Non-resonant *HH* production and Higgs self-coupling at ATLAS

Rachel Hyneman,
on behalf of the **ATLAS Collaboration**

LHCP 2023
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ATLAS EXPERIMENT

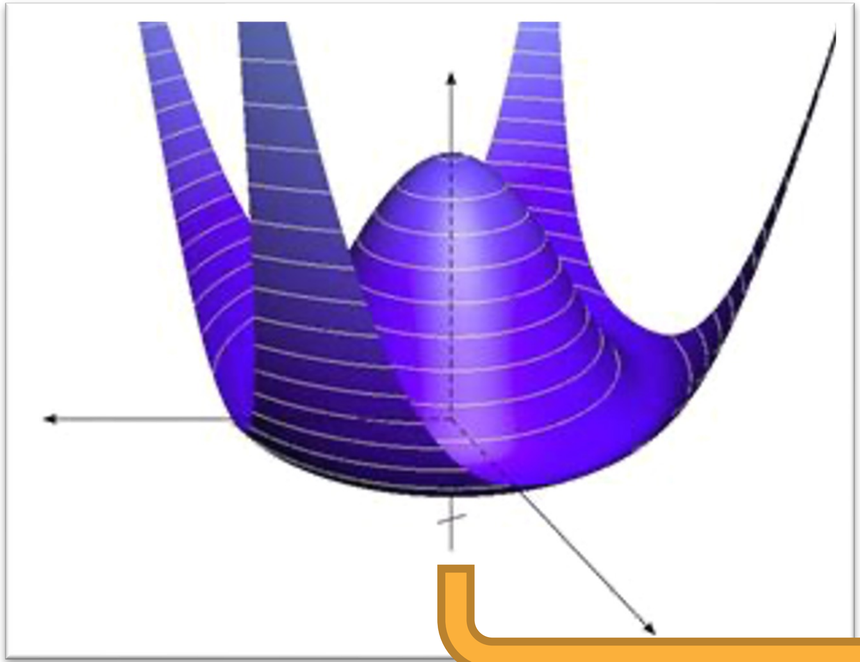
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

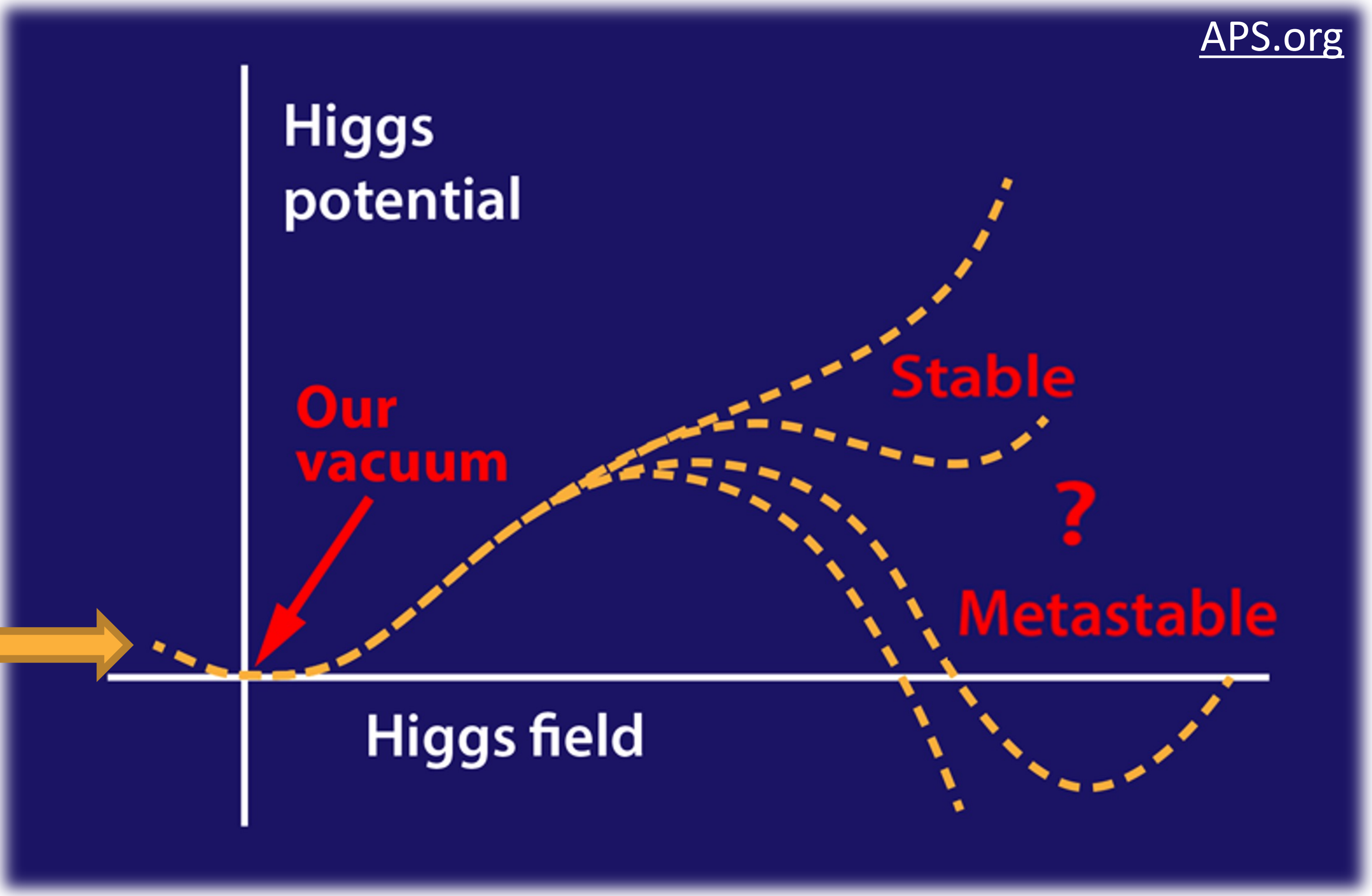
Introduction – The Higgs Boson Self-Coupling

The Higgs Potential

arXiv:1806.02697



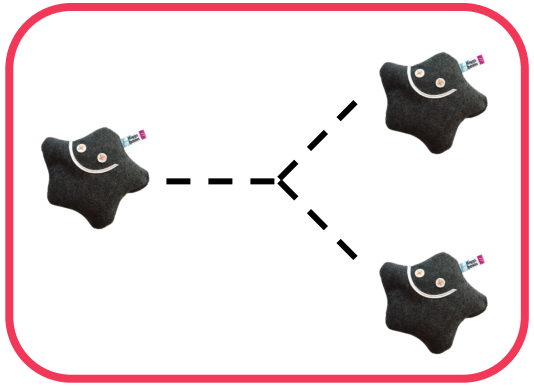
$$V(h) \sim \lambda v h^3 + \frac{1}{4}\lambda h^4$$

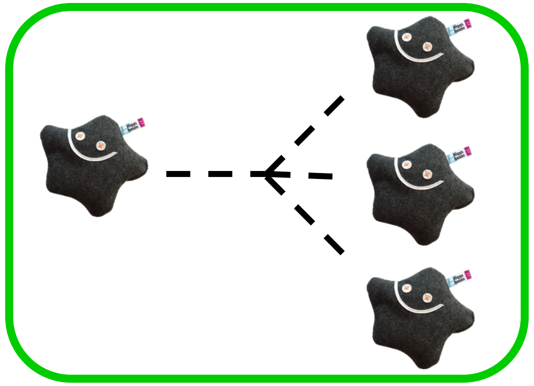


How Do We Measure the Higgs Potential?

"Non-resonant" Production

$$V(h) \sim \lambda v h^3 + \frac{1}{4}\lambda h^4$$





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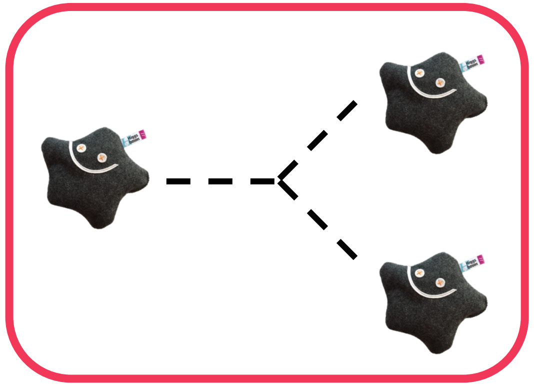
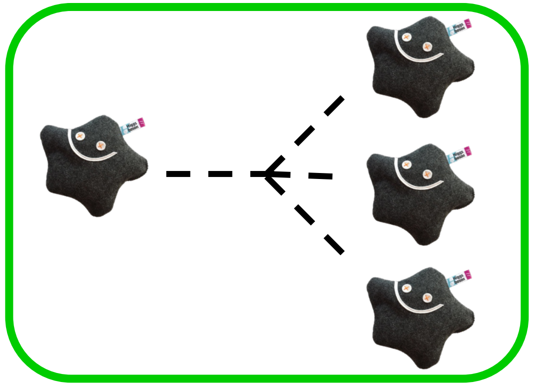
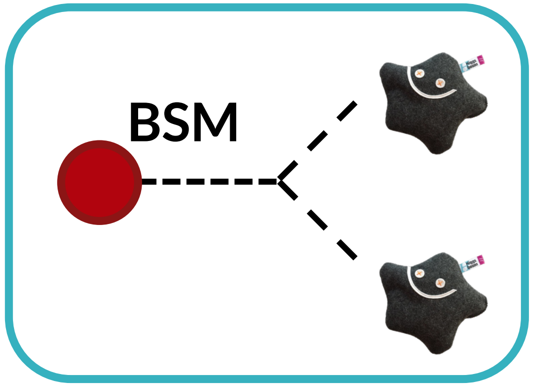






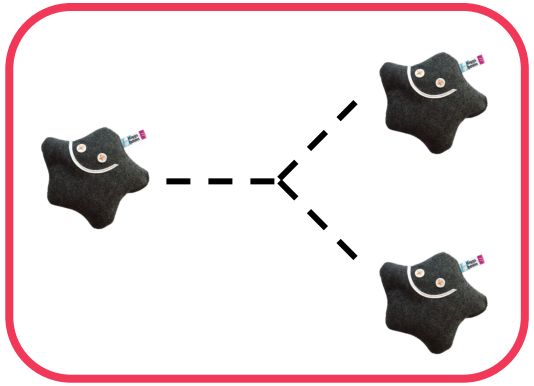
"Resonant" Production

See talks by:
N. Kyriacou
M. Lu

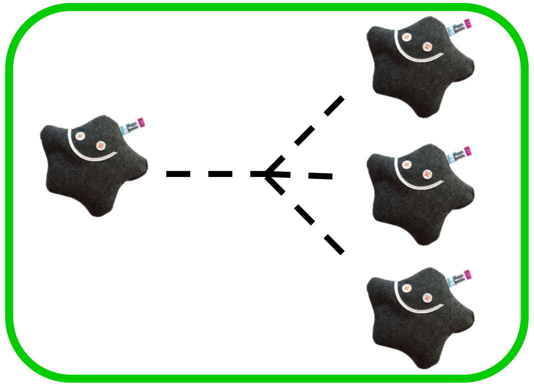
How Do We Measure the Higgs Potential?

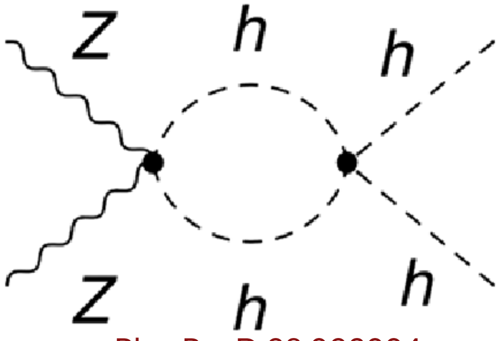
"Non-resonant" Production

$$V(h) \sim \lambda v h^3 + \frac{1}{4} \lambda h^4$$



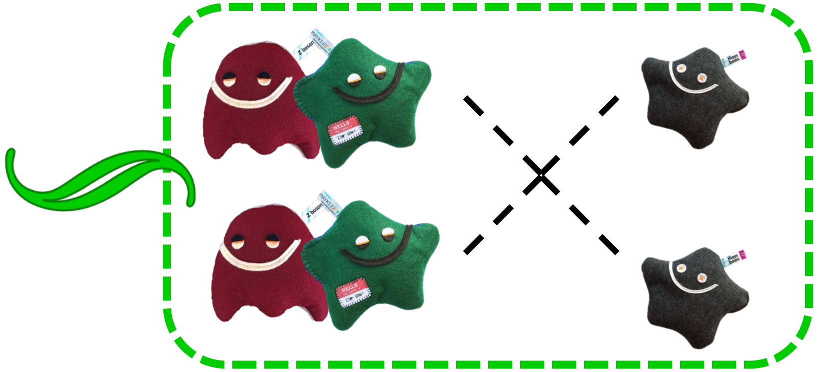
Inaccessible @ 13 TeV





PhysRevD.98.093004

VVHH



Higgs Pair (*HH*) Production and Decay Modes

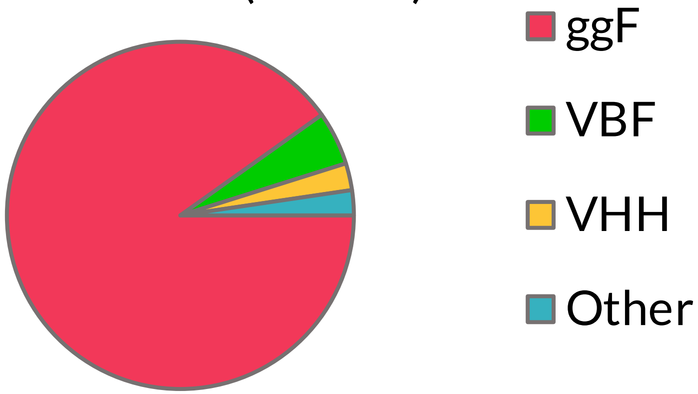
$$\kappa_\lambda = c_{HHH}/c_{HHH}^{\mathrm{SM}}$$
$$\kappa_{2V} = c_{VVHH}/c_{VVHH}^{\mathrm{SM}}$$

gluon-gluon Fusion (ggF)
$\sigma \sim$ 31.0 fb
$\sim\kappa_\lambda$

Vector Boson Fusion (VBF)
$\sigma \sim$ 1.72 fb
$\sim\kappa_\lambda, \kappa_{2V}$

Vector Boson Associated (VHH)
$\sigma \sim$ 0.86 fb
$\sim\kappa_\lambda, \kappa_{2V}$

Cross Section (13 TeV)



HH Decay Modes

	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%

Measurements

$VHH \to (\ell\ell, \ell\nu, \nu\nu) + b\bar{b}b\bar{b}$

arXiv:2210.05415

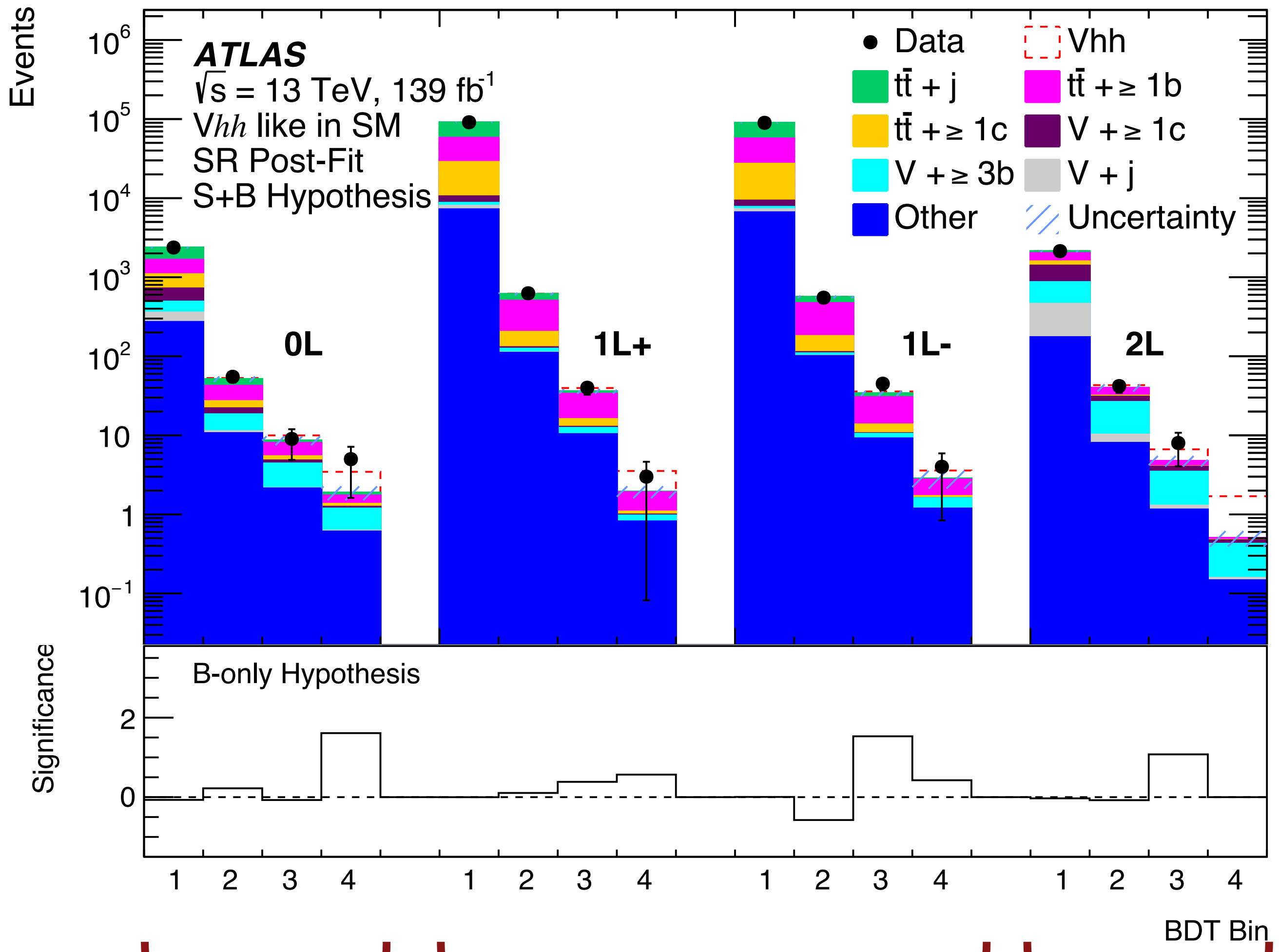
First ATLAS measurement of VHH!

Boosted Decision Tree discriminator used in 3 categories: **(0, 1, 2)L**

Two CRs:

$t\bar{t}$+jets CR

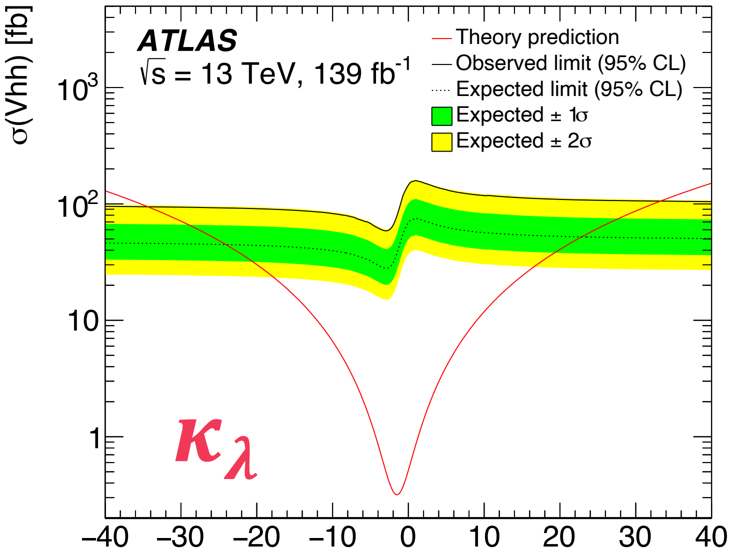
V+jets CR (modeled w/ γ+jets data)



0L: $Z \to \nu\nu$ **1L:** $W^{\pm} \to \ell\nu$ **2L:** $Z \to \ell\ell$

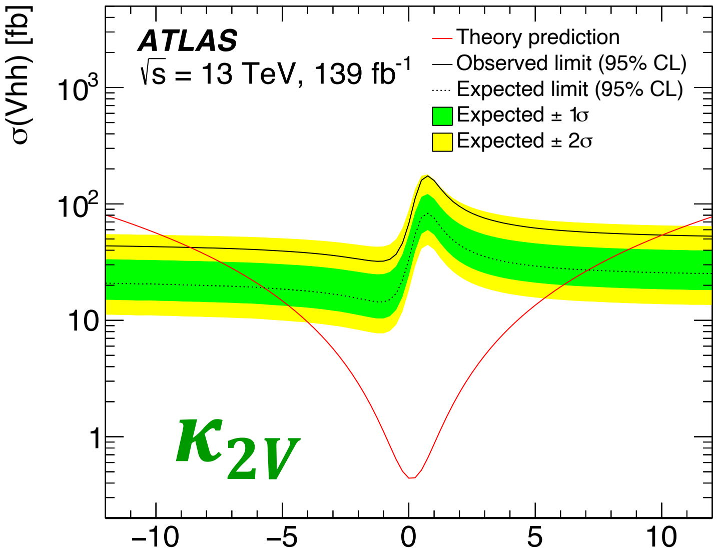
$VHH \to (\ell\ell, \ell\nu, \nu\nu) + b\bar{b}b\bar{b}$

arXiv:2210.05415



$-34.4 < \kappa_\lambda < 33.3$

(Exp: $-24.1 < \kappa_\lambda < 22.9$)



$-8.6 < \kappa_{2V} < 10.0$

(Exp: $-5.7 < \kappa_{2V} < 7.1$)

VHH production allows separation of $ZZHH$ and $WWHH$

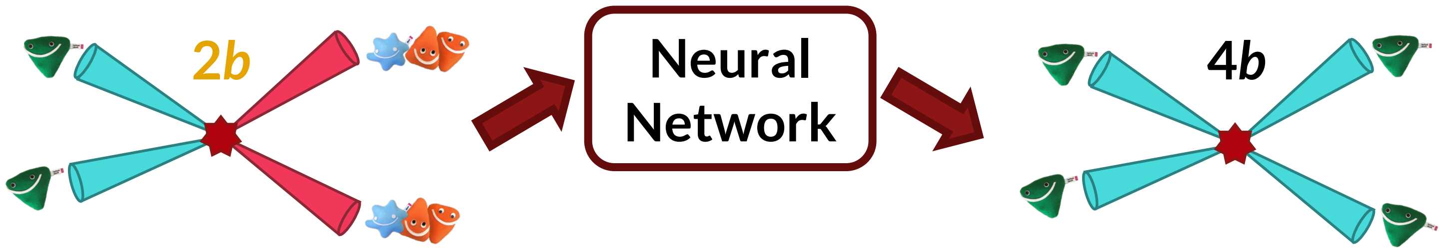
→ $\mathbf{-9.9} < \kappa_{2Z} < \mathbf{11.3}$ (−7.1 < κ_{2Z} < 8.5 Exp.)

$\mathbf{-12.3} < \kappa_{2W} < \mathbf{13.5}$ (−8.6 < κ_{2W} < 9.8 Exp.)

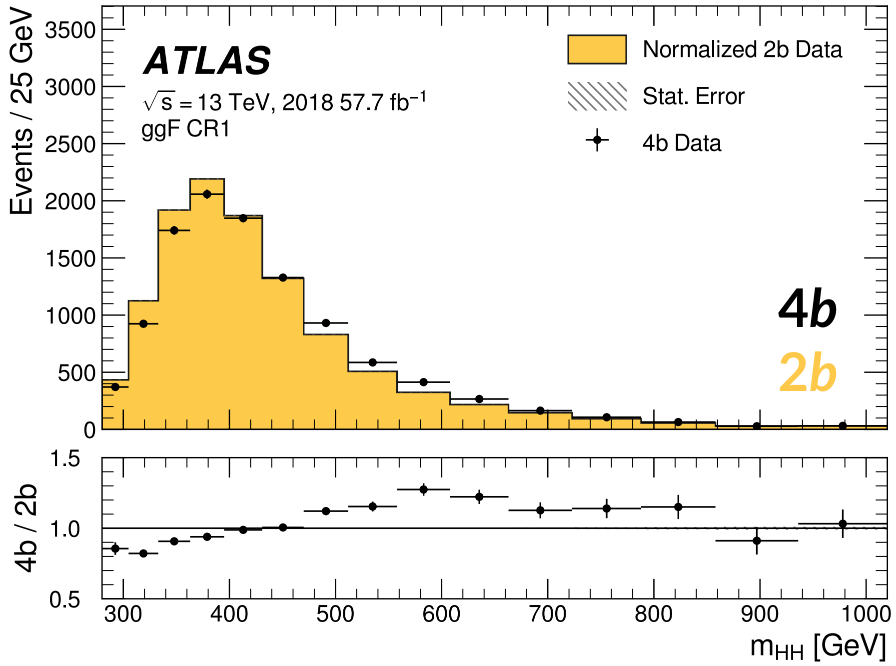
$HH \rightarrow b\bar{b}b\bar{b}$ (ggF+VBF)

arXiv:2301.03212

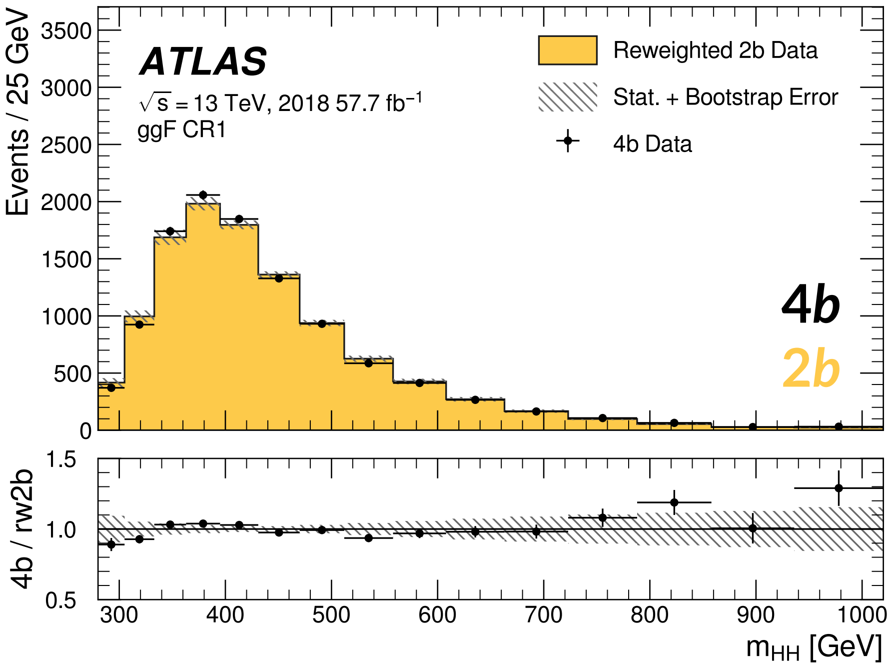
Challenge:
large background from
QCD multi-jet processes



Before Reweighting



After Reweighting



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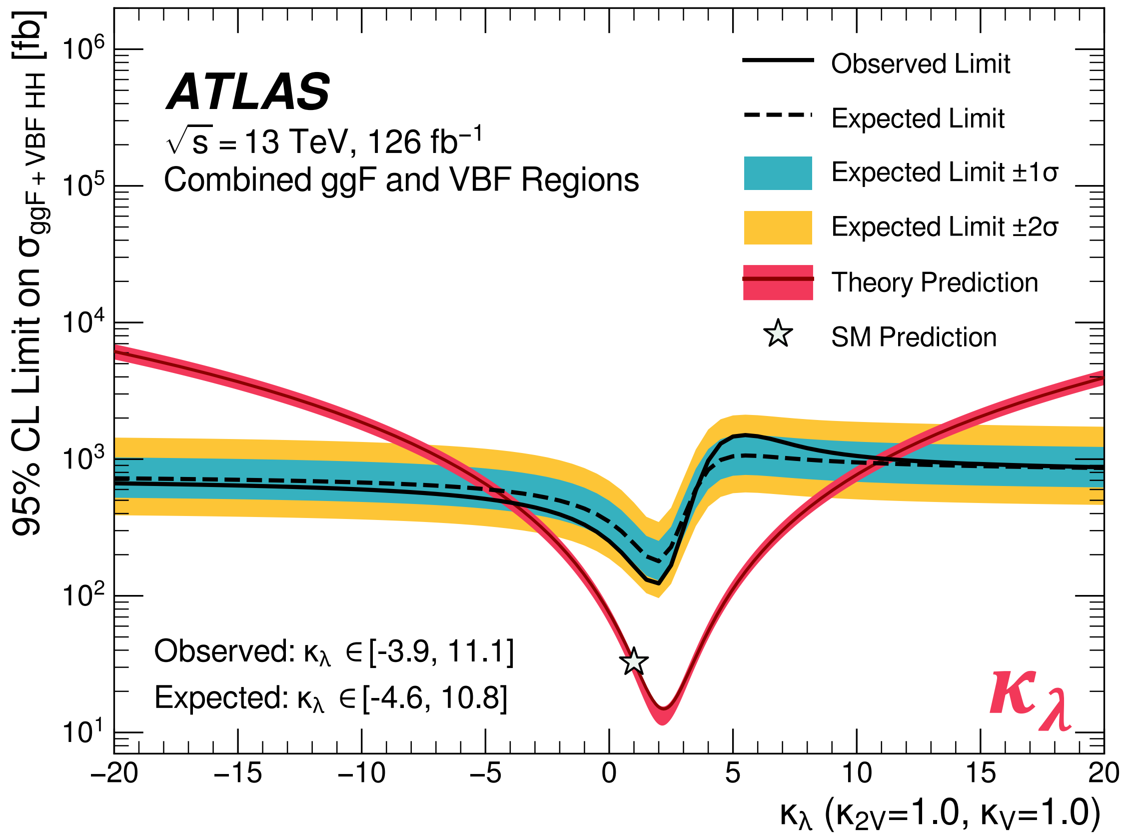
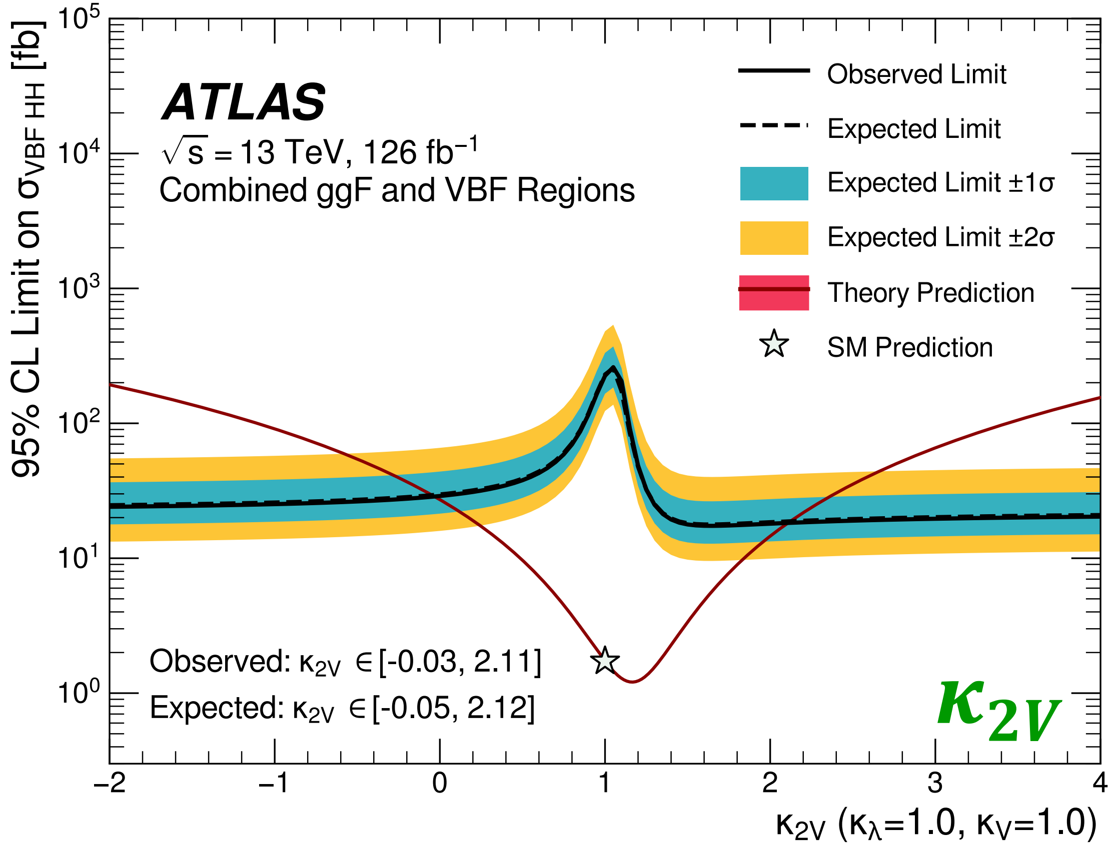


$$-3.9 < \kappa_\lambda < 11.1$$

$(-4.6 < \kappa_\lambda < 10.8)$ (Exp.)



$$-0.03 < \kappa_{2V} < 2.11$$

$(-0.05 < \kappa_{2V} < 2.12)$ (Exp.)

$HH \rightarrow b\bar{b}\tau\tau$ (ggF+VBF)

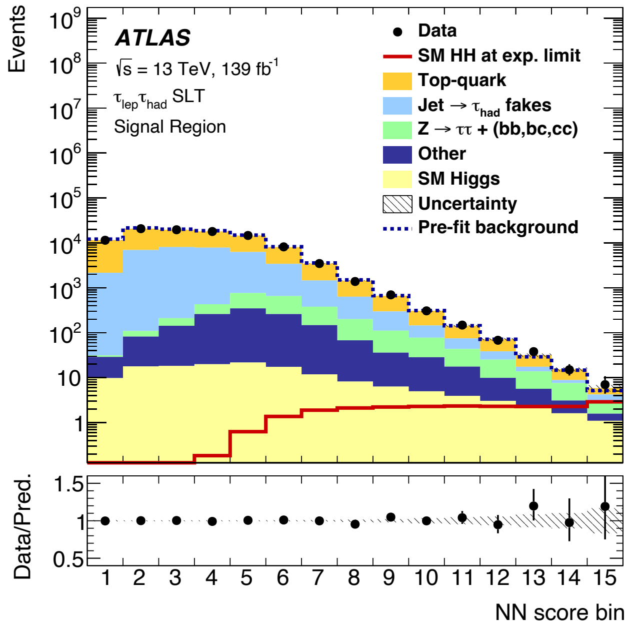
arXiv:2209.10910, ATLAS-CONF-2021-052

Two Hadronic τ's:

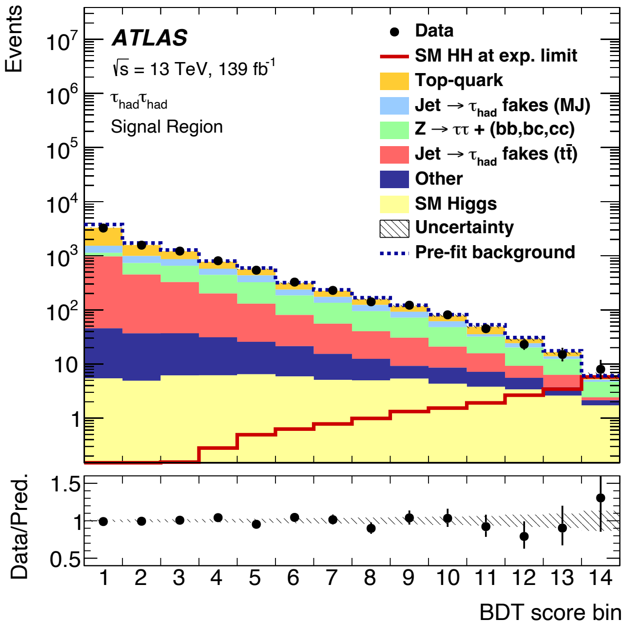
- Single- and Di-τ Triggers (Combined)

One hadronic + one leptonic τ:

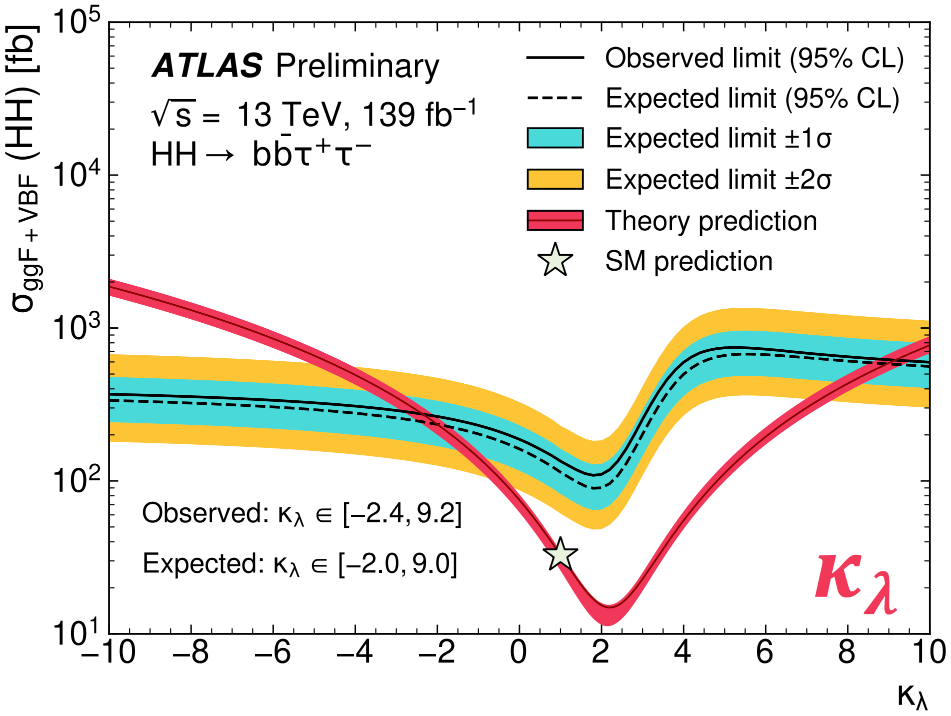
- Single ℓ Trigger
- ℓ+τ Trigger



Neural Network



Boosted Decision Tree

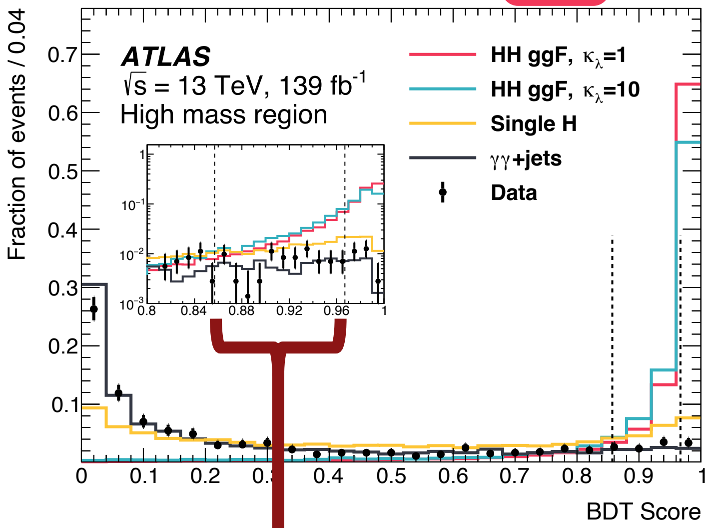


$$-2.4 < \kappa_\lambda < 9.2$$
$(-2.0 < \kappa_\lambda < 9.0)$ (Exp.)

$HH \rightarrow b\bar{b}\gamma\gamma$ (ggF+VBF)

PhysRevD.106.052001

High Mass ~ SM

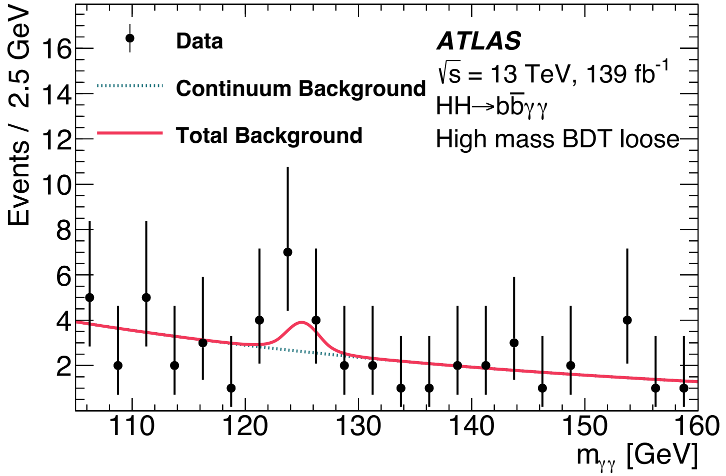


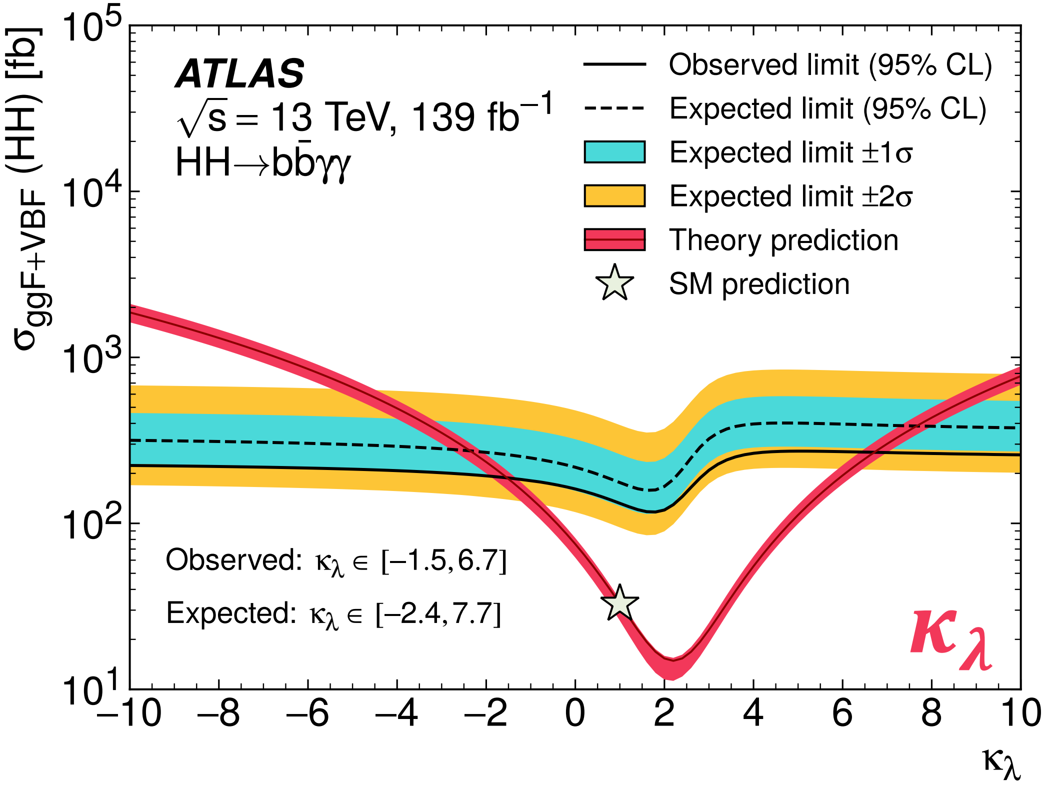
Categorization:

$m^*_{b\bar{b}\gamma\gamma}$ $(= m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250\ \text{GeV})$
and Boosted Decision Tree

$-1.5 < \kappa_\lambda < 6.7$
$(-2.4 < \kappa_\lambda < 7.7)$ (Exp.)

Category:
High Mass,
BDT Loose



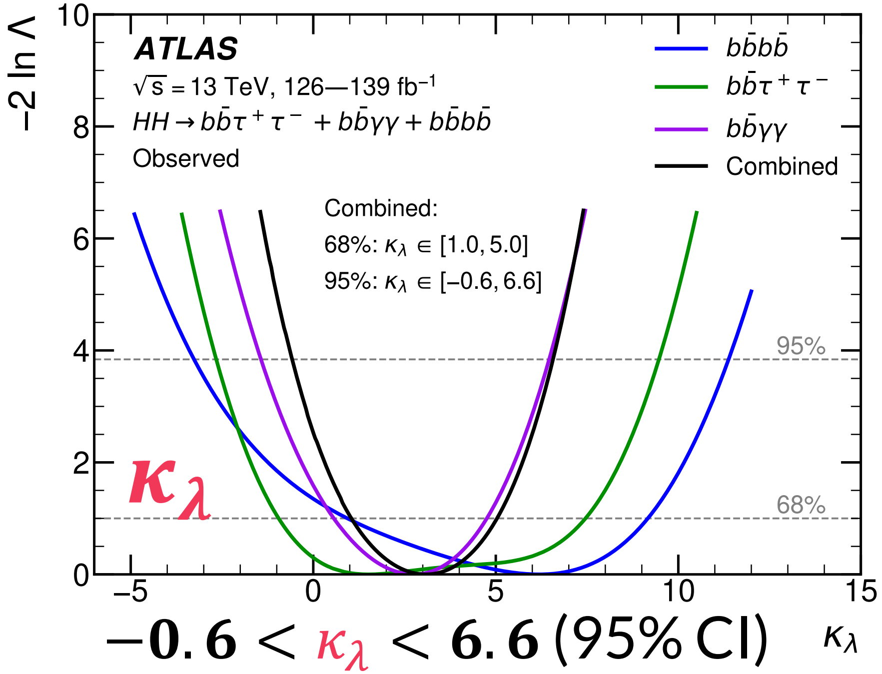


* No *VHH* included!

Combination and Prospects

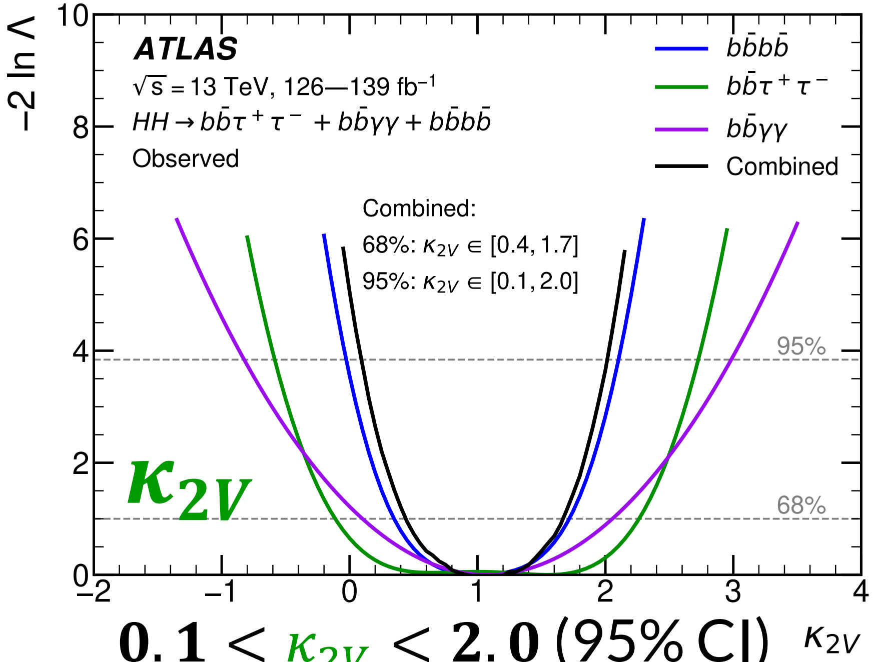
Combination: $HH \to b\bar{b}b\bar{b}, b\bar{b}\tau\tau, b\bar{b}\gamma\gamma$

arXiv:2211.01216



$-0.6 < \kappa_\lambda < 6.6$ (95% CI)

$(-2.1 < \kappa_\lambda < 7.8)$ (Exp.)



$0.1 < \kappa_{2V} < 2.0$ (95% CI)

$(0.0 < \kappa_{2V} < 2.1)$ (Exp.)

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
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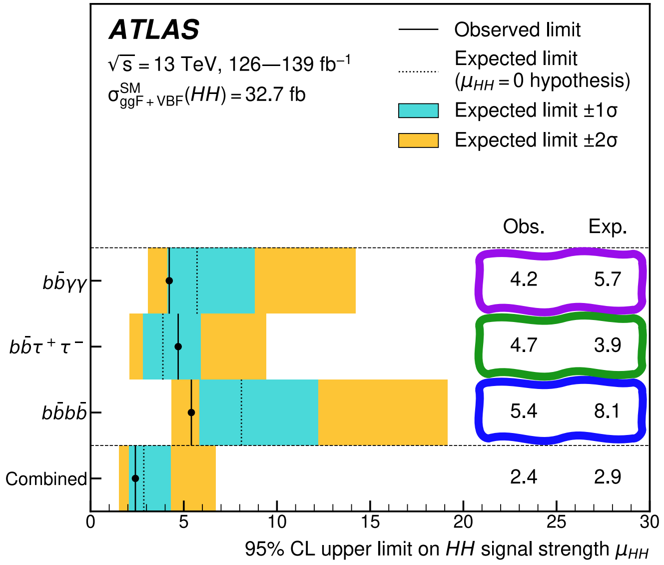


Combined upper-limit on SM HH Cross-Section:

$2.4 \times \sigma_{SM}$ (2.9 Exp.)

☆ "Log Likelihood Scan" limits utilize different assumptions

Combination: Single- and Di-Higgs

arXiv:2211.01216

H+HH Combination (Floating κ_λ):

$-0.4 < \kappa_\lambda < 6.3$ (95% CI)

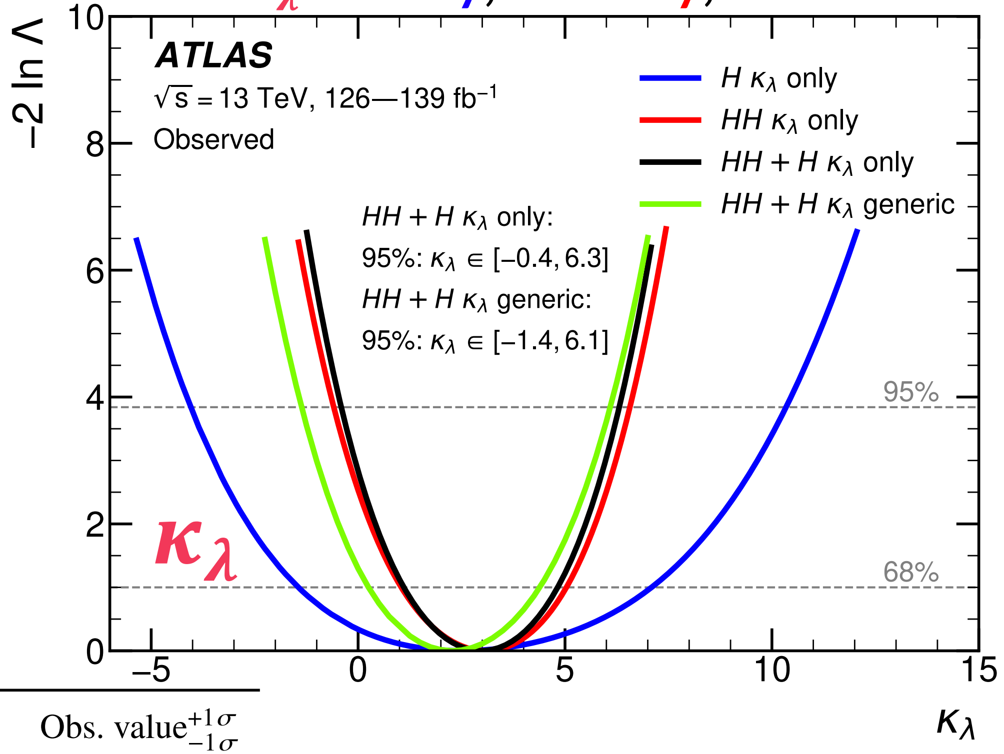
($-1.9 < \kappa_\lambda < 7.6$) (Exp.)

H+HH Combination (Floating $\kappa_\lambda, \kappa_t, \kappa_b, \kappa_\tau, \kappa_V$):

$-1.4 < \kappa_\lambda < 6.1$ (95% CI)

($-2.2 < \kappa_\lambda < 7.7$) (Exp.)

κ_λ: *H*-only, *HH*-only, *H+HH**



Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-*H* combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+*H* combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+*H* combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+*H* combination, $\kappa_t, \kappa_V, \kappa_b, \kappa_\tau$ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

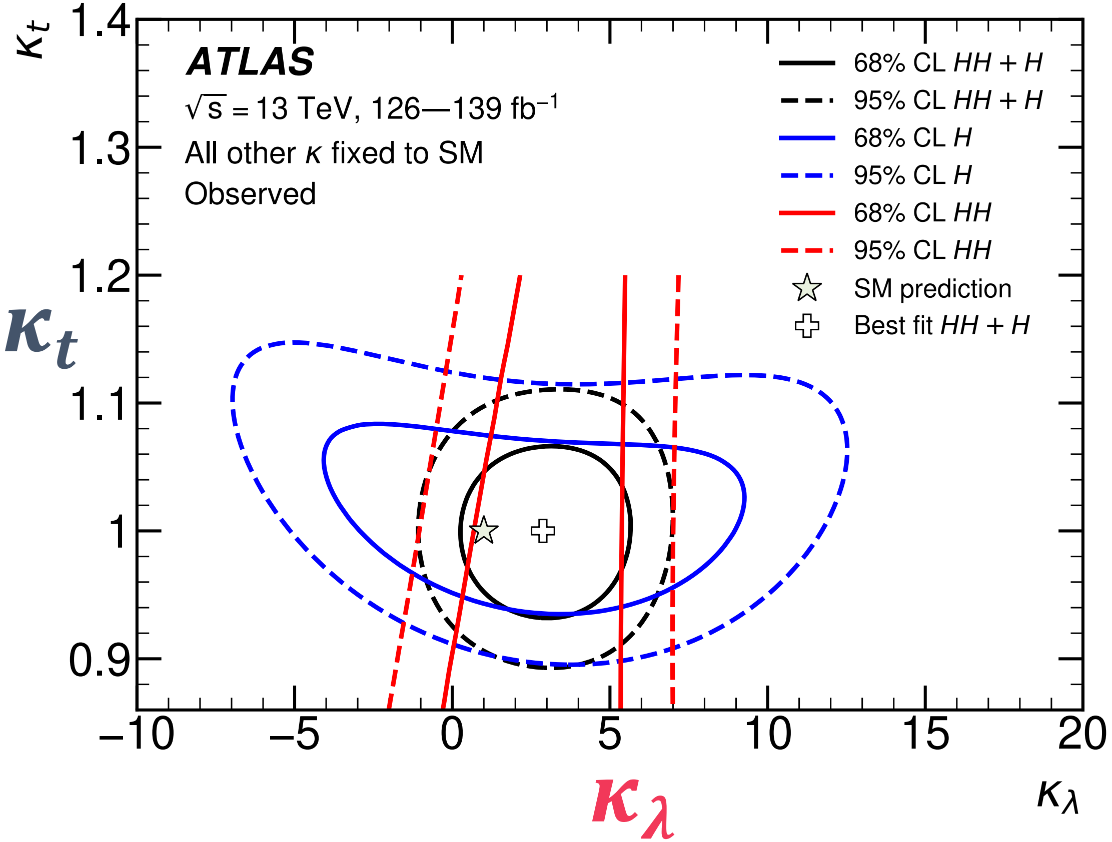
☆ "Log Likelihood Scan" limits utilize different assumptions

Combination: Single- and Di-Higgs

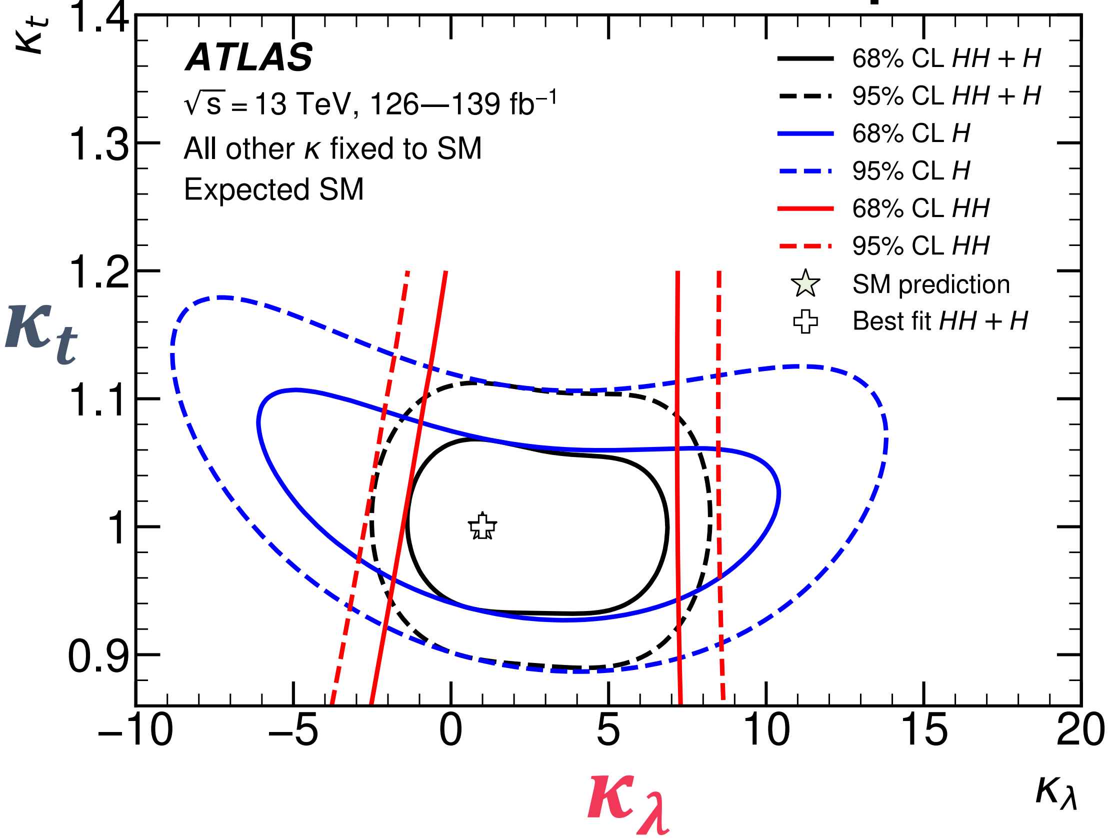
arXiv:2211.01216

κ_t vs κ_λ: *H*-only, *HH*-only, *H*+*HH*

Observed



Expected

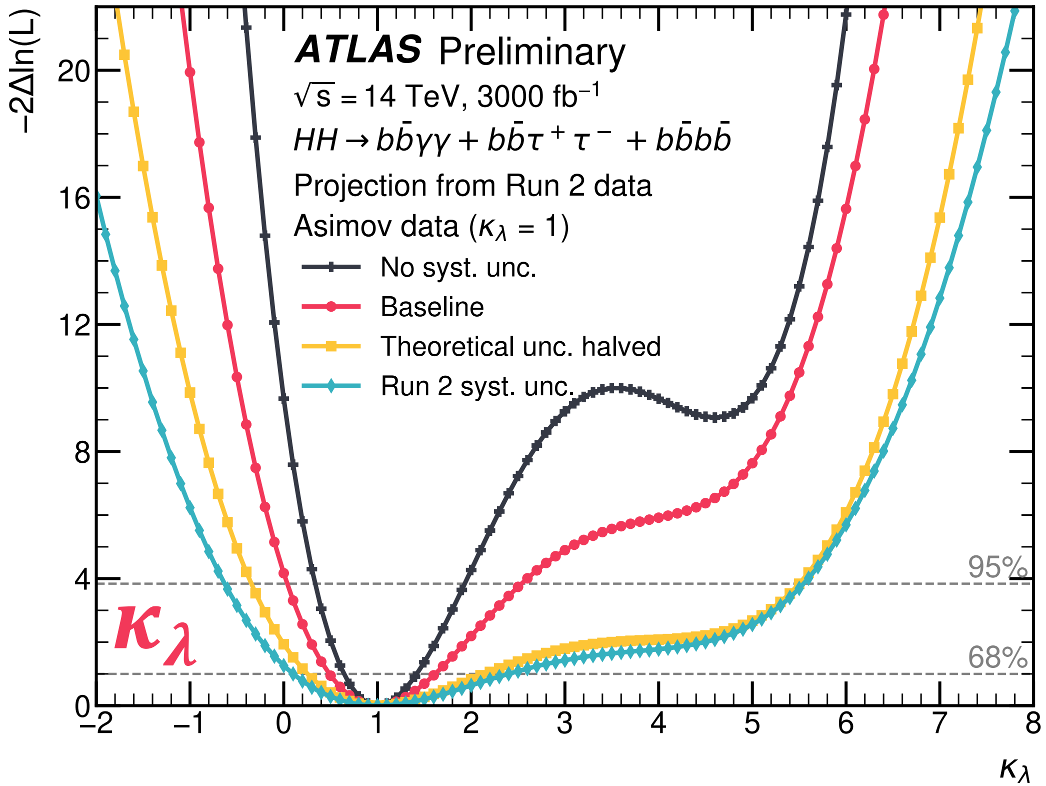


☆ "Log Likelihood Scan" limits utilize different assumptions

HH Prospects @ High Luminosity LHC

ATL-PHYS-PUB-2022-053

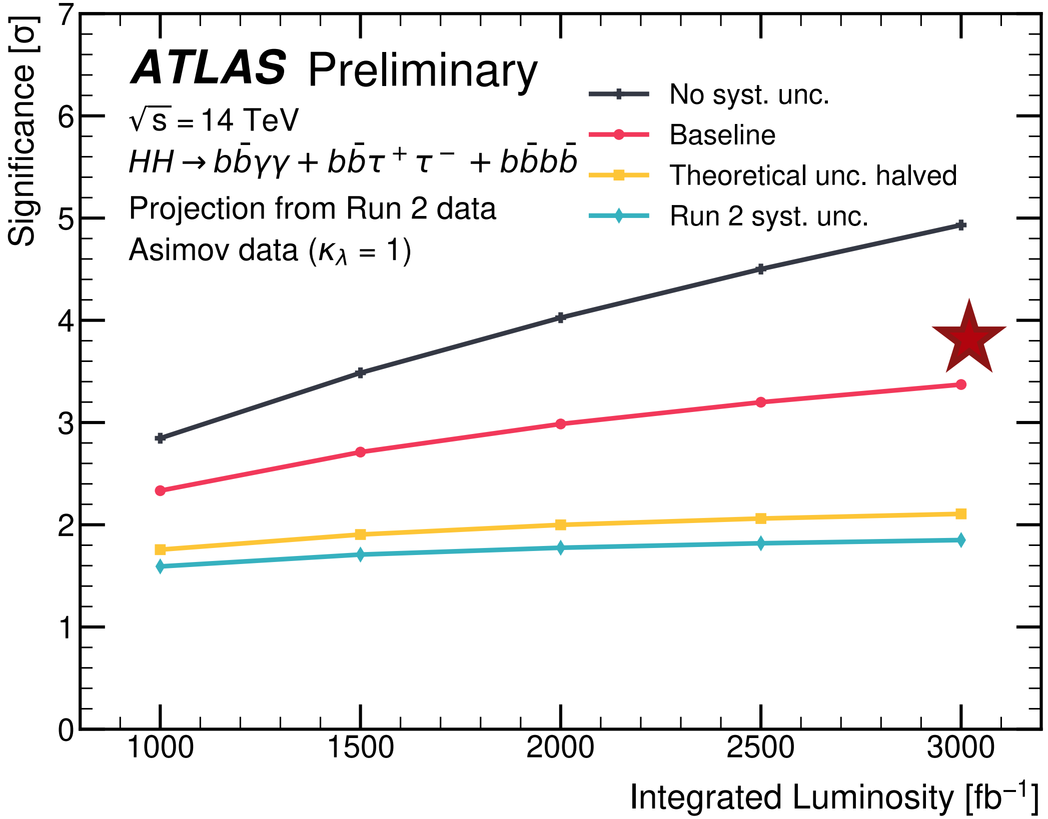
Constraints on κ_λ (3000 fb^{-1})



"Baseline" Uncertainty Scenario:

$\mathbf{0.0} < \kappa_\lambda < \mathbf{2.5}$ (95% CI)

SM Significance vs. Luminosity



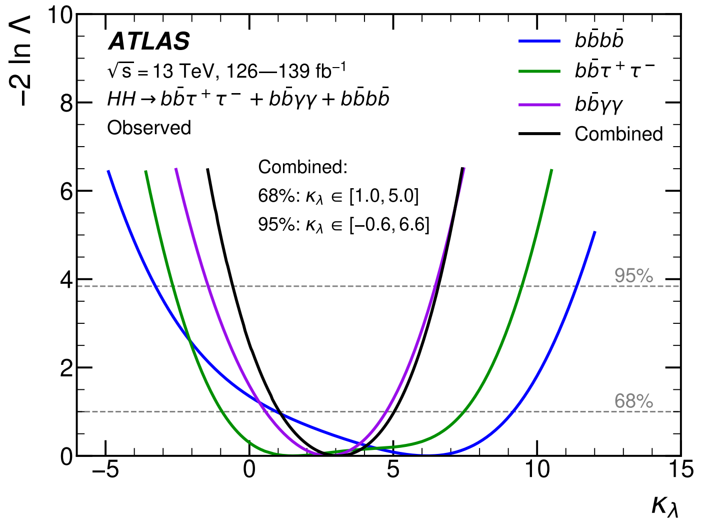
~ Evidence-level sensitivity (3.4σ) to SM *HH* signal by end of HL-LHC

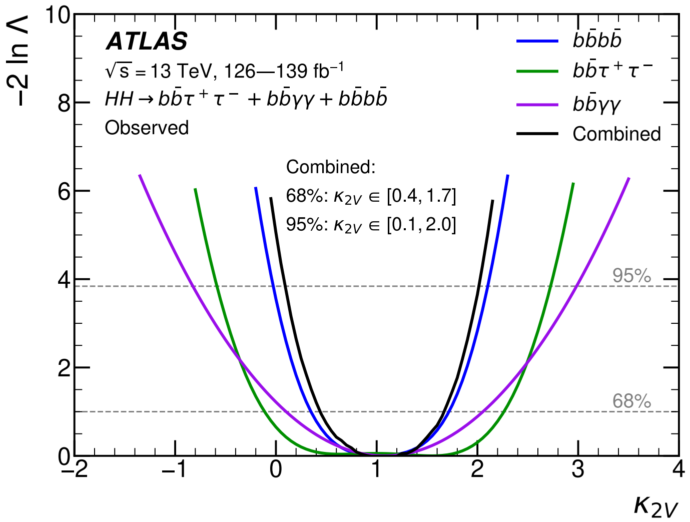
Concluding Remarks

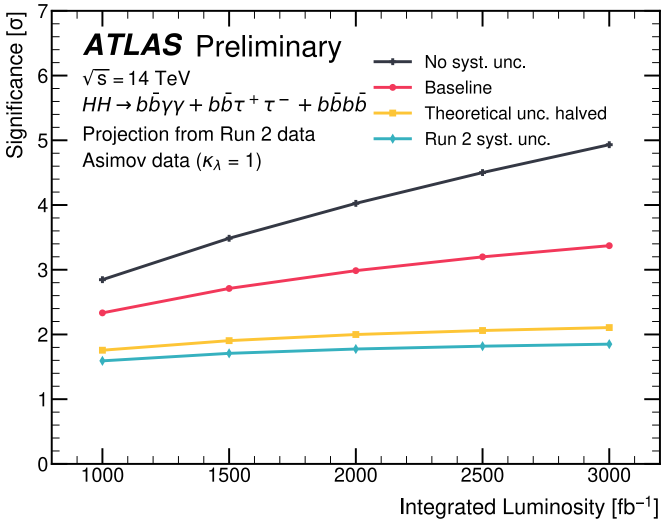
Concluding Remarks

- ATLAS measurements of non-resonant *HH* production in three complementary final states
  - Constrain *HHH* coupling (κ_λ) to within $\mathcal{O}(10)$
  - Constrain *HHVV* coupling (κ_{2V}) to within $\mathcal{O}(2)$
  - First ATLAS constraints on *WWHH* (κ_{2W}) and *ZZHH* (κ_{2Z}) : $\mathcal{O}(10)$
- Promising future for *HH* measurements at HL-LHC
  - "Baseline" uncertainty scenario projects evidence of *HH*!

	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%







Additional Material

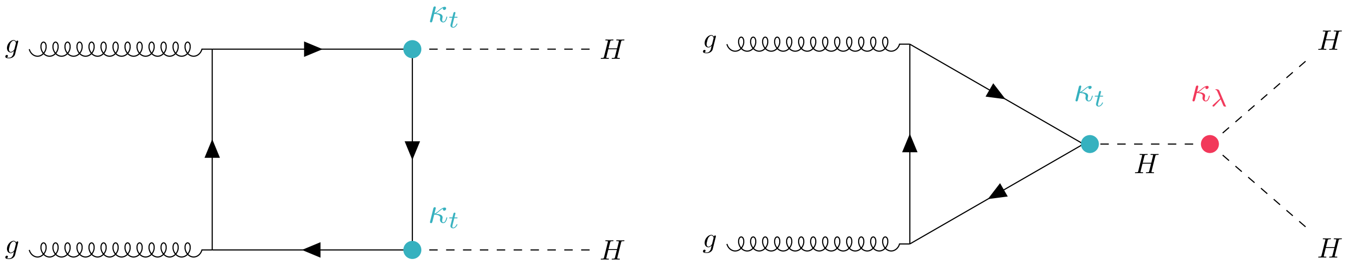
Links to Results

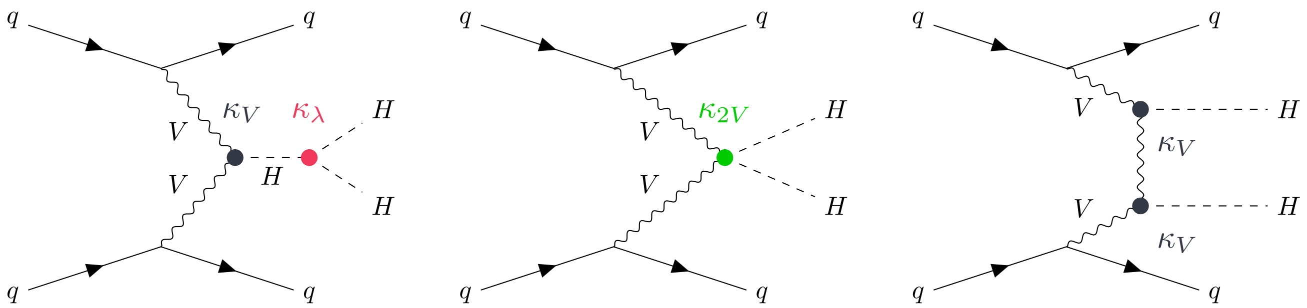
- Individual Measurements:
  - $VHH \to (\ell\ell, \ell\nu, \nu\nu) + b\bar{b}b\bar{b}$: arXiv:2210.05415 (HDBS-2019-31)
  - $HH \to b\bar{b}b\bar{b}$: arXiv:2301.03212 (HDBS-2019-29)
  - $HH \to b\bar{b}\tau\tau$: arXiv:2209.10910 (HDBS-2018-40, ATLAS-CONF-2021-052)
  - $HH \to b\bar{b}\gamma\gamma$: PhysRevD.106.052001 (HDBS-2018-34)
- Single- and Di-Higgs Boson Combination: arXiv:2211.01216 (HDBS-2022-03)
- HL-LHC Prospects: Di-Higgs Boson Measurements: ATL-PHYS-PUB-2022-053

Higgs Pair (*HH*) Production Modes

$\boldsymbol{\kappa_c = c/c_{SM}}$

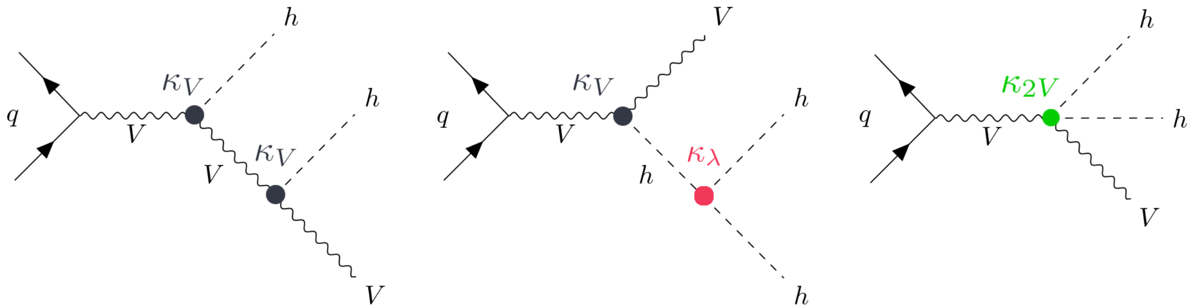
gluon-gluon Fusion (ggF)
$\sigma \sim$ 31.0 fb



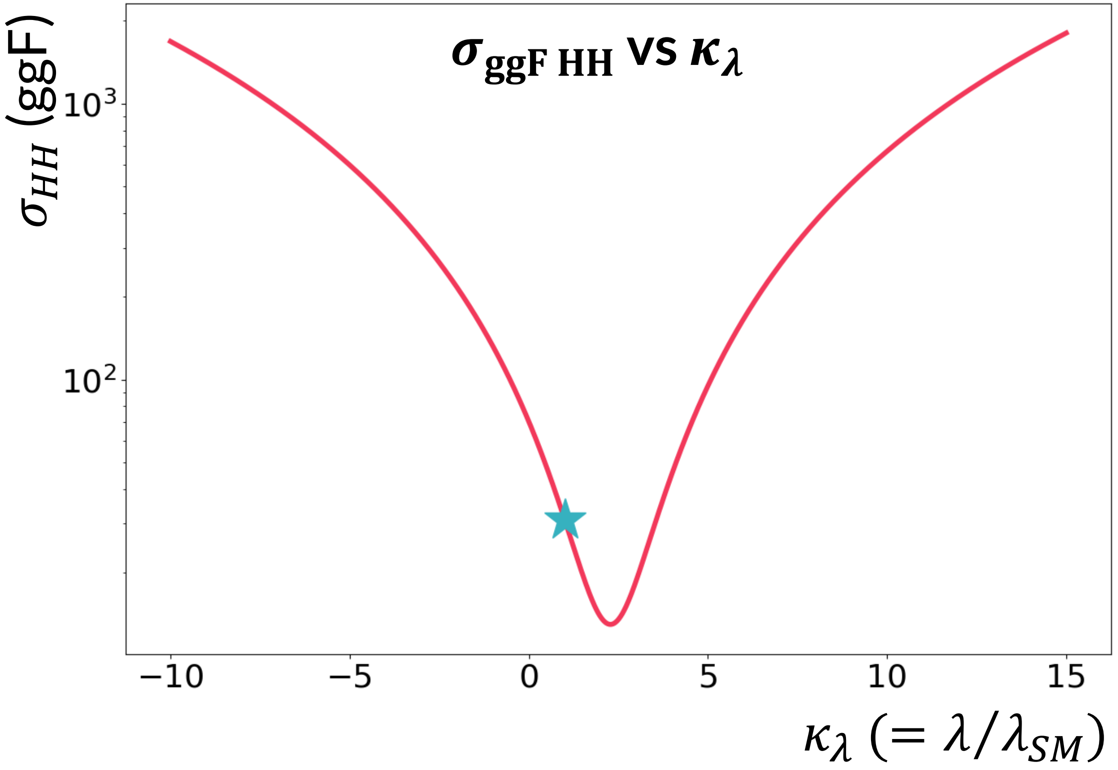


Vector Boson Fusion (VBF)
$\sigma \sim$ 1.72 fb

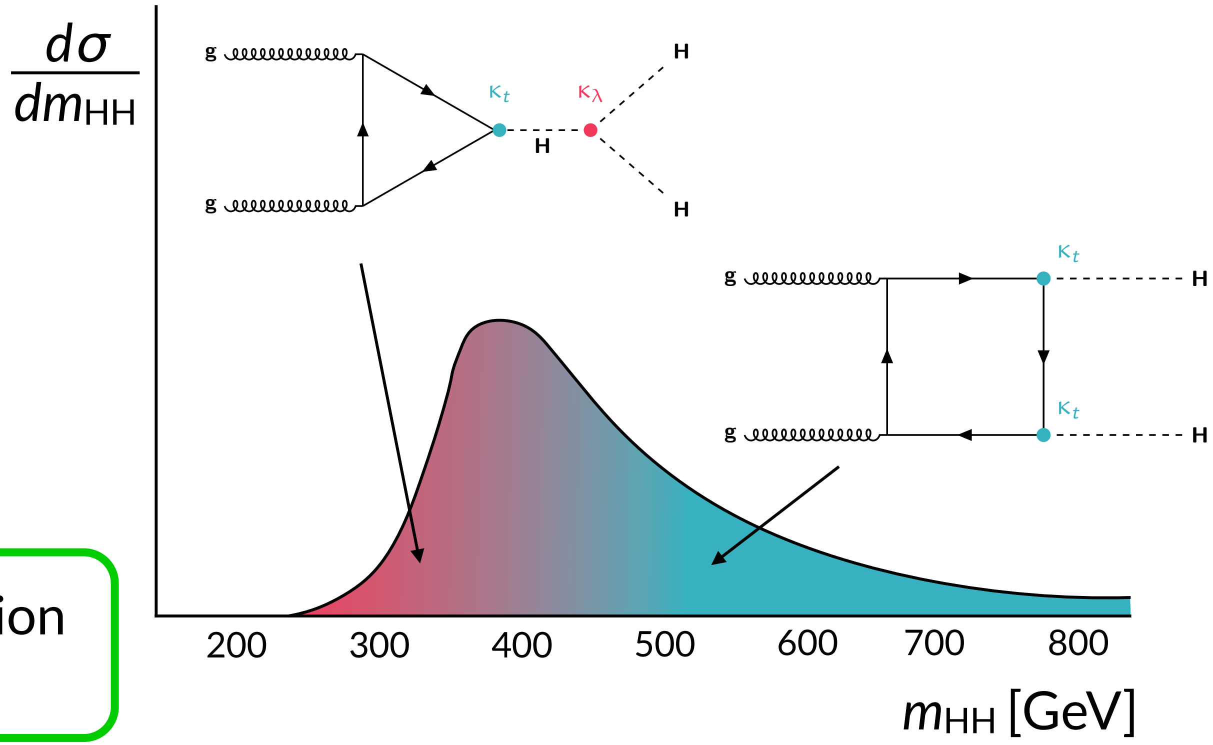
Vector Boson Associated (VHH)
$\sigma \sim$ 0.86 fb



Sensitivity to New Physics in the Self-Coupling



New physics disrupts interference
→ more signal; softer events



(Similar for VBF) new physics breaks cancellation
→ more signal; *harder* events

$VHH \to (1,2)\ell + b\bar{b}b\bar{b}$: Analysis Selection

	Signal regions			Control regions	
	0L	1L (1L+/1L−)	2L	$t\bar{t}$	V + jets
Trigger	E_T^{miss}	single-lepton	single-lepton	single-lepton	single-photon
Lepton or photon	0 *loose* leptons, 0 identified τ_h	= 1 *tight* electron with $p_T > 27$ GeV OR 1 *medium* muon with $p_T > 25$ GeV, 0 additional *loose* leptons, 0 identified τ_h	= 2 *loose* leptons (e^+e^- or $\mu^+\mu^-$), ≥ 1 lepton with $p_T > 27$ GeV, $81 < m_{\ell\ell} < 101$ GeV	= 2 *loose* leptons ($e^\pm\mu^\mp$), ≥ 1 lepton with $p_T > 27$ GeV	= 1 photon with $p_T > 150$ GeV, 0 *loose* leptons, 0 identified τ_h
$\boldsymbol{p}_T^{miss}$	$E_T^{miss} > 150$ GeV, $\mathcal{S}(E_T^{miss}) > 12$, $\lvert\Delta\phi(\boldsymbol{p}_T^{miss}, h)\rvert > 1$	$E_T^{miss} > 30$ GeV	—	—	—
Jets	≥ 4 jets with $p_T > 20$ GeV and passing the 85% b-tagging WP				

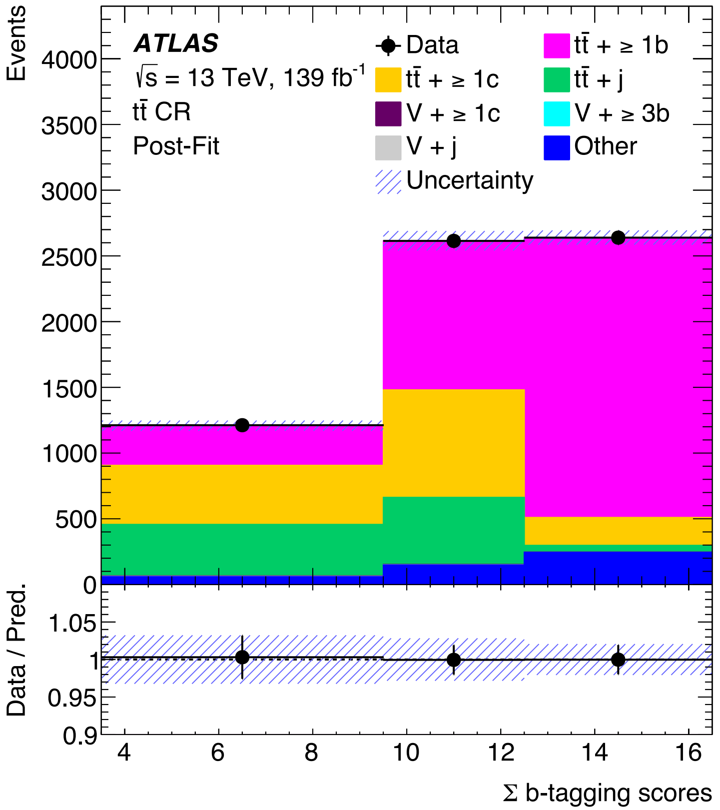
$VHH \to (1,2)\ell + b\bar{b}b\bar{b}$: BDT Input Variables

Variable	Channel and signal model							
	0L			1L		2L		
	Vhh	VH	$A \to ZH$	Vhh	VH	Vhh	VH	$A \to ZH$
$m_{h_1} + m_{h_2}$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_1} - m_{h_2}$	✓	✓	✓	✓	✓	✓	✓	✓
N_{jets}	✓	✓	✓	✓	✓	✓	✓	✓
H_{T}^{ex}	✓	✓	✓	✓	✓	✓	✓	✓
$\sum s_{b\text{-tag}}^{\text{pc}}$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_1}^{\text{FSR}}$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_2}^{\text{FSR}}$	✓	✓	✓	✓	✓	✓	✓	✓
m_{hh}	✓			✓		✓		
p_{T}^{hh}	✓	✓		✓	✓	✓	✓	
$E_{\text{T}}^{\text{miss}}$	✓	✓		✓	✓	✓	✓	✓
p_{T}^{V}				✓	✓	✓	✓	
m_{T}^{W}				✓				
$\cosh(\Delta\eta)_1 - \cos(\Delta\phi)_1$	✓	✓		✓	✓	✓	✓	
$\cosh(\Delta\eta)_2 - \cos(\Delta\phi)_2$	✓	✓		✓	✓	✓	✓	
$\lvert y_{h_1} - y_{h_2} \rvert$	✓	✓		✓	✓	✓	✓	
$\lvert y_V - y_{hh} \rvert$						✓	✓	

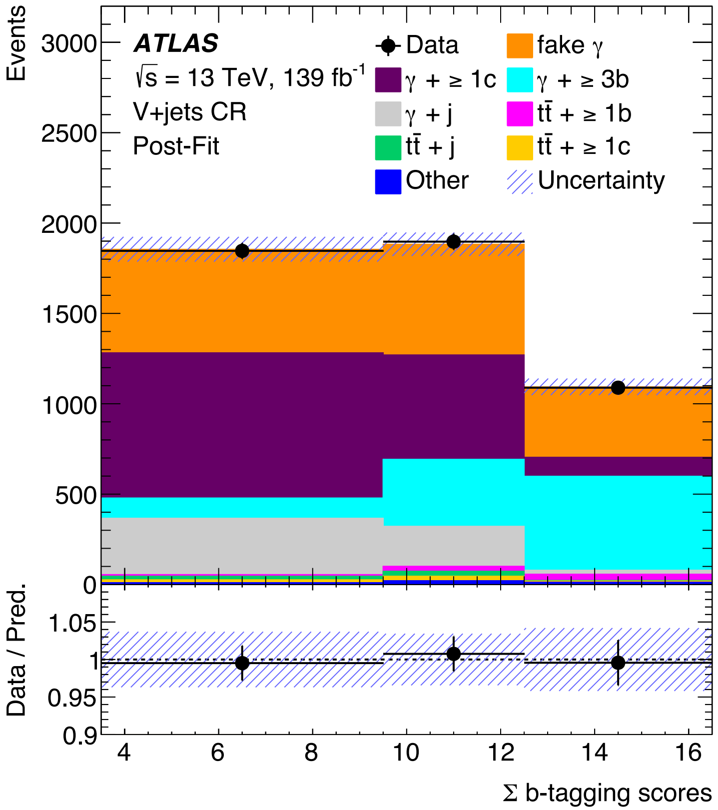
$VH, A \to ZH$:
BSM Resonant Models

$VHH \to (1,2)\ell + b\bar{b}b\bar{b}$: Control Regions

$t\bar{t}$+jets CR



V+jets CR (~γ+jets)



*V+jets ~ γ+jets

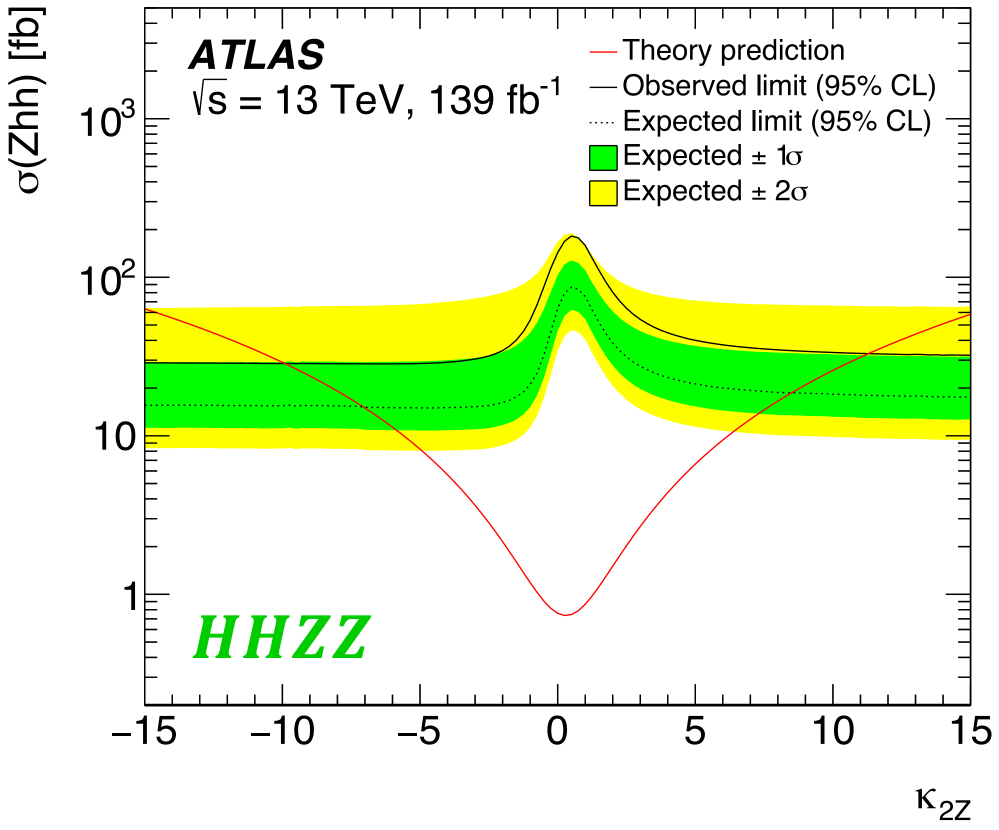
Σ Pseudo-Continuous *b*-Tagging Score

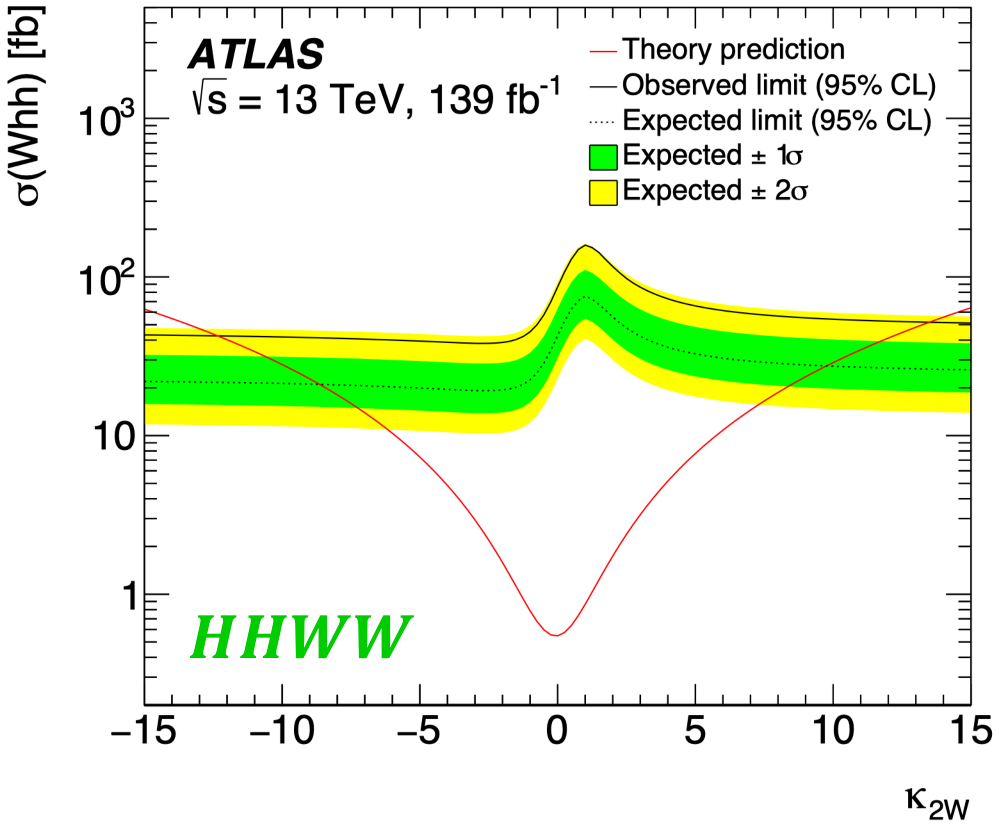
$VHH \rightarrow (1,2)\ell + b\bar{b}b\bar{b}$: Analysis Uncertainties

Model	Vhh like in SM	WH	ZH	NW $A \rightarrow ZH$	LW $A \rightarrow ZH$
Systematic uncertainty source			$\Delta\mu/\mu$ [%]		
Background modelling	+20, −15	+14, −11	+4.7, −3.0	+17, −13	+20, −18
MC statistics	+12, −9.1	+13, −7.8	+4.8, −2.2	+7.2, −4.1	+10, −8.3
Objects	+12, −8.6	+8.0, −5.2	+4.5, −2.2	+19, −11	+16, −12
Signal modelling	+10, −4.7	+12, −4.9	+8.6, −3.0	+14, −5.1	+17, −7.6
VR non-closure	+14, −11	+11, −9.4	+4.4, −3.0	+4.9, −3.7	+12, −10
Total systematic uncertainty	+30, −22	+27, −18	+12, −5.8	+30, −18	+33, −24
Statistical uncertainty	+44, −39	+52, −43	+68, −49	+59, −47	+42, −37
Total	+52, −44	+59, −47	+69, −49	+66, −50	+53, −45

$VH, A \rightarrow ZH$:
BSM Resonant Models

$VHH \to (1,2)\ell + b\bar{b}b\bar{b}$: Upper Limits on κ_{2Z} and κ_{2W} (Plots)



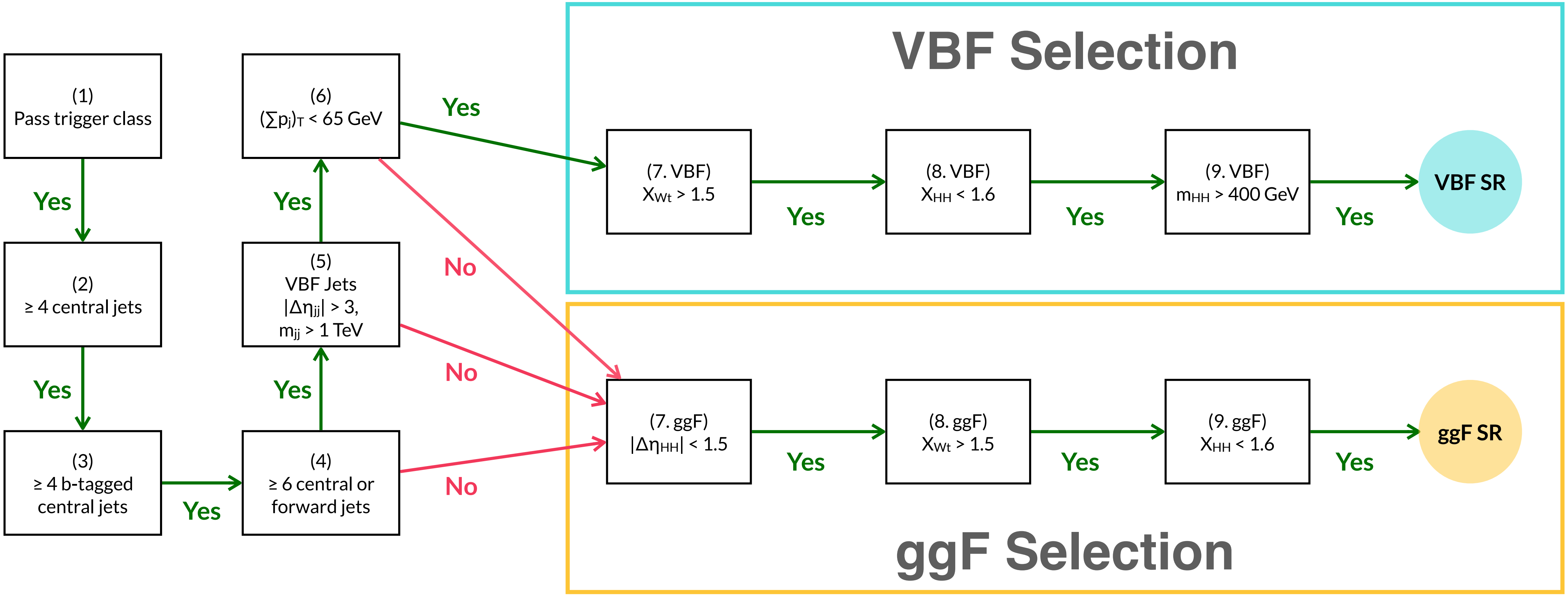


$HH \to b\bar{b}b\bar{b}$: Full Analysis Selection

A Quick Overview

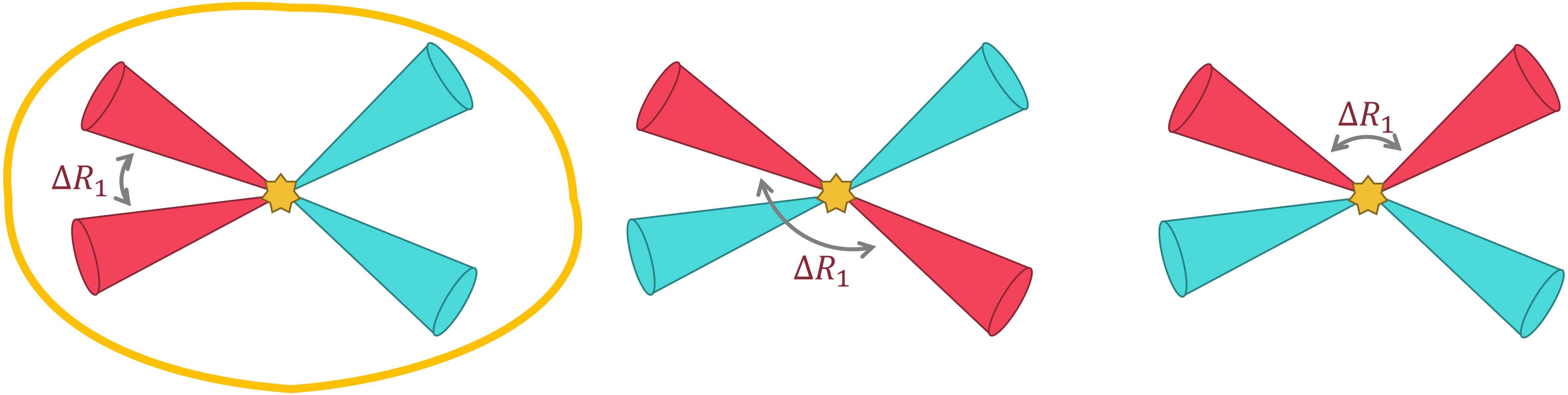
$$X_{Wt} = \min\left[\sqrt{\left(\frac{m_{jj} - m_W}{0.1 m_{jj}}\right)^2 + \left(\frac{m_{jjb} - m_t}{0.1 m_{jjb}}\right)^2}\right]$$

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

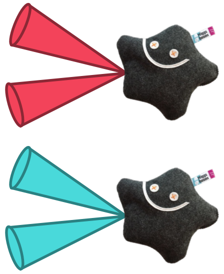


$HH \rightarrow b\bar{b}b\bar{b}$: Higgs Boson Pairing

Choose between three possible pairs of four jets



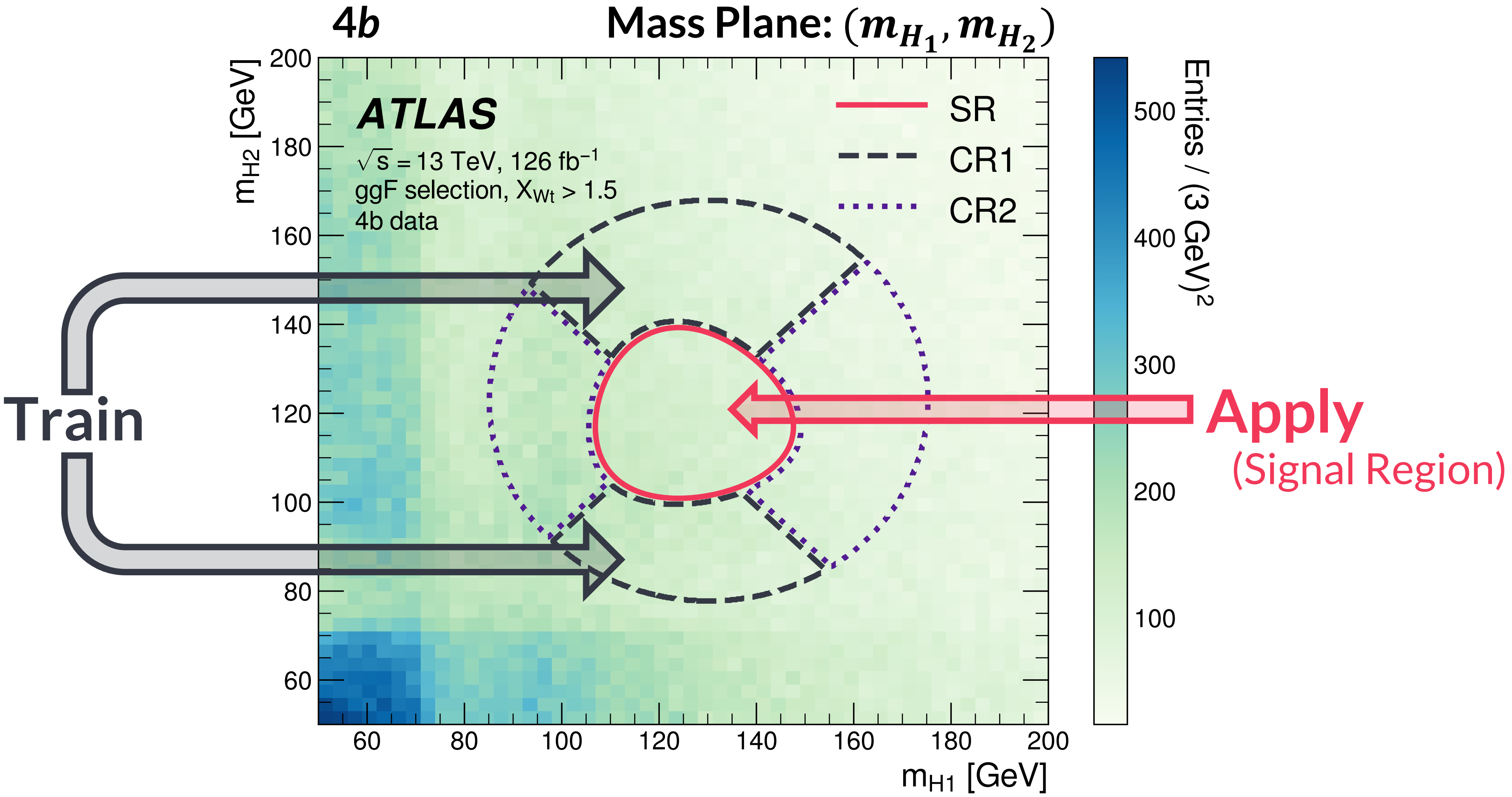
Pairing ≳70% accurate for VBF
(≳90% for κ_{2V} far from 1)



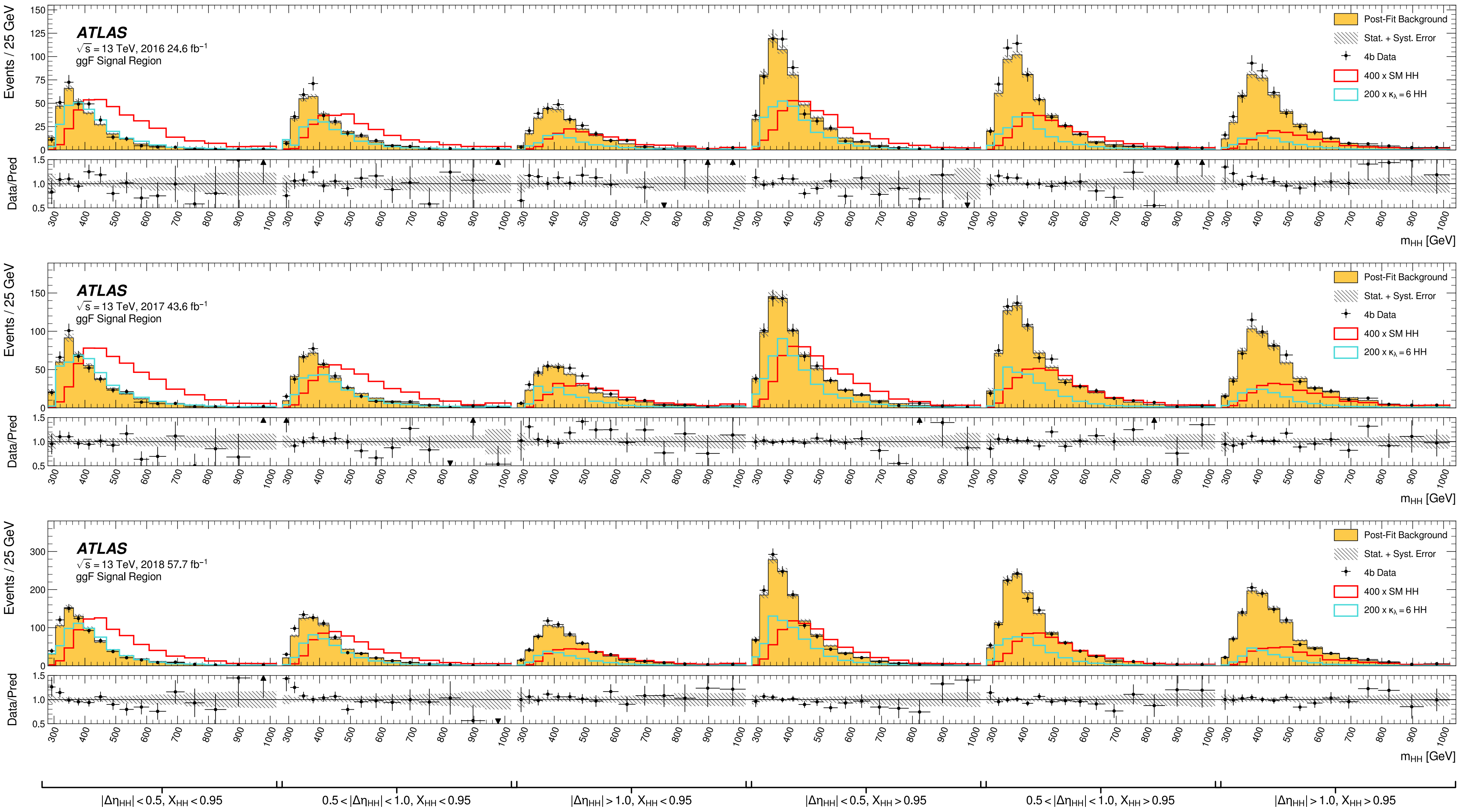
"Leading" Reconstructed Higgs Boson

"Subleading" Reconstructed Higgs Boson

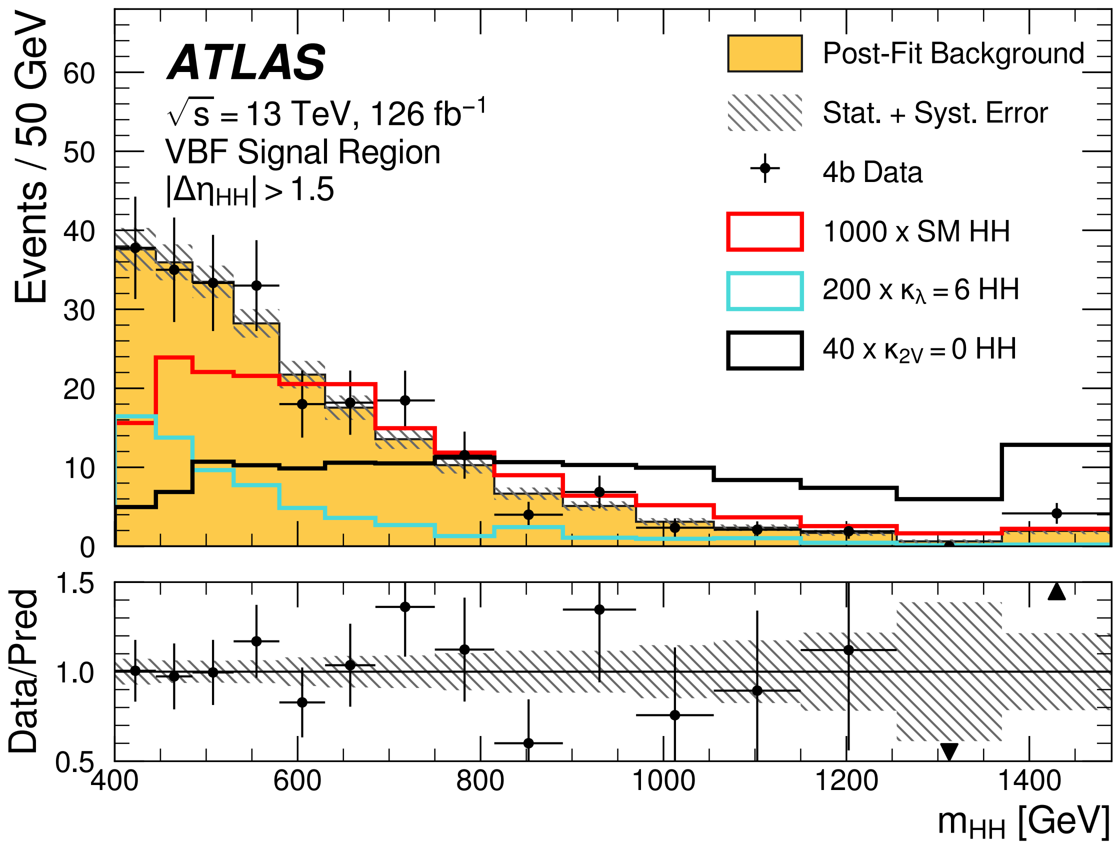
$HH \rightarrow b\bar{b}b\bar{b}$: Reweighting Using the Mass Plane

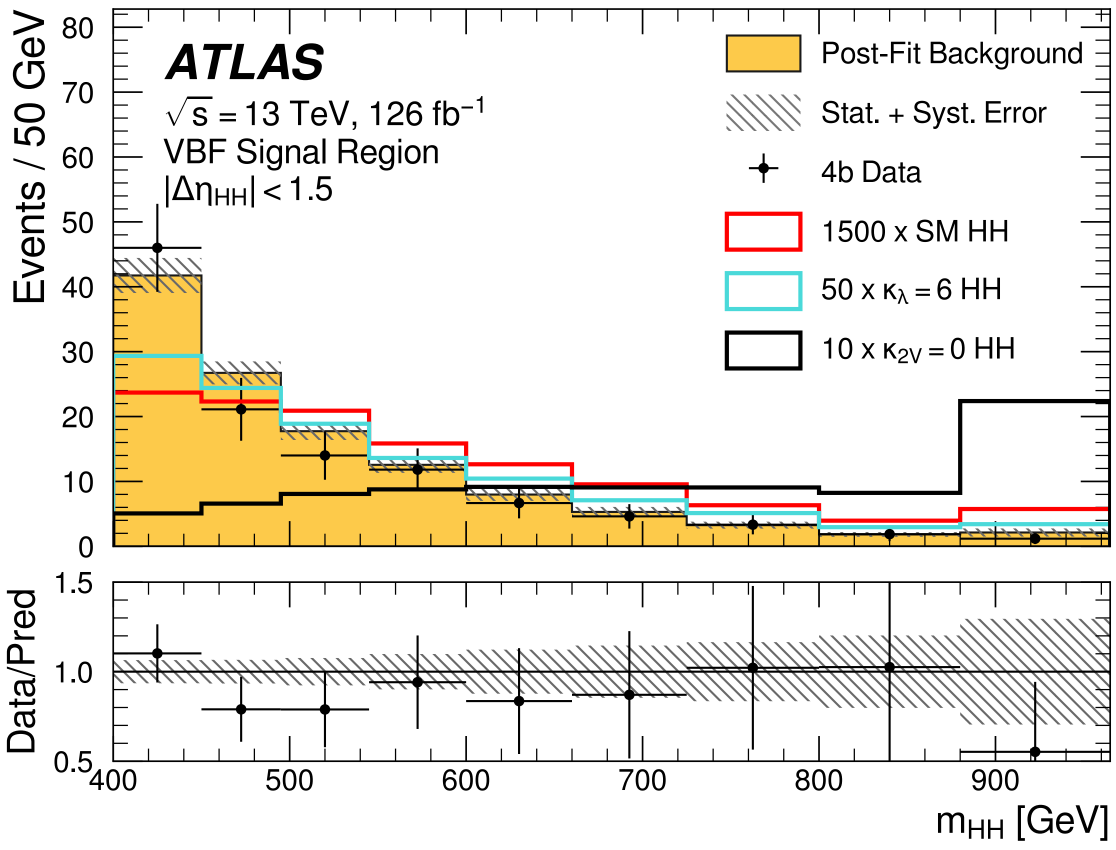


$HH \to b\bar{b}b\bar{b}$: Observed m_{HH} Distributions in ggF Categories



$HH \to b\bar{b}b\bar{b}$: Observed m_{HH} Distributions in VBF Categories





$HH \to b\bar{b}b\bar{b}$: Uncertainties

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%
$3b$1f nonclosure uncertainty	-2.0%

* Impact on measurement of SM HH (ggF+VBF) production

$HH \rightarrow b\bar{b}\tau\tau$: Analysis Selection

$\tau_{\text{had}}\tau_{\text{had}}$ category		$\tau_{\text{lep}}\tau_{\text{had}}$ categories	
STT	DTT	SLT	LTT
e/μ selection			
No loose e/μ		Exactly one loose e/μ	
		e (μ) must be tight (medium and have $\lvert\eta\rvert < 2.5$)	
		$p_{\text{T}}^{e} > 25, 27$ GeV	18 GeV $< p_{\text{T}}^{e} <$ SLT cut
		$p_{\text{T}}^{\mu} > 21, 27$ GeV	15 GeV $< p_{\text{T}}^{\mu} <$ SLT cut
$\tau_{\text{had-vis}}$ selection			
Two loose $\tau_{\text{had-vis}}$		One loose $\tau_{\text{had-vis}}$	
		$\lvert\eta\rvert < 2.3$	
$p_{\text{T}} >$ 100, 140, 180 (25) GeV	$p_{\text{T}} > 40$ (30) GeV		$p_{\text{T}} > 30$ GeV
Jet selection			
≥ 2 jets with $\lvert\eta\rvert < 2.5$			
Leading jet $p_{\text{T}} > 45$ GeV	Trigger dependent	Leading jet $p_{\text{T}} > 45$ GeV	Trigger dependent
Event-level selection			
Trigger requirements passed			
Collision vertex reconstructed			
$m_{\tau\tau}^{\text{MMC}} > 60$ GeV			
Opposite-sign electric charges of $e/\mu/\tau_{\text{had-vis}}$ and $\tau_{\text{had-vis}}$			
Exactly two b-tagged jets			
		$m_{bb} < 150$ GeV	

STT: Single τ Trigger
DTT: Di-τ Trigger
SLT: Single ℓ Trigger
LTT: ℓ+τ Trigger

$HH \to b\bar{b}\tau\tau$: Analysis Selection

Variable	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{had}}$ SLT	$\tau_{\text{lep}}\tau_{\text{had}}$ LTT
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{\text{MMC}}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	
$\Delta p_{\text{T}}(\ell,\tau)$		✓	✓
Sub-leading b-tagged jet p_{T}		✓	
m_{T}^{W}		✓	
$E_{\text{T}}^{\text{miss}}$		✓	
$\mathbf{p}_{\text{T}}^{\text{miss}}$ ϕ centrality		✓	
$\Delta\phi(\ell\tau, bb)$		✓	
$\Delta\phi(\ell, \mathbf{p}_{\text{T}}^{\text{miss}})$			✓
$\Delta\phi(\tau\tau, \mathbf{p}_{\text{T}}^{\text{miss}})$			✓
S_{T}			✓

STT: Single τ Trigger
DTT: Di-τ Trigger
SLT: Single ℓ Trigger
LTT: ℓ+τ Trigger

$HH \to b\bar{b}\gamma\gamma$: BDT Input Variables

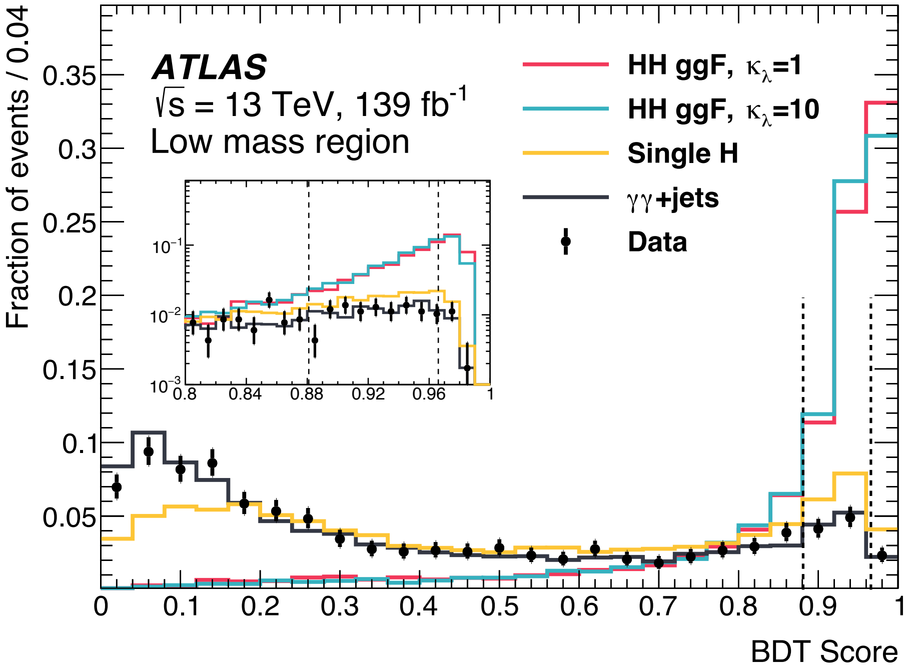
Variable	Definition
Photon-related kinematic variables	
$p_T/m_{\gamma\gamma}$	Transverse momentum of each of the two photons divided by the diphoton invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudorapidity and azimuthal angle of the leading and subleading photon
Jet-related kinematic variables	
b-tag status	Tightest fixed b-tag working point (60%, 70%, or 77%) that the jet passes
p_T, η and ϕ	Transverse momentum, pseudorapidity and azimuthal angle of the two jets with the highest b-tagging score
$p_T^{b\bar{b}}$, $\eta_{b\bar{b}}$ and $\phi_{b\bar{b}}$	Transverse momentum, pseudorapidity and azimuthal angle of the b-tagged jets system
$m_{b\bar{b}}$	Invariant mass of the two jets with the highest b-tagging score
H_T	Scalar sum of the p_T of the jets in the event
Single topness	For the definition, see Eq. (**??**)
Missing transverse momentum variables	
E_T^{miss} and ϕ^{miss}	Missing transverse momentum and its azimuthal angle

BDT Category Definitions

Category	Selection criteria
High mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.967, 1]$
High mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.857, 0.967]$
Low mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.966, 1]$
Low mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.881, 0.966]$

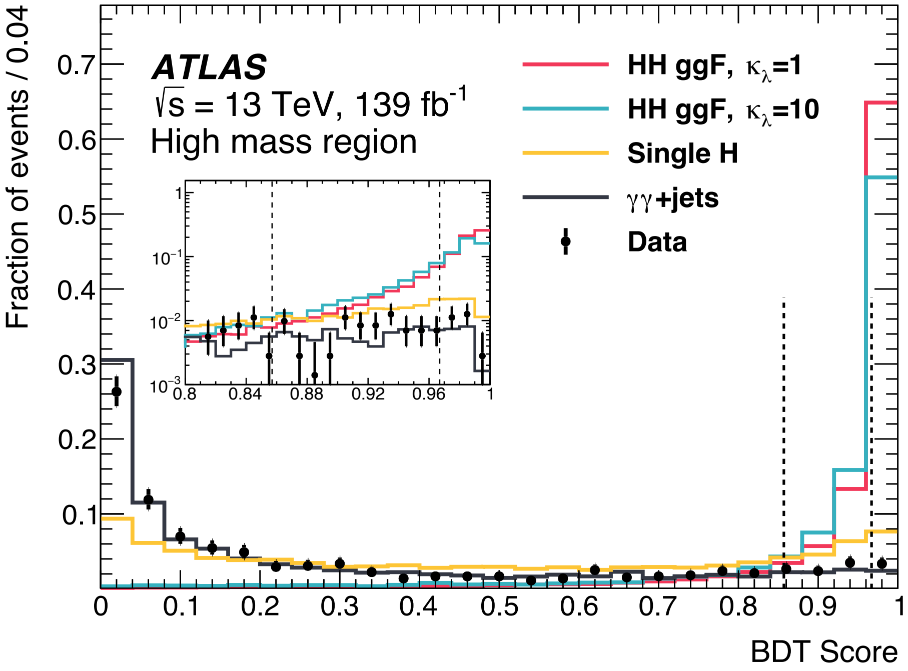
$HH \rightarrow b\bar{b}\gamma\gamma$: BDT Distributions (Low and High Mass)

Low Mass ~ BSM κ_λ



$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV

High Mass ~ SM



$m^*_{b\bar{b}\gamma\gamma} > 350$ GeV

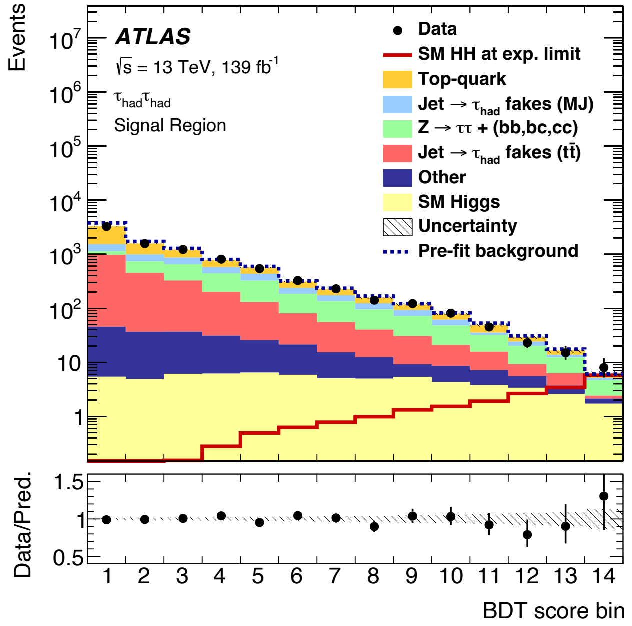
$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250)$

$HH \to b\bar{b}\gamma\gamma$: Uncertainties

		Relative impact of the systematic uncertainties [%]	
Source	Type	Nonresonant analysis HH	Resonant analysis $m_X = 300$ GeV
Experimental			
Photon energy resolution	Norm. + Shape	0.4	0.6
Jet energy scale and resolution	Normalization	< 0.2	0.3
Flavor tagging	Normalization	< 0.2	0.2
Theoretical			
Factorization and renormalization scale	Normalization	0.3	< 0.2
Parton showering model	Norm. + Shape	0.6	2.6
Heavy-flavor content	Normalization	0.3	< 0.2
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	Normalization	0.2	< 0.2
Spurious signal	Normalization	3.0	3.3

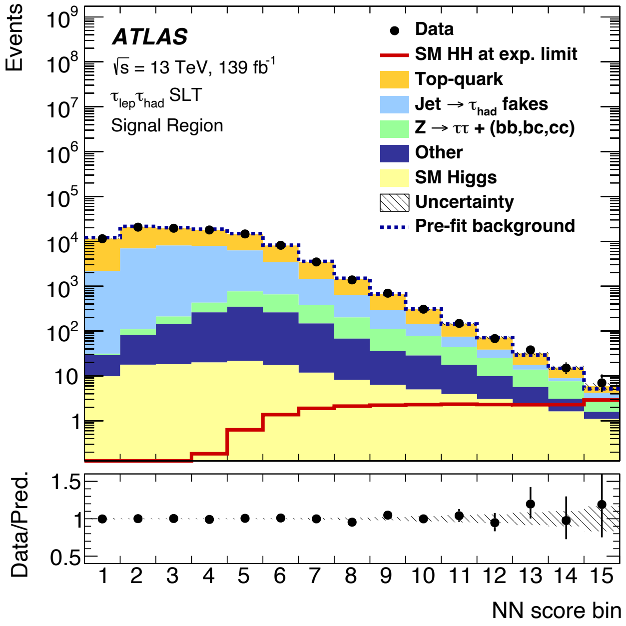
$HH \rightarrow b\bar{b}\tau\tau$: All MVA Distributions

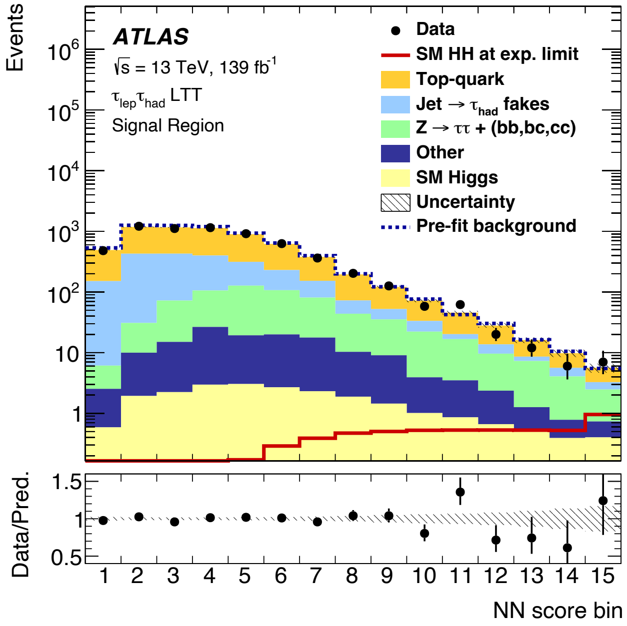
Two Hadronic τ's
Single- and Di-τ Triggers



Boosted Decision Tree

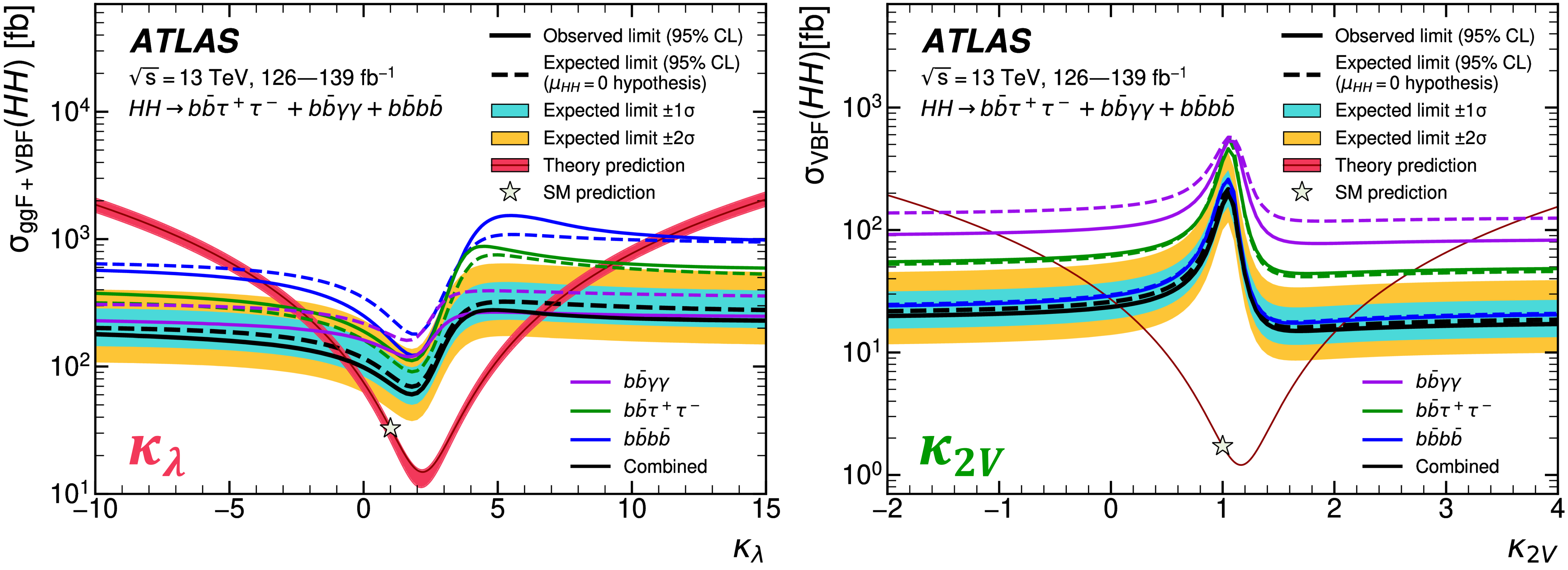
One hadronic + one leptonic τ
Single ℓ Trigger — ℓ+τ Trigger





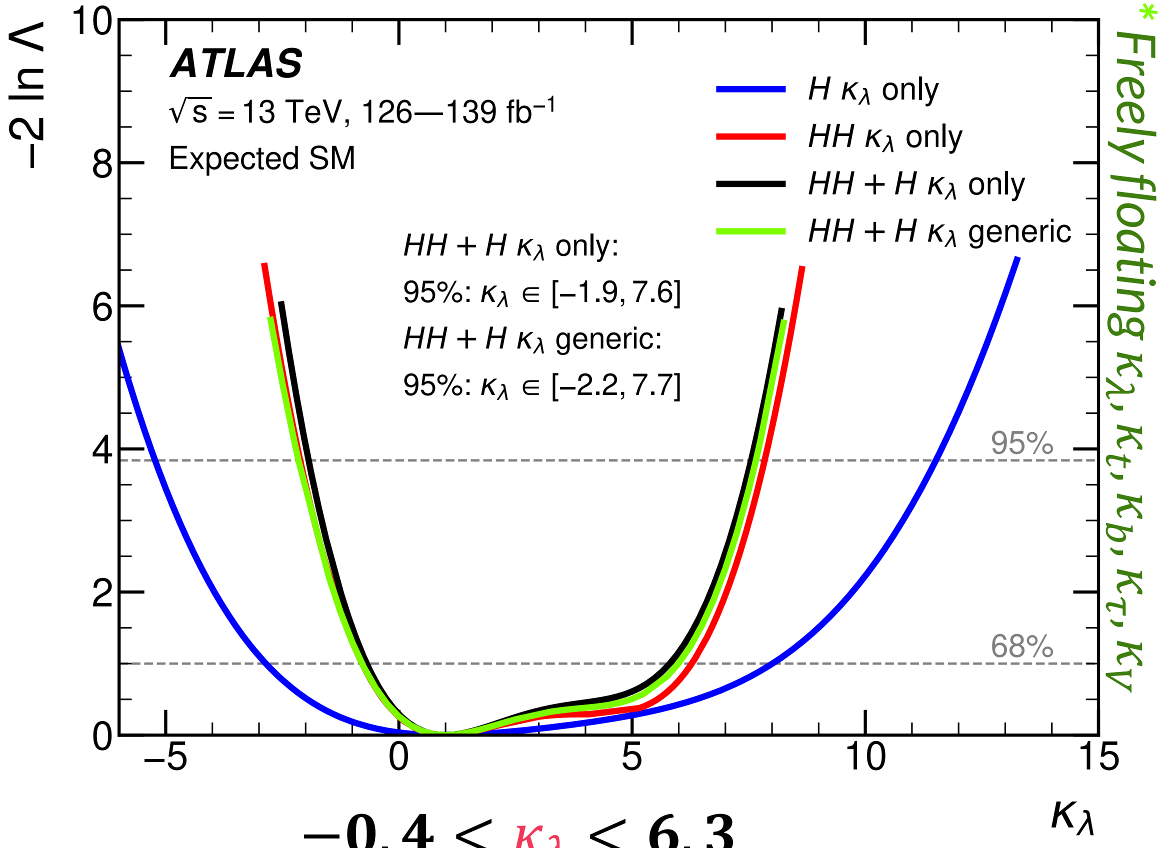
Neural Networks

HH Combination: Cross-Section Scan Limits (95% CL)



Single- and Di-Higgs Measurements (Expected)

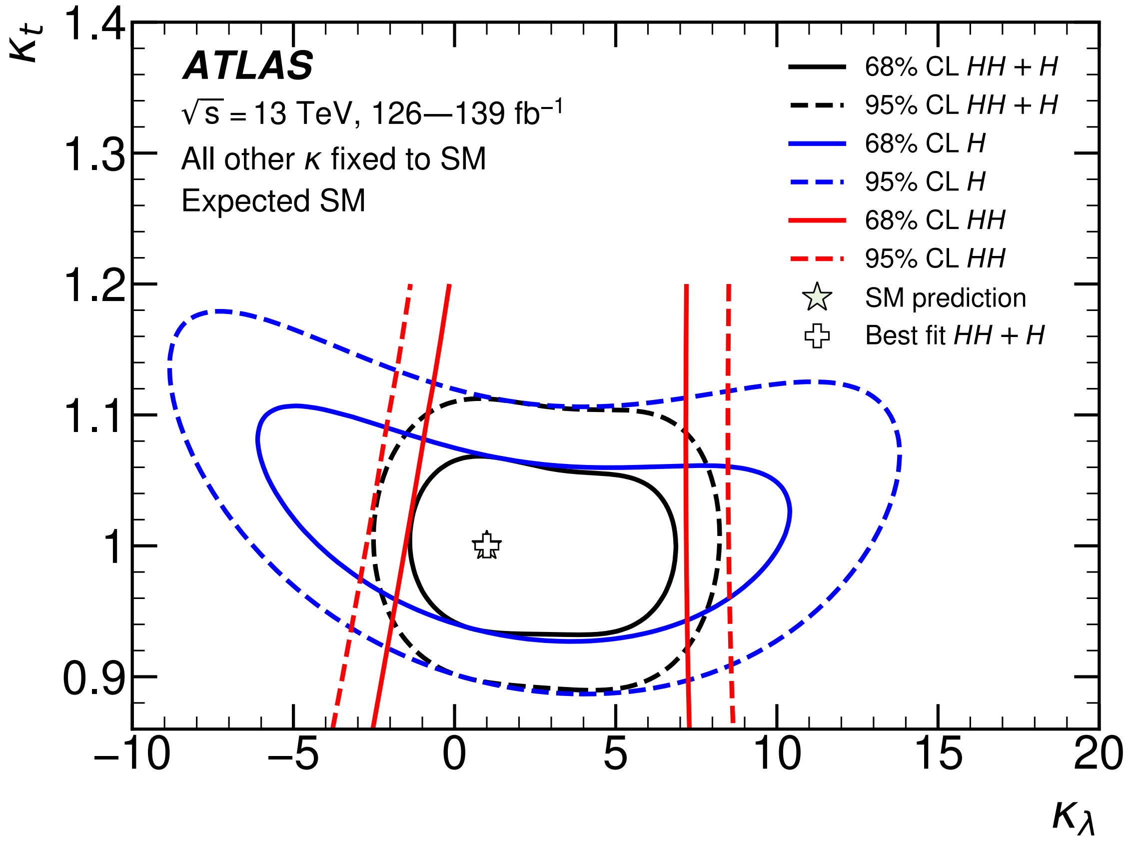
κ_λ: H-only, HH-only, H+HH*



$$-0.4 < \kappa_\lambda < 6.3$$

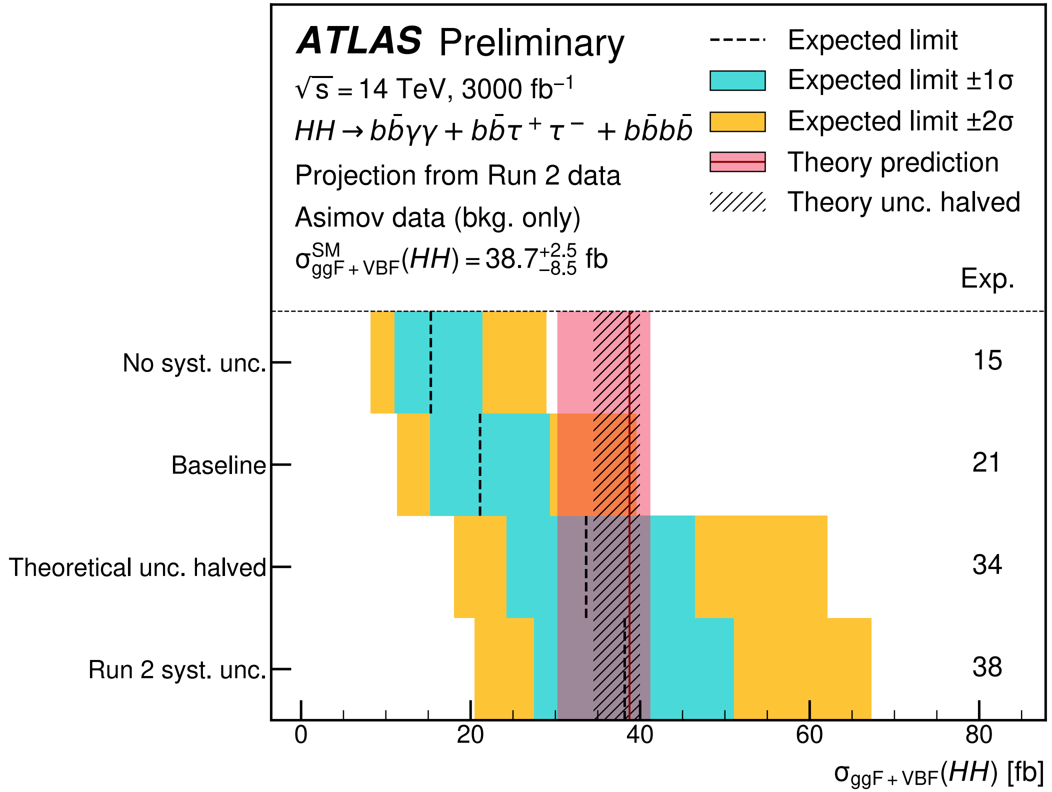
$(-1.9 < \kappa_\lambda < 7.6)$ (Exp.)

κ_t vs κ_λ: H-only, HH-only, H+HH

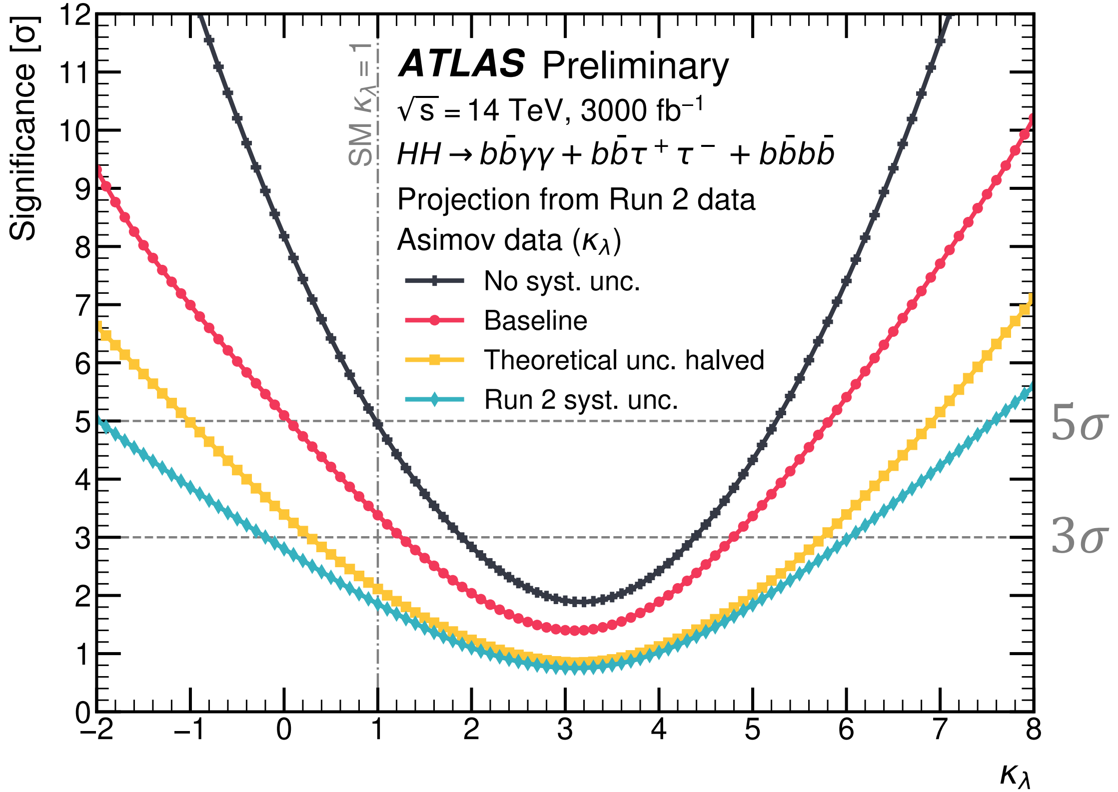


HH Prospects @ HL-LHC: σ_{HH}^{SM} and Significance vs. κ_λ

Upper Limit on σ_{HH}^{SM}



Significance vs. κ_λ (3000 fb^{-1})



Discovery potential if $\kappa_\lambda < 0.0$ or > 5.8

HH Prospects @ HL-LHC: Uncertainty Scenarios

Baseline Scenario

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

Other Scenarios:

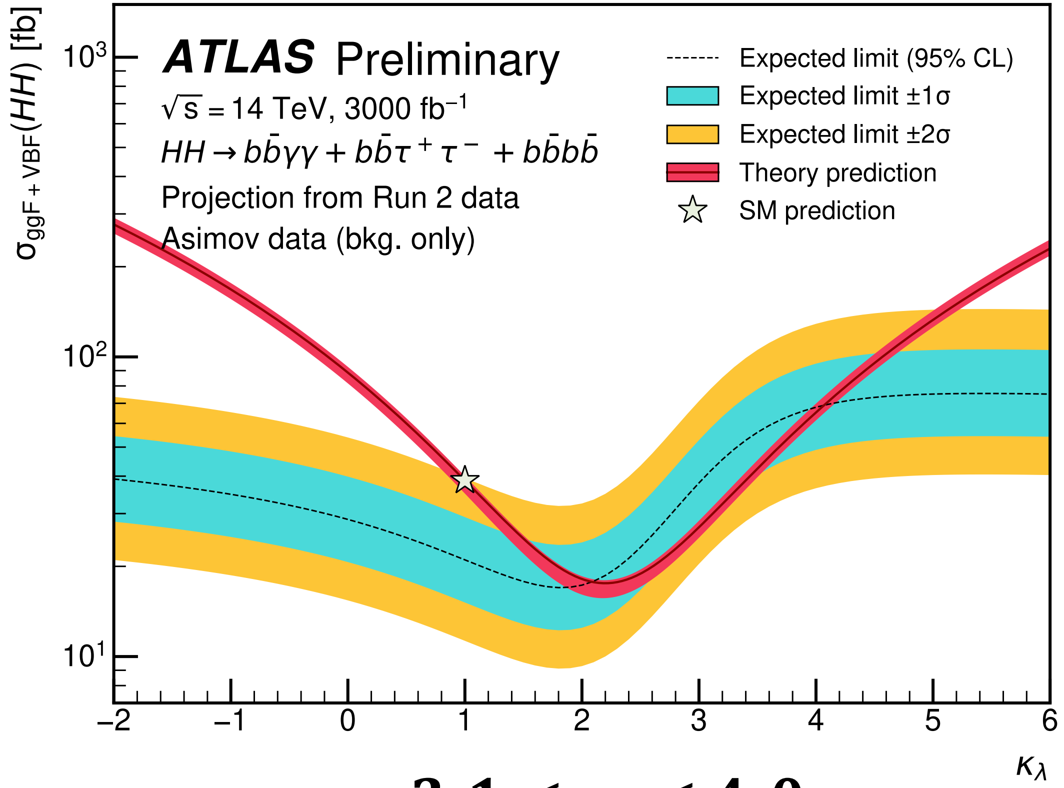
- No Systematic Uncertainties (Statistical Only)

- Run 2 Systematic Uncertainties

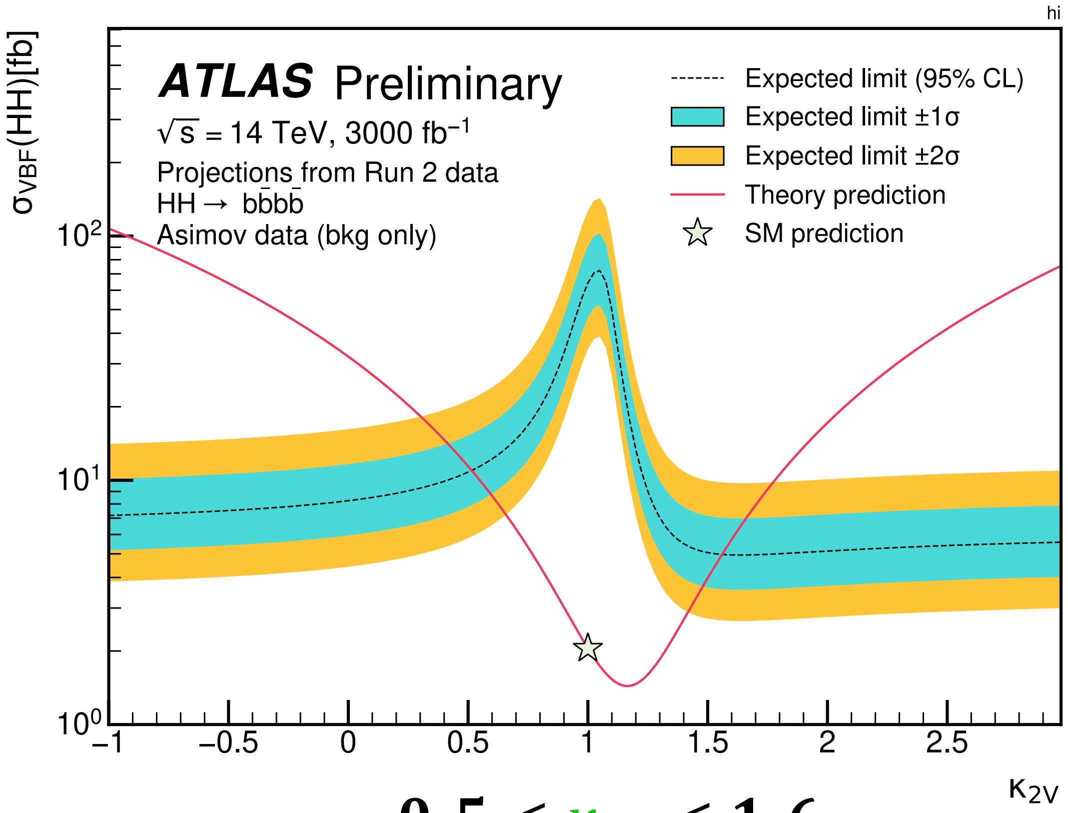
- Run 2 Systematic Uncertainties, with theoretical uncertainties halved

HH Prospects @ HL-LHC: Cross-Section Scan Upper Limits

"Baseline" systematic uncertainty scenario



$-2.1 < \kappa_\lambda < 4.0$



$0.5 < \kappa_{2V} < 1.6$