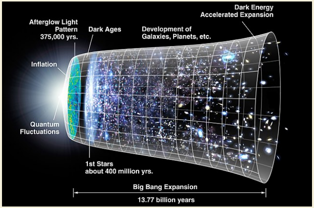
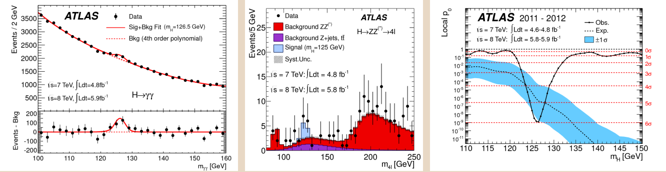


Image: NASA/WMAP Science Team

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.

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*.

About 13.8 billion years later...

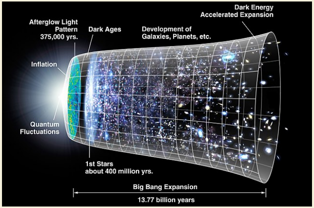


Image: NASA/WMAP Science Team

Then came the Nobel prize.

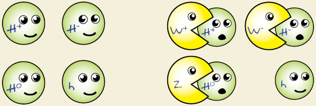
8 October 2013: the Nobel prize in physics was awarded to Englert and Higgs ”for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by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

The Higgs 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:

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

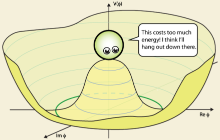
The first term describes the coupling of ϕ to gauge bosons:



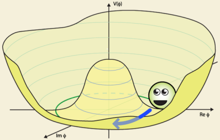
The second term, $V(\phi)$, is the Higgs potential. In its *minimal* form, it is:

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

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

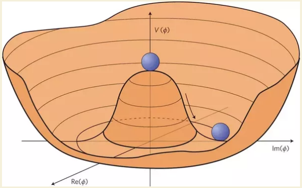


Universe = a cool place to live in

All Sketches from www.quantumdiaries.org

The ultimate probe of the scalar sector

- With the Higgs boson discovery, only a portion of the Higgs potential has been measured.
- Its shape completely determines the properties of the Higgs sector.

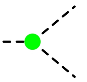


$$\langle \phi_0 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v = \sqrt{\mu^2/\lambda}.$$

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

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

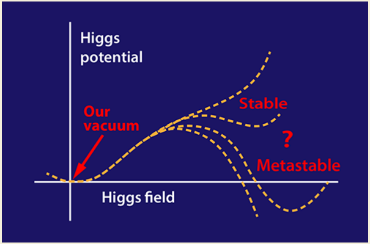
self-interaction terms (never observed)

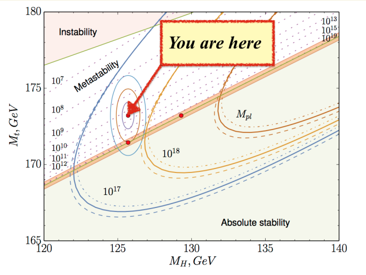


- Higgs boson pair (HH) production allows to probe *directly* the Higgs boson self-interaction and, ultimately, the shape of the Higgs potential.
- Any deviation from the self-interaction predicted by the SM would be a sign of new physics!

Why does it matter?

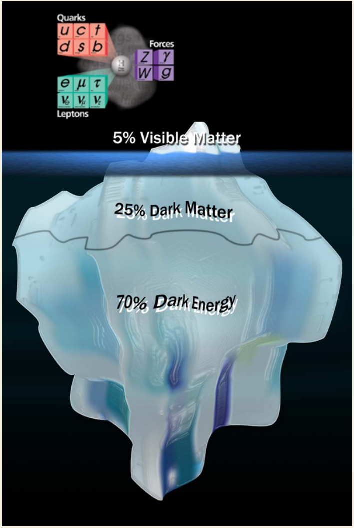
- The shape of the Higgs potential has other implications beyond the mass-generation mechanism.
- In particular, the vacuum state of the Universe depends on the Higgs potential.
- Whether the Universe exists in a true or metastable vacuum can be calculated from the Higgs boson and top-quark masses.
- 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).

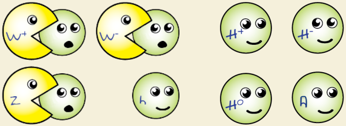
Why does it matter?



Sketches adapted from www.quantumdiaries.com

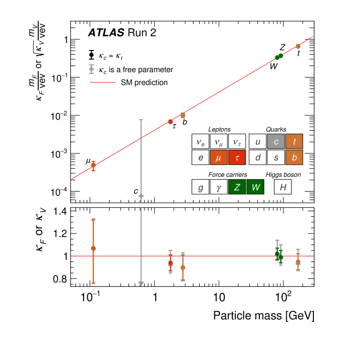
There are already many (indirect) hints of new physics beyond the SM! And its Higgs sector has serious short-comings:

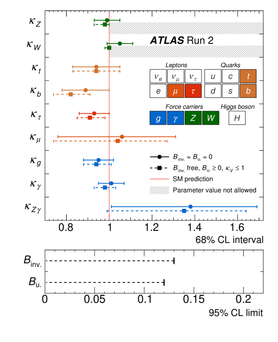
- Why so many orders of magnitude across the fermion couplings to the Higgs field?
- m_H should be driven to a very large scale by quantum loop corrections, why such a remarkably precise cancellation against the bare mass?
- Why should the Higgs potential have a minimal form, and could there be an extended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



A decade of Higgs boson measurements

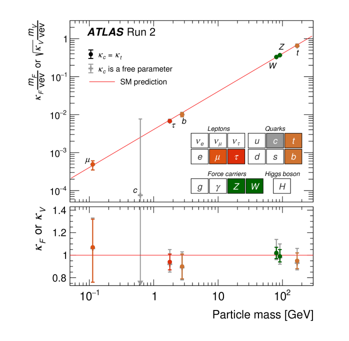
The Higgs boson couplings (or their modifiers $\kappa = c/c_{\mathrm{SM}}$ with respect to the SM predictions) have now been measured for vector bosons, third-generation fermions and muons... See e.g. Nature 607, 52 (2022).

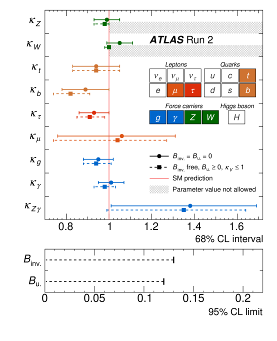




A decade of Higgs boson measurements

The Higgs boson couplings (or their modifiers $\kappa = c/c_{\text{SM}}$ with respect to the SM predictions) have now been measured for vector bosons, third-generation fermions and muons... See e.g. Nature 607, 52 (2022).



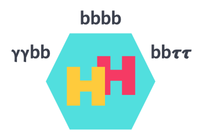


... but the Higgs boson self-coupling has not been observed yet!

HH search channels

- The experimental signature of the Higgs boson self-interaction is the simultaneous production of two Higgs bosons.
- However the corresponding event rate is three orders of magnitude smaller than for single Higgs boson production!
- Multitude of Higgs boson decay modes $\Rightarrow \mathcal{O}(\text{multitude}^2)$ of HH search channels, each with specific experimental challenges.

- Not a single "golden" channel.
- But (at least) three silver bullets!



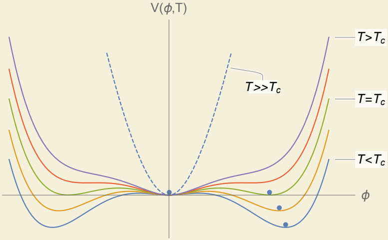
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Image by Katharine Leney

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

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?

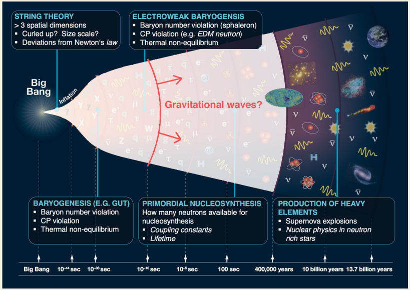


Image by David Weir

- 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
  $\Rightarrow$ First-order phase transition via bubble nucleation, with a huge amount of energy being released.
  $\Rightarrow$ Production of gravitational waves!

The HIPPO project

The HIPPO project aims at addressing, both experimentally and theoretically, the fundamental questions of the Higgs potential and of 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 was submitted to KAW in early 2022 in order to inject funding into the HIPPO project for recruitment of additional person-power at PhD and post-doctoral levels... but it was not selected :(

The HIPPO project

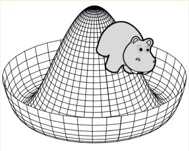
The HIPPO project aims at addressing, both experimentally and theoretically, the fundamental questions of the Higgs potential and of the electroweak phase transition in the early Universe, with pairs of Higgs bosons and gravitational waves as probes.

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 was submitted to KAW in early 2022 in order to inject funding into the HIPPO project for recruitment of additional person-power at PhD and post-doctoral levels... but it was not selected :(

- Where do we stand today?
- And what do we do next?

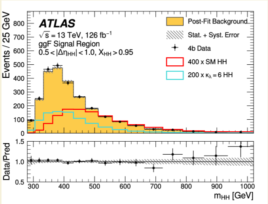
We cannot waste such a nice logo, can we?

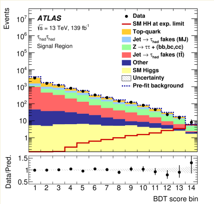


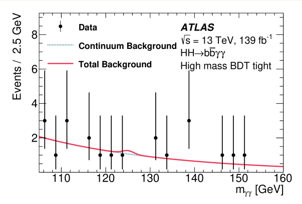
Logo by Sara Strandberg

Back to HH searches now...

Recent HH search results

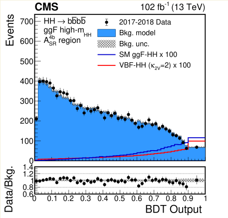


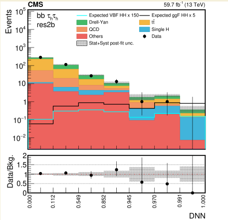


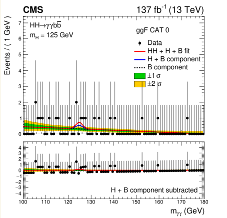


No golden HH search channel: statistical combinations are key!

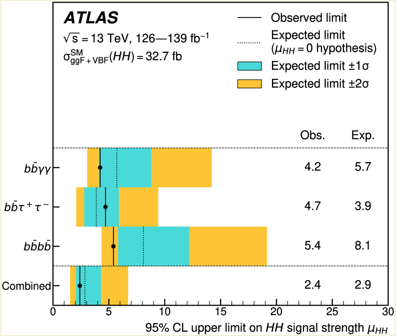
- ATLAS: Phys. Lett. B 843 (2023) 137745
- CMS: Nature 607, 60-68 (2022) + brand new CMS-PAS-HIG-23-006

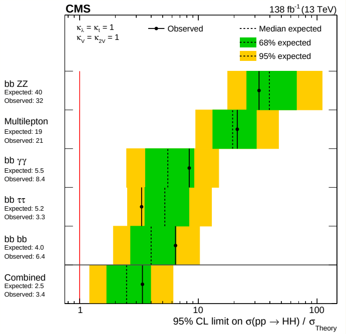






HH combined results: limits on $\sigma^{HH}_{ggF+VBF}$





Obs. (exp.) 95% CL combined limit: 2.4 (2.9) × SM prediction.

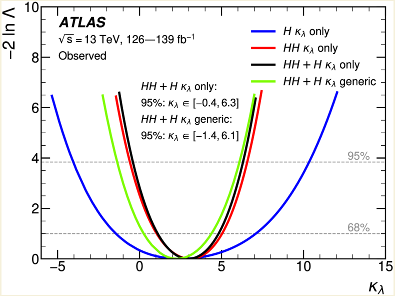
Obs. (exp.) 95% CL combined limit: 3.4 (2.5) × SM prediction.

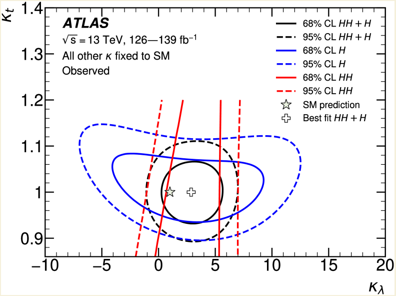
CMS: the individual *bbbb* limit combines resolved and boosted topologies.

HH+H: constraints on κ_λ [ATLAS]

Constraints on κ_λ via a scan of the negative-logarithm of the profile likelihood, for various fit configurations:

• HH searches only, single-H measurements only (via NLO electroweak corrections), or their combinations.





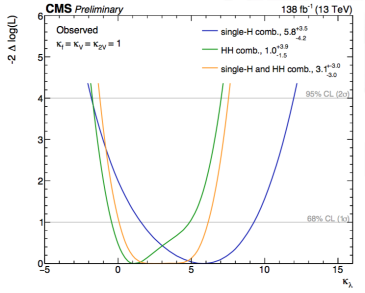
Summary of ATLAS HH+H combined results:

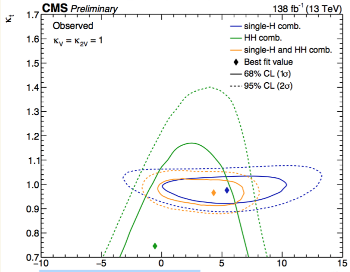
- Profile κ_λ only: $-0.4 < \kappa_\lambda < 6.3$ (95% CL).
- Profile κ_λ, κ_t, κ_V, κ_b, κ_τ: $-1.4 < \kappa_\lambda < 6.1$ (95% CL).

HH+H: constraints on κ_λ [CMS] New!

Constraints on κ_λ via a scan of the negative-logarithm of the profile likelihood, for various fit configurations:

• HH searches only, single-H measurements only (via NLO electroweak corrections), or their combinations.





CMS-PAS-HIG-23-006

Summary of ATLAS HH+H combined results:

- Profile κ_λ only: $-1.2 < \kappa_\lambda < 7.5$ (95% CL).
- Profile κ_λ, κ_t, κ_V, κ_b, κ_τ: $-1.4 < \kappa_\lambda < 7.8$ (95% CL).

Re-interpretations of HH searches in Effective Field Theories

$$\mathscr{L}_{\text{HEFT}} \supset -m_t \left(c_{tth} \frac{h}{v} + c_{tthh} \frac{h^2}{v^2} \right) \bar{t}t - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left(c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G^a_{\mu\nu} G^{a,\mu\nu}$$

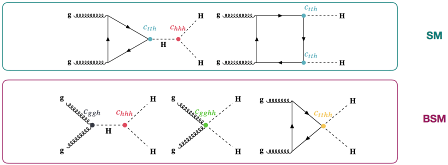
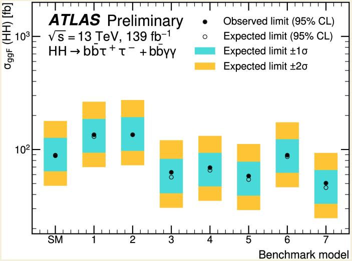


Image by Christina Dimitriadi

Benchmark model	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1	1	0	0	0
BM 1	3.94	0.94	1/2	1/3	−1/3
BM 2	6.84	0.61	0.0	−1/3	1/3
BM 3	2.21	1.05	1/2	1/2	−1/3
BM 4	2.79	0.61	−1/2	1/6	1/3
BM 5	3.95	1.17	1/6	−1/2	−1/3
BM 6	5.68	0.83	−1/2	1/3	1/3
BM 7	−0.10	0.94	1/6	−1/6	1

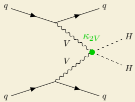
Seven HEFT benchmarks are used, with representative m_{HH} shape features.



ATL-PHYS-PUB-2022-019

Beyond the Higgs boson self-coupling (2)

Searches for VBF Higgs boson pair production allow to uniquely probe the VVHH quartic coupling.



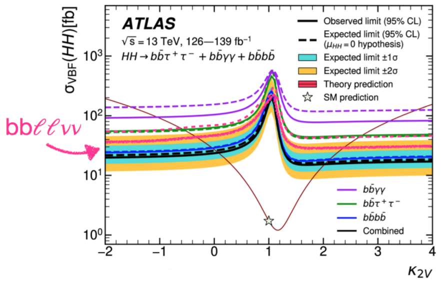
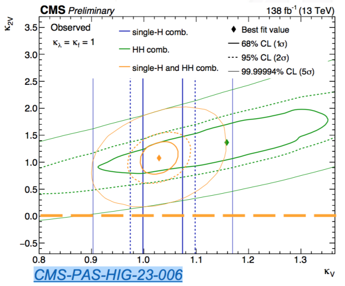


Image by TJ Khoo @ Higgs2023



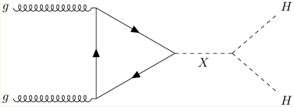
New @ Higgs2023

ATLAS: κ_{2V} values outside [0.1; 2.0] excluded at 95% CL... and additional constraints from recent HH search in $2b\ell\ell\nu\nu$ [arXiv:2310.11286].

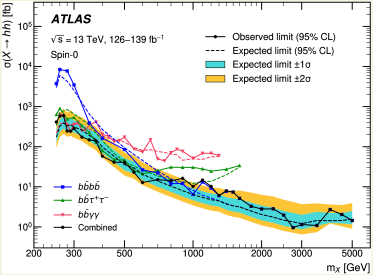
CMS: κ_{2V} values outside [0.7; 1.4] excluded at 95% CL... and $\kappa_{2V} = 0$ excluded with a significance $\geq 5\sigma$ for any value of κ_V.

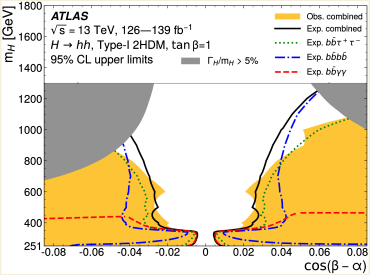
Beyond the Higgs boson self-coupling (3)

Pairs of Higgs bosons can also be produced via the decay of a hypothetical heavy resonance, and many BSM theories predict the existence of such heavy particles.



ATLAS individual and combined resonant HH limits ($bb\gamma\gamma$, $bb\tau\tau$, $bbbb$): the largest excess in the combined limit is found at 1.1 TeV and corresponds to a local (global) significance of 3.3σ (2.1σ).

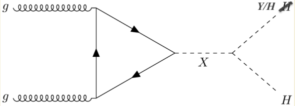




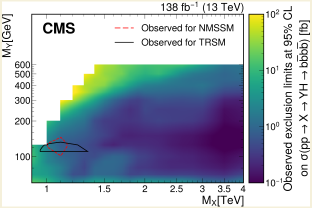
arxiv:2311.15956 (new!)

Beyond the Higgs boson self-coupling (4)

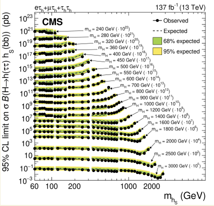
Asymmetric pairs of Higgs bosons can also be resonantly produced in some BSM scenarios, typically beyond the MSSM or CP-conserving 2HDM.



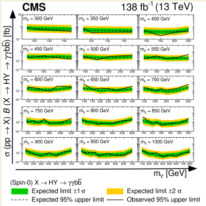
Several YH searches by CMS in $bbbb$, $bb\tau\tau$ and $bb\gamma\gamma$:



Phys. Lett. B 842 (2023) 137392



JHEP 11 (2021) 057



arXiv:2310.01643

YH $\to bb\gamma\gamma$: excess at $m_X = 650$ GeV and $m_Y = 90$ GeV, with a local (global) significance of 3.8 (2.8) standard deviations.

Latest ATLAS results relevant to HIPPO

- Re-analysis of the Run-2 dataset to search for non-resonant HH $\rightarrow b b \tau \tau$ (in Christina's talk).
- HH/YH in the $\rightarrow b b \gamma \gamma$ final state (in David and Olle's talks).
- What do we want to do together with Run-3 data?

09:00	→ 09:20	**Welcome and (extended) introduction** **Speaker:** Arnaud Ferrari (Uppsala University)	20m
09:20	→ 10:20	**Experimental session -- talks** Overview of ATLAS HH/SH results, CMS HH/SH results, plans for Run 3 **Convener:** Arnaud Ferrari (Uppsala University)	
	09:20	**Overview of ATLAS HH/SH Run-2 results and Run-3 plans - UU (15+5)** **Speaker:** Christina Dimitriadi (Uppsala University)	20m
	09:40	**Overview of ATLAS HH/SH Run-2 results and Run-3 plans - KTH (15+5)** **Speaker:** Olof Lundberg (KTH)	20m
	10:00	**Overview of ATLAS HH/SH Run-2 results and Run-3 plans - SU (15+5)** **Speaker:** David Brunner (SU)	20m
10:20	→ 10:40	**Experimental session -- discussions**	20m
10:40	→ 11:00	**Coffee break**	20m