Revealing the Potential of the Higgs Boson:

Recent ATLAS searches for HH production and combination

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on behalf of the ATLAS Collaboration

LHC Seminar, 28 May 2024

The Higgs field and Standard Model

Higgs Field

- Has non-zero vacuum expectation value
- Lead to electroweak symmetry breaking

↓

Higgs Mechanism

- Can explain non-zero gauge boson masses
- Remarkably can also produce fermion masses

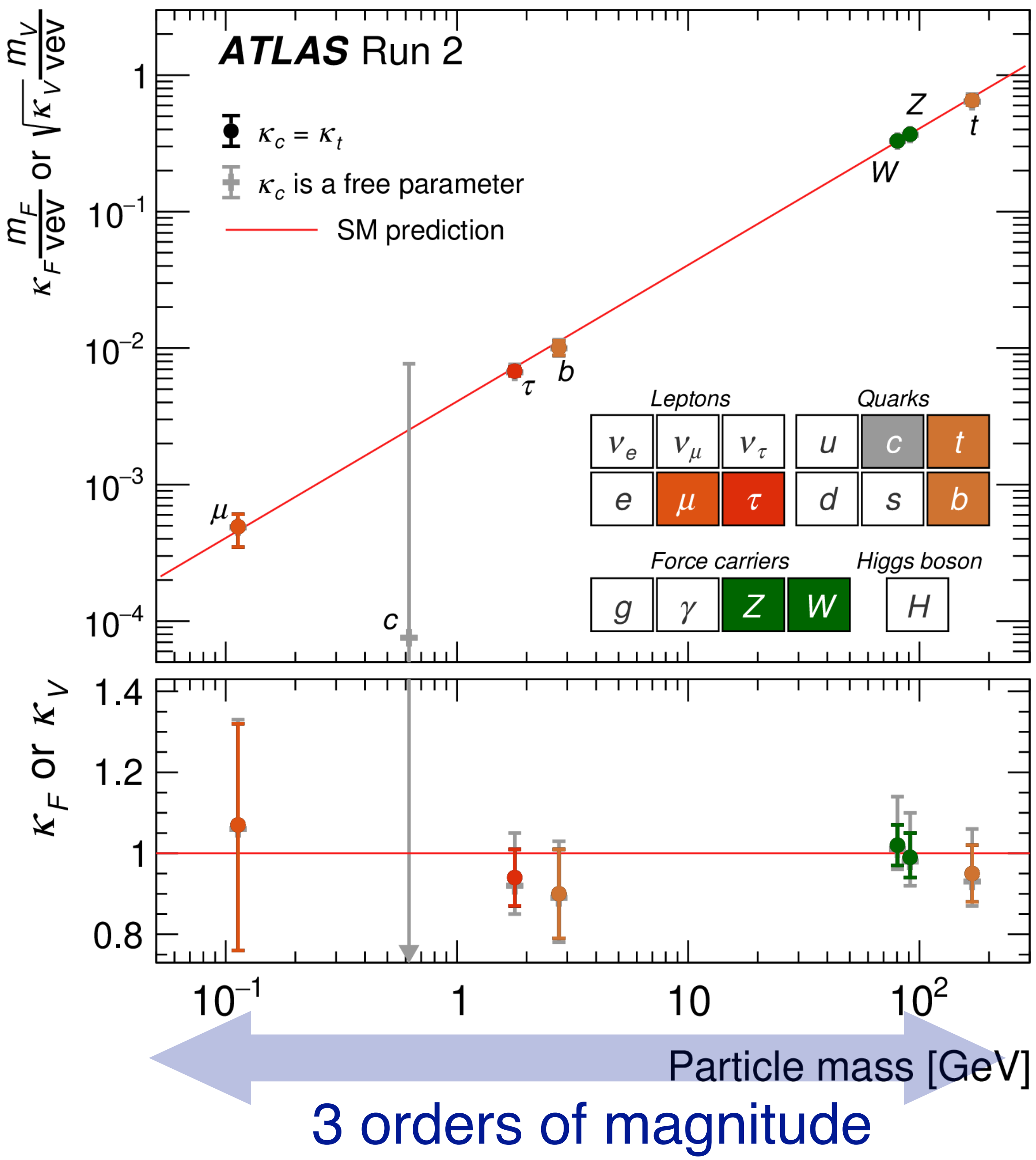
↓

Higgs Boson Particle

- Excitation of the Higgs field
- Unique chance to probe the Higgs field

Englert and Brout & Higgs
& Guralnik, Hagen and Kibble

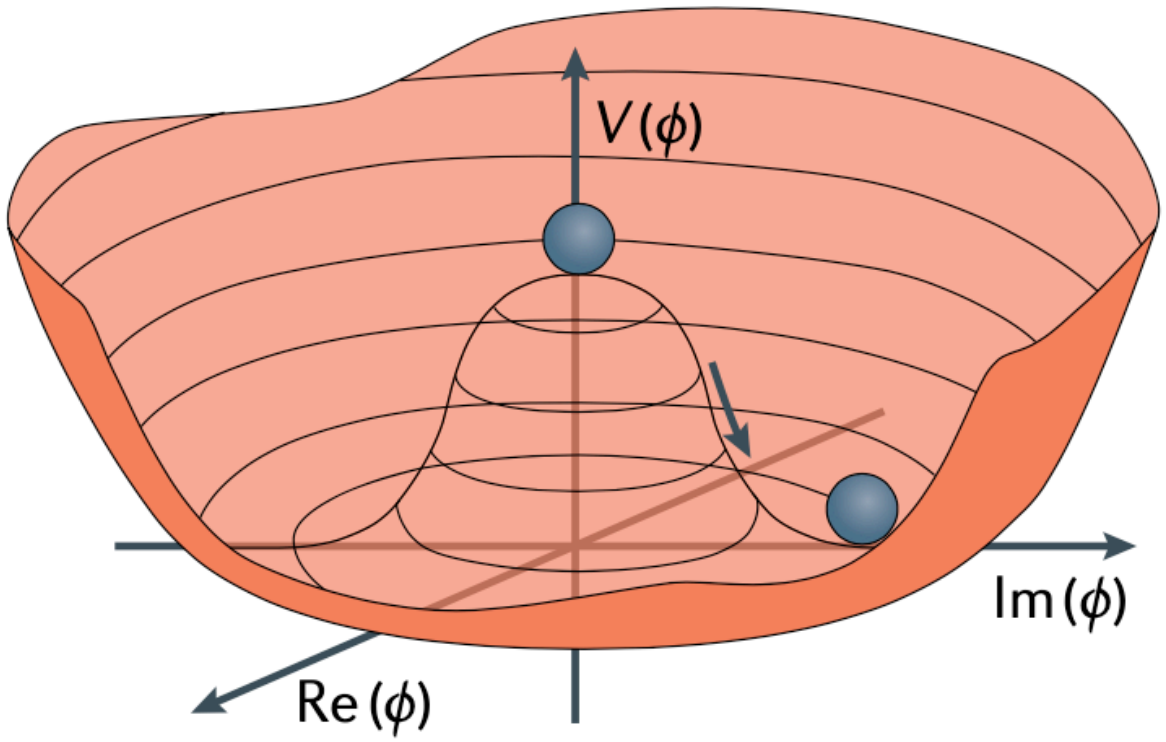
What've been learnt since the discovery?



- All main production modes (ggF, VBF, VH, ttH+tH) established at > 5σ
- Couplings to gauge bosons and 3rd gen. charged fermions observed, evidence for H→Zγ
- Couplings to 2nd gen. charged fermions: evidence for H→μμ; first constraints on H→cc;
- Mass measured to < 0.1%
- $J^{CP} = 0^{++}$ (alternative hypotheses excluded at > 99.9% C.L.)

But still very little knowledge about the shape of the Higgs potential.

The Higgs potential



$$|\phi|_{\text{min}} = \sqrt{-\frac{\mu^2}{2\lambda}} \equiv \frac{\nu}{\sqrt{2}}, \nu = 246 \text{ GeV}$$

When $\mu^2 < 0$ the potential has a minimum at:

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

$$\lambda = m_H^2/2\nu^2 \approx 0.13$$

Measurement of λ is crucial to reconstruction the Higgs potential and therefore test the Higgs mechanism

Baryogenesis requires a first order electroweak phase transition, which would lead to a modification to the Higgs potential ...

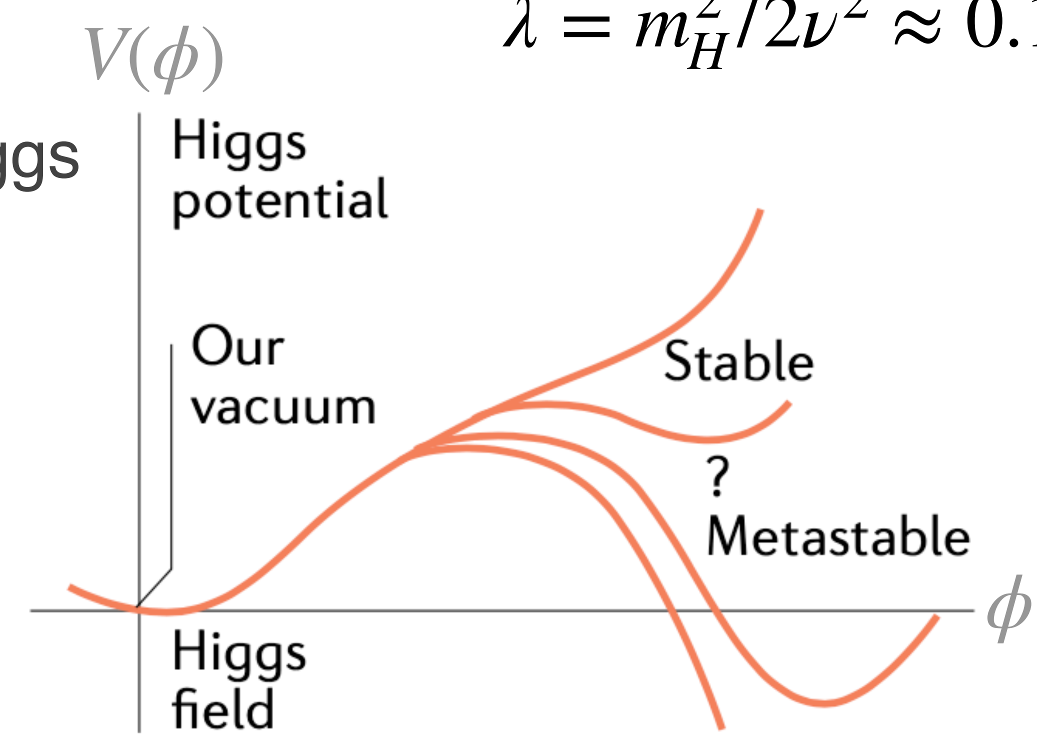


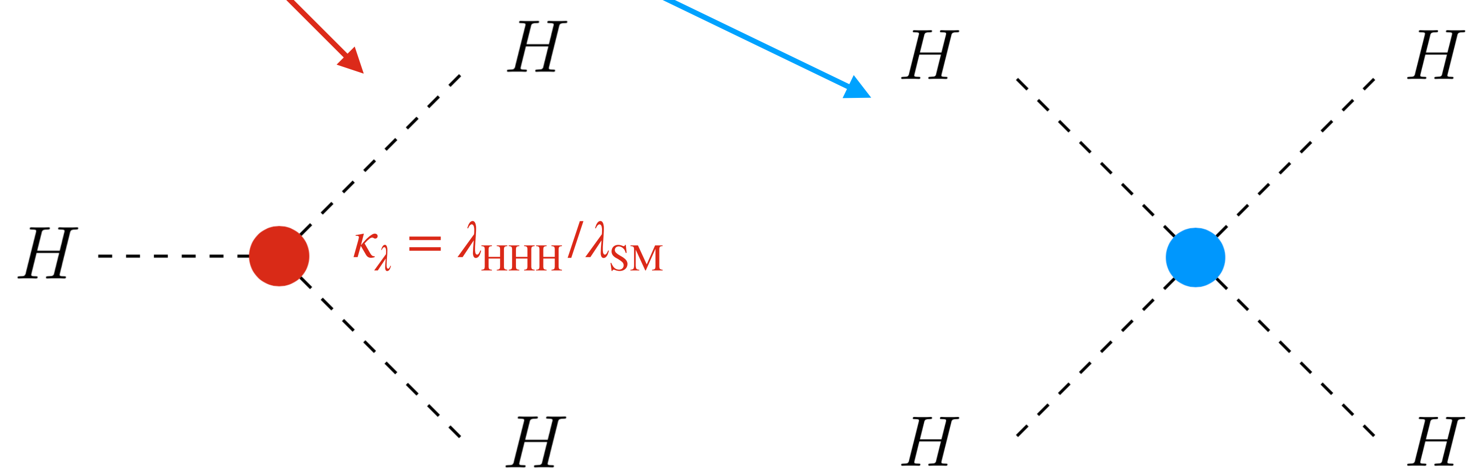
Image credit: Nature Reviews Physics 3.9 (2021)

Higgs self-coupling

- Direct exploring the potential at each Higgs field value ϕ is not possible.

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 \supset \lambda\nu^2h^2 + \lambda\nu h^3 + \frac{\lambda}{4}h^4$$

Mass term



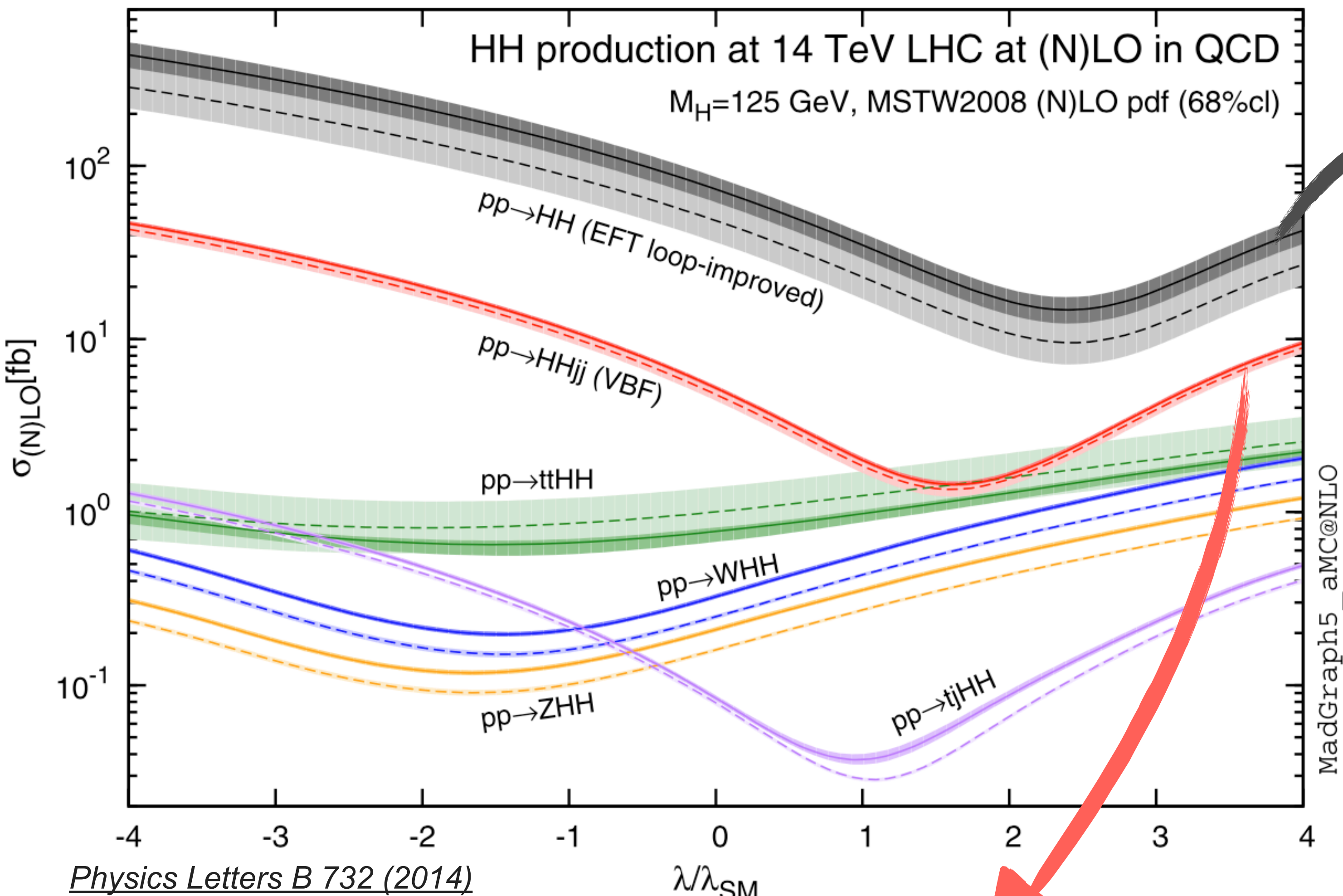
self-coupling

- Probing the Higgs-self coupling is a key towards pinning down exact shape of the potential.

Study of Higgs boson pair production (HH) can shed light

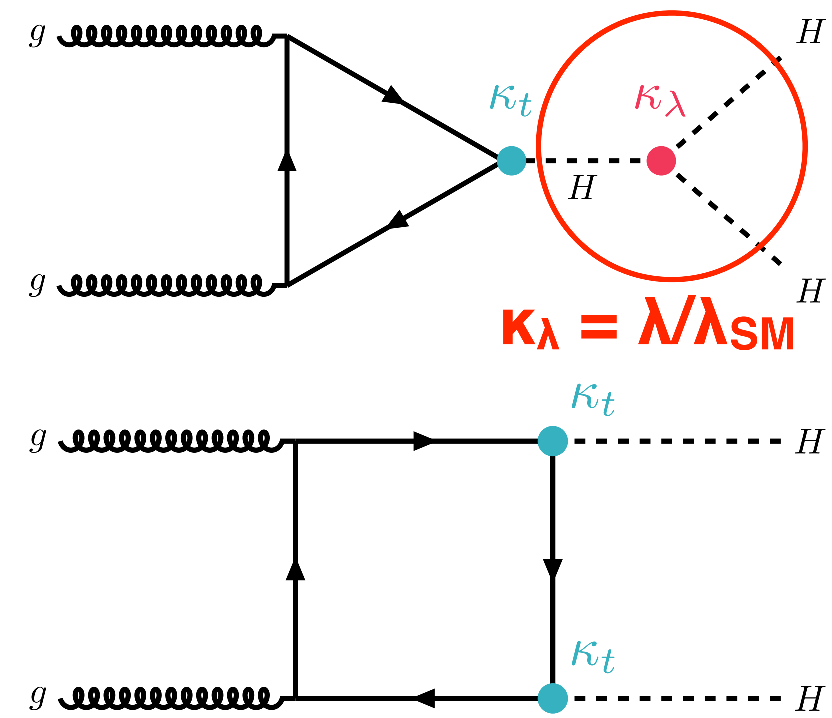
HH production at LHC

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

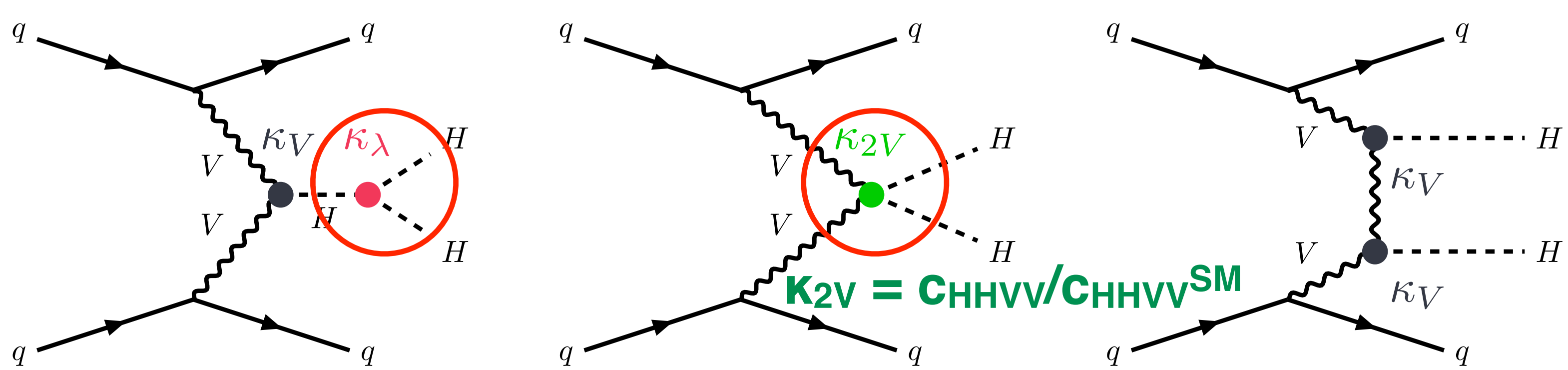


Physics Letters B 732 (2014)

Gluon-gluon Fusion production (ggF)



$\kappa_\lambda = \lambda/\lambda_{SM}$



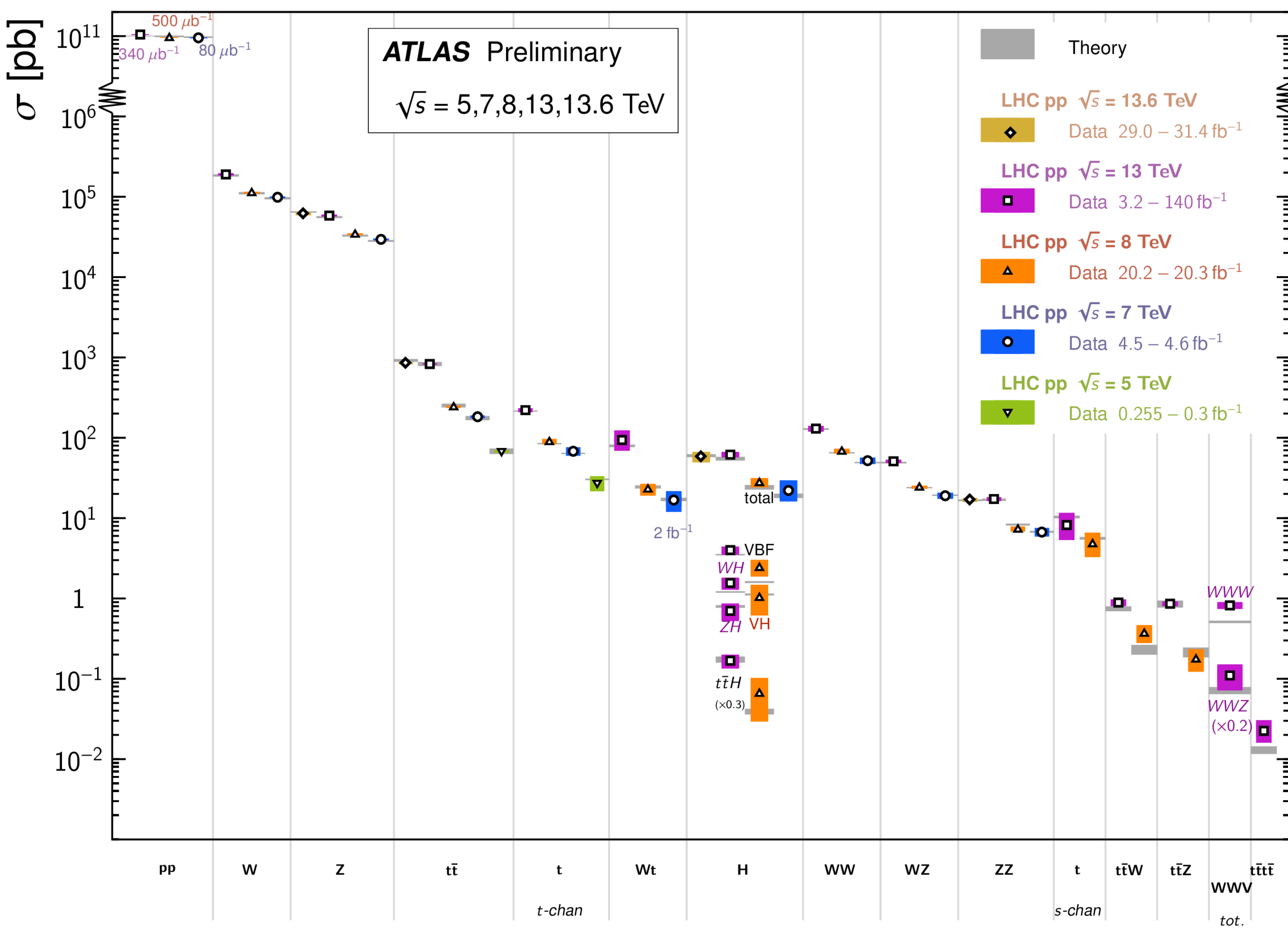
$\kappa_{2V} = c_{HHVV}/c_{HHVV}^{SM}$

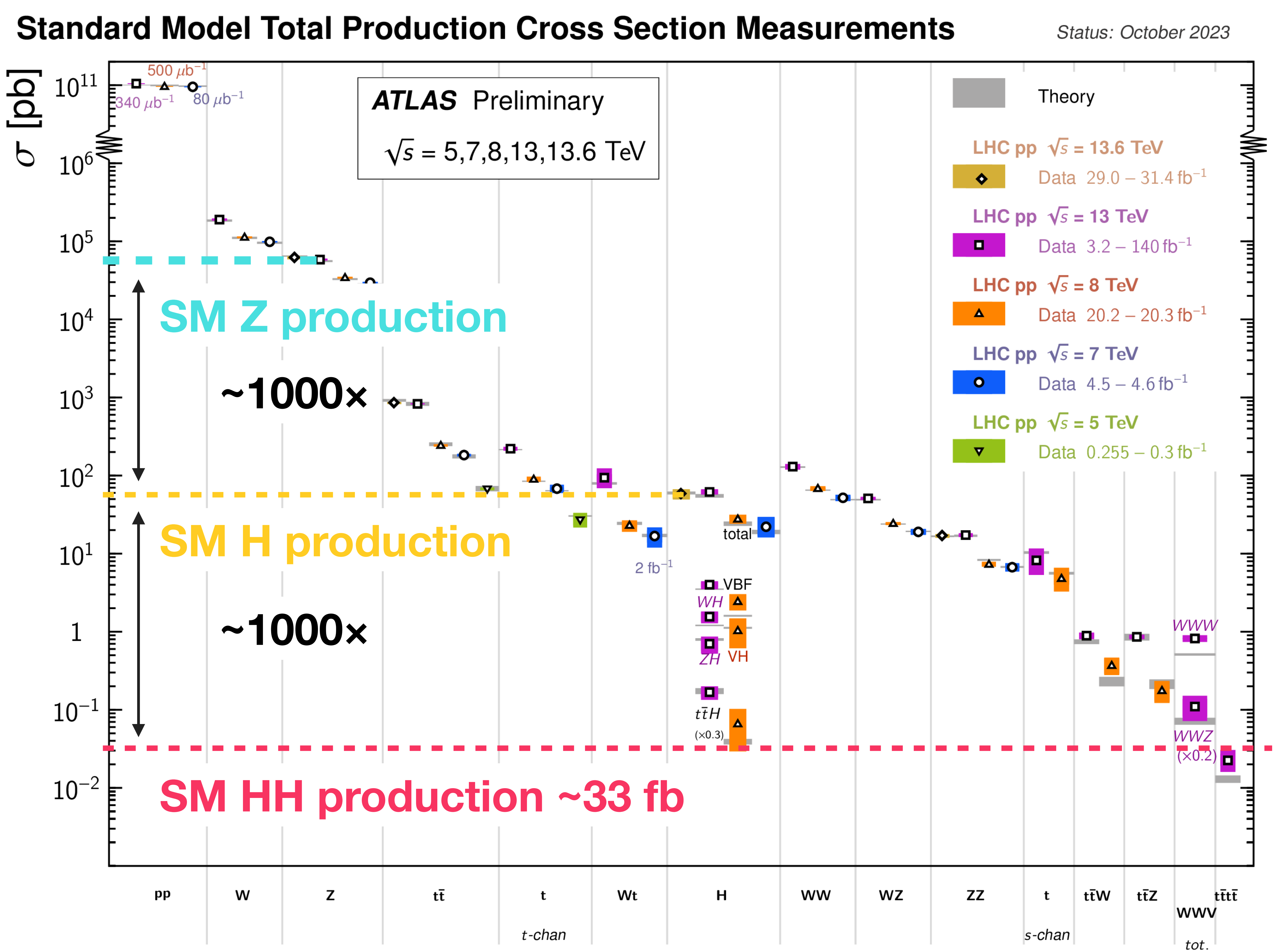
Vector Boson Fusion production (VBF)

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

SM σ_{HH} @ 13 TeV ~ 33 fb

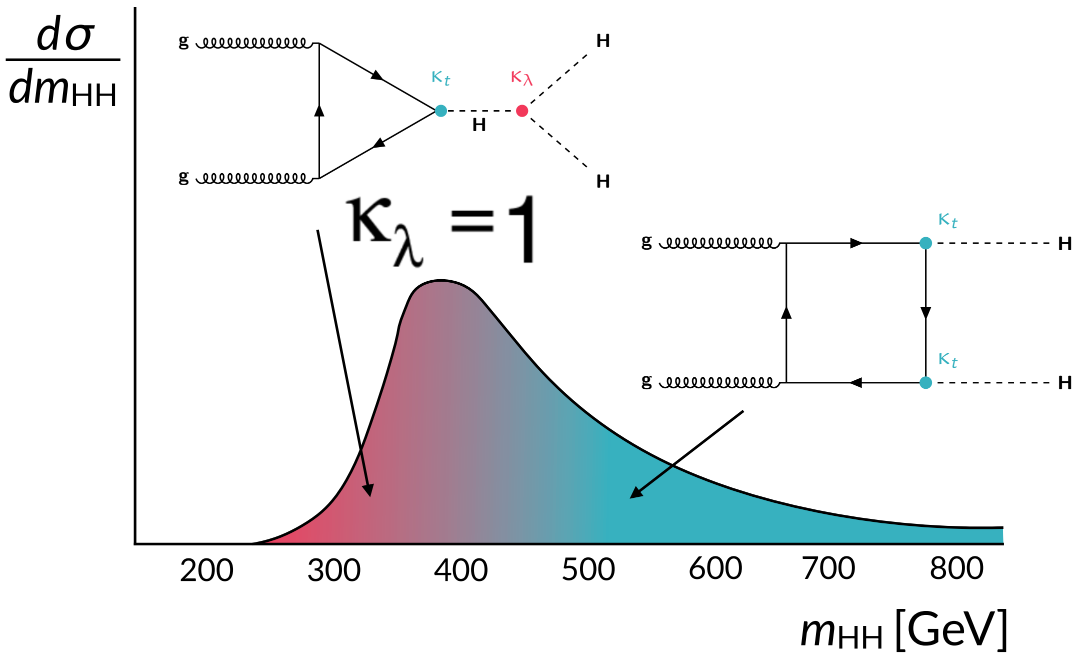
Standard Model Total Production Cross Section Measurements



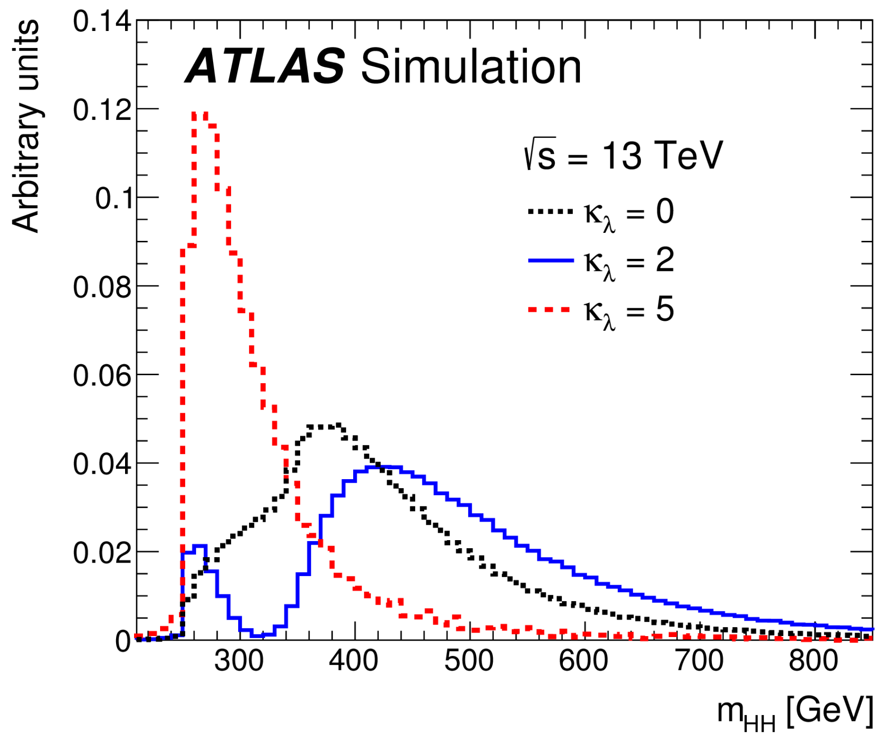


Standard Model Total Production Cross Section Measurements
Status: October 2023
ATLAS Preliminary
$\sqrt{s}$ = 5,7,8,13,13.6 TeV
σ [pb]
500 μb⁻¹
340 μb⁻¹
80 μb⁻¹
Theory
LHC pp $\sqrt{s}$ = 13.6 TeV
Data 29.0 – 31.4 fb⁻¹
LHC pp $\sqrt{s}$ = 13 TeV
Data 3.2 – 140 fb⁻¹
LHC pp $\sqrt{s}$ = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp $\sqrt{s}$ = 7 TeV
Data 4.5 – 4.6 fb⁻¹
LHC pp $\sqrt{s}$ = 5 TeV
Data 0.255 – 0.3 fb⁻¹
SM Z production
~1000×
SM H production
~1000×
SM HH production ~33 fb
2 fb⁻¹
total
VBF
WH
ZH
VH
tt̄H
(×0.3)
WWW
WWZ
(×0.2)
pp
W
Z
tt̄
t
t-chan
Wt
H
WW
WZ
ZZ
t
s-chan
tt̄W
tt̄Z
WWV
tot.
tt̄tt̄

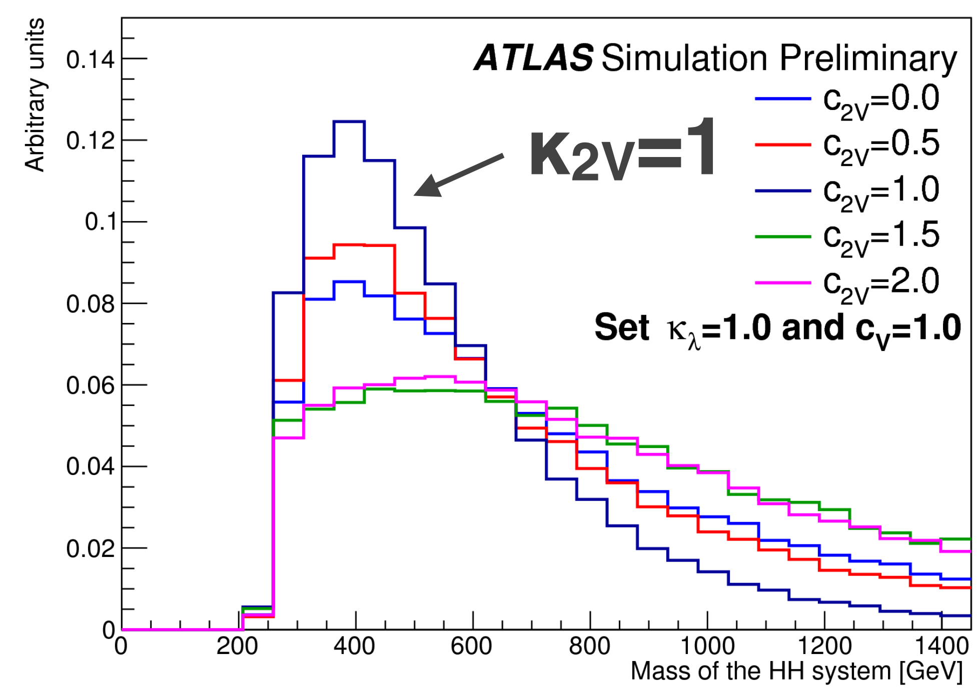
The challenges



- Destructive interference between the triangle and box amplitudes
  - 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 $|\kappa_{2V}|$



reference

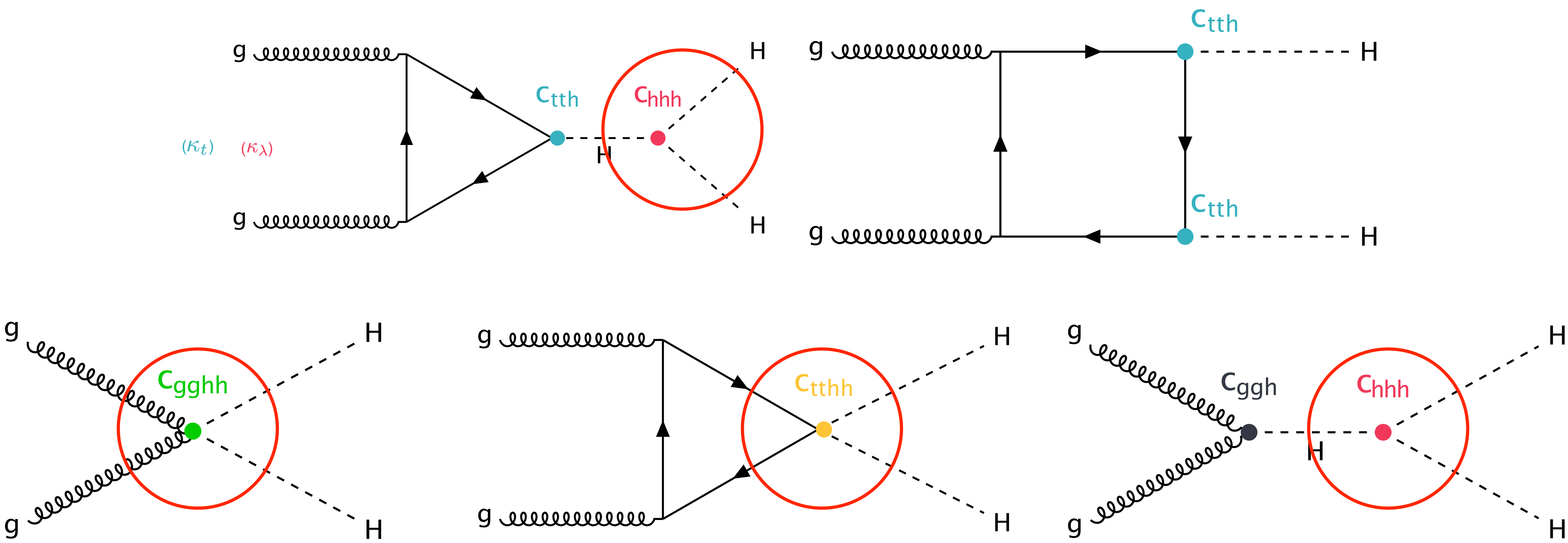


reference

Need excellent experimental performance and analysis techniques

HH from higher energy scales

- Higgs effective field theory (HEFT) framework



HH search can put constraints to the coefficients

HH decay channels

Large decay fraction

	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 final state

- No single "golden channel"
- bbbb (34%):
  - The most abundant final state
  - Challenging multi-jet backgrounds
- bbγγ (0.26%):
  - Low decay fraction
  - Excellent $m_{\gamma\gamma}$ resolution
- bbττ (7.3%):
  - Happy medium

HH decay channels

Large decay fraction

	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 final state

- $bb\ell\ell$ + neutrinos (2.9%):
  - Targeting where one $H \nrightarrow bb$
- multilepton (6.5%):
  - Targeting where both $H \nrightarrow bb$
    - Although including bbZZ(→4l)
  - In total 9 sub-channels
- Combining all above channels
  - Maximise the exploration of full Run 2 ATLAS data
  - Covering > 50% of HH decay

Today's focus

- Recent HH results

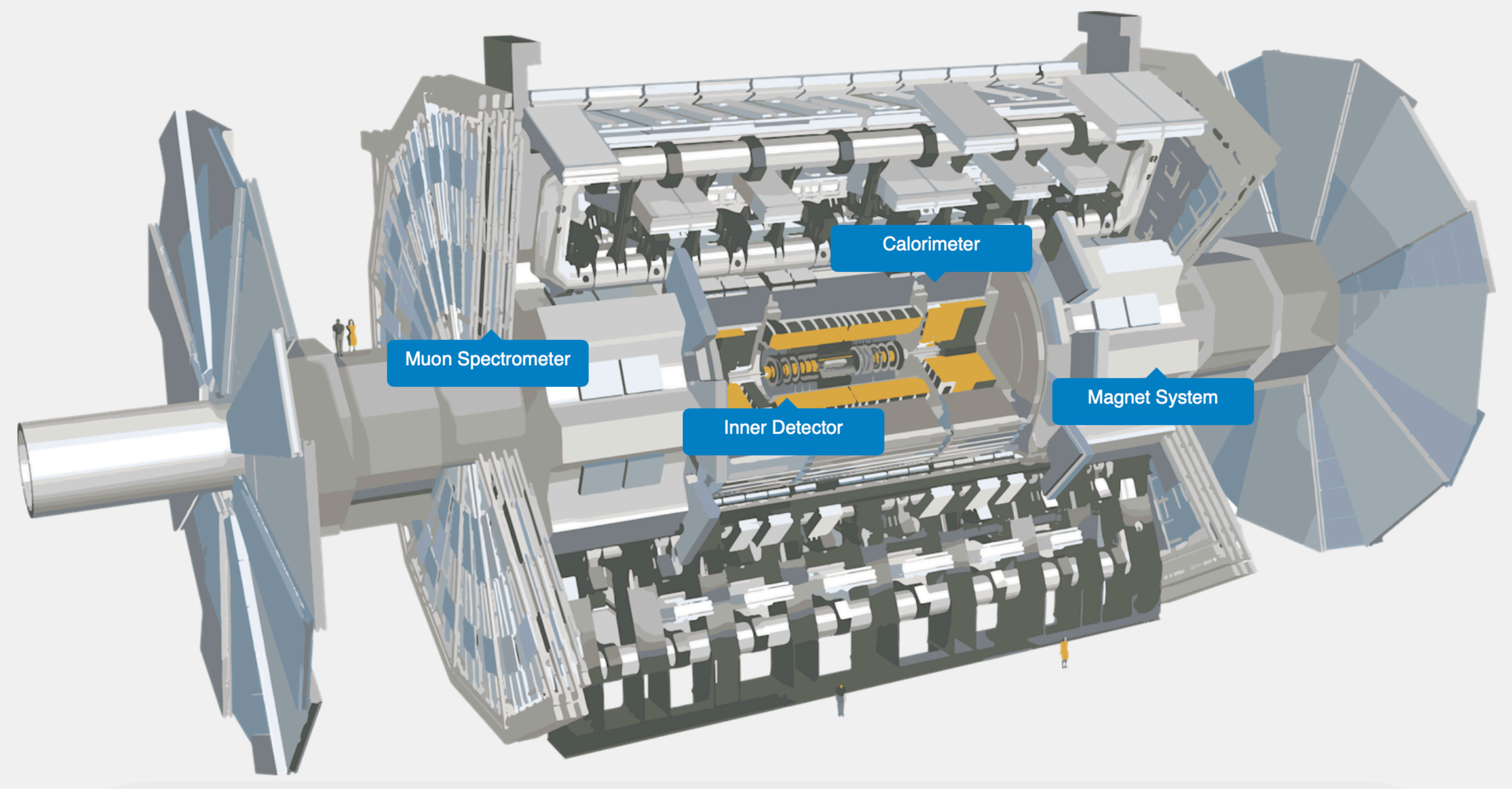
Nonresonant HH results	References
Full Run 2 bbbb	Resolved: Phys. Rev. D 108 (2023) 052003 Boosted: arXiv:2404.17193, submitted to PLB
Full Run 2 bbττ	arXiv:2404.12660, submitted to PRD
Full Run 2 bbγγ	JHEP 01 (2024) 066
Full Run 2 bbℓℓ+E_T^{miss}	JHEP 02 (2024) 037
Full Run 2 multilepton	ATLAS-CONF-2024-005

- HH full Run 2 combination ATLAS-CONF-2024-006 **New**
  - Five analyses above are combined under κ and HEFT frameworks
  - Presented in this seminar for the first time
- HH prospects ATL-PHYS-PUB-2022-053

Earlier results see LHC Seminar on 23rd November 2021 by Katharine Leney (ATLAS)

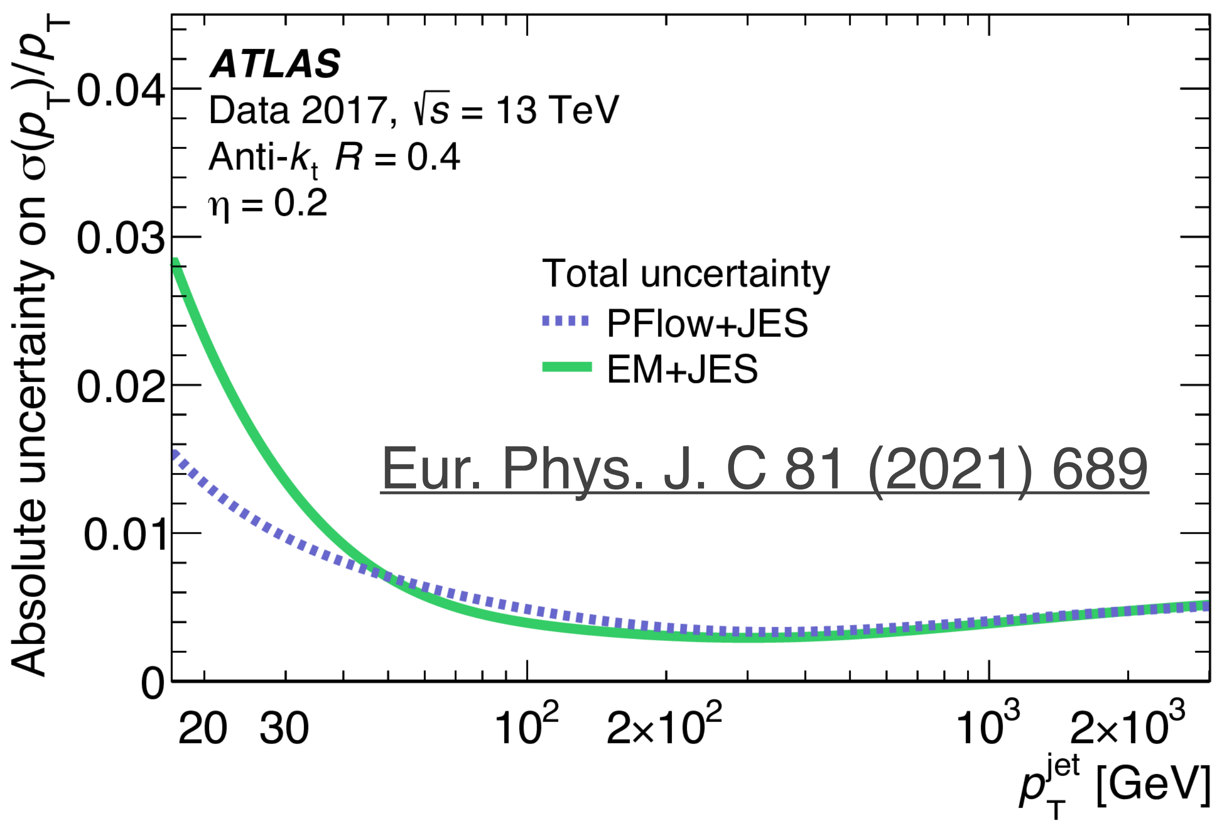
ATLAS detector

A general-purpose detector at the LHC with nearly 4π coverage in solid angle.



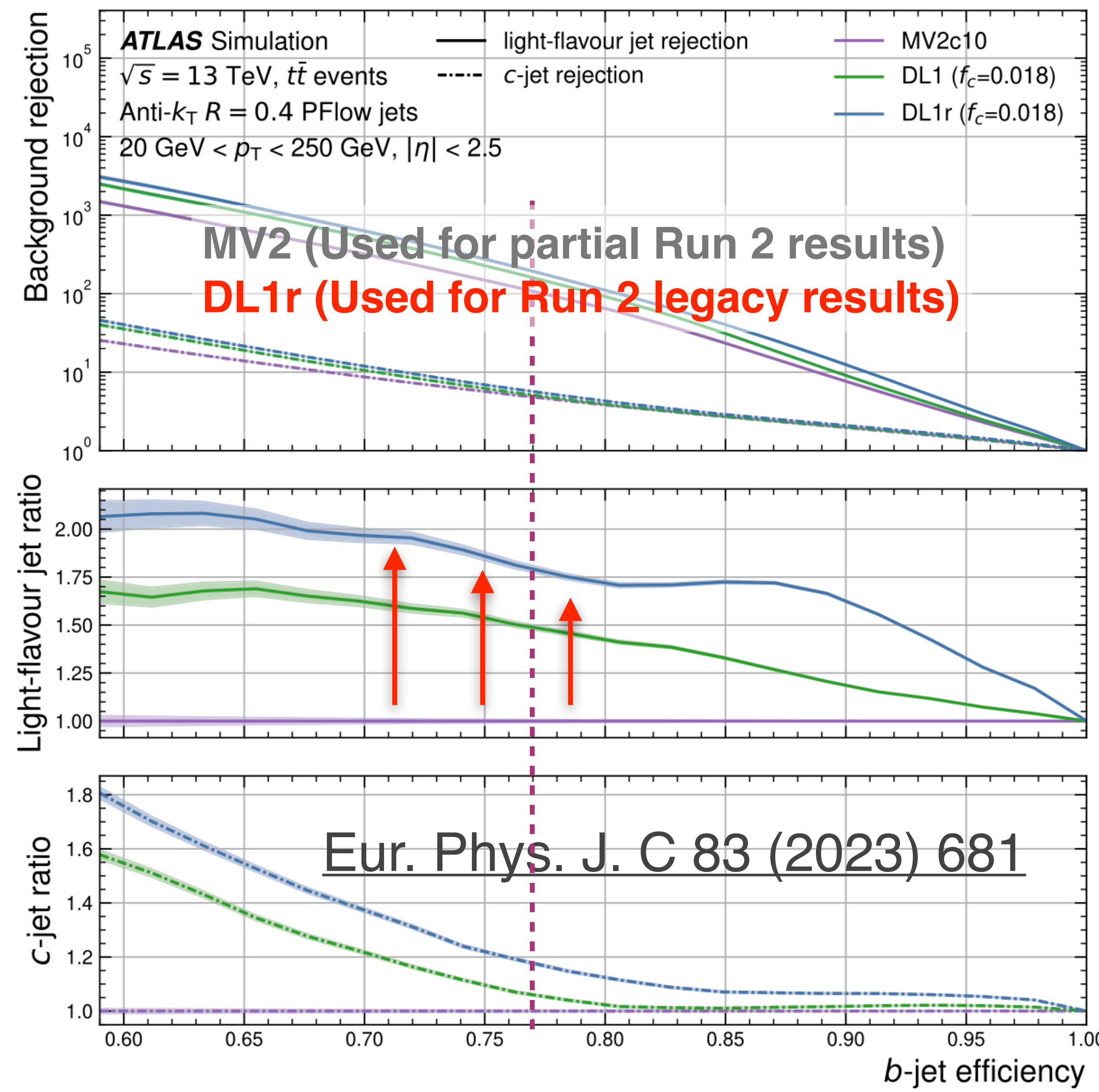
Object reconstruction improvements

Jets



All HH analyses are using particle-flow jets.

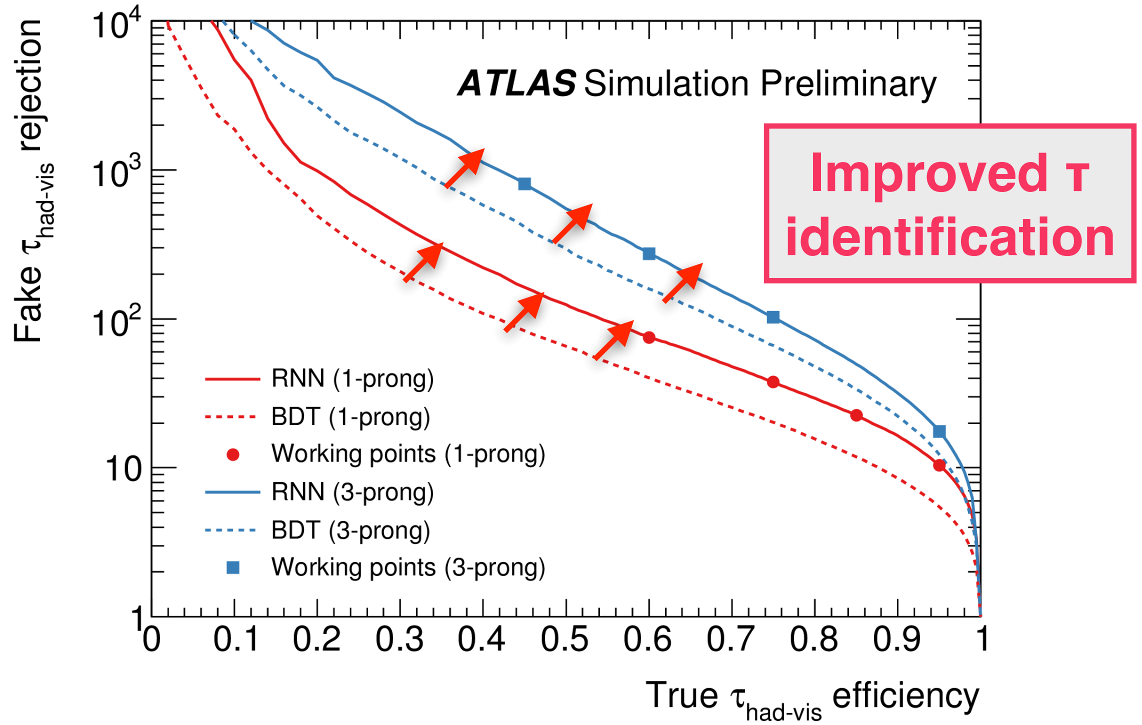
b-tagging



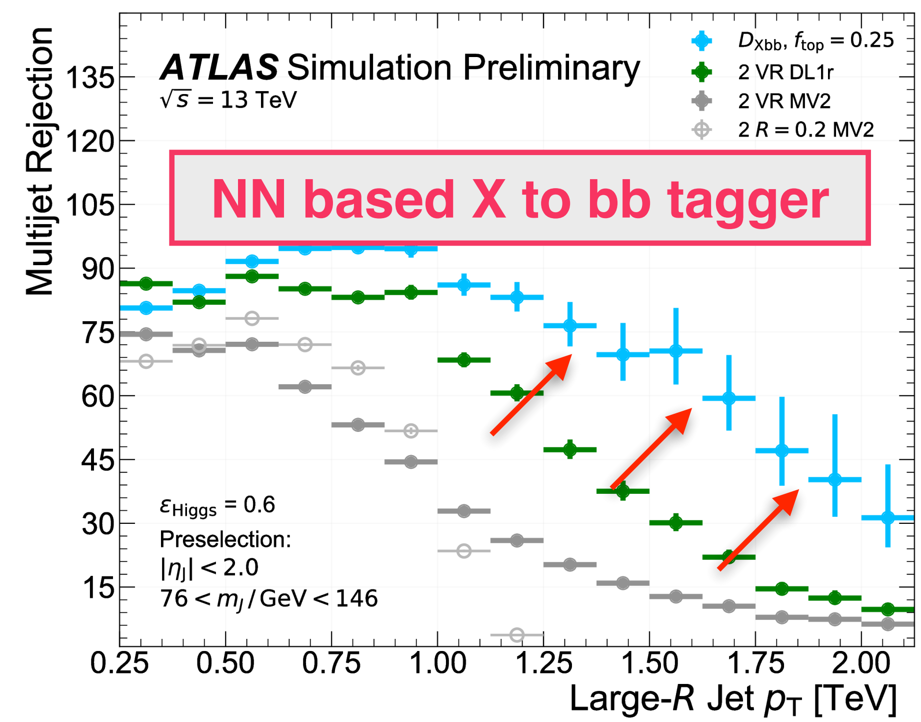
All HH analyses are using DL1r 77% efficiency working point.

Other performance highlights

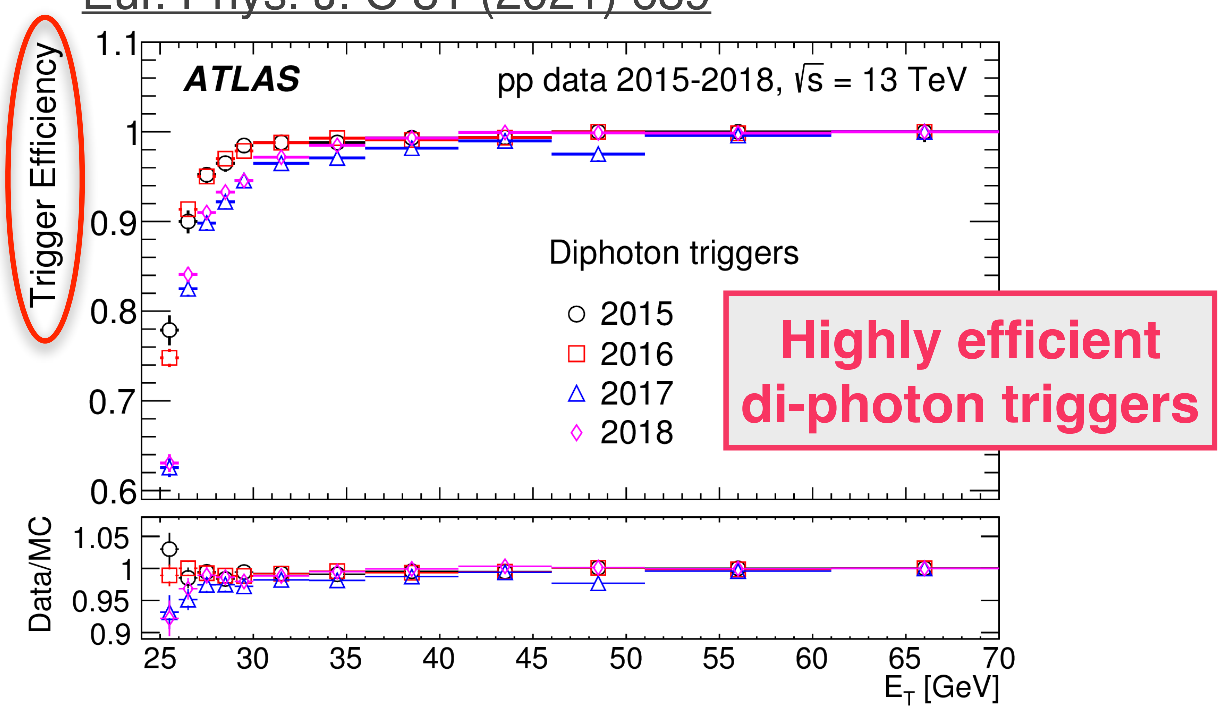
ATL-PHYS-PUB-2019-033



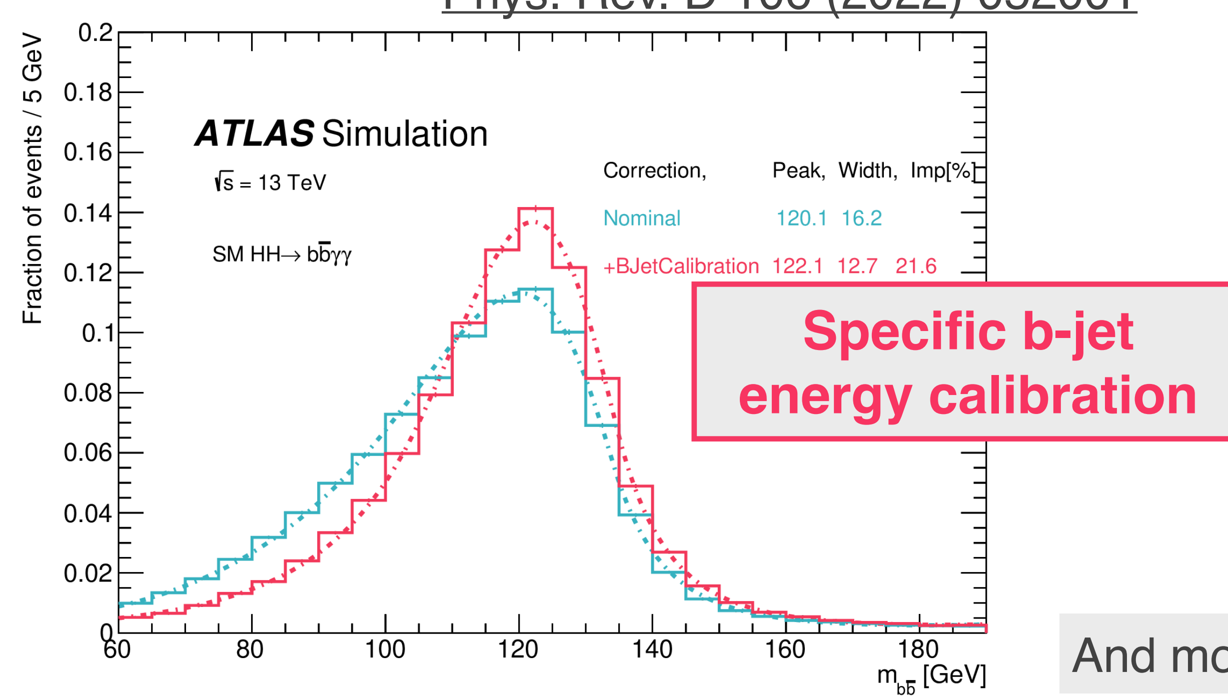
ATL-PHYS-PUB-2020-019



Eur. Phys. J. C 81 (2021) 689



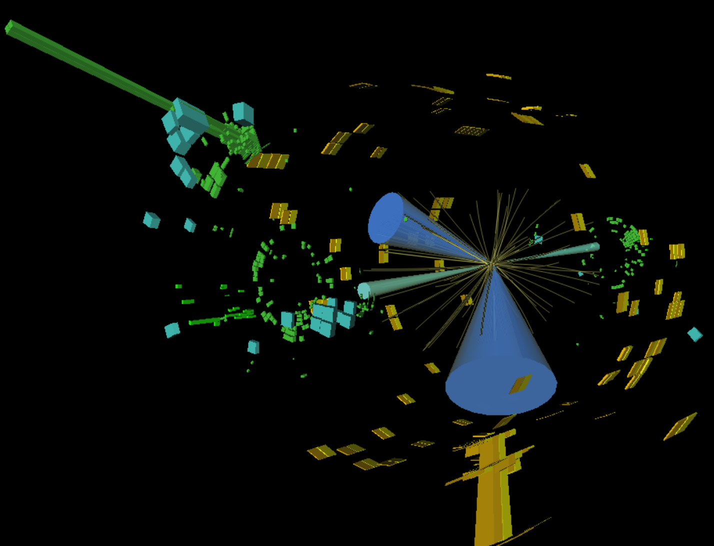
Phys. Rev. D 106 (2022) 052001

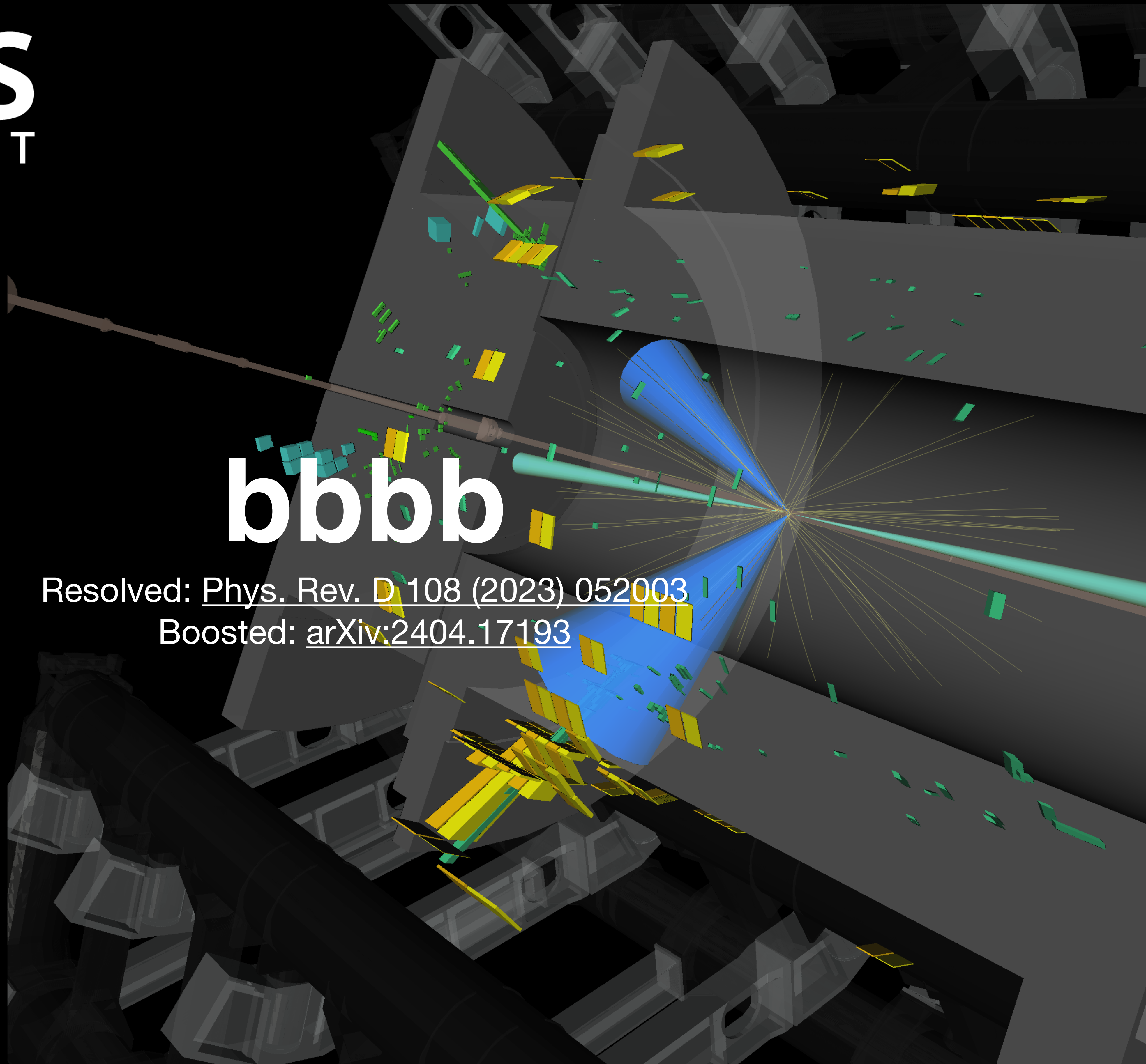


And more ...

ATLAS EXPERIMENT

Run: 311402
Event: 2695204841
2016-10-25 19:04:17 CEST

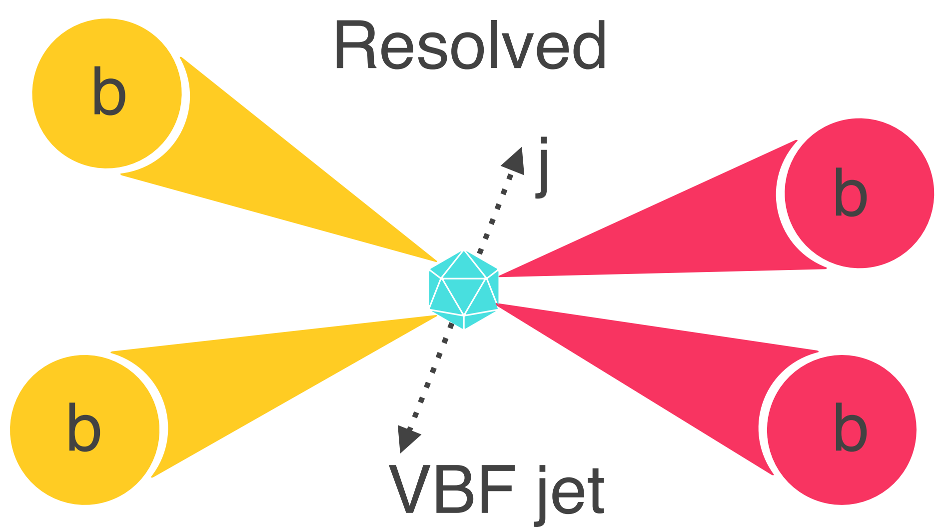




bbbb

Resolved: Phys. Rev. D 108 (2023) 052003
Boosted: arXiv:2404.17193

bbbb selection and categorisation

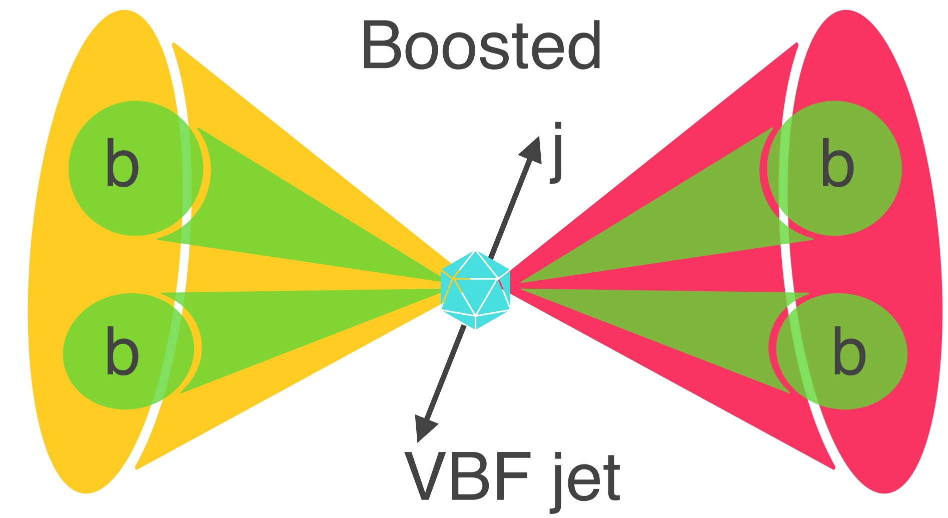


- b-jet trigger
- ≥ 4 b-jets p_T > 40 GeV
- $|\Delta\eta_{HH}| < 1.5$
- Veto Top-quark decay
- Categorised based on $|\Delta\eta_{HH}|$ & X_{HH}

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

→ **ggF categories**

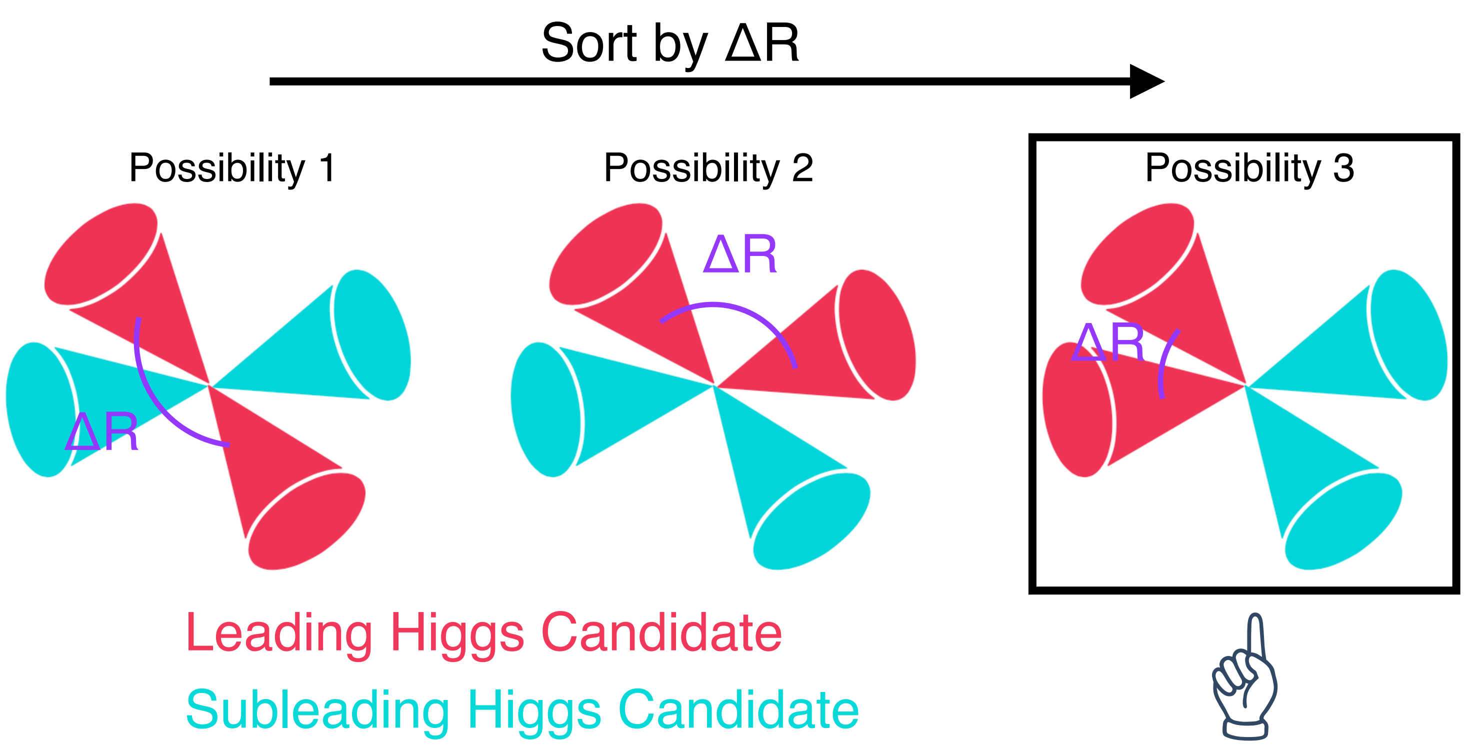
VBF jets $|\Delta\eta_{jj}| > 3$, $m_{jj} > 1$ TeV → **VBF categories**

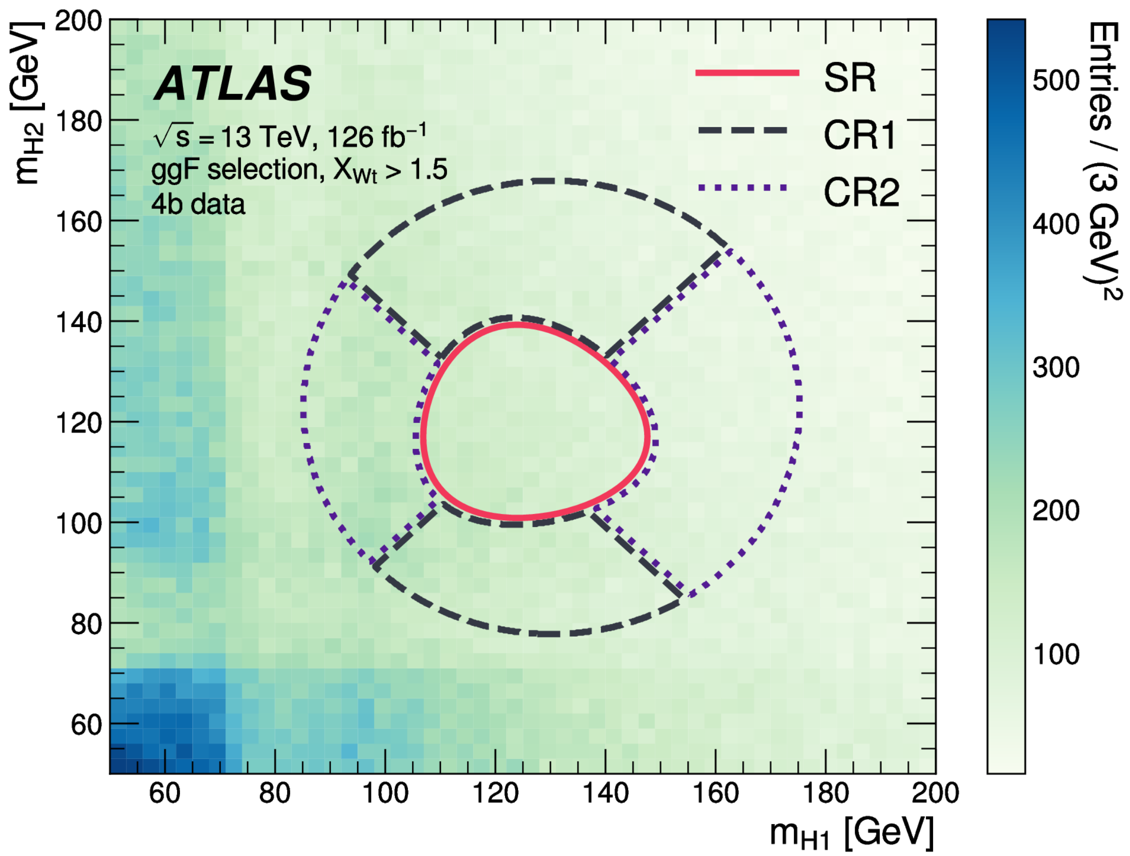


- Large-R jet trigger
- ≥ 2 Xbb-tagged jets
- p_T^H > 450 (lead) 250 (sub) GeV
- VBF jets $|\Delta\eta_{jj}| > 3$, $m_{jj} > 1$ TeV

→ **VBF categories**

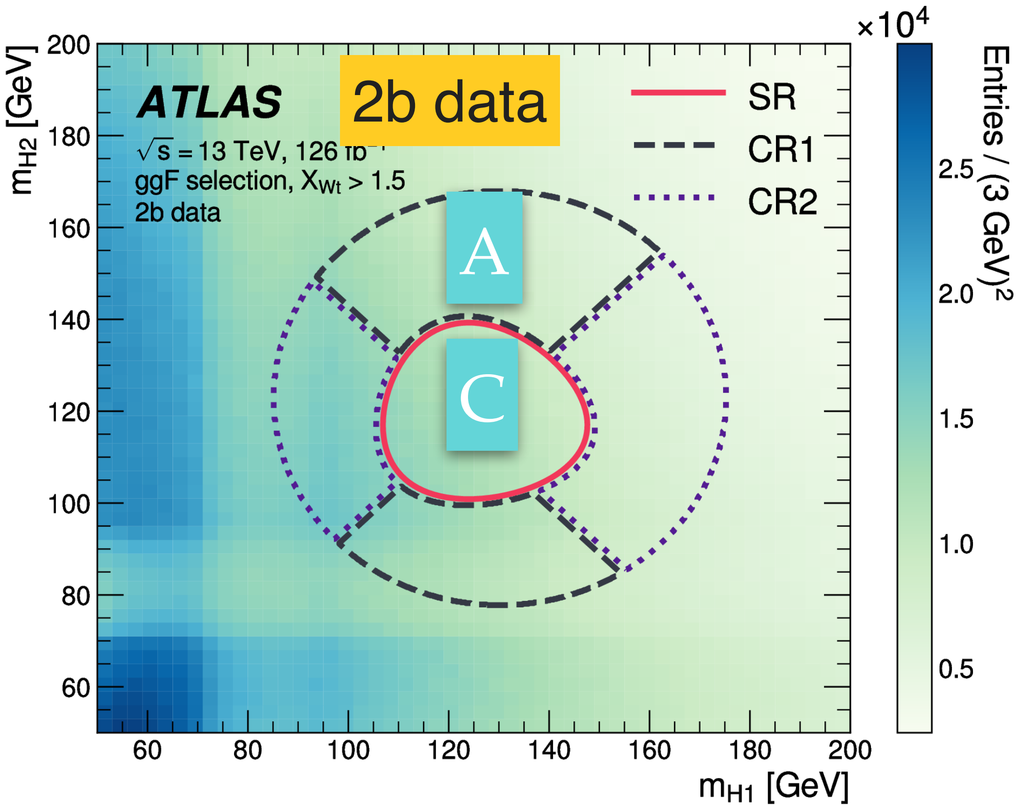
bbbb pairing (resolved)

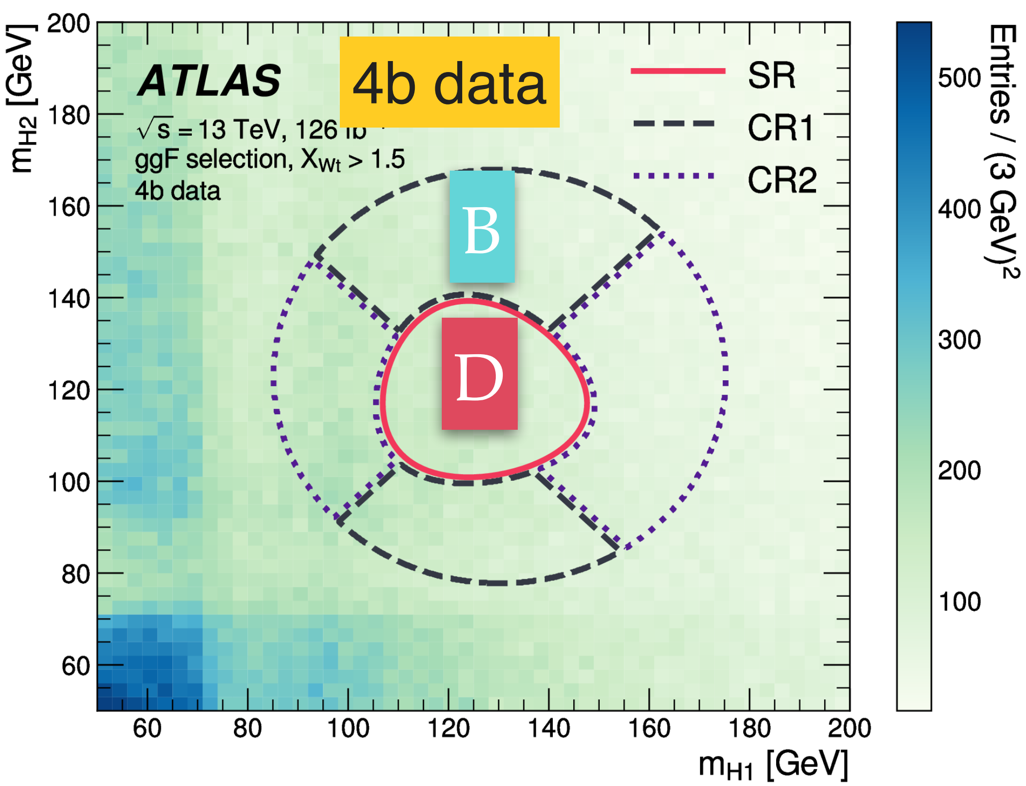




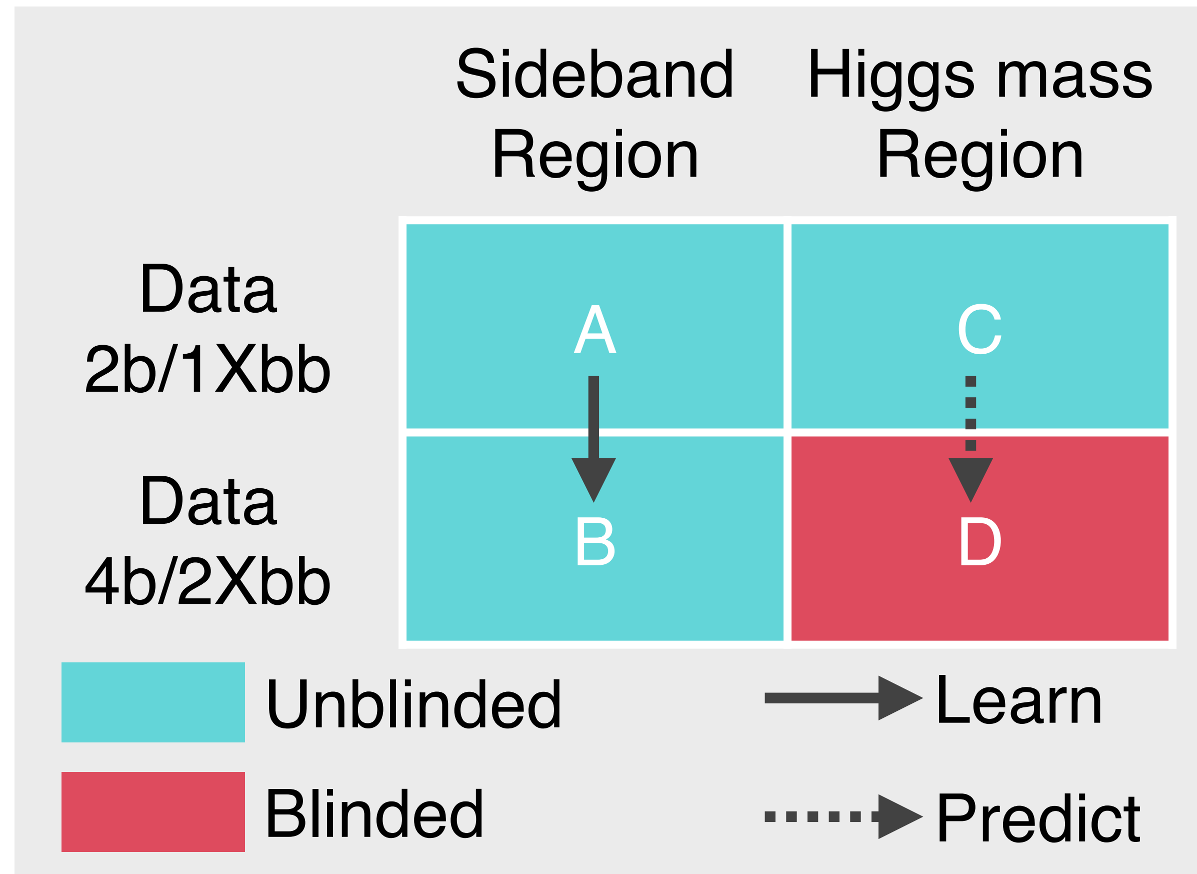
- Minimal ΔR_{jj} in leading Higgs (H_1)
- No mass information used to avoid sculpting the H_1-H_2 mass plane

bbbb background estimation



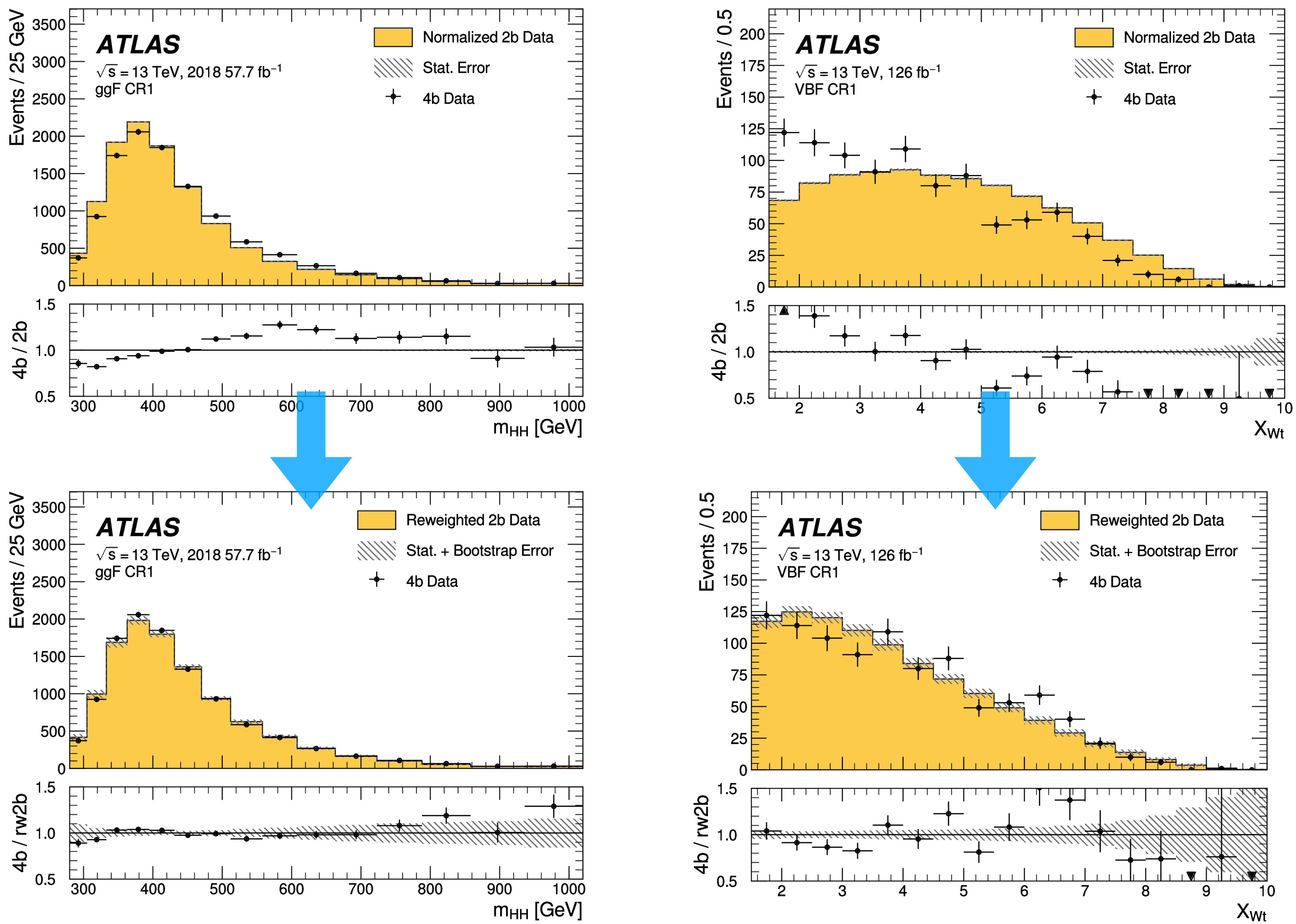


★ Major background: QCD multijet



- In boosted analysis, a normalisation factor is derived
- In resolved analysis, neural networks learn transfer factor.
  - Easily handle multiple inputs simultaneously

bbbb bkg estimation performance



NN improves the agreement with 4b events significantly.

bbbb results

- Fit m_{HH} (resolved) and BDT (boosted) to extract results

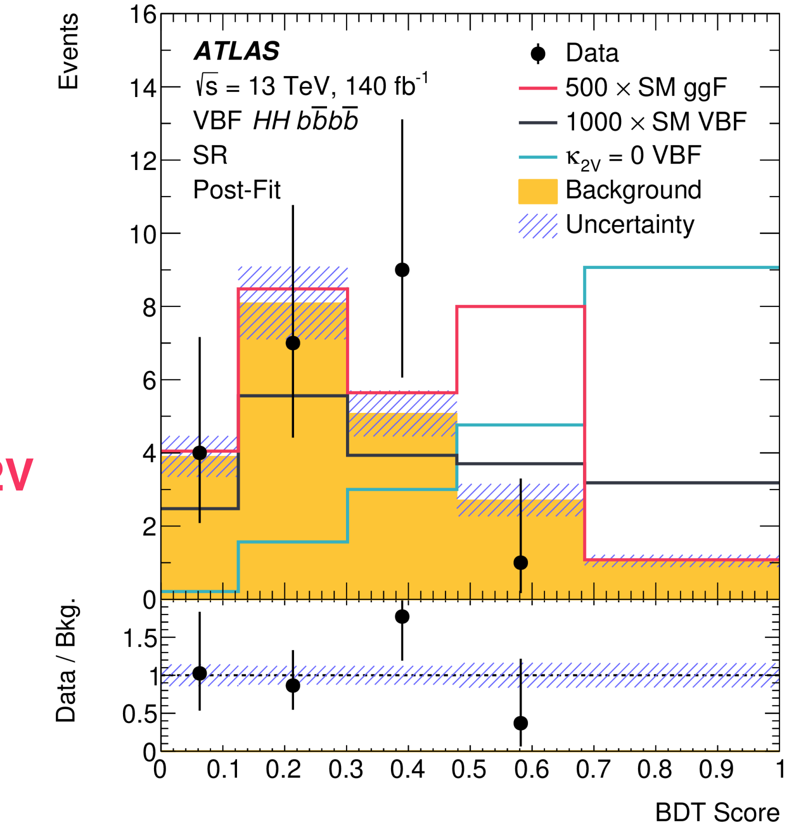
HH 95% CL limit $\mu_{HH} < 5.4$ (exp 8.1 assume no HH)

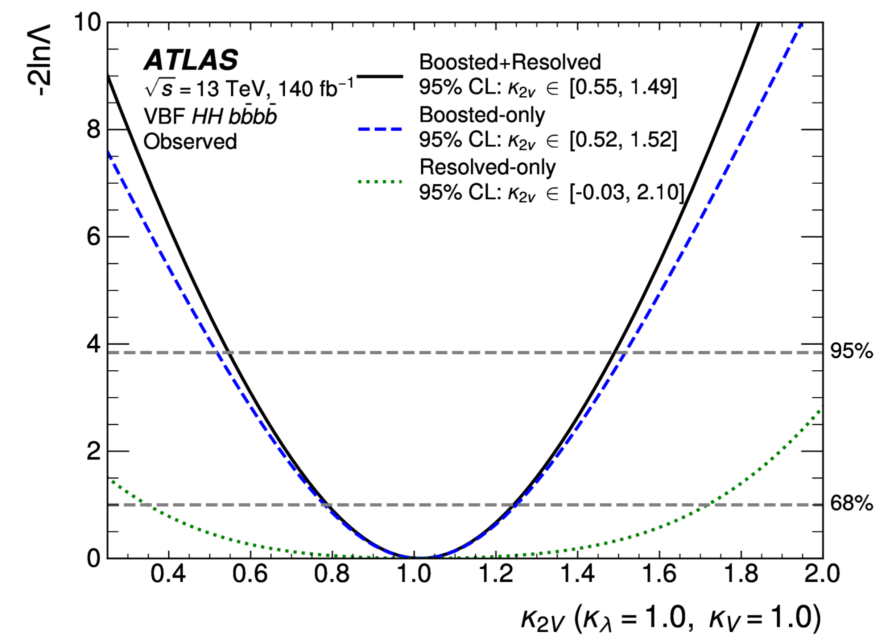
95% CL interval: $0.55 < \kappa_{2V} < 1.49$, leading channel in κ_{2V}

95% CL interval: $-3 < \kappa_{\lambda} < 11$

Factor 2.5 improvement in μ_{HH} and 2-3× improvement in κ intervals

Dominant uncertainties:
- Xbb calibration
- Background estimation
- Signal cross section calculation

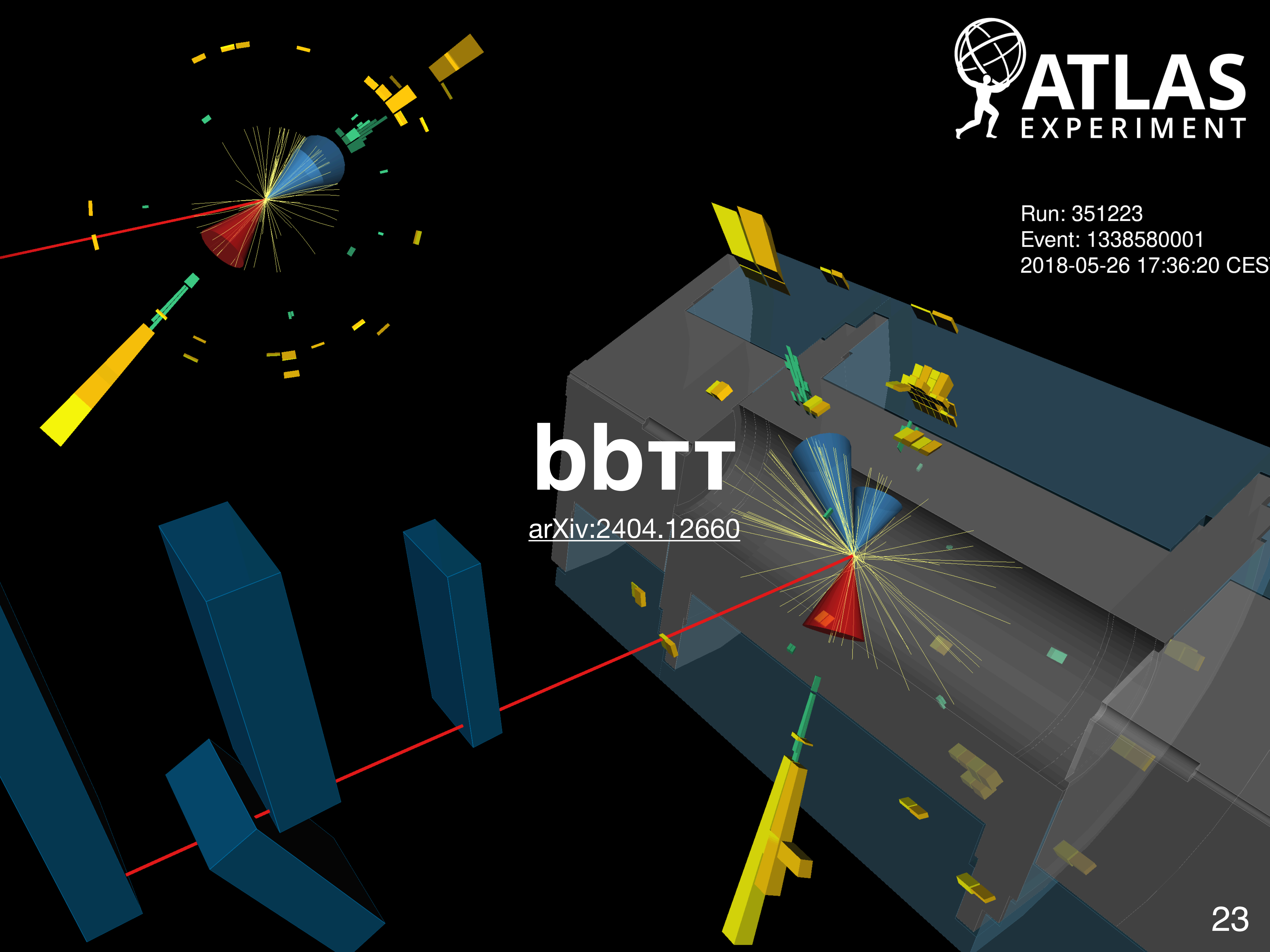




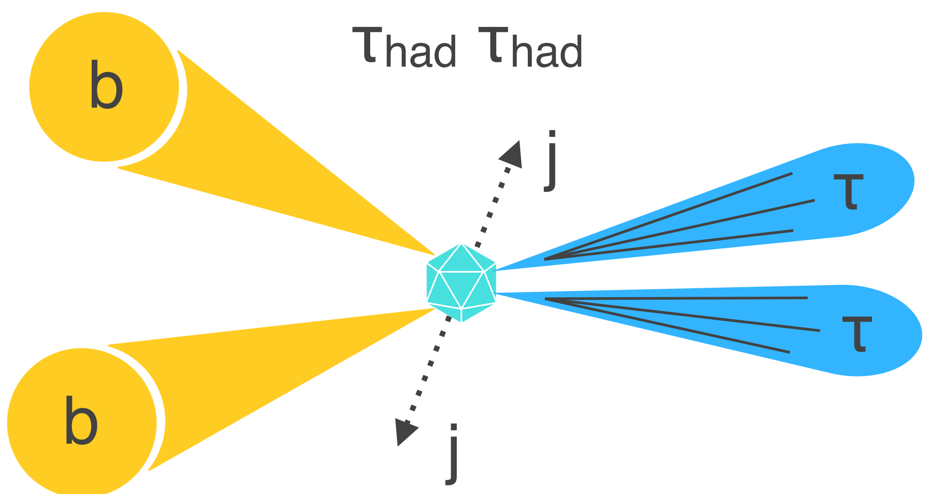
- ☑ Constraints on coefficients are derived under HEFT and SMEFT. Read for more
- ☑ Cross-section limits are placed in seven HEFT benchmark scenarios.

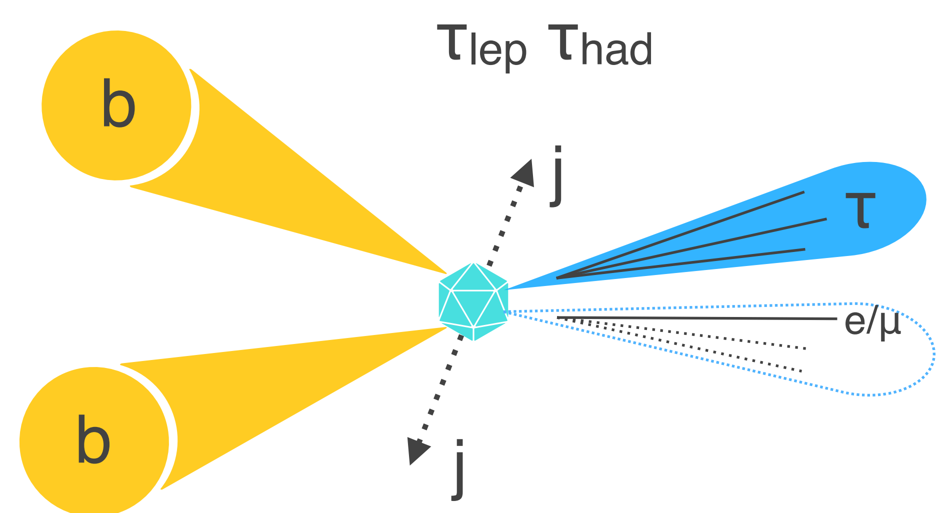
bbττ

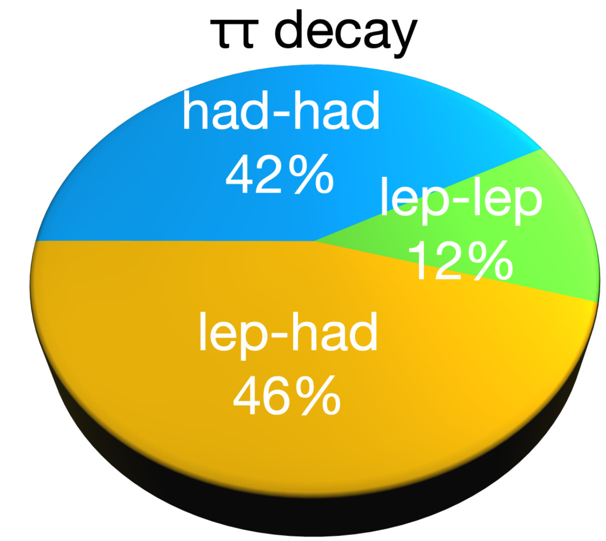
arXiv:2404.12660



bbττ selection and categorisation





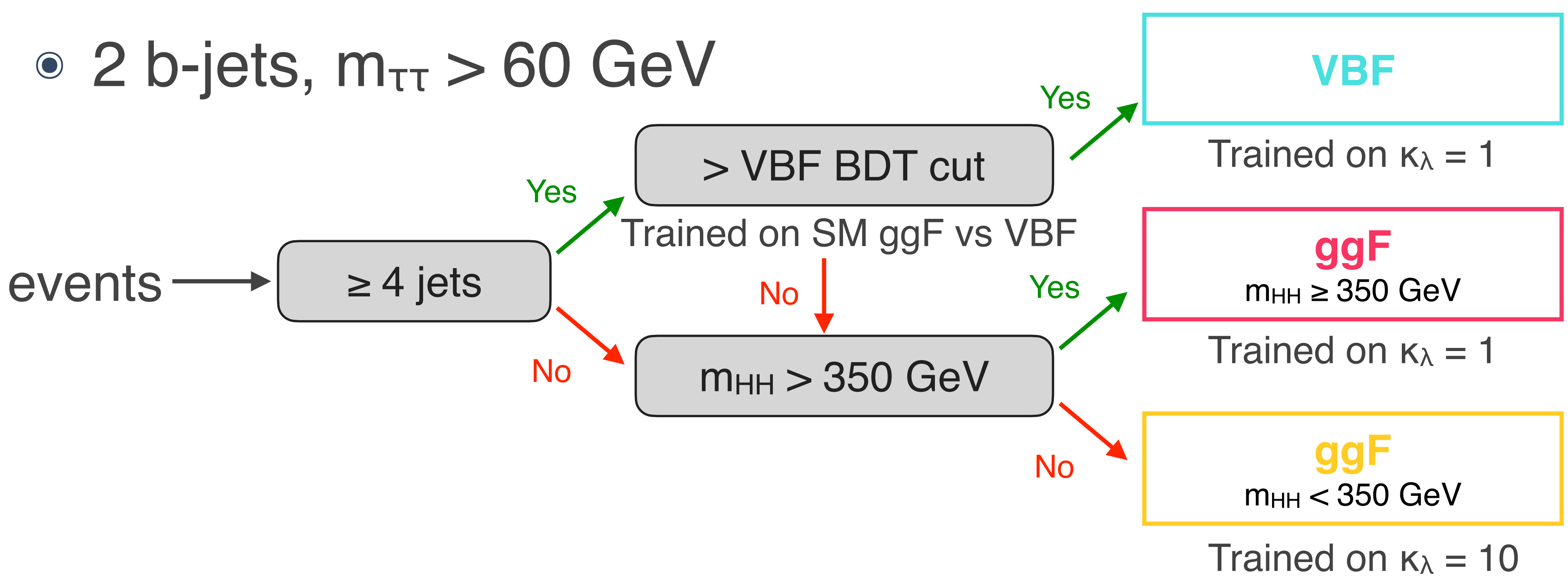


- Single-τ_{had} and di-τ_{had} triggers (high purity)
- 2 τ_{had}, e/μ veto

- Single ℓ trigger (large acceptance)
- 1 τ_{had}, 1 e/μ

- ℓ + τ_{had} trigger (low ℓ p_T)
- 1 τ_{had}, 1 e/μ

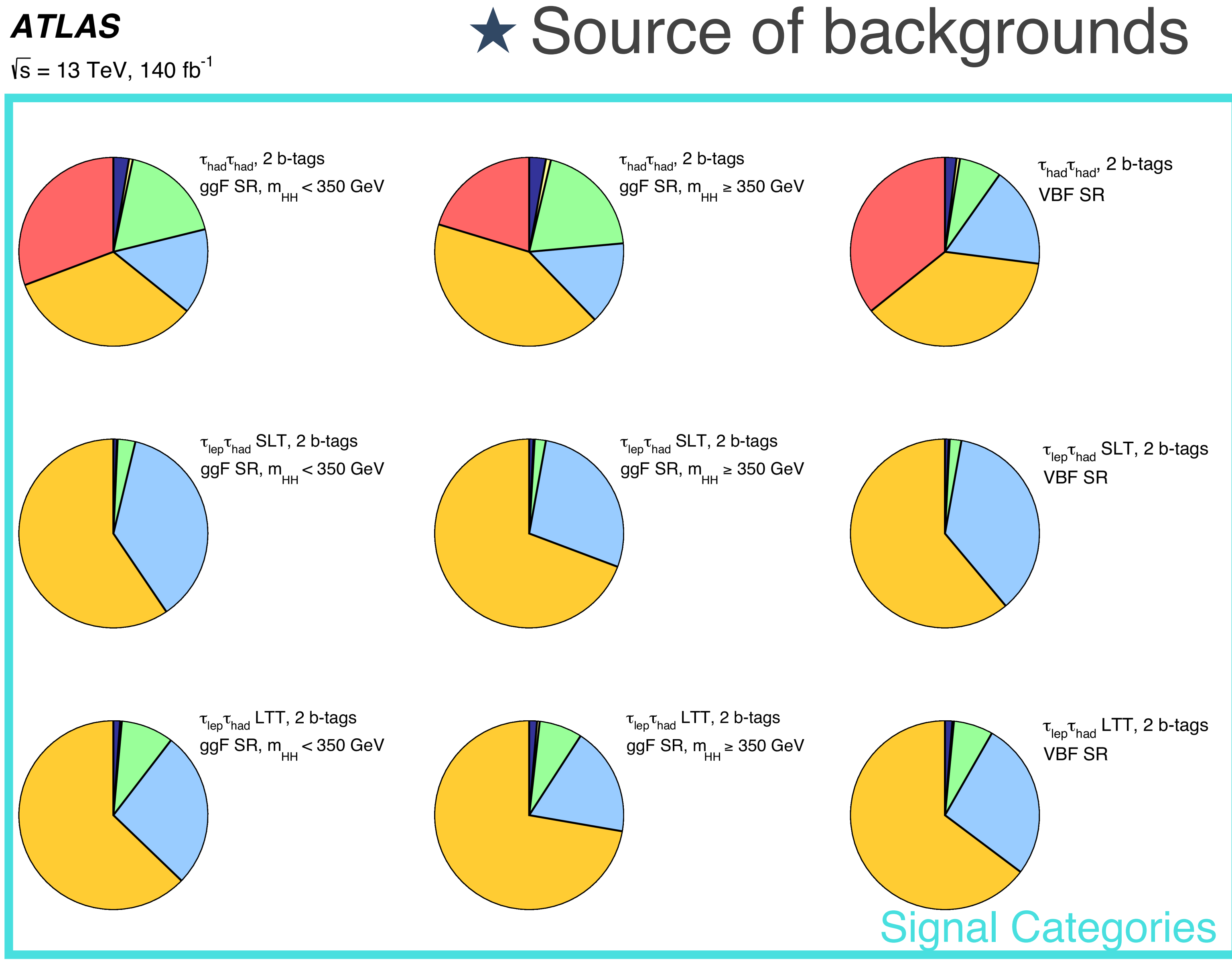
- 2 b-jets, $m_{\tau\tau}$ > 60 GeV

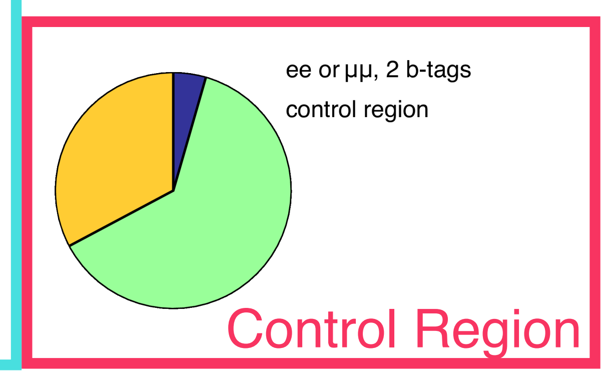


× 3 types of triggers = 9 categories

bbττ background estimation

★ Source of backgrounds





Fake τ_{had}

	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
Multijet	Combined fake factor method	Fake factor method
$t\bar{t}$		Fake τ_{had} scale factor method

Top quark (true τ)

Shape from MC, normalisation from fit

Z(→ττ) + heavy flavour

Shape from MC, normalisation from Z(→ee/μμ)+heavy flavour control region

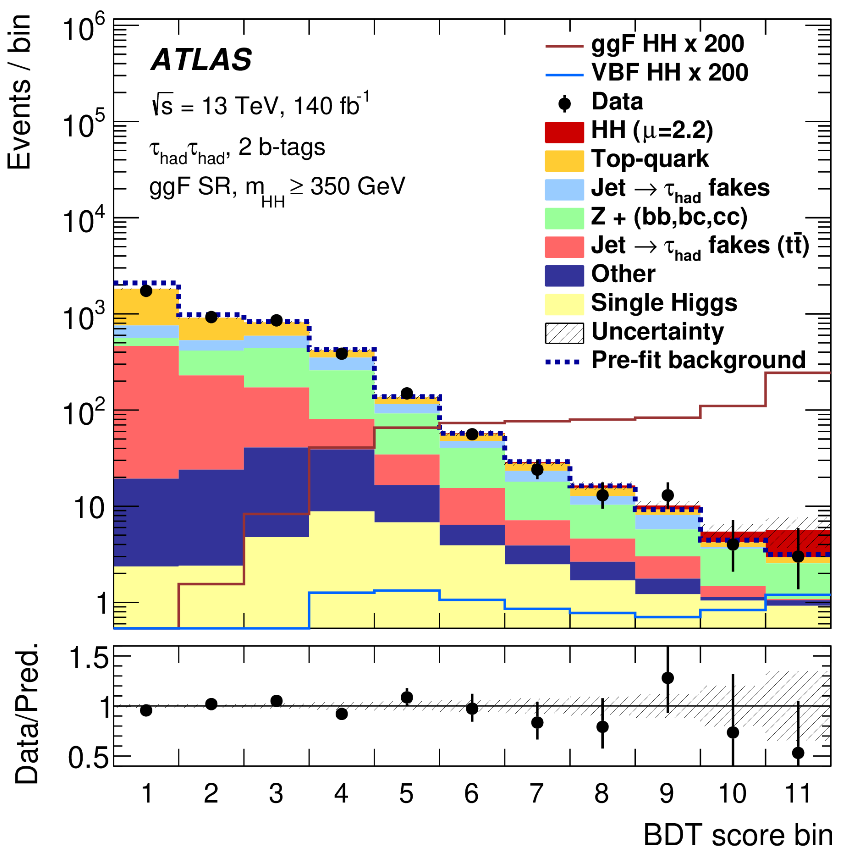
Single H & others

Estimated from MC

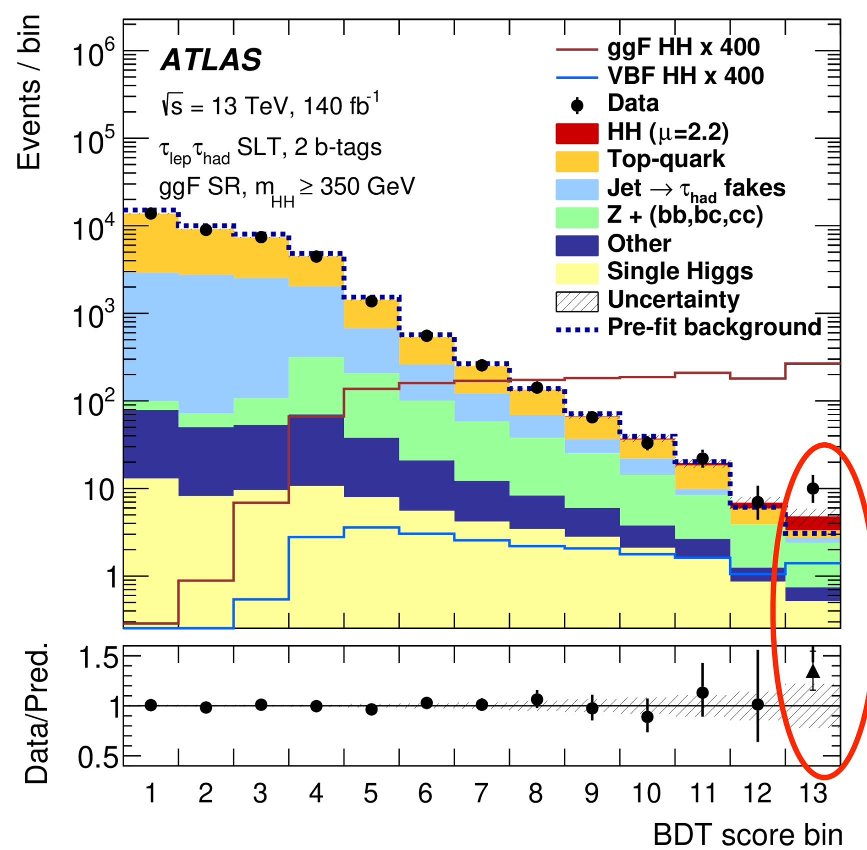
bbττ signal / background separation

- One BDT is trained in each SR – in total 9 BDTs

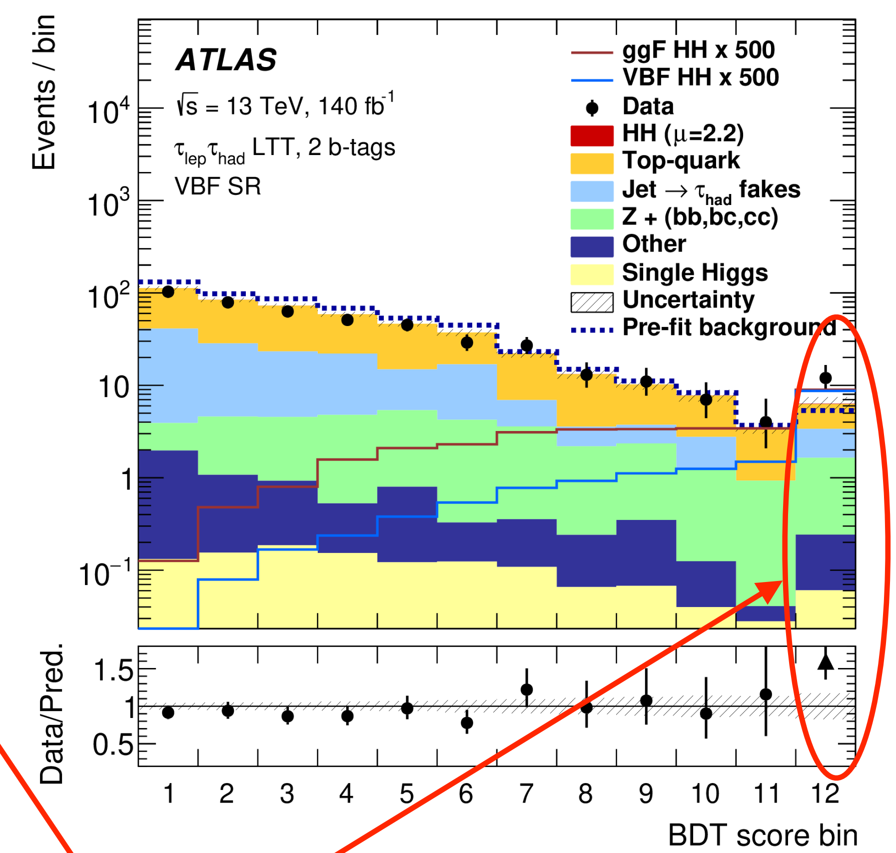
$\tau_{had}\tau_{had}$
ggF $m_{HH} \geq 350$ GeV



$\tau_{lep}\tau_{had}$ single lepton trigger
ggF $m_{HH} \geq 350$ GeV



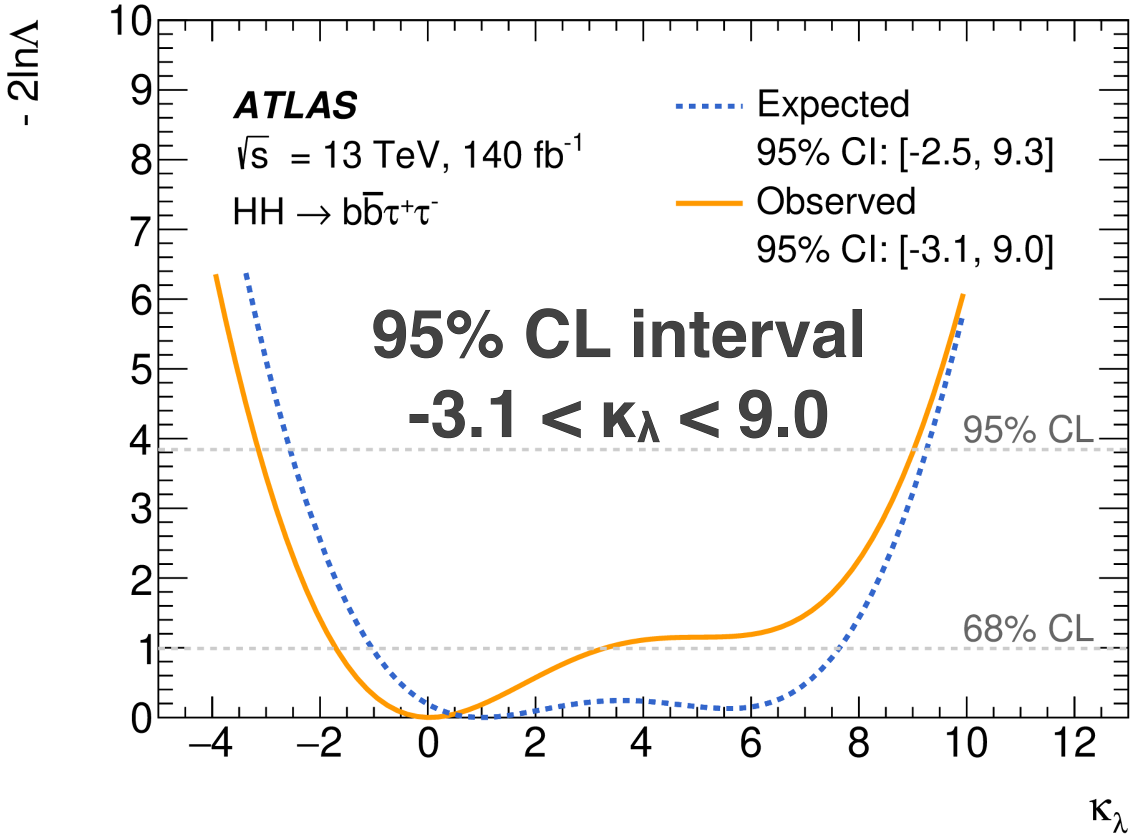
$\tau_{lep}\tau_{had}$ lepton tau trigger
VBF

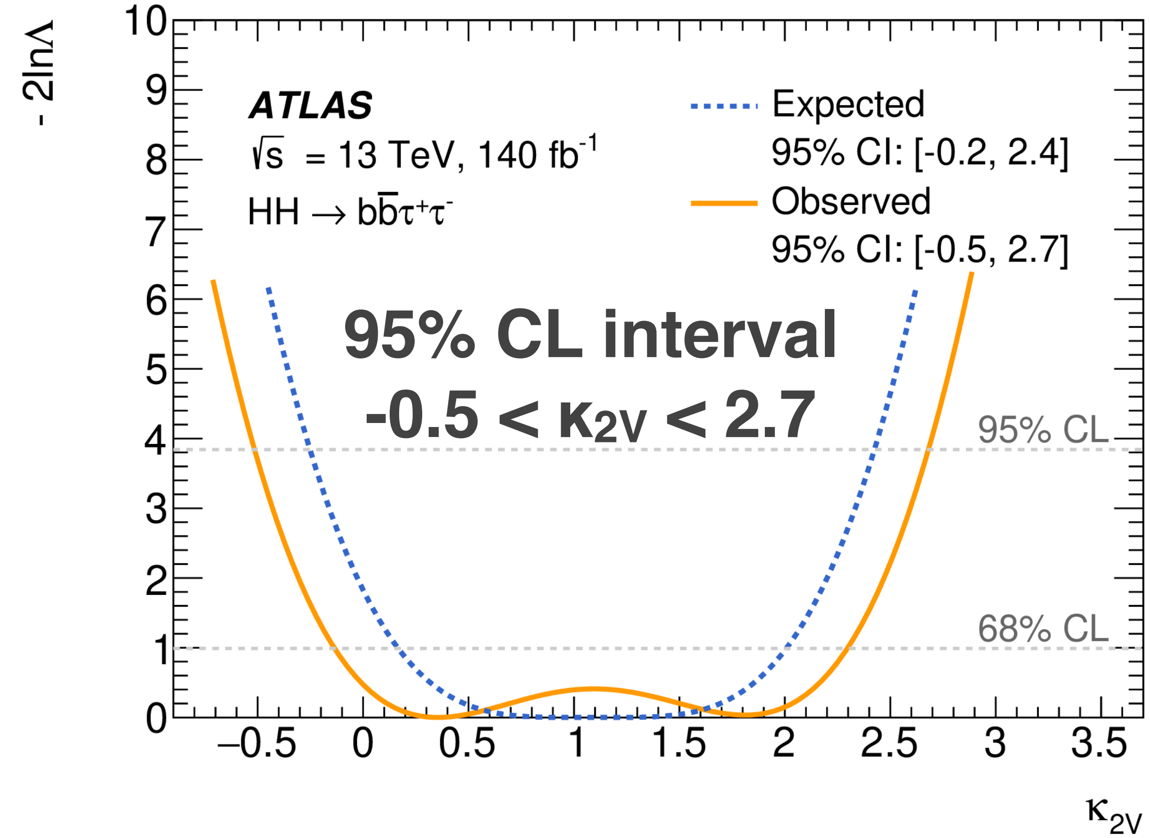


Upward fluctuations in data

Other BDT distributions in backup

bbττ results





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

Up to 20% sensitivity improvement compared to previous full Run 2 result

Dominant uncertainties:

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

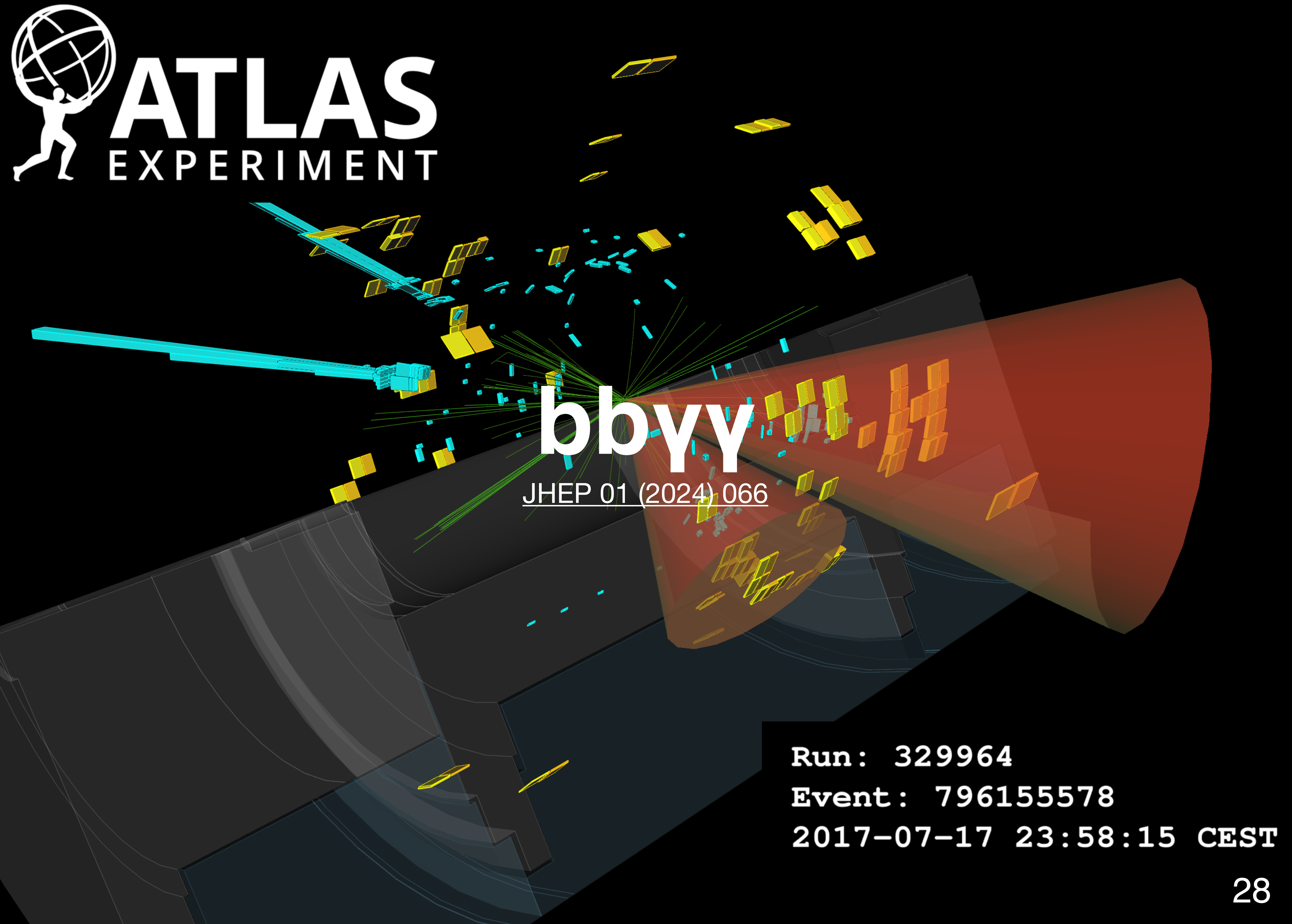
☑ Constraints on HEFT and SMEFT coefficients and seven HEFT benchmark scenarios.

Read for more

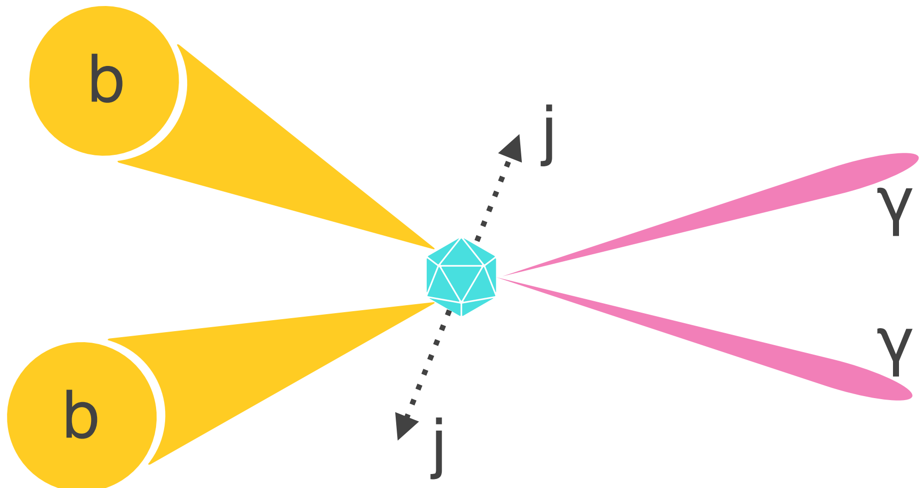
Compatibility with previous full Run 2 result is maximum 2.5σ in SLT.

bbγγ

JHEP 01 (2024) 066



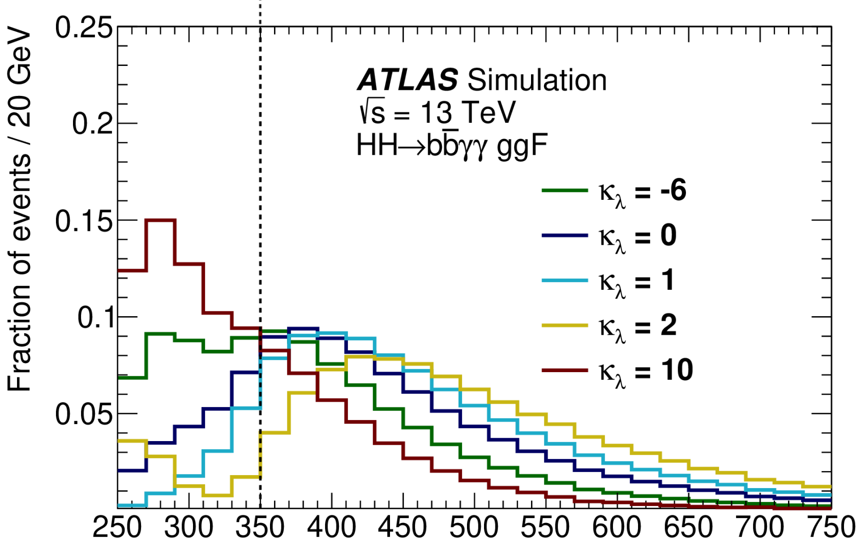
bbγγ selection and categorisation



VBF jet pair selected by a dedicated BDT

- Diphoton triggers
- 2 b-jets and 2 photons
  - $105 < m_{\gamma\gamma} < 160$ GeV
- Suppress $t\bar{t}H$ and $t\bar{t}$
  - Lepton (e, μ) veto
  - < 6 central jets

Targets BSM κ_λ | High mass sensitive for SM and BSM κ_{2V}

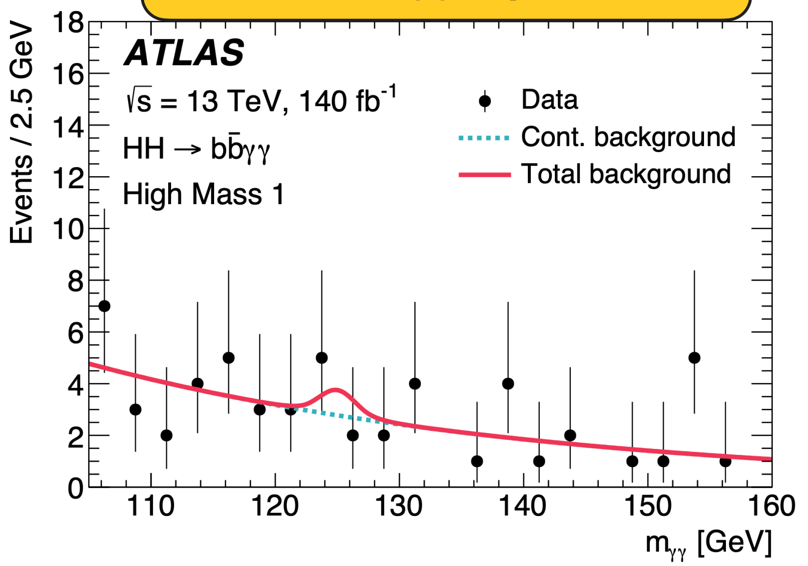


$m_{b\bar{b}\gamma\gamma} + (125 - m_{b\bar{b}}) + (125 - m_{\gamma\gamma})$ GeV

High mass BDT
3 categories defined by BDT score

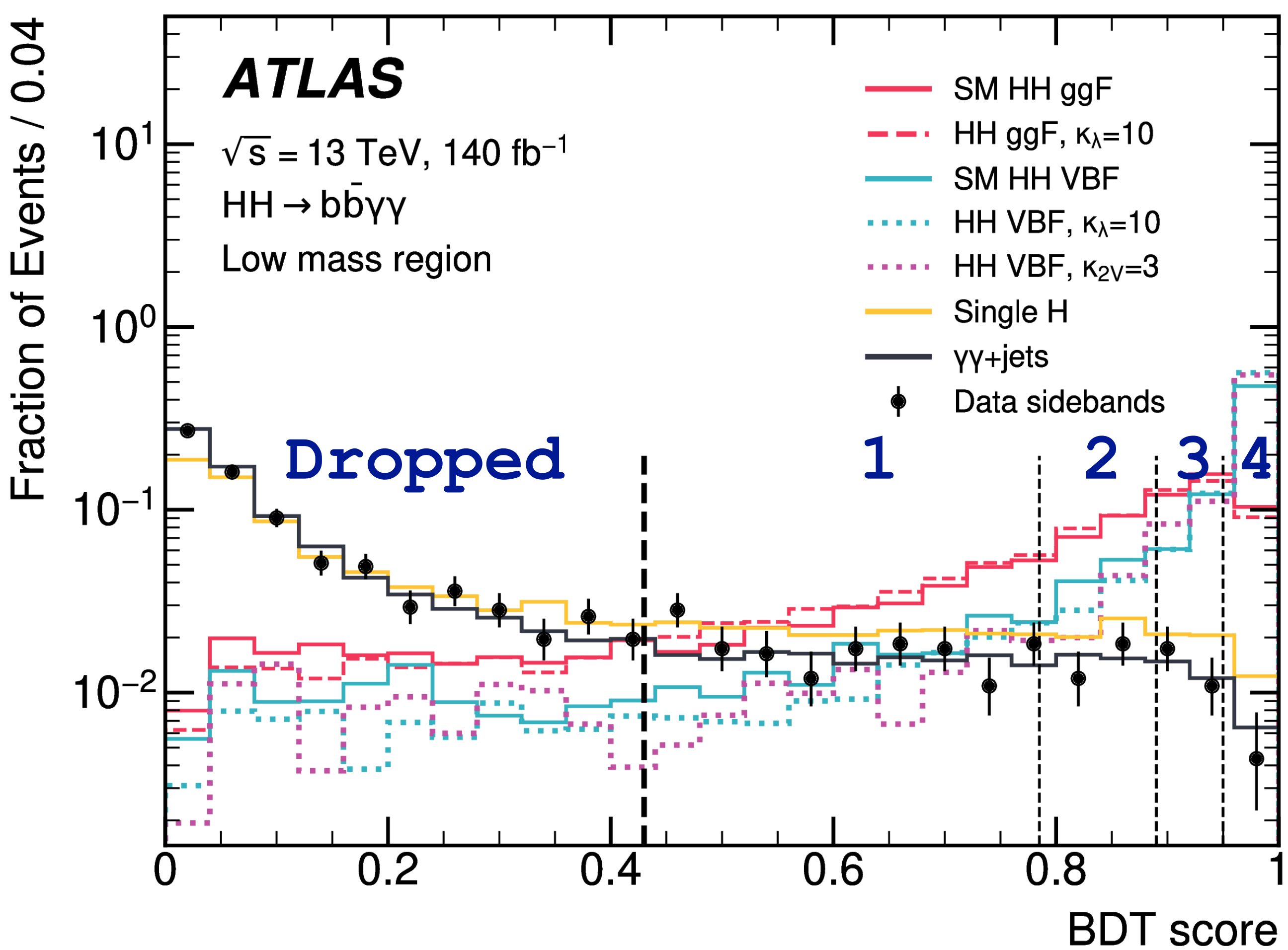
Low mass BDT
4 categories defined by BDT score

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

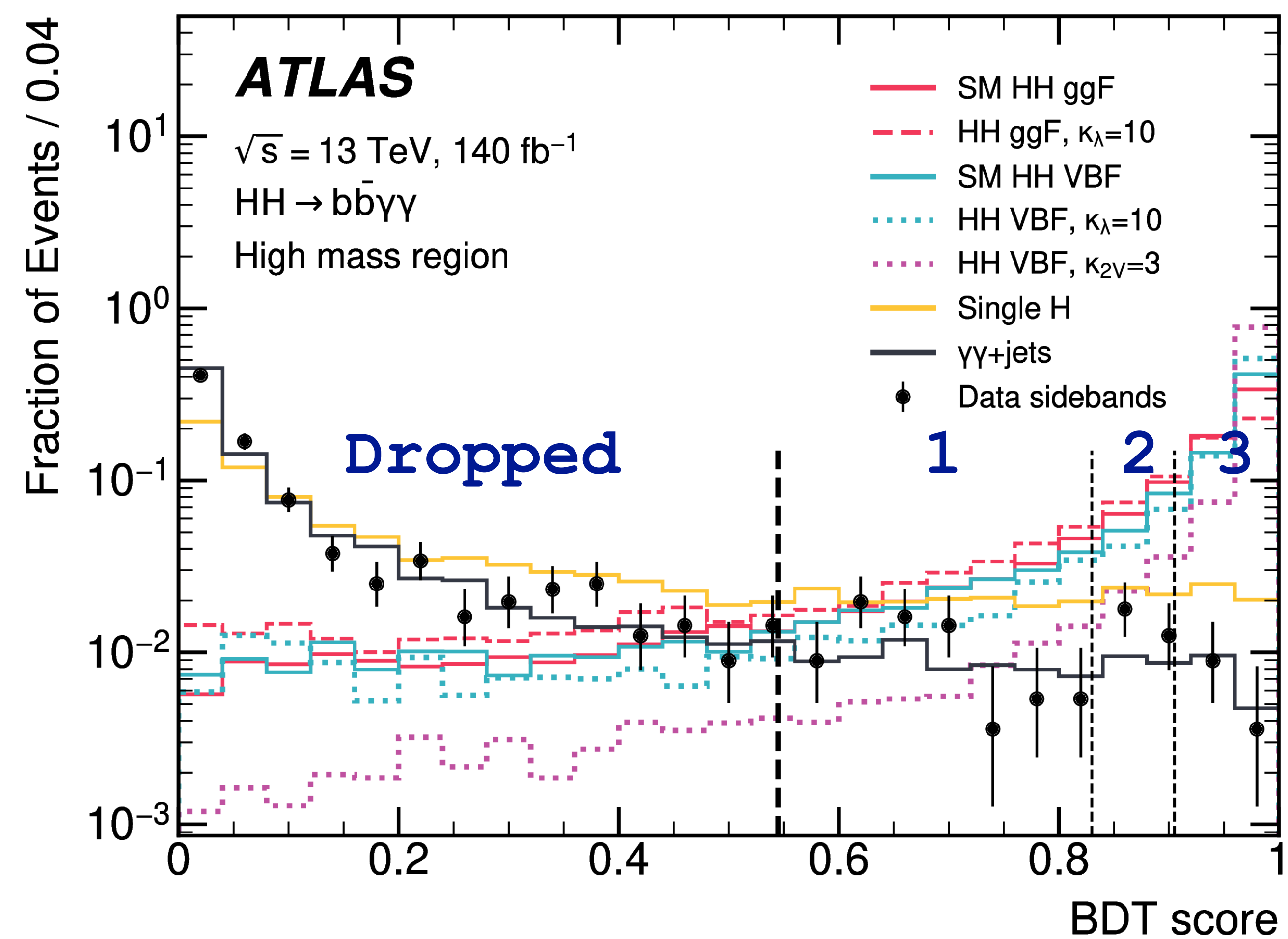


bbγγ categorisation BDT

Low mass BDT
Optimise for large value κ_λ
(soft spectrum)

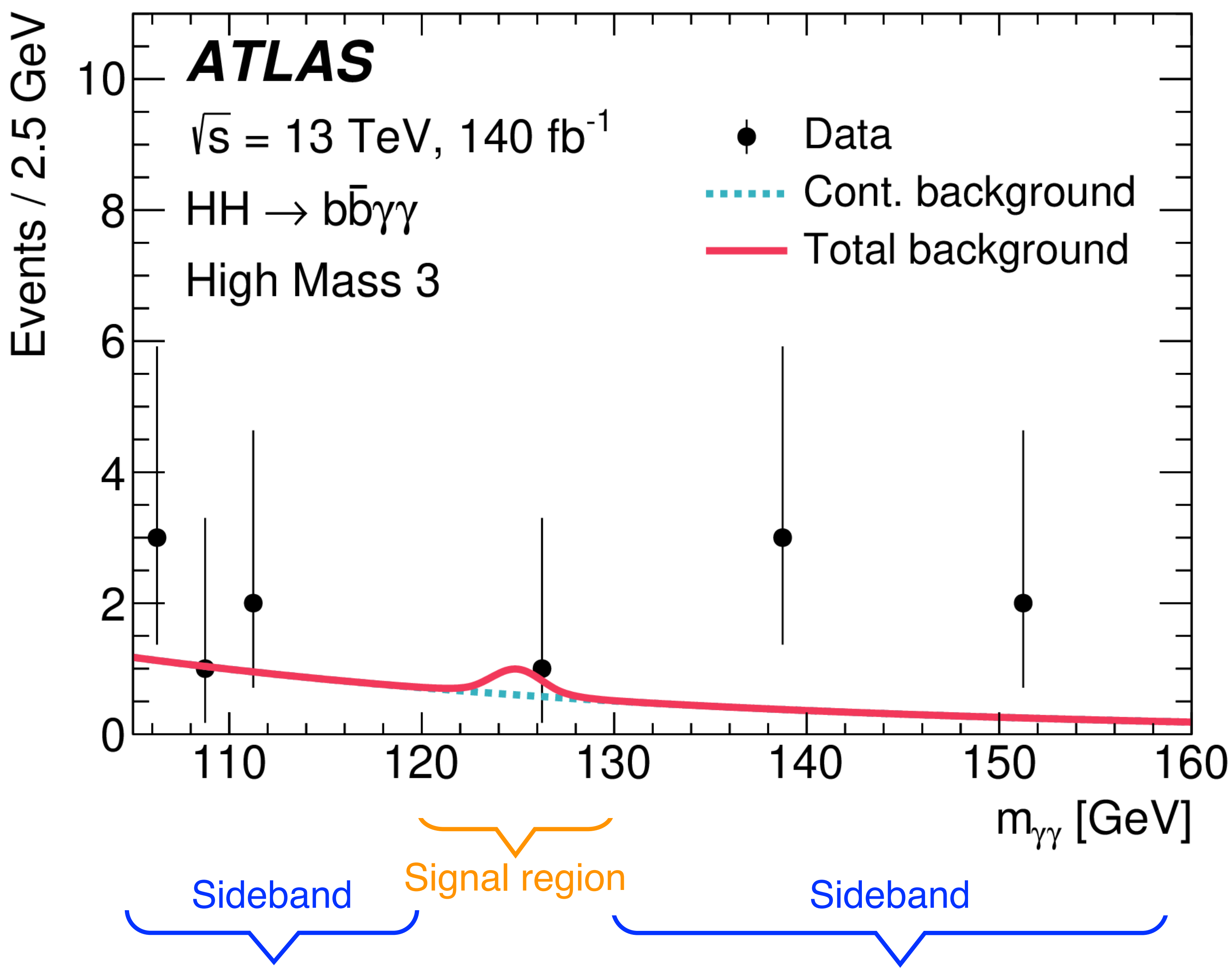


High mass BDT
optimise for SM value κ_λ and κ_{2V}
(hard spectrum)



Training against background:
single H and γγ-continuum

bbγγ signal and background modelling



HH and Single H

Modelled by double-sided Crystal Ball function. Parameters estimated from MC

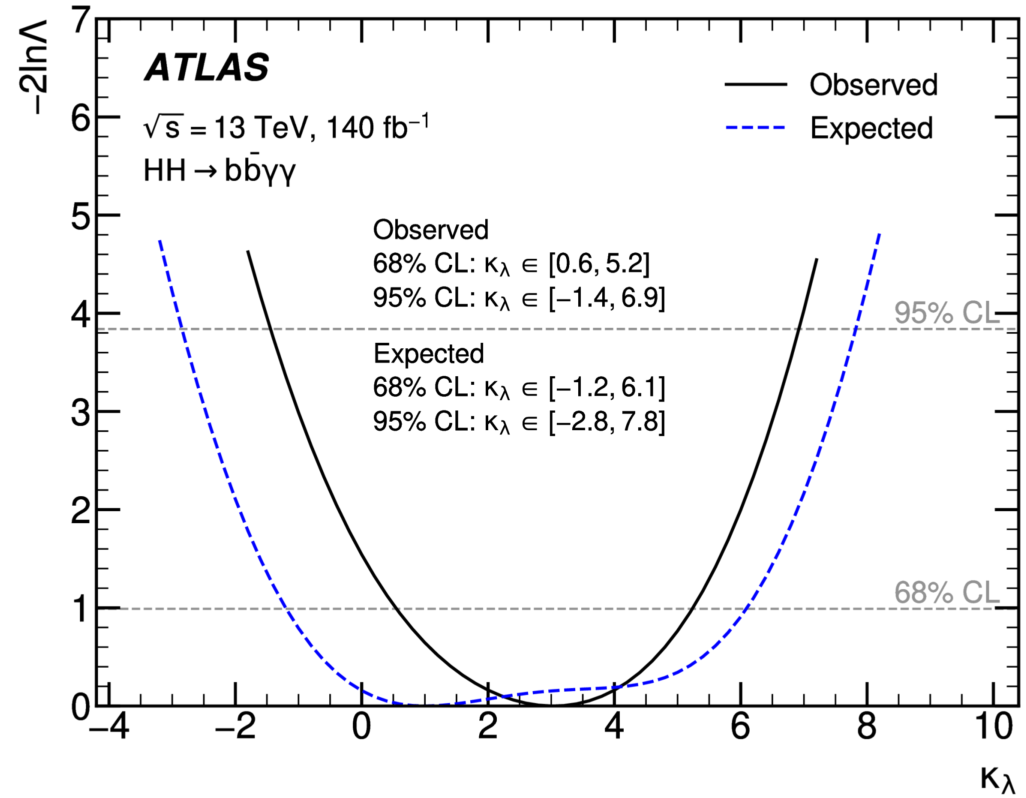
γγ + something

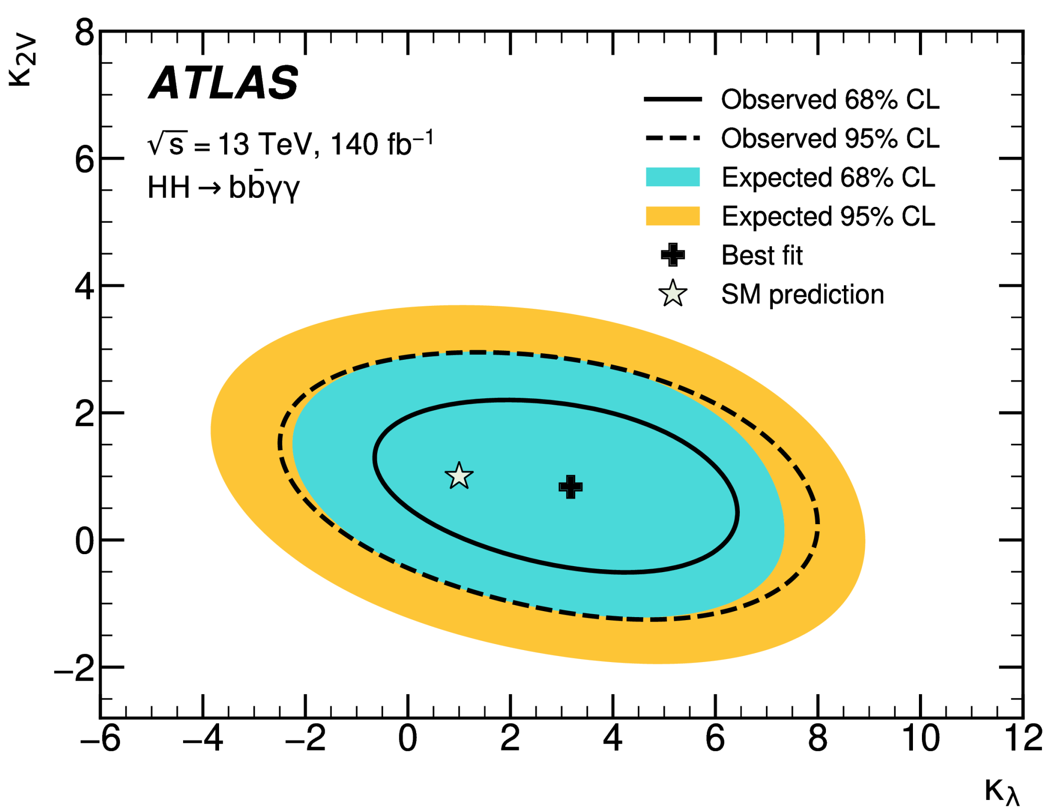
Modelled using exponential function. Parameters derived from data sideband

	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

Downward fluctuations in data

bbγγ results





95% CL interval $-1.4 < \kappa_\lambda < 6.9$:
leading channel in κ_λ constraint

95% CL interval $-0.5 < \kappa_{2V} < 2.7$

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

Up to 17% sensitivity improvement compared to previous full Run 2 result

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

- Constraints on HEFT and SMEFT coefficients and seven HEFT benchmark scenarios. Read for more

$bb\ell\ell+E_T^{miss}$

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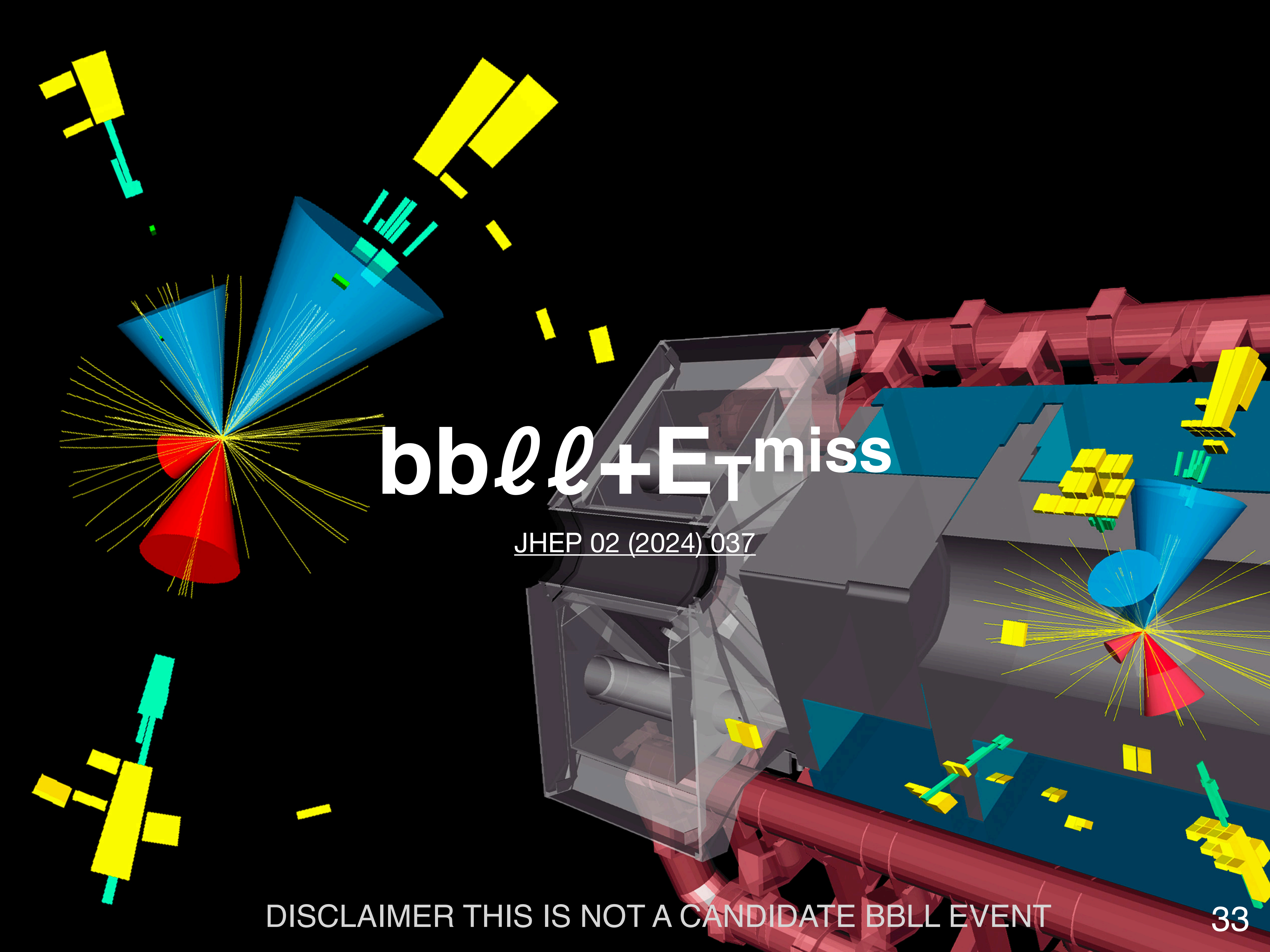
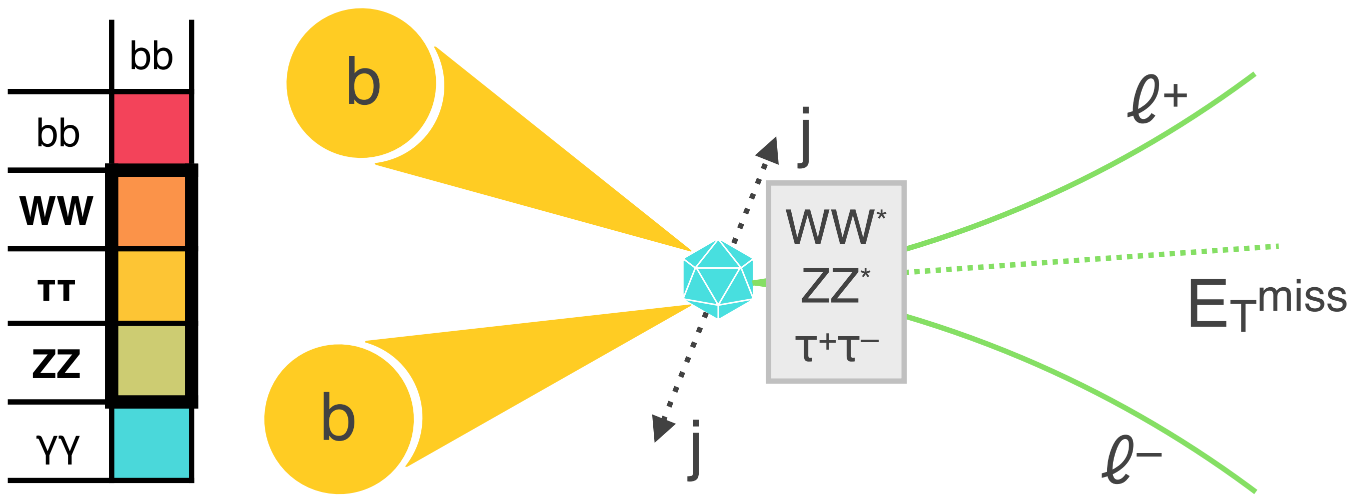
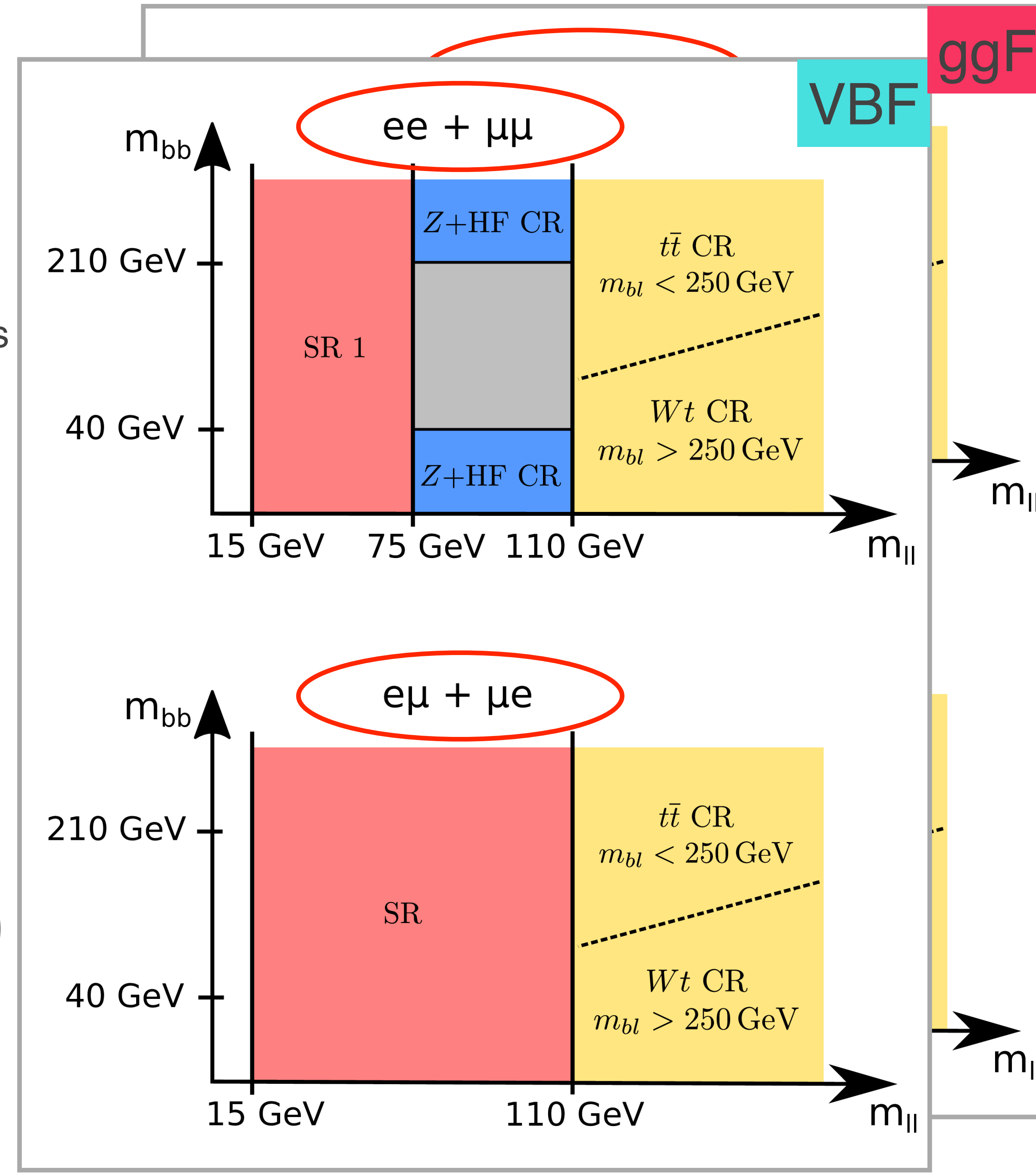


DISCLAIMER THIS IS NOT A CANDIDATE BBLL EVENT

$bb\ell\ell+E_T^{miss}$ selection



- Single lepton and dilepton triggers
- 2 light opposite charge leptons (same flavour or different flavours)
- 2 b-jets



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

Yes → VBF category

No → ggF category

bbℓℓ+E_T^{miss} signal/background separation

- BDT trained in VBF category
  - Signal: VBF HH $\kappa_\lambda = 0$
  - Bkg: ggF HH, other SM processes
- 5 most significant bins are used in final fit

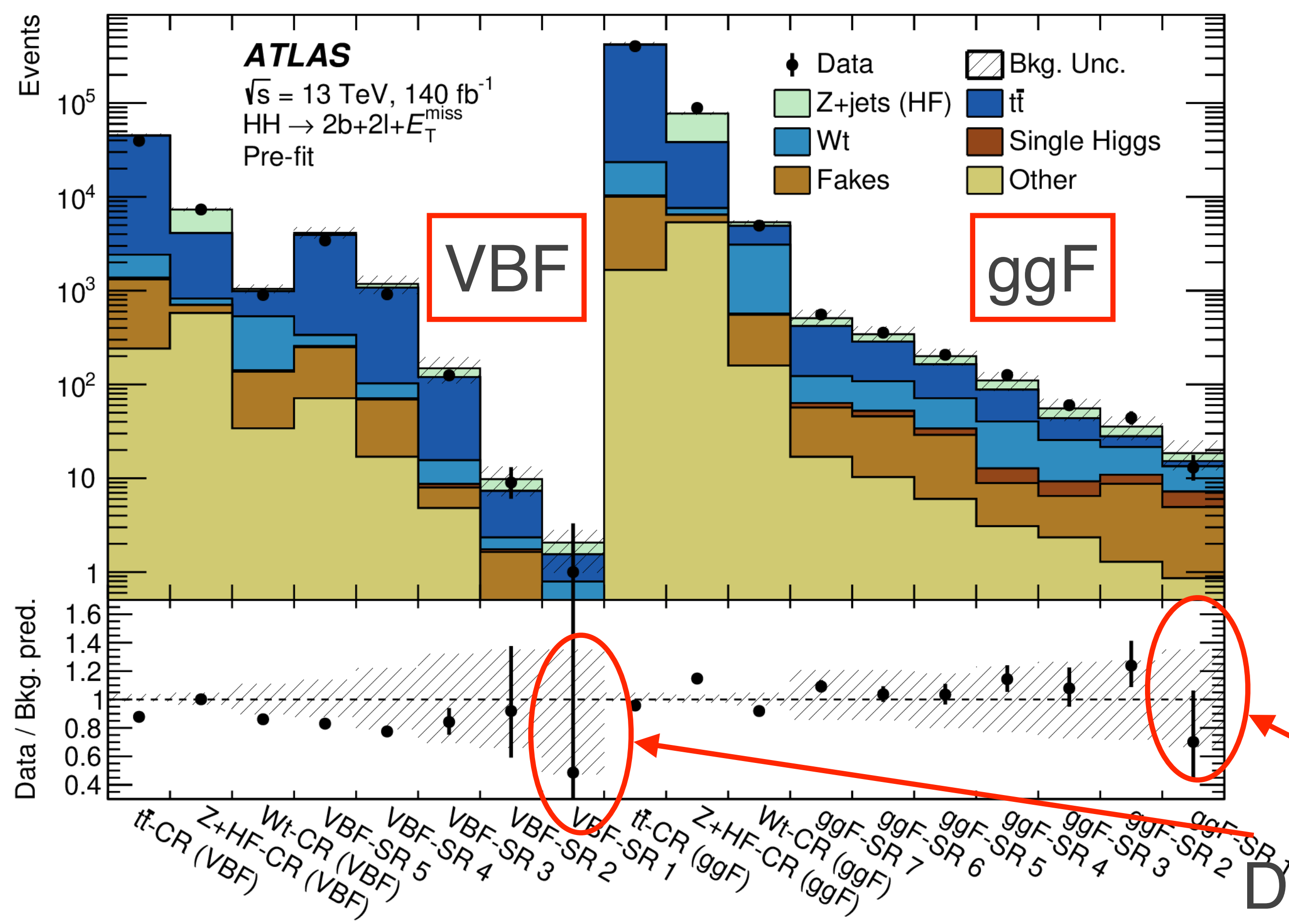
- Network trained in ggF category
  - Signal: ggF HH
  - Bkg 1: $t\bar{t}$ and tW
  - Bkg 2: other bkg
- 7 most significant bins are used in final fit

"Fake" lepton

Data driven

Z + heavy flavour

Shape from MC, normalisation from Z(→ee/μμ) + heavy flavour control region.



$t\bar{t}$ and tW

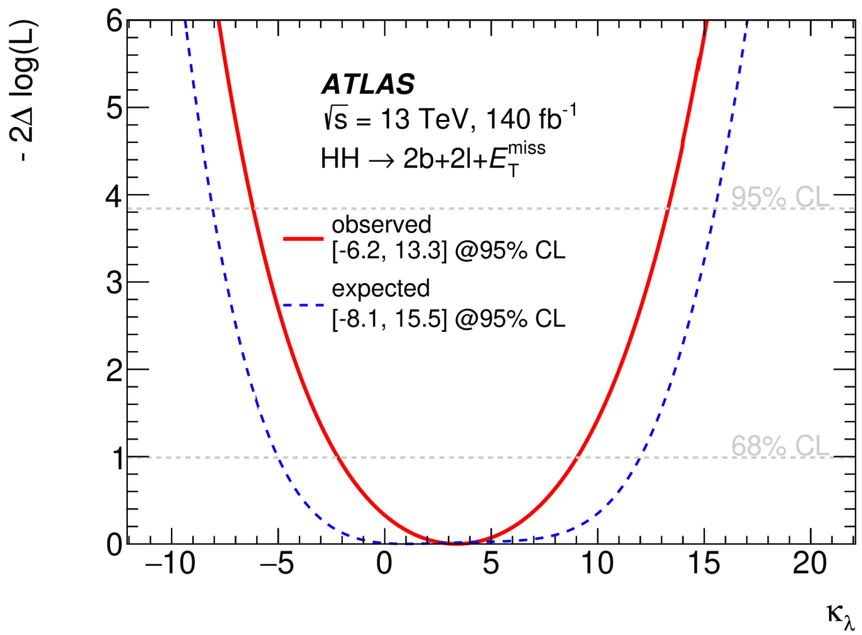
Shape from MC, normalisation from control regions.

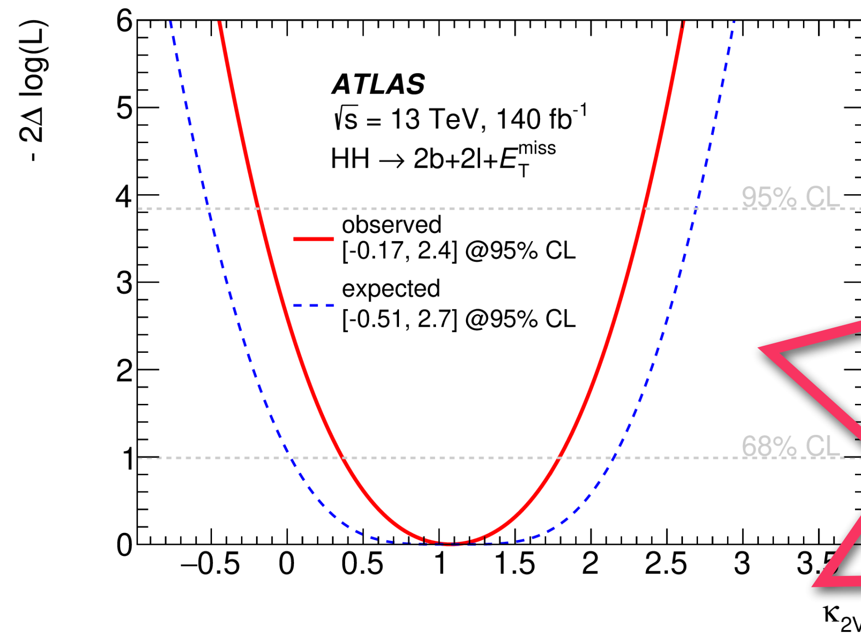
Single Higgs

Estimated from MC

Deficit observed in data

bb$\ell\ell$+E_T^{miss} results



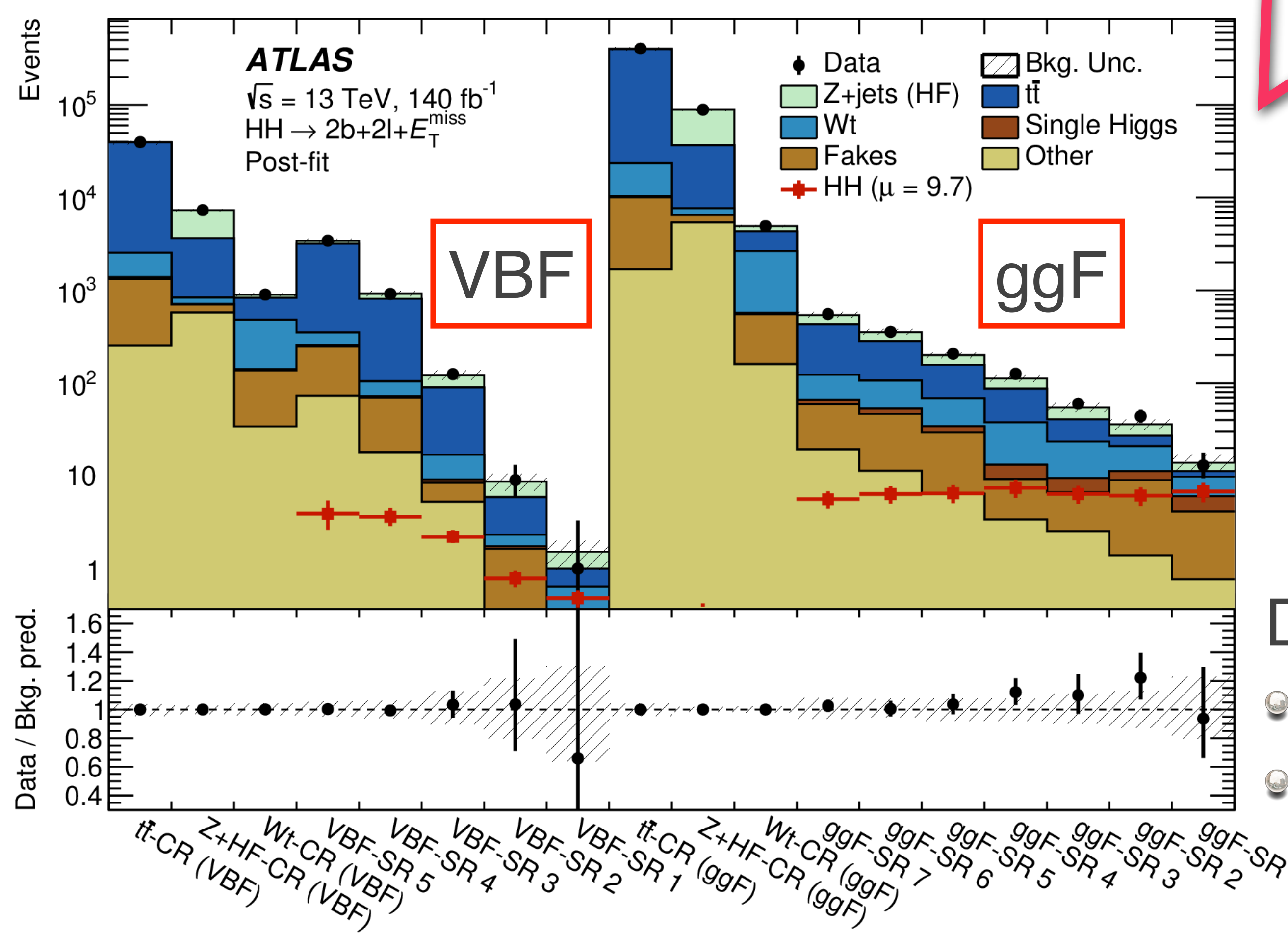


2x sensitivity improvement in μ_{HH} compared to full Run 2 HH→bblvlv result. New κ_{2V} results.

95% CL interval
$-6.2 < \kappa_\lambda < 13.3$

95% CL interval
$-0.17 < \kappa_{2V} < 2.4$

95% CL limit
$\mu_{HH} < 9.7$ (16.2 exp)

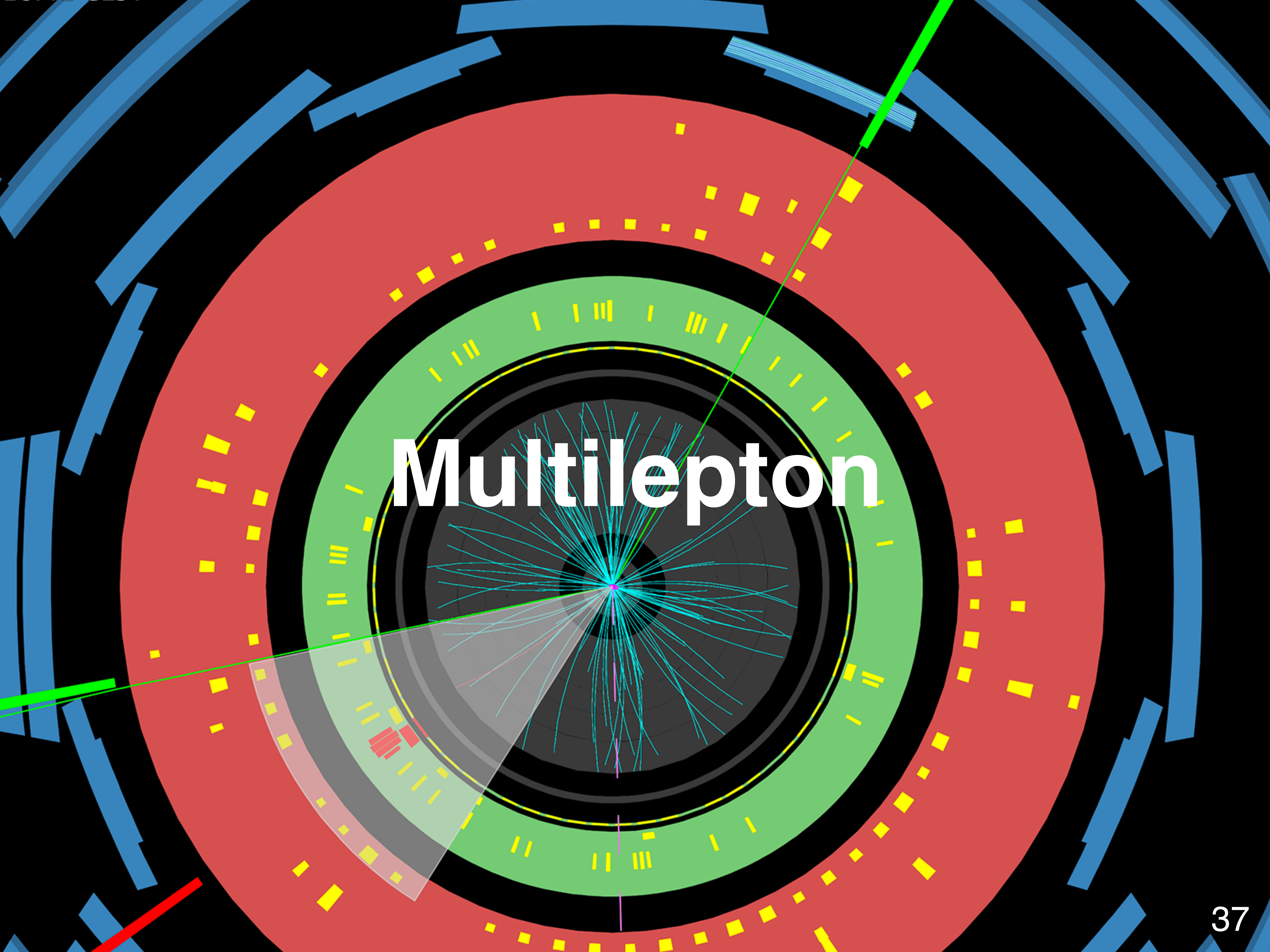


Due to employing multivariate analysis and inclusion of same flavour signals

Dominant uncertainties:

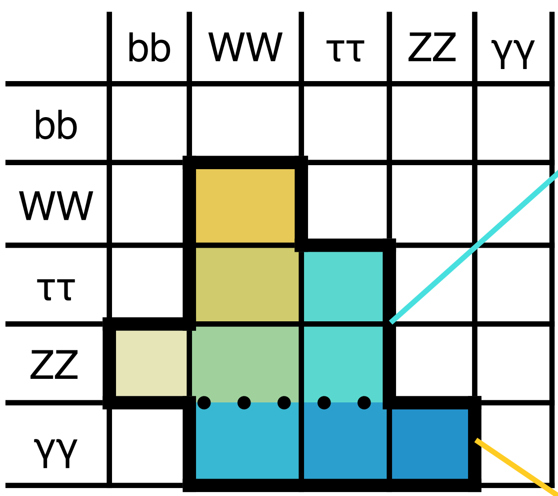
- Data statistics
- Z+jets modelling

Multilepton

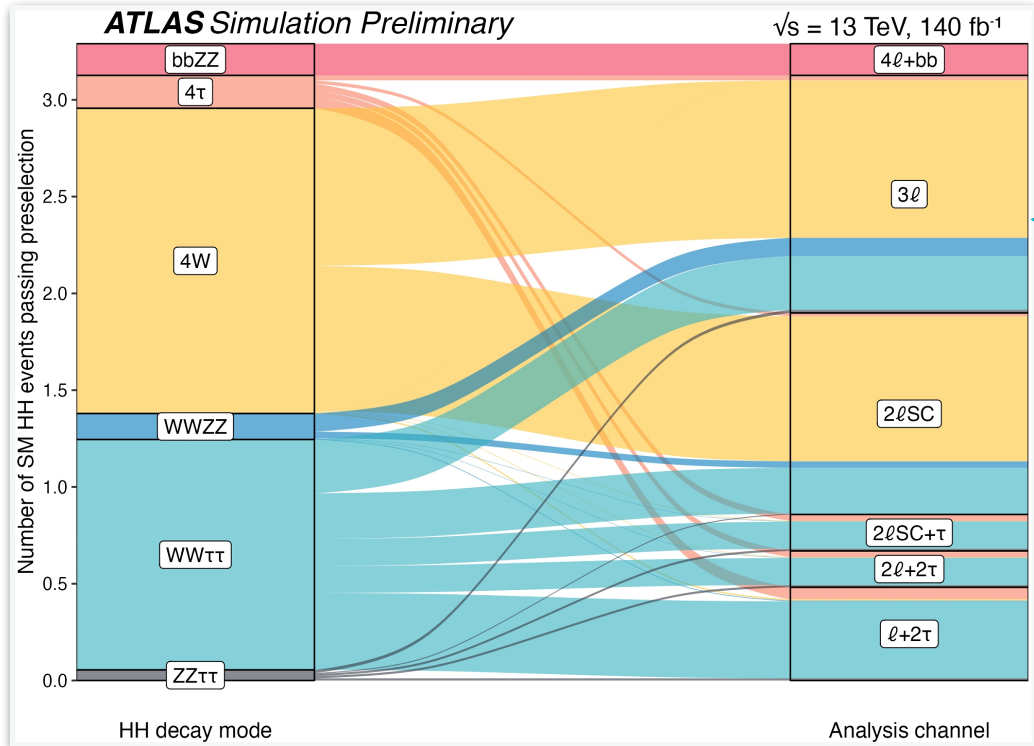


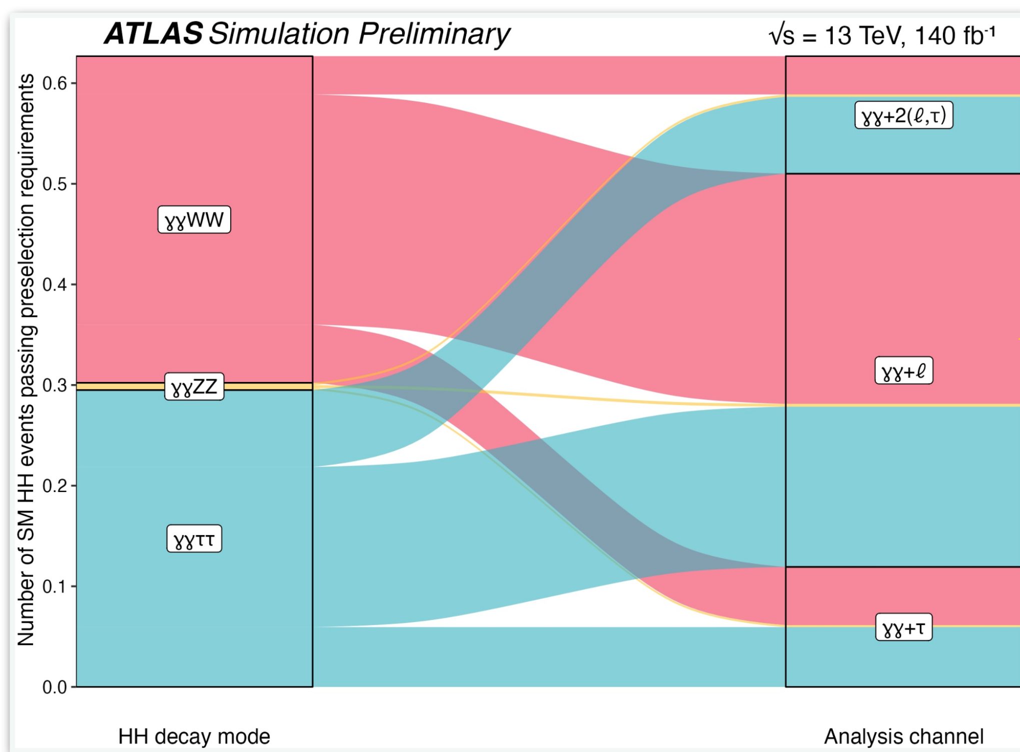
Multilepton

Targeting HH decays:

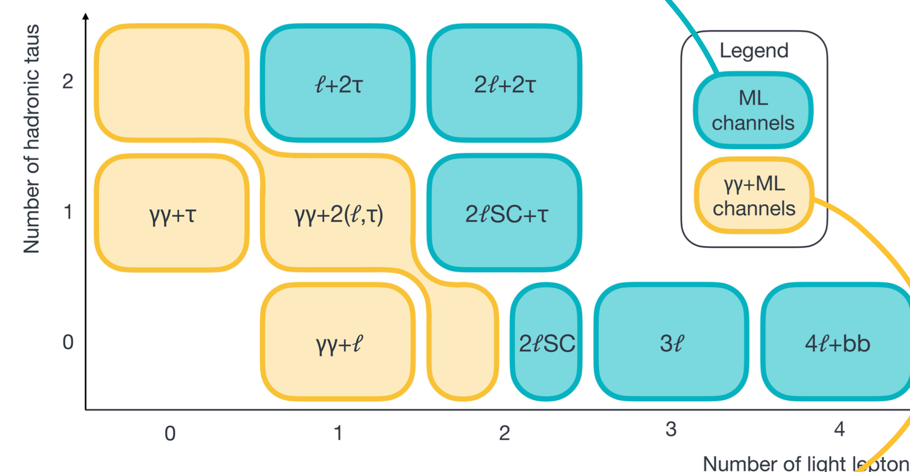


- 4V (V=W/Z)
- VVττ
- 4τ
- γγVV
- γγττ





Final states:



Triggers:

- Single Lepton
- Dilepton
- Diphoton

Multilepton search strategy

Pre-selections → **Background estimation** → **MVA (BDT)** → **Combined fit**

Pre-selections: Object multiplicity requirements ensure orthogonality among sub-channels and with other HH channels

Background estimation:

- ☆ Prompt leptons from SM processes (dominated by diboson)
- ☆ Non-prompt leptons (photon conversion, hadron decay)
- ☆ Mis-assigned charge (bremsstrahlung+conversion, mis-measured track curvature)
- ☆ Mis-identified tau

Fake (scale) factors derived in dedicated control regions or simultaneous fit with signal regions

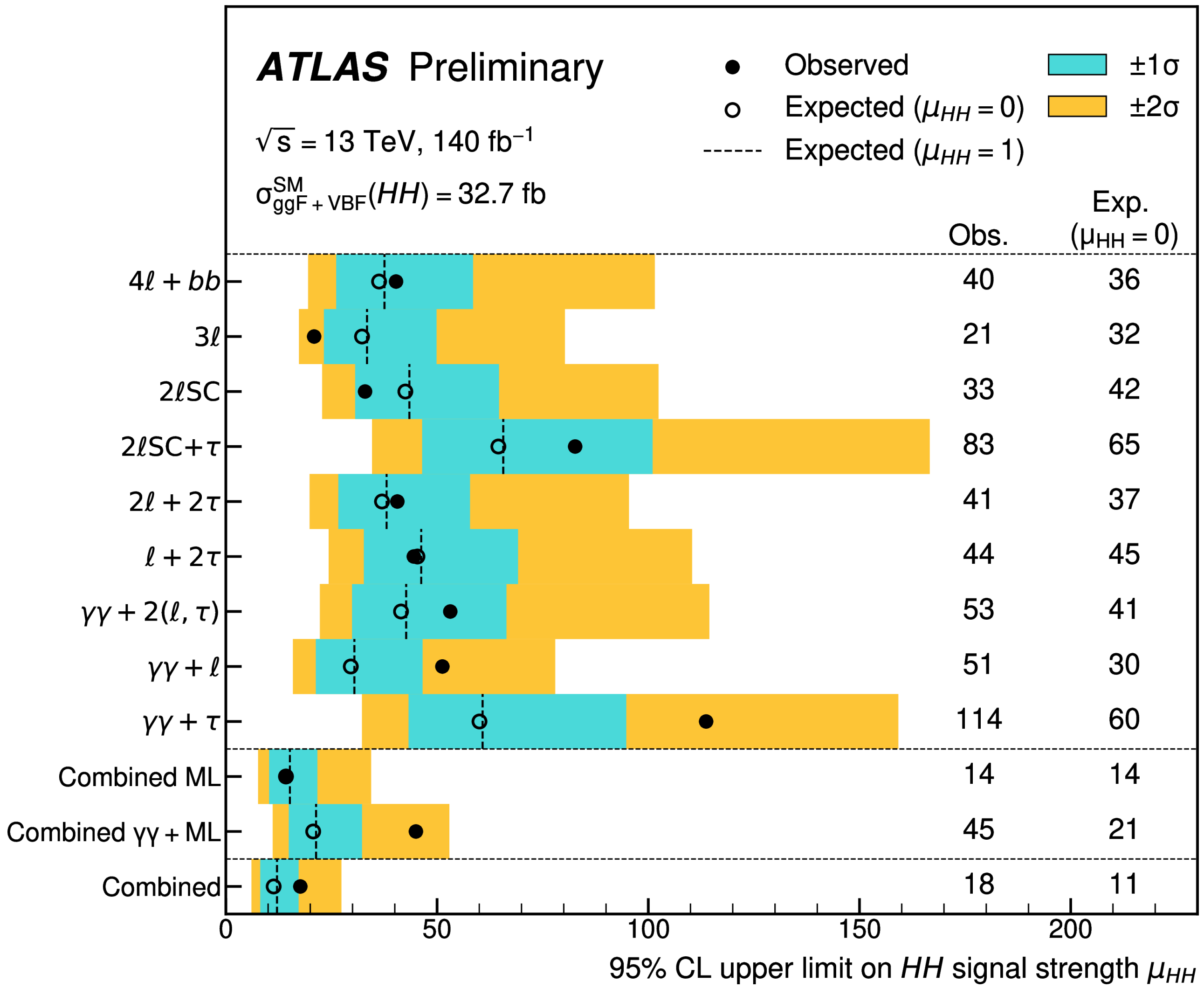
- ☆ Non-resonant $\gamma\gamma$ production

Functional form determined by $m_{\gamma\gamma}$ sideband

MVA (BDT): BDT is trained in each sub-channel

- Used as discriminant
- Or in $\gamma\gamma$ channels used to define categories to fit $m_{\gamma\gamma}$

Multilepton results



6 additional sub-channels included than 36fb^{-1} publications, **4–9x improvement** per existing sub-channel. New κ_{2V} results.

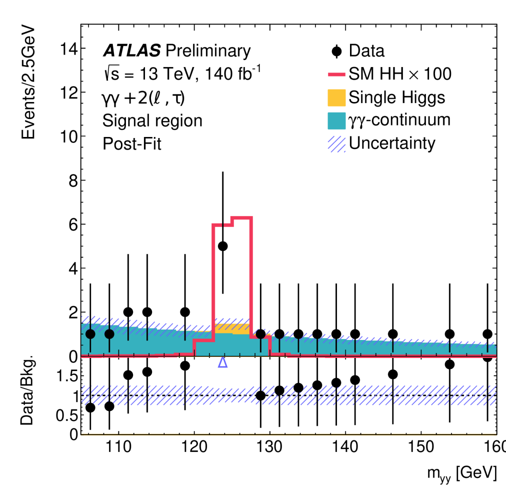
Heavily employed MVA is the key

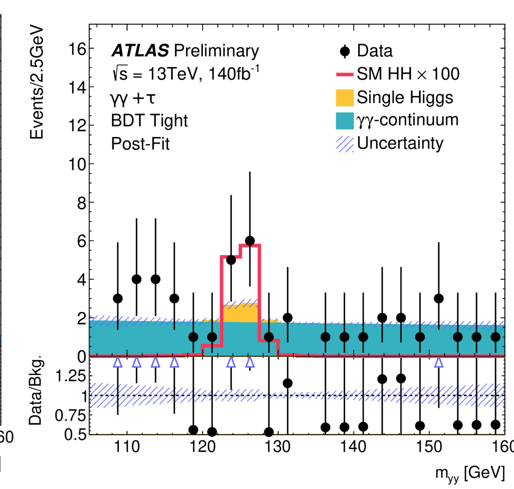
95% CL interval $-6.2 < \kappa_\lambda < 11.6$

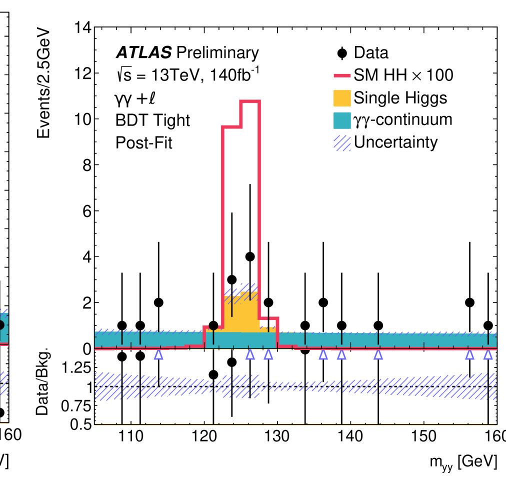
95% CL interval $-2.5 < \kappa_{2V} < 4.6$

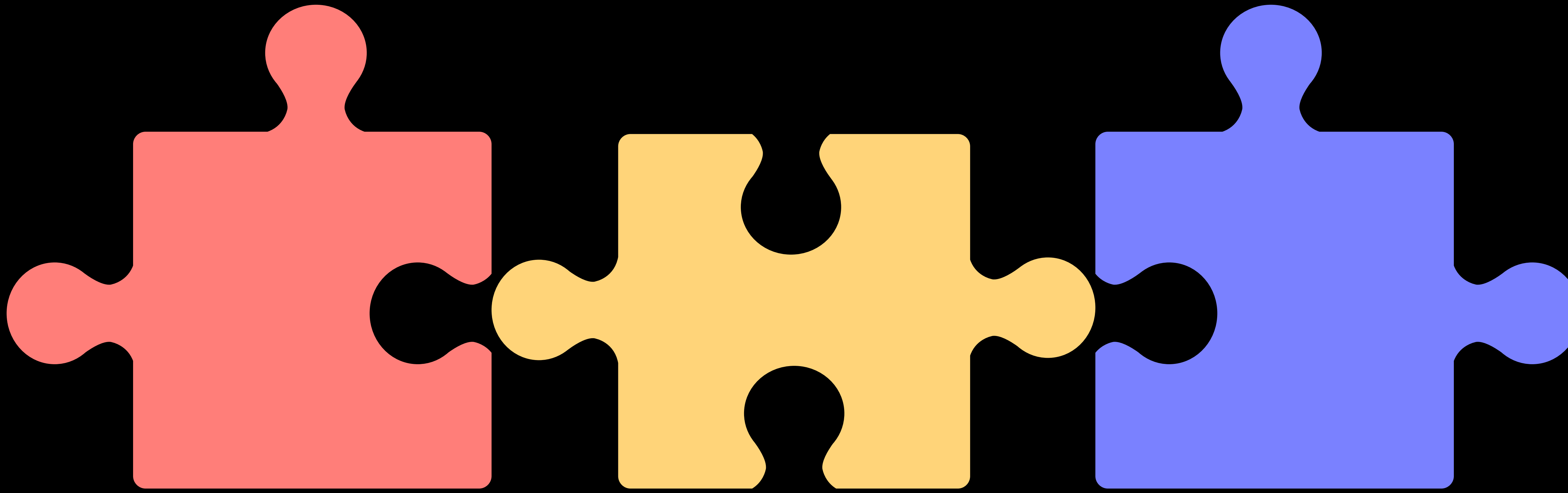
95% CL limit $\mu_{HH} < 17$ (11 exp)

- Dominated by data statistics

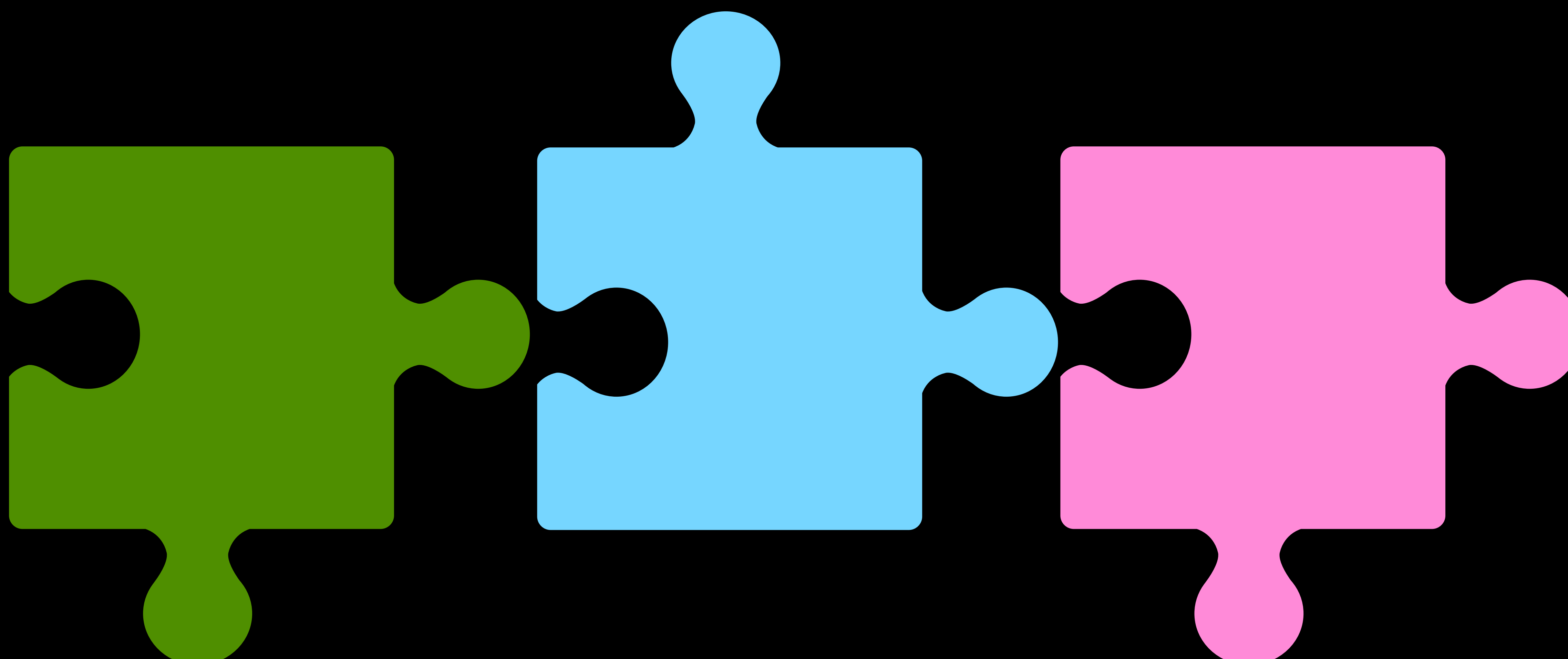








HH combination



Systematic uncertainties and correlation

- No additional pruning is applied in the combination

Final object reconstructions	bbbb	bb$\tau\tau$	bb$\gamma\gamma$	bb$\ell\ell$+E_T^{miss}	multilepton
Luminosity/pileup	✔	✔	✔	✔	✔
Jets	✔	✔	✔	✔	✔
b-tagging	✔	✔	✔	✔	✔
Boosted jet/b-tag	✔				
Electrons		✔		✔	✔
Muons		✔		✔	✔
Taus		✔			✔
Photons			✔		✔
E_T^{miss}		✔	✔	✔	✔

empty: unavailable or negligible

- Common sources are correlated except if:
  - Different calibrations used
  - Different post fit profilings from different phase space

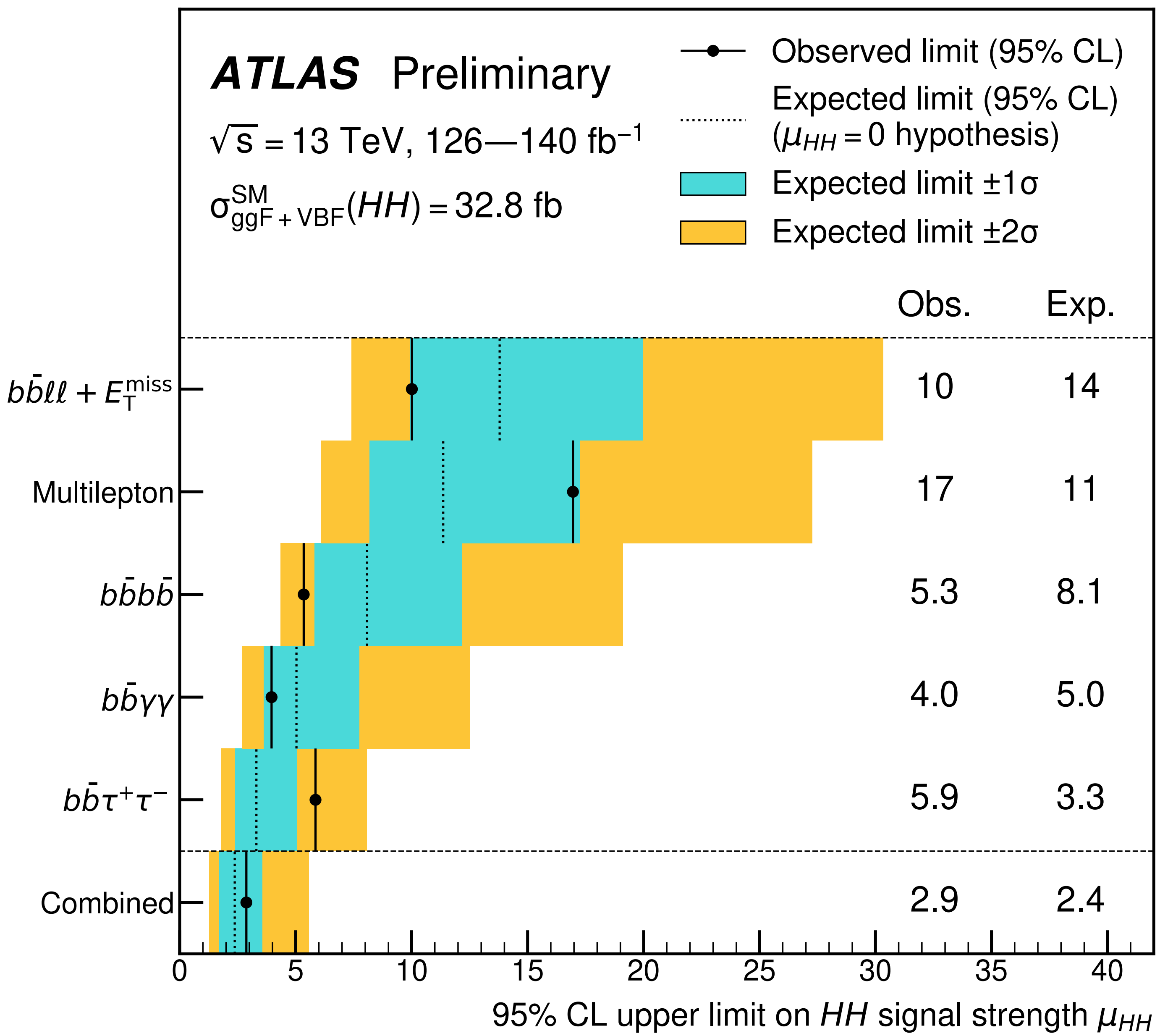
Systematic uncertainties and correlation

HH signal modelling	bbbb	bbττ	bbγγ	$bb\ell\ell+E_T^{miss}$	multilepton
QCD scale + m_{top}	✔	✔	✔	✔	✔
PDF + α_S	✔	✔	✔	✔	✔
H branching ratio	✔	✔	✔	✔	✔
Parton shower	✔	✔	✔	✔	✔
κ interpolation	✔	✔	✔	✔	
Bkg. modelling	**bbbb**	**bbττ**	**bbγγ**	**$bb\ell\ell+E_T^{miss}$**	**multilepton**
Single Higgs		✔	✔		✔
Top quark		✔		✔	
Z + jets		✔		✔	✔
Diboson		✔			✔
Specific per chan.	✔	✔	✔	✔	✔

empty: unavailable or negligible

- Dominant uncertainties
  - HH cross section theory calculation QCD scale + m_{top} (prefit $^{+6\%}_{-23\%}$ on ggF HH)
  - Normalisation of single H plus heavy-flavour jets on ggF (prefit 100% on ggF H yields)
  - These two contribute most to the correlation

Putting all together: HH production



95% CL limits

- $\mu_{HH} < 2.9$ (2.4 exp)
  - $\mu_{ggF} < 2.9$ (2.4 exp)
  - $\mu_{VBF} < 44.3$ (47.5 exp)
- $\sigma_{HH} < 85.8$ (71.1 exp) fb

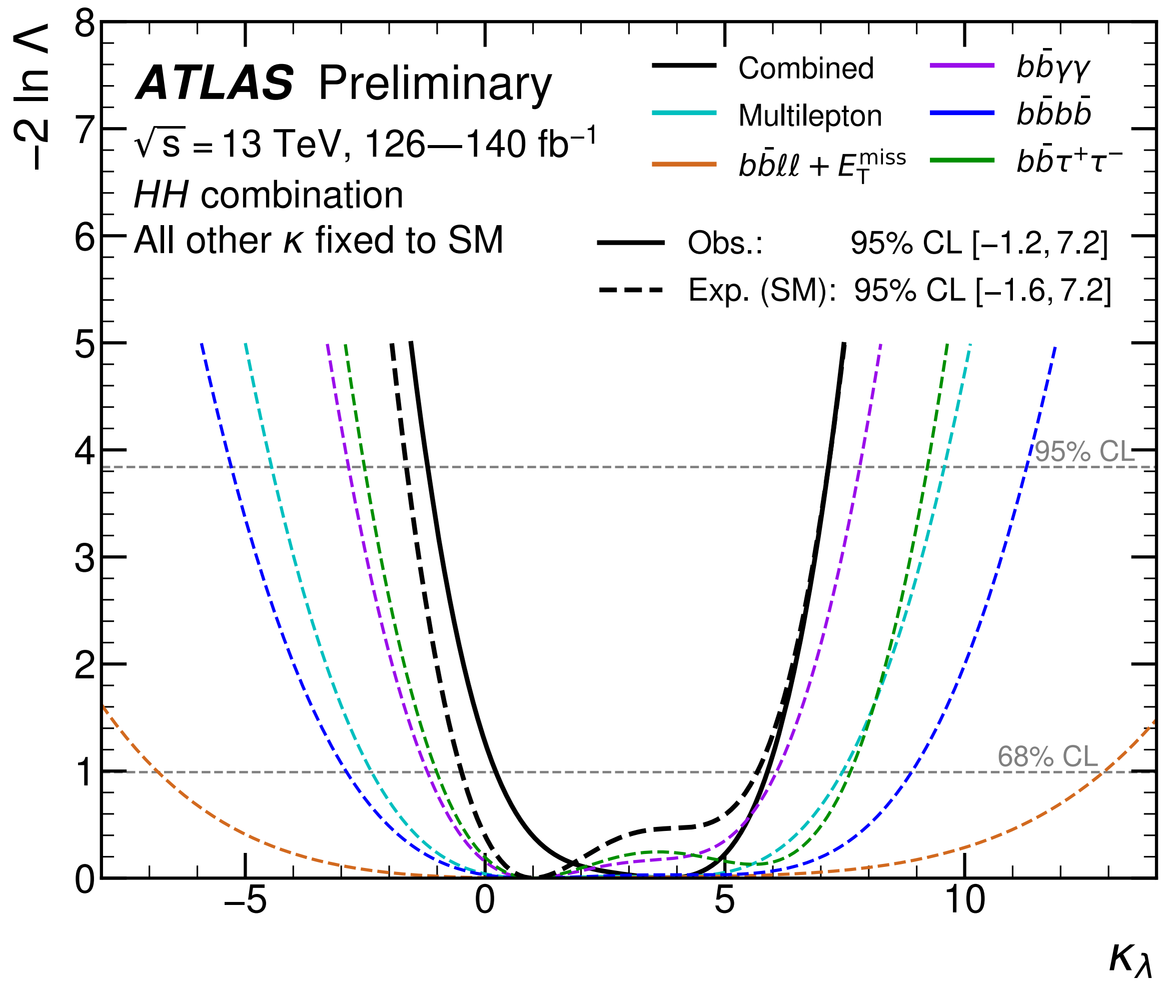
Corresponding to deficit observed in
bbbb, bbγγ, bbℓℓ+E_T^{miss}
and excess observed in
bbττ, multilepton

- Dominant uncertainties: HH theory cross section uncertainty ($^{+6\%}_{-23\%}$ in scale + m_{top})
- Subdominant: modelling of single H associated with b-jets (lack of measurement)
- Dominant experimental uncertainties: 4b background estimation

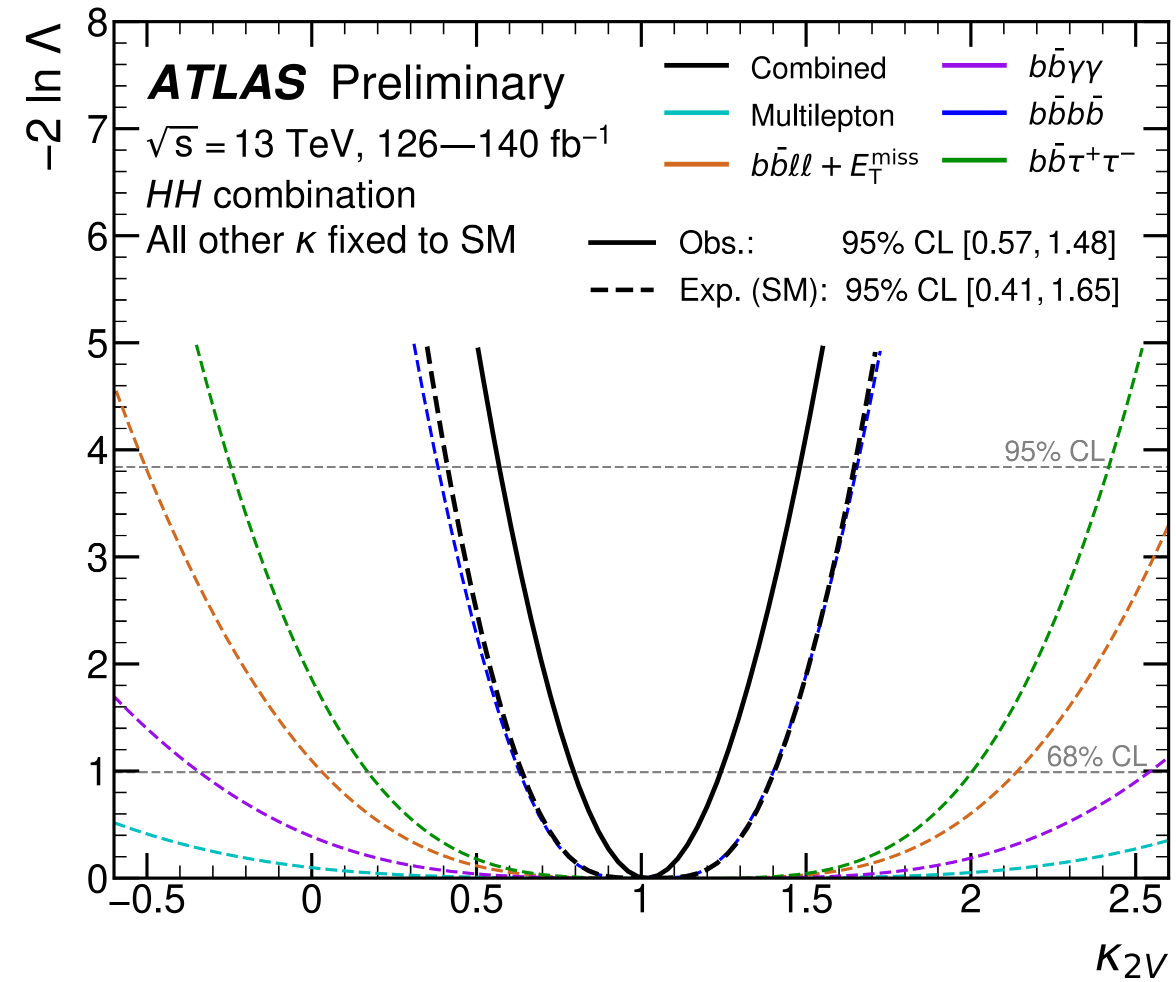
Separated ggF and VBF limits in backup

Putting all together: couplings

κ_λ



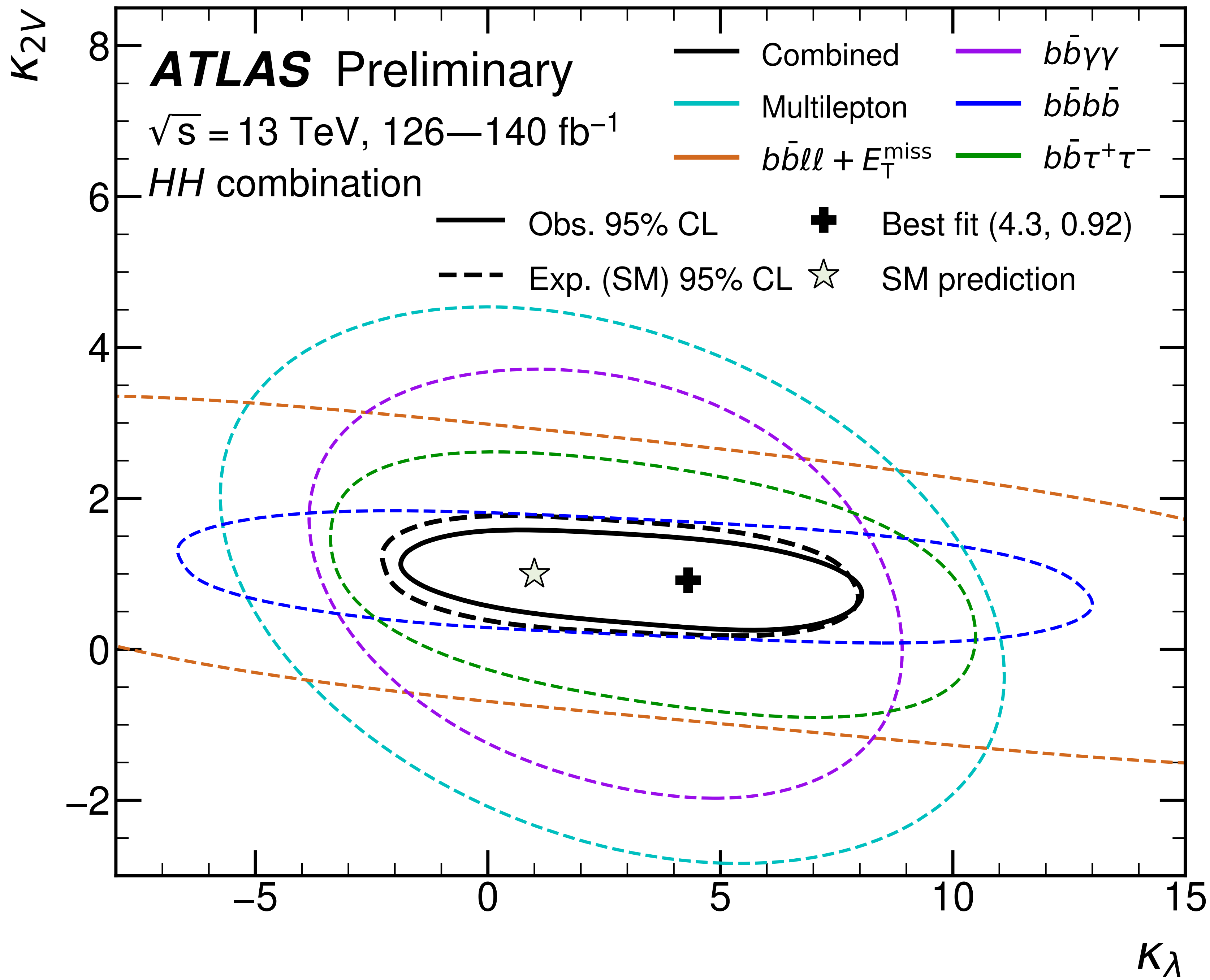
κ_{2V}



	Best fit	Obs 95% CL	Exp 95% CL	Leading channel
κ_λ	3.8	[−1.2, 7.2]	[−1.6, 7.2]	bbγγ, bbττ
κ_{2V}	1.0	[0.6, 1.5]	[0.4, 1.6]	bbbb (boosted)

Detailed table in backup

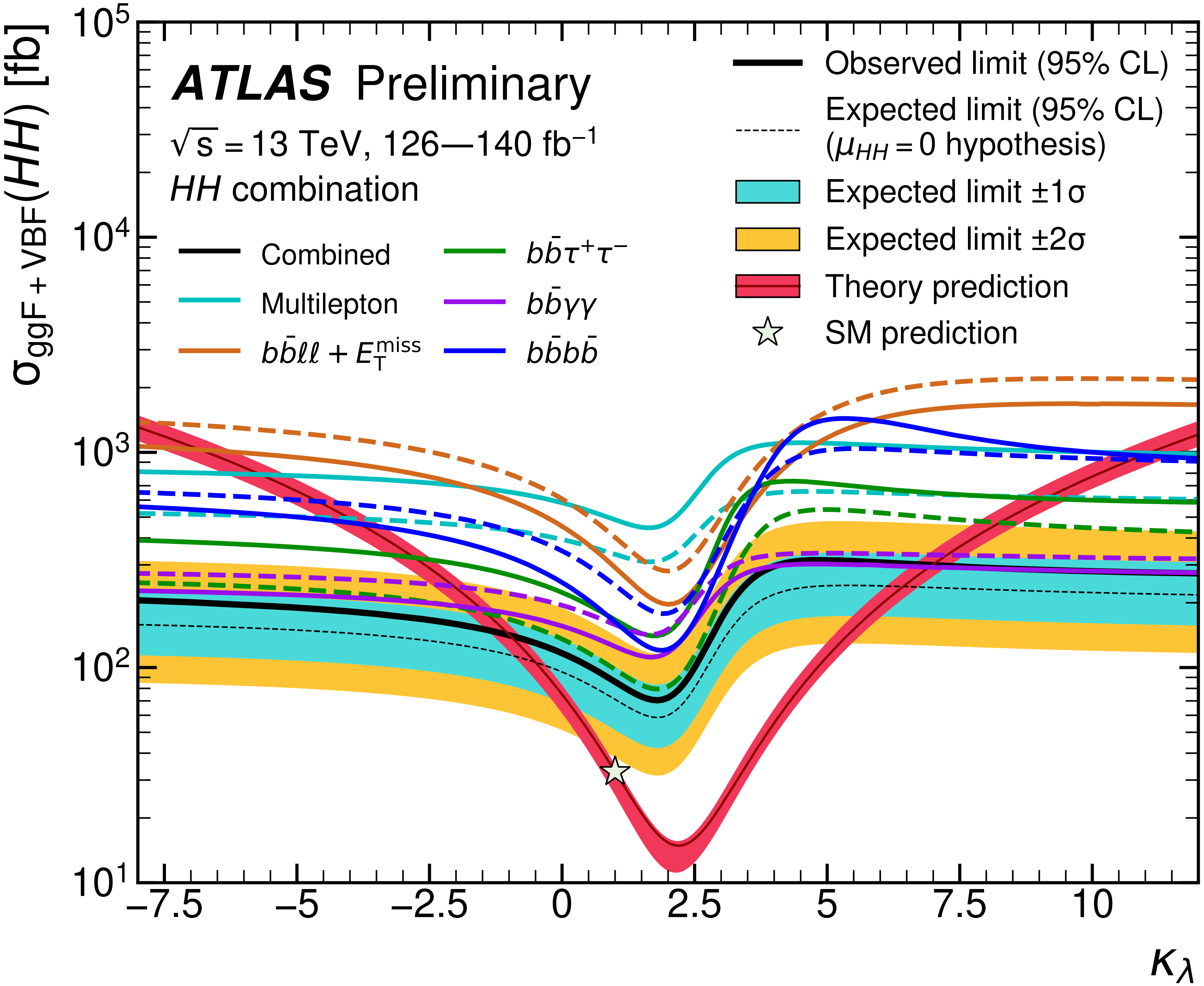
Putting all together: couplings



Relative contribution can be better seen in the 2D contours

Complementary contributions

Reminder: when κ_λ moves away from SM, kinematics gets **softer**

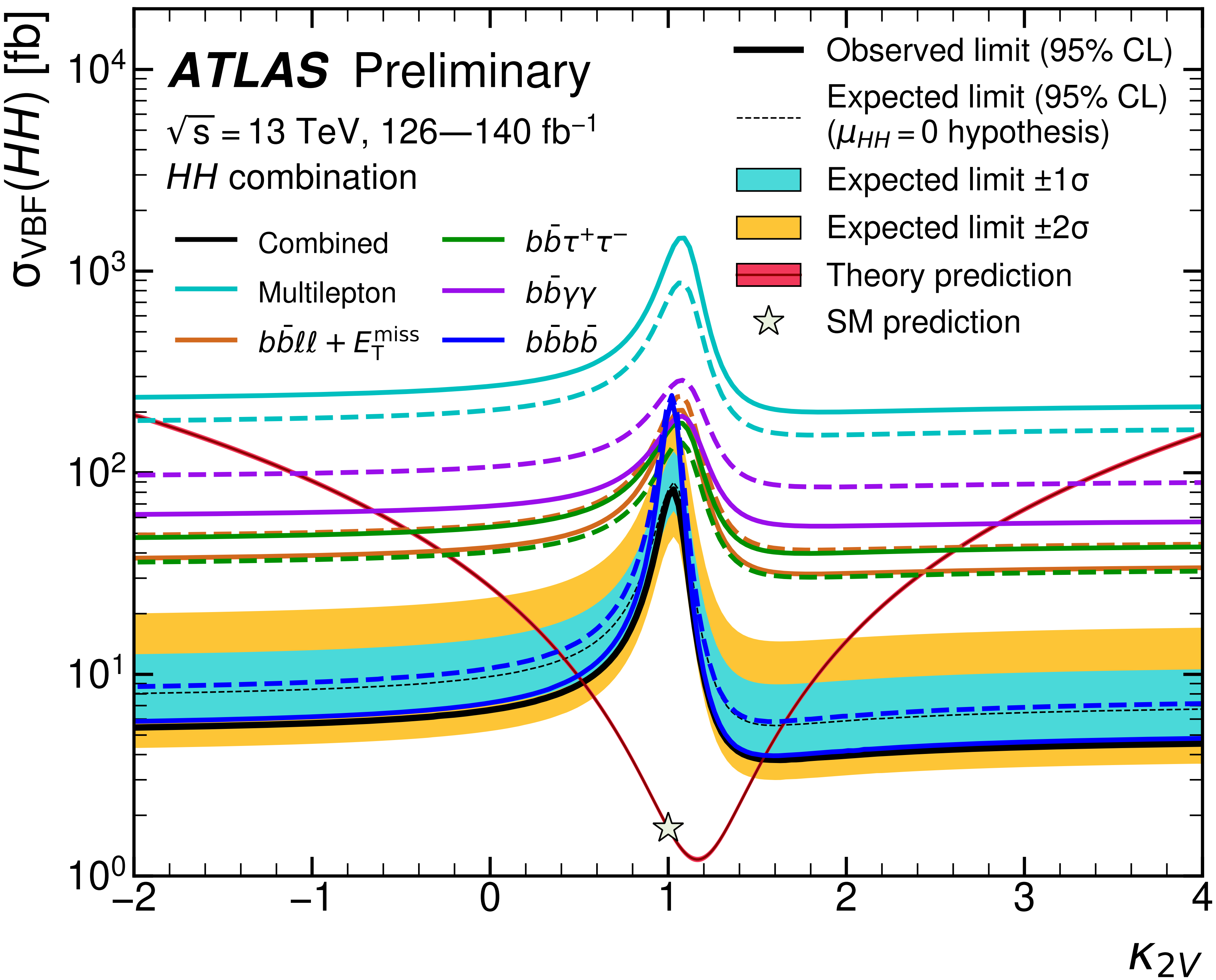


Note:

- bbbb's deficit at SM, excess around κ_λ=6
- bbττ excellent performance at SM, degrading quickly in positive κ_λ
- Similar situation seen in $bb\ell\ell+E_T^{miss}$

Complementary contributions

Reminder: when κ_{2V} moves away from SM, kinematics gets **harder**

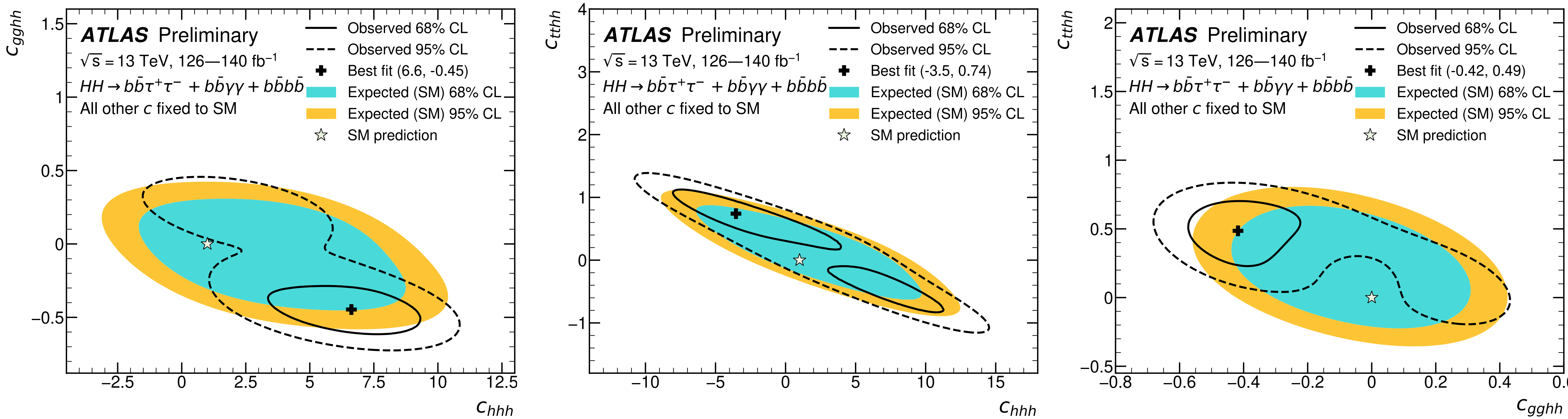


Note:

- bbbb's strong constraint but not the best at SM
- No dedicated VBF signal regions in multilepton
- bbγγ is not super sensitive in high kinematics regime

Putting all together: HEFT

Chhh-Cgghh | Chhh-Cgghh | Cgghh-Ctthh



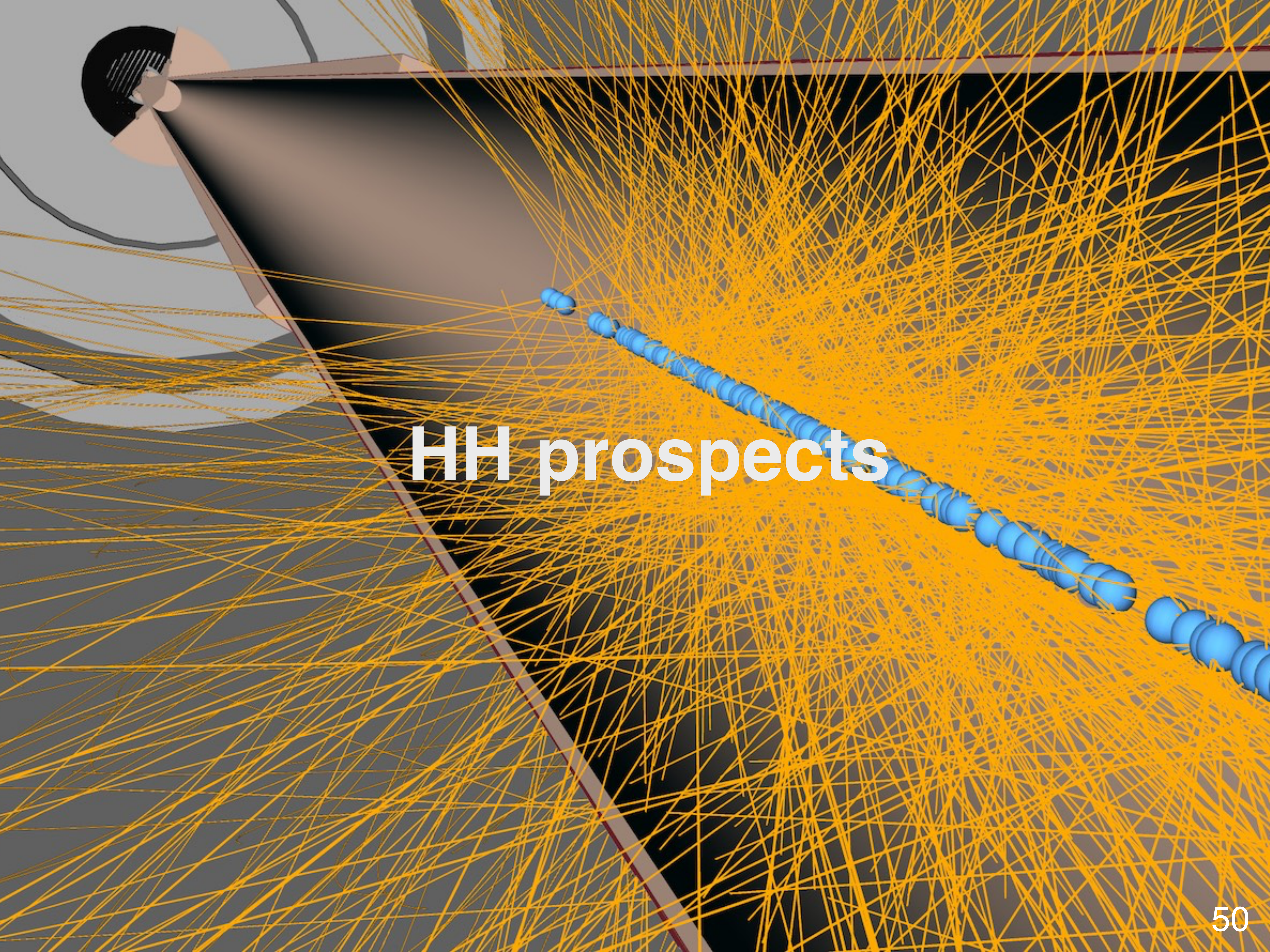
Note:

- Multiple minima due to quadratic structure of HEFT parametrisation
- Best fit driven by bbbb where a signal shape is picked to fit the gap between data and background the best

1D scans in backup

Benchmark results in backup

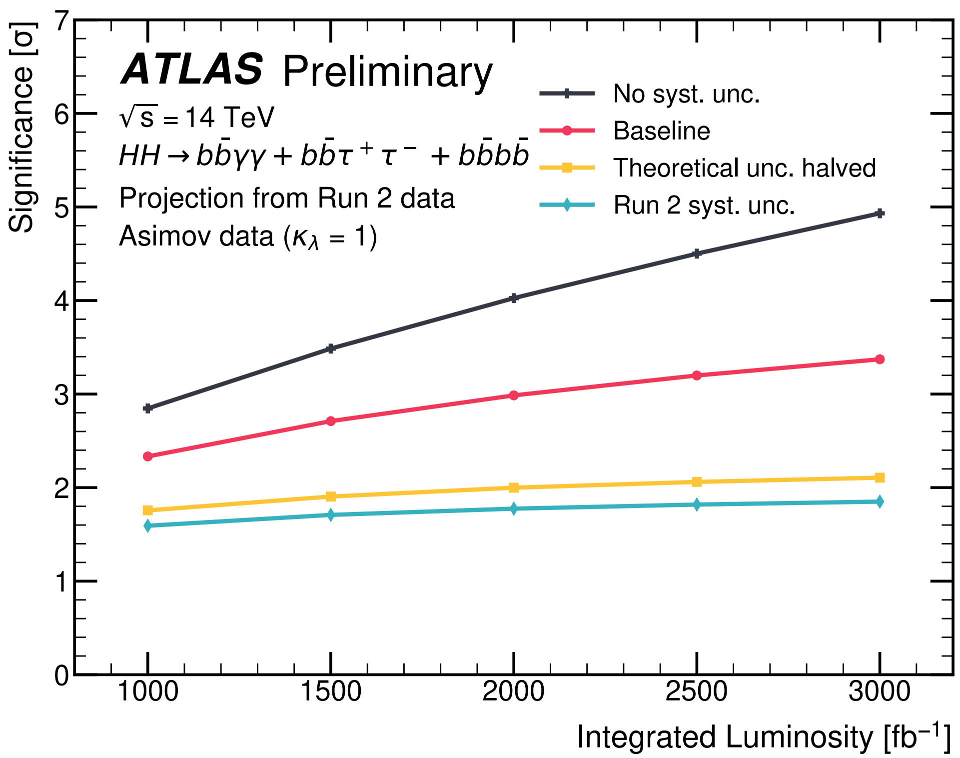
HH prospects

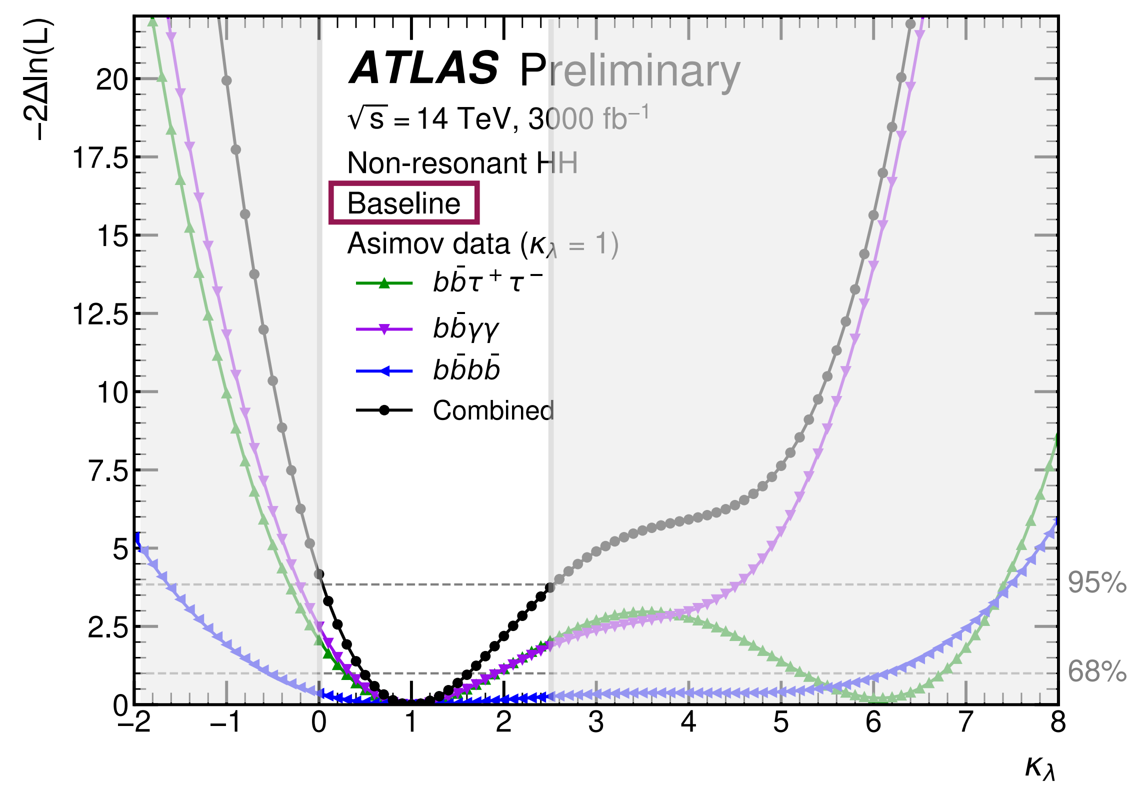


Projection to HL-LHC

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

- Combination of bbbb + bbττ + bbγγ
  - Baseline: 2× theory/modelling, 2× b-tagging, others objects almost Run 2-like (conservative)
  - 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. Already **13%** improvement with this round.



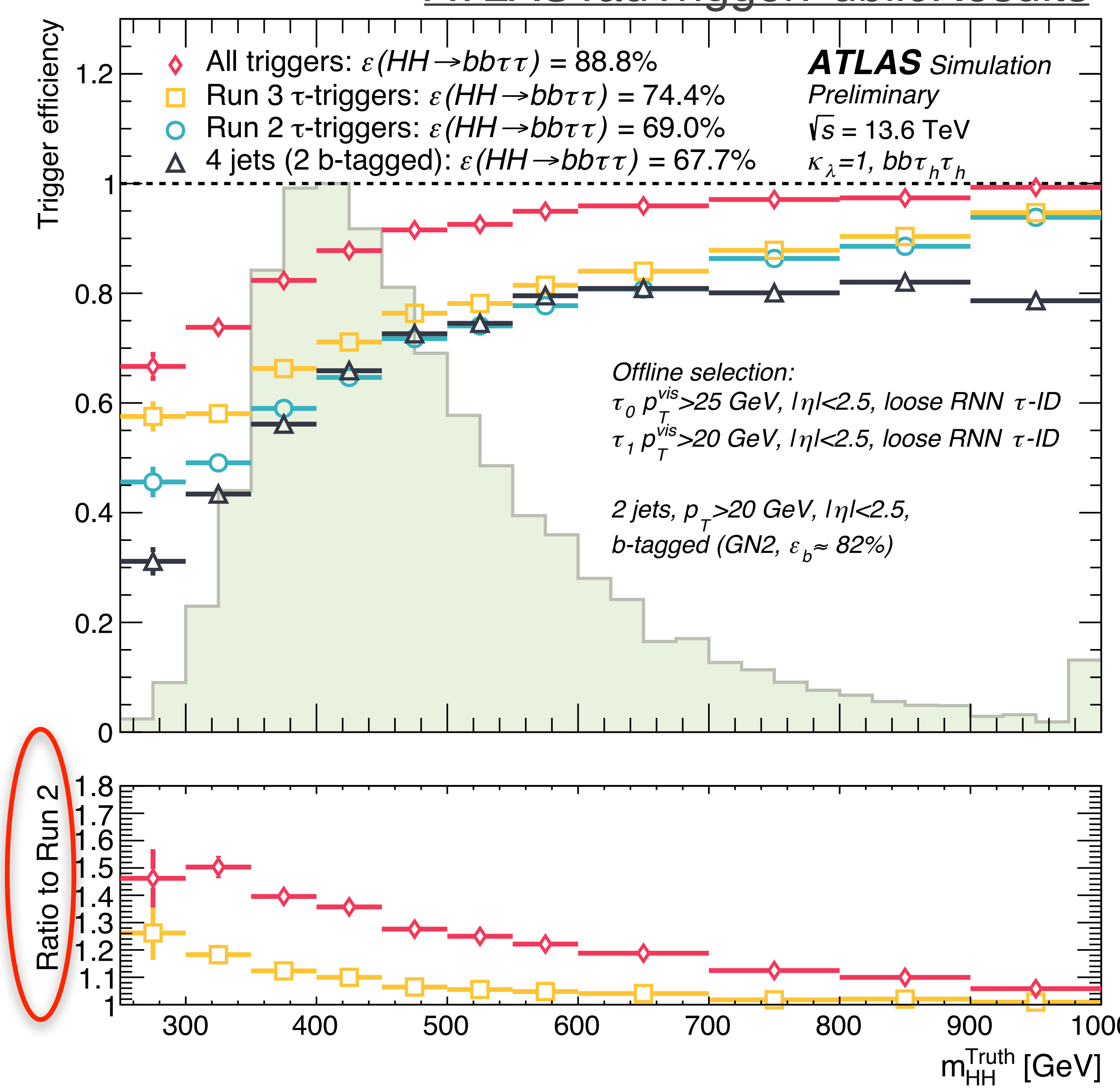


- Sensitivity driven by theoretical uncertainties on HH cross-section and:
  - b-tag performance in bbbb (potential improvement from ITk and better b-tagging)
  - background modelling uncertainty in bbγγ
  - additional heavy-flavour jet radiation in single Higgs background

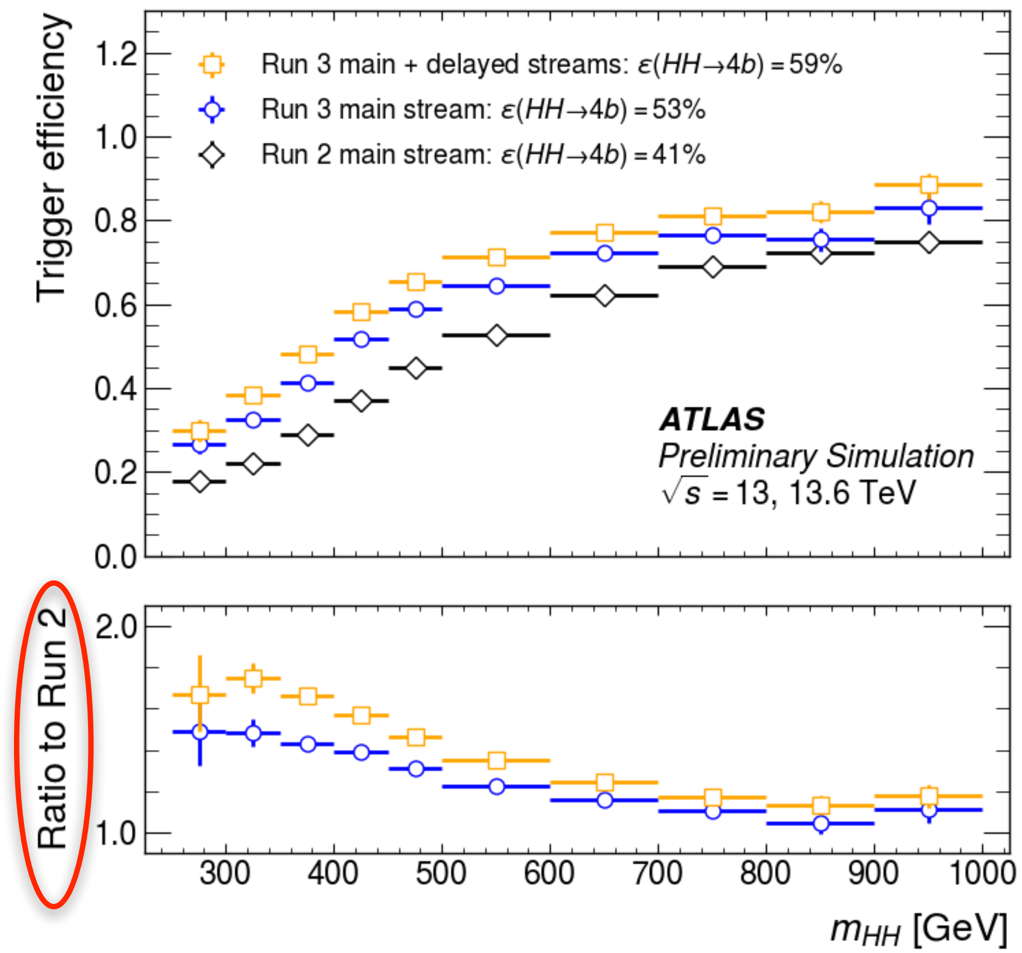
Standing in Run 3

- Benefit from better triggers, improved object ID, more refined analyses ...

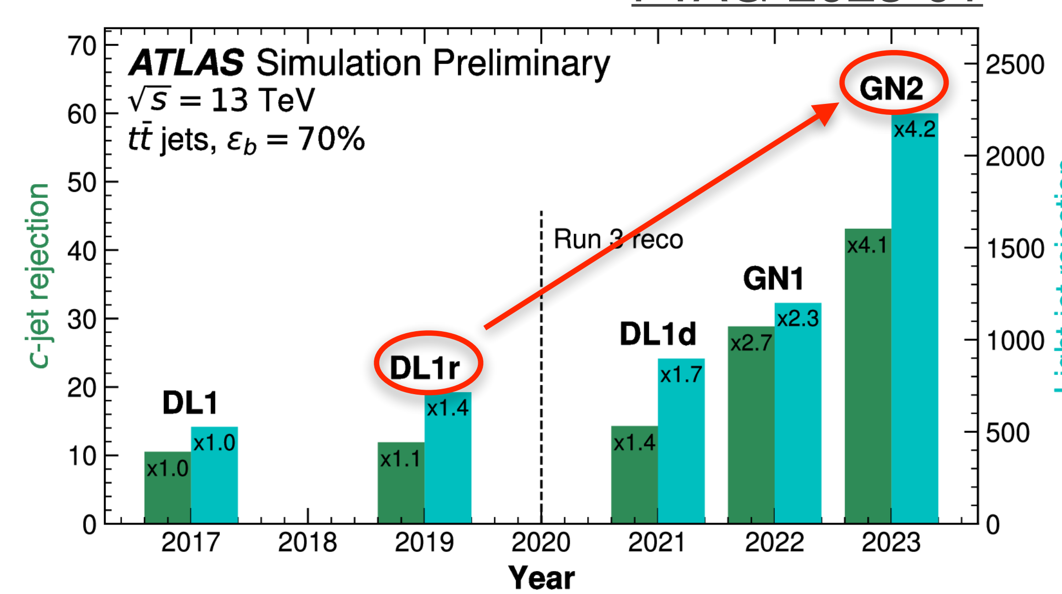
ATLASTauTriggerPublicResults



ATLASBJetTriggerPublicResults

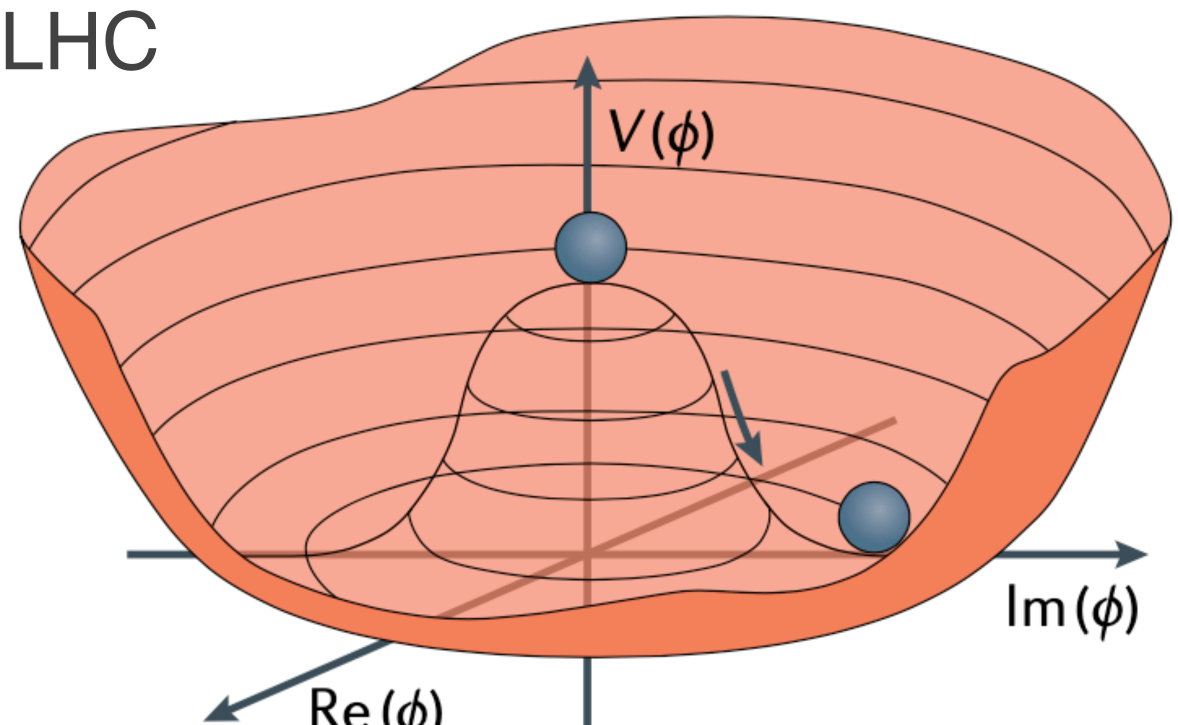


FTAG-2023-01



Summary

- HH is a unique process to probe the Higgs potential
- HH events are rare (33 fb ➔ ~ 4600 SM events in Run 2 dataset)
  - Call for highly efficient analyses
- ATLAS conducted searches in final states covering 50% of decays
  - Reached best expected sensitivity to date on HH cross section, $\mu_{HH} < 2.9$ (2.4 exp)
  - ... and on the Higgs self-coupling, $-1.2 < \kappa_\lambda < 7.2$ ($-1.6 < \kappa_\lambda < 7.2$ exp)
- Promising prospect for Run 3 and HL-LHC
  - Prospects can improve rapidly with the advancement of triggers, objects identifications, and analysis techniques



Much to look forward to in the near future!

Backup

bbbb
- Selection flowchart
- Cutflow, yields, efficiency
- Discriminant
- Resolved category yields, syst table
- Resolved uncertainty decomposition
- k2V scan, XS scan, 2D scan

bbττ
- Selection flowchart
- BDT variables: ggF vs VBF, ggF, VBF
- Discriminant

bbγγ
- BDT variables
- Discriminant
- All results

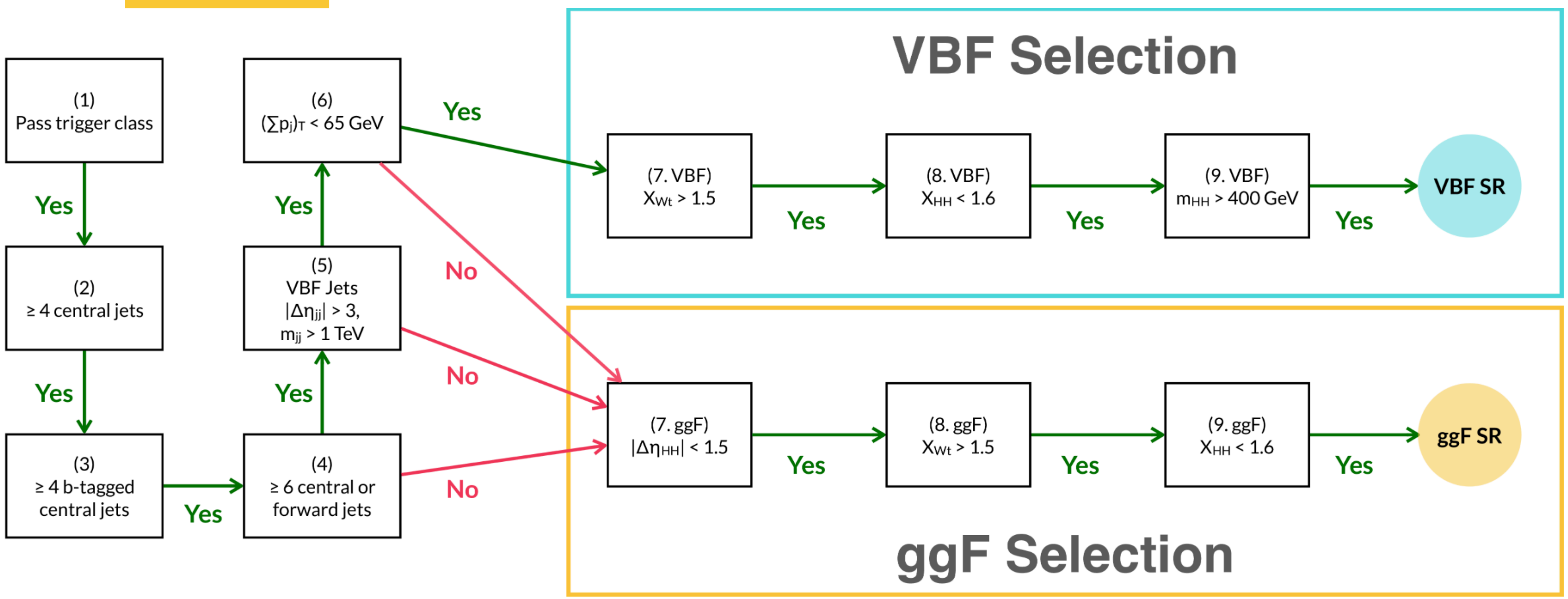
$bb\ell\ell+E_T^{miss}$
- Topology definition and BR
- Prefit yields
- BDT and NN inputs

Multilepton
- Event selection table
- CR definitions
- BDT input (all sub-channels)
- Systematic table

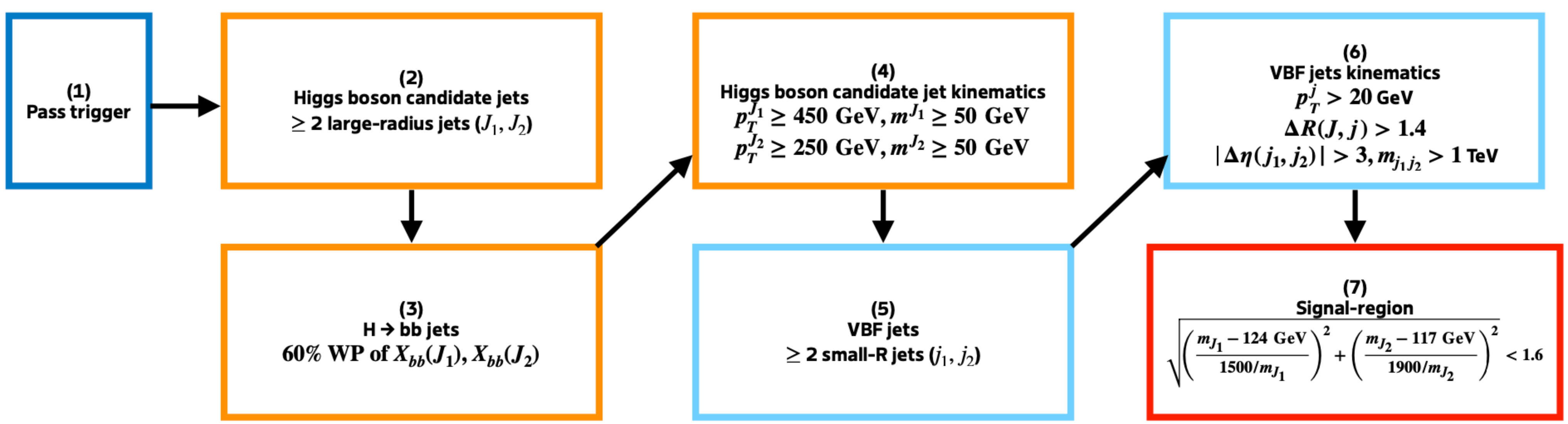
Combination
- EFT benchmark definition
- Combine with single H
- Projection scenarios definition

bbbb event selection

Resolved

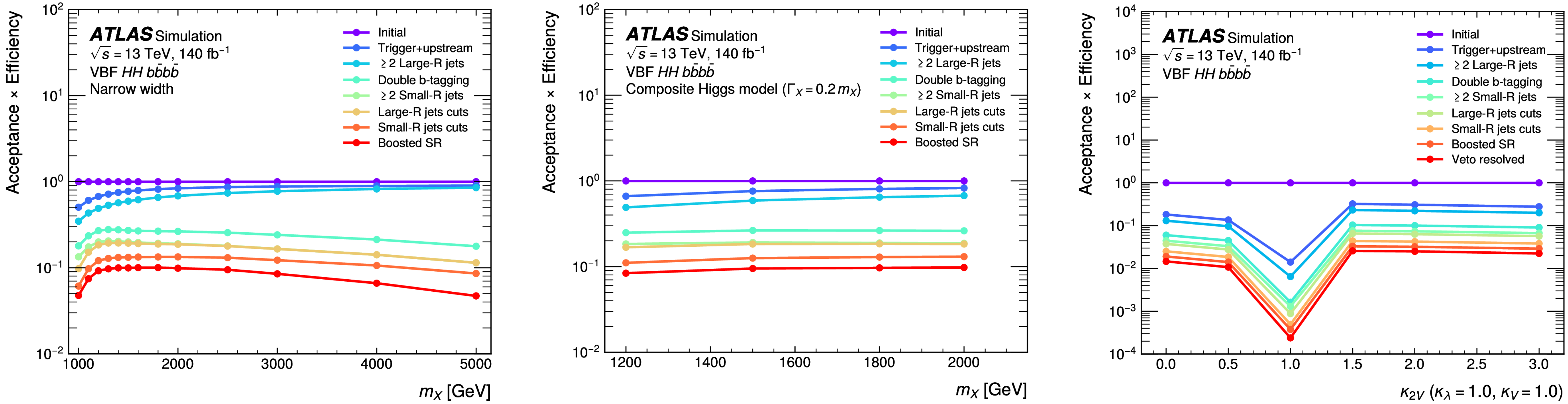


Boosted



Cutflow

Boosted



Resolved

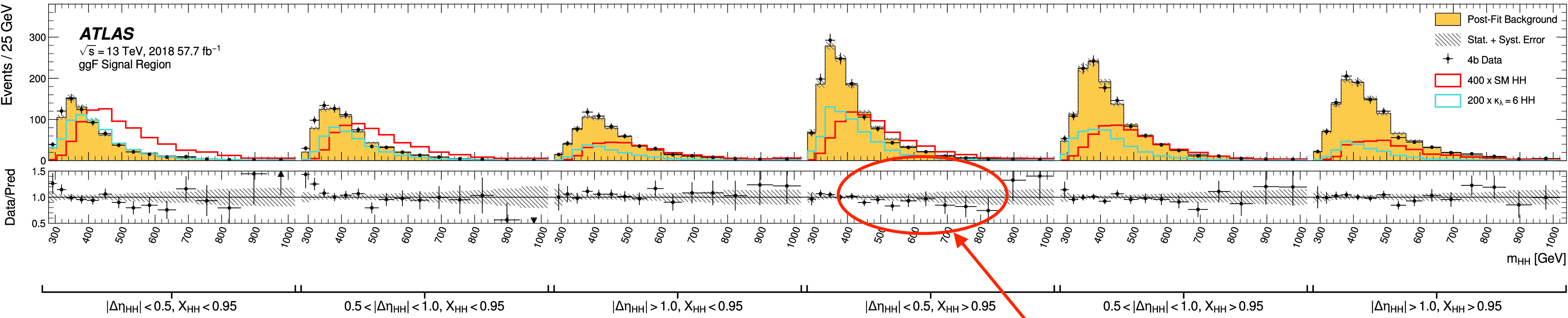
	Data	ggF Signal		VBF Signal	
		SM	$\kappa_\lambda = 10$	SM	$\kappa_{2V} = 0$
Common preselection					
Preselection	5.70×10^8	530	7300	22	630
Trigger class	2.49×10^8	380	5300	16	410
ggF selection					
Fail VBF selection	2.46×10^8	380	5200	14	330
At least 4 b-tagged central jets	1.89×10^6	86	1000	1.9	65
$\lvert\Delta\eta_{HH}\rvert < 1.5$	1.03×10^6	72	850	0.94	46
$X_{Wt} > 1.5$	7.51×10^5	60	570	0.74	43
$X_{HH} < 1.6$ (ggF signal region)	1.62×10^4	29	180	0.24	23
VBF selection					
Pass VBF selection	3.30×10^6	5.2	81	2.2	71
At least 4 b-tagged central jets	2.71×10^4	1.1	15	0.74	28
$X_{Wt} > 1.5$	2.18×10^4	1.0	11	0.67	26
$X_{HH} < 1.6$	5.02×10^2	0.48	3.1	0.33	17
$m_{HH} > 400$ GeV (VBF signal region)	3.57×10^2	0.43	1.8	0.30	16

Boosted

Selection	Data	Nonresonant SM ggF	Nonresonant VBF $(\kappa_\lambda, \kappa_{2V}, \kappa_V)$ =		Spin-0 resonant VBF Narrow-width m_X	
			(1, 1, 1)	(1, 0, 1)	1.00 TeV	5.00 TeV
Raw events	16 854 036 422	1480	82.0	1290	140	140
Trigger & upstream selection	63 944 638	20.9	1.15	235	70.7	126
≥ 2 large-R jets (η, m)	57 510 800	14.1	0.531	168	48.7	119
Double b-tagging	12 875	5.35	0.131	77.4	25.2	24.9
≥ 2 small-R jets	5762	2.24	0.105	57.2	18.8	16.0
Large-R jets (p_T)	3902	1.41	0.0700	48.3	13.7	16.0
Small-R jets ($\Delta\eta(j,j)$, m_{jj})	314	0.148	0.0380	32.3	8.58	12.0
Signal region	23	0.0970	0.0290	24.5	6.68	6.59
Veto resolved selection	21	0.0590	0.0200	18.8	-	-

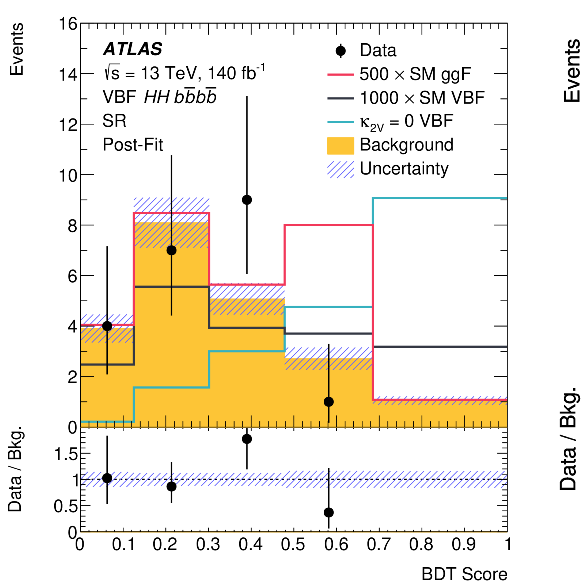
bbbb discriminant

Resolved

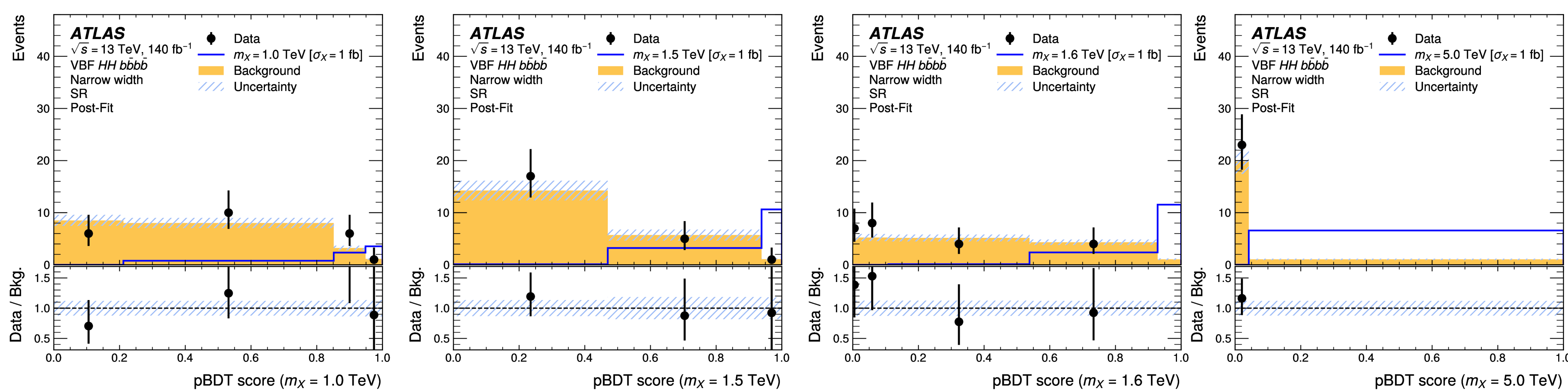


Deficit in SM, excess in κλ = 6, excess in tail

Boosted



Non-resonant BDT



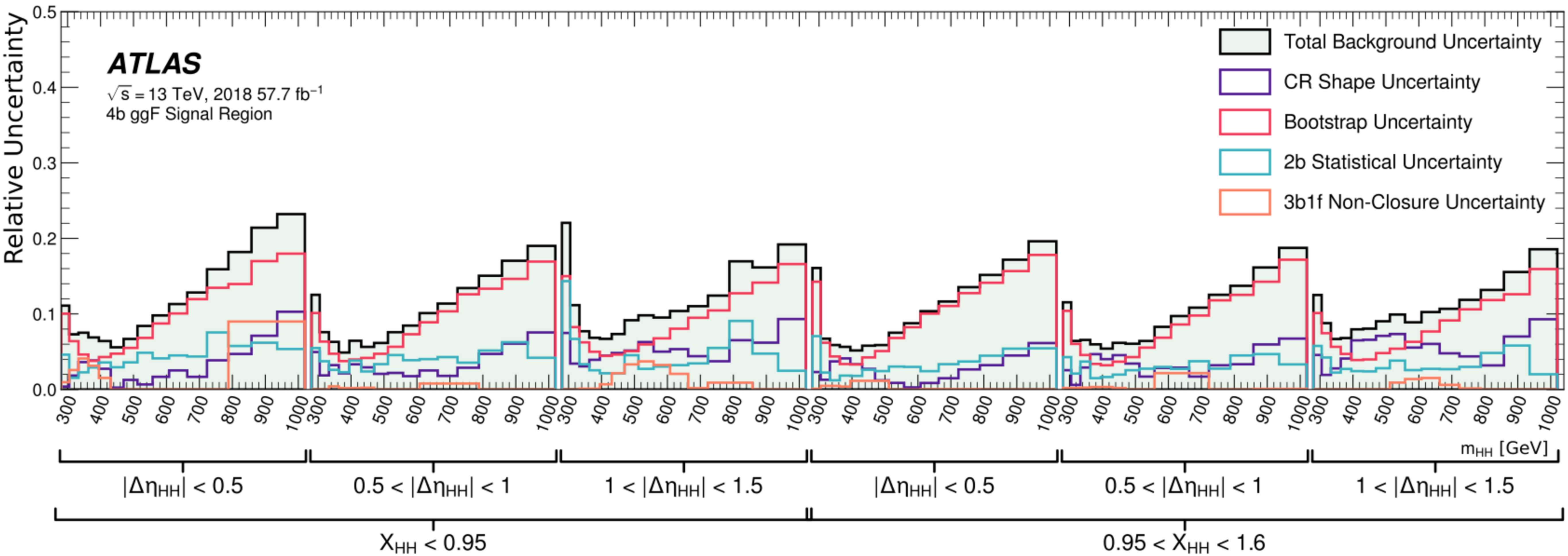
Resonant parameterised BDT

bbbb tables

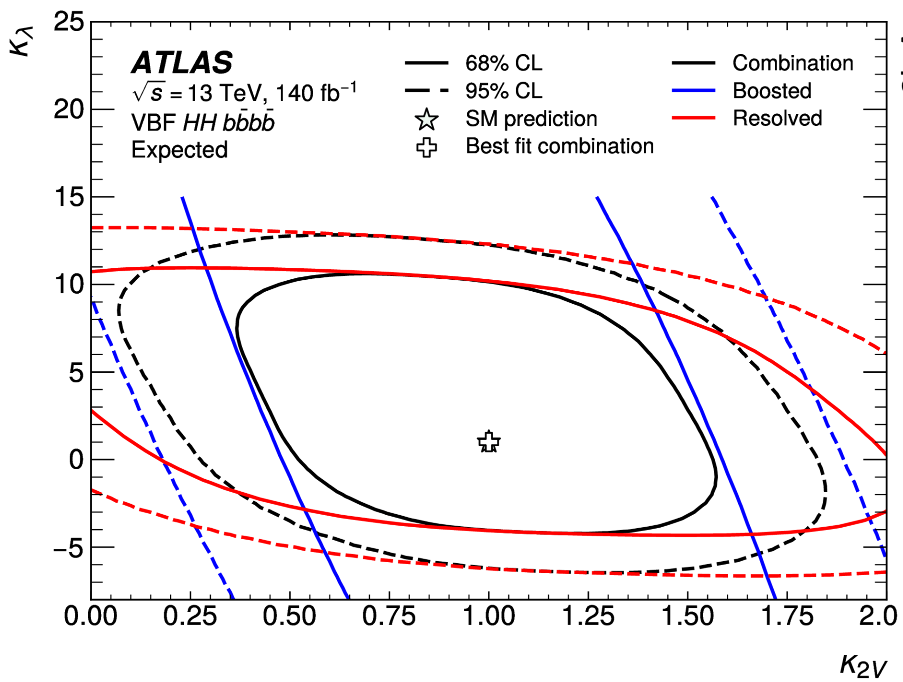
Category	Data	Expected Background	ggF Signal SM	VBF Signal SM
ggF signal region				
$\lvert\Delta\eta_{HH}\rvert < 0.5$, $X_{HH} < 0.95$	1940	1935 ± 25	7.0	0.038
$\lvert\Delta\eta_{HH}\rvert < 0.5$, $X_{HH} > 0.95$	3602	3618 ± 37	6.5	0.036
$0.5 < \lvert\Delta\eta_{HH}\rvert < 1.0$, $X_{HH} < 0.95$	1924	1874 ± 21	5.1	0.037
$0.5 < \lvert\Delta\eta_{HH}\rvert < 1.0$, $X_{HH} > 0.95$	3540	3492 ± 35	4.7	0.040
$\lvert\Delta\eta_{HH}\rvert > 1.0$, $X_{HH} < 0.95$	1880	1739 ± 22	2.9	0.043
$\lvert\Delta\eta_{HH}\rvert > 1.0$, $X_{HH} > 0.95$	3285	3212 ± 37	2.8	0.041
VBF signal region				
$\lvert\Delta\eta_{HH}\rvert < 1.5$	116	125.3 ± 4.4	0.37	0.090
$\lvert\Delta\eta_{HH}\rvert > 1.5$	241	230.6 ± 5.3	0.06	0.21

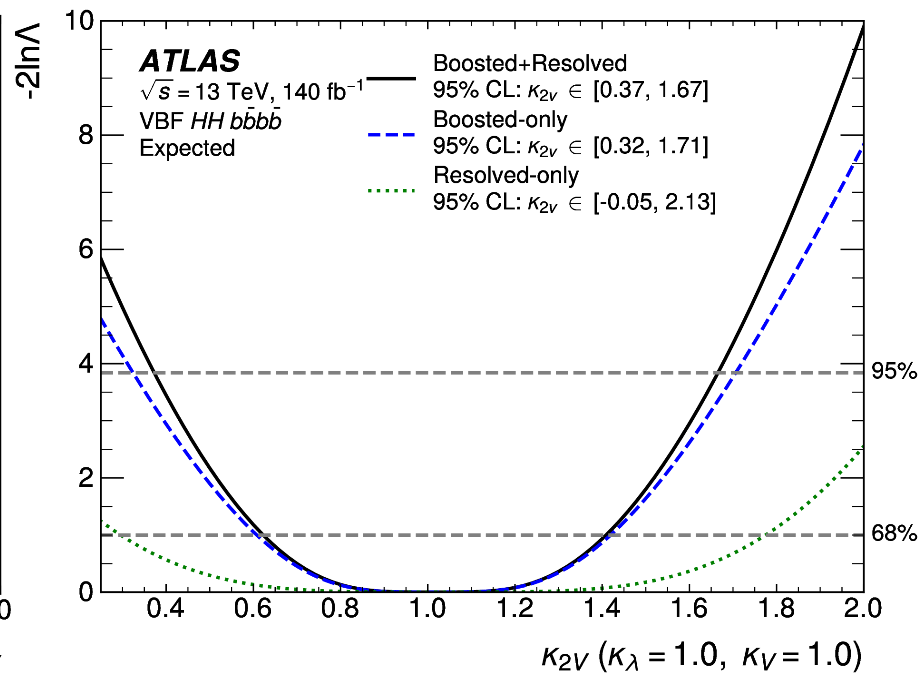
Source of Uncertainty	$\Delta\mu/\mu$
Theory uncertainties	
Theory uncertainty in signal cross-section	−9.0%
All other theory uncertainties	−1.4%
Background modeling uncertainties	
Bootstrap uncertainty	−7.1%
CR to SR extrapolation uncertainty	−7.5%
$3b1$f nonclosure uncertainty	−2.0%

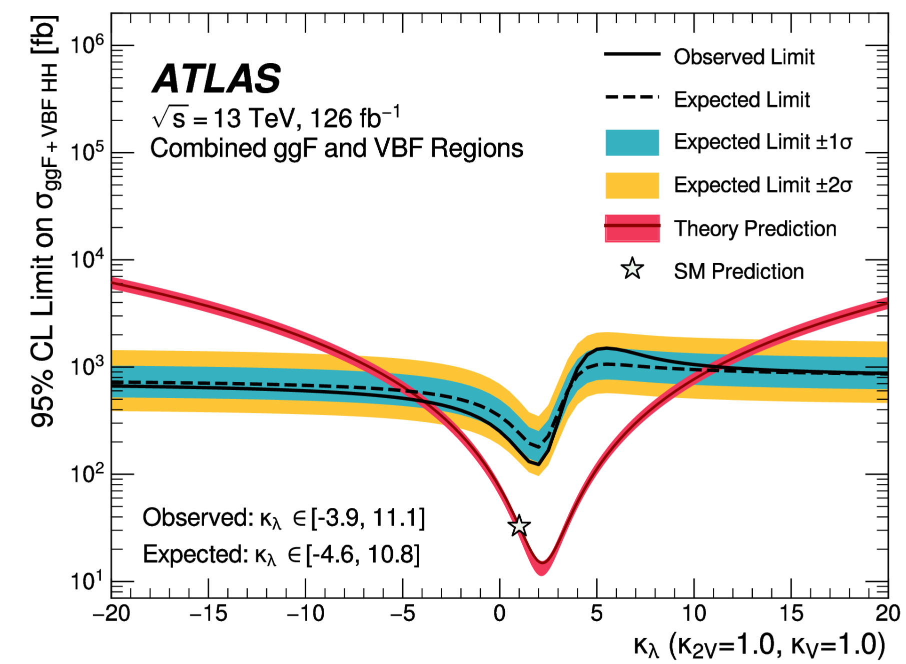
bbbb uncertainty

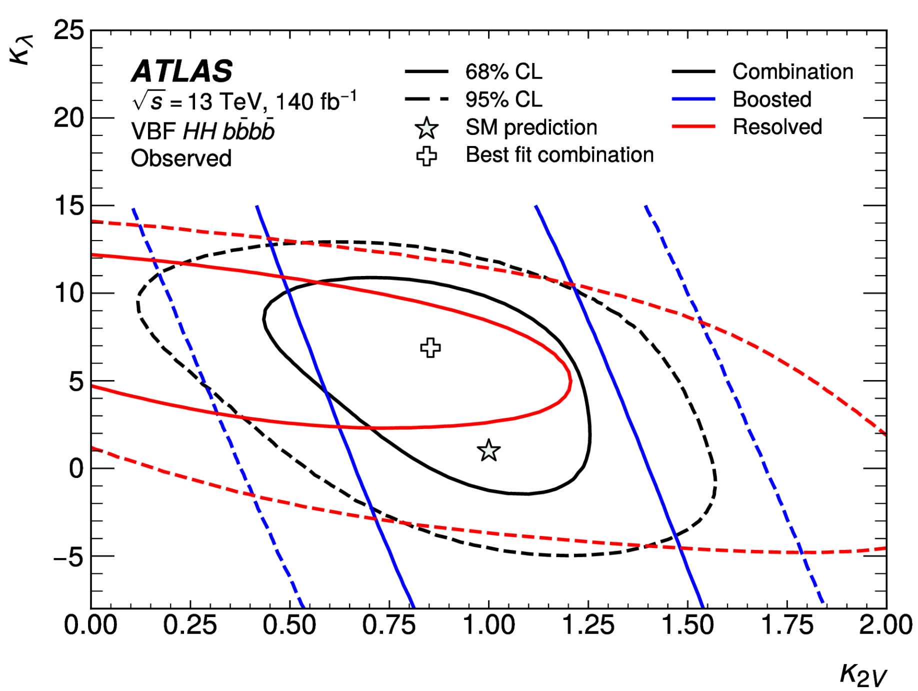


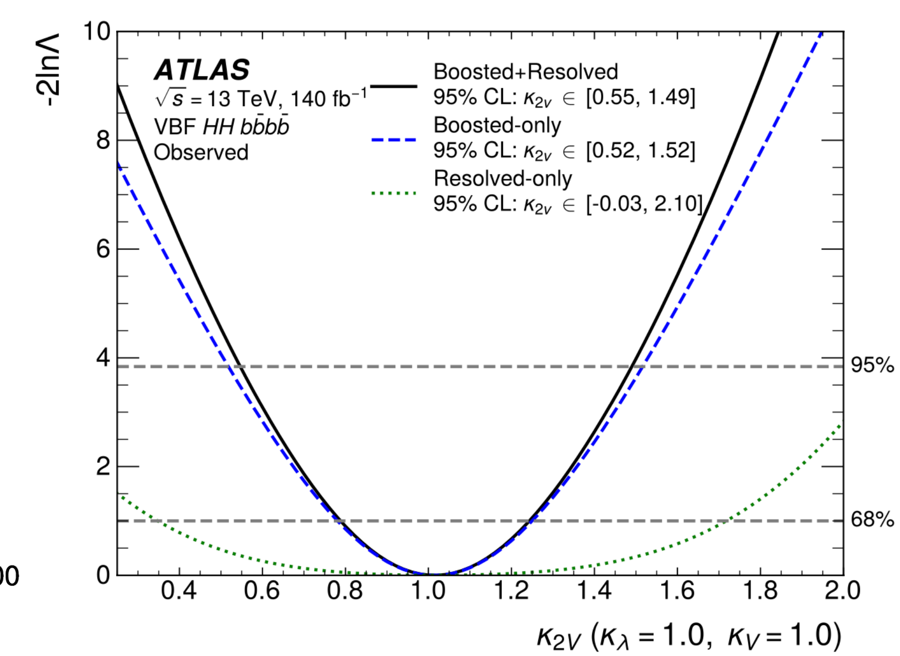
bbbb other results

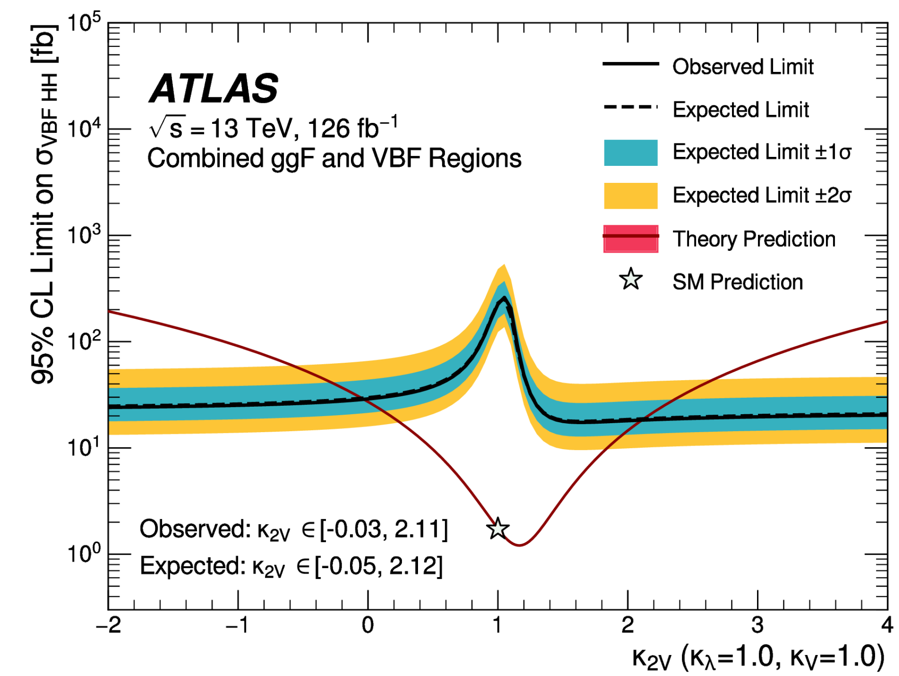




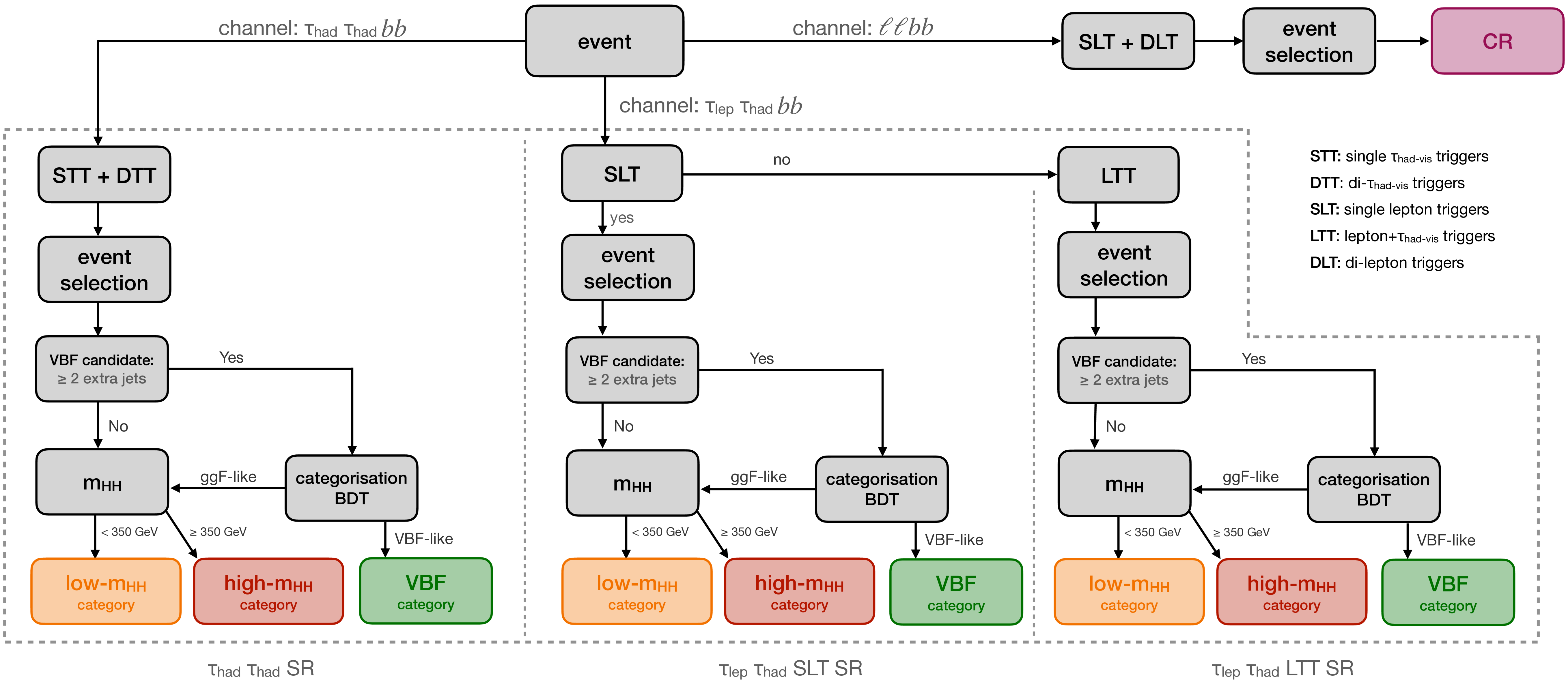








bbττ event selection



bbττ BDT variables

ggF vs VBF

Variable	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{had}$ SLT	$\tau_{lep}\tau_{had}$ LTT
m_{jj}^{VBF}	✓	✓	✓
$\Delta\eta_{jj}^{VBF}$	✓	✓	✓
VBF $\eta_0 \times \eta_1$	✓	✓	
$\Delta\phi_{jj}^{VBF}$	✓		
ΔR_{jj}^{VBF}		✓	✓
$\Delta R_{\tau\tau}$	✓		
m_{HH}	✓		
f_2^a	✓		
C^a		✓	✓
m_{Eff}^a		✓	✓
f_0^c		✓	
f_0^a			✓
h_3^a			✓

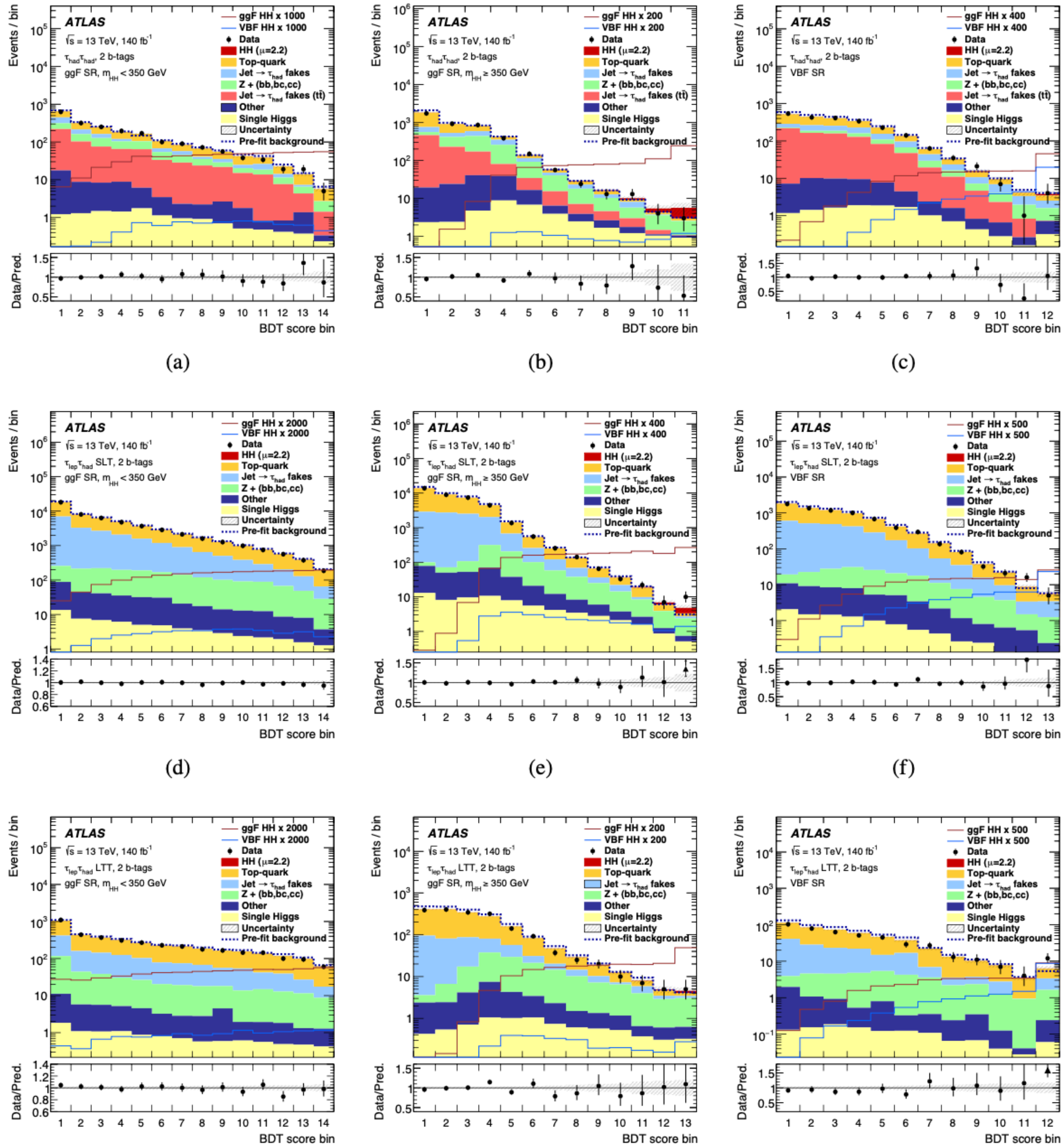
ggF

Variable	$\tau_{had}\tau_{had}$ low-m_{HH}	$\tau_{had}\tau_{had}$ high-m_{HH}	$\tau_{lep}\tau_{had}$ SLT low-m_{HH}	$\tau_{lep}\tau_{had}$ SLT high-m_{HH}	$\tau_{lep}\tau_{had}$ LTT low-m_{HH}	$\tau_{lep}\tau_{had}$ LTT high-m_{HH}
m_{bb}	✓	✓	✓	✓	✓	✓
$m_{\tau\tau}^{MMC}$	✓	✓	✓	✓	✓	✓
m_{HH}	✓	✓	✓	✓	✓	✓
ΔR_{bb}	✓	✓	✓	✓	✓	
$\Delta R(\tau_0, \tau_1)$	✓	✓	✓	✓	✓	✓
N(jets)	✓	✓	✓			
$p_T(HH)$		✓	✓			
H_T	✓			✓	✓	✓
T_1		✓	✓	✓	✓	✓
T_2	✓				✓	✓
E_T^{miss}	✓	✓	✓			
E_T^{miss} centrality					✓	
M_{T2}	✓				✓	
m_T^W			✓	✓	✓	
$m_T(\tau_1)$		✓		✓	✓	
$p_T(\tau_0)$	✓		✓	✓		
$p_T(\tau_1)$	✓		✓	✓		
$p_T(b_0)$	✓		✓			✓
$p_T(b_1)$				✓		
$p_T(bb)$						✓
$p_T(\tau\tau)$						✓
$\Delta p_T(\tau_0, \tau_1)$					✓	✓
$\eta(\tau_0)$	✓	✓				
$\eta(\tau_1)$	✓	✓				
$\Delta\eta(\tau_0, \tau_1)$					✓	
$\Delta\phi(bb, E_T^{miss})$	✓	✓				
$\Delta\phi(bb, \tau\tau)$	✓	✓				✓
$\Delta\phi(\tau\tau, E_T^{miss})$			✓	✓	✓	✓
$\Delta\phi(\tau_1, E_T^{miss})$					✓	✓
DL1r quantile(b_0)	✓	✓		✓		
DL1r quantile(b_1)	✓	✓		✓		
$\Delta R(b_0, \tau_0)$	✓	✓	✓			
$\Delta R(b_1, \tau_1)$		✓	✓			
$\Delta R(b_1, \tau_0)$			✓	✓		
m_{Eff}^c	✓					
m_{Eff}^b						✓
$m(b_0\tau_0)$						✓
$m(b_1\tau_0)$						✓
m_{HH}^*	✓					✓
m_{HH}^{scaled}						✓
C^b	✓	✓				
Sphericity[b]	✓	✓				
Planar flow[b]		✓				
$\cos(\Delta\theta_{bb}^{H\to b\bar{b} \text{ rest frame}})$			✓	✓		

VBF

Variable	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{had}$ SLT	$\tau_{lep}\tau_{had}$ LTT
m_{HH}	✓	✓	✓
m_{bb}	✓	✓	✓
$m_{\tau\tau}^{MMC}$	✓	✓	✓
ΔR_{bb}	✓	✓	
$\Delta R(\tau_0, \tau_1)$	✓	✓	
VBF $\eta_0 \times \eta_1$	✓		✓
$\Delta\eta_{jj}^{VBF}$	✓	✓	
$\Delta\phi_{jj}^{VBF}$	✓		
ΔR_{jj}^{VBF}	✓	✓	
m_{jj}^{VBF}	✓	✓	✓
N(jets)			✓
H_T		✓	
S_T			✓
T_2			✓
m_T^W			✓
$\Delta\eta_{HH}$		✓	
$p_T(HH)$			✓
m_{HH}^*			✓
m_{HH} scaled			✓
$p_T(\tau_0)$			✓
$p_T(\tau\tau)$			✓
$p_T(b_0)$			✓
$\eta(\tau_0)$	✓		
$\eta(\tau_1)$	✓		
$\Delta R(b_0, \tau_0)$			✓
Thrust[a]	✓		
Circularity[a]	✓		
Planar Flow[a]		✓	
f_0^a		✓	
f_2^a		✓	
f_4^a		✓	
m_{Eff}^a		✓	
$\cos\theta^*$			✓
$\cos(\Delta\theta_{\tau\tau}^{H\to\tau\tau \text{ rest frame}})$			✓

bbττ 9 BDTs



(a) (b) (c)

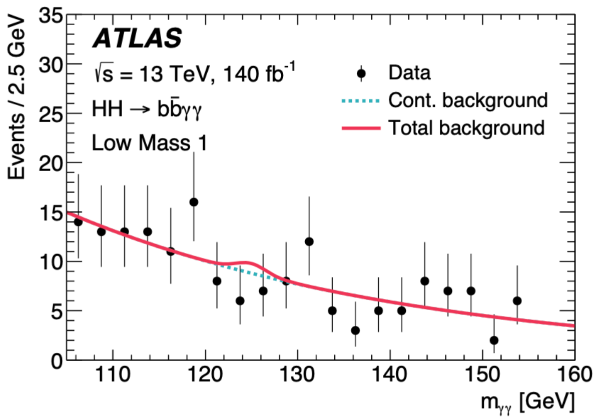
(d) (e) (f)

(g) (h) (i)

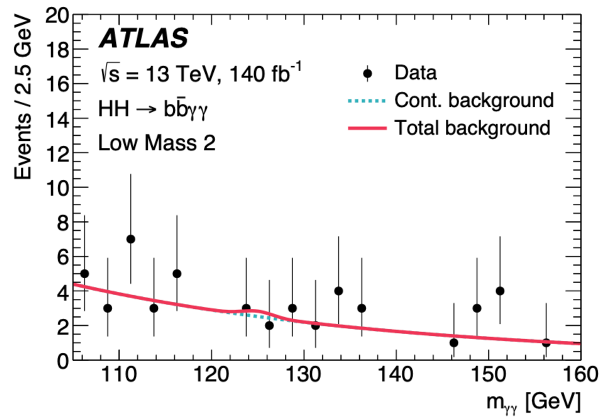
bbγγ BDT training variables

Variable	Definition
Photon candidates	
$p_{\mathrm{T}}/m_{\gamma\gamma}$	Transverse momentum of each photon divided by the diphoton invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudorapidity and azimuthal angle of each photons
$\Delta R(\gamma_1, \gamma_2)$	Angular distance between the two photons
b-jet candidates	
b-tag status	Tightest fixed b-tag working point (60%, 70%, 77%) that each jet passes
p_{T}, η and ϕ	Transverse momentum, pseudorapidity and azimuthal angle of each jet
$p_{\mathrm{T}}^{b\bar{b}}$, $\eta_{b\bar{b}}$ and $\phi_{b\bar{b}}$	Transverse momentum, pseudorapidity and azimuthal angle of the two-b-jet system
$\Delta R(b_1, b_2)$	Angular distance between the two candidate b-jets
$m_{b\bar{b}}$	Invariant mass of the two candidate b-jets
Single topness	Variable used to identify $t \to Wb \to q\bar{q}'b$ decays. For the definition, see Eq.(1).
Other jets (only first two, if present, ranked by discrete b-tagging score)	
b-tag status	Tightest fixed b-tag working point (85% or none) that each jet passes
p_{T}, η and ϕ	Transverse momentum, pseudorapidity and azimuthal angle of each jet
VBF-jet candidates	
$\Delta\eta(j_1, j_2)$, m_{jj}	Pseudorapidity difference and invariant mass of the two jets
Event-level variables	
Transverse sphericity, planar flow, p_{T} balance	For the definitions, see Ref. [83], Ref. [84], and Eq. (2)
H_{T}	Scalar sum of the p_{T} of the jets in the event
$E_{\mathrm{T}}^{\mathrm{miss}}$ and ϕ^{miss}	Missing transverse momentum and its azimuthal angle
$m^*_{b\bar{b}\gamma\gamma}$	The 4-body invariant mass of the two photons and two candidate b-jets, $m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - 125\ \text{GeV}) - (m_{\gamma\gamma} - 125\ \text{GeV})$

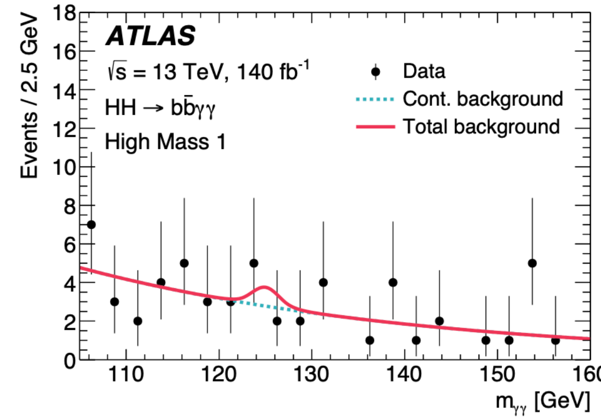
bbγγ discriminant



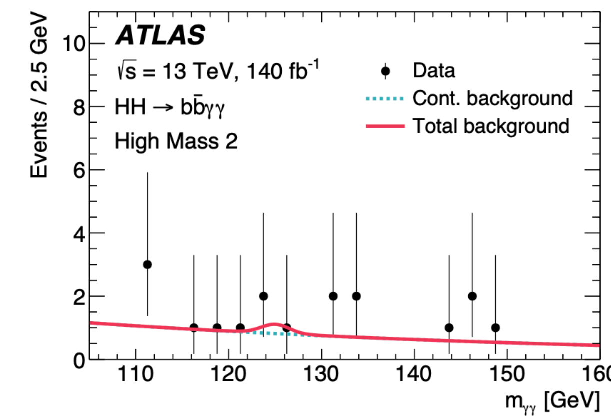
(a) Low Mass 1



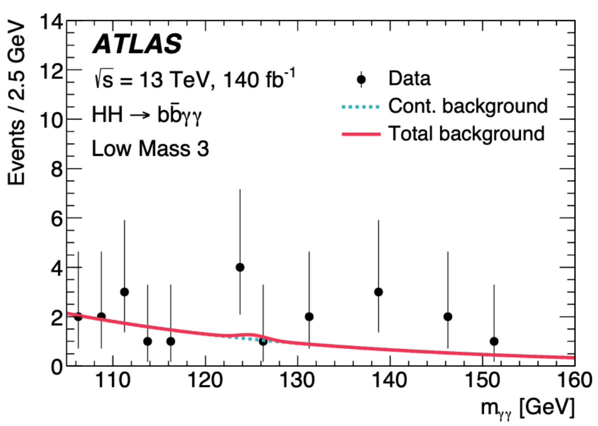
(b) Low Mass 2



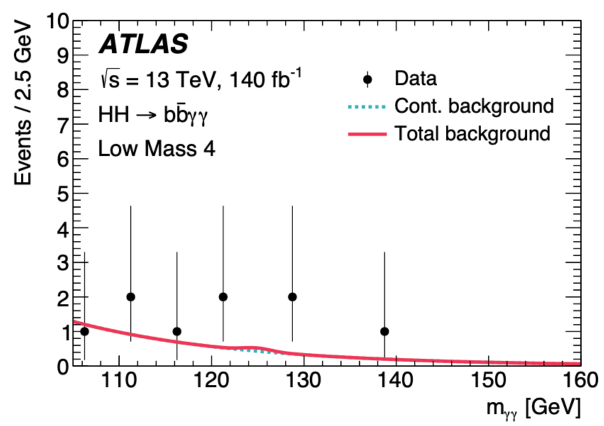
(e) High Mass 1



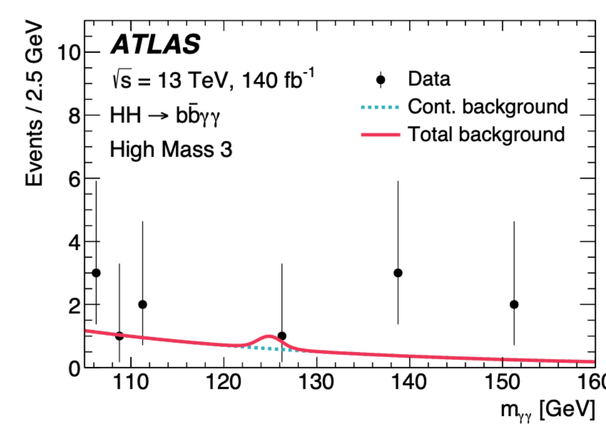
(f) High Mass 2



(c) Low Mass 3

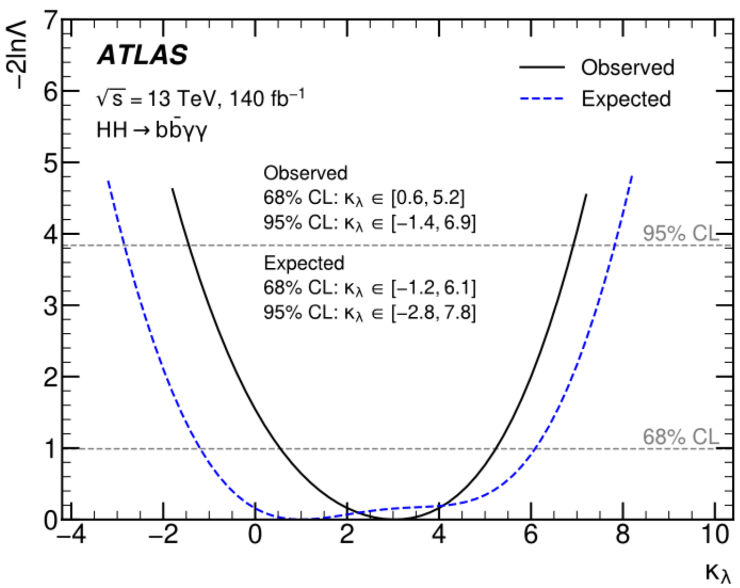


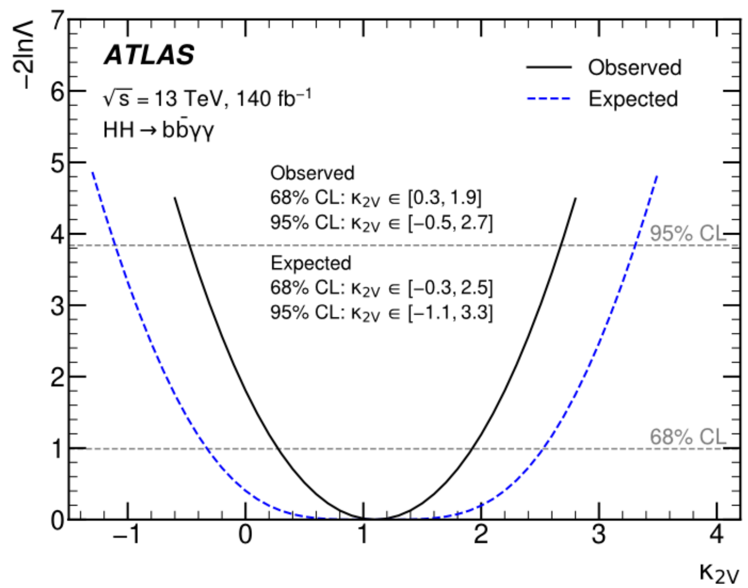
(d) Low Mass 4

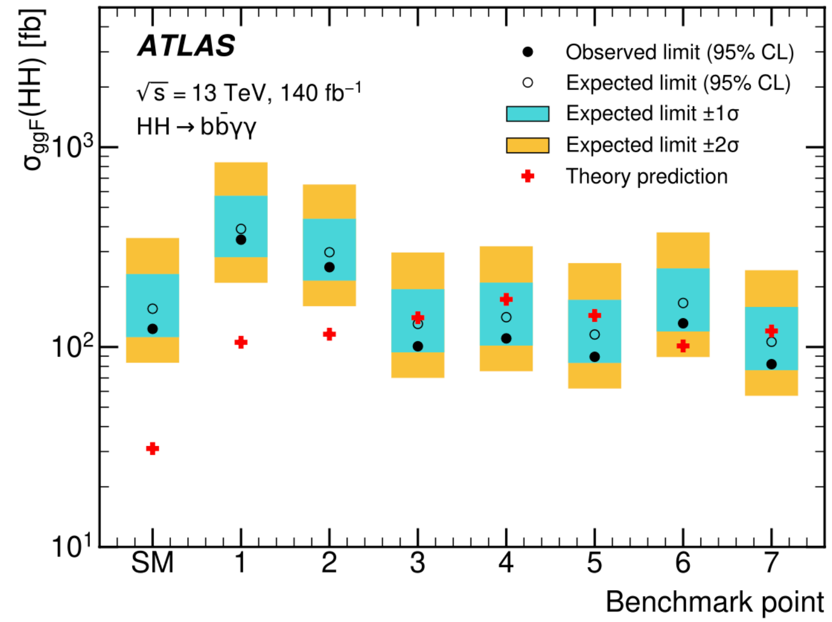


(g) High Mass 3

bbγγ other results

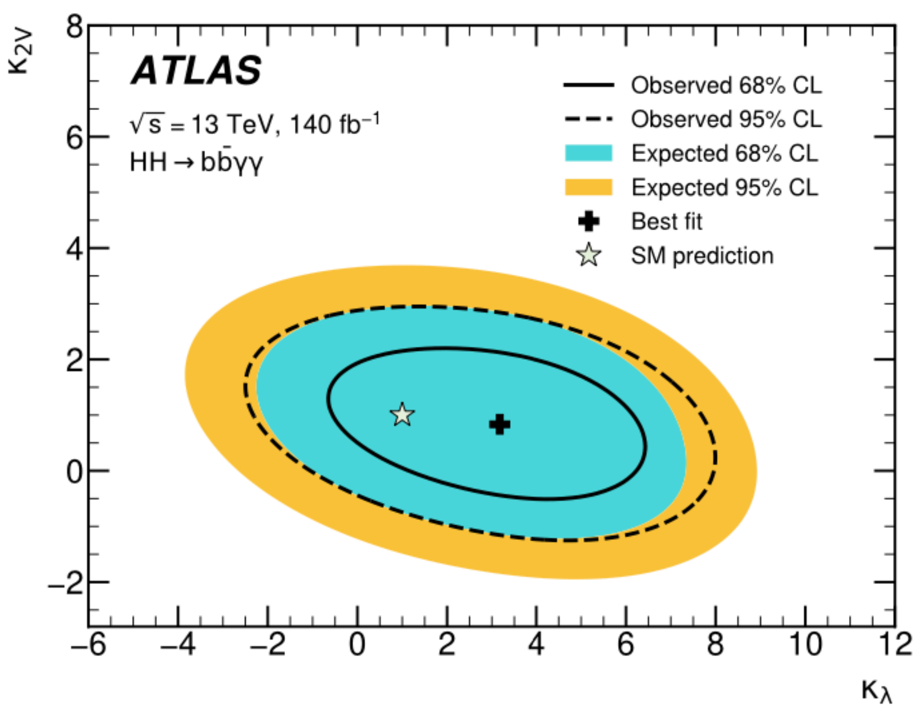


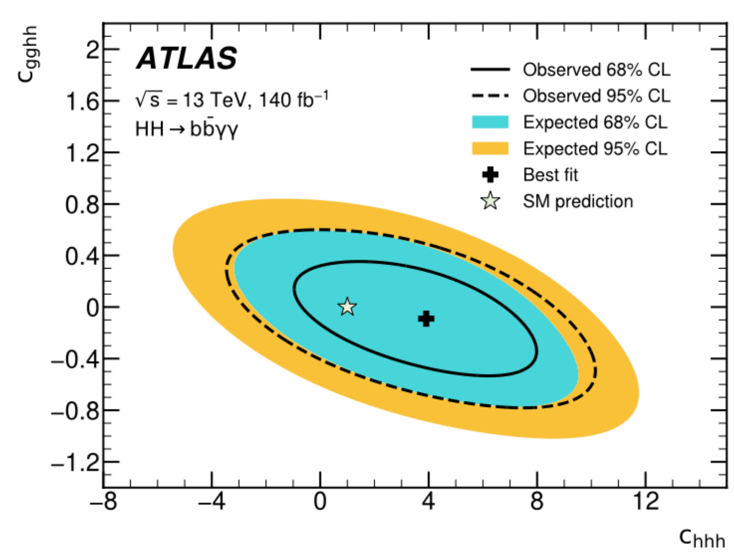


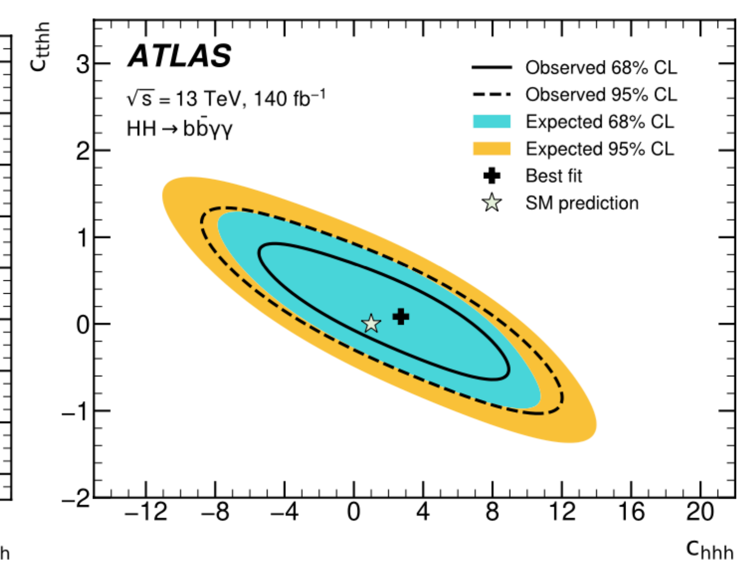


HEFT

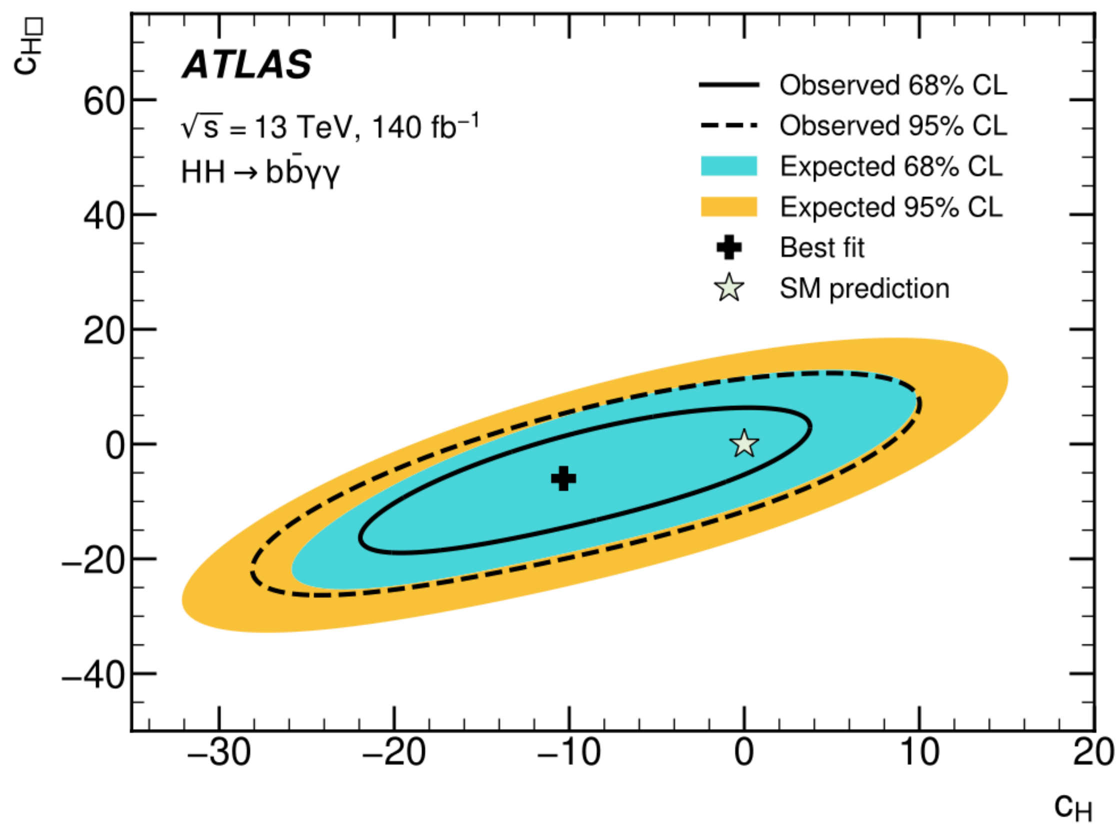
Wilson coefficient	95% CL Observed	95% CL Expected
c_{hhh}	[−1.7 , 7.7]	[−3.4 , 8.9]
c_{tthh}	[−0.28, 0.73]	[−0.48, 0.94]
c_{gghh}	[−0.42, 0.52]	[−0.59, 0.69]



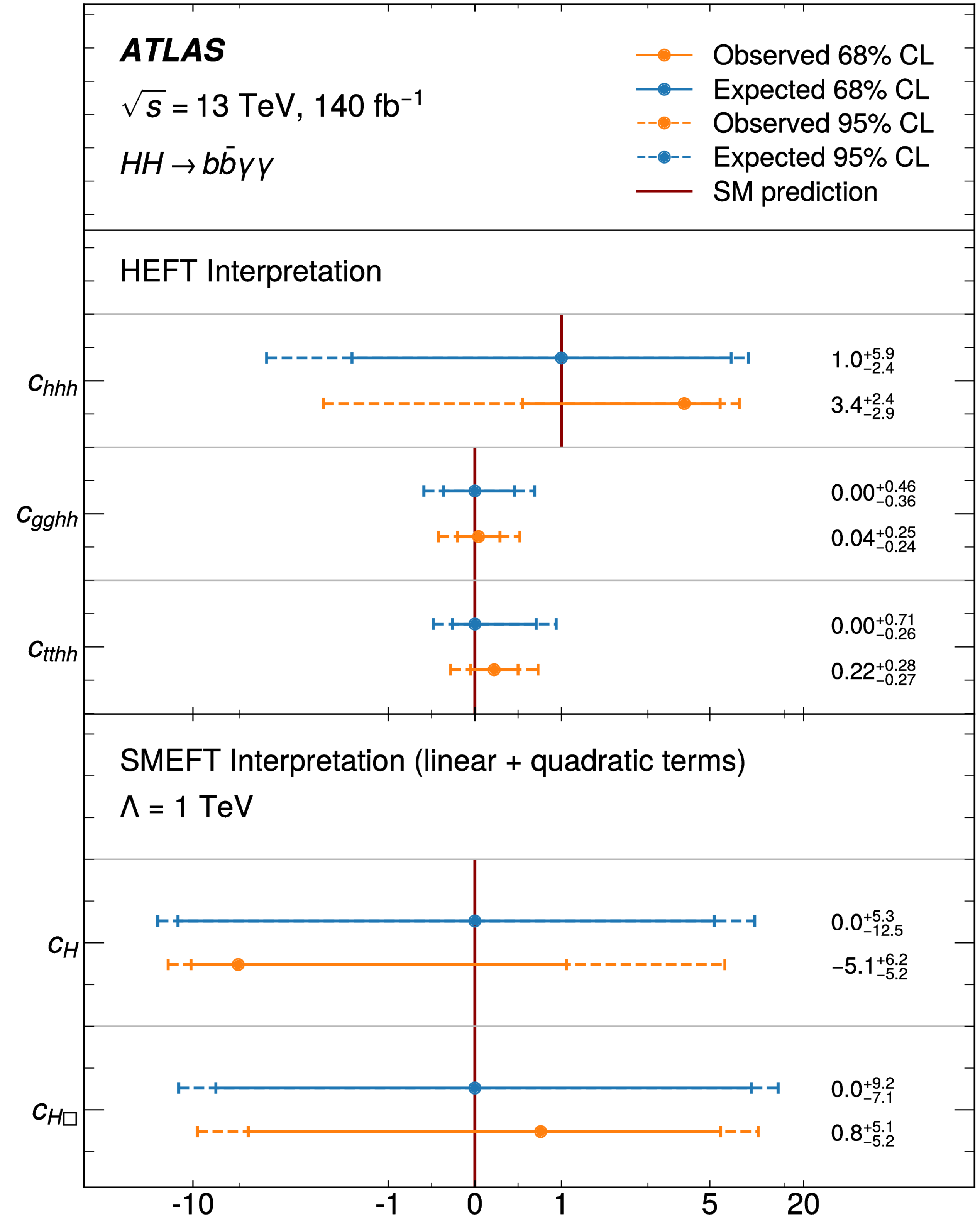




bbγγ other results

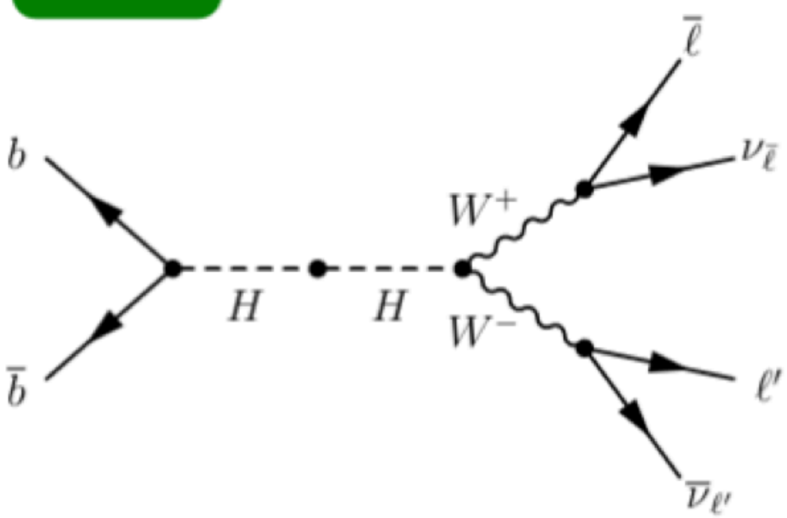


Wilson coefficient	95% CL Observed	95% CL Expected
c_H	[−14.4, 6.2]	[−16.8, 9.7]
$c_{H\Box}$	[− 9.4, 10.2]	[−12.4, 13.7]



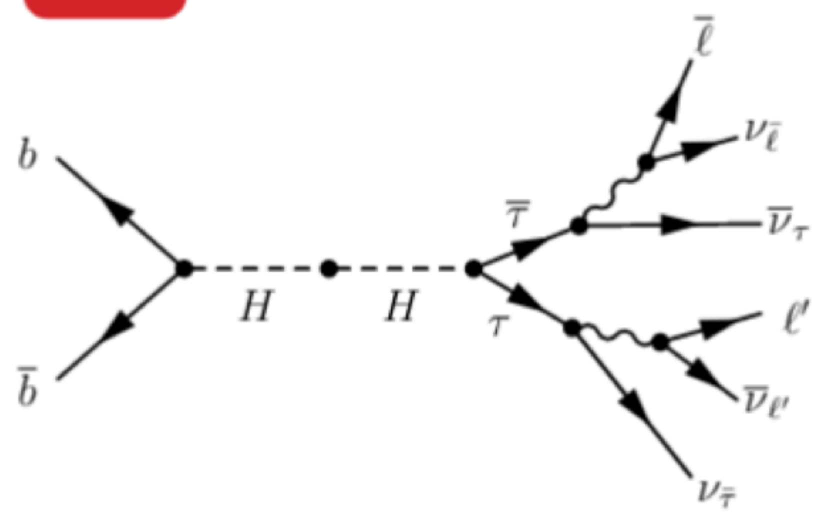
$bb\ell\ell+E_T^{miss}$ targeted processes

bbWW



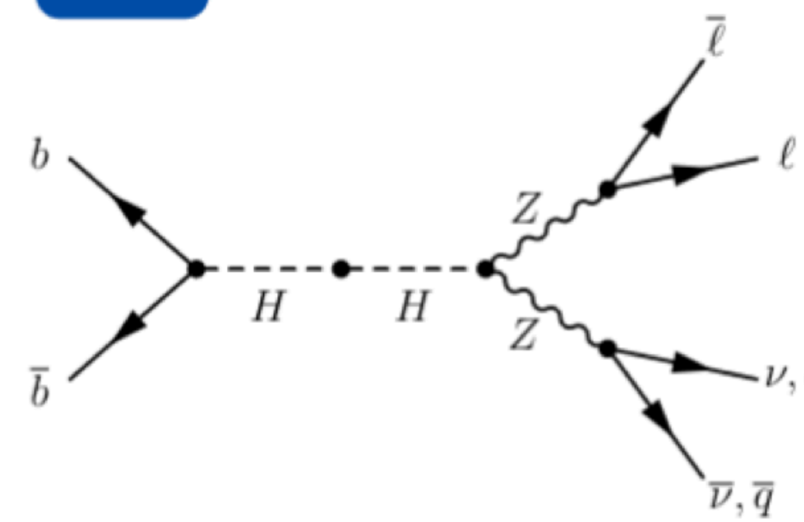
- $BR_{HH\to bb\ell\ell+\text{MET}} = 1.62\,\%^{\dagger}$
- W-pair has spin correlation
- small $m_{\ell\ell}$ and $\Delta\Phi_{\ell\ell}$

bbττ



- $BR_{HH\to bb\ell\ell+\text{MET}} = 0.91\,\%^{\dagger}$
- light leptons are collinear to τ-lepton $\Rightarrow m_{\tau\tau}^{\text{coll}}$

bbZZ



- $BR_{HH\to bb\ell\ell+\text{MET}} = 0.095\,\%^{\dagger}$
- $m_{\ell\ell}$ close to Z peak or small for offshell Z
- only same flavour leptons

Decay	BR	BR/BR ($bb\ell\ell$)	σ/fb	expected events
$bbWW$ ($WW \to \ell\ell$)	0.01624	0.5510	0.5322	73.9758
$bb\tau\tau$	0.009059	0.3074	0.2969	41.2691
$bbZZ$ ($ZZ \to \ell\ell\nu\nu$)	0.0008724	0.0296	0.0286	3.9754
$bbZZ$ ($ZZ \to \ell\ell qq$)	0.00304935	0.1035	0.0999	13.8861
$bb\mu\mu$	0.00025346	0.0086	0.0083	1.1537

bb$\ell\ell$+E_T^{miss} prefit yields

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

$bb\ell\ell$+E_T^{miss} MVA inputs

ggF NN

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 di-lepton 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 [125, 126]
$\Delta R_{\ell\ell}$, ΔR_{bb}	ΔR between the two leptons and two b-tagged jets
$m_{b\ell}$	$\min\{\max(m_{b_0\ell_0}, m_{b_1\ell_1}), \max(m_{b_0\ell_1}, m_{b_1\ell_0})\}$ [54]
$\min \Delta R_{b\ell}$	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 [127]
$m_T(\ell_0, E_T^{miss})$	transverse mass of the p_T-leading lepton with respect 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[6] of the two Higgs bosons

VBF BDT

Input feature	Description
η_{ℓ_0}, η_{ℓ_1}, ϕ_{ℓ_0}, ϕ_{ℓ_1}, $p_T^{\ell_0}$, $p_T^{\ell_1}$	η, ϕ, p_T of the p_T-(sub)leading lepton
η_{b_0}, η_{b_1}, ϕ_{b_0}, ϕ_{b_1}, $p_T^{b_0}$, $p_T^{b_1}$	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}, $p_T^{j_0}$, $p_T^{j_1}$	ϕ, η, p_T of the p_T-(sub)leading non b-tagged jet
E_T^{miss}, $\phi^{E_T^{miss}}$, E_T^{miss}-sig	missing transverse energy, its ϕ and significance [127]
p_T^{bb}, ΔR_{bb}, $\Delta\phi_{bb}$, m_{bb}	p_T, ΔR, $\Delta\phi$ and invariant mass of di-b-jet system
$p_T^{\ell\ell}$, $\Delta R_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, $\phi_{\text{centrality}}^{\ell\ell}$	p_T, ΔR, $\Delta\phi$, p_T and centrality[7] of di-leptons system
$p_T^{bb\ell\ell}$, $m_{bb\ell\ell}$	p_T and invariant mass of the $bb\ell\ell$ system
$p_T^{bb\ell\ell+E_T^{miss}}$, $m_{bb\ell\ell+E_T^{miss}}$	p_T and invariant mass of $bb\ell\ell + E_T^{miss}$ system
$m_{\ell\ell+E_T^{miss}}$	invariant mass of di-lepton + E_T^{miss} system
$p_T^{E_T^{miss}+\ell\ell}$, $\Delta\phi_{E_T^{miss},\ell\ell}$	p_T of and $\Delta\phi$ between E_T^{miss} and di-lepton system
p_T^{tot}	p_T of $bb\ell\ell + E_T^{miss}$+ p_T-leading and -sub-leading jet
m_{tot}	invariant mass of $bb\ell\ell + E_T^{miss}$+ p_T-leading and -sub-leading jet
m_t^{KLF}	Kalman fitter top-quark mass [129]
$\min \Delta R_{\ell_0 j}$, $\min \Delta R_{\ell_1 j}$	minimum ΔR between p_T-(sub)leading ℓ-j couples
$\sum m_{\ell j}$	sum of the invariant masses of all ℓ+jet combinations
$\max p_T^{jj}$, $\max m_{jj}$	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
$N_{\text{forward jets}}$, N_j	number of forward jets, number of non b-tagged jets
m_{T2}^{bb}	stransverse mass of the two b-tagged jets [125, 126]
m_{coll}	collinear mass (reconstruction of $m_{\tau\tau}$) [130]
m_{MMC}	value of the MMC algorithm (reconstruction of $m_{\tau\tau}$) [130]

Multilepton selections

Channel	ℓ	$\tau_{\text{had-vis}}$	Jets	b-jets
$4\ell+bb$	4ℓ(B) $p_T(\ell_1) > 20$ GeV $p_T(\ell_2) > 15$ GeV $p_T(\ell_3) > 10$ GeV ℓ_3 or ℓ_4 pass loose PLV 2 SFOC pairs $50 < m^{SFOC}_{\text{lead-}\ell\ell} < 106$ GeV $5 < m^{SFOC}_{\text{sublead-}\ell\ell} < 115$ GeV All pairs $\Delta R(\ell_i, \ell_j) > 0.02$ 115 GeV $< m_{4\ell} <$ 135 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), $p_T > 15$ GeV ℓ_{SC2}(T), $p_T > 15$ GeV All $m^{SFOC}_{\ell\ell} > 12$ 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), $p_T > 20$ GeV, SC $m_{\ell\ell} > 12$ GeV	$N_\tau = 0$	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$
2ℓSC+τ	2ℓ(T), $p_T > 20$ GeV, SC $m_{\ell\ell} > 12$ GeV	$N_\tau = 1$ $p_T > 25$ GeV OC to ℓ	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$
$2\ell+2\tau$	2ℓ(L), OC $m_{\ell\ell} > 12$ GeV Z-veto	$N_\tau = 2$, OC $\Delta R(\tau_1, \tau_2) < 2$	-	$N_{b\text{-jet}} = 0$
$\ell+2\tau$	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_T^{miss}	b-jets
$\gamma\gamma+2(\ell,\tau)$	N_ℓ(P) + N_τ = 2 $m_{2(\ell,\tau)} > 12$ GeV		$N_\gamma = 2$ $E_T(\gamma_1) > 35$ GeV 105 GeV $< m_{\gamma\gamma} <$ 160 GeV $\gamma_1 : p_T/m_{\gamma\gamma} > 0.35$ $\gamma_2 : p_T/m_{\gamma\gamma} > 0.25$	$E_T^{\text{miss}} > 35$ GeV	$N_{b\text{-jet}} = 0$
$\gamma\gamma+\ell$	1ℓ(P)	$N_\tau = 0$	$N_\gamma = 2$ $E_T(\gamma_1) > 35$ GeV 105 GeV $< m_{\gamma\gamma} <$ 160 GeV $\gamma_1 : p_T/m_{\gamma\gamma} > 0.35$ $\gamma_2 : p_T/m_{\gamma\gamma} > 0.25$	$\gamma\gamma+e$: $E_T^{\text{miss}} > 35$ GeV $\gamma\gamma+\mu$: -	$N_{b\text{-jet}} = 0$
$\gamma\gamma+\tau$	$N_{\ell(P)} = 0$	$N_\tau = 1$	$N_\gamma = 2$ $E_T(\gamma_1) > 35$ GeV 105 GeV $< m_{\gamma\gamma} <$ 160 GeV $\gamma_1 : p_T/m_{\gamma\gamma} > 0.35$ $\gamma_2 : p_T/m_{\gamma\gamma} > 0.25$	$E_T^{\text{miss}} > 35$ GeV	$N_{b\text{-jet}} = 0$

Multilepton CR definitions

Channel	Region	Leptons	Jets	b-jets	Additional selections
$4\ell+bb$	$t\bar{t}$ CR*	Off-shell-$\ell\ell$ not SFOC Z-veto	-	-	-
	$t\bar{t}Z$ CR*	Off-shell-$\ell\ell$ not SFOC All ℓ pass loose PLV Z-req. $m_{4\ell}$ req. removed	-	-	-
	VV, H CR*	All ℓ pass loose PLV	-	$N_{b\text{-jet}} = 0$	-
	Z+jets CR*	$p_T(\ell_3) < 10$ GeV $p_T(\ell_4) < 10$ GeV Z-req.		-	- -
	VR	-	-	-	$\lvert m_{4\ell} - m_H \rvert > 10$ GeV
3ℓ	WZ CR	Z-req.	-	-	$E_T^{miss} > 30$ GeV
	HF-e CR*	ℓ_{SC1}, ℓ_{SC2} both e No PLV on any ℓ	$N_{jet} \geq 2$	$N_{b\text{-jet}} \geq 2$	
	HF-μ CR*	ℓ_{SC1},ℓ_{SC2} both μ No PLV on any ℓ	$N_{jet} \geq 2$	$N_{b\text{-jet}} \geq 2$	
	Mat. conv. CR*	$\lvert m_{3\ell} - m_Z \rvert < 10$ GeV $r_{vtx} > 20$ mm $0 < m_{trk,trk} < 100$ MeV	-	-	-
	VR	-	-	-	BDT < 0.55
2ℓSC	WZ CR*	$\geq 3\ell$(T), $p_T > 20$ GeV One SFOC pair Z-req. $m_{\ell\ell}$ (any pair) > 12 GeV $\lvert m_{3\ell} - m_Z \rvert > 10$ GeV	-	-	$E_T^{miss} > 30$ GeV
	VVjj CR*	Z-veto (SFSC pair)	$m_{jj} > 300$ GeV	-	BDT < -0.4 BDT$_{V+jets} > -0.8$
	HF-e CR1*	ℓ(T)e(T), no PLV	$2 \leq N_{jet} \leq 3$	$N_{b\text{-jet}} = 1$	-
	HF-e CR2*	ℓ(T)e(T), no PLV	$2 \leq N_{jet} \leq 3$	$N_{b\text{-jet}} \geq 2$	-
	HF-μ CR*	ℓ(T)μ(T), no PLV	$2 \leq N_{jet} \leq 3$	$N_{b\text{-jet}} \geq 1$	-
	Mat. conv. CR*	$r_{vtx} > 20$ mm $m_{trk,trk} < 100$ MeV	-	-	-
	Int. conv. CR*	$r_{vtx} < 20$ mm $m_{trk,trk} < 100$ MeV	-	-	-
	Q mis-ID	$2e$(T), OC or SC	$N_{jet} < 2$	-	-
	VR	-	-	-	BDT < -0.4

Channel	Region	Leptons	(anti-)$\tau_{had\text{-}vis}$	Jets	b-jets	Additional selections
2ℓSC+τ	VV CR*	-	-	-	-	BDT < -0.2
	HF-e CR1*	ℓ(T)e(T), no PLV	-	$N_{jet} \geq 2$	$N_{b\text{-jet}} = 1$	-
	HF-e CR2*	ℓ(T)e(T), no PLV	-	$N_{jet} \geq 2$	$N_{b\text{-jet}} \geq 2$	-
	HF-μ CR*	ℓ(T)μ(T), no PLV	-	-	-	-
	Fake-$\tau_{had\text{-}vis}$ CR	OC leptons Z-veto	-	-	-	-
	Z+jets VR	OC leptons Z-req.	-	-	-	-
	$t\bar{t}$ VR	OC leptons Z-veto	-	$N_{jet} = 2$	$N_{b\text{-jet}} = 1$	-
	VR	-	-	$N_{jet} < 2$	-	
$2\ell+2\tau$	Fake-$\tau_{had\text{-}vis}$ CR	-	$N_\tau = 1$ and $N_{anti\text{-}\tau} = 1$ or $N_{anti\text{-}\tau} = 2$		-	-
	Z+jets CR	Z-req.	$N_\tau \geq 1$ or $N_{anti\text{-}\tau} \geq 1$	-	-	-
	$t\bar{t}$ VR	-	$N_\tau \geq 1$ or $N_{anti\text{-}\tau} \geq 1$	-	$N_{b\text{-jet}} = 1$	-
	VR	-	SC $\tau_{had\text{-}vis}$	-	-	-
$\ell+2\tau$	Fake-$\tau_{had\text{-}vis}$ CR	-	$N_\tau = 1$ and $N_{anti\text{-}\tau} = 1$ or $N_{anti\text{-}\tau} = 2$		-	-
	Z+jets CR	2ℓ(T), OC Z-req.	$N_\tau \geq 1$ or $N_{anti\text{-}\tau} \geq 1$	-	-	-
	$t\bar{t}$ VR	2ℓ(T), OC Z-veto	$N_\tau \geq 1$ or $N_{anti\text{-}\tau} \geq 1$	-	$N_{b\text{-jet}} = 1$	-
	VR	-	SC $\tau_{had\text{-}vis}$	-	-	-

Multilepton BDT inputs

Variable	Description	4ℓ+bb	3ℓ	2ℓSC
$p_T(\ell_i)$	p_T of the ith lepton	$i = 1,2,3,4$	-	-
$\eta(\ell_i)$	η of the ith lepton	$i = 1,2,3,4$	-	$i = 1,2$
$E_T^{\Delta R<0.3}/E_T(\ell_i)$	Isolation metric ($E_T^{\Delta R<0.3}$ = total energy deposited in a cone of radius $R = 0.3$ around the lepton, and E_T = lepton energy)	$i = 1,2,3,4$	-	-
Dilepton type	$\mu\mu = 1$, $e\mu/\mu e = 2$, $ee = 3$	-	-	✓
m_{ℓ_i,ℓ_j}	Invariant mass of the ith and jth leptons	$i,j = 1,2$ $i,j = 3,4$	$i,j = 1,2$ $i,j = 1,3$ $i,j = 2,3$	$i,j = 1,2$
$m_{\ell\ell}^{Z\text{-match}}$	Invariant mass of pair of SFOS leptons that minimises the difference with the Z boson mass	-	✓	-
$m_{\ell\ell}^{\text{other}}$	Invariant mass of the other SFOS lepton pair	✓	-	-
min. $m_{\ell\ell}^{\text{SFOS}}$	Minimum invariant mass out of all SFOS pairs	-	✓	-
$m_{4\ell}$	Invariant mass of four leptons	✓	-	-
$m_{3\ell}$	Invariant mass of three leptons	-	✓	-
$m_{\ell_i,\text{close-jet}}$	Invariant mass of the ith lepton and its closest jet	-	$i = 1,2,3$	$i = 1,2$
$m_{3\ell\text{jj}}$	Invariant mass of the three leptons and the leading (or two leading, for events with $N_{\text{jet}} \geq 2$) jets	-	✓	-
m_{jj}	Invariant mass of the two leading jets	✓	-	-
m_{all}	Invariant mass of all selected objects in the event	-	-	✓
$m_T^W(\ell_i, E_T^{\text{miss}})$	Transverse mass of a leptonically decaying W-boson reconstructed from the ith lepton and its closest jet	-	-	$i = 1,2$
$\Delta\eta(\ell_i,\ell_j)$	Separation in η between the ith and jth leptons	-	-	$i = 1,2$
$\Delta R(\ell_i,\ell_j)$	Separation in R between the ith and jth leptons		$i,j = 1,2$ $i,j = 1,3$ $i,j = 2,3$	$i,j = 1,2$
$\Delta R(\ell_i, \text{close-j})$	Separation in R between the ith lepton and its closest jet	-	$i = 1,2,3$	$i = 1,2$
min. $\Delta R(\ell, \text{jet})$	Minimum separation in R between any lepton and any jet	-	-	✓
L_T	Scalar sum of the p_T of all leptons and the E_T^{miss}	-	✓	✓
H_T	Scalar sum of the p_T of all jets	-	✓	✓
S_T	Scalar sum of the p_T of all objects in the event	✓	✓	-
ΣQ_ℓ	Sum of all lepton charges	-	-	✓
N_{jet}	Number of jets in the event	-	-	✓
$N_{b\text{-jet}}$	Number of b-jets in the event	✓	-	-
$p_T(\text{j}_1)$	p_T of the leading jet	✓	-	-
$p_T(\text{jj})$	p_T of the leading di-jet system	✓	-	-
E_T^{miss}	Magnitude of the missing transverse momentum	✓	✓	✓
$\Delta\phi(E_T^{\text{miss}}, \text{j}_1)$	ϕ angle between the E_T^{miss} and the leading jet	✓	-	-

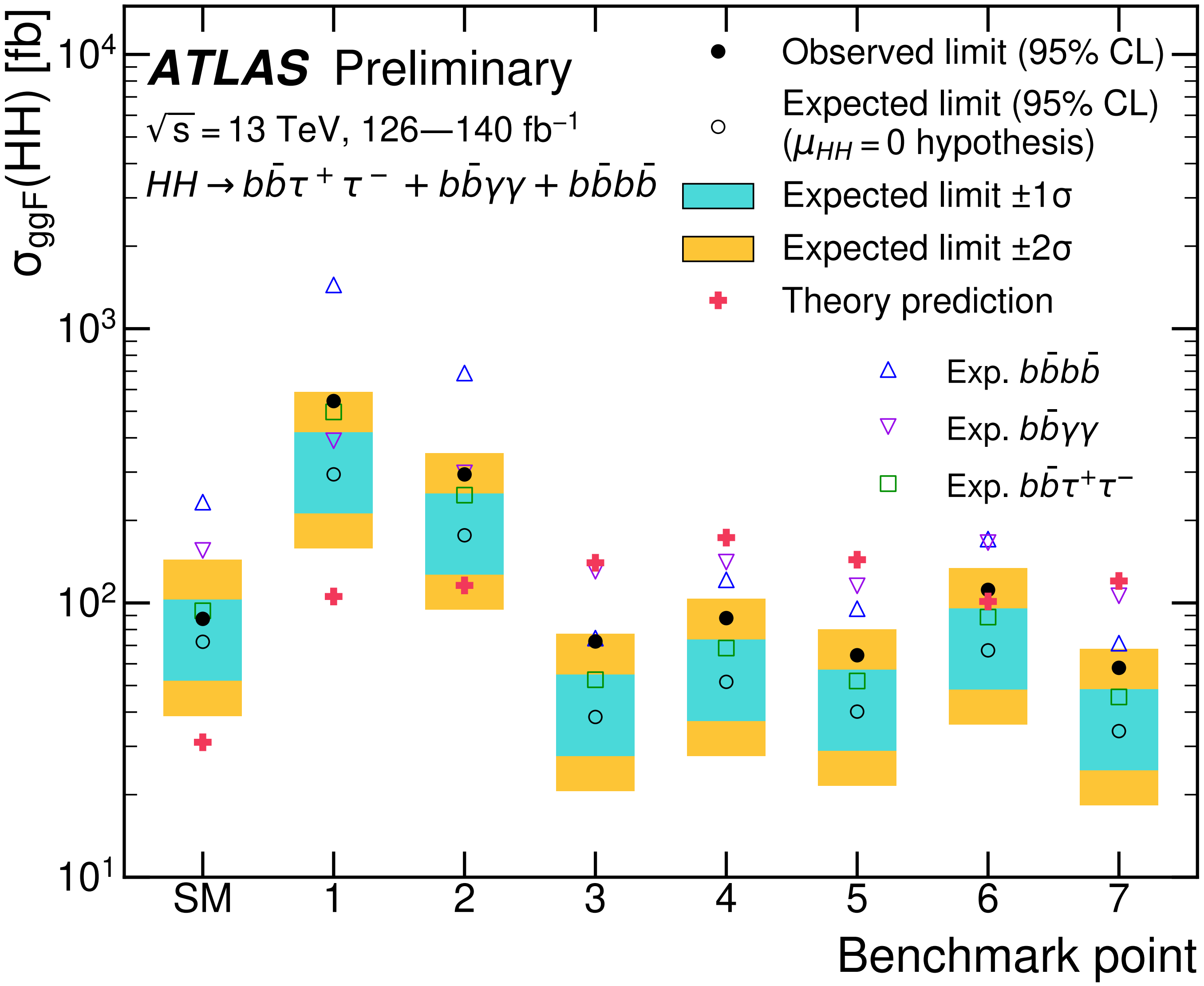
Variable	Description	2ℓSC+τ	2ℓ+2τ	ℓ+2τ
Dilepton type	$\mu\mu = 1$, $e\mu/\mu e = 2$, $ee = 3$	-	✓	-
m_{ℓ_i,ℓ_j}	Invariant mass of the ith and jth leptons	-	$i,j = 1,2$	-
$m_{\ell_i,\text{close-jet}}$	Invariant mass of the ith lepton and its closest jet	$i = 1$	-	$i = 1$
$m_{\ell_i \text{j}_j}$	Invariant mass of the ith lepton and jth jet	$i,j = 1,1$ $i,j = 1,2$ $i,j = 2,1$	-	-
$\Delta\eta(\ell_i,\ell_j)$	Separation in η between the ith and jth leptons	$i,j = 1,2$	-	-
$\Delta R(\ell_i,\ell_j)$	Separation in R between the ith and jth leptons	$i,j = 1,2$	$i,j = 1,2$	-
$\Delta R(\ell_i,\text{j}_j)$	Separation in R between the ith lepton and jth jet	$i,j = 1,1$	-	$i,j = 1,1$ $i,j = 1,2$
$\Delta R(\ell_i, \text{close-j})$	Separation in R between the ith lepton and its closest jet	$i = 1,2$	-	-
$p_T(\text{j}_1)$	p_T of the leading jet	-	-	✓
E_T^{miss}	Magnitude of the missing transverse momentum	-	-	✓
$\theta^{\text{boost-}\ell\ell}_{\tau_{\text{had}},\text{jet}_i}$	Polar angle between the $\tau_{\text{had-vis}}$ and the ith jet after a Lorentz boost to the dilepton system	$i = 1,2$	-	-
$\Delta R^{\text{boost-}\ell_i\tau_{\text{had}}}_{\ell_i,\text{jet}_j}$	Separation in R between the ith lepton and jth jet after a Lorentz boost to the $\tau_{\text{had-vis}}$ and ith lepton system	$i,j = 1,2$ $i,j = 2,1$	-	-
$m_{\tau\tau}$	Invariant mass of the two $\tau_{\text{had-vis}}$	-	✓	✓
$\Delta R(\ell_i,\tau_j)$	Separation in R between the ith lepton and jth $\tau_{\text{had-vis}}$	-	$i,j = 2,1$	-
$\Delta R(\ell_i,\tau\tau)$	Separation in R between the ith lepton and the di-$\tau_{\text{had-vis}}$ system	-	$i = 1$	$i = 1$
$m_{\ell_i\tau_j}$	Invariant mass of the ith lepton and jth $\tau_{\text{had-vis}}$	-	$i,j = 2,1$	-
$m_{\ell\tau\tau}$	Invariant mass of the lepton and two $\tau_{\text{had-vis}}$	-	-	✓
$\vec{p}_T(\ell) + \vec{p}_T(\text{close-j})$	Vector sum of the p_Ts of the lepton and its closest jet	-	-	✓
$\vec{p}_T(\tau_1) + \vec{p}_T(\tau_2)$	Vector sum of the p_Ts of the two $\tau_{\text{had-vis}}$	-	✓	✓

Variable	Description	$\gamma\gamma$+ℓ	$\gamma\gamma$+τ
$p_T(\gamma\gamma)$	p_T of the diphoton system	✓	✓
$p_T(\ell)$	p_T of the lepton	✓	-
$p_T(\tau_{\text{had-vis}})$	p_T of the $\tau_{\text{had-vis}}$	-	✓
E_T^{miss}	Magnitude of the missing transverse momentum	✓	✓
$\phi(E_T^{\text{miss}})$	ϕ direction of the E_T^{miss}	-	✓
$\eta(\ell E_T^{\text{miss}})$	η of the lepton-E_T^{miss} system	✓	-
$\eta(\gamma_i)$	η of the ith photon	-	✓
$N_{\text{central-jets}}$	Number of jets with $\lvert\eta\rvert < 2.5$	✓	✓
$\Delta R(\ell, E_T^{\text{miss}})$	ΔR between the lepton and the E_T^{miss}	✓	-
$\Delta R(\gamma\gamma, \ell E_T^{\text{miss}})$	ΔR between the diphoton system and the lepton-E_T^{miss} system	✓	-
$\Delta\phi(\ell/\tau_{\text{had}}, \gamma\gamma)$	Separation in ϕ between the lepton or $\tau_{\text{had-vis}}$ and the diphoton system	✓	✓
$\Delta\phi(\gamma_1, \gamma\gamma)$	Separation in ϕ between the leading photon and the diphoton system	✓	✓
min.$\Delta\phi(E_T^{\text{miss}}, \text{j}, \ell)$	Minimum ϕ angle between the E_T^{miss}, the lepton, and any jet	✓	-
$\Delta\phi(E_T^{\text{miss}}, \gamma\gamma)$	Separation in ϕ between the E_T^{miss} and the diphoton system	✓	✓

Multilepton systematic table

Uncertainty source	Relative impact of systematic uncertainties [%]		
	ML channels	$\gamma\gamma$+ML channels	Combination
Systematic	22	14	19
MC statistics	5	<1	3
Experimental	5	<1	3
Detector response	4	<1	3
Luminosity and pile-up	<1	<1	<1
Electrons	<1	<1	<1
Muons	<1	<1	<1
$\tau_{\text{had-vis}}$	<1	<1	<1
Jets and $E_{\text{T}}^{\text{miss}}$	3	<1	2
Flavour-tagging	1	<1	<1
Photons	<1	<1	<1
Background estimation	<1	<1	<1
Theoretical	13	14	13
Signal	10	12	11
Backgrounds	4	2	3
Top quark	1	-	<1
Vector boson	3	-	2
Single Higgs	1	2	1
Other	<1	-	<1

HEFT benchmark

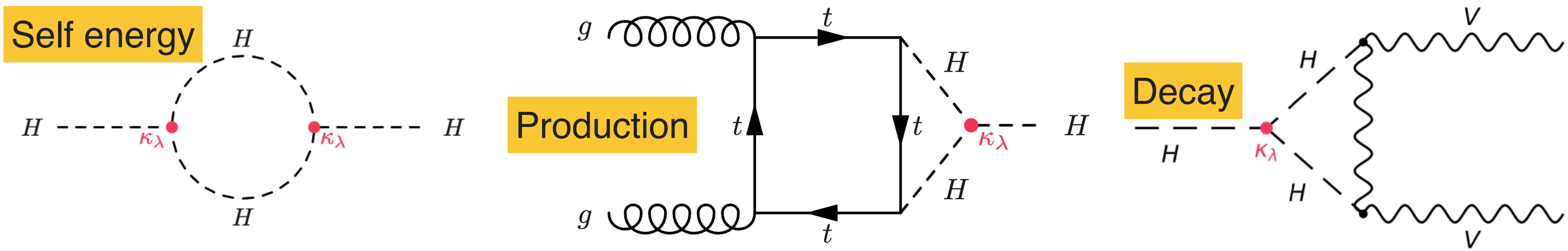


Benchmark	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1.00	1.00	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	−1/3	0	1/6
3	2.21	1.05	1/2	1/2	−1/3
4	2.79	0.90	−1/3	−1/2	−1/6
5	3.95	1.17	1/6	−1/2	−1/3
6	−0.68	0.90	1/2	1/4	−1/6
7	−0.10	0.94	1/6	−1/6	1

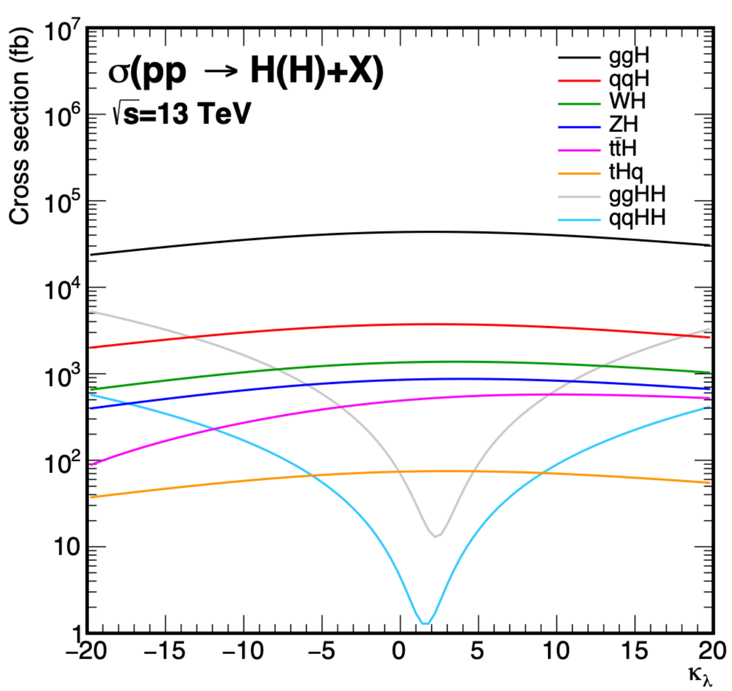
- Complementary sensitivities contributed from different channels, driven by the softness/hardness of the kinematics in a given benchmark

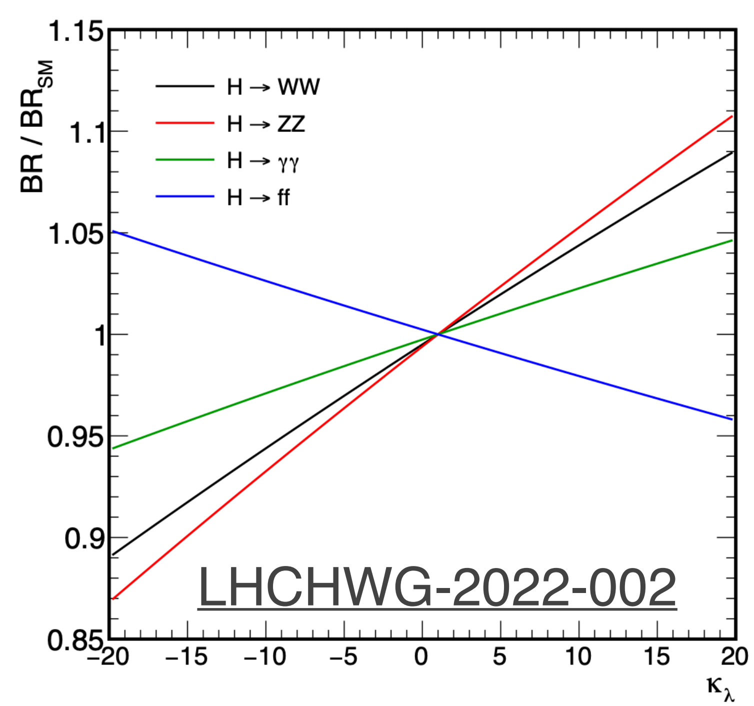
Combine with single Higgs measurements

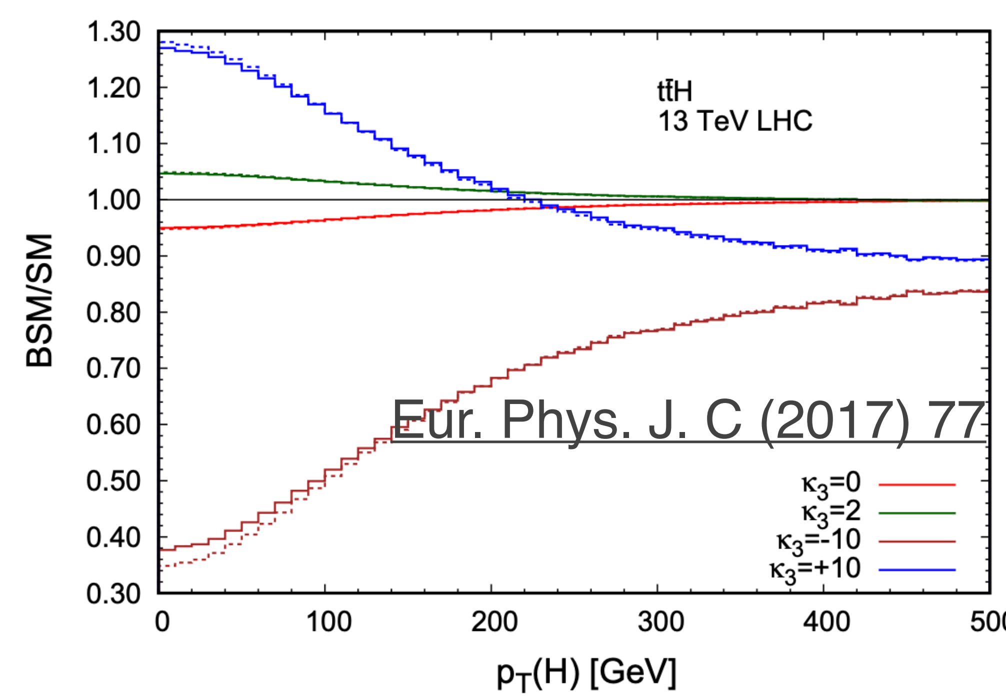
- κλ can affect single Higgs processes via NLO electroweak corrections



  - Affect the inclusive cross-sections, decay branching fractions and differential distributions

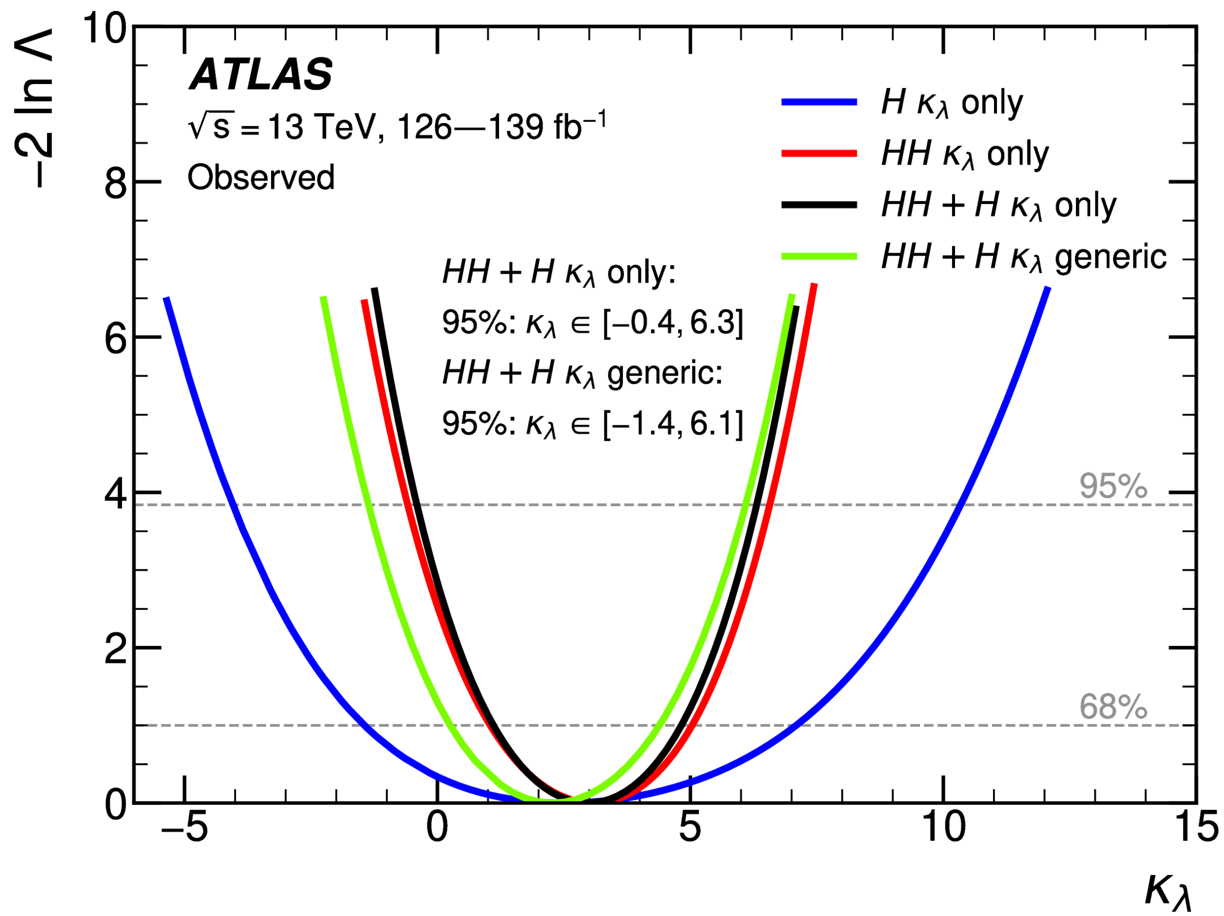


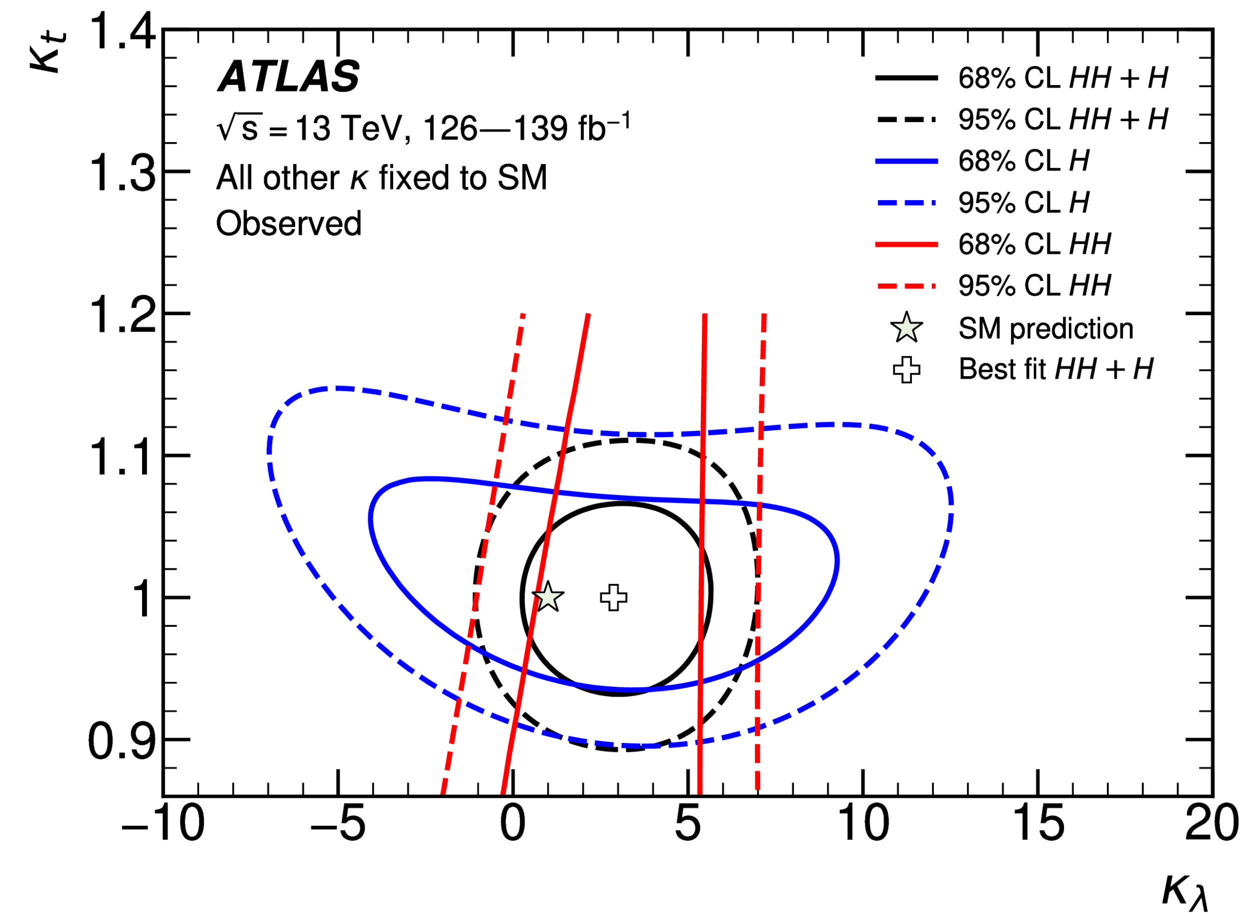




κ_λ constraints with least assumptions

- Generic fit: couplings (κ_λ, κ_t, κ_b, κ_τ, κ_V) are all floating in the fit





	Best fit	Obs	Exp
κ_λ only	3.0	[−0.4, 6.3]	[−1.9, 7.6]
Generic fit	2.3	[−1.4, 6.1]	[−2.2, 7.7]

- Dominated by HH while H provide strong constraints to other couplings.

Projection scenarios

- No systematic uncertainties.
- Baseline: systematic uncertainties are scaled as in Table 2.
- Theoretical uncertainties halved: theoretical systematic uncertainties are scaled as in Table 2, while experimental systematic uncertainties are assumed to keep their Run 2 values.
- Run 2 systematic uncertainties: both the theoretical and experimental systematic uncertainties are assumed to keep their Run 2 values.

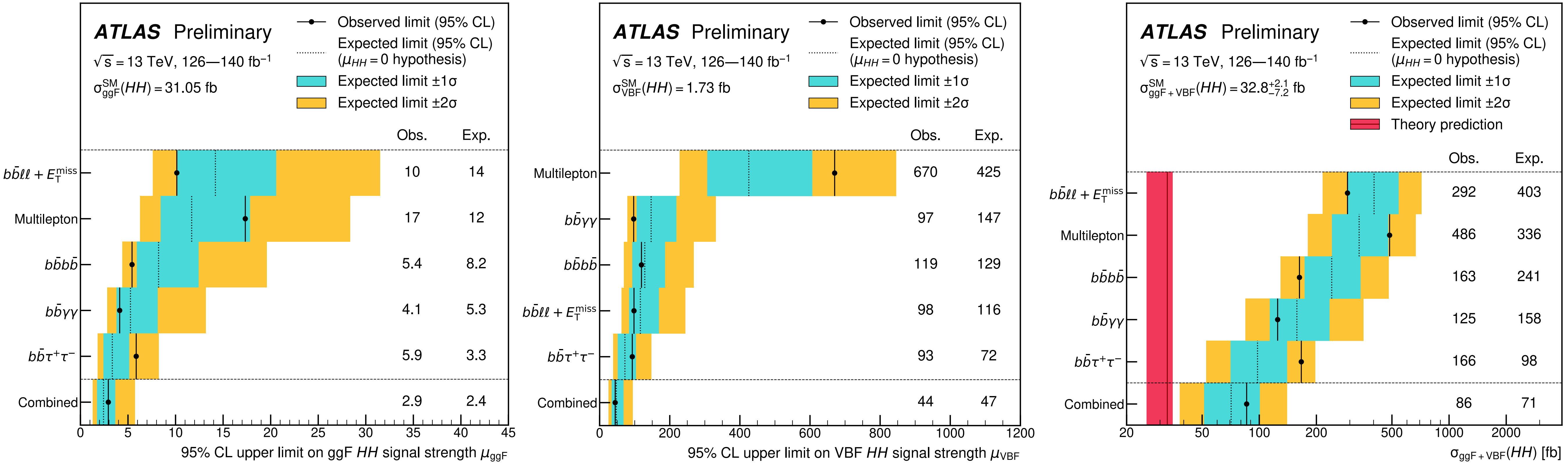
Source	Scale factor	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$
Experimental Uncertainties			
Luminosity	0.6	*	*
b-jet tagging efficiency	0.5	*	*
c-jet tagging efficiency	0.5	*	*
Light-jet tagging efficiency	1.0	*	*
Jet energy scale and resolution, E_T^{miss}	1.0	*	*
κ_λ reweighting	0.0	*	*
Photon efficiency (ID, trigger, isolation efficiency)	0.8	*	
Photon energy scale and resolution	1.0	*	
Spurious signal	0.0	*	
Value of m_H	0.08	*	
τ_{had} efficiency (statistical)	0.0		*
τ_{had} efficiency (systematic)	1.0		*
τ_{had} energy scale	1.0		*
Fake-τ_{had} estimation	1.0		*
MC statistical uncertainties	0.0		*
Theoretical Uncertainties	0.5	*	*

bbbb

Systematic uncertainties	Scale factors for HL-LHC baseline scenario
Theoretical uncertainty	0.5
b-jet tagging efficiency	0.5
c-jet tagging efficiency	0.5
Light-jet tagging efficiency	1.0
Jet energy scale and resolution	1.0
Luminosity	0.6
Background bootstrap uncertainty	0.5
Background shape uncertainty	1.0

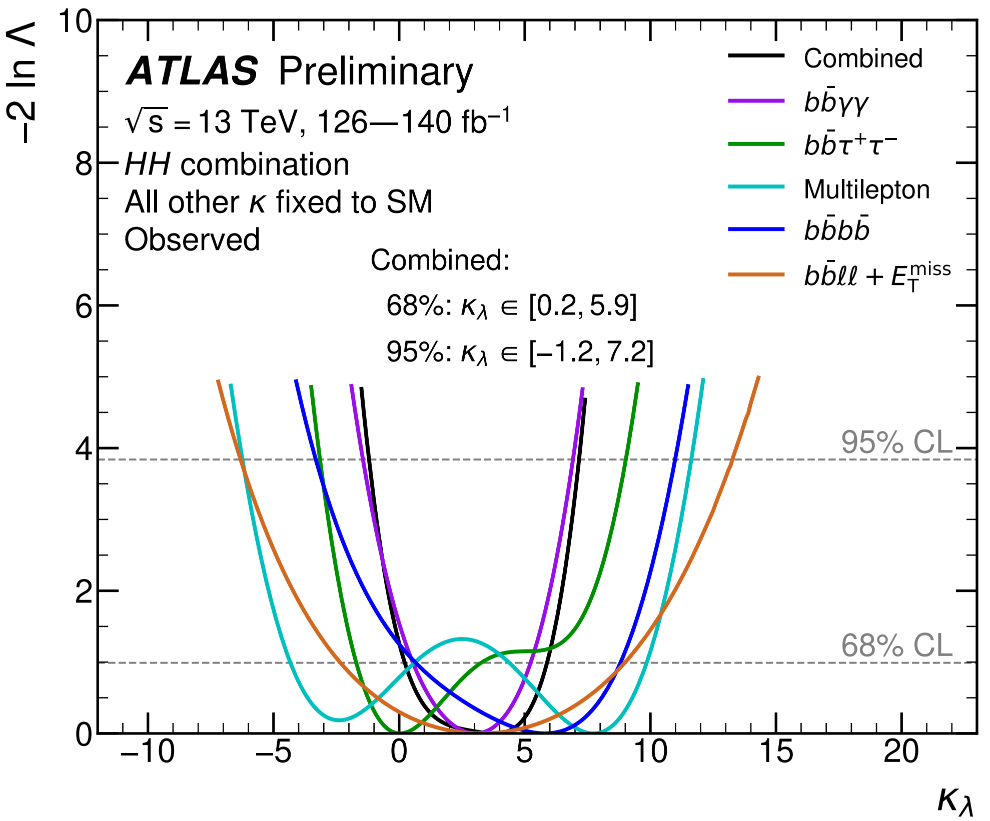
Table 2

Combined μ results

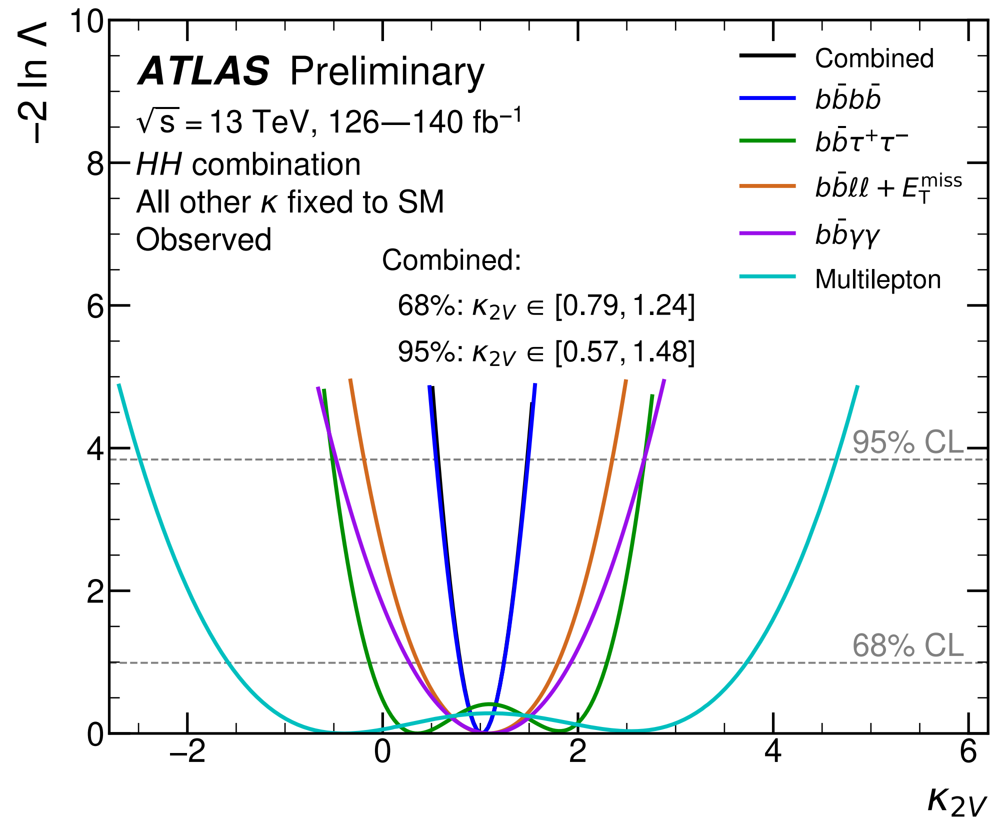


Combined κ results

κ_λ

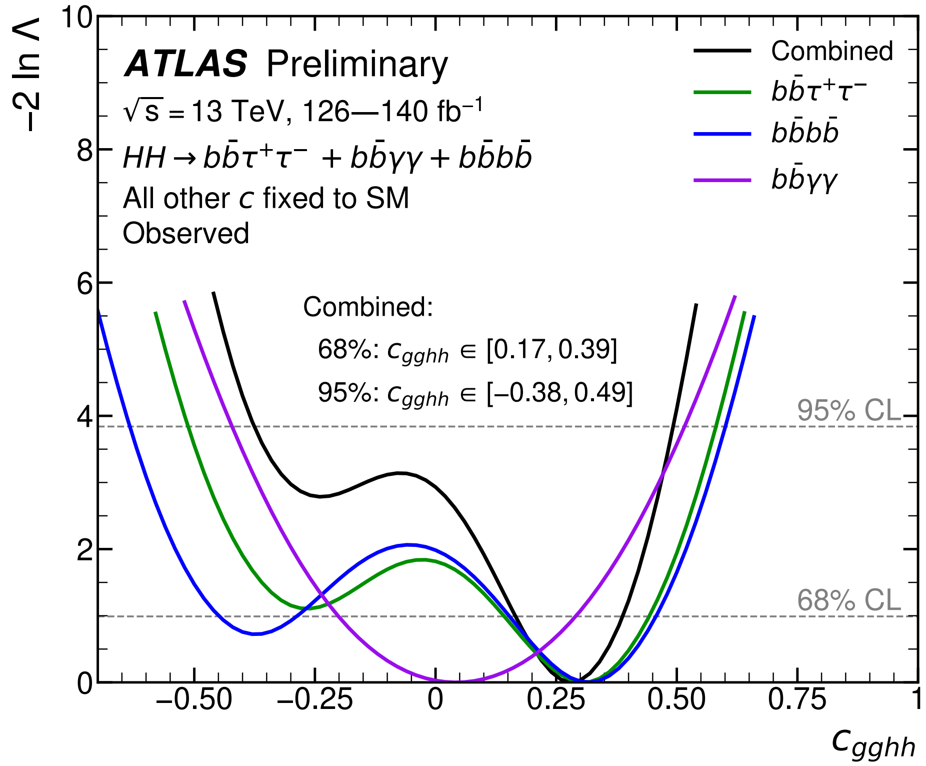


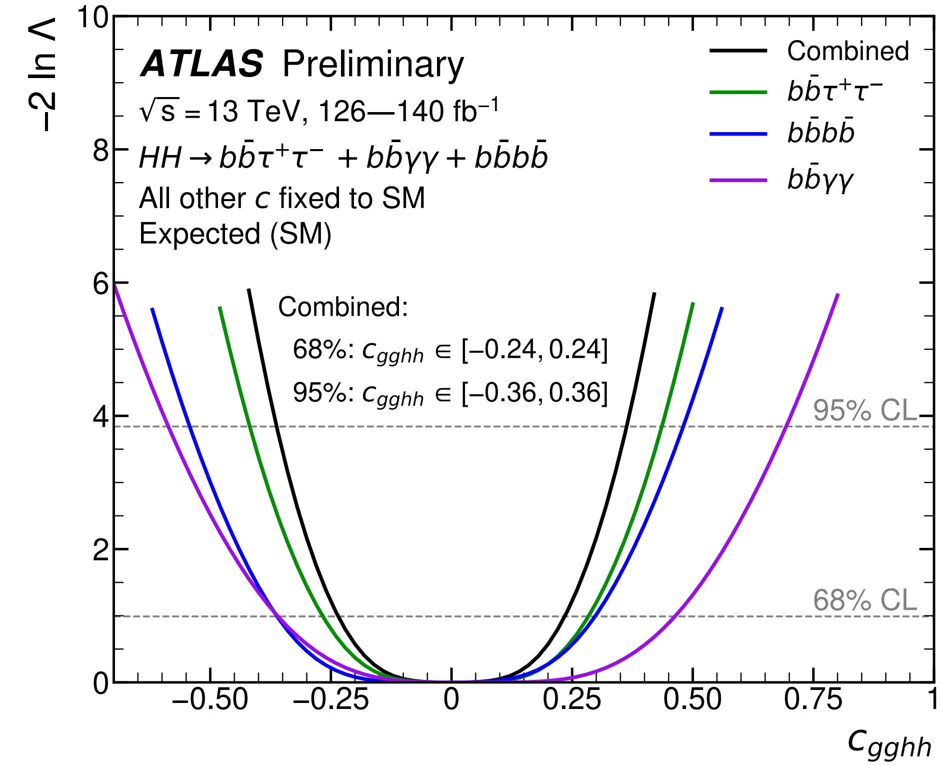
κ_{2V}

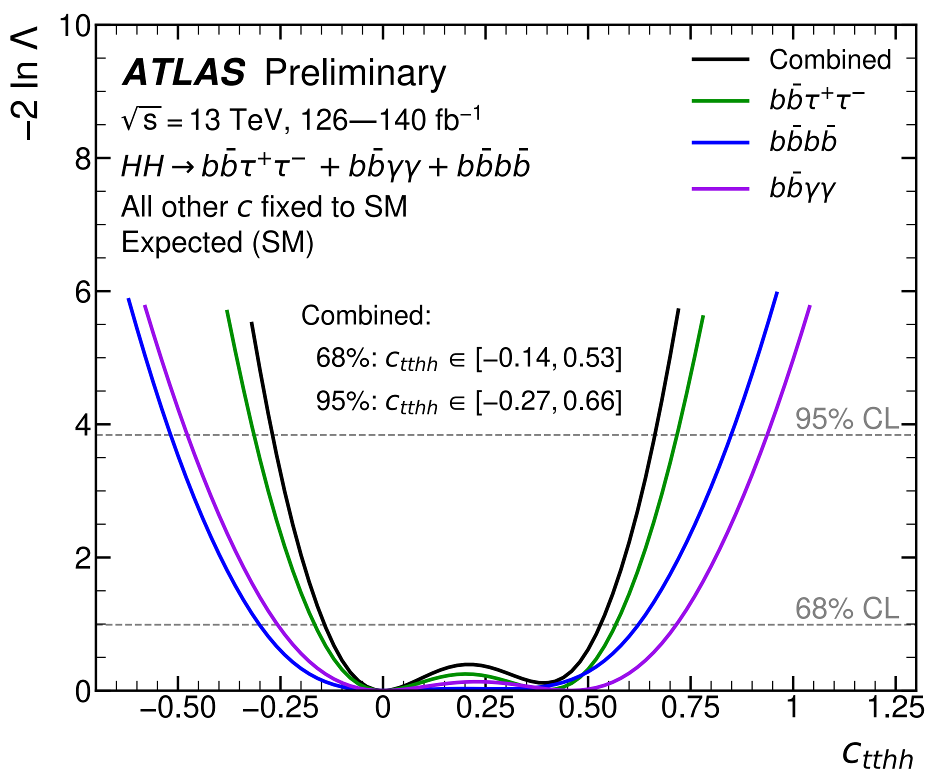


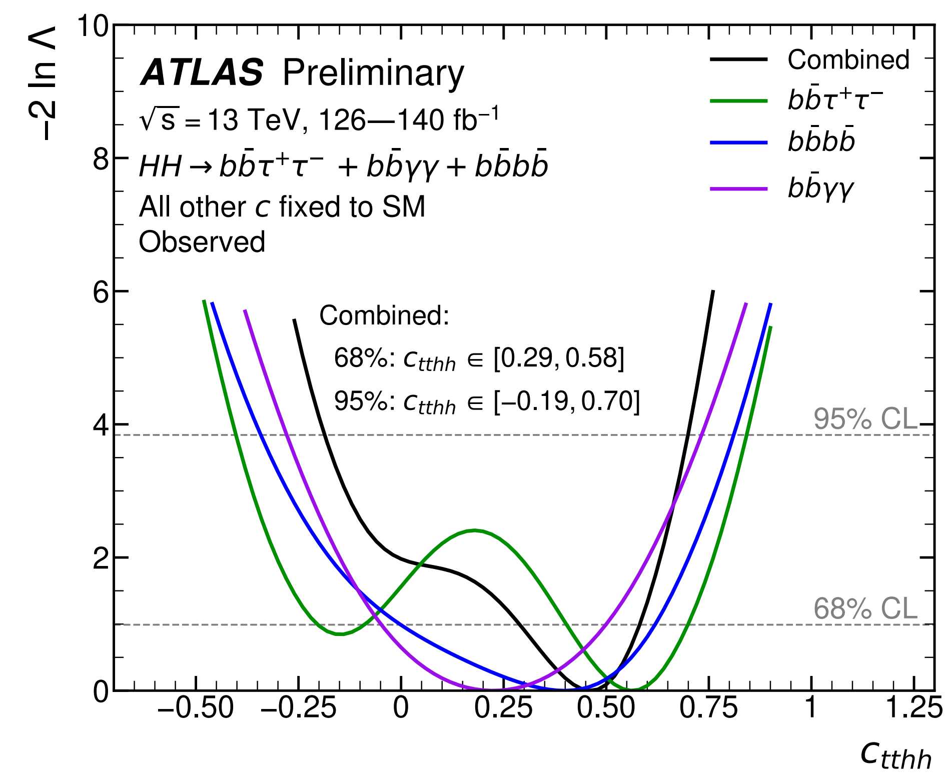
Measurement	κ_λ				κ_{2V}			
	68% CL		95% CL		68% CL		95% CL	
	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
κ_λ float, $\kappa_{2V}=1$	$3.8^{+2.1}_{-3.6}$	$1.0^{+4.7}_{-1.5}$	$[-1.2, 7.2]$	$[-1.6, 7.2]$	–	–	–	–
κ_{2V} float, $\kappa_\lambda=1$	–	–	–	–	$1.02^{+0.22}_{-0.23}$	$1.00^{+0.40}_{-0.36}$	$[0.57, 1.48]$	$[0.41, 1.65]$
κ_λ, κ_{2V} float	$4.3^{+1.9}_{-4.0}$	$1.0^{+4.8}_{-1.5}$	$[-1.2, 7.5]$	$[-1.7, 7.4]$	$0.92^{+0.27}_{-0.25}$	$1.00^{+0.41}_{-0.38}$	$[0.40, 1.45]$	$[0.32, 1.65]$

HEFT 1D scans



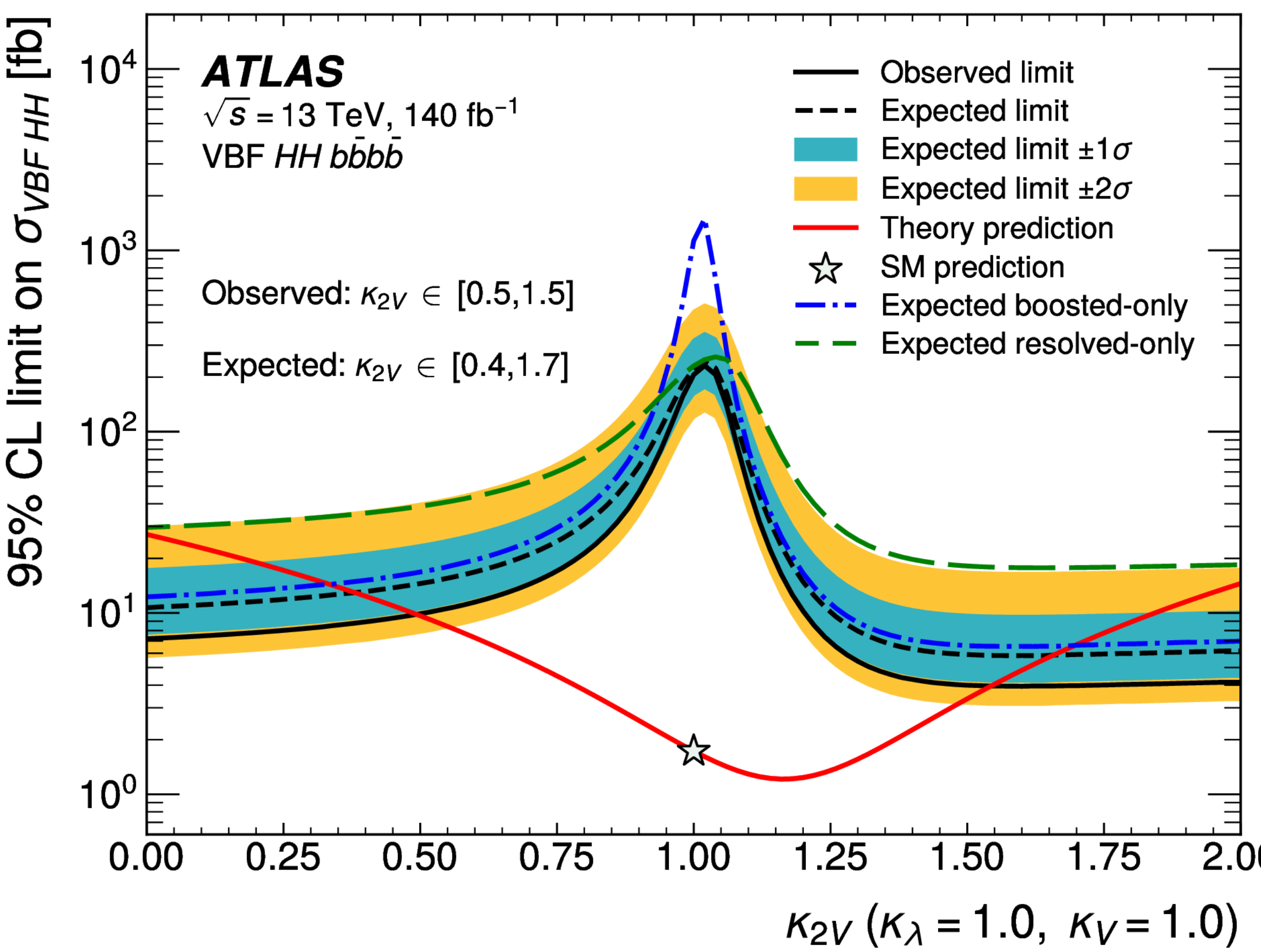






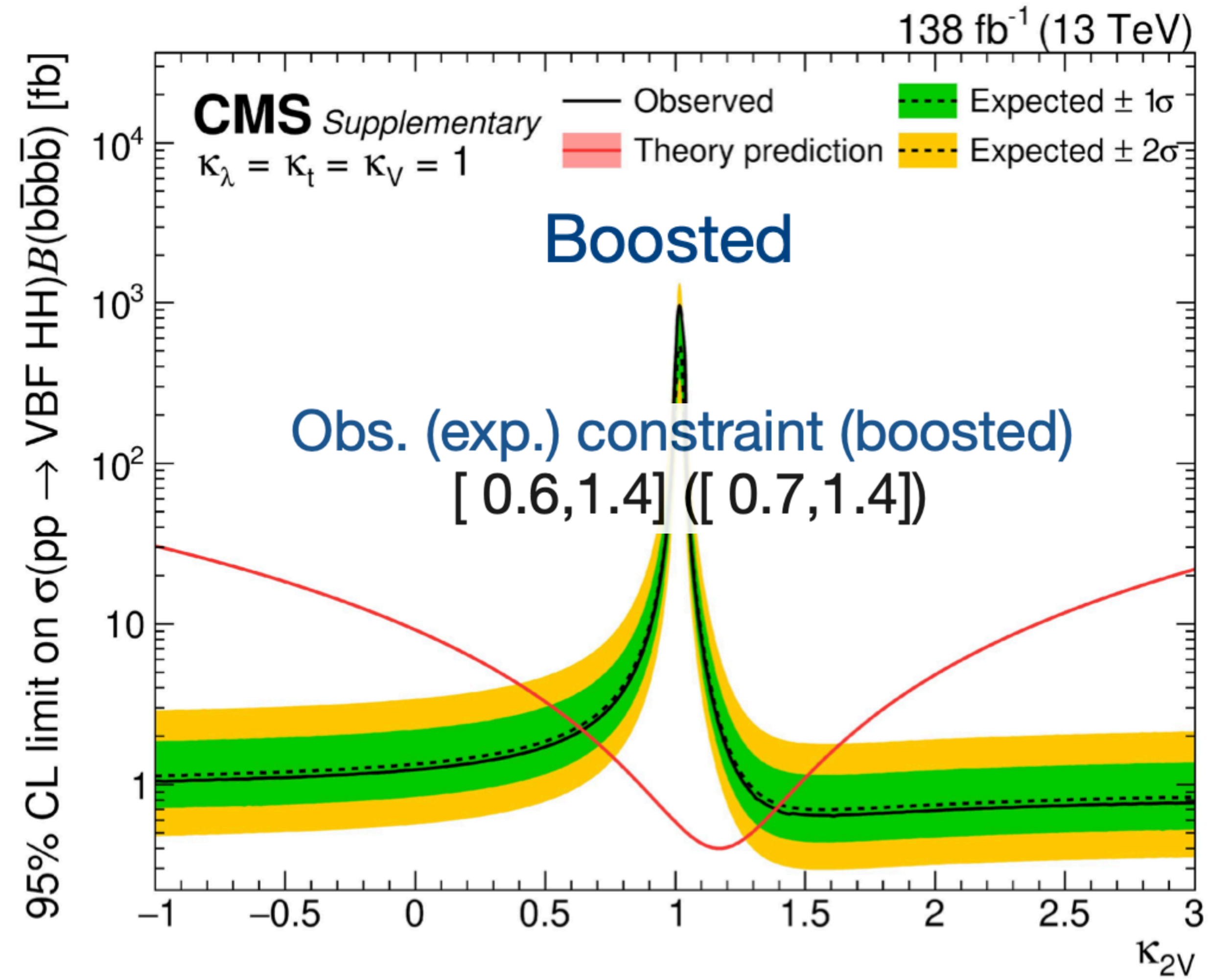
Compare with CMS - bbbb

ATLAS



$\kappa_{2V} = 0$ exclusion 3.4 (exp 2.9) σ

CMS



$\kappa_{2V} = 0$ exclusion 6.3 σ

Phys. Rev. Lett. 129 (2022) 081802

Phys. Rev. Lett. 131 (2023) 041803

- Difference mainly comes from powerful Xbb tagger in CMS in boosted analysis
- κ_λ and μ_{HH} are similar driven by resolved analysis

Compare with CMS - bbττ

Trigger Strategy

Phys. Lett. B 842 (2023) 137531

ATLAS EXPERIMENT reference

CMS

ATLAS and CMS use a similar trigger strategy based only on leptons and τ_{had}

ATLAS:

- $\tau_{had}\tau_{had}$:
  - single τ trigger with p_T of 80-160 GeV
  - di-τ trigger with p_T of 35 and 25 GeV
    - In 2016, 1 jet (> 25 GeV) at L1
    - 2017-2018, 1 jet (> 25 GeV) or 2 jets (> 12 GeV) at L1
- $\tau_{lep}\tau_{had}$:
  - **SLT**: single lepton trigger with 24-26 (20-26) GeV for e (μ);
  - **LTT**: lepton+τ_{had} trigger with 17 (14) GeV for e (μ) and 25 GeV for τ_{had}
    - From 2017, 1 jet (> 25 GeV) or 2 jets (> 12 GeV) at L1

CMS:

- $\tau_{had}\tau_{had}$:
  - di-τ trigger with p_T>35 GeV
  - di-τ (p_T>25 GeV) + 2 jets (p_T>45/115 GeV)
- $\tau_{lep}\tau_{had}$:
  - single-e with p_T>25 (32) GeV (2017-2018)
  - e-τ trigger with
    - ele p_T>24 GeV
    - τ p_T>30 GeV
  - Single-μ with p_T>22 (24) GeV (2017-2018)
  - μ-τ trigger with
    - μ p_T>19 (20) GeV (2017-2018)
    - τ p_T>20 (27) GeV (2017-2018)

Previous round in ATLAS

Obs. (exp.) constraint on κ_λ:
$-2.4 \leq \kappa_\lambda \leq 9.2$ ($-2.0 \leq \kappa_\lambda \leq 9.0$)

Obs. (exp.) constraint on κ_λ:
$-1.7 < \kappa_\lambda < 8.7$ ($-2.9 < \kappa_\lambda < 9.8$)

- Different signal accxeff

ATLAS acceptance 4+4+1% for ggF and 2.5+2.5+0.7 VBF SM

CMS acceptance 5.5 (3.4)% for the ggF (VBF) SM

Compare with CMS - bbγγ

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- Close results between the two
  - CMS: $\mu_{HH} < 8.4$ (5.5 exp)
  - ATLAS this round: $\mu_{HH} < 4.0$ (5.0 exp)
  - CMS: $-1.5 < \kappa_\lambda < 6.7$ (68% exp)
  - ATLAS: $-1.2 < \kappa_\lambda < 6.1$ (68% exp)
- Slightly better results from ATLAS coming from
  - Slightly better signal resolution
  - High/low mass categorisation

Compare with CMS - bbWW ($bb\ell\ell+E_T^{miss}$)

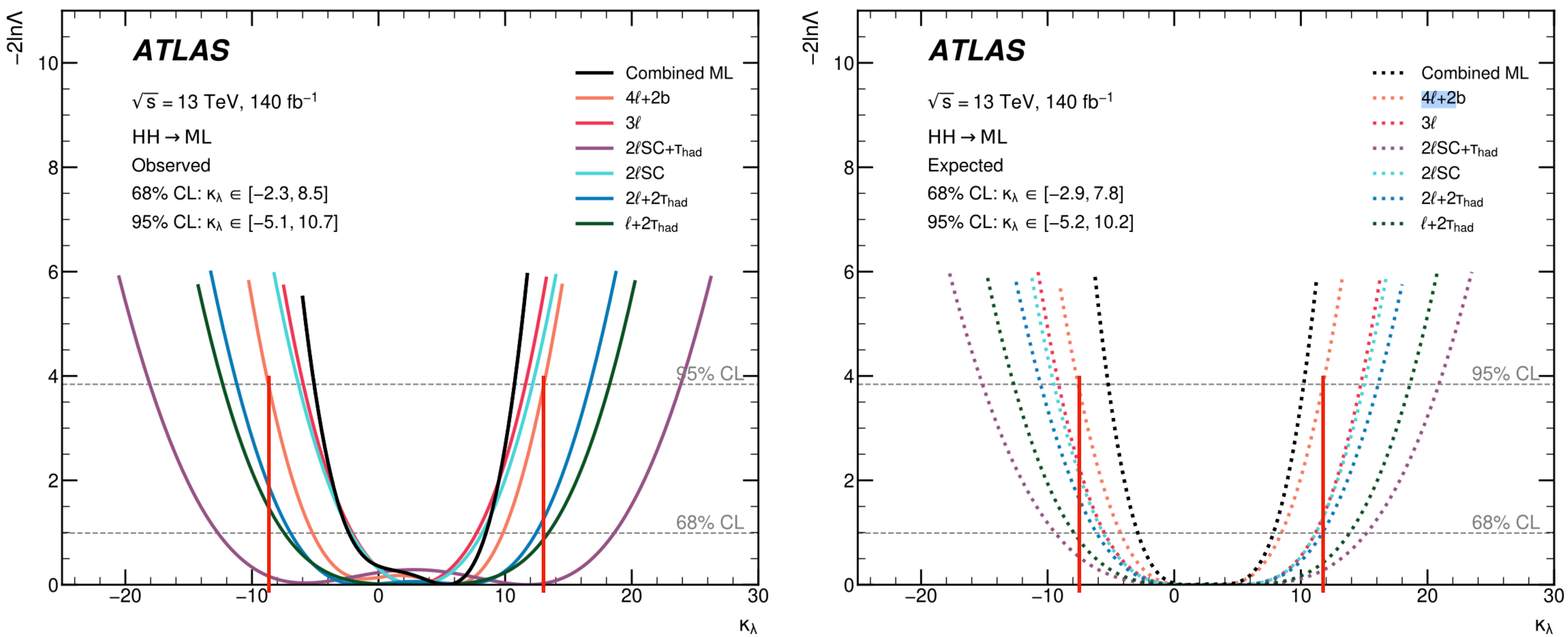
CMS: arXiv:2403.09430

- Close results between the two
  - CMS: $\mu_{HH} < 14$ (18 exp)
  - ATLAS: $\mu_{HH} < 9.7$ (16.2 exp)
  - CMS: $-7.2 < \kappa_\lambda < 13.8$ ($-8.7 < \kappa_\lambda < 15.2$ exp)
  - ATLAS: $-6.2 < \kappa_\lambda < 13.3$ ($-8.1 < \kappa_\lambda < 15.5$ exp)
  - CMS: $-1.1 < \kappa_\lambda < 3.2$ ($-1.4 < \kappa_\lambda < 3.5$ exp)
  - ATLAS: $-0.17 < \kappa_{2V} < 2.4$ ($-0.51 < \kappa_{2V} < 2.7$ exp)
- Stronger constraints in κ_{2V} from ATLAS
  - A dedicated VBF signal region / category may have helped

Compare with CMS - bbZZ(4ℓ)

- CMS http://www.arxiv.org/abs/2206.10657
  - $\mu_{HH} < 32.4$ (39.6 exp)
  - -8.8 (-9.8) $< \kappa_\lambda <$ 13.4 (15.0)
- ATLAS:
  - $\mu_{HH} < 39$ (35 exp)
  -

- Accxeff
  - ggF ATLAS 0.164, CMS 0.168
  - Bkg: ATLAS 30, CMS 67.06



Compare with CMS multilepton

CMS: JHEP 07 (2023) 095