Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS

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on behalf of the ATLAS Collaboration

5 November 2024

Overview

1. **Motivation and context**

All today's results use full Run 2 dataset

2. **ATLAS nonresonant di-Higgs analyses**
   - $bb\gamma\gamma$, $bb\tau\tau$, bbbb, bbll, and multilepton shown today.
   - Condensed summary of each channel, then all results together after

3. **New: First ever tri-Higgs analysis (6b final state)**

4. **A brief look to the future**

Motivation

Higgs potential and EW interactions have deep connections to origin of mass, early-universe matter formation, BSM physics, etc.

- Plenty of detail in today's other talks!

Potential commonly expressed as a quartic function at low energy

- Higher derivatives only accessible with multi-Higgs interactions

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \lambda_4 H^4$$

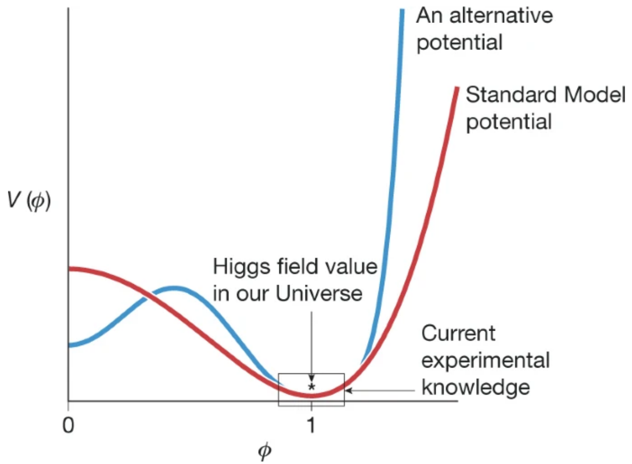


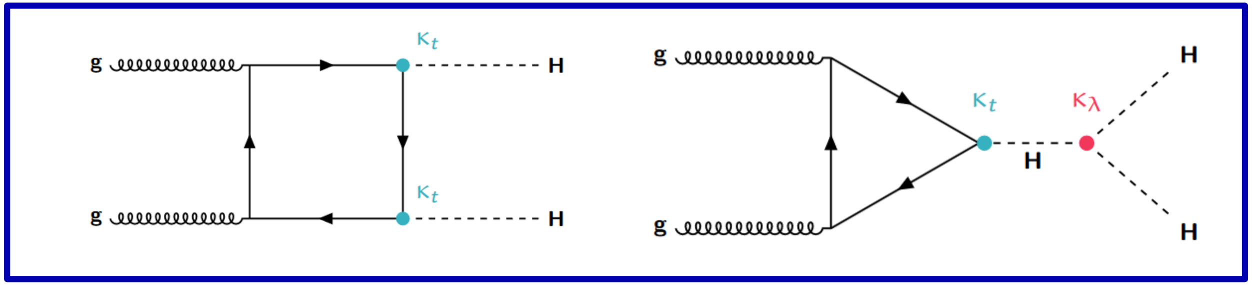
Figure: Salam, Wang, & Zanderighi

At LHC, multi-Higgs production is the best way to measure these parameters

- Can also probe via loop effects in single Higgs production

Production Modes

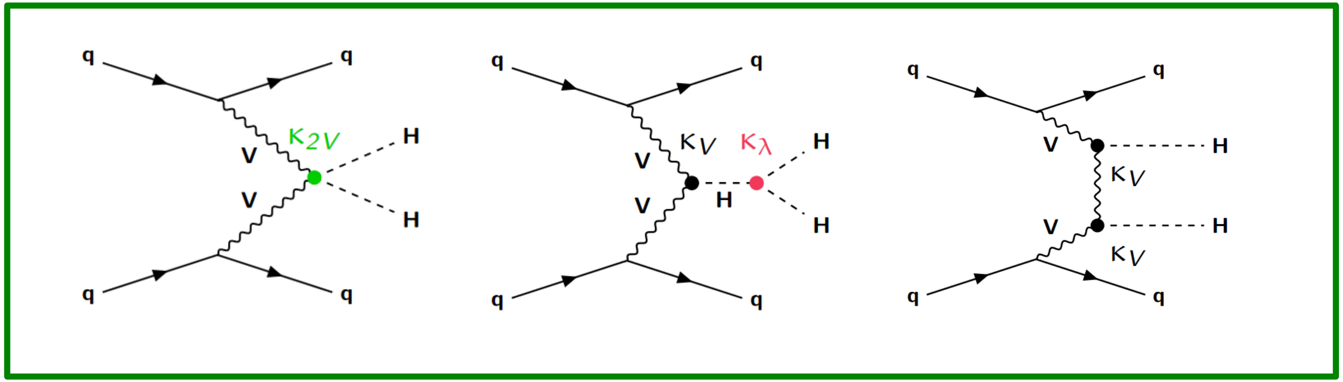
Gluon-gluon fusion (ggF) has the largest cross section at LHC



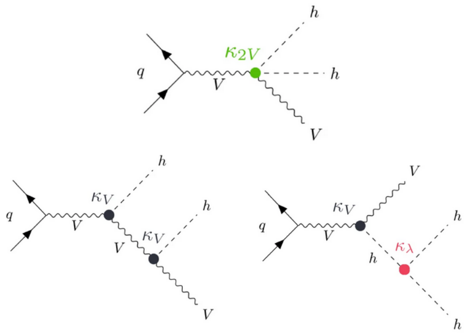
κ defined as ratio to SM coupling

Weak vector boson fusion (VBF) and VHH production also interesting

- Additionally probe Higgs electroweak vertices (e.g. VVHH)



Not discussed today, but see our results in Eur. Phys. J. C 83 (2023) 519



Effective Field Theories

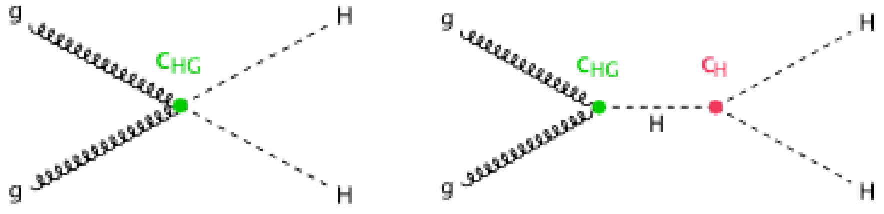
High-scale physics in loops can be treated like contact interactions.

– We use two different EFT parameterizations for our experimental results.

SMEFT

Standard Model Effective Field Theory

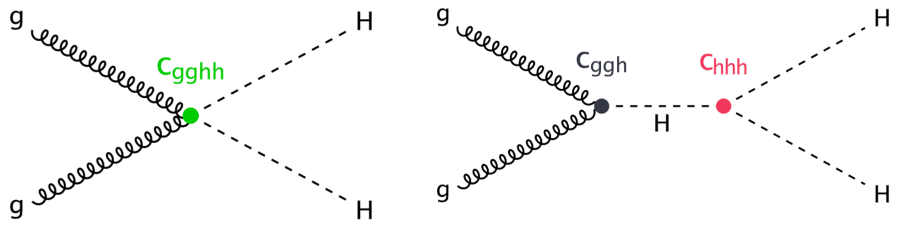
Add higher-dimension operators invariant under SM gauge group using only SM fields



HEFT

Higgs Effective Field Theory

Expand around EW vacuum ("after" symmetry breaking).
Use singlet h and Goldstone d.o.f. instead of doublet H.



Experimental Overview

HH itself has many decay modes.

Which ones to search in?

- A complicated trade-off between signal rates, mass resolution, backgrounds, ease of triggering…
- We cover final states including bbγγ, bbττ, bbbb, bbll, and multilepton.
- bbll and multilepton involve multiple decay modes which are experimentally similar.

	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%

Current status at ATLAS

A summary of the past ~year's ATLAS (non-resonant) di-Higgs results:

Decay	Reference	Release date
bbγγ	JHEP 01 (2024) 066	18 Oct 2023
bbττ	Phys. Rev. D 110 (2024) 032012	19 Apr 2024
bbbb (resolved jets)	Phys. Rev. D 108 (2023) 052003	09 Jan 2023
bbbb (VBF w/ merged jets)	Phys. Lett. B 858 (2024) 139007	24 Apr 2024
bbll (+MET)	JHEP 02 (2024) 037	17 Oct 2023
Multilepton	JHEP 08 (2024) 164	30 May 2024
Combination	Phys. Rev. Lett. 133 (2024) 101801	14 Jun 2024

We also have several results on resonant di-Higgs production

- Maggie Chen will cover these in her talk later today

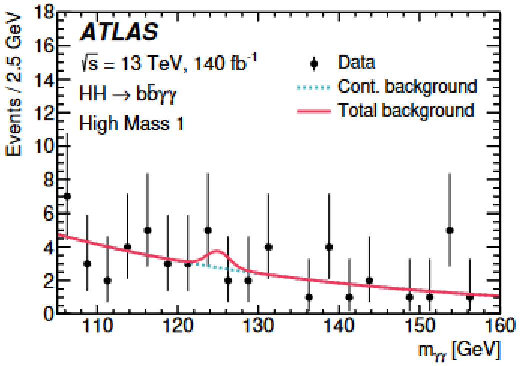
HH→bbγγ

HH→bbττ

Use BDTs to cut away background, then fit $m_{\gamma\gamma}$

Background modeled as double-sided Crystal Ball (H→γγ) plus exponential (the rest)

- Crystal Ball parameters determined using simulation



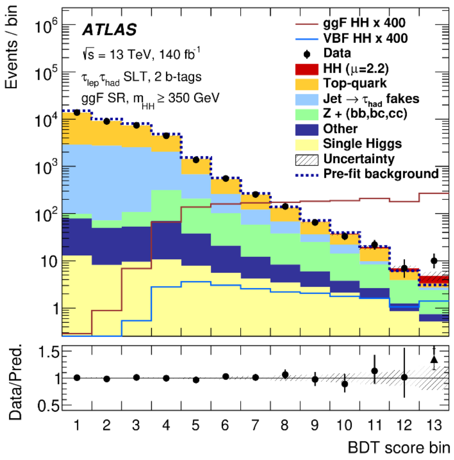
+6 other categories

JHEP 01 (2024) 066

Use $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ final states

- Complex set of triggers and categories

Select events using object-based cuts, then fit on a BDT discriminant.



+8 other categories

Phys. Rev. D 110 (2024) 032012

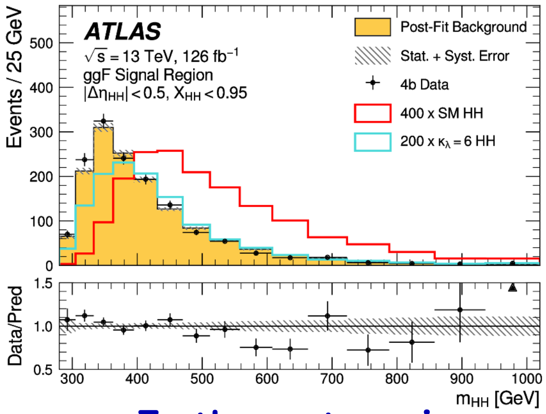
HH→bbbb

Resolved

Pair jets to form H candidates, then fit on m_{HH}

Background extrapolated from 2b data and control regions in m_{H1}-m_{H2} space

- Mostly QCD, can't model well with MC



+7 other categories

Phys. Rev. D 108 (2023) 052003

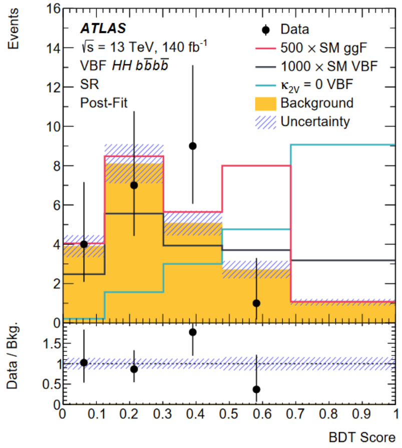
VBF Merged

Modified κ_{2V} → harder Higgs p_T spectrum

Use DNN-based H→bb tagger

- Far better performance than previous results!

Fit on BDT score



Phys. Lett. B 858 (2024) 139007

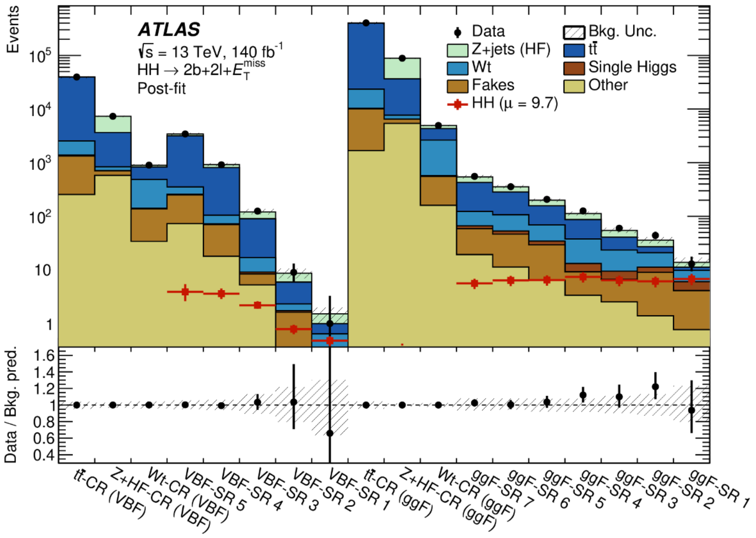
HH→bbll

HH→multilepton

Construct signal and control regions based on m_{bb} and m_{ll}

Fit on DNN (BDT) score in ggF (VBF) regions

- Background modeled with mix of CRs and MC



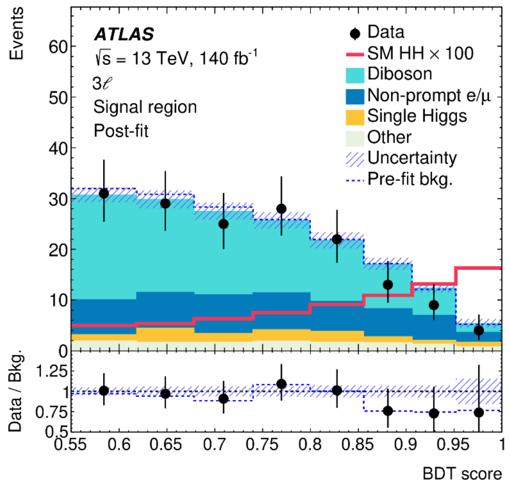
JHEP 02 (2024) 037

Many analysis categories for many final states!

- Includes photons as well as leptons

In each category, fit on BDT discriminant

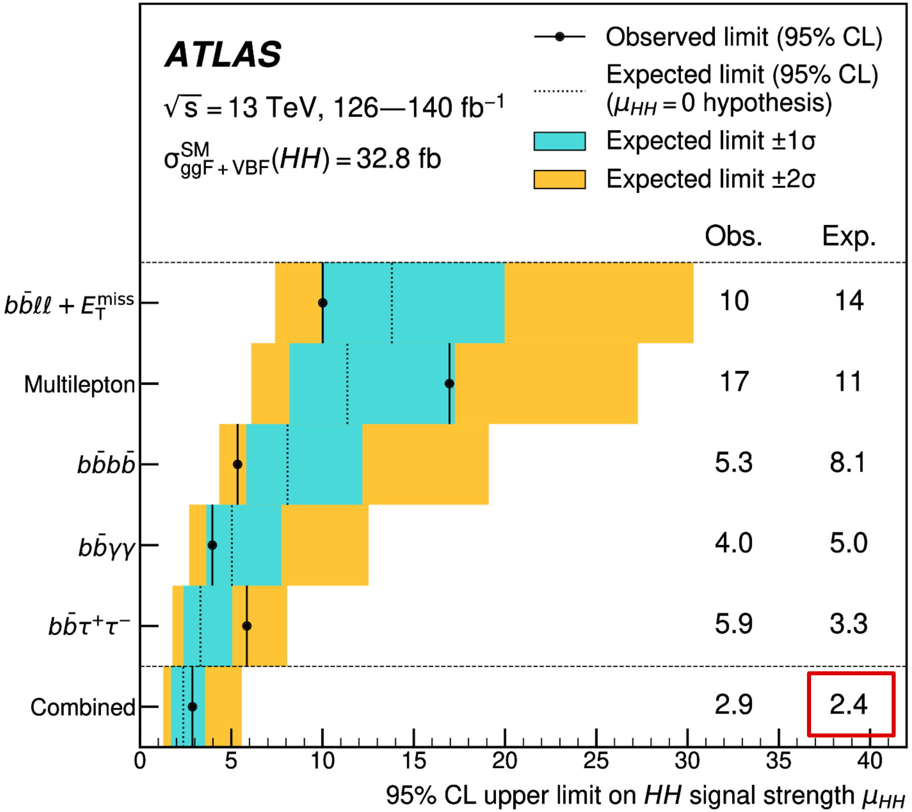
- Exception: Fit on $m_{\gamma\gamma}$ for diphoton channels



+8 other channels

JHEP 08 (2024) 164

Results: HH Signal Strength



Soon it will be time to start reporting measured values with uncertainties instead of upper limits!

Resolved channel drives bbbb sensitivity

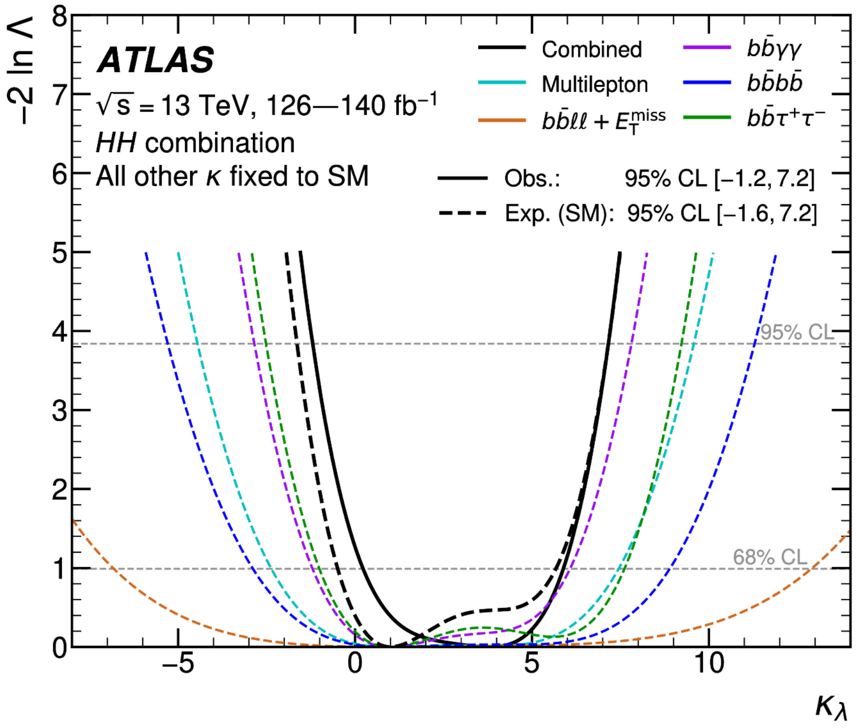
All-hadronic channel drives bbττ sensitivity

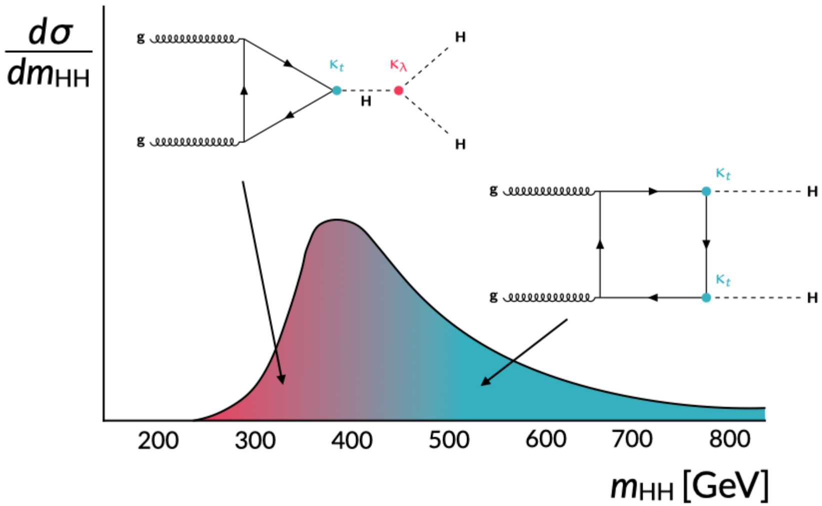
Our best sensitivity to date

Phys. Rev. Lett. 133 (2024) 101801

Results: Higgs self-coupling

bbγγ channel most sensitive, and bbττ at negative κ_λ



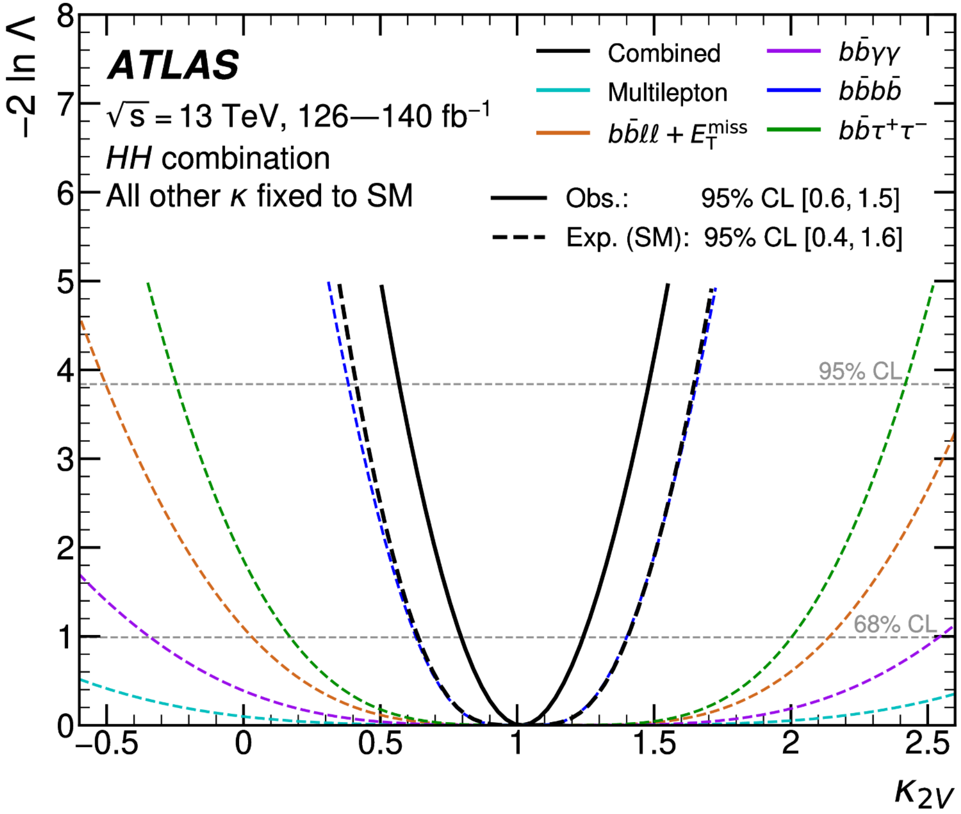


Phys. Rev. Lett. 133 (2024) 101801

Triangle diagram contributes most at low m_{HH}

→ Analyses that can reach down there do best on κ_λ

Results: VVHH coupling



Phys. Rev. Lett. 133 (2024) 101801

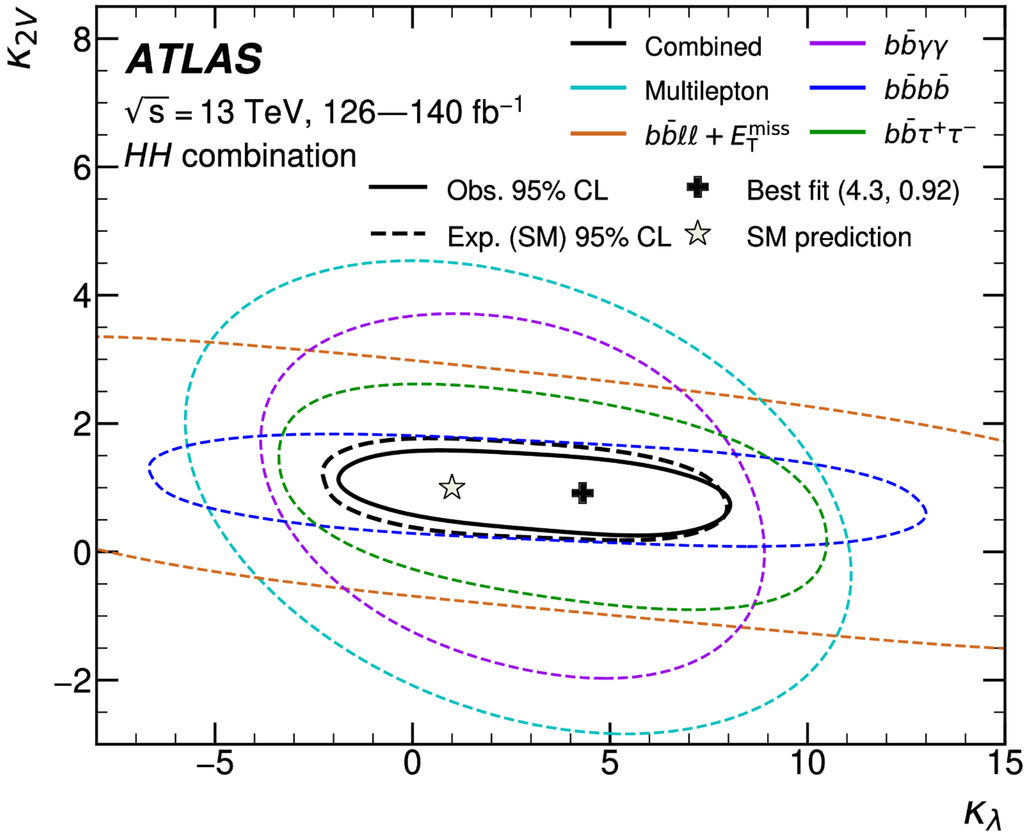
bbbb channel dominates κ_{2V} sensitivity

- All VBF channels very stats-limited and low-background, so large BR wins out

Merged-jet channel provides most sensitivity for bbbb

- SM production has finely-balanced destructive interference in VBF
- Changing κ_{2V} slightly produces a lot more events at fairly high p_T

Results: 2D coupling constraints

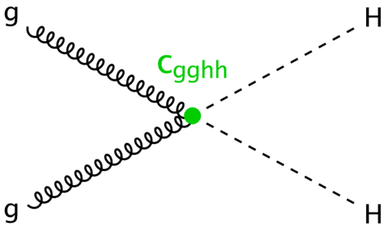


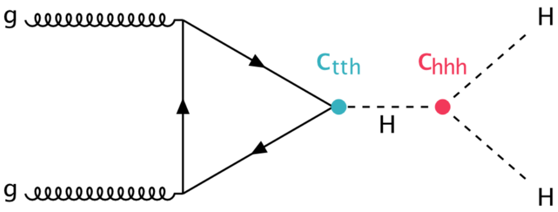
Sensitivity driven mainly by bbγγ, bbττ, and bbbb

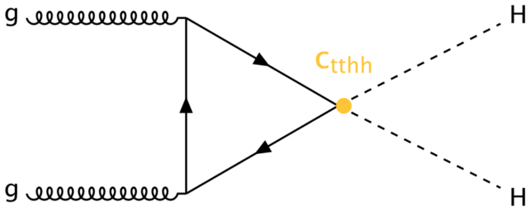
Differing exclusion contour shapes between channels demonstrate complementarity

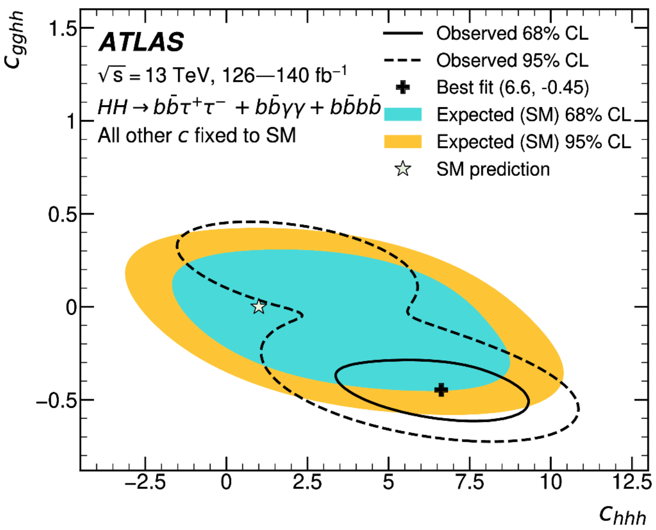
Phys. Rev. Lett. 133 (2024) 101801

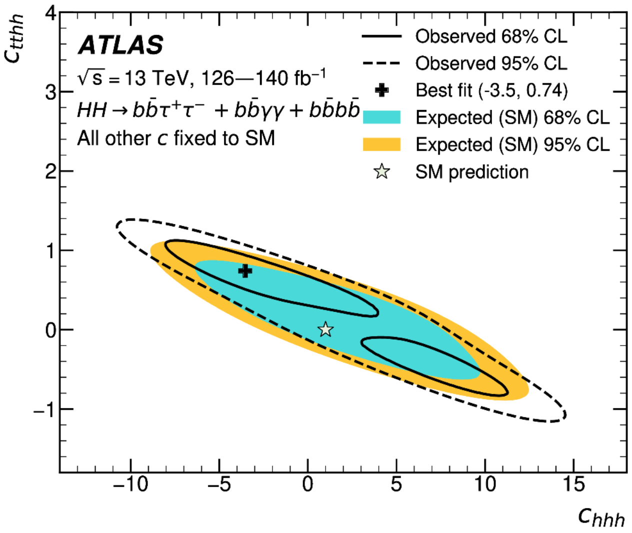
Results: HEFT parameters

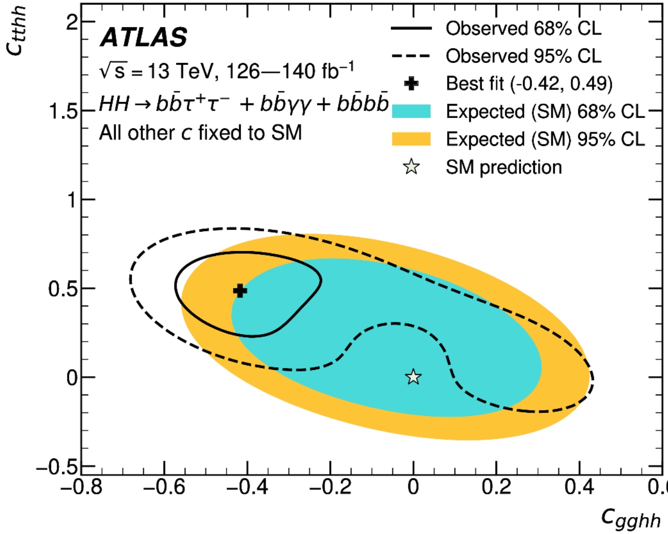












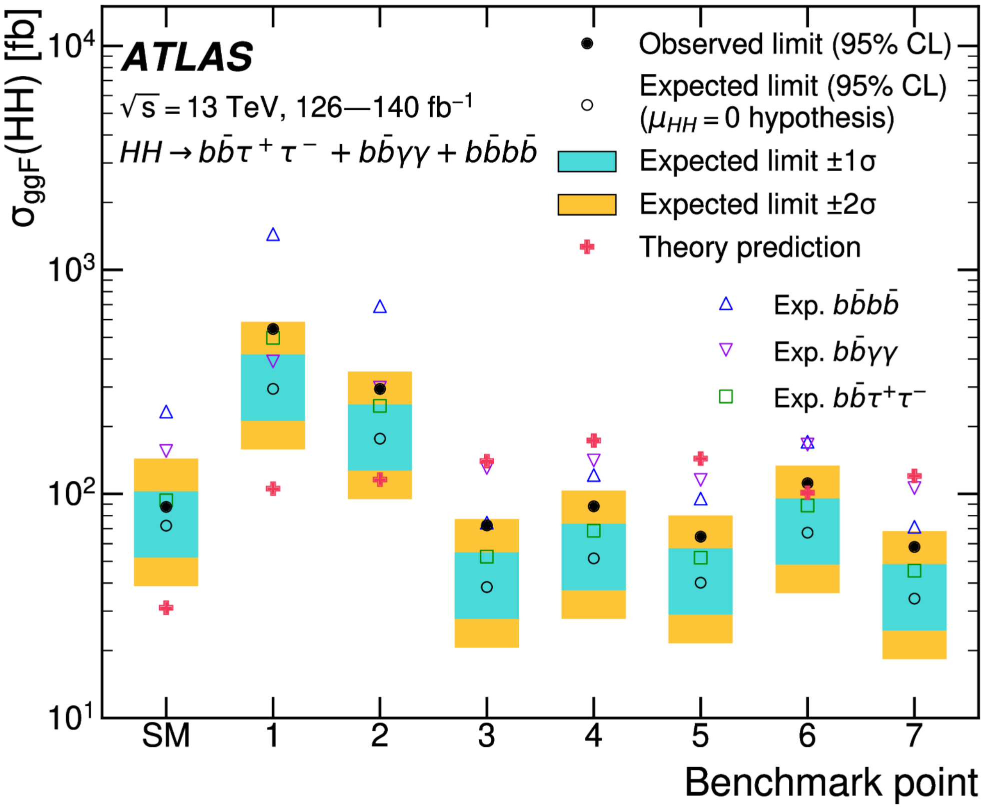
[Phys. Rev. Lett. 133 (2024) 101801]

Results: HEFT Benchmarks

7 benchmark points defined in arXiv:2304.01968

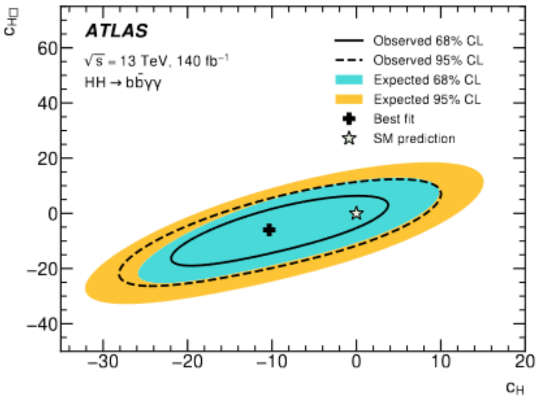
- 5 of these now excluded by ATLAS

Benchmark Model	c_{HHH}	c_{ttH}	c_{ggH}	c_{ggHH}	c_{ttHH}
SM	1	1	0	0	0
BM1	3.94	0.94	1/2	1/3	−1/3
BM2	6.84	0.61	0.0	−1/3	1/3
BM3	2.21	1.05	1/2	1/2	−1/3
BM4	2.79	0.61	−1/2	1/6	1/3
BM5	3.95	1.17	1/6	−1/2	−1/3
BM6	5.68	0.83	−1/2	1/3	1/3
BM7	−0.10	0.94	1/6	−1/6	1

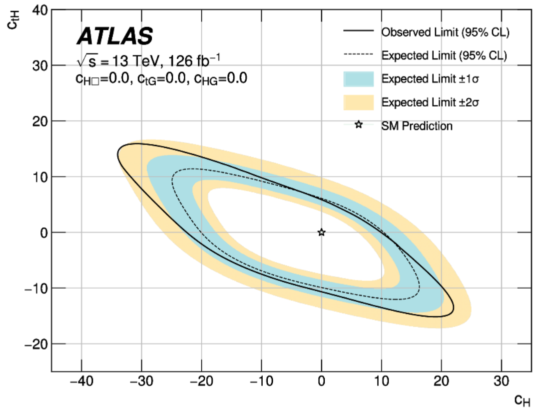


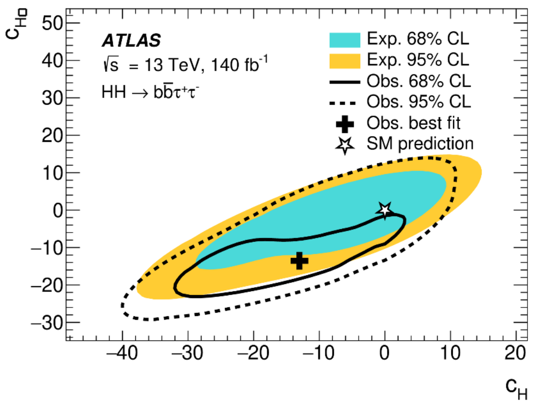
Phys. Rev. Lett. 133 (2024) 101801

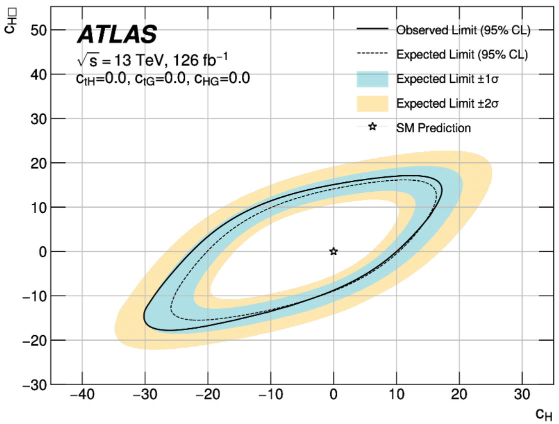
Results: SMEFT parameters

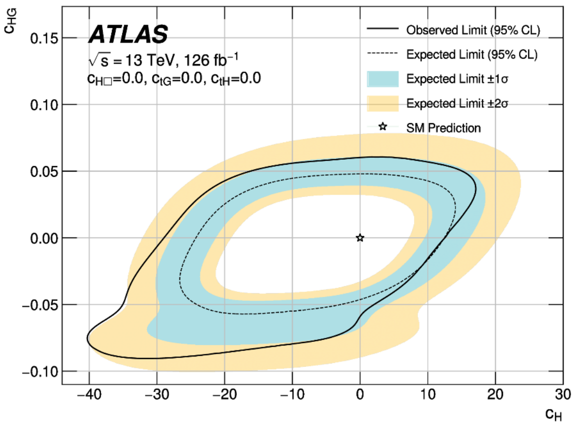


Wilson Coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$
c_{HG}	$H^\dagger H G^A_{\mu\nu} G^{\mu\nu}_A$
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}G^A_{\mu\nu}$







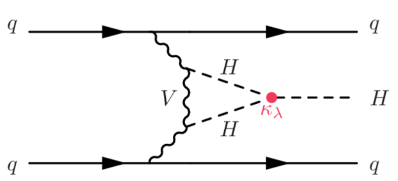


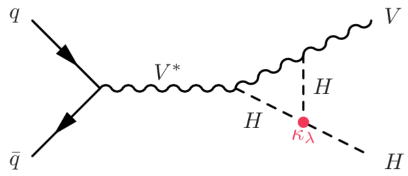
Combination with Single Higgs

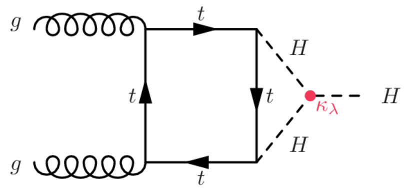
[Phys. Lett. B 843 (2023) 137745]

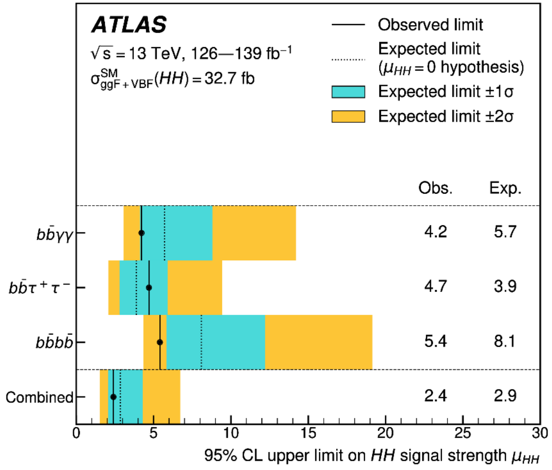
Most recent H+HH combination is from late 2022. Reminder of results:

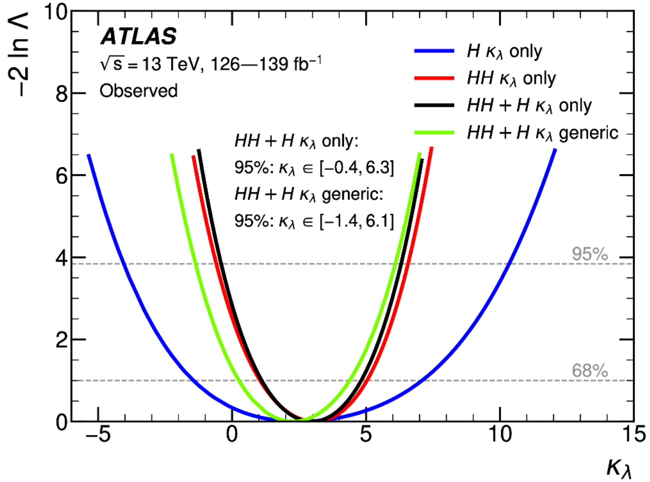
- Only bbγγ, bbττ, and bbbb included for HH

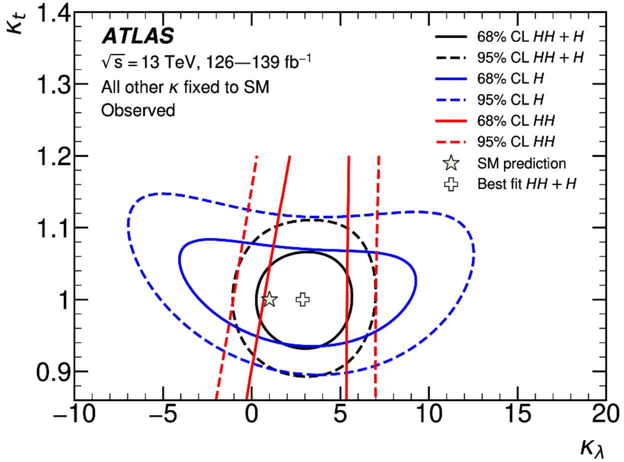




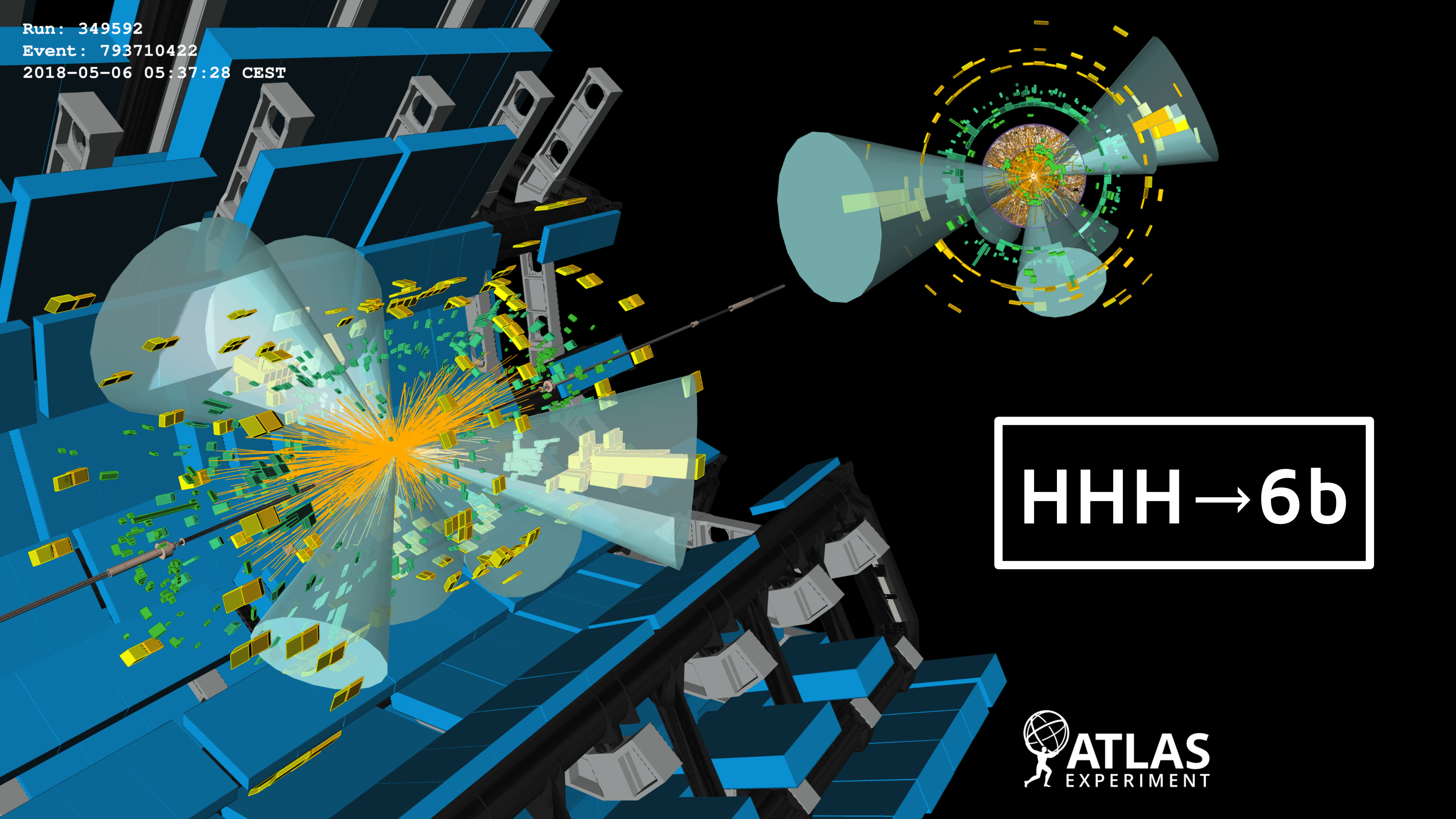








N.B. Some observed limits are tighter than more recent HH combination, but expected aren't: (un)lucky fluctuation.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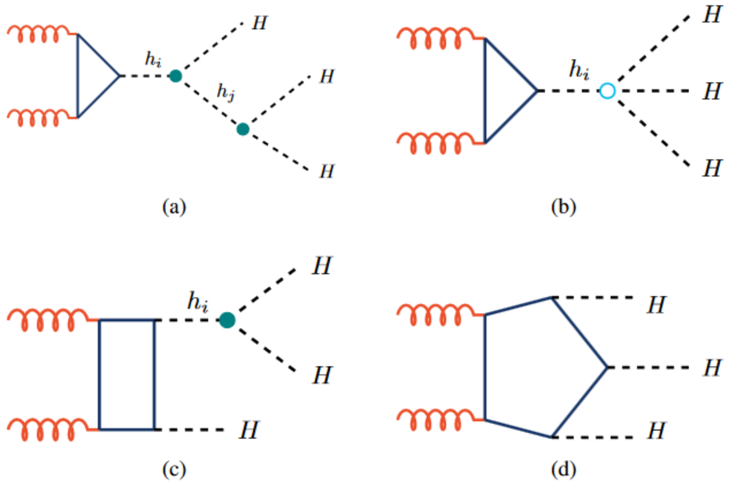
HHH→6b
ATLAS
EXPERIMENT

HHH→6b

Some BSM theories predict nontrivial HHH production

- Either via resonance or strongly modified couplings
- Cross sections lower than HH, but so are backgrounds



Quartic coupling can only be accessed directly this way

- No experimental bounds on this exist before now

Rare process: use 6b final state to retain large branching fraction

- Initially conceived as a resonance search, but can include non-resonant interpretations too
- See Maggie Chen's talk today for the resonant results

arXiv:2411.02040

HHH→6b

Pair jets based on consistency of H candidates with Higgs boson mass

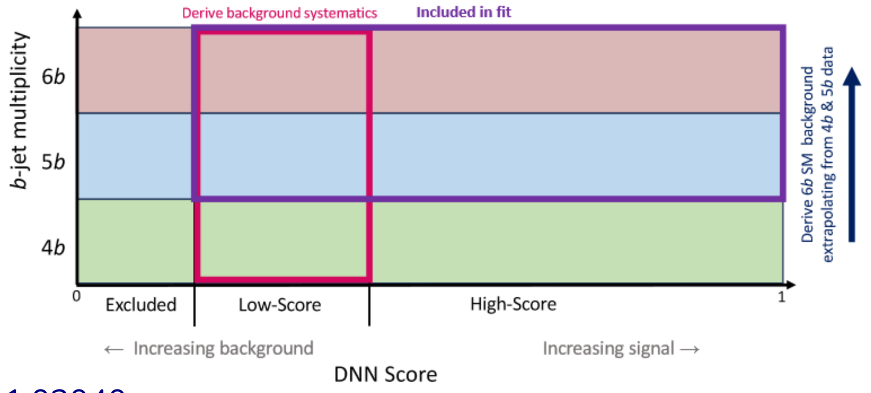
- Difficult combinatorics, but this gets it right ~60% of the time for SM kinematics

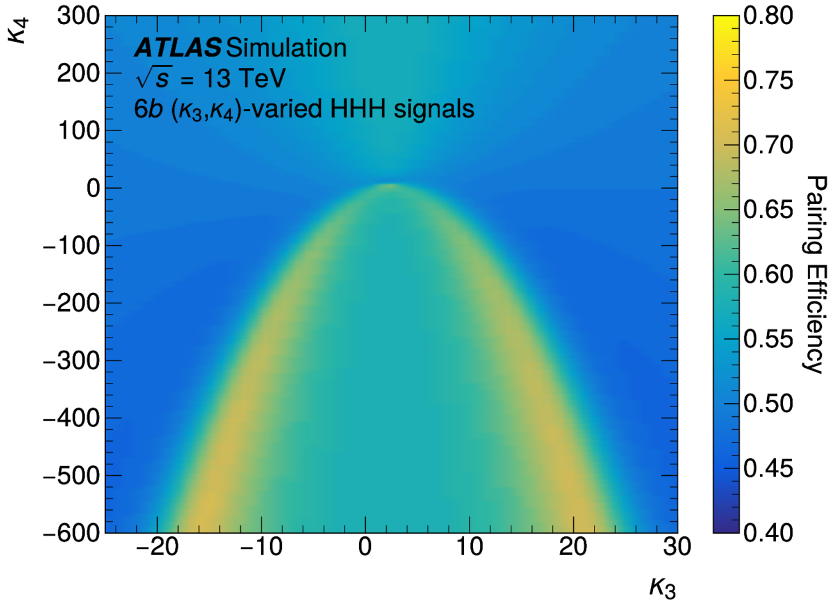
Train DNN to separate signal from background, fit score distribution

- Use variables with minimal b-tag correlation

Model background using lower-DNN-score data and 5b selection

- 4b data also used to evaluate systematic uncertainties





arXiv:2411.02040

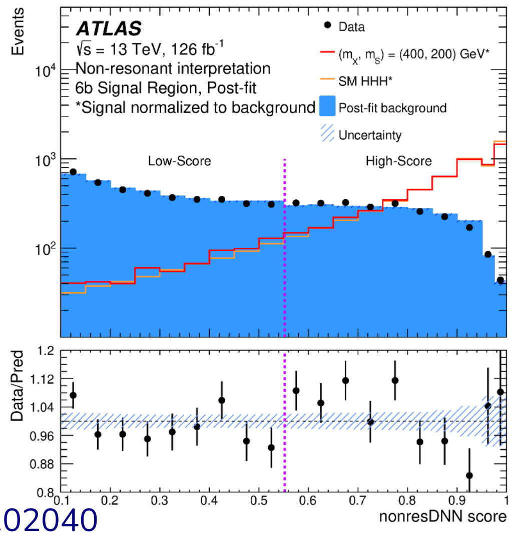
HHH→6b: Results

Data consistent with SM. 95% CL cross section limit for pp→HHH set at **59.4 fb** (μ < 747)

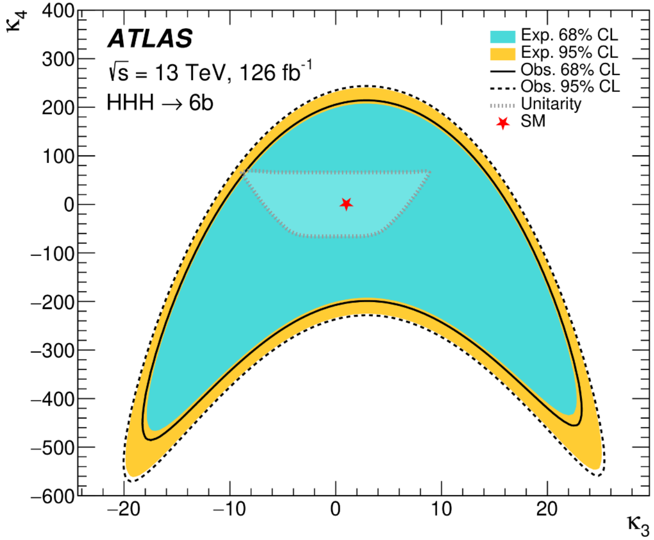
Constraints on quartic coupling set for the first time

- Already at the edge of kappa framework's perturbative unitarity bounds (don't take model too seriously outside this – it's meant as a reference point)

We're making recasting information public for easy reinterpretability (available very soon!)



arXiv:2411.02040

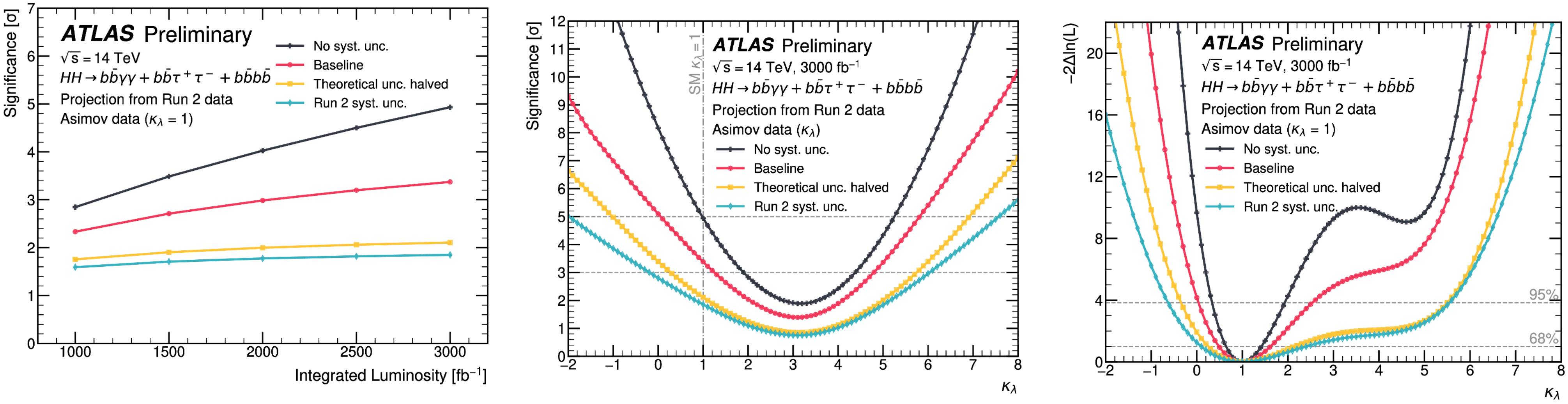


Unitarity calculation from Eur. Phys. J. C 84 (2024) 366

Looking Ahead: HH at HL-LHC

Projections show a very promising future for these measurements

- These are all simple extrapolations using today's analysis methods.
- New techniques in the next 15 years are very likely to do better!



See Alex's talk tomorrow for more on HL-LHC prospects

ATL-PHYS-PUB-2022-053

Looking Ahead: HH at HL-LHC

Table 9: Expected significance for several channel combinations, for a luminosity of 3 ab^{-1}, including the expected uncertainties quoted in the text, using the asymptotic approximation. This table only takes into account the $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels.

Channel	Significance	Combined in channel	Total combined
e + jets	0.31	0.43	0.60
μ+jets	0.30		
$\tau_{had}\tau_{had}$	0.41	0.41	

HL-LHC bbττ significance expected in 2015
(ATL-PHYS-PUB-2015-046)

assuming SM kinematics for the signal, the 95% CL upper limit on the HH signal strength is projected to be at 0.71 times the SM prediction with respect to the background-only hypothesis assuming an integrated luminosity of 3000 fb^{-1} and $\sqrt{s}$ = 14 TeV. The signal significance is extrapolated to 2.8σ, ~~and assuming a~~ true value of $\kappa_\lambda = 1$, the self-coupling modifier is constrained to the 1σ CI [0.3, 1.9] ∪ [5.2, 6.7]. If no HH

HL-LHC bbττ significance expected in 2021
(ATL-PHYS-PUB-2021-044)

a variety of integrated luminosities ranging from 1000 to 3000 fb^{-1}. Assuming SM HH production, a signal significance of 3.5 σ ~~(4.6 σ) is expected in the baseline (statistical only)~~ extrapolation scenario for an integrated luminosity of 3000 fb^{-1}. This translates into expected

HL-LHC bbττ significance expected in 2024
(ATL-PHYS-PUB-2024-016)

Summary

ATLAS has completed a comprehensive set of di-Higgs analyses to investigate the Higgs boson's interactions with itself and with EW bosons

- Data are consistent with the Standard Model in all cases
- Tightest observed limits on self-coupling stand at **$-0.4 < \kappa_\lambda < 6.3$** @ 95% CL (assuming no other BSM physics)
- VVHH coupling currently constrained to **$0.6 < \kappa_{2V} < 1.5$** @ 95% CL (assuming no other BSM physics)
- Interpretations in terms of HEFT and SMEFT Wilson coefficients and benchmarks also provided

First ever results on HHH production are now available

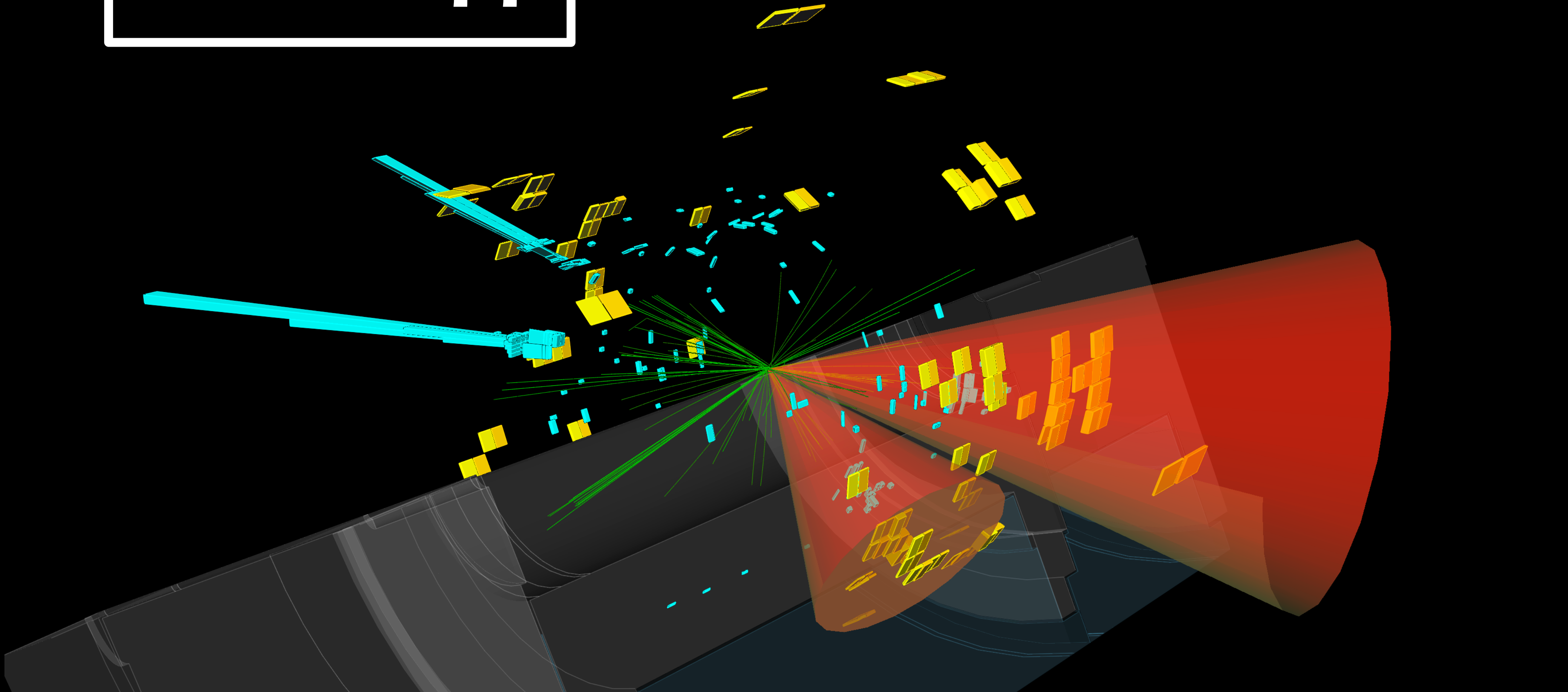
- Will remain far from SM sensitivity for a long time, but already probing BSM theory spaces

Run 3 and HL-LHC provide much opportunity to take this even further

- 5σ observation of HH production could be a reality within HL-LHC lifespan!

Backup

$HH \to b b \gamma \gamma$



HH→bbγγ

The bbγγ final state is very clean, but has low branching fraction (~0.26% in SM)

- Very statistically limited, and will remain so for a long time to come
- VBF channel included for sensitivity to VVHH vertex

Method: Use BDTs to cut away background, then fit the $m_{\gamma\gamma}$ distribution in categories

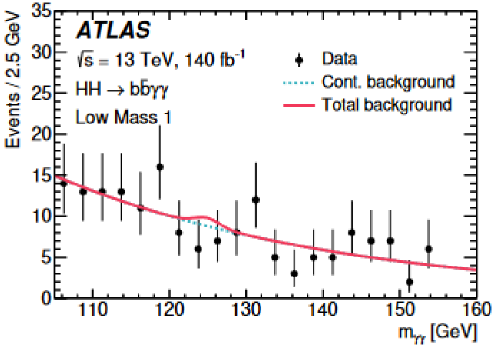
- Events split into 2 categories based on $m_{bb\gamma\gamma}$, corrected for m_{bb} and $m_{\gamma\gamma}$ deviations from 125 GeV
- Events split again into 7 total categories based on BDT score
- Input features are a broad set of kinematic variables: momenta, masses, angles (but not $m_{\gamma\gamma}$)
  - Some additional variables added since previous result for improved performance

Background modeled as double-sided Crystal Ball (H→γγ) plus exponential (the rest)

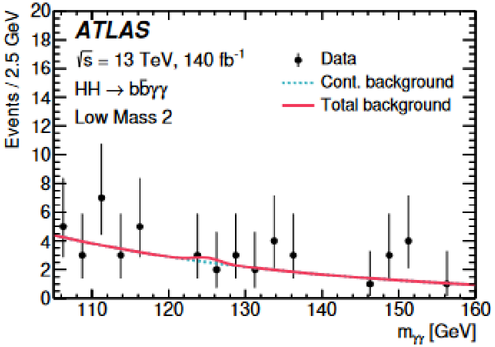
- Crystal Ball parameters determined using simulation

HH→bbγγ: Mass distributions

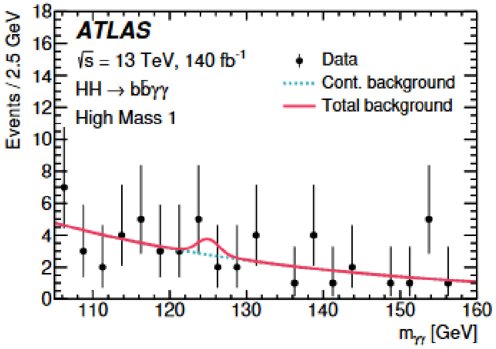
Background-only fits



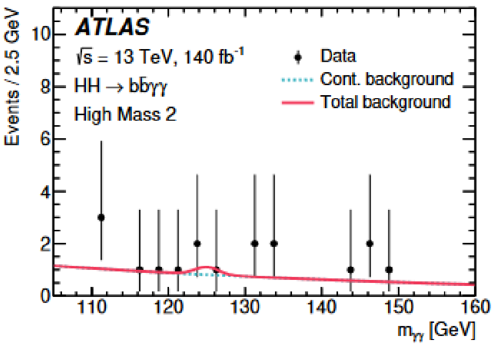
(a) Low Mass 1.



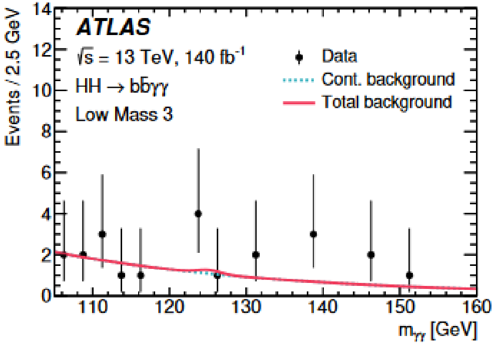
(b) Low Mass 2.



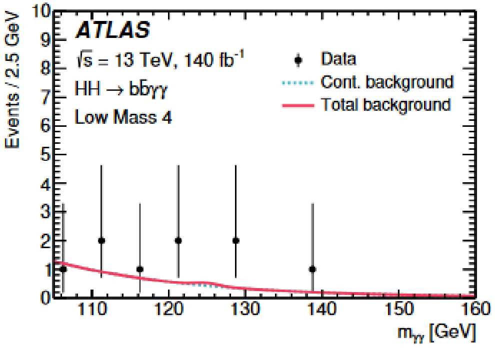
(e) High Mass 1.



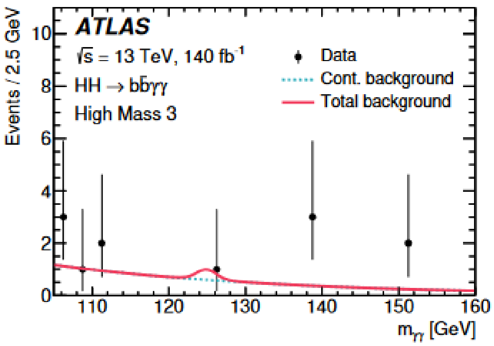
(f) High Mass 2.



(c) Low Mass 3.



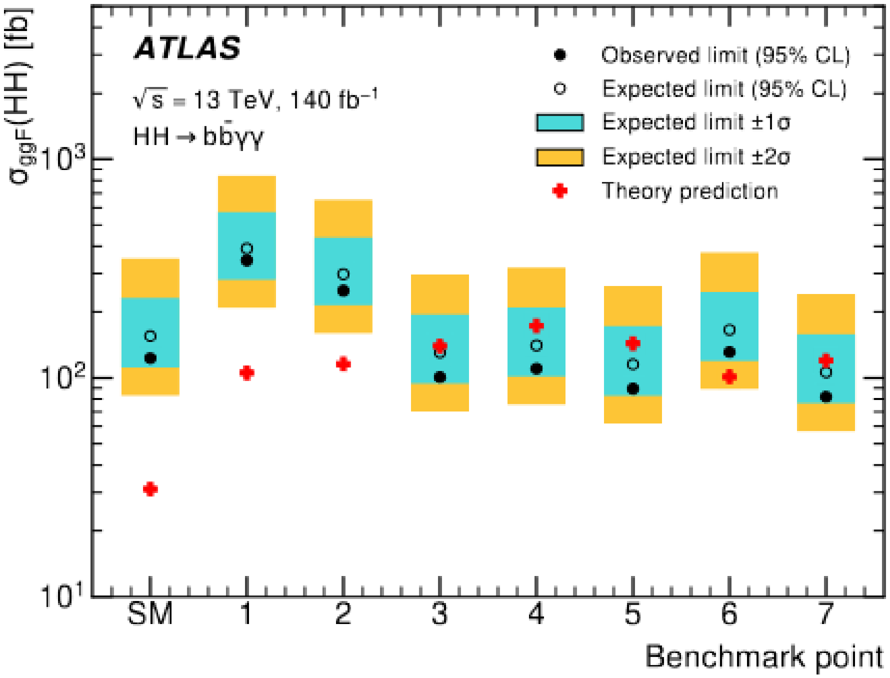
(d) Low Mass 4.

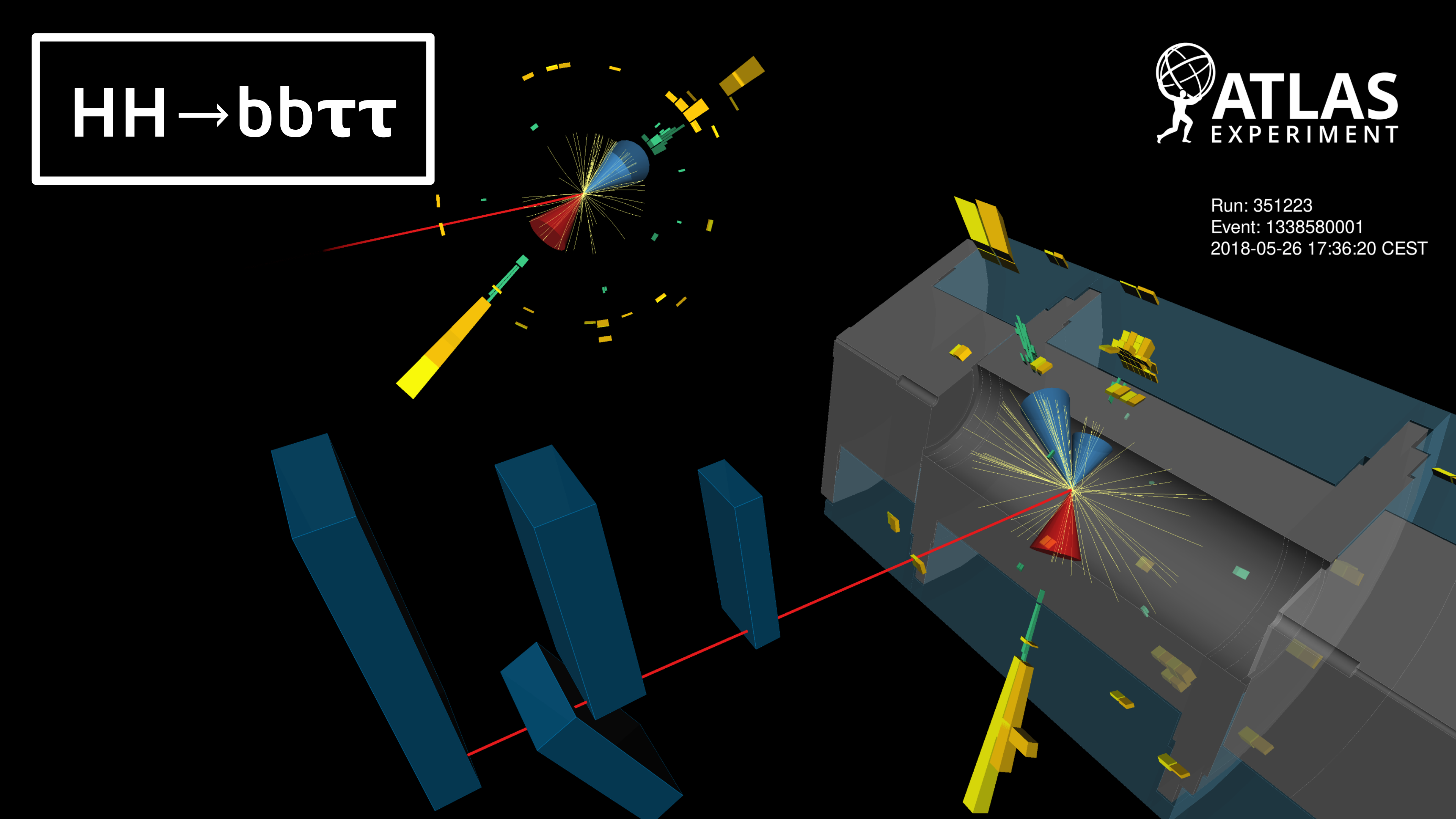


(g) High Mass 3.

HH→bbγγ: HEFT Benchmarks

Benchmark	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1.00	1.00	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	1/4	−1/6
7	−0.10	0.94	1/6	−1/6	1




HH→bbττ
ATLAS
EXPERIMENT
Run: 351223
Event: 1338580001
2018-05-26 17:36:20 CEST

HH→bbττ

Higher branching fraction (~7.3% in SM) than bbγγ, but bigger and more complex backgrounds

- We consider the semi-leptonic ($\tau_{lep}\tau_{had}$) and fully-hadronic ($\tau_{had}\tau_{had}$) cases in this search.
- VBF also included with dedicated event selection categories

Method: Select events using object-based cuts, then use a BDT to construct a discriminant, which we fit.

- BDT input features are kinematic variables (momenta, masses, angles)

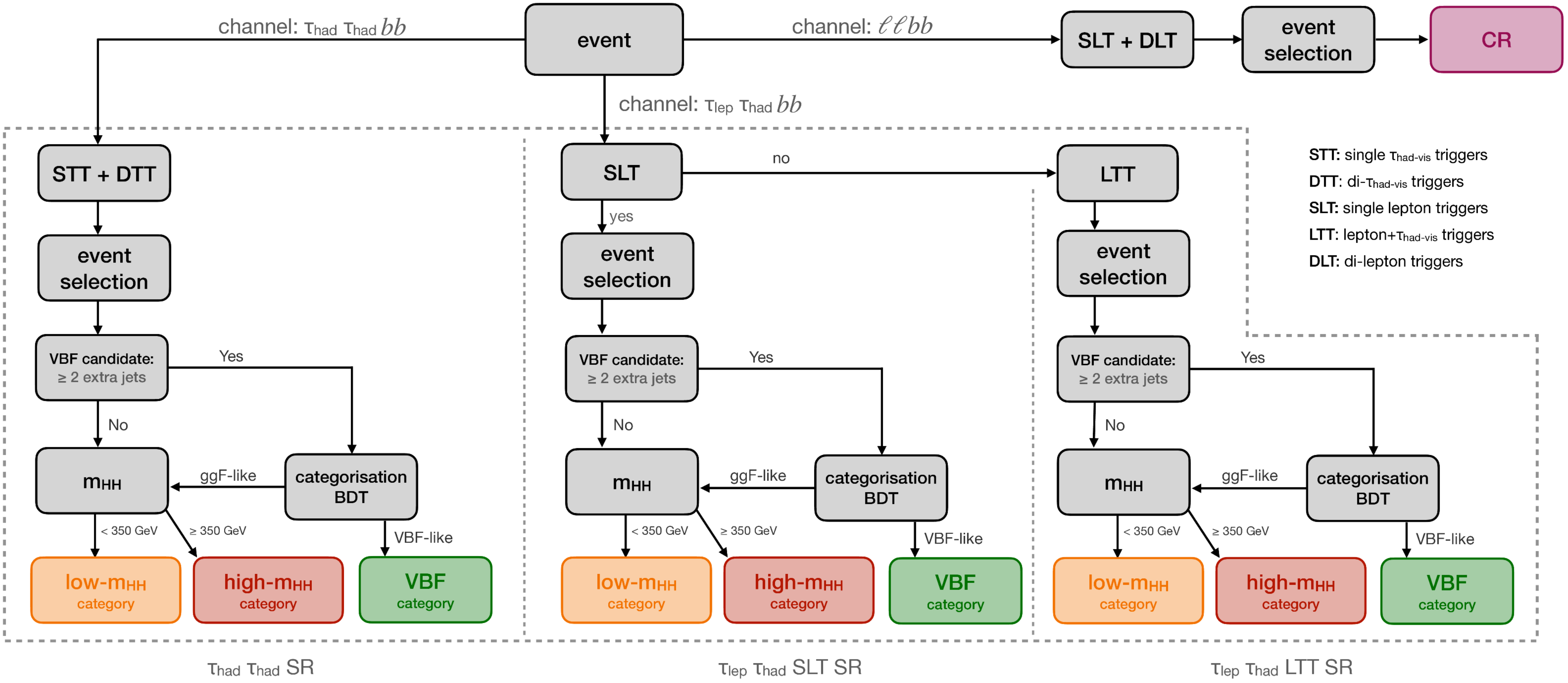
Complex trigger strategy using a mixture of hadronic single-/di-τ triggers and lepton/lepton+τ triggers

- Separate event categories constructed according to these, as background composition varies
- Further categorization based on m_{HH}

Background model uses mixture of simulation and data-driven methods

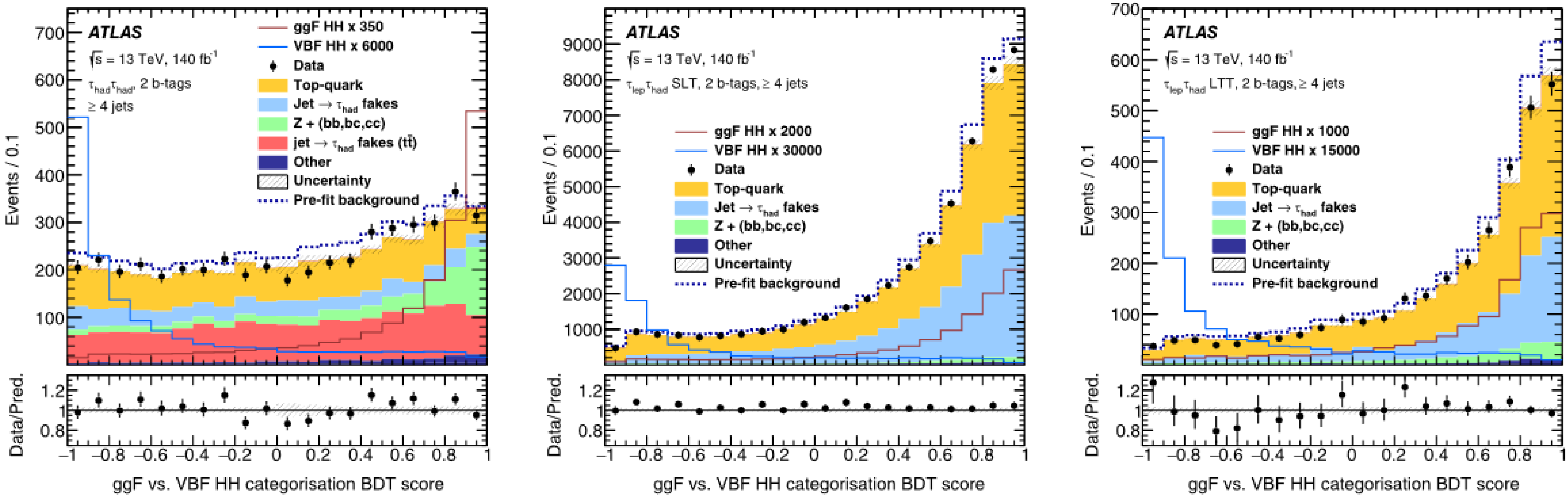
- Many components (top, Z+heavy flavor, fake τ_{had}, …), too much to show here – see paper for details

HH→bbττ: Event categorization



STT: single $\tau_{had\text{-}vis}$ triggers
DTT: di-$\tau_{had\text{-}vis}$ triggers
SLT: single lepton triggers
LTT: lepton+$\tau_{had\text{-}vis}$ triggers
DLT: di-lepton triggers

HH→bbττ: VBF BDT distributions



ATLAS
EXPERIMENT

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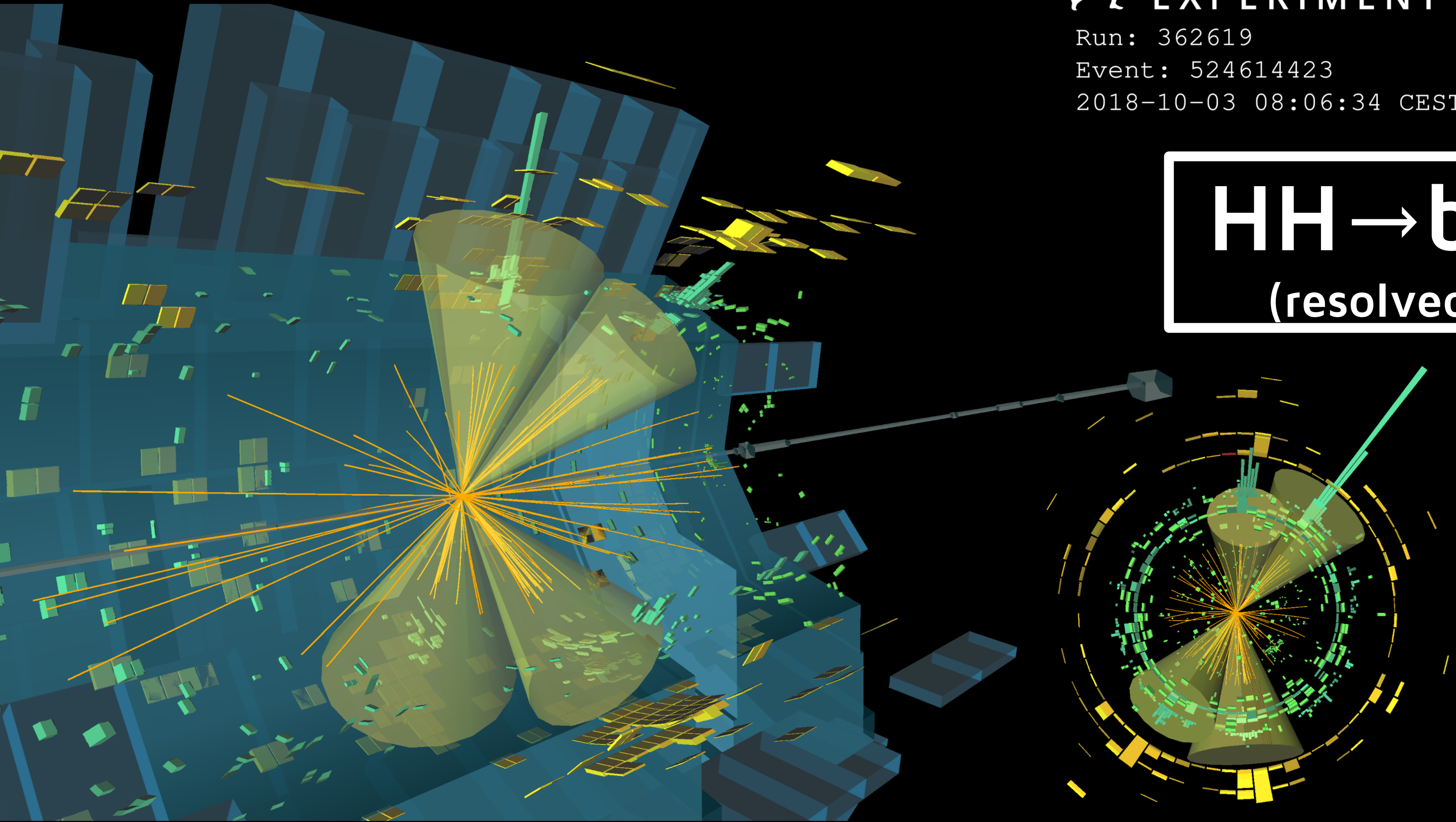
2018-10-03 08:06:34 CEST

HH→bbbb
(resolved jets)



HH→bbbb resolved

bbbb has the highest branching fraction but the largest background

1. Select events with 4 b-tagged jets and categorize based on kinematics (and VBF)

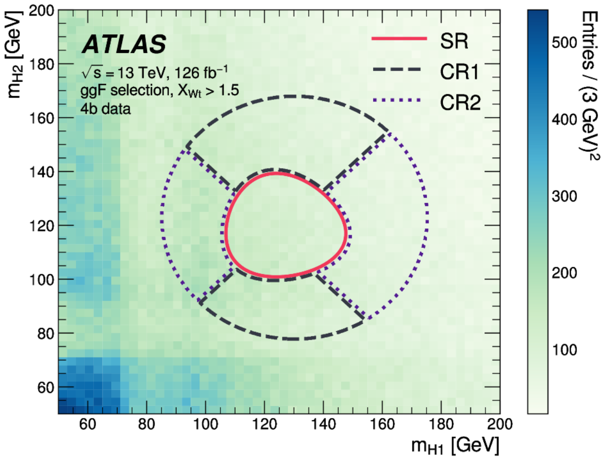
2. Pair these jets into 2 Higgs boson candidates by minimizing ΔR_{bb} for leading H

3. Construct signal and control regions based on the *H* candidate masses

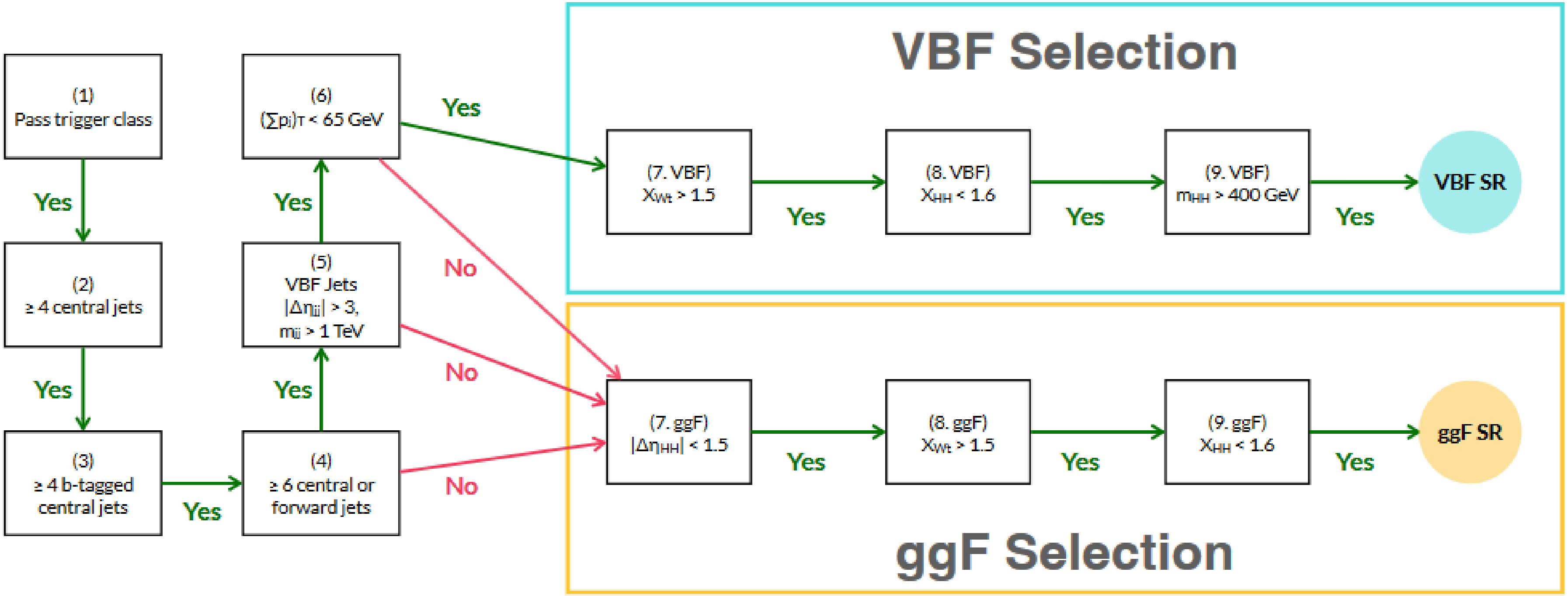
4. Model background by using data with 2 b-tags

- ML-based method to reweight 2b kinematics based on CR data

5. Fit m_{HH} spectrum



HH→bbbb (resolved): Selection



HH→bbbb resolved

bbbb has the highest branching fraction but the largest background

1. Select events with 4 b-tagged jets and categorize based on kinematics (and VBF)

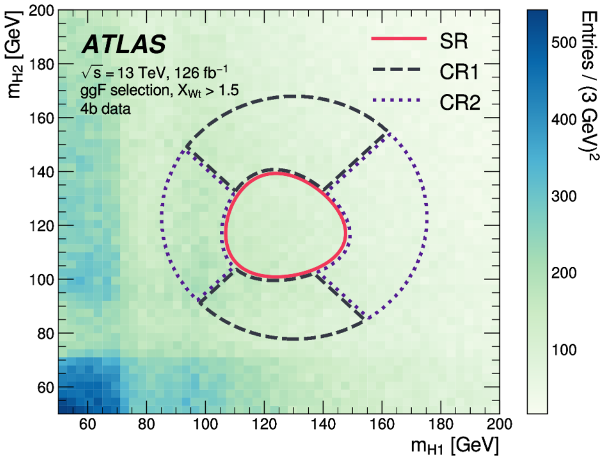
2. Pair these jets into 2 Higgs boson candidates by minimizing ΔR_{bb} for leading H

3. Construct signal and control regions based on the *H* candidate masses

4. Model background by using data with 2 b-tags

- ML-based method to reweight 2b kinematics based on CR data

5. Fit m_{HH} spectrum



ATLAS
EXPERIMENT

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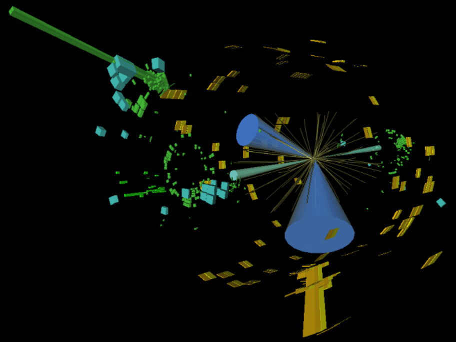
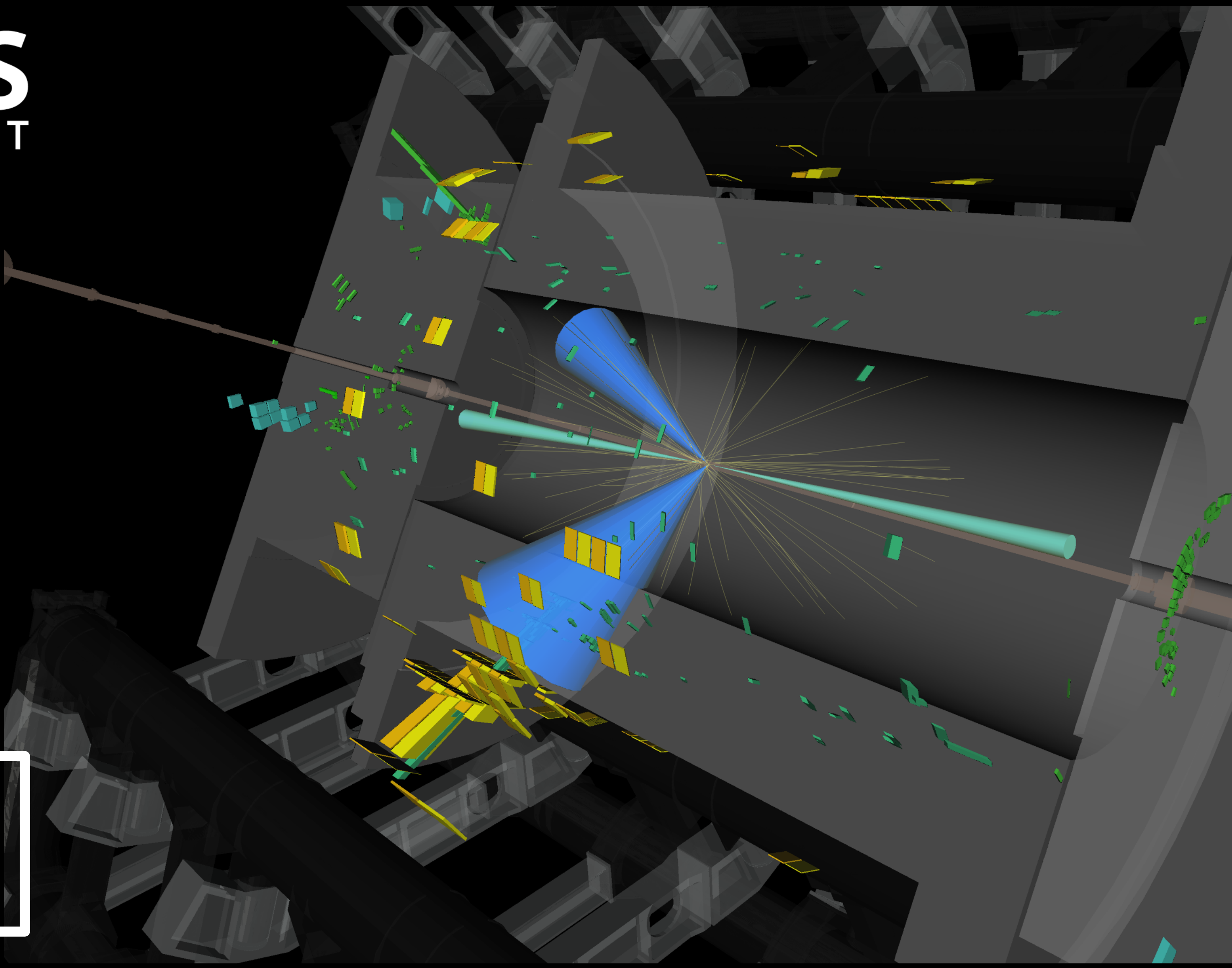
2016-10-25 19:04:17 CEST





HH→bbbb
(VBF, merged jets)

HH→bbbb VBF merged

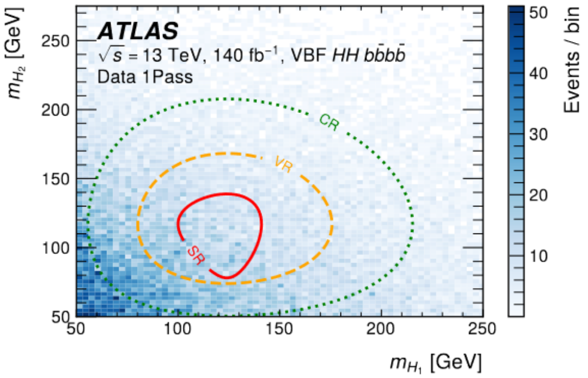
Modified κ_{2V} values result in harder Higgs p_T spectrum: merged jets useful for this

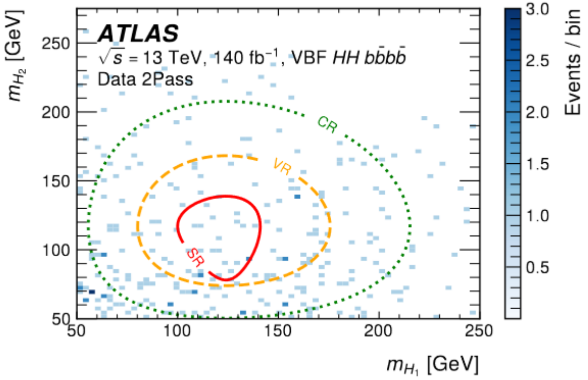
Similar strategy to resolved analysis, but…

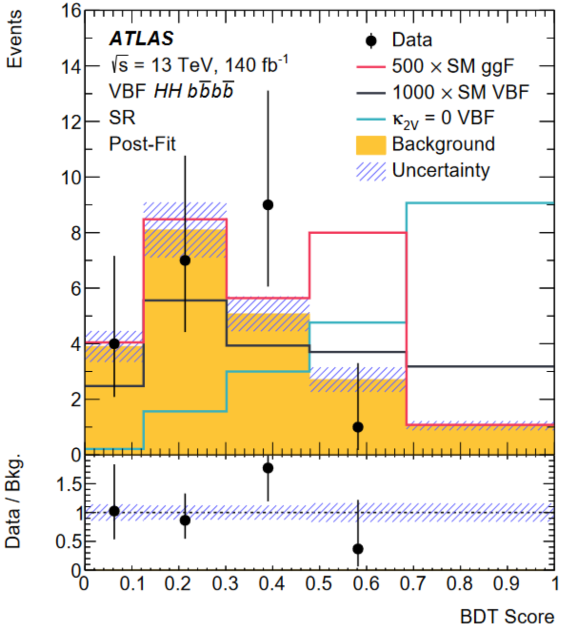
- Use 2 R=1.0 jets instead of 4 R=0.4 jets (still use R=0.4 for the additional VBF jets)
- Use DNN-based H→bb tagger on these jets (much better performance than older methods!)

Fit BDT discriminant instead of m_{HH}

- Trained to discriminate BSM values of κ_{2V} from background and SM HH processes







HH→bbll (+MET)

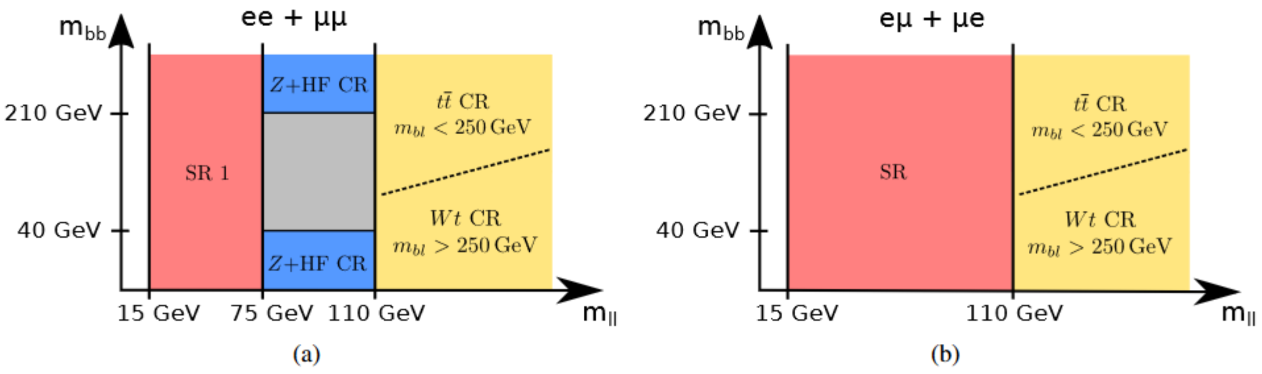
Select events with 2 leptons and 2 b-tagged jets. Also include VBF category (2 more jets)

- Same-sign and opposite-sign leptons treated as separate categories
- No explicit requirement on MET

Construct signal and control regions based on m_{bb} and m_{ll}

- CRs used in conjunction with MC to model background (mainly top, Z+heavy flavor, and fake leptons)

Train DNN (BDT) to discriminate signal from background in ggF (VBF) category and fit on its score



ATLAS EXPERIMENT

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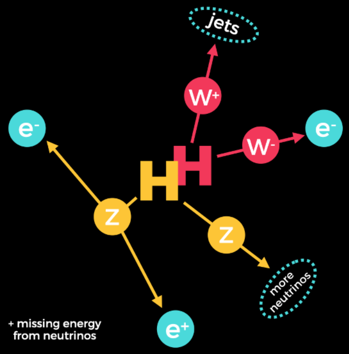
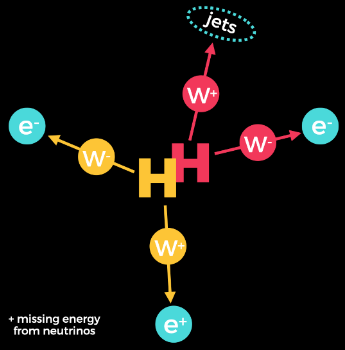
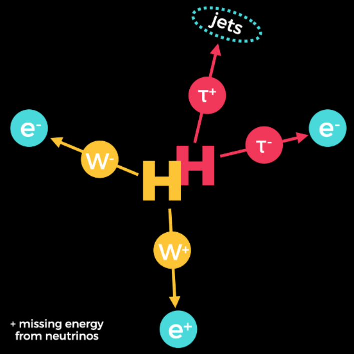
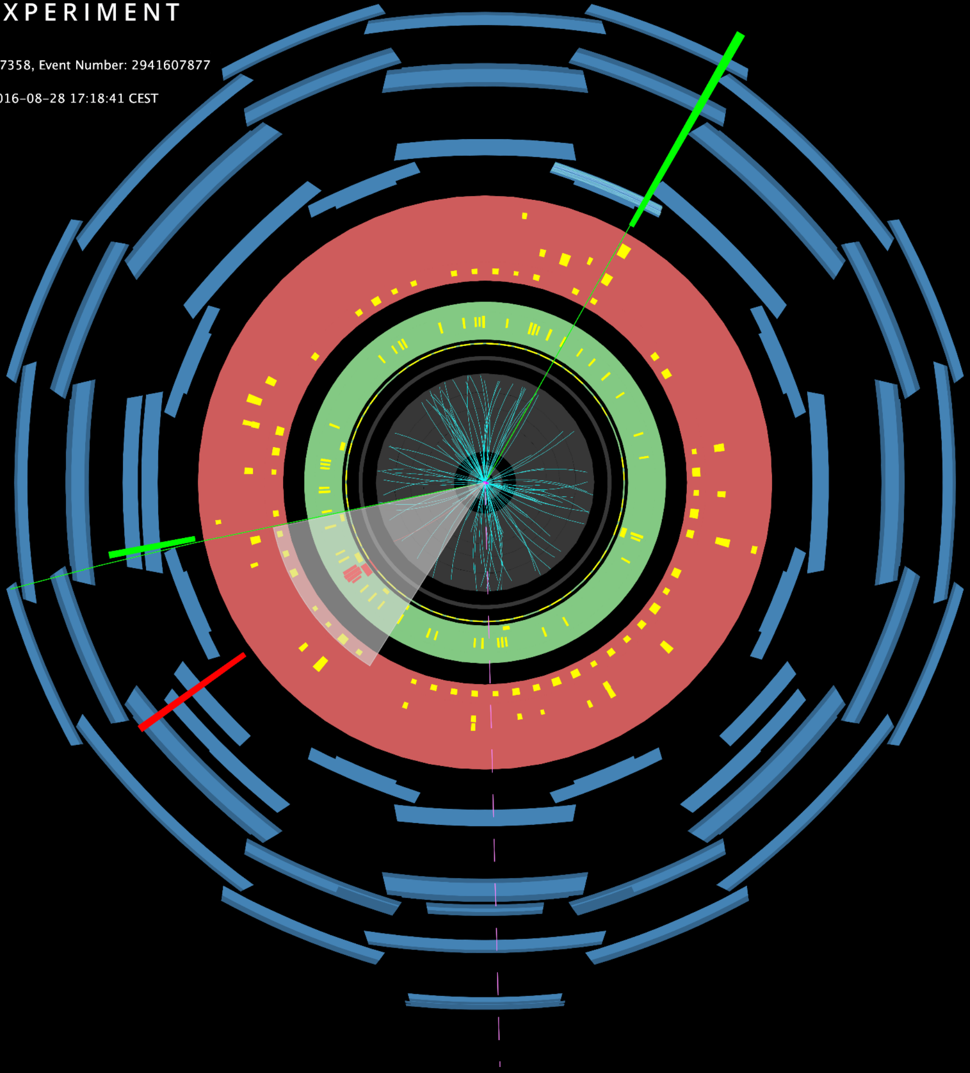


HH→leptons
(including some photon decays)







HH→multilepton

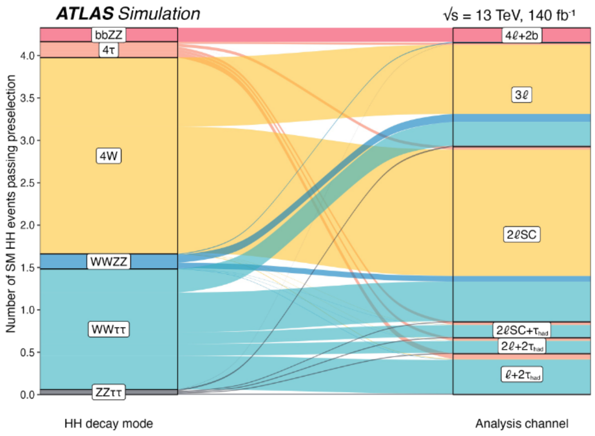
Many analysis categories for many final states! Each one individually weak, but combined they give valuable sensitivity

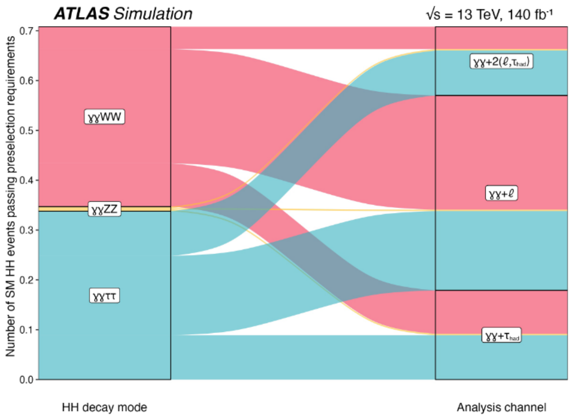
In each category, train a BDT to use as final discriminant

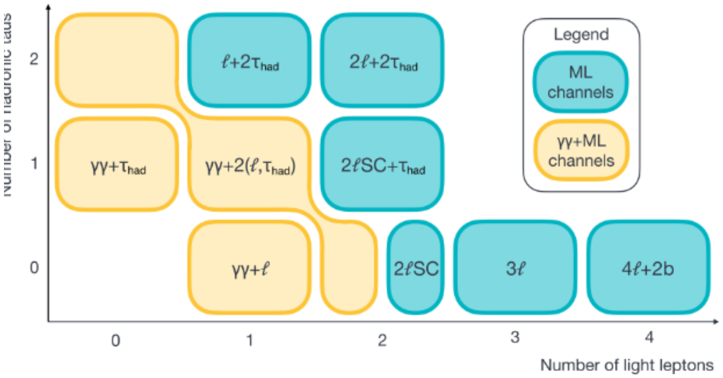
- Exception: fit on $m_{\gamma\gamma}$ instead for diphoton channels (still use BDT for categorization)

Estimate background using very wide array of control regions together with MC simulation

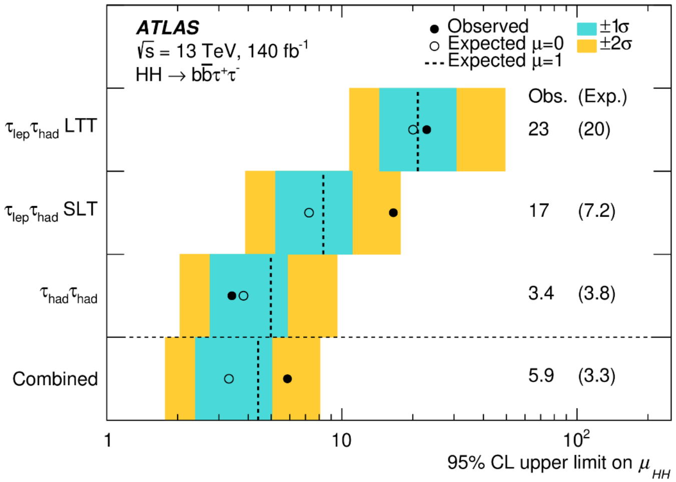
- Too complex to summarize here, see paper for details!

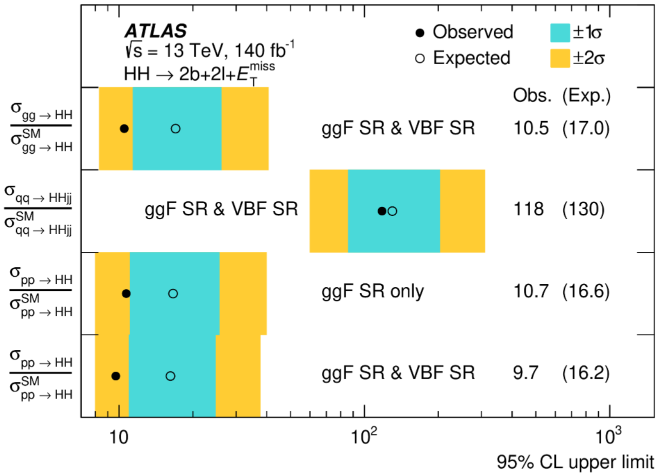


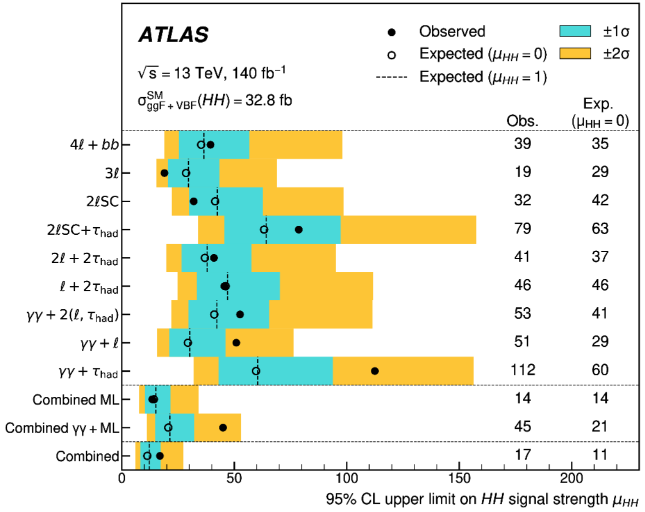




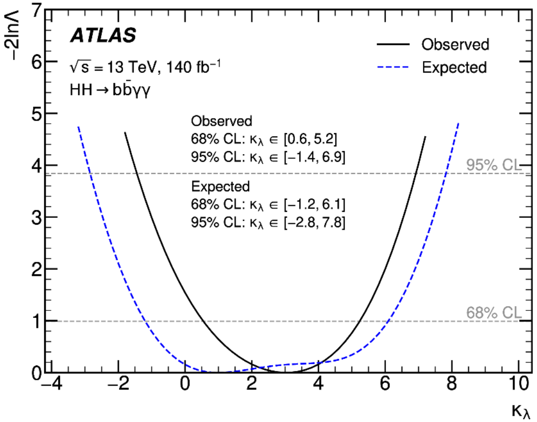
HH signal strength by sub-channel

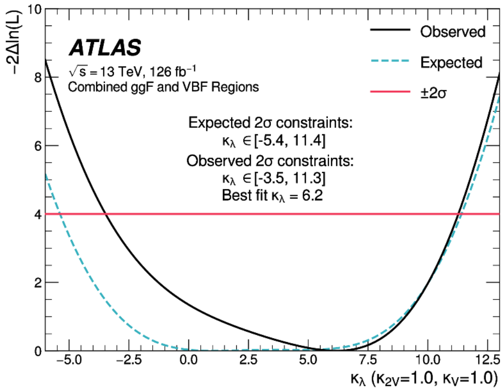


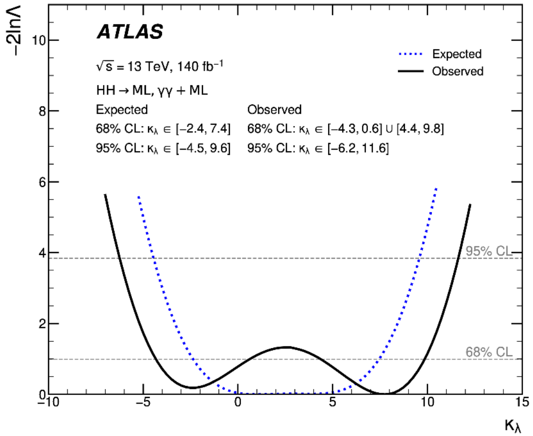


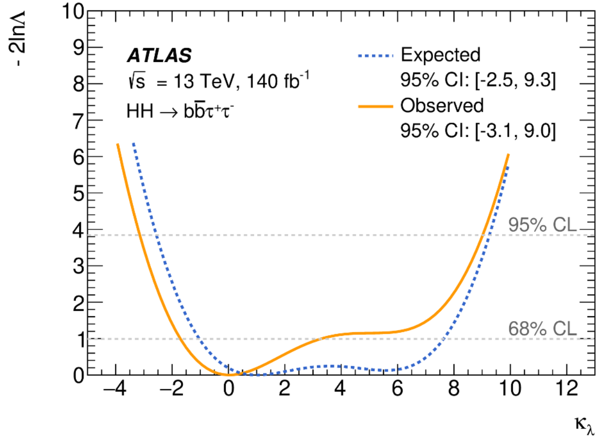


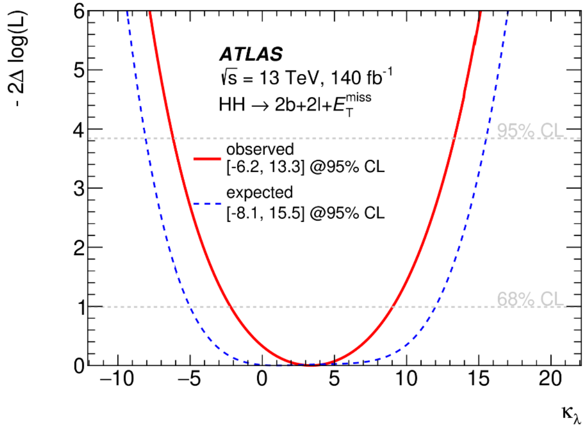
Higgs self-coupling by channel



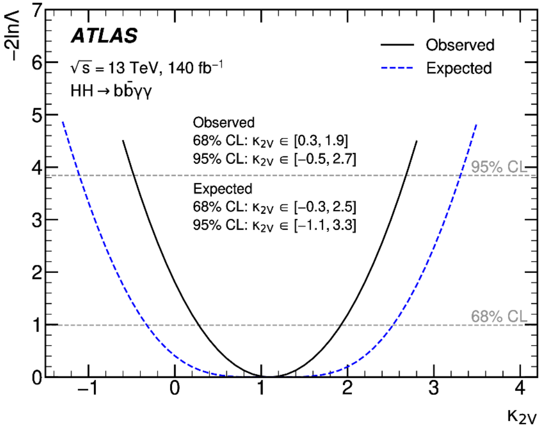


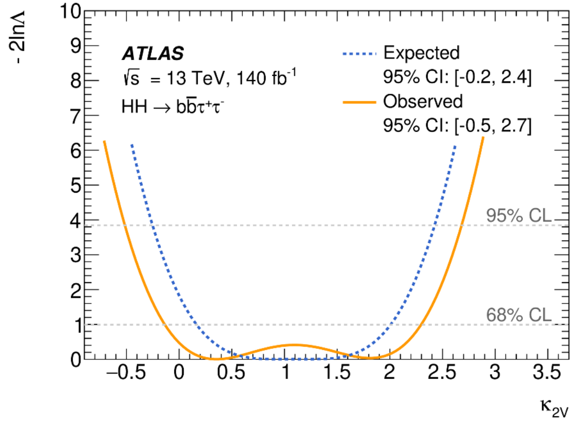


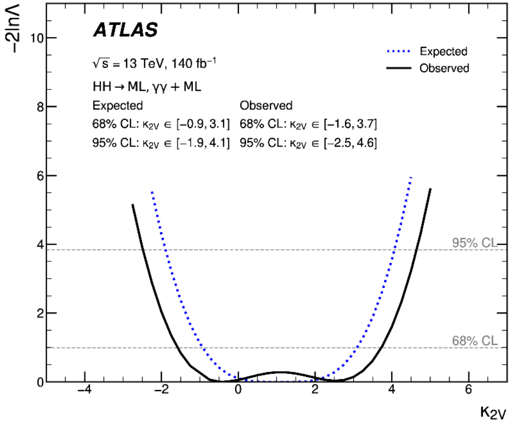


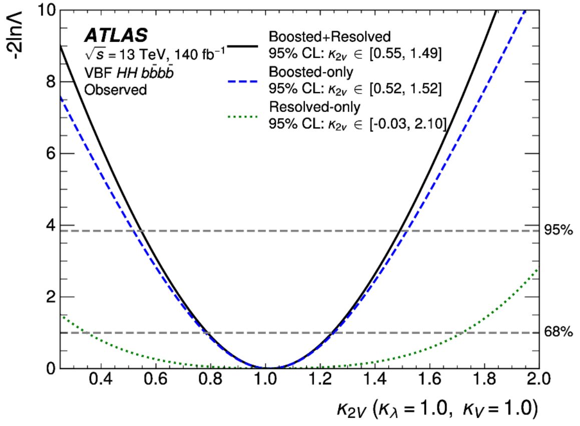


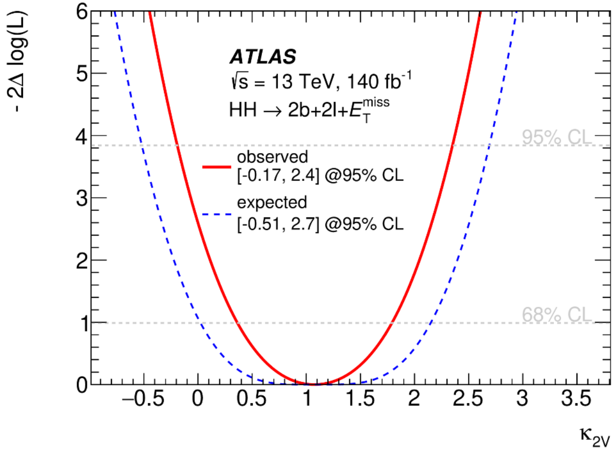
VVHH coupling by channel



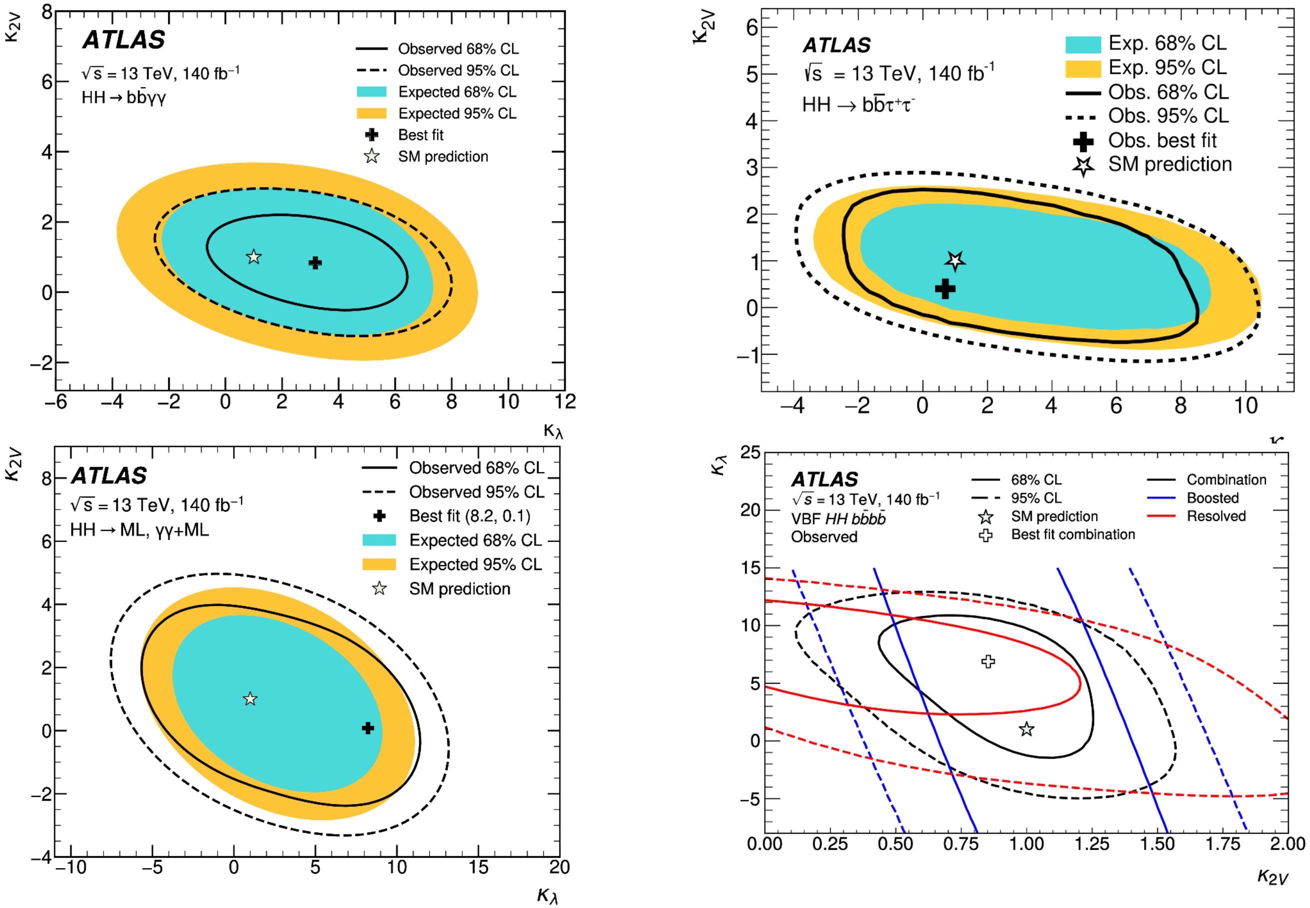




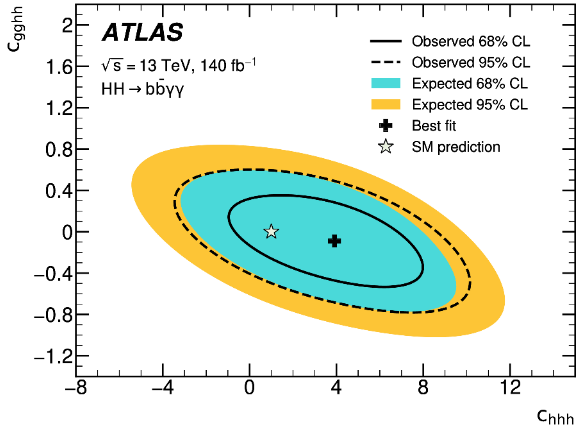


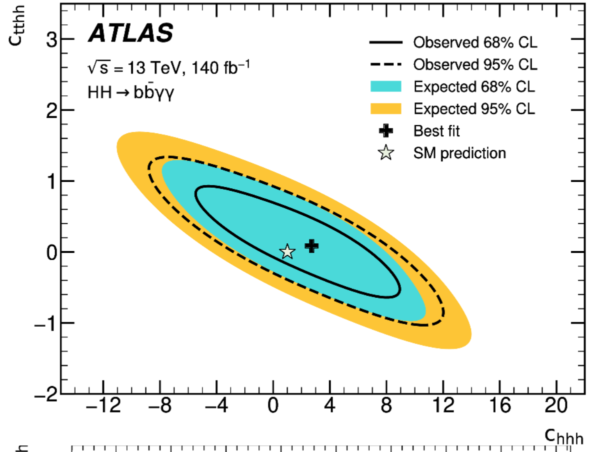


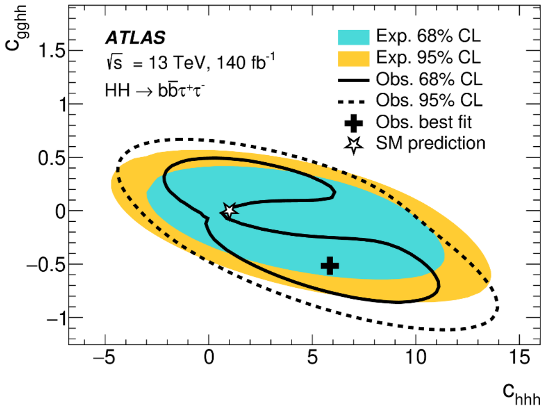
2D coupling constraints by channel

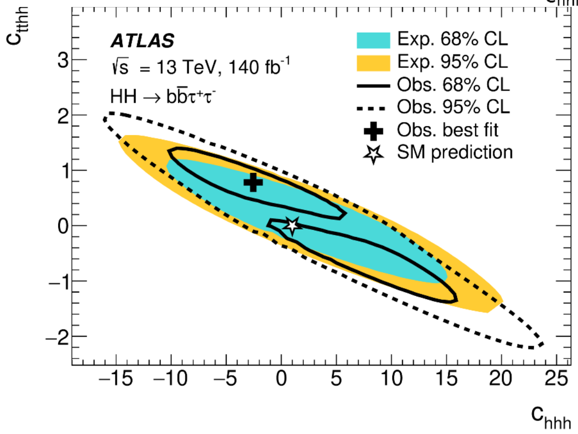


HEFT parameters by channel









HEFT Benchmark results by channel

Benchmark Model	c_{HHH}	c_{ttH}	c_{ggH}	c_{ggHH}	c_{ttHH}
SM	1	1	0	0	0
BM1	3.94	0.94	1/2	1/3	−1/3
BM2	6.84	0.61	0.0	−1/3	1/3
BM3	2.21	1.05	1/2	1/2	−1/3
BM4	2.79	0.61	−1/2	1/6	1/3
BM5	3.95	1.17	1/6	−1/2	−1/3
BM6	5.68	0.83	−1/2	1/3	1/3
BM7	−0.10	0.94	1/6	−1/6	1