Searches for DiHiggs production in ATLAS

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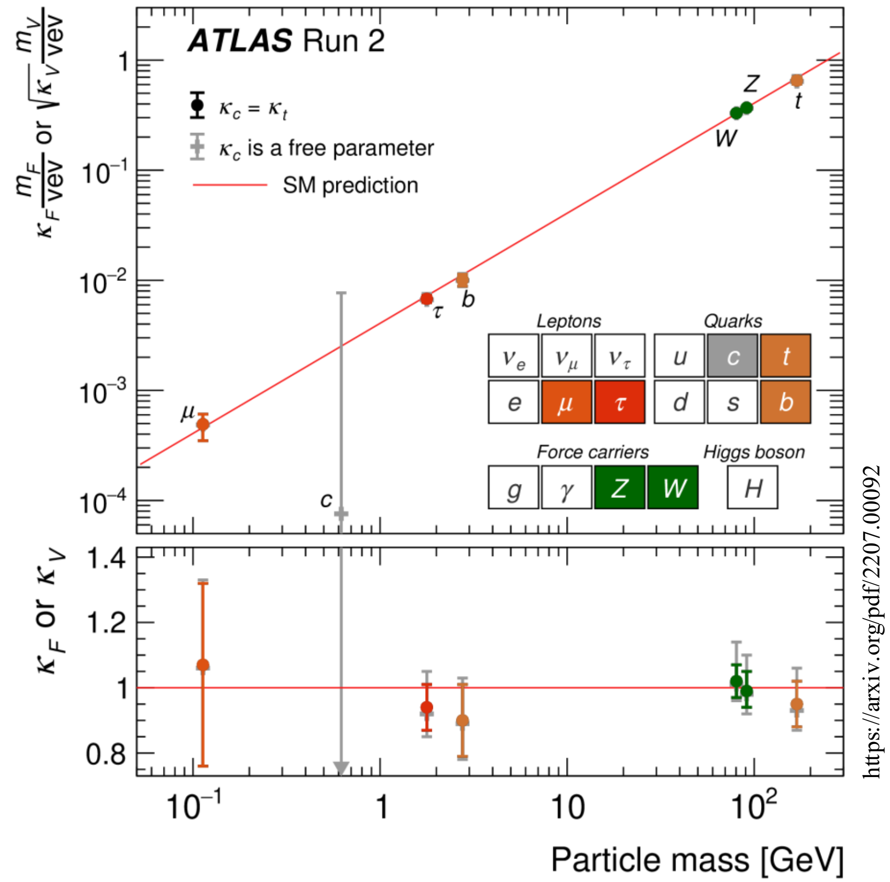
A Brief History of the Higgs Boson

Significant progress in our understanding of the Higgs boson since its discovery in 2012.

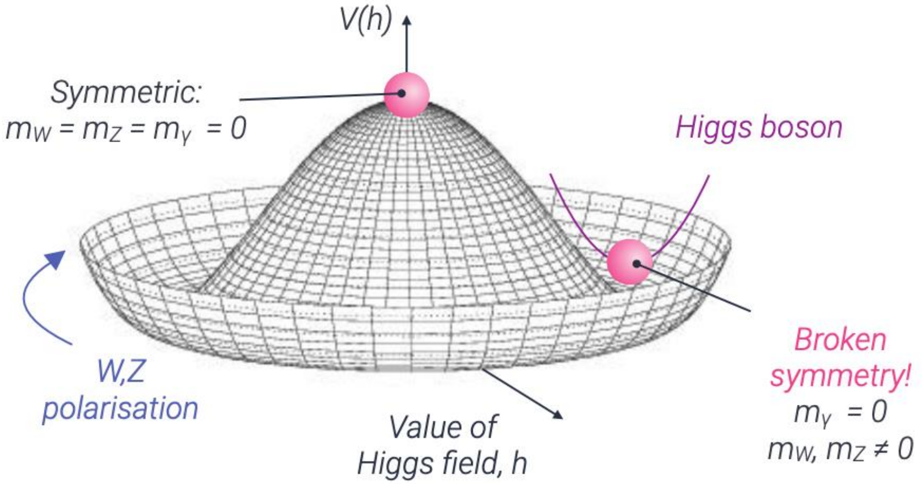
All the main production modes established: ggF, VBF, VH, and ttH+tH

François Englert and **Peter W. Higgs**



But we still know very little about the shape of the Higgs potential.

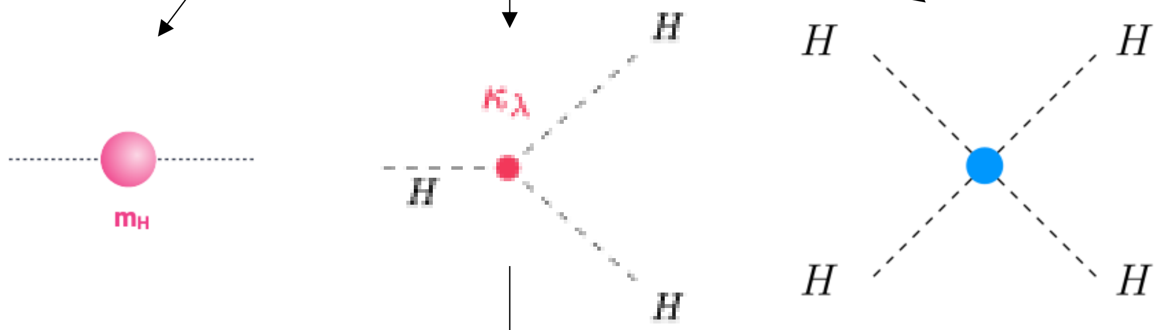
Electroweak Symmetry Breaking



$$V(h) \simeq \lambda \upsilon^2 h^2 + \lambda \upsilon h^3 + \frac{1}{4}\lambda h^4 \ldots$$

$$m_H^2 = 2\lambda\upsilon^2$$

$$V(h) \simeq \frac{1}{2} m_H^2 h^2 + {\color{red}\lambda \upsilon h^3} + {\color{blue}\frac{1}{4}\lambda h^4} \ldots$$



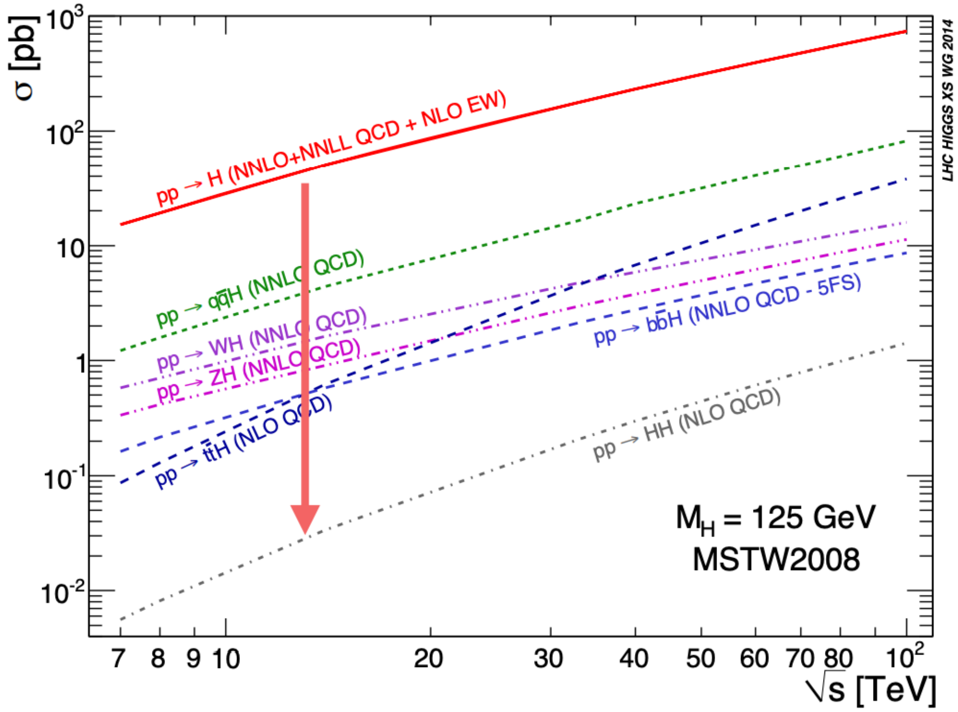
Directly measure λ_{HHH} via HH production

Strength of λ_{HHH} relative to SM prediction $\kappa_\lambda = \lambda_{HHH} / \lambda_{SM}$

Probing the Higgs self-coupling is key to understanding the shape of the potential

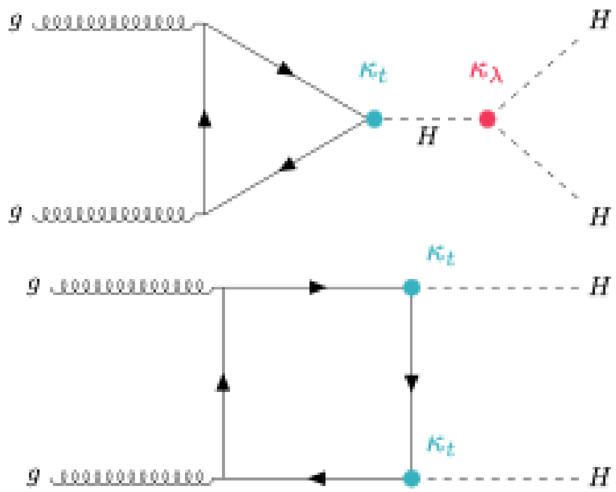
HH production at LHC

Cross-section ~ 1000x smaller than the single Higgs production



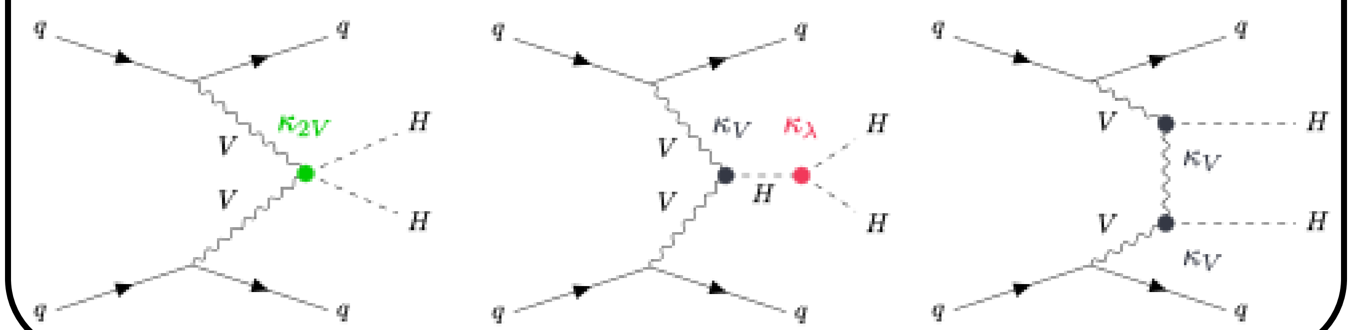
Gluon-gluon fusion

$$\sigma^{\mathrm{SM}}_{\mathrm{ggF}}(HH) = 31.05^{+6\%}_{-23\%}\,(\mathrm{scale} + m_{\mathrm{top}}) \pm 3.0\,\%\,(\mathrm{PDF} + \alpha_s)\ \mathrm{fb}$$

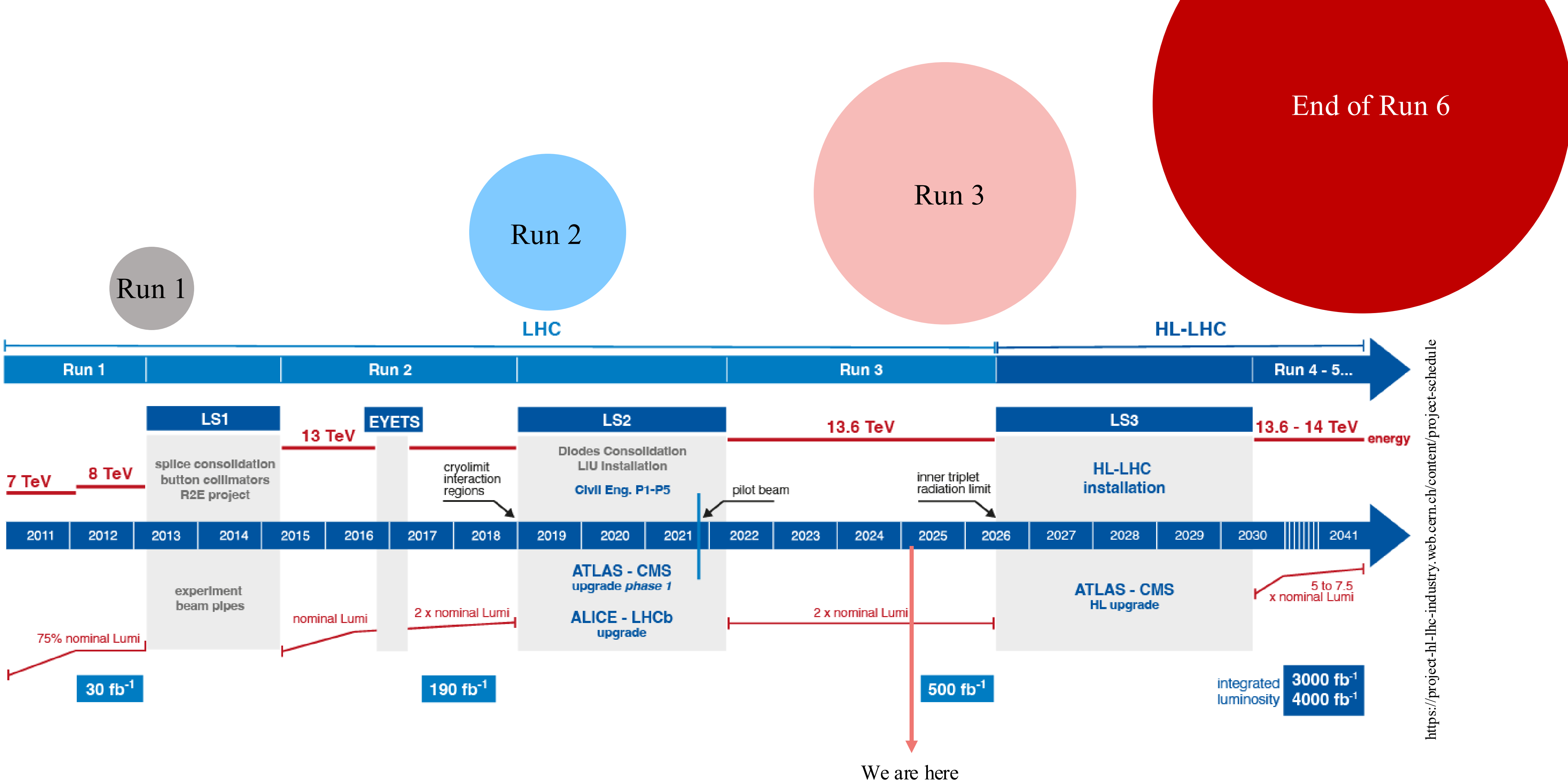


Vector Boson fusion

$$\sigma^{\mathrm{SM}}_{\mathrm{VBF}}(HH) = 1.73^{+0.03\%}_{-0.04\%}\,(\mathrm{scale})\ \pm 2.1\,\%\,(\mathrm{PDF} + \alpha_s)\ \mathrm{fb}$$



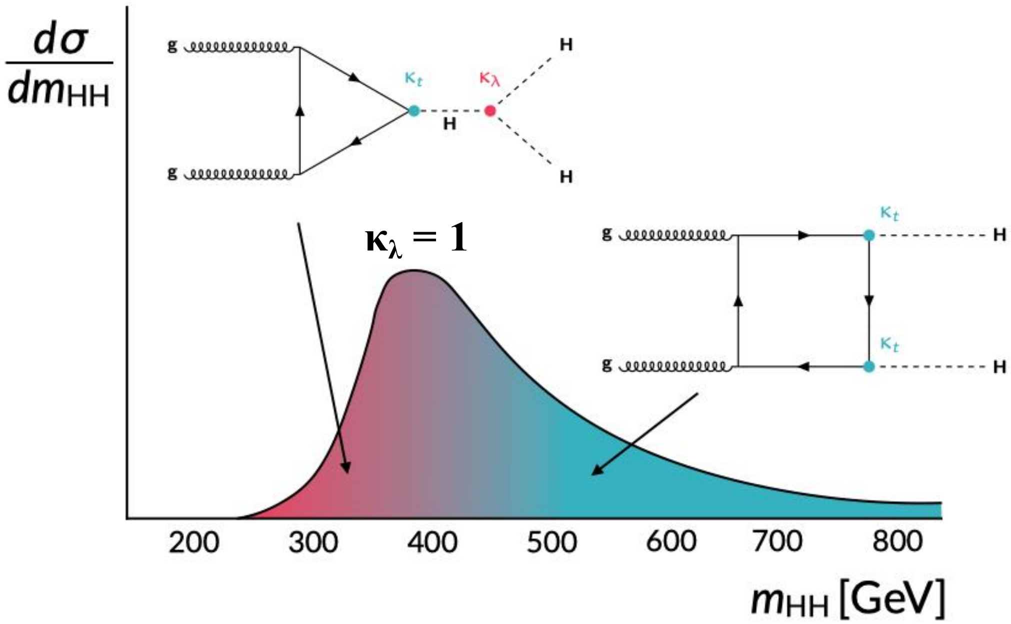
HH at the HL-LHC



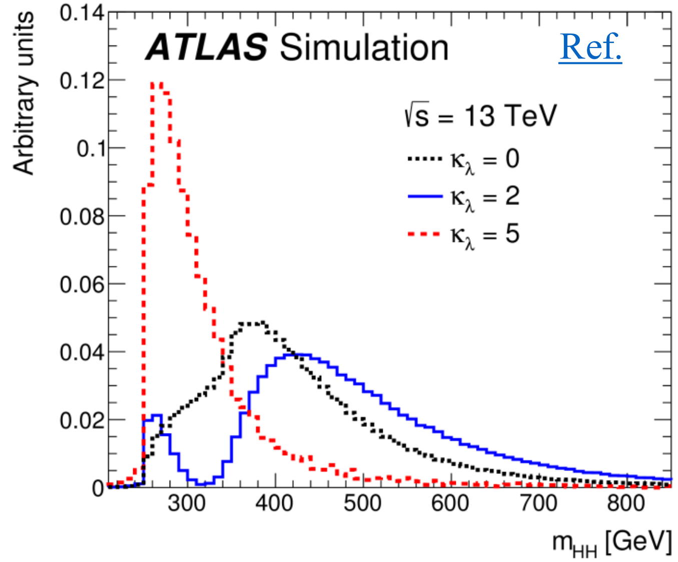
σ_{HH} increases with $\sqrt{s}$
13 TeV → 13.6 TeV: +11%
13.6 TeV → 14 TeV: + 7 %

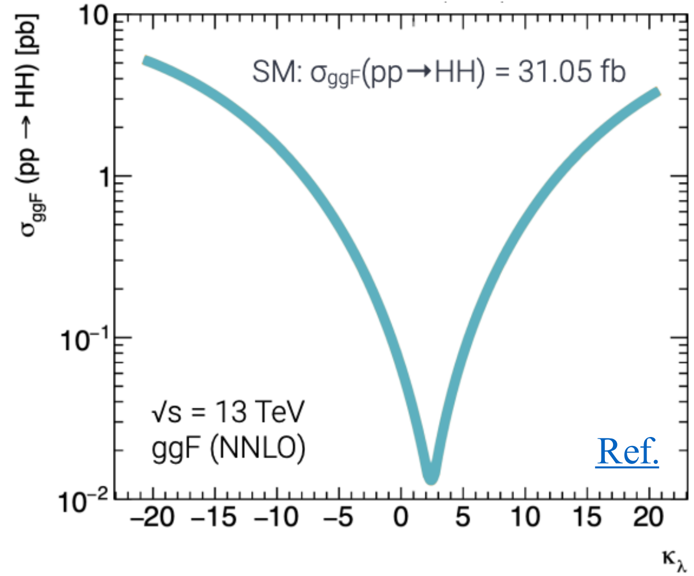
The challenges

Destructive interference between the triangle and box diagrams

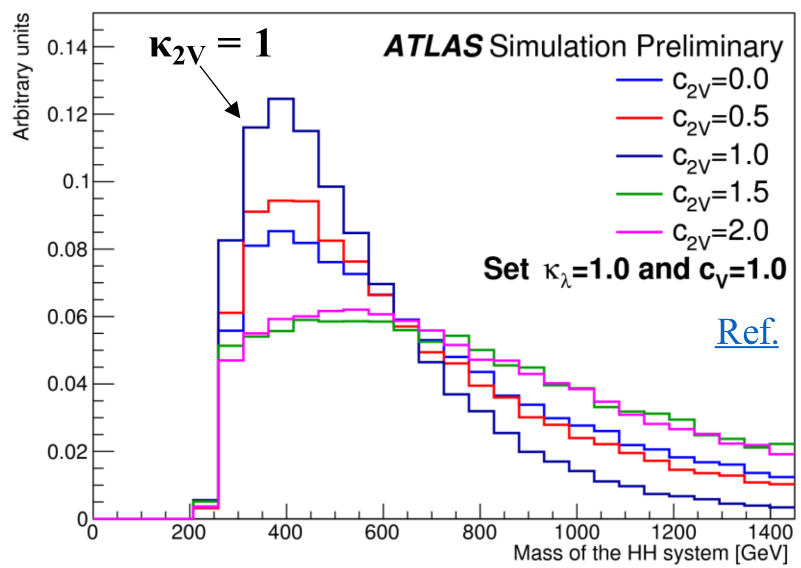


m_{HH} shape strongly depends on κ
$\kappa_\lambda \sim 2.4$ max. destruction at $m_{HH} \sim 350$ GeV





- Soft kinematics for large $|\kappa_\lambda|$
    - decay production difficult to detect
- Hard kinematics for large $|\kappa_{2V}|$



Excellent experimental performance and advanced analysis techniques are crucial

How do we search for HH production

No single "golden channel"

Large fractions

	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%

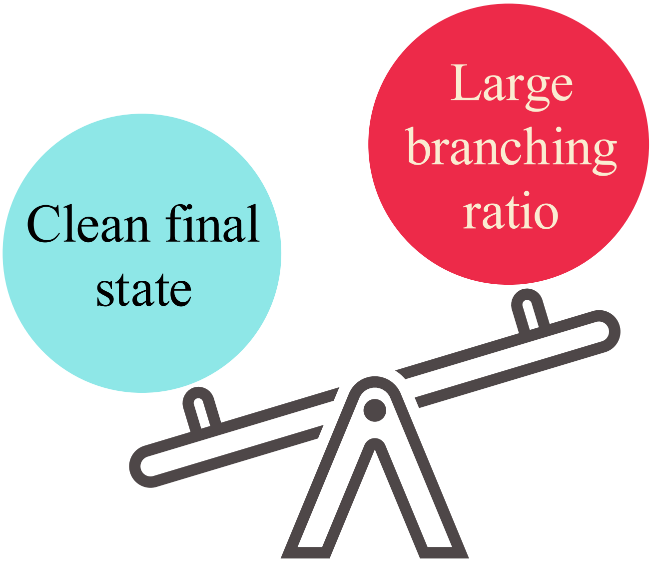
Clean states

bbbb (34%):
- The most abundant final state
- Challenging multi-jet backgrounds

bbττ (7.3%): Happy medium

bbγγ (0.26%):
- Low decay fraction
- Excellent $m_{\gamma\gamma}$ resolution

All channels have trade-offs between branching ratios and backgrounds.



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Clean states

Multilepton (6.5%):

- Targeting all the other final states
- In total, 9 sub-channels

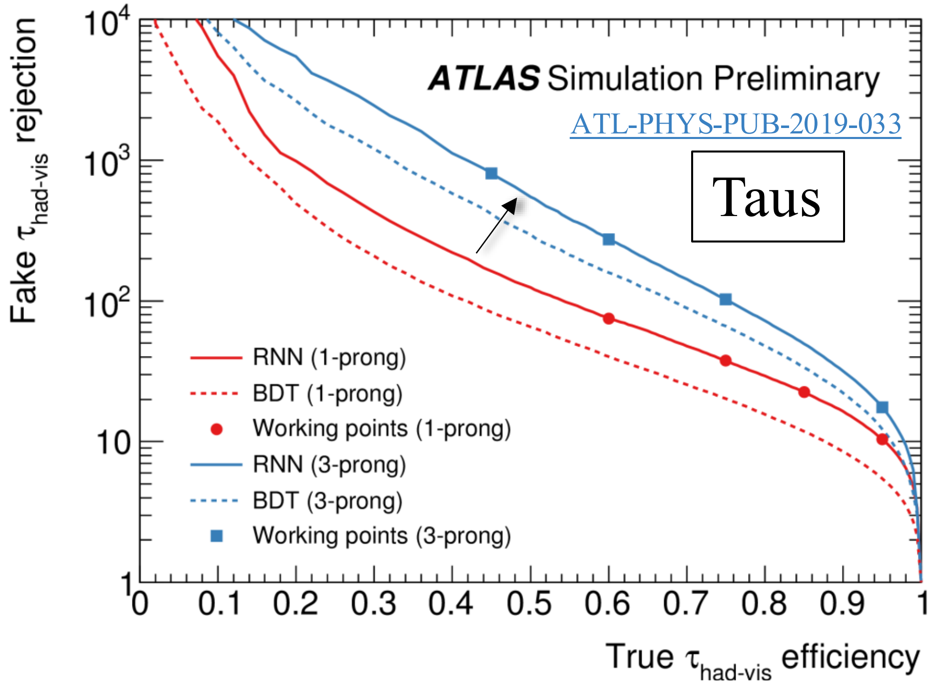
bbℓℓ (2.9%)

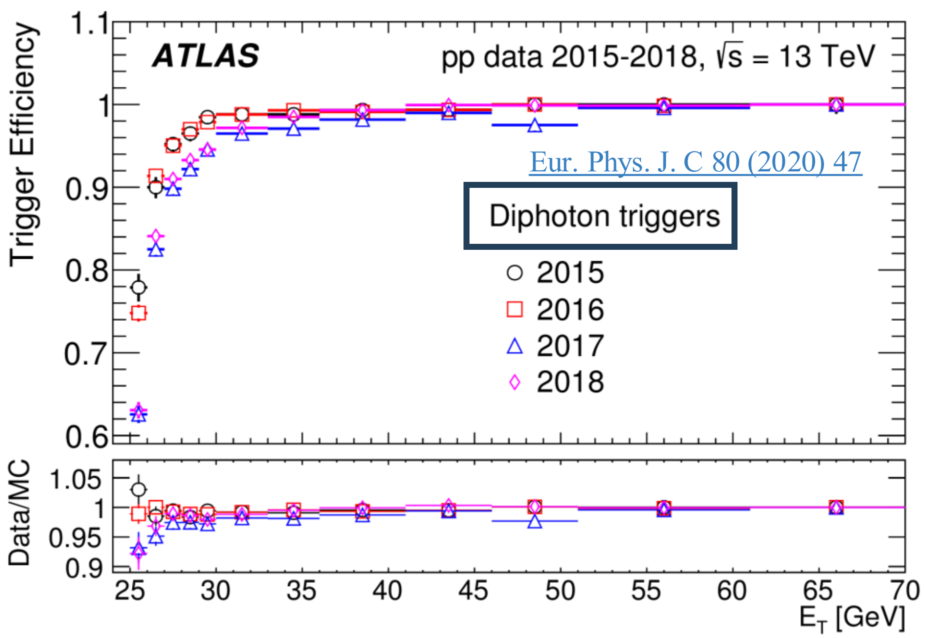
Combining all the channels:

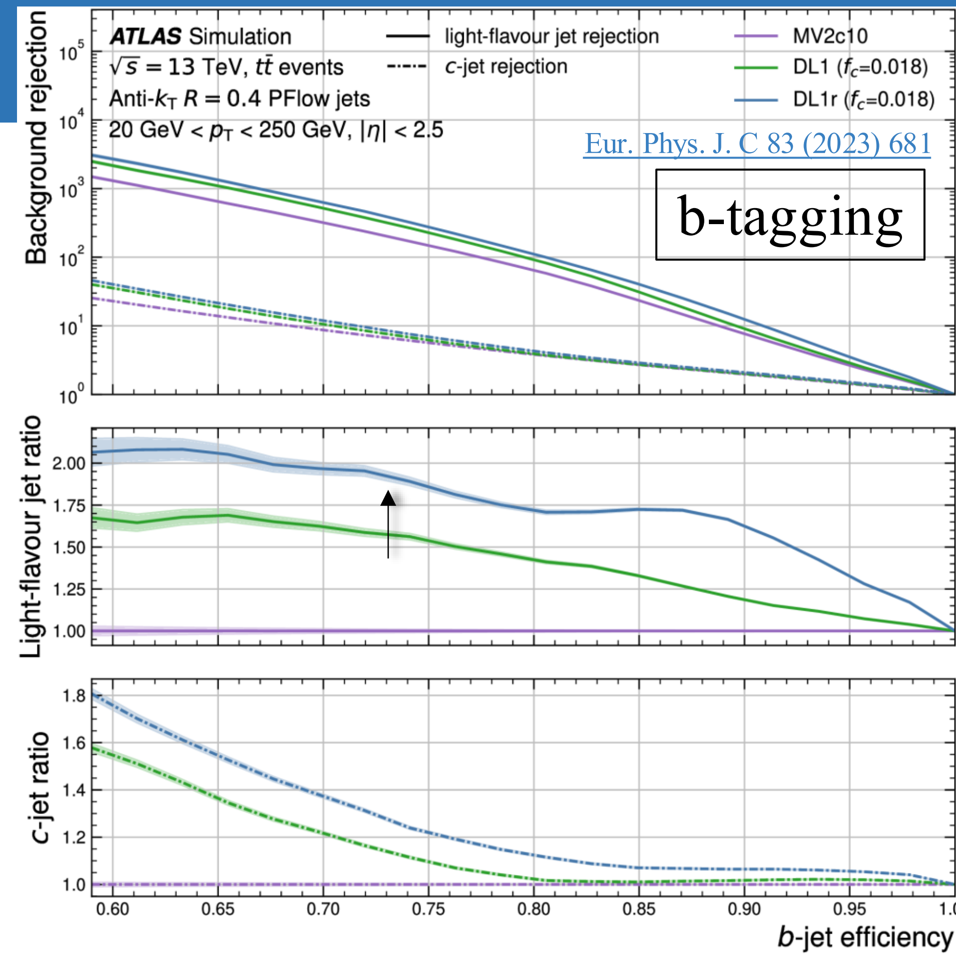
- Covering > 50% of HH decay

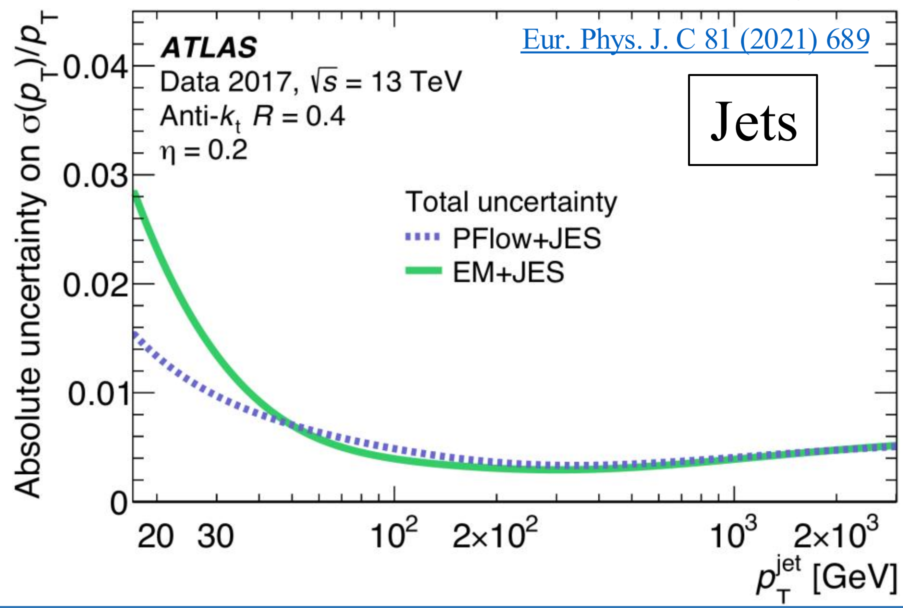
Object reconstruction highlights

All HH analyses are using same objects.

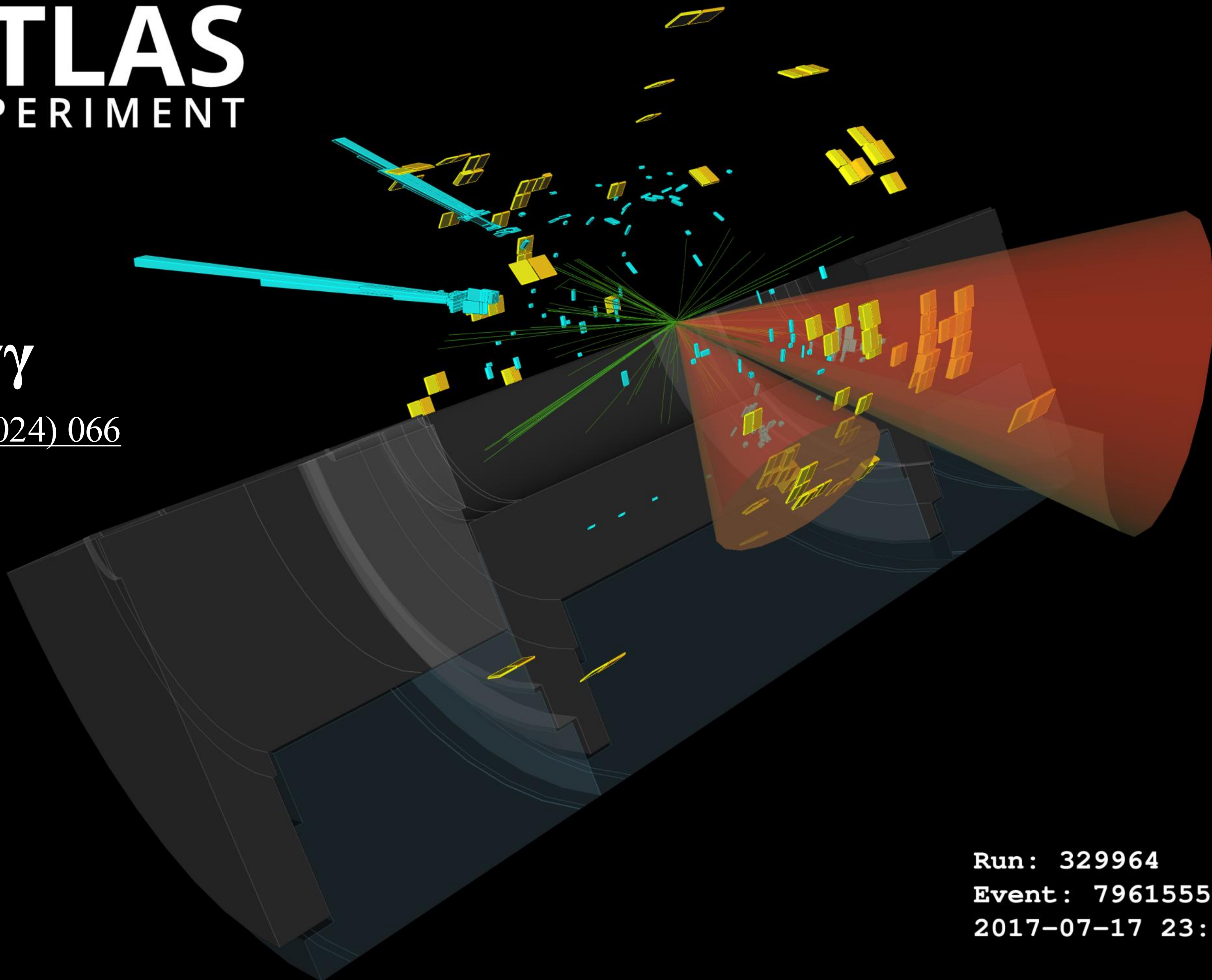








ATLAS EXPERIMENT



bbγγ

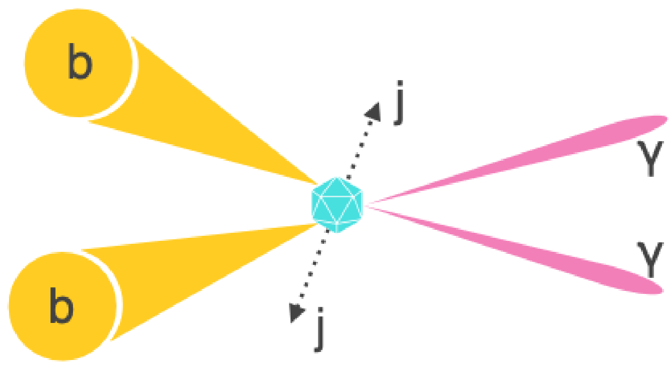
JHEP 01 (2024) 066

Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST

$bb\gamma\gamma$ selection and categorization

☆ Diphoton triggers
☆ 2 b-jets and 2 photon
☆ $105 < m_{\gamma\gamma} < 160$ GeV

Supress ttH and tt
☆ Light lepton veto
☆ < 6 central jets



$m_{b\bar{b}\gamma\gamma} + (125 - m_{b\bar{b}}) + (125 - m_{\gamma\gamma})$ GeV

> 350 GeV

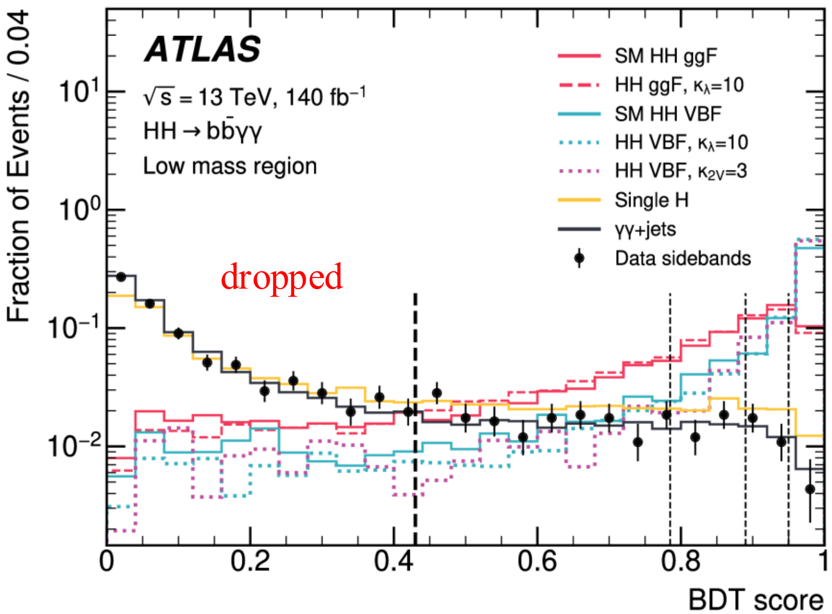
High mass BDT
3 categories defined by BDT score

≤ 350 GeV

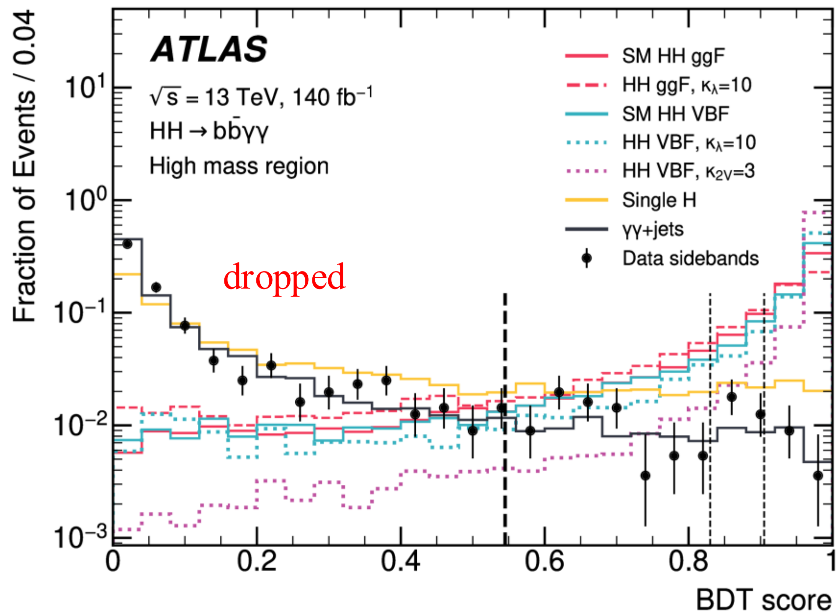
Low mass BDT
4 categories defined by BDT score

Fit 7 $m_{\gamma\gamma}$ spectra

BDT training against background: single H and $\gamma\gamma$-continuum



optimise for large value κ_λ (soft spectrum)



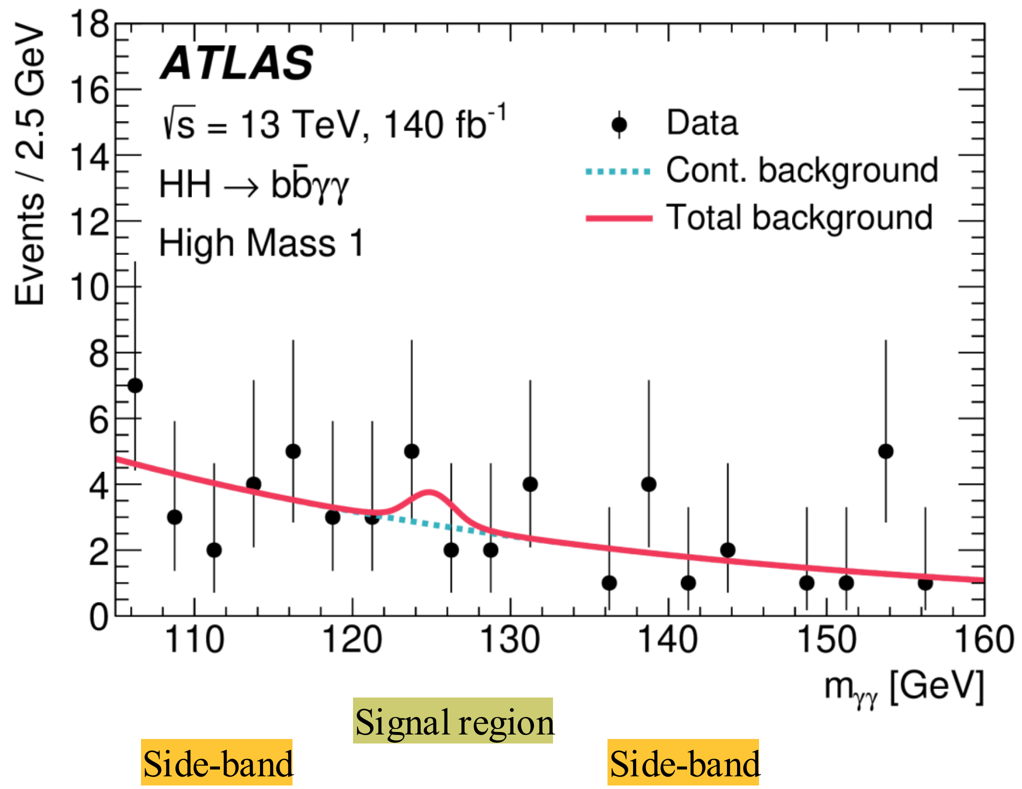
optimise for SM value κ_λ and κ_{2V} (hard spectrum)

bbγγ results

HH and single H
Modelled by double-sided Crystal Ball function. Parameters estimated from MC

γγ-continuum
Modelled using exponential function. Parameters derived from data sideband

Dominant uncertainties:
- Data statistics
- Theory uncertainties on HH xsec

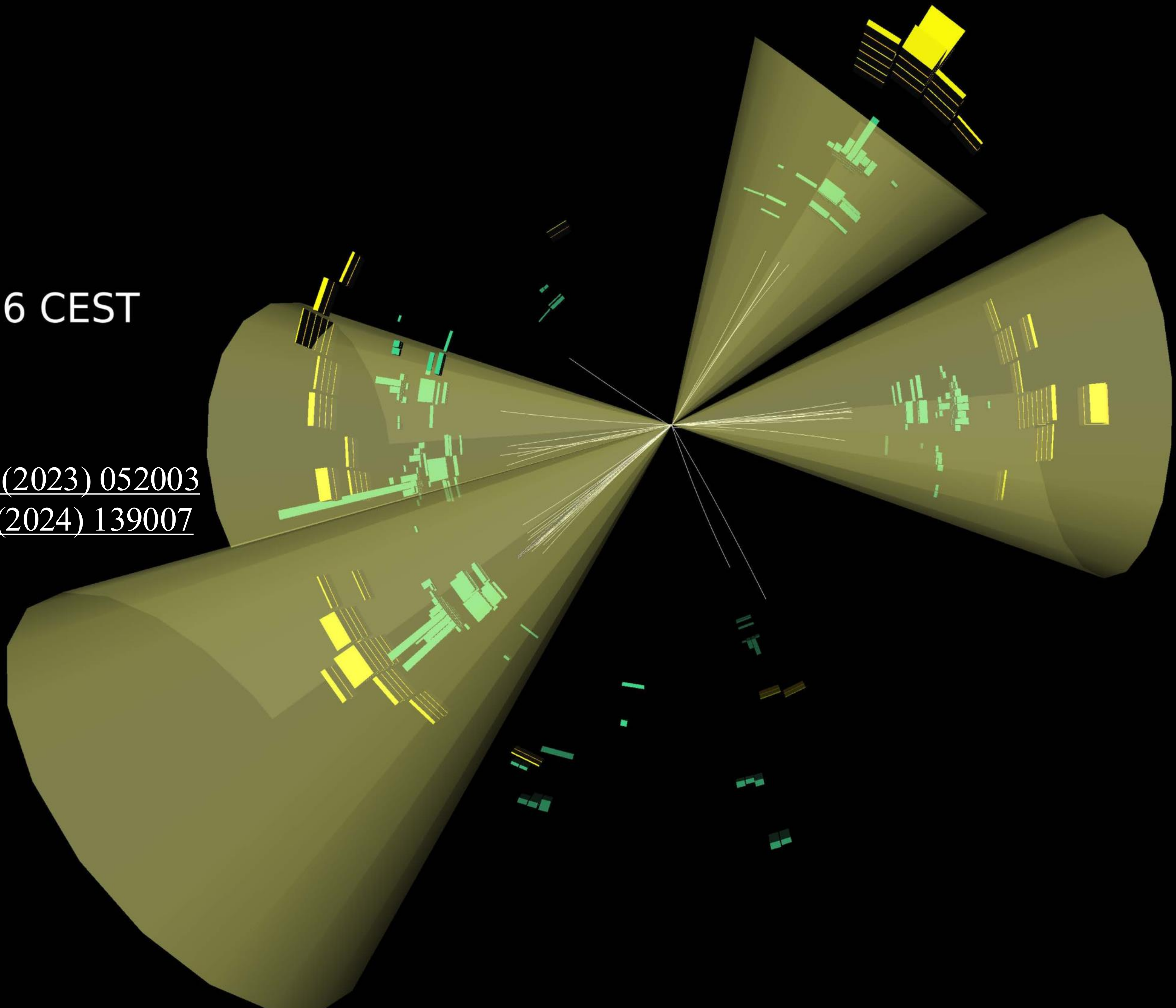


	High Mass 1	High Mass 2	High Mass 3	Low Mass 1	Low Mass 2	Low Mass 3	Low Mass 4
Total background	$12.8^{+1.6}_{-1.6}$	$3.7^{+0.9}_{-0.8}$	$3.4^{+0.8}_{-0.8}$	$38.9^{+2.9}_{-2.9}$	$11.3^{+1.5}_{-1.5}$	$4.7^{+0.9}_{-1.0}$	$1.3^{+0.5}_{-0.5}$
Data	12	4	1	29	8	5	4

95% CL limit $\mu_{HH} < 4.0$ (5.0 exp)

ATLAS EXPERIMENT

Run: 350013
Event: 1556168518
2018-05-11 01:39:26 CEST



bbbb

Resolved: Phys. Rev. D 108 (2023) 052003
Boosted: Phys. Lett. B 858 (2024) 139007

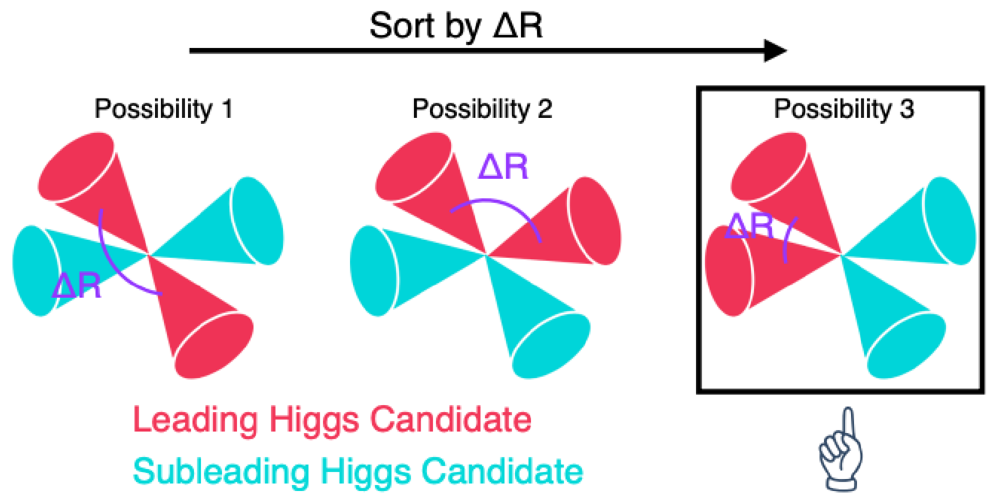
bbbb selection and results

Resolved

- ☆ b-jet trigger
- ☆ ≥ 4 b-jets, pT > 40 GeV
- ☆ Veto top quark

$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\text{ GeV}}{0.1\, m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\text{ GeV}}{0.1\, m_{H2}}\right)^2}$$

ggF & VBF categories based on $|\Delta\eta_{HH}|$ & X_{HH}



Rui Zhang LHC seminar

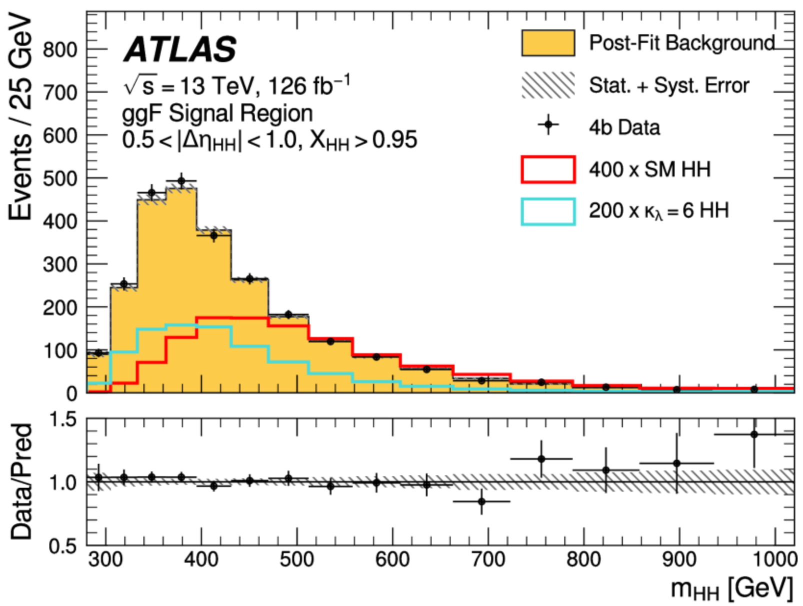
- Minimal ΔR_{jj} in leading Higgs (H1)
- No mass information used to avoid sculpting the H1-H2 mass plane

Major background:

- ❖ QCD multiJet estimated using NN transfer factor

Dominant uncertainties:

- ❖ Background estimation
- ❖ Signal cross section calculation



95% CL limit μ_{HH} < 5.4 (8.1 exp)

ATLAS EXPERIMENT

bbττ

Phys. Rev. D 110 (2024) 032012

Run: 339535
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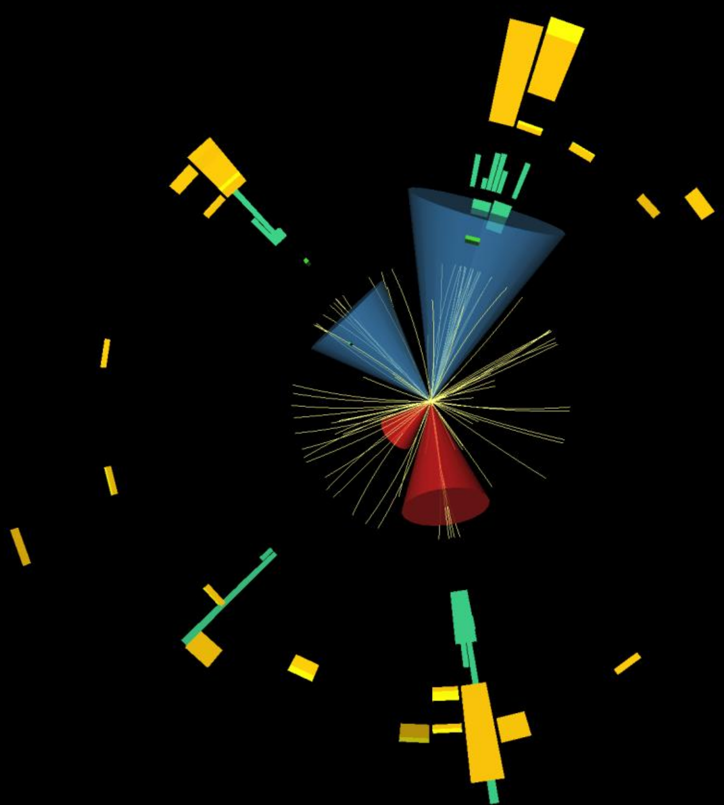
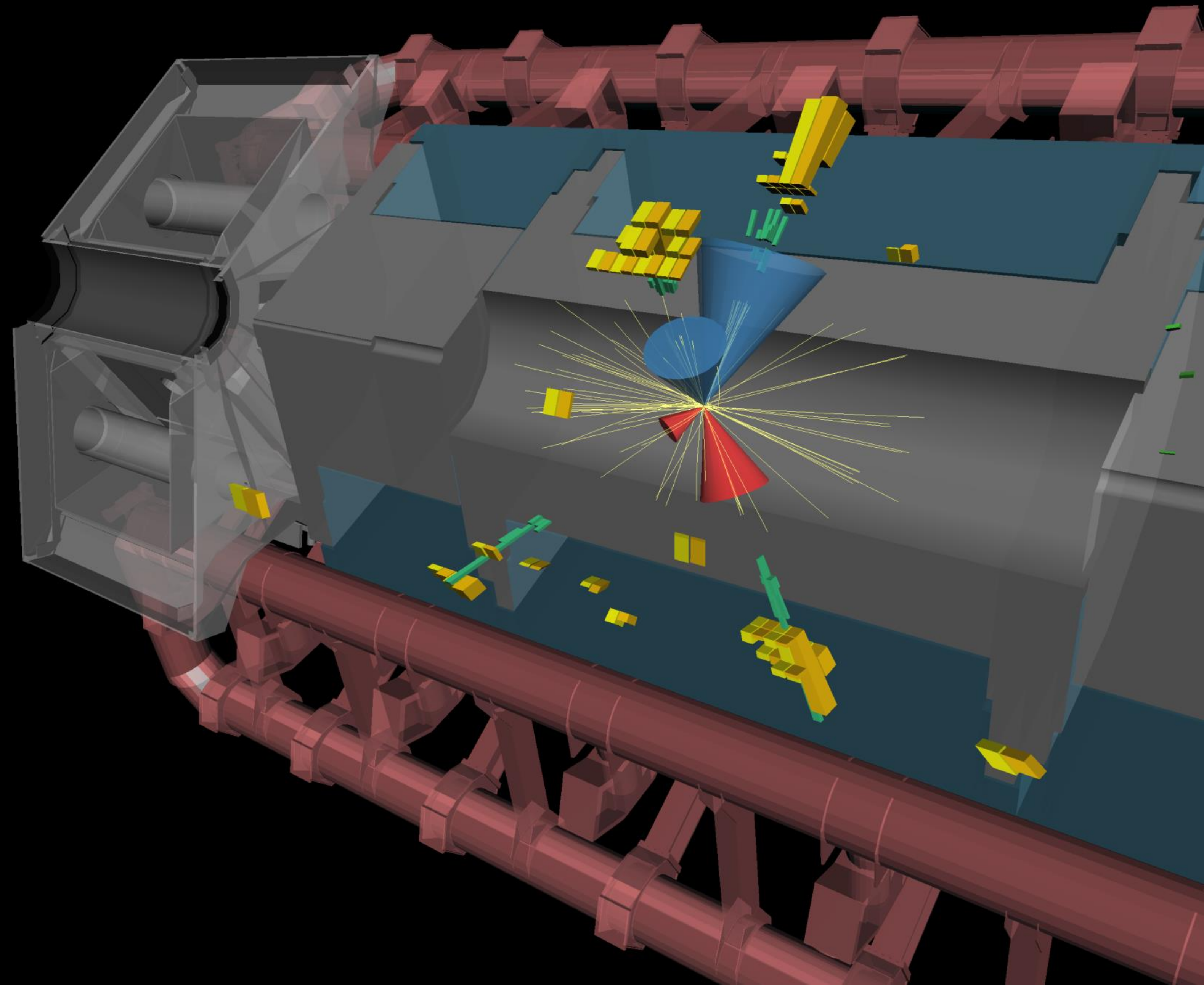
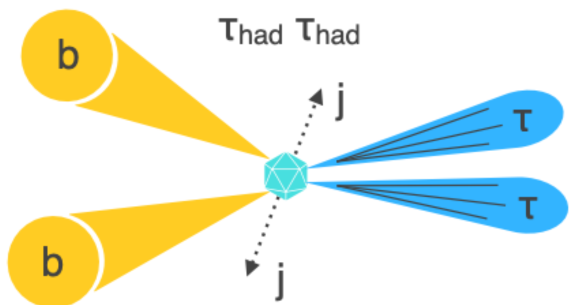


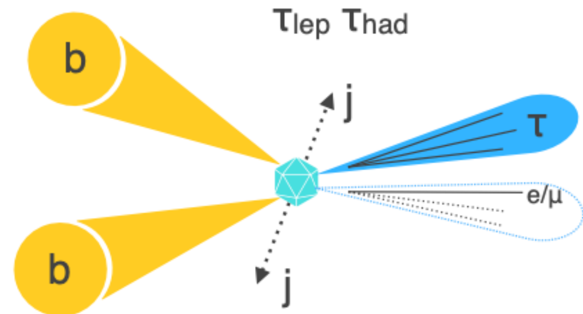


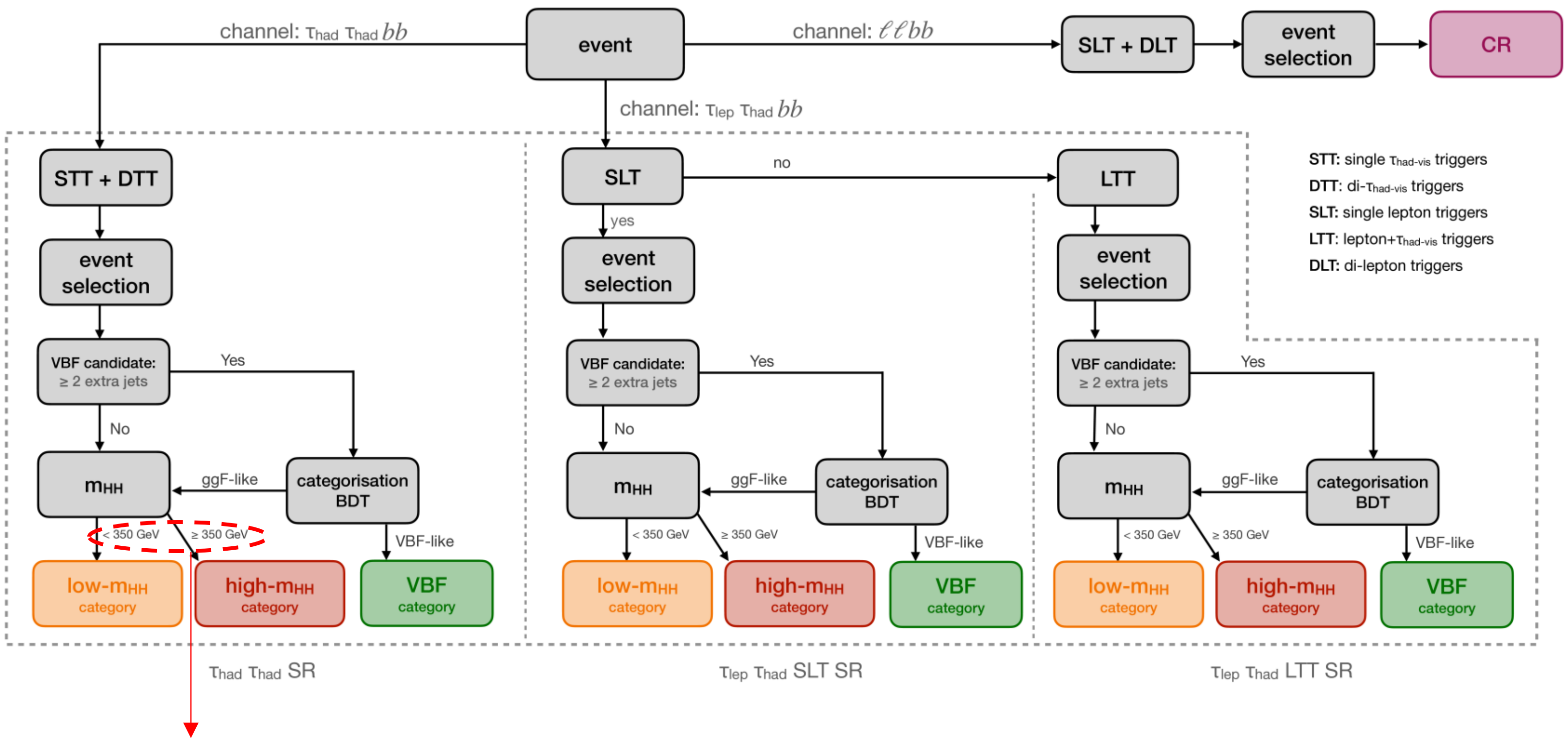
bb$\tau\tau$ selection and categorization

- ☆ Tau or leptons triggers
- ☆ 2 τ_{had} or 1 τ_{had} + 1 e/μ
- ☆ 2 b-jets, $m_{\tau\tau}$ > 60 GeV

3 types of triggers
9 signal regions







m_{HH} < 350 GeV – low-m_{HH}
$m_{HH} \geq$ 350 GeV – high-m_{HH}

Background sources

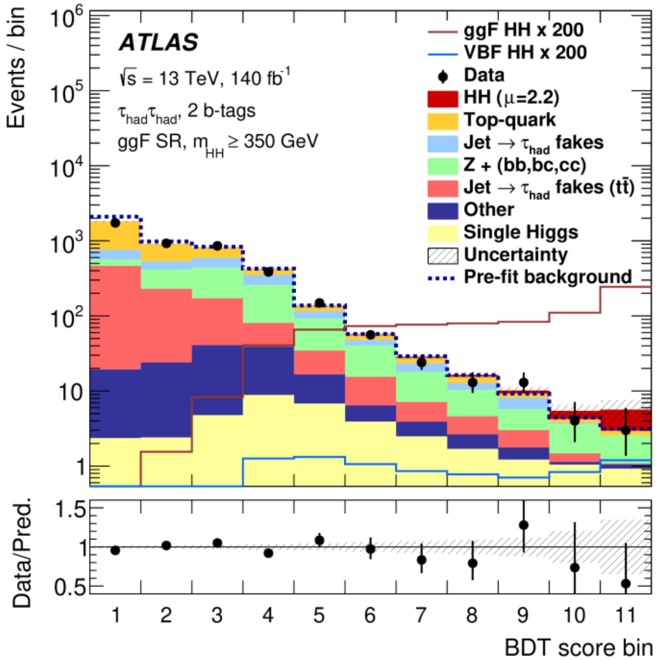
Top quark
Shape for MC, normalization from fit

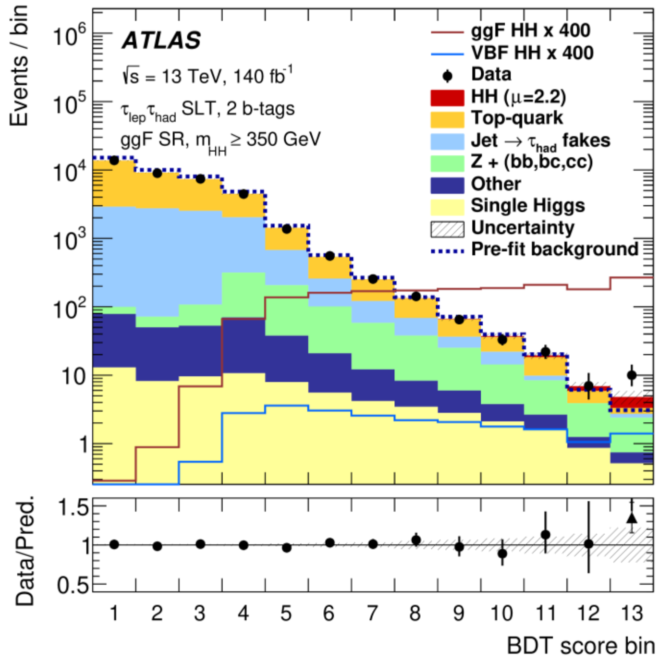
$Z\to\tau\tau$ + heavy flavor
Shape for MC, normalization from $Z\to ee/\mu\mu$ + HF control region

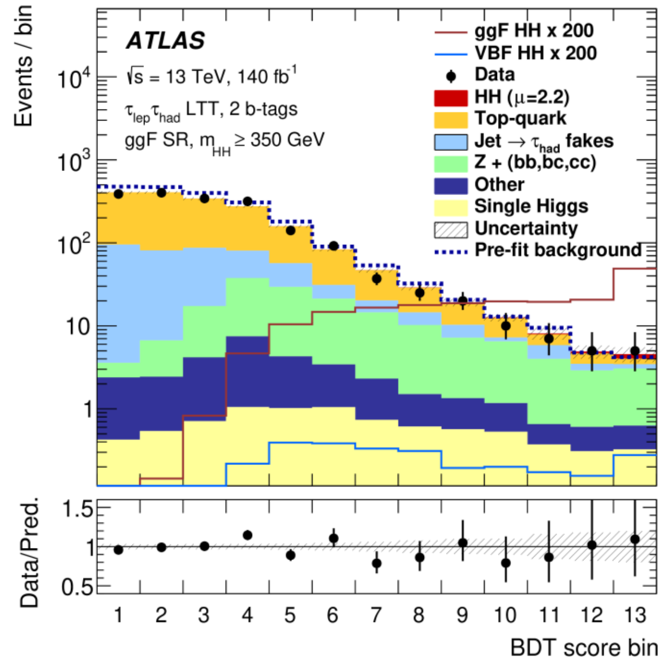
Fake τ_{had}
Data-driven fake factor method

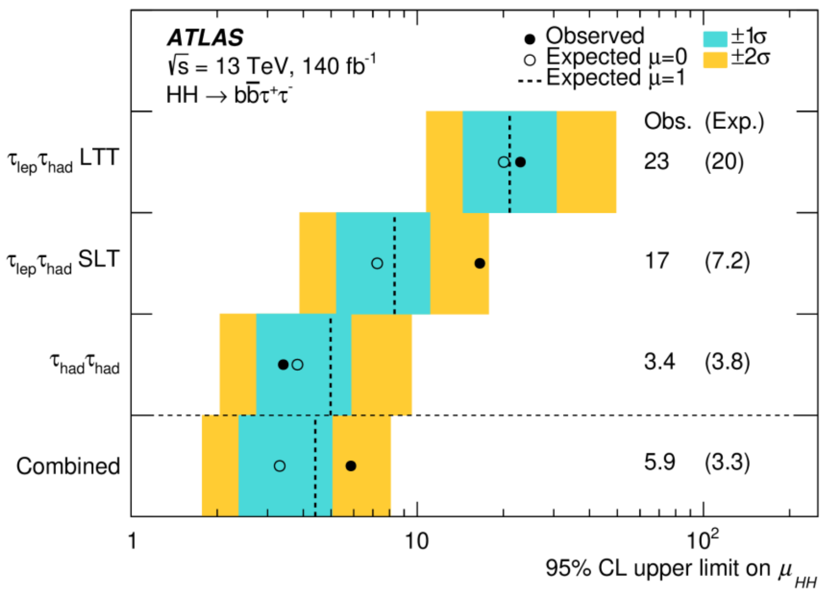
bbττ results

- BDT is trained in each signal region – 9 BDTs









Dominant uncertainties

- Data statistics
- Modelling uncertainties on top-quark and single H

95% CL limit μ_{HH} < 5.9 (3.3 exp)
Leading channel in SM HH search

$bb\ell\ell + E_T$miss

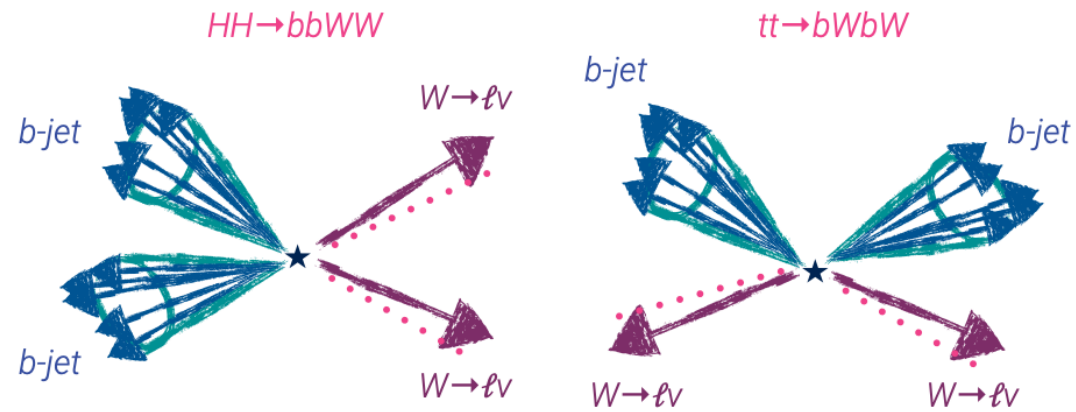
JHEP 02 (2024) 037

bbℓℓ + $E_T$miss selection and results

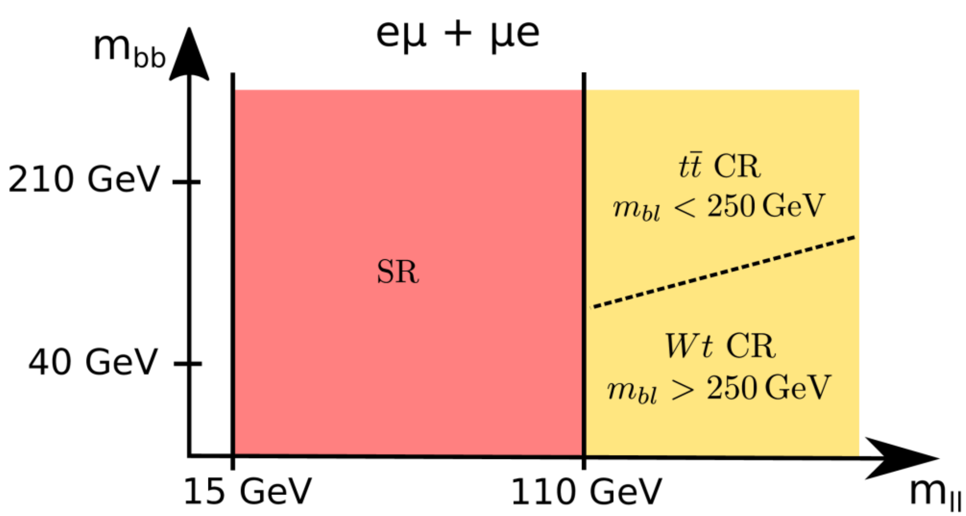
	bb
bb	34%
WW	25%
ττ	7.3%
ZZ	3.1%
γγ	0.26%

- ☆ Single or dilepton triggers
- ☆ 2 light lepton (e/μ), opposite charge
- ☆ Same or different flavours
- ☆ 2 b-jets

Same final state as dileptonic tt background



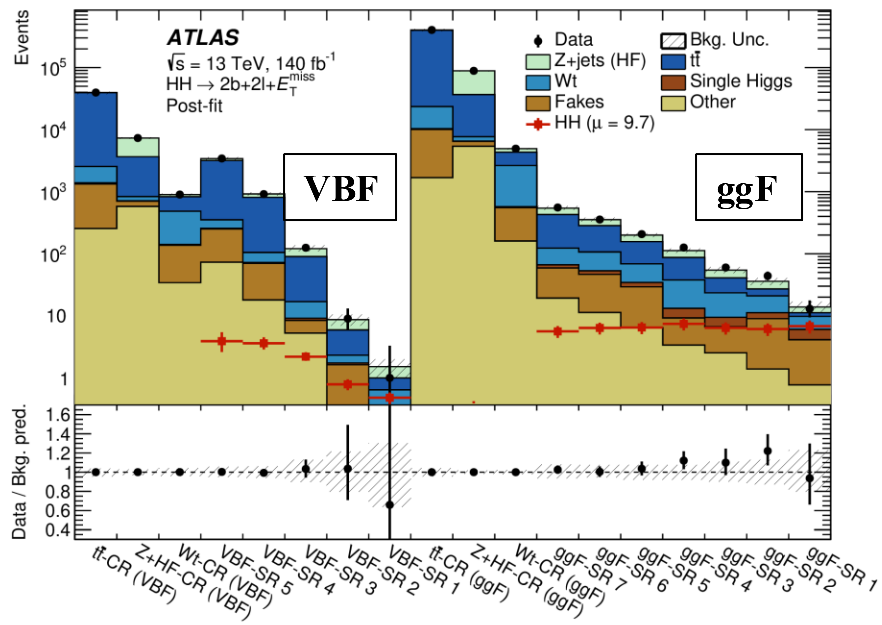
MVA training against backgrounds



≥ 2 VBF jets with pT > 30 GeV,
max($\Delta\eta_{jj}$) > 4, max(m_{jj}) > 600 GeV

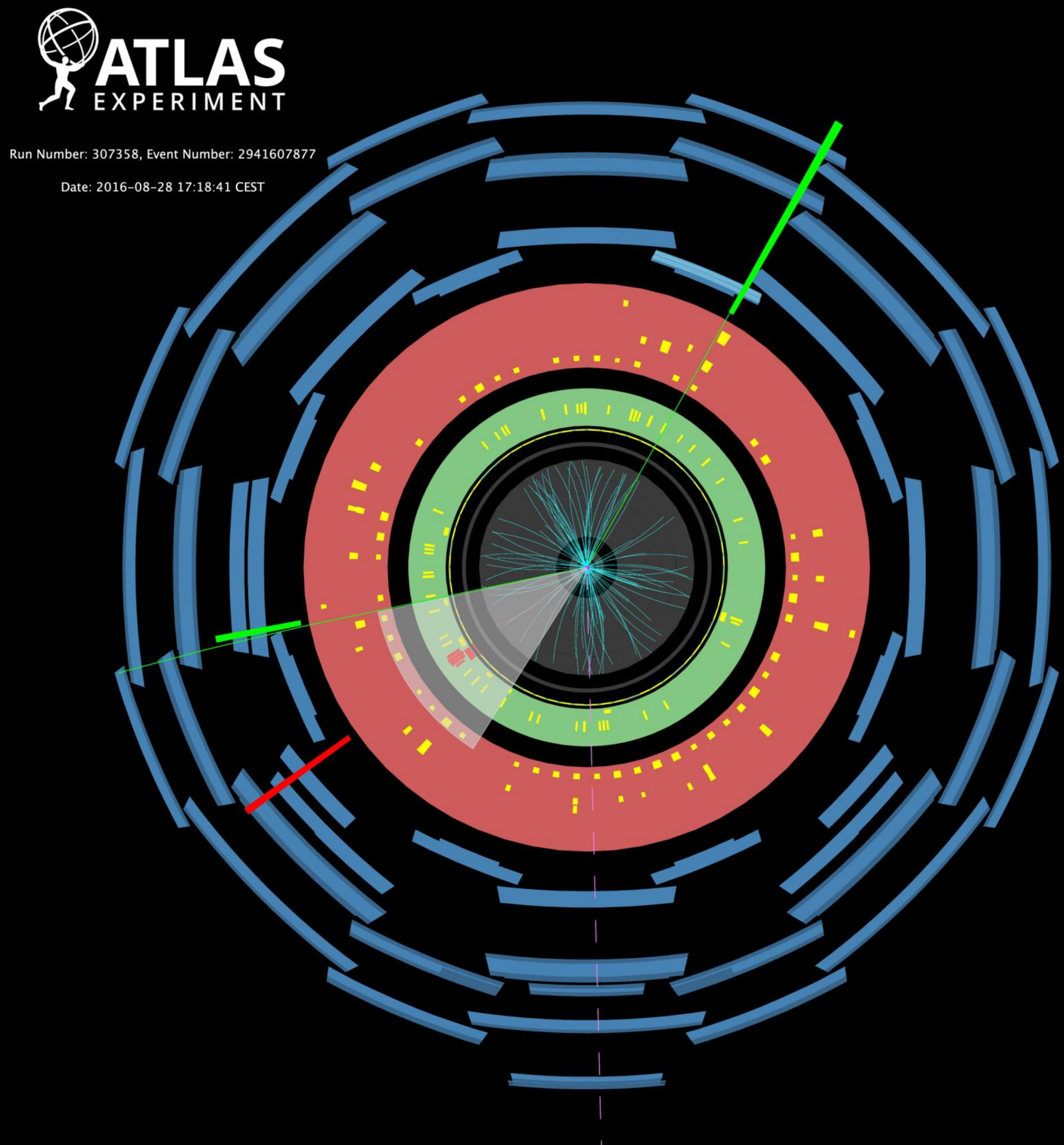
tt background

Shape for MC, normalization from control regions



95% CL limit μ_{HH} < 9.7 (16.2 exp)

Multilepton
JHEP 08 (2024) 164



Multilepton

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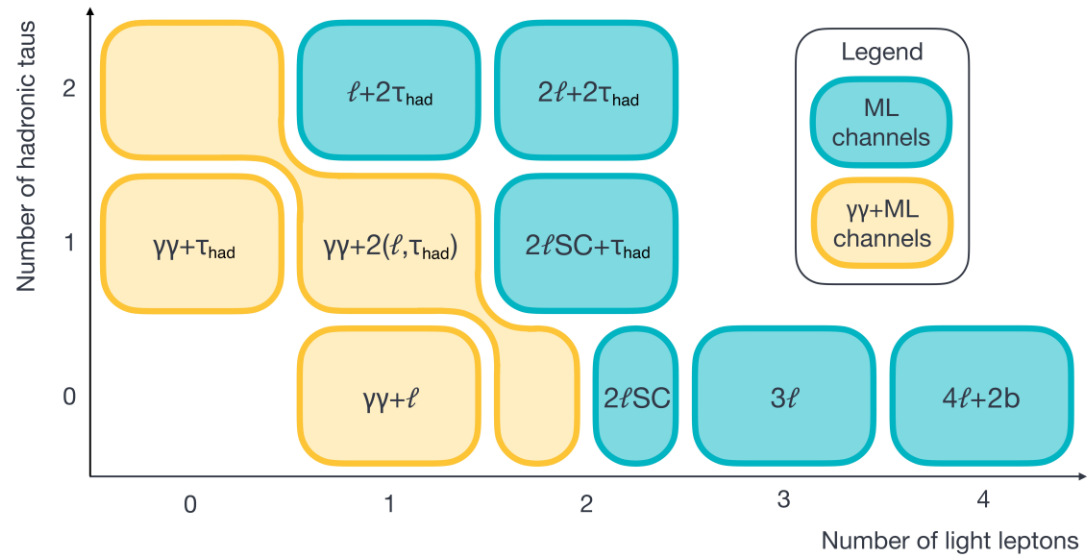
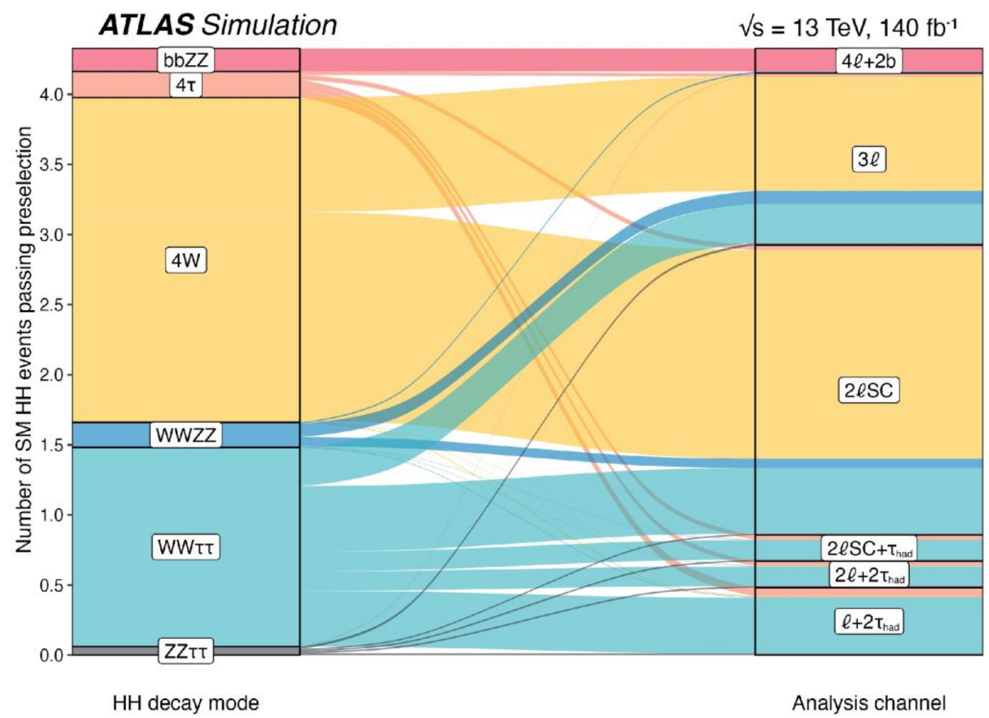
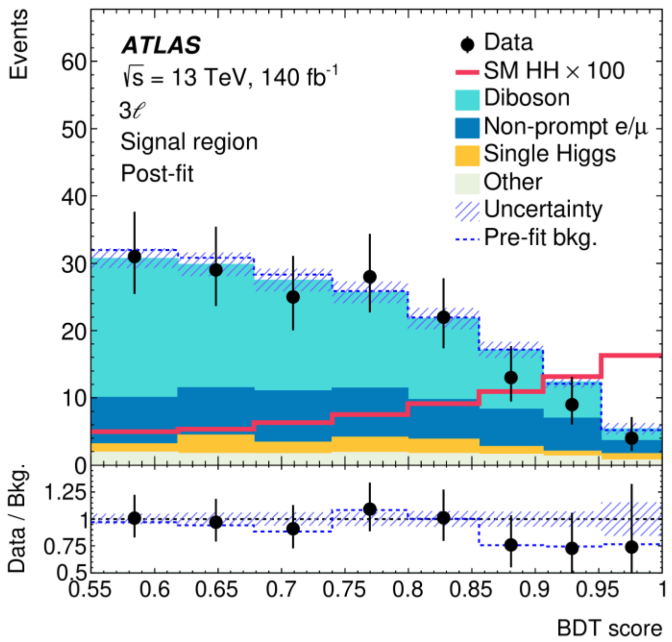
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

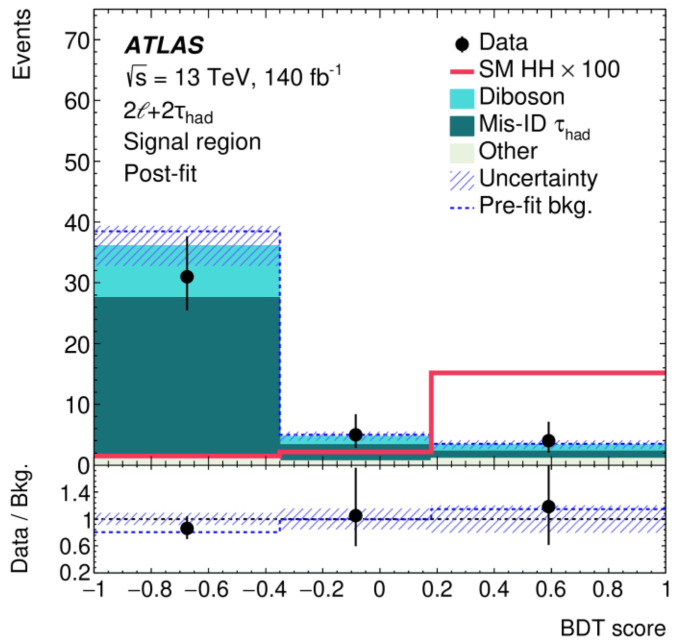
- ~6.5% of HH events decay to final states where the HH system is not fully reconstructible.
- Categorise events based on number of light leptons, hadronic taus, and photon
- Single or dilepton triggers

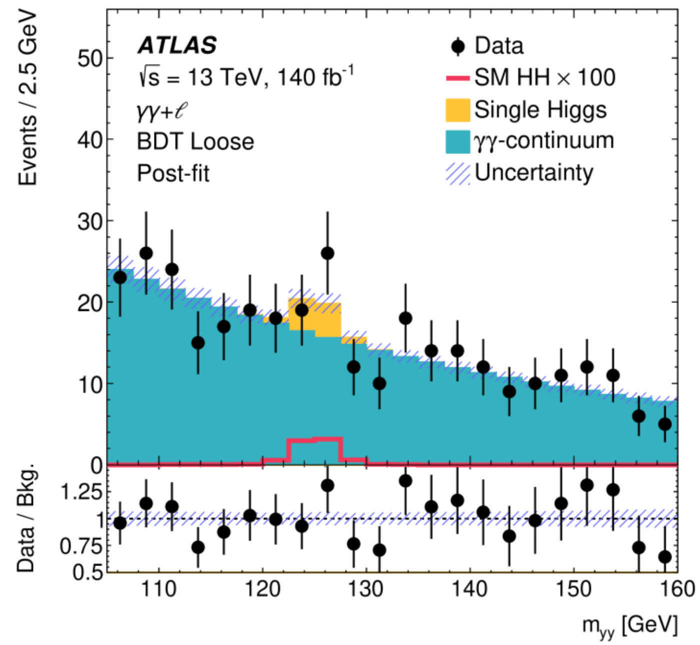




Multilepton

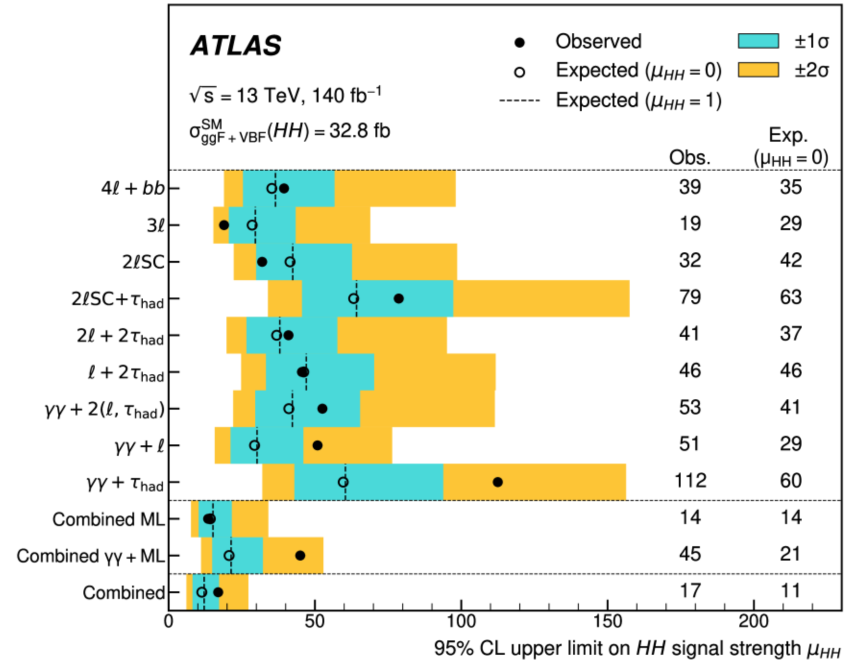






- BDTs used in each channel to separate signal from backgrounds
- Backgrounds with prompt leptons estimated from MC.
- Processes with non-prompt or charge mis-ID light leptons, and mis-ID hadronic taus estimated using data-driven methods.

- Dominated by data statistics



95% CL limit μ_{HH} < 17 (11 exp)

HH combination

Phys. Rev. Lett. 133 (2024) 101801

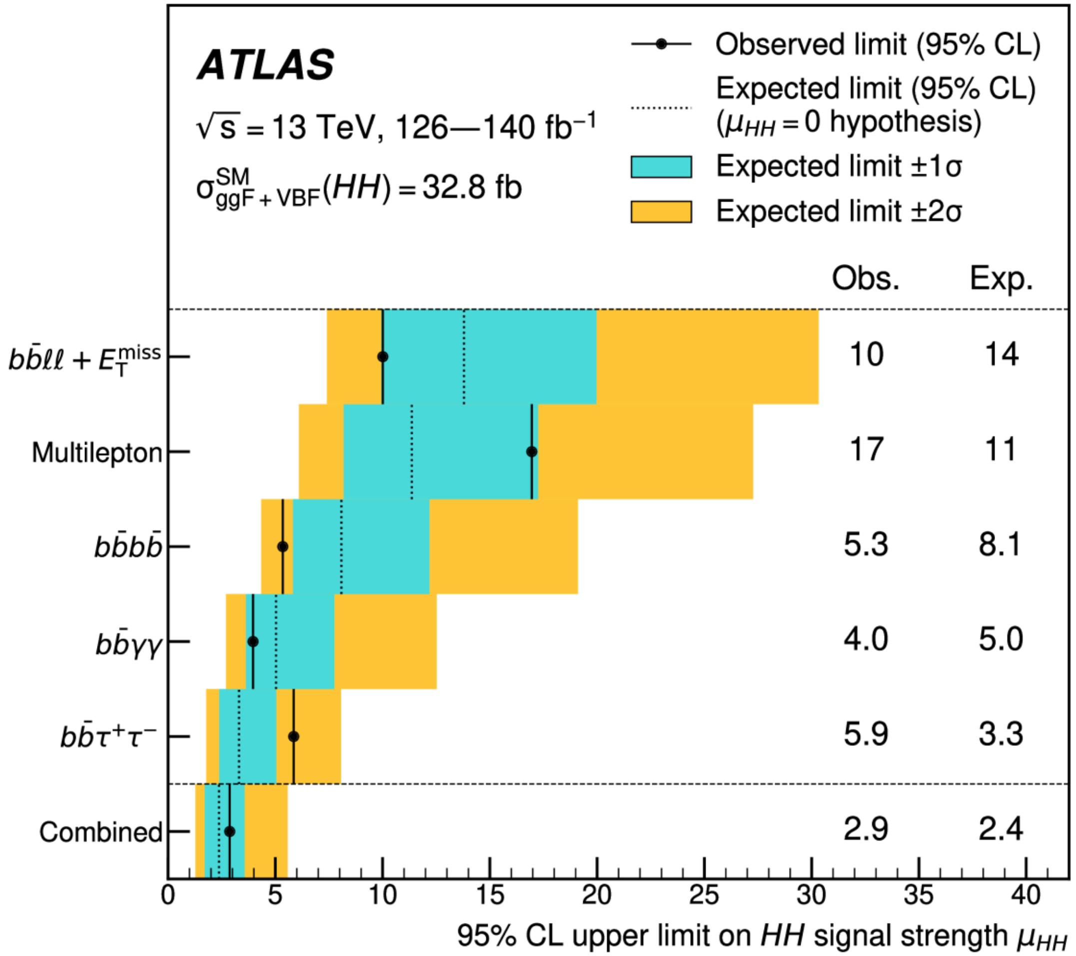
HH production combination

95% CL limit
$\mu_{HH} < 2.9$ (2.4 exp)
$\mu_{VBF} < 44.3$ (47.5 exp)

$\sigma_{HH} < 85.8$ (71.1 exp) fb

deficit observed in bbbb, bbγγ, bbℓℓ+$E_T$miss
excess observed in bbττ, multilepton

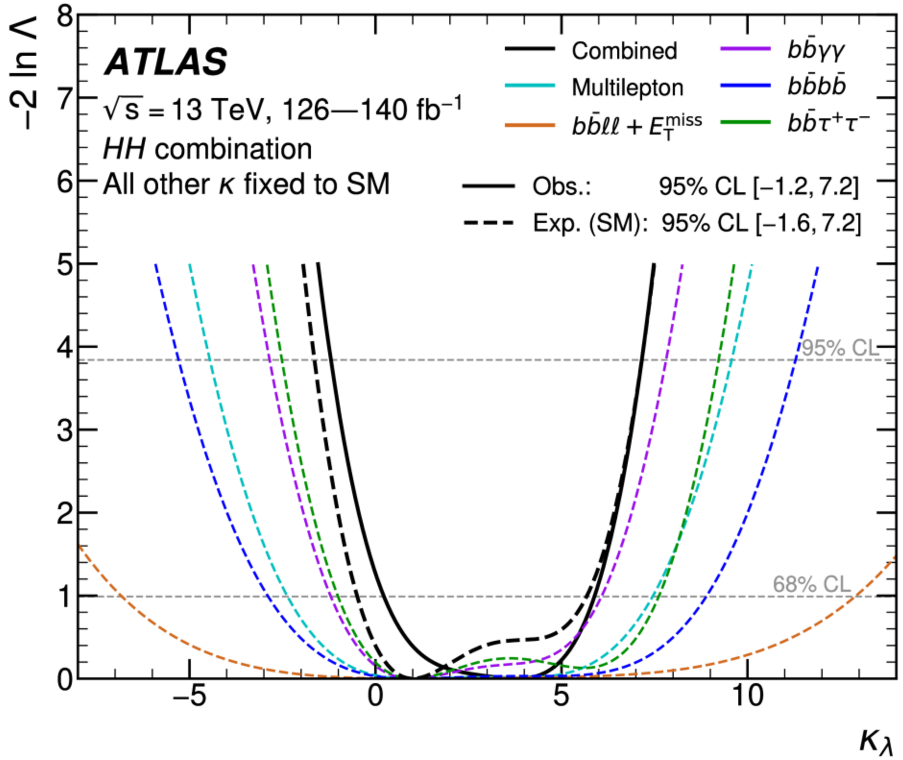
- Dominant uncertainties: HH theory cross section uncertainty +6% −23% in scale + m_{top}
- Modelling of single H associated with b-jets
- Experimental uncertainties: 4b background estimation

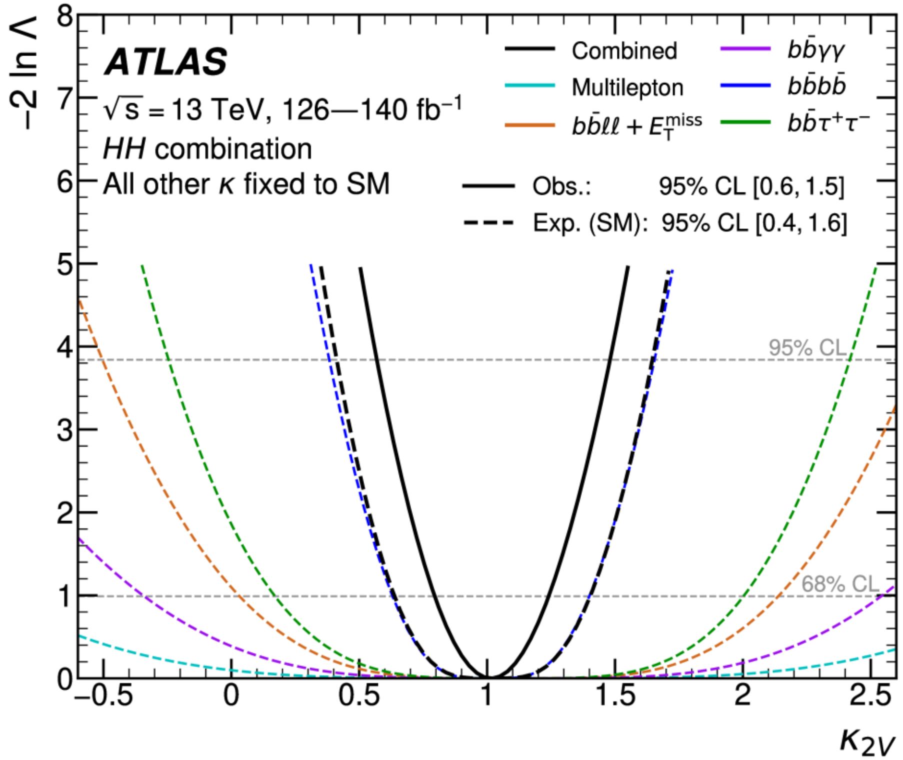


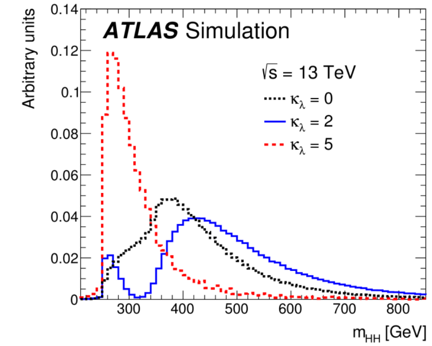
Couplings: likelihood scans

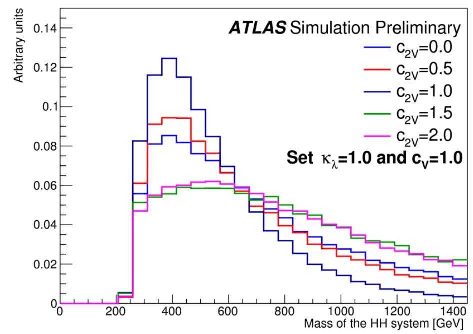
Best fit: $\kappa_\lambda = 3.8$, $\kappa_{2V} = 1.0$

Remember m_{HH} changes when κ_λ, κ_{2V} moves away from SM

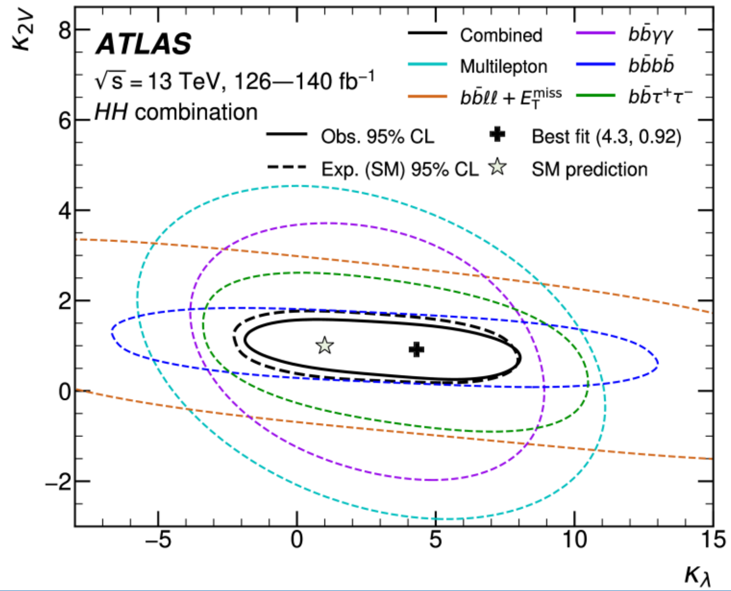






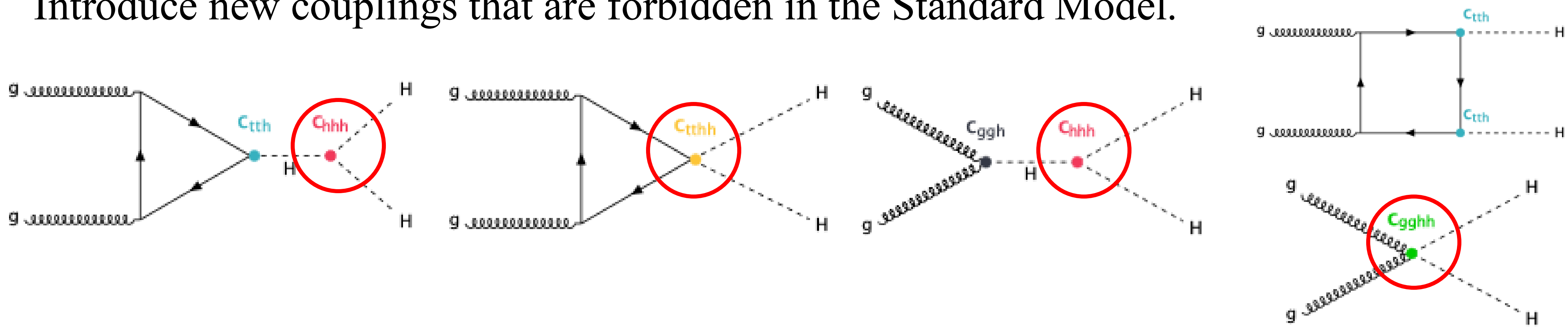


- $bb\tau\tau$ and $bb\gamma\gamma$ channels dominate sensitivity at low κ_λ values, where kinematics closely resemble the SM and these channels are most effective.
- $bb\gamma\gamma$ is sensitive at high κ_λ values – best sensitivity in the low m_{HH} region.
- bbbb channel (boosted) provides dominant sensitivity to κ_{2V} values.

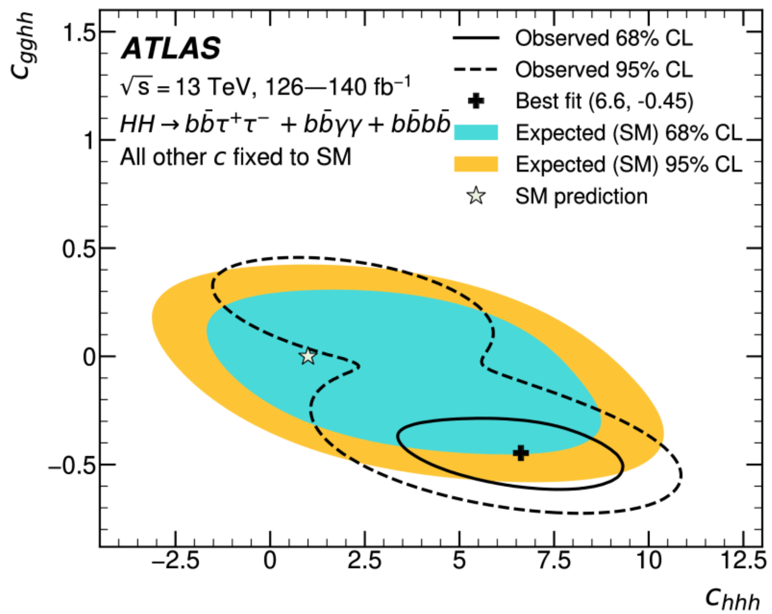


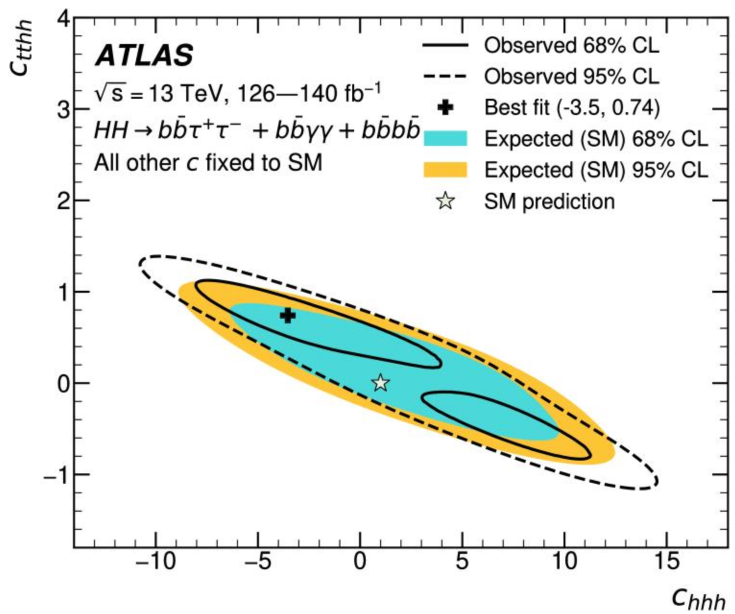
HH in Effective Field Theories (HEFT)

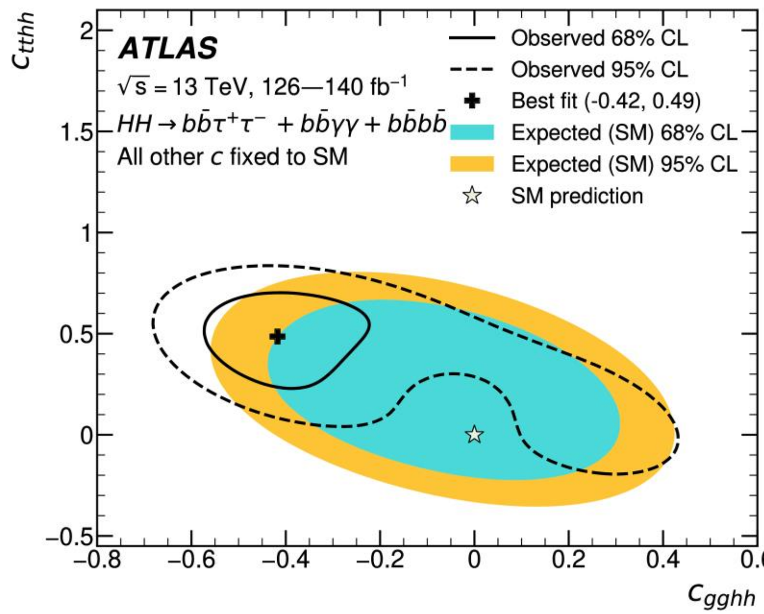
- Effective Field Theories provide new physics in a model-independent.
- They help us explore the broader impact of new physics across various measurements.
- Introduce new couplings that are forbidden in the Standard Model.



HH search can put constraints to the coefficients







Resonant production

- Many BSM models predict new particles that decay to a pair of Higgs bosons.
- Many models also predict additional Higgs-like scalars

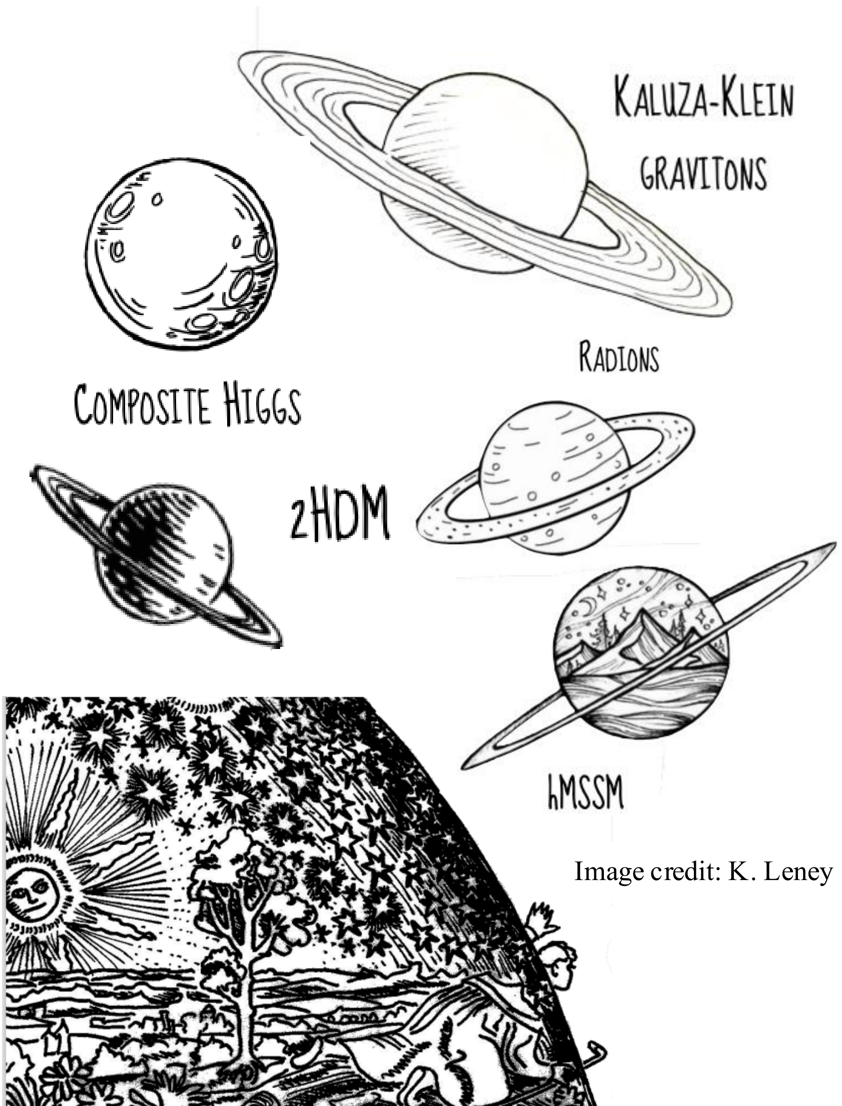
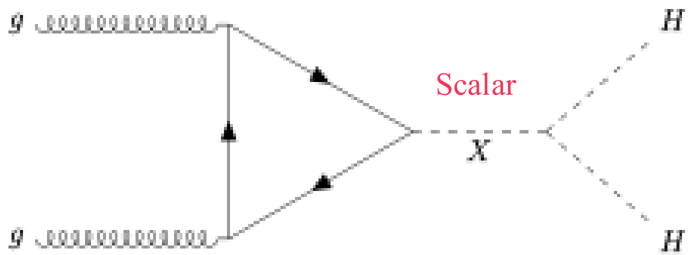
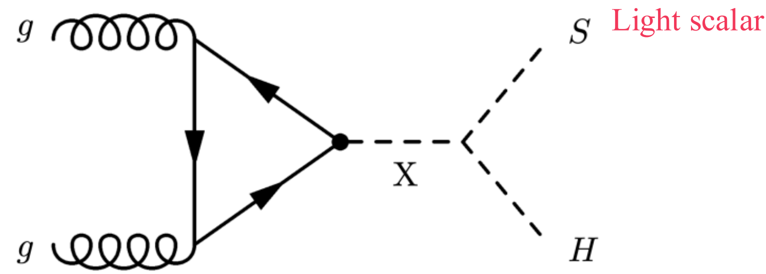


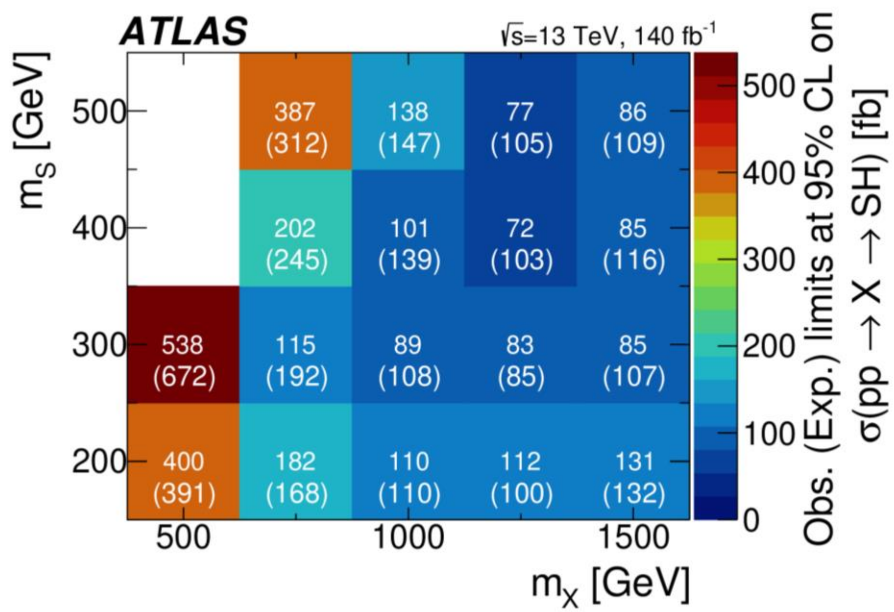
Image credit: K. Leney





X→HH and X→SH searches are closely connected to non-resonant HH searches, both in the physics they explore, and in their analyses.

X→SH search in VVττ



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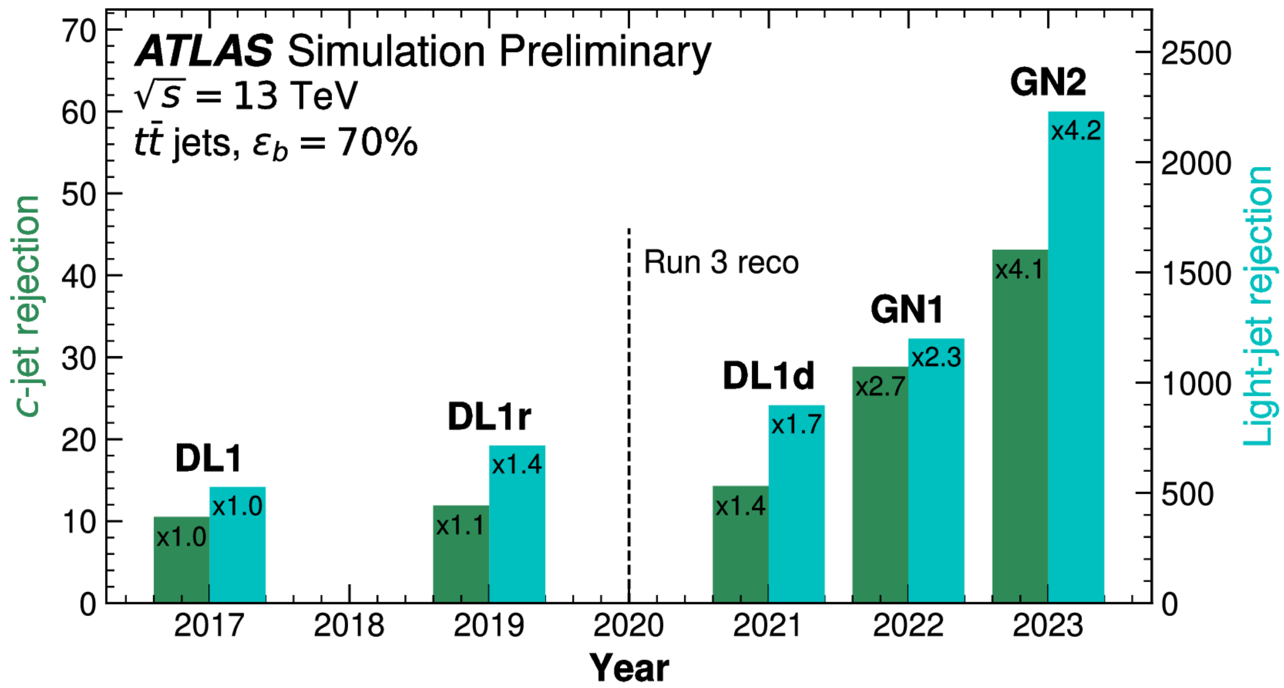
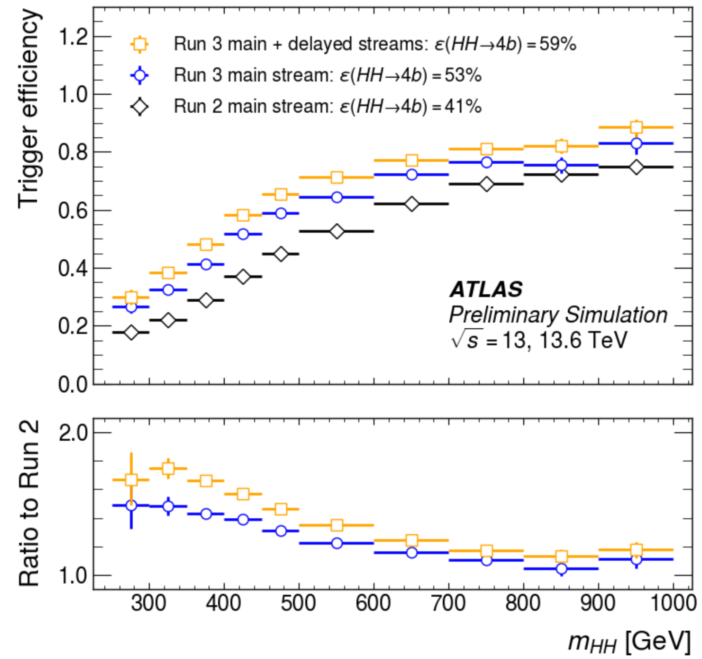
HH in Run 3

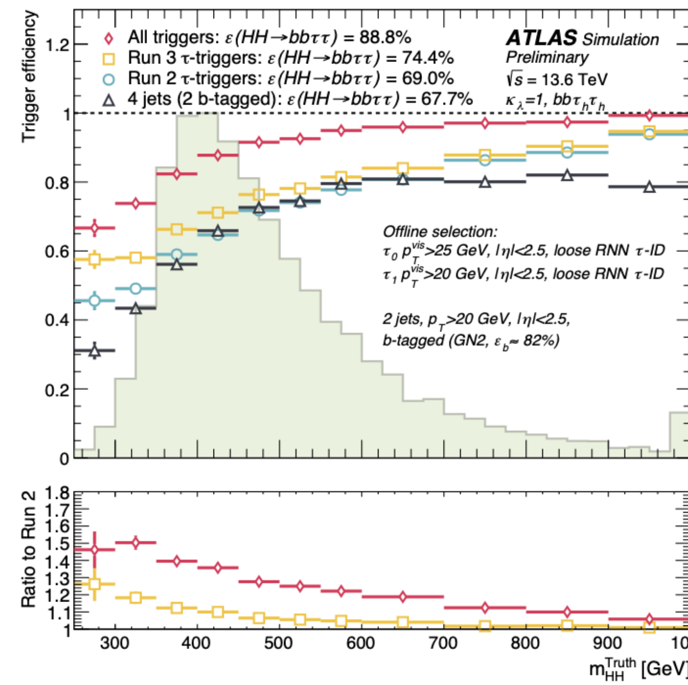
- Improved object identification, b-tagging algorithms, dedicated triggers and many more refined analyses….

[FTAG-2023-01]





ATLASBJetTriggerPublicResults

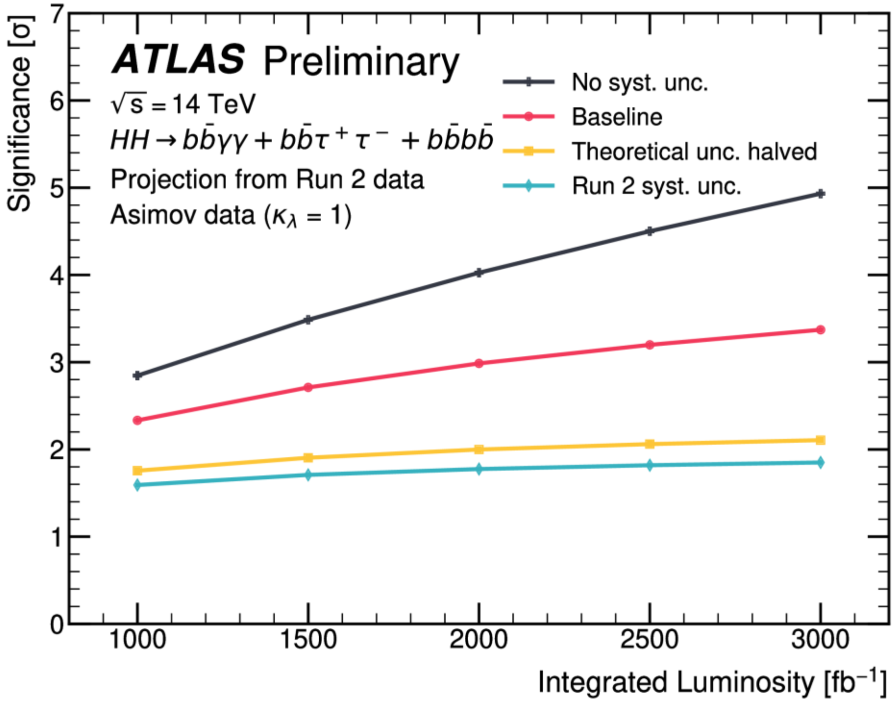


ATLASTauTriggerPublicResults

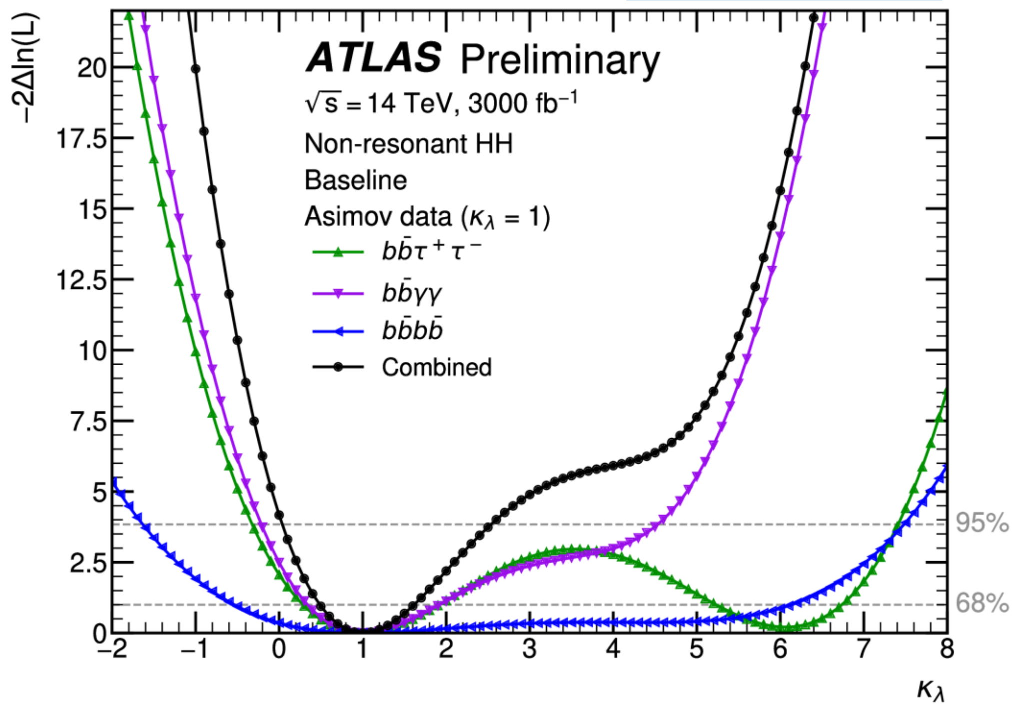
HH at the HL-LHC

- Combination of bbbb + bbττ + bbγγ.
- HH discovery significance of 3.4σ; κ_λ constrained within [0.0, 2.5] at 95% CL.
- Based on previous round of full Run 2 results.

Baseline scenario rely on assumptions in ATL-PHYS-PUB-2021-023



ATL-PHYS-PUB-2022-053

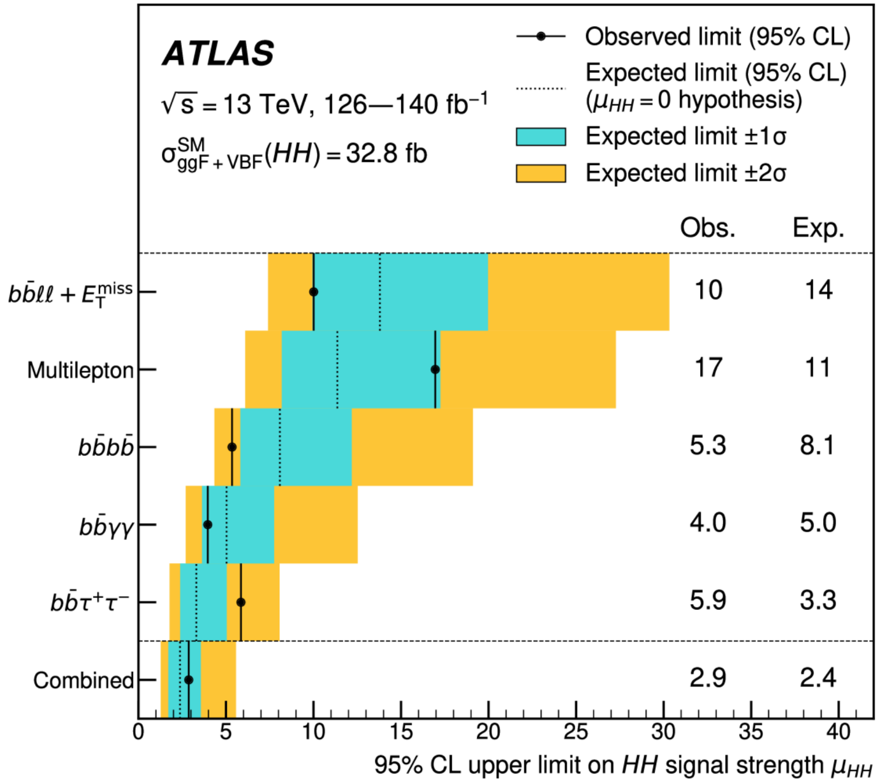


Combination of ATLAS+CMS projections
5σ for SM HH
~30% on κ_λ

- Sensitivity driven by theoretical uncertainties on HH cross-section.
- b-tag performance in bbbb, and background modelling uncertainty in bbγγ.
- additional heavy-flavour jet radiation in single Higgs background.

Summary

- DiHiggs production is a rare and unique process to probe the Higgs potential.
- Significant improvements in various aspects of the analyses compared to previous results.
- Excellent performance of ATLAS detector and LHC in Run 2.
- ATLAS searches for HH production in final states covering 50% of decays:
  - Reached the best expected sensitivity to date $\mu_{HH} < 2.9$ (2.4 exp.)
  - Higgs self-coupling $-1.2 < \kappa_\lambda$ 7.2 ($-1.6 < \kappa_\lambda < 7.2$ exp.)
- Promising prospects for both Run 3 and HL-LHC



Looking forward to exciting Higgs pair production results in the near future from Run 3 and the HL-LHC!

Backup

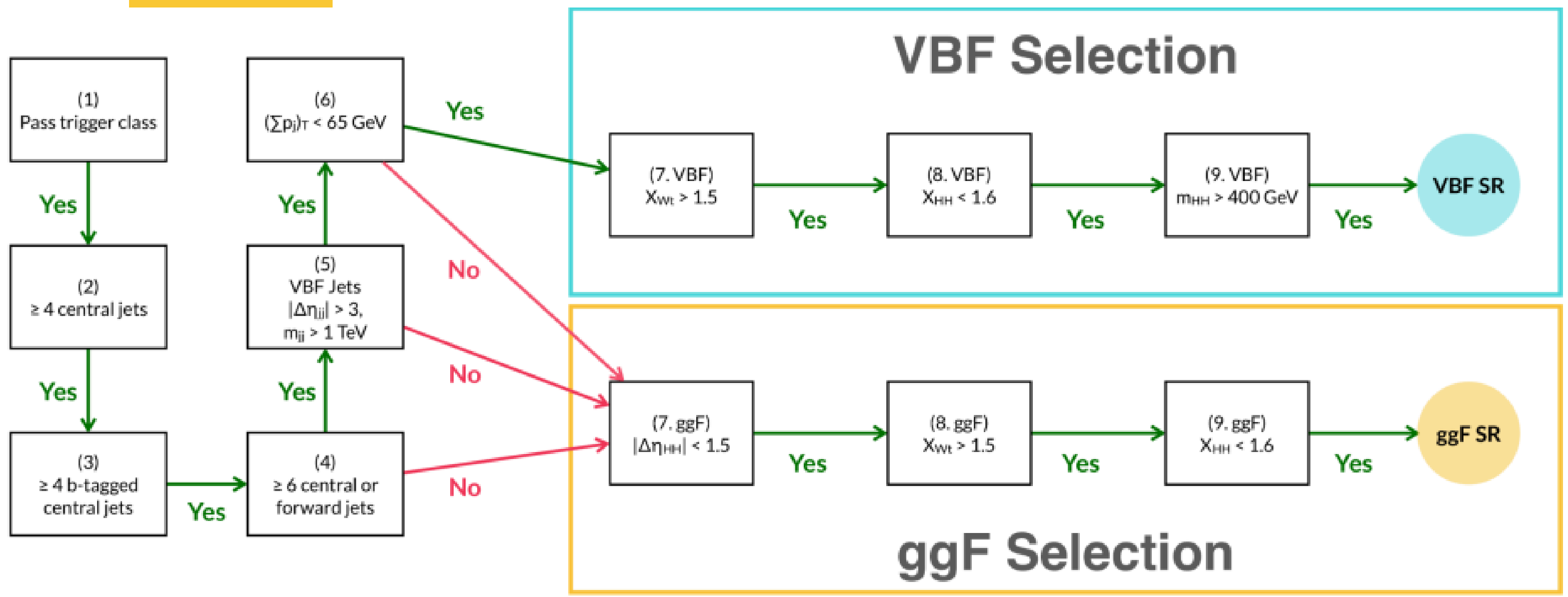
Multilepton selection

Channel	ℓ	$\tau_{\text{had-vis}}$	Jets	b-jets
4ℓ+$2b$	4ℓ(B) $p_{\mathrm{T}}(\ell_1) > 20$ GeV $p_{\mathrm{T}}(\ell_2) > 15$ GeV $p_{\mathrm{T}}(\ell_3) > 10$ GeV ℓ_3 or ℓ_4 pass loose PLV 2 SFOC pairs $50 < m^{\text{SFOC}}_{\text{on-shell-}\ell\ell} < 106$ GeV $5 < m^{\text{SFOC}}_{\text{off-shell-}\ell\ell} < 115$ GeV All 4 pairs $\Delta R(\ell_i, \ell_j) > 0.02$ $\lvert m_{4\ell} - m_Z \rvert > 10$ GeV	$N_\tau = 0$	$N_{\text{jet}} \geq 2$	$1 \leq N_{b\text{-jet}} \leq 3$
3ℓ	3ℓ, sum of charges = ±1 ℓ_{OC}(L) ℓ_{SC1}(T), $p_{\mathrm{T}} > 15$ GeV ℓ_{SC2}(T), $p_{\mathrm{T}} > 15$ GeV All $m^{\text{SFOC}}_{\ell\ell} > 12$ GeV Z-veto $\lvert m_{3\ell} - m_Z \rvert > 10$ GeV	$N_\tau = 0$	$N_{\text{jet}} \geq 1$	$N_{b\text{-jet}} = 0$
2ℓSC	2ℓ(T), $p_{\mathrm{T}} > 20$ GeV, SC $m_{\ell\ell} > 12$ GeV	$N_\tau = 0$	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$
2ℓSC+τ_{had}	2ℓ(T), $p_{\mathrm{T}} > 20$ GeV, SC $m_{\ell\ell} > 12$ GeV	$N_\tau = 1$ $p_{\mathrm{T}} > 25$ GeV OC to ℓ	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$
2ℓ+$2\tau_{\text{had}}$	2ℓ(L), OC $m_{\ell\ell} > 12$ GeV Z-veto	$N_\tau = 2$, OC $\Delta R(\tau_1, \tau_2) < 2$	$N_{\text{jet}} \geq 0$	$N_{b\text{-jet}} = 0$
ℓ+$2\tau_{\text{had}}$	1ℓ(L)	$N_\tau = 2$, OC $\Delta R(\tau_1, \tau_2) < 2$	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$

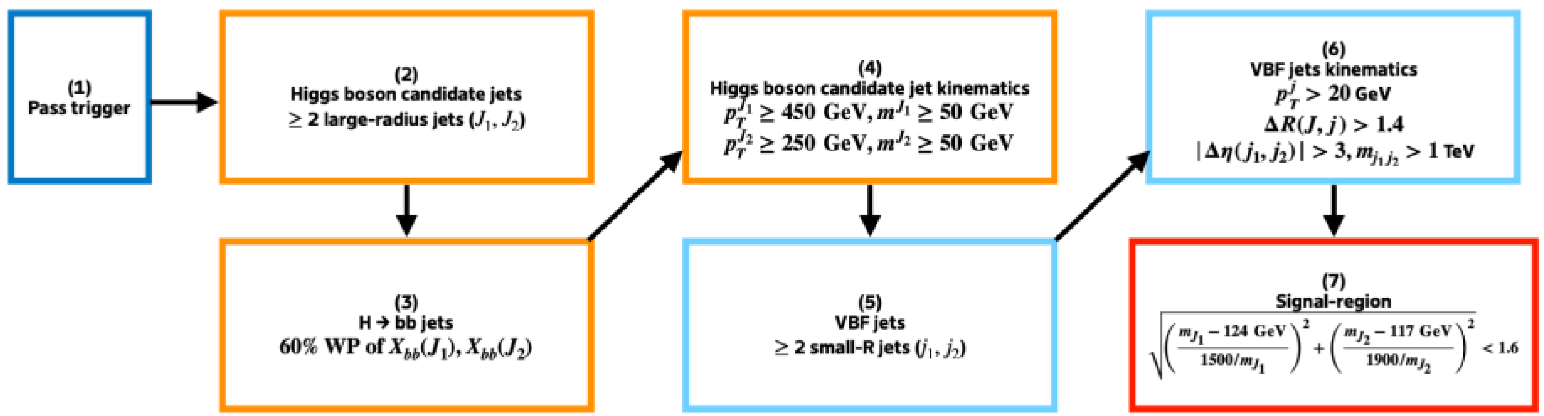
Channel	ℓ	$\tau_{\text{had-vis}}$	Photons	$E_{\mathrm{T}}^{\text{miss}}$	b-jets
$\gamma\gamma$+$2(\ell, \tau_{\text{had}})$	$N_{\ell(\mathrm{P})} + N_\tau = 2$, OC $m_{2(\ell,\tau)} > 12$ GeV		$N_\gamma = 2$ $E_{\mathrm{T}}(\gamma_1) > 35$ GeV 105 GeV $< m_{\gamma\gamma} <$ 160 GeV $\gamma_1 : p_{\mathrm{T}}/m_{\gamma\gamma} > 0.35$ $\gamma_2 : p_{\mathrm{T}}/m_{\gamma\gamma} > 0.25$	$E_{\mathrm{T}}^{\text{miss}} > 35$ GeV	$N_{b\text{-jet}} = 0$
$\gamma\gamma$+ℓ	$N_{\ell(P)} = 1$	$N_\tau = 0$		$\gamma\gamma$+e: $E_{\mathrm{T}}^{\text{miss}} > 35$ GeV $\gamma\gamma$+μ: –	
$\gamma\gamma$+τ_{had}	$N_{\ell(P)} = 0$	$N_\tau = 1$		$E_{\mathrm{T}}^{\text{miss}} > 35$ GeV	

bbbb selection

Resolved



Boosted



Combined results

	Obs.	-2σ	-1σ	Exp.	$+1\sigma$	$+2\sigma$	Exp. SM
$b\bar{b}\tau^+\tau^-$	5.9	1.8	2.4	3.3	5.0	8.1	4.3
$b\bar{b}\gamma\gamma$	4.0	2.7	3.6	5.0	7.8	13	6.4
$b\bar{b}b\bar{b}$	5.3	4.3	5.8	8.1	12	19	9.1
Multilepton	17	6	8	11	17	27	12
$b\bar{b}\ell\ell + E_T^{miss}$	10	7	10	14	20	30	15
Combined	2.9	1.3	1.7	2.4	3.6	5.6	3.4

Channel	κ_λ 68% CL		κ_λ 95% CL		κ_{2V} 68% CL		κ_{2V} 95% CL	
	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
$b\bar{b}\gamma\gamma$	$3.0^{+2.2}_{-2.5}$	$1.0^{+5.1}_{-2.2}$	$[-1.4, 6.9]$	$[-2.9, 7.8]$	1.1 ± 0.8	$1.0^{+1.5}_{-1.3}$	$[-0.5, 2.7]$	$[-1.1, 3.3]$
$b\bar{b}\tau^+\tau^-$	$0.0^{+3.3}_{-1.7}$	$1.0^{+6.6}_{-2.0}$	$[-3.2, 9.0]$	$[-2.5, 9.2]$	$0.4^{+1.9}_{-0.5}$	$1.0^{+1.0}_{-0.8}$	$[-0.5, 2.7]$	$[-0.2, 2.4]$
Multilepton	$[-4.4, 0.6] \cup [4.3, 9.8]$	$1.0^{+6.5}_{-3.4}$	$[-6, 12]$	$[-4.5, 9.6]$	$-0.4^{+4.1}_{-1.2}$	$1.0^{+2.1}_{-1.9}$	$[-2.5, 4.6]$	$[-1.9, 4.1]$
$b\bar{b}b\bar{b}$	$5.8^{+3.0}_{-5.2}$	$1.0^{+7.9}_{-3.9}$	$[-3, 11]$	$[-5, 11]$	1.01 ± 0.23	$1.00^{+0.40}_{-0.37}$	$[0.5, 1.5]$	$[0.4, 1.7]$
$b\bar{b}\ell\ell + E_T^{miss}$	3 ± 6	1^{+12}_{-8}	$[-6, 13]$	$[-10, 17]$	1.1 ± 0.7	$1.0^{+1.1}_{-1.0}$	$[-0.2, 2.4]$	$[-0.5, 2.7]$
Combination	$3.8^{+2.1}_{-3.6}$	$1.0^{+4.7}_{-1.5}$	$[-1.2, 7.2]$	$[-1.6, 7.2]$	$1.02^{+0.22}_{-0.23}$	$1.00^{+0.40}_{-0.36}$	$[0.6, 1.5]$	$[0.4, 1.6]$