Searching for beauty with beauty in the Higgs sector

Abraham Tishelman-Charny

Thursday, 7 March 2024
Union College colloquium

ATLAS EXPERIMENT
Brookhaven National Laboratory

Who am I?

- Abraham (Abe) Tishelman-Charny

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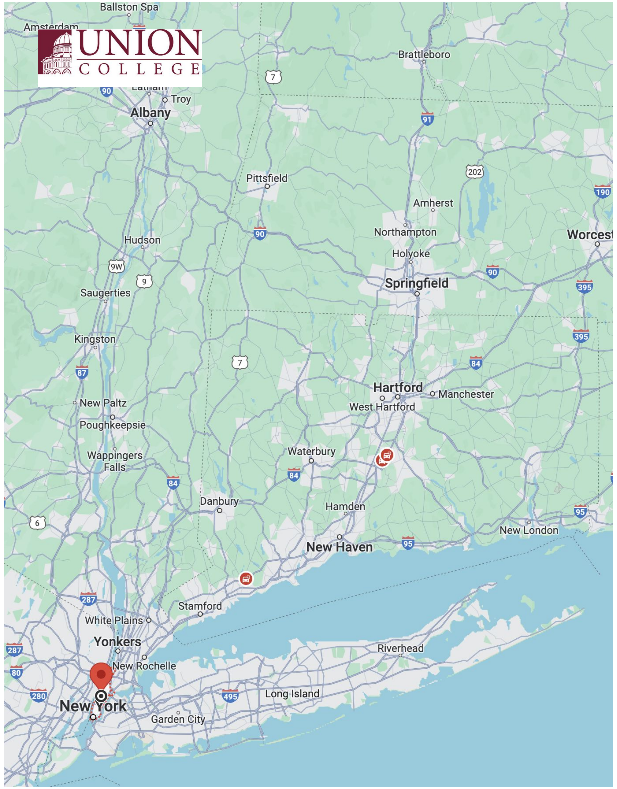
- 1994: Born, not far from here: **Manhattan, NY**



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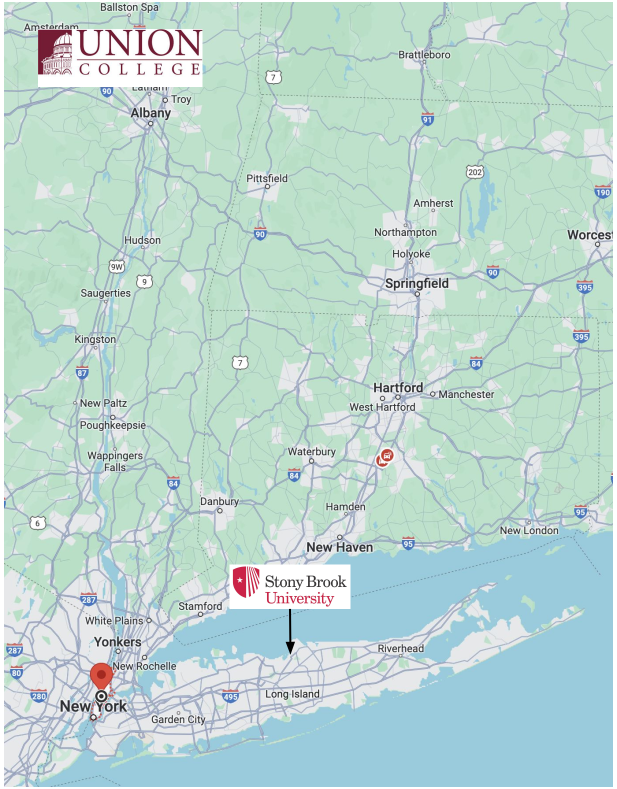

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- 2022: PhD from **Northeastern University** on the CMS experiment (Boston, then 4 years at CERN)

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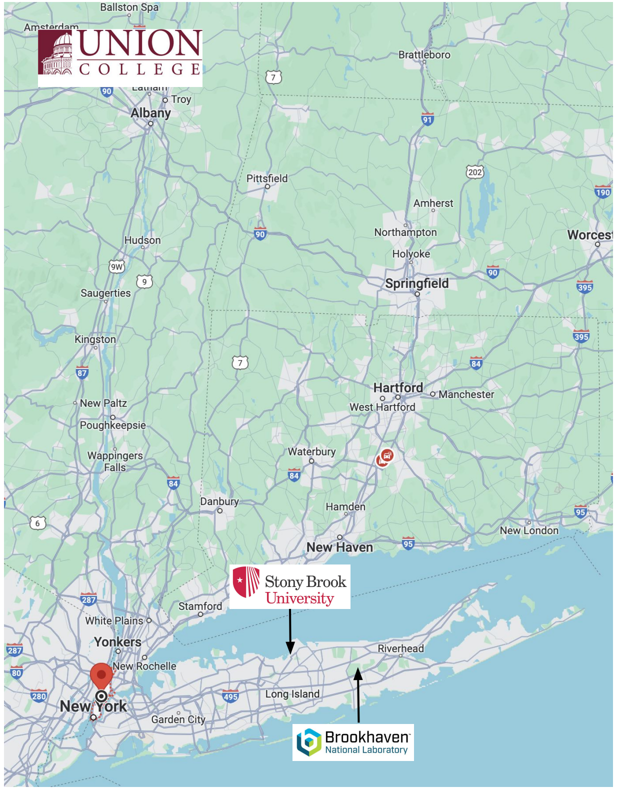
- 1994: Born, not far from here: **Manhattan, NY**
- 2016: B.S. in Physics:
  Stony Brook University
- 2022: PhD from **Northeastern University** on the CMS experiment (Boston, then 4 years at CERN)
- 2022: Started as a postdoc at **BNL**:
  - <u>**Experimental particle physics**</u>



Outline

I. The Higgs self-coupling
II. The ATLAS detector
III. Search for Higgs pair production at ATLAS
IV. Beyond the LHC

Next section

I. **The Higgs self-coupling**
II. The ATLAS detector
III. Search for Higgs pair production at ATLAS
IV. Beyond the LHC

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The standard model

- What do we know? What is our theoretical basis?

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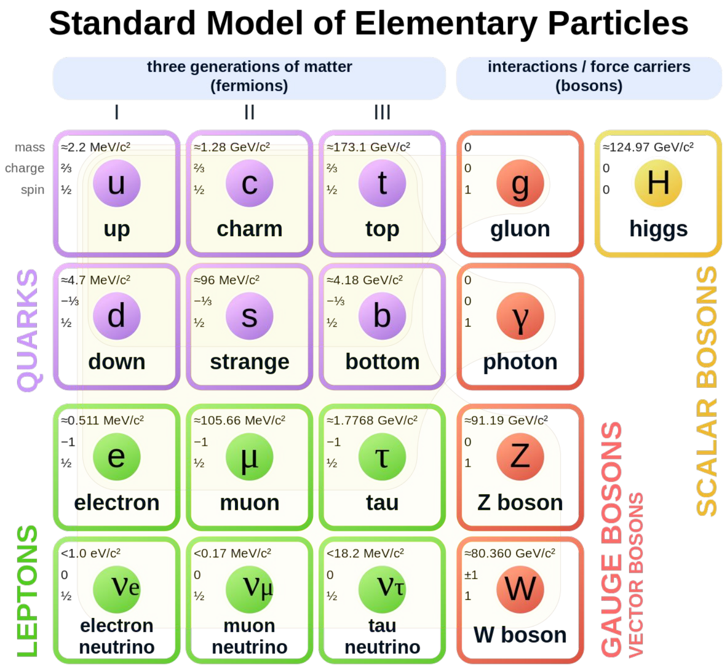
The standard model

- What do we know? What is our theoretical basis?

- The **Standard Model** (SM) of particle physics:
    - Defines elementary **particles**, and their **interactions**



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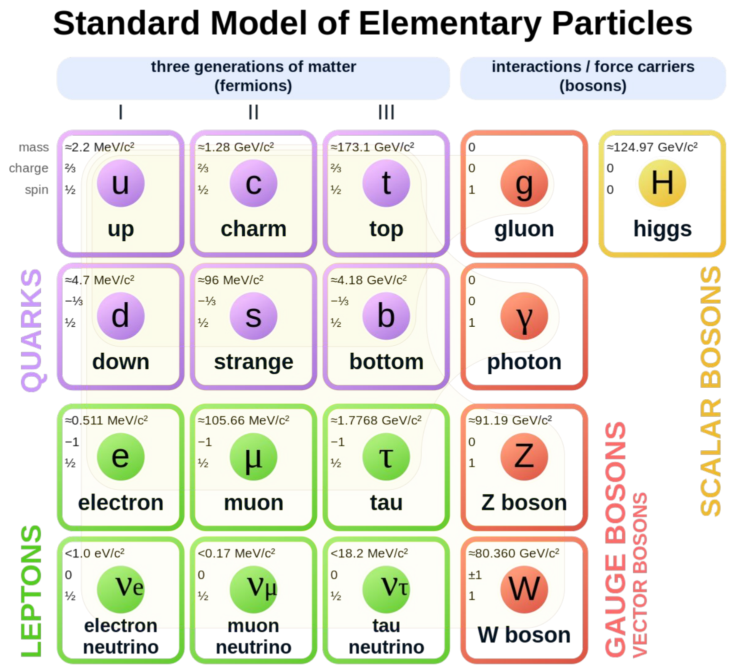
The standard model

- What do we know? What is our theoretical basis?

- The **Standard Model** (SM) of particle physics:
  - Defines elementary **particles**, and their **interactions**

- Extremely successful! Predicts **vast majority** of observed phenomena



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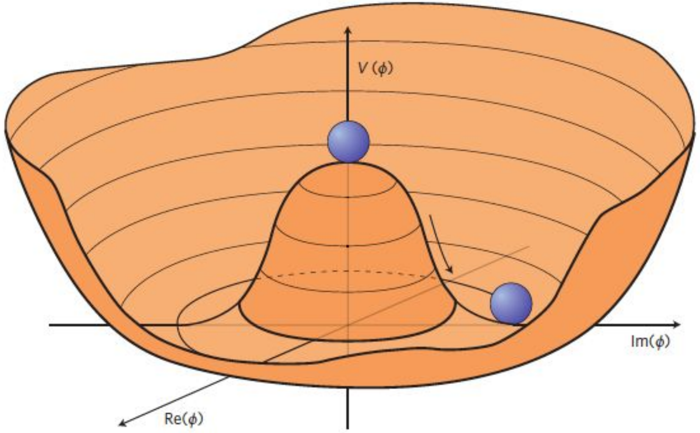
The Higgs boson

- **Higgs potential** determines nature of Higgs interactions with **other particles**

- Intertwined with **electroweak symmetry breaking** - process by which particles acquire **mass**



Higgs potential and mechanism

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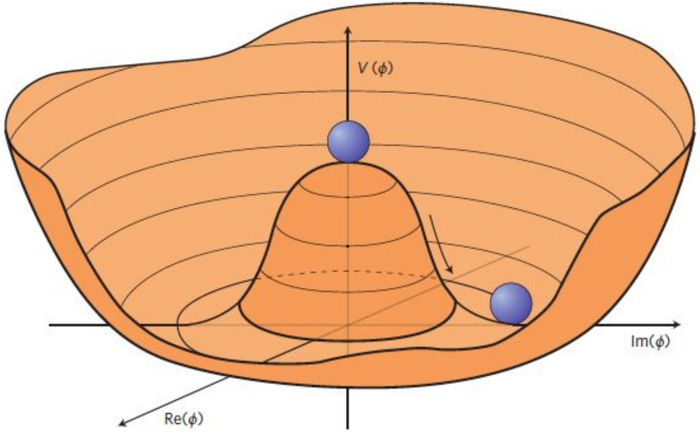
The Higgs boson

- **Higgs potential** determines nature of Higgs interactions with **other particles**
- Intertwined with **electroweak symmetry breaking** - process by which particles acquire **mass**
- Coupling lacking a precise measurement: **Higgs self-coupling (λ)**
  - Determines magnitude of Higgs interaction with itself, shape of the **Higgs potential**
- **<u>Has SM prediction we can compare to</u>**



Higgs potential and mechanism

$$V(h) = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$$

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The Higgs boson

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The Higgs boson

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- Experimentally observed in 2012!

4 July 2012: CERN main auditorium

The Higgs boson

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- Experimentally observed in 2012!
- Made expected splash in the **scientific** community

Physics Letters B 716 (2012) 1–29

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

PLB 716 (2012) 1-29

PLB 716 (2012) 30-61

The Higgs boson

- The **Higgs boson**: Theorized in the **1960s**

- Experimentally observed in 2012!

- Made expected splash in the **scientific** community

- Also made **international** news!

The New York Times

Physicists Find Elusive Particle Seen as Key to Universe

Share full article | 122

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson. Pool photo by Denis Balibouse

By Dennis Overbye

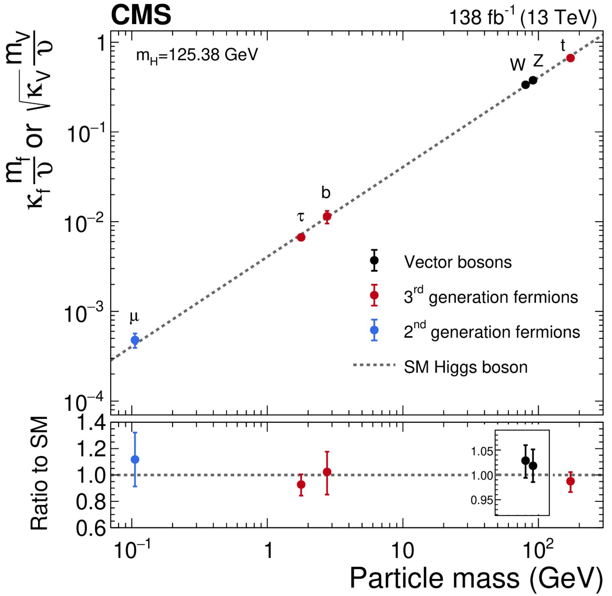
July 4, 2012

Characterizing the Higgs

- What do you do after observing a new particle?

Characterizing the Higgs

- What do you do after observing a new particle?
- You **characterize** it, and compare to **theory**



Nature 607, 60-68 (2022)

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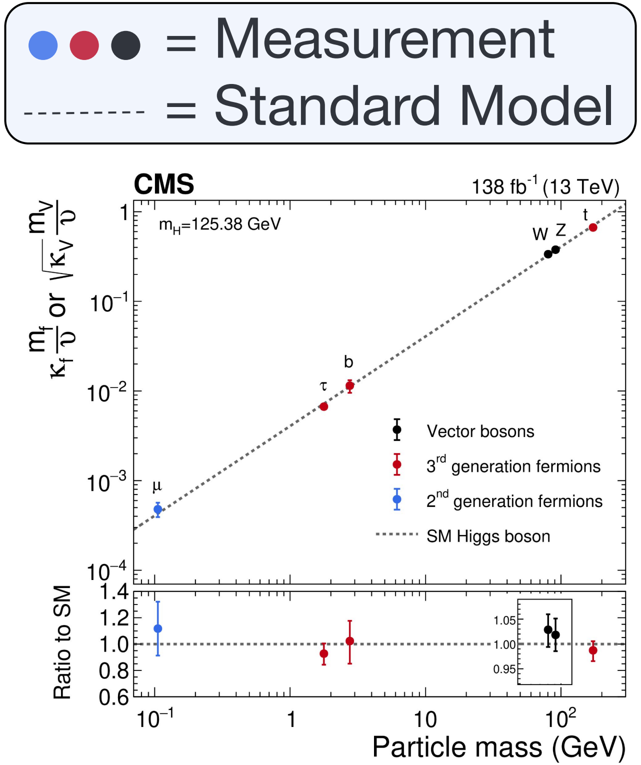
Characterizing the Higgs

- What do you do after observing a new particle?
- You **<u>characterize</u>** it, and compare to **theory**
- Since 2012, precise measurements of couplings, mass, spin, width, CP
- Came a long way,
  but **<u>there is more to measure</u>**:
  - The Higgs self-coupling



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Higgs pair production

Can directly access Higgs self-coupling via **Higgs pair production (HH)**

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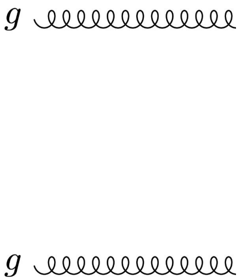
<u>Gluon fusion:</u>



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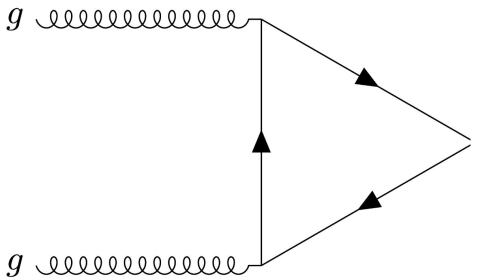

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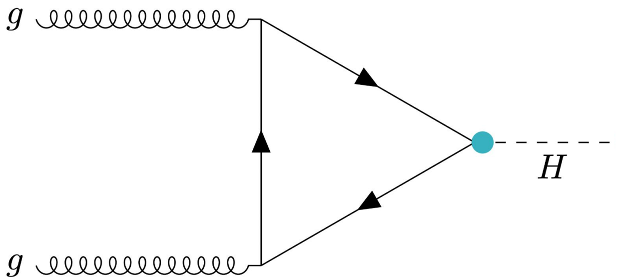

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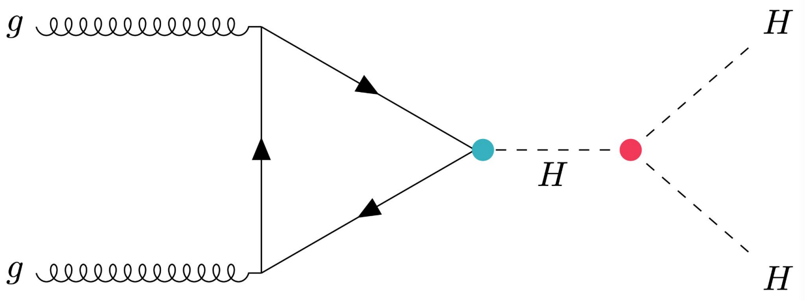

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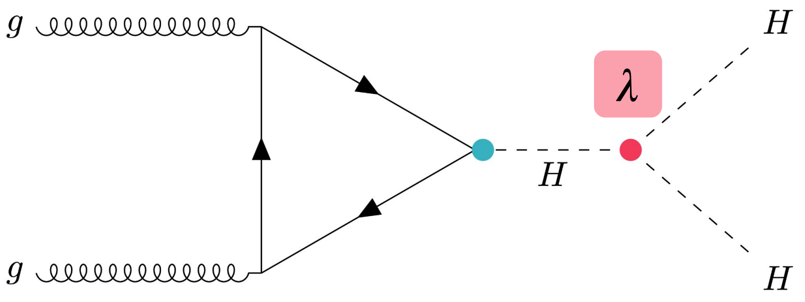

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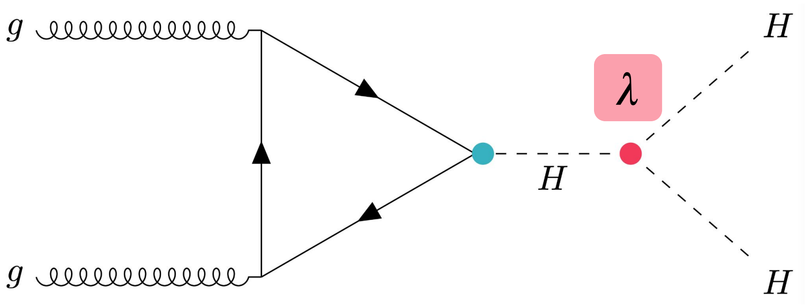
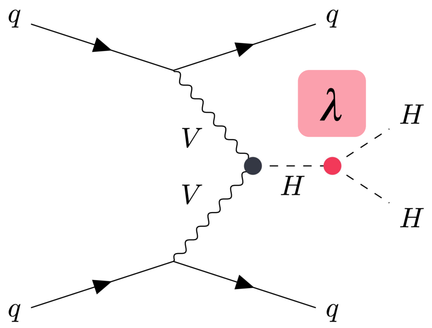


Vector boson fusion:



Higgs pair production

Can directly access Higgs self-coupling via **Higgs pair production (HH)**

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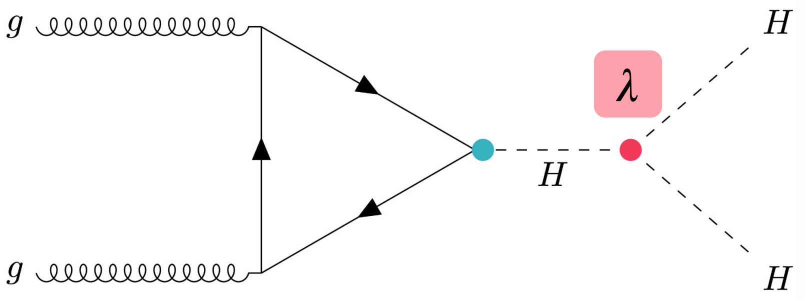

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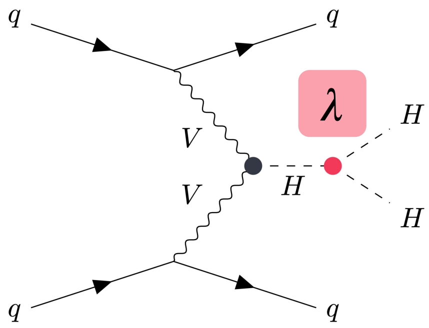

- Self-coupling affects **rate** of HH production, **momentum spectrum** of Higgs produced
- **Rare** process - need to select **final states** with good signal to background ratio

HH final states

- **Higgs boson** has many decay modes

Some Higgs decay modes

bb	WW	ττ	ZZ	γγ

HH final states

- **Higgs boson** has many decay modes
- Therefore, many **HH** decay modes

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
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γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

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HH final states

- **Higgs boson** has many decay modes
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- Most common: H→bb (and HH→bbbb) (~58% at 125 GeV)

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HH final states

- **Higgs boson** has many decay modes
- Therefore, many **HH** decay modes
- Most common: H→bb
  [(~58% at 125 GeV)]
- Final states have different **likelihoods**, leave different **detector signatures**

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= Existing results

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IV. Beyond the LHC

LHC

- Need a **machine** capable of producing HH pairs

LHC

- Need a **machine** capable of producing HH pairs: **Large Hadron Collider (LHC)**

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- Collides **protons**, heavy ions up to ~ 99.999999% the speed of light!

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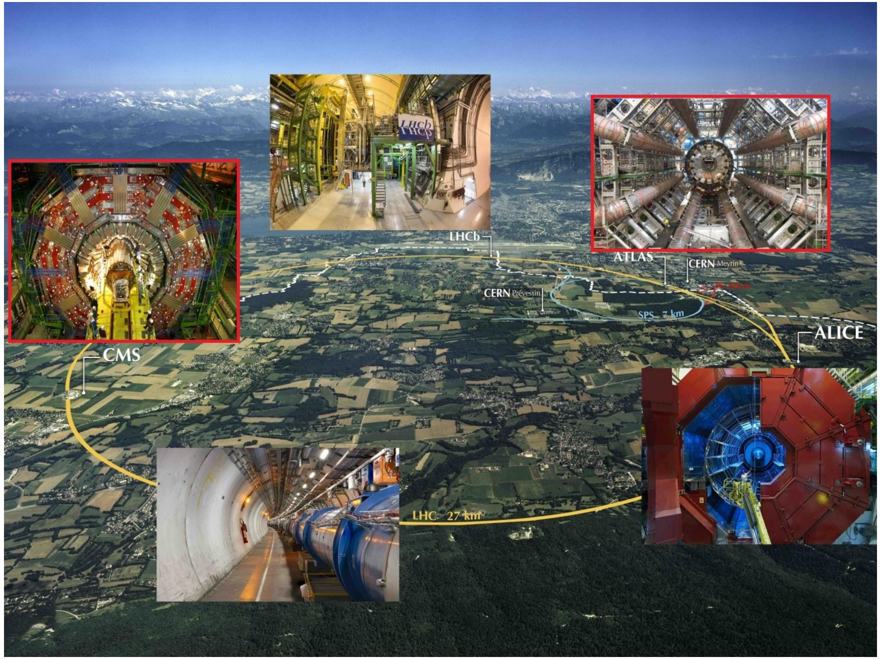
LHC

- Need a **machine** capable of producing HH pairs: **Large Hadron Collider (LHC)**

- Collides **protons**, heavy ions up to ~ 99.999999% the speed of light!

- Has **four detectors** stationed



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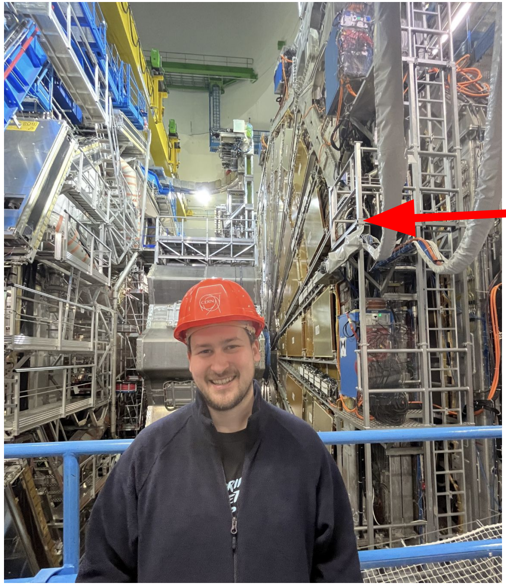
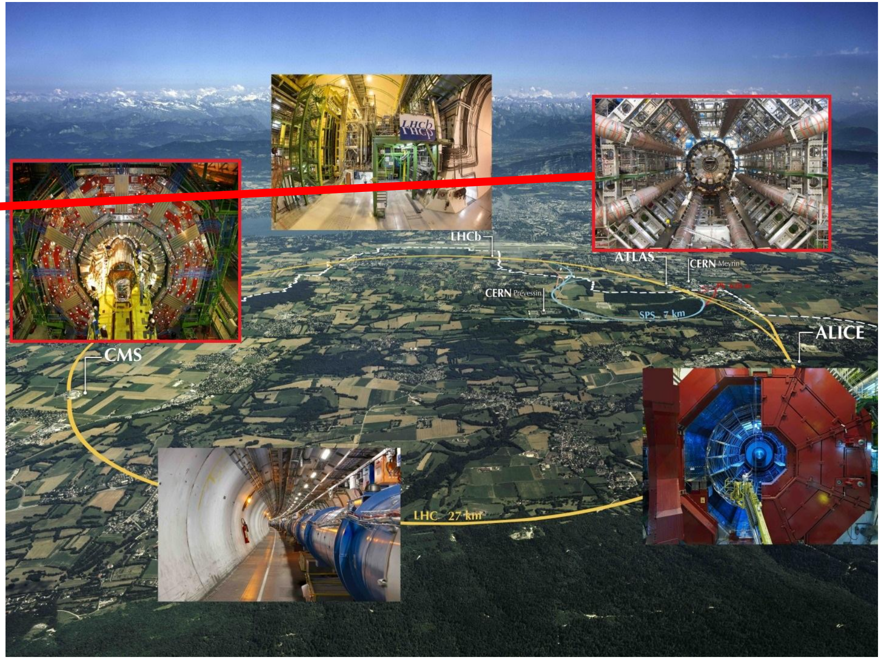


January 2024



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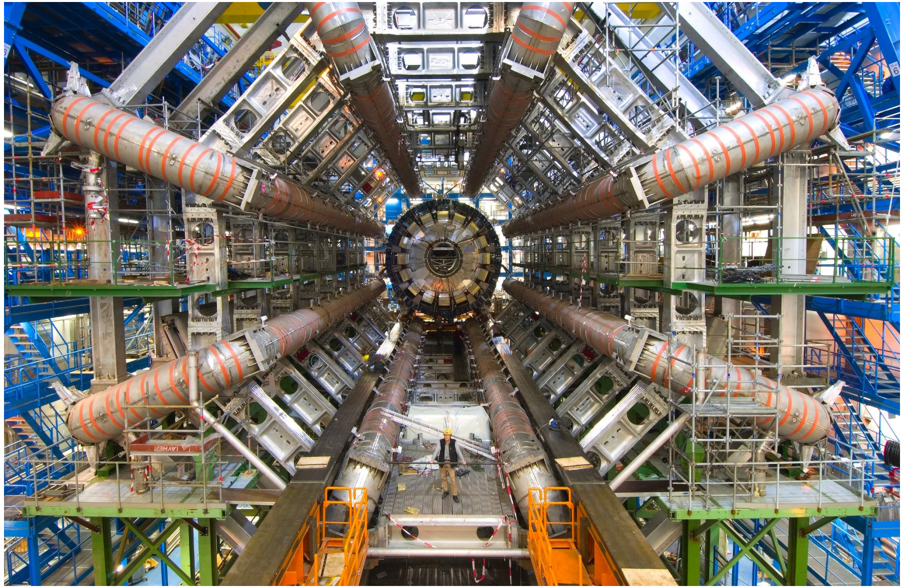
ATLAS

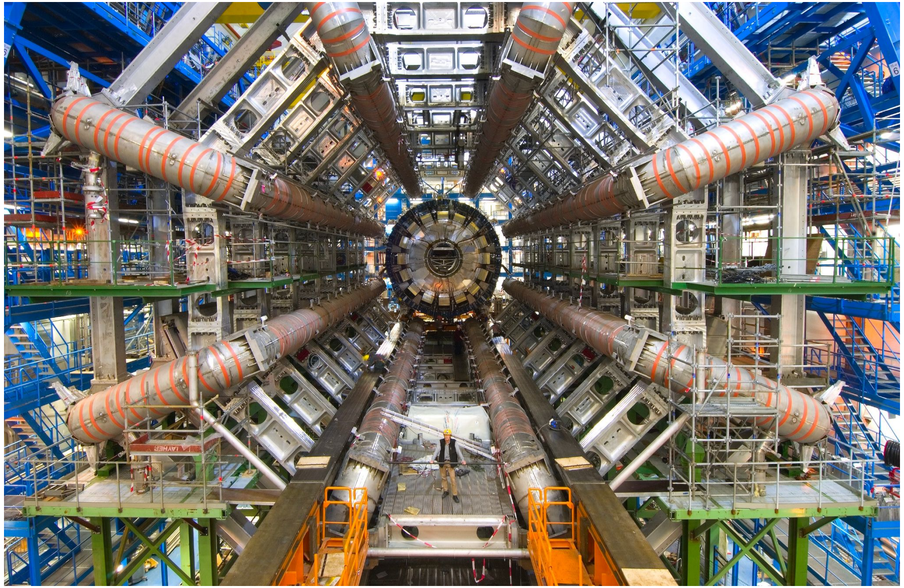
- ATLAS detector

- One of two **general purpose** LHC detectors



ATLAS

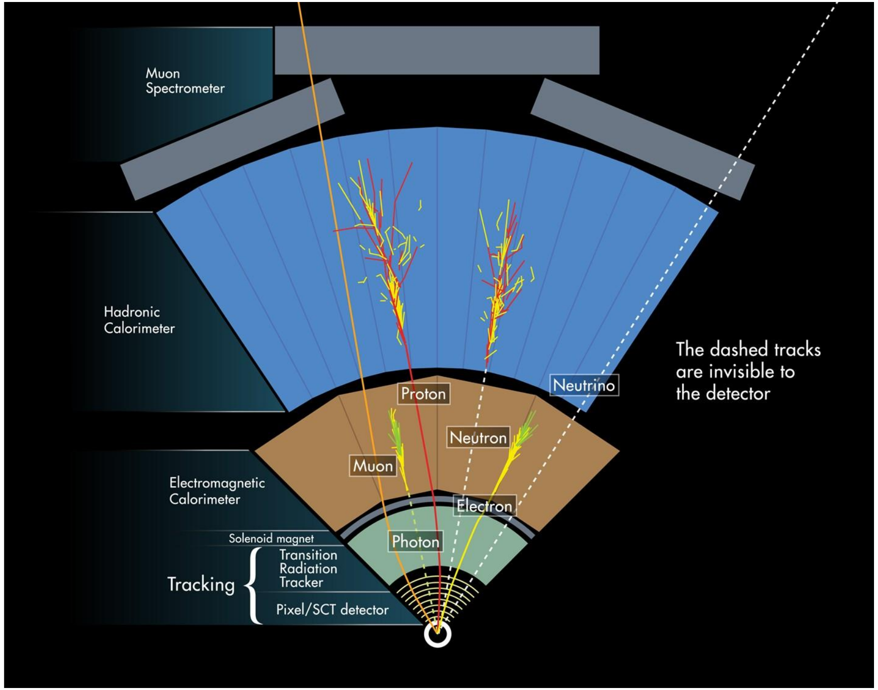
- ATLAS detector
- One of two **general purpose** LHC detectors
- Rich physics program:
    - **Higgs**, Dark matter, Electroweak, Supersymmetry, …



ATLAS

- Different **layers** detect different **particles** (needed for different final states!)

- Requires use of different detector **technologies**



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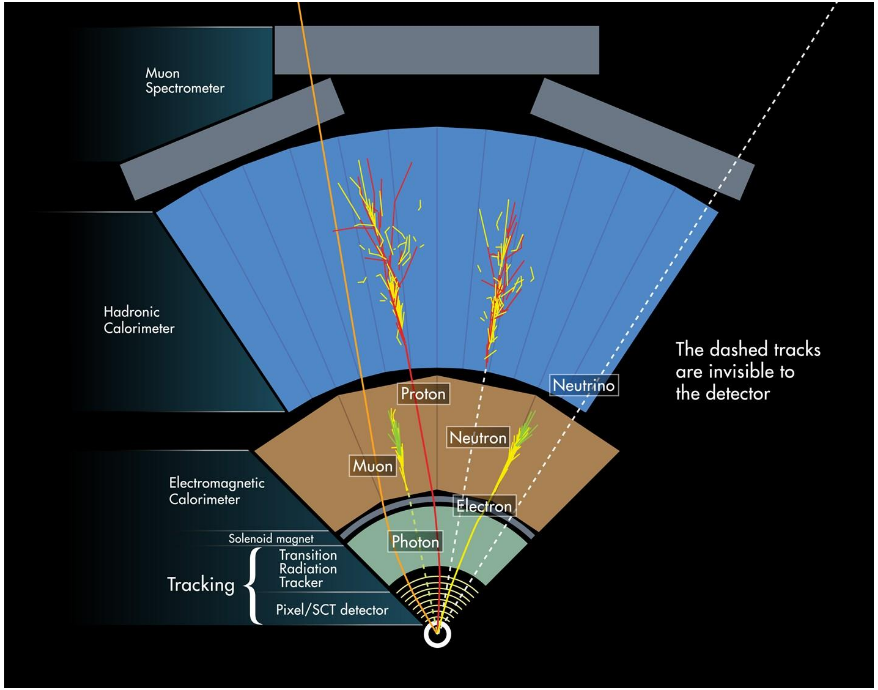
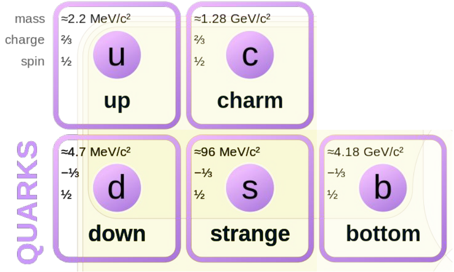
ATLAS

- Different **layers** detect different **particles** (needed for different final states!)
- Requires use of different detector **technologies**
- **Reconstruct** underlying physics **event** by working backwards from detector information



Hadronization

- In SM: **Quarks cannot exist freely**. Must bind with other quarks



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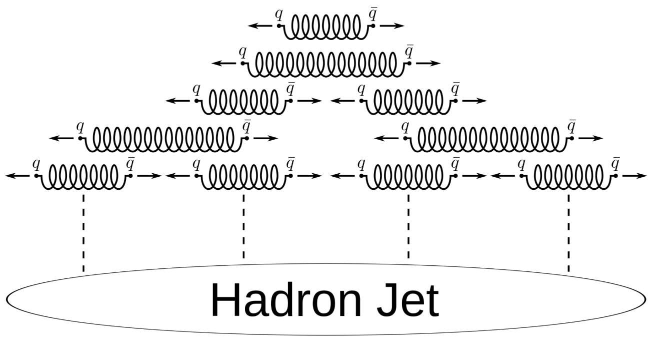
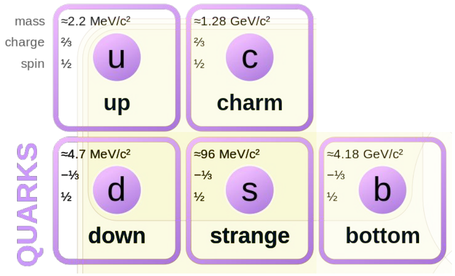
- When produced from Higgs decays, quarks separate and form **new pairs**, repeats





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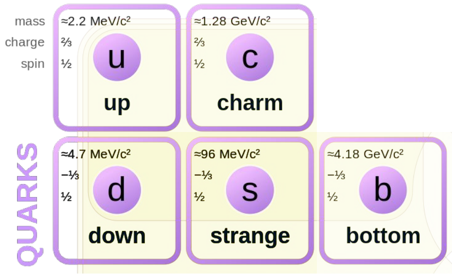
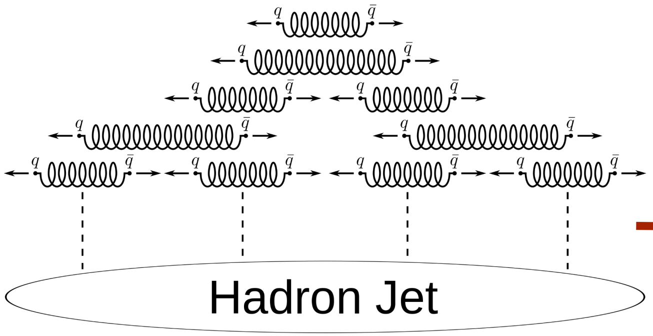
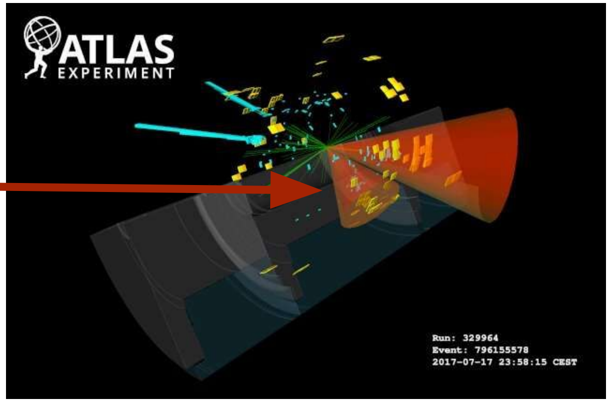


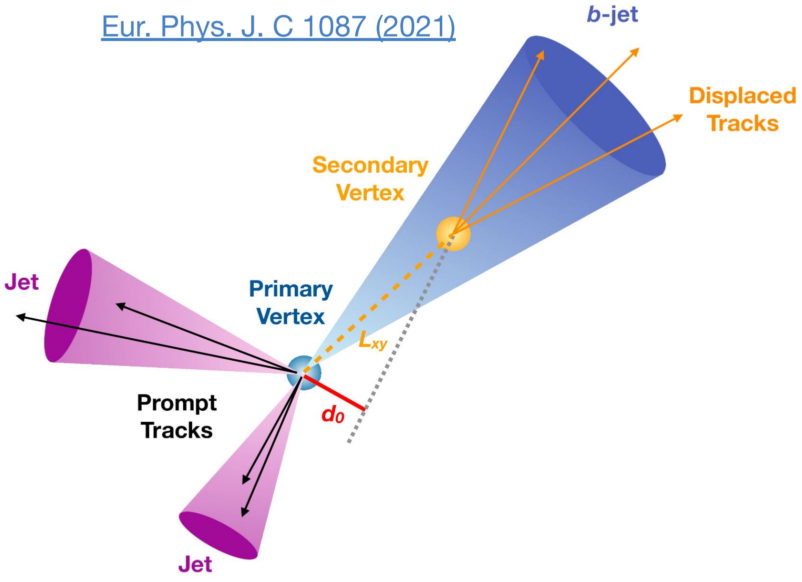




Bottom quarks

- The **bottom** (or **beauty**) quark: Relatively **heavy**

Eur. Phys. J. C 1087 (2021)



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- Propagates before hadronization: **b-jet**

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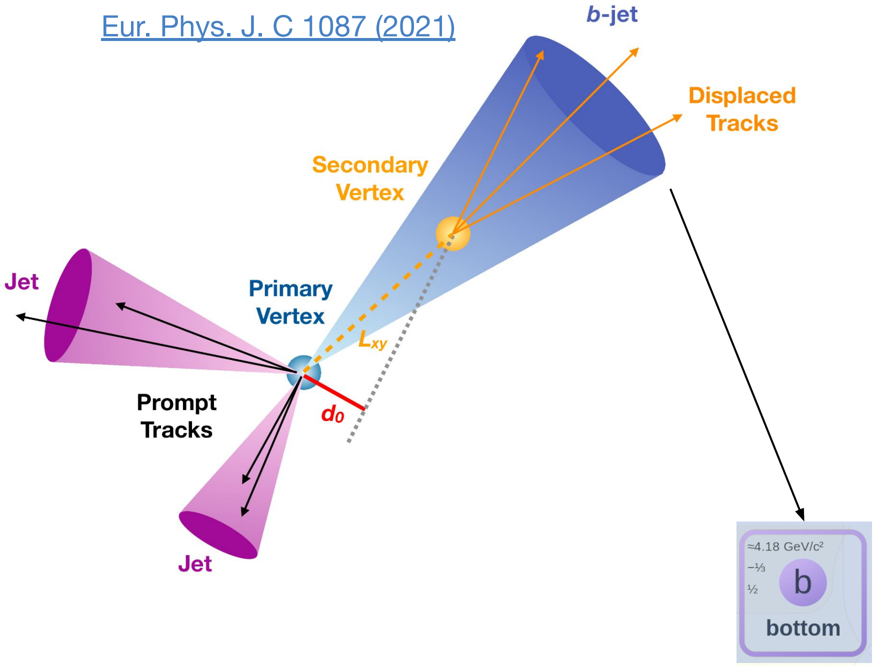
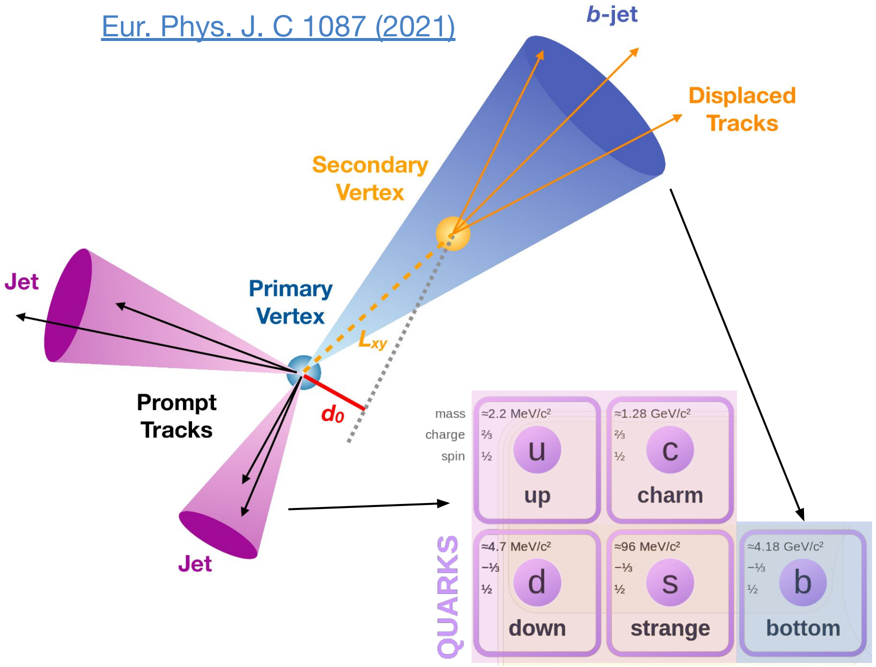


Bottom quarks

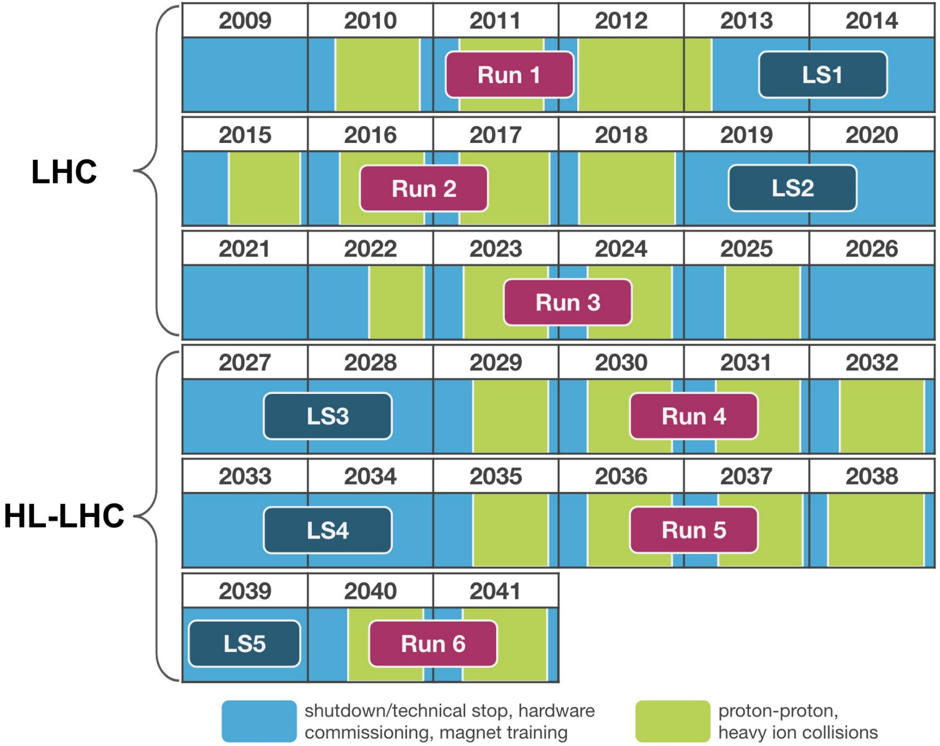
- The **bottom** (or **beauty**) quark: Relatively **heavy**
- Propagates before hadronization: **b-jet**
- **Distinctly different** signature! Can use to differentiate from **"lighter"** jets

Eur. Phys. J. C 1087 (2021)



Schedule

- LHC and ATLAS in operation since ~ 2009



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Schedule

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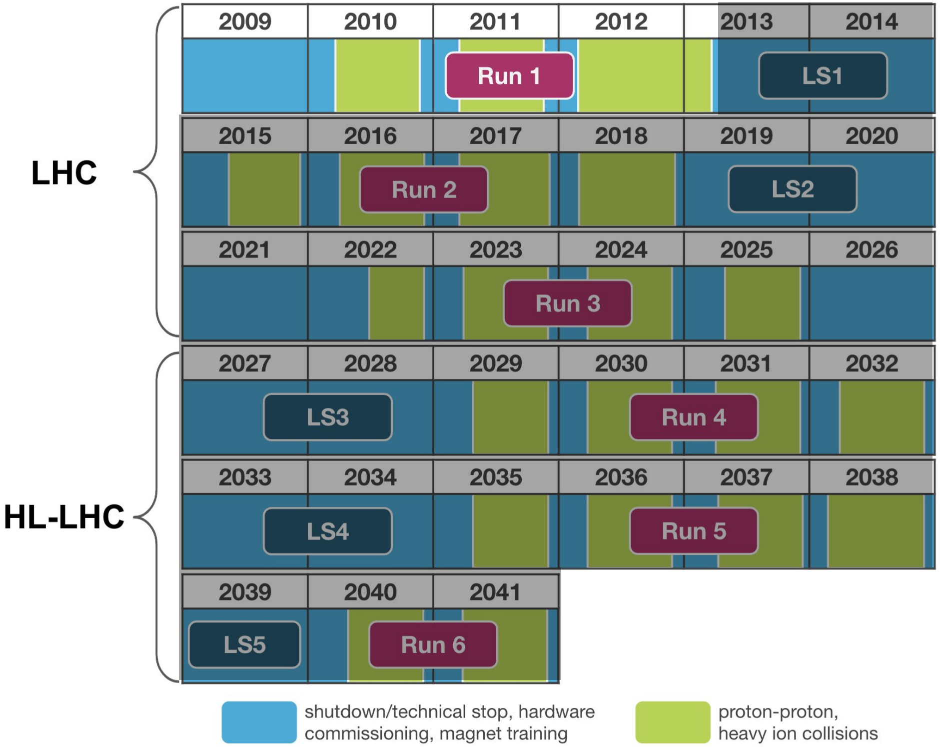
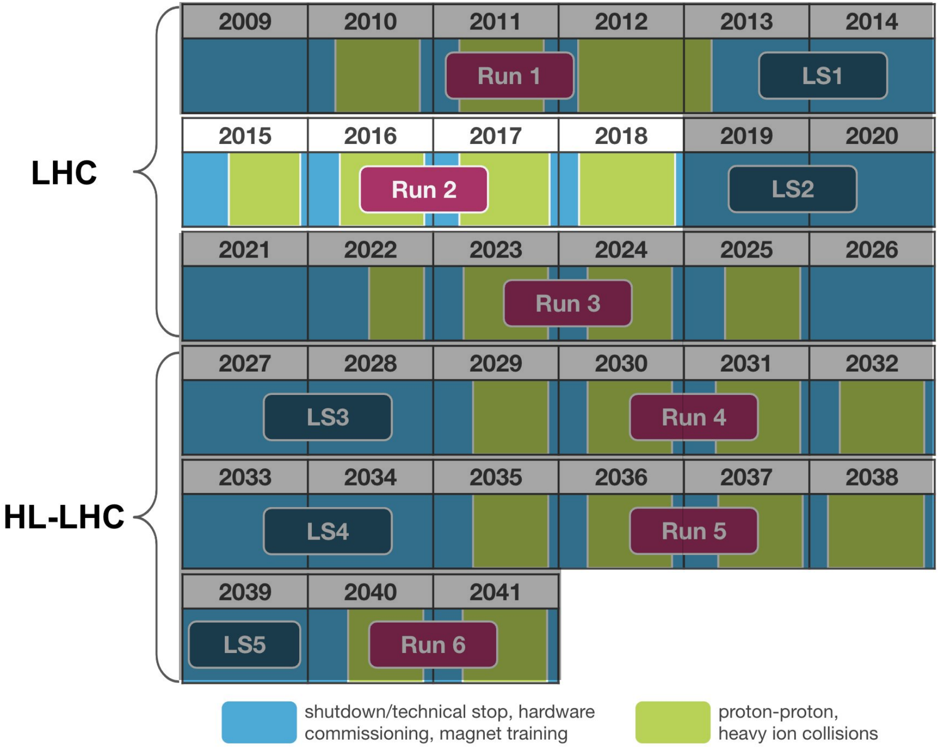


Schedule

- LHC and ATLAS in operation since ~ 2009
- Run 1: 2009-2013 (took data used for Higgs observation)
- **Run 2: 2015-2018**



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Outline

Search for Higgs pair production

- The Higgs can decay into different pairs of particles

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WW	25%	4.6%			
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Search for Higgs pair production

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- In ATLAS, look for HH in many final states and **combine** for more sensitive results

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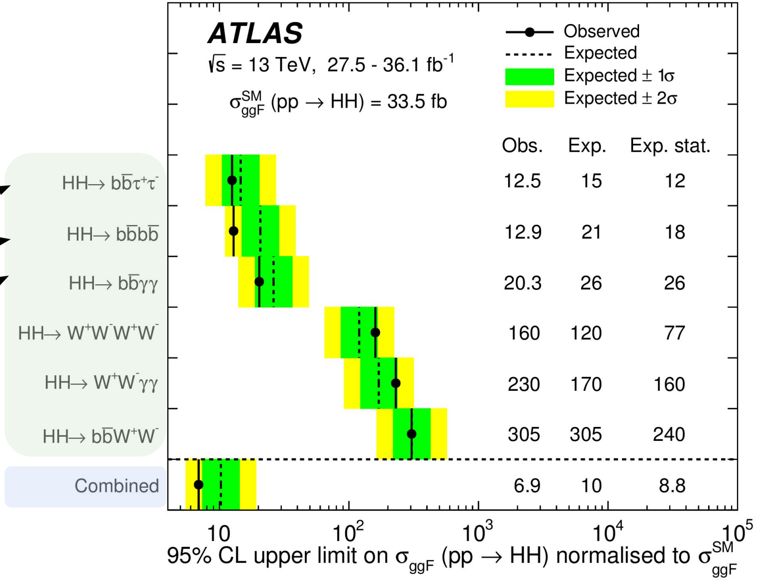

Partial Run 2 HH combination

Phys. Lett. B 800 (2020) 135103

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Search for Higgs pair production

- The Higgs can decay into different pairs of particles
- In ATLAS, look for HH in many final states and **combine** for more sensitive results
- Not enough data to **see** HH yet, but can set **upper limits**:
  - The closer to 1, the closer we are to seeing it!

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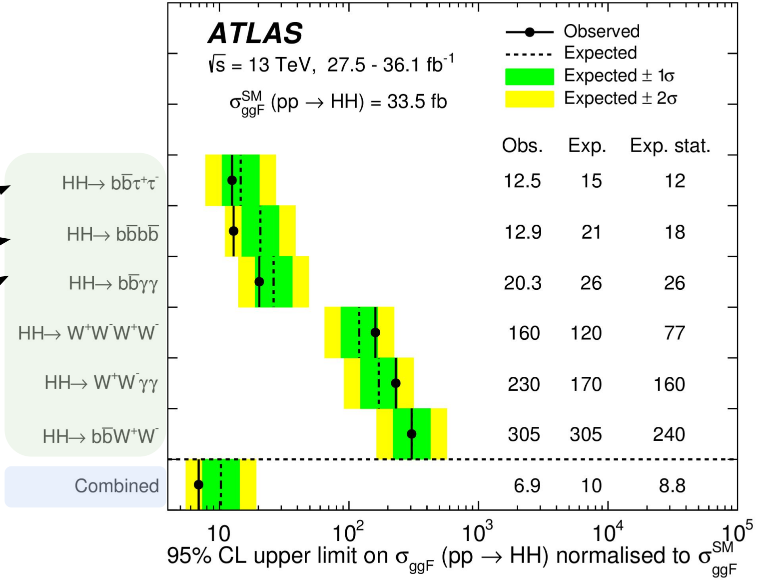

Phys. Lett. B 800 (2020) 135103

Partial Run 2 HH combination

HH→bb$\gamma\gamma$

- HH in H(bb)H($\gamma\gamma$) final state:
  - Clean $\gamma\gamma$ signature
  - High bb branching ratio

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- 2022: Search for HH in bb$\gamma\gamma$ with ATLAS **Run 2** dataset published in PRD

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PHYSICAL REVIEW D **106,** 052001 (2022)

Search for Higgs boson pair production in the two bottom quarks plus two photons final state in *pp* collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

G. Aad *et al.*[*]
(ATLAS Collaboration)

(Received 23 December 2021; accepted 1 August 2022; published 6 September 2022)

[Phys. Rev. D 106, 052001]

Brookhaven National Laboratory

HH→bb$\gamma\gamma$

- HH in H(bb)H($\gamma\gamma$) final state:
  - Clean $\gamma\gamma$ signature
  - High bb branching ratio

- 2022: Search for HH in bb$\gamma\gamma$ with ATLAS **Run 2** dataset published in PRD
- Recently extended effort with **new analysis**:
  - More **interpretations**
  - **Re-optimized** event categorization

	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%

JHEP
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ACCEPTED: December 27, 2023
PUBLISHED: January 12, 2024

Studies of new Higgs boson interactions through nonresonant HH production in the $b\bar{b}\gamma\gamma$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

JHEP01(2024)066

PHYSICAL REVIEW D **106,** 052001 (2022)

Search for Higgs boson pair production in the two bottom quarks plus two photons final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

G. Aad *et al.*[*]
(ATLAS Collaboration)

(Received 23 December 2021; accepted 1 August 2022; published 6 September 2022)

[Phys. Rev. D 106, 052001]

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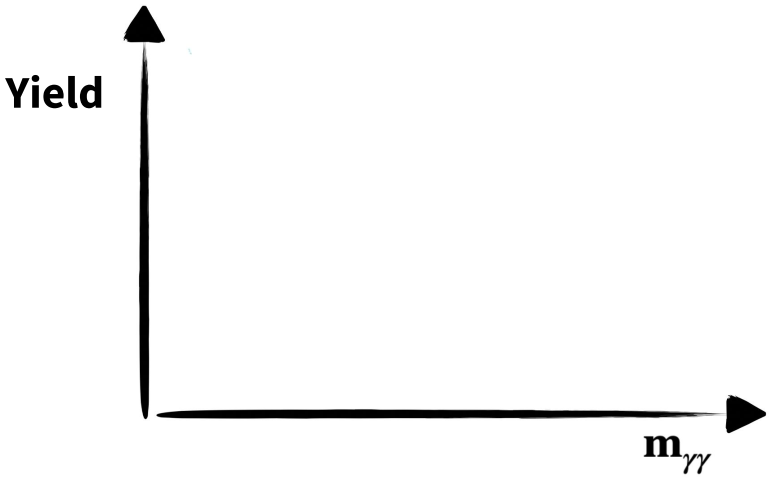
HH→bb$\gamma\gamma$: Strategy

- Take advantage of clean **di-photon mass** signature



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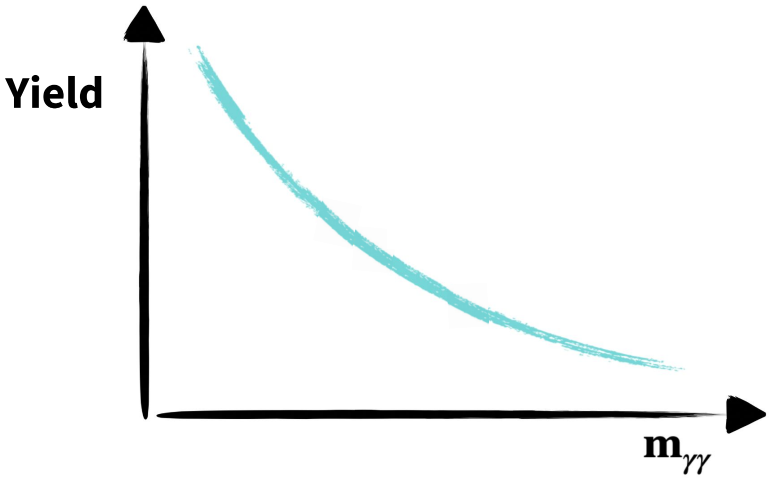
    - Continuum background ($\gamma\gamma$+jets, tt$\gamma\gamma$)



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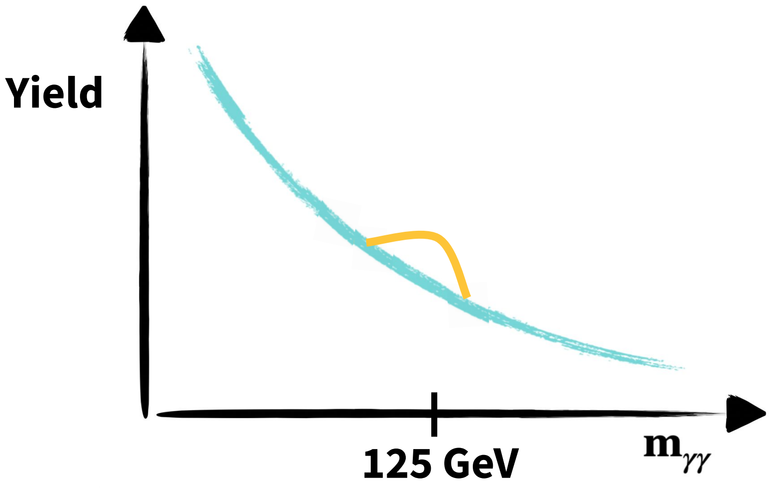

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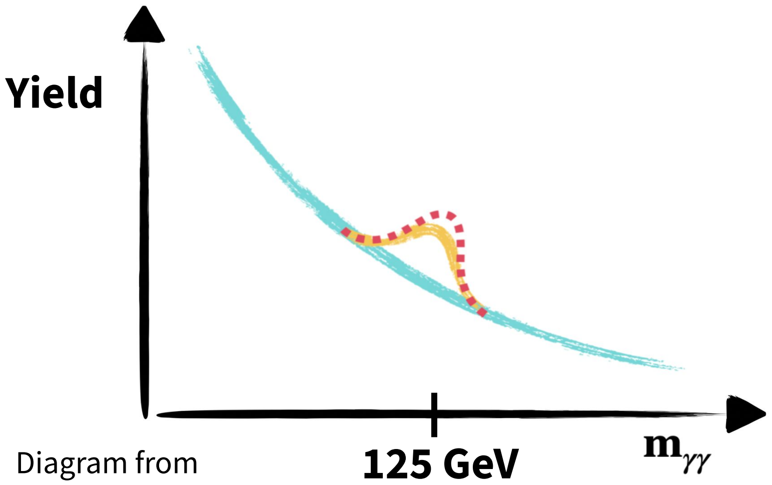
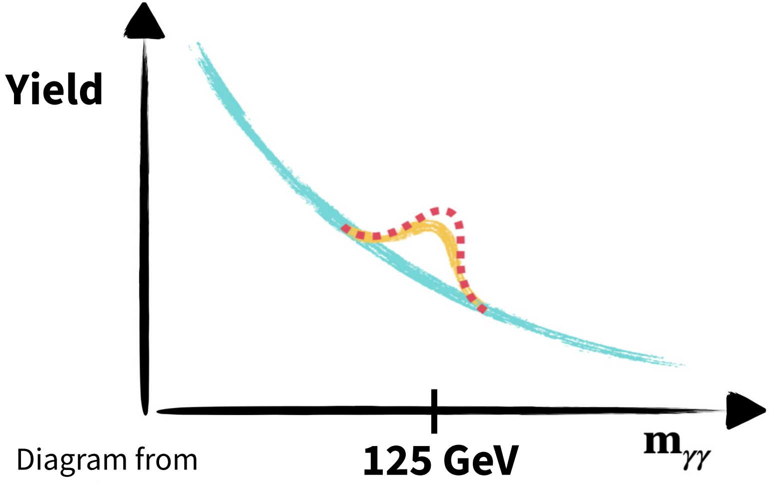


Diagram from
Elena Mazzeo

HH→bb$\gamma\gamma$: Strategy

- Take advantage of clean **di-photon mass** signature
- Three physics signatures:
  - Continuum background ($\gamma\gamma$+jets, tt$\gamma\gamma$)
  - H (Resonant background)
  - HH (Signal)
- Need to **separate** single Higgs and continuum backgrounds from HH
- HH and H modelled with **simulation.** Continuum background modeled with **data**



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HH→bb$\gamma\gamma$: Pre-selections

- Initial “skimming” of our massive datasets: Pre-selections

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- Make selections on **photons** and **jets** to identify H→$\gamma\gamma$ and H→bb legs:

H→$\gamma\gamma$ selection	H→bb selection
Two **high energy**, **isolated** photons	Exactly 2 b-jets

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H→$\gamma\gamma$ selection	H→bb selection	ttH($\gamma\gamma$) reduction
Two **high energy**, **isolated** photons	Exactly 2 b-jets	Exactly 0 leptons Less than 6 central jets

- Use **machine learning** techniques to find **b-jets**
- ttH($\gamma\gamma$) is a major single Higgs background - reduce based on its **final state particles**

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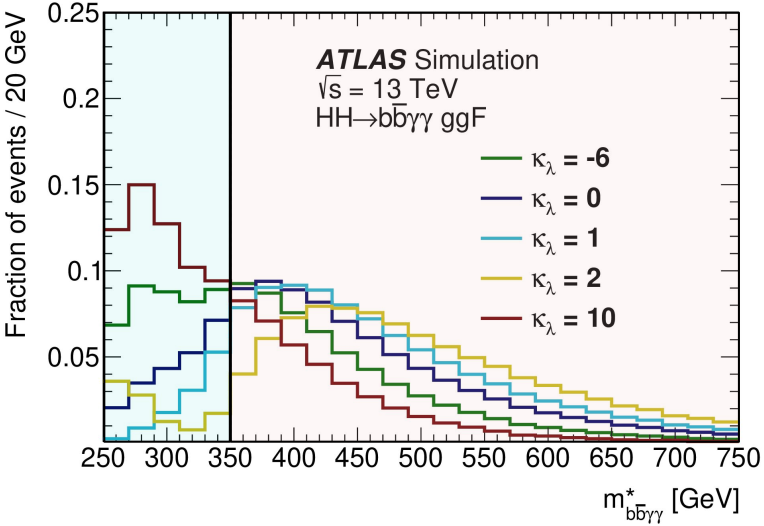
HH→bb$\gamma\gamma$: Reduced mass

- Define **reduced mass**: → $m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - (m_{bb} - 125\ \text{GeV}) - (m_{\gamma\gamma} - 125\ \text{GeV})$

- Split analysis into 2 regions:
  - **High mass:** > 350 GeV: Targets SM HH
  - **Low mass:** < 350 GeV: Targets deviations from self-coupling



[Phys. Rev. D 106, 052001]

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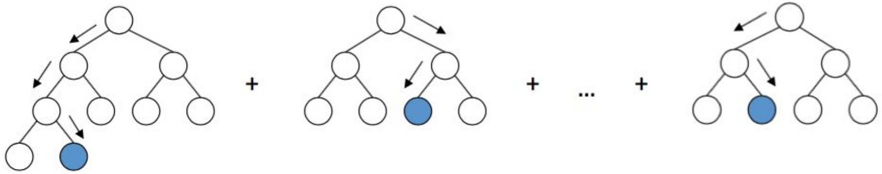
HH→bb$\gamma\gamma$: BDT

- Train **boosted decision tree** to separate **signal** and **background** signatures



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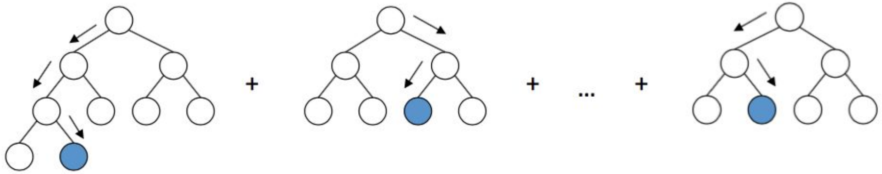

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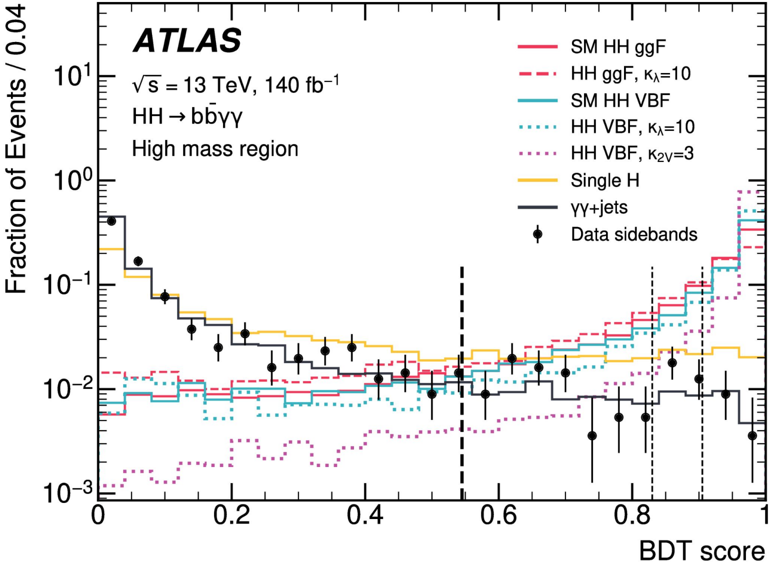

BDT score in high mass region, **data sideband**

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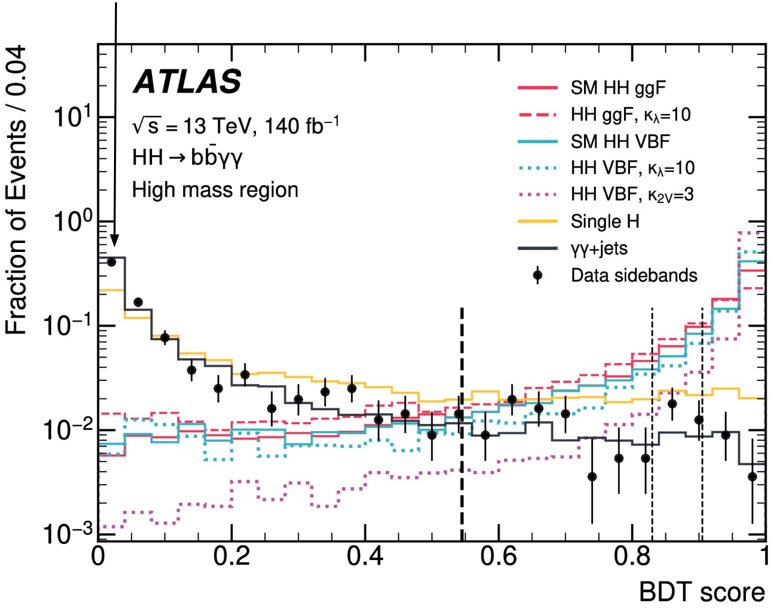
Continuum background, single higgs



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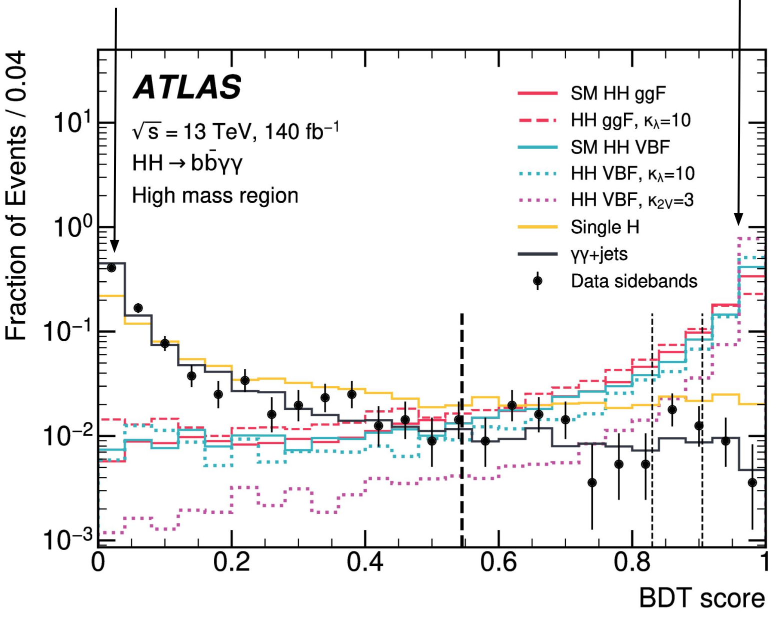

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HH→bb$\gamma\gamma$: Di-Photon mass

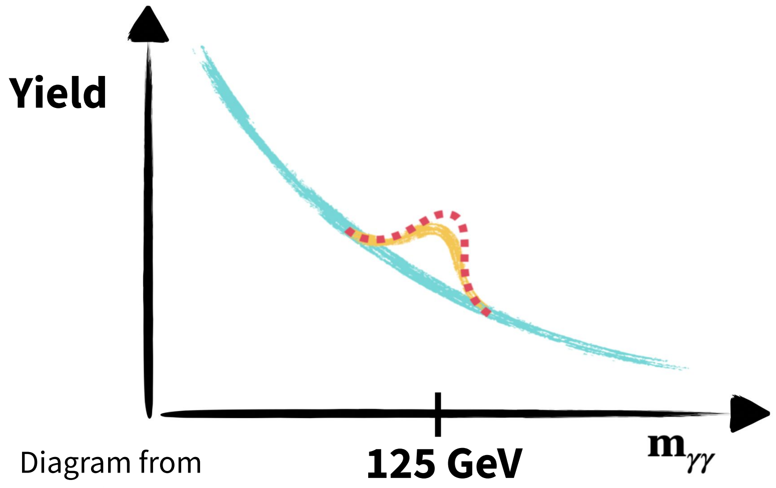
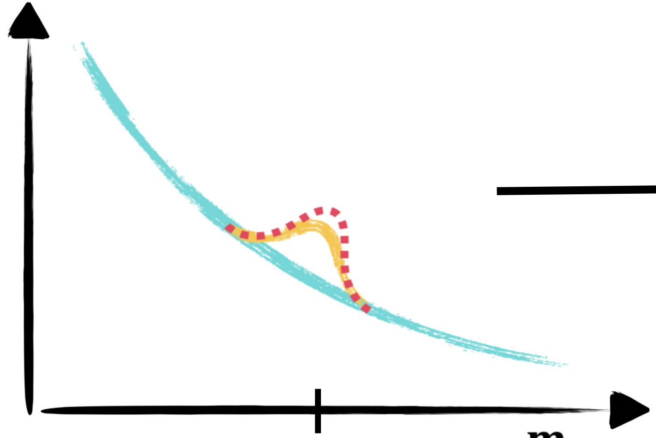


Diagram from
Elena Mazzeo

Strategy

HH→bbγγ: Di-Photon mass

Model HH, H with **double sided crystal ball**
Model continuum background with **data**



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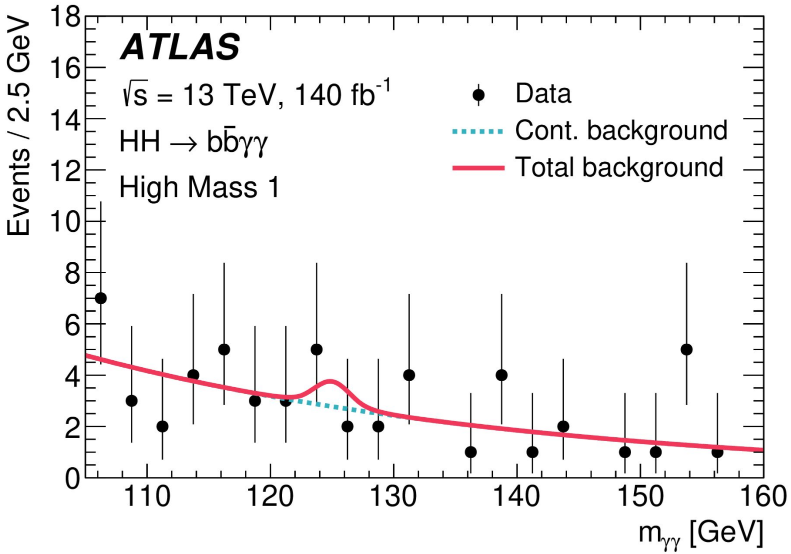

Strategy

Applied to real data!

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HH→bb$\gamma\gamma$: Systematics

- Uncertainties can be **systematic** or **statistical** in nature

HH→bb$\gamma\gamma$: Systematics

- Uncertainties can be **systematic** or **statistical** in nature
- In this analysis, **experimental** systematic with largest impact on results: **Photon energy modelling**
- Leading **theoretical** uncertainty has impact **~ 5%** - crucial to consider!
- However, small w.r.t. **Statistical uncertainty**

Systematic uncertainty source	Relative impact [%]
Experimental	
Photon energy resolution	0.4
Photon energy scale	0.1
Flavour tagging	0.1
Theoretical	
Factorisation and renormalisation scale	4.8
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	0.2
Parton showering model	0.2
Heavy-flavour content	0.1
Background model (spurious signal)	0.1

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HH→bb$\gamma\gamma$: SM Results

- Statistical interpretation: How compatible is the simulation/data with the **background only hypothesis?**

- Not near evidence level (yet!) so compute **upper limits:** (**Near 1** means we are starting to see HH)

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- Not near evidence level (yet!) so compute **upper limits:** (**Near 1** means we are starting to see HH)

	Partial Run 2 analysis	This analysis
Expected **(Simulation driven)**	≤ 26	≤ 5
Observed **(What we conclude from data)**	≤ 20	≤ 4

- **Big improvement by adding more data!**

Values near 1 mean close to seeing HH

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HH→bb$\gamma\gamma$: Coupling modifiers

- **Kappa framework**: Re-interpret results

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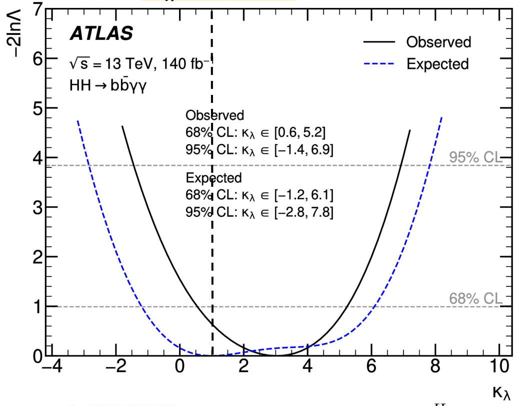
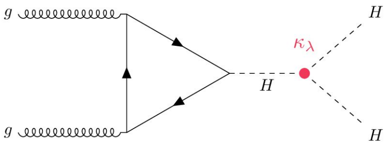
HH→bbγγ: Coupling modifiers

- **Kappa framework**: Re-interpret results as a function of **non-SM Higgs self-coupling**

κ_λ = 1: SM





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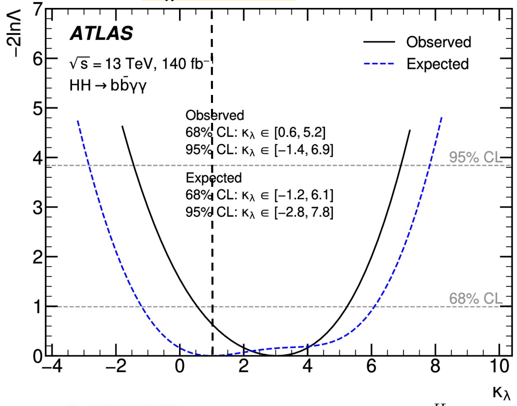
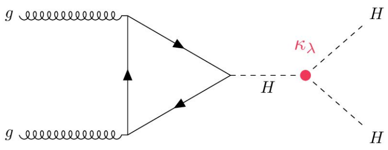
HH→bbγγ: Coupling modifiers

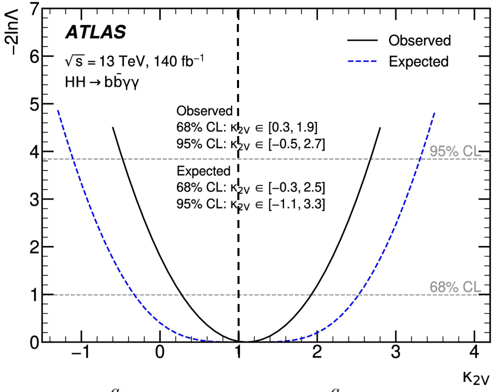
- **Kappa framework**: Re-interpret results as a function of **non-SM Higgs self-coupling, HHVV couplings**

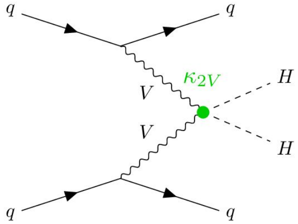
κ_λ = 1: SM





κ_{2V} = 1: SM





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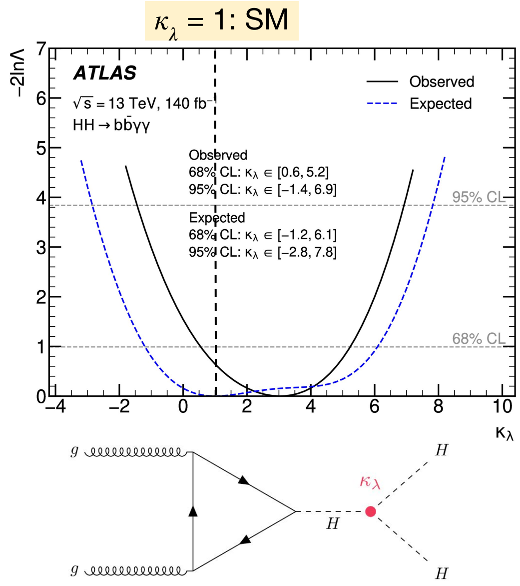

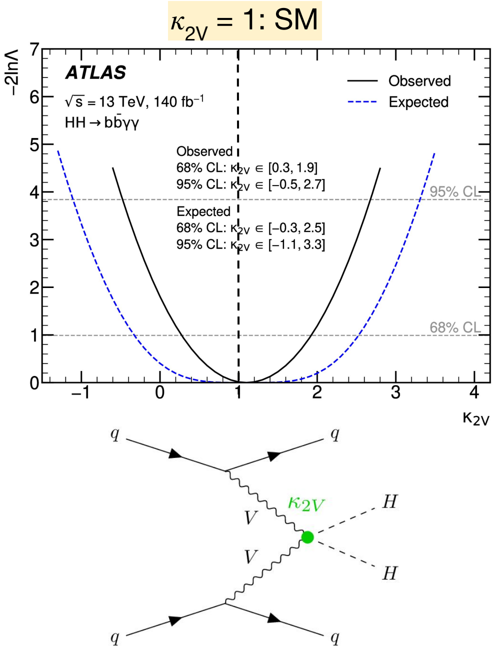

Improvement compared to **partial** analysis:

	Partial Run 2 analysis	This analysis
Expected	-8.1 ≤ κ_λ ≤ 13.1	-2.8 ≤ κ_λ ≤ 7.8
Observed	-8.1 ≤ κ_λ ≤ 13.1	-1.4 ≤ κ_λ ≤ 6.9

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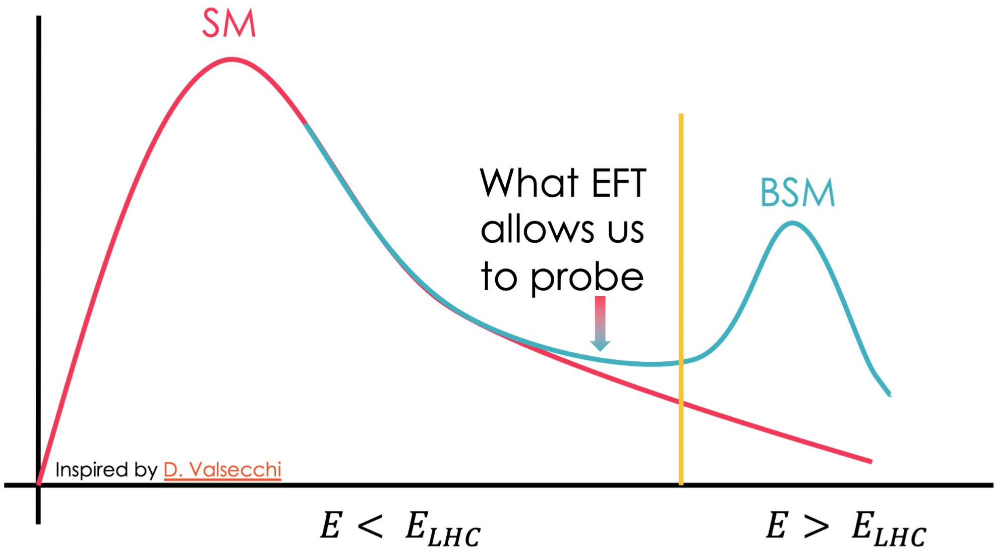
HH→bb$\gamma\gamma$: EFT

- Effective field theory: A theory which holds true up to a given **energy scale**
- Allows for **re-interpretation** of results using this framework
- May allow us to see **BSM** effects, if they exist, at **LHC energy**



From Valentina Cairo [Lepton Photon 2023]

HH→bb$\gamma\gamma$: HEFT

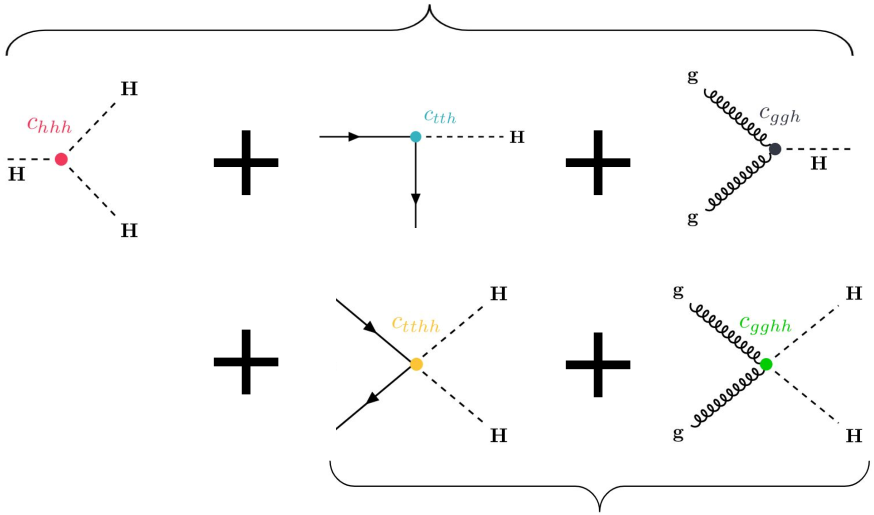
- **HEFT**: Higgs Effective Field Theory. **Parameterized** theory allowing for deviations from SM

HH→bb$\gamma\gamma$: HEFT

- **HEFT**: Higgs Effective Field Theory. **Parameterized** theory allowing for deviations from SM
- Useful for **HH** re-interpretation

SM-like processes (modified by couplings)

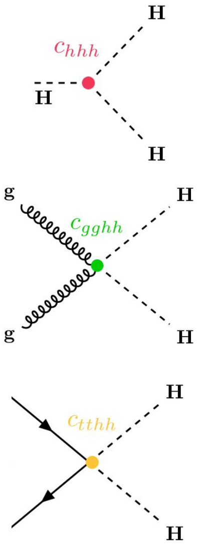
Particle interactions determined by:



BSM processes

HH→bb$\gamma\gamma$: HEFT scan results

- Simultaneously vary c_{hhh}, and modifier of HH coupling to gg/tt



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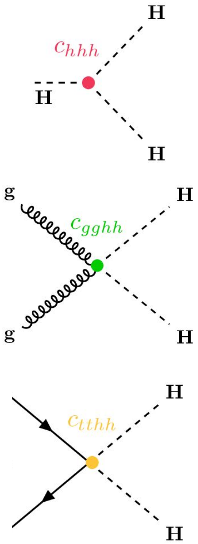

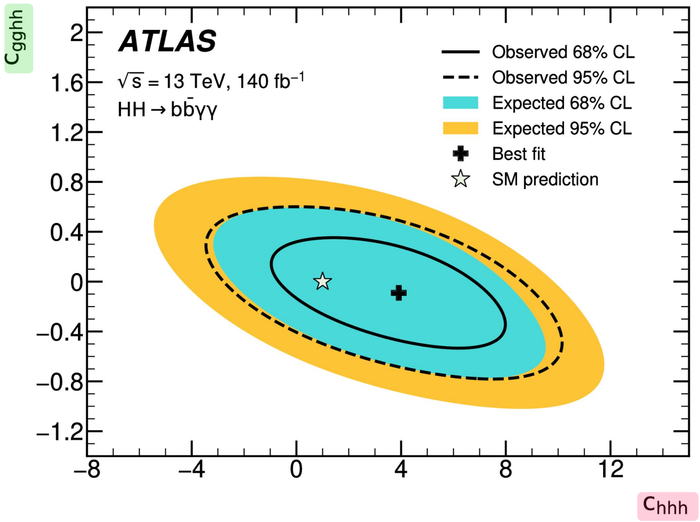

Best fit (✚) contains SM prediction within **68% CL**

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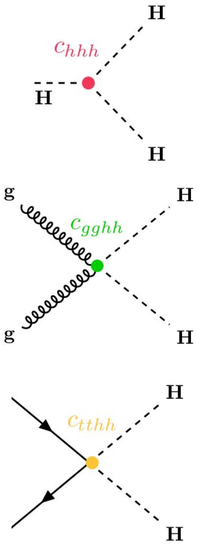
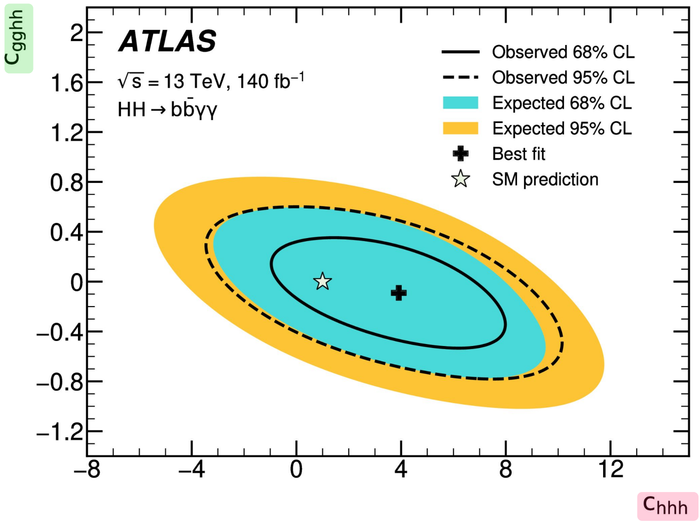
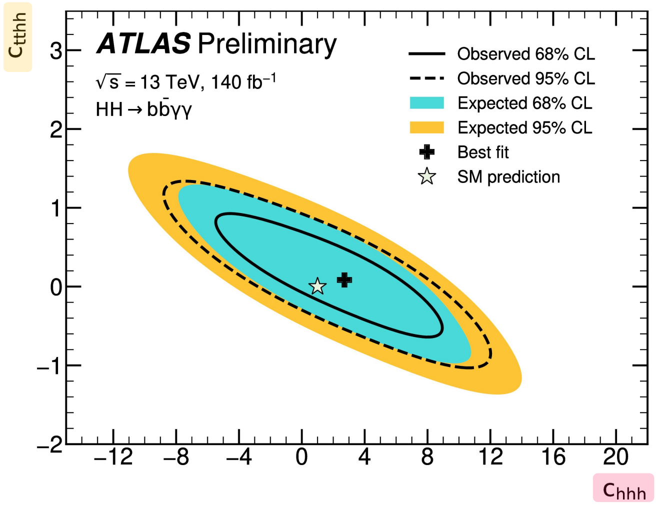
HH→bbγγ: HEFT scan results

- Simultaneously vary c_{hhh}, and modifier of HH coupling to **gg**/**tt**







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Best fit (✚) contains SM prediction within **68% CL -** Also true for c_{tthh} vs. c_{hhh} scan

Results are consistent with SM prediction

Outline

I. The Higgs self-coupling
II. The ATLAS detector
III. Search for Higgs pair production at ATLAS
IV. Beyond the LHC

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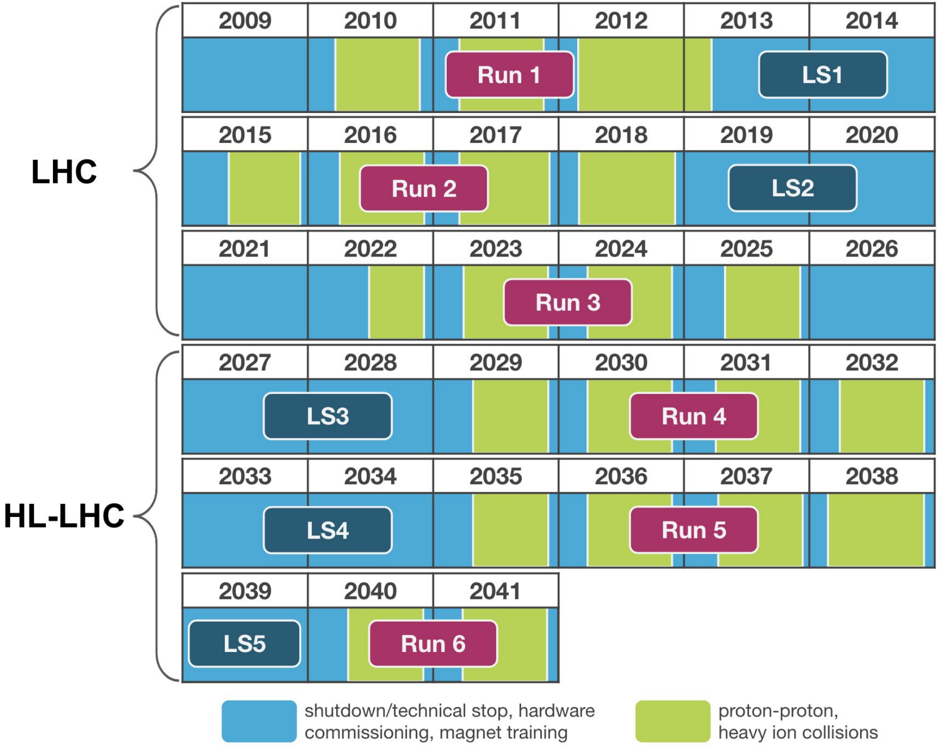
Aside: Run 3

- Reminder - **LHC and ATLAS schedule**:



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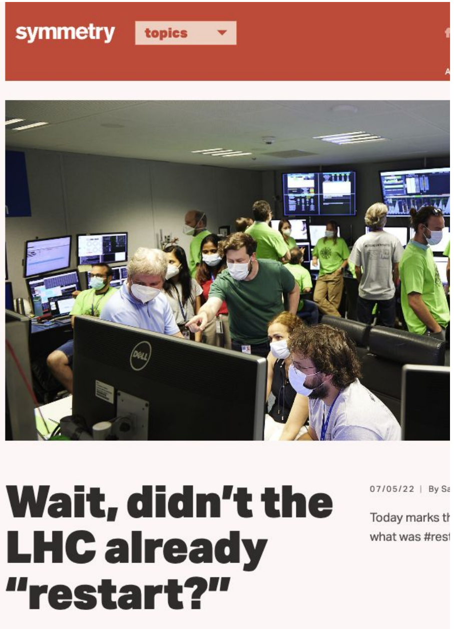

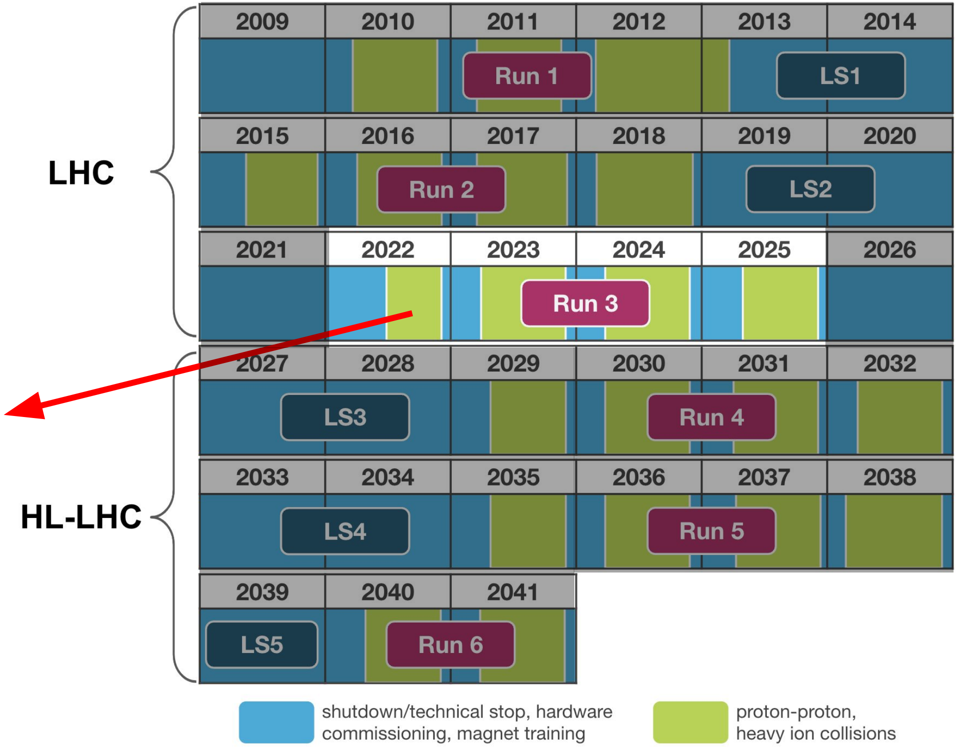

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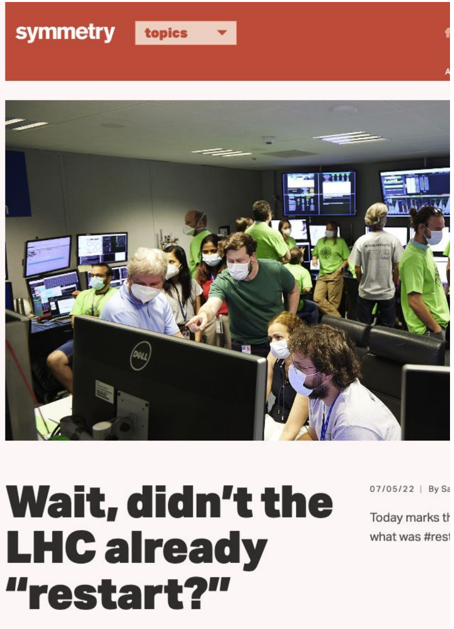
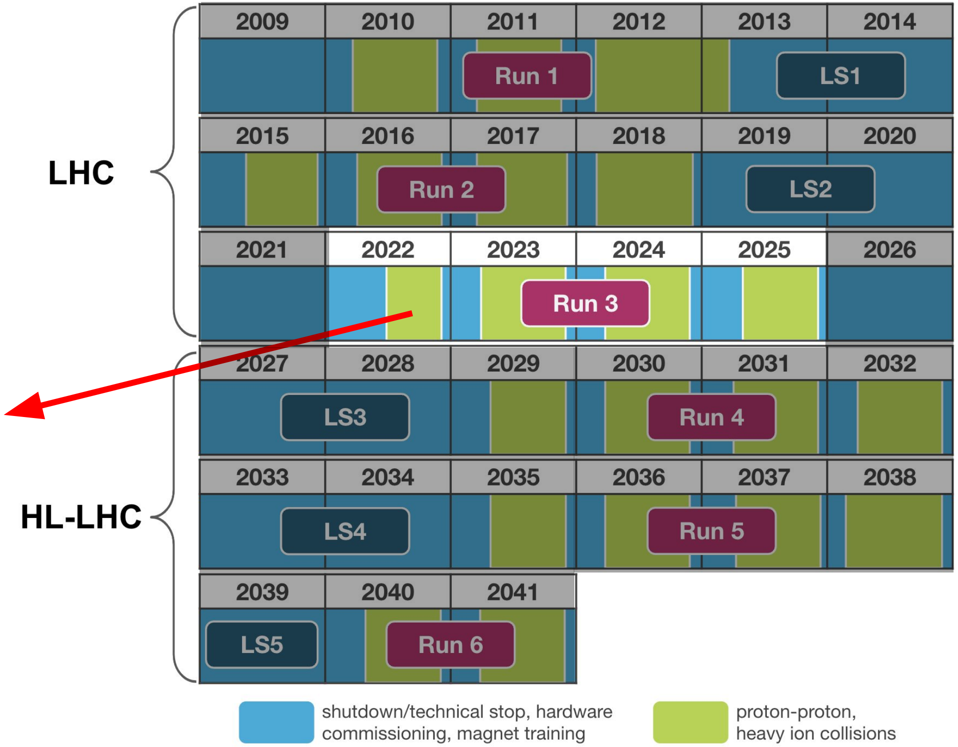
Working hard analyzing Run 3 data…

Expect HH improvement from more data - but not ultimate precision!





High-Luminosity LHC

- 2029: LHC will finish upgrade to
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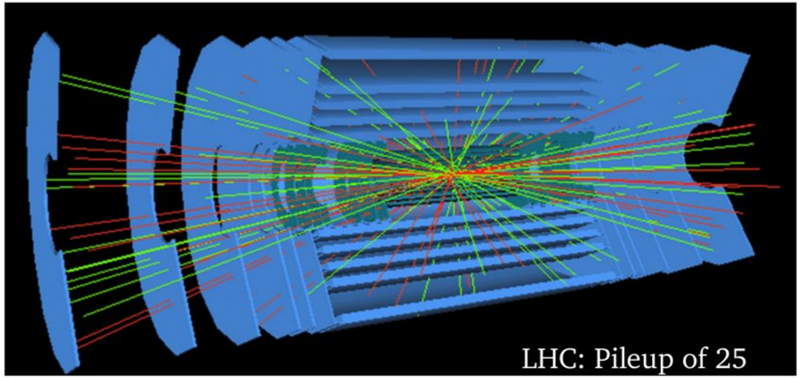

Development and Evaluation of Novel, Large Area, Radiation Hard Silicon Microstrip Sensors for the ATLAS ITk Experiment at the HL-LHC

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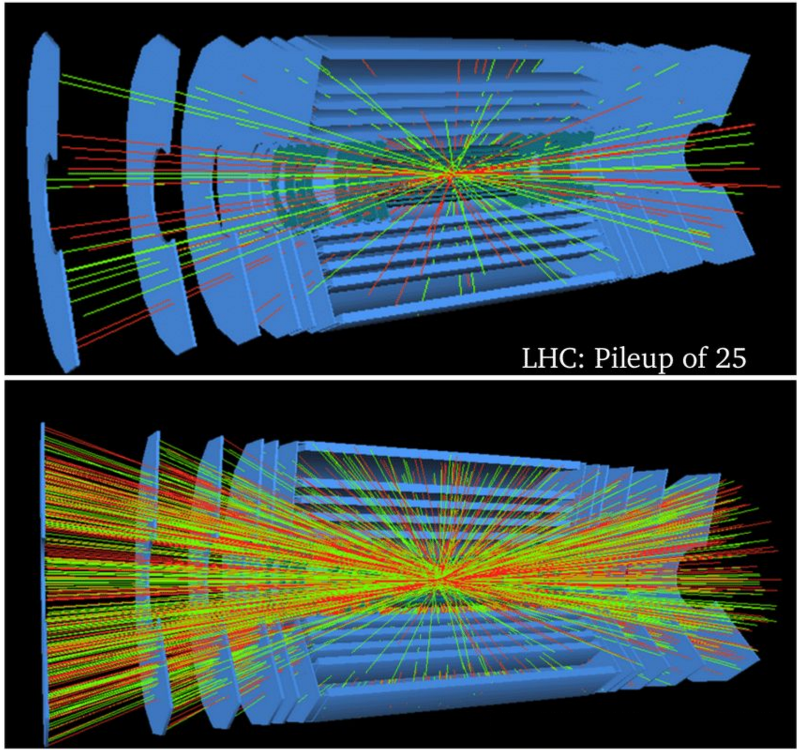

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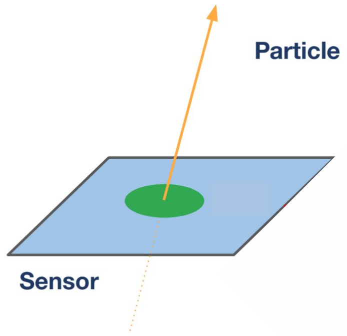
Silicon based tracking

- Particle hits silicon



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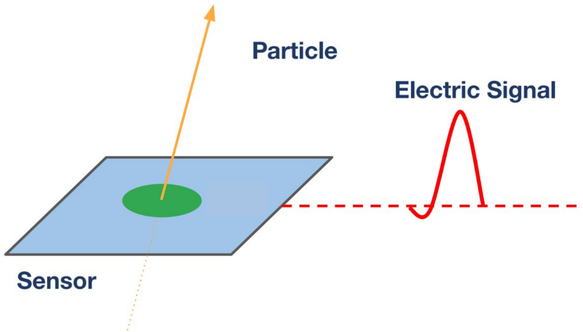

G. D'amen - BNL physics seminar series

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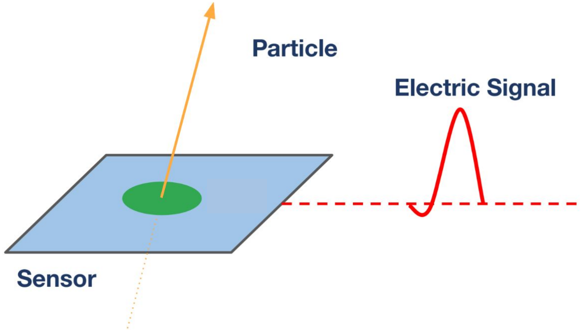

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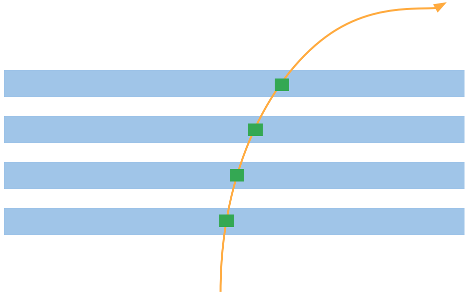

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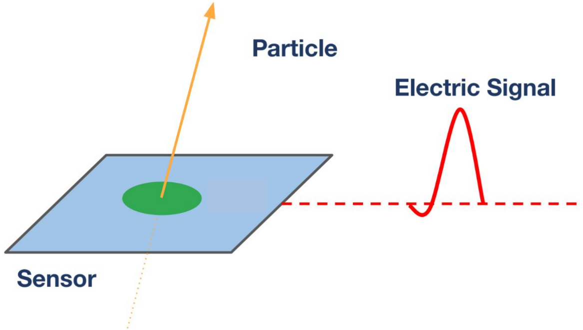
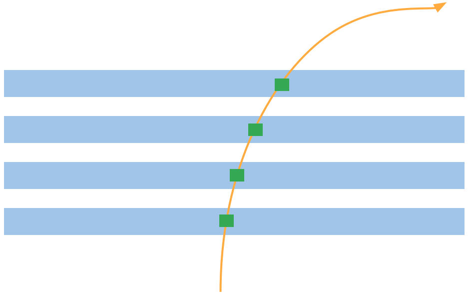


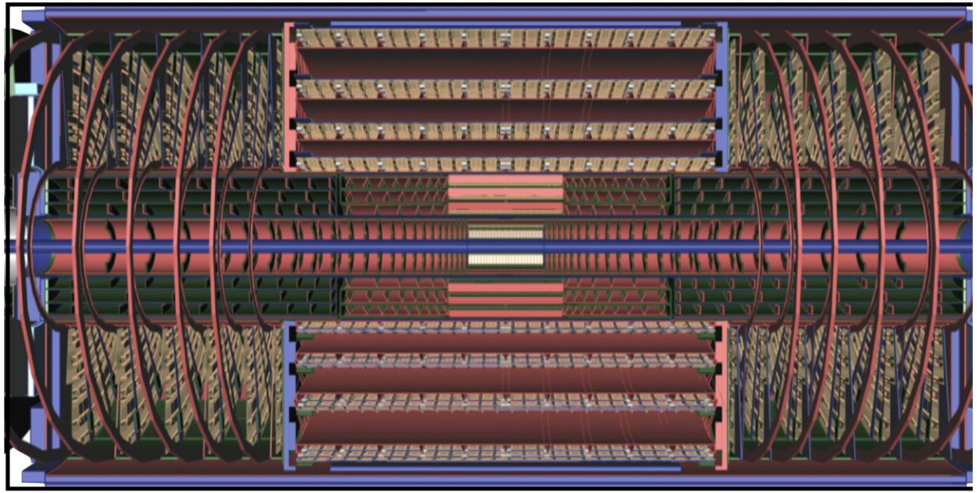
G. D'amen - BNL physics seminar series

Silicon trackers actively used by ATLAS and CMS!



The ATLAS ITk: Layout

- Part of ATLAS **upgrade**: Full replacement of tracker with **full silicon pixel** and **strip** subdetectors - **ITk** (Inner Tracker):



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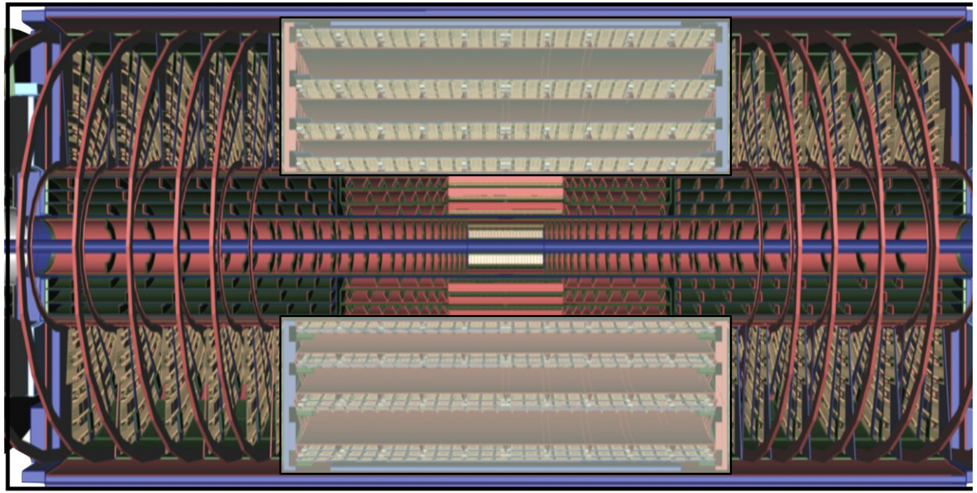
The ATLAS ITk: Layout

- Part of ATLAS **upgrade**: Full replacement of tracker with **full silicon pixel** and **strip** subdetectors - **ITk** (Inner Tracker):

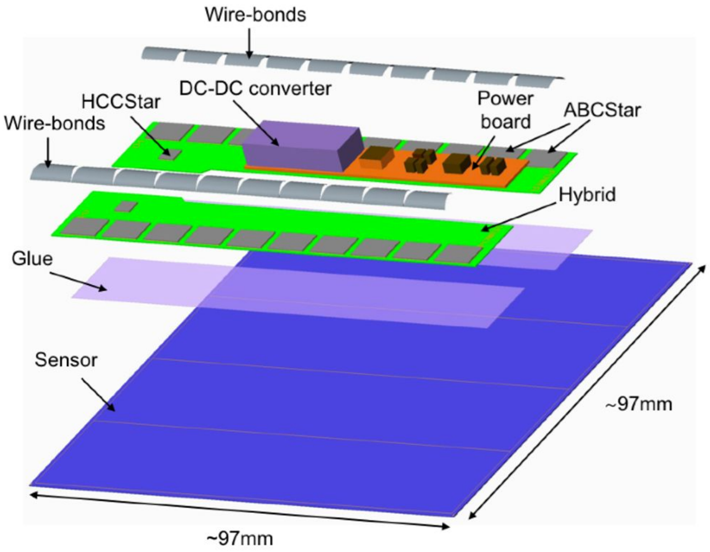


ITk strips barrel

- Will contain 10,976 **modules** (individual detection unit)
- Need to build **robust** modules to last ~**10 years**!

The ATLAS ITk: Modules

- Strips modules: **Electronics glued to sensors**



The ATLAS ITk: Modules

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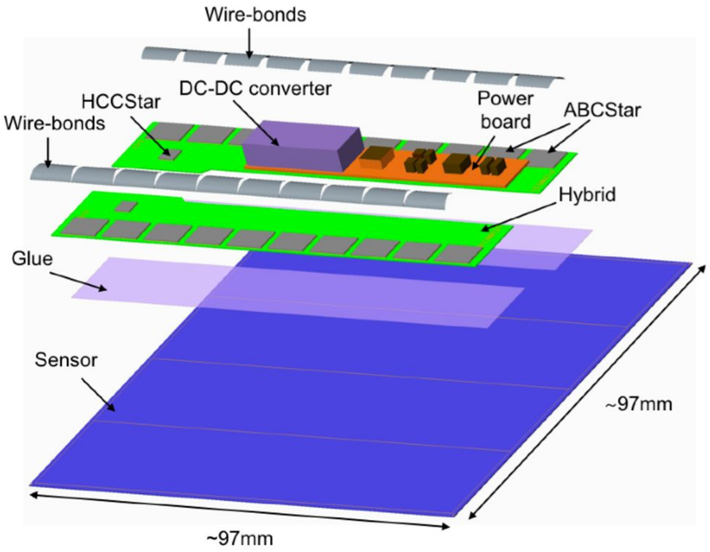
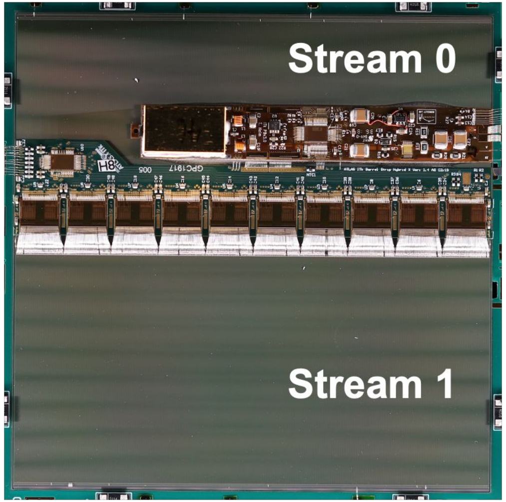
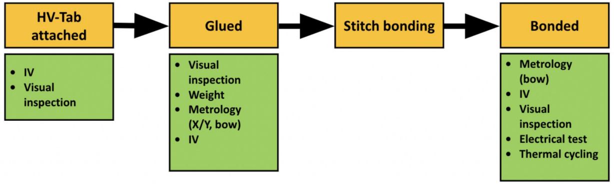


Example module



The ATLAS ITk: QC

- To ensure robust modules, a well-defined quality control procedure is defined:



arXiv:2401.17054

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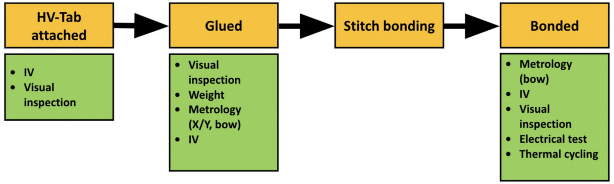

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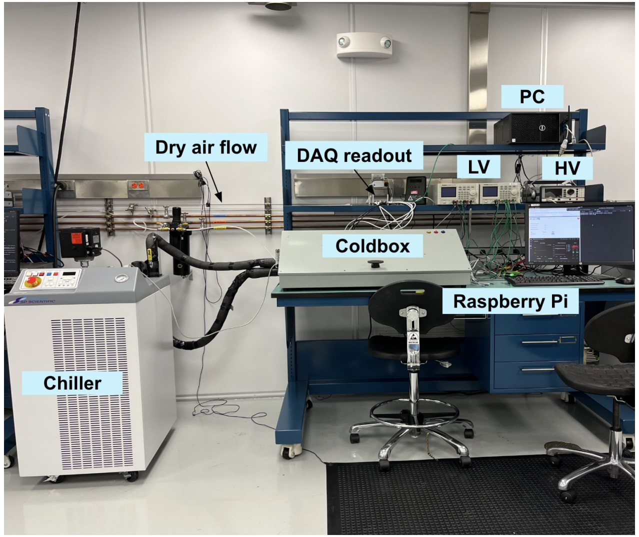

- These steps require a robust test setup

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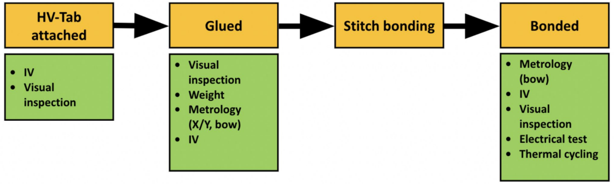

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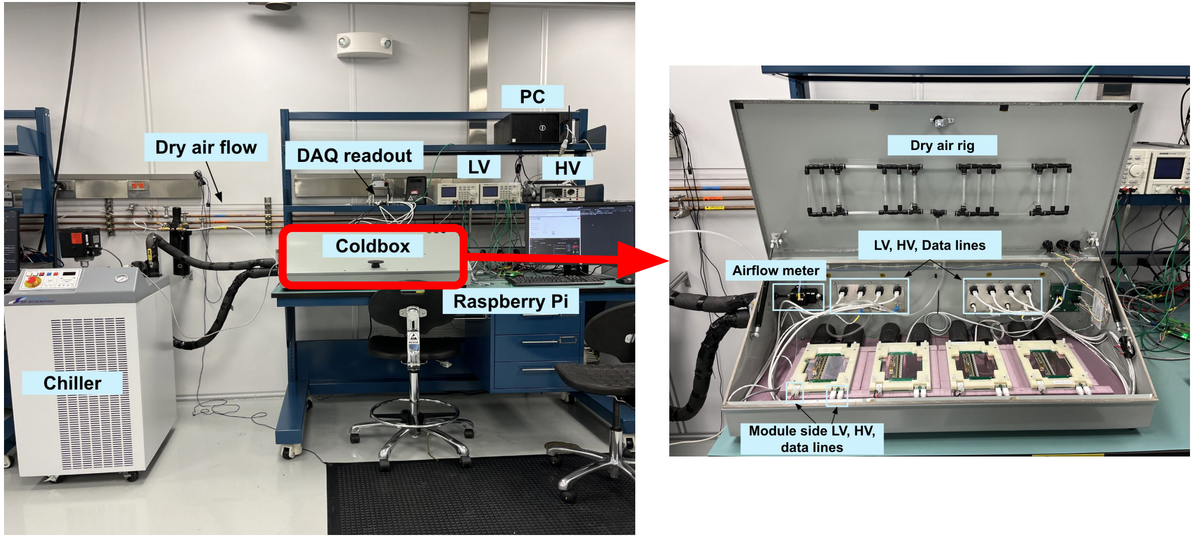
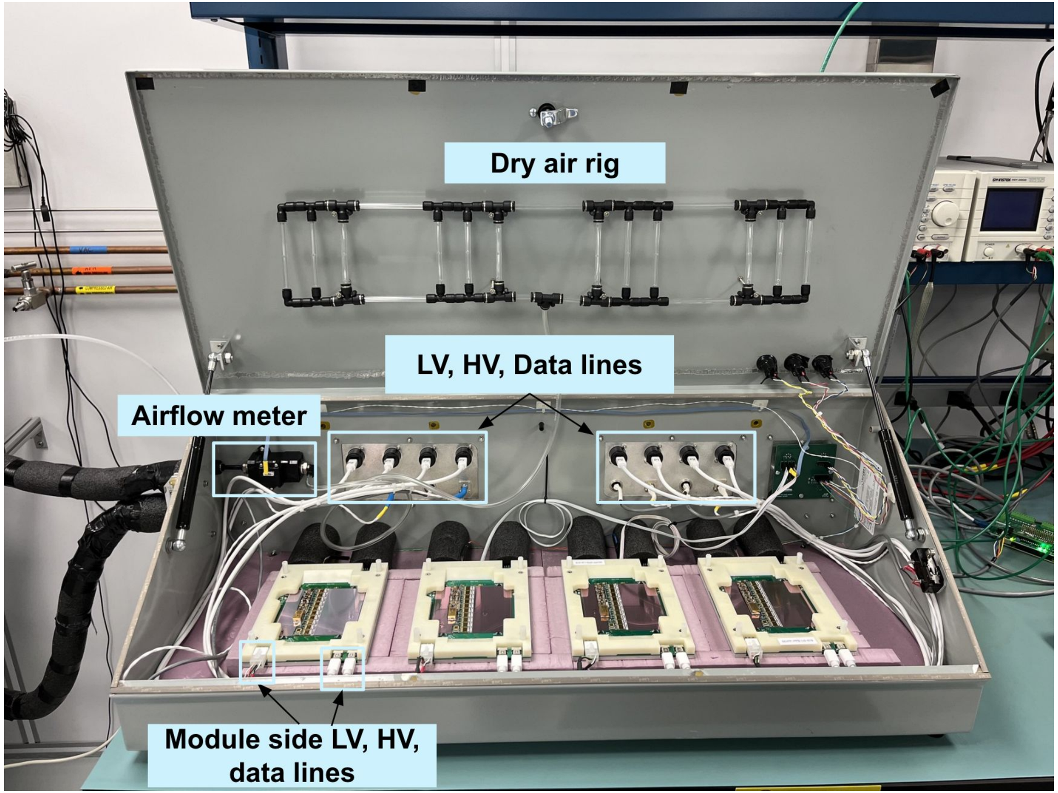


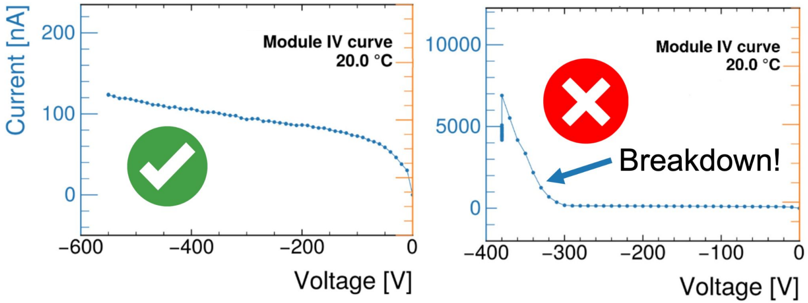
- These steps require a robust test setup
- Only modules **passing all QC steps** will end up in the ITk!

The ATLAS ITk: QC



The ATLAS ITk: QC

- A few examples of modules passing/failing QC:



IV: Increase voltage, check for **spike in current**

The ATLAS ITk: QC

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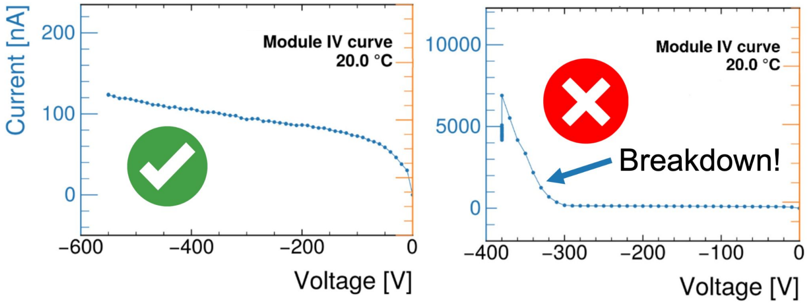

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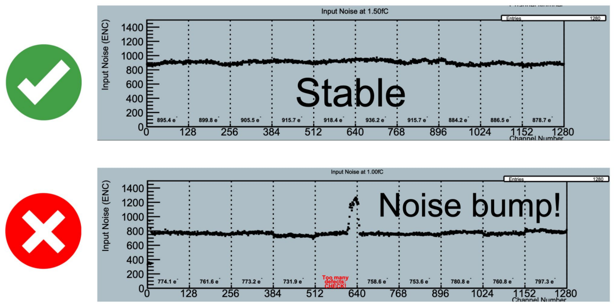

Measure noise - ensure it’s roughly **flat**

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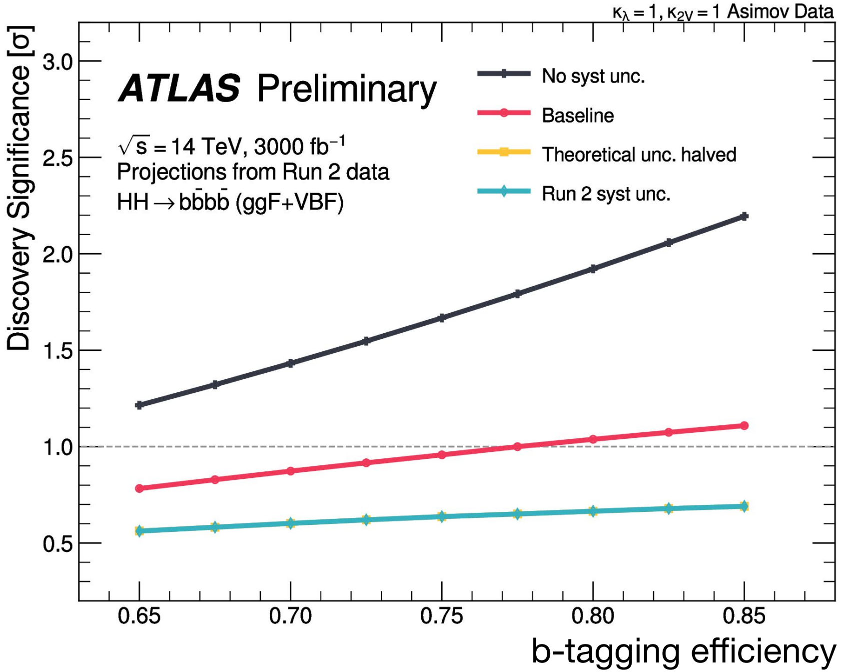
HL-LHC: HH projections

- Projected significance of HH→bbbb channel **as function of b-tagging efficiency**

- If we can improve b-tagging, combine with other H(bb) channels, can significantly increase HH discovery chances

- <u>**This relies on a robust ITk!**</u>



ATL-PHYS-PUB-2023-023

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FCC

- What about **after LHC**?

FCC

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- Planning next collider with future physics goals in mind, including Higgs self-coupling measurement

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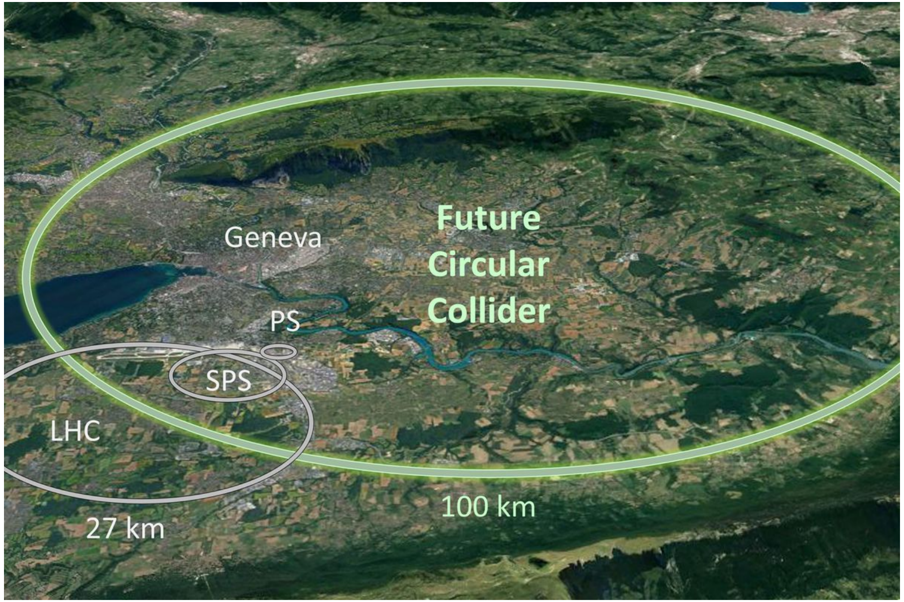
- <u>**Example:**</u> Future Circular Collider (FCC)
    - FCC-ee: Higgs precision
    - FCC-hh: **100 TeV** proton-proton collisions. Self-coupling precision



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FCC

- What about **after LHC**?

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- <u>**Example:**</u> Future Circular Collider (FCC)
  - FCC-ee: Higgs precision
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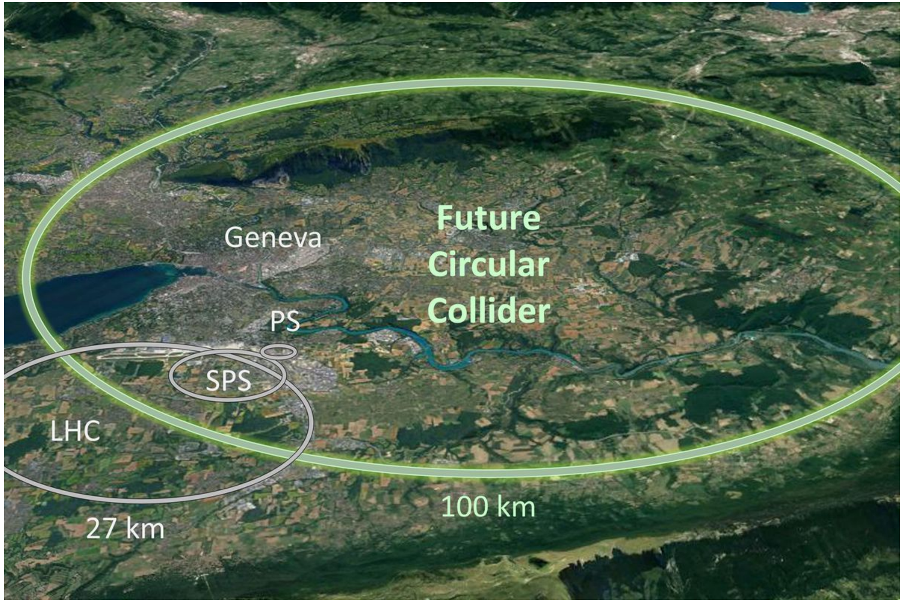
- Aiming for **even more precise Higgs measurements**



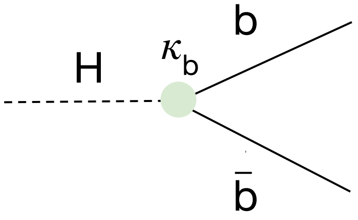
FCC projections

- Expect the FCC-ee phase of FCC to **improve Higgs precision measurements**

FCC projections

- Expect the FCC-ee phase of FCC to **improve Higgs precision measurements**
- **Example:** Higgs to bb coupling
- With FCC-ee, project improvement of ~ factor 4-5
  - Improvement in characterization
  - Search for BSM

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
BR_{inv} (<%, 95% CL)	1.9*	0.20 / 0.15
BR_{unt} (<%, 95% CL)	4*	1.0 / 0.88



The P5 report

- December 2023: P5 panel releases recommendations to DOE of how to **prioritize particle physics projects** over the next **10 years** within context of **20 year vision:**

> c. **An off-shore Higgs factory**, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined (see also Recommendation 6), the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US on-shore program in particle physics (section 3.2).

- Recommendation 2c: "**The US should actively engage in feasibility and design studies**" for an off-shore Higgs factory.
  - **Current designs of FCC-ee and ILC meet our scientific requirements**

FCC feasibility studies consistent with US plan for future colliders

Summary

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- Ongoing searches for **Higgs pair production** - recent result: ATLAS looks for **HH→bb$\gamma\gamma$ decay**:
  - Upper limit **~ 4-5 times SM**
  - Additional self-coupling modifier, EFT results
  - <u>**Results agree with SM**</u>

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Summary

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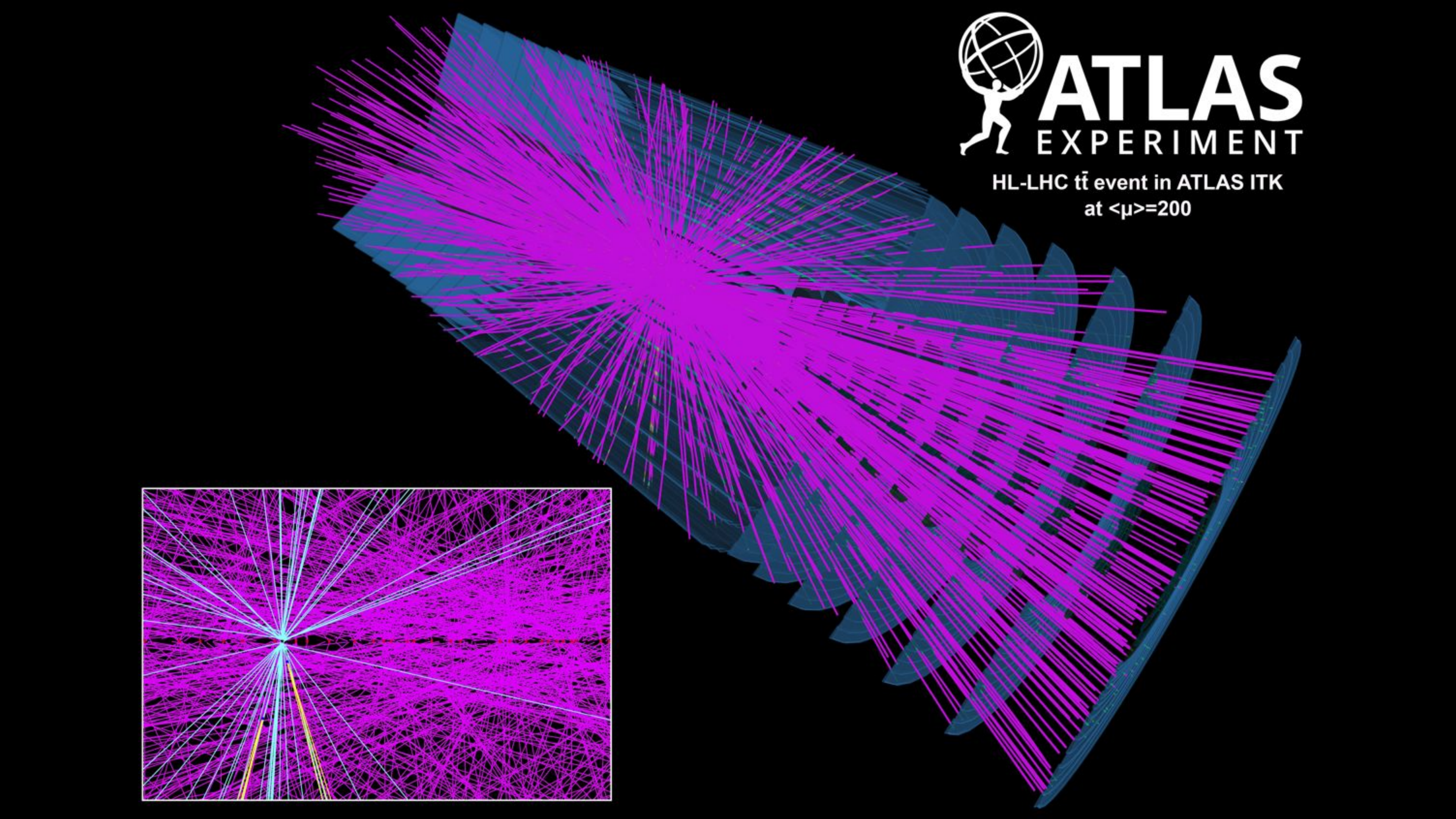
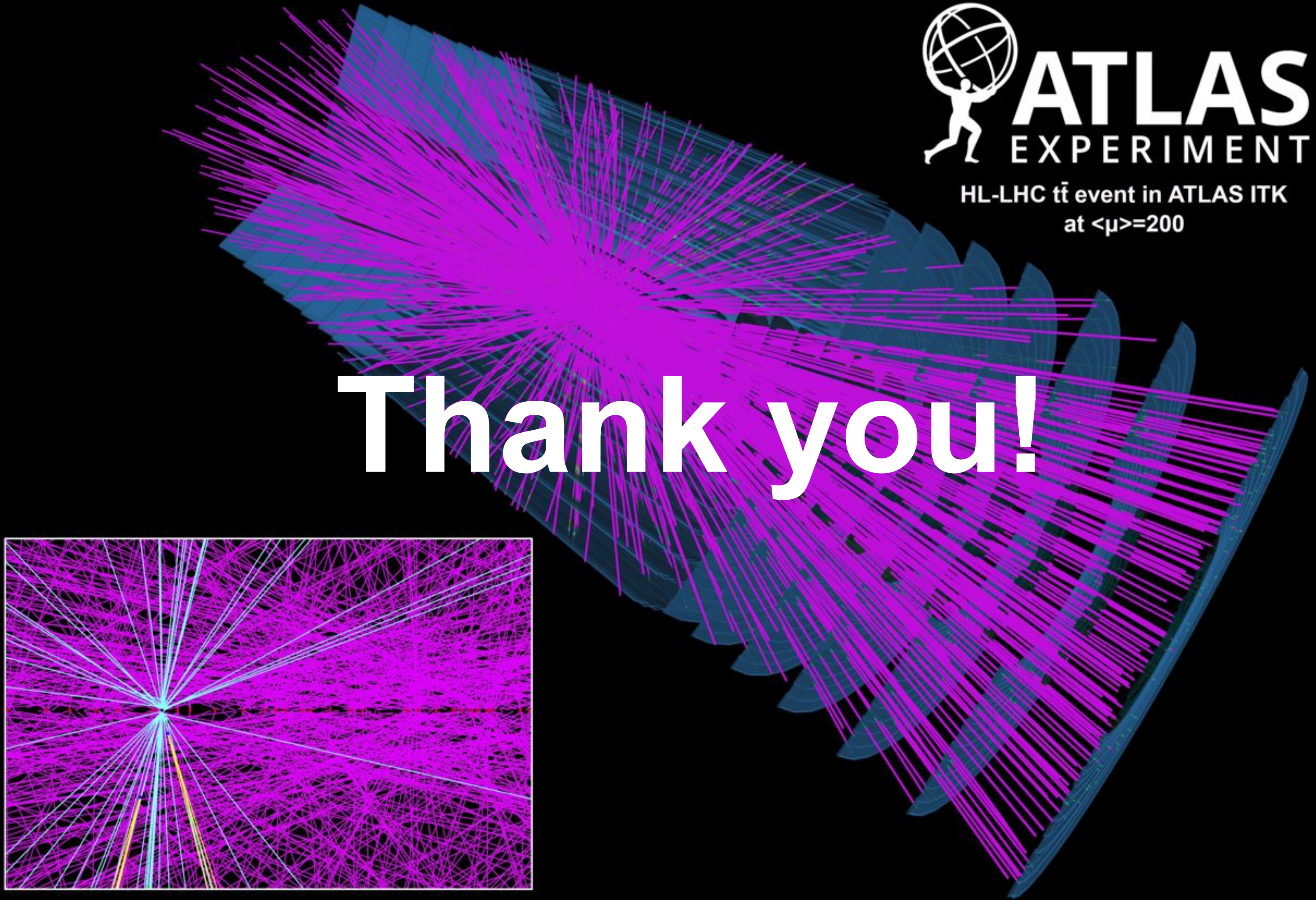
  - **Results agree with SM**

- Expect **more sensitive results** from **HL-LHC**
  - Requires **upgraded** detector, including **new, robust tracker (The ITk)**

- Expect **even more sensitive results** with a future collider, for example **FCC**


ATLAS
EXPERIMENT
HL-LHC tt̄ event in ATLAS ITK
at <μ>=200

Thank you!



ATLAS EXPERIMENT

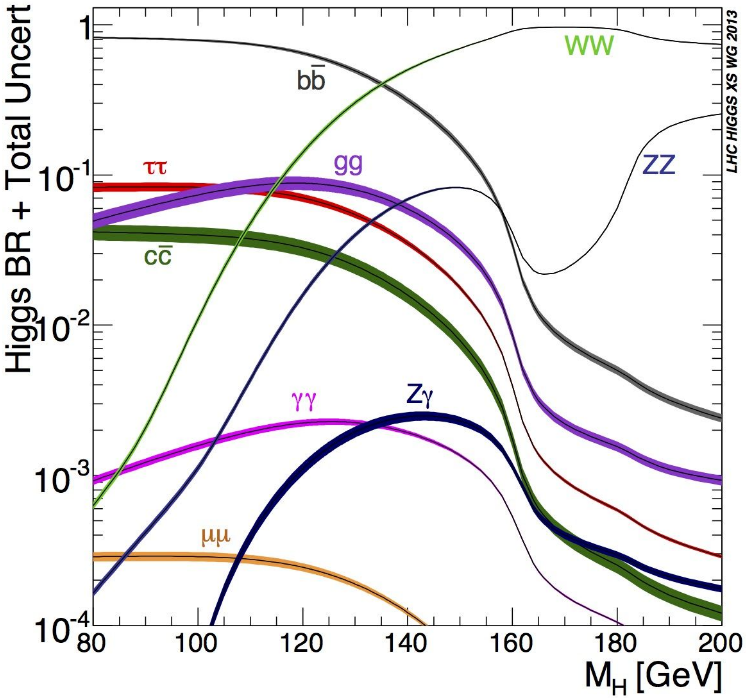
HL-LHC $t\bar{t}$ event in ATLAS ITK
at <μ>=200

Backup

Theoretical basis

Higgs decays

- Higgs decays as function of mass:



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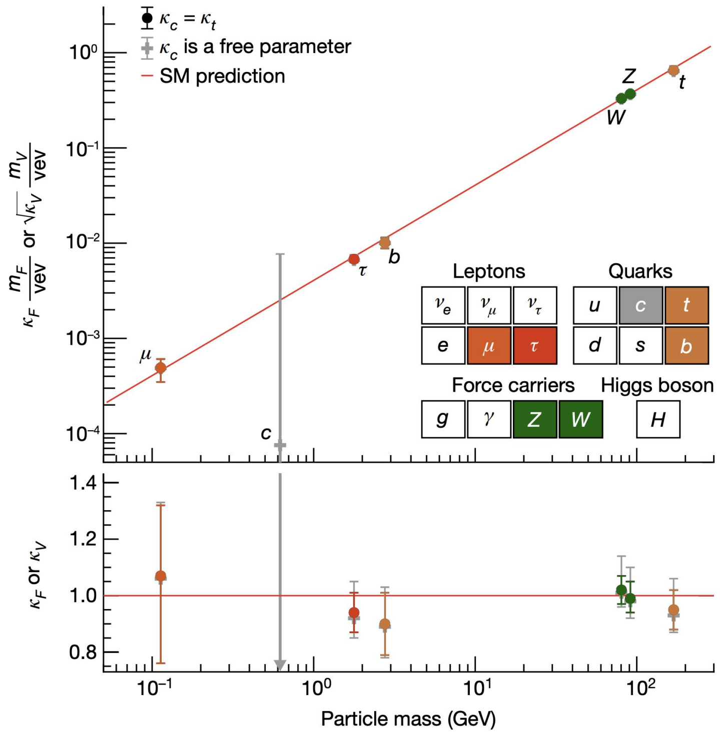
Self-coupling: The Higgs boson

- ATLAS version of higgs coupling plot:



Nature 607, 52-59 (2022)

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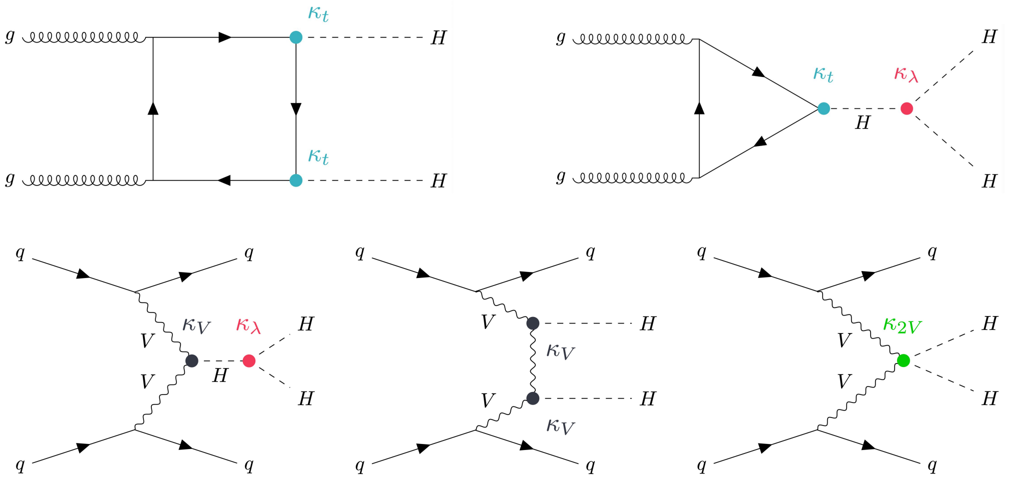
Self-coupling: Higgs pair production

Can directly access Higgs self-coupling via **Higgs pair production (HH)**:

Gluon fusion:

- **Leading** production mode
- Access to **self-coupling**
- $\sigma_{\text{NNLO, FTapprox}}$ ~ **31.05 fb** @ 13 TeV, m_H = 125.0 GeV [1803.02463]



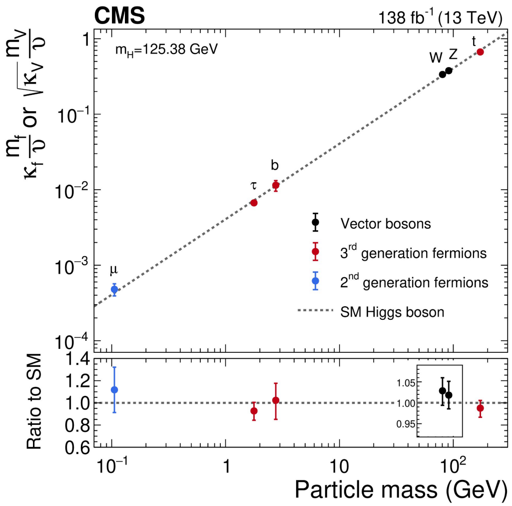
Vector boson fusion:

- **Subleading** production mode
- Access to self-coupling, κ_{2V}, κ_V
- **Quarks** in final state
- σ_{N3LO} QCD ~ **1.73 fb** @ 13 TeV, m_H = 125.0 GeV [1811.07906]

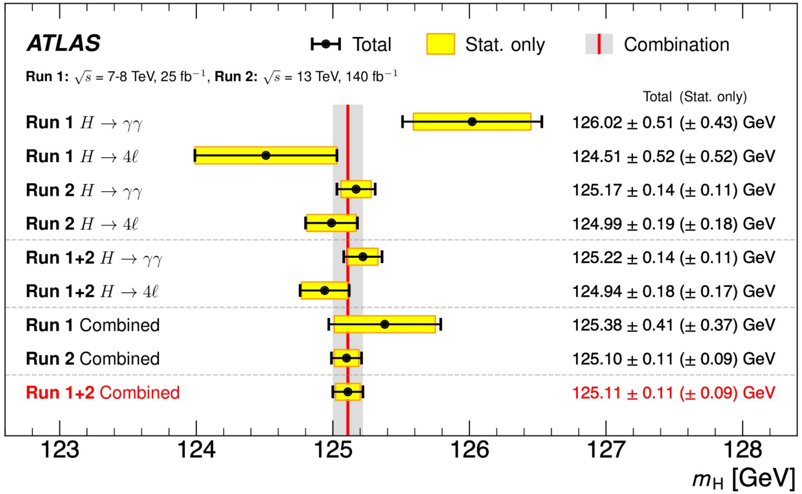
- Self-coupling affects HH **cross-section** and **differential distributions** in leading production modes
- **Rare** process - need to select **final states** with good signal to background ratio

Self-coupling: The Higgs boson

- What do you do after discovering a particle? You **characterize** it, and compare to **theory:**



Nature 607, 60-68 (2022)



arXiv:2308.04775

- Very precise **mass**, **coupling** measurements. Have come a long way, but more to measure

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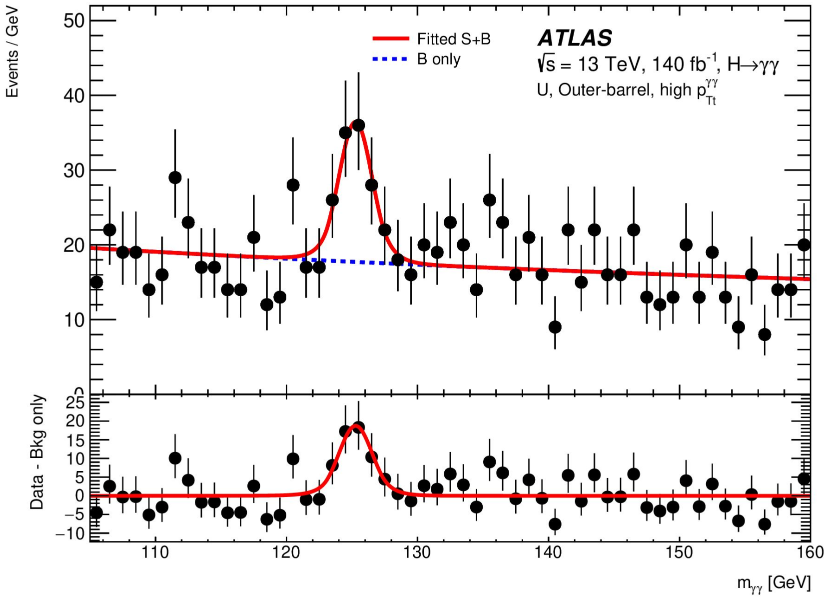
Run 2 ATLAS $H_{\gamma\gamma}$ mass measurement

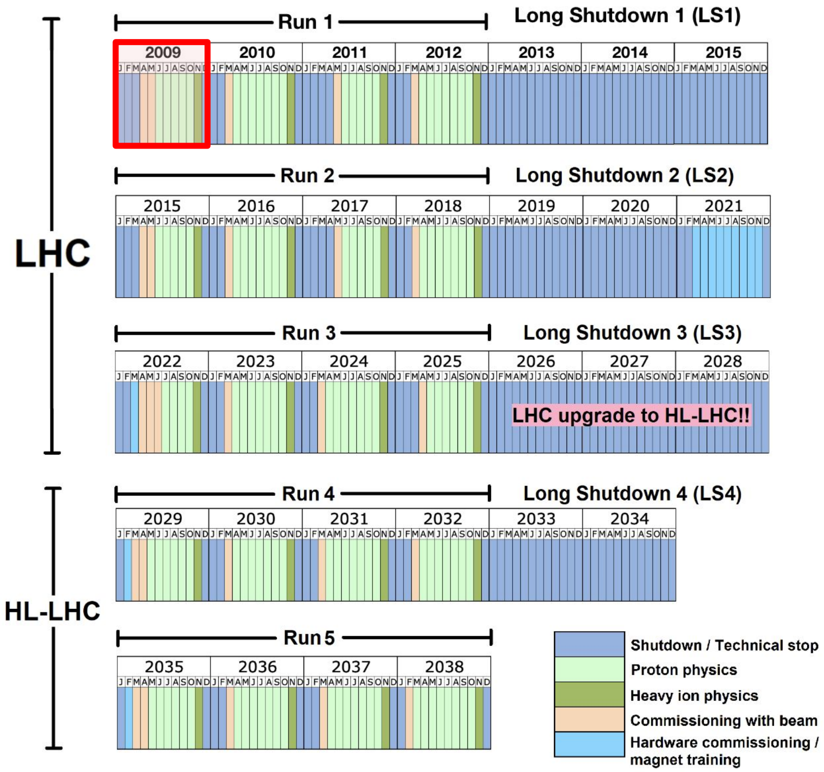
- For comparison of Hgam peak
- From Run 2 Hyy mass measurement
- [Phys. Lett. B 847 (2023) 138315]



ATLAS

The ATLAS detector: Schedule

- LHC and ATLAS in operation since ~ 2009



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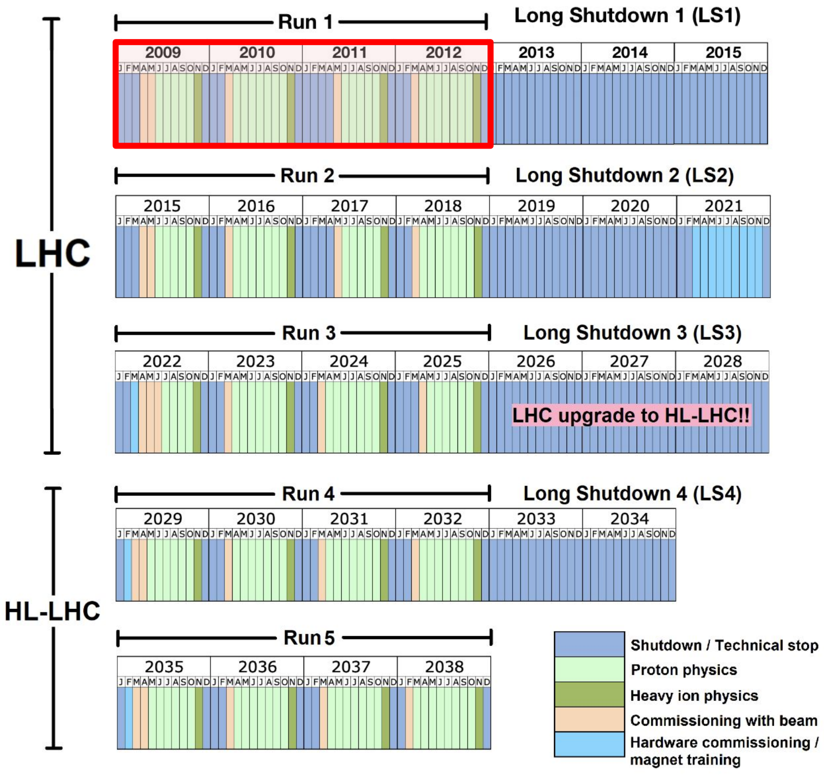

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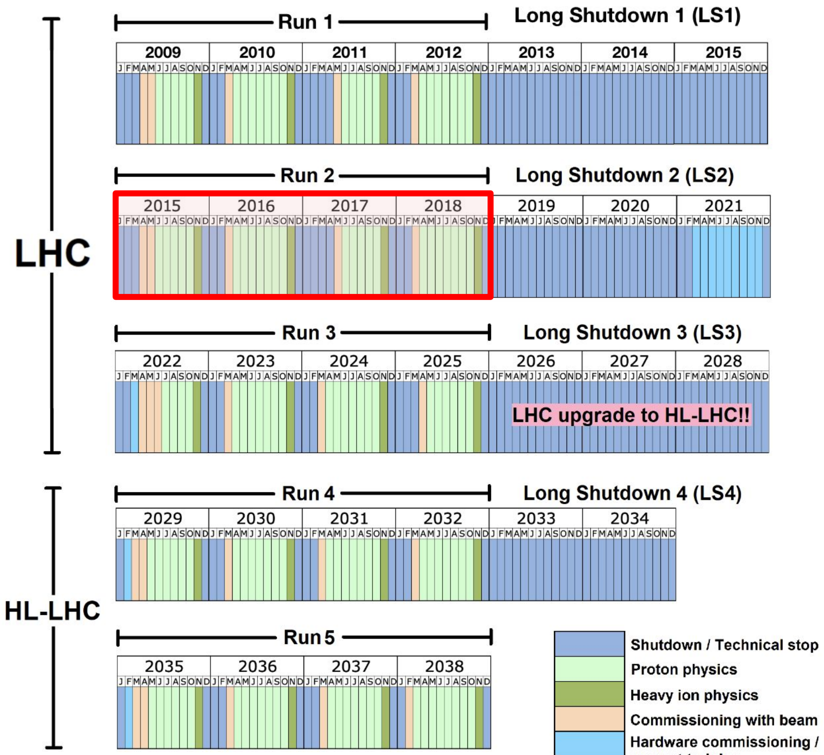
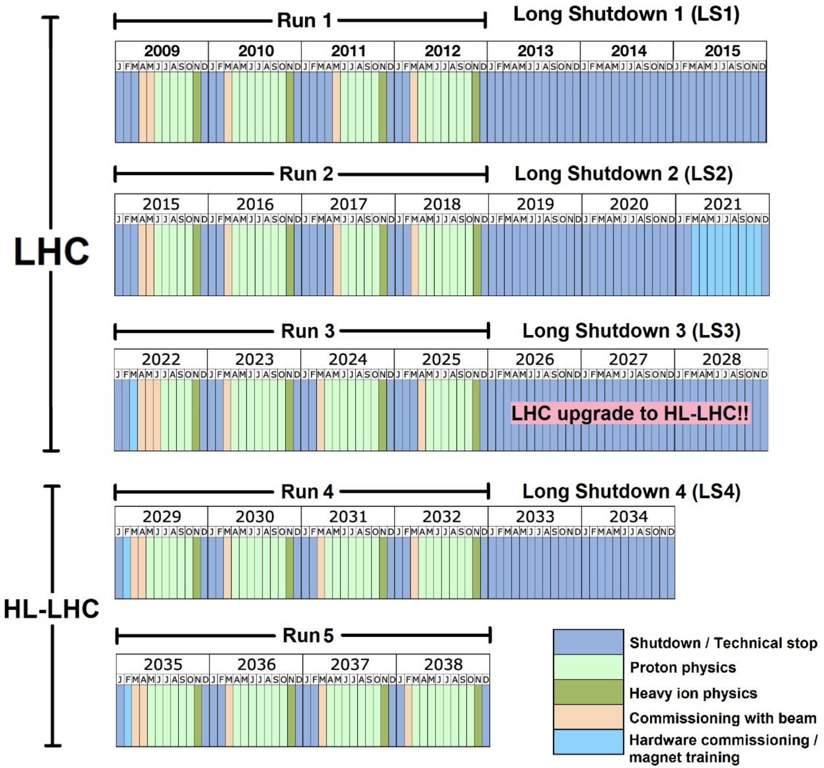
The ATLAS detector: Schedule

- LHC and ATLAS in operation since ~ 2009
- Run 1: 2009-2013 (data used for Higgs observation)
- **Run 2: 2015-2018**



Aside: Run 3

- Reminder - **LHC and ATLAS schedule**:



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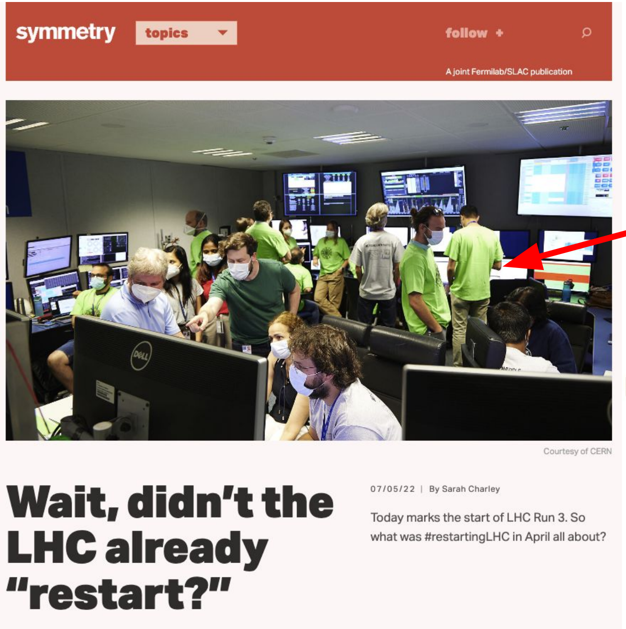
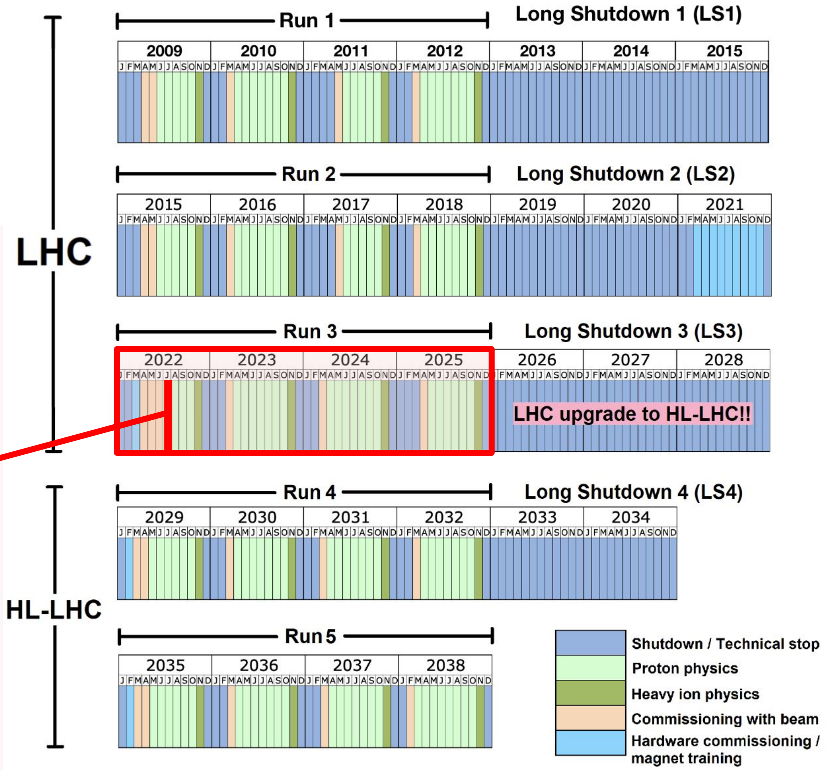
- Start of Run 3: **5 July 2022**



Wait, didn't the LHC already "restart?"

07/05/22 | By Sarah Charley

Today marks the start of LHC Run 3. So what was #restartingLHC in April all about?



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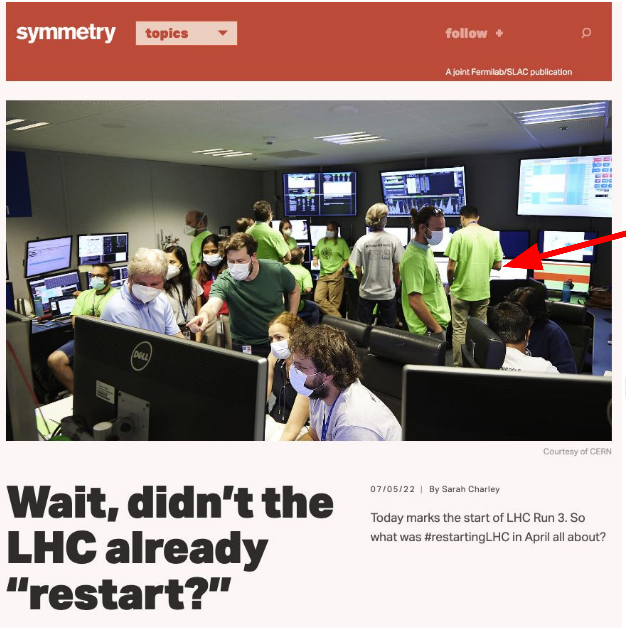
Some early results out!

Working hard analyzing Run 3 data…


symmetry topics follow +

A joint Fermilab/SLAC publication

Courtesy of CERN

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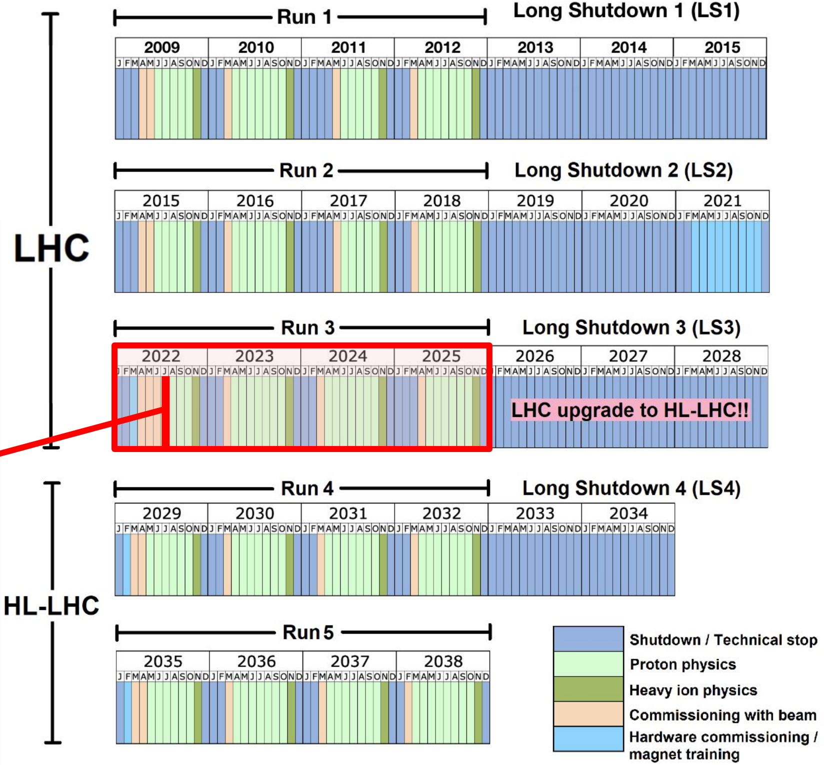

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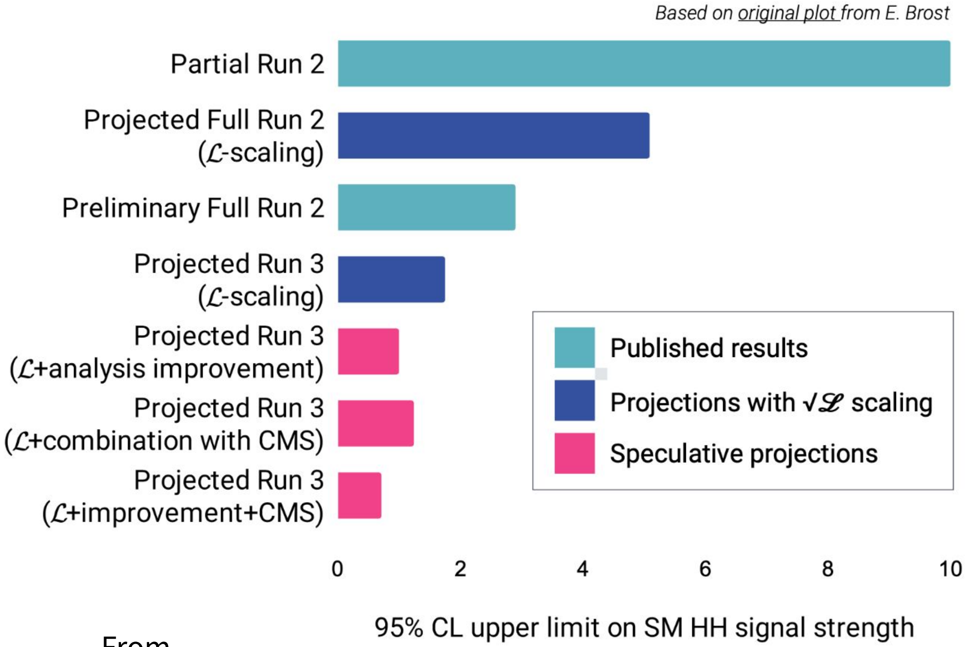
  - → Implies close to HH observation!

- Relies on improvement of analysis techniques



From
Katharine Leney

Brookhaven National Laboratory

The ATLAS detector: Flavor tagging

- Dedicated algorithms to identify b-quarks

The ATLAS detector: Flavor tagging

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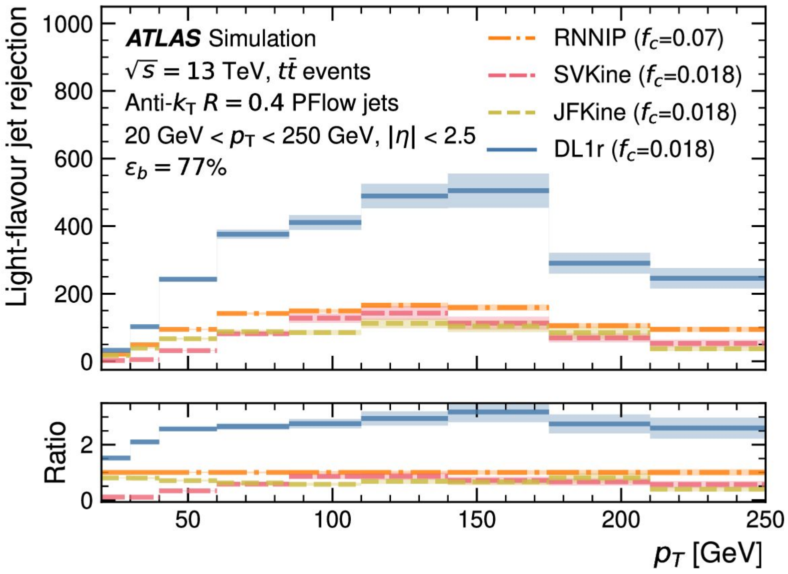
- **Low-level** tagging outputs input to **high-level** tagging algorithms: Recurrent and Deep neural networks



Eur. Phys. J. C 83 (2023) 681

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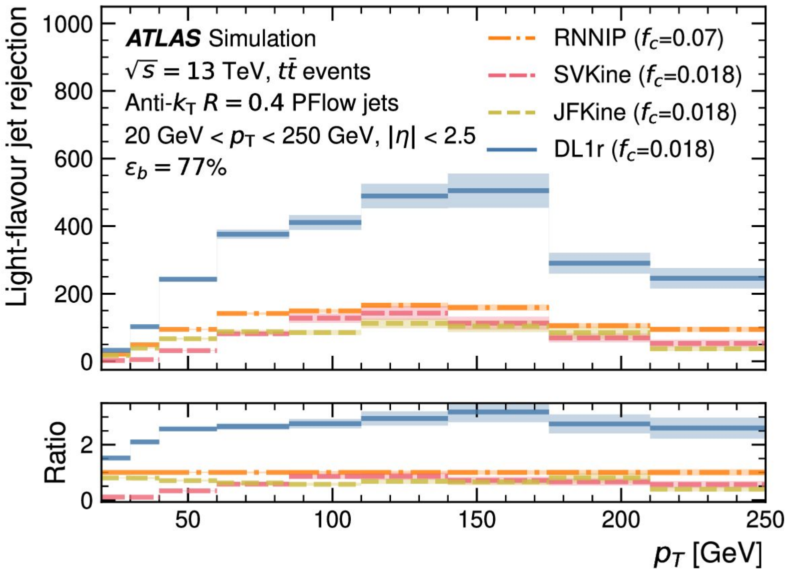
The ATLAS detector: Flavor tagging

- Dedicated algorithms to identify b-quarks
- **Low-level** tagging outputs input to **high-level** tagging algorithms: Recurrent and Deep neural networks
- Train on simulated tt, Z′→qq, evaluate performance on tt sample
- At DL1r 77% b-jet eff. point, **light-jet (charm-jet) rejection** factors of **170 (5)**



Eur. Phys. J. C 83 (2023) 681

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HH searches

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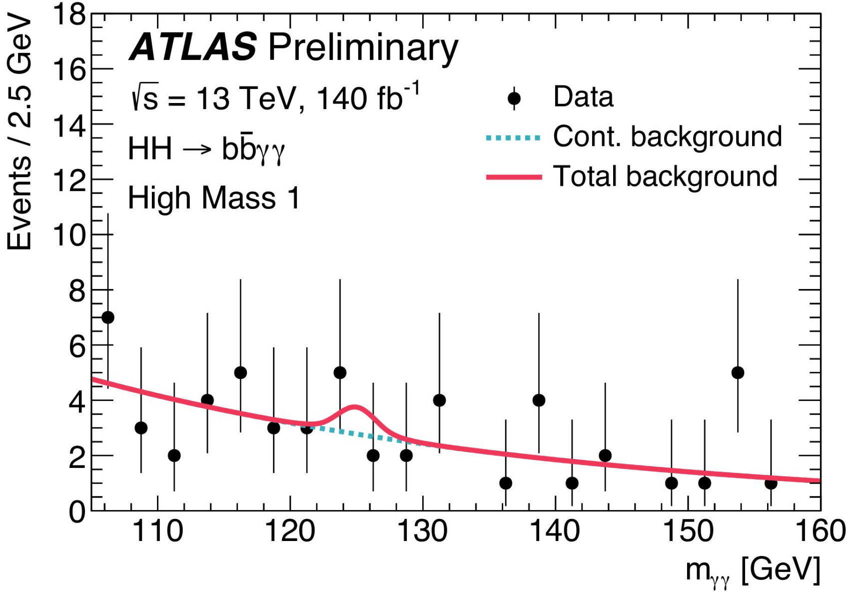
HH→bb$\gamma\gamma$: Di-Photon mass

- Di-Photon mass distribution in High Mass 1 category

- HH and H signatures modelled with **double sided crystal ball**

- Continuum background modelled by **fit to data sidebands**
  - Fit exponential functions. Normalization and shape obtained from fit to data



Di-Photon mass distribution in High Mass 1 category

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HH→bb$\gamma\gamma$: SM Results

- Perform simultaneous **unbinned** maximum likelihood fit in all categories
- Not near evidence level (yet!) so compute **upper limits**
- 95% CL_S upper limit extracted on HH signal strength
- Combining gluon fusion and VBF channels, upper limit on HH signal strength of **4.0** times the SM prediction
  - Improvement over previous analysis **observed (expected)** 95% UL on signal strength of **4.2 (5.7)** times SM due to updated event classification

	Observed	**Median expected**
μ_{VBF}	≤ 96	≤ 145
μ_{ggF}	≤ 4.1	≤ 5.3
$\mu_{(ggF+VBF)}$	≤ 4.0	≤ 5.0 (Background only hypothesis)

95% CL upper limits on **signal strength** (μ)

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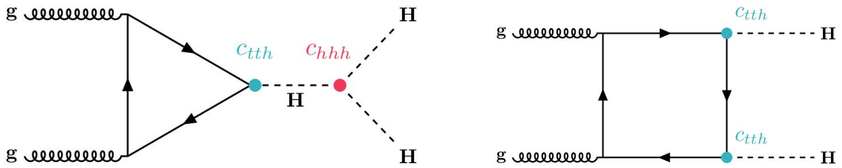
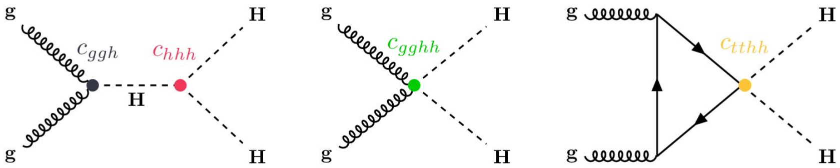
HH→bb$\gamma\gamma$: HEFT

- **HEFT**: Higgs Effective Field Theory. **Parameterized** Lagrangian allowing for deviations from SM
- Useful for **HH** re-interpretation: Higgs field is singlet, c_{gghh} and c_{tthh} do not affect the **background**

$$\mathcal{L}_{BSM} = -c_{hhh}\lambda_{HHH}^{SM} v h^3 - \frac{m_t}{v}\left(c_{tth} h + \frac{c_{tthh}}{v} h^2\right)\left(\bar{t}_L t_R + h.c.\right) + \frac{\alpha_S}{12\pi v}\left(c_{ggh} h - \frac{c_{gghh}}{2v} h^2\right) G^a_{\mu\nu} G^{a,\,\mu\nu}$$

$$c_{hhh} = \kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}},\quad \lambda_{HHH}^{SM} = \frac{m_H^2}{2v^2},\quad c_{tth} = \frac{y_t}{y_t^{SM}},\quad y_t^{SM} = \frac{\sqrt{2}m_t^2}{v}$$





SM-like processes (modified by couplings)

BSM processes

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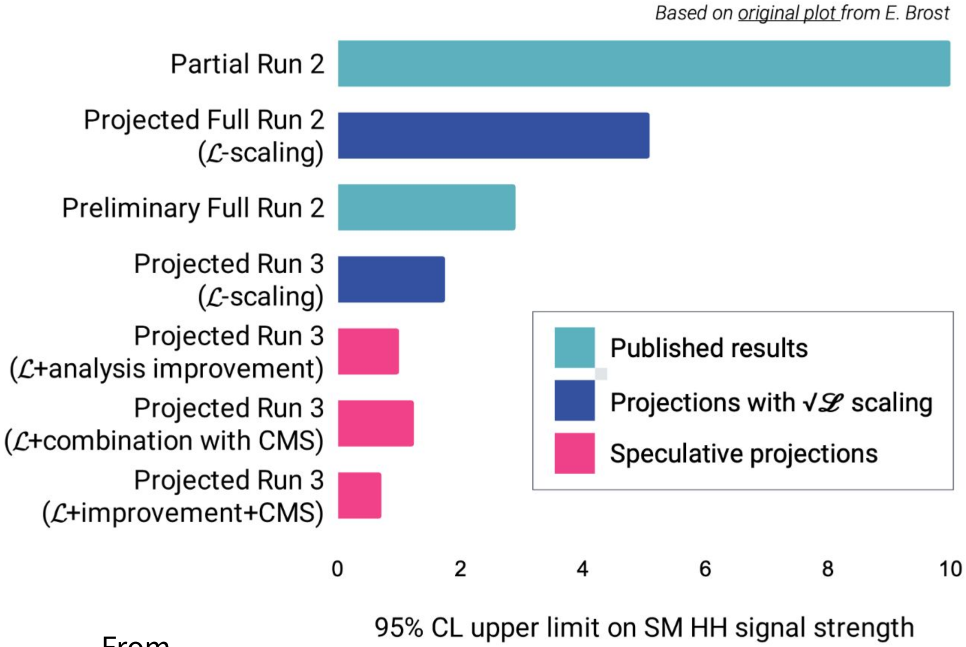

From
Katharine Leney

Brookhaven National Laboratory

HH→bb$\gamma\gamma$: Pre-selections

- Initial "skimming" of our massive datasets: Pre-selections
- Make selections on **photons** and **jets** to identify H→$\gamma\gamma$ and H→bb legs:

H→$\gamma\gamma$ selection	H→bb selection
Two high energy, isolated photons Lead (subleading) photon p_T > **35 (25) GeV**	Exactly 2 b-jets

- Use ML techniques to find b-jets
- Jets defined as **anti-kt** jets with R = 0.4
  - Identify "b-jets" with ATLAS "DL1r" algorithm, 77% efficiency working point, low misidentification rate [2211.16345]

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HH→bb$\gamma\gamma$: Pre-selections

- Initial “skimming” of our massive datasets: Pre-selections
- Make selections on **photons** and **jets** to identify H→$\gamma\gamma$ and H→bb legs:

H→$\gamma\gamma$ selection	H→bb selection	ttH($\gamma\gamma$) reduction
Two high energy, isolated photons Lead (subleading) photon p_T > **35 (25) GeV**	Exactly 2 b-jets	Exactly 0 leptons Less than 6 central jets

- Use ML techniques to find b-jets
- ttH($\gamma\gamma$) is a major single Higgs background - reduce based on its topology

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HH→bb$\gamma\gamma$: Introduction

- HH in H(bb)H($\gamma\gamma$) final state:
  - Clean $\gamma\gamma$ signature
  - High bb branching ratio

- 2022: Search for HH in bb$\gamma\gamma$ with ATLAS **Run 2** dataset published in PRD

- Observed (Expected) upper limit of σ_{HH} **4.2 (5.7) times SM prediction**
  - Also constrain Higgs self-coupling: observed (expected) [-1.5, 6.7] ([-2.4, 7.7])
  - Resonant search performed

	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%

PHYSICAL REVIEW D **106,** 052001 (2022)

Search for Higgs boson pair production in the two bottom quarks plus two photons final state in *pp* collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

G. Aad *et al.*[*]
(ATLAS Collaboration)

(Received 23 December 2021; accepted 1 August 2022; published 6 September 2022)

[Phys. Rev. D 106, 052001]

HH→bb$\gamma\gamma$: New studies

- Want to improve our HH results. Recently release new search for HH→bb$\gamma\gamma$ with the **Full Run 2 dataset**
- Want to **extend** upon effort with:
  - Further **EFT** interpretations - way to search for deviations
  - Improved sensitivity for **VBF** results
  - Re-optimized BDT **categorization**

JHEP
PUBLISHED FOR SISSA BY SPRINGER
RECEIVED: *October 20, 2023*
ACCEPTED: *December 27, 2023*
PUBLISHED: *January 12, 2024*

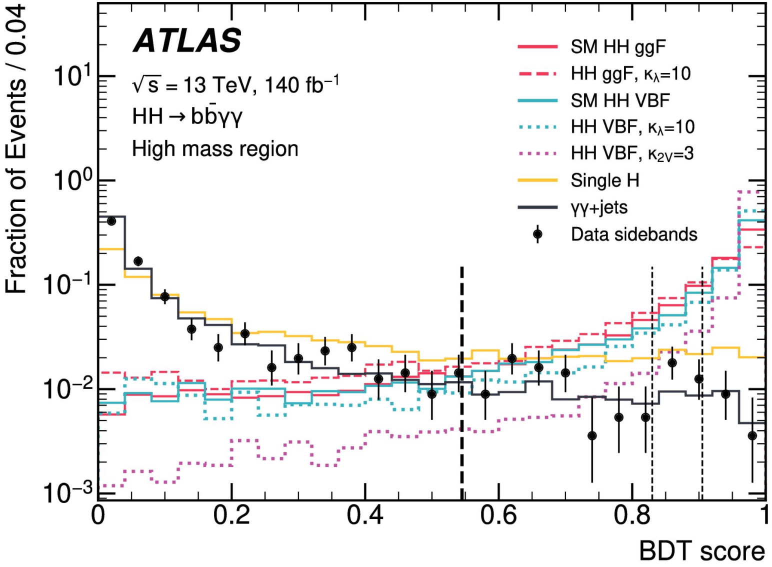
Studies of new Higgs boson interactions through nonresonant HH production in the $b\bar{b}\gamma\gamma$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

JHEP01(2024)066

- Published in JHEP in January! ATLAS website entry with all plots and tables

HH→bb$\gamma\gamma$: BDT

- Train **boosted decision tree** to separate **signal** and **background** signatures
- Use photon, jet kinematics as main inputs. Separate BDT trained to identify **VBF jets**
- Optimize category boundaries based on number-counting significance
- Good separation achieved



BDT score in high mass region, **data sideband**

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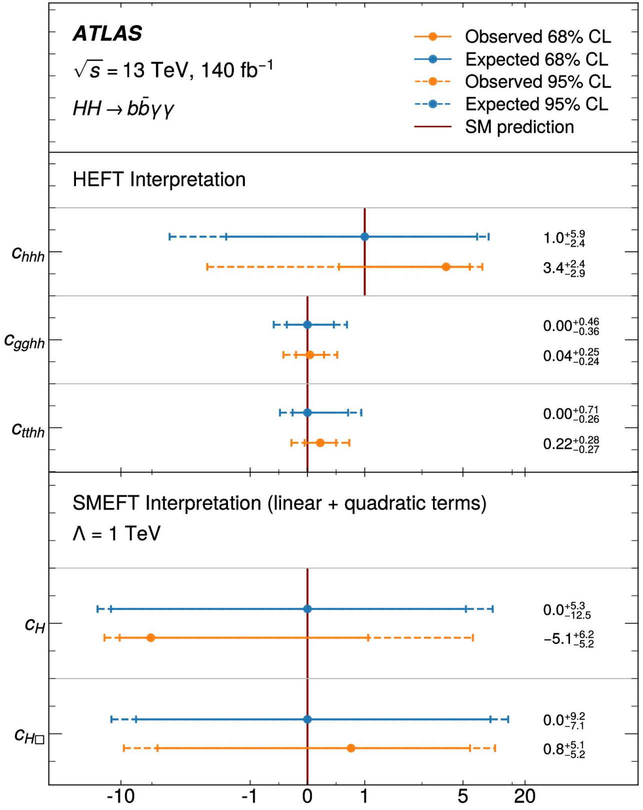
EFT: Results summary

- **Summary** of EFT results varying one parameter at a time, keeping others **fixed** to SM values

- **No deviations** w.r.t. SM predictions observed



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HH→bb$\gamma\gamma$: HEFT benchmark results

- Additionally search for HEFT **benchmarks** which represent **distinct, representative kinematic shapes** in 5D HEFT phase space [1908.09923], [CDS]:

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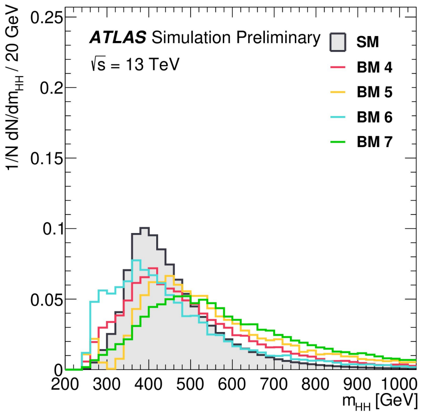
Benchmark	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1	1	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	-1/3	0	1/6
3	2.21	1.05	1/2	1/2	-1/3
4	2.79	0.90	-1/3	-1/2	-1/6
5	3.95	1.17	1/6	-1/2	-1/3
6	-0.68	0.90	1/2	0.25	-1/6
7	-0.10	0.94	1/6	-1/6	1



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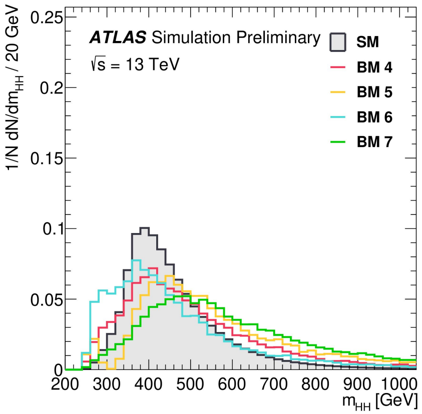

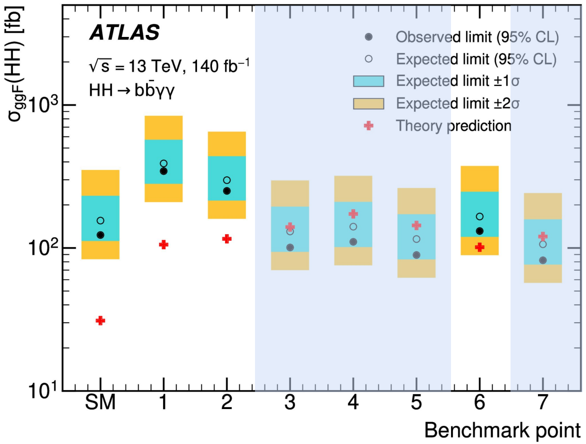

- Benchmarks **3, 4, 5, 7** excluded at a 95% CL - partially due to **harder m_{HH} spectrum**

● lower than ✚ = Excluded!

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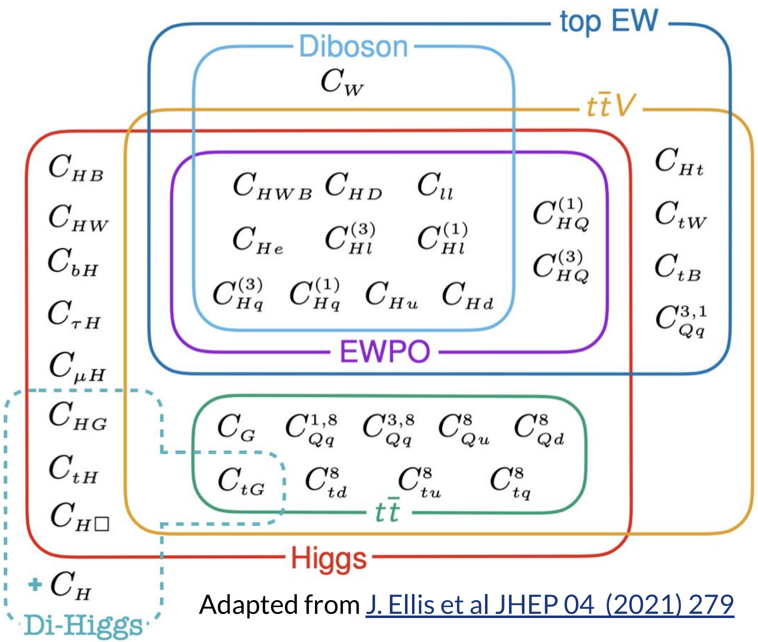
HH→bb$\gamma\gamma$: SMEFT

- **SMEFT**: Standard Model Effective Field Theory

HH→bbγγ: SMEFT

- **SMEFT**: Standard Model Effective Field Theory
- Expansion of SM Lagrangian with dim-6 operators, includes 5 Wilson Coefficients
- This analysis uses **linear + quadratic** truncation scheme (not sensitive to linear only)
- **Operators** considered in this analysis: C_H $C_{H\Box}$ C_{tH} C_{tG} C_{HG} → [LHCWG-2022-004]



Adapted from J. Ellis et al JHEP 04 (2021) 279

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HH→bbγγ: SMEFT

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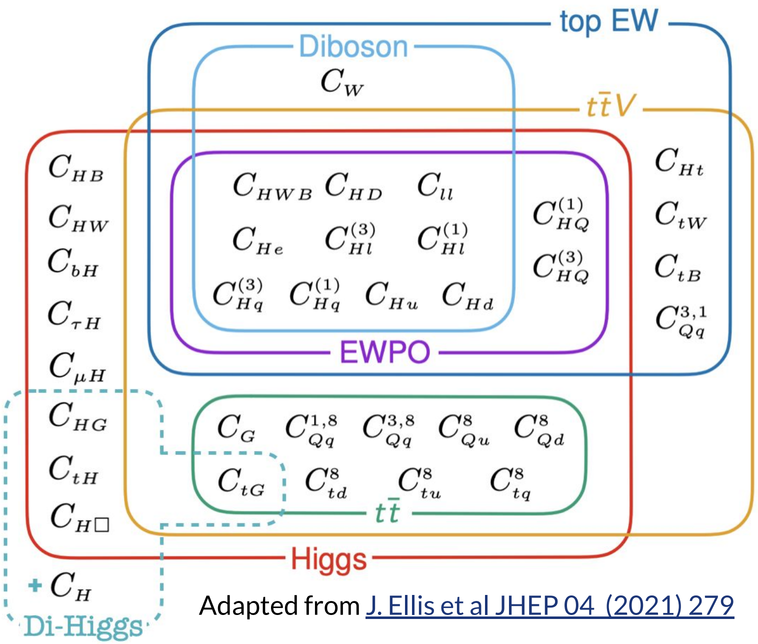
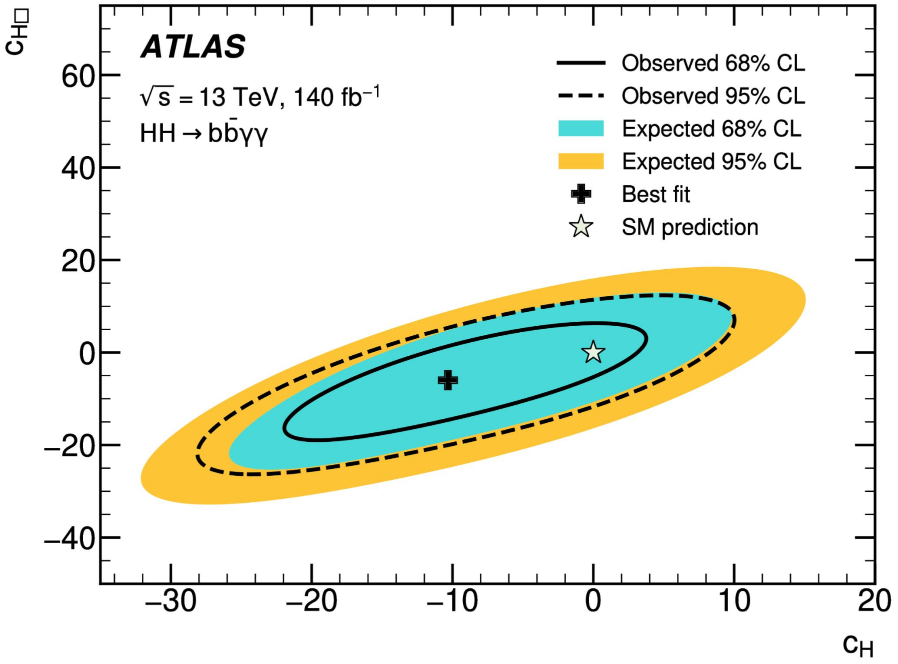
- **Operators** considered in this analysis:
  C_H $C_{H\Box}$ C_{tH} C_{tG} C_{HG} → [LHCWG-2022-004]
- Compared to **HEFT**:
  - Less general. h is contained in SU(2) doublet (same as SM).
  - More useful for **global combination** - many other LHC searches use SMEFT



Adapted from J. Ellis et al JHEP 04 (2021) 279

HH→bbγγ: SMEFT

- Simultaneously vary **two** SMEFT parameters, effect on **single Higgs** backgrounds
- Similar to κ_λ, κ_{2V}, HEFT interpretations, reweight **SM signal** based on expected cross-section and branching ratios of given point
  - c_H at tree level, and $c_{H\Box}$ do not affect branching ratios
- Fit to **data**, compute **likelihood**
- Again, no deviation seen w.r.t. SM. Agrees within 1 sigma



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HH→bb$\gamma\gamma$: Coupling modifiers

- **Kappa framework**: **Reweight SM sample** with m_{HH} information, estimate **shape** and **yields** at non-SM Higgs self-coupling, HHVV couplings

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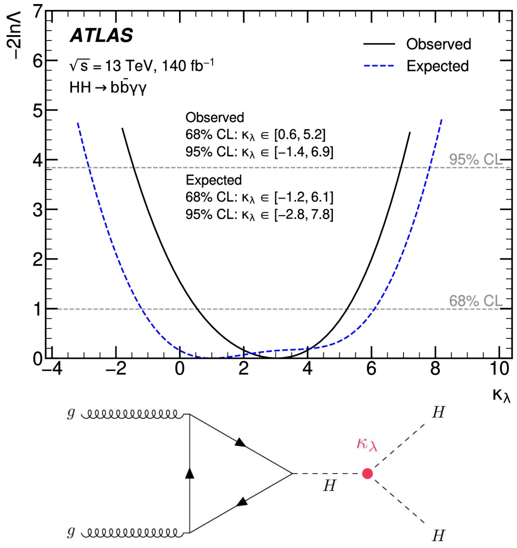
- Fit to data, extract **likelihood** at each point:



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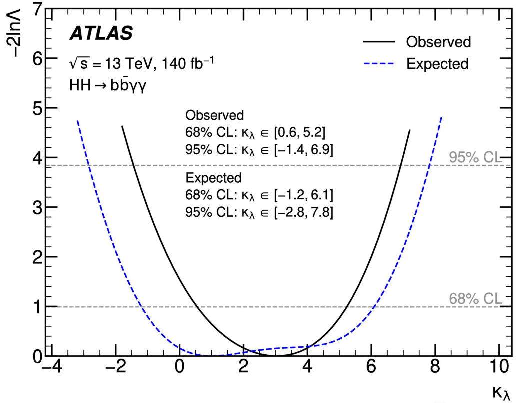

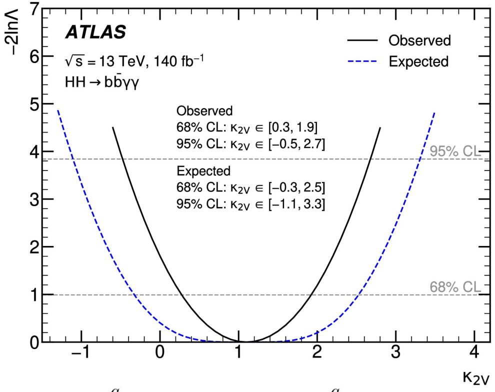

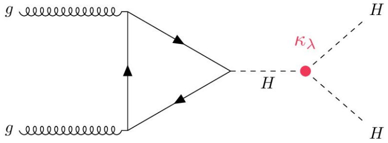

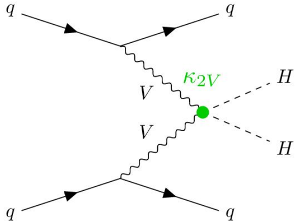

HH→bb$\gamma\gamma$: Coupling modifiers

- **Kappa framework**: **Reweight SM sample** with m_{HH} information, estimate **shape** and **yields** at non-SM Higgs self-coupling, HHVV couplings
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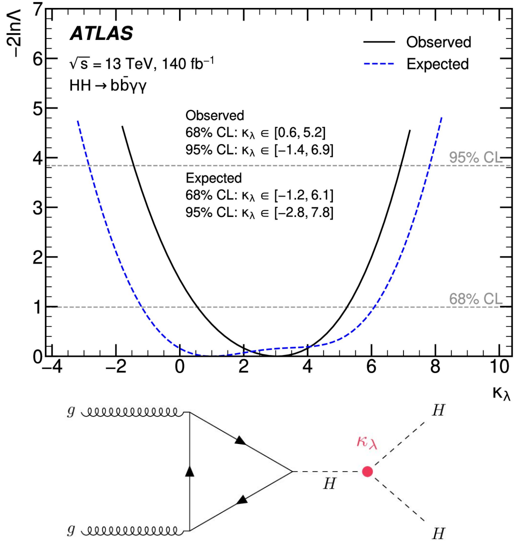

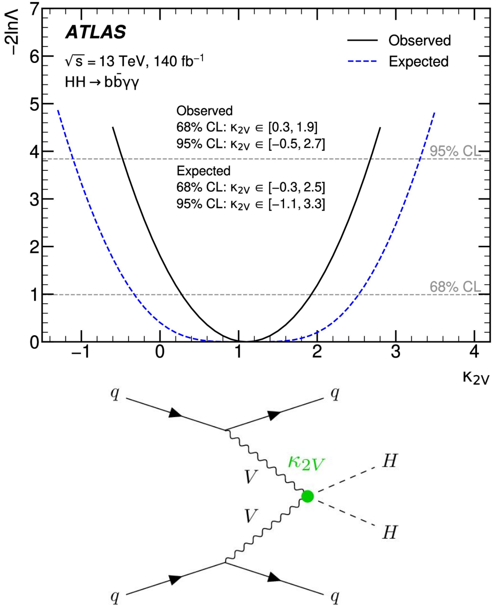

- Improvement on **expected** κ_λ range, **part** of observed range w.r.t. previous analysis: **[-2.4, 7.7] ([-1.5, 6.7])** Expected (observed) @ 95% CL

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Partial Run 2 kl constraints

Partial Run 2 analysis kl constraints

Table 2
Allowed κ_λ intervals at 95% CL for the $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$ final states and their combination. The column "Obs." lists the observed results, "Exp." the expected results obtained including all statistical and systematic uncertainties in the fit, and "Exp. stat." the expected results obtained including only the statistical uncertainties. The effect of non-SM Higgs decay branching fractions due to κ_λ variations is not taken into account, which impacts the κ_λ intervals by no more than 7%.

Final state	Allowed κ_λ interval at 95% CL		
	Obs.	Exp.	Exp. stat.
$b\bar{b}b\bar{b}$	−10.9 – 20.1	−11.6 – 18.8	−9.8 – 16.3
$b\bar{b}\tau^+\tau^-$	−7.4 – 15.7	−8.9 – 16.8	−7.8 – 15.5
$b\bar{b}\gamma\gamma$	−8.1 – 13.1	−8.1 – 13.1	−7.9 – 12.9
Combination	−5.0 – 12.0	−5.8 – 12.0	−5.3 – 11.5

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bbyy theory uncertainty

- Theory uncertainty in recent bbyy result:

Theoretical uncertainties due to missing higher-order terms in the perturbative expansion of the cross-section, the PDF set, and the value of α_s affect the total expected yields of single Higgs boson and Higgs boson pair events, and their fractional contributions to each category. These uncertainties are evaluated by considering alternative choices of factorisation and renormalisation scales, PDF sets, and the value of α_s. For SM Higgs boson pair production, the values of the QCD scale and PDF+α_s total cross-section uncertainties are taken from ref. [93]. For SM HH production through ggF, the QCD scale and PDF+α_s cross-section uncertainties are further combined with the top-quark mass scale uncertainty according to the prescription described in ref. [28]. The uncertainties in the $H \to \gamma\gamma$ and $H \to b\bar{b}$ branching ratios are also included [94].

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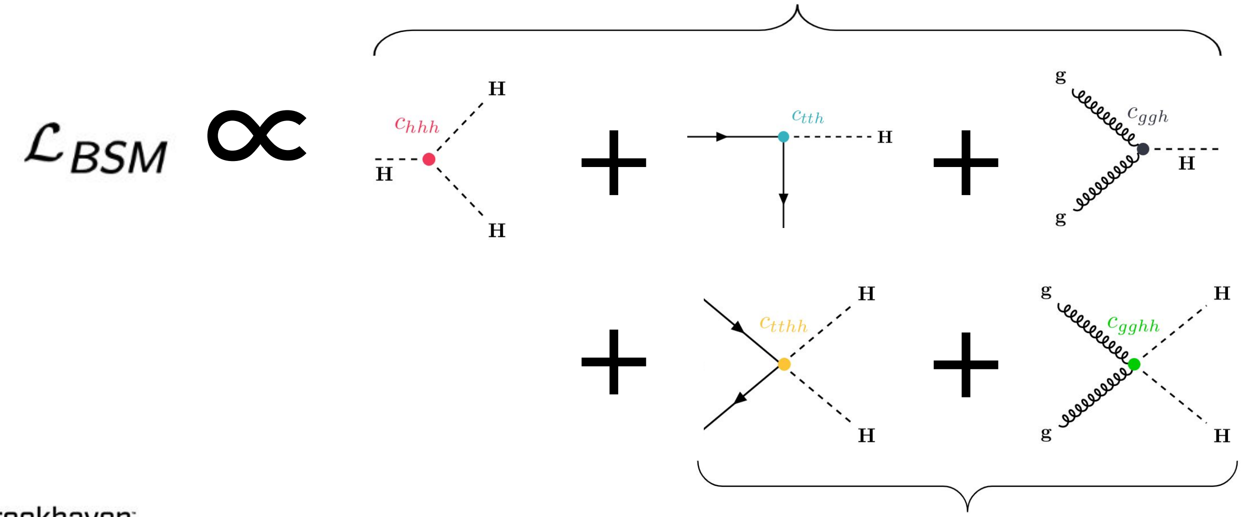
HH→bb$\gamma\gamma$: HEFT

- **HEFT**: Higgs Effective Field Theory. **Parameterized** theory allowing for deviations from SM
- Useful for **HH** re-interpretation: Higgs field is singlet, c_{gghh} and c_{tthh} do not affect the **background**

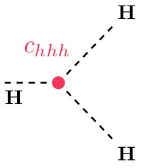
SM-like processes (modified by couplings)

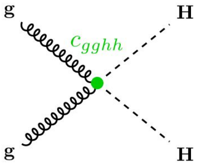


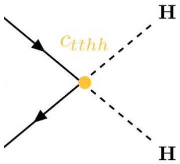
BSM processes

HH→bb$\gamma\gamma$: HEFT scan results

- Simultaneously vary c_{hhh}, and modifier of HH coupling to gg/tt
- **Implementation** difference from κ_λ: Reweight **SM** samples. κ_λ results use a **sum of three** samples to estimate shape and yields for non-SM values

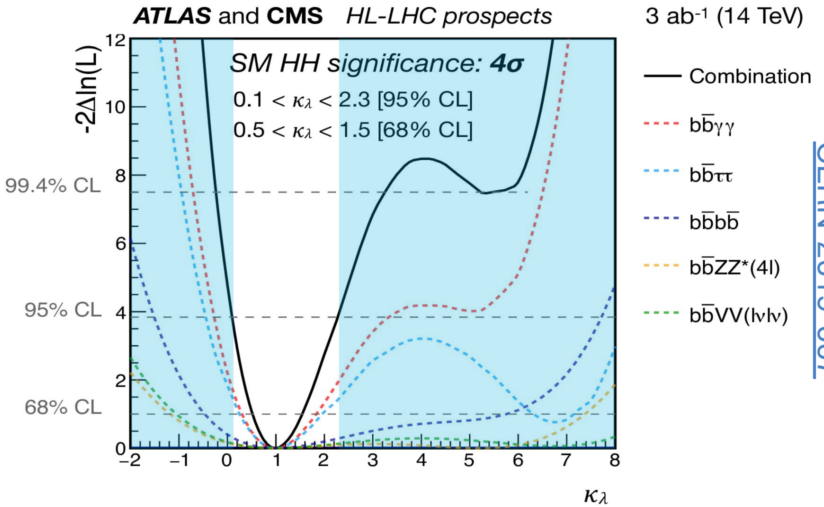




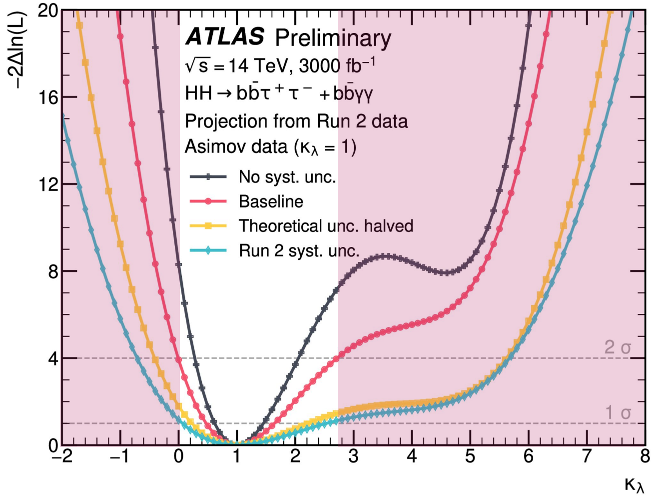


Beyond the LHC

HL-LHC: HH projections



CERN-2019-007



ATL-PHYS-PUB-2022-005

European Strategy (2018)

- Combination of 5 HH channels, many based on partial Run 2 analysis strategy
- 50% precision on self-coupling
- **4σ SM HH significance** (ATLAS+CMS)

Snowmass update (2022)

- ATLAS γγbb+bbττ combination: 3.2σ
- CMS updated γγbb results, added γγWW, γγττ, ttHH(bbbb)