HH non-resonant and self-coupling at ATLAS+CMS

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On behalf of the ATLAS and CMS collaborations

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→

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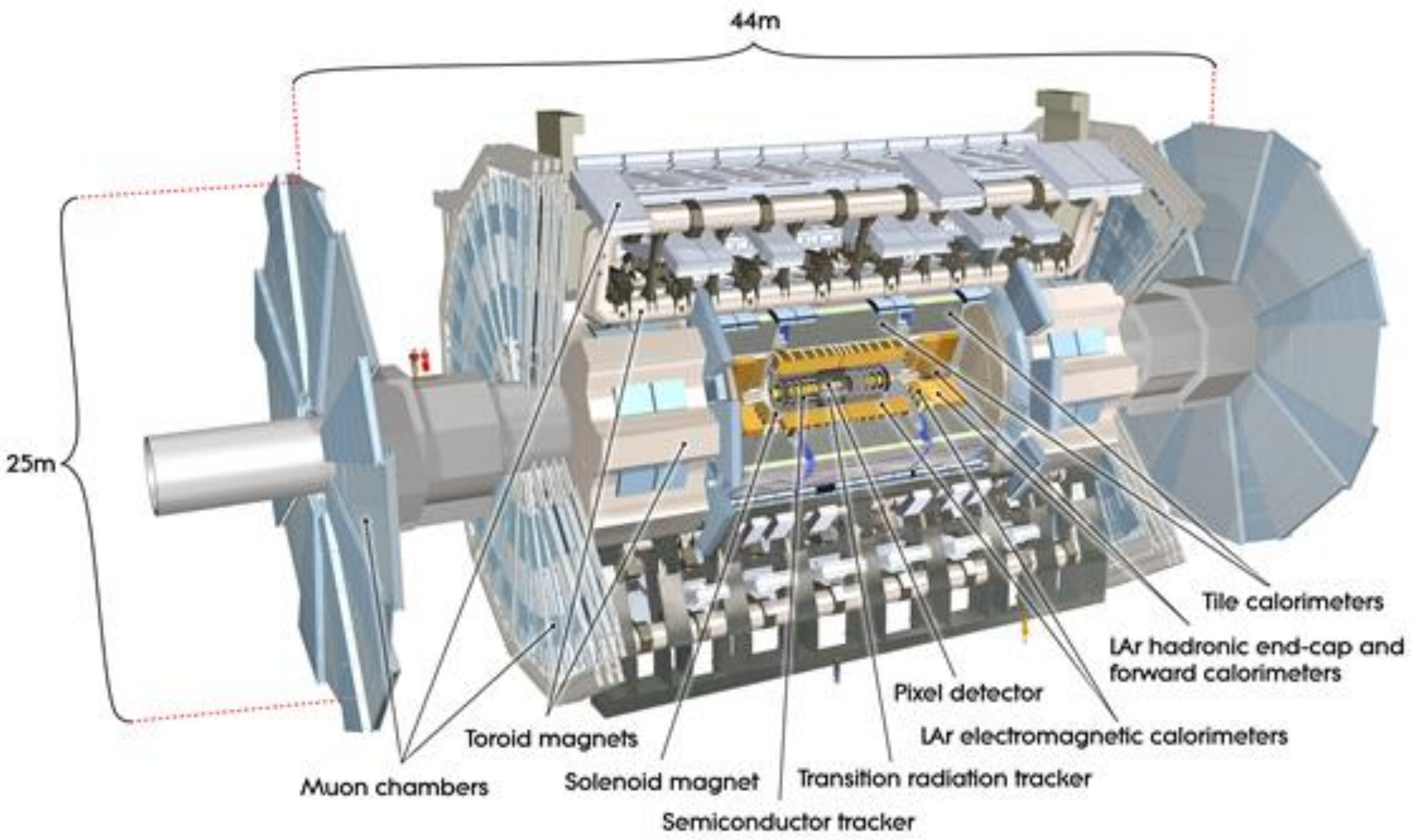
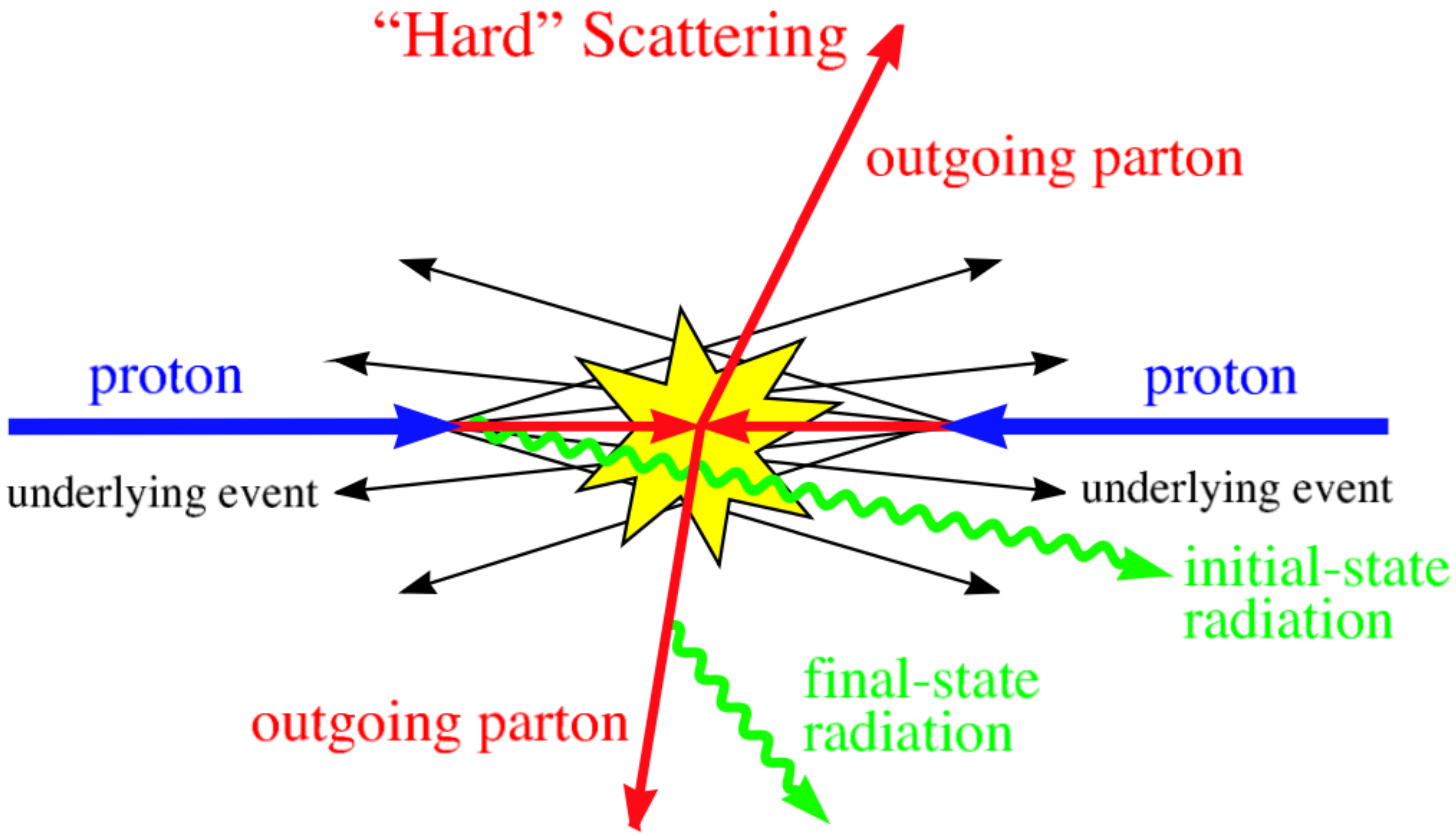
Stockholm University

The same things can be said about CMS!

The ATLAS experiment

- ATLAS is one of the 4 experiments of the Large Hadron Collider (LHC) at CERN, in Geneva, Switzerland.
- Proton bunches are accelerated in opposite directions in the LHC ring and collided at the centre of the experiment with a collision centre of mass energy of 13 TeV.





- The outgoing partons of the p p collision are then detected by the many layers of detecting material that compose ATLAS.
  - Inner tracking detector: charge and momentum of charged particles.
  - Calorimeters: energy of electrons, photons and hadrons.
  - Muon spectrometer: detection of muons.

Object reconstruction

- <u>Tracks and vertices:</u>

Charged particles produce hits in the inner detector (ID)

Tracks → hit trajectories
Vertices → origin of two or more tracks

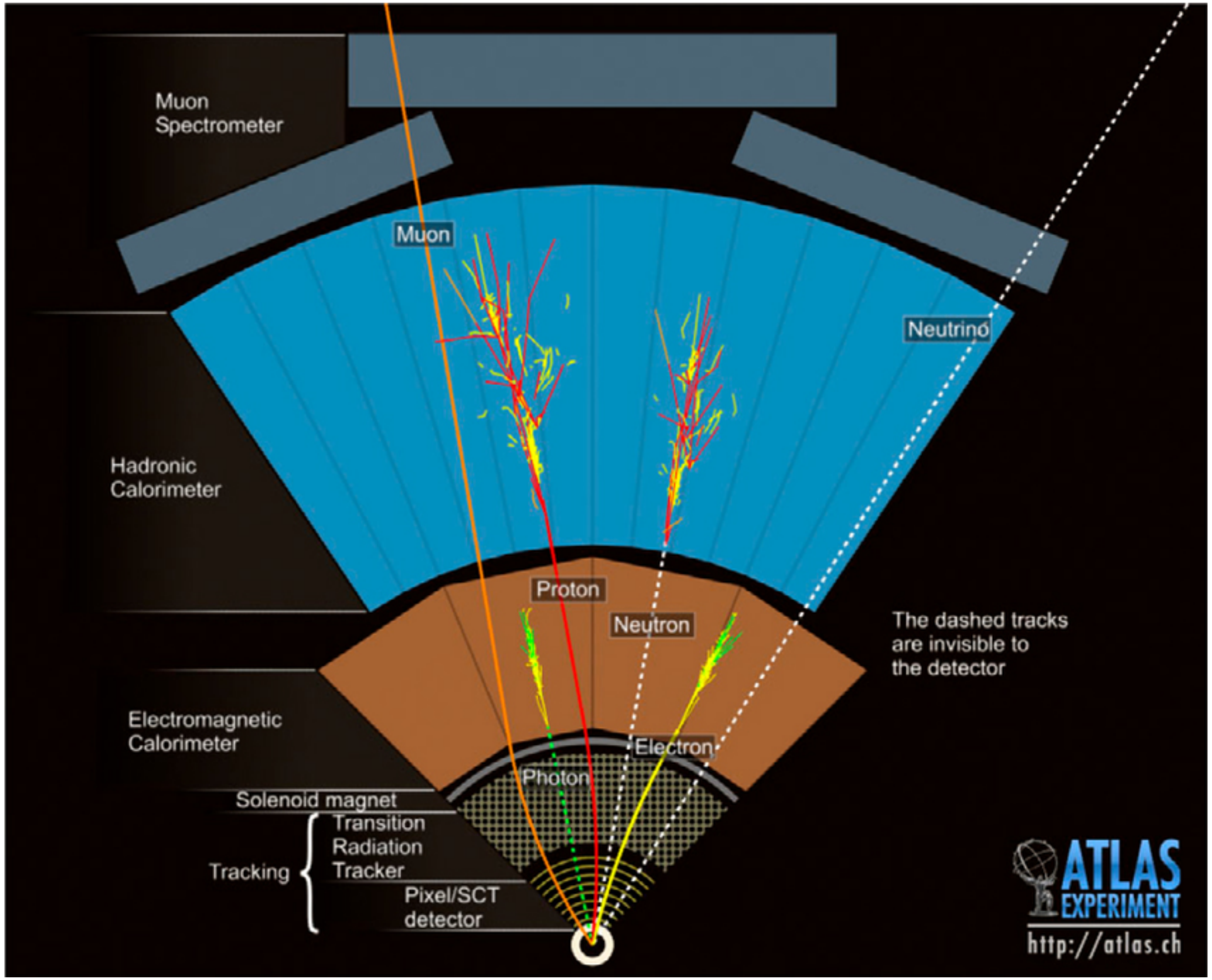
- <u>Electrons and photons:</u>

Deposit all their energy in the electromagnetic calorimeter

Electrons are charged→ leave a track in the ID
Photons are neutral→ no track in the ID

- <u>Muons:</u> Escape the calorimeters and leave hits in both the ID the muon spectrometer

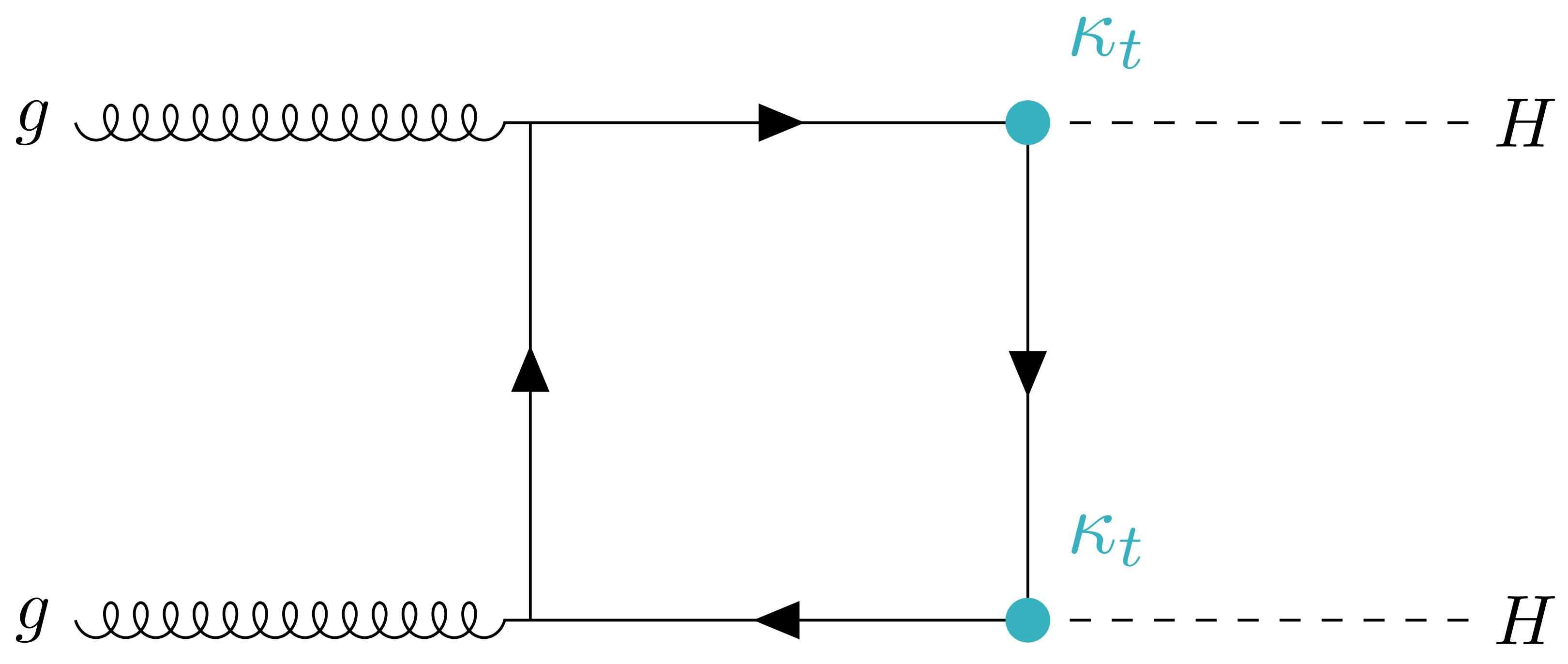
- <u>Jets:</u> The partons produced in the collision form hadrons which will interact with the calorimeter material producing cone-like showers in the hadronic calorimeter.

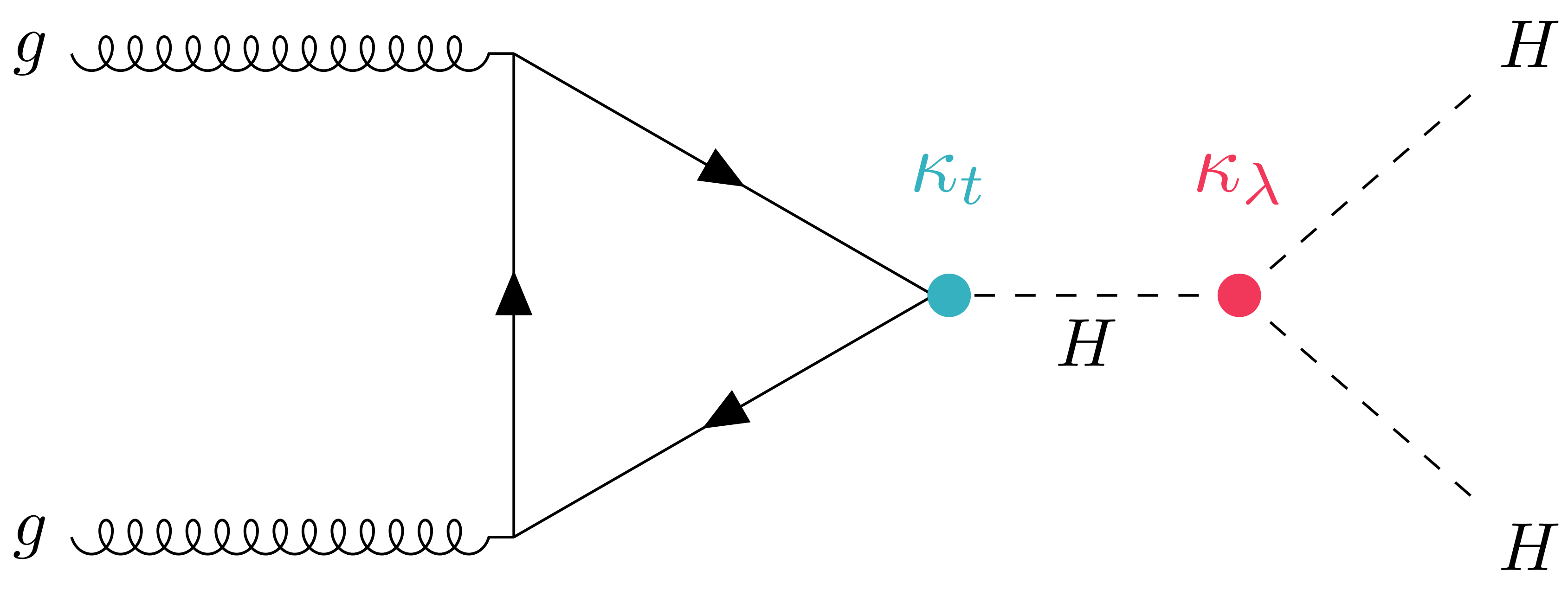


$ggF\ HH$ production

- Measuring HH production will gives us access to the triple Higgs coupling (self coupling) λ_3, which gives information of the shape of the Higgs potential $V(H) = \frac{1}{2}m_H^2H^2 + \lambda_3 \nu H^3 + \frac{1}{4}\lambda_4 \nu H^4 + O(H^5)$.

- The leading HH production mode is gluon gluon fusion (ggF):





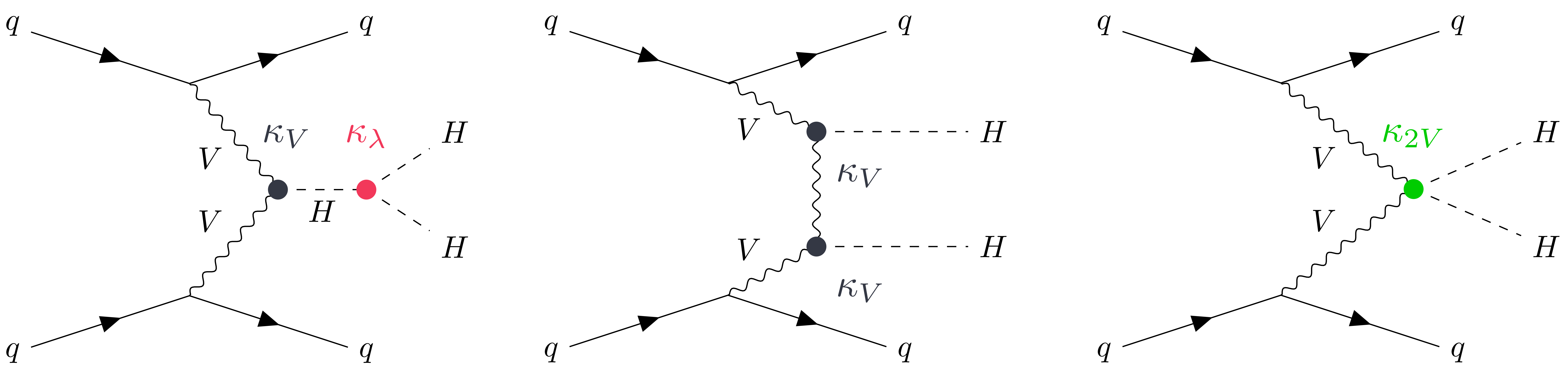
- The coupling modifier κ_λ controls the strength of the Higgs self coupling with respect to SM: $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$

- Destructive interference between the two diagrams results in a very small SM cross section of $\sigma_{ggF}^{HH} = 31.05$ fb at $\sqrt{s} = 13$ TeV.

$VBF\ HH$ production

- HH production through VBF is the sub-leading HH production mode with a SM cross section of $\sigma^{HH}_{VBF} = 1.73$ fb at $\sqrt{s} = 13$ TeV (calculated at N3LO)

- The coupling modifiers κ_λ, κ_V and κ_{2V} control the strength of the $g_{HHH} = \frac{3m_H}{v^2}$, $g_{VVH} = \frac{2m_V^2}{v}$ and $g_{VVHH} = \frac{2m_V^2}{v^2}$ couplings with respect to the SM value.



- Given the larger cross section, searches for $ggF\ HH$ production provide better sensitivity to κ_λ but the VBF topology has a unique sensitivity to κ_{2V}.

HH decay modes

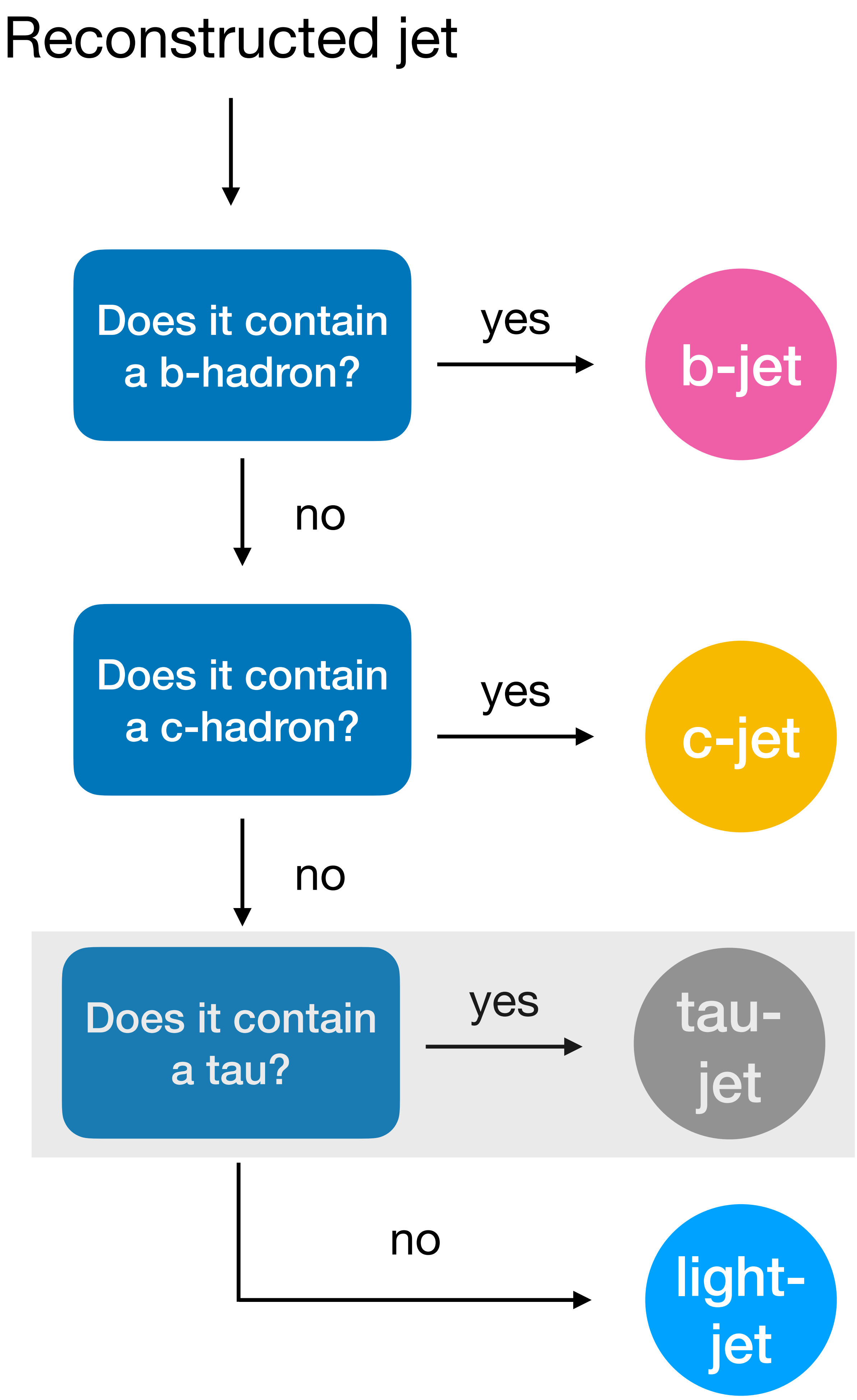
- Due to the large branching ratio (BR), most searches require at least one $H \to b\bar{b}$. Different decay modes of the second Higgs are considered.

Targeted HH decays shown today

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

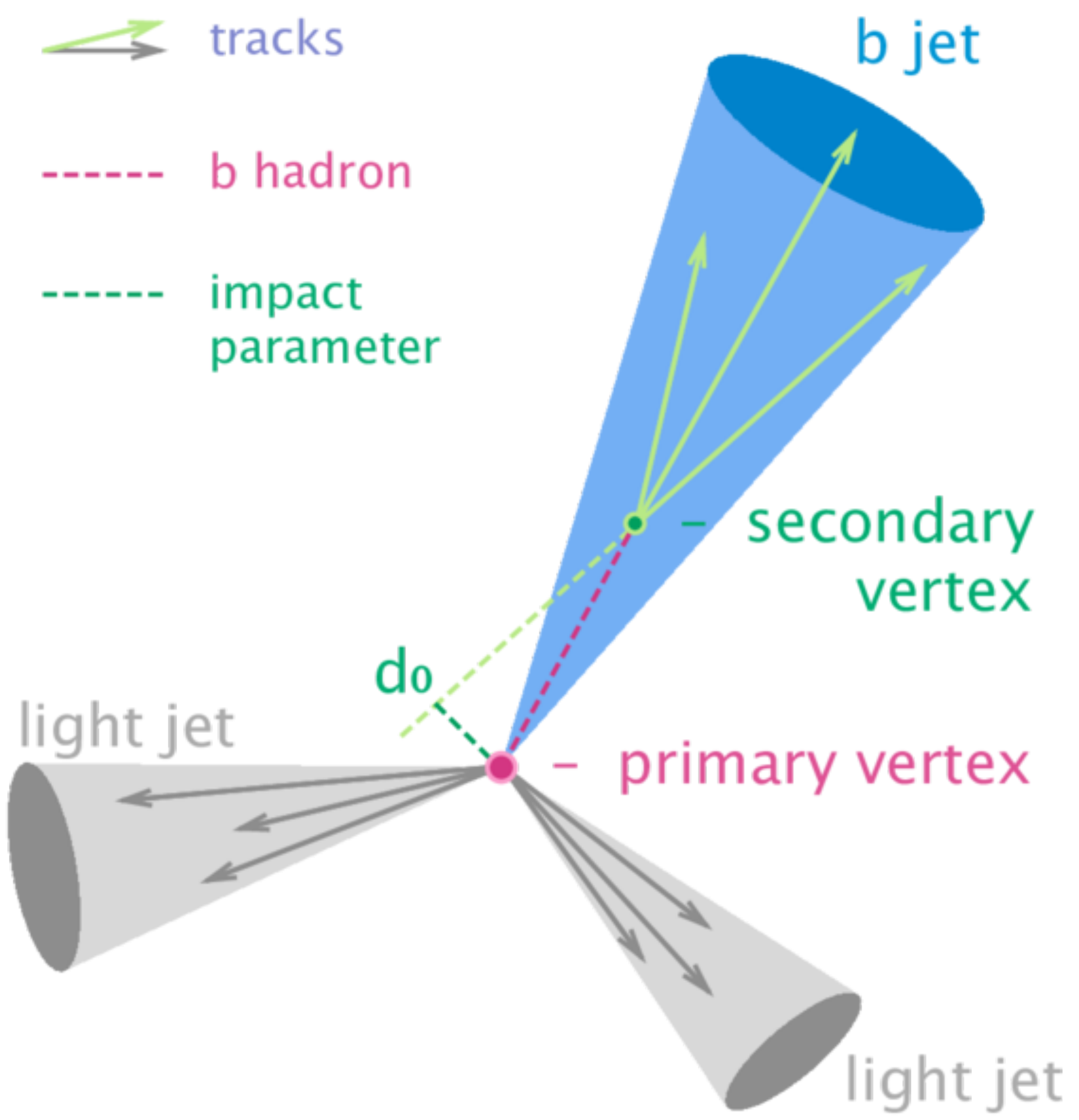
- ATLAS and CMS searches with full run 2 data for the following decay modes are presented:
  - $b\bar{b}b\bar{b}$ has the largest BR but large backgrounds arising from multijet production are challenging.
  - $b\bar{b}WW$, $b\bar{b}ZZ$ and $b\bar{b}\tau\tau$ have smaller BRs and can benefit from using leptons for triggering (hadronic $b\bar{b}\tau\tau$ searches won't be presented).
  - $b\bar{b}\gamma\gamma$ has the smallest BR but it's a very sensitive analysis thanks to the clean $m_{\gamma\gamma}$ resolution.
- Other final states without any $H \to b\bar{b}$ are also included in the combinations with partial run 2 data.

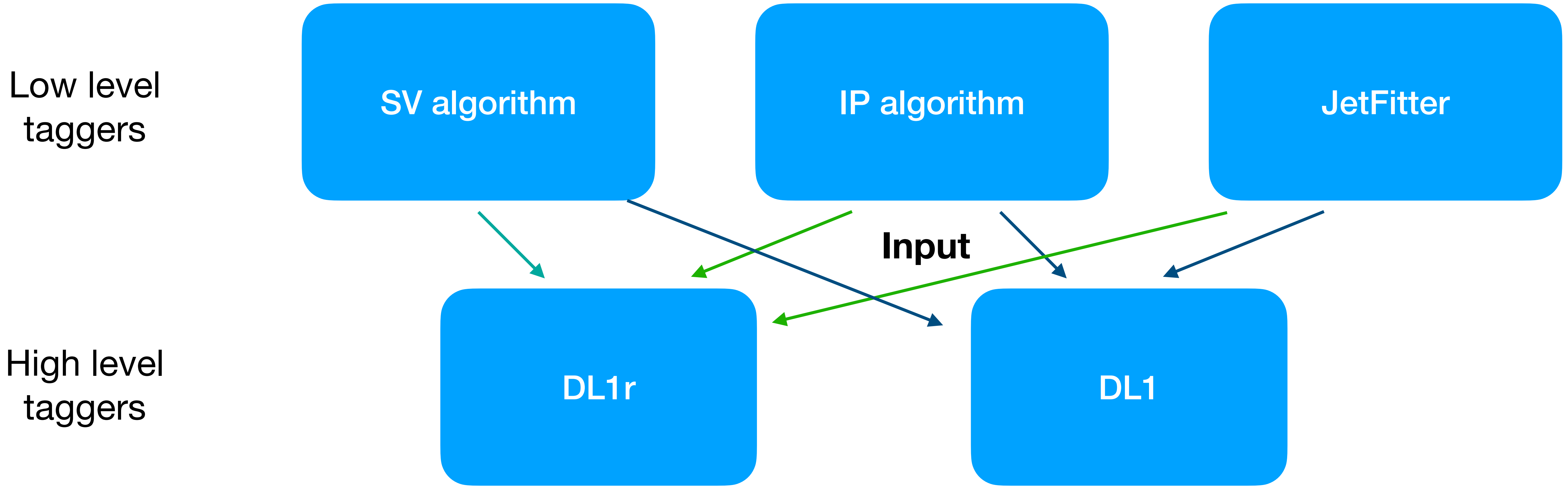
b-tagging



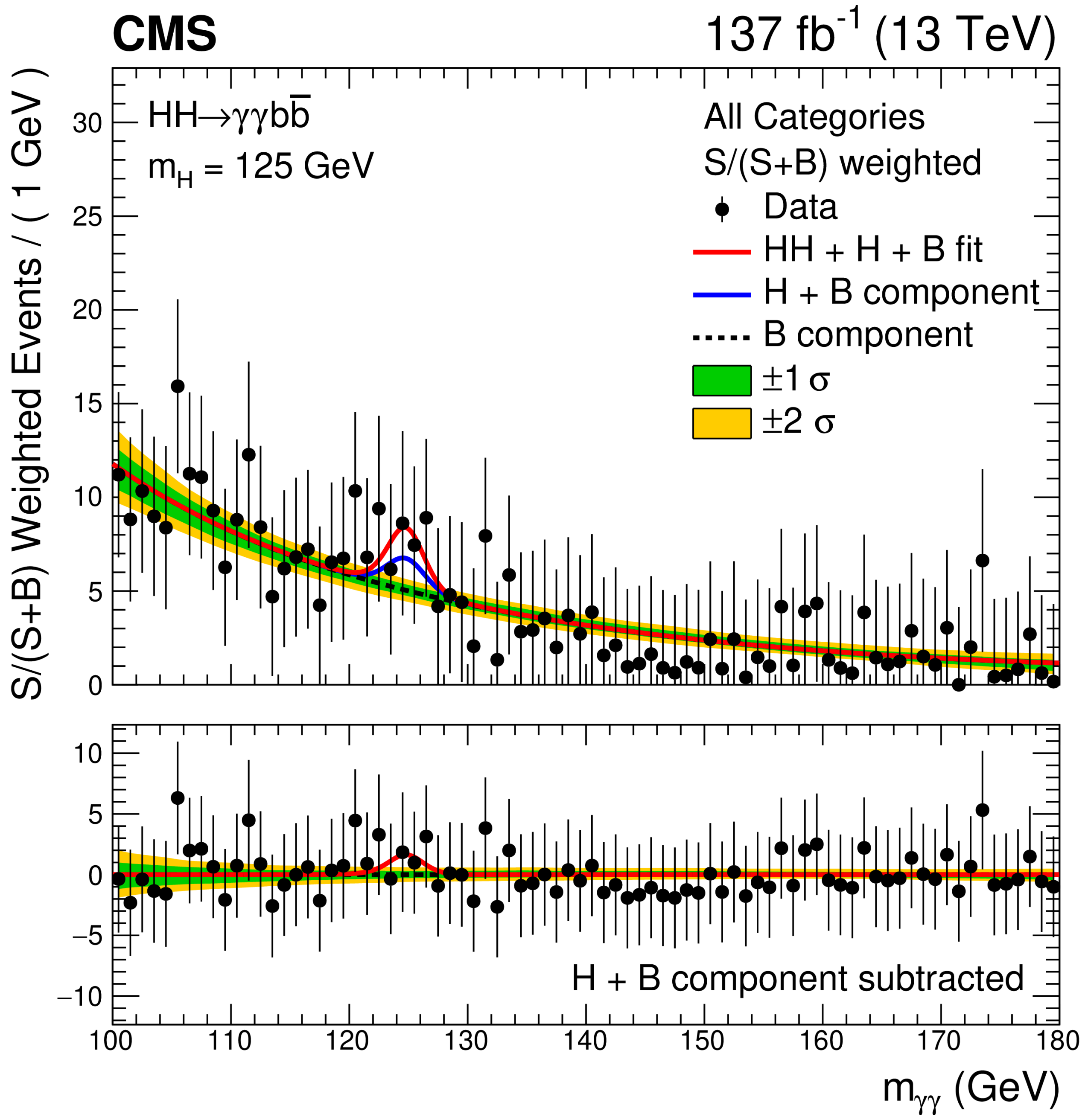
- **Low level taggers** detect b-jets by focusing on features sensitive to the jet flavour (e.g due to the long lifetime of b-hadrons).

- **High level taggers** are trained using low-level taggers as input, resulting in better predictions.
  - DL1 and DL1r taggers = Neural Networks

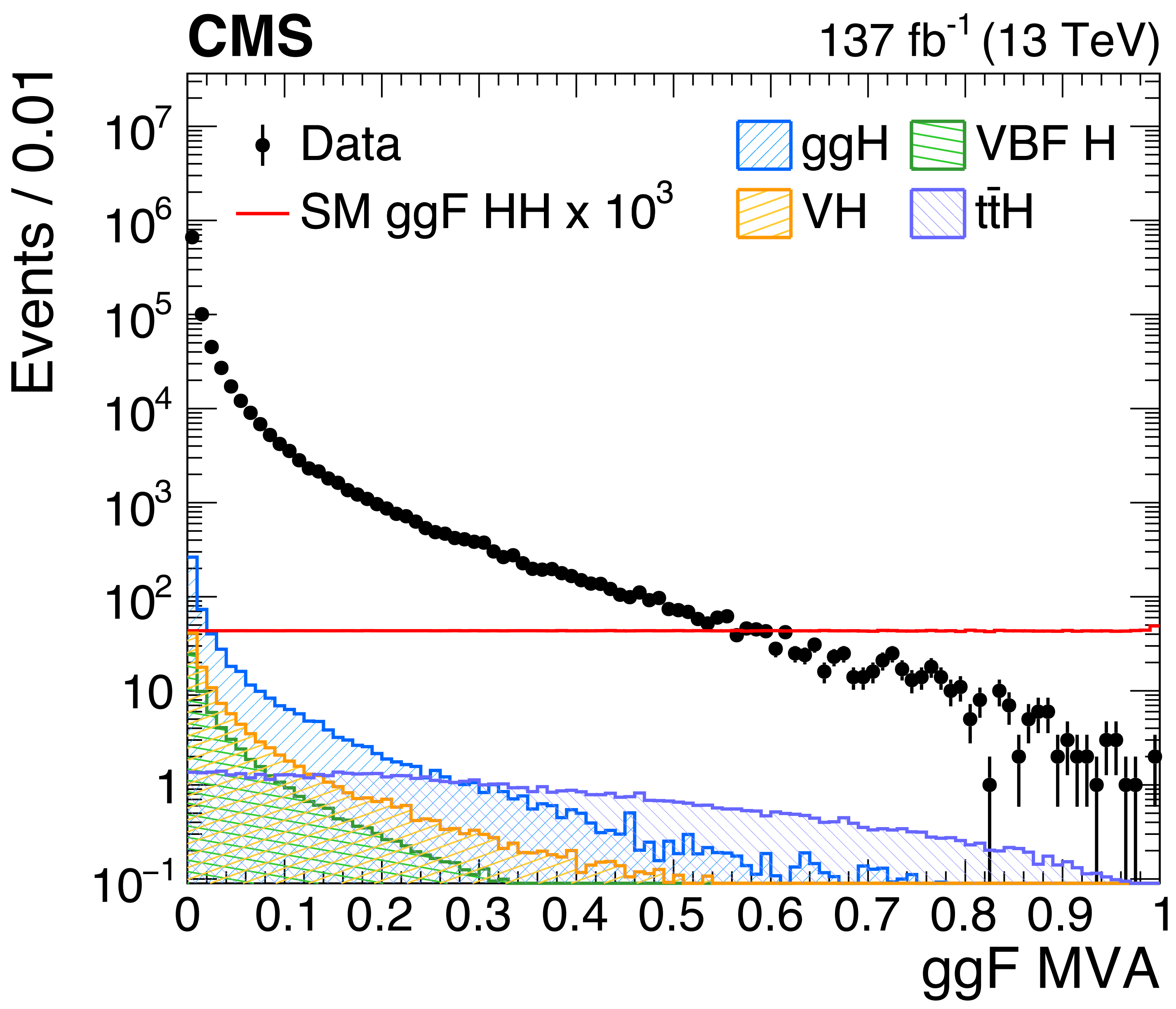


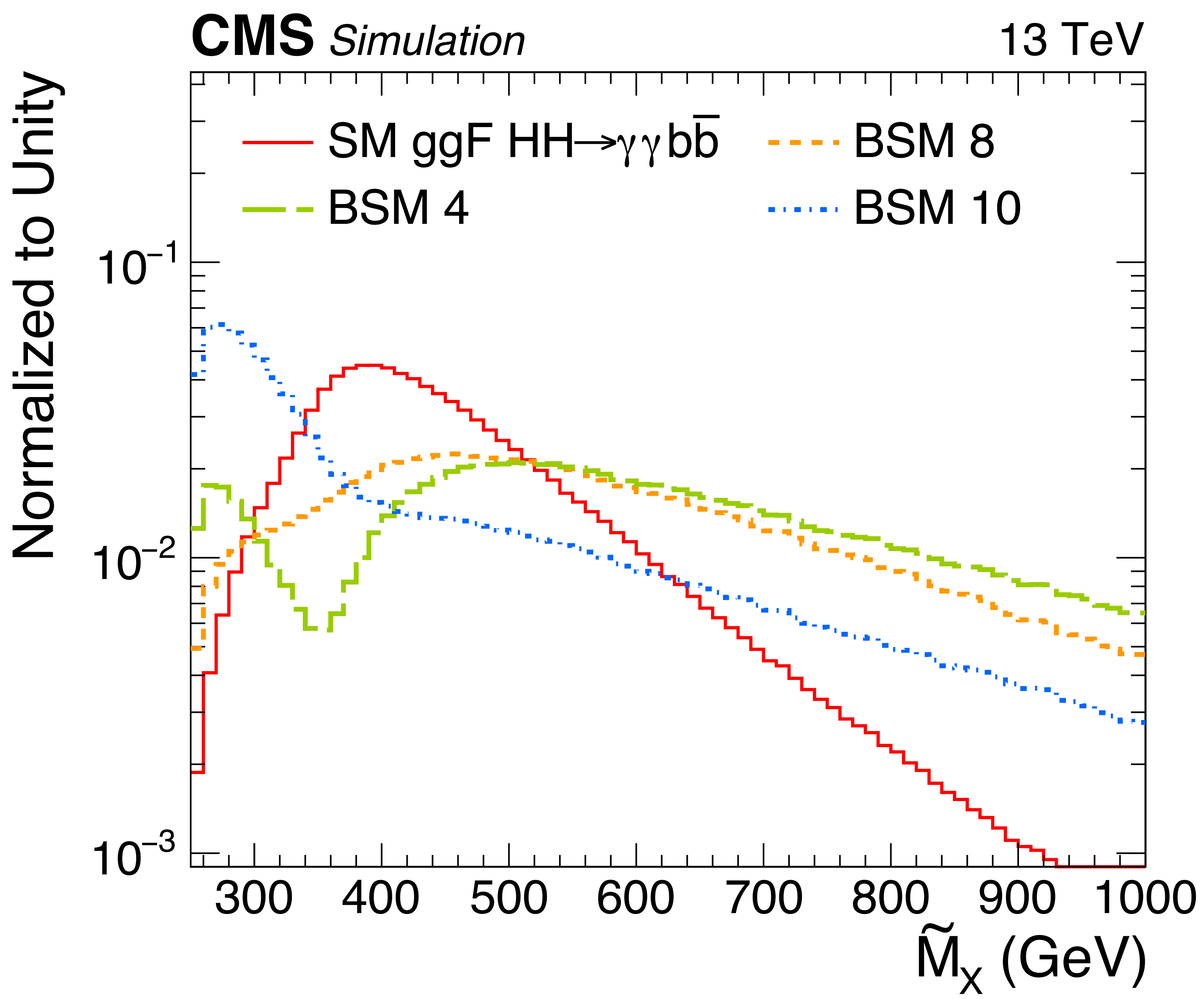


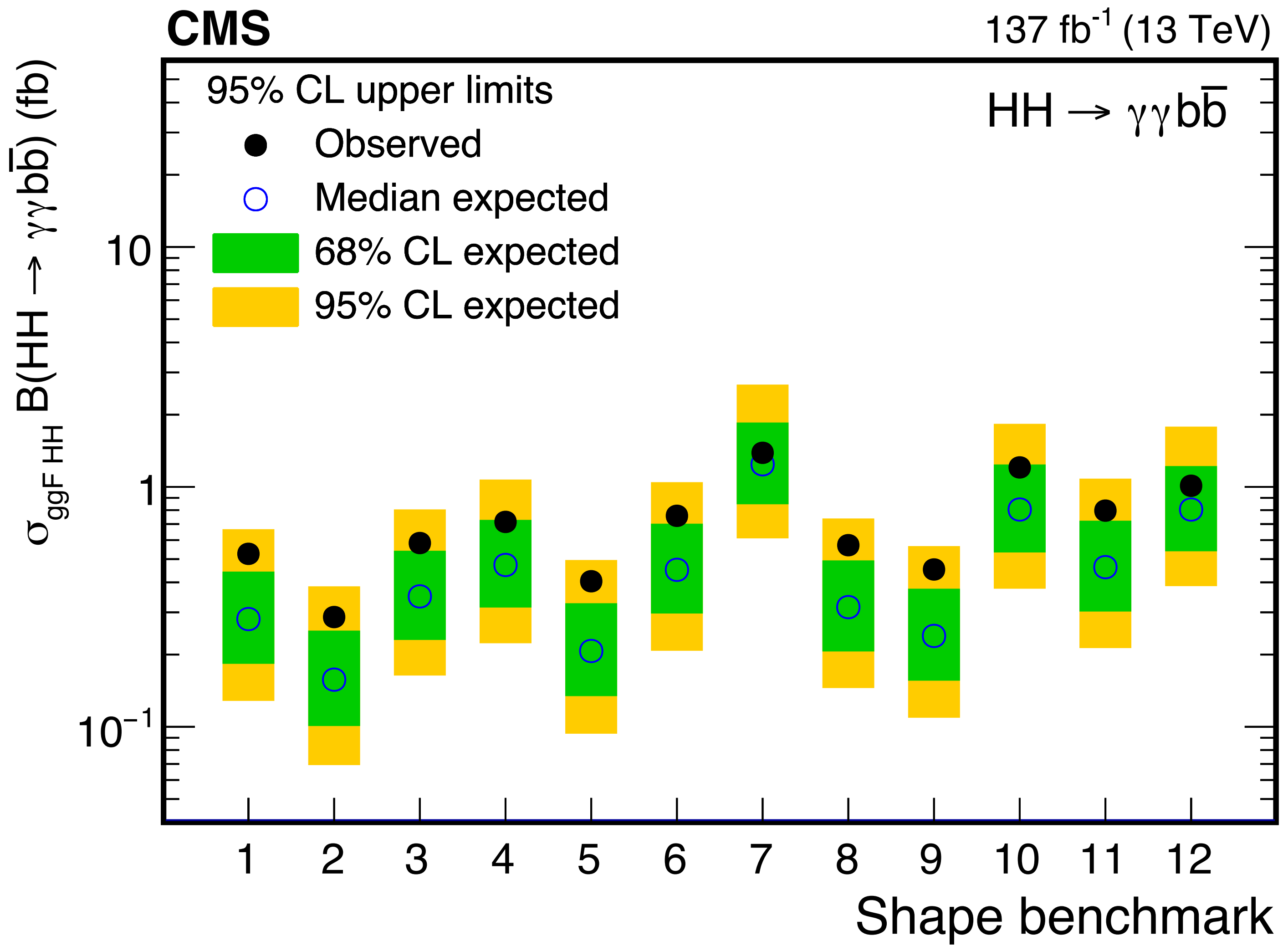
CMS $HH \rightarrow bb\gamma\gamma$ (137 fb^{-1})



- A ggF and VBF BDT are used to discriminate the HH signals against background + a DNN is also used to further discriminate against $t\bar{t}H$.
- Multiple regions optimised for $ggF\ HH$ (12 regions) or $VBF\ HH$ (2 regions) are defined from the MVA scores and $\tilde{M}_X = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 2m_h$.
- A 2D fit to $m_{\gamma\gamma}$ and m_{jj} side bands is performed in all regions to estimate the non-resonant backgrounds with data.







$ggF\ HH$ HEFT shape benchmarks are included in the optimisation of the ggF regions

CMS $HH \to bb\gamma\gamma$ (137 fb^{-1})

Check out Soumya Mukherjee's poster for details

- This search is limited by statistics

Observed (expected) limits are presented for different observables at 95% CL:

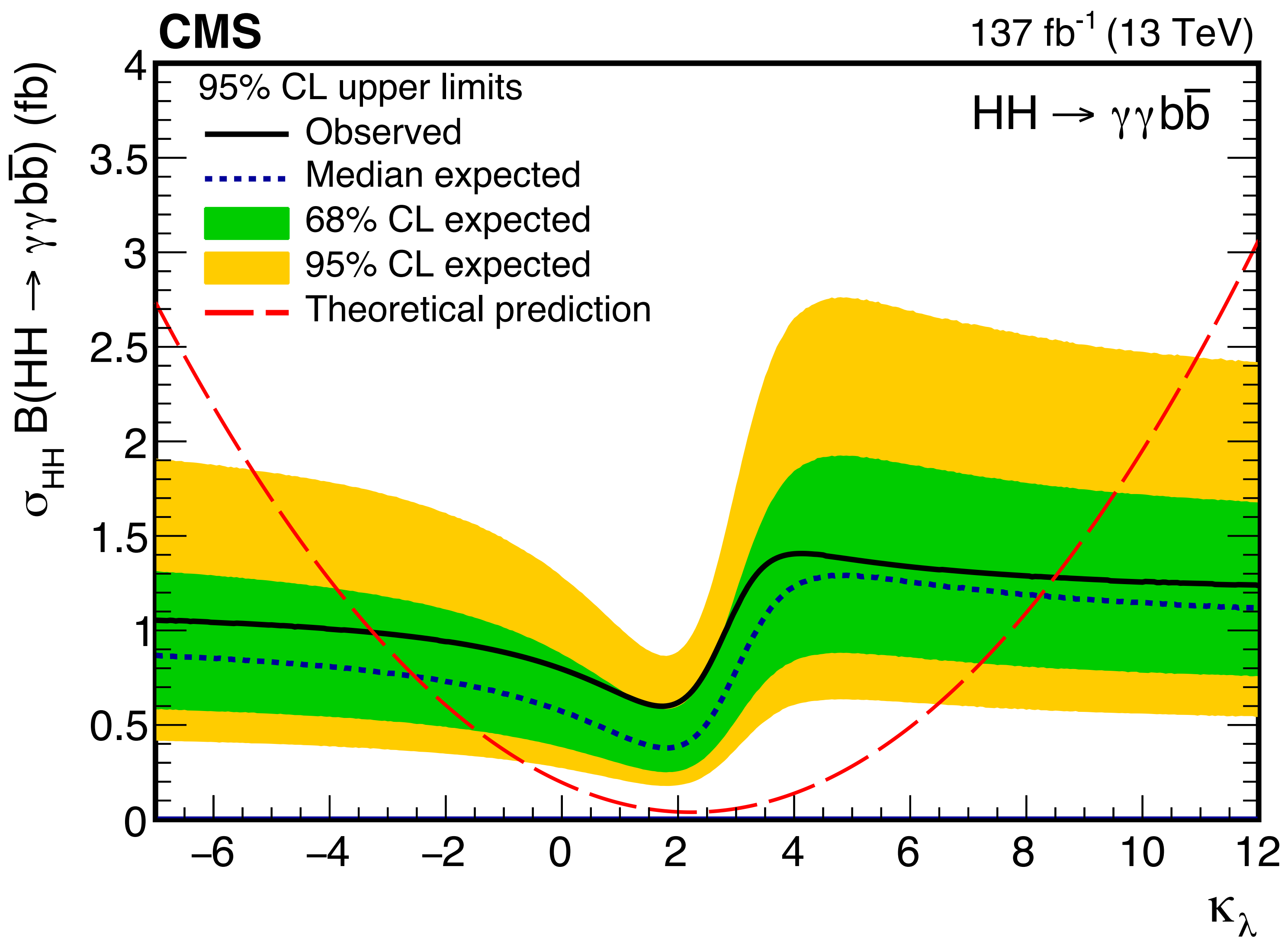
- $\sigma^{HH}_{ggF+VBF} < 7.7\ (5.2) \times \sigma^{HH\ SM}_{ggF+VBF}$
- $-3.3\ (-2.5) < \kappa_\lambda < 8.5\ (8.2)$

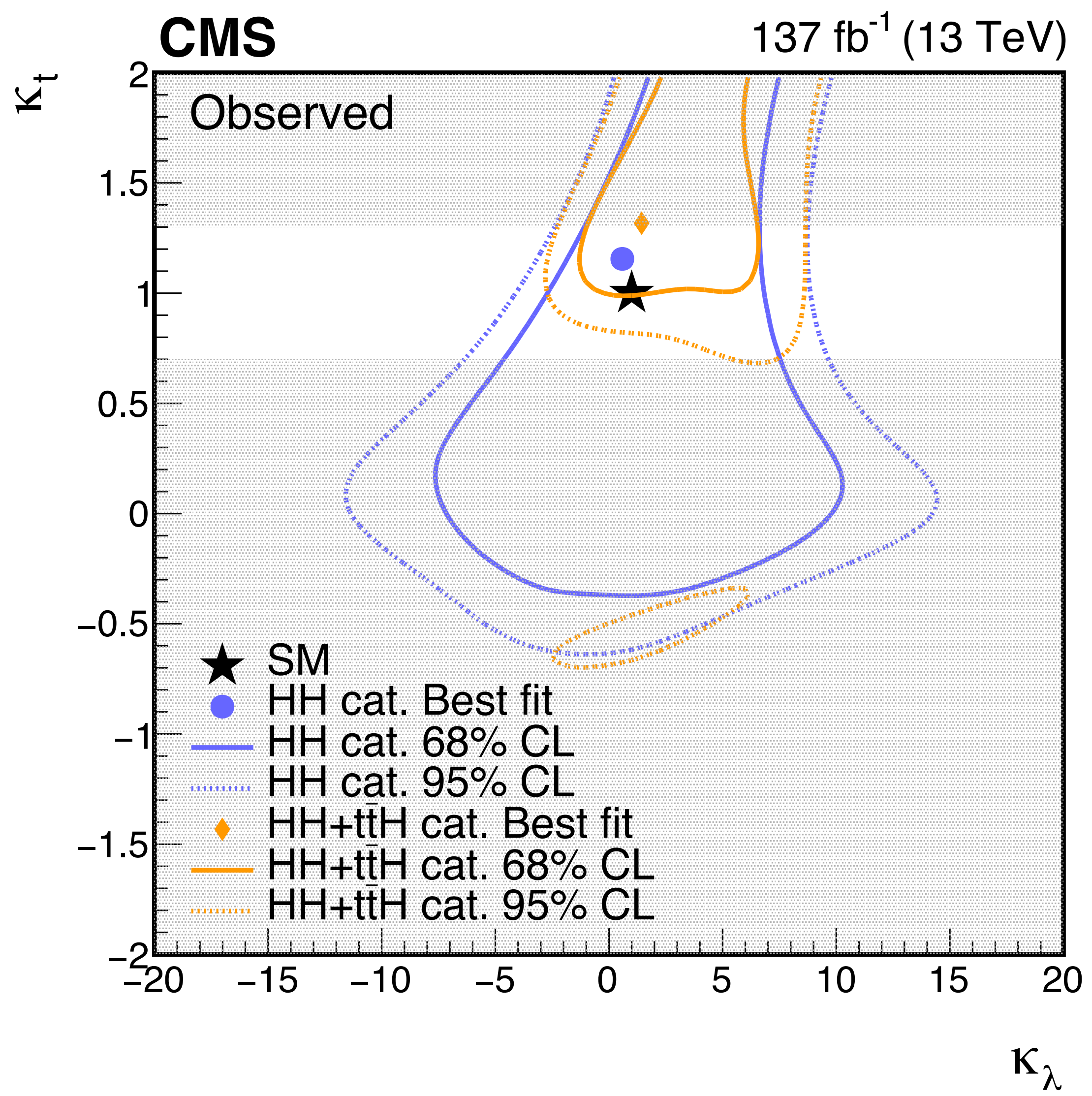
- Fixing $\sigma^{ggF\ HH}$ to SM:

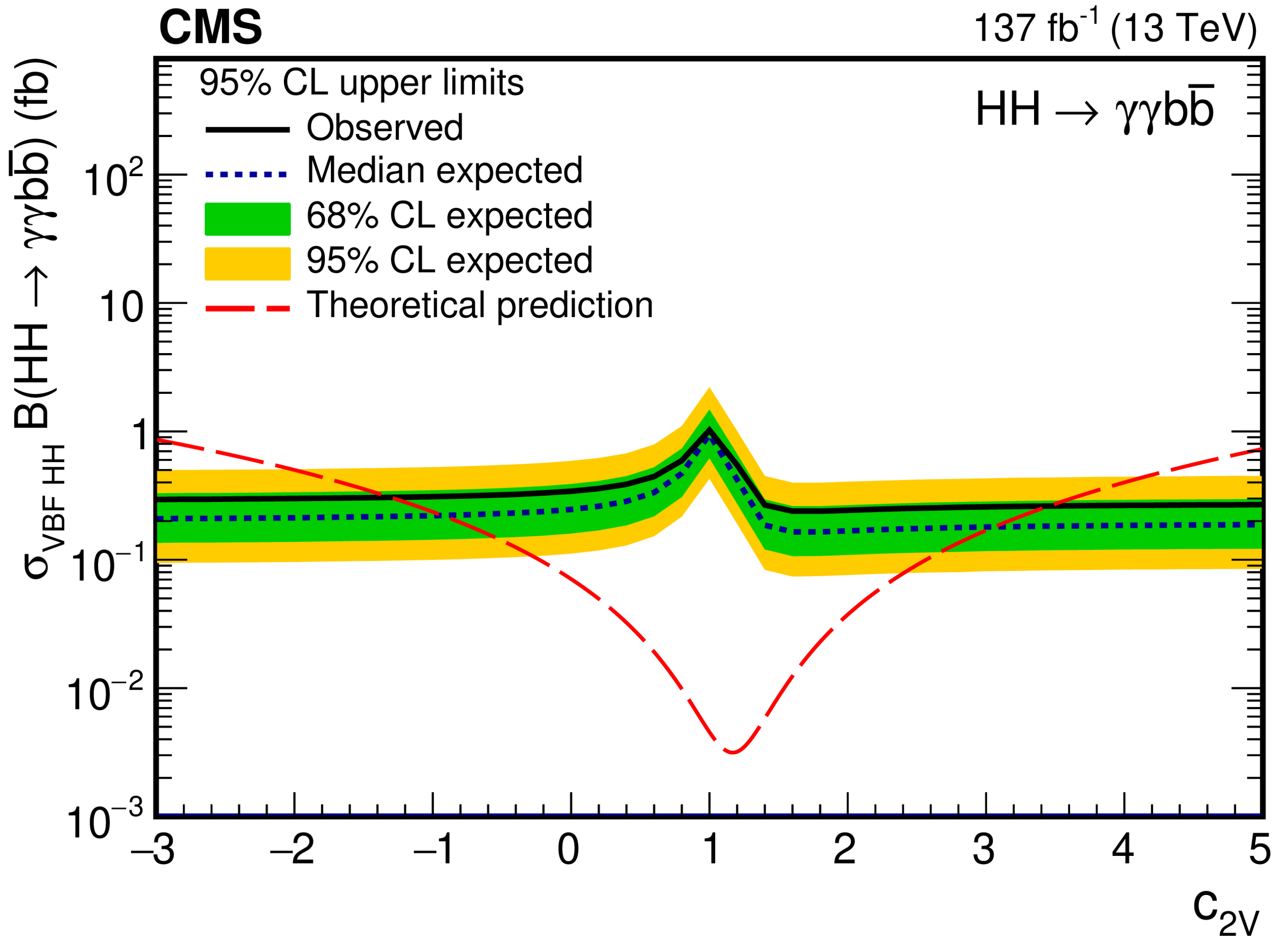
- $\sigma^{HH}_{VBF} < 225\ (208) \times \sigma^{HH\ SM}_{VBF}$
- $-1.3\ (-0.9) < \kappa_{2V} < 3.5\ (3.1)$

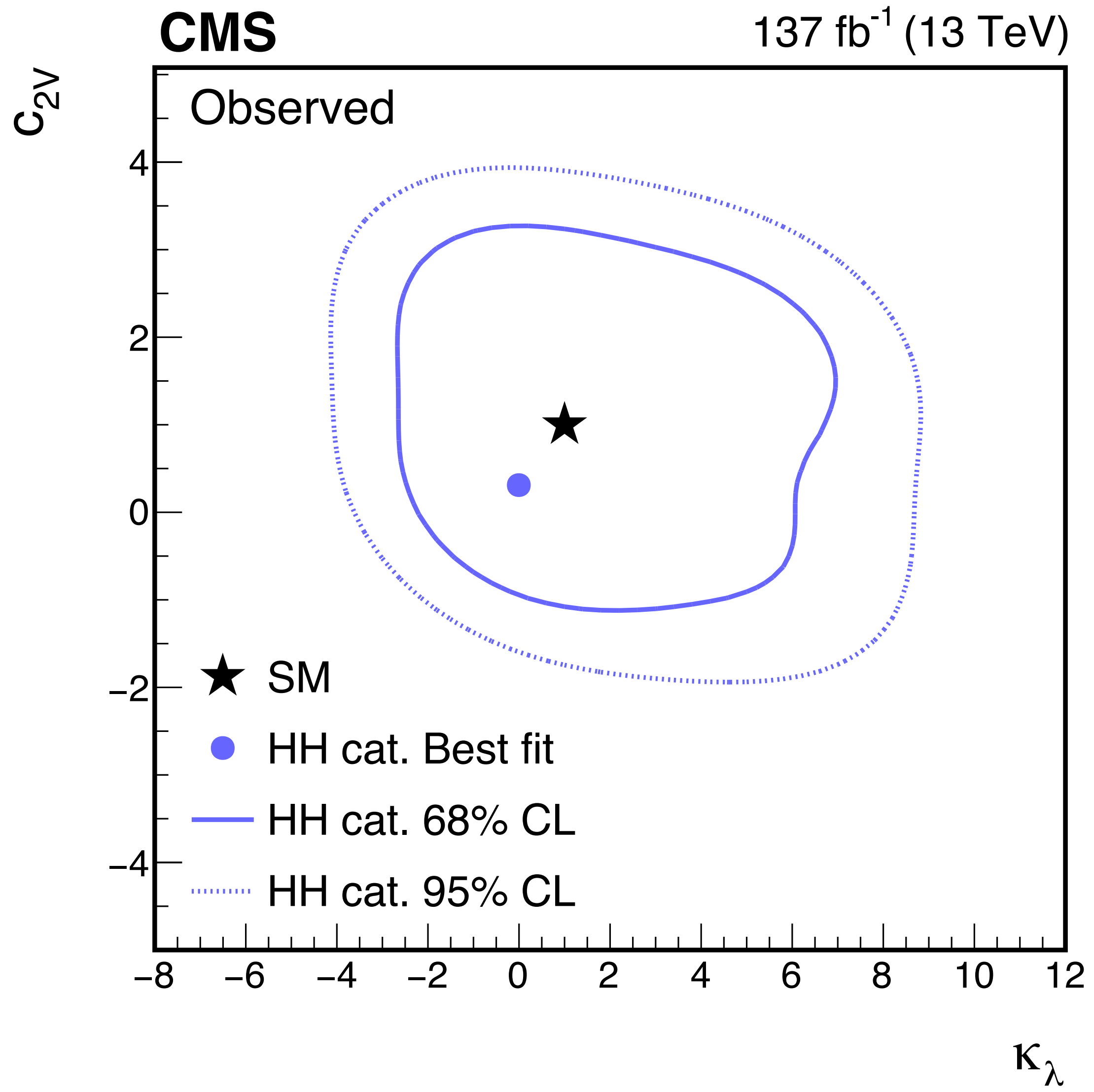
- Fixing σ^{HH}_{VBF} to SM:
  - $\sigma^{HH\ BSM}_{ggF}$ on 12 BSM Higgs EFT shape benchmarks

- 2D scans to the κ_t vs κ_λ and κ_{2V} vs κ_λ planes
  - A $t\bar{t}H$ cat is added to improve sensitivity to κ_t









ATLAS $HH \rightarrow bb\gamma\gamma$ (139 fb^{-1})

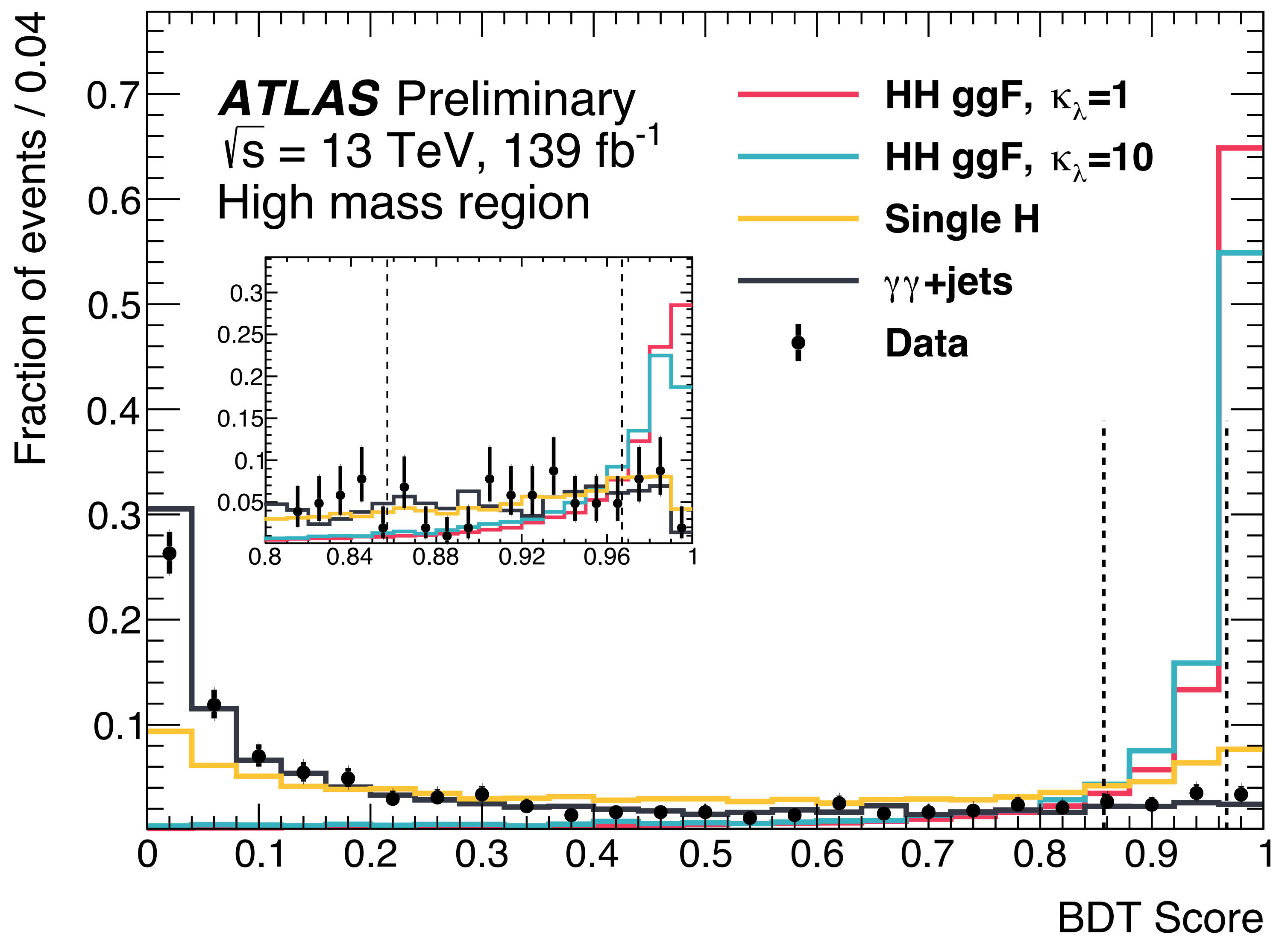
Check out Alex Zeng Wang's poster for details

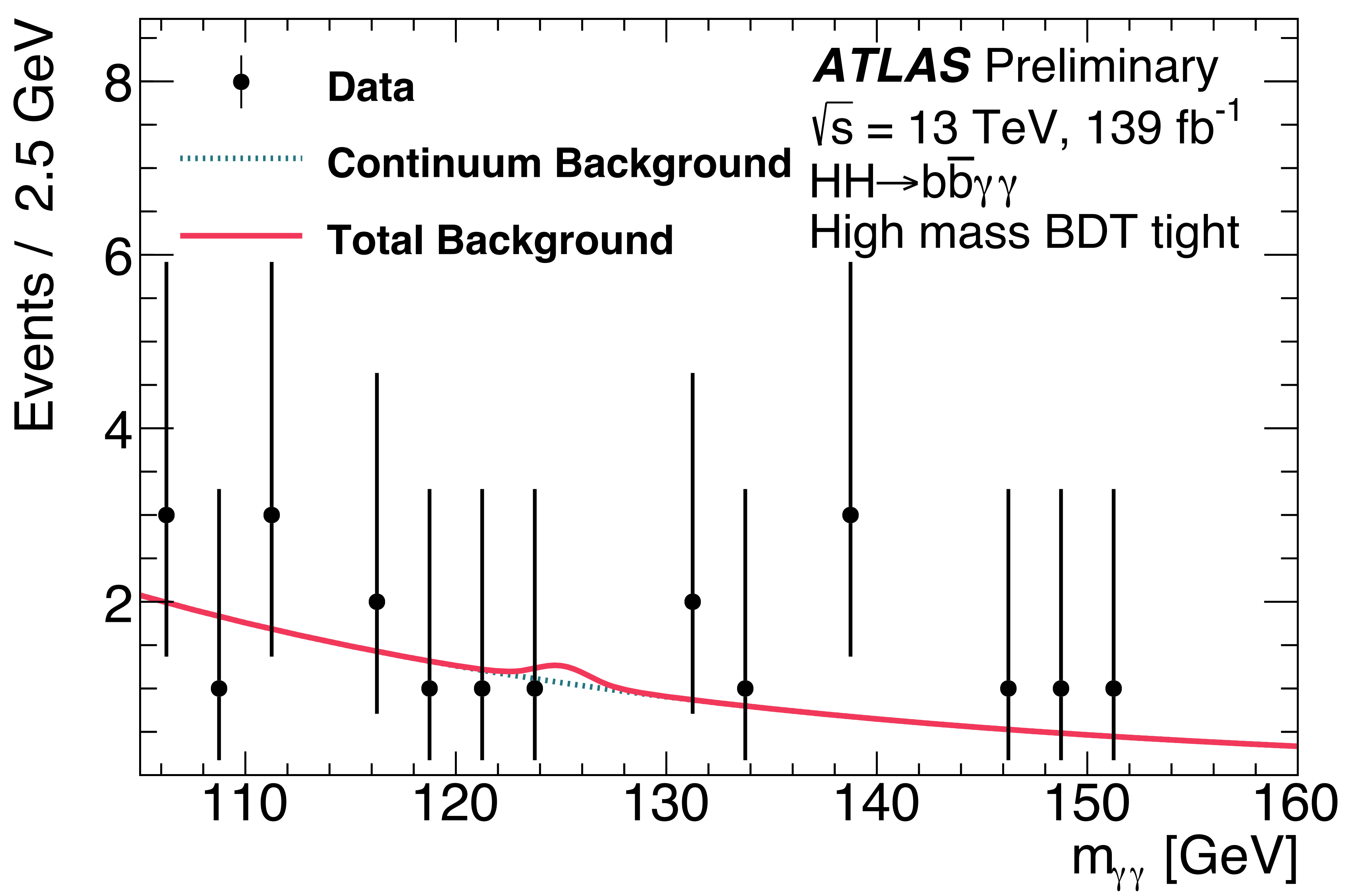
- Two different BDTs are used for events with high/low $\tilde{M}_X$ masses to discriminate $\kappa_\lambda = 1$ or $\kappa_\lambda = 10$ $ggF\ HH$ against background. A total of 4 regions are defined from cuts on the score of the BDTs.
- The analysis is optimised for $ggF\ HH$, however $VBF\ HH$ events are also considered as signal.
- The $m_{\gamma\gamma}$ SB are fit to estimate the non-resonant background with data.

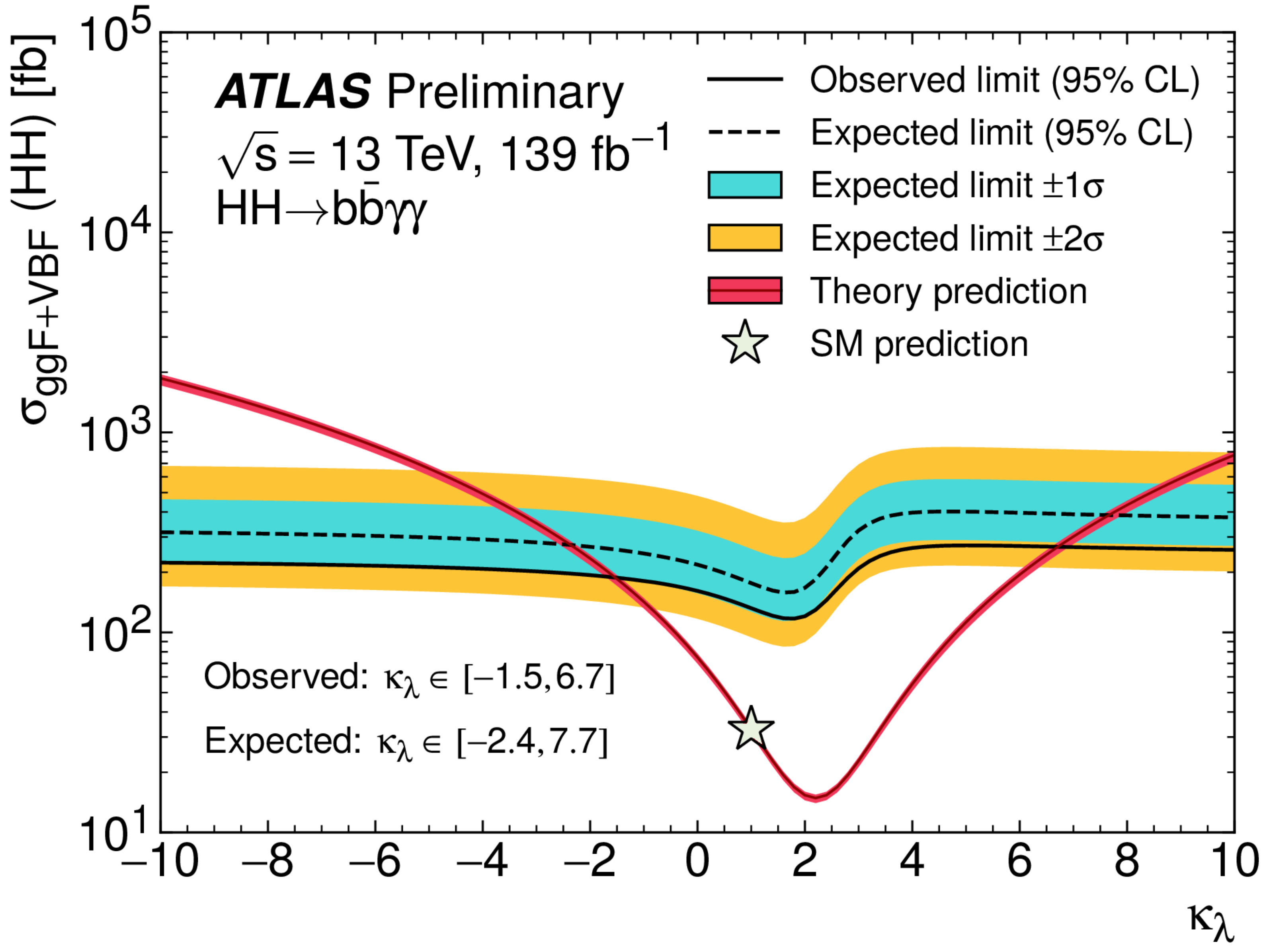
- The sensitivity of the analysis is limited by the statistical precision

Observed (expected) limits:

- $\sigma^{HH}_{ggF+VBF} < 4.1\ (5.5)\ \times \sigma^{HH\ SM}_{ggF+VBF}$
- $-1.5\ (-2.4) < \kappa_\lambda < 6.7\ (7.7)$



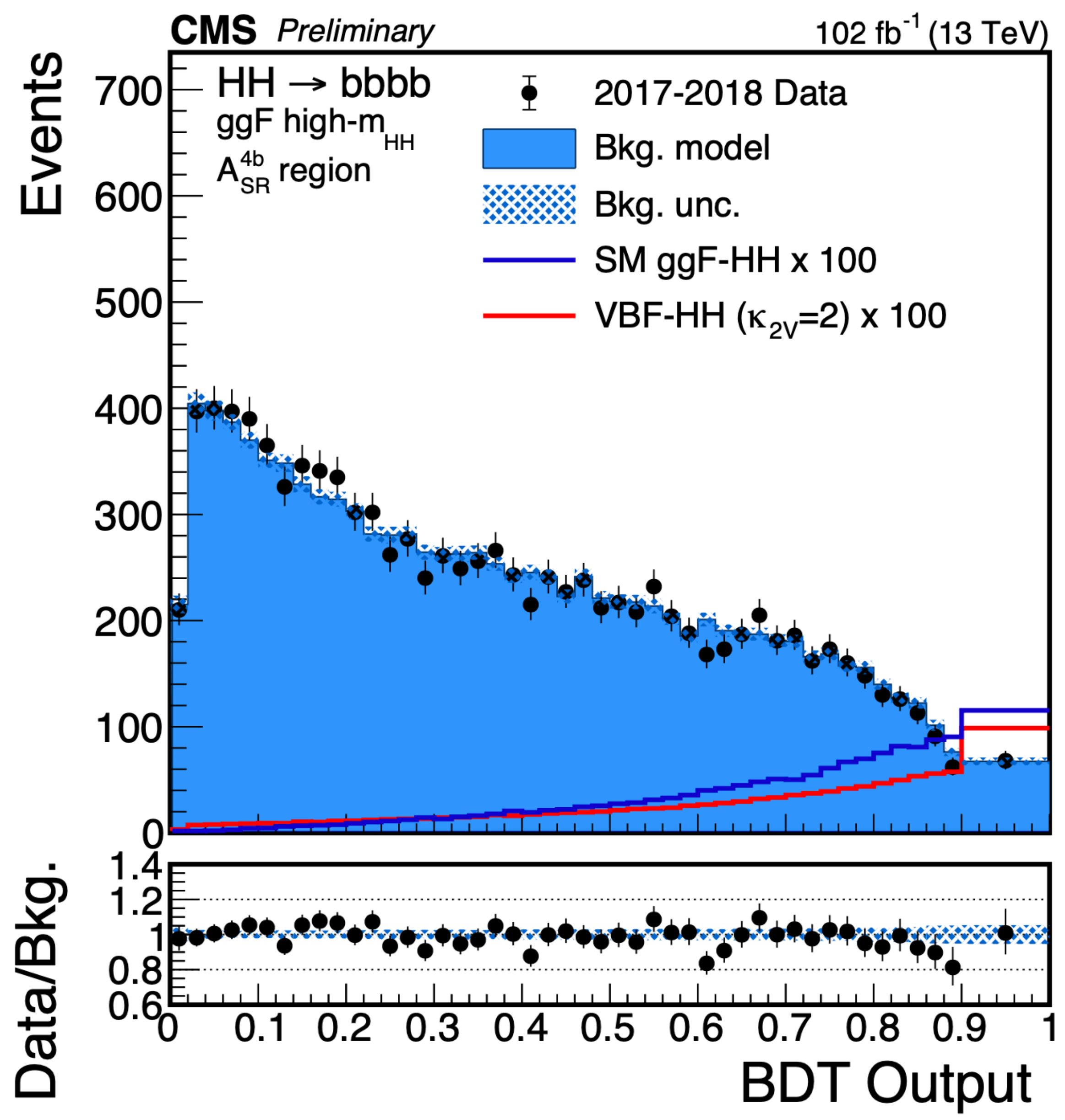




CMS $HH \to bbbb$ (138 fb^{-1})

NEW!

- HH candidates are reconstructed from the 4 jets and $\chi = \sqrt{(m_{H_1} - 125)^2 + (m_{H_2} - 120)^2}$ is used to divide events in SR and CR.
- VBF candidates are selected by requiring 2 additional non b-jets and a VBF-vs-ggF BDT is used to reduce mis-classification of ggF events.
- m_{HH} +VBF-vs-ggF BDT or a dedicated ggF BDT are used to enhance sensitivity to both SM and BSM scenarios, resulting in a total of 4 SRs.



- The large multijet background is estimated from data and a maximum likelihood binned fit is simultaneously performed in all SRs.

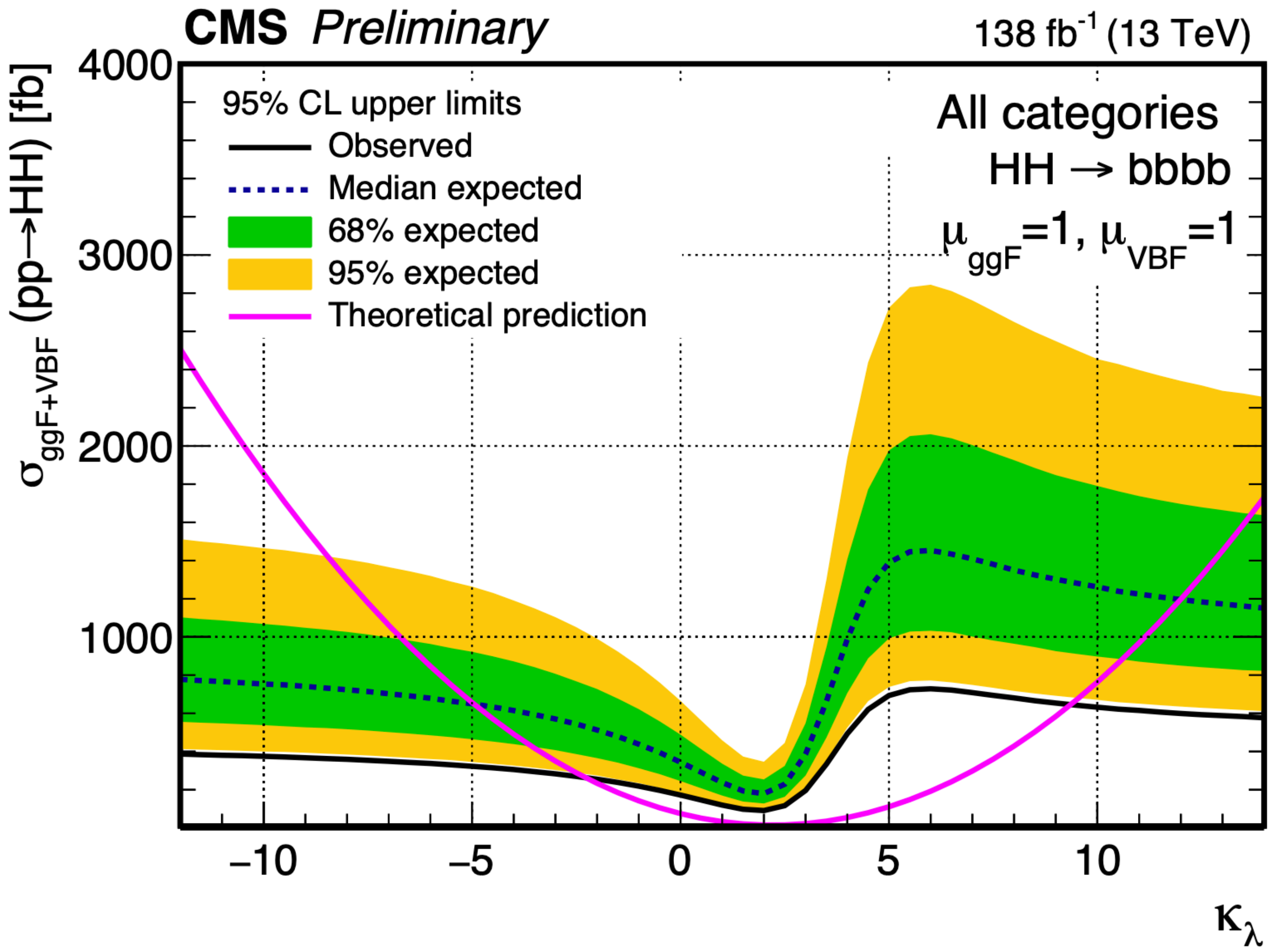
$$\sigma^{HH}_{ggF+VBF} < 3.6\ (7.3) \times \sigma^{HH\ SM}_{ggF+VBF}$$

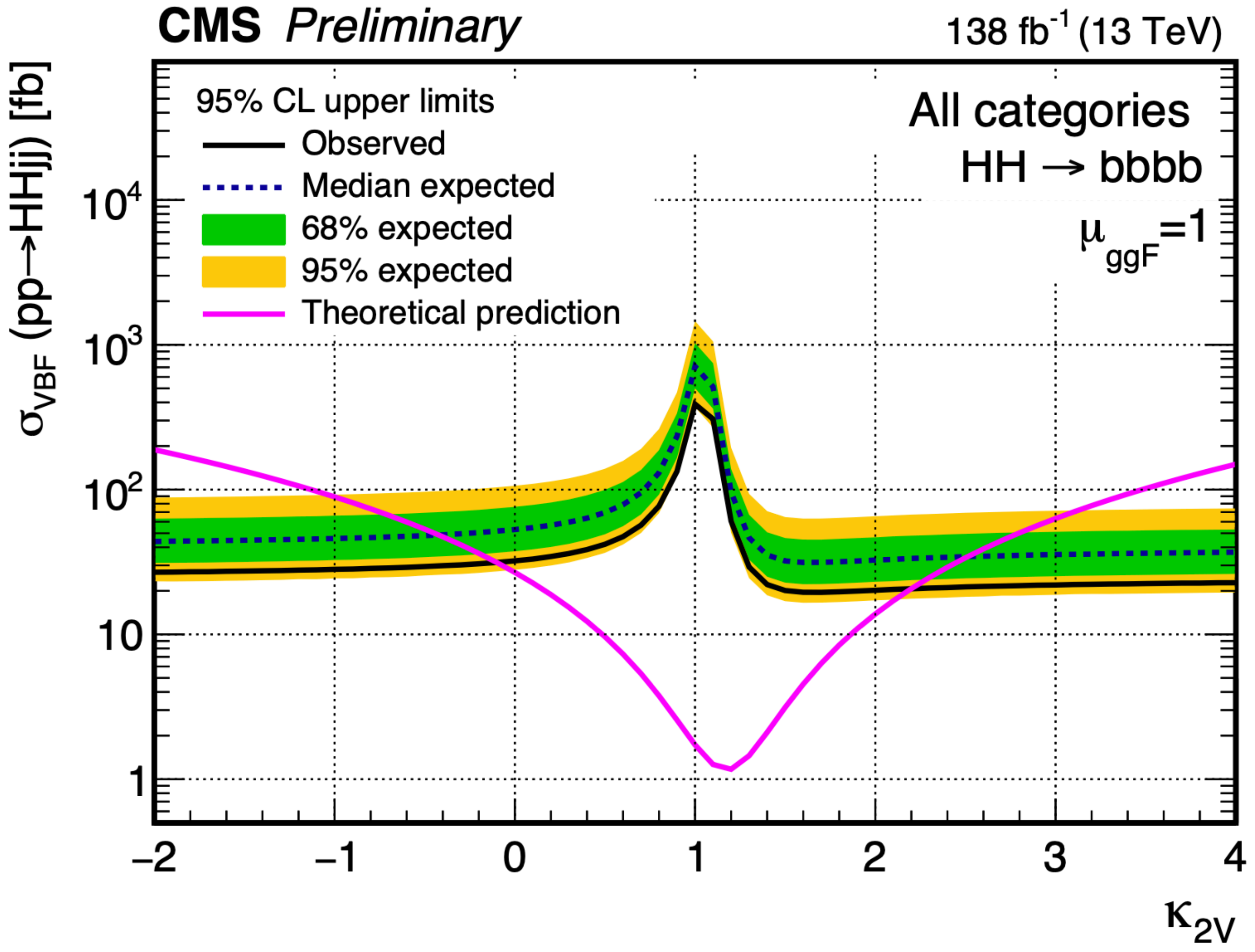
$$-2.3\ (-5.0) < \kappa_\lambda < 9.4\ (12.0)$$

$$-0.1\ (-0.4) < \kappa_{2V} < 2.2\ (2.5)$$

observed (expected)

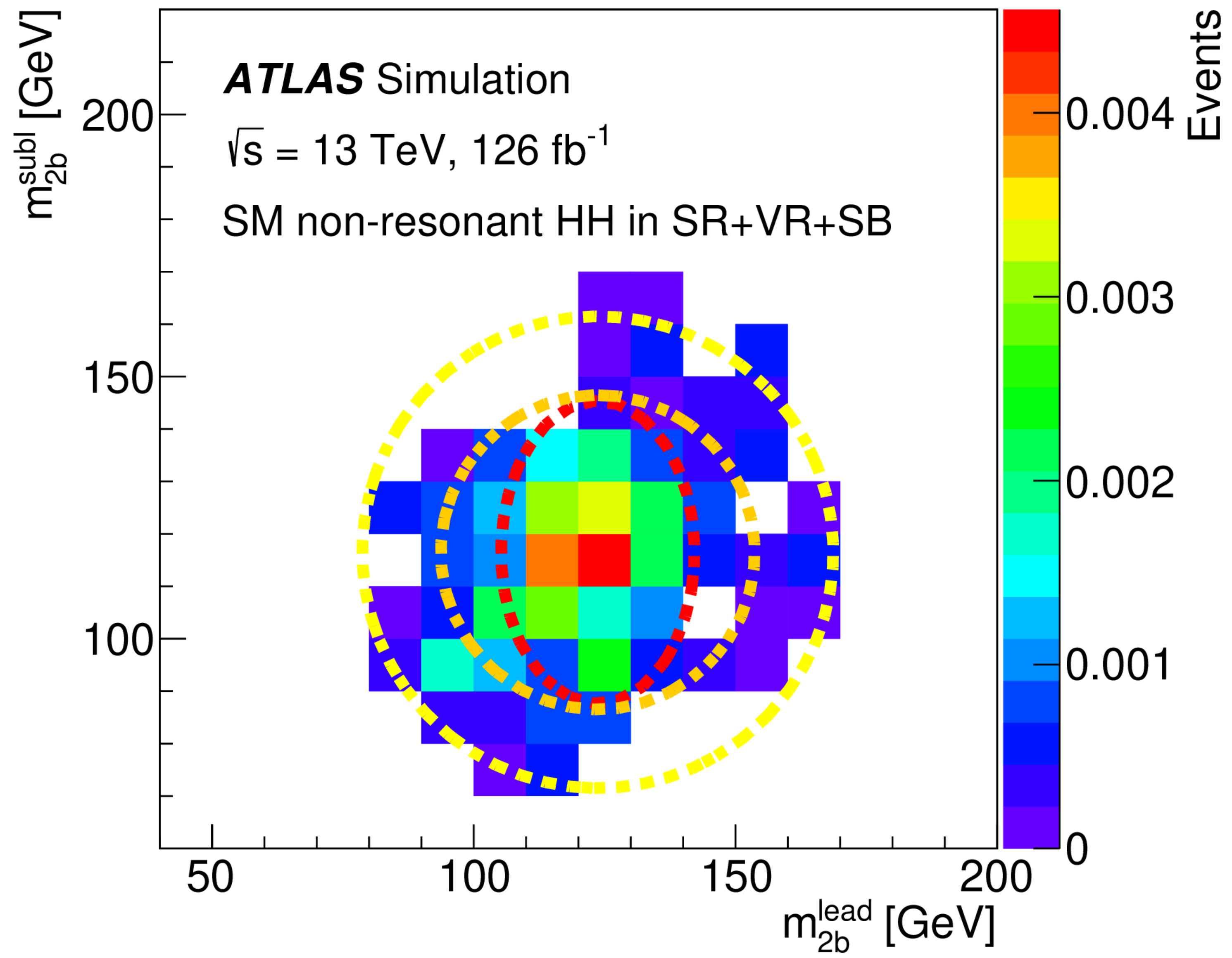
- Dominated by background modelling uncertainties.

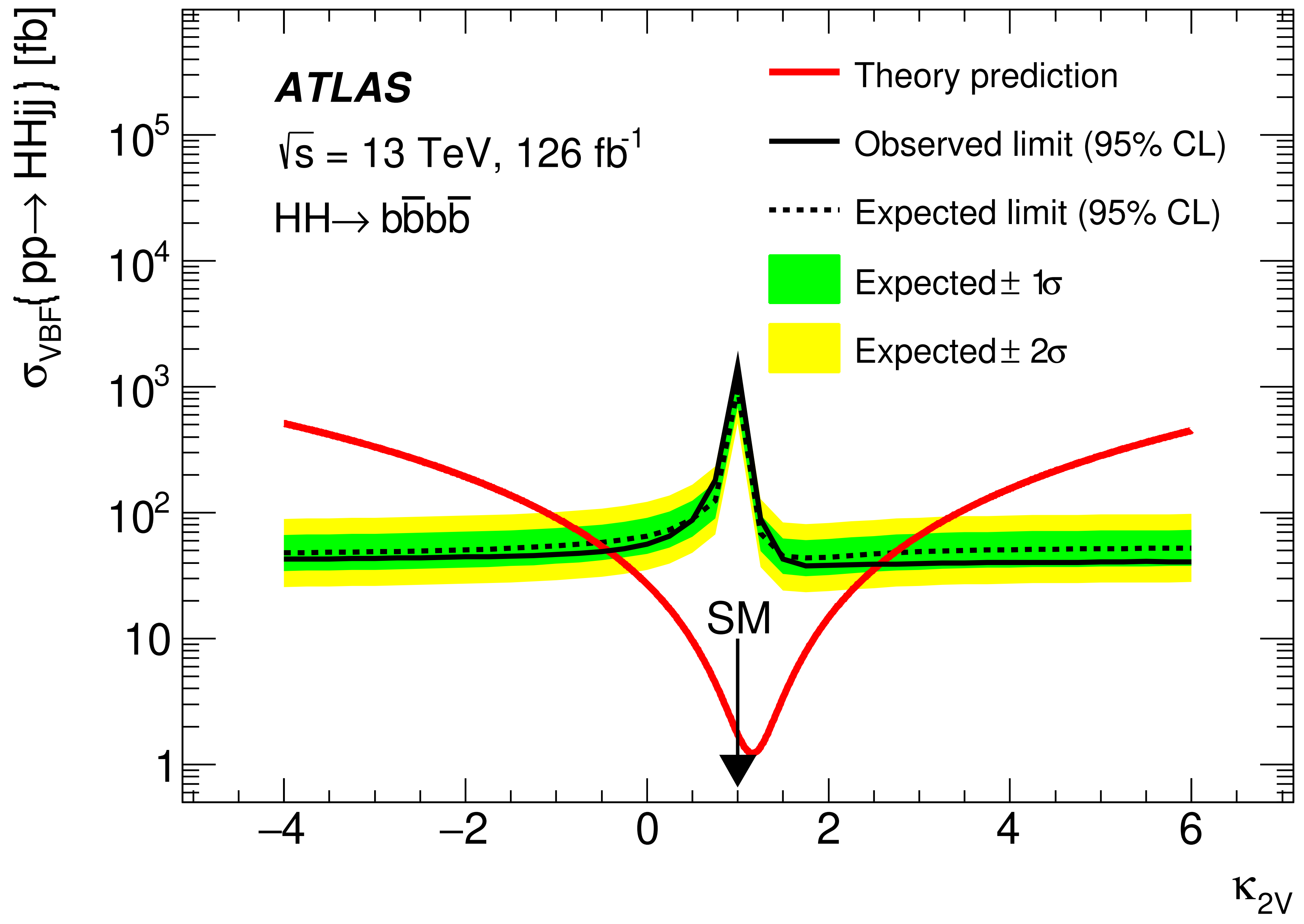




ATLAS $VBF\ HH \to bbbb$ (126 fb^{-1})

- Set limits on σ^{HH}_{VBF} and κ_{2V}.
- Targets $VBF\ HH \to bbbb$ as signal while $ggF\ HH$ events are considered background.
- Concentric signal, validation and side-band regions (SR, VR, and SB) are defined from the 2D (sub-)leading m_{2b} to fit the multijet and all-hadronic $t\bar{t}$ backgrounds to data.



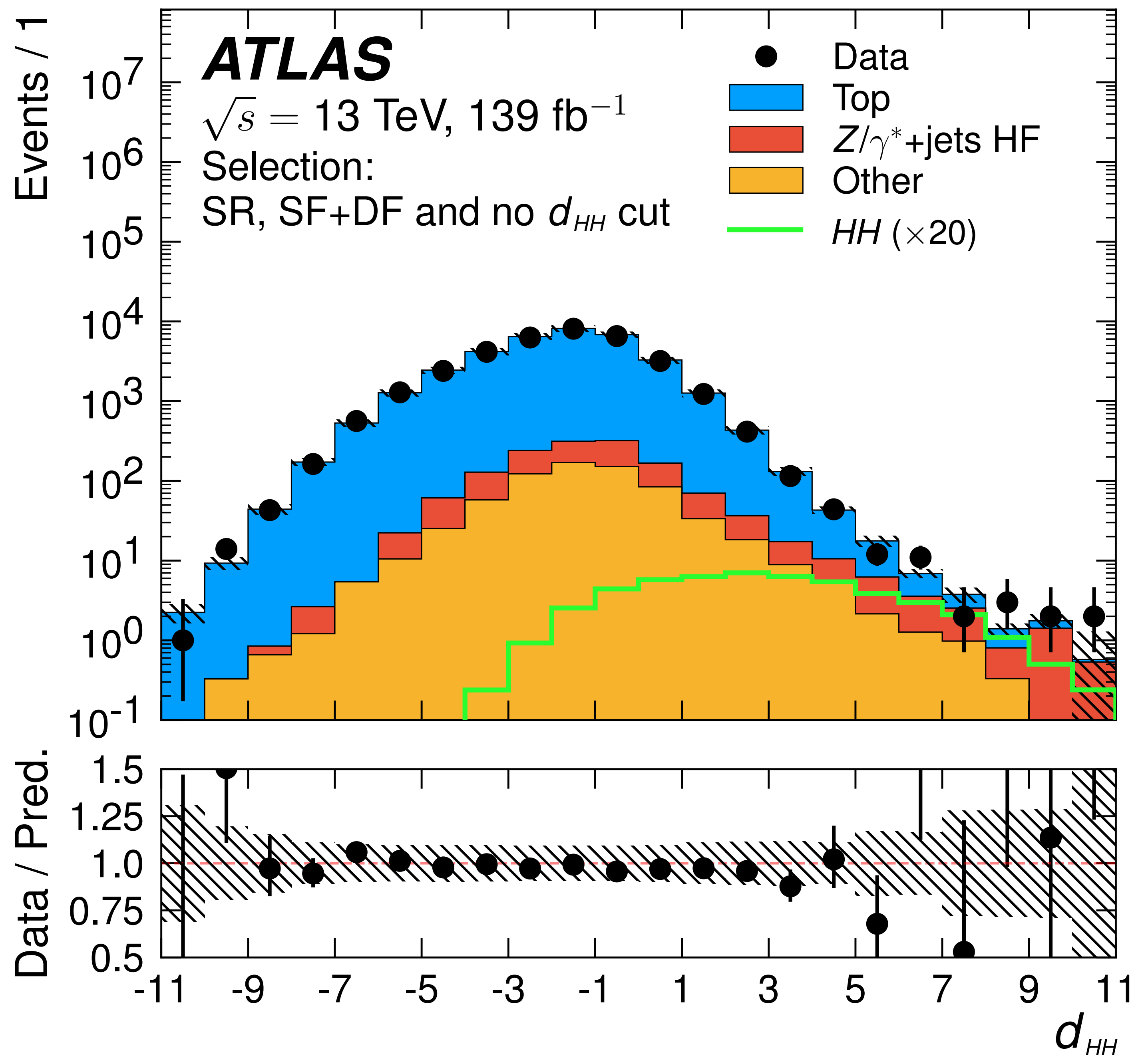


- The sensitivity of the analysis is limited by the statistical precision, followed by systematics on the multi jet background

Observed (expected) limits at 95% CL:

- $\sigma^{HH}_{VBF} < 1000\ (540) \times \sigma^{HH\ SM}_{VBF}$
- $-0.43\ (-0.55) < \kappa_{2V} < 2.56\ (2.72)$

ATLAS $HH \to bbl\nu l\nu$ (139 fb^{-1})



- Targets $ggF\ HH \to bbWW^*$, $bbZZ^*$ and $bb\tau\tau$ in a final state with two b-jets, two leptons ($l = e, \mu$) and missing transverse energy.
- A multi-class classification Neural Network is used to differentiate the $HH \to bbWW^*$ signal (due to its larger branching fraction) from the SM backgrounds.
- The main discriminant is defined as $d_{HH} = \ln(p_{HH}/p_{top} + p_{Zll} + p_{Z\tau\tau})$ where p_i are the NN outputs that represent the probability of an event to belong to a class i.
- A counting experiment is performed, fitting simultaneously the Top CR, the Z+HF CR, the same flavour (SF) and different flavour (DF) SRs with all three HH decays as signal.

- Leading uncertainties arise from MC modelling in the Top and Z+HF background estimates.

	-2σ	-1σ	**Expected**	$+1\sigma$	$+2\sigma$	**Observed**
$\sigma\,(gg \to HH)$ [pb]	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma\,(gg \to HH)\,/\sigma^{\mathrm{SM}}\,(gg \to HH)$	14	20	29	43	62	40

Observed (expected) limit:

- $\sigma^{HH}_{ggF} < 40\ (29) \times \sigma^{HH\ SM}_{ggF}$

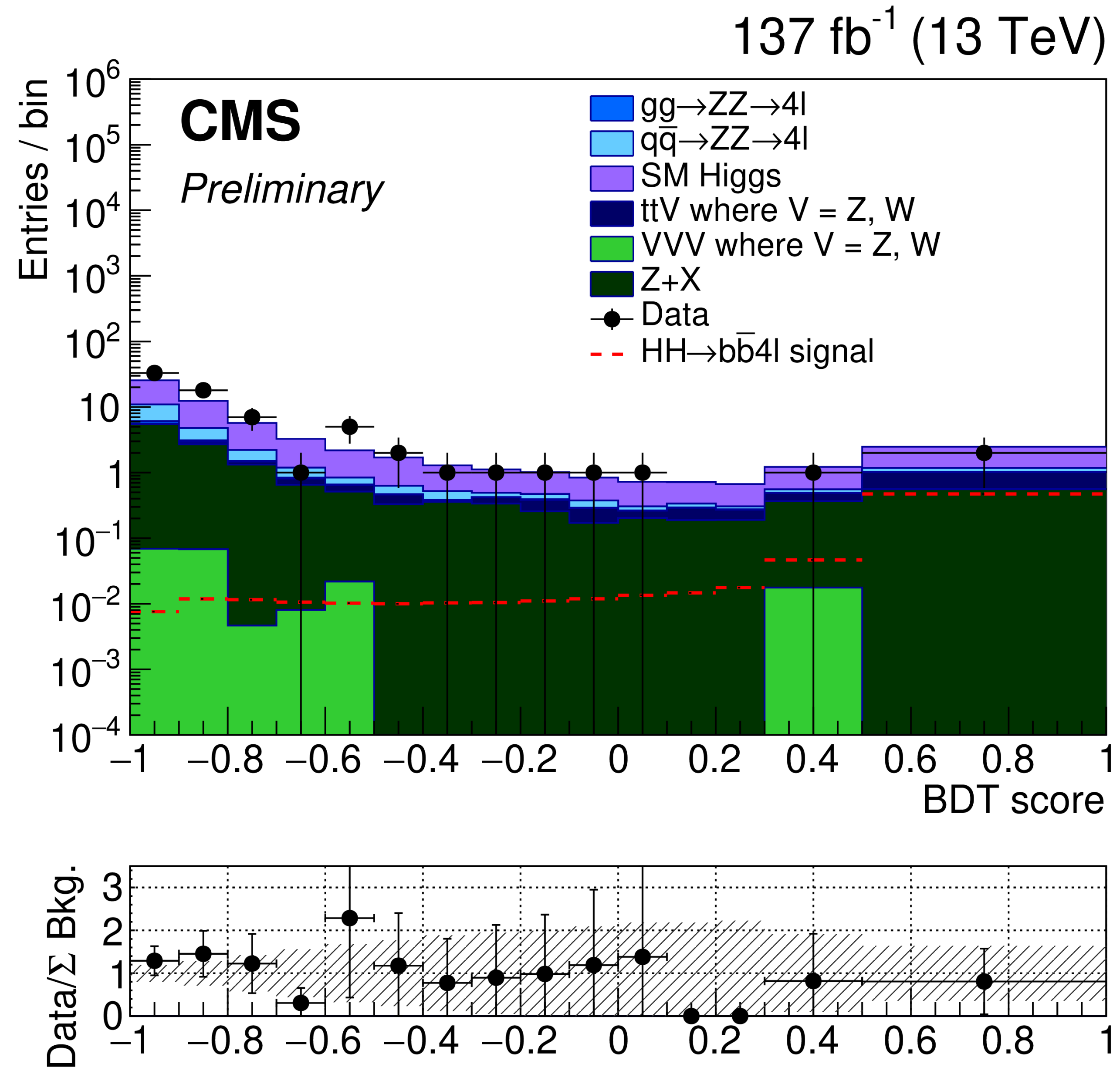
CMS $HH \rightarrow bbllll$ (137 fb^{-1})

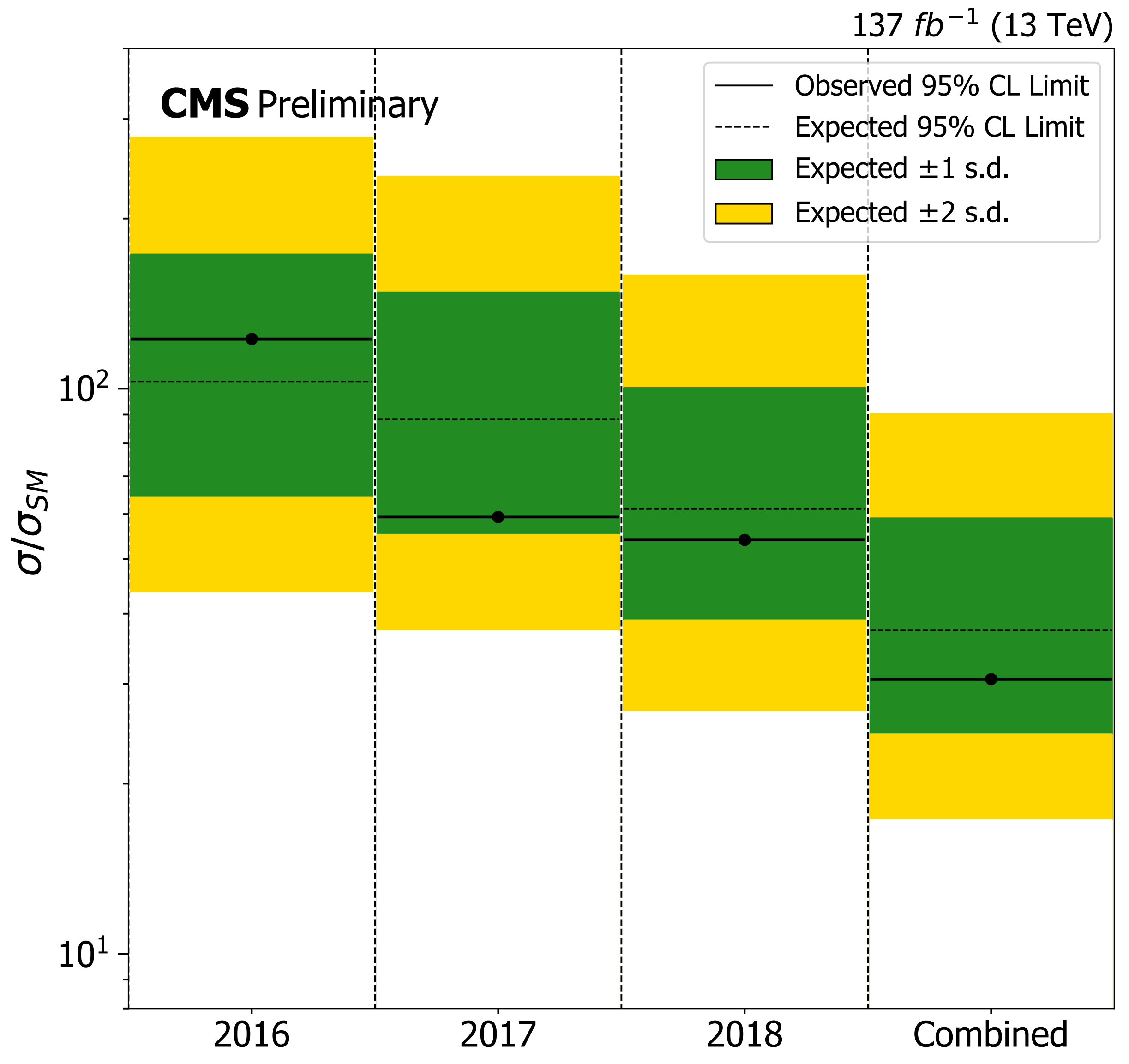
- Targets $ggF\ HH \rightarrow bbZZ*$ in a final state with two b-jets and four leptons ($l = e, \mu$).
- The $m(4l)$ is used to define a CR for the Z+X background and a SR with $m(4l) \sim m_H$. The irreducible single Higgs background is estimated from simulation.
- For further discrimination, a total of 9 BDTs are trained (for each data taking year and leptonic final state e.g. 4μ, $4e$ or $2e2\mu$) using events in the SR.
- A multi-dimensional binned fit to the BDT distribution in data is performed.
- The JES uncertainties, together with the statistical uncertainties of the last bin of the BDT, have the highest impact on the analysis.

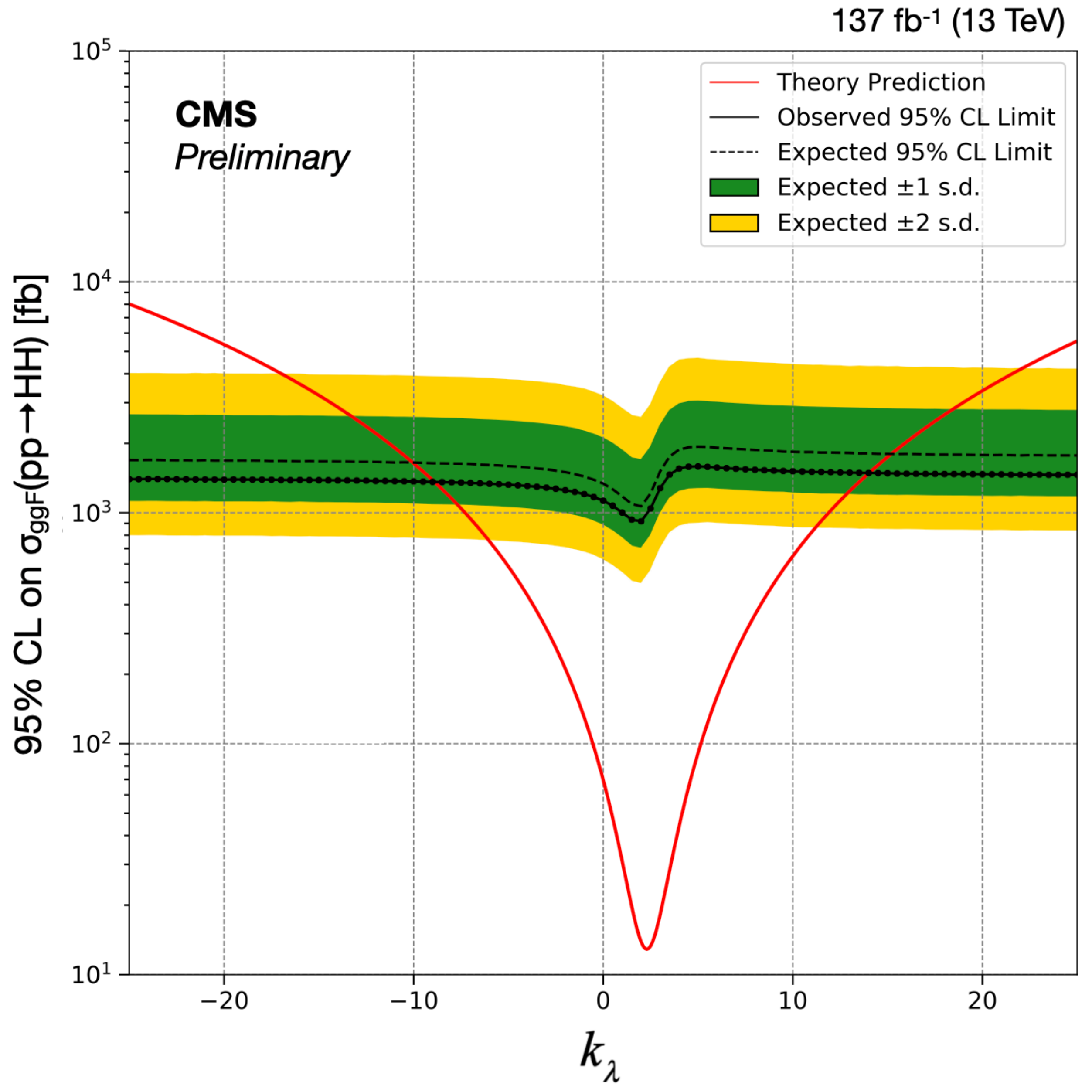
Observed (expected) limits at 95% CL:

- $\sigma_{ggF}^{HH} < 30\ (37) \times \sigma_{ggF}^{HH\ SM}$
- $-9\ (-10.5) < \kappa_\lambda < 14\ (15.5)$

Inclusive BDT distribution







HH combination (25-36.1 fb^{-1})

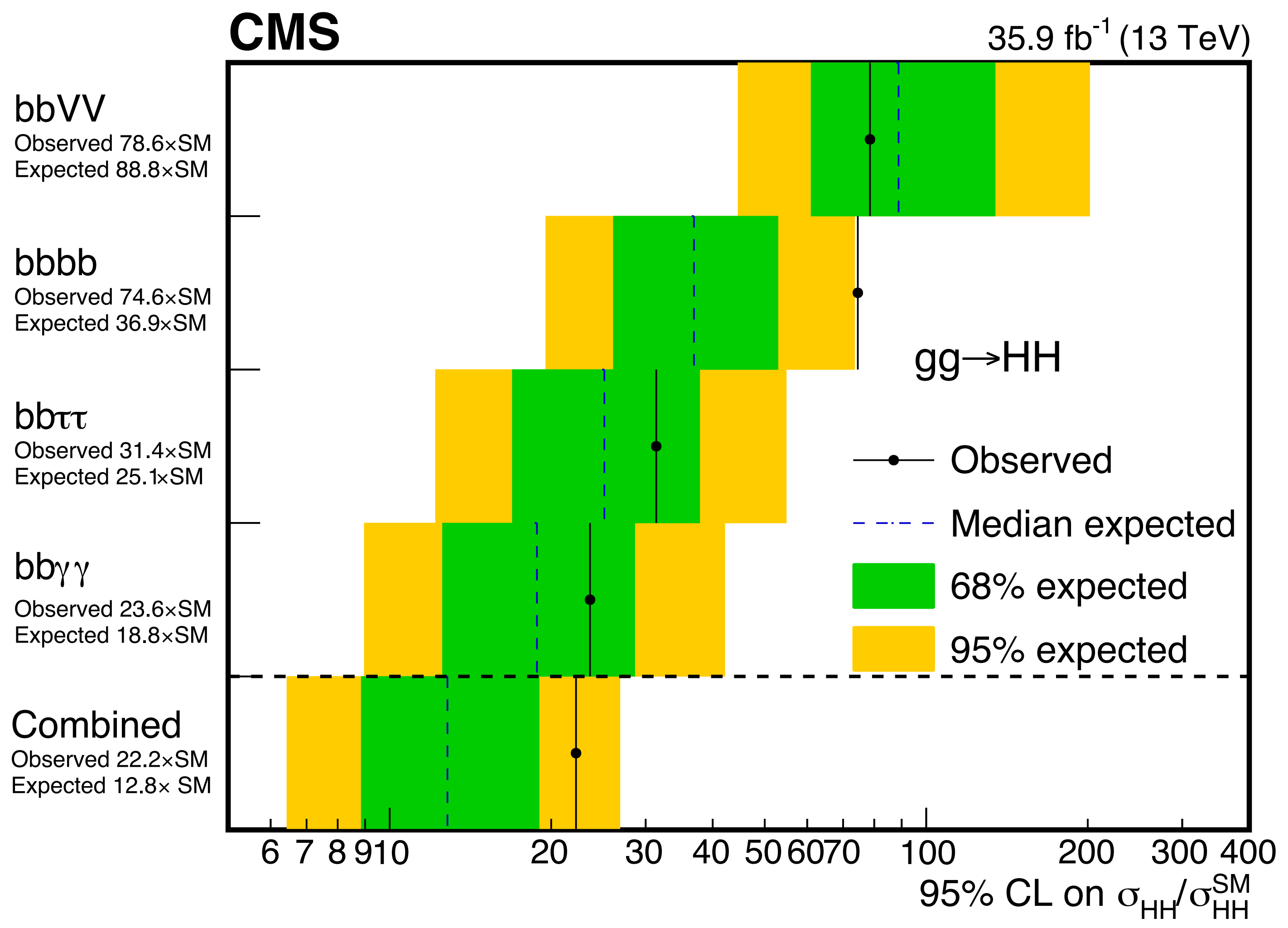
Partial run 2 data

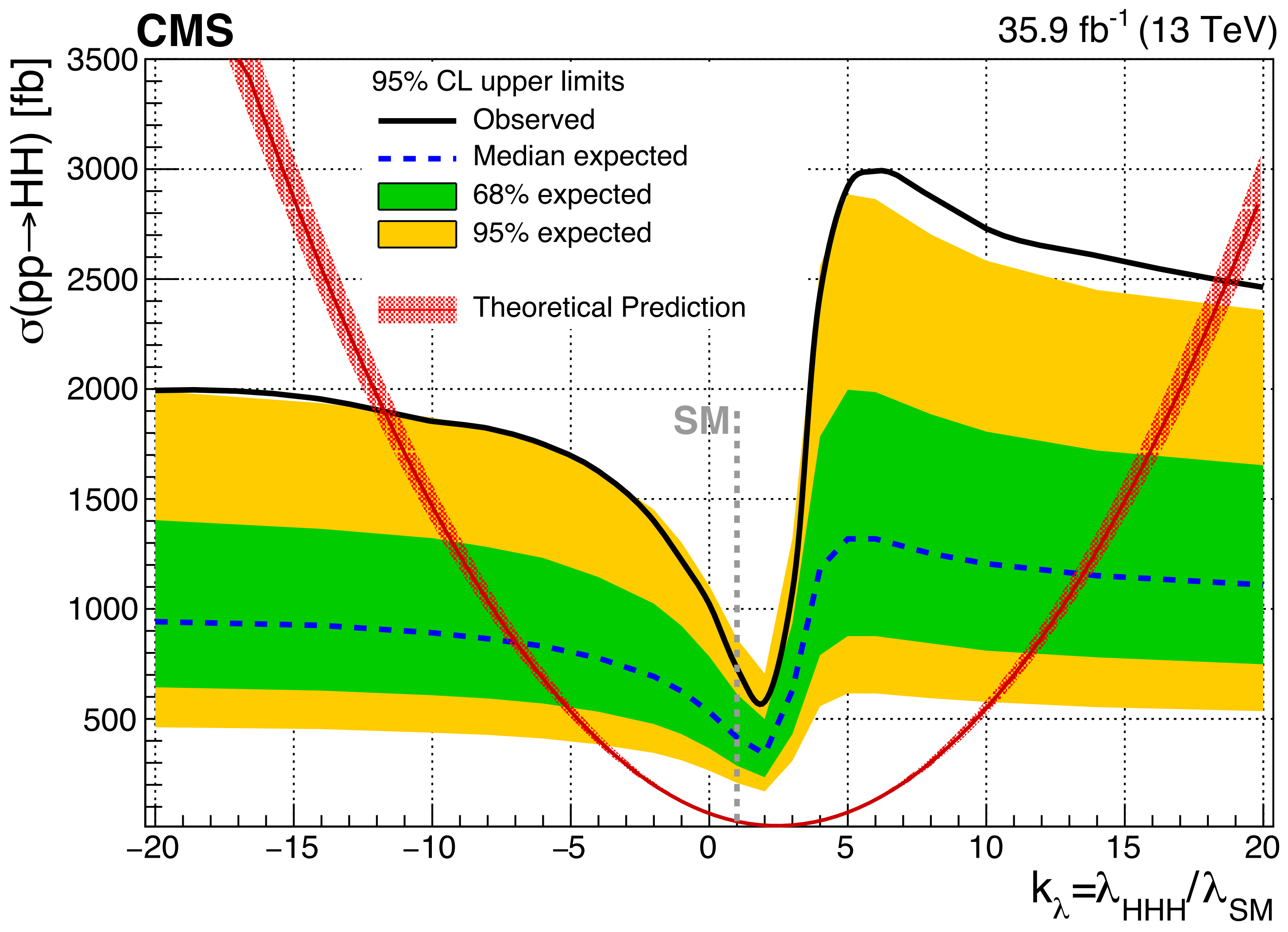
- Searches for $ggF\ HH$ in different decay channels within each experiment are combined.

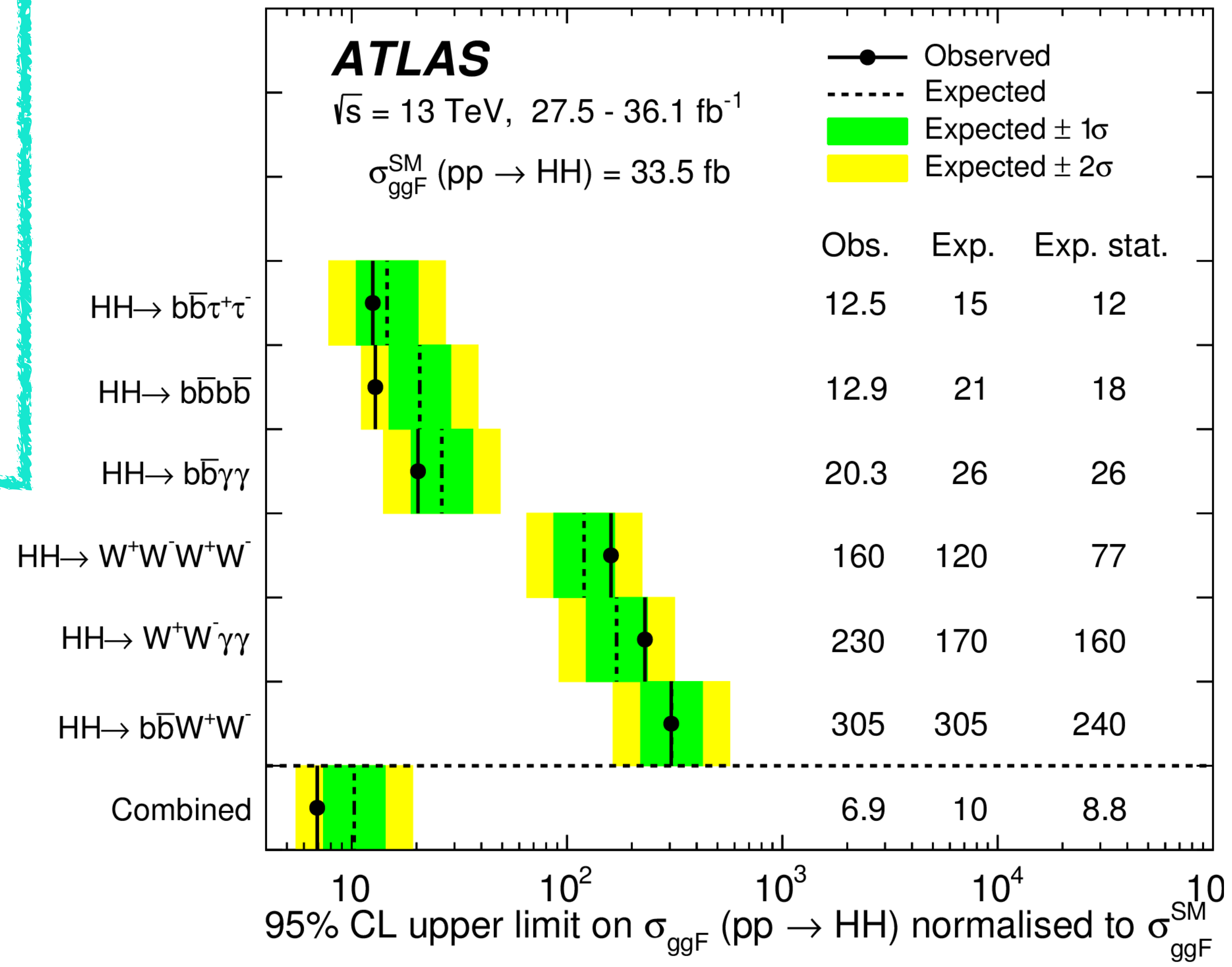
Observed (expected) limits at 95% CL:

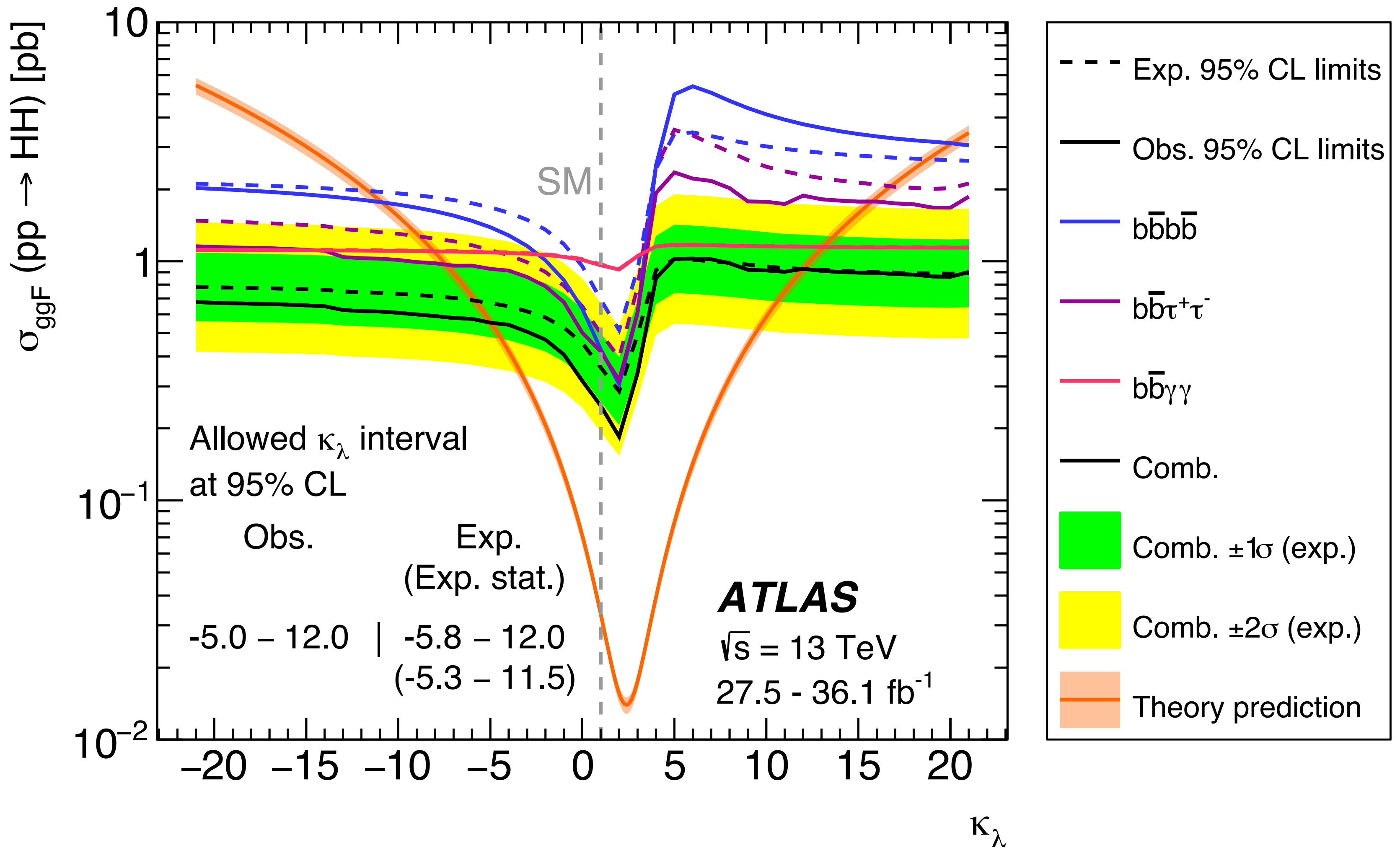
- ATLAS: $\sigma_{ggF}^{HH} < 6.9\ (10) \times \sigma_{ggF}^{HH\ SM}$
- CMS: $\sigma_{ggF}^{HH} < 12.8\ (22.2) \times \sigma_{ggF}^{HH\ SM}$
- ATLAS: $-5\ (-5.8) < \kappa_\lambda < 12\ (12.0)$
- CMS: $-11.8\ (-7.1) < \kappa_\lambda < 18.8\ (13.6)$

- Looser limits than the $HH \to b\bar{b}\gamma\gamma$ and $HH \to b\bar{b}b\bar{b}$ searches with full run 2 data.





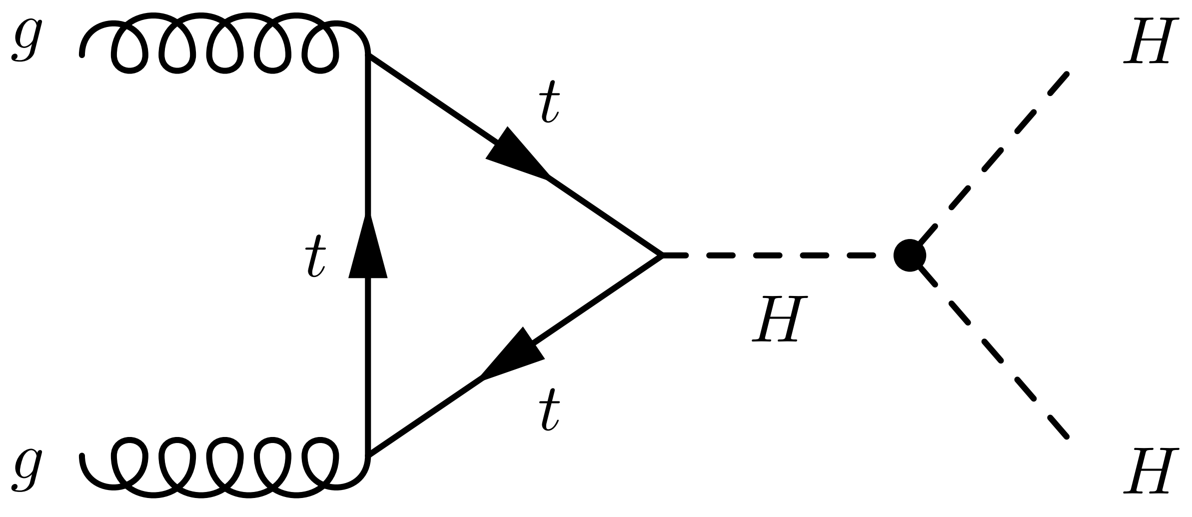


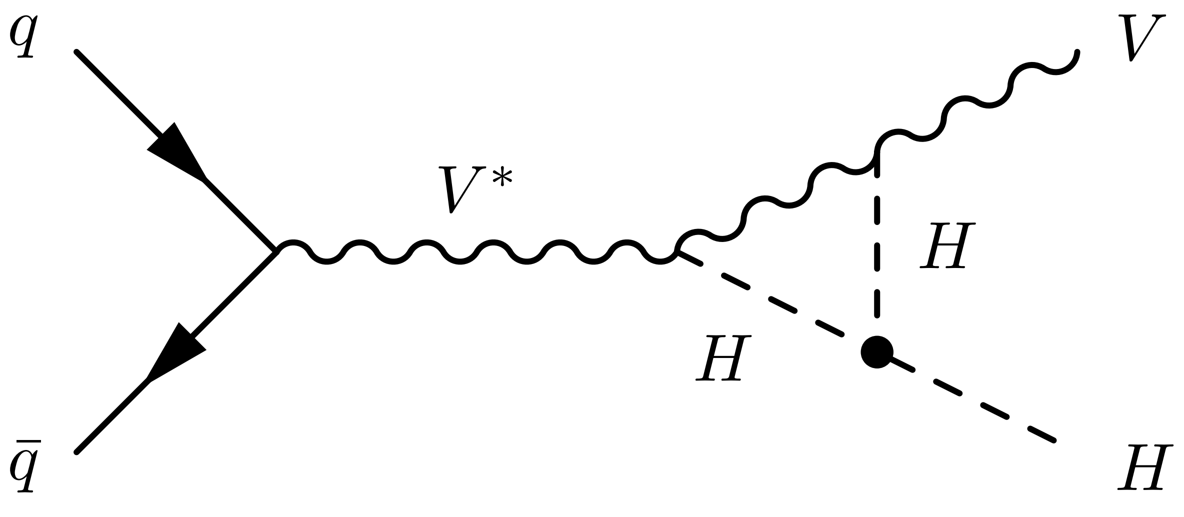


ATLAS H+HH combination (27.5-79.8 fb^{-1})

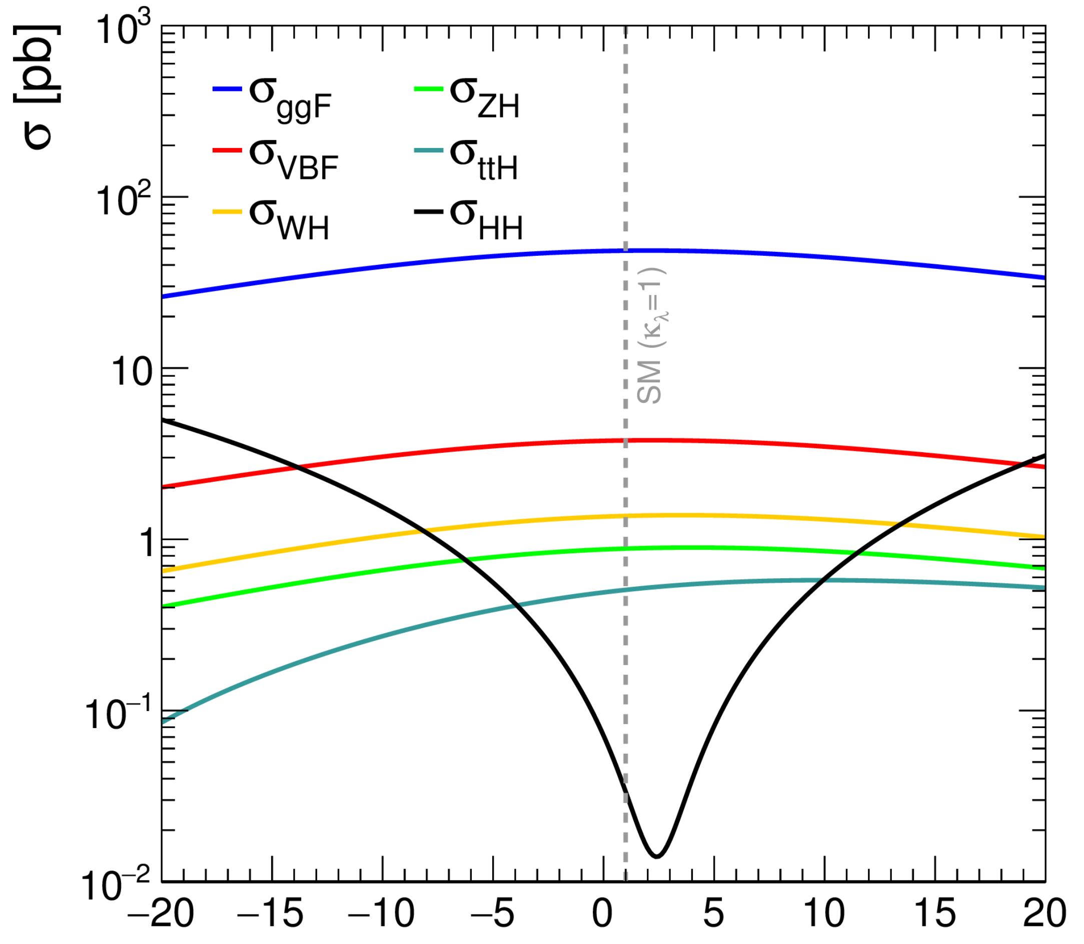
Partial run 2 data

- κ_λ enters at tree (loop level) for HH (H) production affecting σ

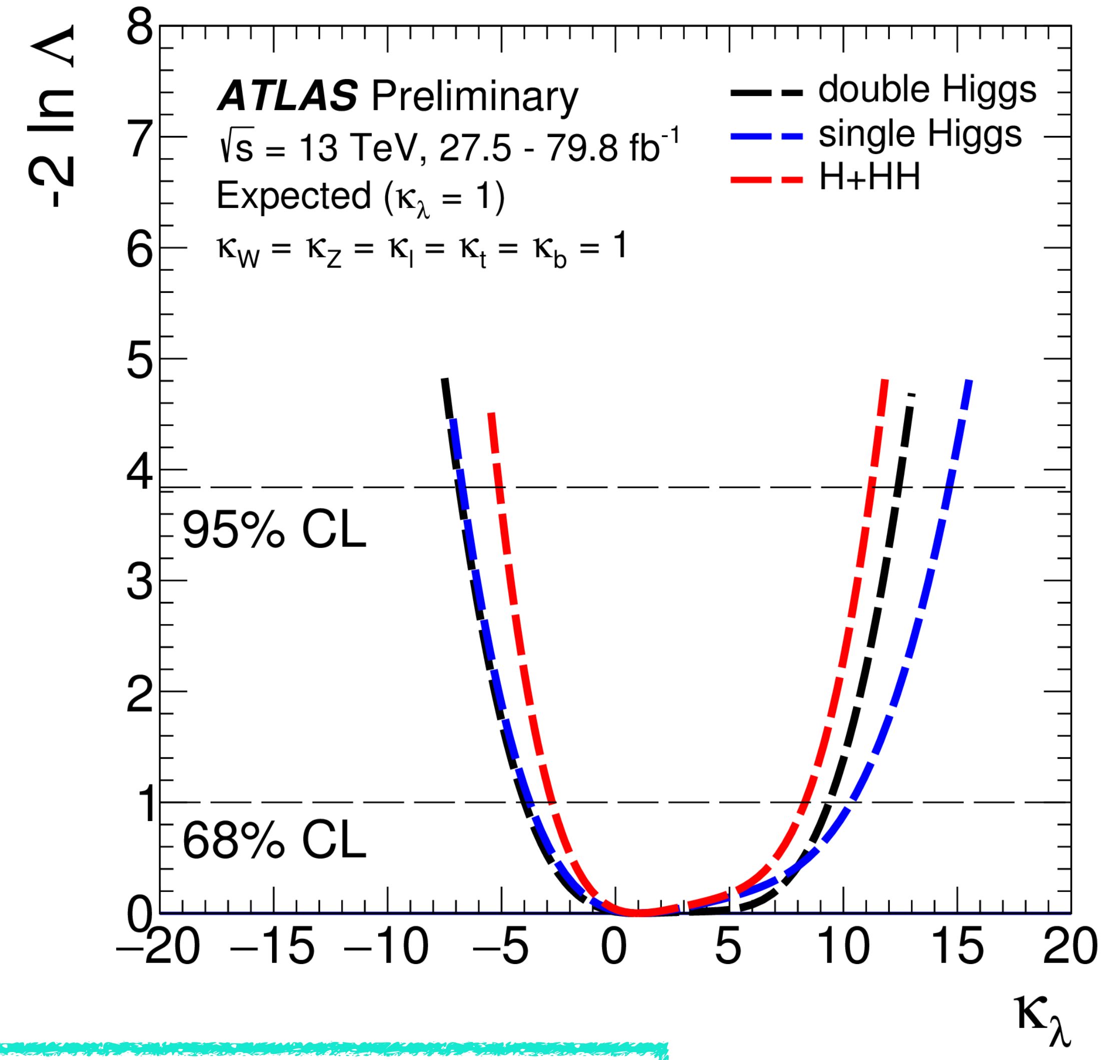




Production mode $\sigma(\kappa_\lambda)$



- Single Higgs and HH analyses with multiple decay and production modes are combined:
  - $H \to \gamma\gamma, H \to ZZ^*$, $H \to WW^*, H \to \tau\tau, H \to b\bar{b}, VH$ with $H \to b\bar{b}$, $t\bar{t}H$ with $H \to b\bar{b}$ and $H \to$ leptons.
  - $HH \to b\bar{b}b\bar{b}, HH \to b\bar{b}\tau\tau$ and $HH \to b\bar{b}\gamma\gamma$



- Observed (expected) limits to the Higgs self coupling are set for different coupling assumptions:
  - **ATLAS HH+H** combination: -2.3 (-5.1) $< \kappa_\lambda <$ 10.3 (11.2)

→The **CMS single Higgs combination** (HIG-19-005-pas) results in slightly looser limits: -3.5 (-5.1) $< \kappa_\lambda <$ 14.5 (13.5)

Conclusions

Check out Amit Adhikary's poster for more info about HH at HL-LHC

- We are not yet sensitive to SM HH production but competitive upper limits to $\sigma^{HH}/\sigma^{HH}_{SM}$ are set by three analyses:

$\sigma^{HH}_{ggF+VBF} = 4.1\ (5.5) \times \sigma^{HH\ SM}_{ggF+VBF}$ (ATLAS $HH \to bb\gamma\gamma$)

$\sigma^{HH}_{ggF+VBF} < 7.7\ (5.2) \times \sigma^{HH\ SM}_{ggF+VBF}$ (CMS $HH \to bb\gamma\gamma$)

$\sigma^{HH}_{ggF+VBF} < 3.6\ (7.3) \times \sigma^{HH\ SM}_{ggF+VBF}$ (CMS $HH \to bbbb$)

- The most stringent limits to κ_λ at 95% CL correspond to:

$$-1.5\ (-2.4) < \kappa_\lambda < 6.7\ (7.7)$$ (ATLAS $HH \to bb\gamma\gamma$)

- Limits have improved considerably with respect to the partial Run 2 combined limits → Stay tuned for full run 2 combinations!
  - HL-LHC prospects: $\sigma^{HH}_{ggF} = 2.6\ \times \sigma^{HH\ SM}_{ggF}$ (CMS - 5 channels) or $\sigma^{HH}_{ggF} = 3.5\ \times \sigma^{HH\ SM}_{ggF}$ (ATLAS - 3 channels)

- First limits on $VBF\ HH$ production are also set in ATLAS and CMS. The current most stringent limits on $\sigma^{VBF\ HH}$ correspond to:

$$\sigma^{HH}_{VBF} = 225\ (208) \times \sigma^{HH\ SM}_{VBF}$$ (CMS $HH \to bb\gamma\gamma$)

- The current most stringent limits on κ_{2V} correspond to:

$$-0.1\ (-0.4) < \kappa_{2V} < 2.2\ (2.5)$$ (CMS $HH \to bbbb$)

Observed (expected) limits at 95% C.L.

Thank you for your time!

Any comments or questions?

Backup

Object reconstruction

- Jets:

The partons produced in the collision form hadrons which will interact with the calorimeter material producing hadronic showers.

Jet reconstruction algorithms are used to detect these cone-like structures by matching the calorimeter showers to tracks in the ID. Different jet types are reconstructed: *pflow*, *topo* and *track* jets.

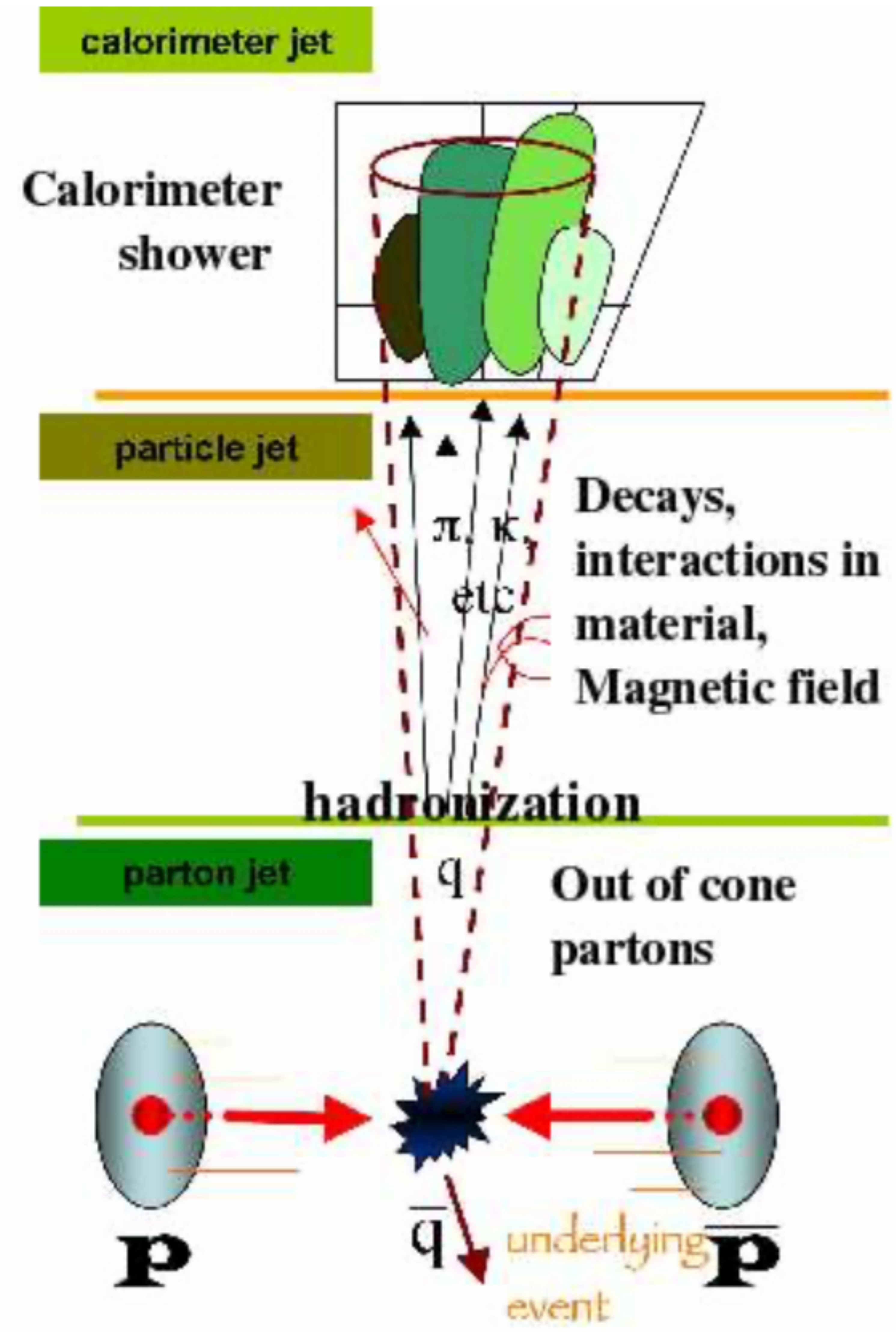
- b-jets:

Jets containing b-hadrons.

- Missing transverse energy (E_T^{miss}):

Some particles escape the detector volume without being detected, e.g. neutrinos.

E_T^{miss} = sum of the transverse momenta of all undetected particles created in the collision. Measured as negative sum of the transverse momenta of all visible particles.



Summary of σ, κ_λ and κ_{2V} limits with full run 2 data

$\sigma^{HH}_{ggF+VBF}$ & κ_λ

- $HH \to bb\gamma\gamma$ (ATLAS)

  $\sigma^{HH}_{ggF+VBF} = 4.1\ (5.5)\ \times \sigma^{HH\ SM}_{ggF+VBF}$

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

- $HH \to bb\gamma\gamma$ (CMS)

  $\sigma^{HH}_{ggF+VBF} < 7.7\ (5.2) \times \sigma^{HH\ SM}_{ggF+VBF}$

  $-3.3\ (-2.5)\ \kappa_\lambda\ < 8.5\ (8.2)$

- $HH \to bbbb$ (CMS)

  $\sigma^{HH}_{ggF+VBF} < 3.6\ (7.3) \times \sigma^{HH\ SM}_{ggF+VBF}$

  $-2.3\ (-5.0) < \kappa_\lambda < 9.4\ (12.0)$

σ^{HH}_{ggF} & κ_λ

- $HH \to bbl\nu l\nu$ (ATLAS)

  $\sigma^{HH}_{ggF} < 40\ (29) \times \sigma^{HH\ SM}_{ggF}$

- $HH \to bbllll$ (CMS)

  $\sigma^{HH}_{ggF} < 30\ (37) \times \sigma^{HH\ SM}_{ggF}$

  $-9\ (-10.5) < \kappa_\lambda < 14\ (15.5)$

σ^{HH}_{VBF} & κ_{2V}

- $VBF\ HH \to bbbb$ (ATLAS)

  $\sigma^{HH}_{VBF} < 1000\ (540) \times \sigma^{HH\ SM}_{VBF}$

  $-0.43\ (-0.55) < \kappa_{2V} < 2.56\ (2.72)$

- $HH \to bb\gamma\gamma$ (CMS)

  $\sigma^{HH}_{VBF} < 225\ (208) \times \sigma^{HH\ SM}_{VBF}$

  $-1.3\ (-0.9) < \kappa_{2V} < 3.5\ (3.1)$

- $HH \to bbbb$ (CMS)

  $-0.1\ (-0.4) < \kappa_{2V} < 2.2\ (2.5)$

CMS $HH \rightarrow bbbb$ (138 fb^{-1})

NEW!

- The HH candidates are reconstructed from the 4 jets and the expected distance between the m_{H_i} peak positions $\chi = \sqrt{(m_{H_1} - 125)^2 + (m_{H_2} - 120)^2}$ is used to divide events in a SR and CR.

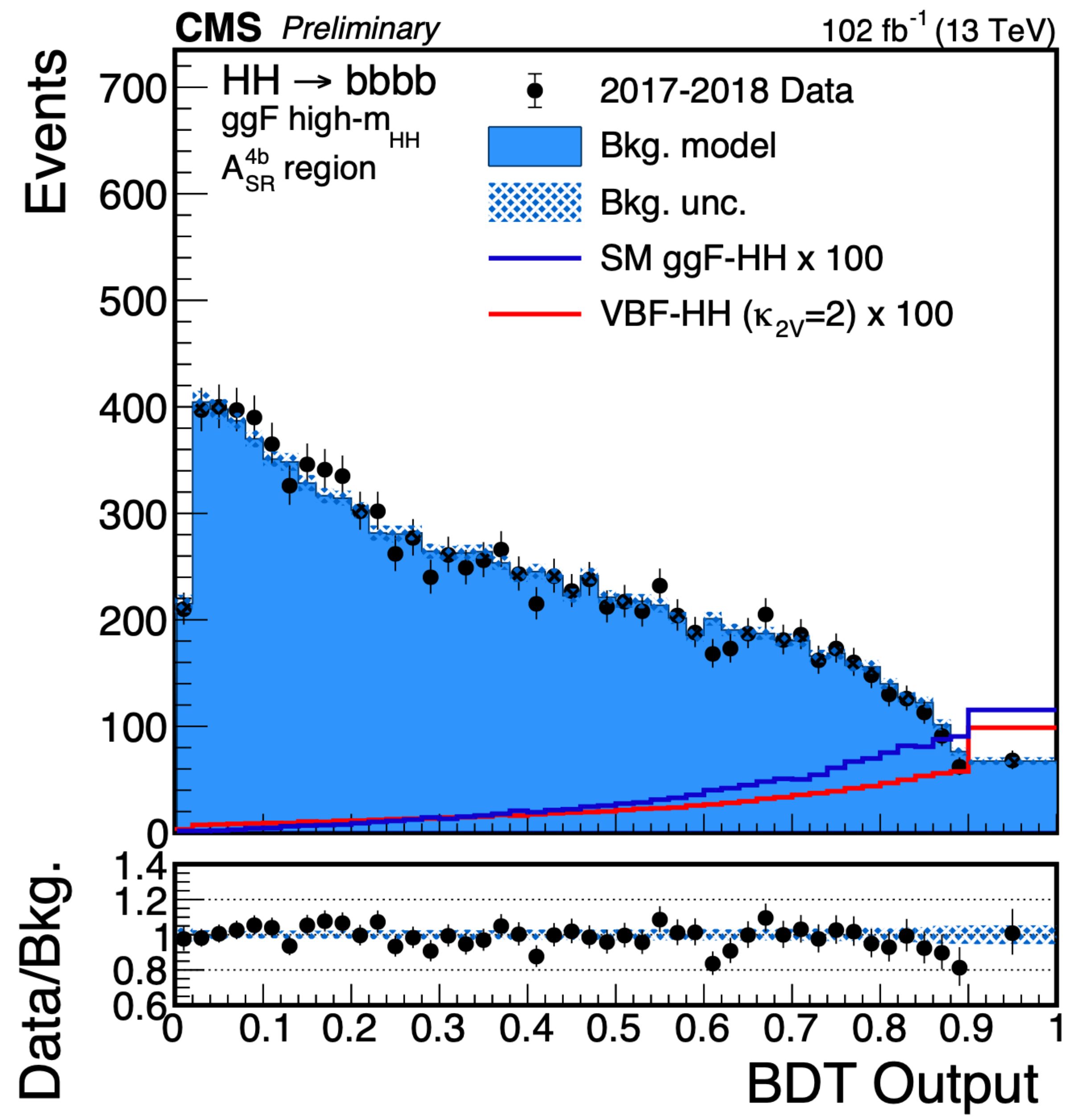
- VBF candidates are selected by requiring 2 additional non b-jets. Additionally, a BDT is used to separate SM ggF from $\kappa_{2V} = 2$ VBF signal and correctly classify the ggF HH events that are misclassified as VBF.

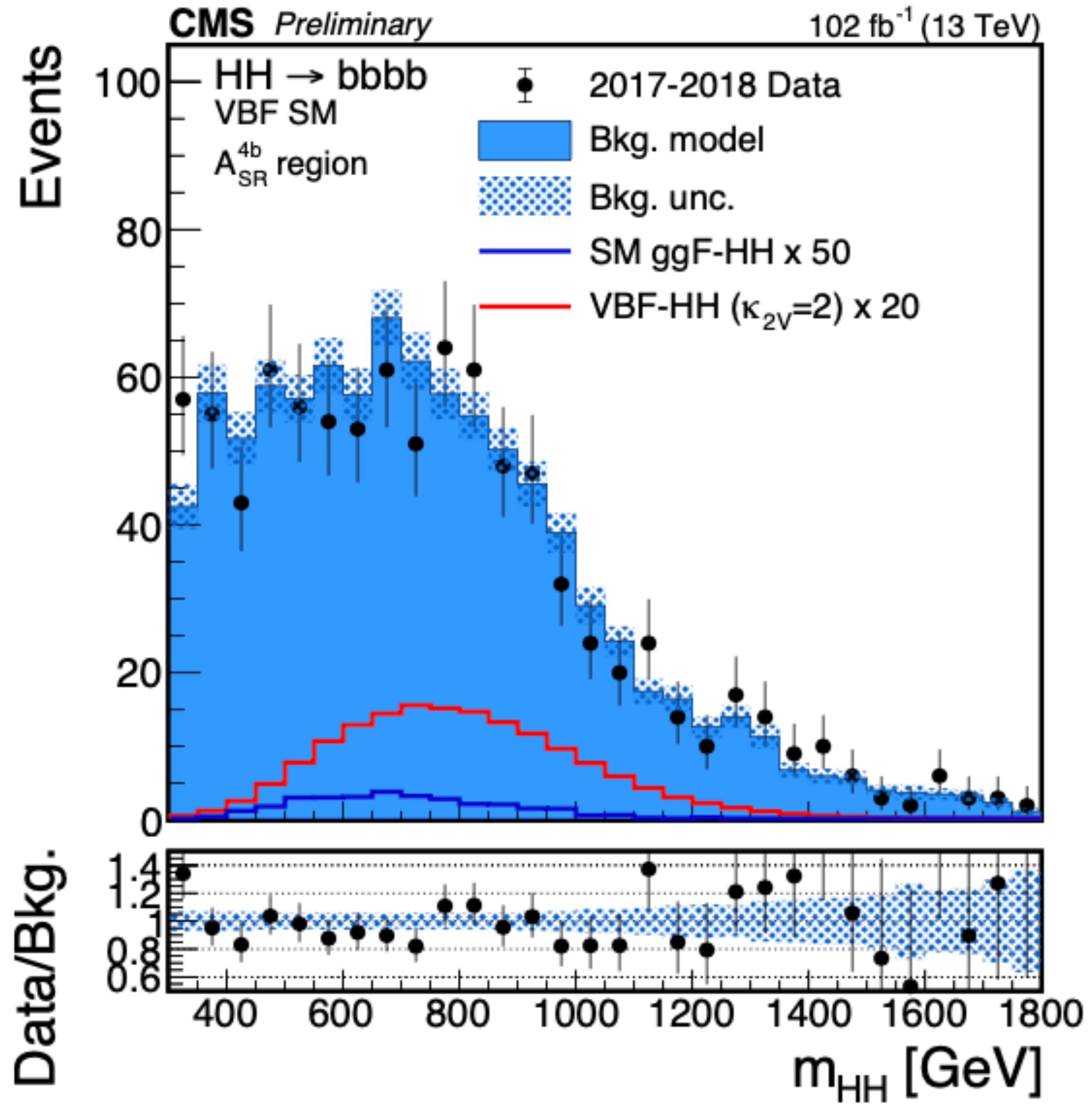
- To enhance sensitivity to both SM and BSM, the ggF category is divided in high/low m_{HH} regions and the BDT score is used divide the VBF category in SM/anomalous κ_{2V}. A BDT is then trained in the two ggF categories to further discriminate signal from bkg.

- The large multi jet background is estimated from data in a SR with 3 b-jets and extrapolated to the 4 b-jet SR using a transfer factor from the CR with 3/4 b-jets. Differences in the distributions of the $3b$ and $4b$ categories are addressed with a BDT based reweighting.

- A maximum likelihood fit binned to the BDT score (ggF), m_H (VBF SM) or unbinned (anomalous VBF) is simultaneously performed in the four categories.

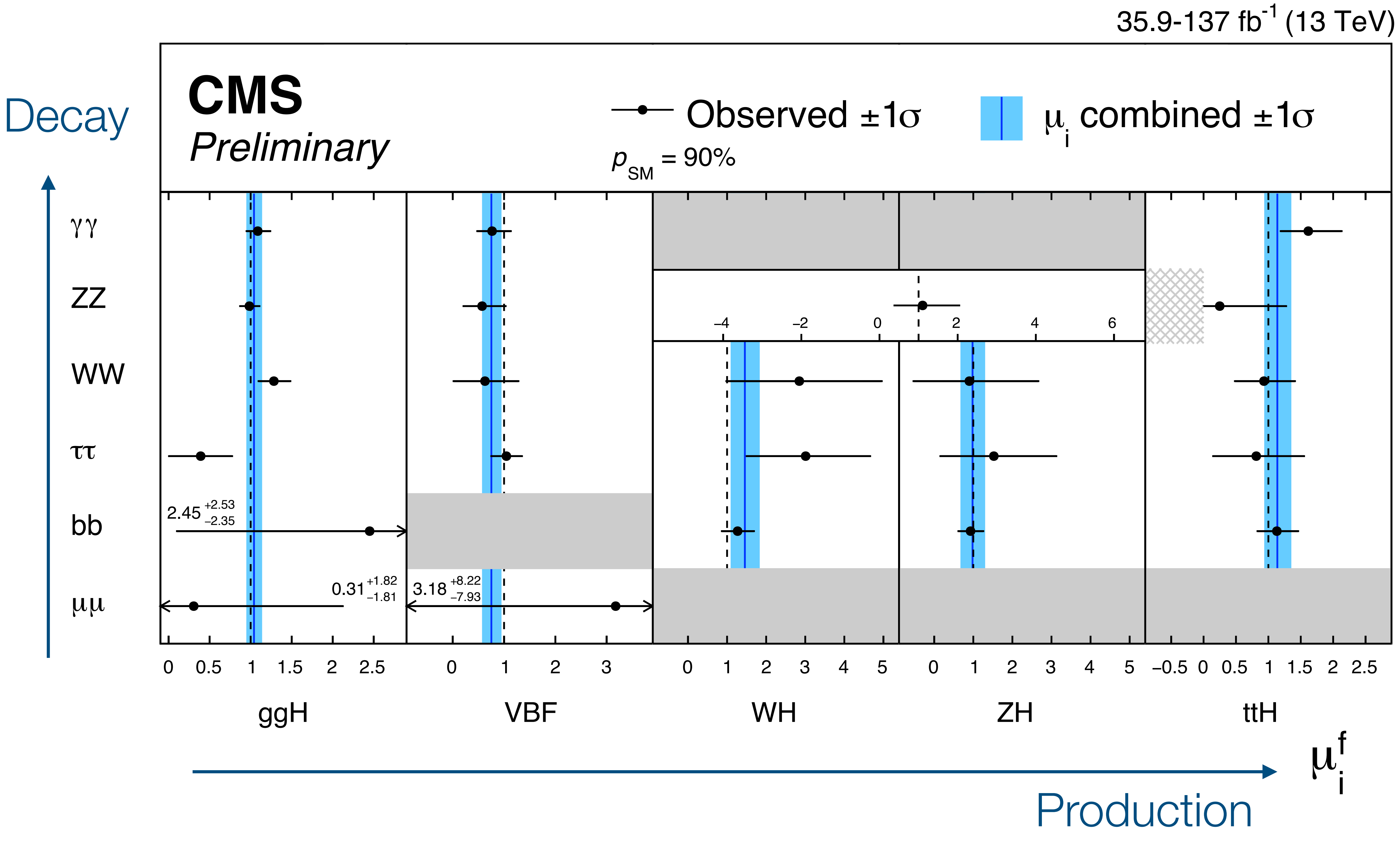
- The dominant uncertainties arise from the background modelling.

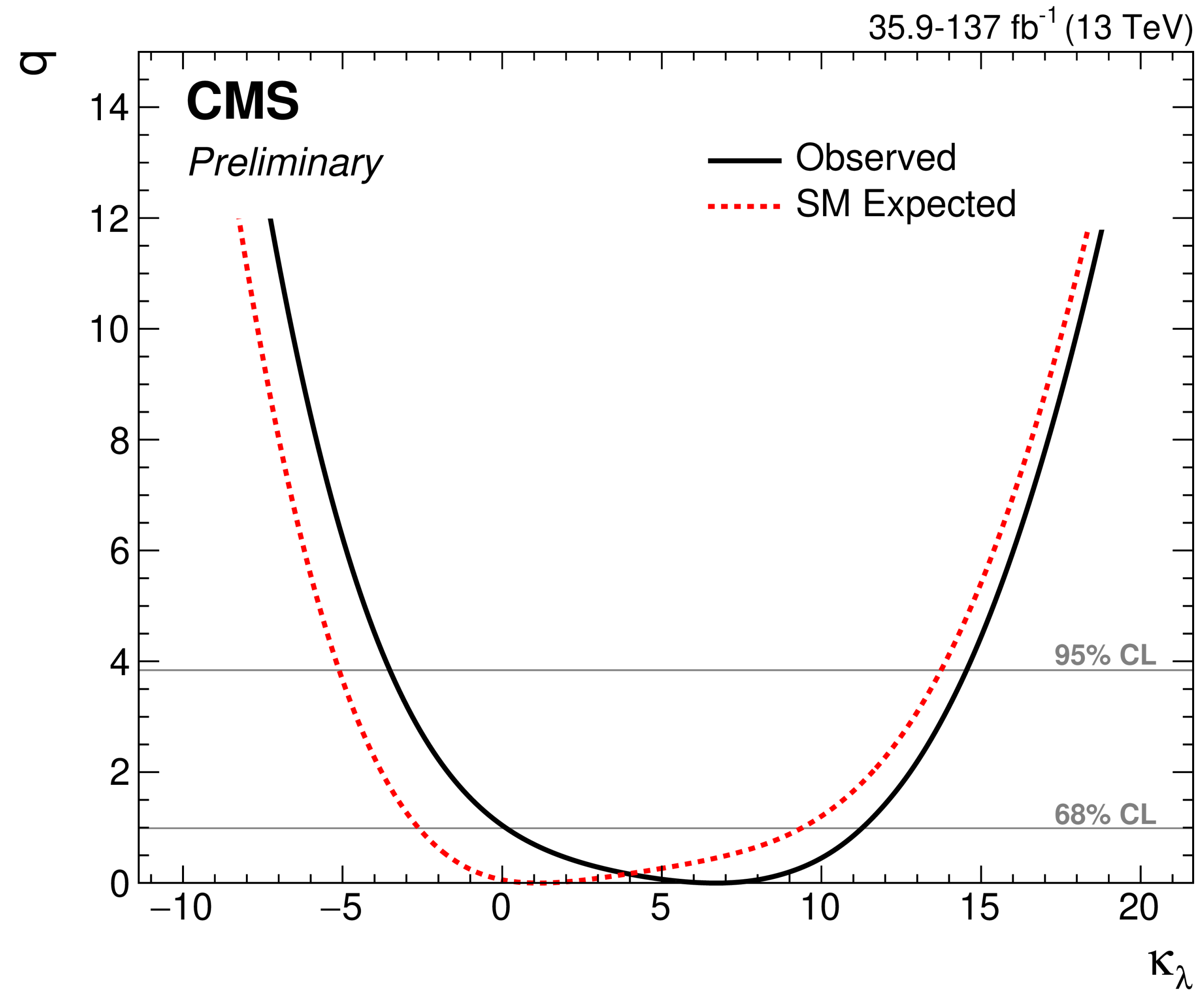




CMS Higgs combination (35.9-137 fb^{-1})

- Results from $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow WW^* \rightarrow l\nu l\nu$, $H \rightarrow \tau\tau$, $H \rightarrow \mu\mu$ and $t\bar{t}H$ with H decaying to leptons are combined considering both their decays and production modes.
- The signal strength modifier is calculated for production ($\mu^i = \sigma/\sigma^{SM}$), decay ($\mu^f = \mathscr{B}/\mathscr{B}^{SM}$) and production times decay $\mu_i^f = \mu_i \mu^f$
- Limits on multiple coupling modifiers $\kappa_j^2 = \sigma_j/\sigma_j^{SM}$ or $\kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$ are performed e.g. $\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_g, \kappa_\gamma, \kappa_\mu$

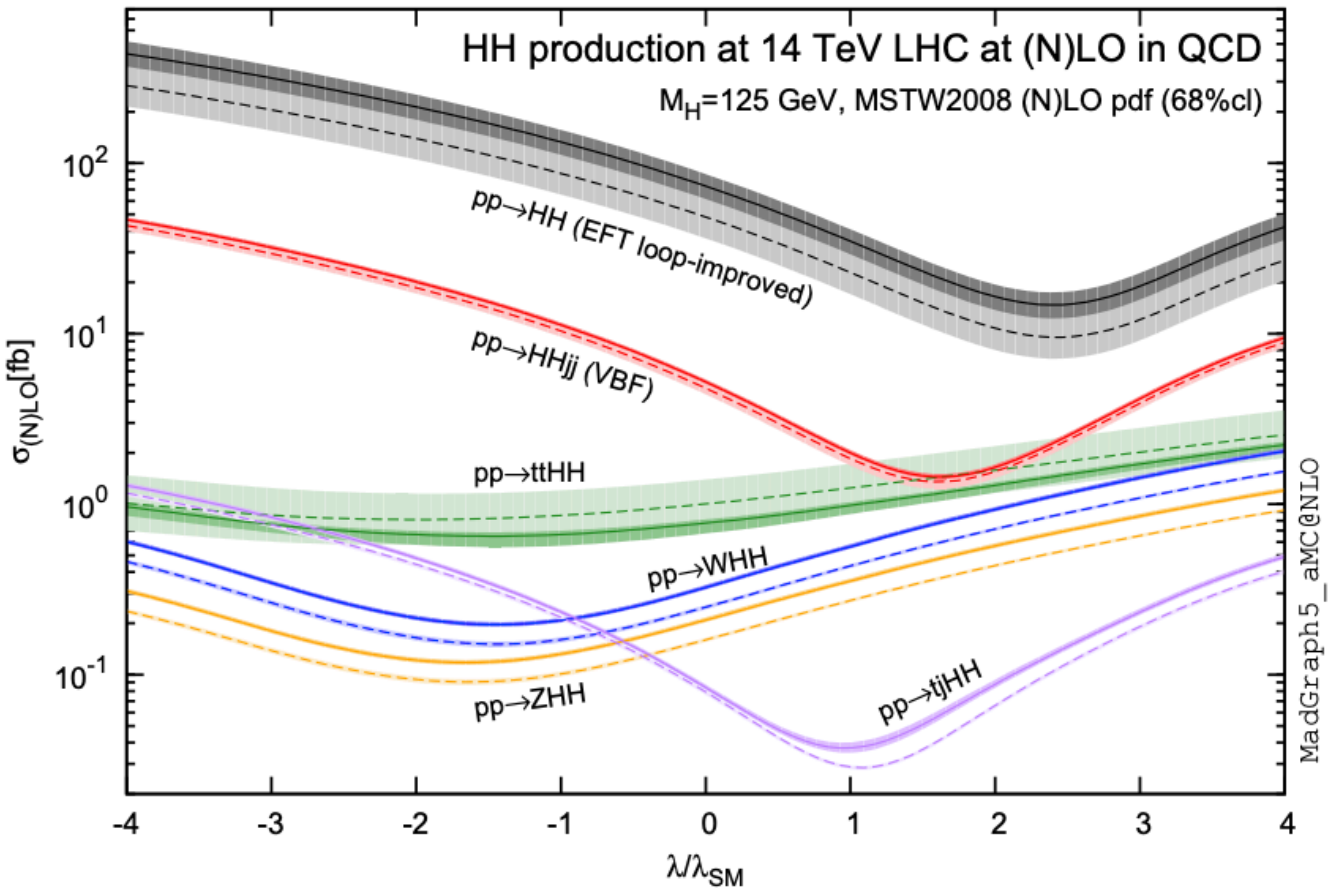




- Limits to κ_λ, $\kappa_\lambda(\kappa_V)$ and $\kappa_\lambda(\kappa_F)$ are set, where κ_λ is the Higgs boson production self coupling κ_λ and κ_F, κ_V are the LO coupling modifiers for Higgs boson coupling to fermions and vector bosons.
  - Observed (expected) limits at 95% CL (assuming $\kappa_F = \kappa_V = 1$):

    -3.5 (-5.1) $< \kappa_\lambda <$ 14.5 (13.5)

$\sigma(\kappa_\lambda)$: LO (solid), NLO (dashed)



Phys.Lett. B732 (2014) 142-149

Results presented today

Independent analyses

$VBF + ggF\ HH \to bb\gamma\gamma$
ATLAS

$HH \to bbllll$
CMS

$VBF + ggF\ HH \to bb\gamma\gamma$
CMS

$HH \to bbl\nu l\nu$
ATLAS

$VBF\ HH \to bbbb$*
ATLAS

Full Run 2

* 2015 data not included

Combinations

$ggF\ HH$ combination
ATLAS

$ggF\ HH$ combination
CMS

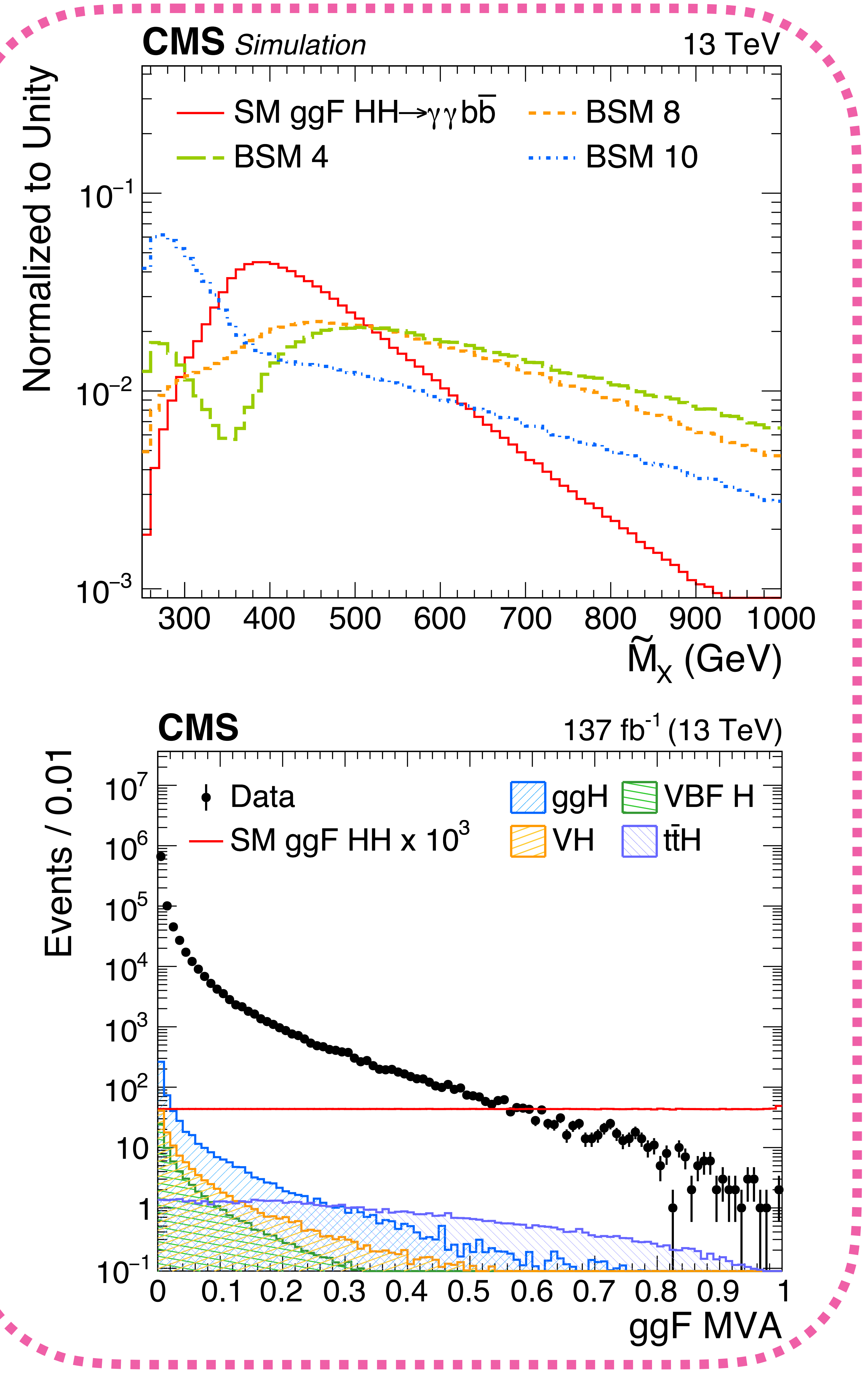
$HH + H$ combination
ATLAS

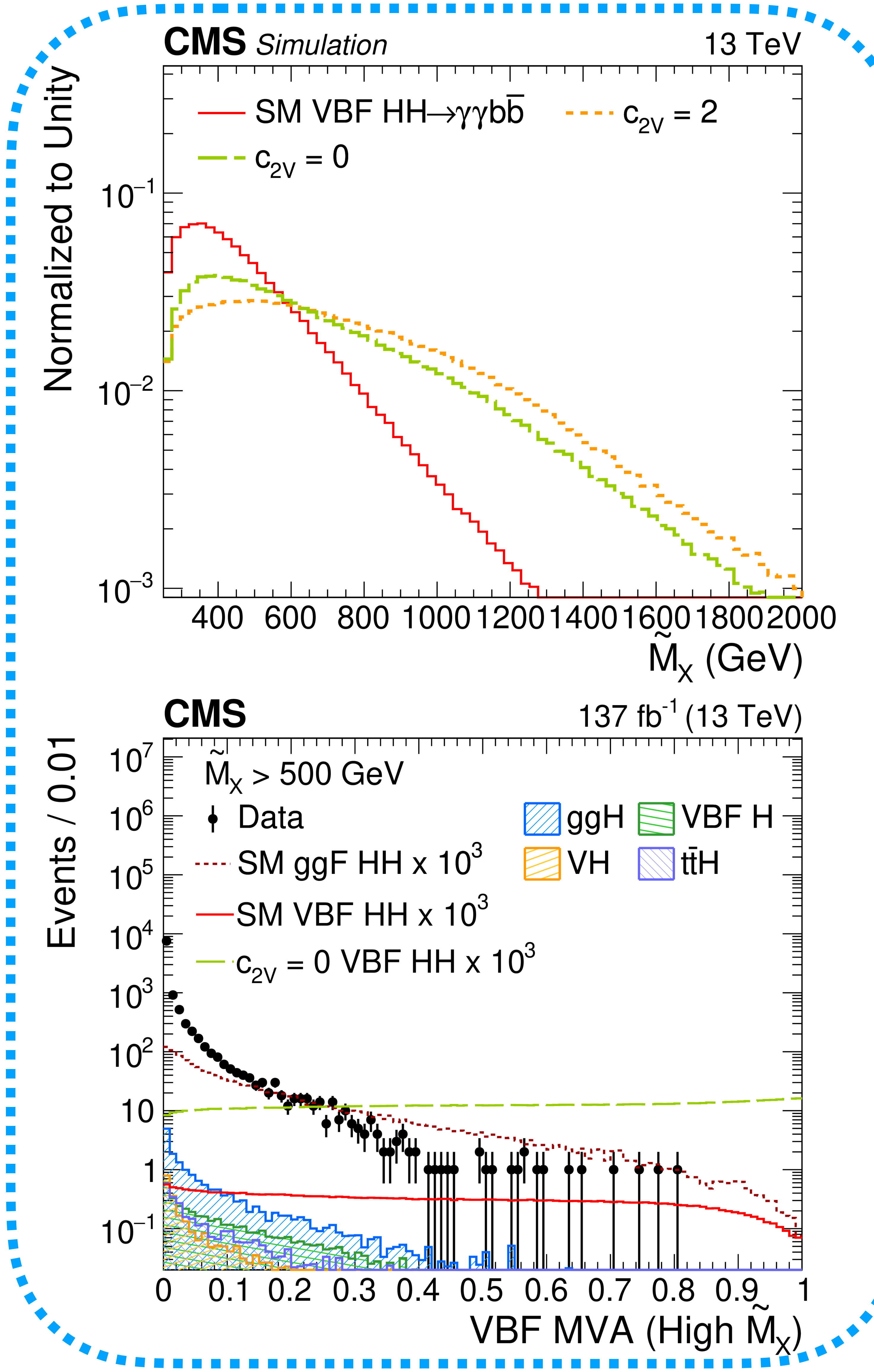
H combination
CMS

Partial Run 2

Extra: CMS $HH \rightarrow bb\gamma\gamma$ (137 fb^{-1})

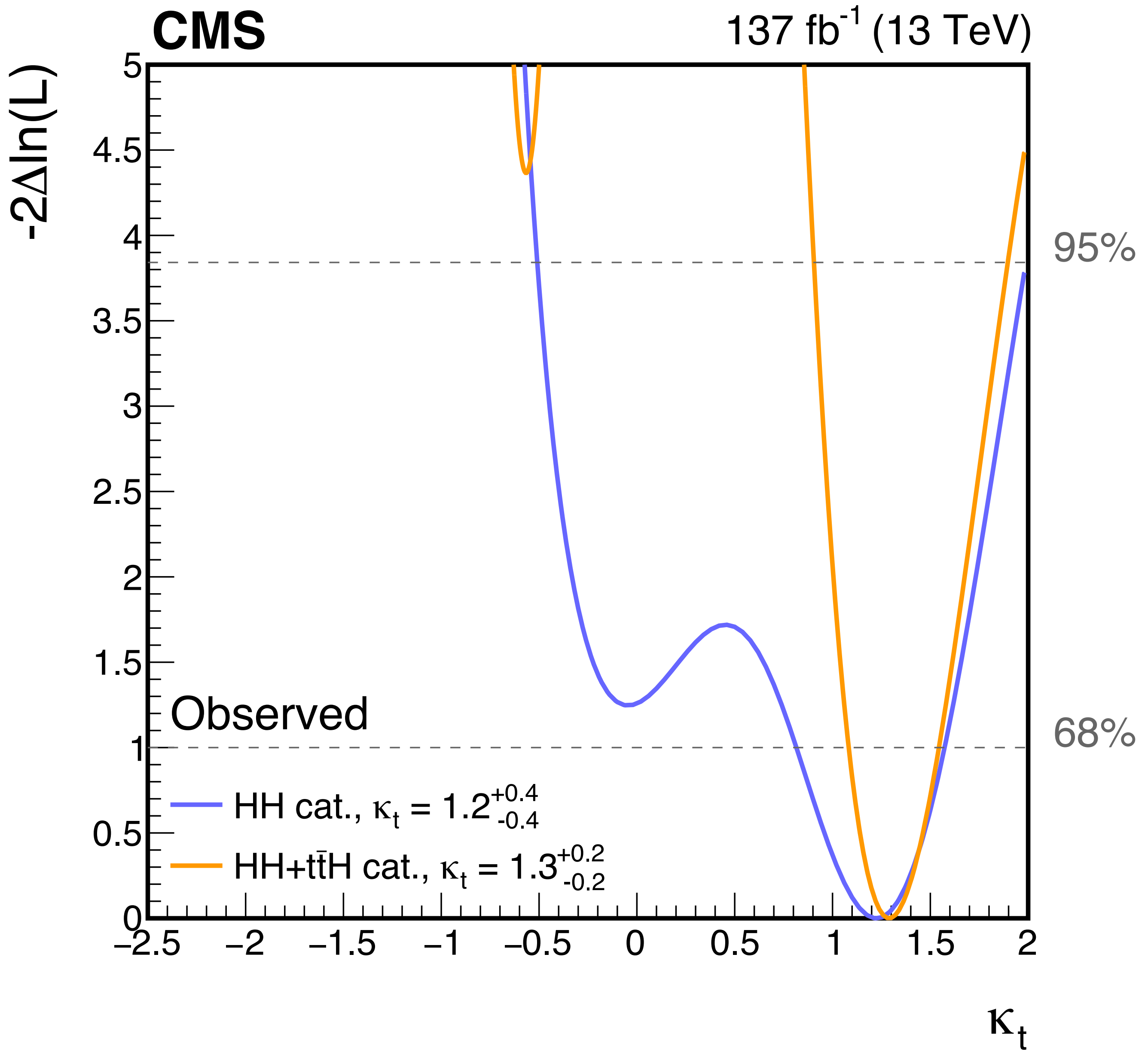
Category	MVA	$\widetilde{M}_X$ (GeV)
VBF CAT 0	0.52–1.00	>500
VBF CAT 1	0.86–1.00	250–500
ggF CAT 0	0.78–1.00	>600
ggF CAT 1		510–600
ggF CAT 2		385–510
ggF CAT 3		250–385
ggF CAT 4	0.62–0.78	>540
ggF CAT 5		360–540
ggF CAT 6		330–360
ggF CAT 7		250–330
ggF CAT 8	0.37–0.62	>585
ggF CAT 9		375–585
ggF CAT 10		330–375
ggF CAT 11		250–330

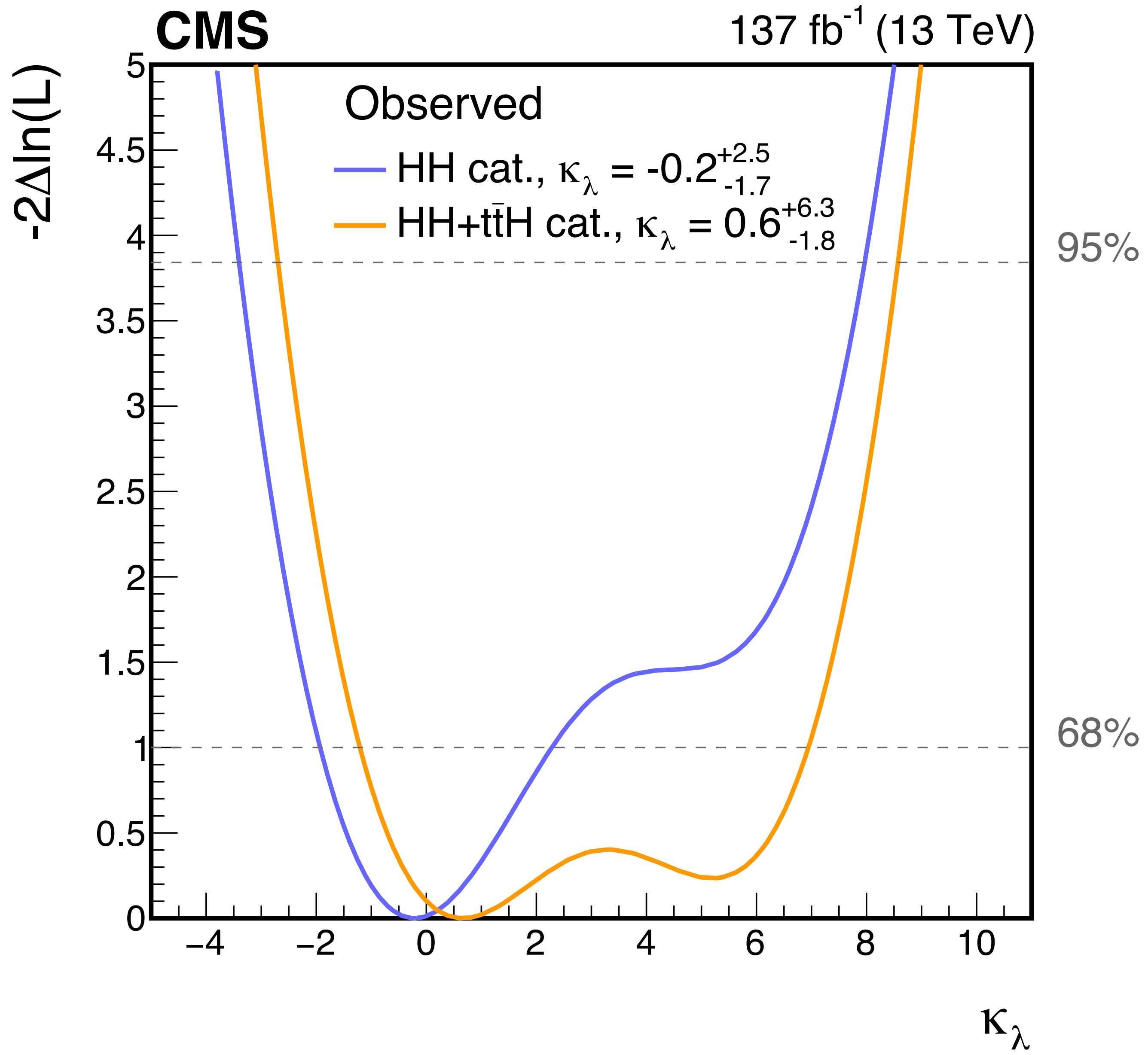




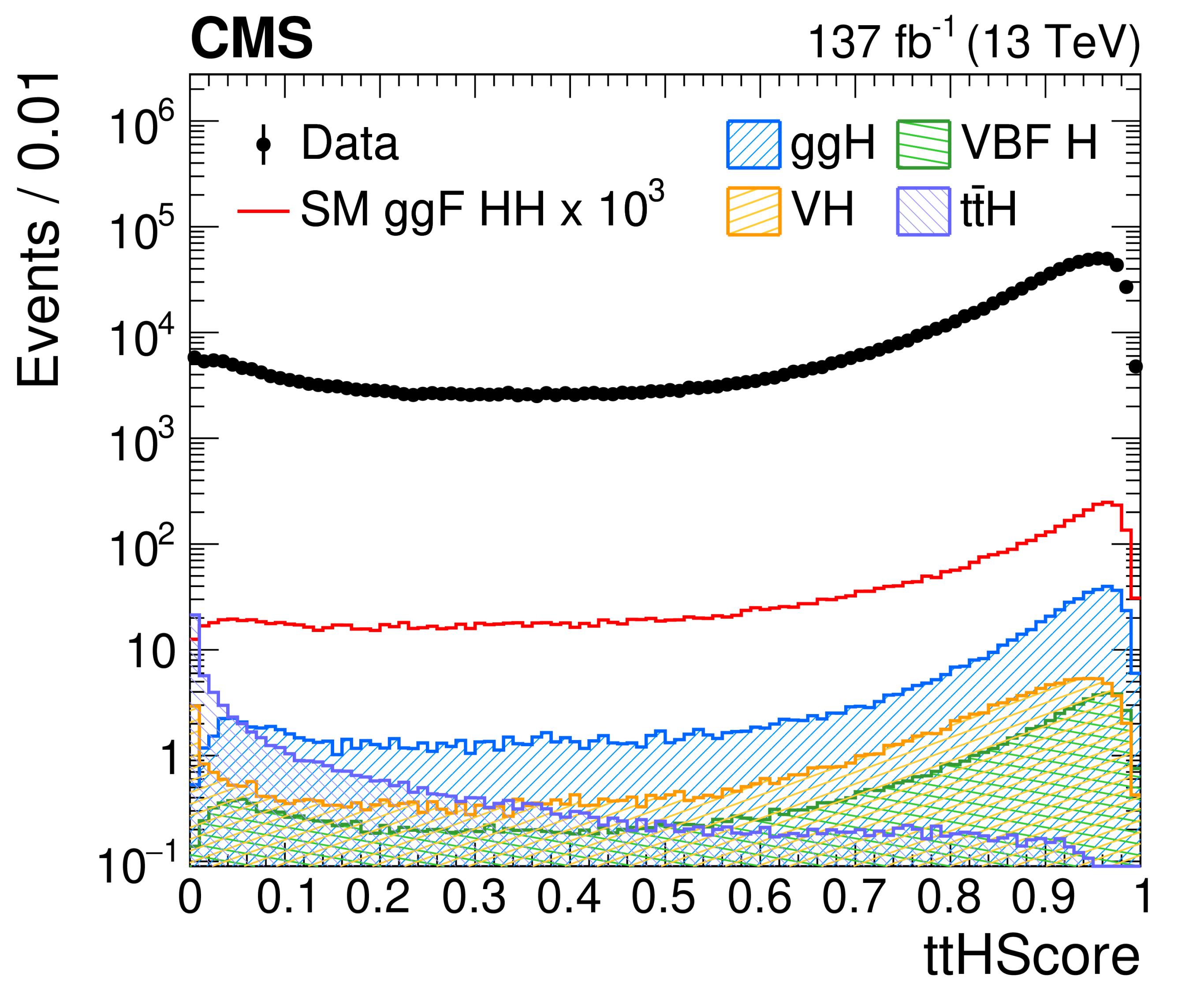
Extra: CMS $HH \to bb\gamma\gamma$ (137 fb^{-1})

1D limits to κ_t and κ_λ with/out the $t\bar{t}H$ category





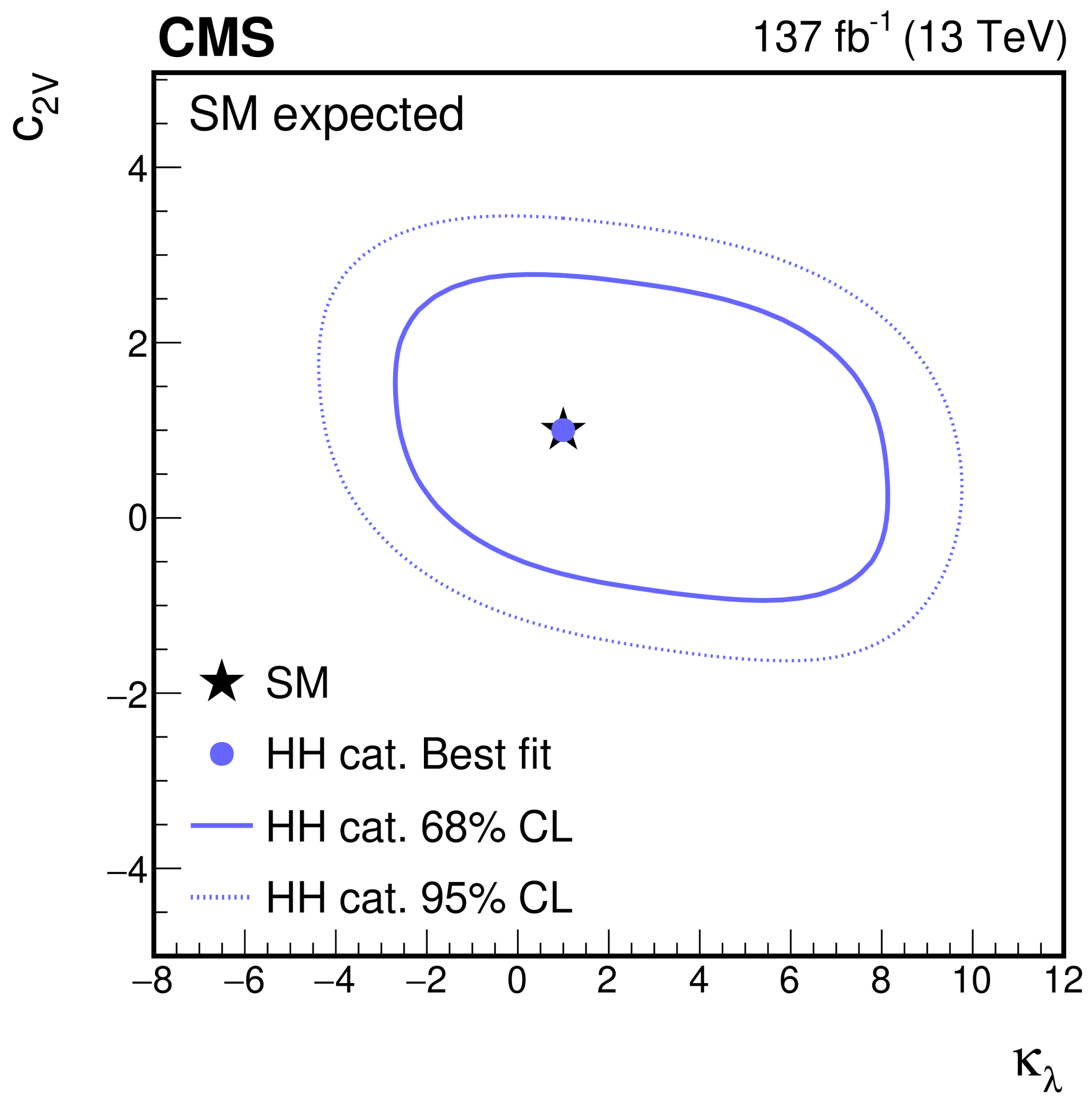
DNN score ($t\bar{t}H$ discrimination)

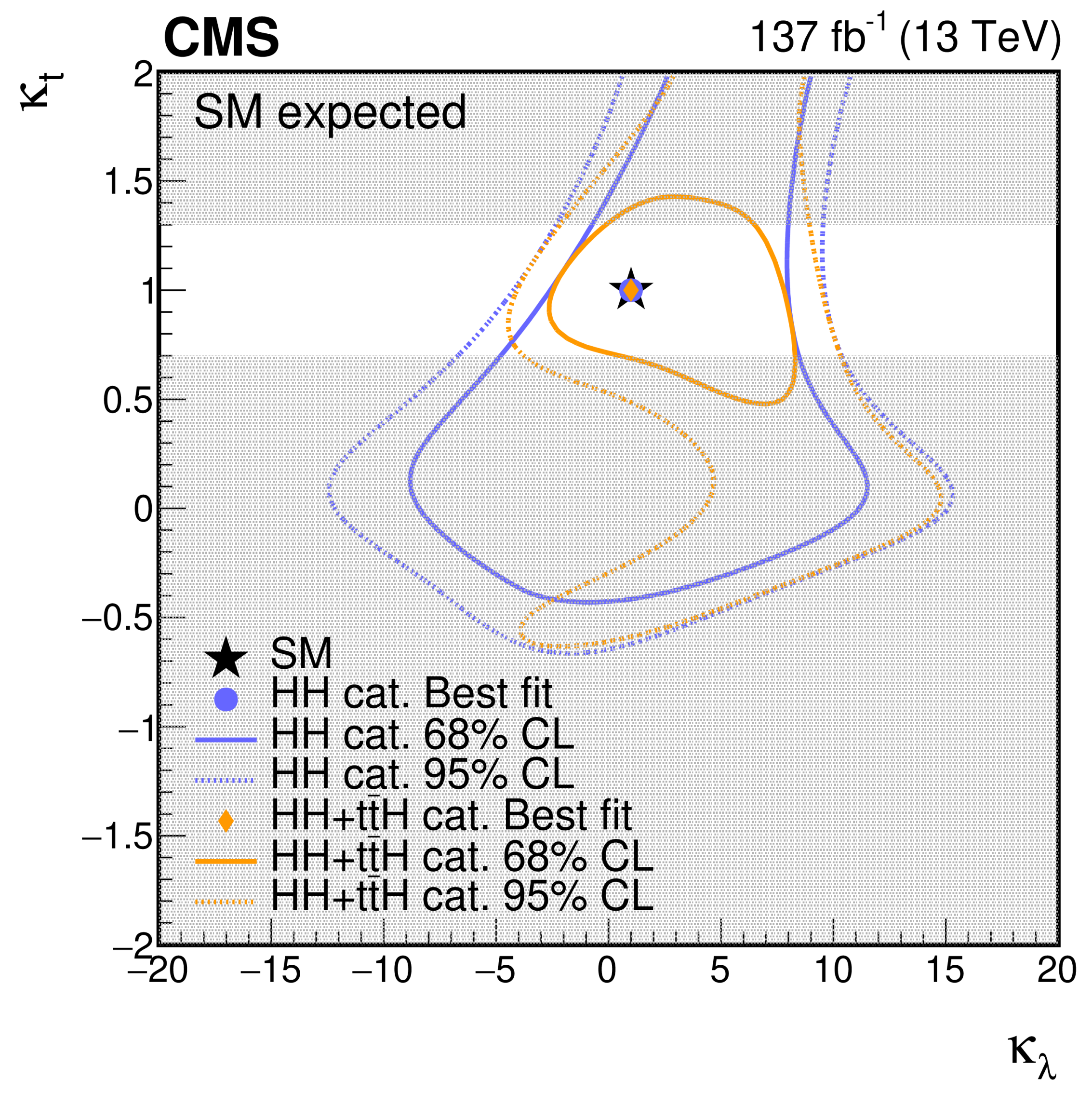


ggF HH HEFT shape benchmarks

	1	2	3	4	5	6	7	8	9	10	11	12	SM
κ_λ	7.5	1.0	1.0	−3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0	1.0
κ_t	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0
c_2	−1.0	0.5	−1.5	−3.0	0.0	0.0	0.0	0.0	1.0	−1.0	0.0	1.0	0.0
c_g	0.0	−0.8	0.0	0.0	0.8	0.2	0.2	−1.0	−0.6	0.0	1.0	0.0	0.0
c_{2g}	0.0	0.6	−0.8	0.0	−1.0	−0.2	−0.2	1.0	0.6	0.0	−1.0	0.0	0.0

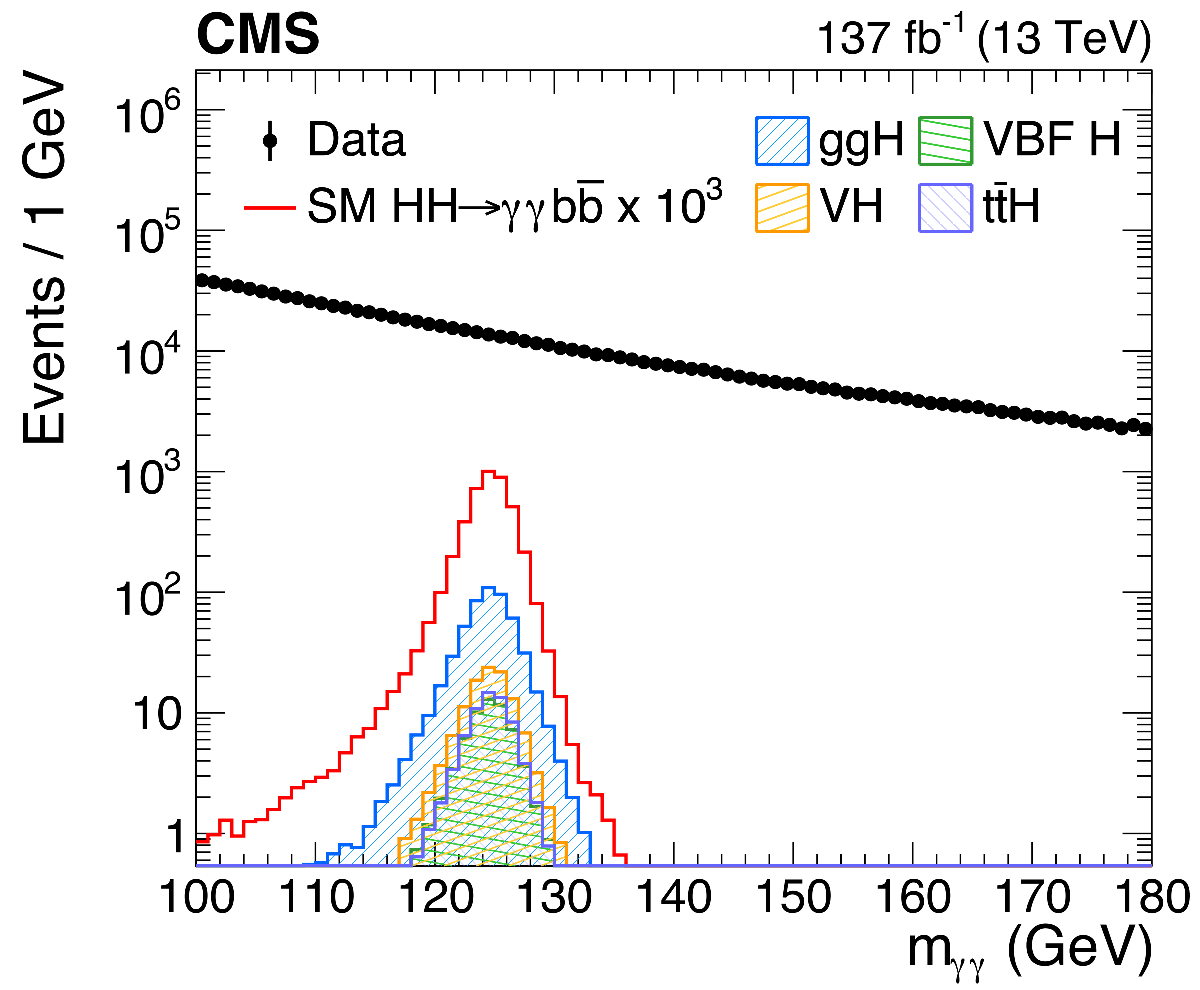
Expected 2D limits

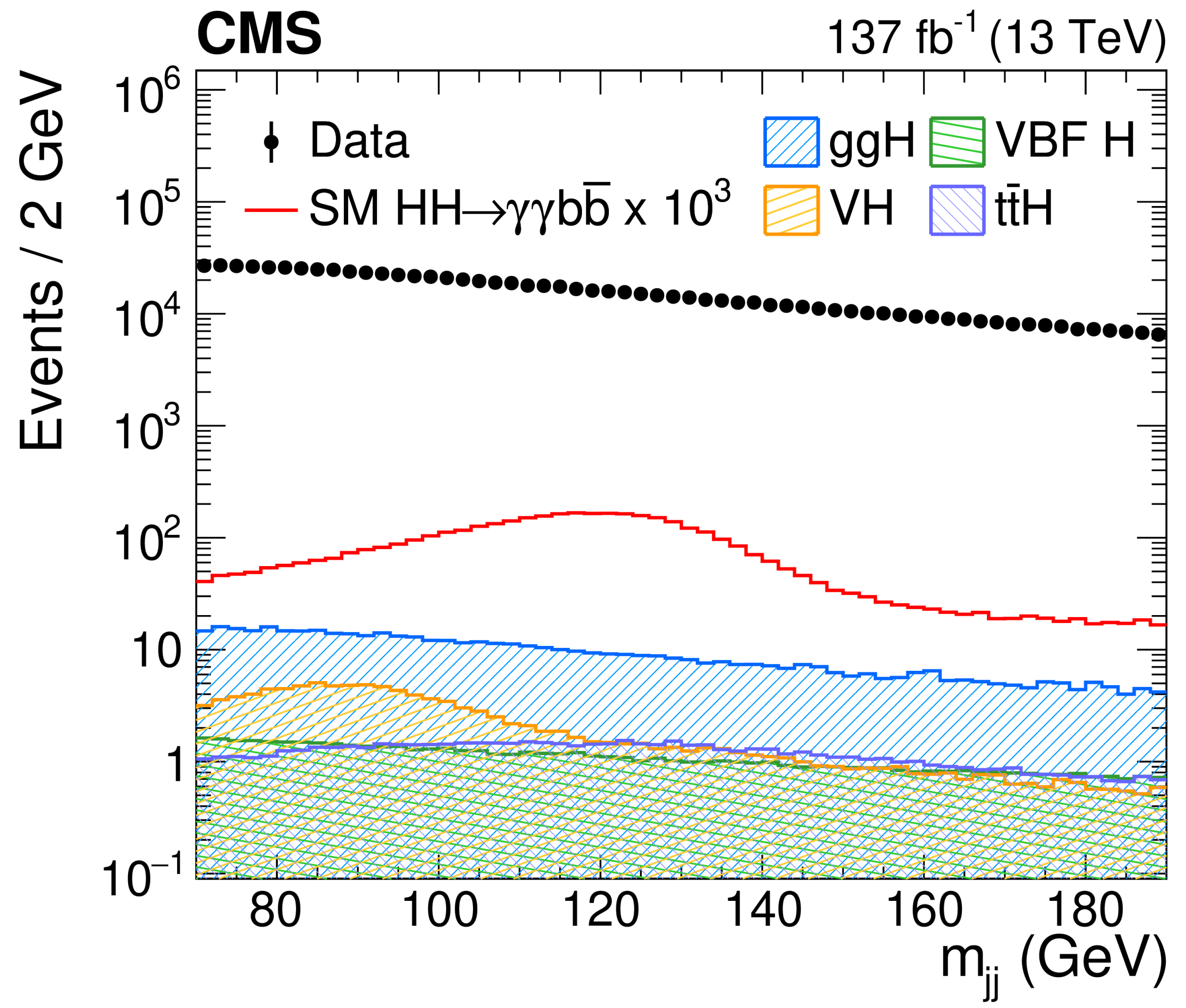


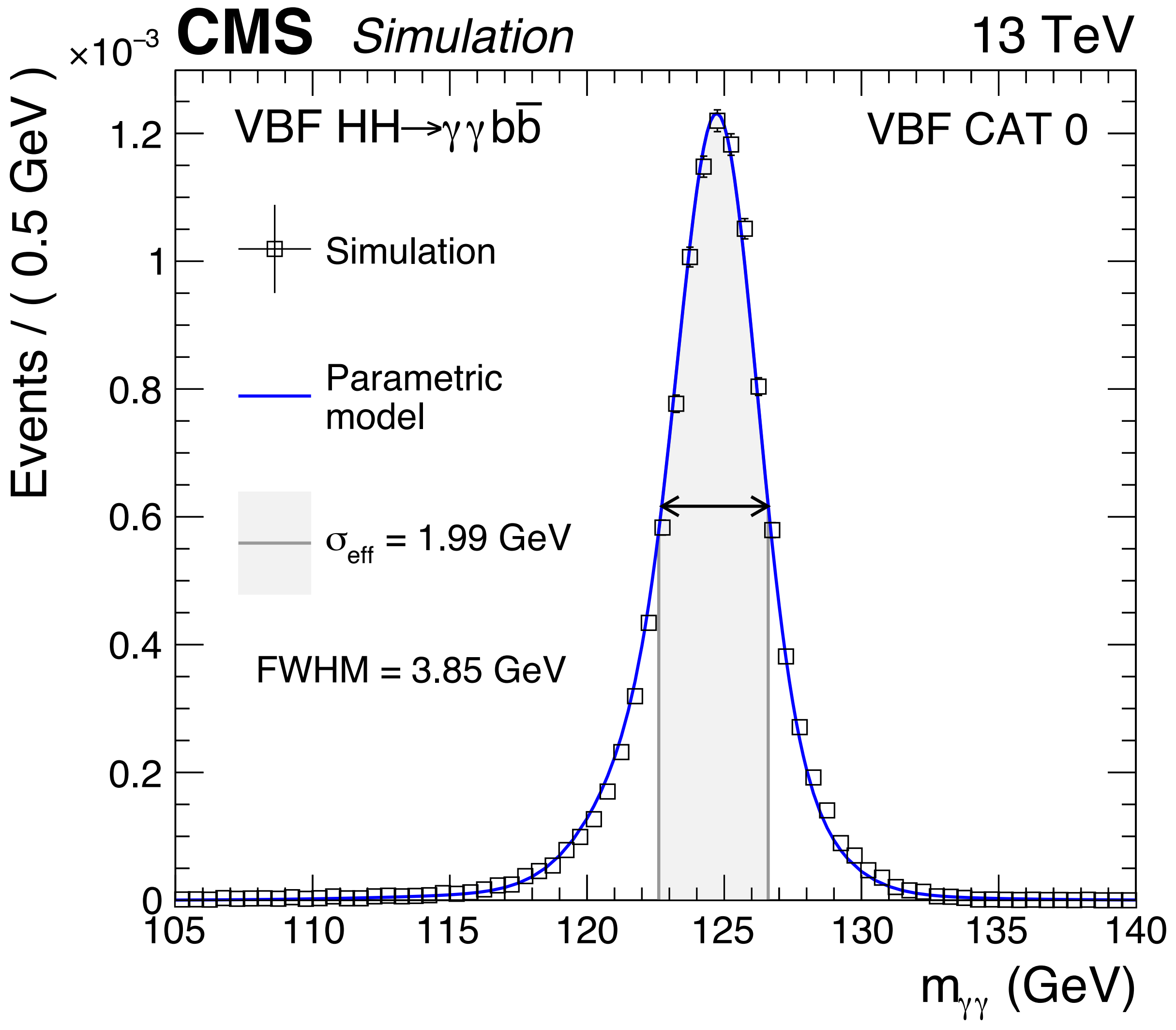


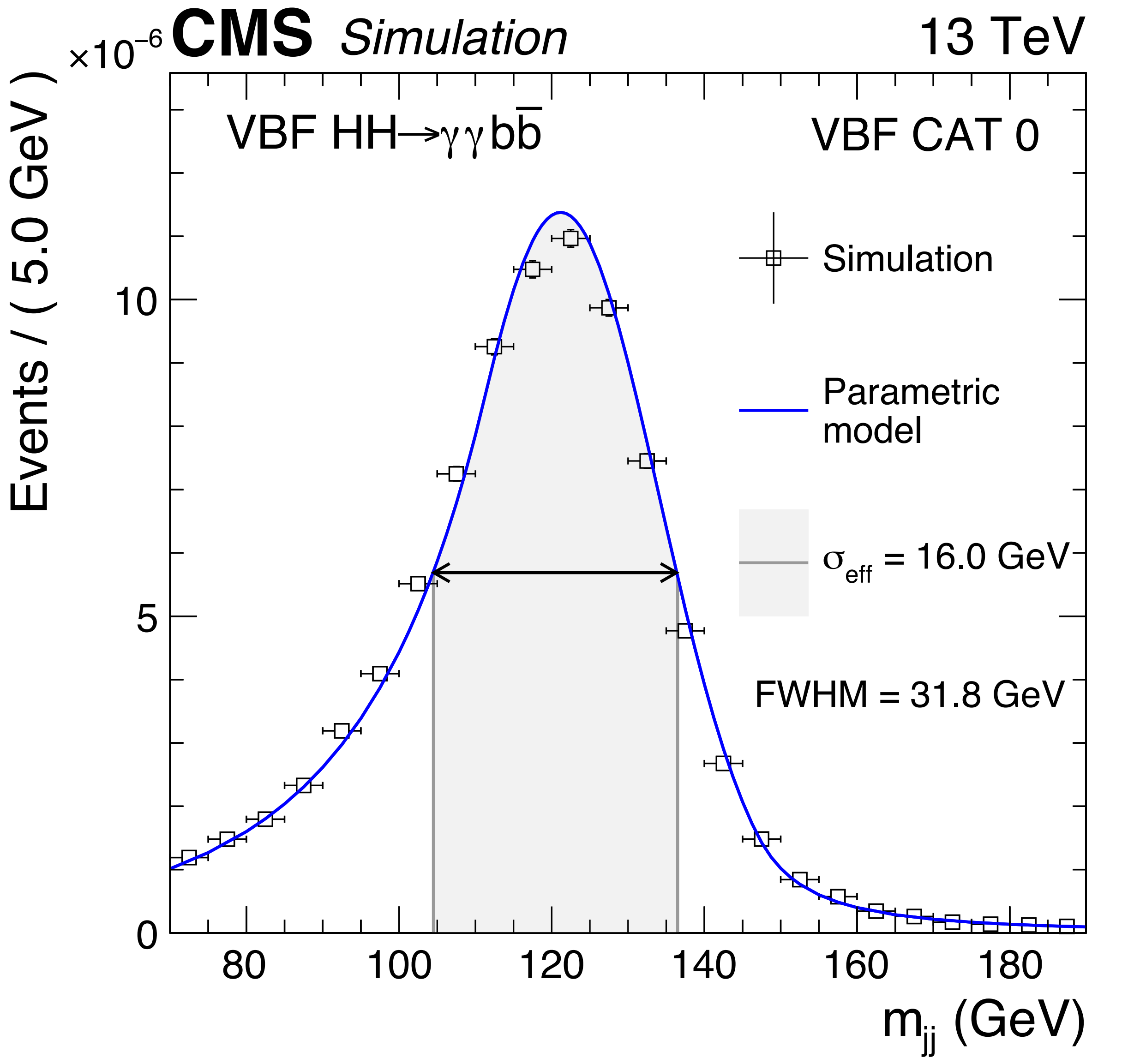
Extra: CMS $HH \rightarrow bb\gamma\gamma$ (137 fb^{-1})

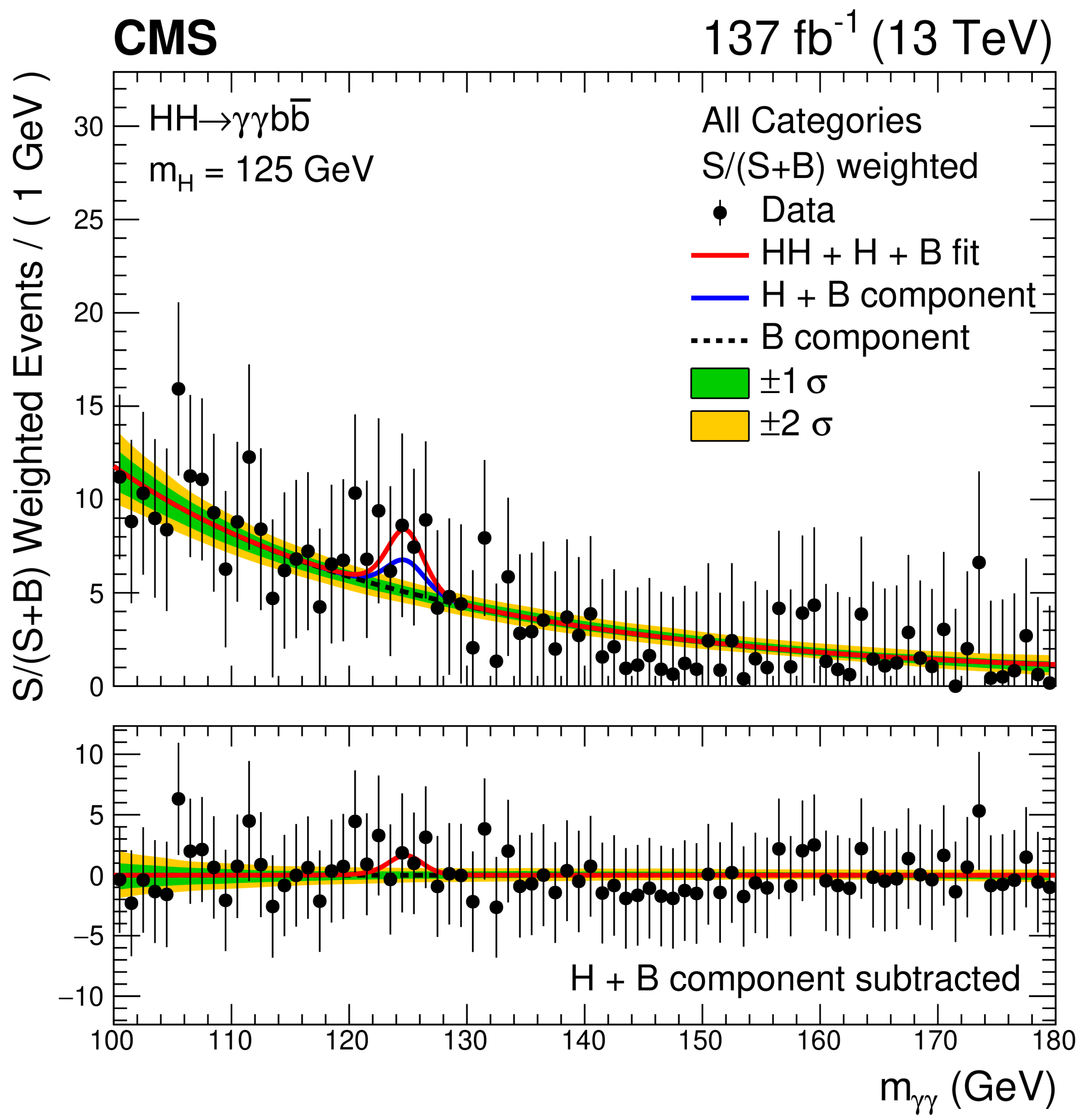
A 2D fit to $m_{\gamma\gamma}$ and m_{jj} is performed to estimate the non-resonant background with data

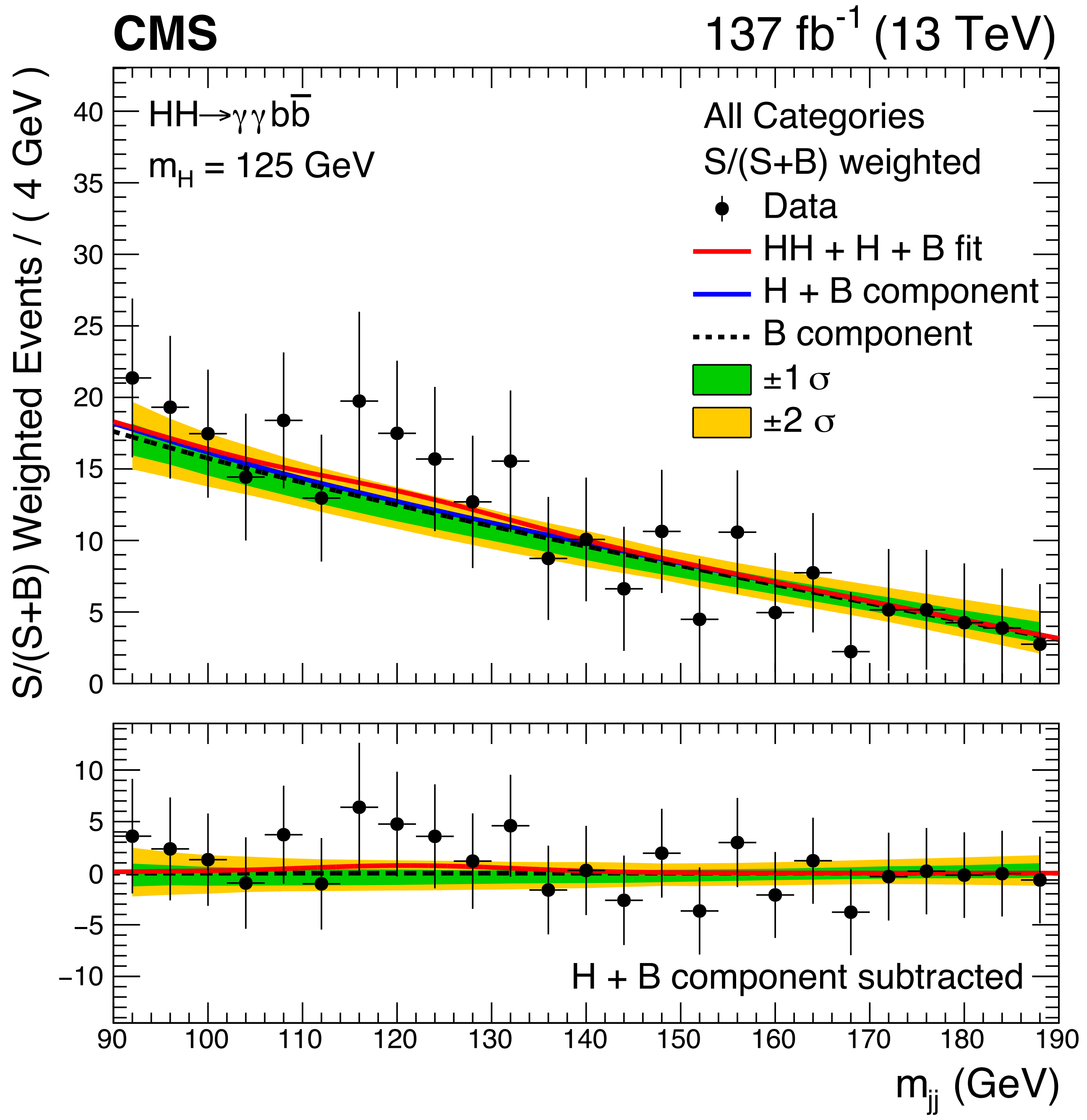




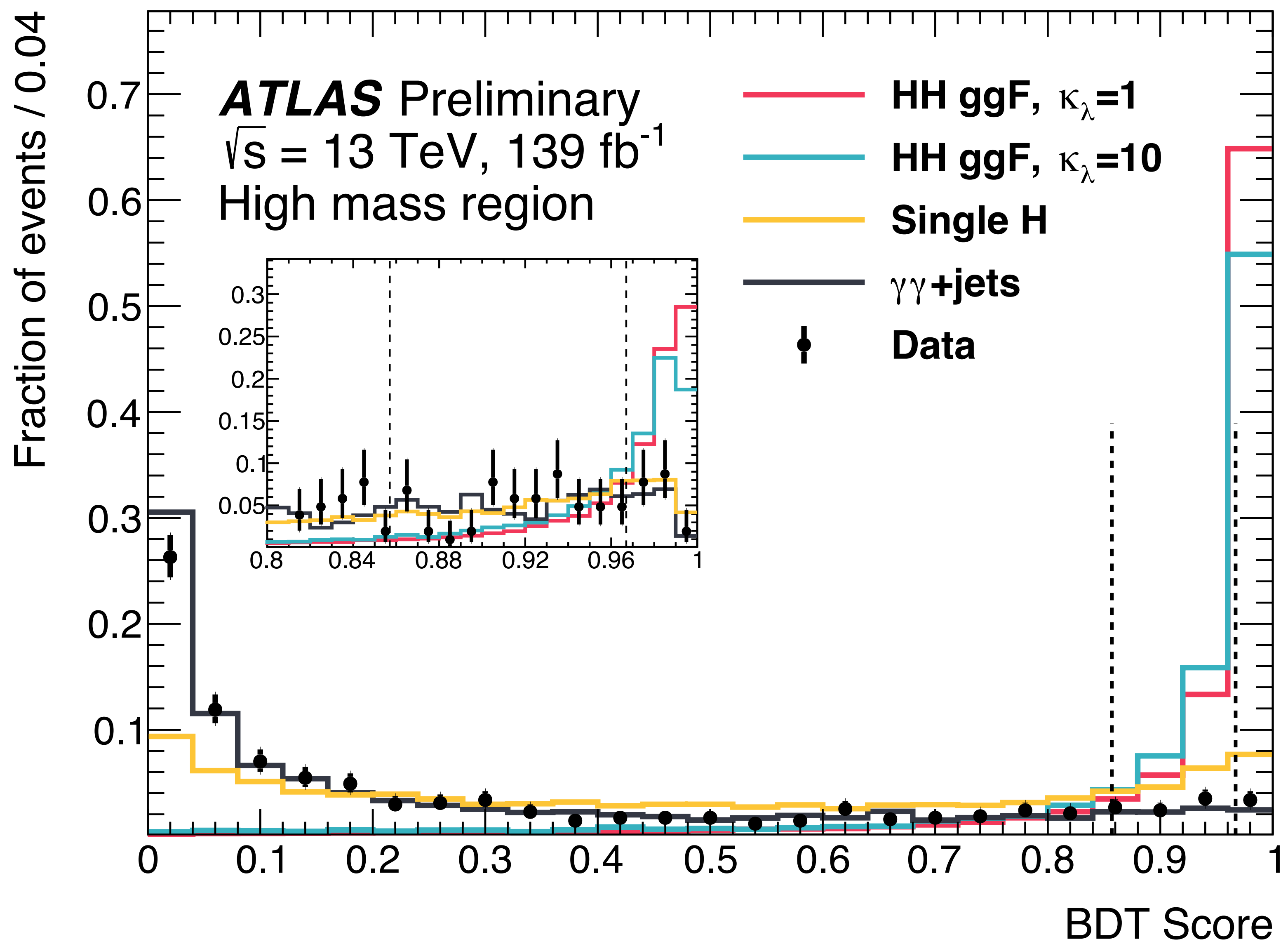


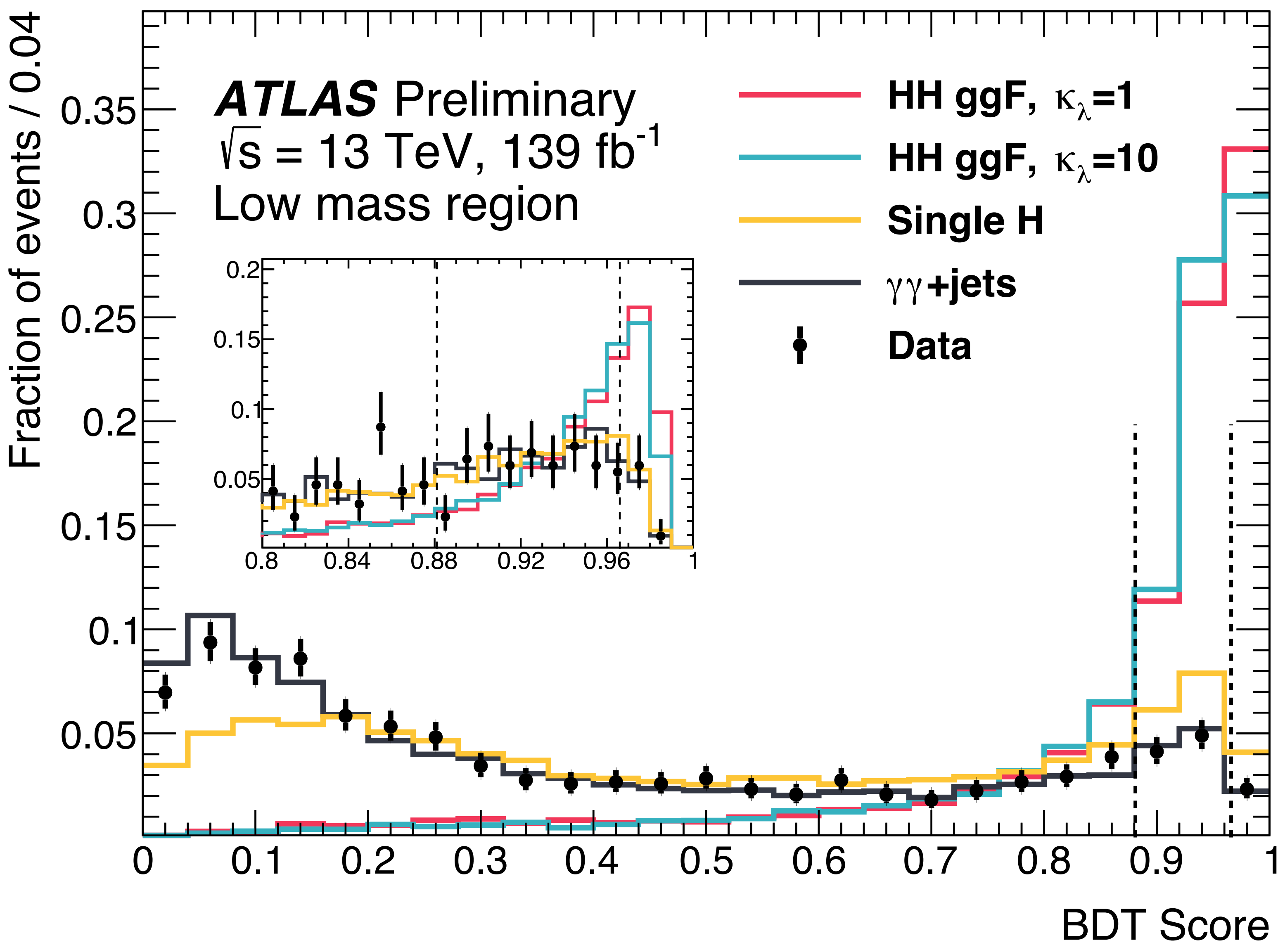


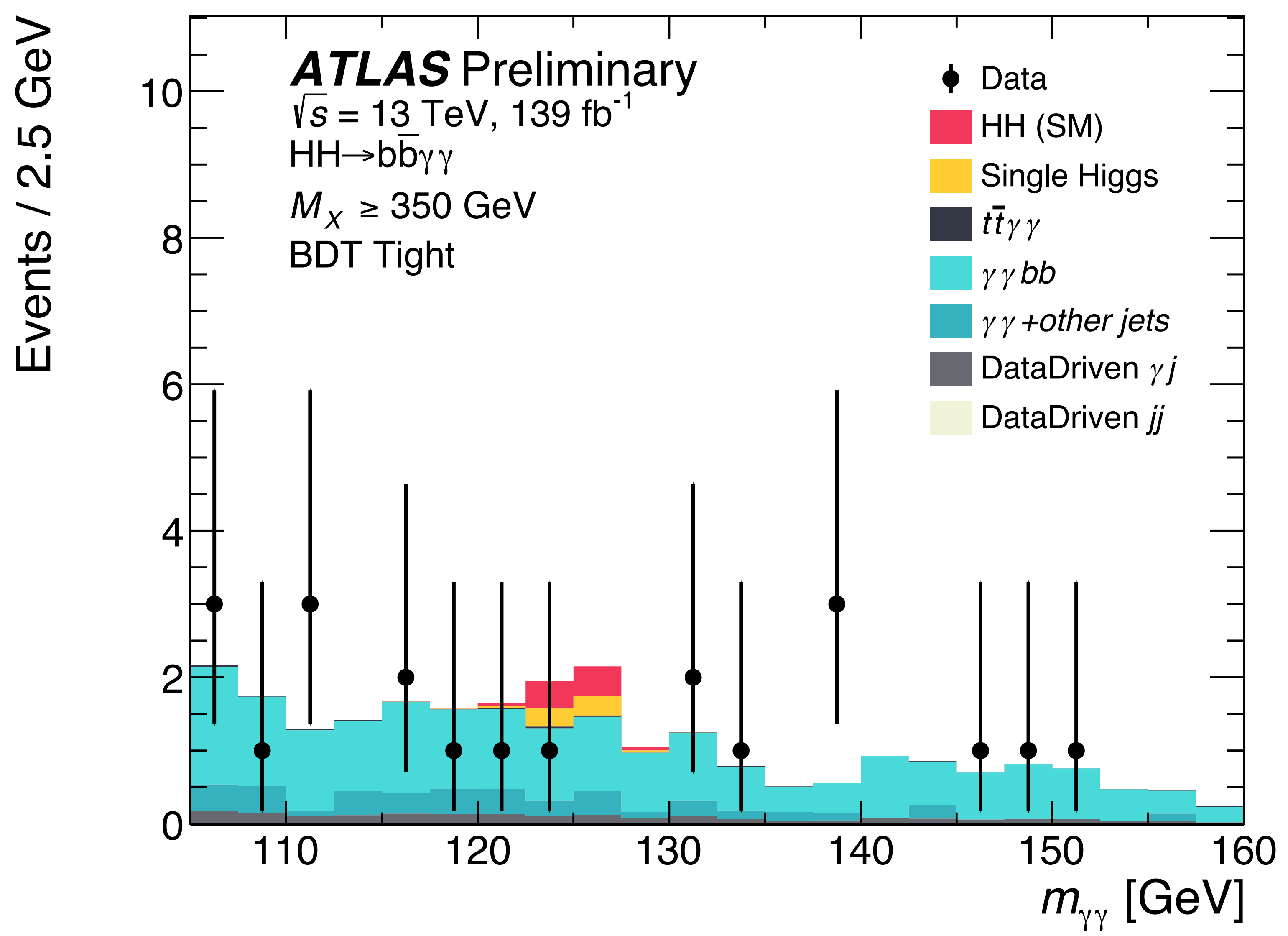




Extra: ATLAS $HH \rightarrow bb\gamma\gamma$ (139 fb^{-1})



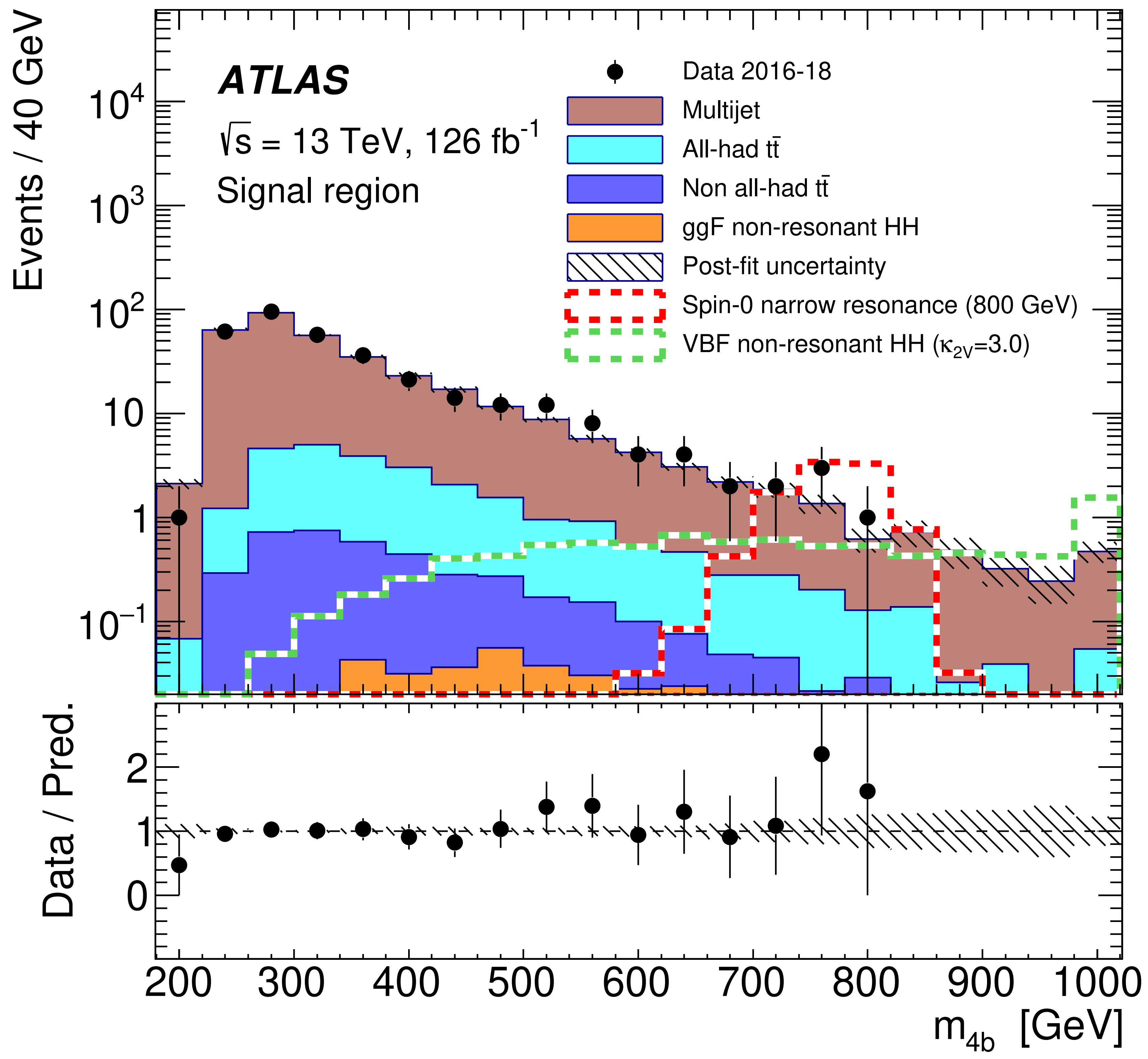


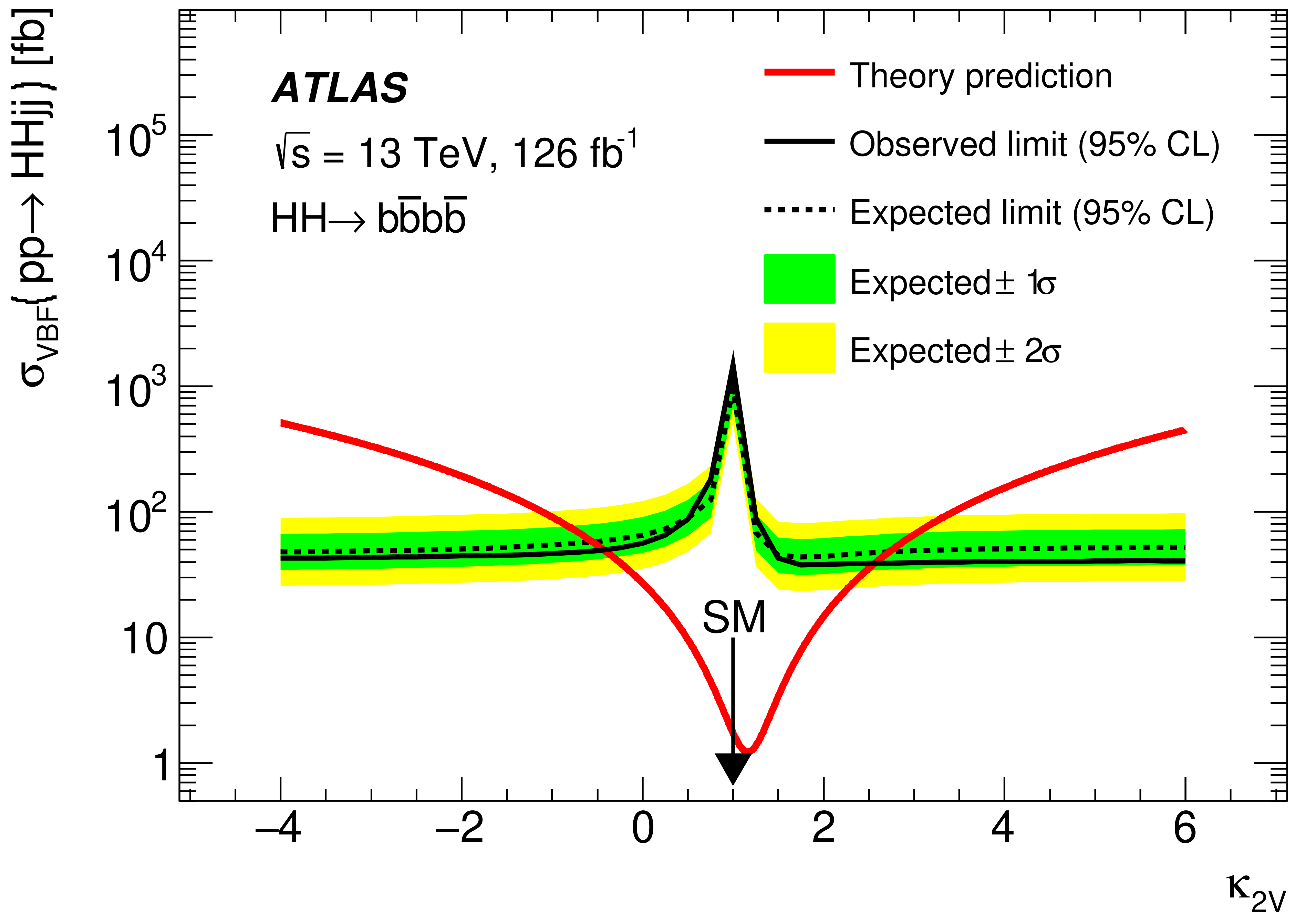


ATLAS *VBF HH* → *bbbb* (126 fb^{-1})

- Set limits on σ^{HH}_{VBF} and κ_{2V}
- Targets $VBF\ HH \to bbbb$ as signal while $ggF\ HH$, $t\bar{t}$ and multi-jet events are considered backgrounds.

	Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
σ_{VBF} [fb]	1450	500	660	920	1280	1720
$\sigma_{\mathrm{VBF}}/\sigma^{\mathrm{SM}}_{\mathrm{VBF}}$	840	290	390	540	750	1000





The observed (excluded) region corresponds to $-0.43 < \kappa_{2V} < 2.56$ ($-0.55 < \kappa_{2V} < 2.72$)are excluded at the 95% CL

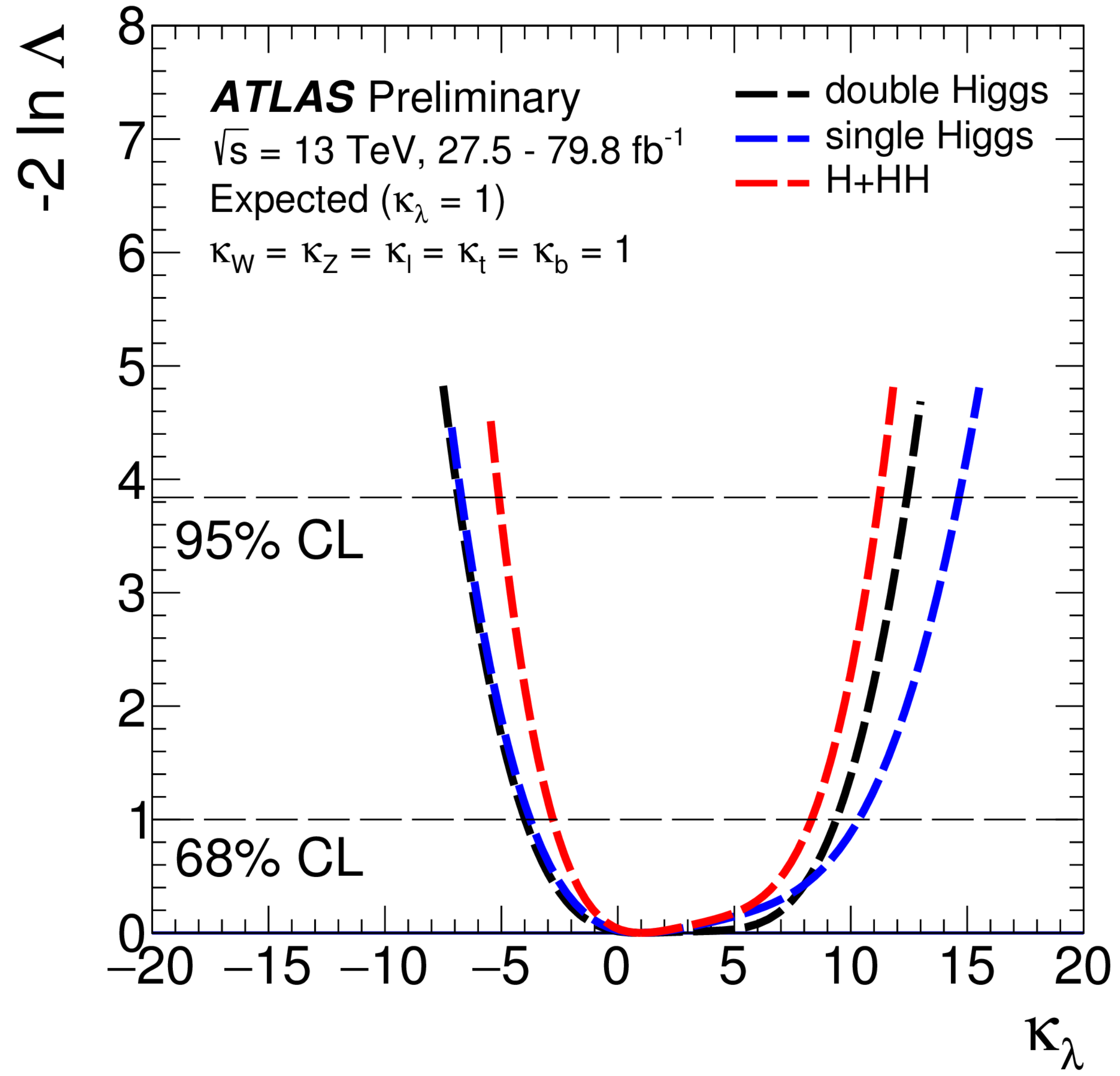
ATLAS $HH \to bbl\nu l\nu$

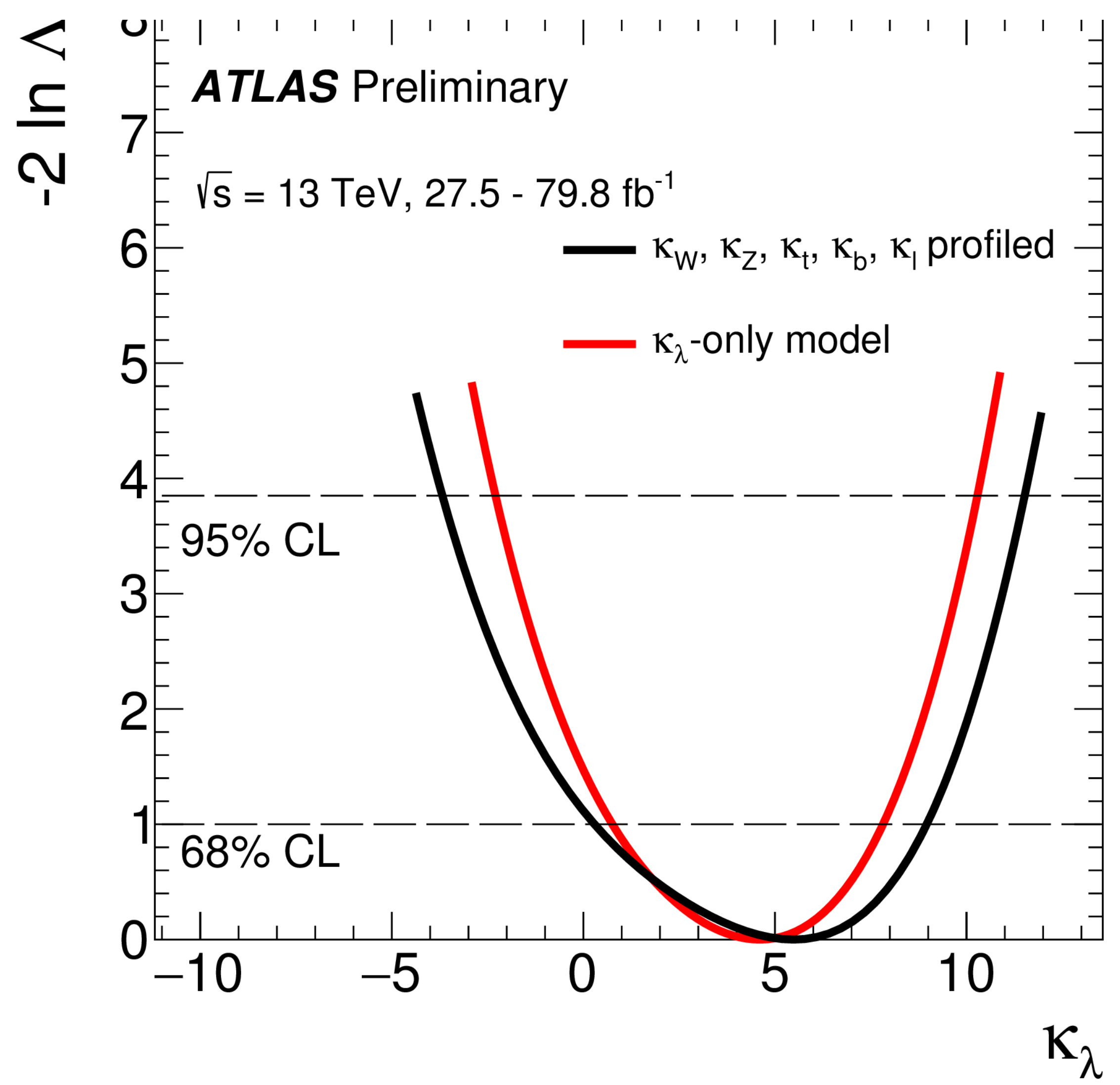
Region Definitions						
Observable	**CR-Top**	**VR-1**	**CR-Z+HF**	**VR-2**	**SR-SF**	**SR-DF**
Dilepton Flavour	DF	SF	DF or SF	SF	SF	DF
$m_{\ell\ell}$ [GeV]	(20, 60)	(20, 60)	(81.2, 101.2)	(71.2, 81.2) or (101.2, 115)	(20, 60)	(20, 60)
m_{bb} [GeV]	$\notin$ (100, 140)	> 140	(100, 140)	(100, 140)	(110, 140)	(110, 140)
d_{HH}	> 4.5	> 4.5	> 0	> 0	> 5.45	> 5.55
Event Yields						
Data	108	171	852	157	16	9
Total Bkg.	108 ± 10	162 ± 10	852 ± 29	147 ± 11	14.9 ± 2.1	4.9 ± 1.2
Top	92 ± 11	77 ± 10	55 ± 7	71 ± 10	4.8 ± 1.4	3.8 ± 1.1
Z/γ^*+ HF	3.2 ± 0.5	70 ± 4	686 ± 33	60 ± 4	7.8 ± 1.4	0.21 ± 0.05
Other	13.1 ± 3.4	14.2 ± 1.9	110 ± 13	15.8 ± 1.2	2.3 ± 0.5	0.9 ± 0.4
HH (×20)	2.70 ± 0.25	1.03 ± 0.22	1.97 ± 0.11	1.22 ± 0.05	5.0 ± 0.6	4.8 ± 0.8
Post-fit Normalisation						
$\mu_{\text{Top}} = 0.79 \pm 0.10$			$\mu_{Z/\gamma^* + \text{HF}} = 1.36 \pm 0.07$			

ATLAS HH Combination

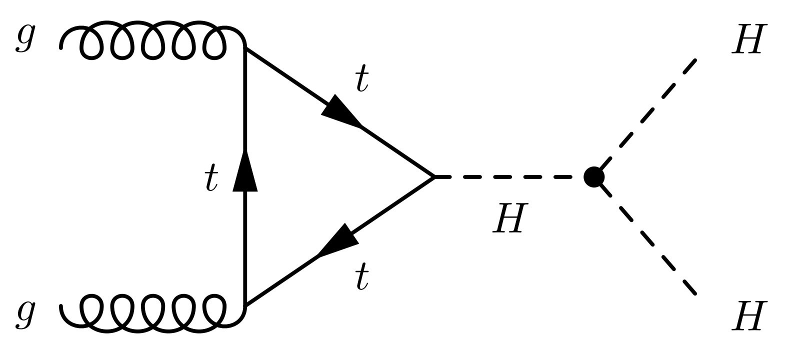
	Allowed κ_λ interval at 95% CL		
Final state	Obs.	Exp.	Exp. stat.
$b\bar{b}b\bar{b}$	−10.9 — 20.1	−11.6 — 18.8	−9.8 — 16.3
$b\bar{b}\tau^+\tau^-$	−7.4 — 15.7	−8.9 — 16.8	−7.8 — 15.5
$b\bar{b}\gamma\gamma$	−8.1 — 13.1	−8.1 — 13.1	−7.9 — 12.9
Combination	−5.0 — 12.0	−5.8 — 12.0	−5.3 — 11.5

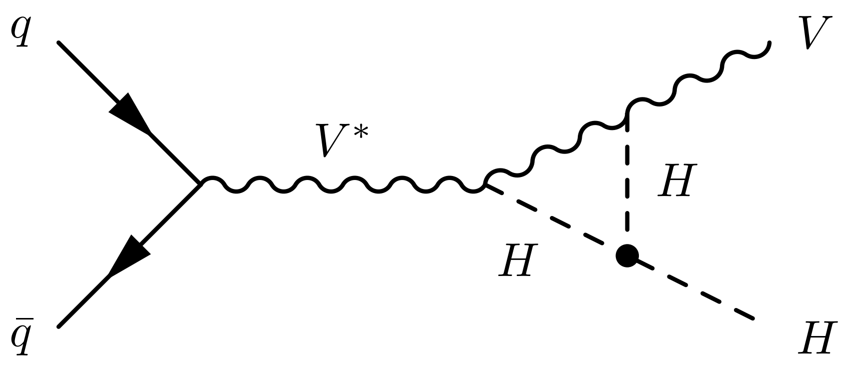
ATLAS H+HH combination (27.5-79.8 fb^{-1})



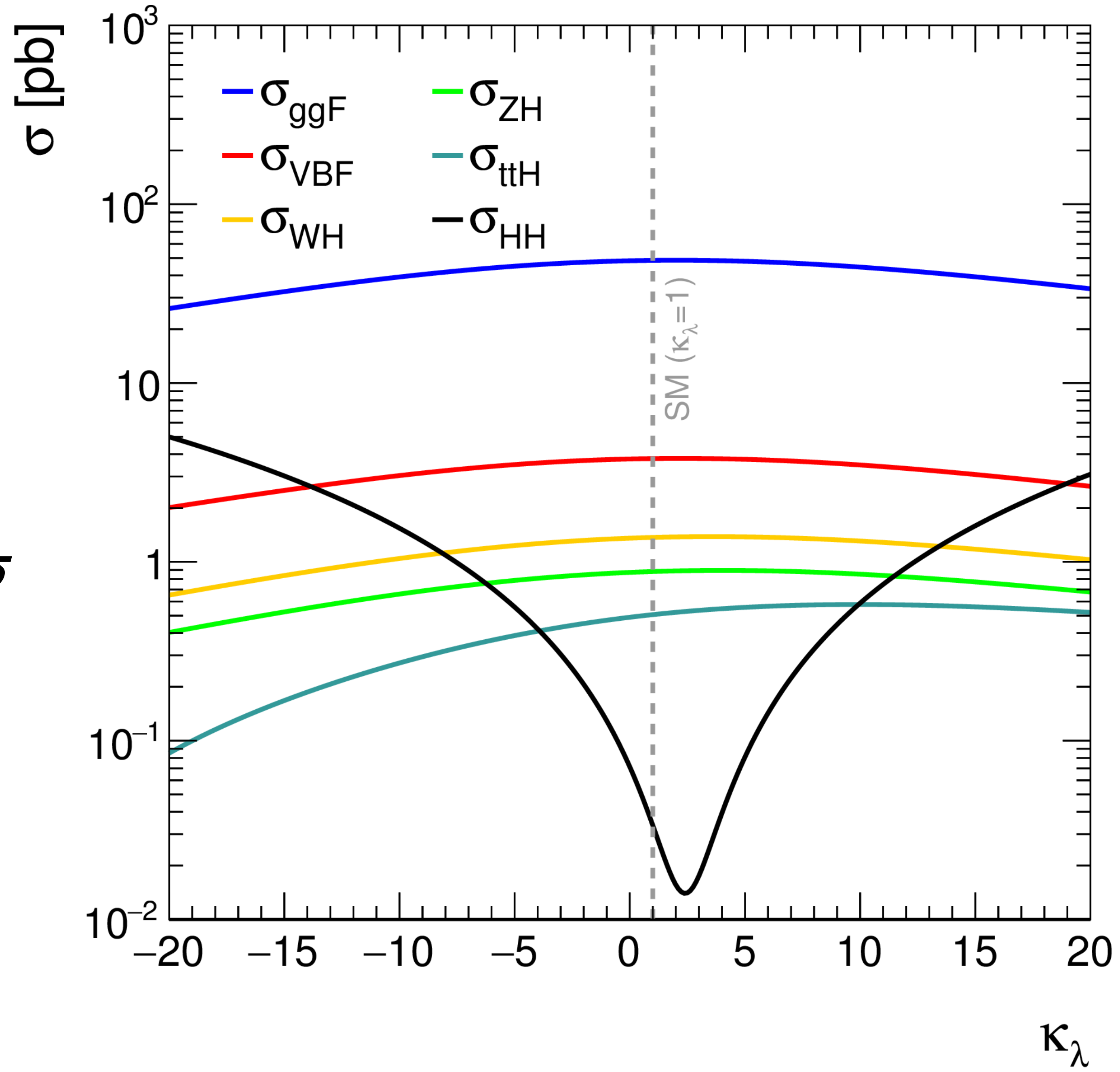


- Results from single Higgs and Higgs pair production analyses with multiple decay and production modes are combined:
  - $H \to \gamma\gamma$, $H \to ZZ^*$, $H \to WW^*$, $H \to \tau\tau$, $H \to b\bar{b}$, VH with $H \to b\bar{b}$, $t\bar{t}H$ with $H \to b\bar{b}$ and $H \to$ leptons.
  - $HH \to b\bar{b}b\bar{b}$, $HH \to b\bar{b}\tau\tau$ and $HH \to b\bar{b}\gamma\gamma$
- κ_λ enters at tree (loop level) for HH (H) production affecting σ





Production mode $\sigma(\kappa_\lambda)$



- Observed (expected) limits to the Higgs self coupling are set for the combinations under two different assumptions:

  A. New physics affects only the Higgs self coupling: -2.3 (-5.1) $< \kappa_\lambda <$ 10.3 (11.2)

  B. Including the couplings $\kappa_W, \kappa_Z, \kappa_t, \kappa_b$ and κ_l (more relaxed limits): -3.7 (-6.2) $< \kappa_\lambda <$ 11.5 (11.6)

- CMS uses single Higgs combination to set limits to κ_λ (assuming $\kappa_F = \kappa_V = 1$):

  -3.5 (-5.1) $< \kappa_\lambda <$ 14.5 (13.5)