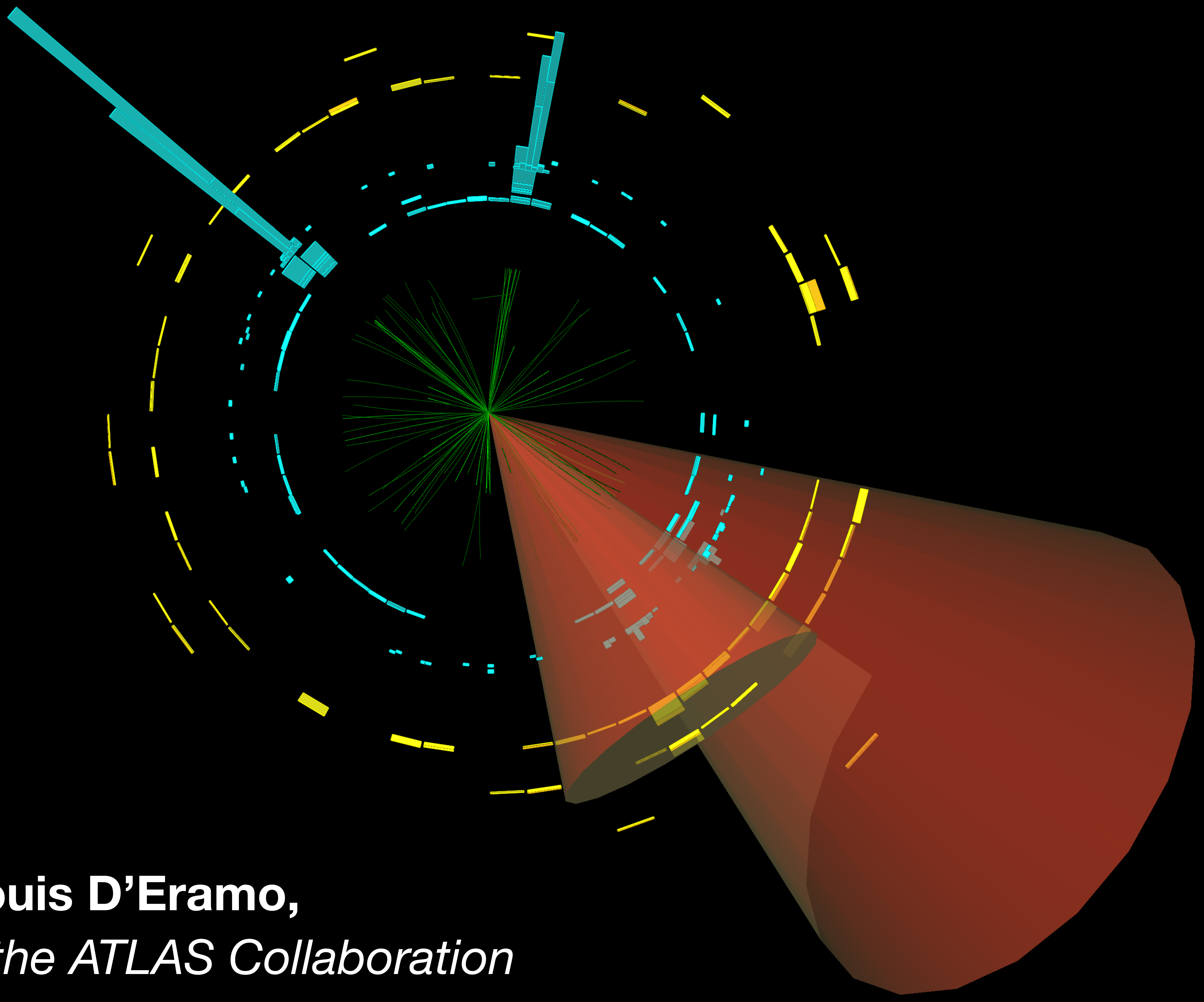
Higgs self-coupling at ATLAS

2022 LHCP TAIPEI

ATLAS EXPERIMENT



Louis D'Eramo,

On behalf of the ATLAS Collaboration

Northern Illinois University

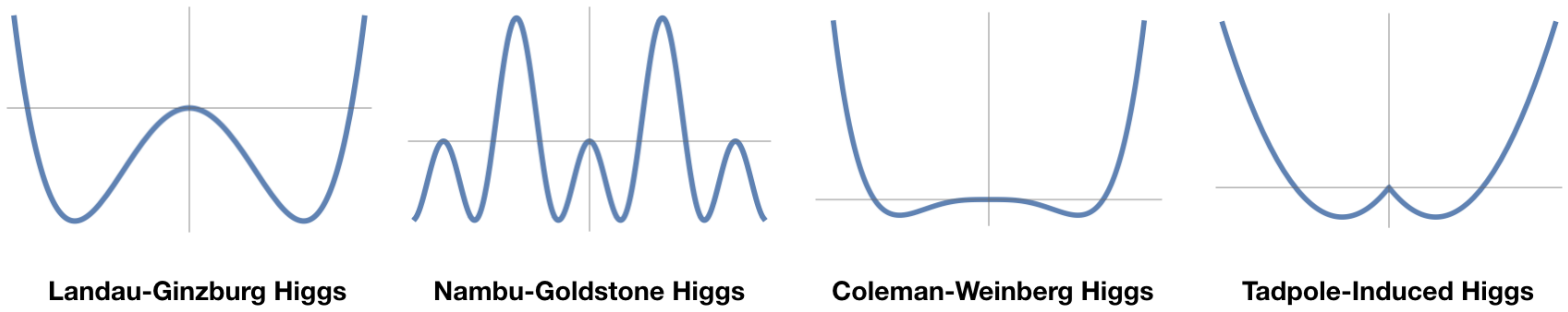
Investigating the Higgs potential

The full expression of the Higgs potential is encoded with parameters μ and λ as:

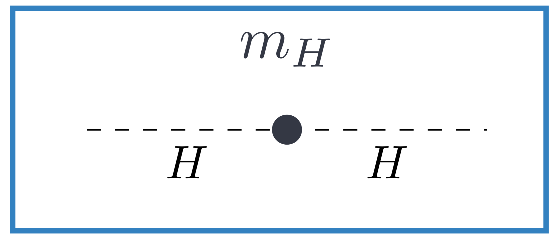
$$V(\phi^\dagger\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$\supset \underbrace{\mu^2}_{\frac{1}{2}m_H^2} H^2 + \sqrt{\frac{\lambda}{2}}\mu\, H^3 + \frac{\lambda}{4} H^4$$

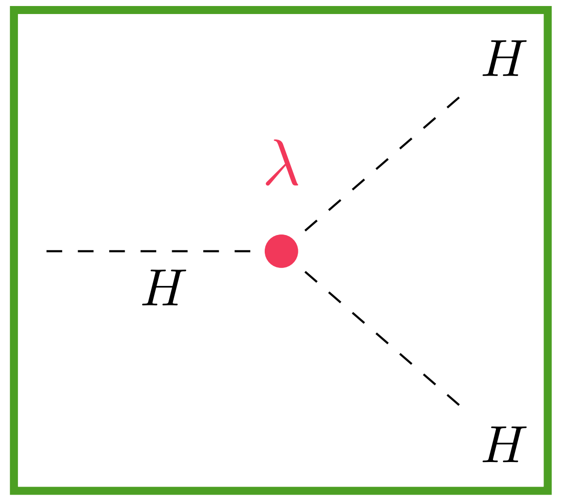
[Phys. Rev. D 101, 075023](#)



- First estimation from the Higgs mass measurement:
  - Combined with the v.e.v computation: $\lambda_{SM} \sim 0.13$

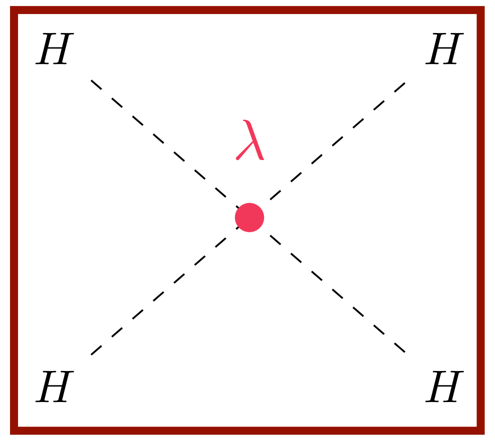


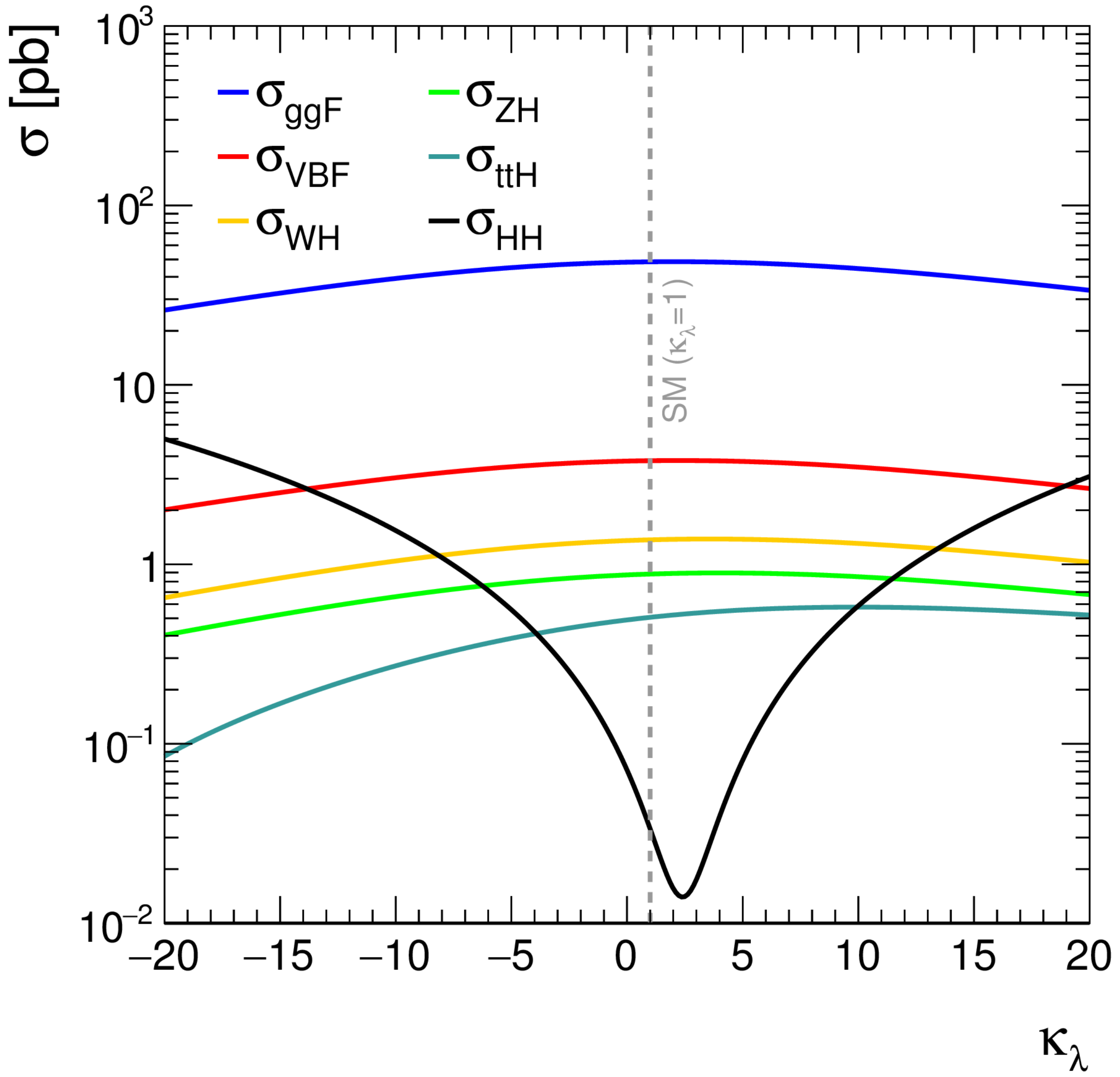
- Direct access to λ through Higgs pair creation:



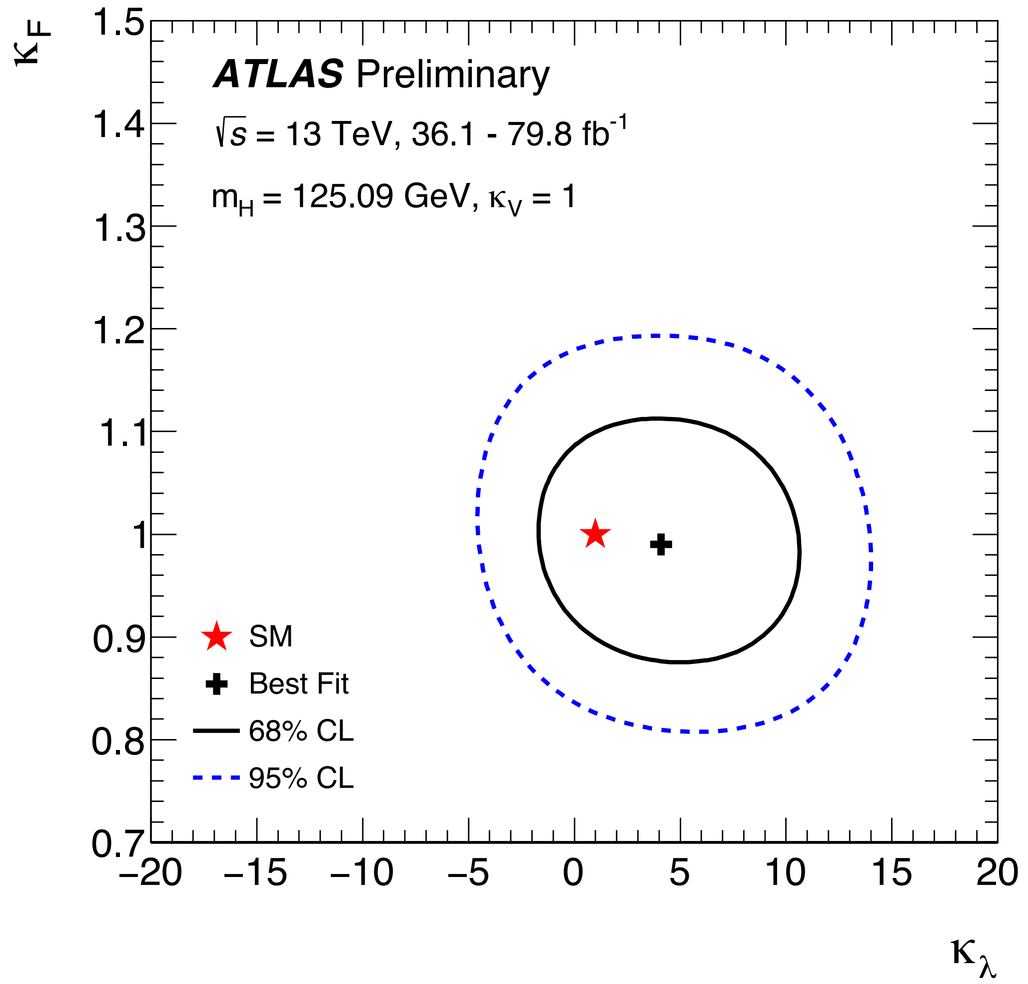
  - Coupling strength denoted as $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$
  - Wide range of BSM models predicting different shapes / values for κ_λ

- Quartic interaction even rarer : out of reach even for HL-LHC



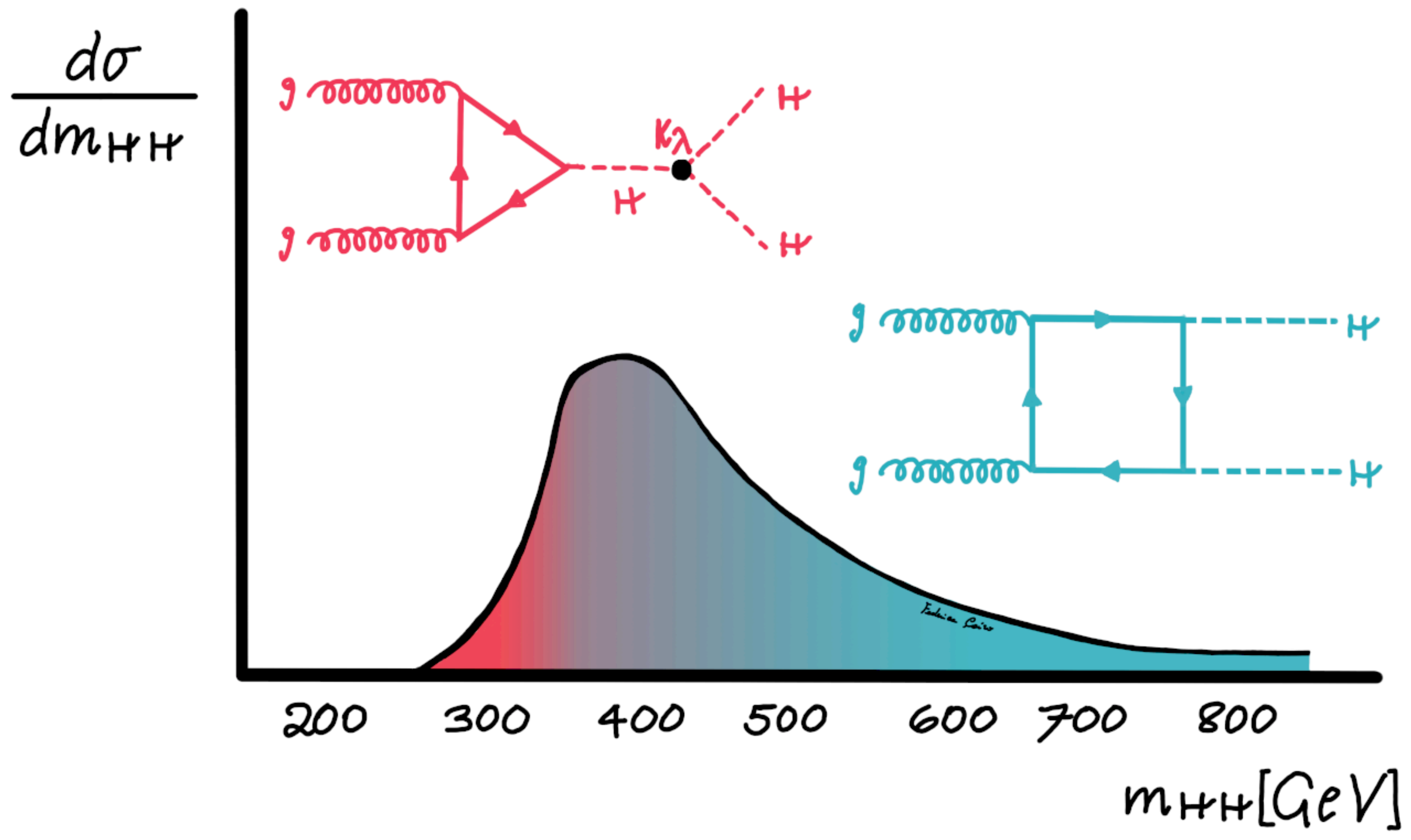


- At tree level: production of pair of Higgs bosons → strong effect on XS.
- At loop level: effect on the single Higgs cross-section and deviations in kinematics: ATL-PHYS-PUB-2019-009

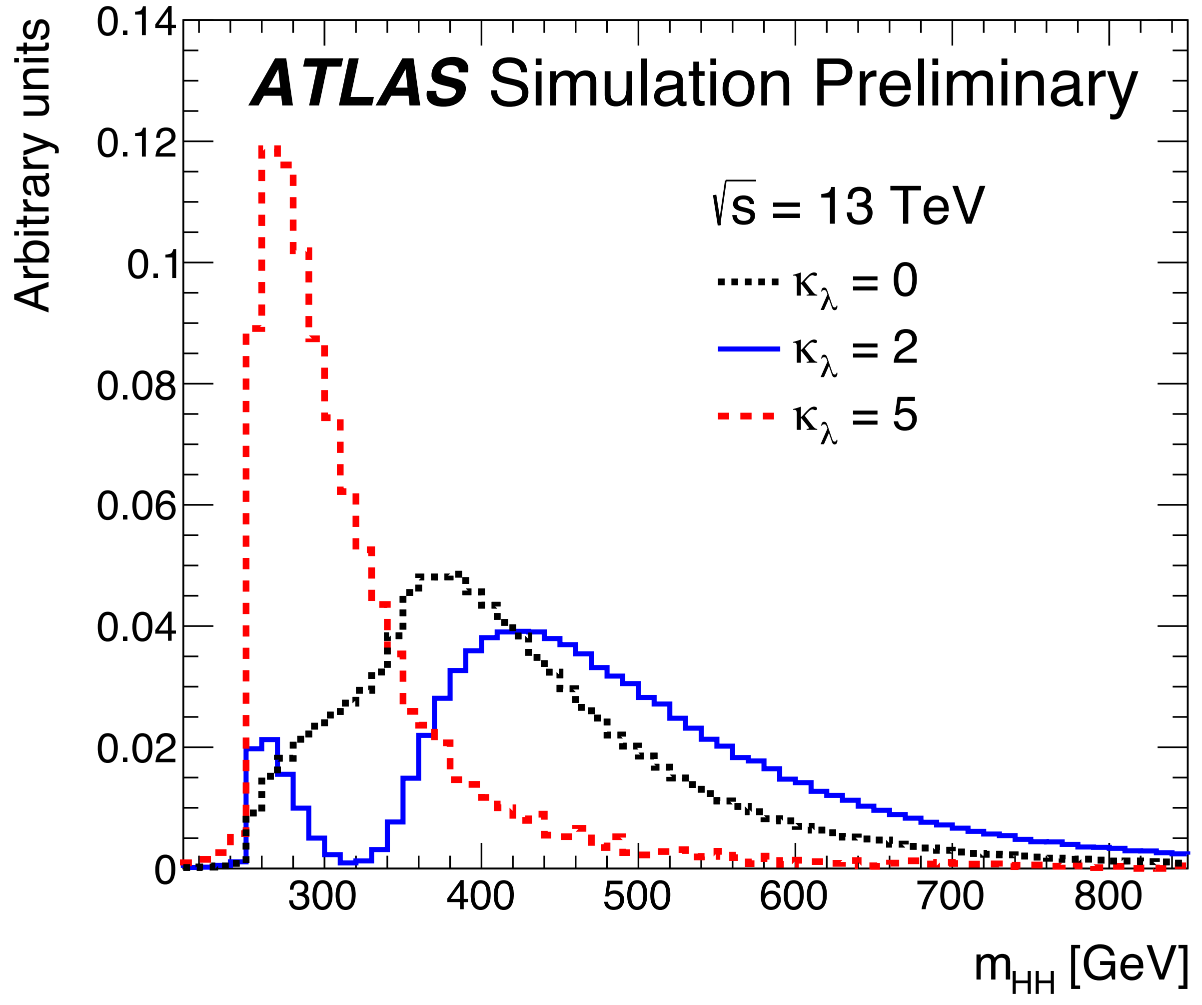


How are Higgs pairs produced?

- **gluon-gluon Fusion (ggF):** $\sigma_{HH}^{ggF} = 31.02$ fb

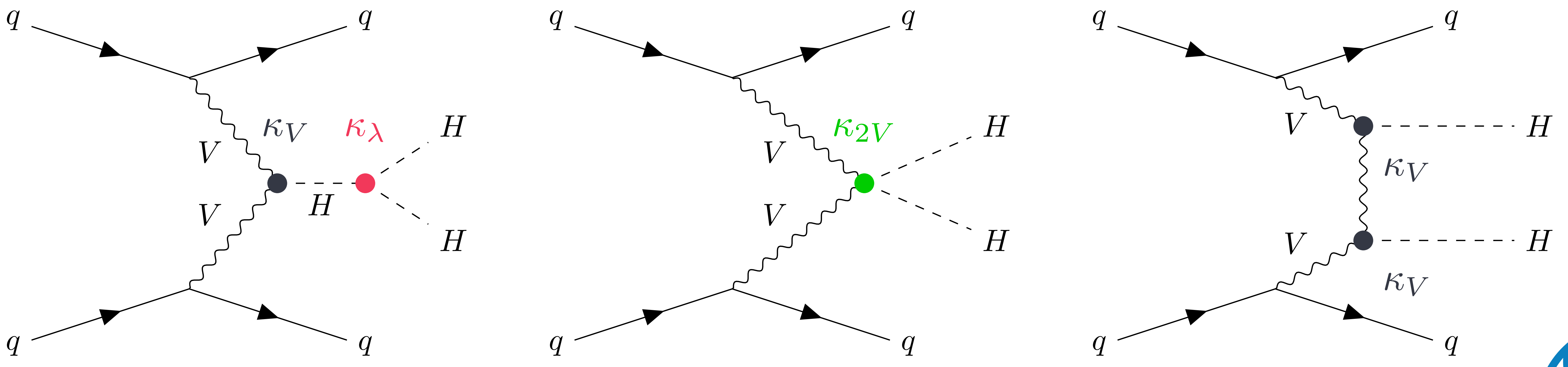


- Destructive interference between triangle and box diagrams makes the cross-section tiny (1000x smaller than single Higgs).
- Low m_{HH}: essential to constrain trilinear coupling κ_λ
- m_{HH} shape very dependent on the κ_λ



- **Vector Boson Fusion (VBF):** $\sigma_{HH}^{VBF} = 1.72$ fb

  - Second-order contribution to total production.
  - Direct handle to vector boson coupling modifiers κ_{2V} and κ_V.



How to look for Higgs pairs?

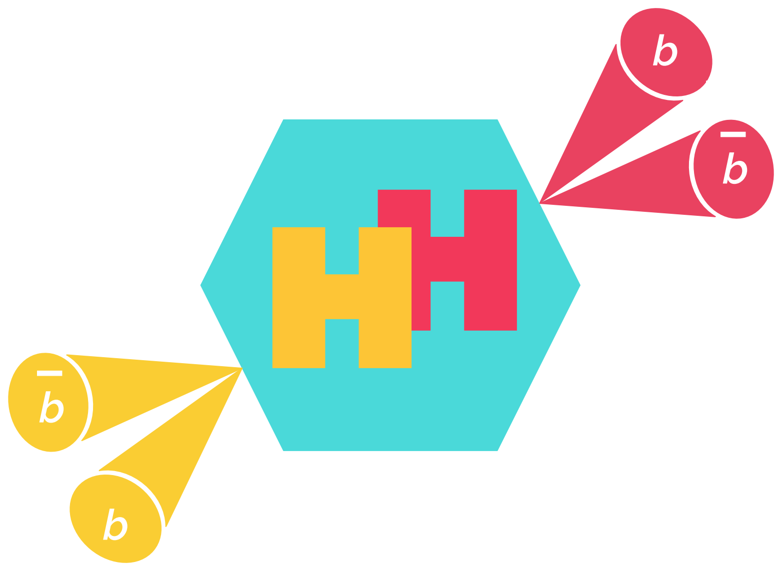
No clear *Golden channel*, but several promising signatures:

$BR(HH \rightarrow XXYY)$

	bb	WW	gg	ττ	cc	ZZ	γγ	Zγ	μμ
bb	33%								
WW	25%	4.6%							
gg									
ττ	7.4%								
cc									
ZZ	3.1%								
γγ	0.26%	0.1%							
Zγ									
μμ									

☐ = results from ATLAS

Combining the results is necessary **for observation**.

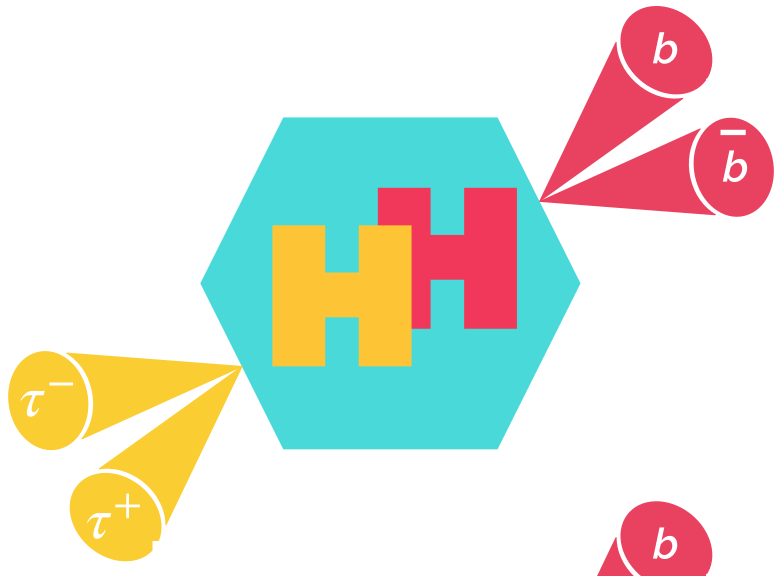


$HH \rightarrow b\bar{b}b\bar{b}$

- $H \rightarrow b\bar{b}$: High BR
- Large hadronic background

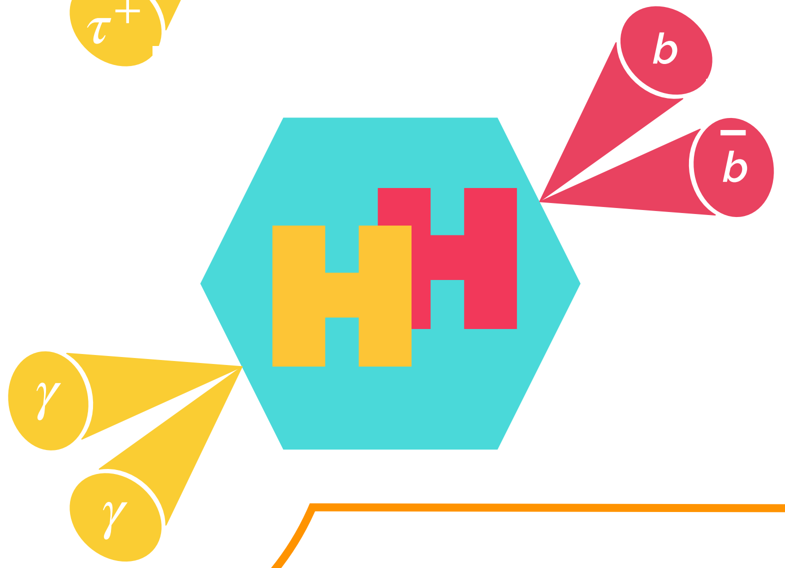
ggF: $\mathscr{L} = 36\text{fb}^{-1}$ JHEP 01 (2019) 030

VBF: $\mathscr{L} = 126\text{fb}^{-1}$ JHEP 07 (2020) 108



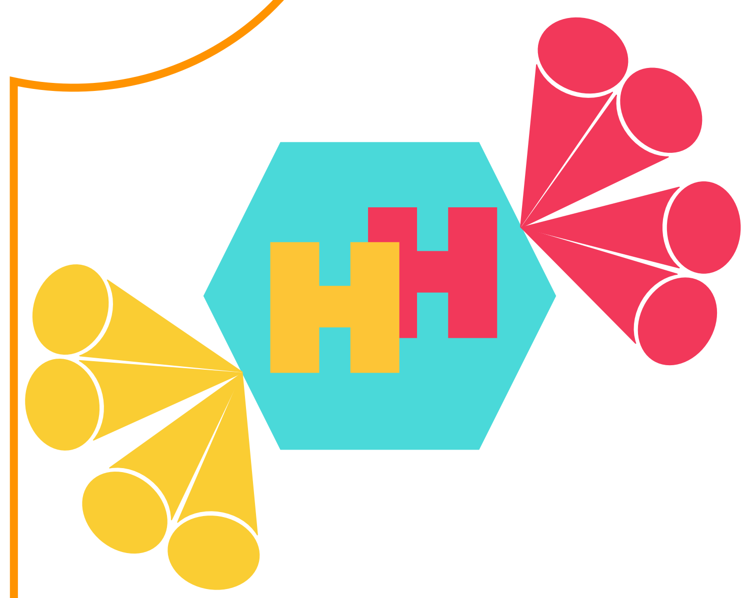
$HH \rightarrow b\bar{b}\tau^+\tau^-$ $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-030

- $H \rightarrow b\bar{b}$: High BR
- $H \rightarrow \tau^+\tau^-$: Low background



$HH \rightarrow b\bar{b}\gamma\gamma$ $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-016

- $H \rightarrow b\bar{b}$: High BR
- $H \rightarrow \gamma\gamma$: Good mass resolution



$HH \rightarrow W^+W^- + XX$ / $HH \rightarrow b\bar{b}ZZ$ **Not shown today**

- Decent BR from $H \rightarrow VV$
- Complex final signatures due to the decay of Vs

$b\bar{b}l\nu l\nu$: $\mathscr{L} = 139\text{fb}^{-1}$ Phys. Lett. B 801 (2020) 135145

$\gamma\gamma WW^*$: $\mathscr{L} = 36\text{fb}^{-1}$ Eur. Phys. J. C 78 (2018) 1007

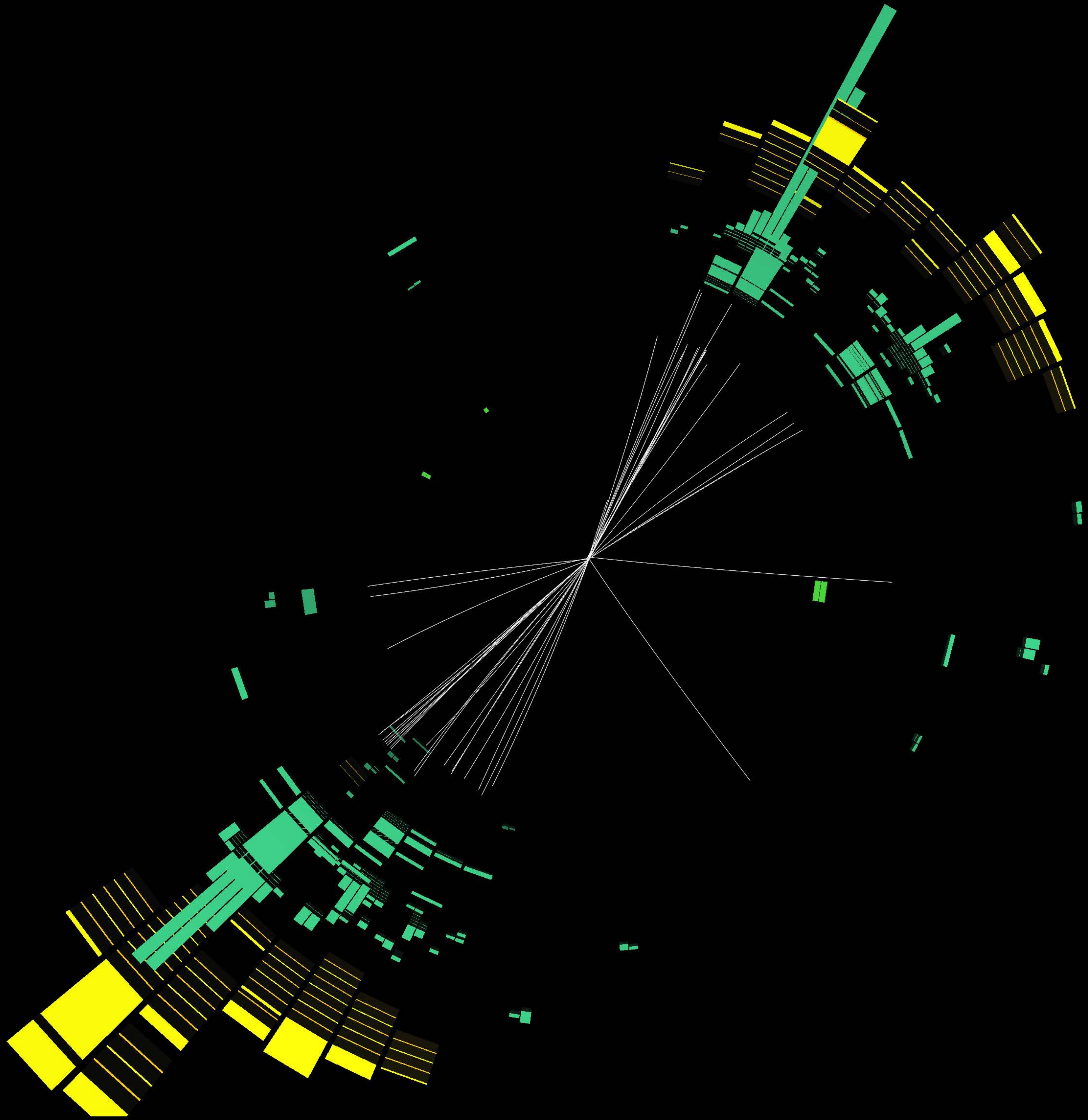
$b\bar{b}l\nu q\bar{q}$: $\mathscr{L} = 36\text{fb}^{-1}$ JHEP 04 (2019) 092

WW^*WW^*: $\mathscr{L} = 36\text{fb}^{-1}$ JHEP 05 (2019) 124

ATLAS EXPERIMENT

Run: 356259
Event: 311347503
2018-07-22 20:00:32 CEST

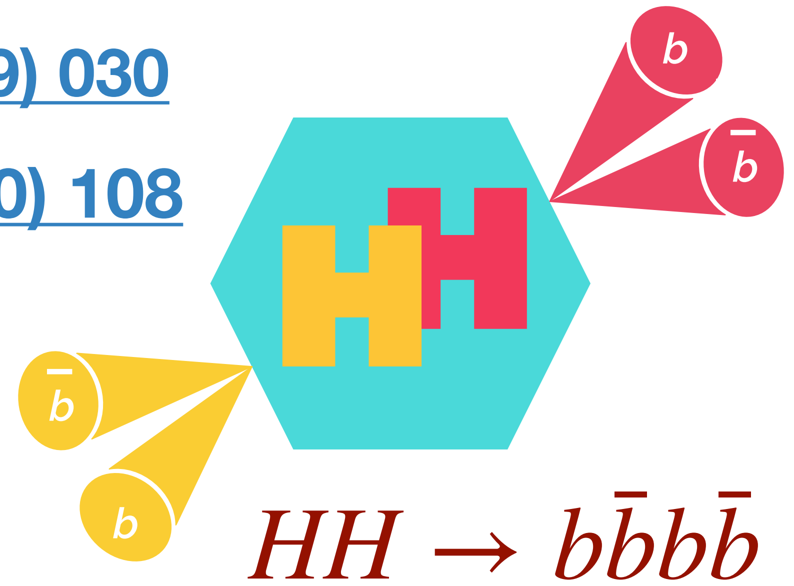
$HH \rightarrow b\bar{b}b\bar{b}$



Strategy

ggF: $\mathscr{L} = 36\text{fb}^{-1}$ JHEP 01 (2019) 030

VBF: $\mathscr{L} = 126\text{fb}^{-1}$ JHEP 07 (2020) 108



$HH \rightarrow b\bar{b}b\bar{b}$

Two dedicated analyses **ggF** / **VBF** were made with similar strategies, on different datasets.

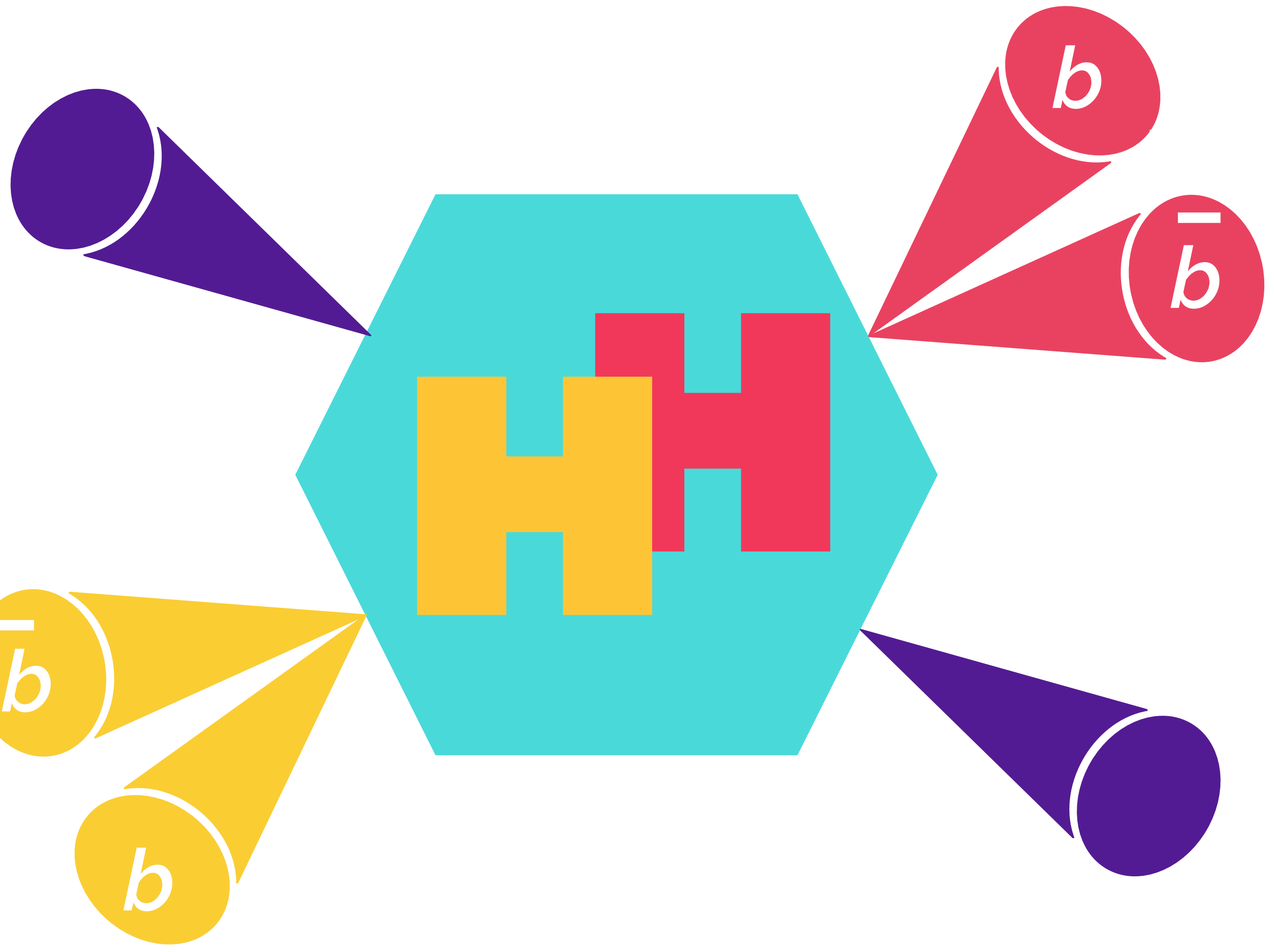
Fit:
using the *HH invariant mass*

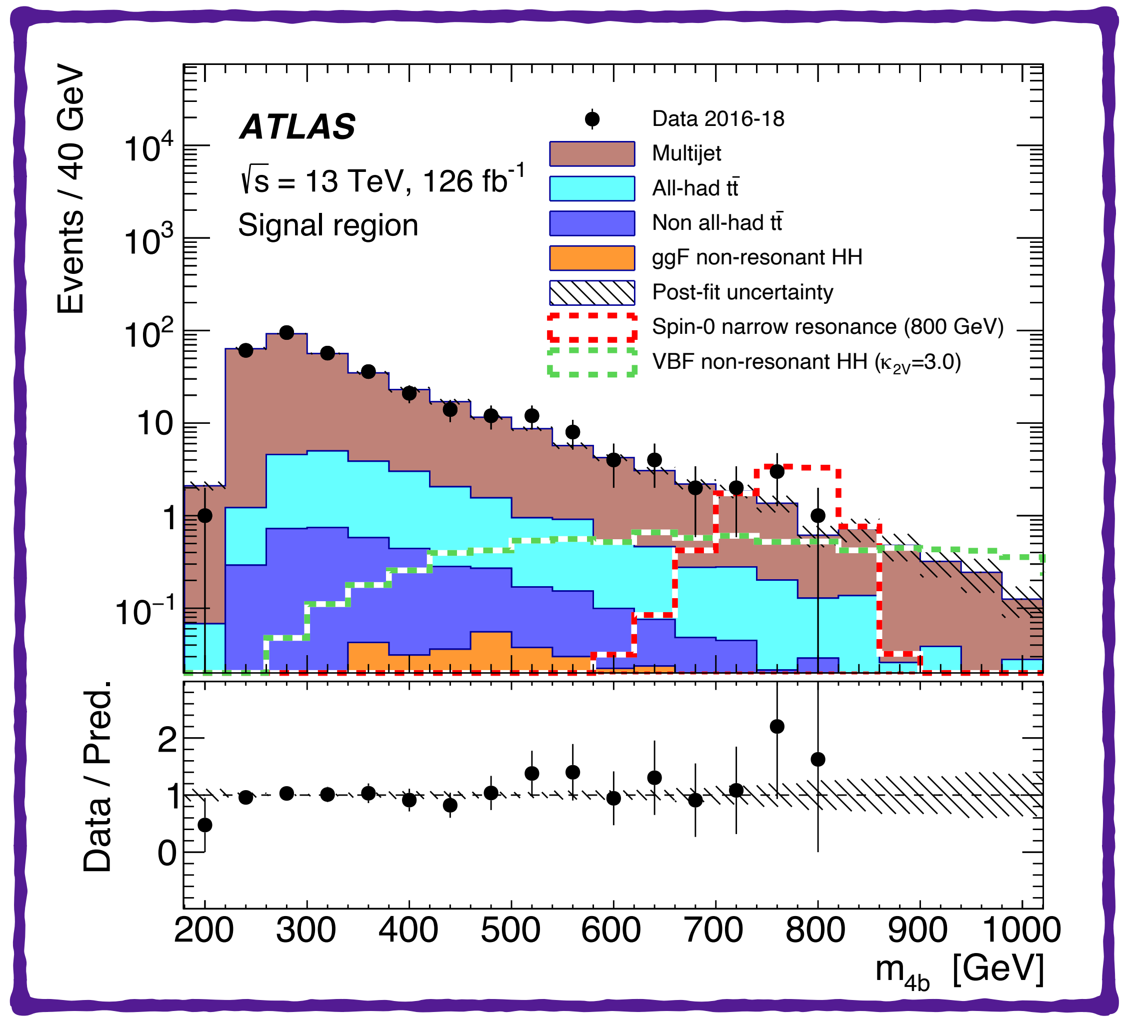
Central jets:

- At least 4 central b-tagged jets.

Only for VBF analysis:

- At least 2 forward jets with opposite η sign.

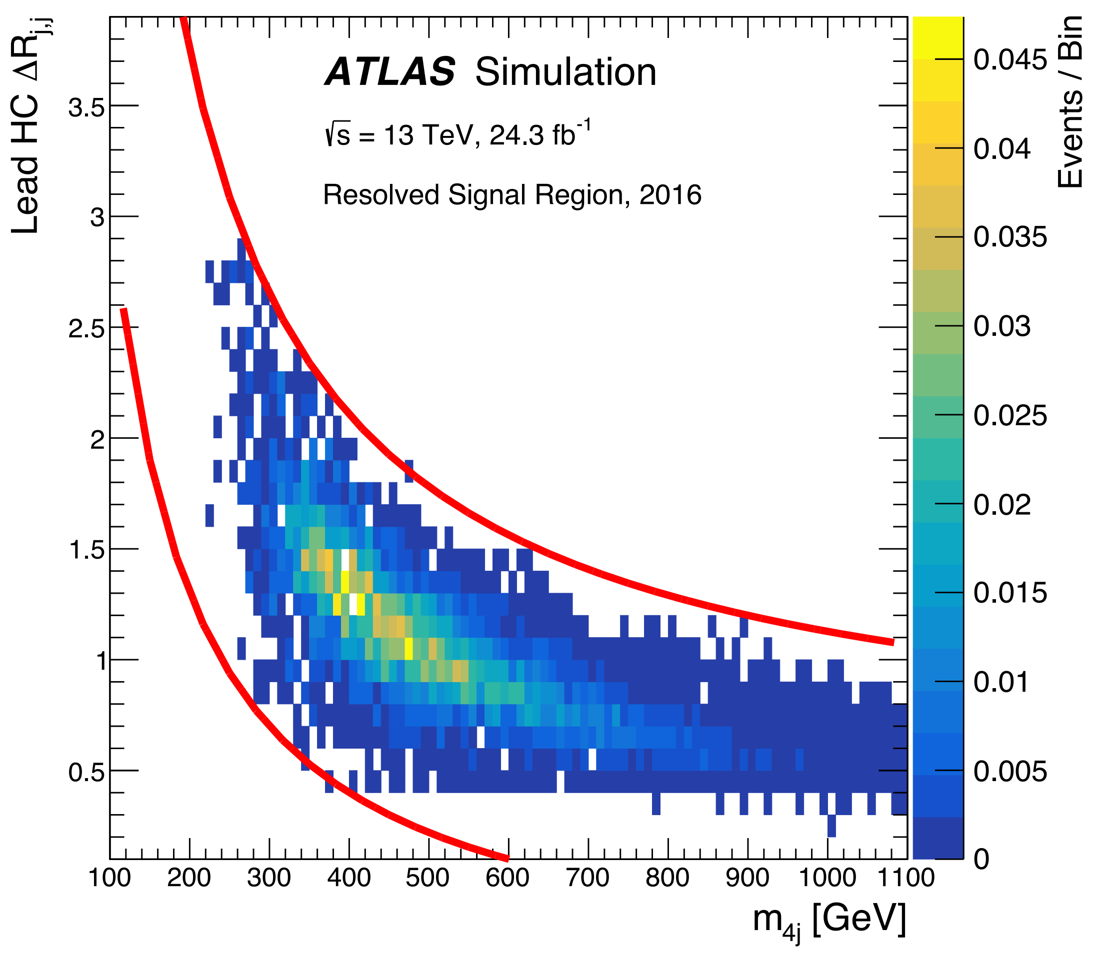




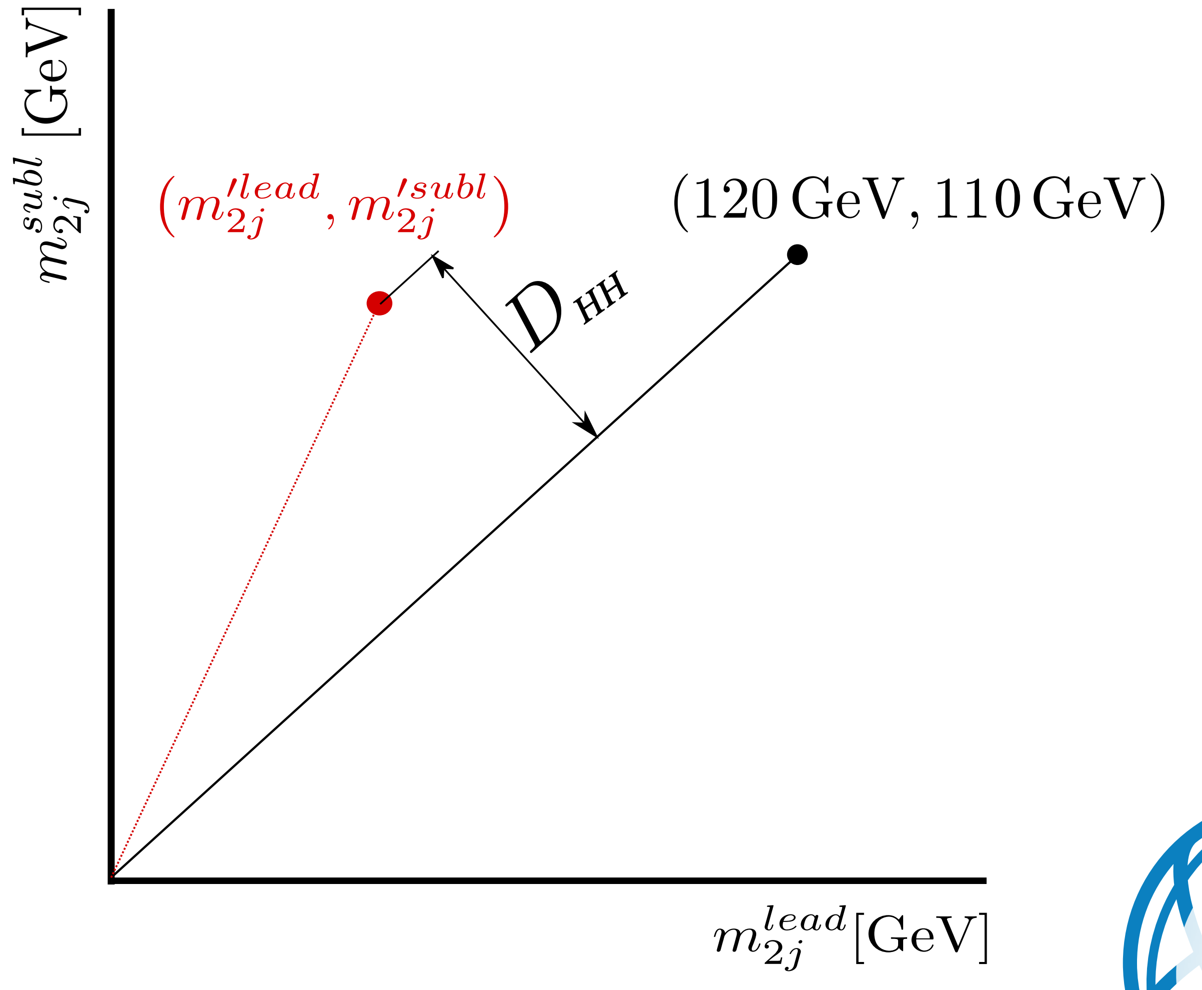
*Example from **VBF***

Pairing Jets

1. Angular distance between jets in each Higgs candidate $|\Delta R_{jj}|$ is compared to the 4 body invariant mass m_{4j}



2.
- Both reconstructed masses are expected to be similar;
- Distance to expected median is minimised.



Results

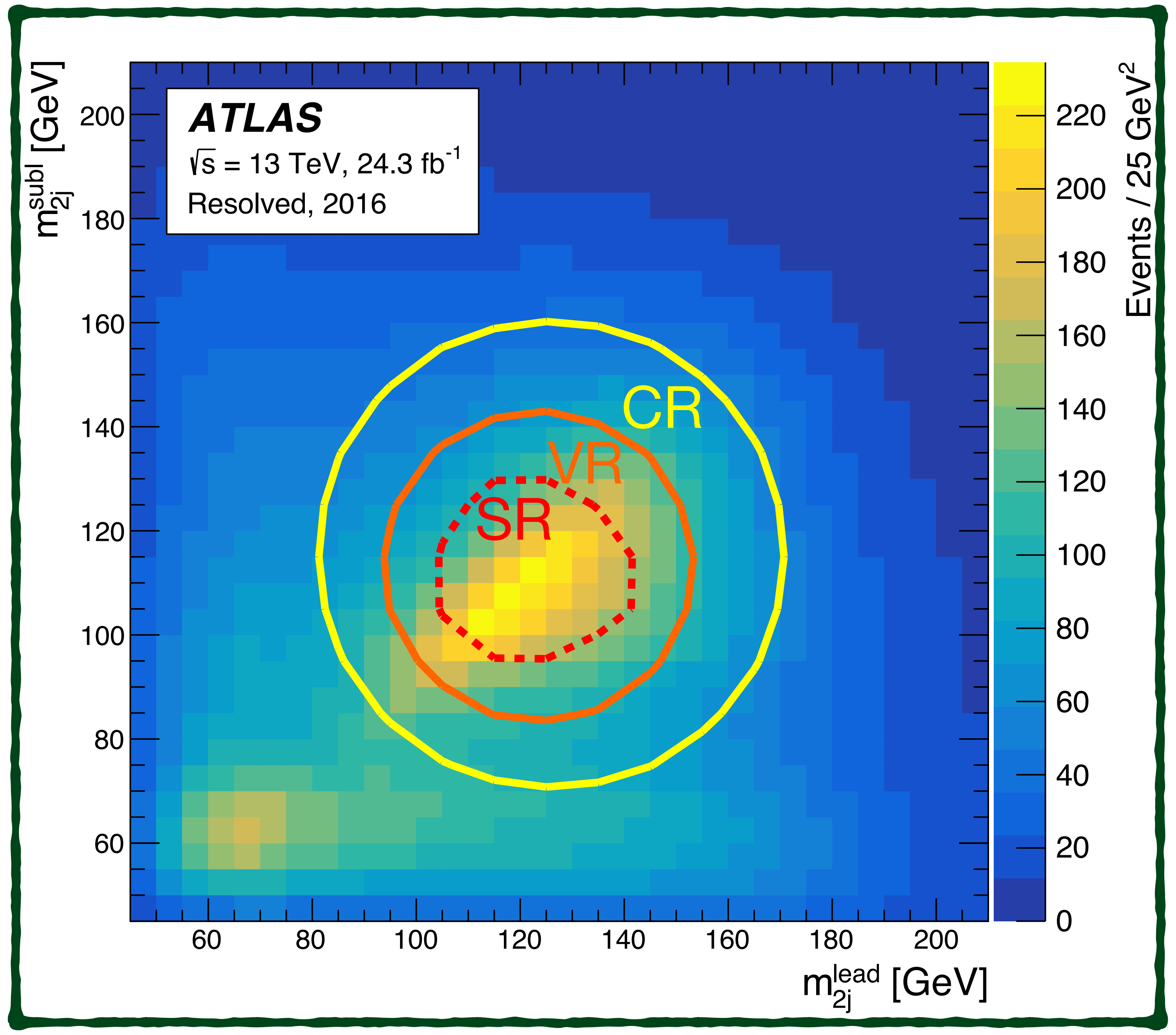
ggF: $\mathscr{L} = 36\text{fb}^{-1}$ JHEP 01 (2019) 030

VBF: $\mathscr{L} = 126\text{fb}^{-1}$ JHEP 07 (2020) 108

$HH \rightarrow b\bar{b}b\bar{b}$

Backgrounds modelling:
Similar between the two analyses

- multi-jets:
  - The shape is obtained by **reweighting data** in the 2 b-tagged SR: correcting jet activity and b-tagging efficiency;
  - Dedicated Signal, Validation, and Control Regions based on the Higgs bosons masses.
- $t\bar{t}$: **Rejected** by specific variable measuring consistency of jet originating from top quark.



*Example from **ggF***

Results:

ggF analysis, Partial Run-2

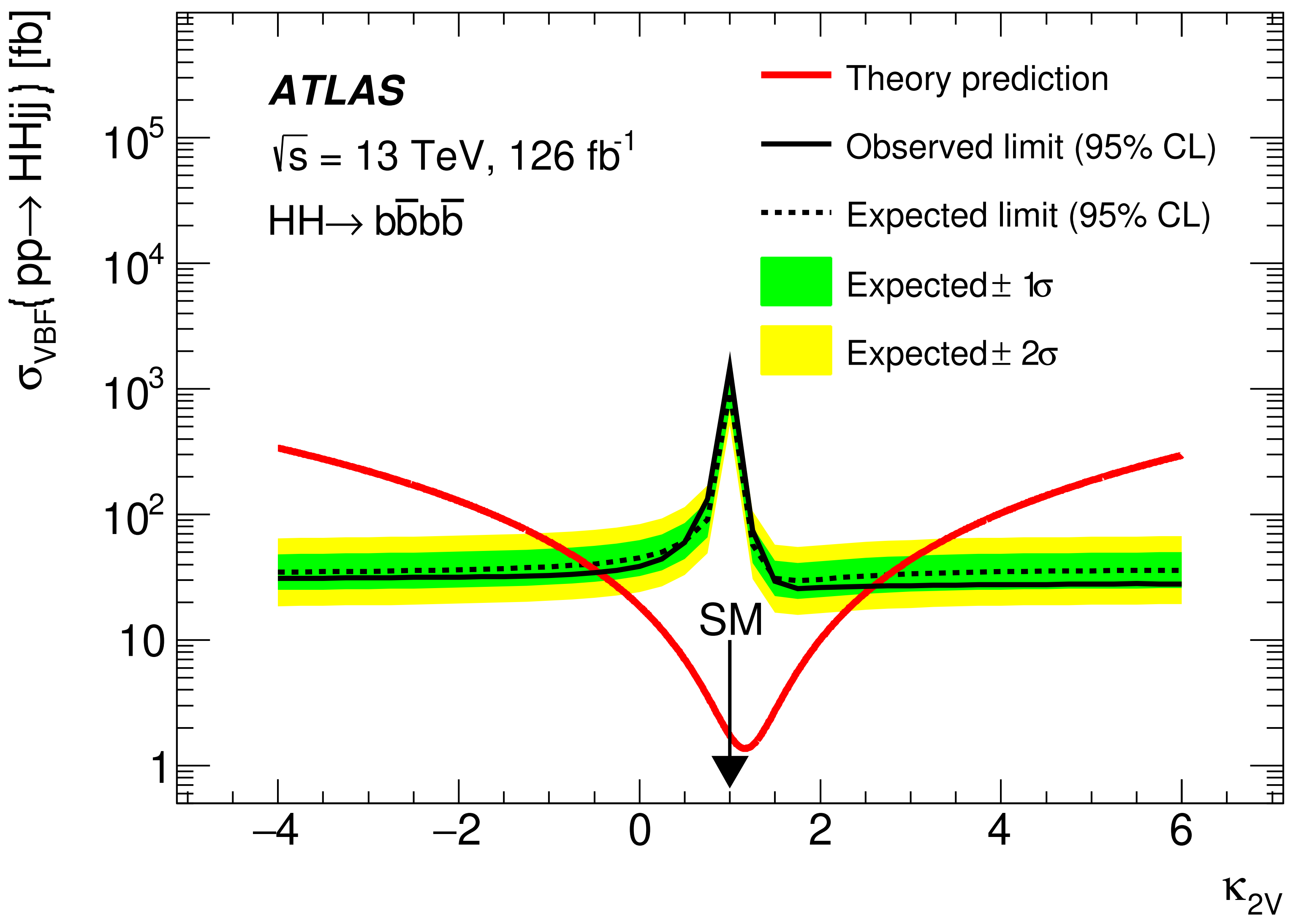
$\sigma_{HH}^{ggF} \times BR(HH \rightarrow b\bar{b}b\bar{b})$ **observed (expected)** limit is **12.9 (14.8)** x SM prediction.

σ_{HH}^{VBF} **observed (expected)** limit is **840 (550)** x SM prediction.

Limits are set on κ_{2V}:

$-0.4 < \kappa_{2V} < 2.6$ (observed),

$-0.6 < \kappa_{2V} < 2.7$ (expected).

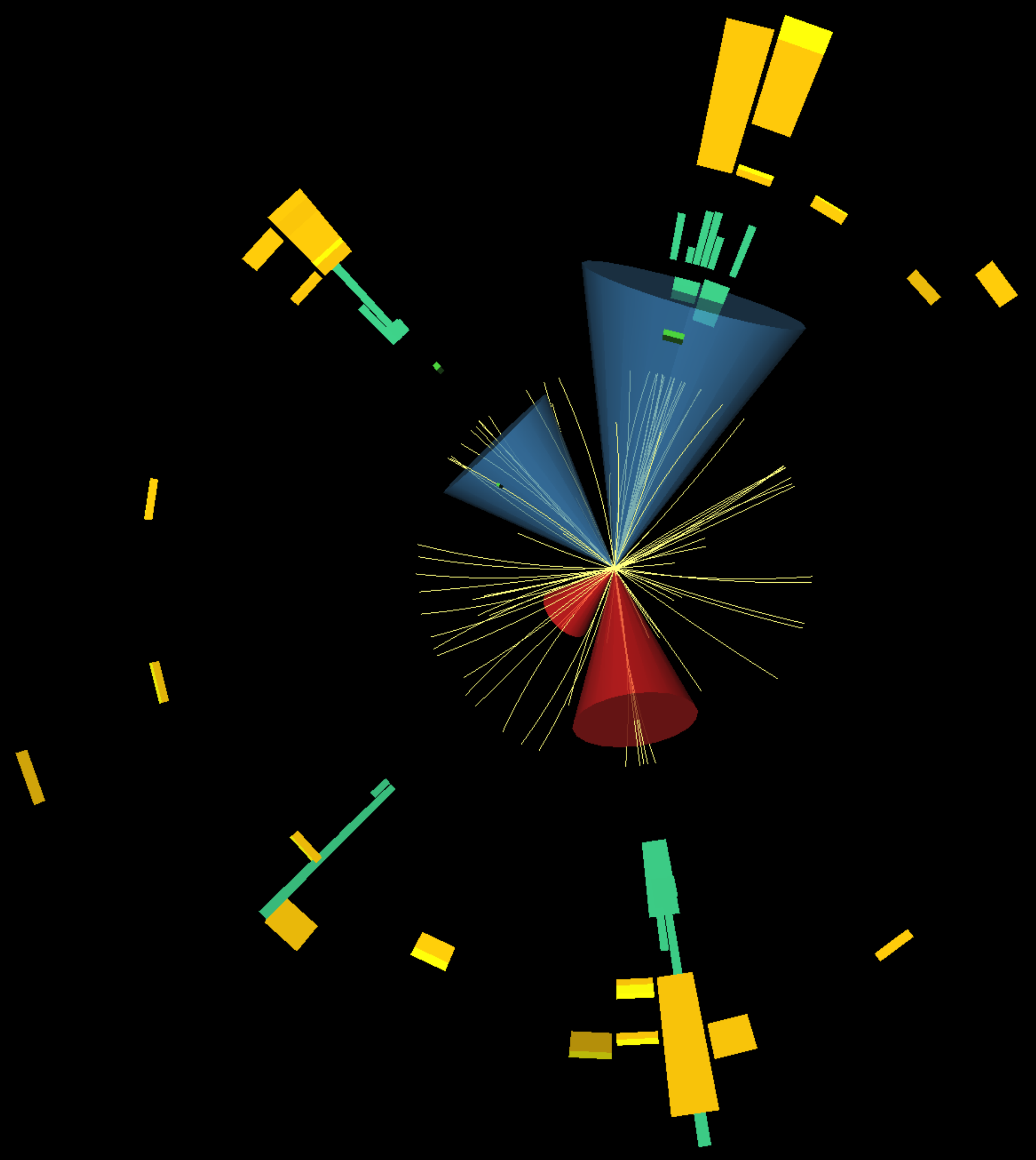


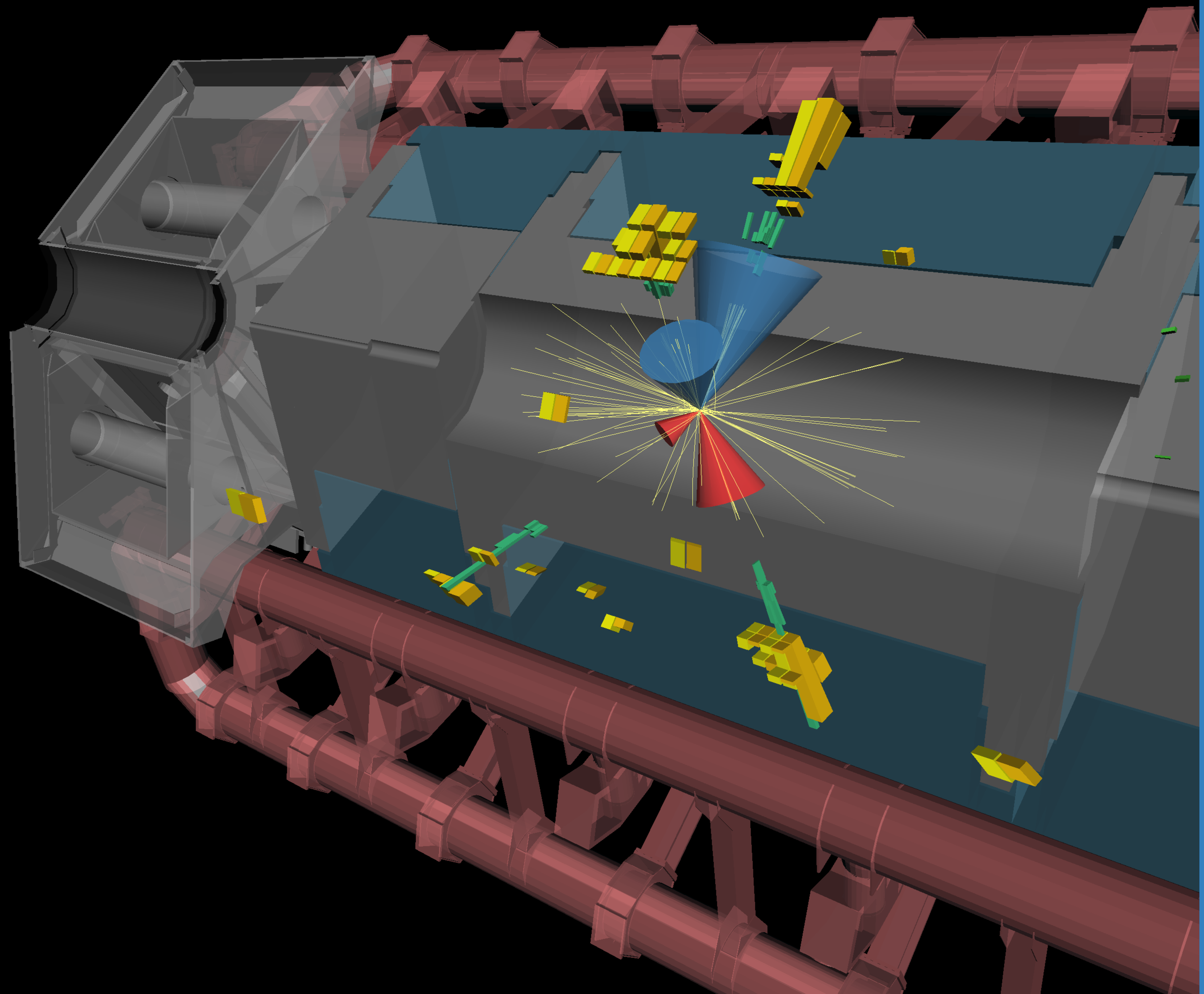
VBF analysis, Full Run-2

ATLAS EXPERIMENT

$HH \to b\bar{b}\tau^+\tau^-$

Run: 339535
Event: 996385095
2017-10-31 00:02:20 CEST





Strategy

ATLAS-CONF-2021-030

$HH \rightarrow b\bar{b}\tau^+\tau^-$

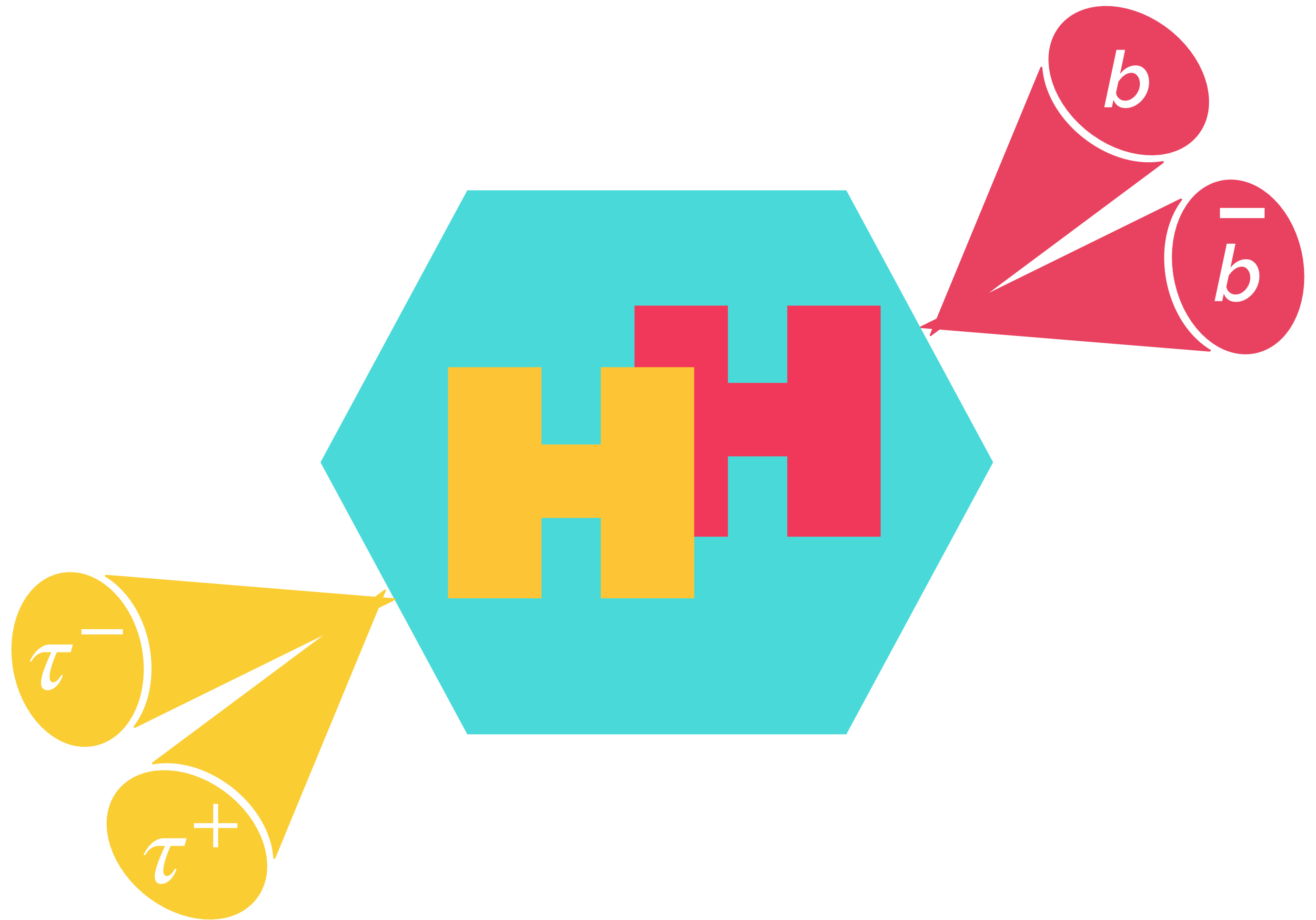
The analysis is built on the final state of the τ decay:

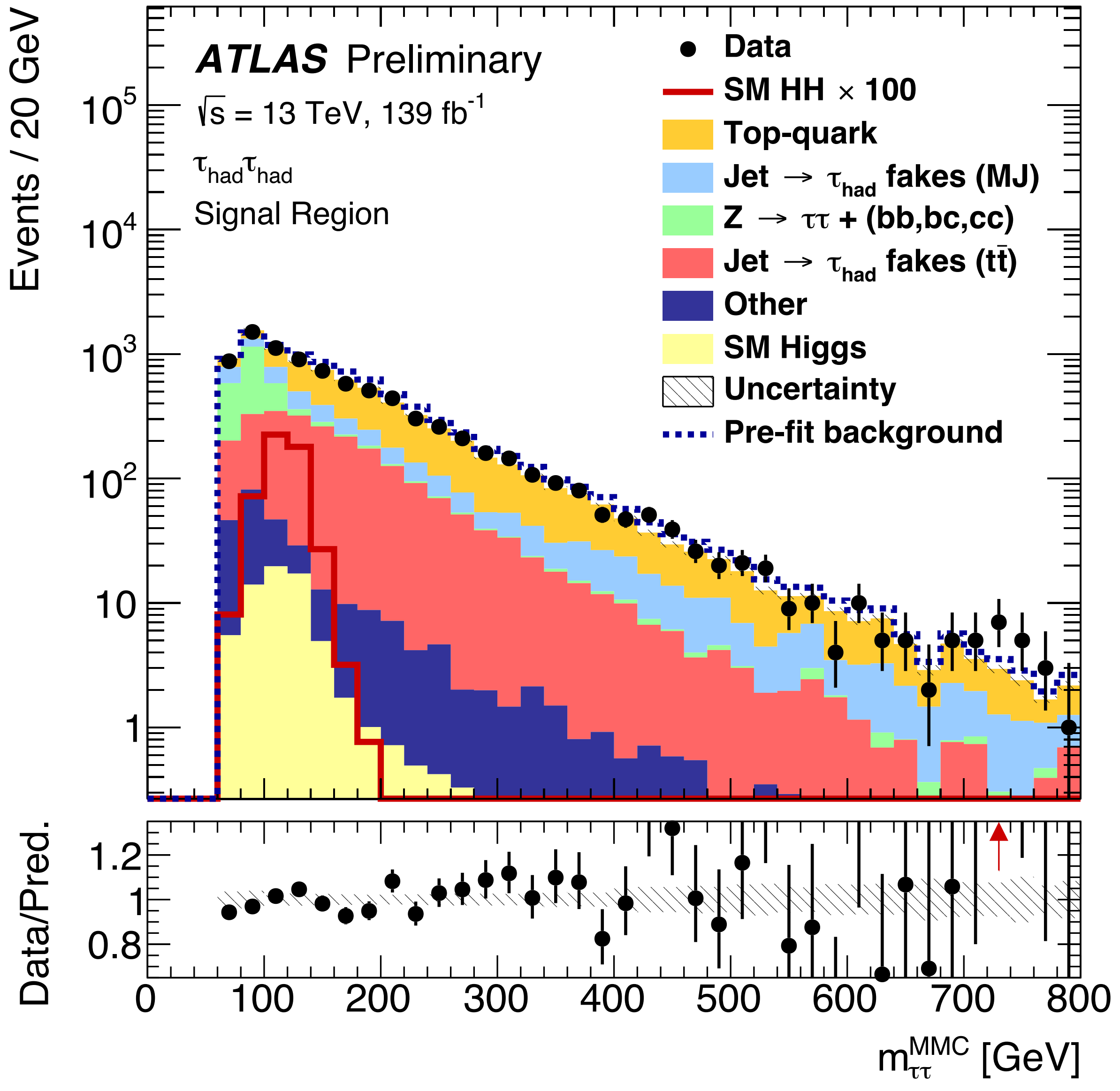
At least one τ_{had} is requested:

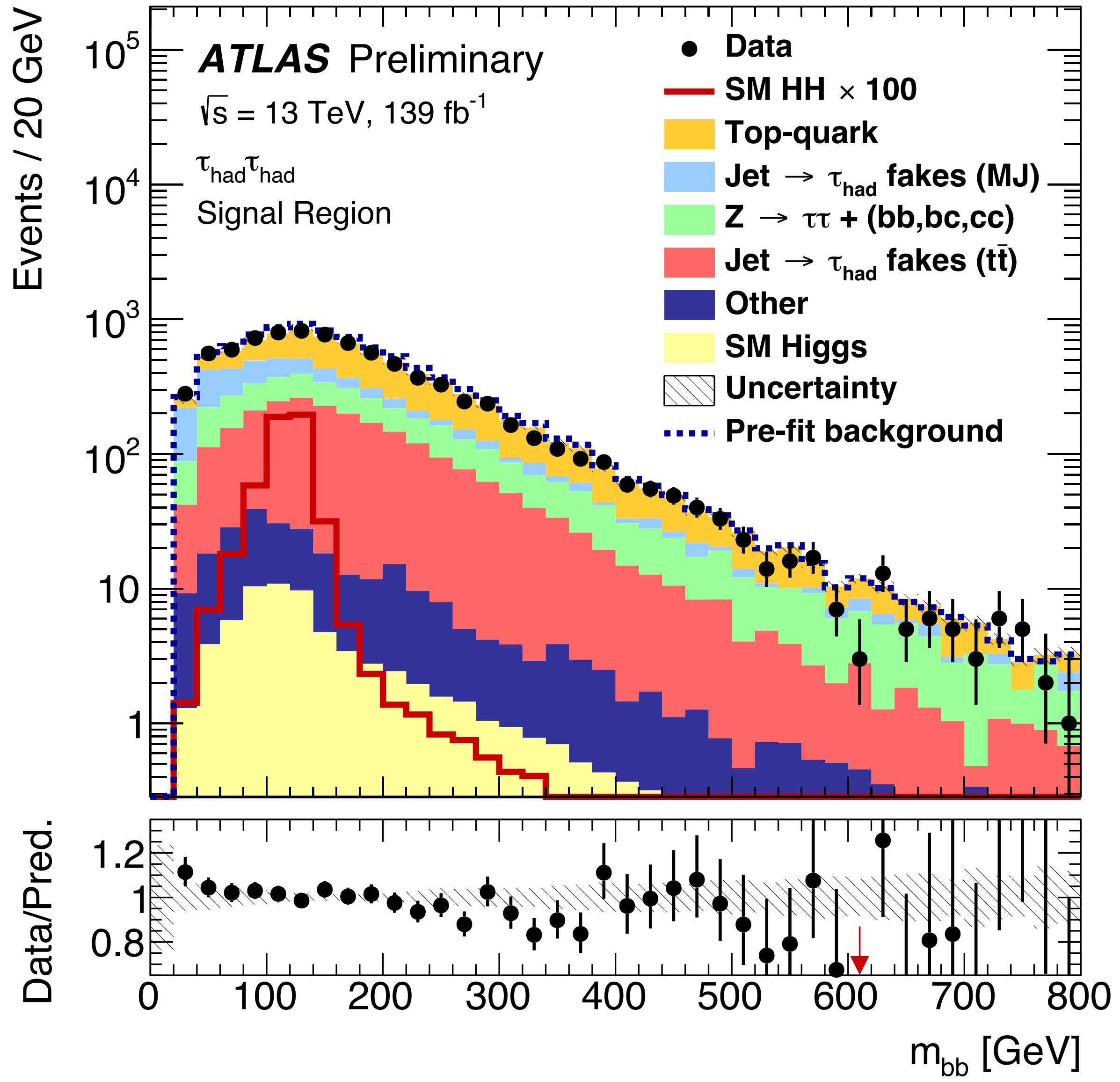
- $\tau_{lep}\tau_{had}$: exactly 1 lepton + 1 hadronic τ;
- $\tau_{had}\tau_{had}$: exactly two hadronic τs.

A Missing Mass Calculator is used to estimate the di-tau invariant mass.

Exactly 2 b-jets

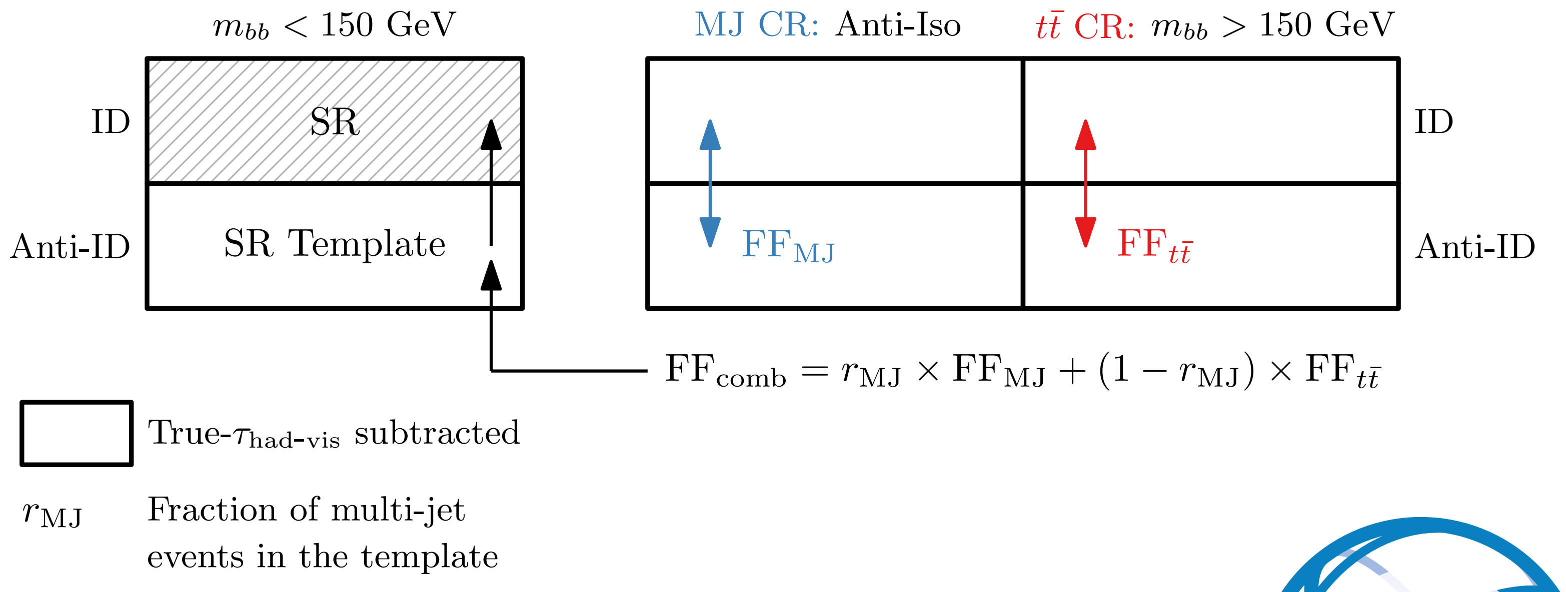






Backgrounds modelling:

$t\bar{t}$ and multi-jets can lead to fake τ_{had} reconstruction. Dedicated control regions, scale and transfer factors are designed to provide MC and data-driven estimates.



Example for $\tau_{lep}\tau_{had}$ category

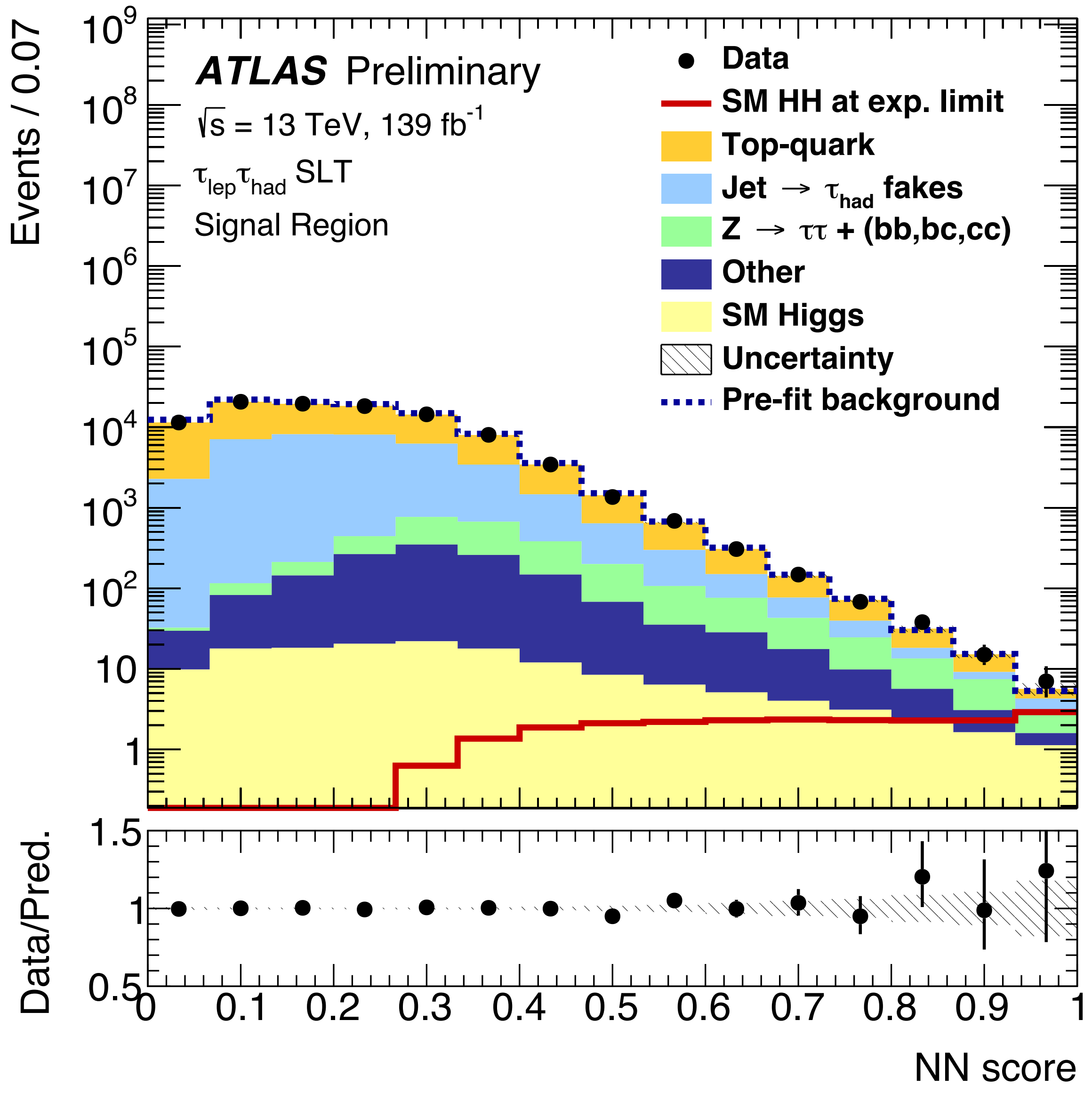
Results

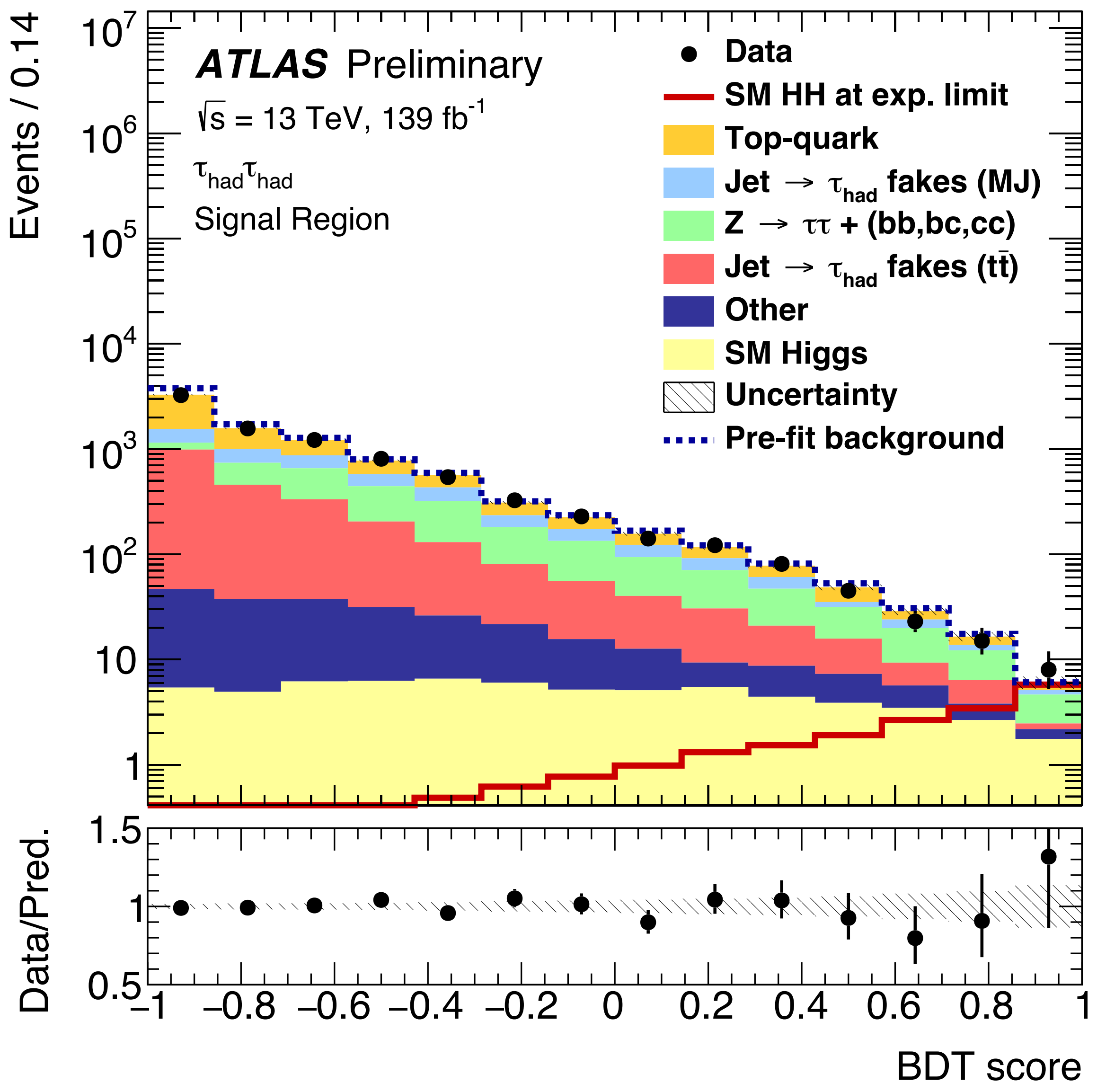
ATLAS-CONF-2021-030

$HH \to b\bar{b}\tau^+\tau^-$

Fit: based on a **MVA distribution** trained in 3 SRs:

- $\tau_{\text{lep}}\tau_{\text{had}}$: Single Lepton Trigger (SLT), Lepton + Tau Trigger (LTT)
  Neural Network;
- $\tau_{\text{had}}\tau_{\text{had}}$: Single/Di Tau Triggers
  BDT.





Dedicated $Z \to \tau\tau$ Control Region for Z+hf and $t\bar{t}$ normalisation.

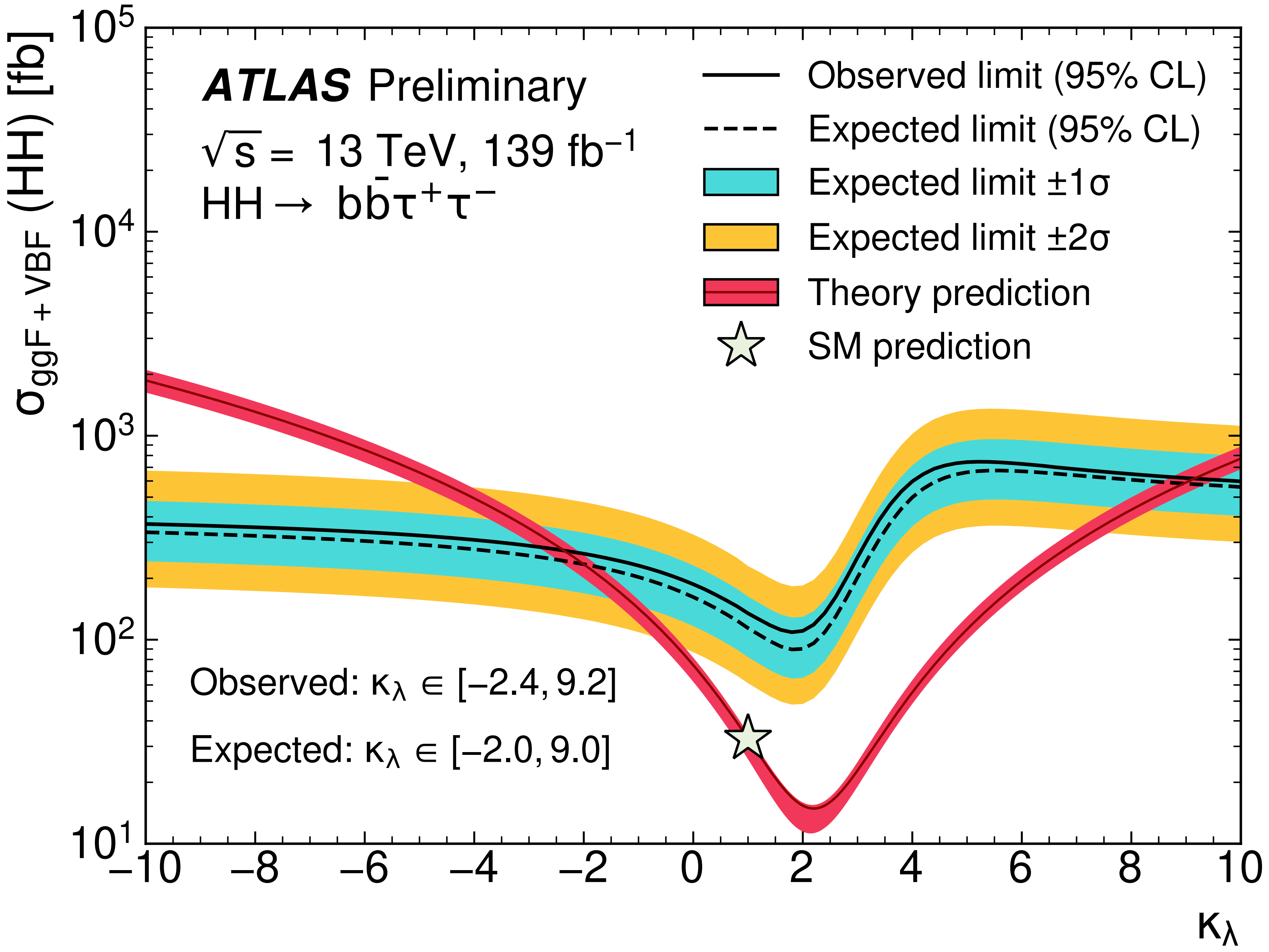
Results:

$\sigma_{HH}^{ggF+VBF}$ **observed (expected)** limit is **4.7 (3.9)** x SM prediction.

Limits are set on κ_λ:

$-2.4 < \kappa_\lambda < 9.2$ observed,

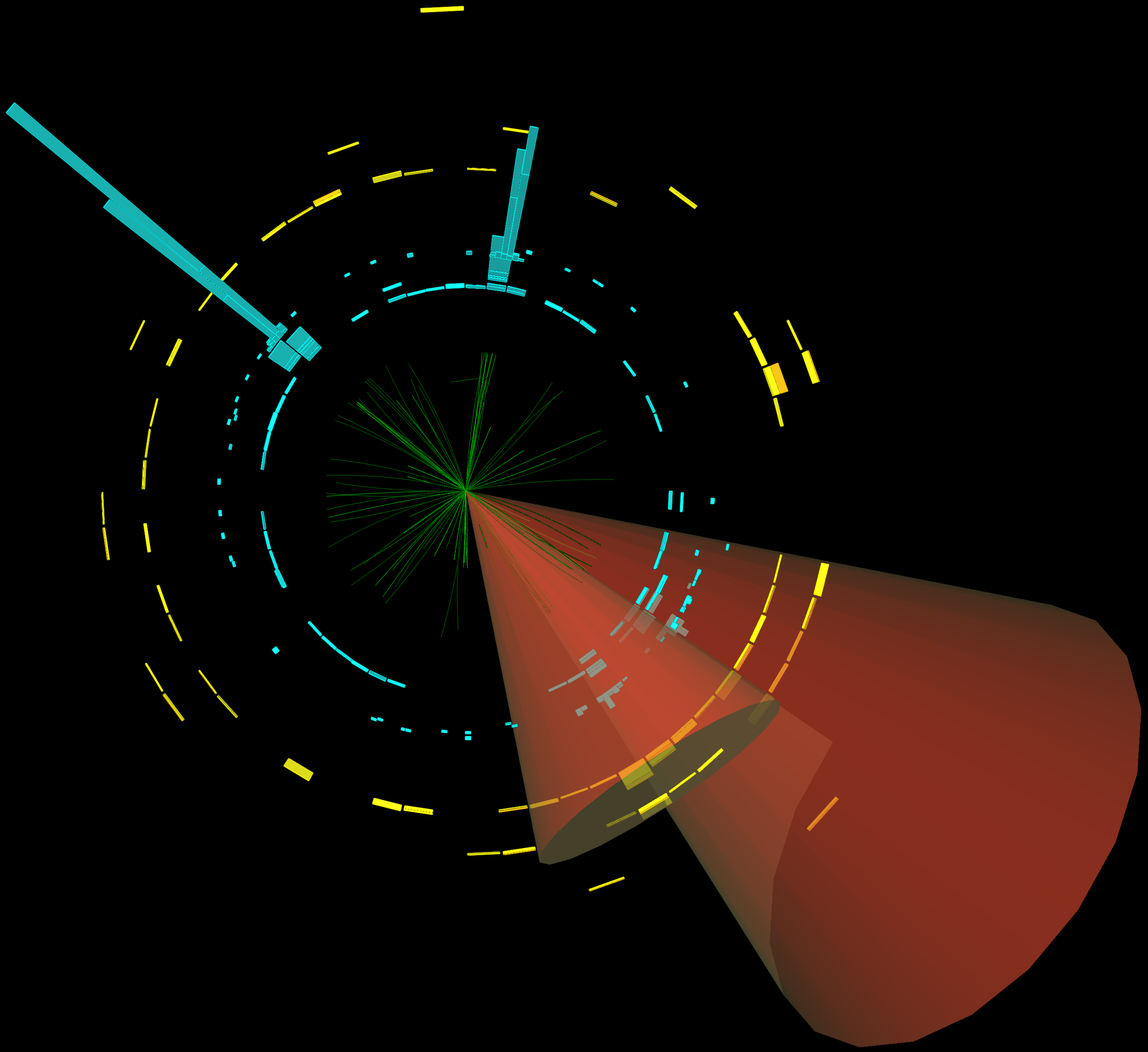
$-2.0 < \kappa_\lambda < 9.0$ expected.



ATLAS EXPERIMENT

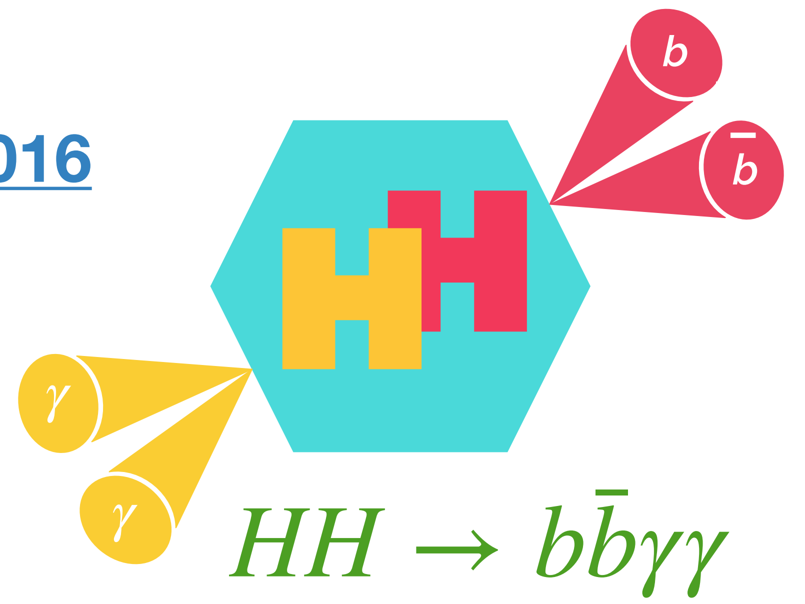
Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST

$HH \rightarrow b\bar{b}\gamma\gamma$



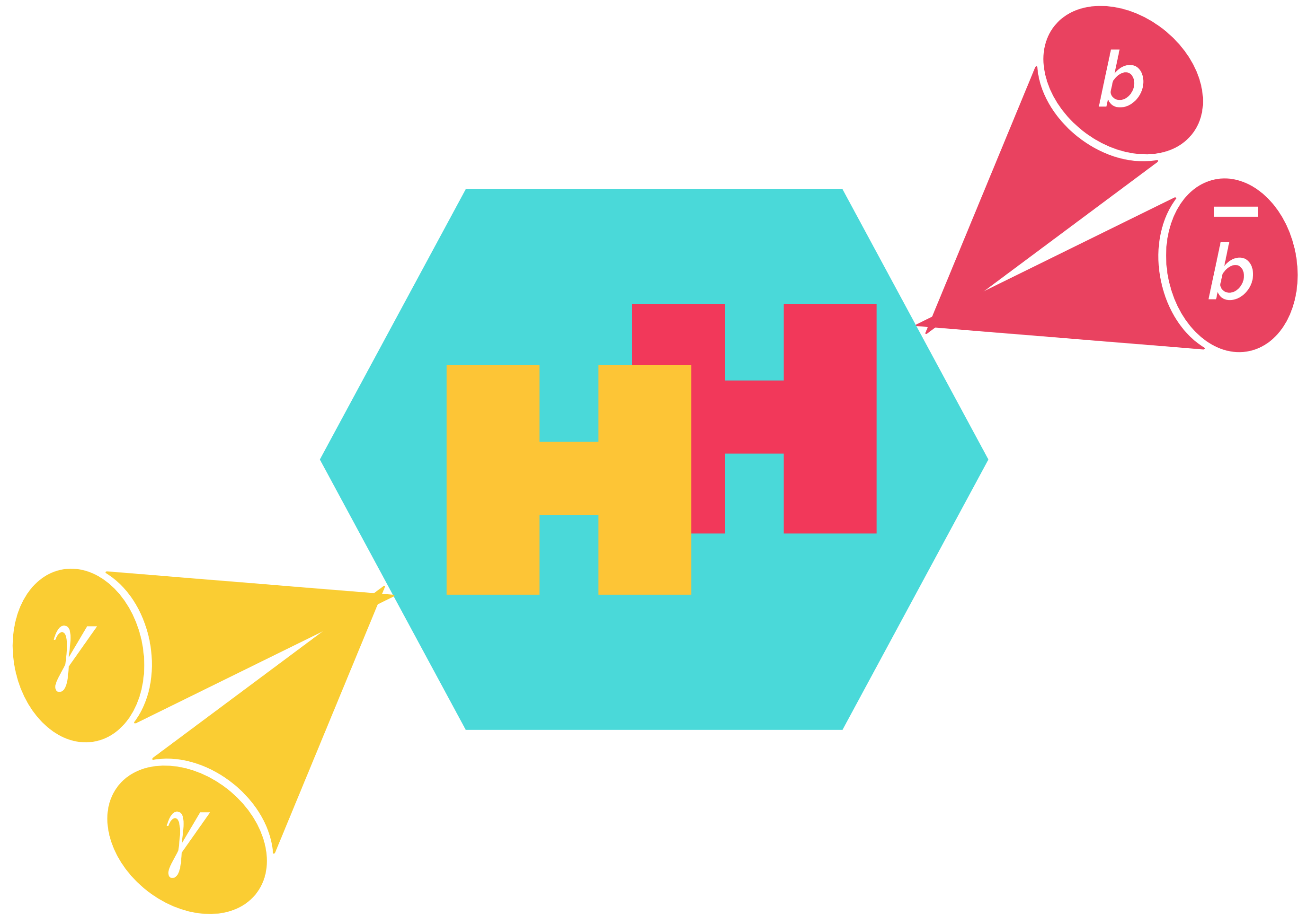
Strategy

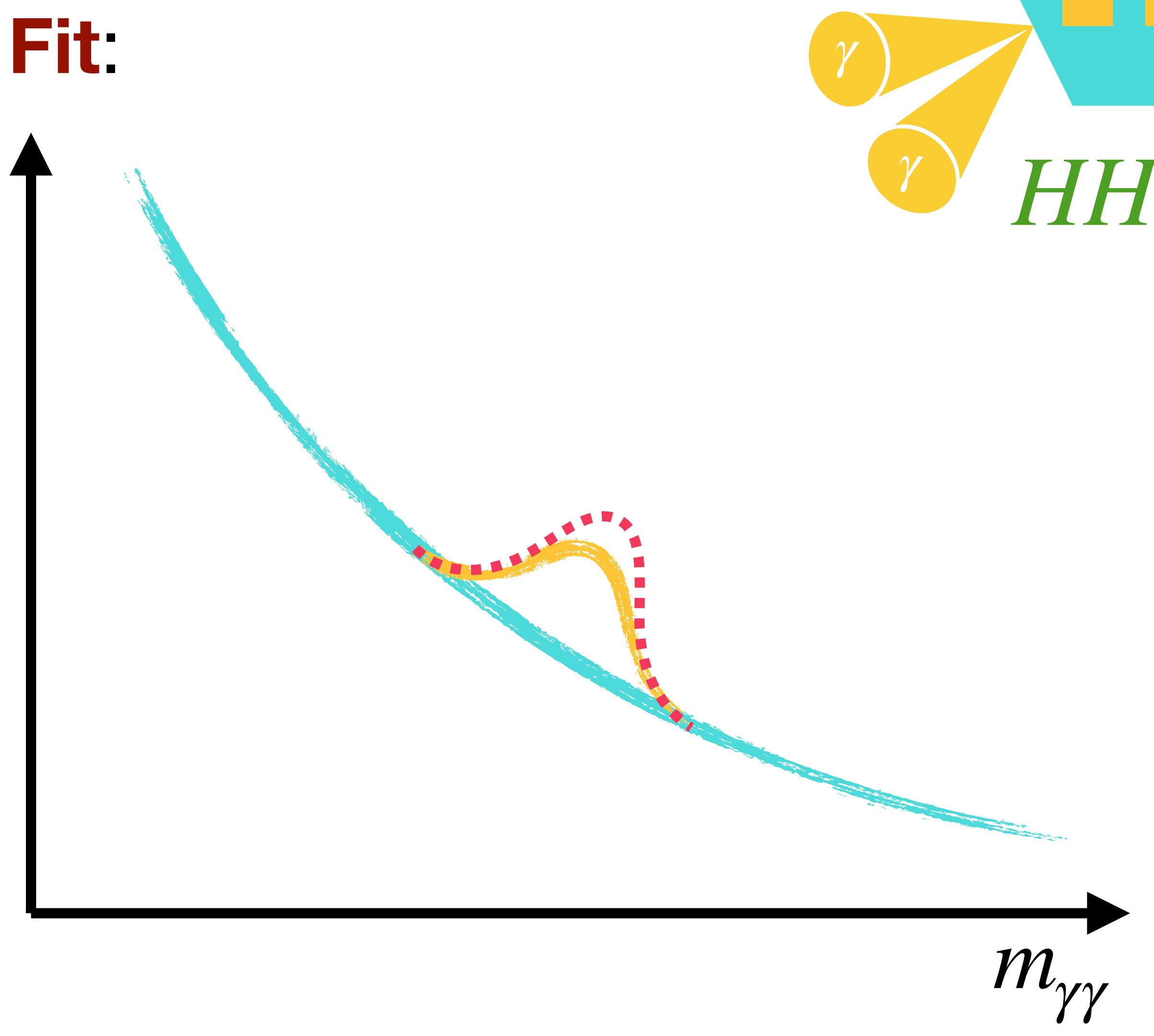
ATLAS-CONF-2021-016

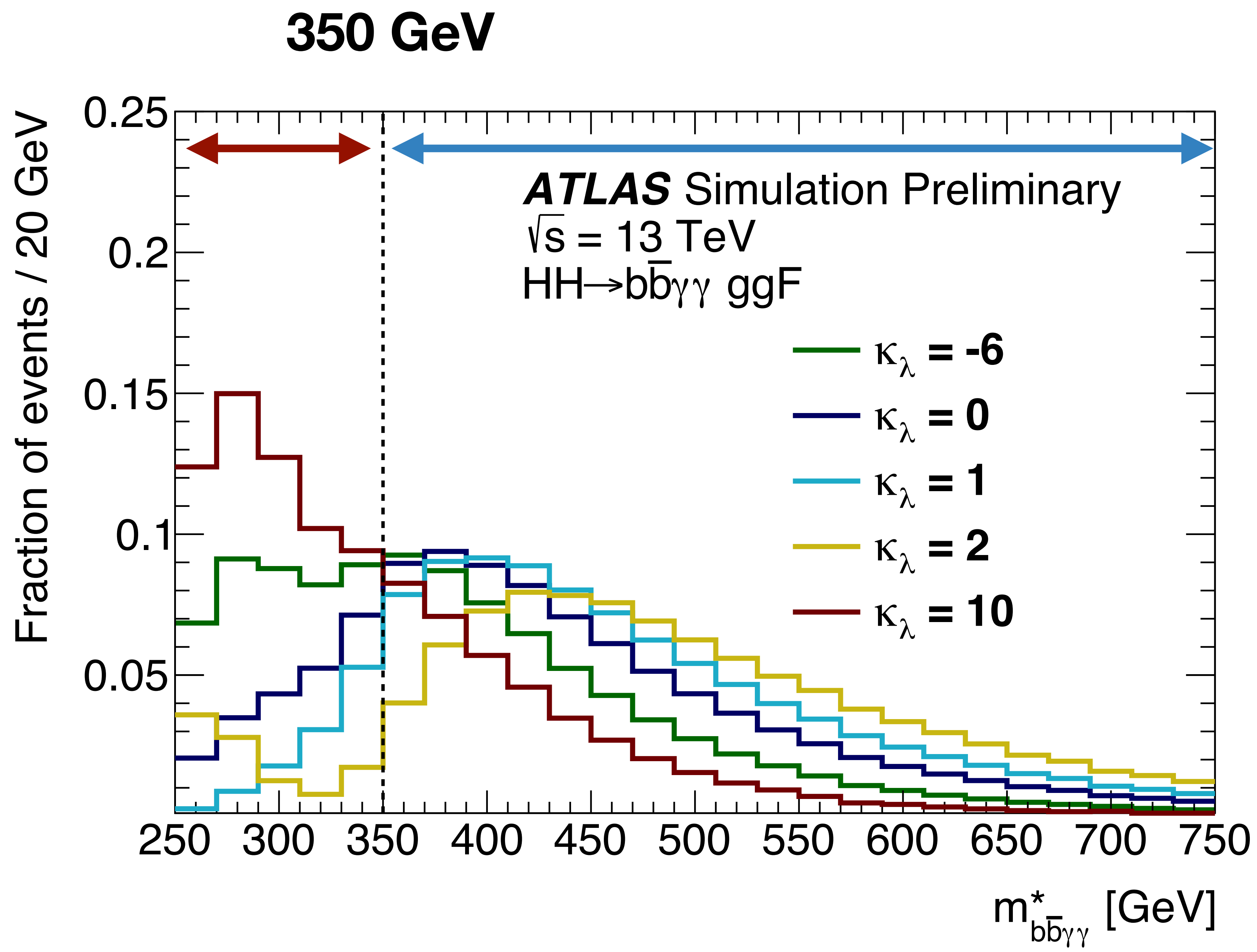


- Exactly 2 b-jets;
- < 6 central jets.

- Exactly 2 high-quality photons;
- No lepton.







The HH invariant mass is also sensitive to κ_λ.
Due to experimental resolution effects, a corrected version is used in the analysis:

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

A *BDT* is used to select signal-like events w.r.t di-photon + single Higgs.
Categories are created from $m^*_{b\bar{b}\gamma\gamma}$:

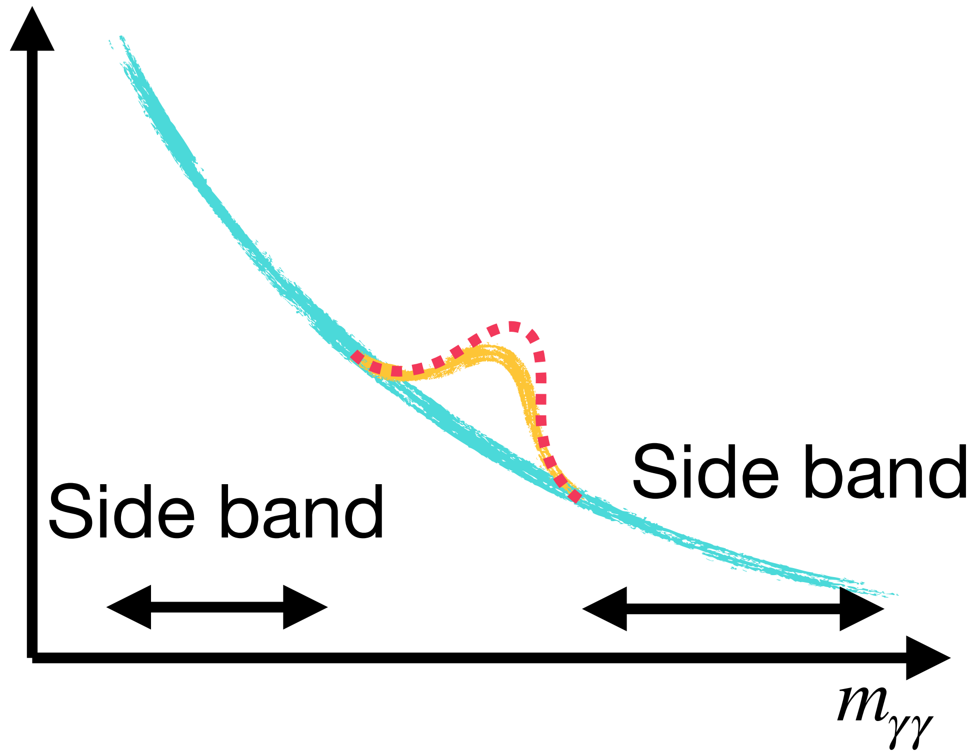
- Low mass, focused on BSM
  - $\kappa_\lambda = 10$ ggF HH used as signal;
- High mass, focused on SM
  - $\kappa_\lambda = 1$ ggF HH used as signal.

How to look for signal?

ATLAS-CONF-2021-016

Backgrounds modelling:

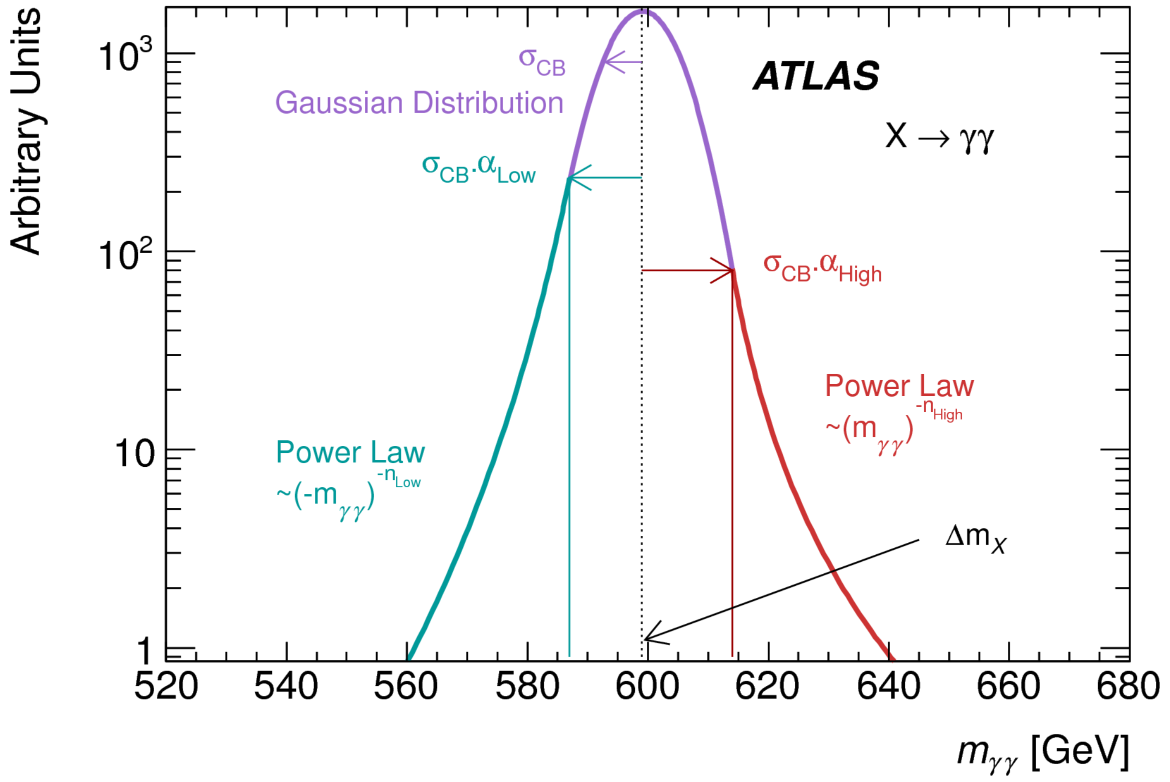
The background and signal processes are modelled thanks to functional forms used in the final fit:



Diphoton Background

- Several monotonic functions fitted to background template normalised to data sideband are tested;
- Minimisation of the signal bias.
- Final choice: **exponential**.

Single Higgs **HH signal**



- Single Higgs and HH (ggF and VBF) processes can be modelled with a **double-sided Crystal Ball** function.

Results:

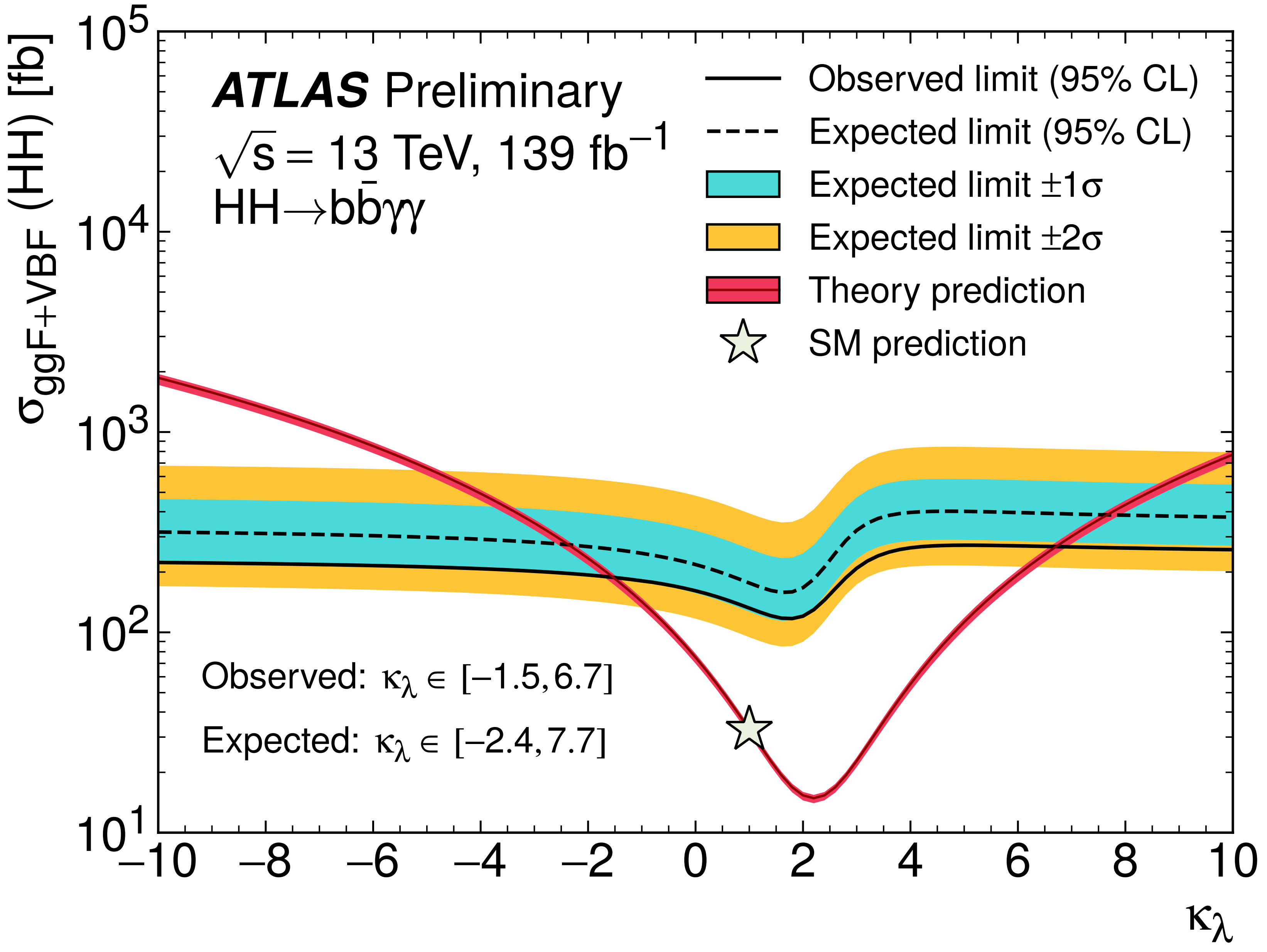
$HH \rightarrow b\bar{b}\gamma\gamma$

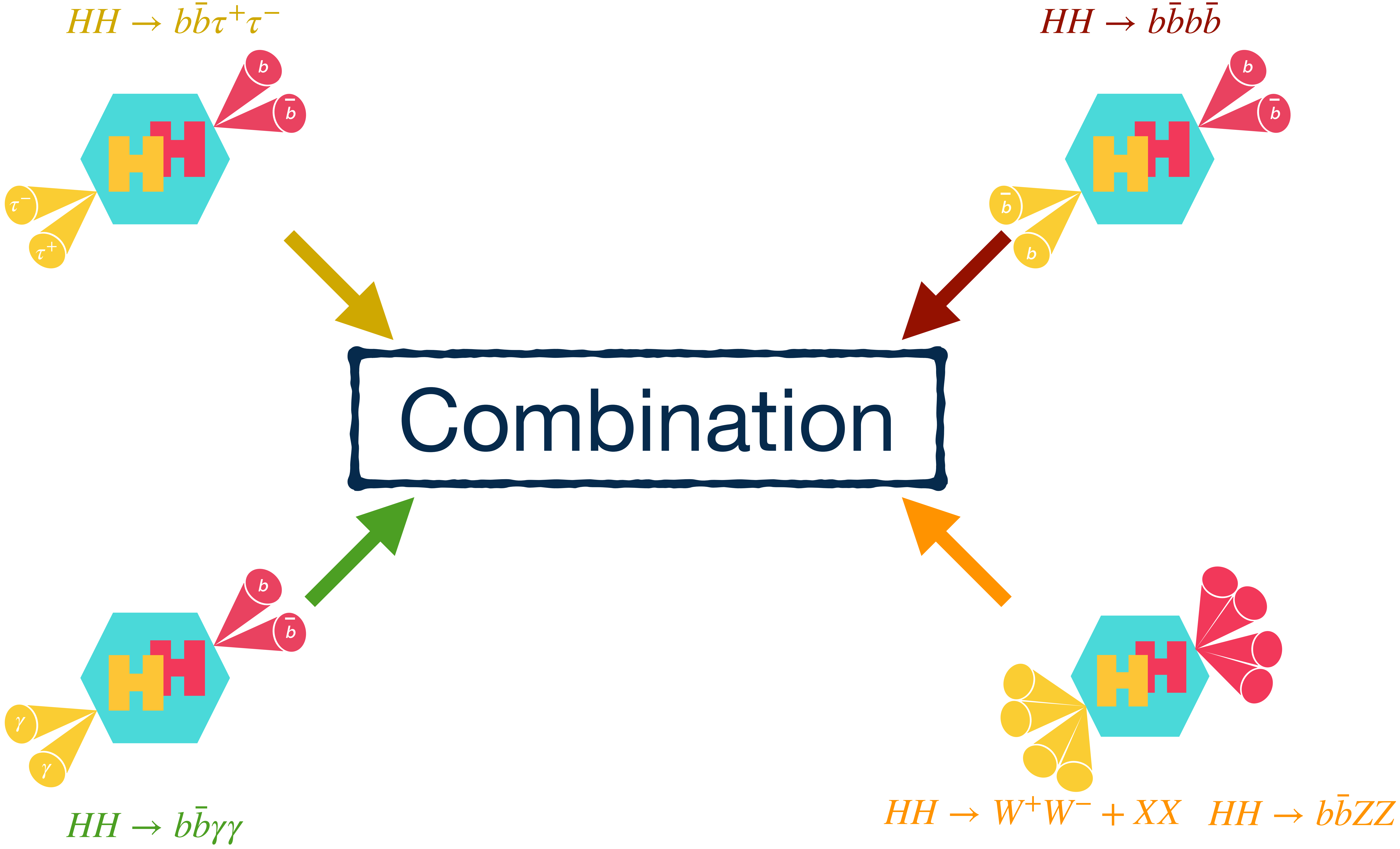
$\sigma_{HH}^{ggF+VBF}$ **observed (expected)** limit is **4.1 (5.5)** x SM prediction.

Limits are set on κ_λ:

$-1.5 < \kappa_\lambda < 6.7$ observed

$-2.4 < \kappa_\lambda < 7.7$ expected.



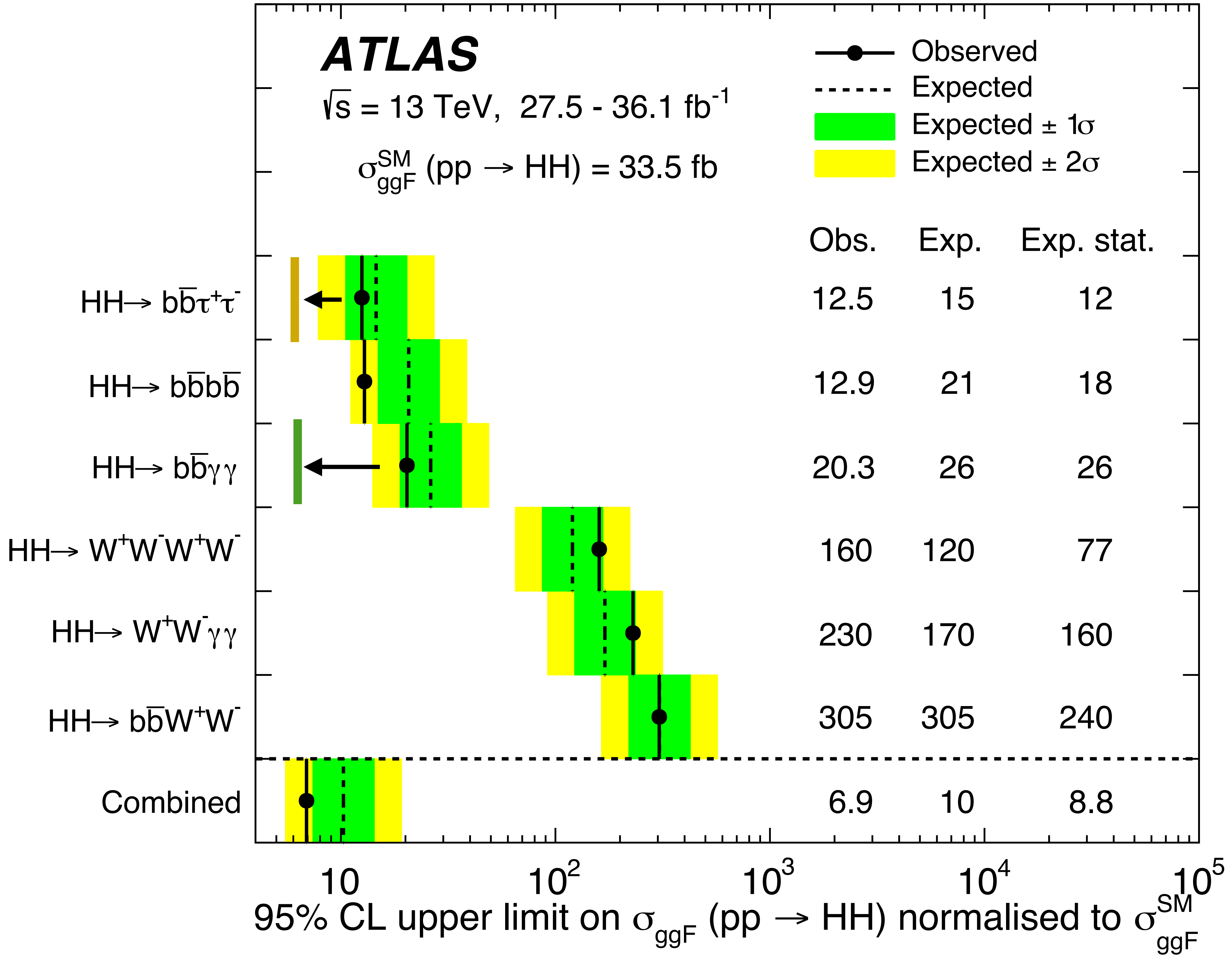


$HH \to b\bar{b}\tau^+\tau^-$
$HH \to b\bar{b}b\bar{b}$
Combination
$HH \to b\bar{b}\gamma\gamma$
$HH \to W^+W^- + XX$
$HH \to b\bar{b}ZZ$

Combination

$b\bar{b}l\nu l\nu$ final state : $\mathscr{L} = 139\text{fb}^{-1}$ Phys. Lett. B 801 (2020) 135145
Combination: $\mathscr{L} = 36\text{fb}^{-1}$ Phys. Lett. B 800 (2020) 135103
Combination: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-052

Combination done with most of the analyses with $\mathscr{L} = 36\text{fb}^{-1}$:



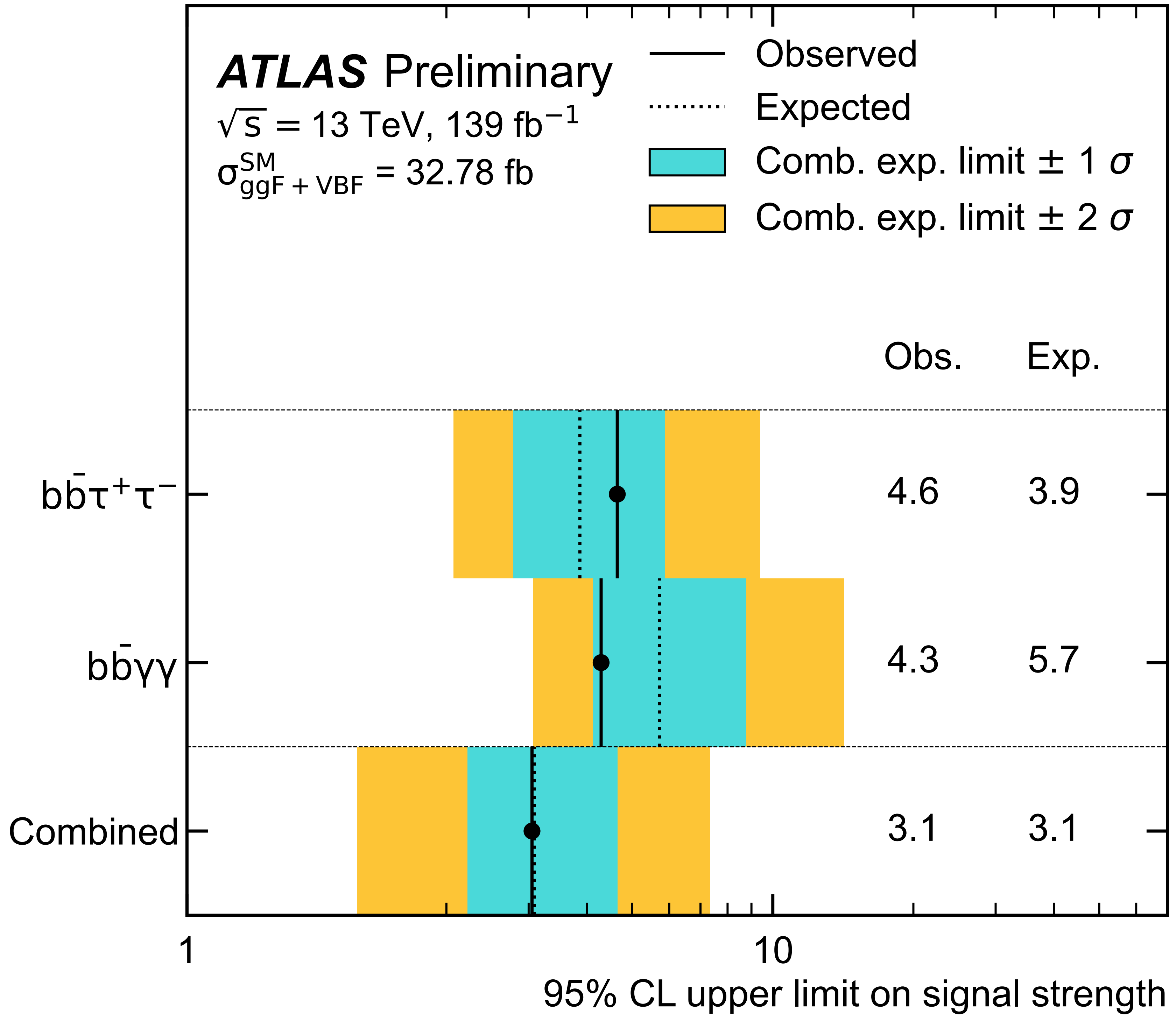
Additional results with $\mathscr{L} = 139\text{fb}^{-1}$:

$b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ final states:

New full Run-2 combination with the two strongest channels.

$\mu_{HH}^{ggF+VBF}$ **observed (expected)** limit is **3.1 (3.1).**

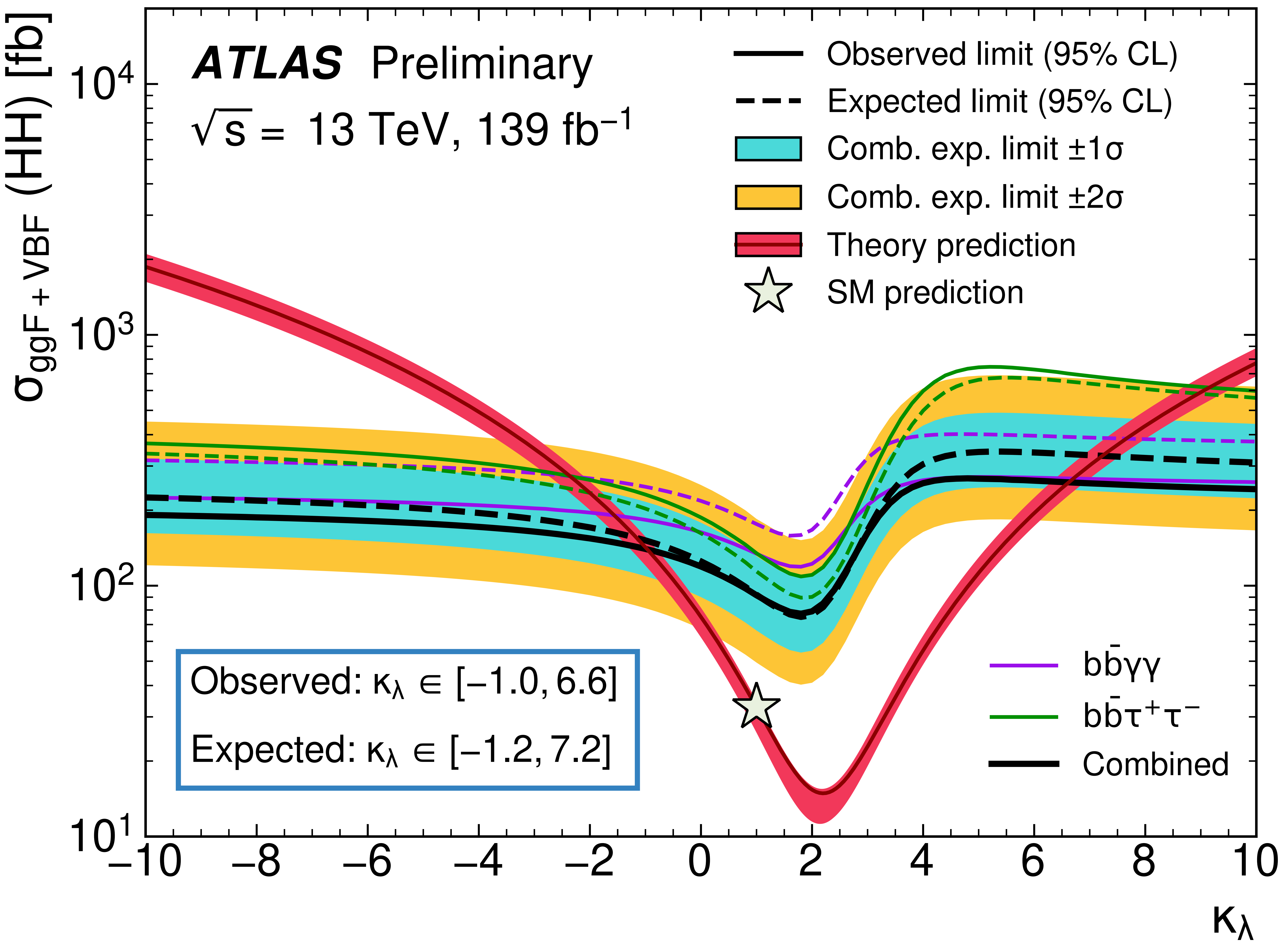
Best limit observed up to now!



Combination

Combinaison: $\mathscr{L} = 139\text{fb}^{-1}$ ATLAS-CONF-2021-052

Combination done with Full Run-2 analyses with $\mathscr{L} = 139\text{fb}^{-1}$



Best limit set so far on κ_λ so far.

Benefits from the nice complementarity between the two channels to improve the global limit.

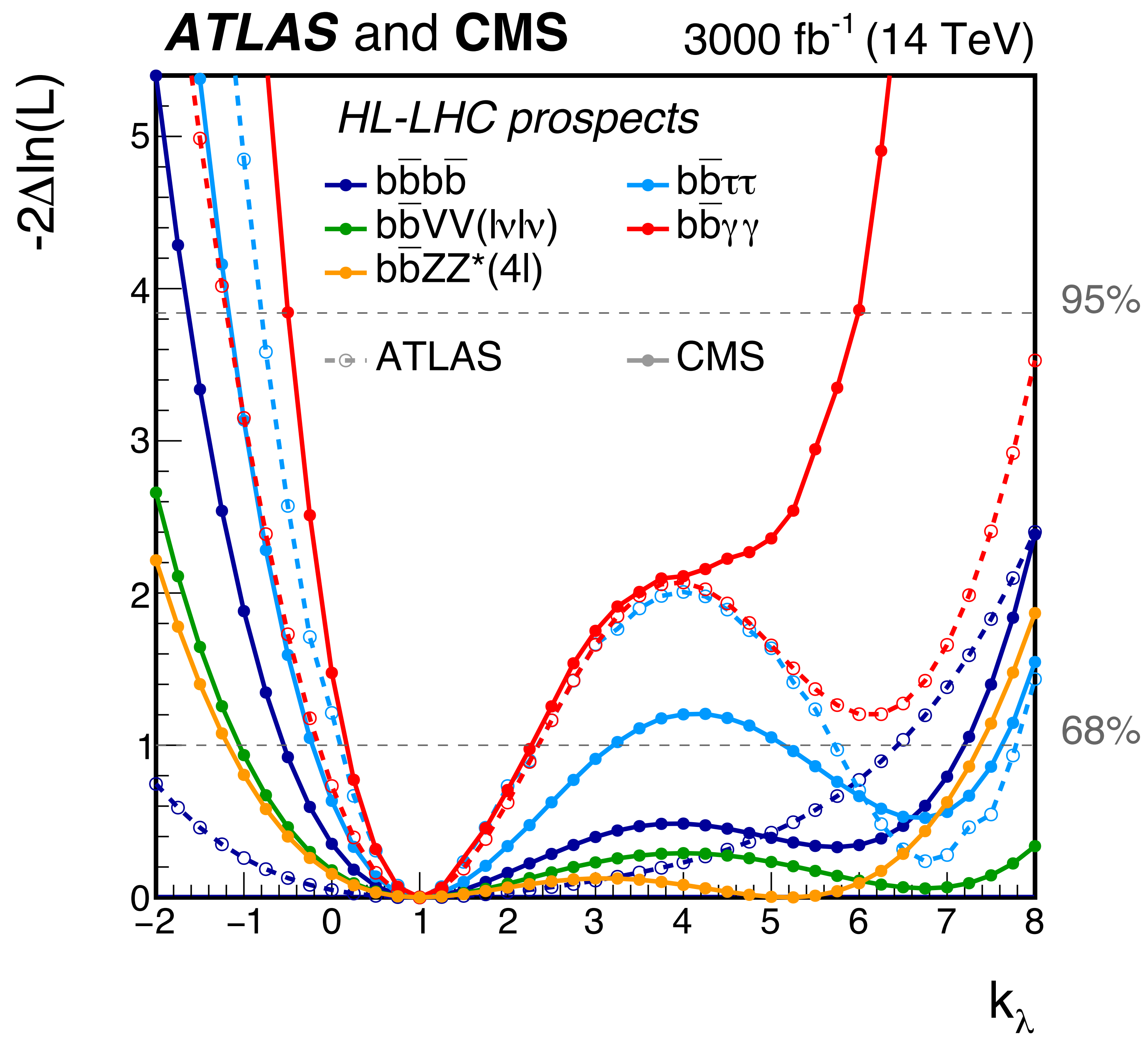
A look into the future

The story is not over yet: the **High Luminosity** phase of the LHC aims at collecting more than **10 x** the runs 1-3 datasets.

CERN published a **Yellow report** to provide estimated performances: CERN-LPCC-2018-04
Since then we have improved our limits, far beyond the luminosity gain:

- $HH \rightarrow b\bar{b}\tau^{+}\tau^{-}$ (ATL-PHYS-PUB-2021-044);
- $HH \rightarrow b\bar{b}\gamma\gamma$ (ATL-PHYS-PUB-2022-001).

combination (ATL-PHYS-PUB-2022-005)

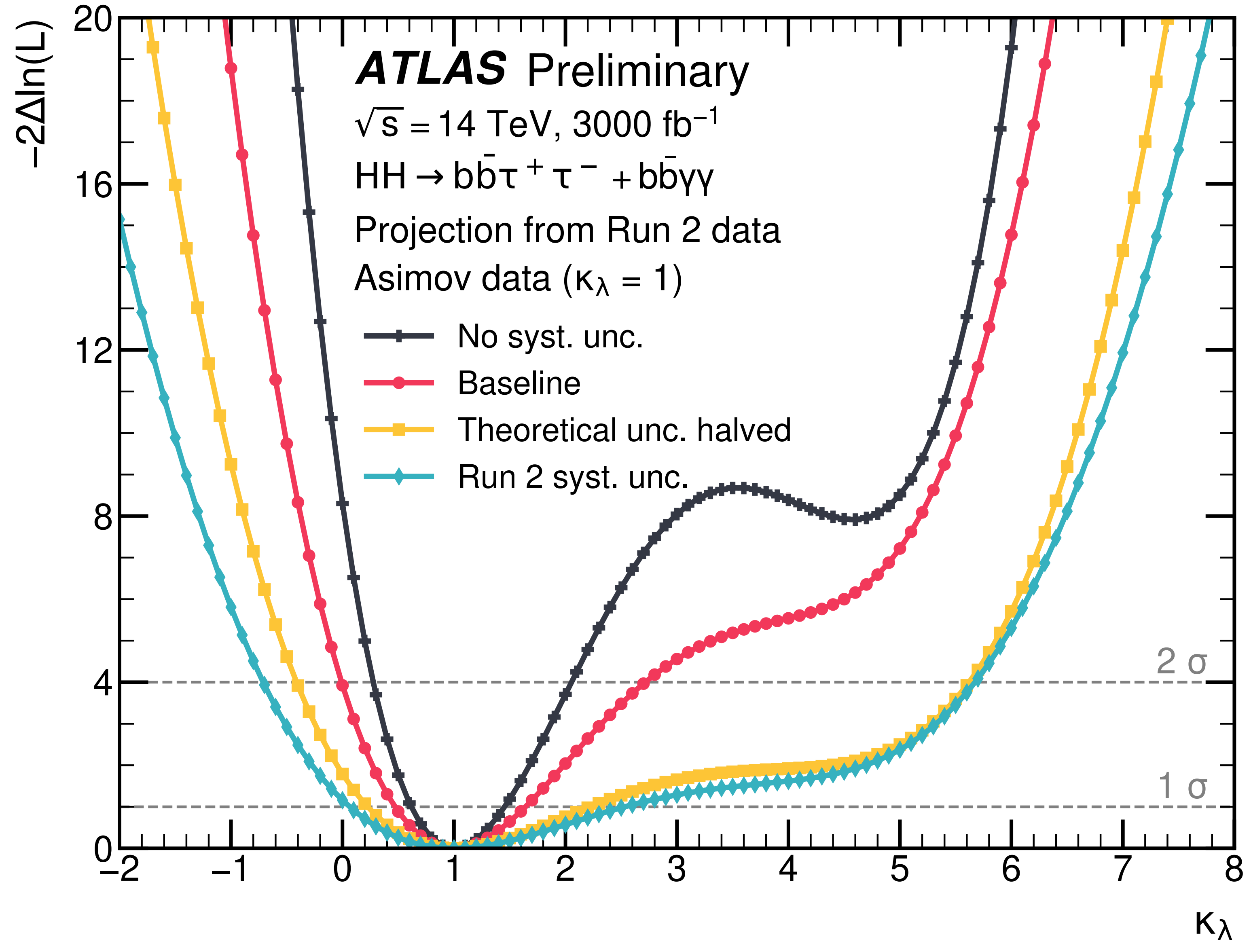


$\hookrightarrow 0.57 \leq \kappa_\lambda \leq 1.5$ @ 68% C.L.

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \rightarrow b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \rightarrow b\bar{b}\tau\tau$	2.5 **4.0**	1.6	2.1 **2.8**	1.4
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1 **2.3**	1.8	2.0 **2.2**	1.8
$HH \rightarrow b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \rightarrow b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5 **4.6**	2.8	3.0 **3.2**	2.6
	Combined 4.5		Combined 4.0	

The **limitations** mainly arise from:

- Theoretical uncertainties on single Higgs production and top-related backgrounds;
- Modelling of the diphoton background.



$\hookrightarrow 0.5 \leq \kappa_\lambda \leq 1.6$ @ 68% C.L.

ATLAS
EXPERIMENT

Thanks for your attention.

BACK-UP

Investigating the Higgs potential

The full expression of the Higgs potential is encoded with parameters μ and λ as:

$$V(\phi^\dagger\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

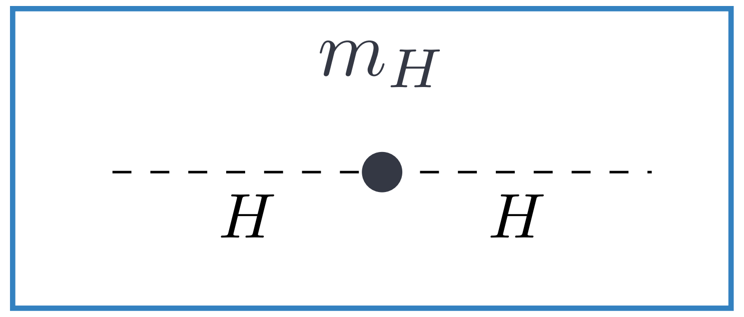
When linearising the Higgs field after the EWSB around the vacuum expected value ν one gets:

$$V(H) \supset \underbrace{\mu^2}_{\frac{1}{2}m_H^2} H^2 + \lambda\nu H^3 + \frac{\lambda}{4}H^4$$

Where the potential parameters are linked by :

$$\nu = \sqrt{\frac{\mu^2}{\lambda}} = \sqrt{\frac{1}{\sqrt{2}G_F}}$$

Relationship between the electron charge, the weak boson masses, and the Fermi Constant.



- The first piece of information came from the Higgs boson discovery:
  - Existence of a new particle with couplings according to prediction from EWSB;
  - First measurement of Higgs mass:

$$m_H = 125.09\ \text{GeV} \leftrightarrow \mu = 88.45\ \text{GeV}$$

- The Fermi constant can be determined thanks to the muon lifetime measurement:

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^2}{192\pi^3}(1+\Delta q)$$

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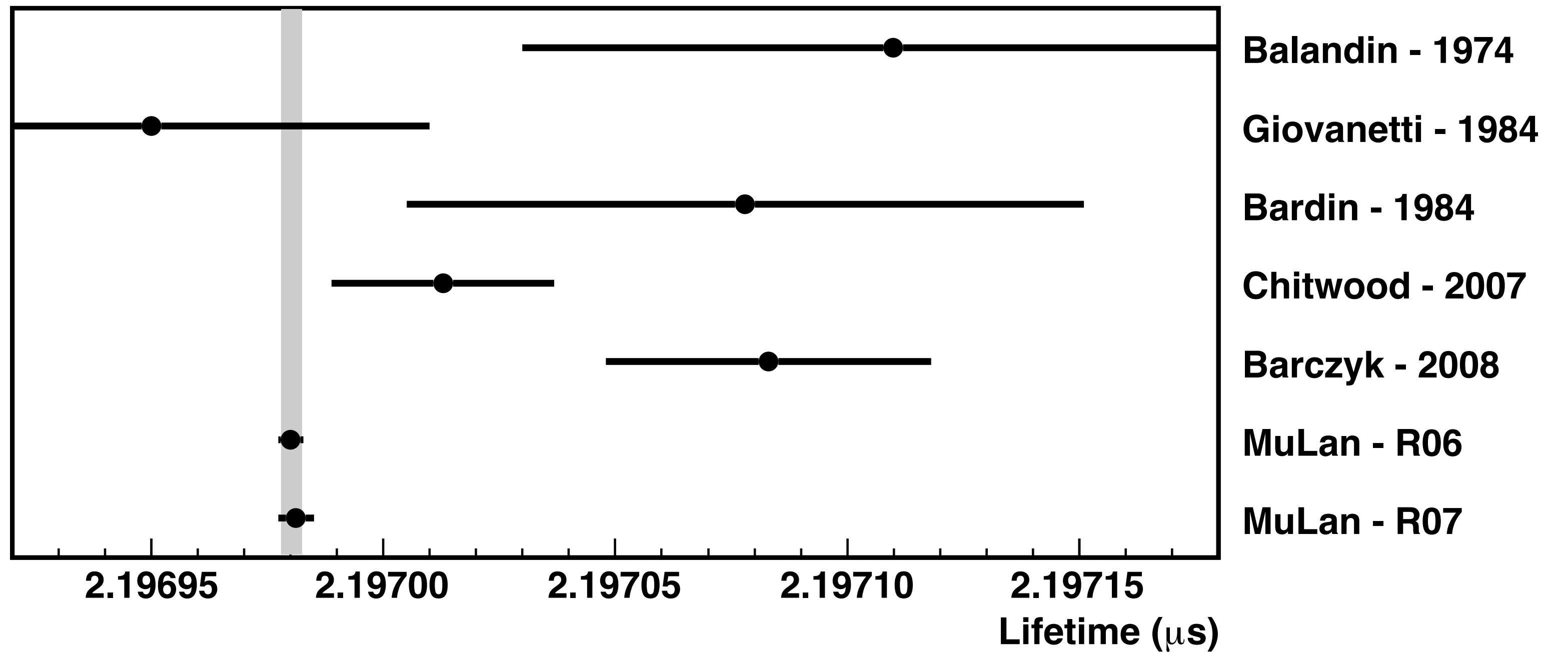


- From most precise MuLan experiment:

$$G_F = 1.1663788(7) \times 10^{-5}\ \text{GeV}^{-2}$$

$\hookrightarrow \nu \simeq 246.23$ GeV

$\hookrightarrow \lambda \sim 0.13$

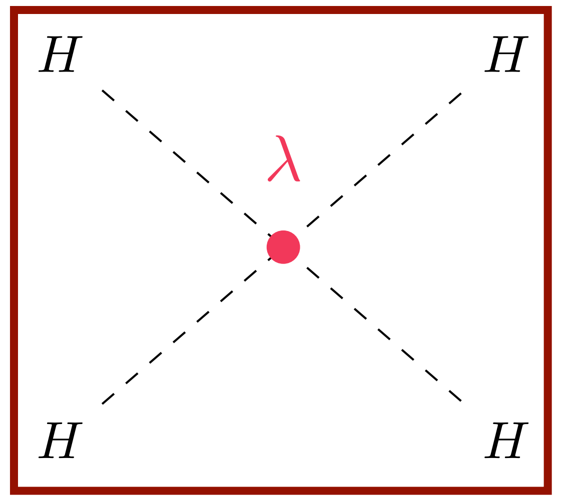
Investigating the Higgs potential

The full expression of the Higgs potential is encoded with parameters μ and λ as:

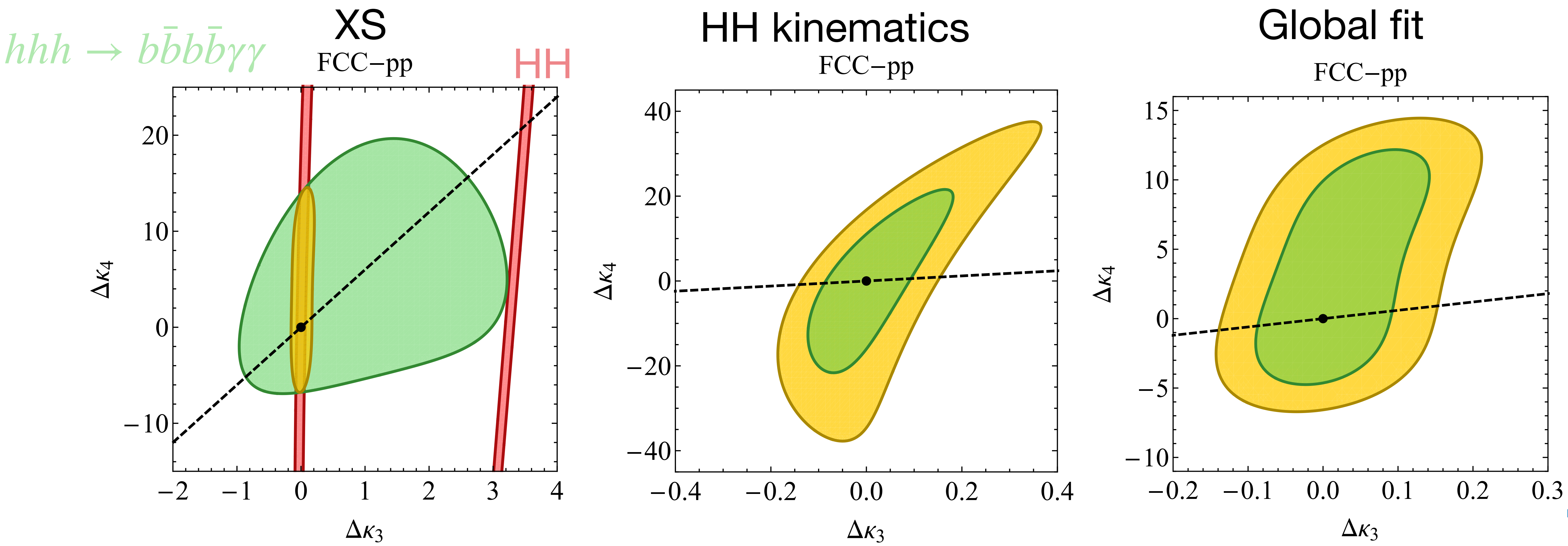
$$V(\phi^\dagger\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

When linearising the Higgs field after the EWSB around the vacuum expected value ν one gets:

$$V(H) \supset \underbrace{\mu^2}_{\frac{1}{2}m_H^2} H^2 + \lambda\nu H^3 + \frac{\lambda}{4}H^4$$



- Quartic interaction even rarer :
  - At tree level: very mild effect on XS and kinematic distributions.
  - At loop level: similar constraints obtained on XS, but stronger effect kinematics.
  - No strong constraints even with FCC 100 TeV collider ($\kappa_4 \in [-3,13]$) or the CLIC 3000 GeV ($\kappa_4 \in [-5,7]$).



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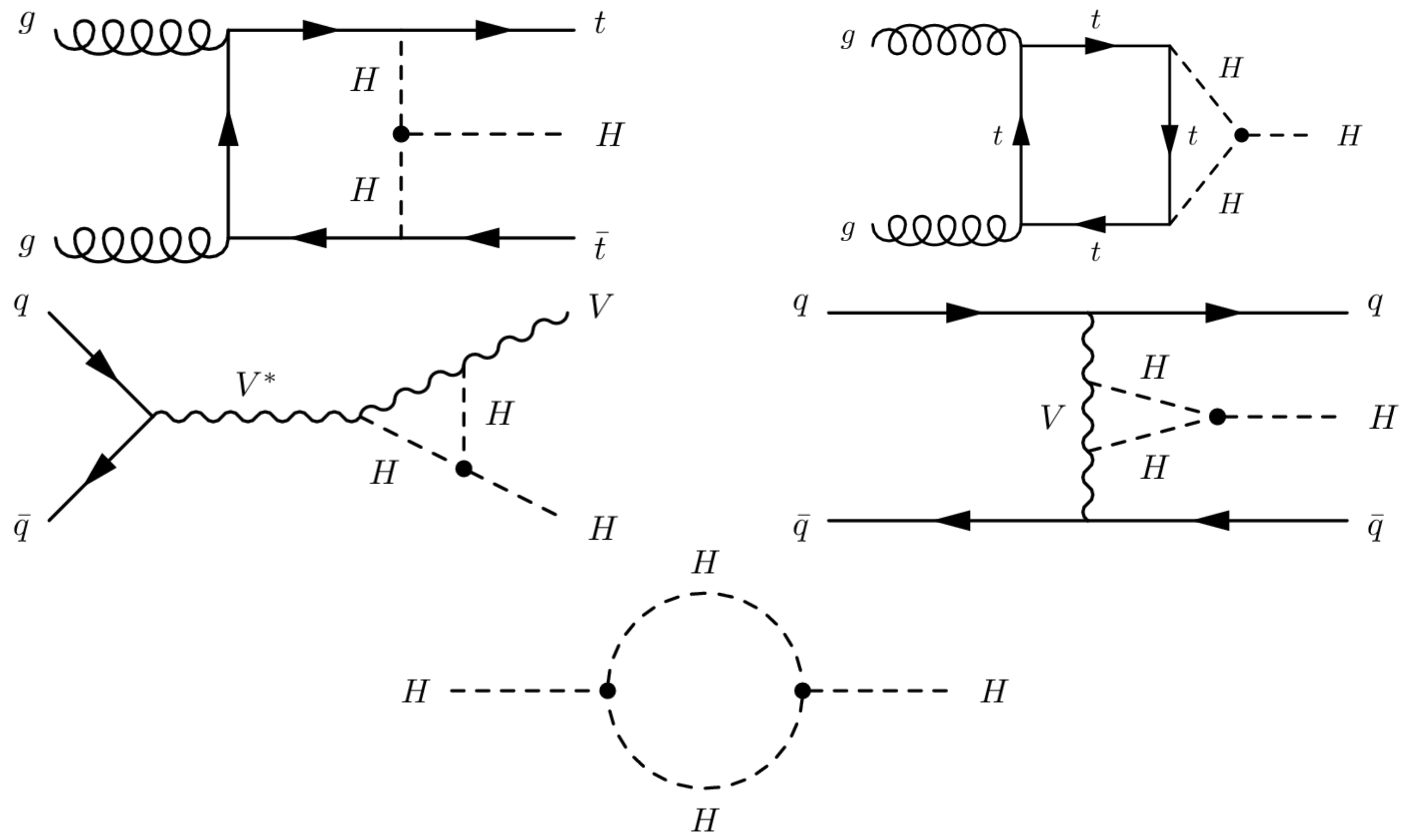
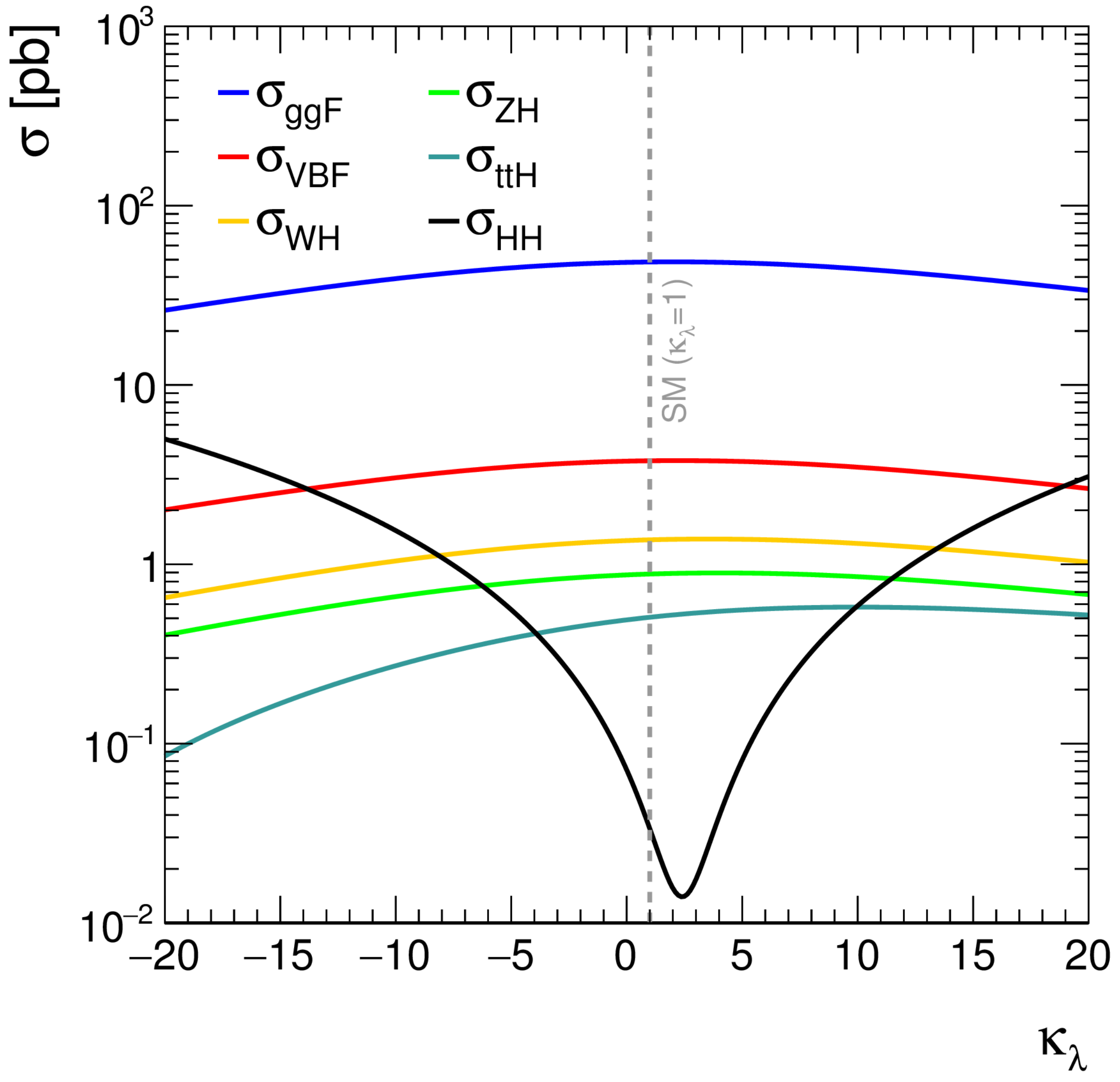
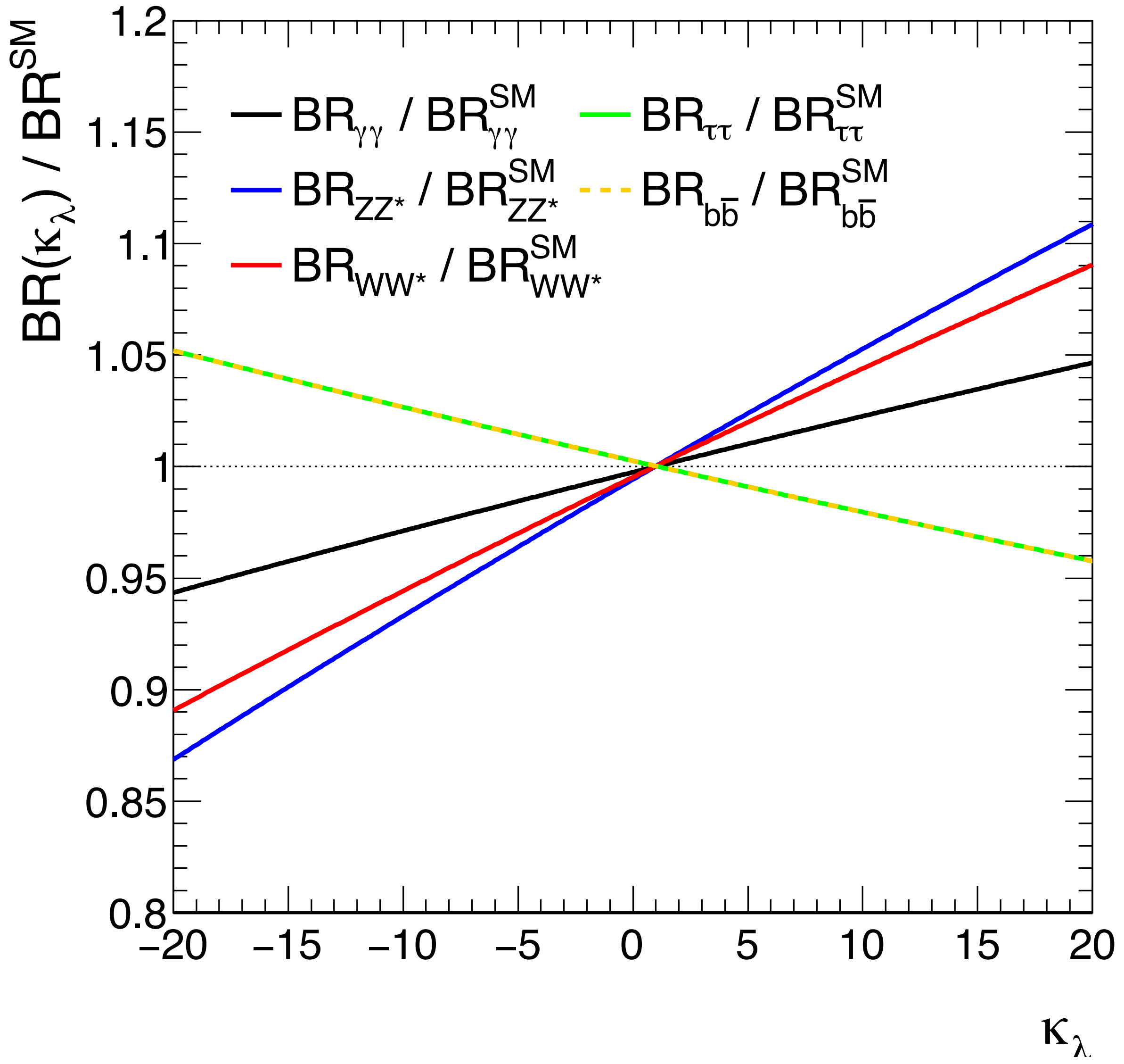
Single Higgs constrains



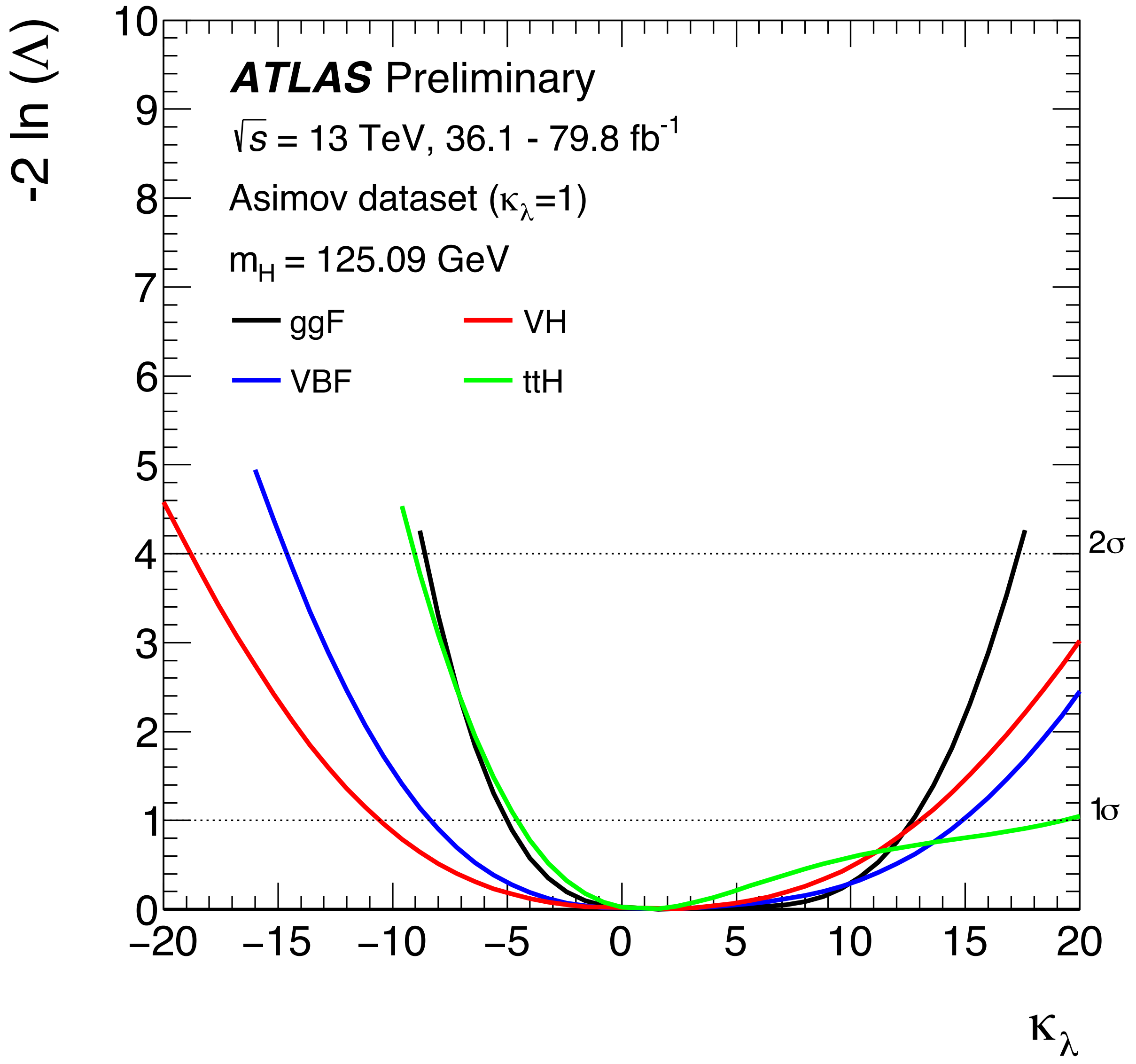


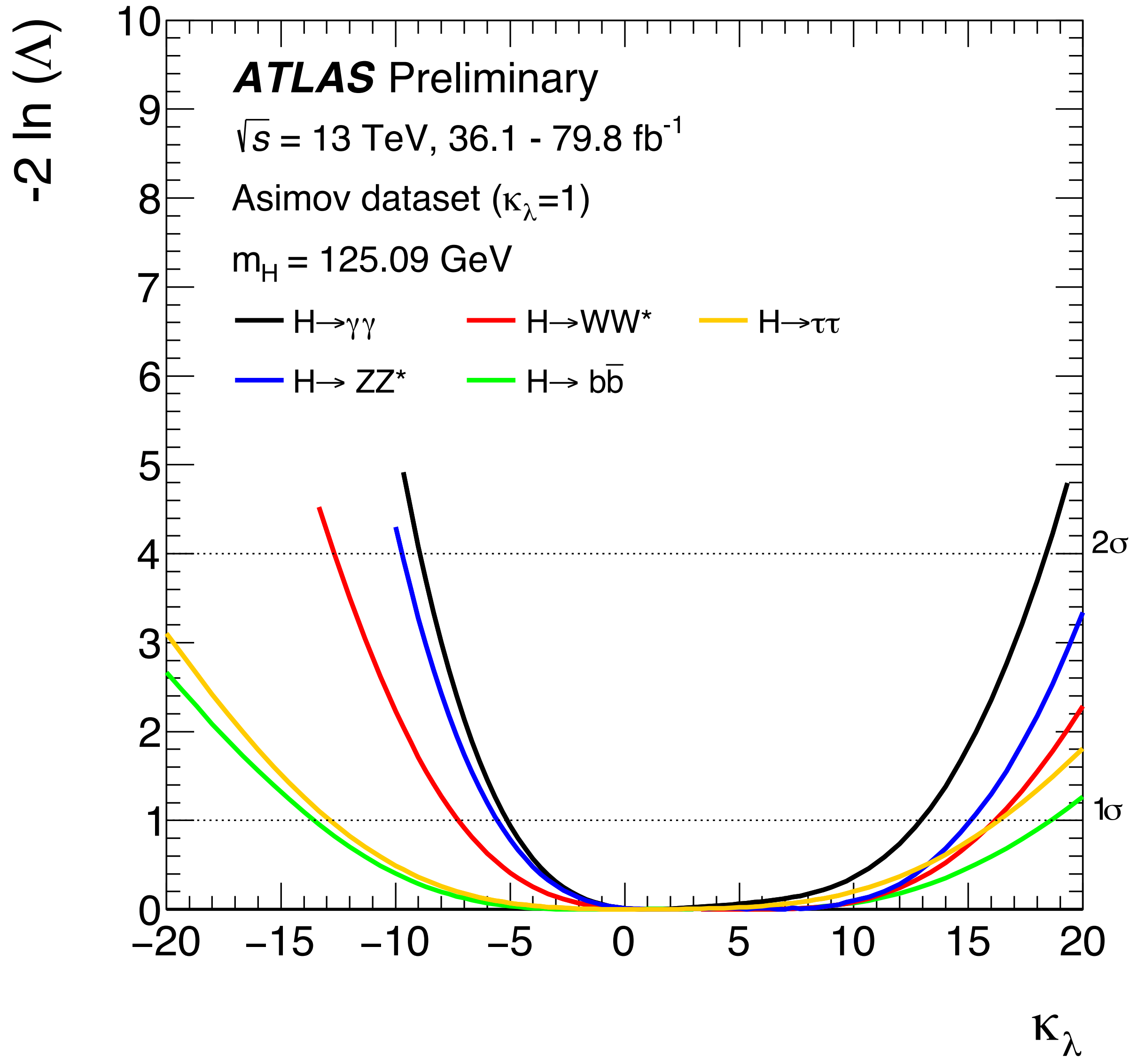


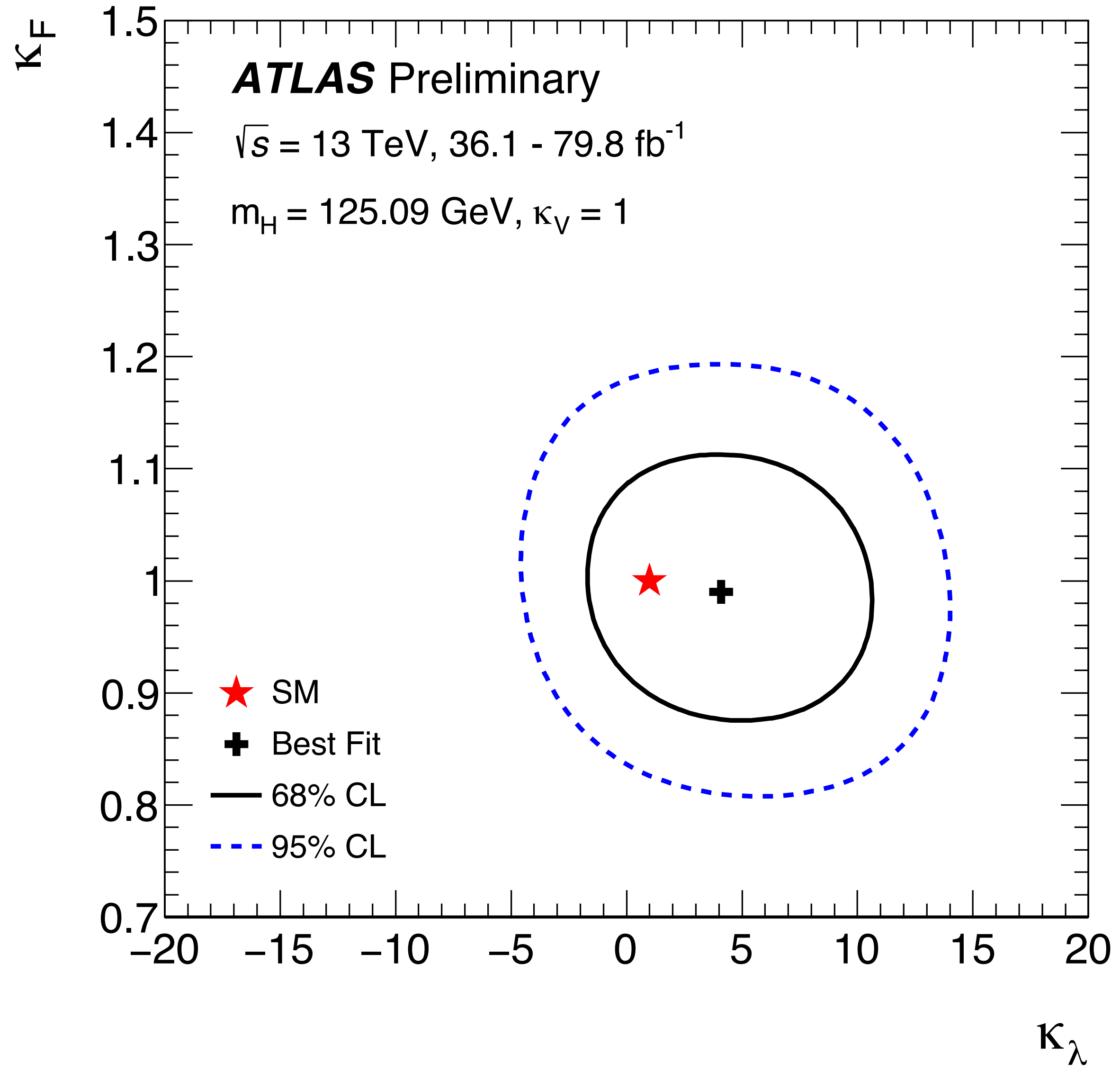
ATL-PHYS-PUB-2019-009

Combinaison of single Higgs channels with $\mathscr{L} = 80\text{fb}^{-1}$ yielding: $-3.2 < \kappa_\lambda < 11.9$
And in combination with partial Run-2 HH: $-2.3 < \kappa_\lambda < 10.3$

ATL-CONF-2019-049





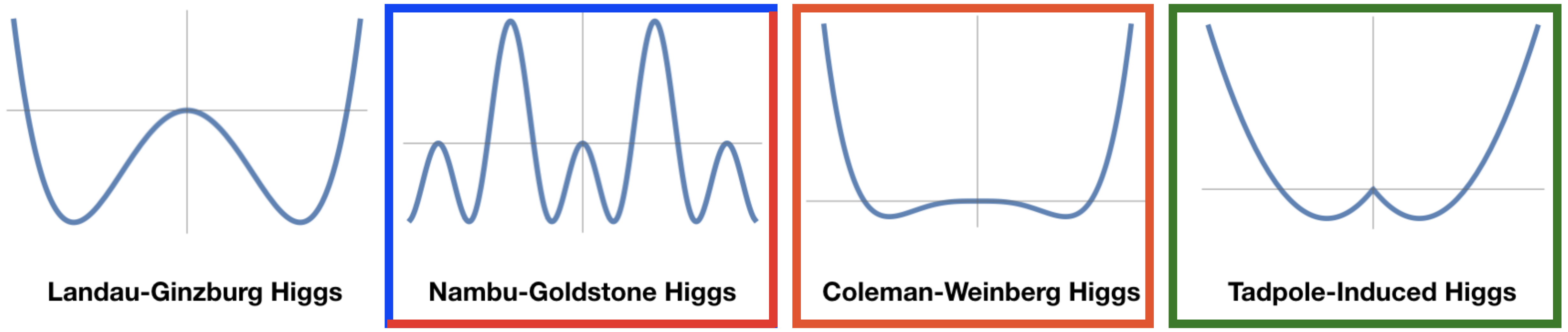


Exploring alternative scenarios

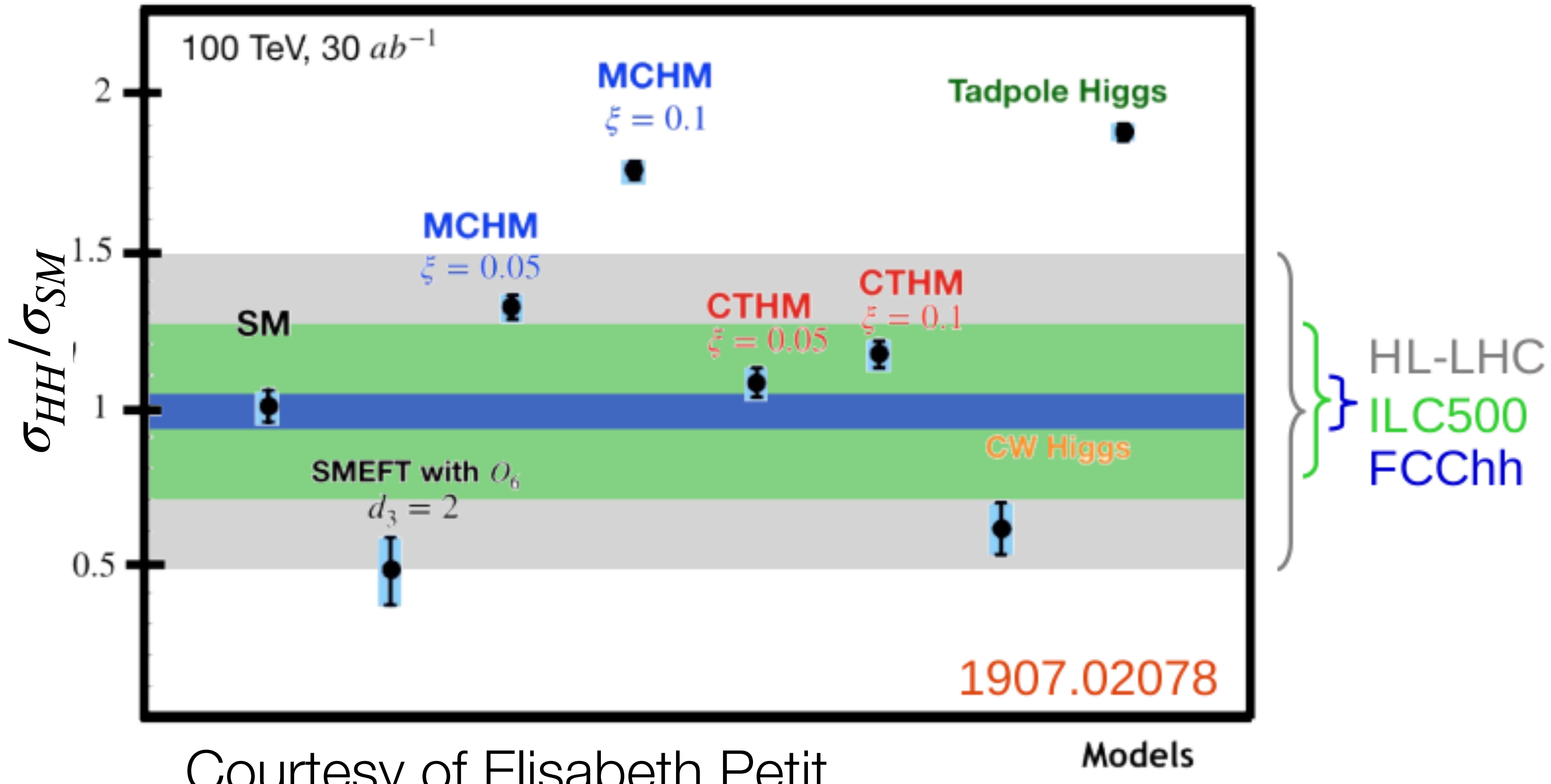
The measurement of the Higgs potential is answering the fundamental question of its nature.
Several other models can show a non zero vacuum expected value with a different second order contribution:

$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2}(H^\dagger H)^3, & \text{Elementary Higgs} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + \epsilon (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

- Nambu-Goldstone Higgs: pseudo Nambu-Goldstone boson emerging from strong dynamics at a high scale
- Coleman-Weinberg Higgs: EWSB is triggered by renormalization group (RG) running effects
- Tadpole-induced Higgs: EWSB is triggered by the Higgs tadpole

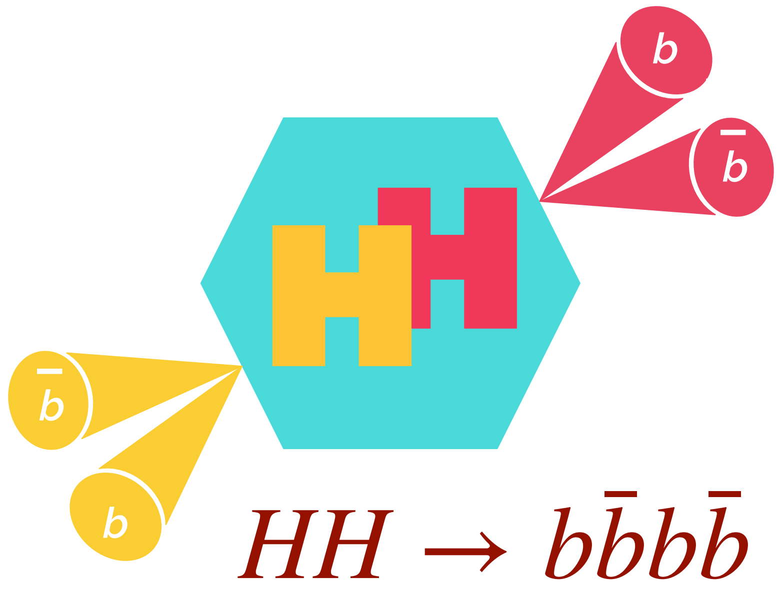


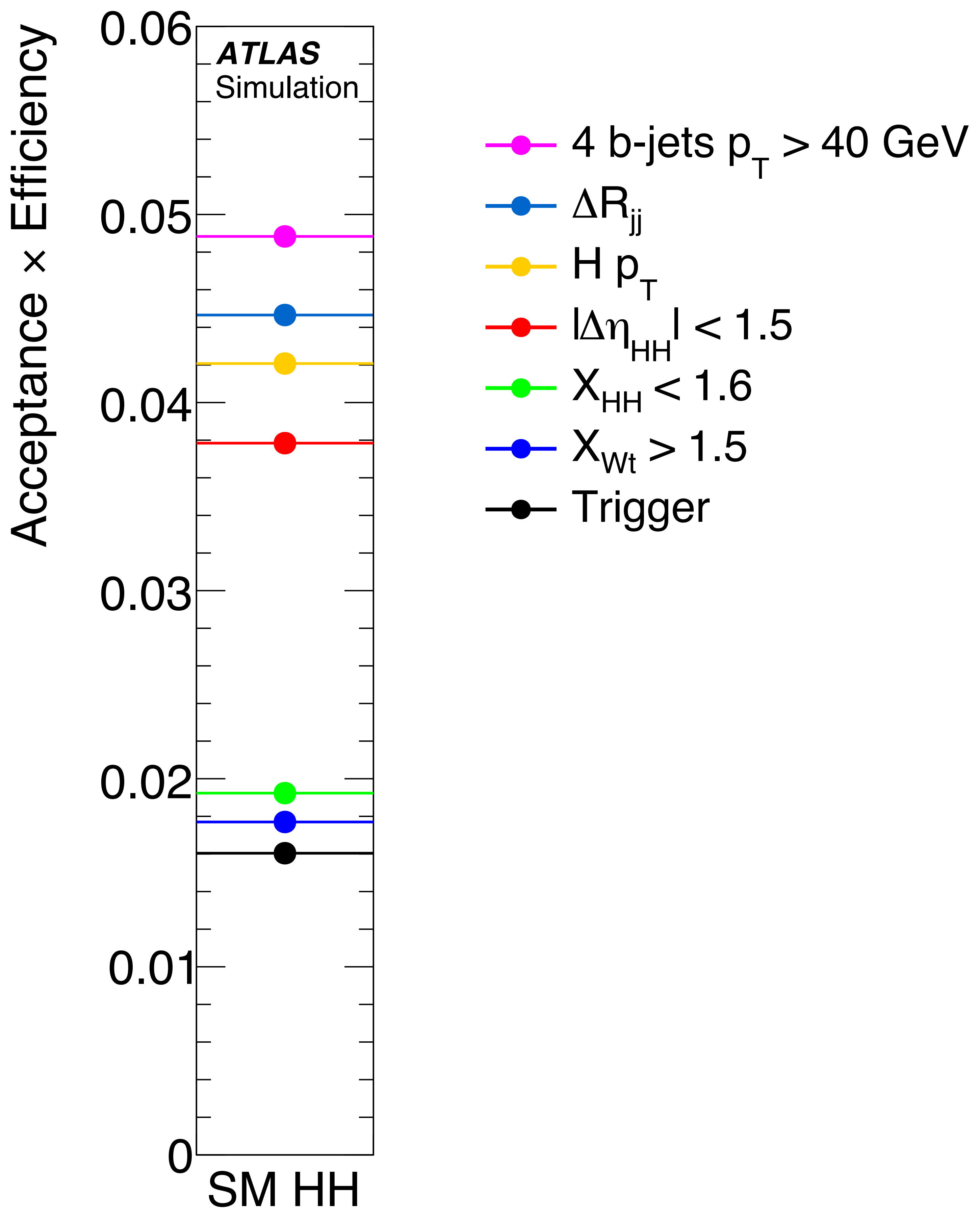
minimal composite Higgs model/
composite twin Higgs model :
different coupling to top quark



Courtesy of Elisabeth Petit

bbbb details





	2015				2016			
Source	Background	Scalar	SM HH	G_{KK}	Background	Scalar	SM HH	G_{KK}
Luminosity	–	2.1	2.1	2.1	–	2.2	2.2	2.2
Jet energy	–	17	7.1	3.7	–	17	6.4	3.7
b-tagging	–	13	12	14	–	13	12	14
b-trigger	–	4.0	2.3	1.3	–	2.6	2.5	2.5
Theoretical	–	23	7.2	0.6	–	23	7.2	0.6
Multijet stat	4.2	–	–	–	1.5	–	–	–
Multijet syst	6.1	–	–	–	1.8	–	–	–
$t\bar{t}$ stat	2.1	–	–	–	0.8	–	–	–
$t\bar{t}$ syst	3.5	–	–	–	0.3	–	–	–
Total	7.5	31	16	15	1.8	31	16	15

systematic relative uncertainties (expressed in percentage yield) in the total background and signal event yields

Bbtautau details

BDT input variables:

Variable	$\tau_{lep}\tau_{had}$ channel (SLT resonant)	$\tau_{lep}\tau_{had}$ channel (SLT nonresonant & LTT)	$\tau_{had}\tau_{had}$ channel
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{MMC}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	✓
E_T^{miss}	✓		
E_T^{miss} ϕ centrality	✓		✓
m_T^W	✓	✓	
$\Delta\phi(H,H)$	✓		
$\Delta p_T(\text{lep}, \tau_{\text{had-vis}})$	✓		
Subleading b-jet p_T	✓		

Non resonant limits per channel:

		Observed	-1σ	Expected	$+1\sigma$
$\tau_{lep}\tau_{had}$	$\sigma(HH \to bb\tau\tau)$ [fb]	57	49.9	69	96
	σ/σ_{SM}	23.5	20.5	28.4	39.5
$\tau_{had}\tau_{had}$	$\sigma(HH \to bb\tau\tau)$ [fb]	40.0	30.6	42.4	59
	σ/σ_{SM}	16.4	12.5	17.4	24.2
Combination	$\sigma(HH \to bb\tau\tau)$ [fb]	30.9	26.0	36.1	50
	σ/σ_{SM}	12.7	10.7	14.8	20.6

Impact of systematics on SM limit:

Source	Uncertainty (%)
Total	±54
Data statistics	±44
Simulation statistics	±16
Experimental uncertainties	
Luminosity	±2.4
Pileup reweighting	±1.7
τ_{had}	±16
Fake-τ estimation	±8.4
b tagging	±8.3
Jets and E_T^{miss}	±3.3
Electron and muon	±0.5
Theoretical and modeling uncertainties	
Top	±17
Signal	±9.3
$Z \to \tau\tau$	±6.8
SM Higgs	±2.9
Other backgrounds	±0.3

Bbyy details

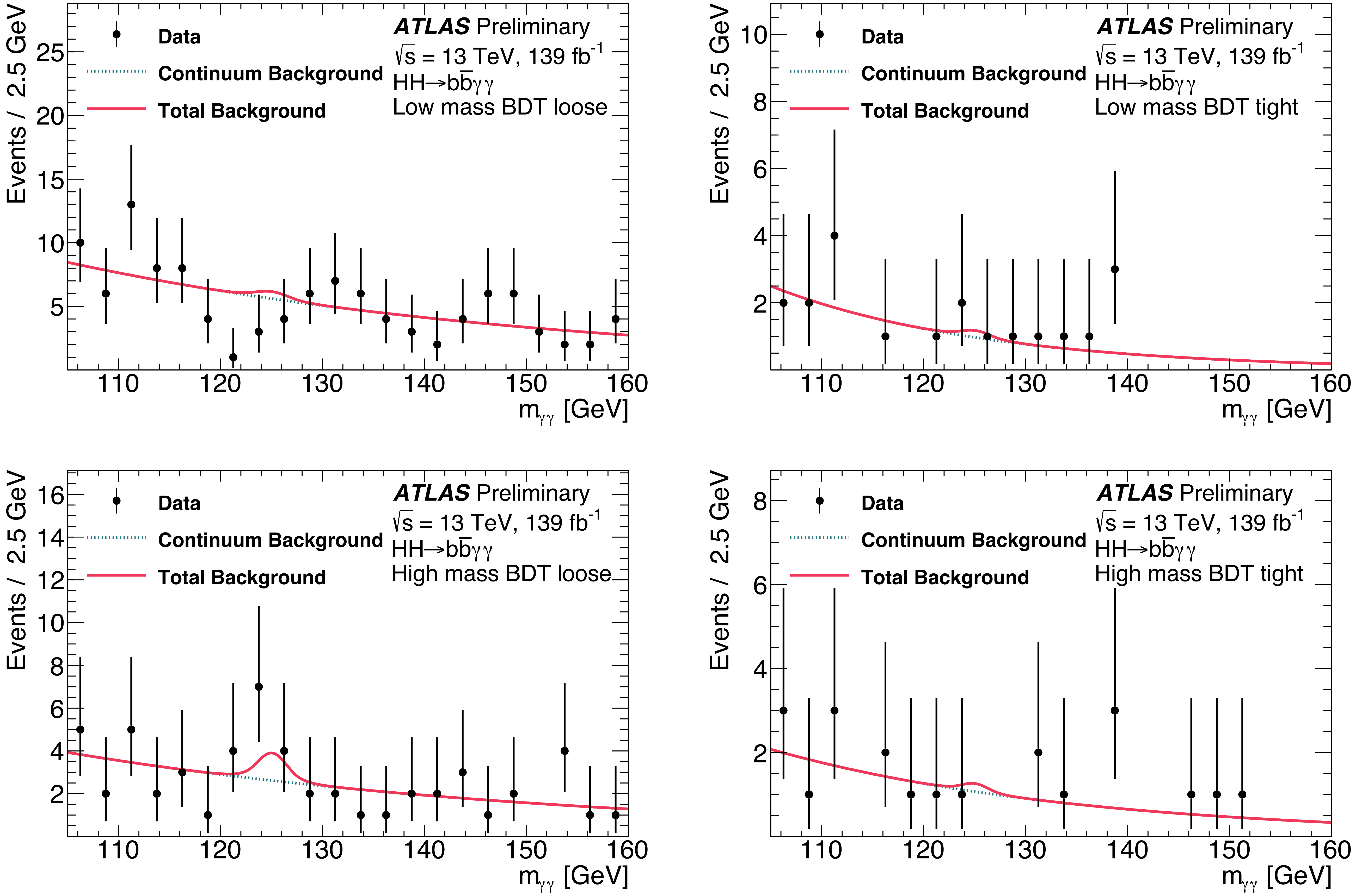
ATLAS-CONF-2021-016

$HH \rightarrow b\bar{b}\gamma\gamma$

BDT loose | BDT tight

Low mass

High mass

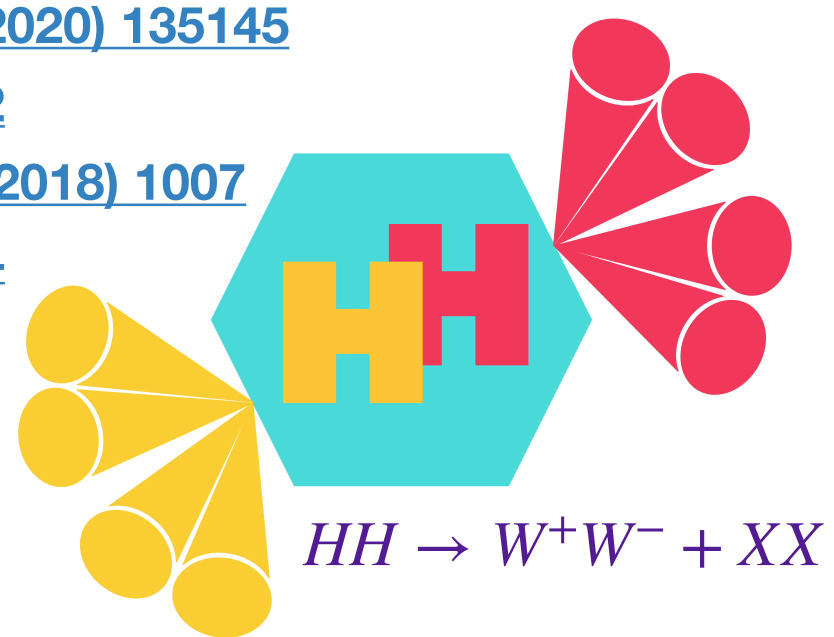


Source	Type	Nonresonant analysis HH
Experimental		
Photon energy resolution	Norm. + Shape	0.4
Jet energy scale and resolution	Normalization	< 0.2
Flavor tagging	Normalization	< 0.2
Theoretical		
Factorization and renormalization scale	Normalization	0.3
Parton showering model	Norm. + Shape	0.6
Heavy-flavor content	Normalization	0.3
$\mathcal{B}(H \rightarrow \gamma\gamma, b\bar{b})$	Normalization	0.2
Spurious signal	Normalization	3.0

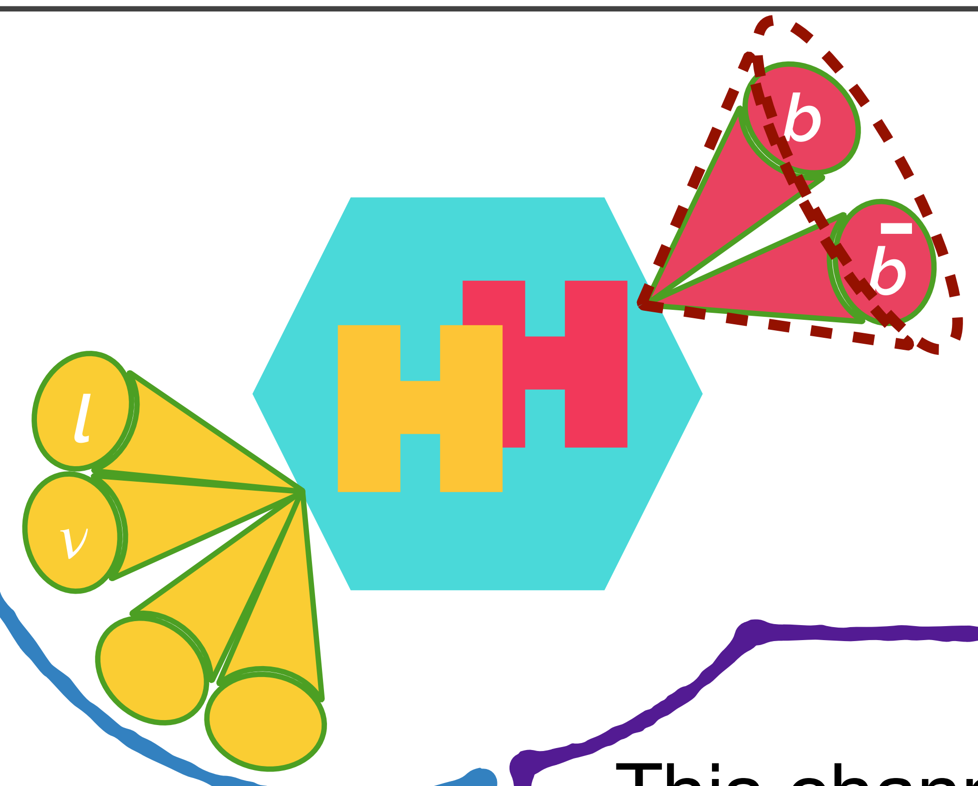
Relative variation of the expected upper limit on the cross-section (%)

Selection

$b\bar{b}l\nu l\nu$ final state : $\mathscr{L} = 139\text{fb}^{-1}$ — Phys. Lett. B 801 (2020) 135145
$b\bar{b}l\nu q\bar{q}$ final state : $\mathscr{L} = 36\text{fb}^{-1}$ — JHEP 04 (2019) 092
$\gamma\gamma WW^*$ final state : $\mathscr{L} = 36\text{fb}^{-1}$ — Eur. Phys. J. C 78 (2018) 1007
WW^*WW^* final state : $\mathscr{L} = 36\text{fb}^{-1}$ — JHEP 05 (2019) 124



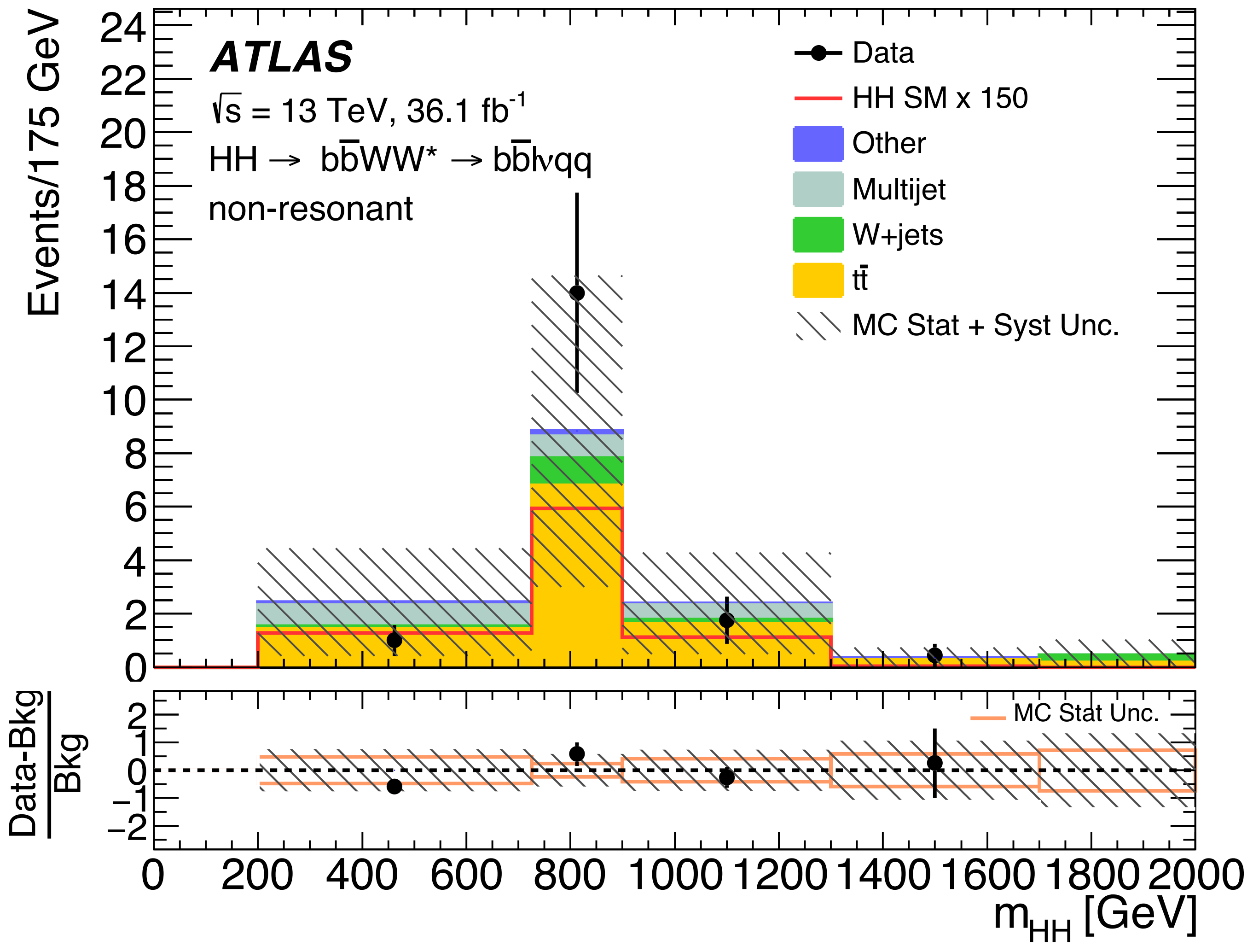
$b\bar{b}l\nu q\bar{q}$ final state



This channel is aiming at reducing the contamination of $t\bar{t}$ events by requesting one W boson to decay leptonically:

$H \to b\bar{b}$:
- exactly 2 b-tagged jets.

$H \to WW^* \to l\nu q\bar{q}$:
- ≥ 1 high-quality lepton.
- ≥ 2 additional jets, pair chosen with minimising $\Delta R(jet, jet)$
- Kinematic fit to find the neutrino momentum assuming $m_H = 125$ GeV

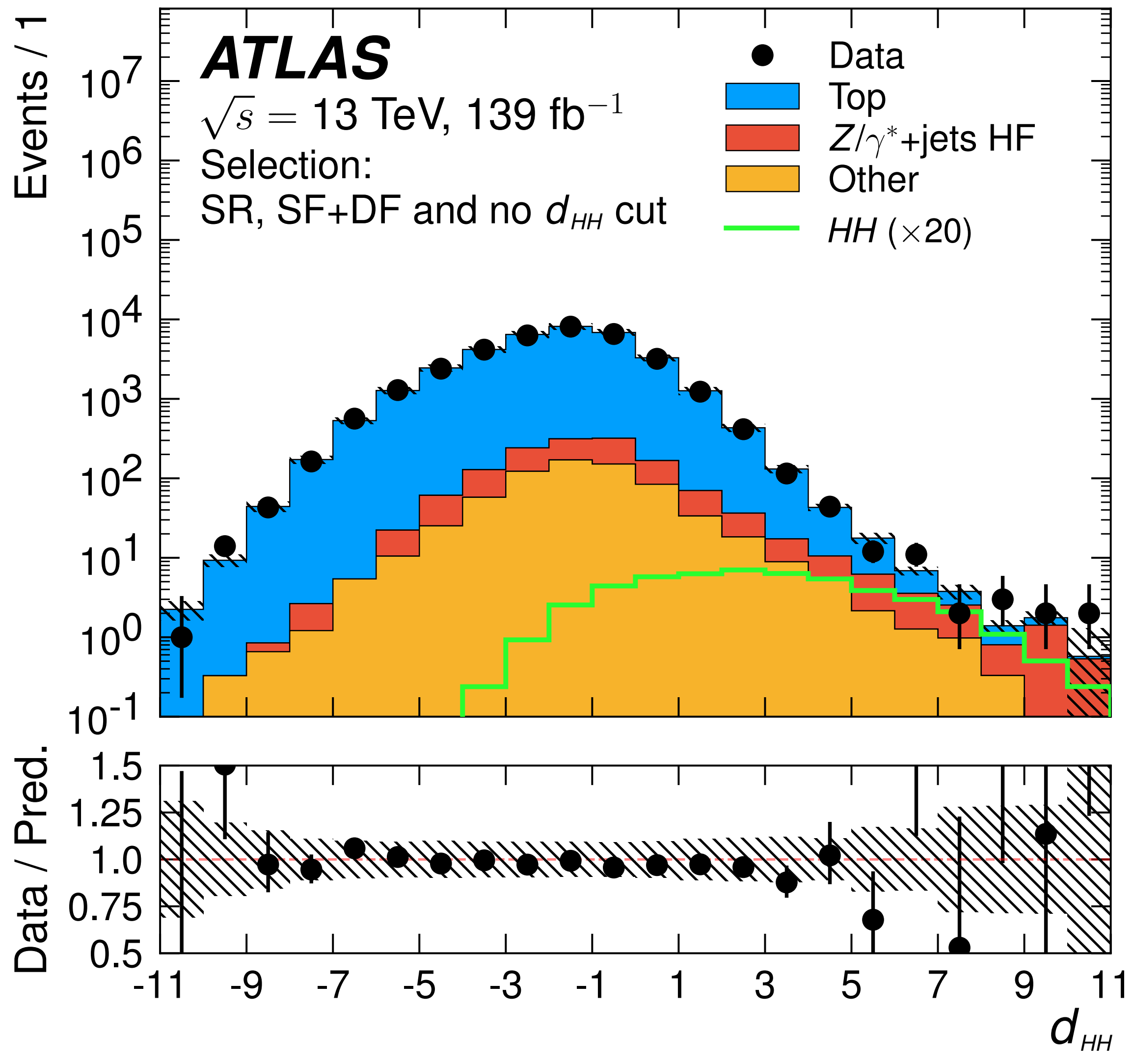


Fit: m_{HH} in different categories

$b\bar{b}l\nu l\nu$ final state

Resolved

This channel is aiming at $HH \to b\bar{b}WW^*$ signal, but is also sensitive to $HH \to b\bar{b}ZZ^*$ and $HH \to b\bar{b}\tau\tau$

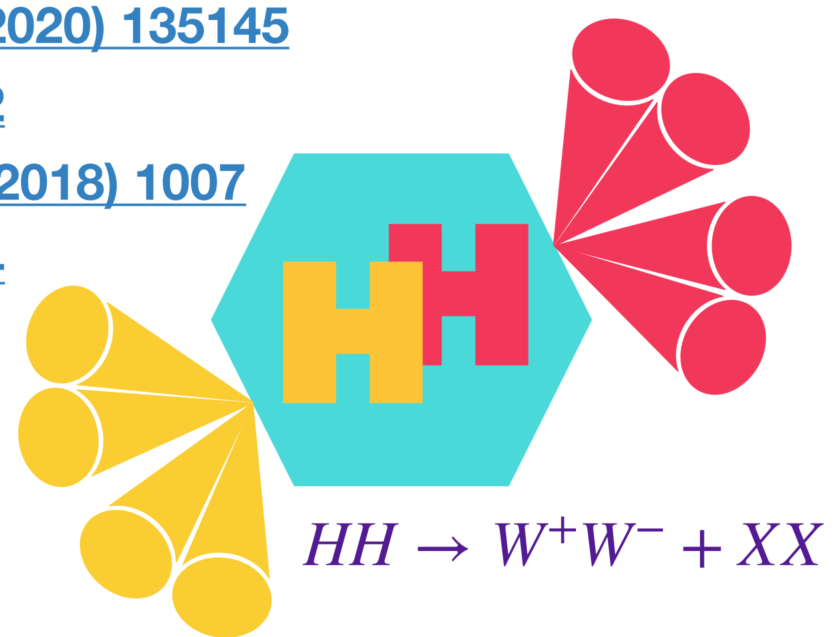


- $H \to b\bar{b}$:
  - Exactly 2 b-tagged jets
- $H \to WW^* \to l\nu l\nu$:
  - Exactly 2 opposite charge high quality leptons.
  - Categories: based on flavour.
- *Deep neural Network:*
  - To remove dominant backgrounds

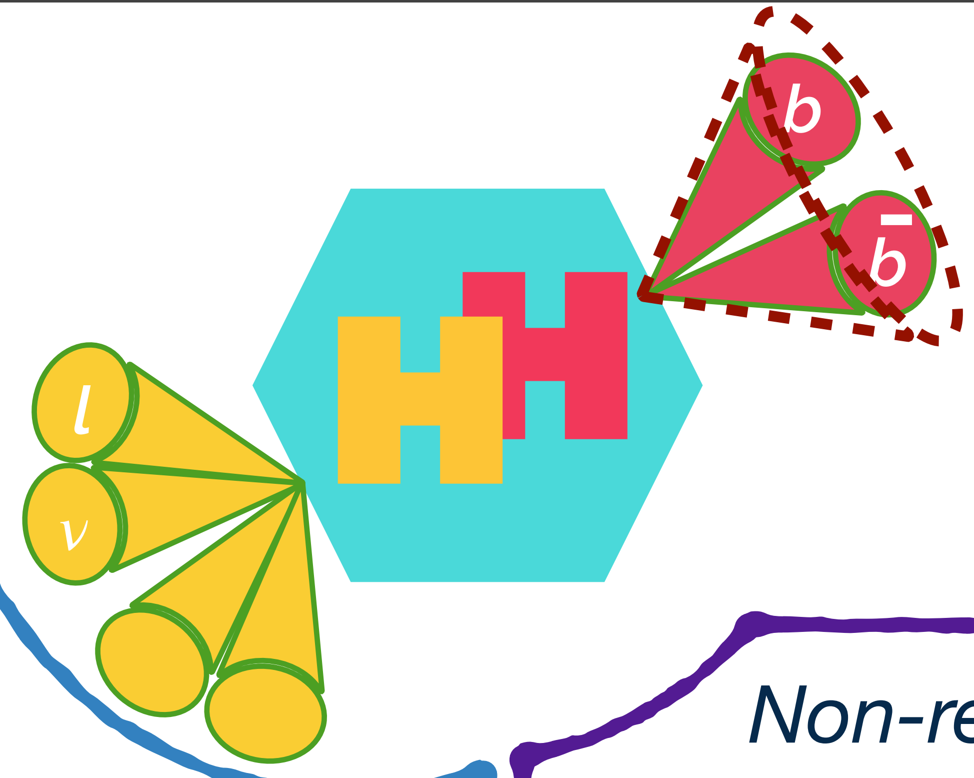
Fit: single bin in different categories

Results

$b\bar{b}l\nu l\nu$ final state : $\mathscr{L} = 139\text{fb}^{-1}$ Phys. Lett. B 801 (2020) 135145
$b\bar{b}l\nu q\bar{q}$ final state : $\mathscr{L} = 36\text{fb}^{-1}$ JHEP 04 (2019) 092
$\gamma\gamma WW^*$ final state : $\mathscr{L} = 36\text{fb}^{-1}$ Eur. Phys. J. C 78 (2018) 1007
WW^*WW^* final state : $\mathscr{L} = 36\text{fb}^{-1}$ JHEP 05 (2019) 124



$b\bar{b}l\nu q\bar{q}$ final state



σ_{HH}^{ggF} **observed (expected)** limit is **300 (190)** times the SM prediction.

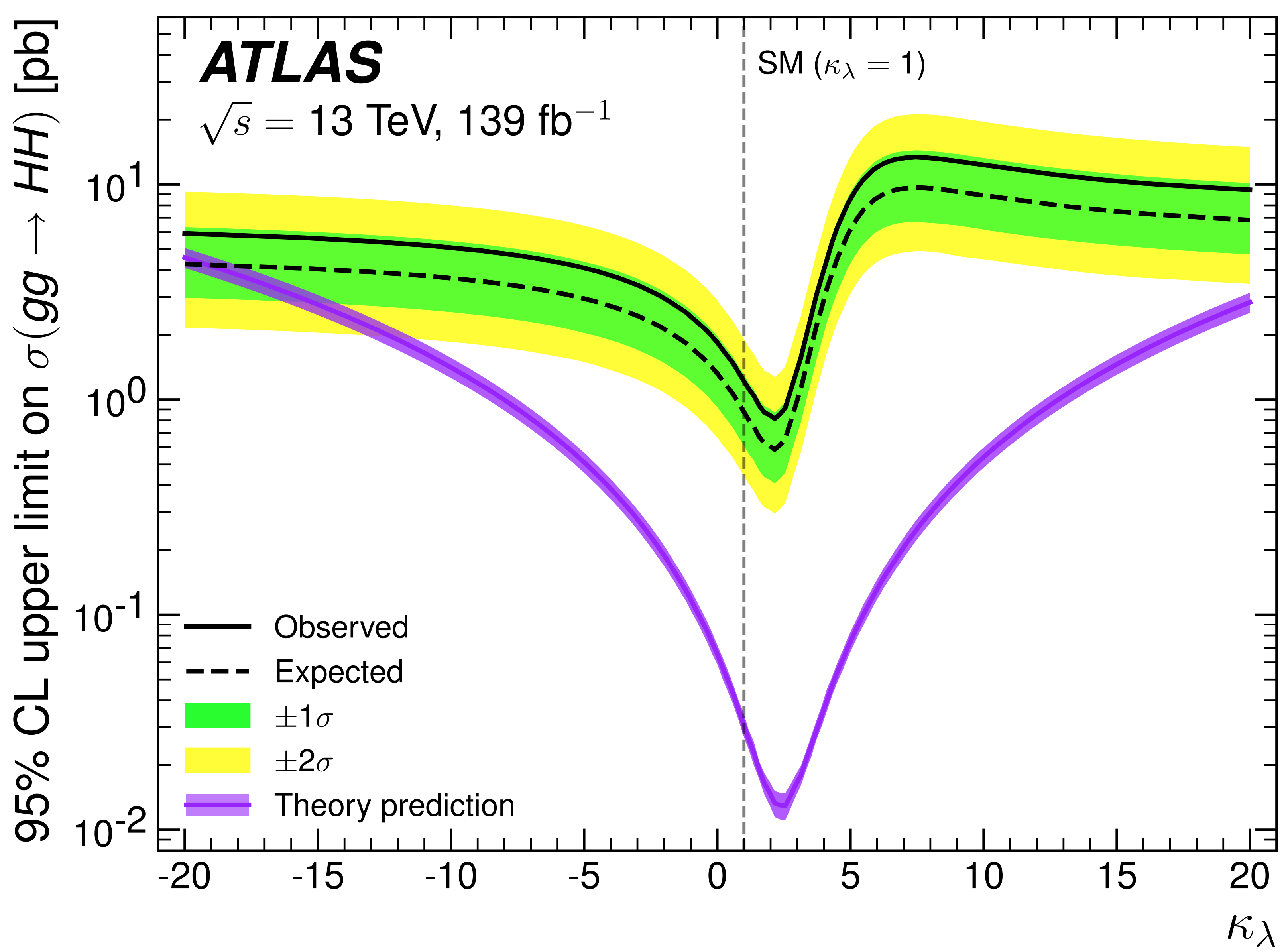
Systematic source	
	Non-Res (%)
$t\bar{t}$ modelling ISR/FSR	+30/−20
Multijet uncertainty	+10/−10
$t\bar{t}$ Matrix Element	+10/−10
W+jets modelling PDF	+4/−7
W+jets modelling scale	+9/−10
W+jets modelling gen.	+10/−8
$t\bar{t}$ modelling PS	+3/−2
b-tagging	+30/−20
JES/JER	+13/−20
E_T^{miss} soft term res.	+20/−20
Pile-up reweighting	+3/−10
Total systematic	+60/−80

Relative uncertainty on the signal yield scale factor

$b\bar{b}l\nu l\nu$ final state Resolved

Non-resonant

σ_{HH}^{ggF} **observed (expected)** limit is **40 (29)** times the SM prediction.



Comparison to CMS

$\frac{\sigma(pp\to HH)}{\sigma_{SM}}$ at 13 TeV		Partial Run 2 (2015-16)		Ful Run 2 (2015-18)	
		Obs	Exp	Obs	Exp
$HH \to bbyy$	ATLAS	20.3	26	4.1	5.5
	CMS	23.6	18.8	7.7	5.2
$HH \to bb\tau\tau$	ATLAS	12.5	15	4.7	3.9
	CMS	31.4	25.1	5.2	3.3
$HH \to bbbb$	ATLAS	12.9	21		
	CMS	74.6	36.9	3.6	7.3
Combination	ATLAS	6.9	10	2.8	2.8
	CMS	22.2	12.8		

Limit on $\kappa\lambda$ at 95% C.L.		Observed	Expected
$HH \to bb\gamma\gamma$	ATLAS	-1.5 – 6.7	-2.4 – 7.7
	CMS	-3.3 – 8.5	-2.5 – 8.2
$HH \to bb\tau\tau$	ATLAS	-2.4 – 9.2	-2.0 – 9.0
	CMS	-1.8 – 8.8	-3.0 – 9.9
$HH \to bbbb$	ATLAS		
	CMS	-2.3 - 9.4	-5.0 - 12.0
Combination	ATLAS	-1.0 - 6.6	-1.2 - 7.2
	CMS		

Limit on κ2v at 95% C.L.		Observed	Expected
$HH \to bb\tau\tau$	ATLAS		
	CMS	-0.4 - 2.6	-0.6 - 2.8
$HH \to bb\gamma\gamma$	ATLAS		
	CMS	-1.3 - 3.5	-0.9 - 3.1
$HH \to bbbb$	ATLAS	-0.4 - 2.6	-0.6 - 2.7
	CMS	-0.1 - 2.2	-0.4 - 2.5