Searching for beauty with beauty in the Higgs sector

Abraham Tishelman-Charny

Thursday, 21 September 2023
Particle Physics Seminar at BNL

ATLAS EXPERIMENT

Brookhaven National Laboratory

Who am I?

- Abraham (Abe) Tishelman-Charny

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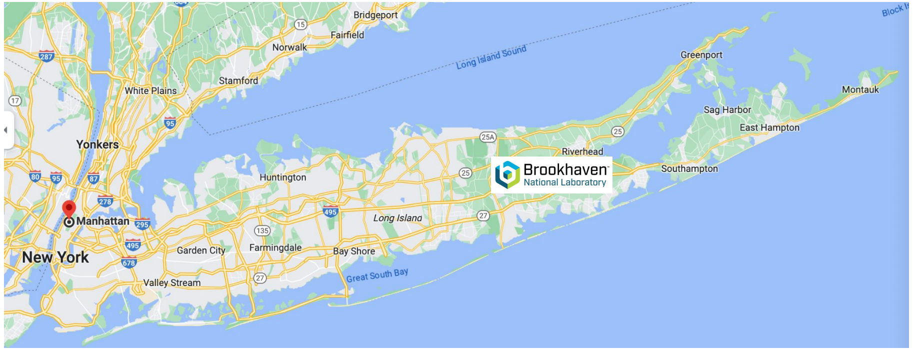
- 1994: Born, not far from here: **Manhattan, NY**



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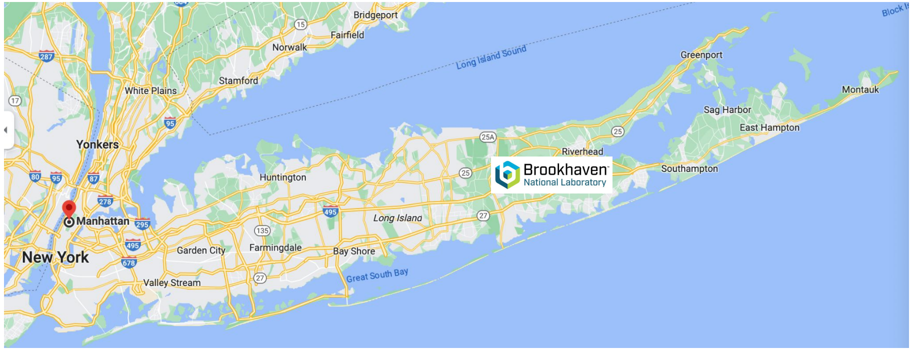
- 2016: Got my B.S. in Physics even closer to here: **Stony Brook University**

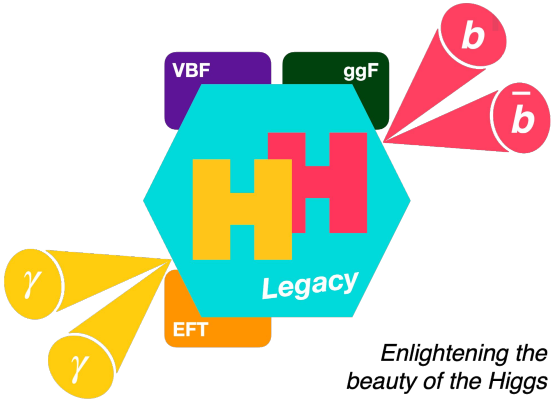
- 2022: PhD from **Northeastern University** on the CMS experiment (Boston, then 4 years at CERN)

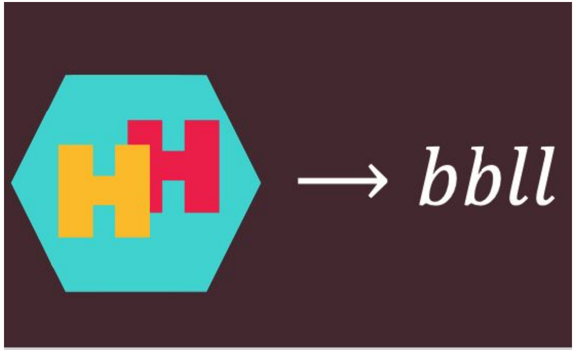
- 2022: Started as a postdoc here at **BNL**:
    - ATLAS collaboration
    - ATLAS tracker upgrade for HL-LHC (ITk)
    - Future Circular Collider studies
    - Working on **Higgs pair production**



Outline

I. The Higgs self-coupling
II. The ATLAS detector
III. ATLAS Run 2 HH→bb$\gamma\gamma$
IV. ATLAS Run 2 HH→bb$\ell\ell$
V. Future prospects
VI. Summary



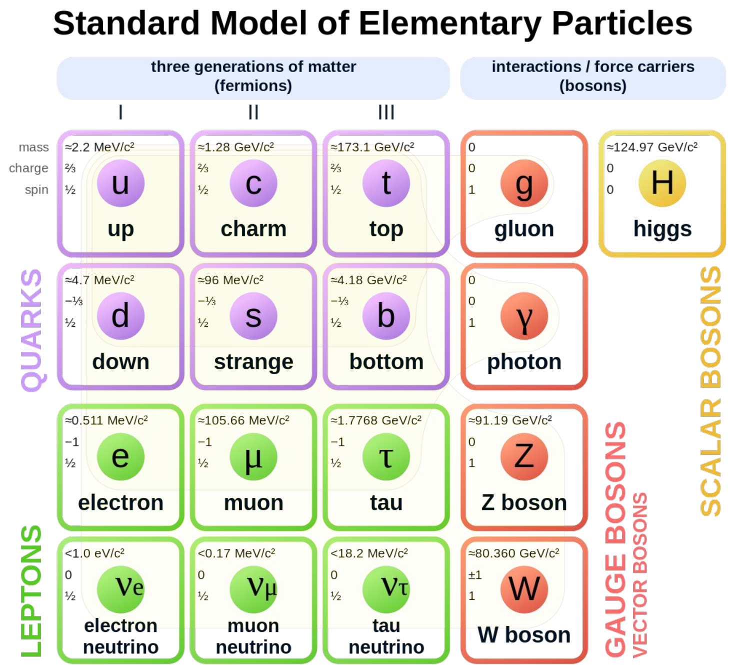


Higgs self-coupling

Self-coupling: The SM

- The Standard Model (SM) of particle physics:
    - Extremely successful - predicts vast majority of observed phenomena

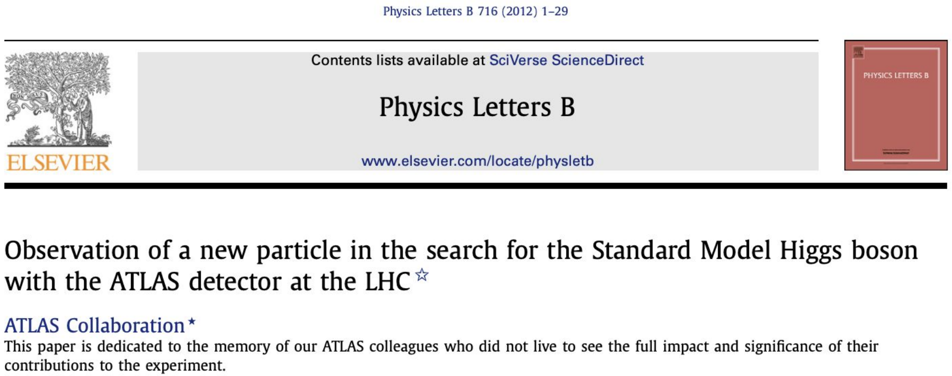
- Defines **elementary particles**, and their **interactions**



Self-coupling: The Higgs boson

- **4 July 2012**: Experimental discovery of the **Higgs boson**, the final undiscovered **SM particle**

4 July 2012: CERN main auditorium



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]

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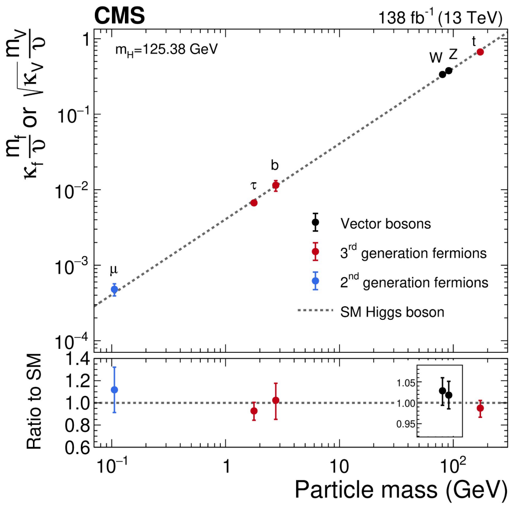
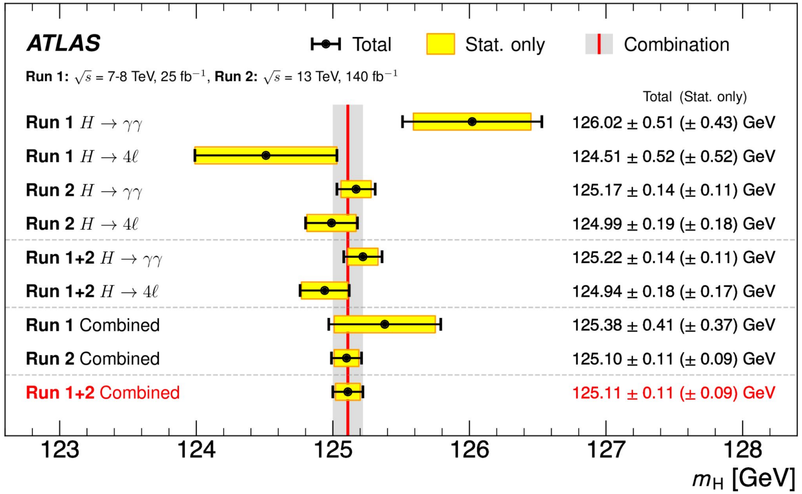
Self-coupling: The Higgs boson

- 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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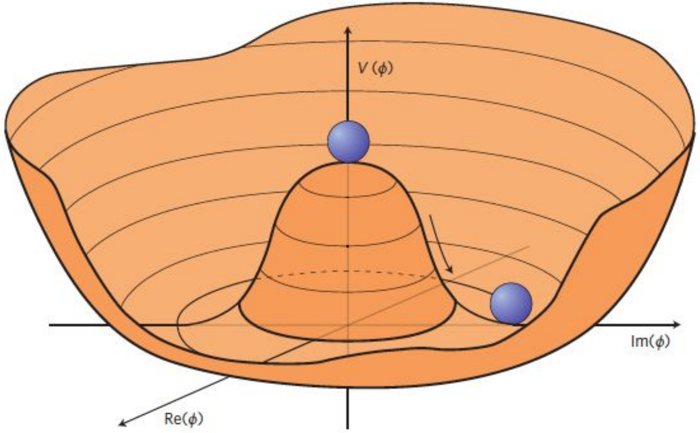
Self-coupling: Higgs potential

- **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

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

Self-coupling: Higgs pair production

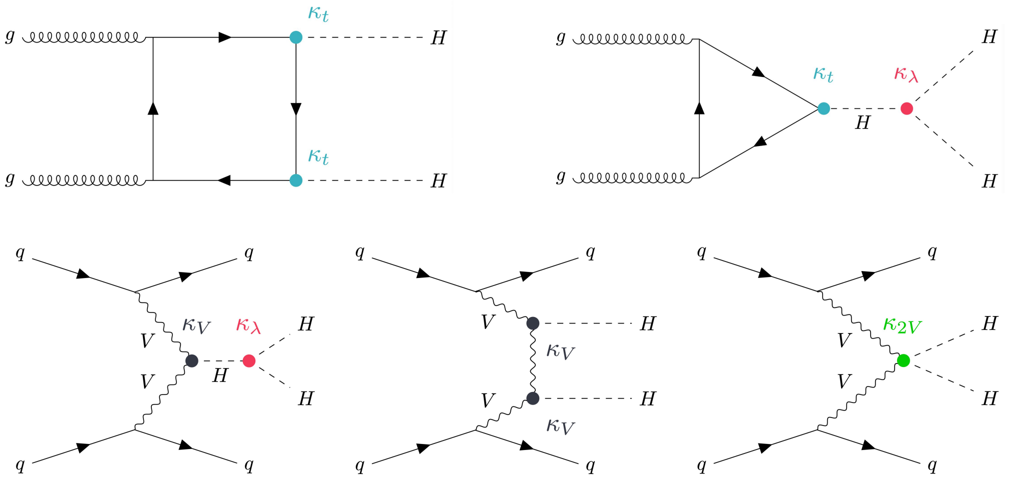
Can directly access Higgs self-coupling via **Higgs pair production (HH)**:

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

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Self-coupling: HH final states

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

	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%

= Studied by ATLAS/CMS

The ATLAS detector

The ATLAS detector: LHC

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

- Began operation at $\sqrt{s} = 7$ TeV, now up to 13.6 TeV

- Collides protons, heavy ions

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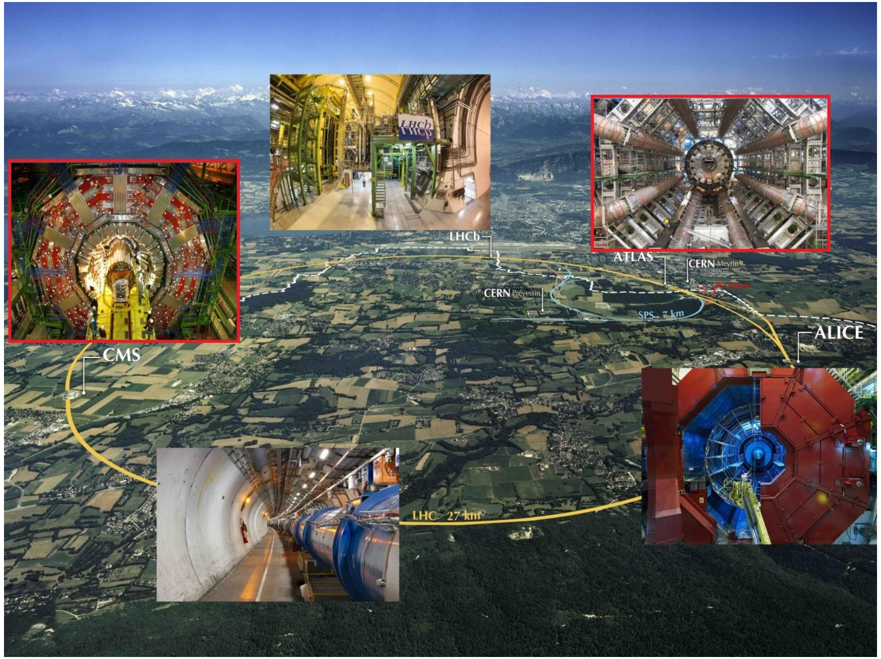
The ATLAS detector: LHC

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

- Began operation at $\sqrt{s}$ = 7 TeV, now up to 13.6 TeV

- Collides protons, heavy ions
- Has **four detectors** stationed

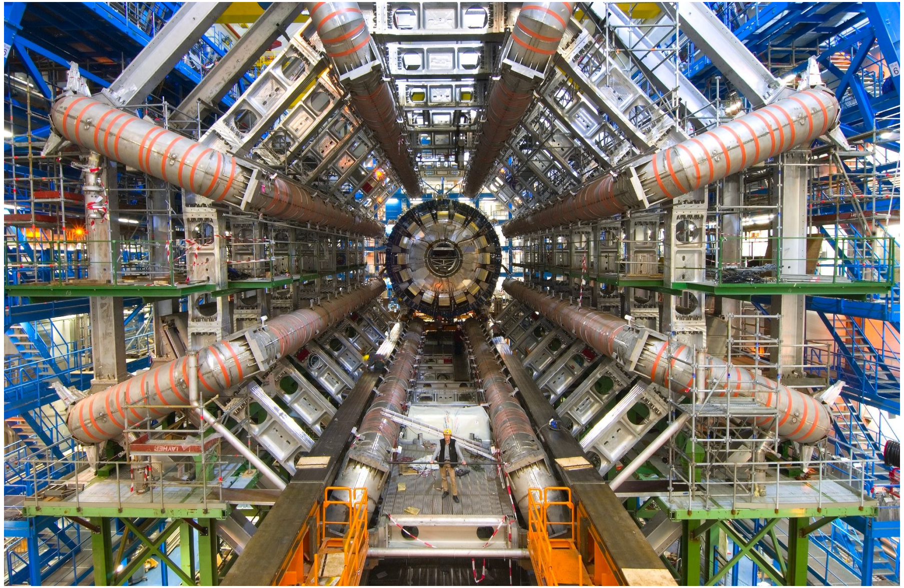


The ATLAS detector: Layout

- ATLAS detector

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

- Rich physics program:
    - Higgs, Dark matter, Electroweak, Supersymmetry, …

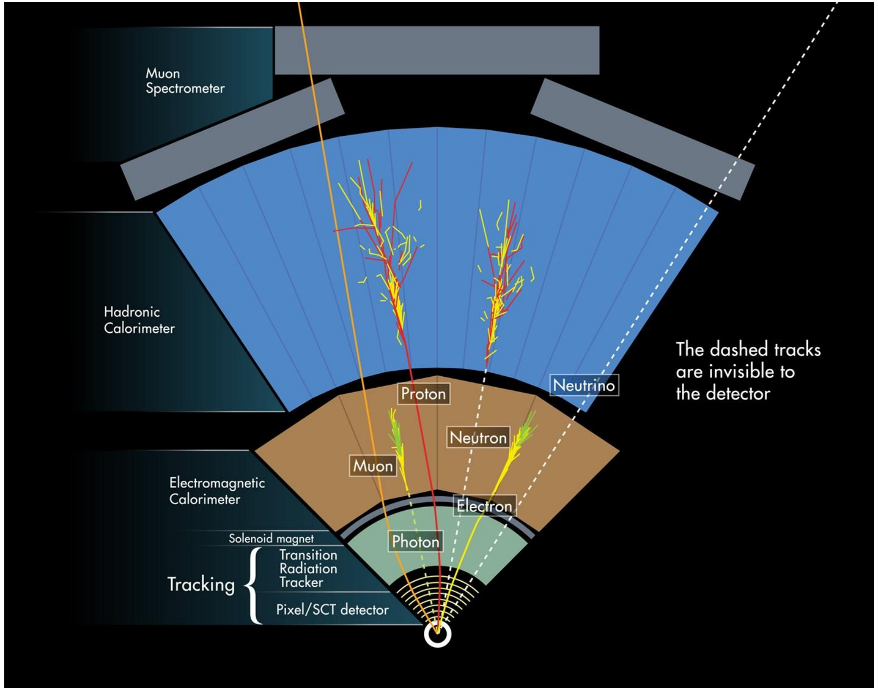


The ATLAS detector: Layout

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

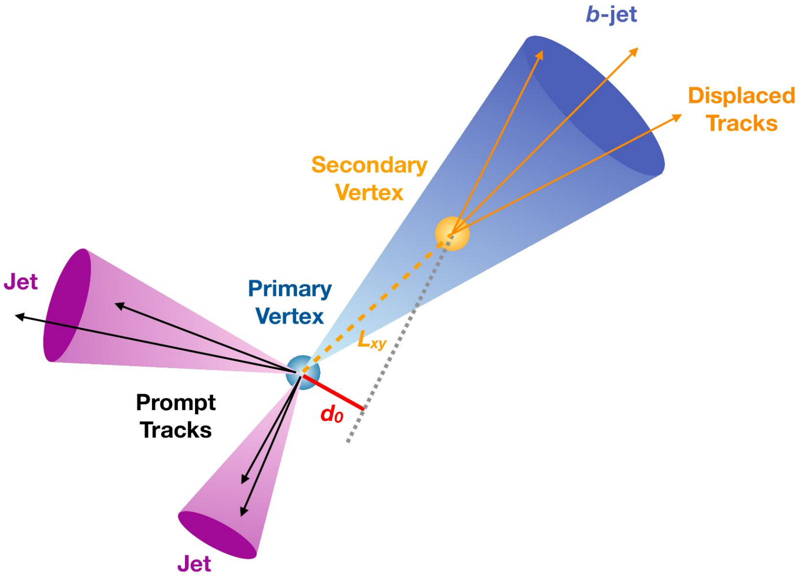
- Requires use of different detector **technologies**

- **Reconstruct** underlying physics **event** by working backwards from detector information



The ATLAS detector: Bottom quarks

- Quarks hadronize, leave **jets** seen by detector
- The bottom (or beauty) quark: Relatively **heavy**
- Forms a b-meson and propagates before hadronization
- **Distinctly different** signature! Can use to differentiate from “light” jets



[Eur. Phys. J. C 1087 (2021)]

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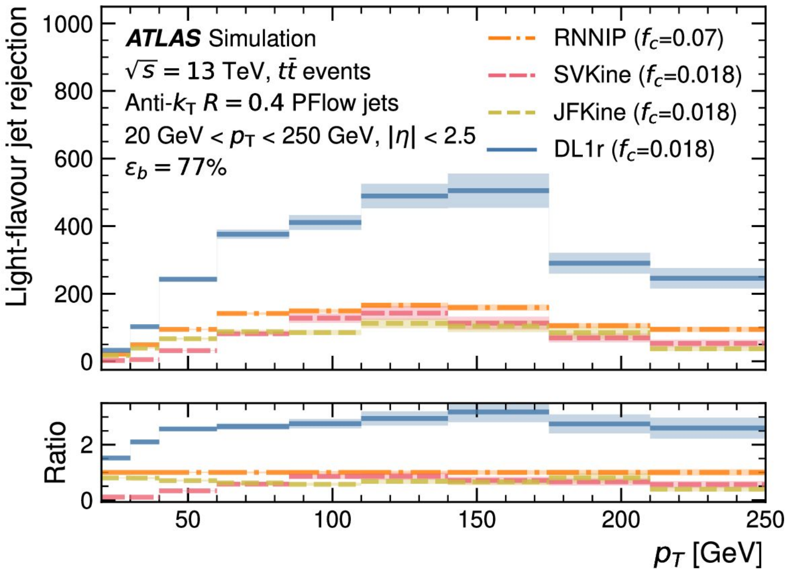
The ATLAS detector: Flavor tagging

- 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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ATLAS Run 2 $HH \rightarrow bb\gamma\gamma$

HH→bb$\gamma\gamma$: Introduction

- HH in H($\gamma\gamma$)H(bb) final state benefits from **clean $\gamma\gamma$** signature, high bb branching ratio

- 2022: Search for HH in $\gamma\gamma$bb 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
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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]

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HH→bb$\gamma\gamma$: New studies

- Want to **extend** upon this strong Run 2 analysis effort with:
    - Further **EFT** interpretations - way to search for deviations
    - Improved sensitivity for **VBF** results
    - Re-optimized BDT **categorization**

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

ATLAS-CONF-2023-050

18 August 2023

ATLAS-CONF-2023-050

- Webpage includes public note, figures and tables of the analysis

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HH→bb$\gamma\gamma$: Strategy

- Three physics signatures:
  - HH (Signal)
  - H (Resonant background)
  - Continuum background
    - $\gamma\gamma$+jets, tt$\gamma\gamma$

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

- Need to separate single Higgs and continuum backgrounds from HH

- HH and H modelled with **MC**. Data-driven continuum background using data sidebands

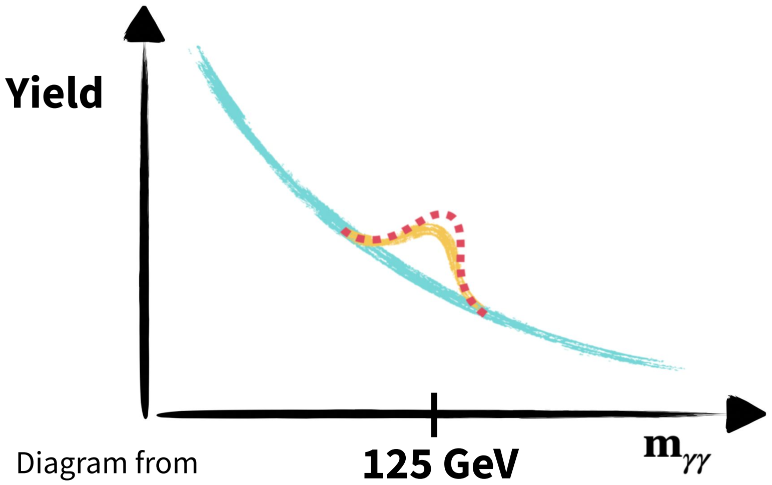

Diagram from
Elena Mazzeo

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HH→bb$\gamma\gamma$: 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

- 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]

- ttH($\gamma\gamma$) is a major single Higgs background - reduce based on its final state topology

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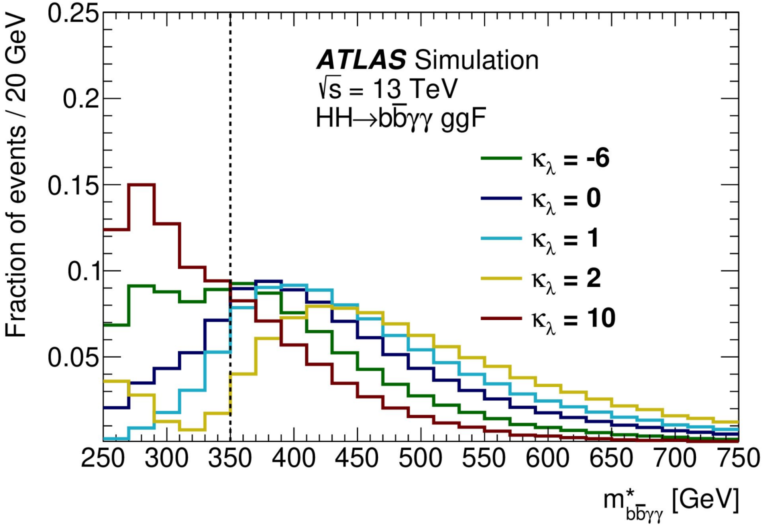
HH→bbγγ: Reduced mass

- 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:
  - Reduced mass less-than or greater-than 350 GeV
  - **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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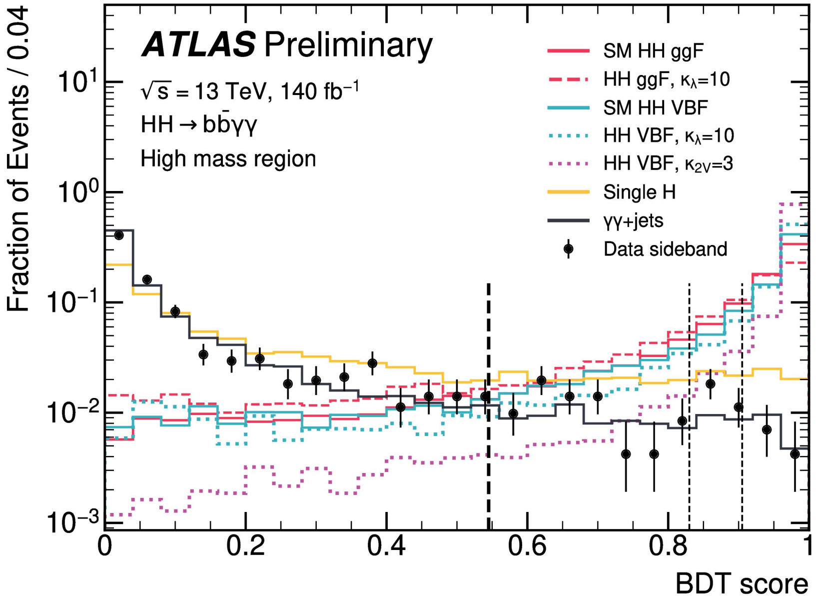
HH→bb$\gamma\gamma$: BDT

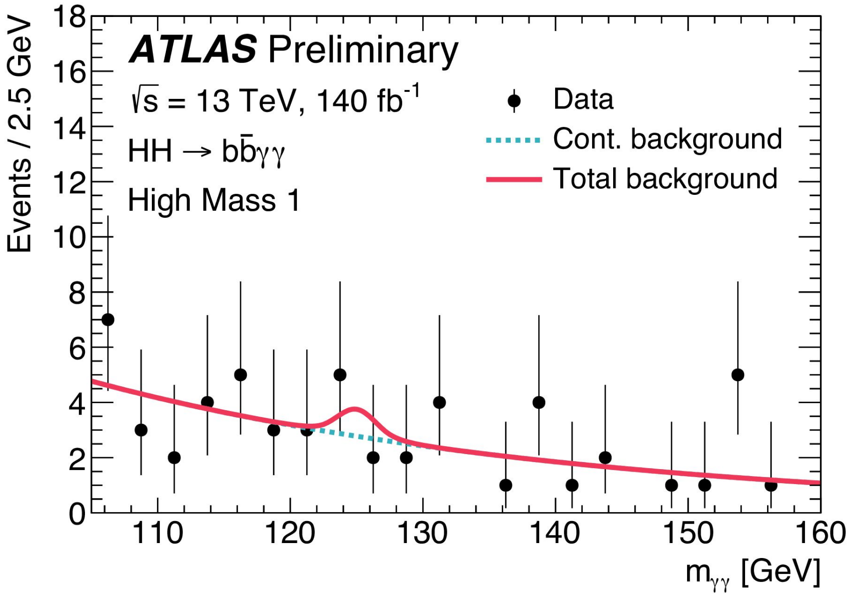
- Train **boosted decision tree** to separate **signal** and **background** signatures
- Use photon, jet kinematics as main inputs. Separate BDT trained to identify **VBF jets**
- Optimize category boundaries based on number-counting significance
- Good separation achieved



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

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

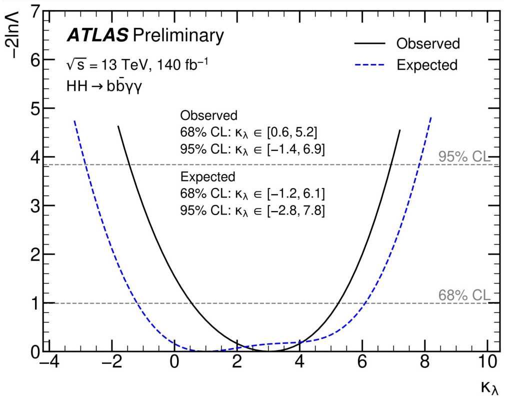
- Perform simultaneous **unbinned** maximum likelihood fit in all categories
- Not near evidence level (yet!) so compute **upper limits**
- 95% CL_S upper limit extracted on HH signal strength
- Combining gluon fusion and VBF channels, upper limit on HH signal strength of **4.0** times the SM prediction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

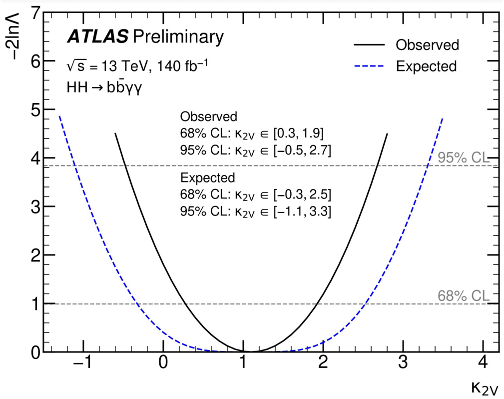
	Observed	**Median expected**
μ_{VBF}	≲ 96	≲ 145
μ_{ggF}	≲ 4.1	≲ 5.3
$\mu_{(ggF+VBF)}$	≲ 4.0	≲ 5.0 (Background only hypothesis)

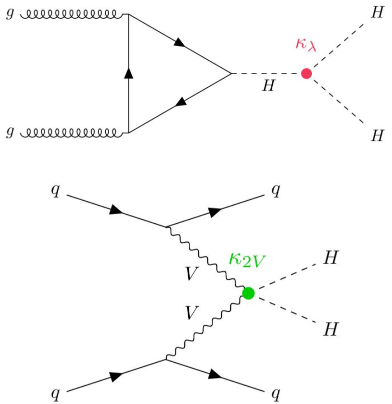
95% CL upper limits on **signal strength** (μ)

HH→bbγγ: Coupling modifiers

- <u>**Kappa framework**</u>: **Reweight SM sample** with m_{HH} information, estimate **shape** and **yields** at non-SM Higgs self-coupling, HHVV couplings
- Fit to data, extract **likelihood** at each point:



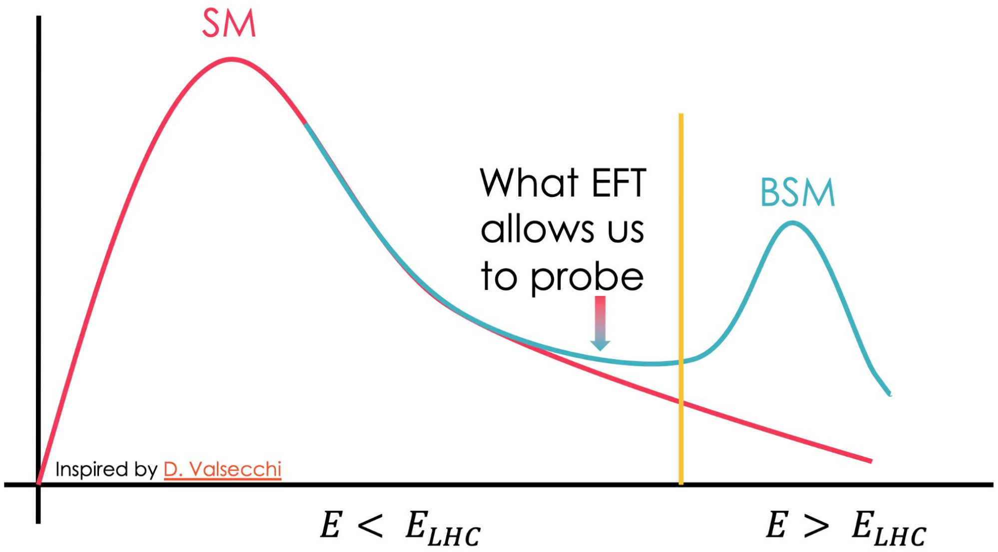




- Best fit agrees with SM prediction within 1 sigma
- Improvement on **expected** κ_λ range, **part** of observed range w.r.t. previous analysis: **[-2.4, 7.7] ([-1.5, 6.7])** Expected (observed) @ 95% CL

HH→bb$\gamma\gamma$: EFT

- Effective field theory: A **QFT** 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]

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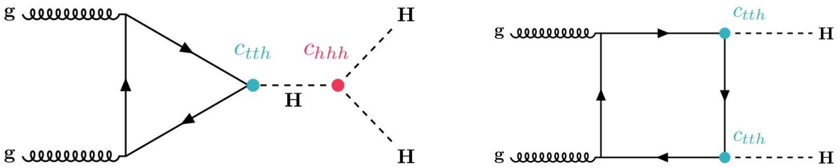
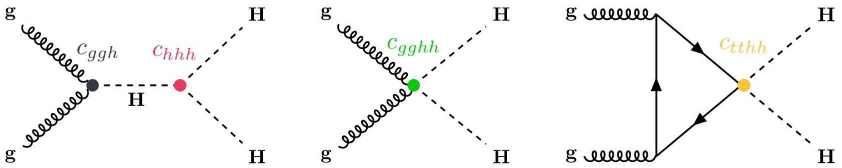
HH→bb$\gamma\gamma$: HEFT

- **<u>HEFT</u>**<u>: Higgs Effective Field Theory.</u> **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**

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

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





<u>SM-like processes (modified by couplings)</u>

<u>BSM processes</u>

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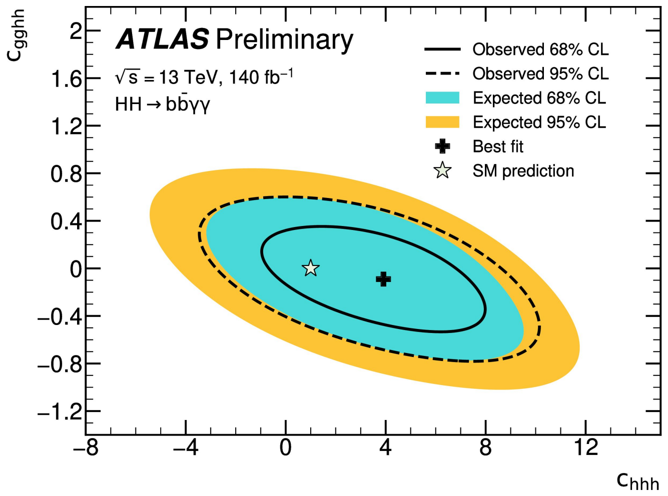
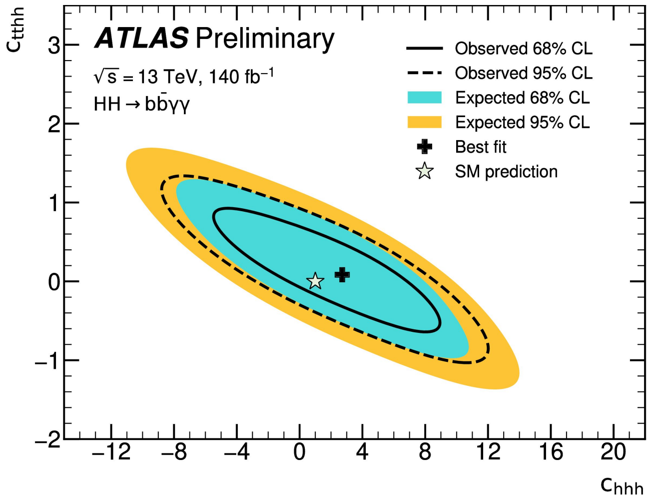
HH→bb$\gamma\gamma$: HEFT scan results

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





- **No significant deviations** from SM seen. Best fit agrees with SM within **1σ**

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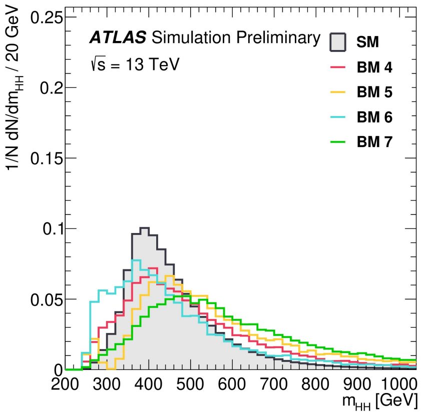
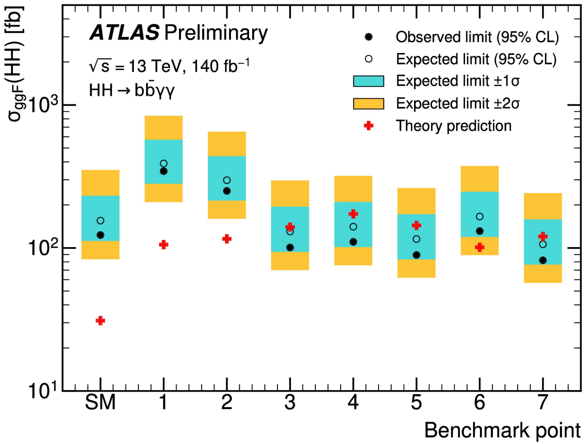
HH→bb$\gamma\gamma$: HEFT benchmark results

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

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





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

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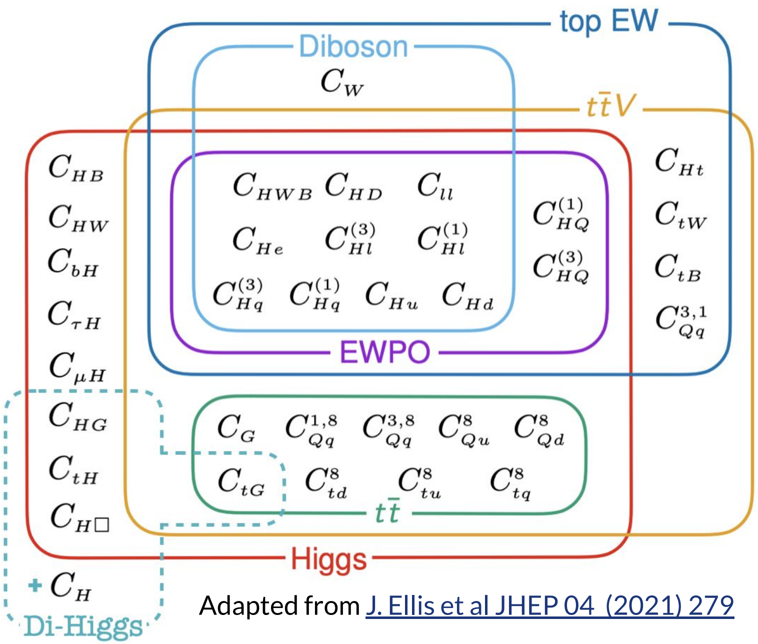
HH→bb$\gamma\gamma$: SMEFT

- **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]
- 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

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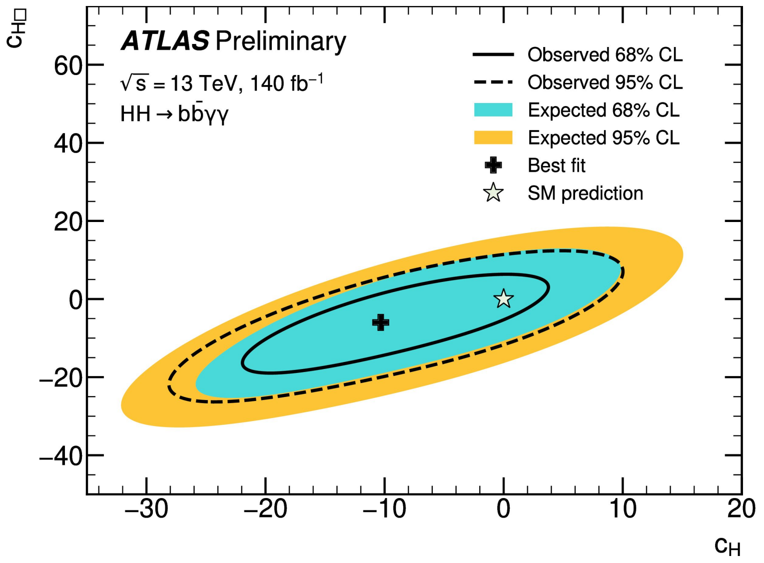
HH→bb$\gamma\gamma$: SMEFT

- 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



ATLAS Run 2 HH→bbℓℓ

HH→bbℓℓ: Introduction

- **HH→bbℓℓ + MET** benefits from high branching ratio, clean **lepton** signatures:
  - HH→bbW(ℓν)W(ℓν)
  - HH→bbτ(ℓ)τ(ℓ)
  - HH→bbZ(ℓℓ)Z($\nu\nu$)
  - HH→bbZ(ℓℓ)Z(qq)

- 2020: Search for HH in bbℓℓ + MET final state with ATLAS **Run 2** dataset published in PRB

- Observed (Expected) upper limit on σ_{HH}: 40 (29) times SM prediction

	bb	WW	ττ	ZZ	γγ
bb	34%				
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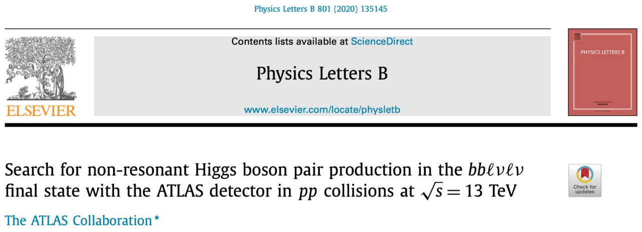
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%


Physics Letters B 801 (2020) 135145
Contents lists available at ScienceDirect
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ELSEVIER
Search for non-resonant Higgs boson pair production in the $bb\ell\nu\ell\nu$ final state with the ATLAS detector in pp collisions at $\sqrt{s} = 13$ TeV
The ATLAS Collaboration *

Physics Letters B 801 (2020) 135145

HH→bbℓℓ: New studies

- Once again, **extend** upon this strong Run 2 analysis effort with:
  - Improved sensitivity optimization with DNN
  - Addition of **VBF** production mode
  - κ_λ and κ_{2V} scans

Search for non-resonant Higgs boson pair production in the 2b + 2l + E_T^{miss} final state in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

ATLAS-CONF-2023-064

7 September 2023

ATLAS-CONF-2023-064

- Webpage includes figures and tables of the analysis

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HH→bbℓℓ: Processes

- Background composition from **top quark, vector boson, single Higgs** processes:

	Process	ME Generator	ME PDF	PS/UE model	UE Tune
HH	SM HH (ggF)	Powheg Box v2	PDF4LHC15nlo	Pythia 8.244	A14
	SM HH (VBF)	MadGraph5_aMC@NLO 2.7.3	NNPDF3.0nlo	Pythia 8.244	A14
Top	$t\bar{t}$	Powheg Box v2	NNPDF3.0nlo	Pythia 8.230	A14
	single-top	Powheg Box v2	NNPDF3.0nlo	Pythia 8.230	A14
	$t\bar{t}+W/Z$	MadGraph5_aMC@NLO 2.3.3	NNPDF3.0nlo	Pythia 8.210	A14
V+jets	W/Z + jets	Sherpa 2.2.1	NNPDF3.0nnlo	Sherpa 2.2.1	Sherpa default
VV	WW, WZ, ZZ	Sherpa 2.2.1/Sherpa 2.2.2	NNPDF3.0nnlo	Sherpa 2.2.1/Sherpa 2.2.2	Sherpa default
Single Higgs	ggF, H	Powheg Box v2	NNPDF3.0nlo	Pythia 8.212	AZNLO
	VBF, H	Powheg Box v2	NNPDF3.0nlo	Pythia 8.230	AZNLO
	WH, ZH	Powheg Box v2	NNPDF3.0nlo	Pythia 8.230/Pythia 8.186	AZNLO
	ttH	Powheg Box v2	NNPDF3.0nlo	Pythia 8.230	A14

- Different challenges w.r.t. bb$\gamma\gamma$:
  - More **irreducible**, and **common** backgrounds
  - More particle types to consider

HH→bbℓℓ: Pre-Selections

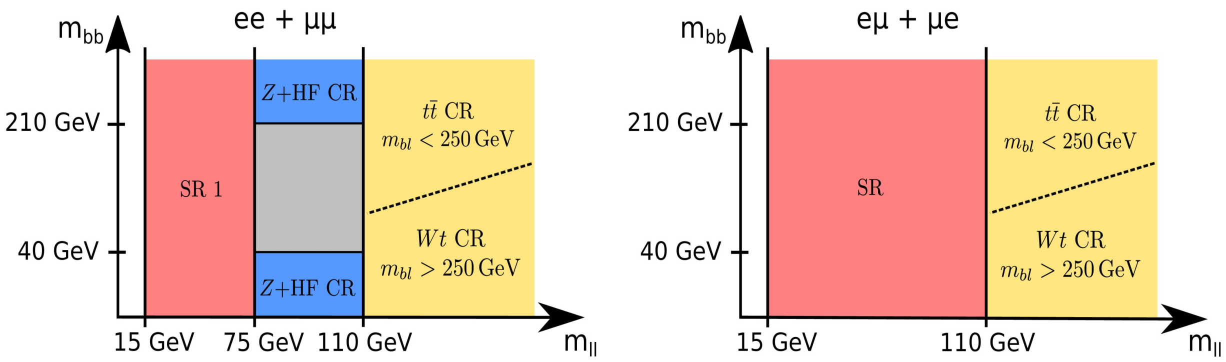
- Select vertex with highest sum p_T^2
- High p_T, isolated **Electrons** and **Muons**
- Jets: Anti-k_T with R = 0.4, 77% WP **b-tag** (same as bb$\gamma\gamma$!)
- Expect MET, but no selection: More events for MVA training
- Require **exactly 2 b-jets**, **exactly 2 opposite sign leptons**

ggF and VBF event selection cut	$bbWW$		$bb\tau\tau$		$bbZZ(\to 2\ell 2\nu)$		$bbZZ(\to 2\ell 2q)$	
	ggF	VBF	ggF	VBF	ggF	VBF	ggF	VBF
Initial number of events ($\mathcal{L} \times \sigma \times \mathcal{B}$)	70	3.9	39	2.2	3.8	0.21	18	1.0
$N_{\text{leptons}} = 2$, opposite sign, pass trigger requirement	22	0.99	8.3	0.35	1.3	0.057	3.6	0.17
$N_{b\text{-jets}} = 2$	9.8	0.39	3.7	0.14	0.57	0.022	1.6	0.067

- Reduces signal yield, but expect much **cleaner, lower-background** phase space.

HH→bbℓℓ: Signal and control regions

- After pre-selections, further categorize based on mass of b-pair, lepton-pair:



- Define **control regions** to constrain background normalization in **signal region**
  - Use data to decrease result uncertainty!

- Additional VBF requirement for orthogonal region: **<u>At least two forward jets</u>**

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HH→bbℓℓ: Pre-selection yields

- Even after pre-selections, **<u>huge</u>** amount of background left in signal region!
  - About **620,000** events in ggF SR
  - About **58,000** events in VBF SR
- Only about **1 to 13** signal events expected!
- Need a way to **massively** reduce this…

Process	ggF-SR	VBF-SR	$t\bar{t}$-CR	Wt-CR	Z+HF-CR
		SM background			
$t\bar{t}$	561220 ± 150	52670 ± 50	436840 ± 130	2270 ± 10	34700 ± 40
$t\bar{t}+V$	1121 ± 4	194.7 ± 1.9	1133 ± 5	97.0 ± 1.1	440.1 ± 1.9
Single top (Wt)	16260 ± 50	1165 ± 12	14100 ± 40	2901 ± 20	1237 ± 13
Single top (s/t-channel)	12.7 ± 0.8	2.48 ± 0.35	1.21 ± 0.28	0.35 ± 0.14	0.25 ± 0.11
$Z \to \ell\ell$ (HF)	16090 ± 180	1178 ± 34	3610 ± 70	525 ± 11	43390 ± 260
$Z \to \ell\ell$ (LF)	2720 ± 170	260 ± 40	600 ± 90	55 ± 8	5470 ± 190
$Z \to \tau\tau$ (HF)	2200 ± 40	154 ± 13	3 ± 7	1.9 ± 0.5	4 ± 6
$Z \to \tau\tau$ (LF)	370 ± 50	24 ± 4	-1.3 ± 1.5	0.11 ± 0.06	0.8 ± 0.5
W+jets	0.7 ± 0.5	0.09 ± 0.08	-0.2 ± 0.4	—	—
Diboson	288 ± 4	32.6 ± 0.8	159.0 ± 2.8	39.0 ± 0.9	226.8 ± 3.3
Single Higgs	601.0 ± 1.1	105.1 ± 0.4	336.5 ± 0.5	22.06 ± 0.12	48.28 ± 0.29
Fakes	18510 ± 170	2390 ± 60	10020 ± 140	529 ± 35	1360 ± 50
Total SM bkg.	619390 ± 350	58170 ± 100	466810 ± 230	6440 ± 40	86890 ± 330
		HH signal, ggF			
ggF $HH \to bbWW$	8.318 ± 0.016	0.857 ± 0.005	0.00113 ± 0.00019	0.00033 ± 0.00010	0.0014 ± 0.0002
ggF $HH \to bb\tau\tau$	3.138 ± 0.009	0.3284 ± 0.0029	0.00332 ± 0.00029	0.00068 ± 0.00015	0.0047 ± 0.0004
ggF $HH \to bbZZ$	0.633 ± 0.005	0.0873 ± 0.0018	0.00083 ± 0.00018	0.00020 ± 0.00009	0.0442 ± 0.0013
$\sum$ ggF HH	12.088 ± 0.019	1.272 ± 0.006	0.0053 ± 0.0004	0.00121 ± 0.00020	0.0504 ± 0.0014
		HH signal, VBF			
VBF $HH \to bbWW$	0.1518 ± 0.0014	0.2138 ± 0.0017	0.00013 ± 0.00004	—	0.00009 ± 0.00004
VBF $HH \to bb\tau\tau$	0.0537 ± 0.0006	0.0769 ± 0.0007	0.000086 ± 0.000022	0.000048 ± 0.000018	0.00024 ± 0.00004
VBF $HH \to bbZZ$	0.0097 ± 0.0004	0.0184 ± 0.0006	0.000040 ± 0.000024	0.0000029 ± 0.0000016	0.00236 ± 0.00023
$\sum$ VBF HH	0.2152 ± 0.0016	0.3091 ± 0.0019	0.00026 ± 0.00005	0.000051 ± 0.000018	0.00269 ± 0.00024
		HH signal, ggF+VBF			
$\sum$ ggF+VBF HH	12.303 ± 0.019	1.582 ± 0.006	0.0055 ± 0.0004	0.00126 ± 0.00020	0.0531 ± 0.0014

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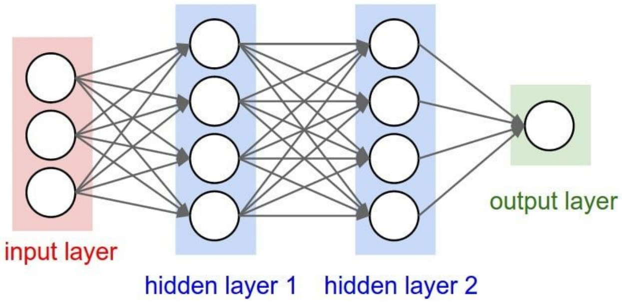
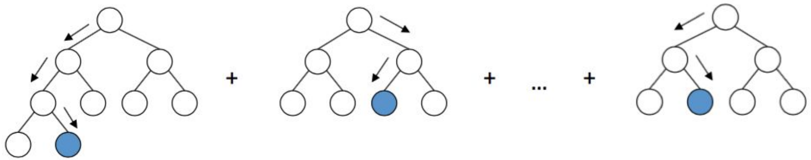
HH→bbℓℓ: MVAs

- Design and run **Multivariate Analyses** (MVA) to further discriminate **signal** from **background** events:

Gluon fusion category: Deep Neural Network (DNN)



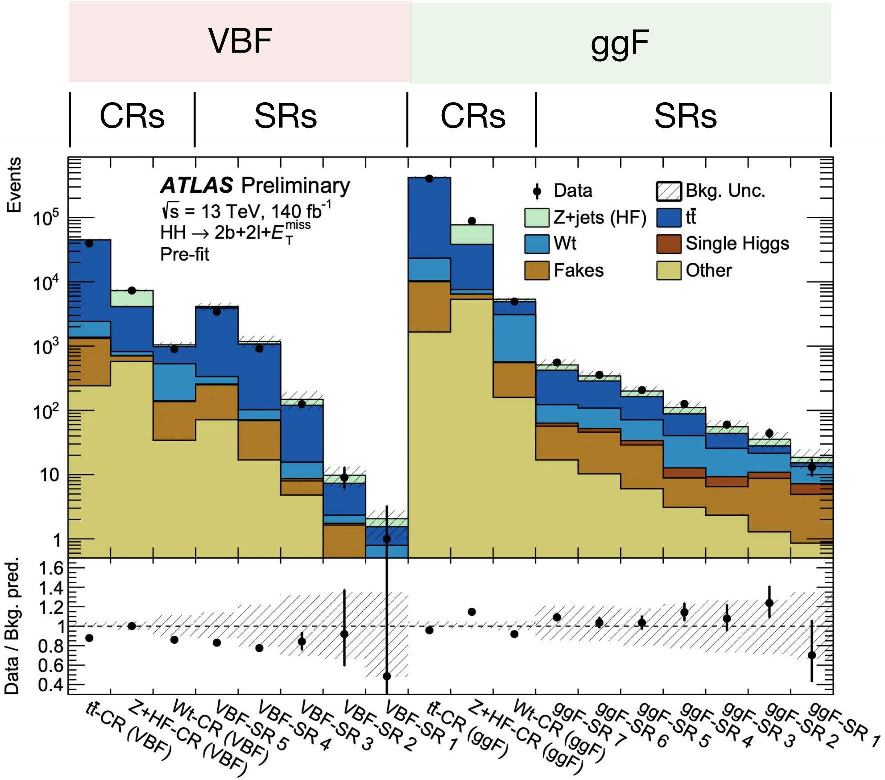
Vector boson fusion category: Boosted Decision Tree (BDT)



- VBF phase space too tight, too few events to fully exploit DNN.
- Both: Input variables with different **signal and background** shapes - MVAs output discriminating **score**

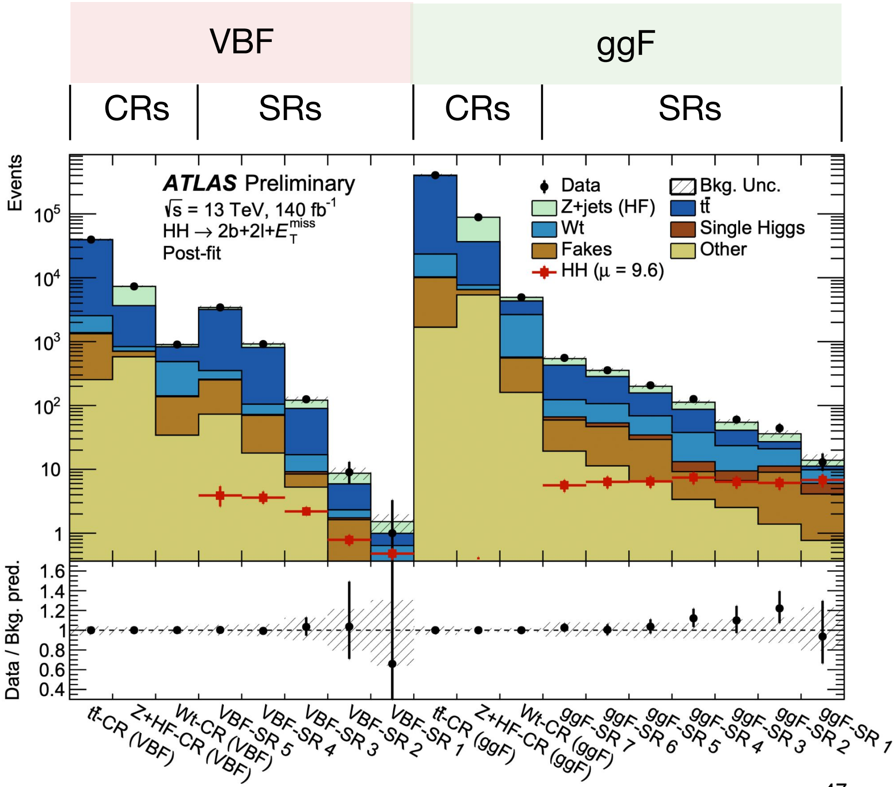
HH→bbℓℓ: Pre-fit yields

- Train MVAs, bin signal and background MC based on **MVA discriminant scores**
- High background yields in CR useful!
- Tighter MVA bins, lower background yield. Down to ~ 2-10 background events
- Deficit of data in tightest **VBF** and **GF** signal region bins



HH→bbℓℓ: Post-fit yields

- **Fit MC to data** in **signal** and **control** regions
- Show HH signal, scaled to upper limit, for comparison
- This is how final results are extracted. How **compatible** is our expected signal with the **data**?



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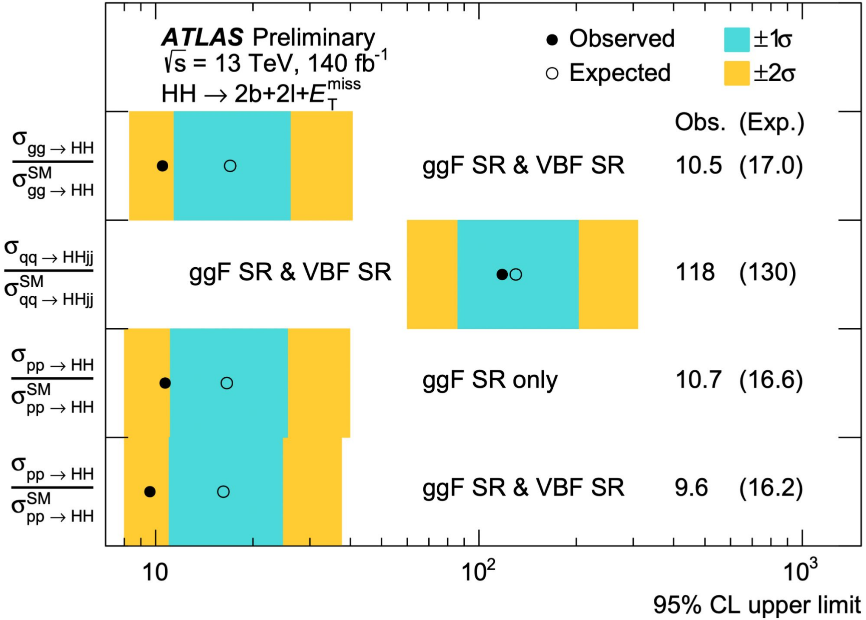
HH→bbℓℓ: SM results

- Upper limits (assumes no signal)
- Extract by fitting MVA score of signal + background to the **data**
- Under-fluctuation of data leads to observed < expected
- **Improvement** w.r.t. Previous analysis in observed (expected) thanks to re-optimized DNN:
    - Here: 9.6 (16.2) times SM
    - Previous: 40 (29) times SM
- Results **consistent** with the SM



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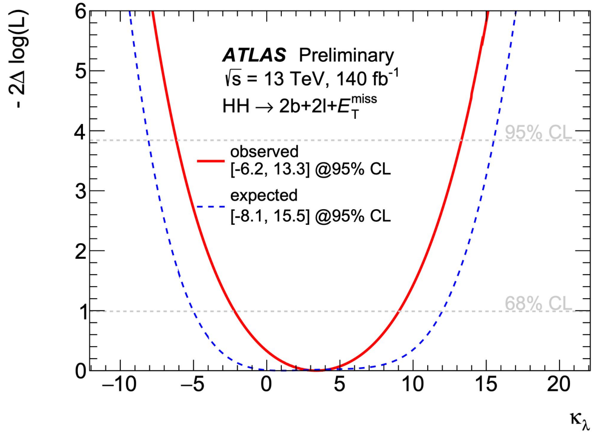
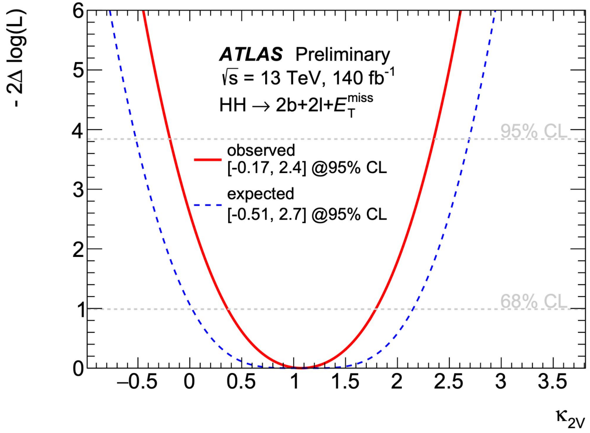
HH→bbℓℓ: Coupling modifier results

- Combine multiple MC samples, **reweight** to model MC at given BSM point. Compute likelihood w.r.t. the data:



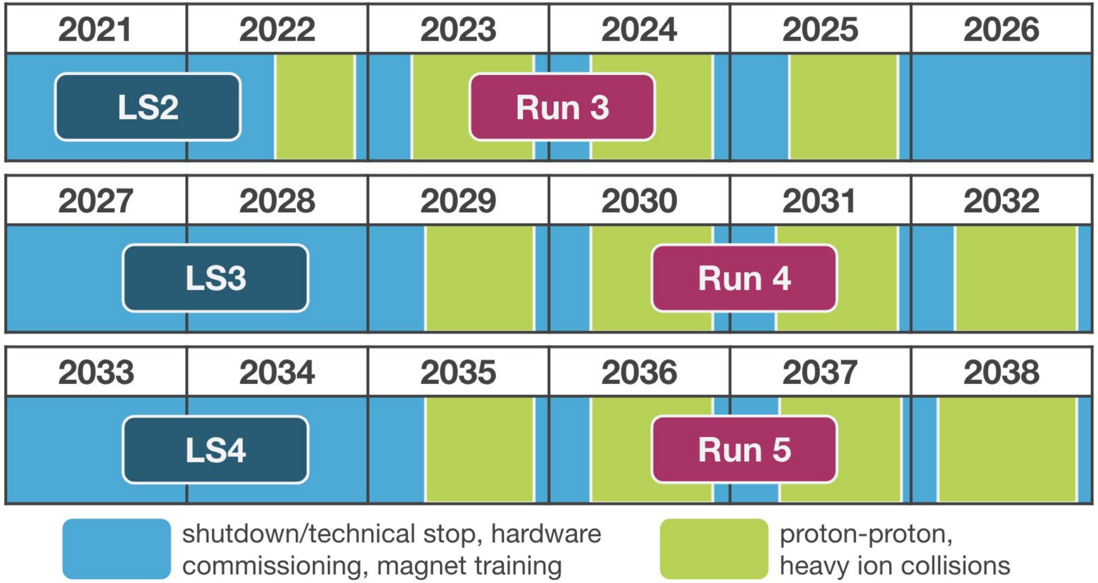


- Constraints on κ_λ and κ_{2V}
- Observed result more **constrained** due to **under-fluctuation** of data
- Results **consistent with SM** within 68% CL.

Future prospects

Future prospects: LHC timeline

- LHC timeline:
- **Run 2** analyses **wrapping up**
- Analysis of early **Run 3** data has **begun**
- **HL-LHC** data-taking and analysis to follow



… up to 2042

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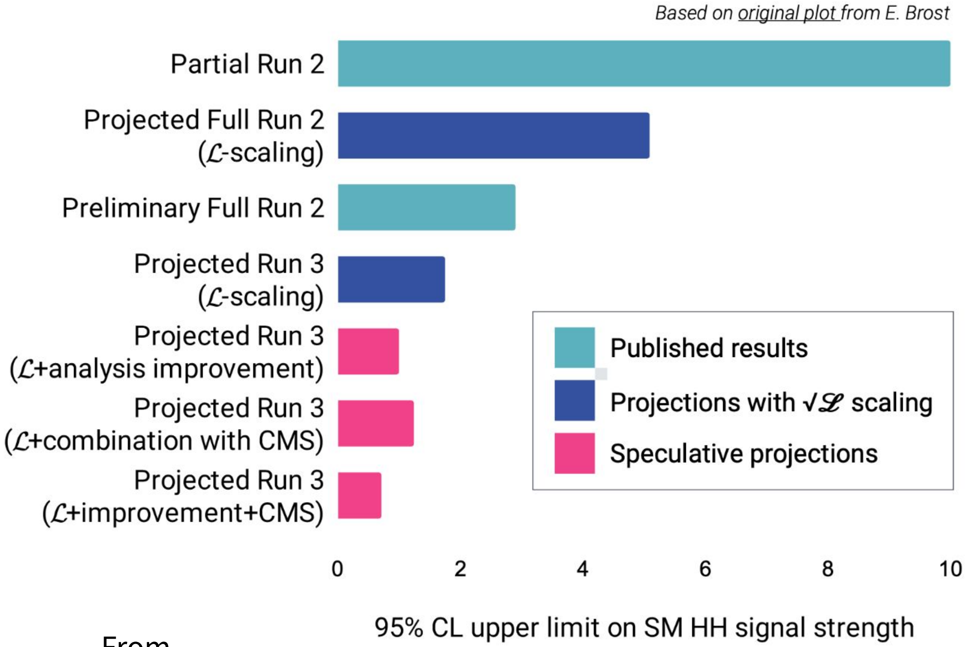
Future prospects: Run 3

- Project that combining full Run 3 datasets of ATLAS + CMS may lead to **upper limit** on signal strength **< 1**
  - → Implies close to HH observation!

- Relies on improvement of analysis techniques



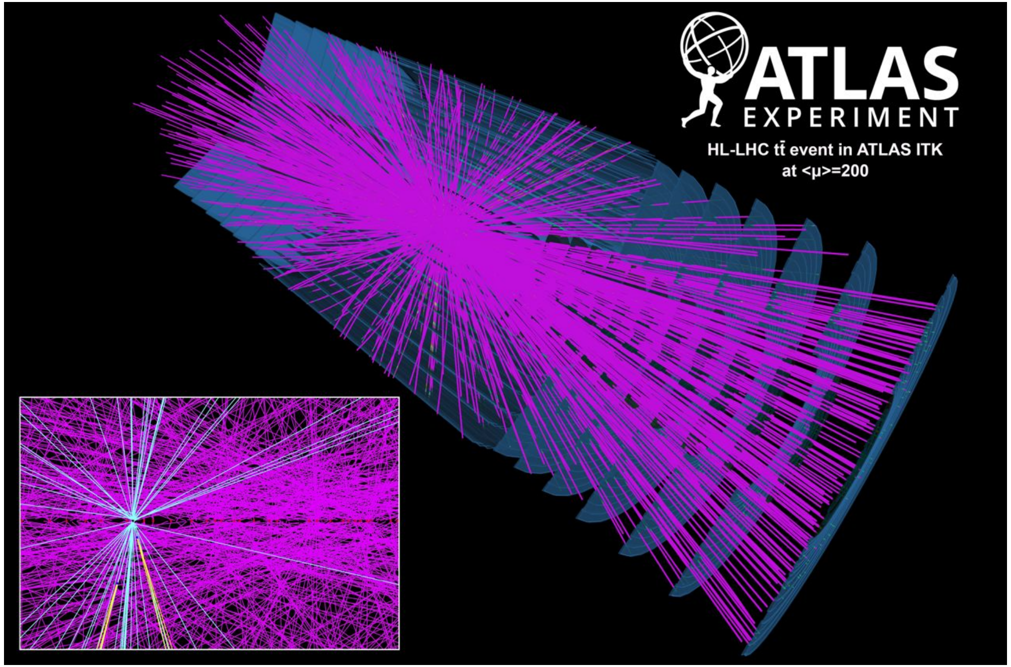
From
Katharine Leney

Future prospects: HL-LHC

- 2029: LHC will finish upgrade to
  <u>High Luminosity LHC</u>

- **<u>Pro:</u>** Will increase ATLAS + CMS datasets by ~ factor of 10

- **<u>Con:</u>** Extremely challenging data-taking environment
    - Extensive **detector upgrades** in progress to handle this



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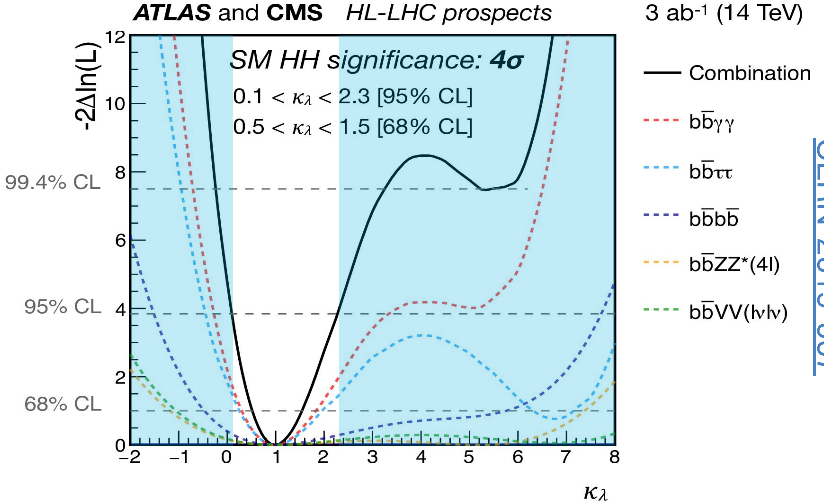
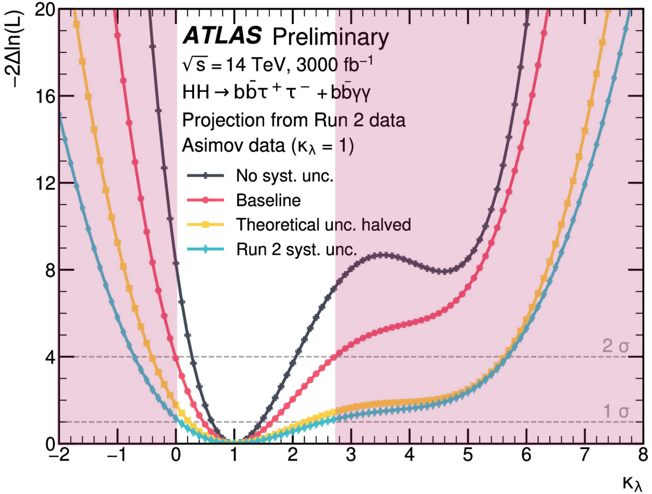
Future prospects: HH projections



CERN-2019-007



ATL-PHYS-PUB-2022-005

European Strategy (2018)

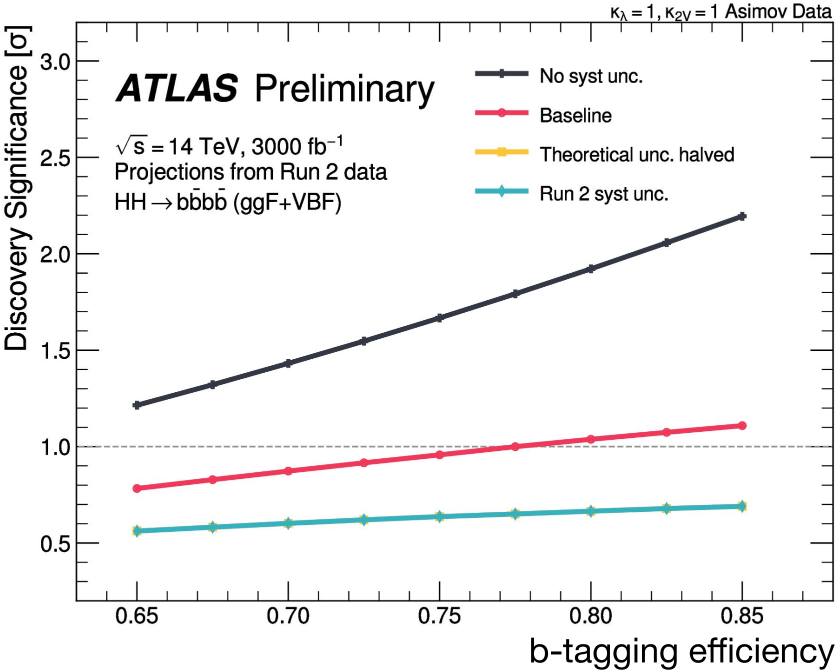
- Combination of 5 HH channels, many based on partial Run 2 analysis strategy
- 50% precision on self-coupling
- **4σ SM HH significance** (ATLAS+CMS)

Snowmass update (2022)

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

Future prospects: HL-LHC

- 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
- Part of b-tagging improvements: An **excellent** tracker - part of **BNL ITk** efforts



ATL-PHYS-PUB-2023-023

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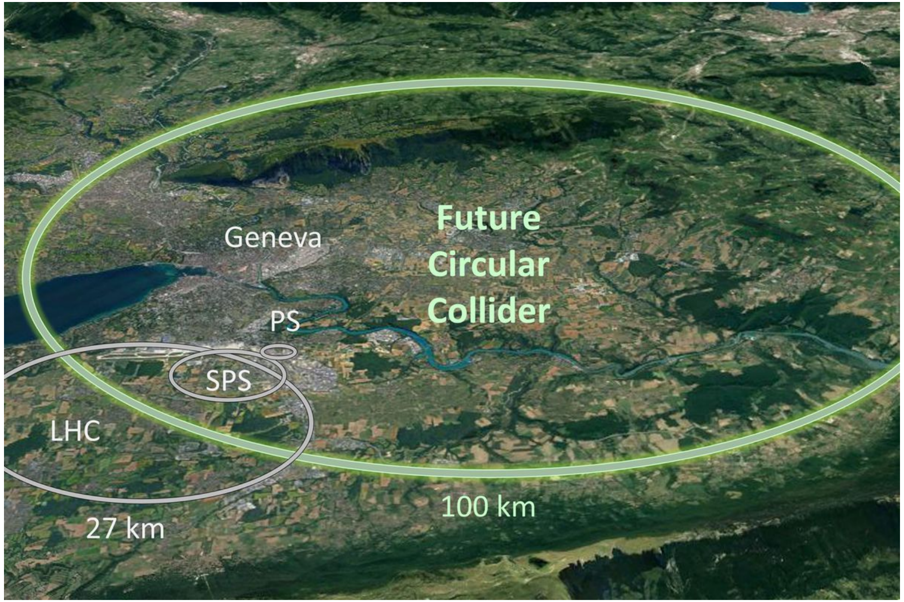
Future prospects: Future colliders

- What about **after LHC**?
- Planning next collider with future physics goals in mind, including Higgs self-coupling measurement
- Example: Future Circular Collider (FCC)
    - Would include **100 TeV** proton-proton collisions
- Aiming for **precise** measurement of Higgs self-coupling



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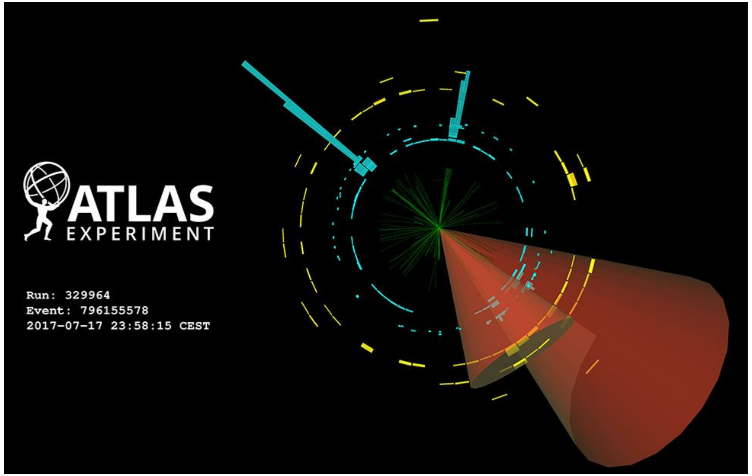
Summary

Summary

- Since Higgs discovery, extensive studies to **characterize it** via mass, coupling, width, CP measurements
- Ongoing searches for **Higgs pair production** - recent results from ATLAS make use of **H→bb decay**:
    - Observed (Expected) 95% CL upper limits on μ_{HH}:
    - HH→bb$\gamma\gamma$: **4.0 (5.0)**
    - HH→bb$\ell\ell$: **9.6 (16.2)**
    - Both include constraints on self-coupling modifier, κ_{2V} , bb$\gamma\gamma$ includes HEFT and SMEFT interpretations
    - **<u>Results agree with SM</u>**



- HL-LHC will be challenging, but maybe enough HH pairs to **aim** for 5σ significance on the HH cross-section

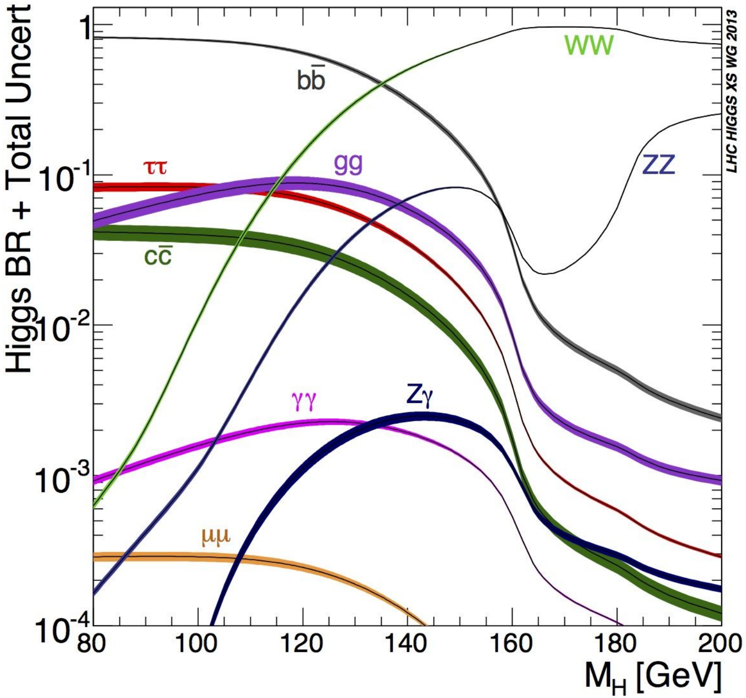
- Enter Higgs coupling **precision** era with future colliders

Thank you!

Backup: SM

Higgs decays

- Higgs decays as function of mass:



Z boson decays

- Z boson decay modes, branching ratios:

Decay Modes

Mode		Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	e^+e^-	[1] $(3.3632 \pm 0.0042)\%$		45594
Γ_2	$\mu^+\mu^-$	[1] $(3.3662 \pm 0.0066)\%$		45594
Γ_3	$\tau^+\tau^-$	[1] $(3.3696 \pm 0.0083)\%$		45559
Γ_4	$\ell^+\ell^-$	[2][1] $(3.3658 \pm 0.0023)\%$		
Γ_5	$\mu^+\mu^-\mu^+\mu^-$			45593
Γ_6	$\ell^+\ell^-\ell^+\ell^-$	[3] $(4.55 \pm 0.17) \times 10^{-6}$		45594
Γ_7	invisible	[1] $(20.000 \pm 0.055)\%$		
Γ_8	hadrons	[1] $(69.911 \pm 0.056)\%$		
Γ_9	$(u\,\overline{u} + c\,\overline{c})/2$	$(11.6 \pm 0.6)\%$		
Γ_{10}	$(d\,\overline{d} + s\,\overline{s} + b\,\overline{b})/3$	$(15.6 \pm 0.4)\%$		
Γ_{11}	$c\,\overline{c}$	$(12.03 \pm 0.21)\%$		
Γ_{12}	$b\,\overline{b}$	$(15.12 \pm 0.05)\%$		
Γ_{13}	$b\overline{b}b\overline{b}$	$(3.6 \pm 1.3) \times 10^{-4}$		
Γ_{14}	ggg	$< 1.1\%$	CL=95%	

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τ lepton decays

- τ lepton decay modes, branching ratios:

The branching fractions of the dominant hadronic tau decays are:[3]

- 25.49% for decay into a charged pion, a neutral pion, and a tau neutrino;
- 10.82% for decay into a charged pion and a tau neutrino;
- 9.26% for decay into a charged pion, two neutral pions, and a tau neutrino;
- 8.99% for decay into three charged pions (of which two have the same electrical charge) and a tau neutrino;
- 2.74% for decay into three charged pions (of which two have the same electrical charge), a neutral pion, and a tau neutrino;
- 1.04% for decay into three neutral pions, a charged pion, and a tau neutrino.

The branching fractions of the common purely leptonic tau decays are:[3]

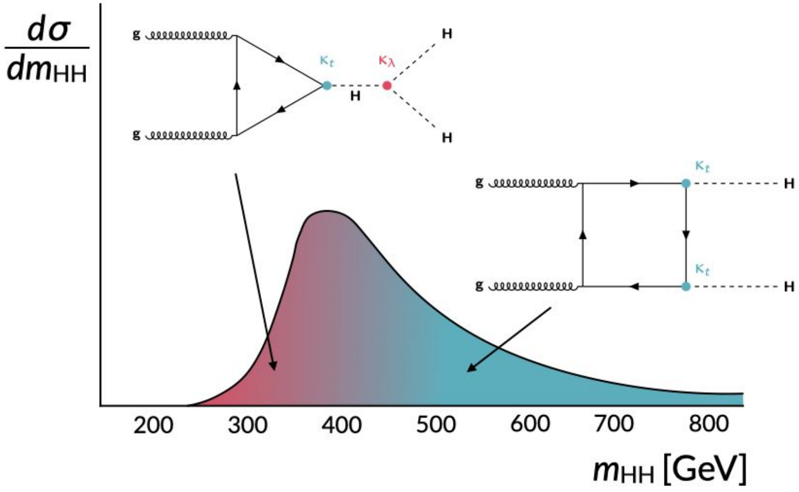
- 17.82% for decay into a tau neutrino, electron and electron antineutrino;
- 17.39% for decay into a tau neutrino, muon, and muon antineutrino.

Backup: HH

Self-coupling: Cross-section

- Low production cross-section from **destructive interference** of diagrams

- Need to search for HH final states sensitive to modern **detectors** and analysis **techniques**



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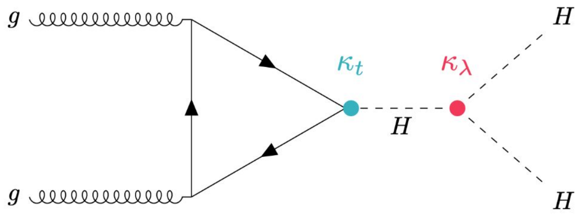
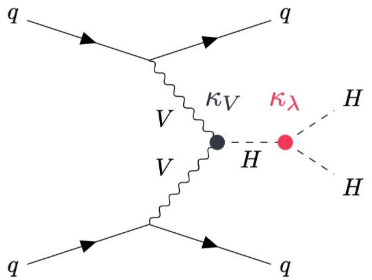
Self-coupling: Higgs pair production

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





Gluon fusion: $\sigma_{\text{NNLO, FTapprox}}$ **~ 31.05 fb @ 13 TeV** [1803.02463]
Assuming m_H = 125.0 GeV

Vector boson fusion: $\sigma_{\text{N3LO QCD}}$ **~ 1.73 fb @ 13 TeV** [1811.07906]
Assuming m_H = 125.0 GeV

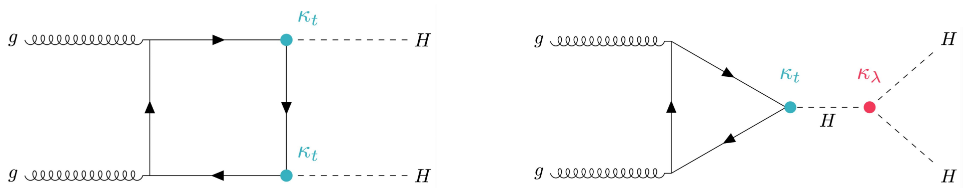
- Higgs self-coupling affects **cross-section** and **differential distributions** of Higgs pair production in leading production modes: **Gluon fusion, Vector boson fusion**
- **Rare** process - need to select final states with good signal to background ratio

HH→bbℓℓ: Production modes

Same HH production modes considered as bb$\gamma\gamma$ analysis:

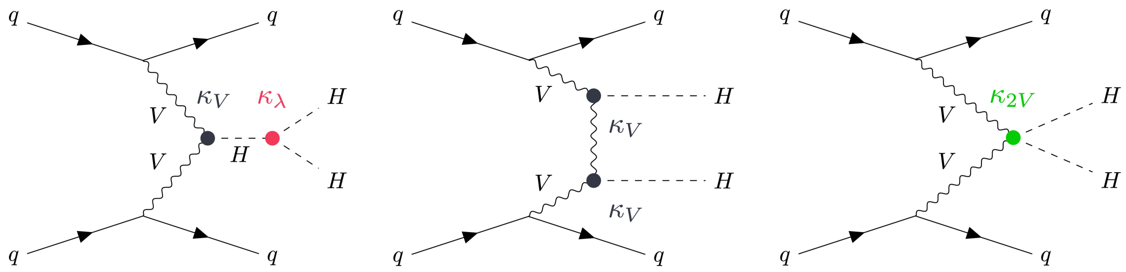
Gluon fusion:

- Leading HH production mode
- Access to self-coupling

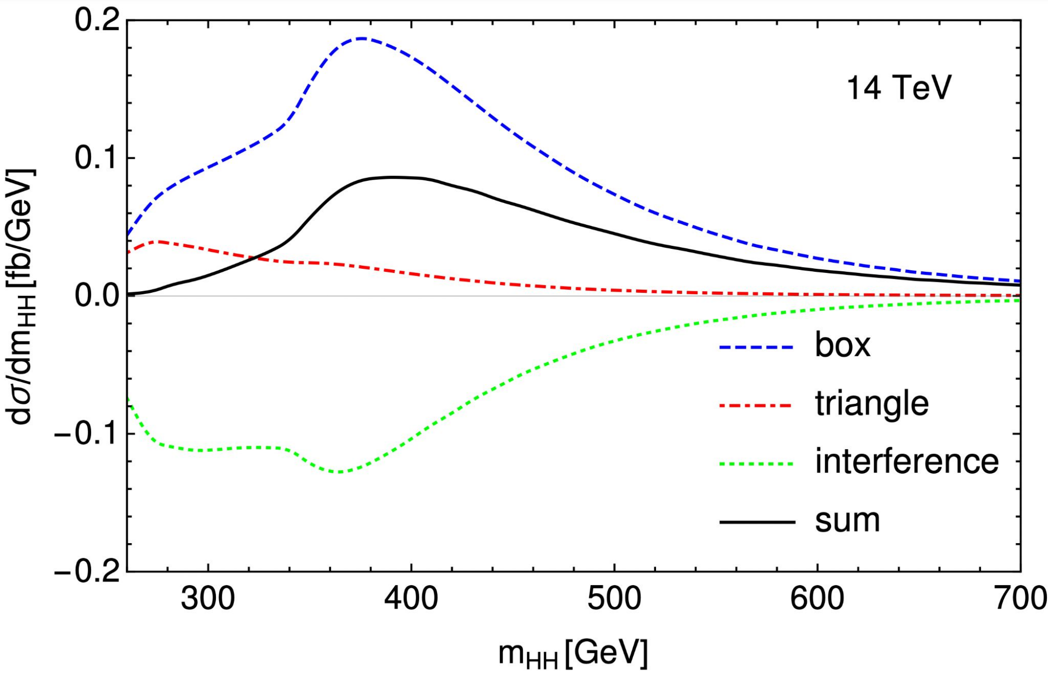


Vector boson fusion:

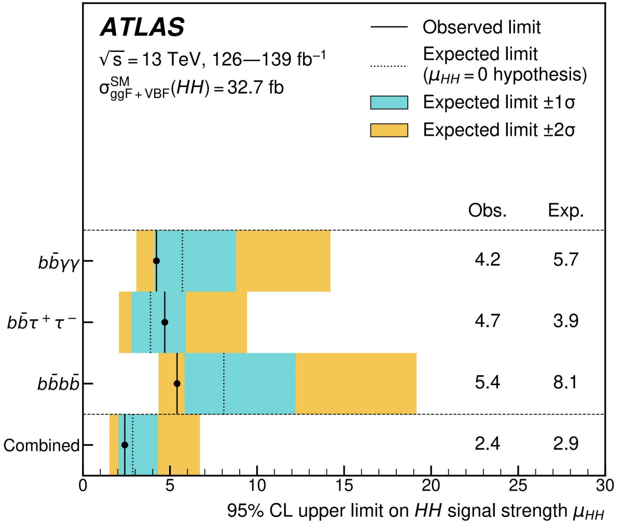
- Subleading production mode
- Access to κ_{2V}
- Quarks in final state



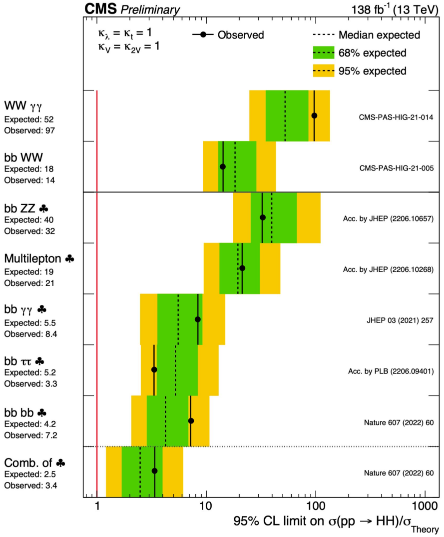
HH cross-section



ATLAS and CMS μ results

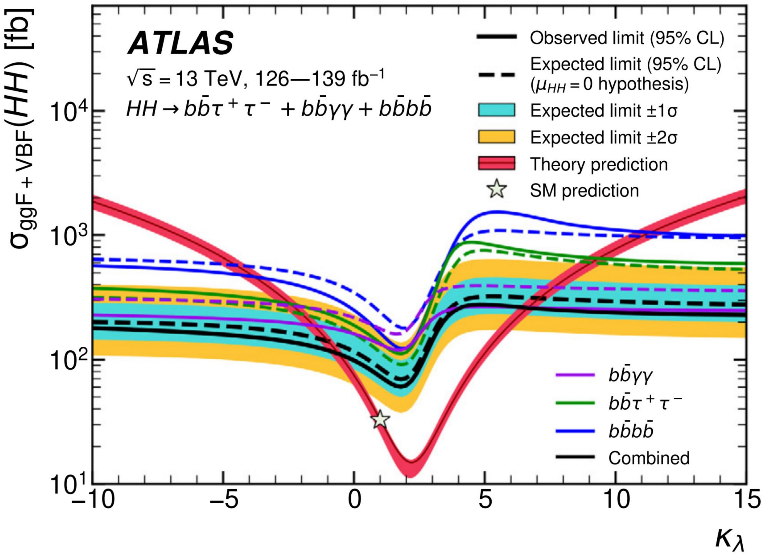


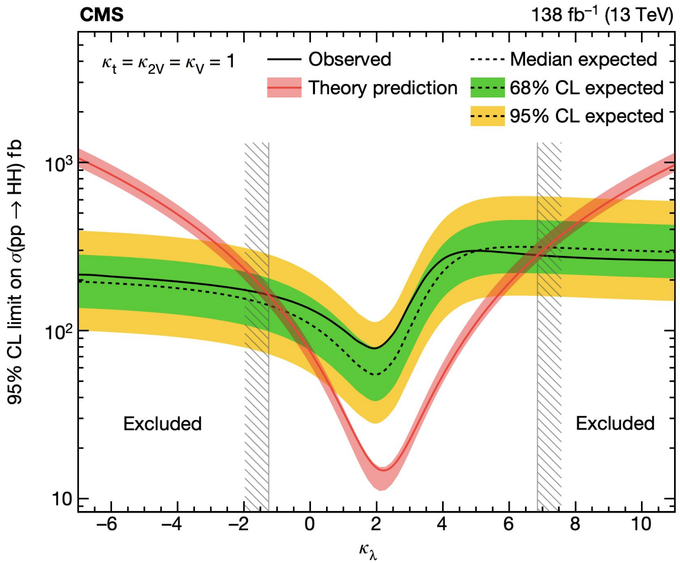
[Phys. Lett. B 843 (2023) 137745](#)
[ATLAS website with plots](#)



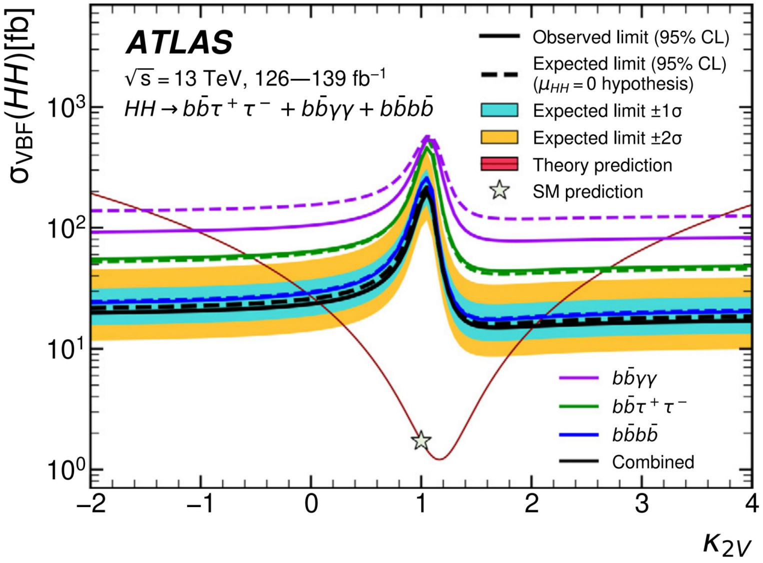
[Nature 607 (2022) 60](#)
[Summary plots webpage](#)

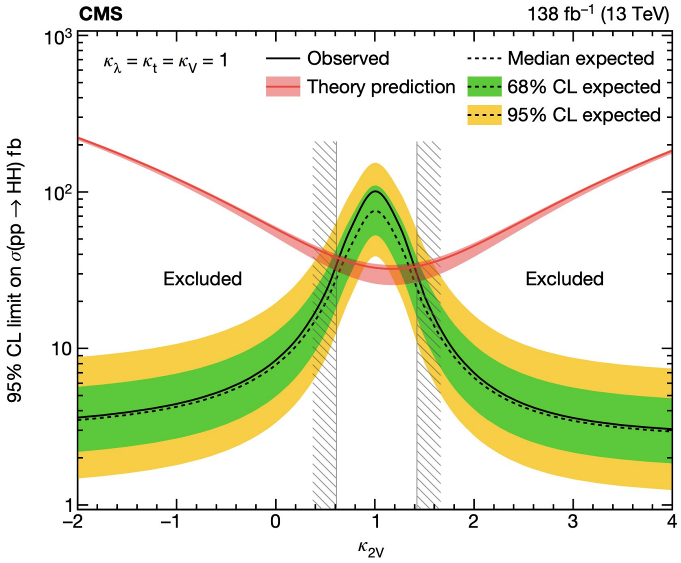
ATLAS and CMS κ_λ results





ATLAS and CMS κ_{2V} results



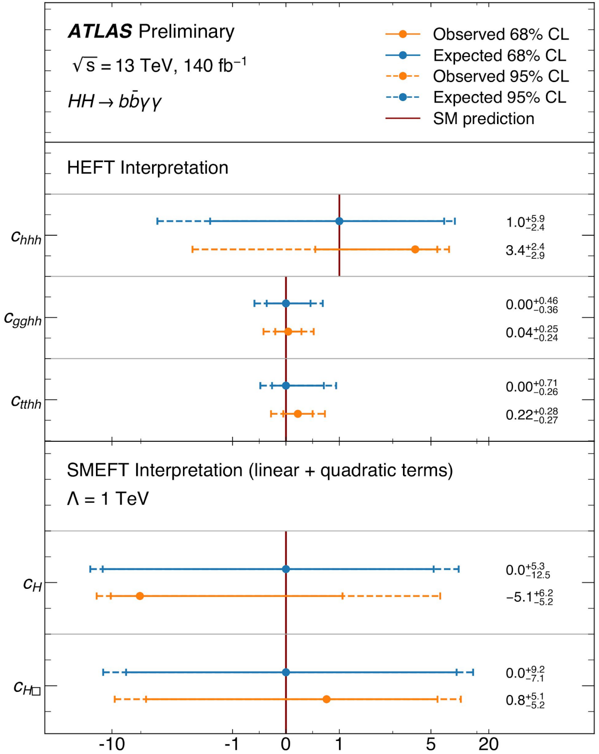


Backup: HH→bb$\gamma\gamma$

HH→bbγγ: 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



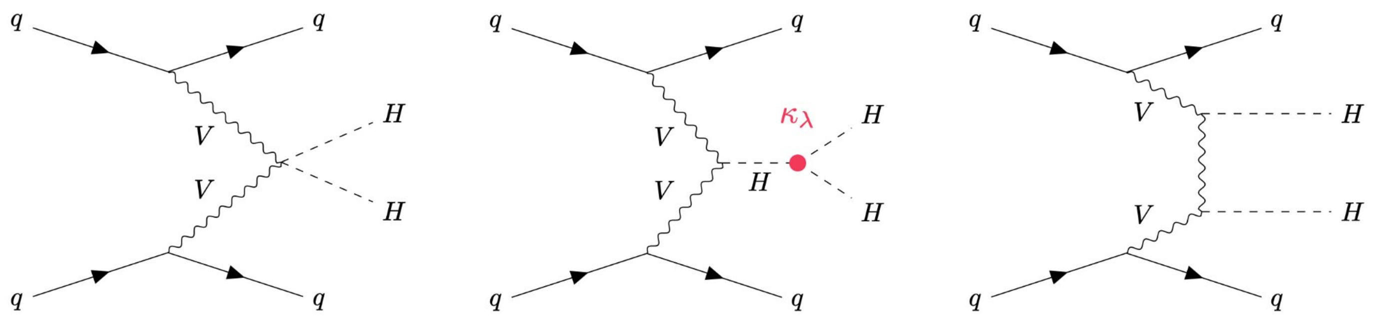
Introduction: Full top approximation

- FT approx (Full Top approximation) definition from https://arxiv.org/pdf/1803.02463.pdf:

In Refs. [4, 22] an approximation for Higgs boson pair production at NLO, labelled "$\mathrm{FT}_{\mathrm{approx}}$", was introduced, in which the real radiation matrix elements contain the full top quark mass dependence, while the virtual part is calculated at NLO in the HEFT approximation and rescaled at the event level by the re-weighting factor $B_{\mathrm{FT}}/B_{\mathrm{HEFT}}$. At the inlusive cross section level this approximation suggests at the LHC a correction with respect to the "Born-improved HEFT" approximation of about -10%, close to the corresponding correction of -14% later obtained in the full NLO calculation [16, 17].

Introduction: VBF diagrams

- HH VBF diagrams from [2112.11876]:



(a) $HHVV$ vertex (b) Trilinear coupling (c) VVH Production mode

- All diagrams and figures [here]

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Per-category yields

- Number of **expected events** per category
- For comparison, number of **observed data events** ($120 < m_{\gamma\gamma} < 130$) GeV

	High Mass 1	High Mass 2	High Mass 3	Low Mass 1	Low Mass 2	Low Mass 3	Low Mass 4
SM $HH(\kappa_\lambda = 1)$ signal	$0.26^{+0.03}_{-0.04}$	$0.194^{+0.021}_{-0.032}$	$0.84^{+0.10}_{-0.14}$	$0.048^{+0.007}_{-0.008}$	$0.038^{+0.004}_{-0.006}$	$0.039^{+0.004}_{-0.006}$	$0.032^{+0.004}_{-0.004}$
ggF	$0.25^{+0.03}_{-0.04}$	$0.188^{+0.021}_{-0.032}$	$0.81^{+0.10}_{-0.14}$	$0.046^{+0.007}_{-0.008}$	$0.036^{+0.004}_{-0.006}$	$0.037^{+0.004}_{-0.006}$	$0.025^{+0.004}_{-0.004}$
VBF $\times 10^3$	$7.9^{+0.6}_{-0.5}$	$5.3^{+0.5}_{-0.4}$	29^{+4}_{-3}	$1.98^{+0.28}_{-0.24}$	$1.71^{+0.16}_{-0.14}$	$1.96^{+0.21}_{-0.19}$	$7.4^{+0.6}_{-0.5}$
Alternative $HH(\kappa_\lambda = 10)$ signal	$2.5^{+0.4}_{-0.3}$	$1.81^{+0.25}_{-0.20}$	$6.2^{+0.8}_{-0.6}$	$5.0^{+1.2}_{-0.9}$	$3.8^{+0.7}_{-0.5}$	$3.7^{+0.7}_{-0.6}$	$3.6^{+0.4}_{-0.4}$
ggF	$2.3^{+0.4}_{-0.3}$	$1.64^{+0.25}_{-0.19}$	$4.9^{+0.8}_{-0.6}$	$4.7^{+1.0}_{-0.8}$	$3.6^{+0.7}_{-0.6}$	$3.3^{+0.7}_{-0.5}$	$2.04^{+0.34}_{-0.27}$
VBF	$0.231^{+0.019}_{-0.017}$	$0.170^{+0.019}_{-0.017}$	$1.29^{+0.15}_{-0.14}$	$0.28^{+0.20}_{-0.11}$	$0.23^{+0.23}_{-0.12}$	$0.36^{+0.10}_{-0.08}$	$1.57^{+0.17}_{-0.16}$
Alternative VBF $HH(\kappa_{2V} = 3)$ signal	$0.23^{+0.04}_{-0.04}$	$0.20^{+0.05}_{-0.04}$	$3.8^{+0.7}_{-0.6}$	$0.03^{+0.04}_{-0.02}$	$0.03^{+0.06}_{-0.02}$	$0.048^{+0.023}_{-0.015}$	$0.17^{+0.04}_{-0.03}$
Single Higgs boson background	$1.5^{+0.5}_{-0.3}$	$0.48^{+0.21}_{-0.10}$	$0.57^{+0.25}_{-0.14}$	$1.72^{+0.31}_{-0.19}$	$0.53^{+0.08}_{-0.06}$	$0.29^{+0.14}_{-0.07}$	$0.16^{+0.06}_{-0.03}$
ggH	$0.5^{+0.5}_{-0.2}$	$0.14^{+0.21}_{-0.09}$	$0.25^{+0.25}_{-0.12}$	$0.29^{+0.31}_{-0.15}$	$0.08^{+0.08}_{-0.04}$	$0.07^{+0.13}_{-0.06}$	$0.04^{+0.06}_{-0.03}$
$t\bar{t}H$	$0.302^{+0.034}_{-0.032}$	$0.069^{+0.009}_{-0.008}$	$0.063^{+0.008}_{-0.007}$	$0.77^{+0.09}_{-0.08}$	$0.214^{+0.029}_{-0.026}$	$0.100^{+0.012}_{-0.012}$	$0.048^{+0.005}_{-0.005}$
ZH	$0.61^{+0.06}_{-0.05}$	$0.174^{+0.020}_{-0.016}$	$0.188^{+0.035}_{-0.029}$	$0.49^{+0.05}_{-0.04}$	$0.149^{+0.028}_{-0.025}$	$0.069^{+0.033}_{-0.023}$	$0.028^{+0.010}_{-0.007}$
Rest	$0.17^{+0.08}_{-0.04}$	$0.089^{+0.030}_{-0.016}$	$0.07^{+0.04}_{-0.02}$	$0.181^{+0.030}_{-0.019}$	$0.089^{+0.016}_{-0.009}$	$0.046^{+0.007}_{-0.004}$	$0.039^{+0.008}_{-0.004}$
Continuum background	$11.3^{+1.5}_{-1.6}$	$3.2^{+0.8}_{-0.8}$	$2.8^{+0.8}_{-0.8}$	$37.2^{+2.9}_{-2.9}$	$10.8^{+1.5}_{-1.5}$	$4.4^{+0.9}_{-1.0}$	$1.1^{+0.5}_{-0.5}$
Total background	$12.8^{+1.6}_{-1.6}$	$3.7^{+0.9}_{-0.8}$	$3.4^{+0.8}_{-0.8}$	$38.9^{+2.9}_{-2.9}$	$11.3^{+1.5}_{-1.5}$	$4.7^{+0.9}_{-1.0}$	$1.3^{+0.5}_{-0.5}$
Data	12	4	1	29	8	5	4

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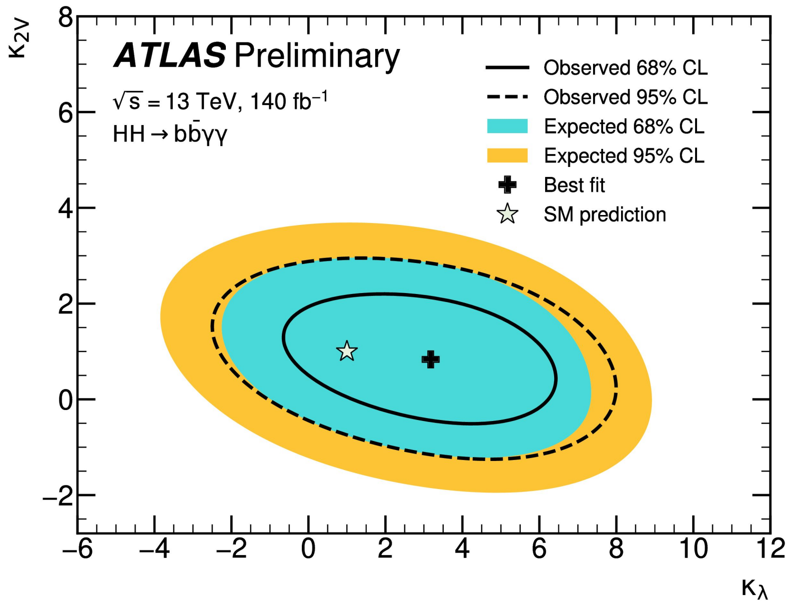
Coupling modifier exclusion

- 2D version of kappa framework result - simultaneously vary **two parameters**

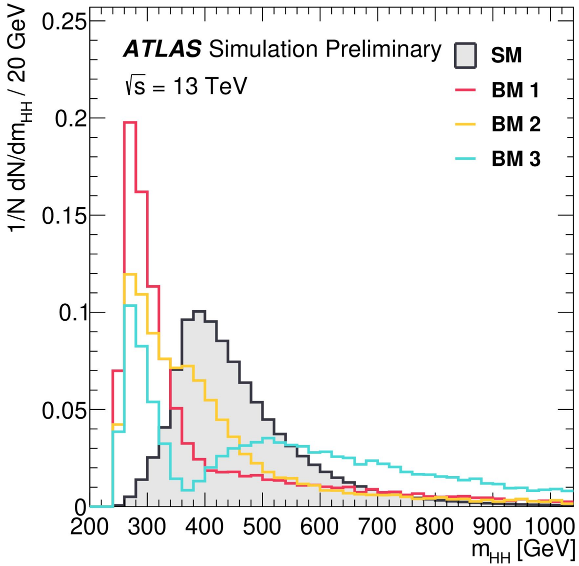


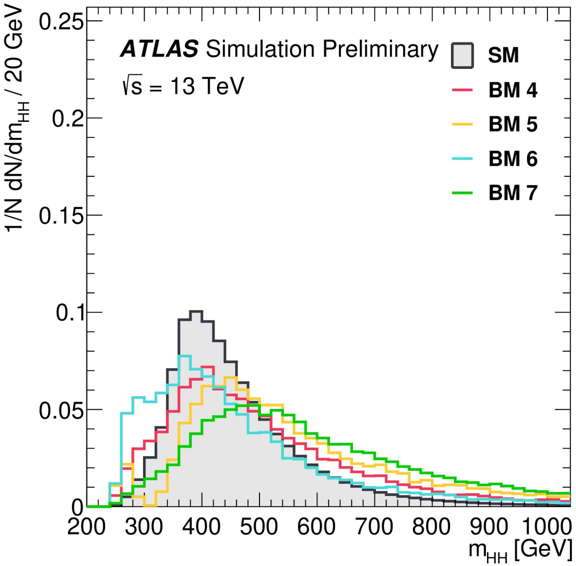
EFT: References

- Diagrams from public result:
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2022-03/
- PUB note from ATLAS:
  - https://cds.cern.ch/record/2806411/files/ATL-PHYS-PUB-2022-019.pdf
  - Public website
- Published yybb result:
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-34/

EFT: HEFT benchmarks

- m_{HH} distributions of 7 benchmarks [reference]:





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EFT: SMEFT matrix element squared

- Matrix element squared of **SMEFT**:

$$|\mathcal{M}_{\mathrm{SM}}|^2 + \underbrace{\sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\,\mathrm{Re}\left(\mathcal{M}_i^{(6)}\mathcal{M}_{\mathrm{SM}}^*\right)}_{\text{linear model}} + \underbrace{\sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4}\left|\mathcal{M}_i^{(6)}\right|^2}_{\text{quadratic terms}} + \underbrace{\sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\,\mathrm{Re}\left(\mathcal{M}_i^{(6)}\mathcal{M}_j^{(6)*}\right)}_{\text{cross terms}} + \ldots$$

- And lagrangian in Warsaw basis:

$$\begin{aligned}
\Delta\mathcal{L}_{\mathrm{Warsaw}} = {} & \frac{C_{H,\Box}}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \frac{C_{HD}}{\Lambda^2}(\phi^\dagger D_\mu\phi)^*(\phi^\dagger D^\mu\phi) + \frac{C_H}{\Lambda^2}(\phi^\dagger\phi)^3 \\
& + \left(\frac{C_{uH}}{\Lambda^2}\phi^\dagger\phi\bar{q}_L\tilde{\phi}\,t_R + h.c.\right) + \frac{C_{HG}}{\Lambda^2}\phi^\dagger\phi G^a_{\mu\nu}G^{\mu\nu,a} \\
& + \frac{C_{uG}}{\Lambda^2}(\bar{q}_L\sigma^{\mu\nu}T^a G^a_{\mu\nu}\tilde{\phi}\,t_R + \mathrm{h.c.})\,.
\end{aligned}$$

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Backup: $HH \rightarrow bb\ell\ell$

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HH→bbℓℓ: ggF DNN variables

- Gluon fusion: DNN
- m_{bl} definition below
  - From: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.152002

Input feature	Description
same flavour	Unity if final state leptons are ee or $\mu\mu$, zero otherwise
p_T^ℓ, p_T^b	transverse momenta of the leptons, b-tagged jets
$m_{\ell\ell}$, $p_T^{\ell\ell}$	invariant mass and the transverse momentum of the dilepton system
m_{bb}, p_T^{bb}	invariant mass and the transverse momentum of the b-tagged jet pair system
m_{T2}^{bb}	stransverse mass of the two b-tagged jets
$\Delta R_{\ell\ell}$, ΔR_{bb}	ΔR between the two leptons and two b-tagged jets
$m_{b\ell}$	$\min\{\max(m_{b_0\ell_0}, m_{b_1\ell_1}), \max(m_{b_0\ell_1}, m_{b_1\ell_0})\}$
$\min \Delta R_{b\ell}$	minimum ΔR of all b-tagged jet and lepton combinations
$m_{bb\ell\ell}$	invariant mass of the $bb\ell\ell$ system
E_T^{miss}, E_T^{miss}-sig	missing transverse energy and its significance
$m_T(\ell_0, E_T^{miss})$	transverse mass of the p_T-leading lepton w.r.t. to E_T^{miss}
$\min m_{T,\ell}$	minimum value of $m_T(\ell_0, E_T^{miss})$ and $m_T(\ell_1, E_T^{miss})$
H_{T2}^R	measure for boostedness of the two Higgs bosons, see definition in footnote[1]

[1] $H_{T2}^R = \frac{\left|\boldsymbol{E}_T^{miss}+\boldsymbol{p}_T^{\ell_0}+\boldsymbol{p}_T^{\ell_1}\right|+\left|\boldsymbol{p}_T^{b_0}+\boldsymbol{p}_T^{b_1}\right|}{\left|\boldsymbol{E}_T^{miss}\right|+\left|\boldsymbol{p}_T^{\ell_0}\right|+\left|\boldsymbol{p}_T^{\ell_1}\right|+\left|\boldsymbol{p}_T^{b_0}\right|+\left|\boldsymbol{p}_T^{b_1}\right|}$

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$m_{b\ell}$ $\min\{\max(m_{b_0\ell_0}, m_{b_1\ell_1}), \max(m_{b_0\ell_1}, m_{b_1\ell_0})\}$

HH→bbℓℓ: VBF BDT variables

- VBF: BDT (not enough events to fully exploit DNN)
- Include kinematic quantities from **forward jets**

Input feature	Description
η_{ℓ_0}, η_{ℓ_1}, ϕ_{ℓ_0}, ϕ_{ℓ_1}, $p_{\mathrm{T}}^{\ell_0}$, $p_{\mathrm{T}}^{\ell_1}$	η, ϕ, p_{T} of the p_{T}-(sub)leading lepton
η_{b_0}, η_{b_1}, ϕ_{b_0}, ϕ_{b_1}, $p_{\mathrm{T}}^{b_0}$, $p_{\mathrm{T}}^{b_1}$	η, ϕ, p_{T} of the p_{T}-(sub)leading b-tagged jet
η_{j_0}, η_{j_1}, ϕ_{j_0}, ϕ_{j_1}, $p_{\mathrm{T}}^{j_0}$, $p_{\mathrm{T}}^{j_1}$	ϕ, η, p_{T} of the p_{T}-(sub)leading non b-tagged jet
$E_{\mathrm{T}}^{\mathrm{miss}}$, $\phi^{E_{\mathrm{T}}^{\mathrm{miss}}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$-sig	missing transverse energy, its ϕ and significance
p_{T}^{bb}, ΔR_{bb}, $\Delta\phi_{bb}$, m_{bb}	p_{T}, ΔR, $\Delta\phi$ and invariant mass of di-b-jet system
$p_{\mathrm{T}}^{\ell\ell}$, $\Delta R_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, $\phi^{\ell\ell}_{\mathrm{centrality}}$	p_{T}, ΔR, $\Delta\phi$, p_{T} and centrality of di-leptons system
$p_{\mathrm{T}}^{bb\ell\ell}$, $m_{bb\ell\ell}$	p_{T} and invariant mass of the $bb\ell\ell$ system
$p_{\mathrm{T}}^{bb\ell\ell+E_{\mathrm{T}}^{\mathrm{miss}}}$, $m_{bb\ell\ell+E_{\mathrm{T}}^{\mathrm{miss}}}$	p_{T} and invariant mass of $bb\ell\ell$ + $E_{\mathrm{T}}^{\mathrm{miss}}$ system
$m_{\ell\ell+E_{\mathrm{T}}^{\mathrm{miss}}}$	invariant mass of dilepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ system
$p_{\mathrm{T}}^{E_{\mathrm{T}}^{\mathrm{miss}}+\ell\ell}$, $\Delta\phi_{E_{\mathrm{T}}^{\mathrm{miss}},\ell\ell}$	p_{T} of and $\Delta\phi$ between $E_{\mathrm{T}}^{\mathrm{miss}}$ and di-lepton system
$p_{\mathrm{T}}^{\mathrm{tot}}$	p_{T} of $bb\ell\ell$ + $E_{\mathrm{T}}^{\mathrm{miss}}$+ p_{T}-leading and -subleading jet
m_{tot}	invariant mass of $bb\ell\ell$ + $E_{\mathrm{T}}^{\mathrm{miss}}$+ p_{T}-leading and -subleading jet
m_t^{KLF}	Kalman fitter top-quark mass
$\min\Delta R_{\ell_0 j}$, $\min\Delta R_{\ell_1 j}$	minimum ΔR between p_{T}-(sub)leading ℓ-j couples
$\sum m_{\ell j}$	sum of the invariant masses of all ℓ+jet combinations
$\max p_{\mathrm{T}}^{jj}$, $\max m_{jj}$	maximum p_{T} and invariant mass of any two non b-tagged jets
$\max\Delta\eta_{jj}$, $\max\Delta\phi_{jj}$	maximum $\Delta\eta$ and $\Delta\phi$ between any two non b-tagged jets
$\min\Delta R_{b\ell}$	minimum ΔR of all b-tagged jet and lepton combinations
$N_{\mathrm{forward\ jets}}$, N_j	number of forward jets, number of non b-tagged jets
m_{T2}^{bb}	stransverse mass of the two b-tagged jets
m_{coll}	collinear mass (reconstruction of $m_{\tau\tau}$)
m_{MMC}	value of the MMC algorithm (reconstruction of $m_{\tau\tau}$)

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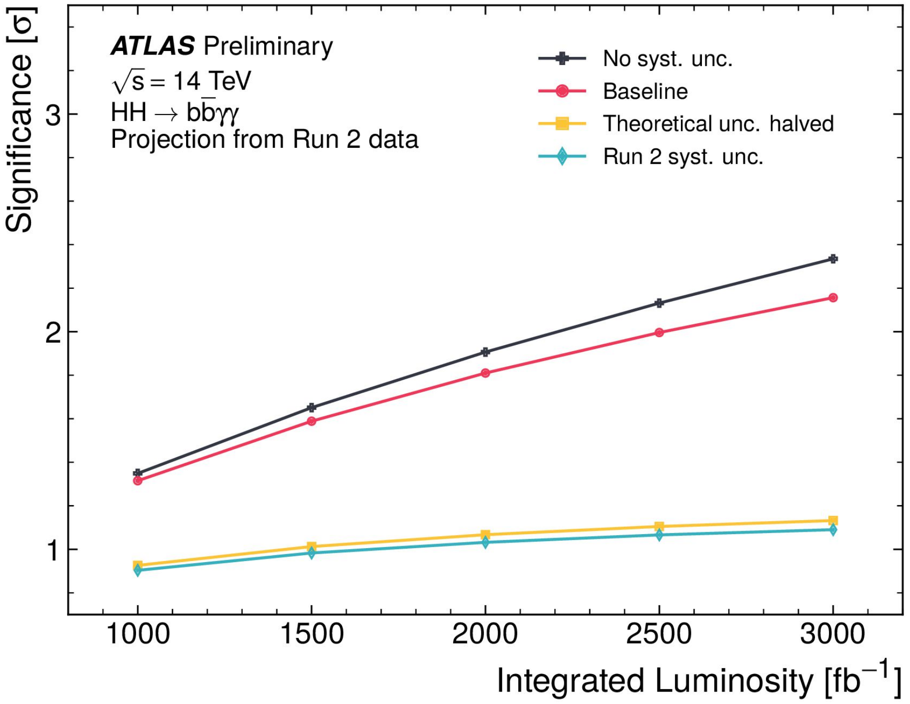
HH→bbℓℓ: Background estimation

- Can have processes **faking** something bbll-like
- Use transfer factors and (data - prompt_MC) in SS region to estimate fake lepton yields in OS region.

Backup: Future prospects

Future prospects: HL-LHC extrapolation

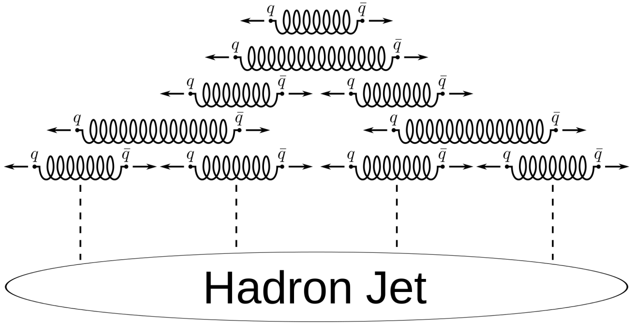
- Measurement prospects of Higgs boson pair production in the $b\bar{b}\gamma\gamma$ final state with the ATLAS experiment at the HL-LHC:
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-001/
- **Extrapolated** precision on signal strength measurement of ~ **50%**, significance ~ **2.2-2.3 sigma** with no syst. unc.
- With (without) systematic uncertainties, κ_λ, the modifier of the trilinear Higgs boson self-coupling, is projected to be constrained to the 1σ confidence interval [0.3,1.9] ([0.4,1.8])
- With $bb\tau\tau$:
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-005/

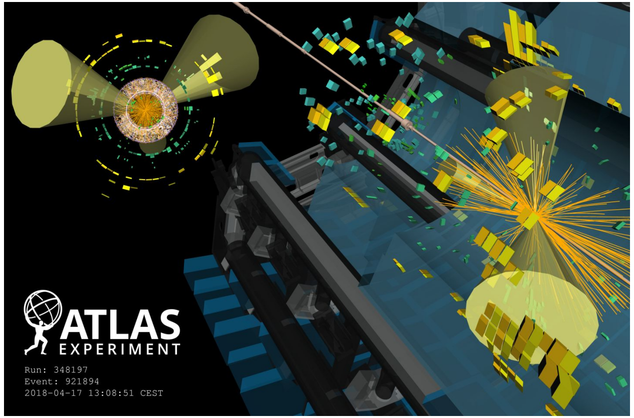


Backup

The ATLAS detector: Jets

- What about quarks? In SM, quarks cannot **freely** exist. Instead quark pairs are produced from vacuum, detector sees process of **hadronization**

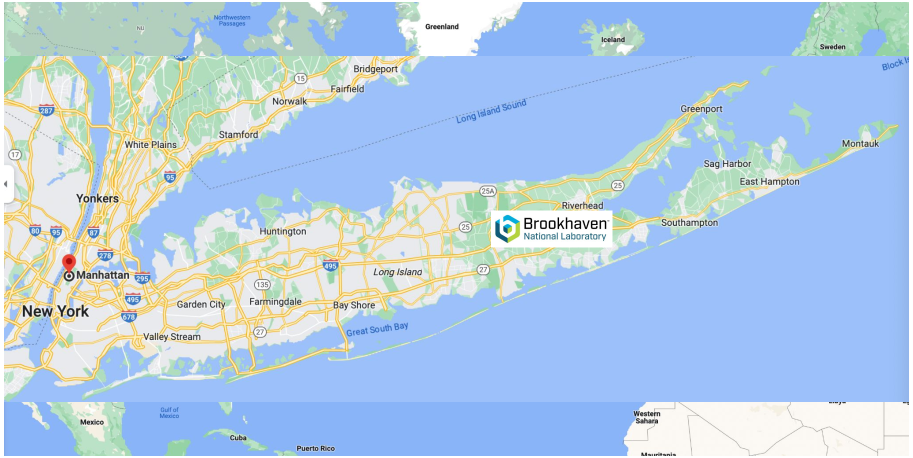




- See **spray** of particles in detector. In **reconstruction**, choose to group together in a cone called a **jet**

Who am I?

- Abraham (Abe) Tishelman-Charny
- 1994: Born, not far from here: **Manhattan, NY**
- 2016: Got my B.S. in Physics even closer to here: **Stony Brook University**
- 2022: PhD from **Northeastern University** on the CMS experiment (Boston, then 4 years at CERN)
- 2022: Started as a postdoc here at **BNL**:
    - ATLAS collaboration
    - ATLAS tracker upgrade for HL-LHC (ITk)
    - Future Circular Collider studies
    - Working on Higgs pair production



The ATLAS detector: LHC

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

- Began operation at $\sqrt{s} = 7$ TeV, now up to 13.6 TeV

- Collides protons, heavy ions
- Has **four detectors** stationed