Search for HH production at the LHC

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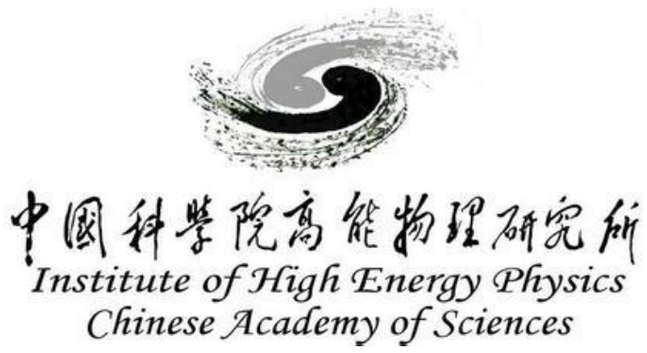
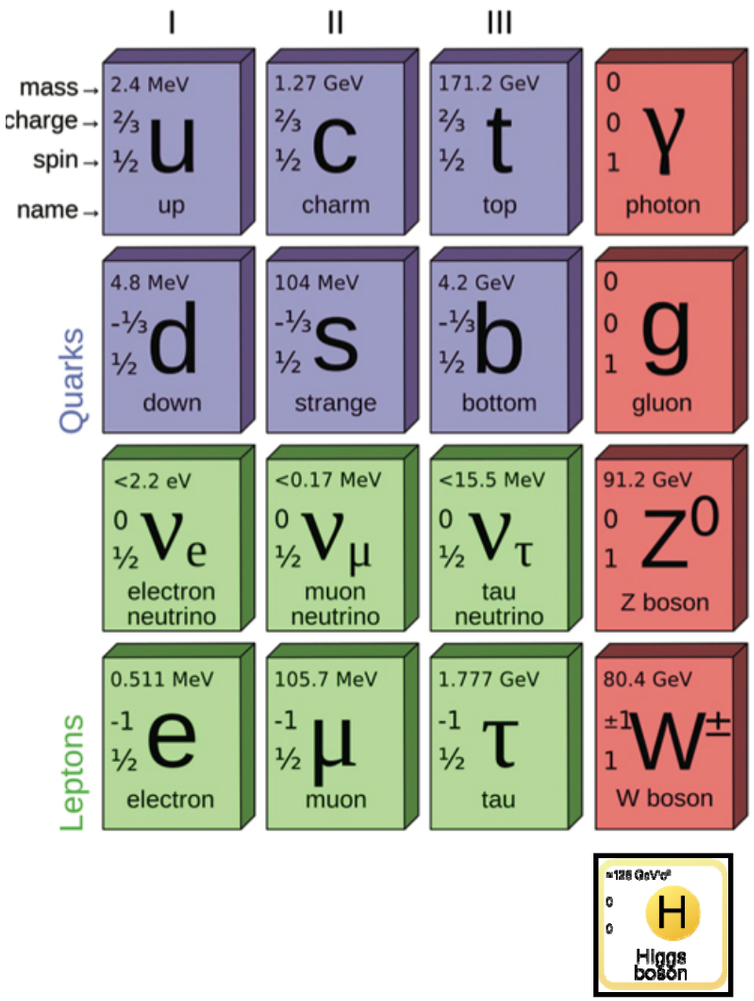


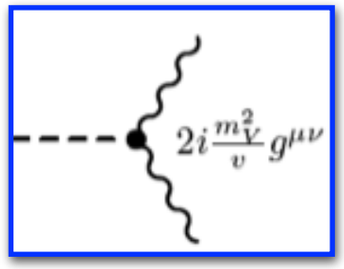
24 - 28th Nov, CLHCP 2021

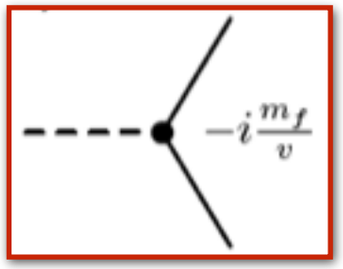
Introduction

- **The Higgs particle is responsible for the masses of elementary particles.**

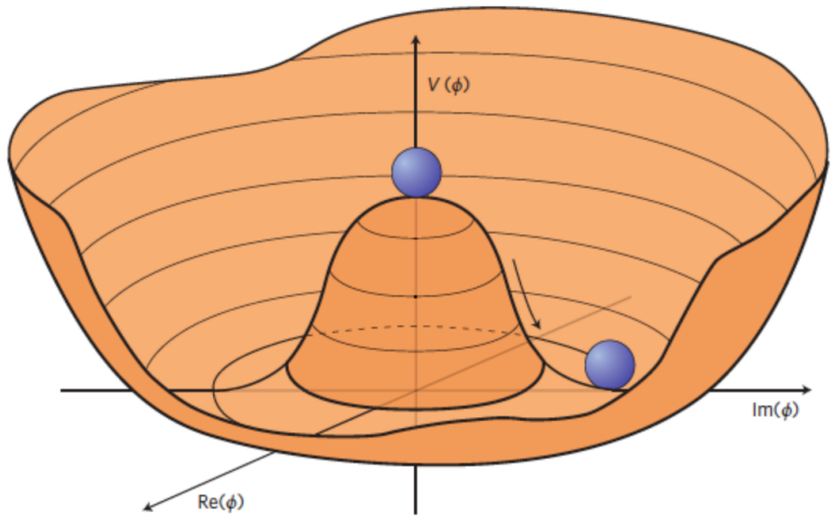


$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$





Gauge coupling **Yukawa coupling**



- **Higgs potential approximation:**

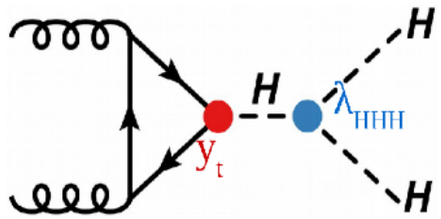
$$V(h) = \frac{1}{2}m_H^2h^2 + \boxed{\lambda_3 vh^3 + \frac{1}{4}\lambda_4 h^4} \quad \text{with} \quad \lambda_3^{\text{SM}} = \lambda_4^{\text{SM}} = \frac{m_H^2}{2v^2}$$

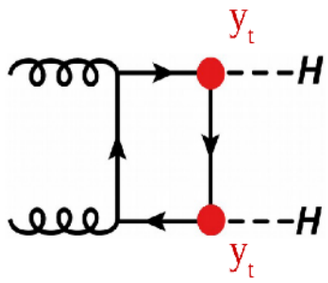
Self-coupling

$$\kappa_\lambda = \kappa_3 = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

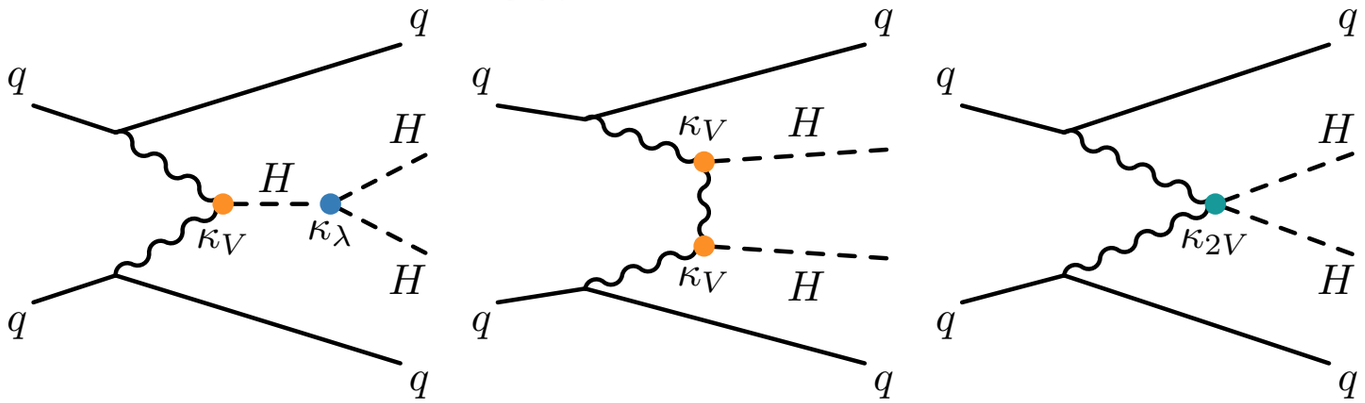
Higgs self-coupling is crucial to understand the EW symmetry breaking mechanism

HH production and decays

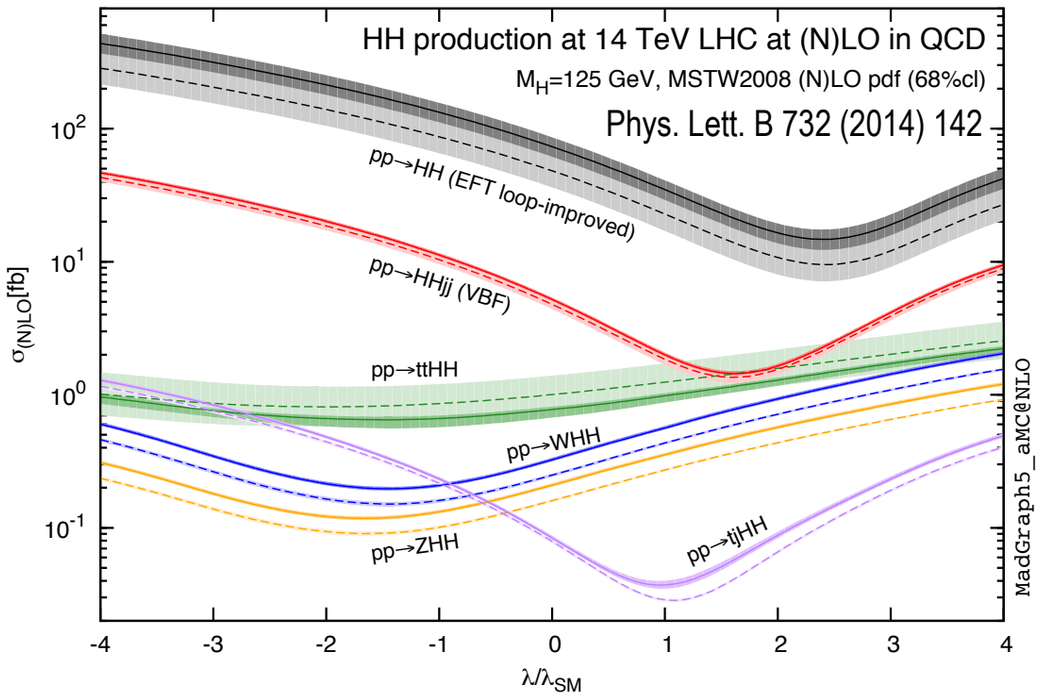




NNLO $\sigma_{HH}(\text{ggF}) = 31.02^{+2.2\%}_{-5.0\%}$ (Scale) ±3.0% (α_s+PDF) ±2.6% (m_{top}) fb



N3LO $\sigma_{HH}(\text{VBF}) = 1.72^{+0.03\%}_{-0.04\%}$ (Scale) ±2.1% (α_s+PDF) fb



HH production —> direct determination of Higgs trilinear coupling λ_{HHH}

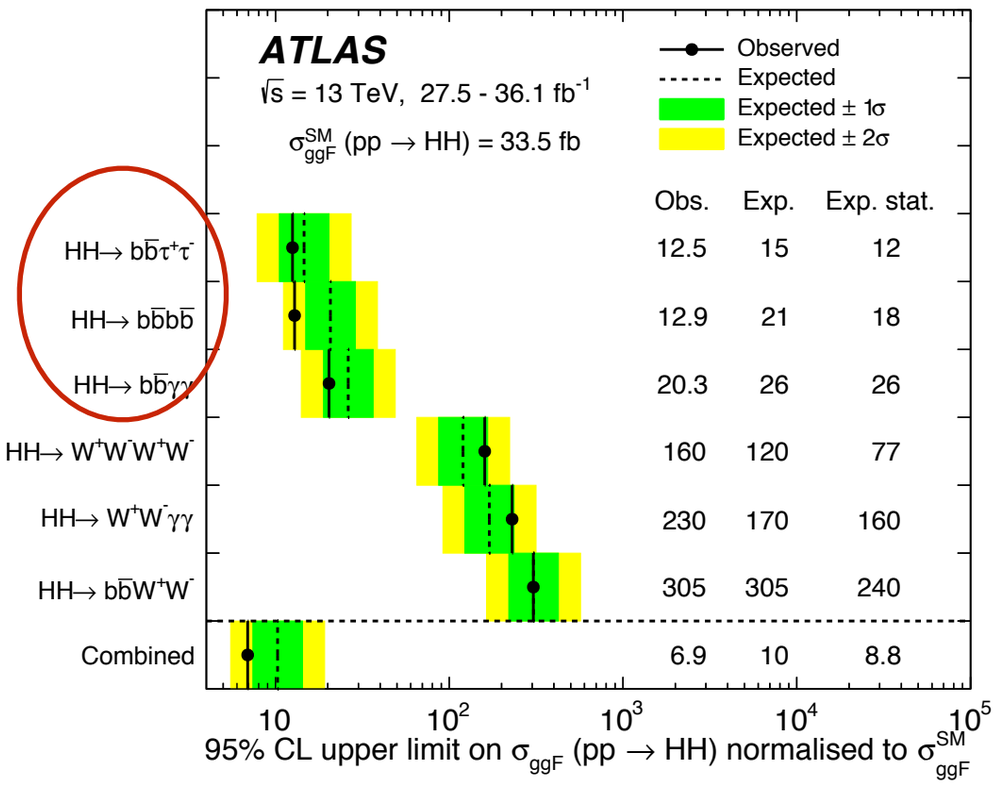
- **Difficulty of the HH search:**
  - Destructive interference between triangle and box diagrams
  - Tiny σ_{HH}: $\sigma(gg \to HH) \sim 0.1\% \times \sigma(gg \to H)$
- **VBF:**
  - second production mode, but open a window for VVHH coupling (c_{2v})

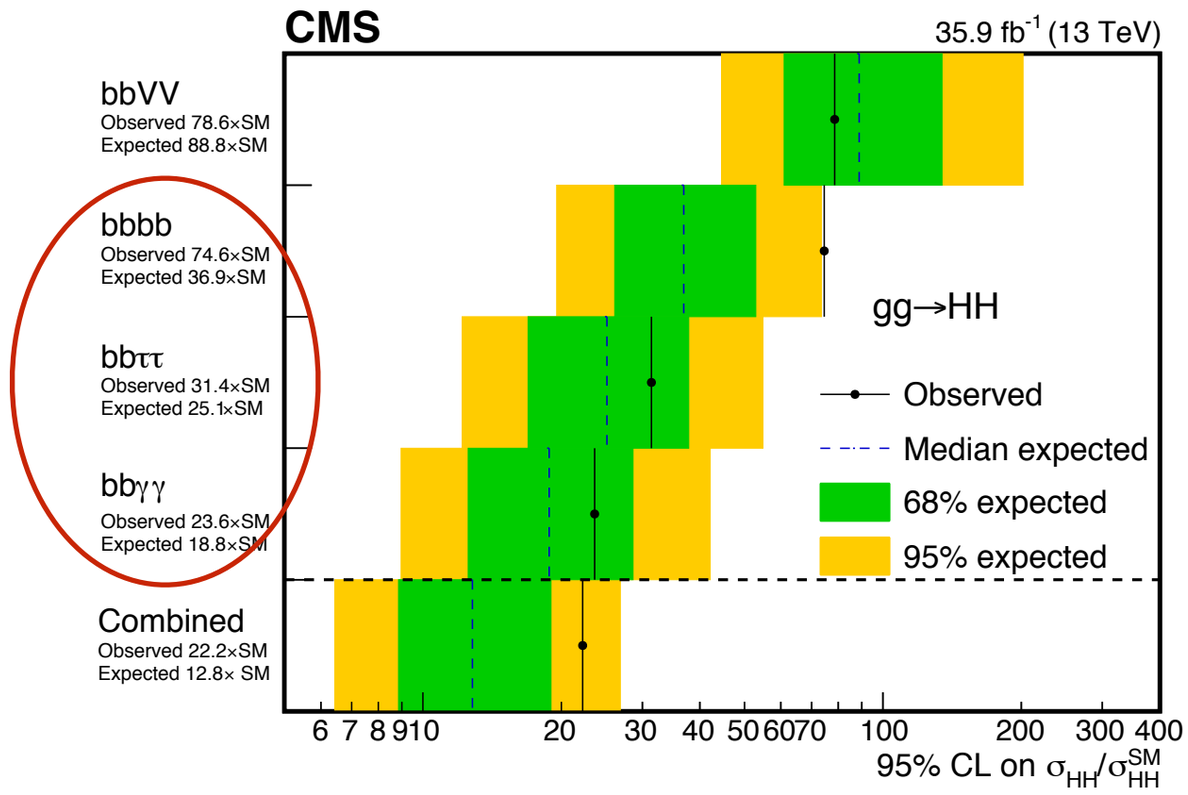
	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

Complementarity from the final states

Di-Higgs combination

- Only used partial Run2 dataset
- Assume all kinematic properties of HH pair are same as SM prediction, and only ggF XS can deviate from SM



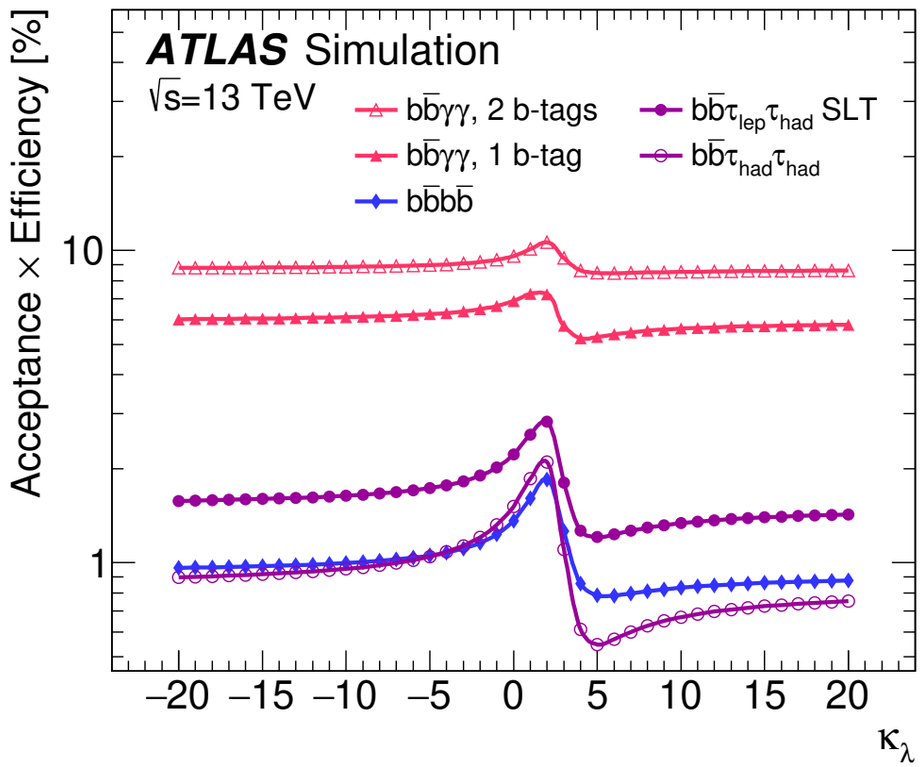


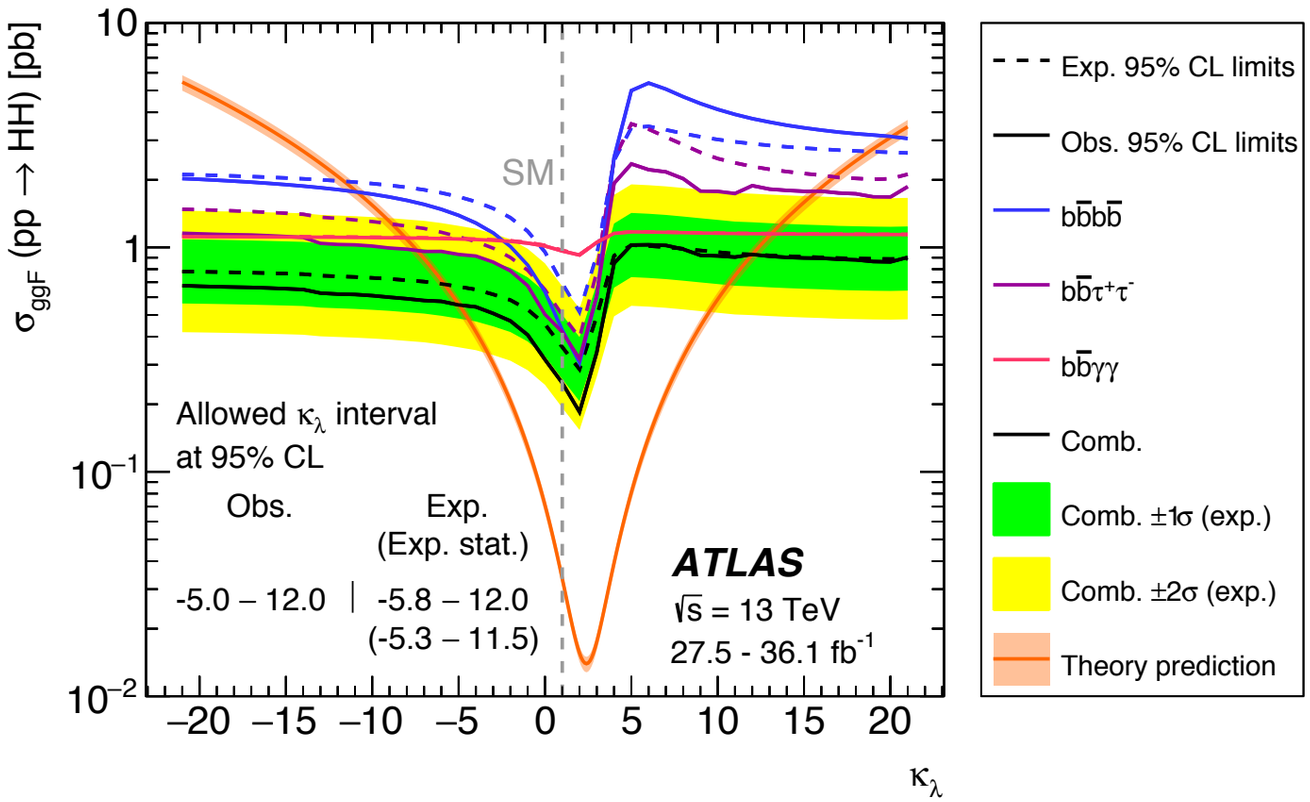
A sensitivity of ~**10*SM** for Di-Higgs production rate

Constraint on the Higgs self-coupling

- **Kinematic dependence on κ_λ is estimated with LO prediction,** and K-factor is only estimated with κ_λ=1
- Amplitude dependence on κ_λ can be expressed with 3 reference samples

$$|A(k_t,k_\lambda)|^2 = k_t^2\left[\frac{90k_t^2+9k_\lambda^2-99k_tk_\lambda}{90}|A(1,0)|^2+\frac{100k_tk_\lambda-10k_\lambda^2}{90}|A(1,1)|^2+\frac{k_\lambda^2-k_tk_\lambda}{90}|A(1,10)|^2\right]$$



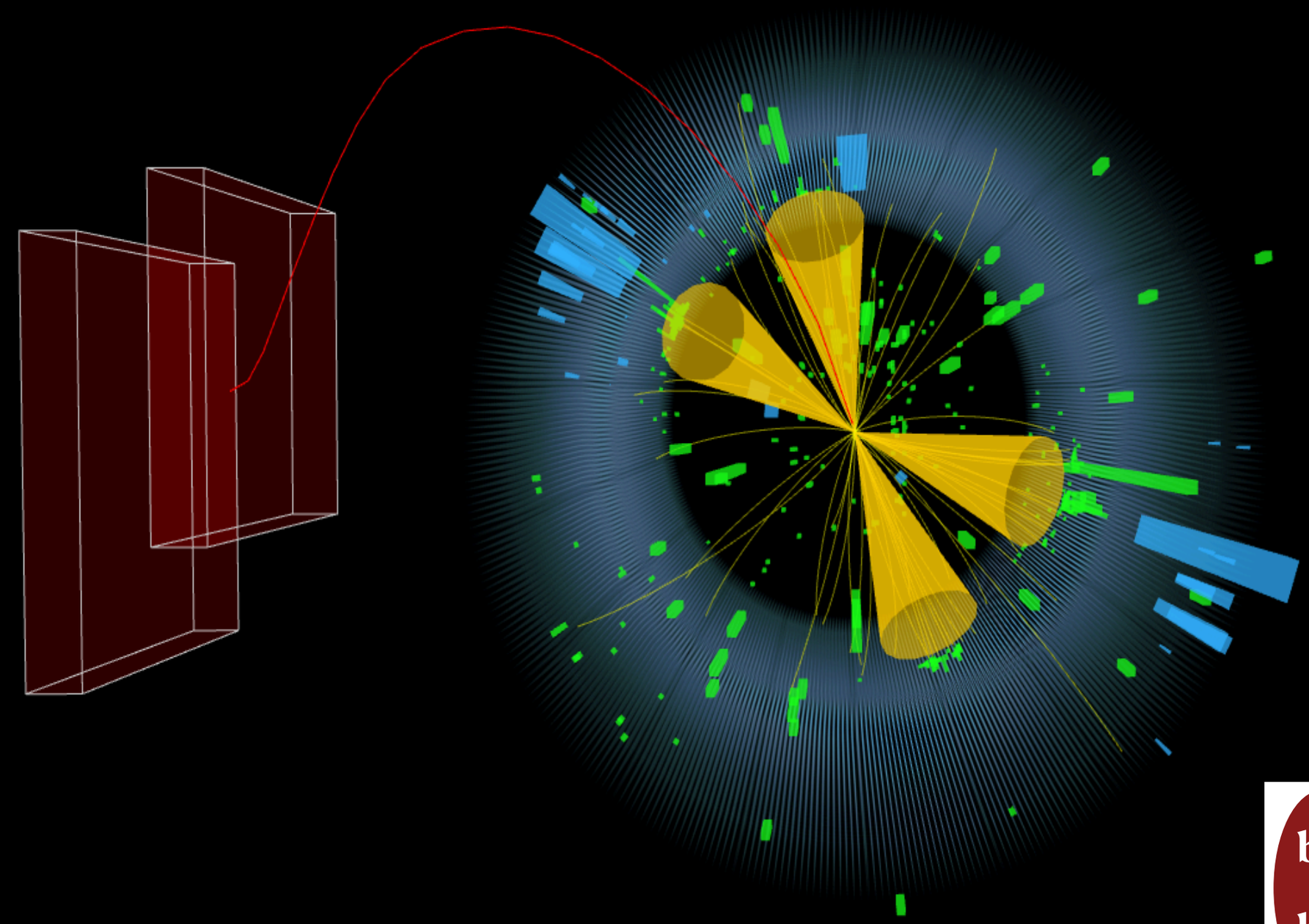


Constraint on self-coupling (obs/exp) @ 95% CL: -5.0<κ_λ<12.0 / -5.8<κ_λ<12.0

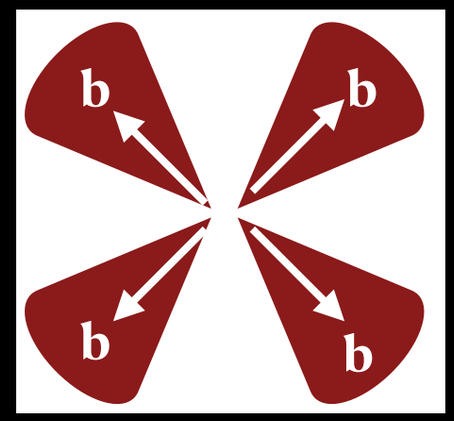
Will focus on HH search with full Run2 data

HH→bbbb

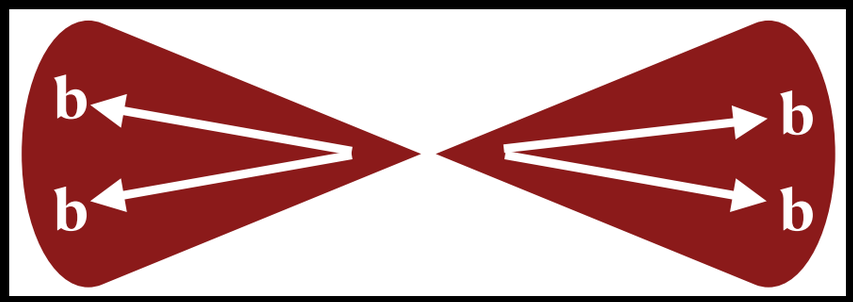
Large BR of H→bb, low S/B



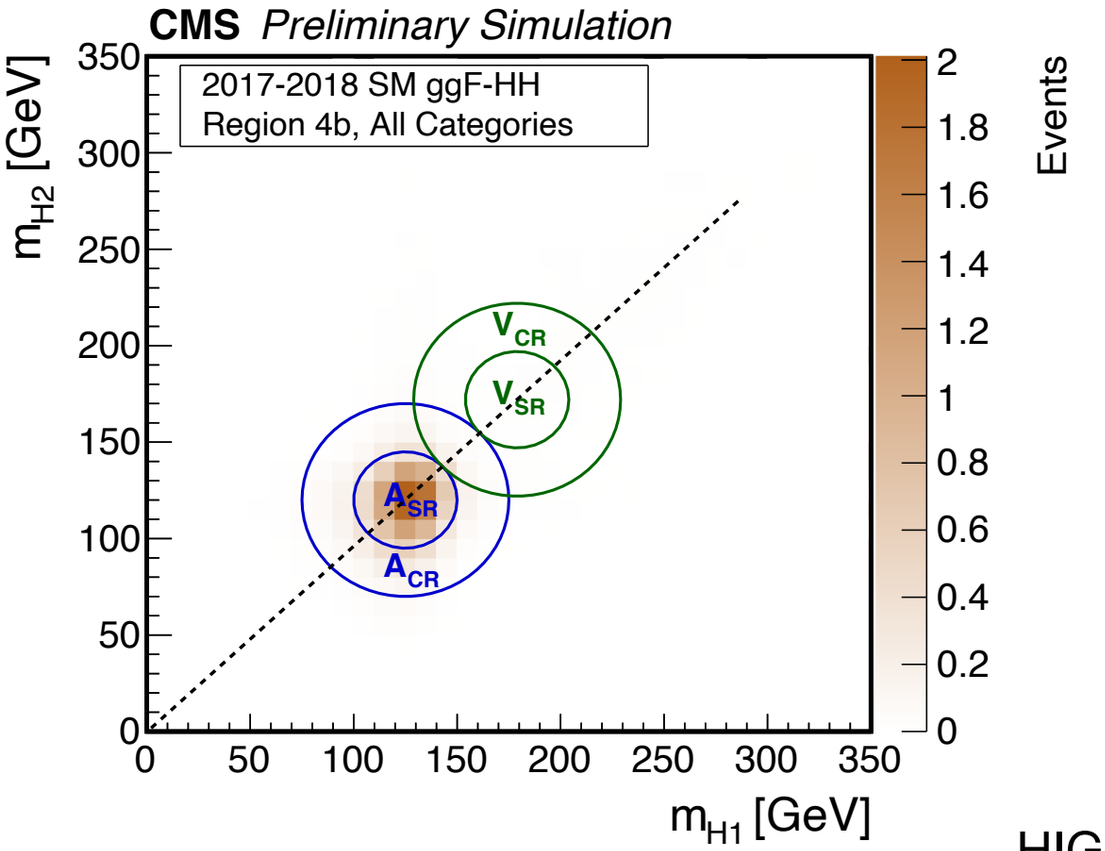
Resolved channel

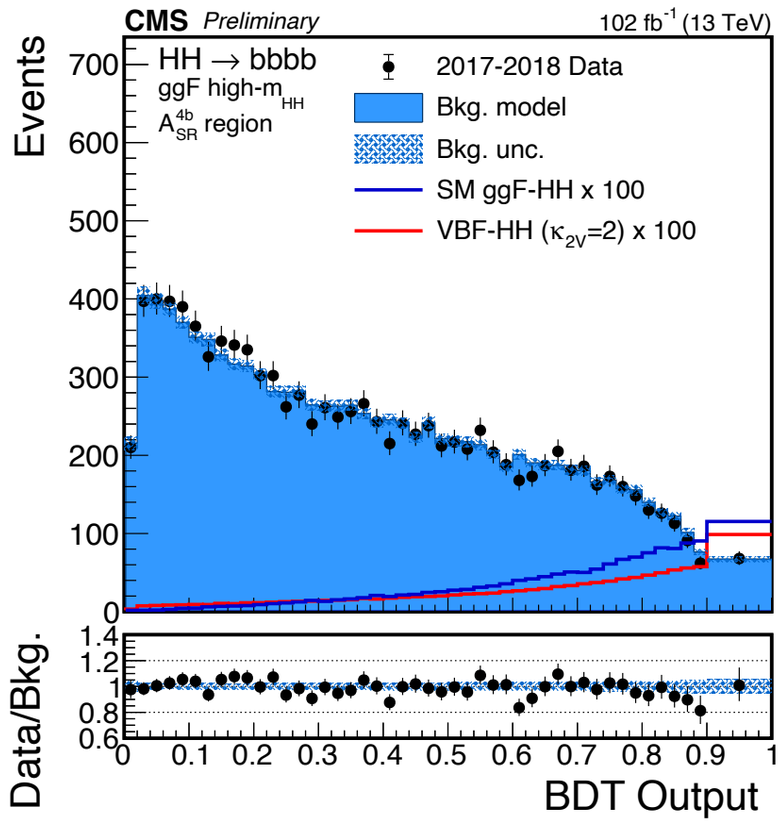


Boosted channel



HH→bbbb @ CMS

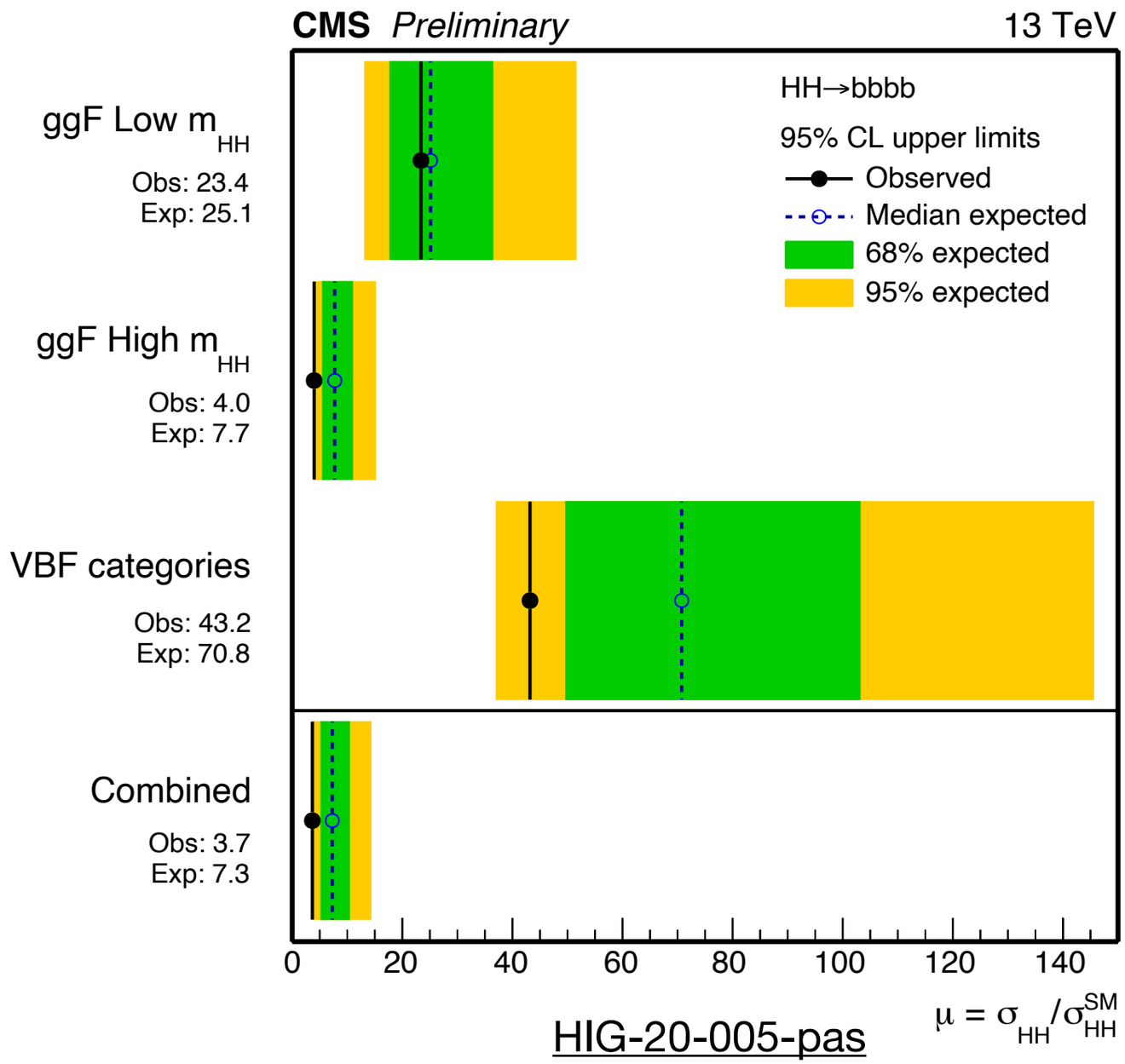




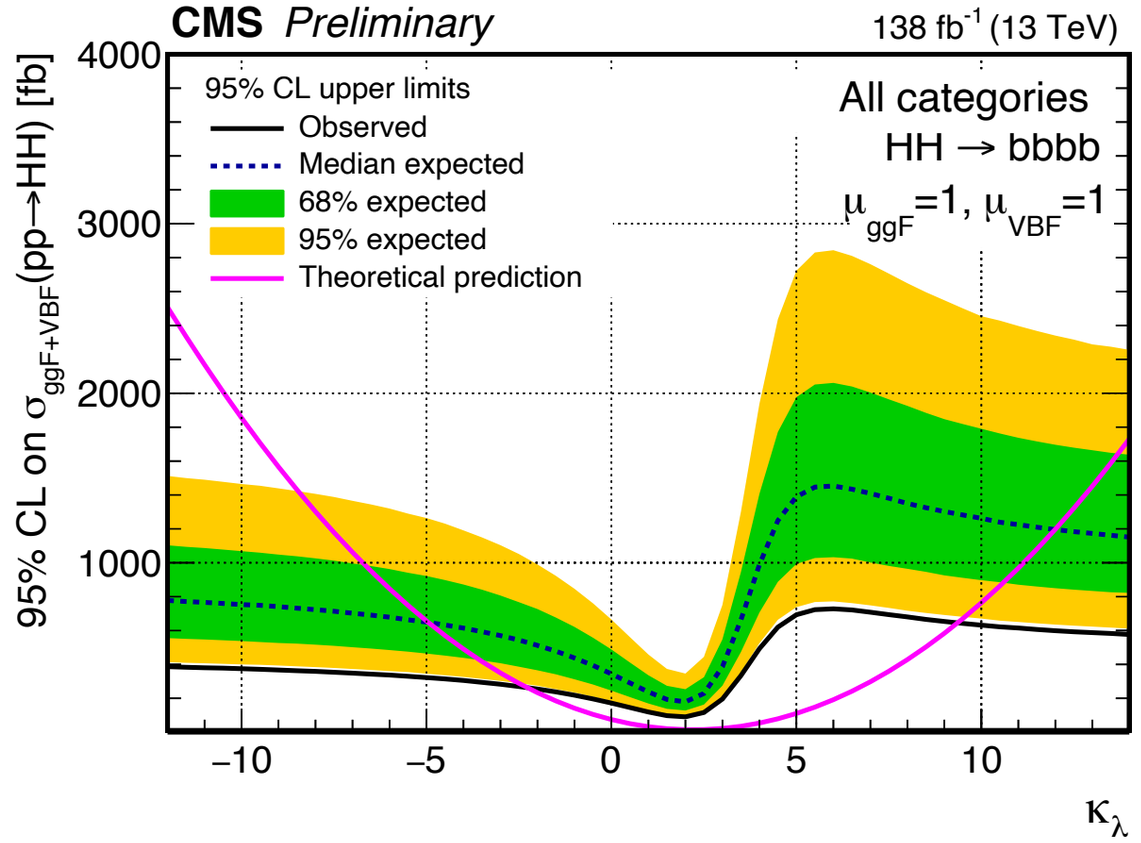
HIG-20-005-pas

- **Combination of di-bjet pairs** solved with the HH mass distance and Higgs Pt: correct rate ranging 82 - 96% (91 - 98%) for ggF (VBF).
- **Advanced categorization**: low vs high m_{HH} in ggF and SM-like vs anomalous κ_{2V}-like in VBF
- **Powerful multivariate discriminant** to separate background from signal.

HH→bbbb @ CMS



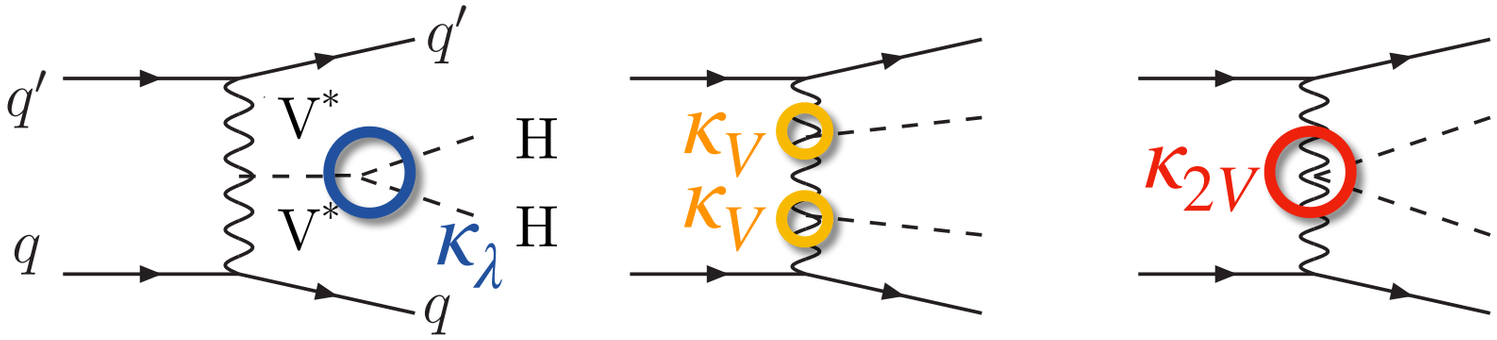
HIG-20-005-pas



Observed (Expected) 95% CL < 3.6 (7.3)×SM

$-2.3<\kappa_\lambda<9.4$ ($-5<\kappa_\lambda<12$)

HH→bbbb (VBF boosted) @ CMS

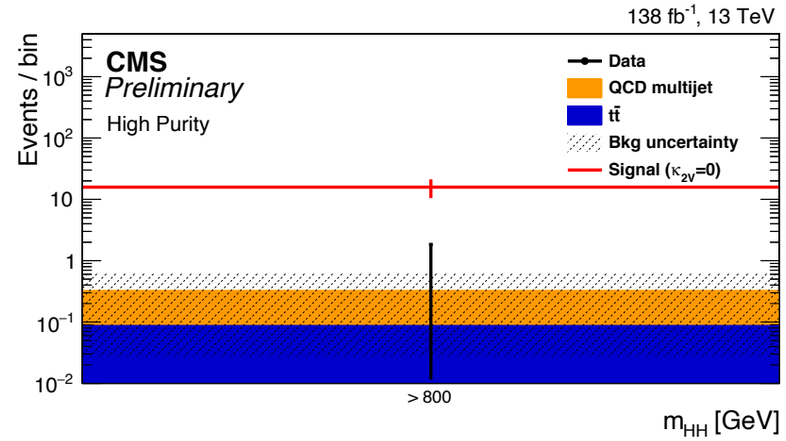


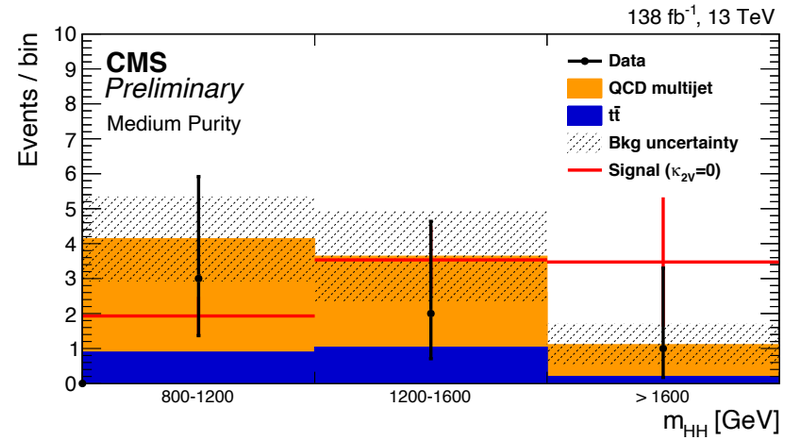
$$\mathscr{A}(V_L V_L \to HH) \simeq \frac{\hat{s}}{v^2}(\kappa_{2V} - \kappa_V^2)$$

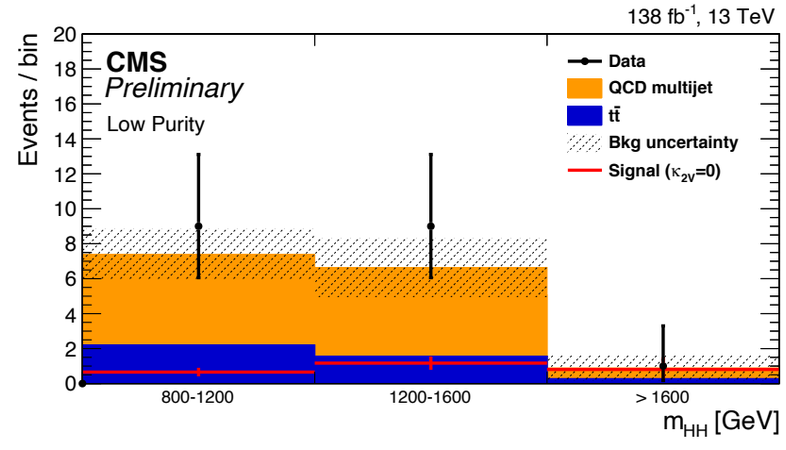
Highly sensitive to anomalous κ_{2V}

- Select events with 2 large-radius jets + 2 small-radius jets
- ParticleNet discriminate D_{bb} to identify the bb candidates
- 3 purity categories based on D_{bb}

Excellent separation at high m_{HH} leading to good S/B ratio

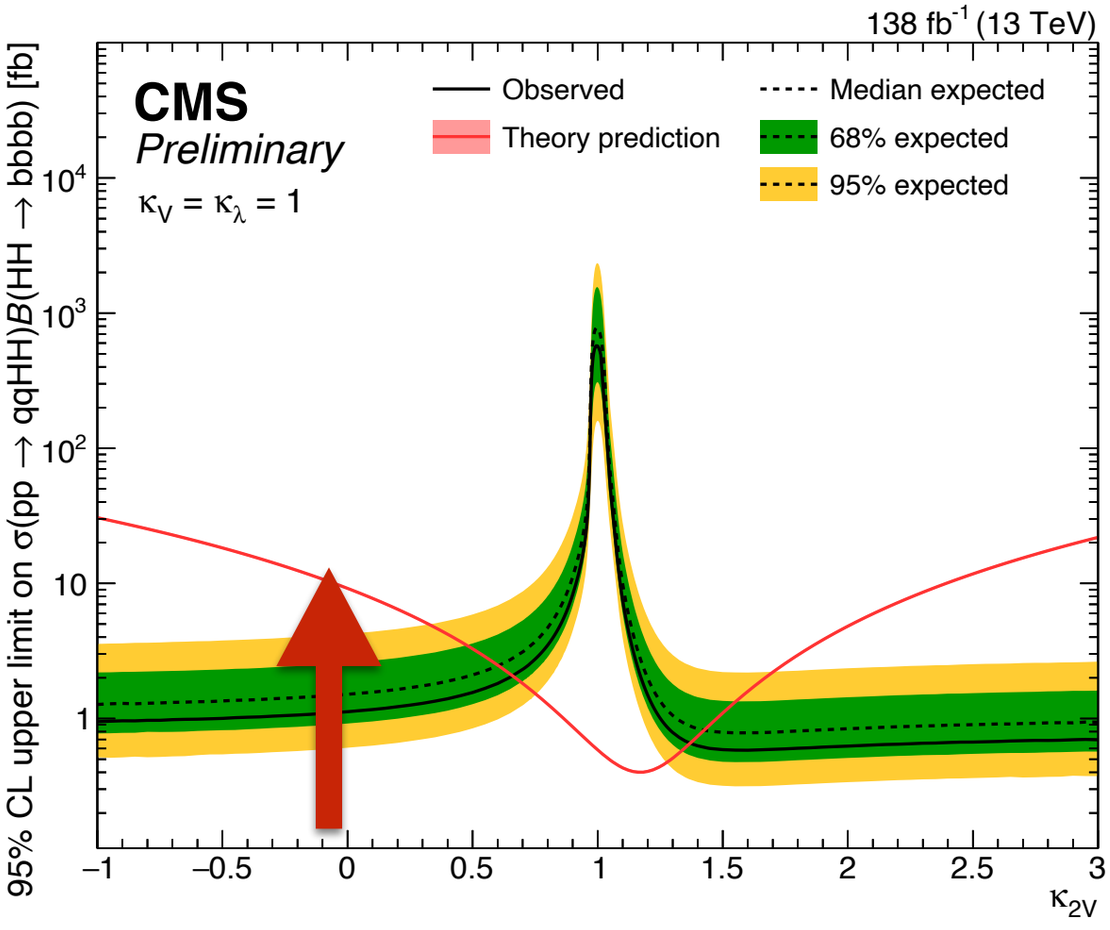


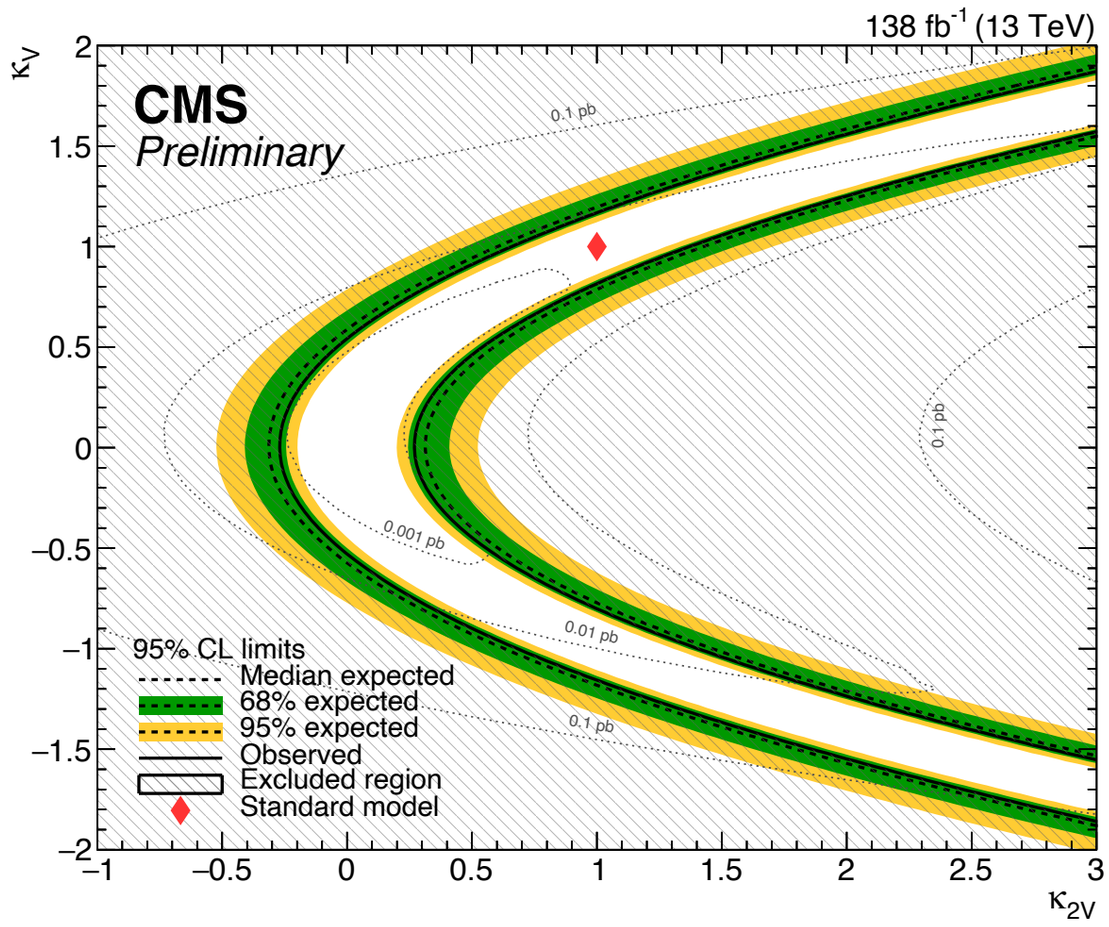




B2G-21-001-pas

HH→bbbb (VBF boosted) @ CMS





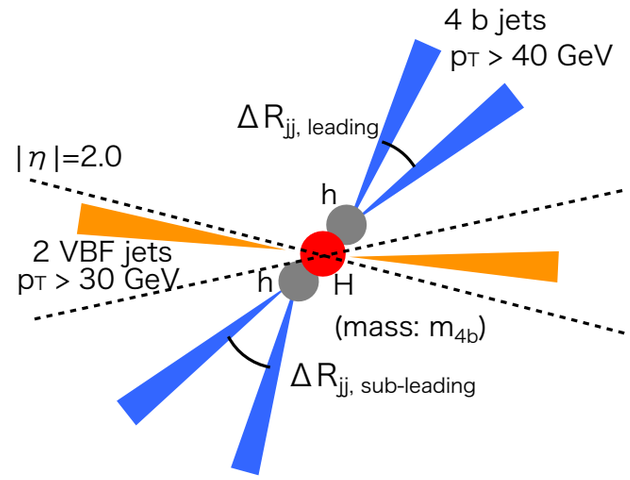
Observed constraint: $0.6 < \kappa_{2\lambda} < 1.4$

Further constraint is expected with the combination with single H measurement

B2G-21-001-pas

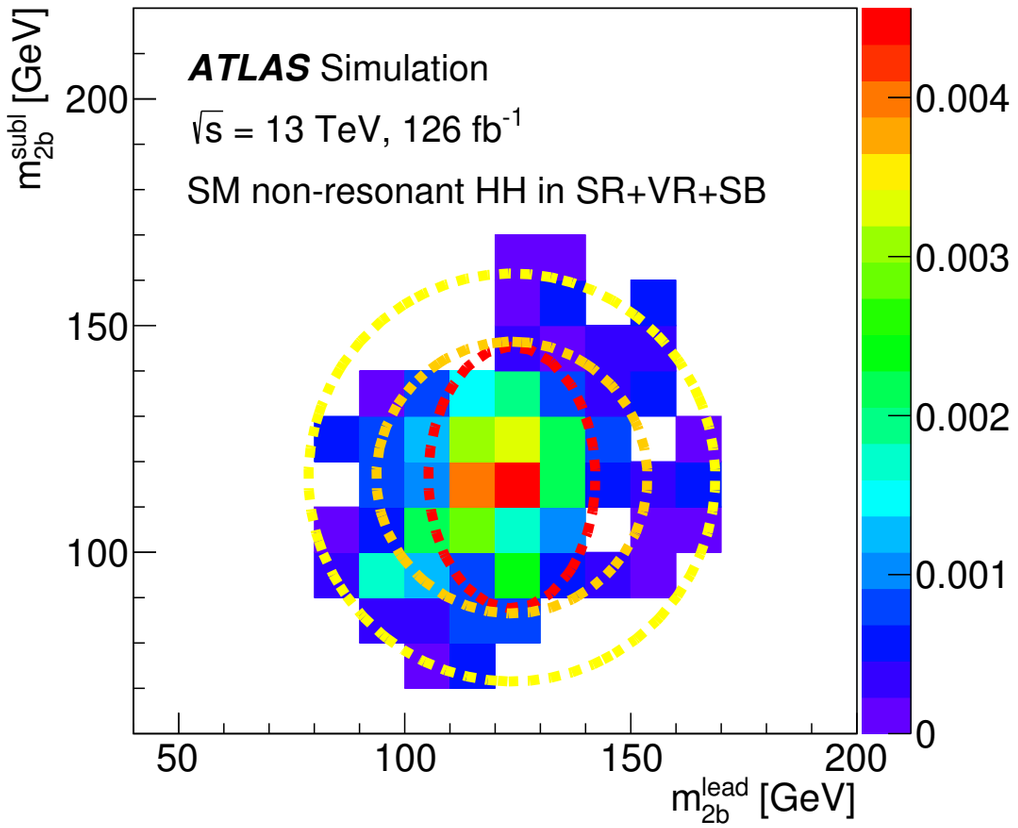
HH→bbbb (VBF) @ ATLAS

- Based on early Run2 ggF resolved analysis strategy, optimization for the VBF HH



	Selections	
VBF topology	At least two jets with $p_{\mathrm{T}} > 30$, $\lvert\eta\rvert > 2.0$	Two highest-p_{T} jets with opposite sign η
		$\lvert\Delta\eta_{jj}^{\mathrm{VBF}}\rvert > 5.0$ and $m_{jj}^{\mathrm{VBF}} > 1000$
Signal topology	Exactly 4 b-tagged jets with $p_{\mathrm{T}} > 40$, $\lvert\eta\rvert < 2.0$	
	If $m_{4b} < 1250$	$\frac{360}{m_{4b}} - 0.5 < \Delta R_{bb}^{\mathrm{lead}} < \frac{653}{m_{4b}} + 0.475$ $\frac{235}{m_{4b}} < \Delta R_{bb}^{\mathrm{subl}} < \frac{875}{m_{4b}} + 0.35$
	If $m_{4b} \geq 1250$	$\Delta R_{bb}^{\mathrm{lead}} < 1$ $\Delta R_{bb}^{\mathrm{subl}} < 1$
	Pairs with minimum $D_{HH} = \sqrt{(m_{2b}^{\mathrm{lead}})^2 + (m_{2b}^{\mathrm{subl}})^2}\left\lvert\sin\left(\tan^{-1}\left(\frac{m_{2b}^{\mathrm{subl}}}{m_{2b}^{\mathrm{lead}}}\right) - \tan^{-1}\left(\frac{116.5}{123.7}\right)\right)\right\rvert$	
Background rejection	Multijet	$\lvert\Delta\eta_{HH}\rvert < 1.5$
		$\lvert\Sigma_i \vec{p_{\mathrm{T}_i}}\rvert < 60$, where i = b-jets and VBF-jets
		$p_{\mathrm{T},H}^{\mathrm{lead}} > 0.5 m_{4b} - 103$
		$p_{\mathrm{T},H}^{\mathrm{subl}} > 0.33 m_{4b} - 73$
	$t\bar{t}$	Veto if $X_{Wt} = \sqrt{\left(\frac{m_W - 80.4}{0.1 m_W}\right)^2 + \left(\frac{m_t - 172.5}{0.1 m_t}\right)^2} \leq 1.5$
Region definition	Signal region (SR)	$X_{HH} = \sqrt{\left(\frac{m_{2b}^{\mathrm{lead}} - 123.7}{11.6}\right)^2 + \left(\frac{m_{2b}^{\mathrm{subl}} - 116.5}{18.1}\right)^2} < 1.6$
	Validation region (veto SR)	$\sqrt{\left(m_{2b}^{\mathrm{lead}} - 123.7\right)^2 + \left(m_{2b}^{\mathrm{subl}} - 116.5\right)^2} < 30$
	Sideband region (veto SR, VR)	$\sqrt{\left(m_{2b}^{\mathrm{lead}} - 123.7\right)^2 + \left(m_{2b}^{\mathrm{subl}} - 116.5\right)^2} < 45$

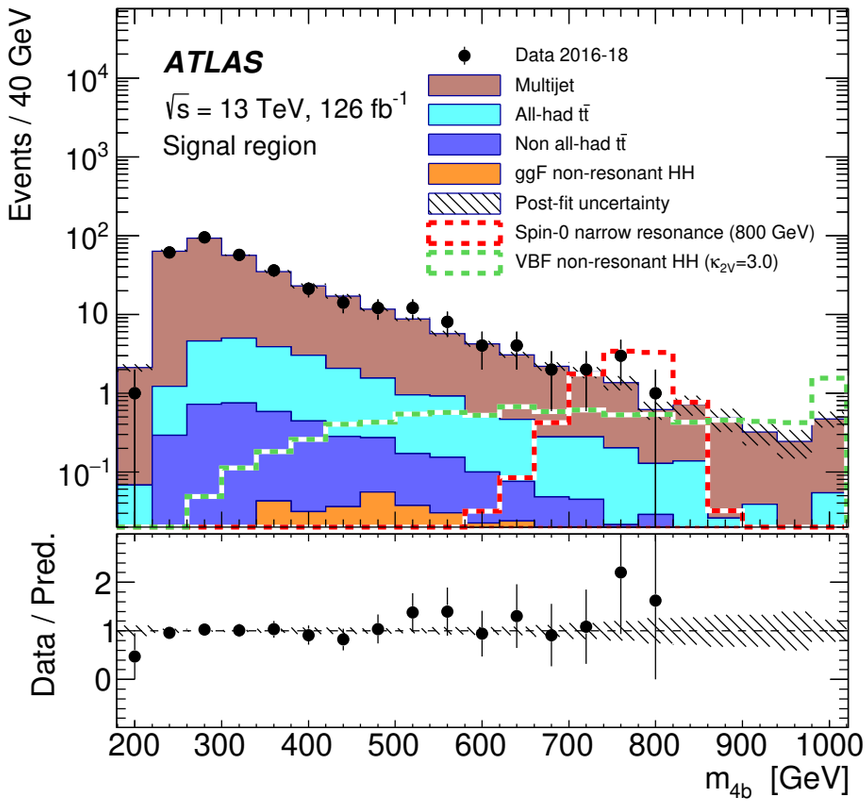
Higgs pair selection

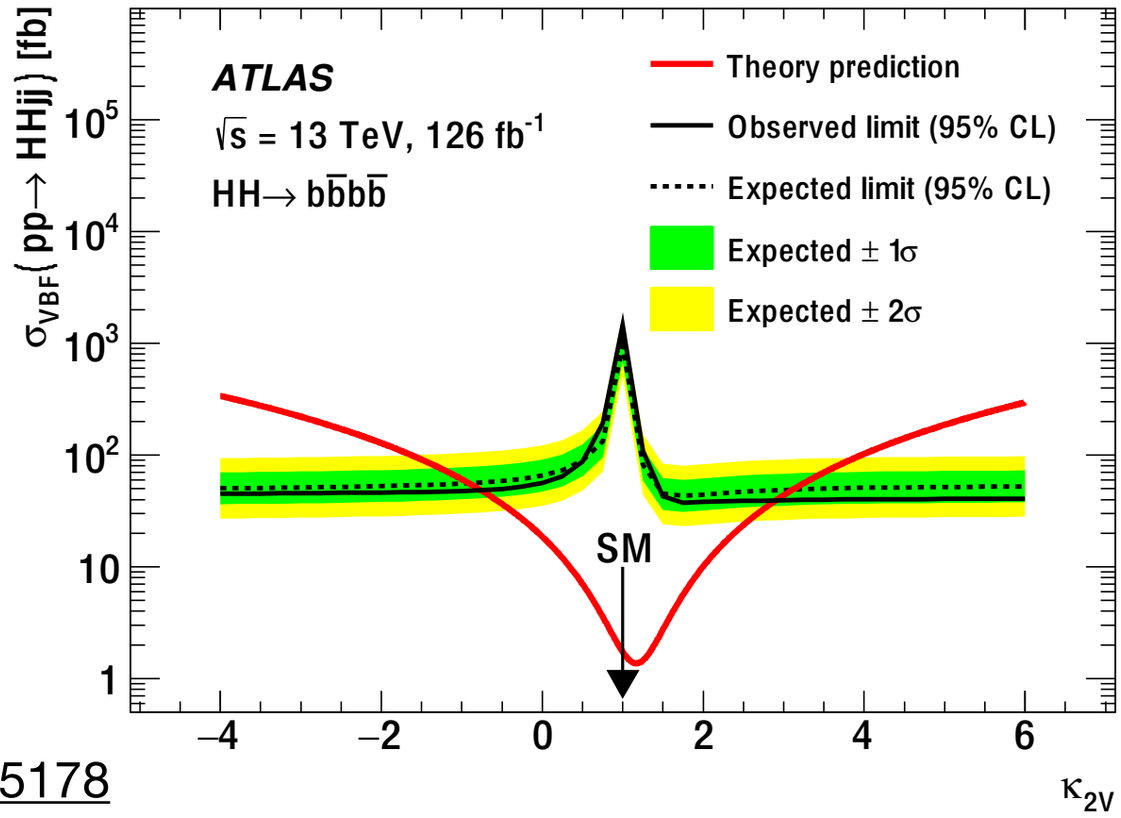


arxiv:2001.05178

HH→bbbb (VBF) @ ATLAS

	Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
σ_{VBF} [fb]	1460	510	690	950	1330	1780
$\sigma_{\mathrm{VBF}}/\sigma_{\mathrm{VBF}}^{\mathrm{SM}}$	840	290	400	550	770	1030





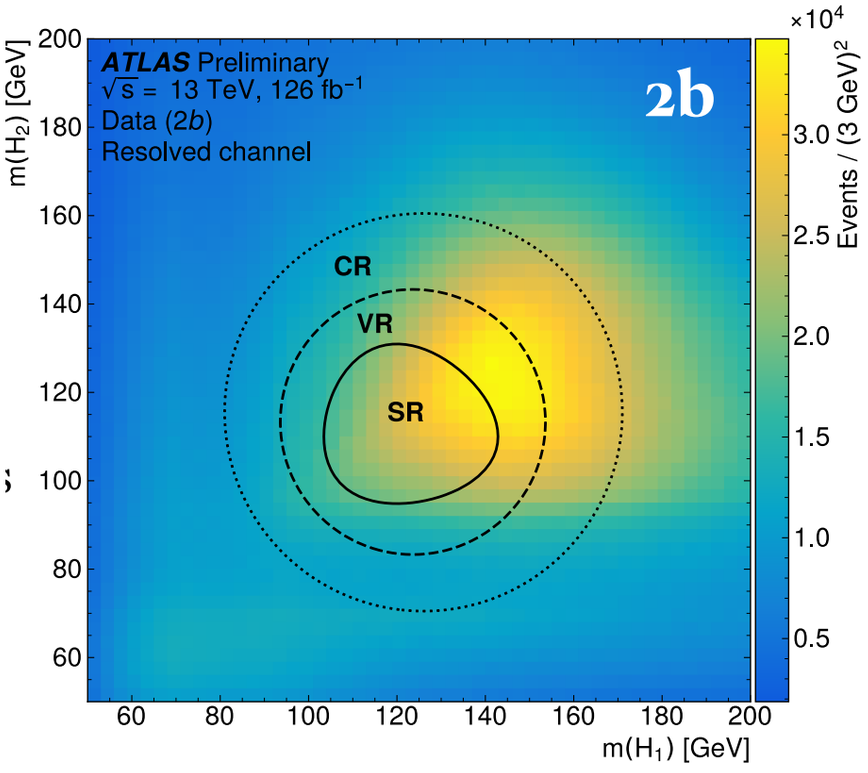
arxiv:2001.05178

- Largest deviation from background-only hypothesis has a local significance of 1.5σ at 550GeV
- Observed limit on σ_{HH} is compatible with the expectation at a level of <2σ
- Observed (expected) constraint on κ_{2V}: [-0.76, 2.9] ([-0.91, 3.11])
- Dominant uncertainty is from the mis-modelling of multi-jet background

HH→bbbb @ ATLAS

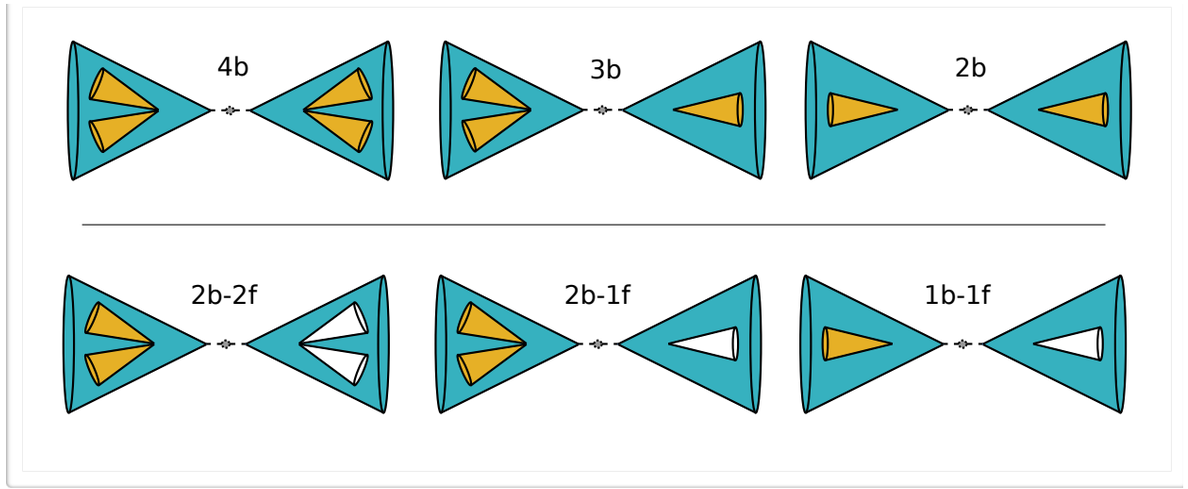
Resolved Analysis

- Targets low-medium mass resonances
- 4 small R-jet (R=0.4)
- 4b signal region



Boosted Analysis

- Targets high mass resonances
- 2 large R-jet (R=1.0)
- 3SR are defined : 2b, 3b, 4b



HH→bbbb @ ATLAS

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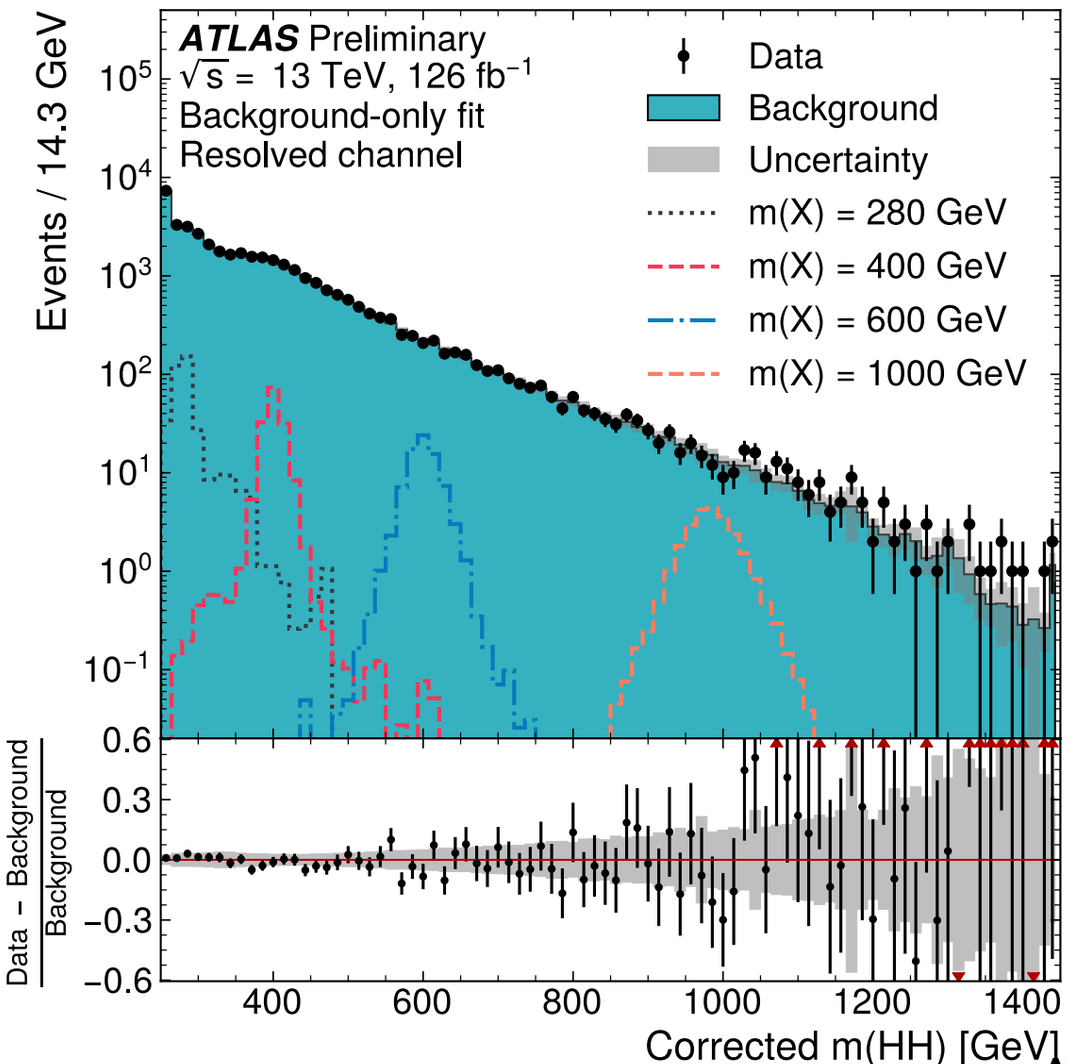

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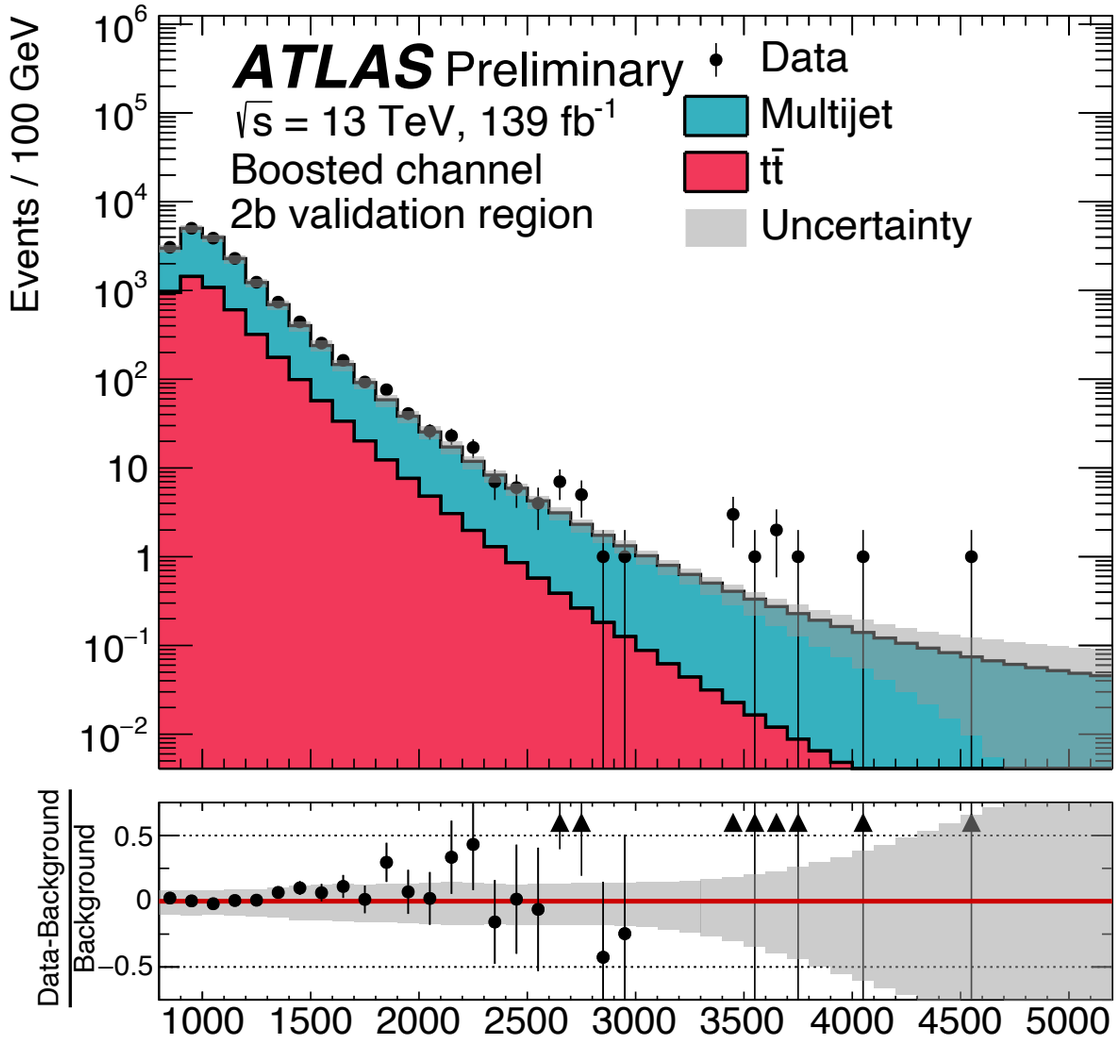
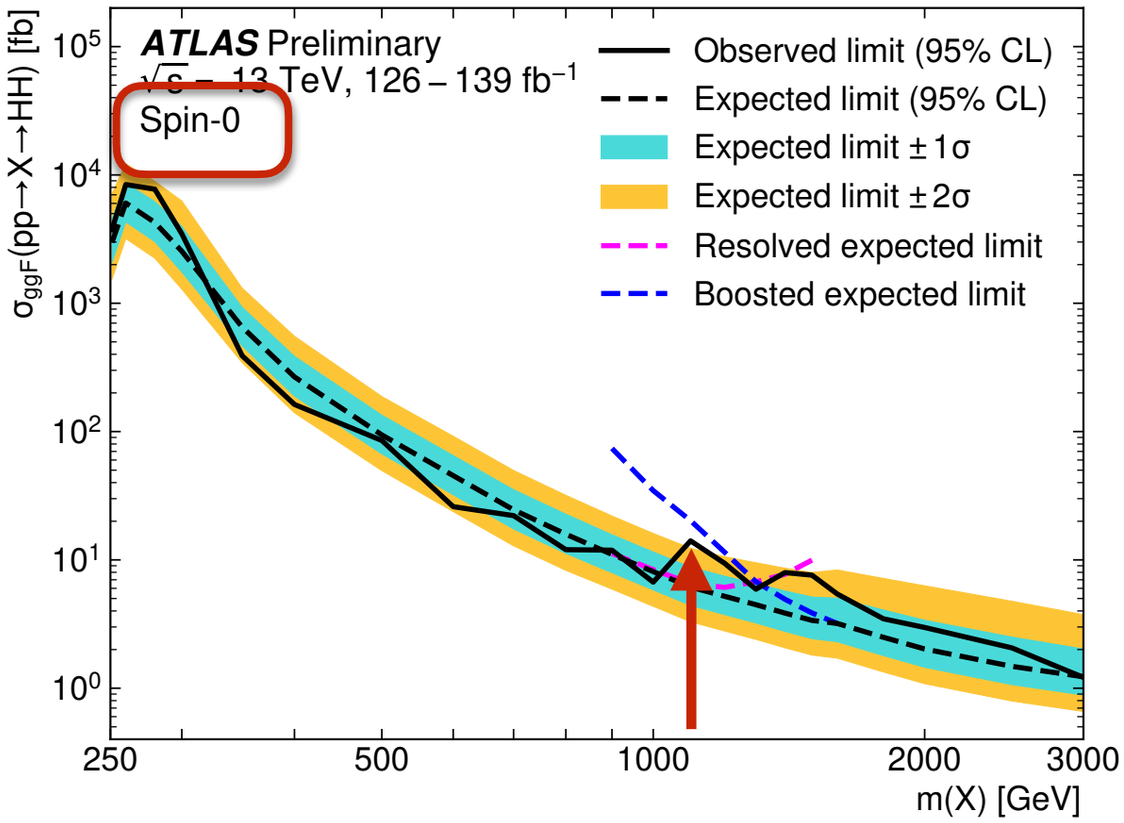
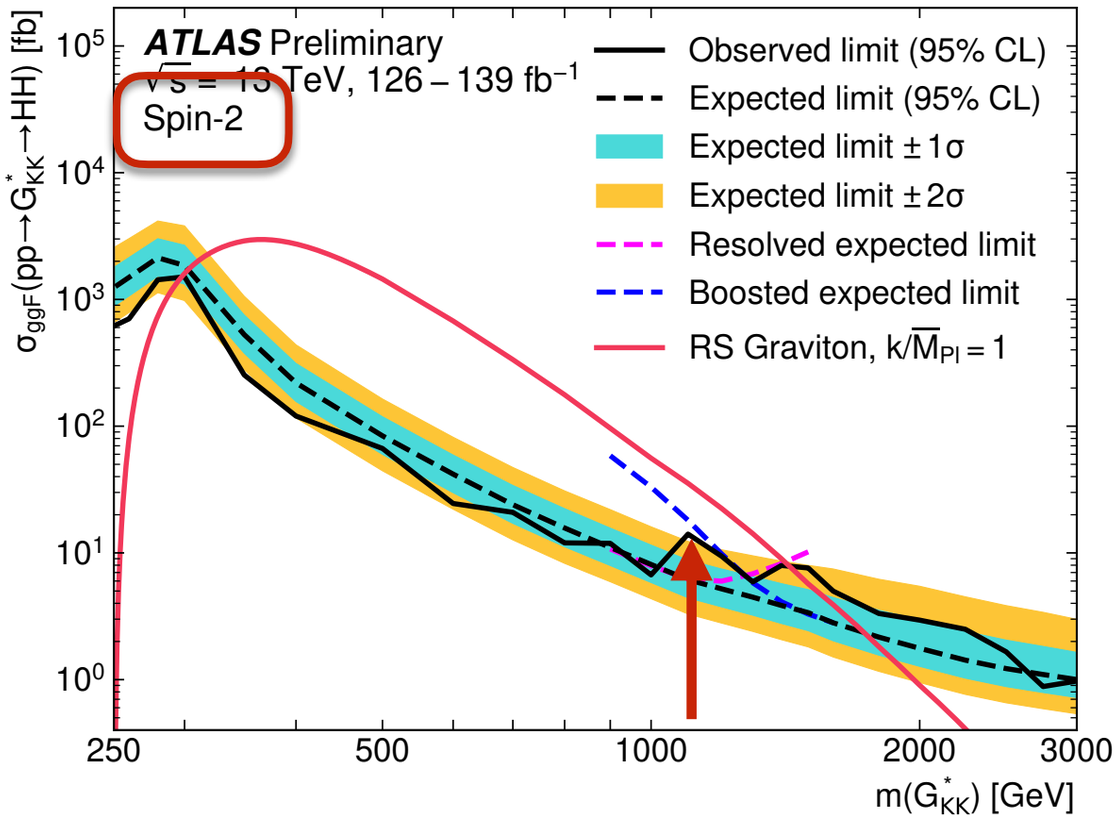


ATLAS-CONF-2021-035

HH→bbbb @ ATLAS



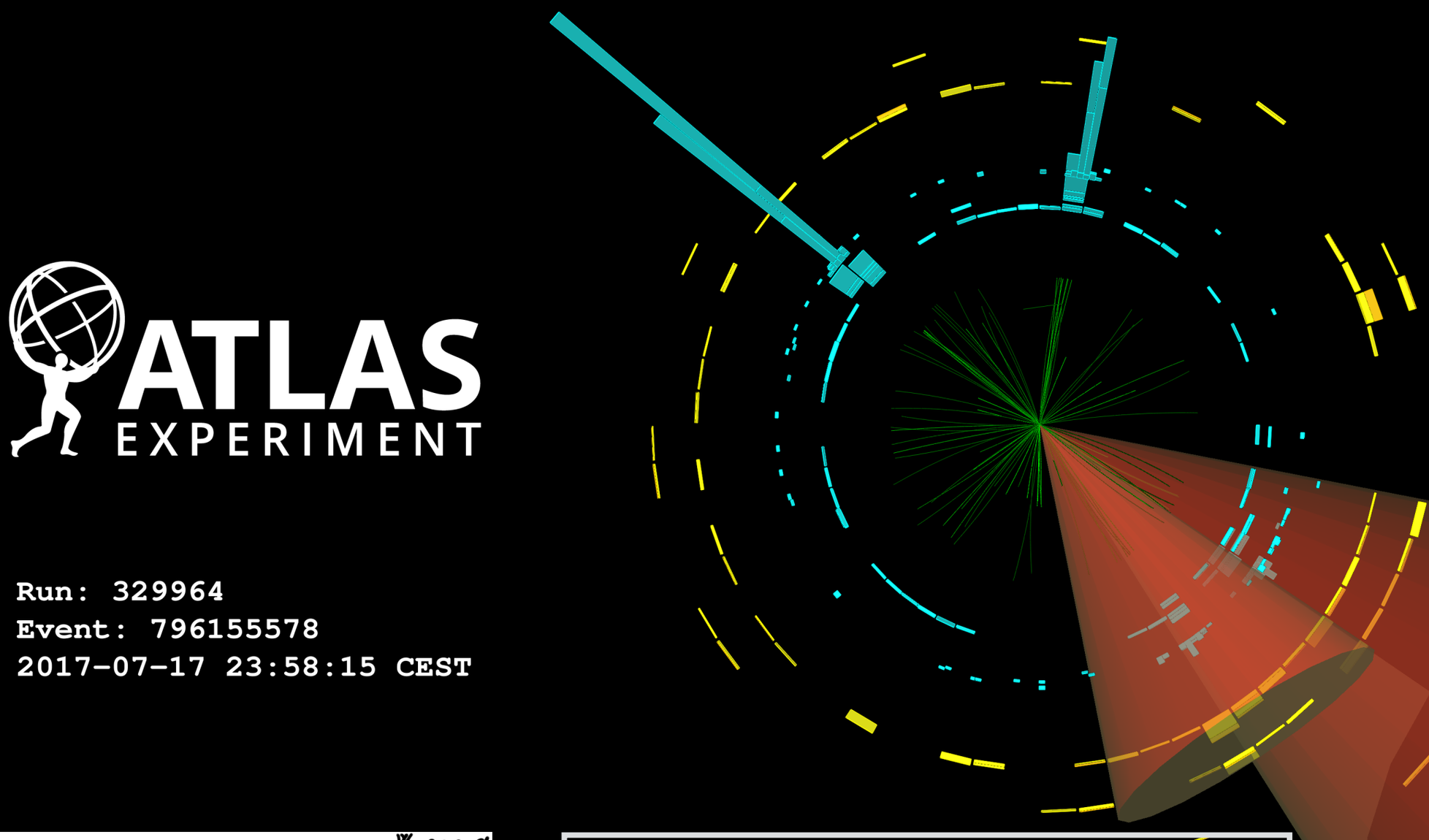


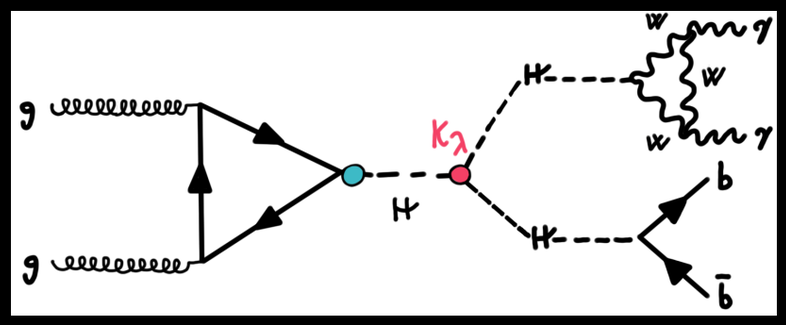
- **The most significant excess @ 1.1 TeV**
  - **Local significance 2.6σ (2.7σ)** for the spin-0 (spin-2) model
  - **Global significance 1.0σ (1.2σ)** for the spin-0 (spin-2) model

ATLAS-CONF-2021-035

$HH \rightarrow \gamma\gamma bb$

One of the golden channels for HH search





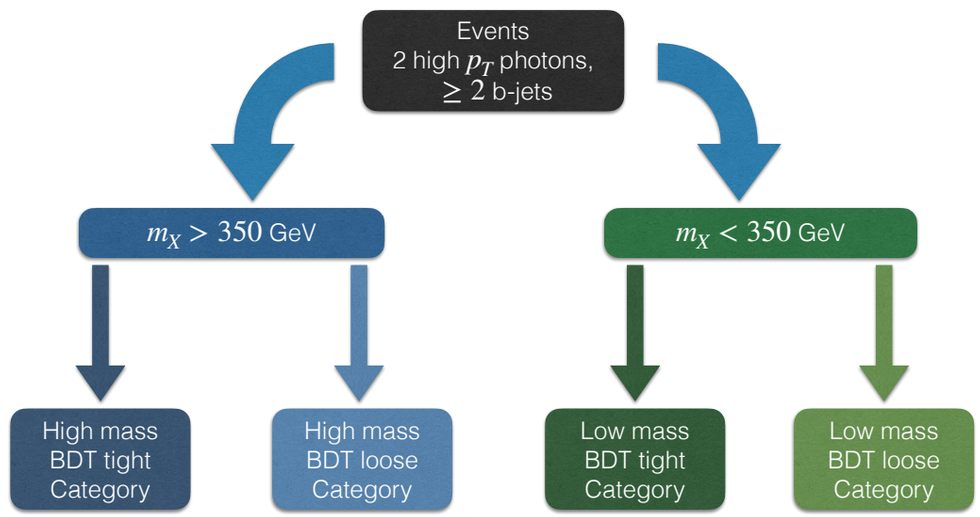
- Full reconstructable final state
- Excellent di-photon resolution
- Large BR of H→bb

HH→γγbb @ ATLAS and CMS

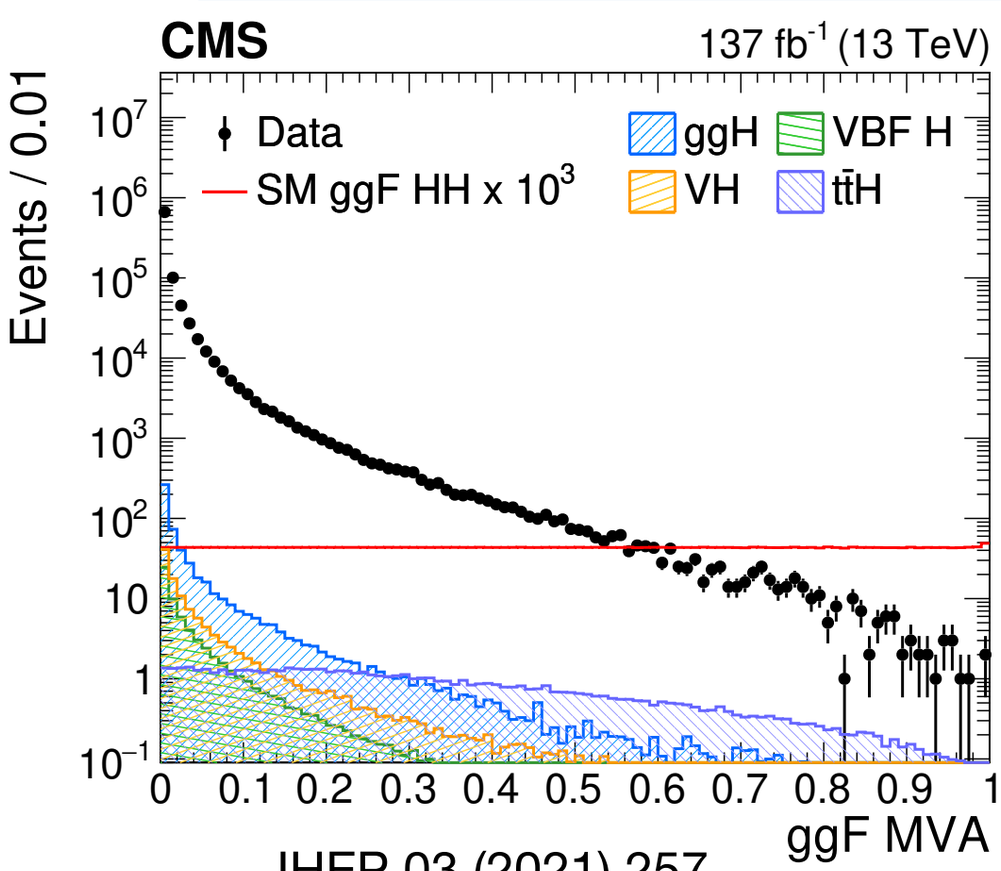
CMS

- Dedicated MVA for ttH suppression
- MVA optimization with the separation of ggH/VBF and m_X cases.

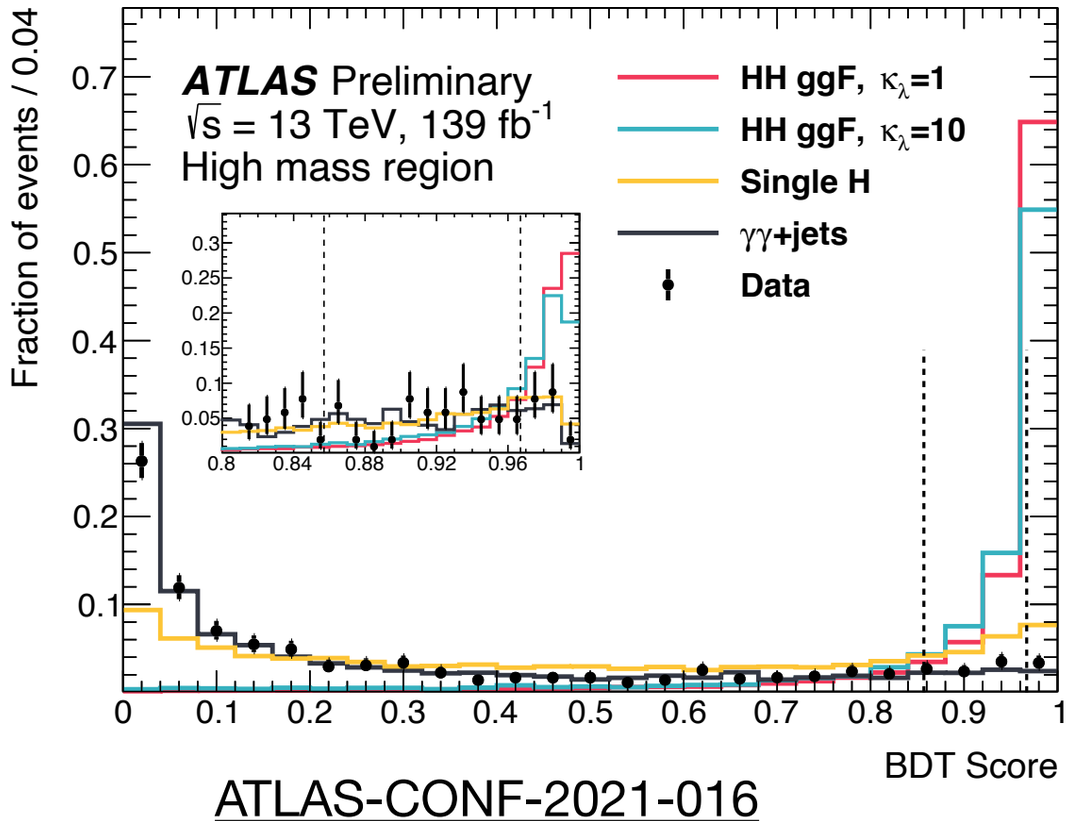
ATLAS



$$m_X^* = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250 \text{ GeV} \Longrightarrow \textbf{Better mass resolution}$$

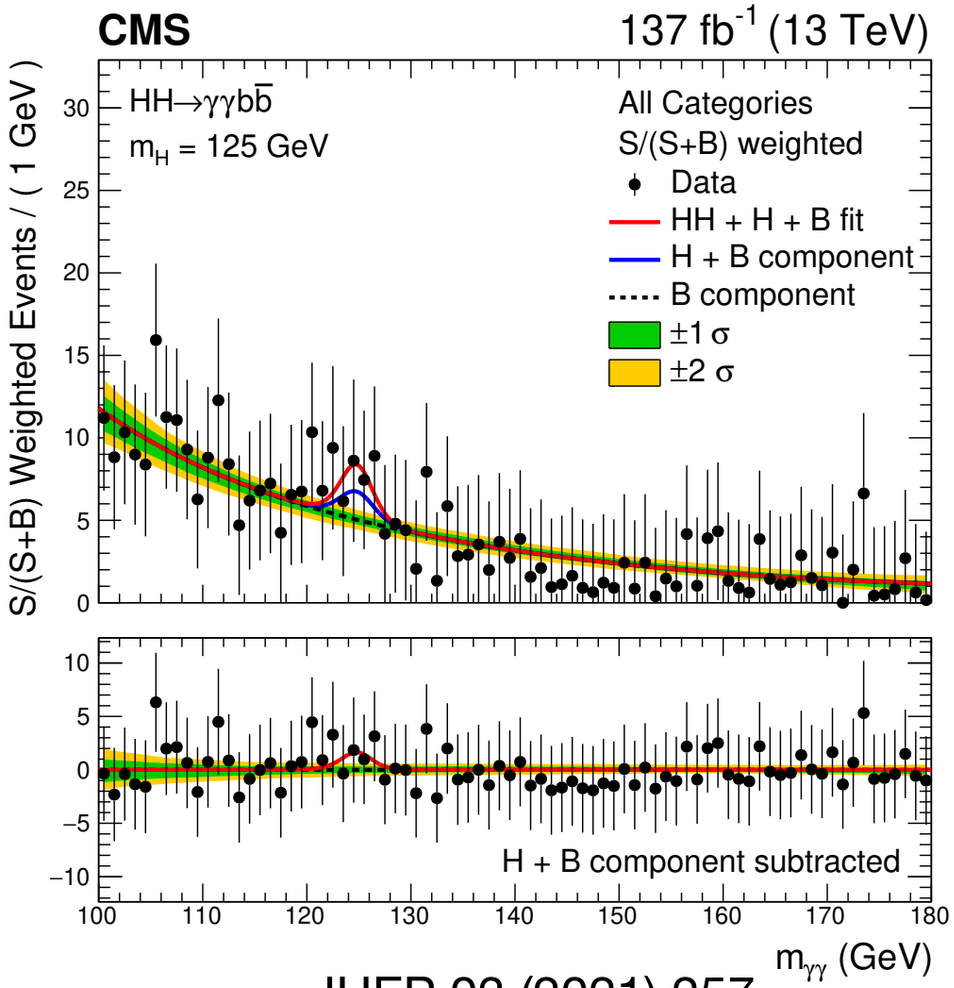


JHEP 03 (2021) 257

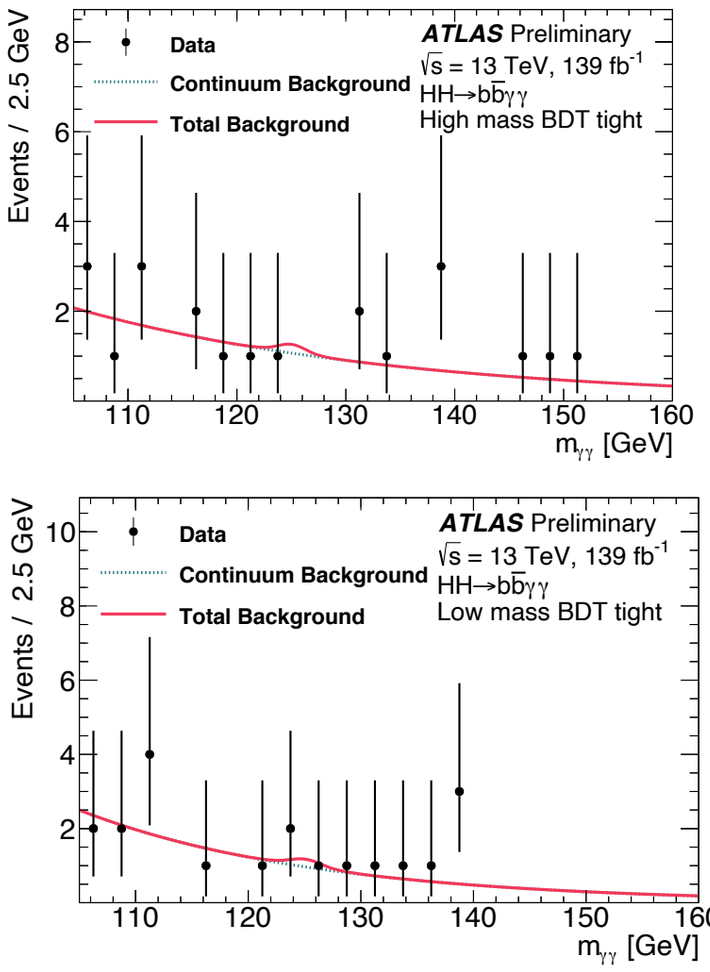


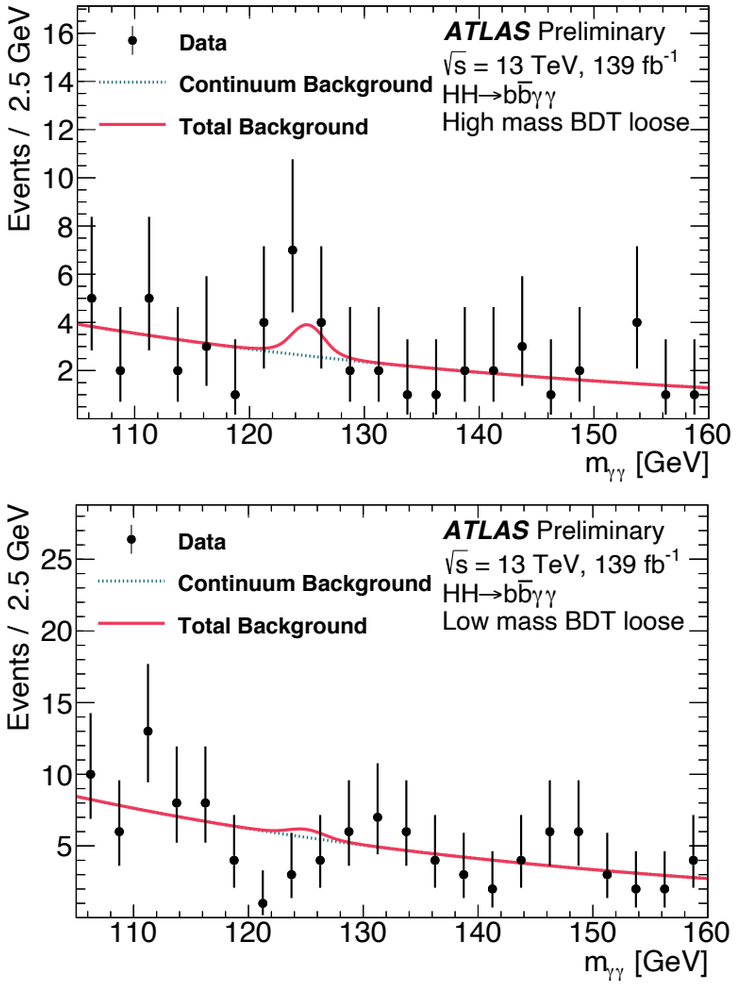
ATLAS-CONF-2021-016

HH→γγbb @ ATLAS and CMS



JHEP 03 (2021) 257

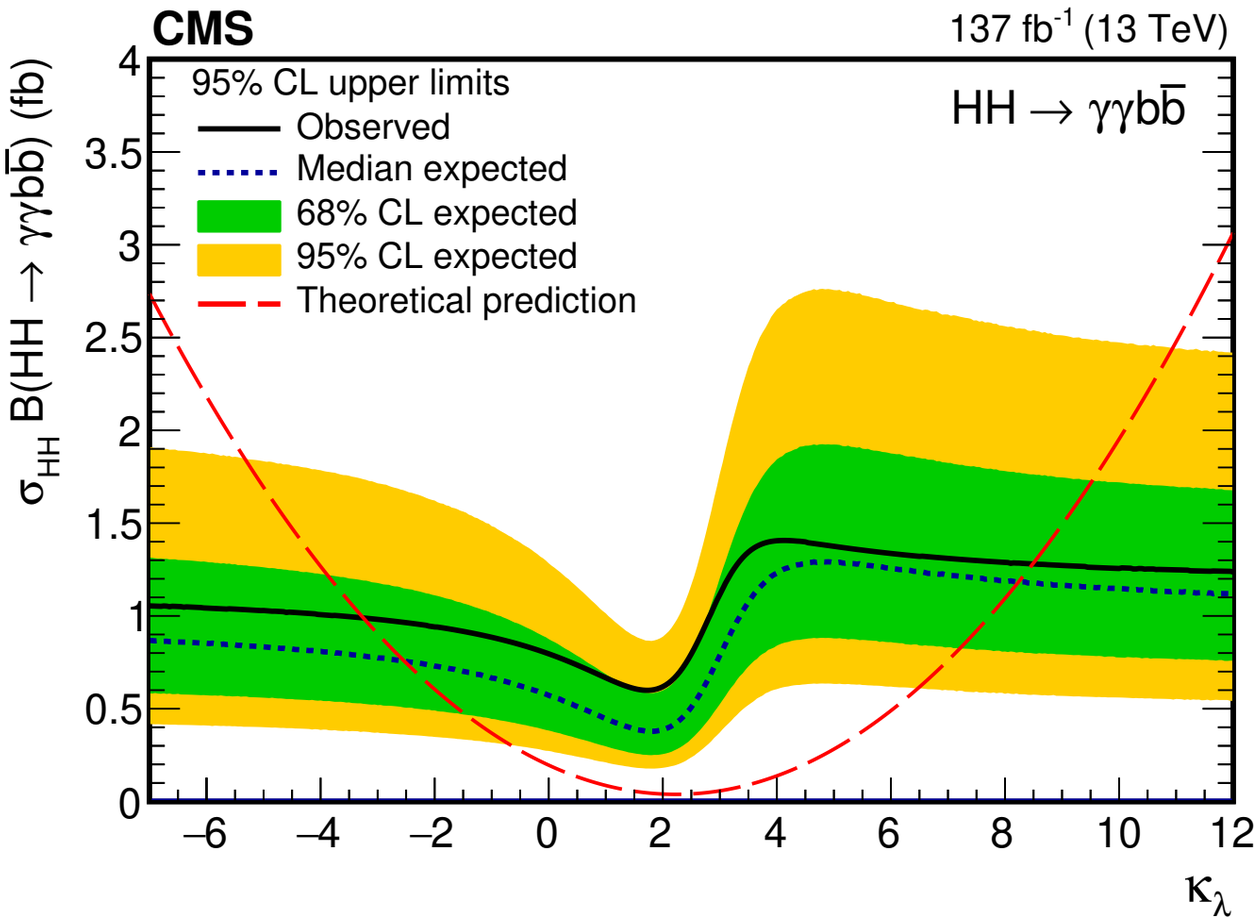




ATLAS-CONF-2021-016

- **CMS**: 2D fit over $m_{\gamma\gamma}$ and m_{bb} with the negligible correlation treatment
- **ATLAS**: signal extraction in the $m_{\gamma\gamma}$ spectrum over all categories

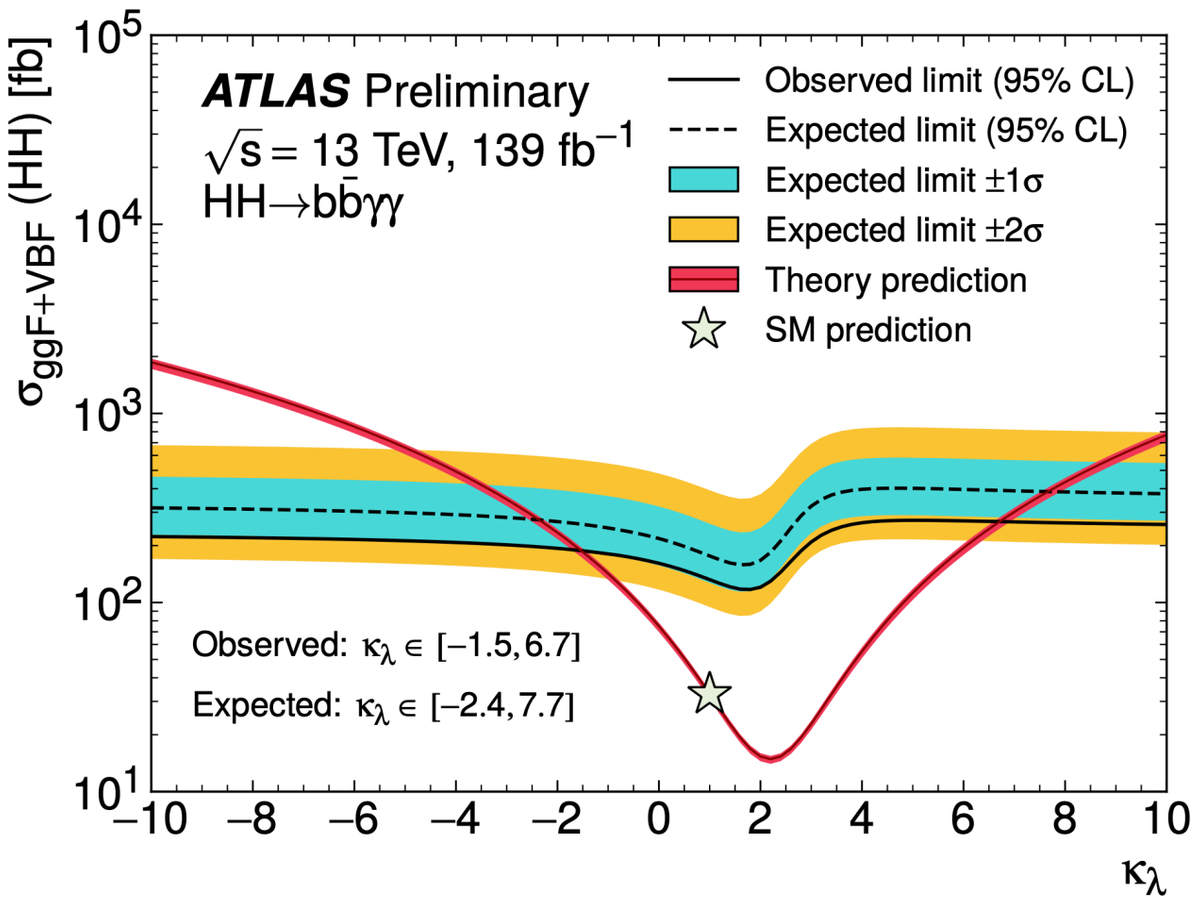
HH→γγbb @ ATLAS and CMS



Observed (Expected) 95% CL < $-3.3<\kappa_\lambda<8.5$ ($-2.5<\kappa_\lambda<8.2$)

$\sigma(pp\rightarrow HH) = 7.7\ (5.2)*SM$ @95% CL

JHEP 03 (2021) 257

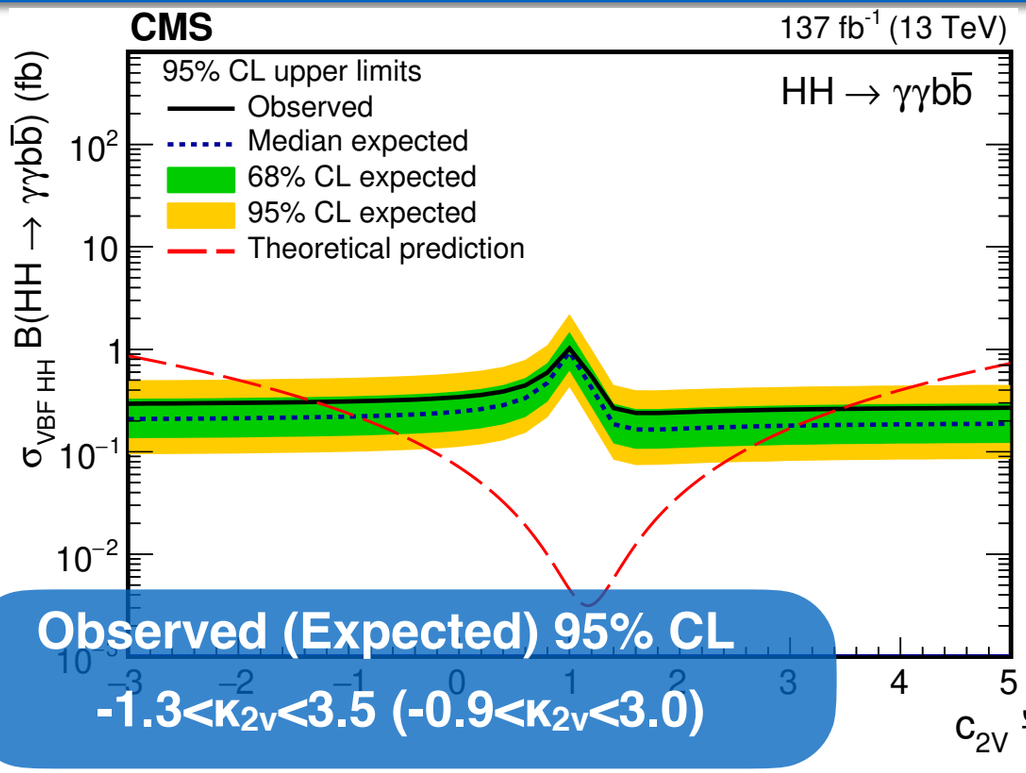


Observed (Expected) 95% CL < $-1.5<\kappa_\lambda<6.7$ ($-2.4<\kappa_\lambda<7.7$)

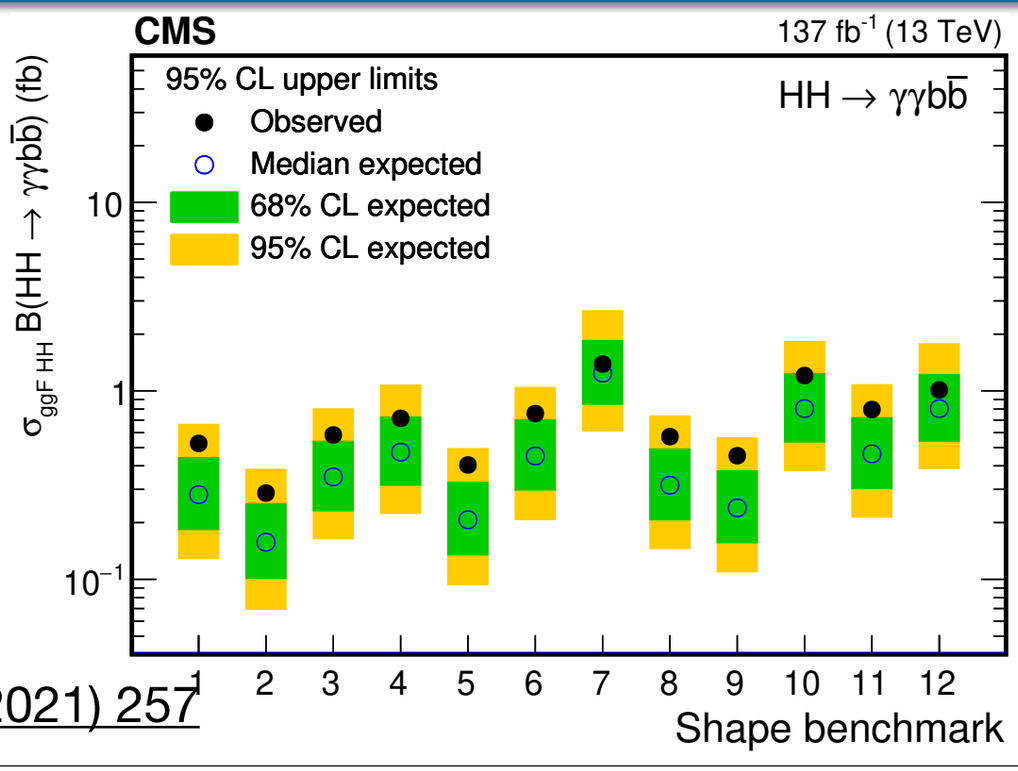
$\sigma(pp\rightarrow HH) = 4.1\ (5.5)*SM$ @95% CL

ATLAS-CONF-2021-016

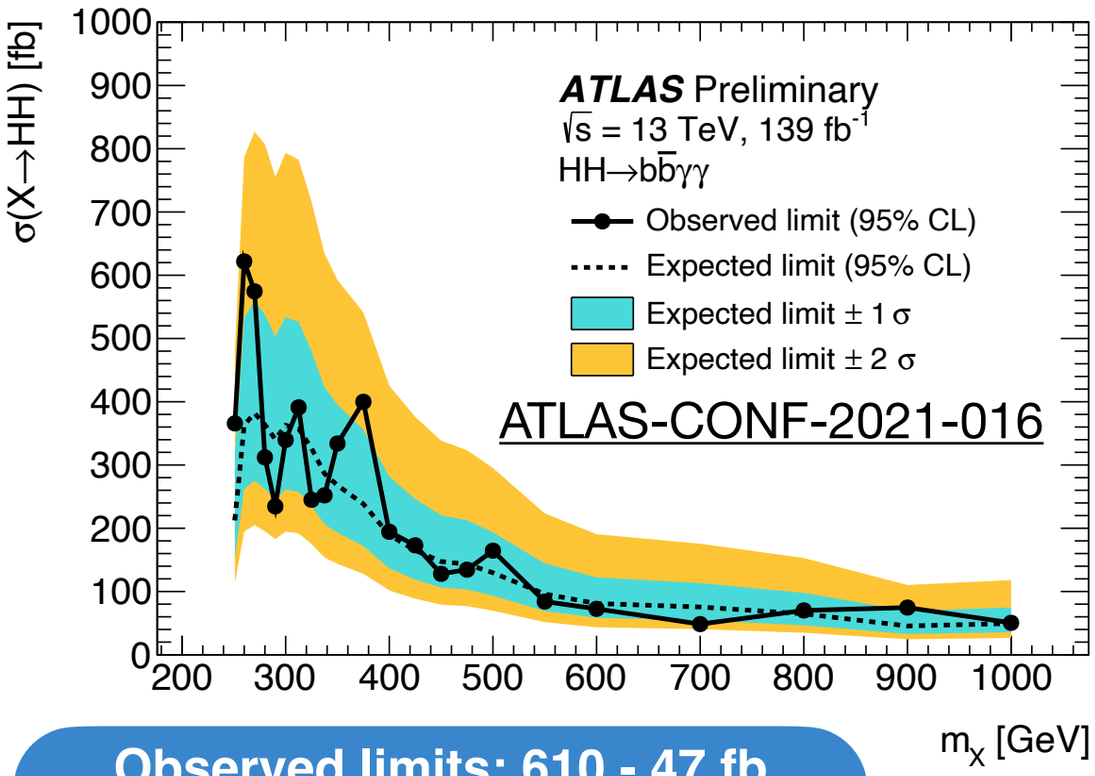
HH→γγbb @ ATLAS and CMS



Observed (Expected) 95% CL
-1.3<κ2V<3.5 (-0.9<κ2V<3.0)



JHEP 03 (2021) 257



Observed limits: 610 - 47 fb for [251, 1000] GeV

	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

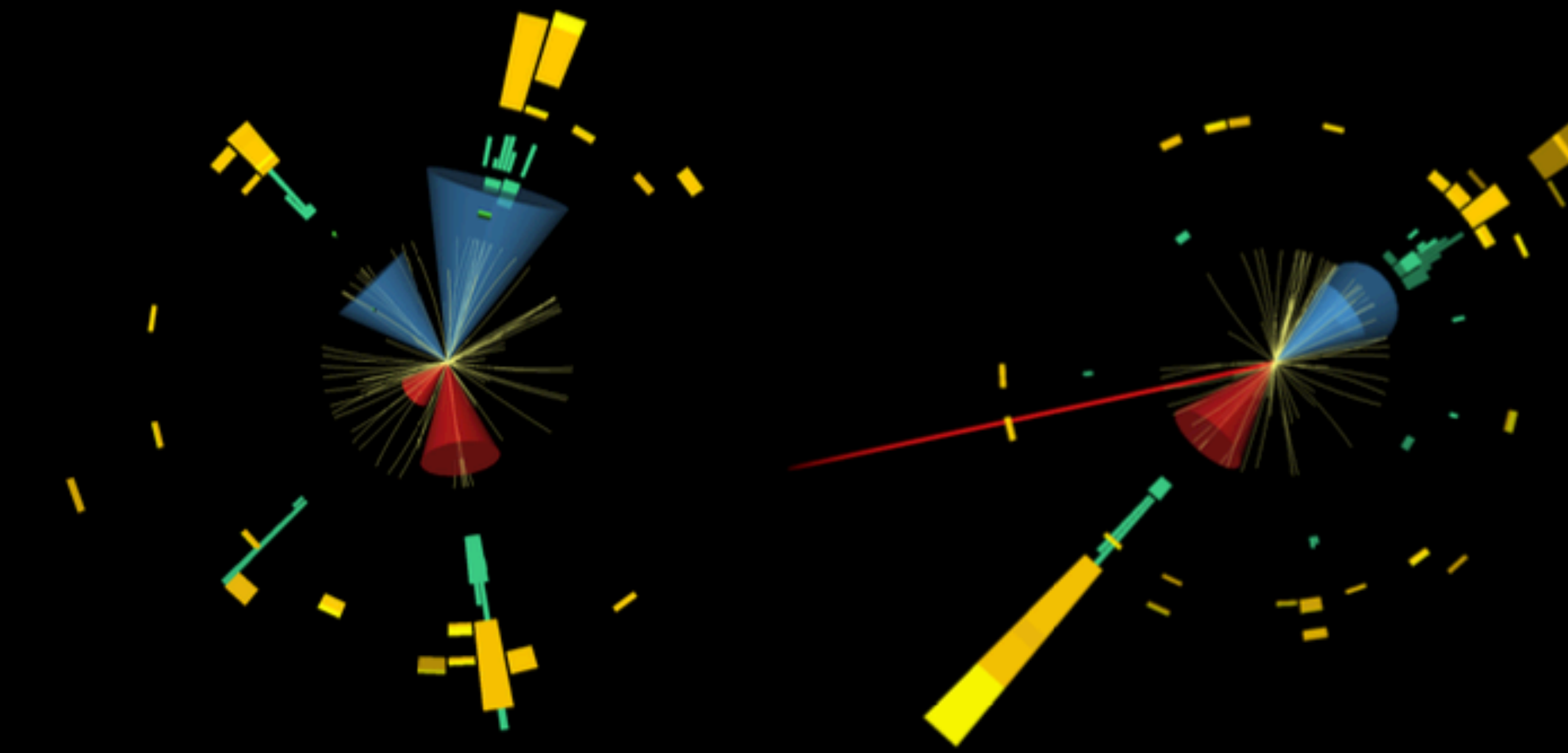
- Modification on non resonance HH ggF production from BSM effects parametrized with EFT (6-dim)

$$\mathcal{L}_{\mathrm{HH}} = \kappa_\lambda \lambda_{\mathrm{HHH}}^{\mathrm{SM}} v \mathrm{H}^3 - \frac{m_\mathrm{t}}{v}\left(\kappa_\mathrm{t}\mathrm{H} + \frac{c_2}{v}\mathrm{H}^2\right)(\bar{\mathrm{t}}_\mathrm{L}\mathrm{t}_\mathrm{R} + \mathrm{h.c.}) + \frac{1}{4}\frac{\alpha_\mathrm{S}}{3\pi v}\left(c_\mathrm{g}\mathrm{H} - \frac{c_{2\mathrm{g}}}{2v}\mathrm{H}^2\right)G^{\mu\nu}G_{\mu\nu}$$

All results are consistent with the SM predictions

$HH \rightarrow bb\tau\tau$

Medium BR, medium S/B

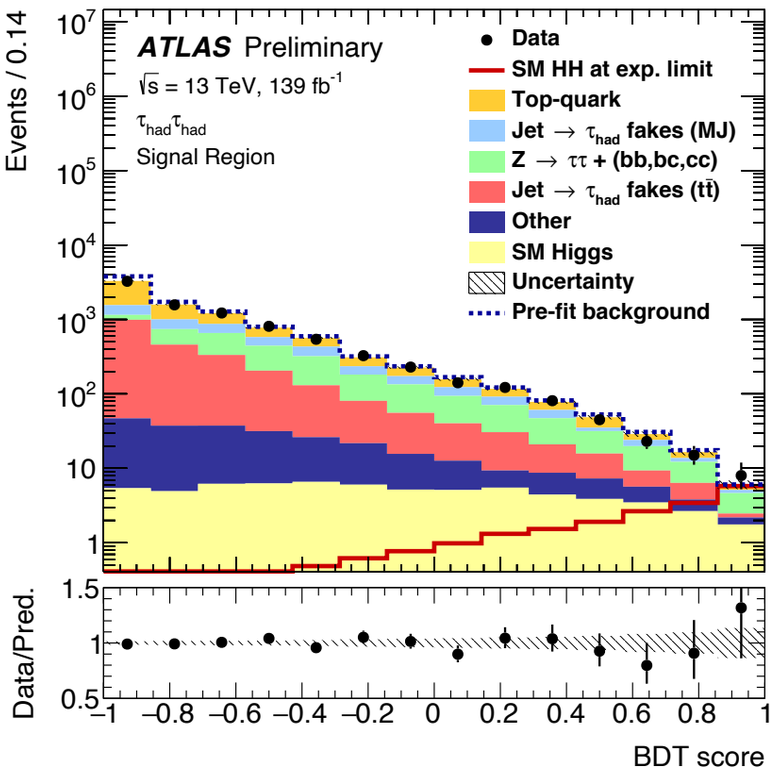


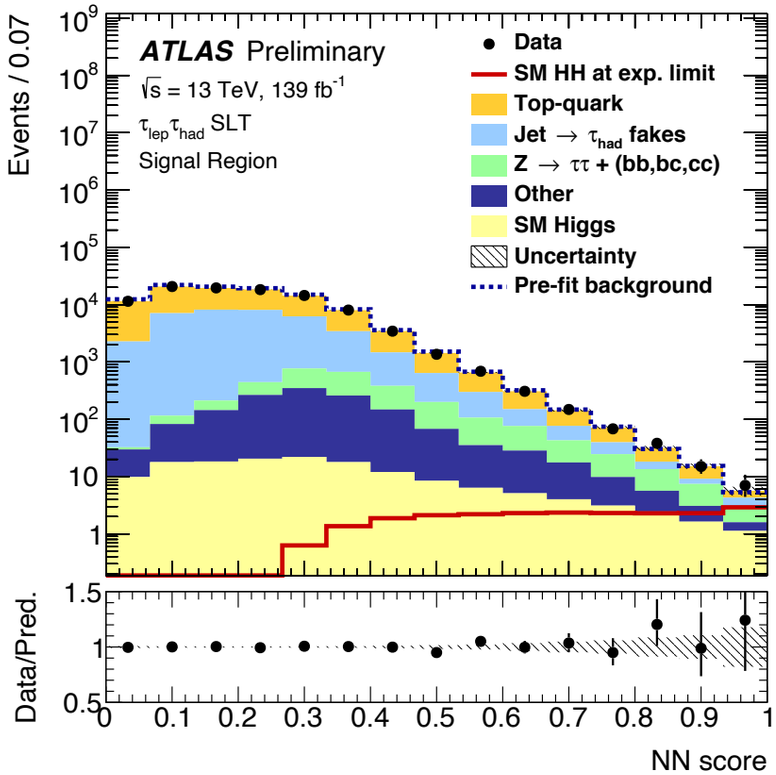
bb $\tau_h\tau_h$

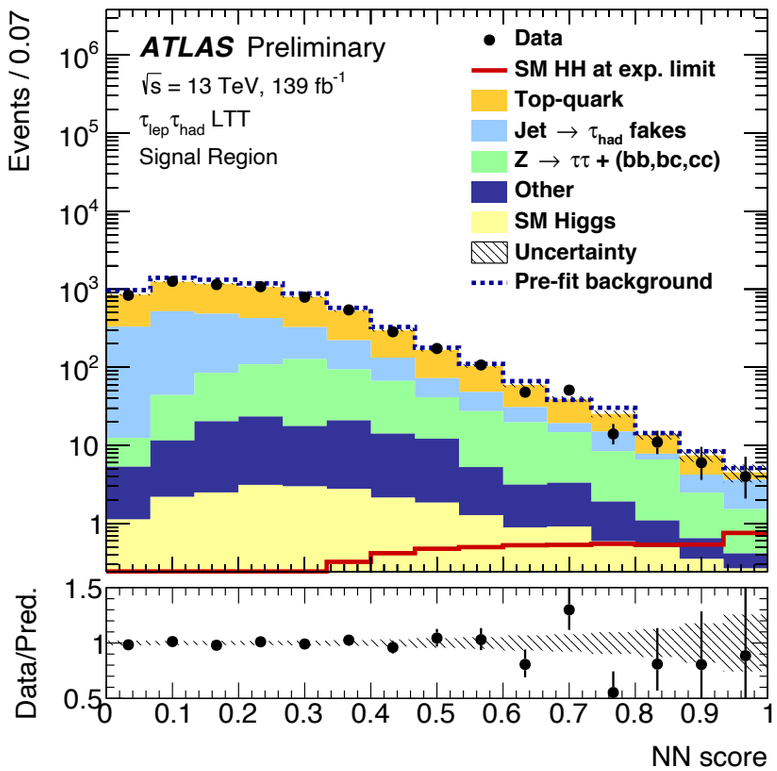
bb $\mu\tau_h$

HH→bbττ @ ATLAS

- Target $\tau_h\tau_h$,eτ_h,$\mu\tau_h$: 88% of the total decays
- BDT/NN used to separate signal from background
- Final fit on the BDT/NN output



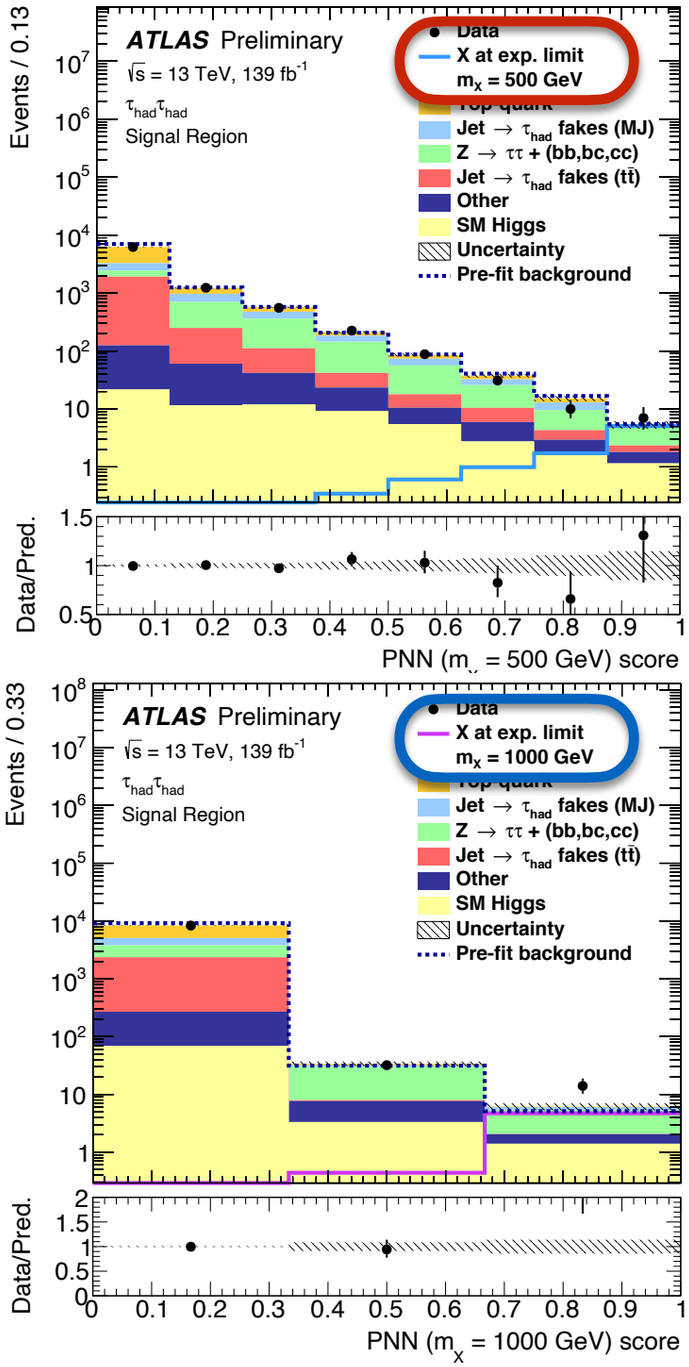


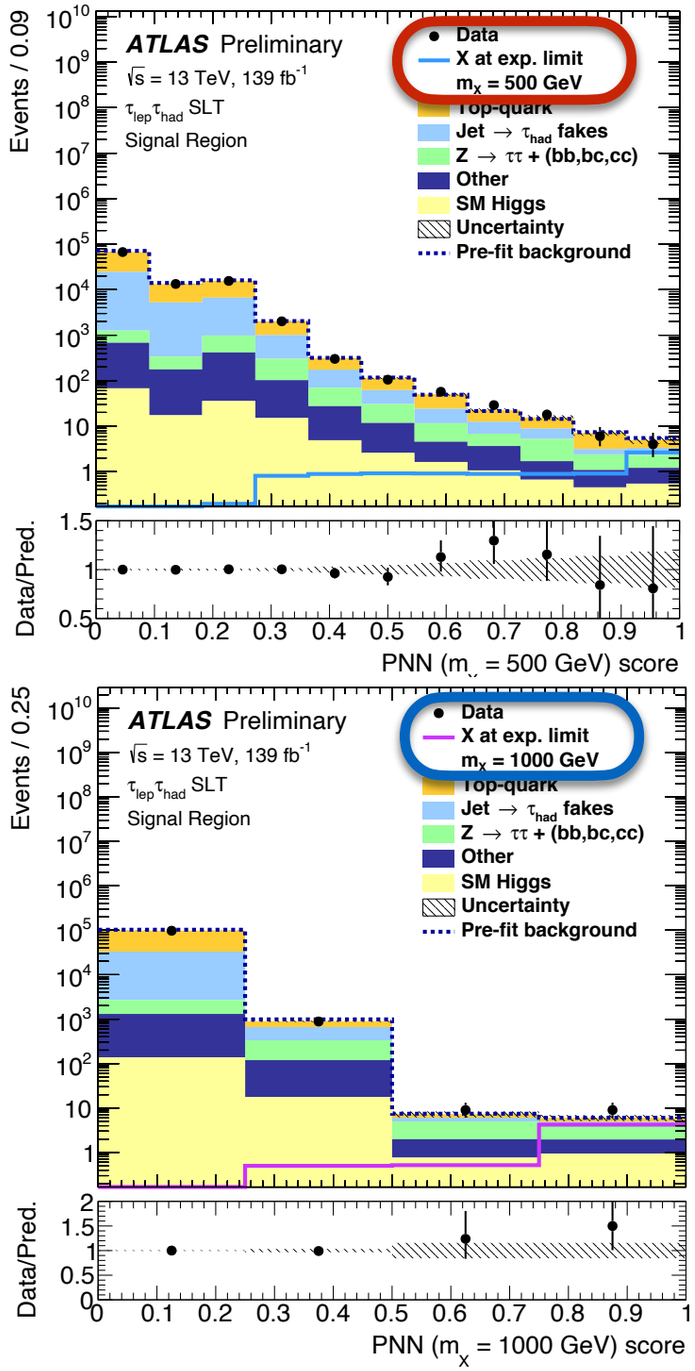


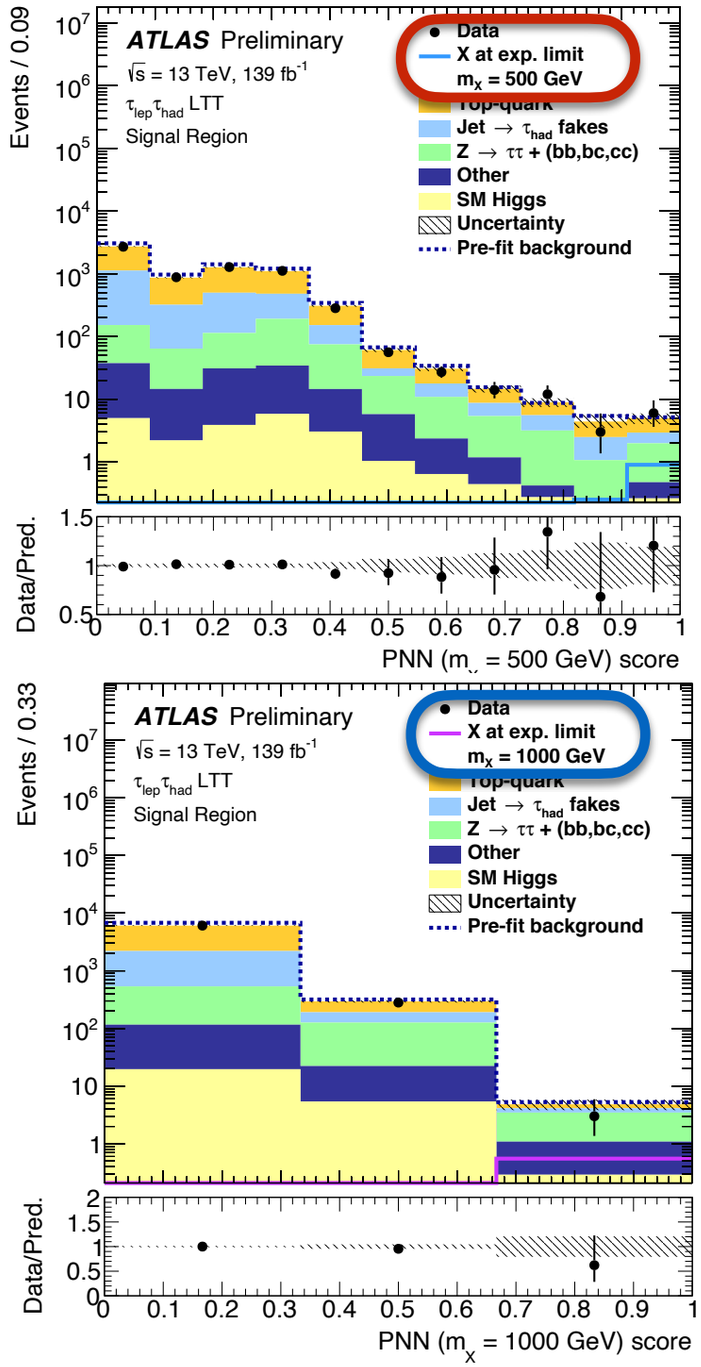
Observed (Expected) HH rate @ 95% CL < 4.7 (3.9) × SM

ATLAS-CONF-2021-030

HH→bbττ @ ATLAS



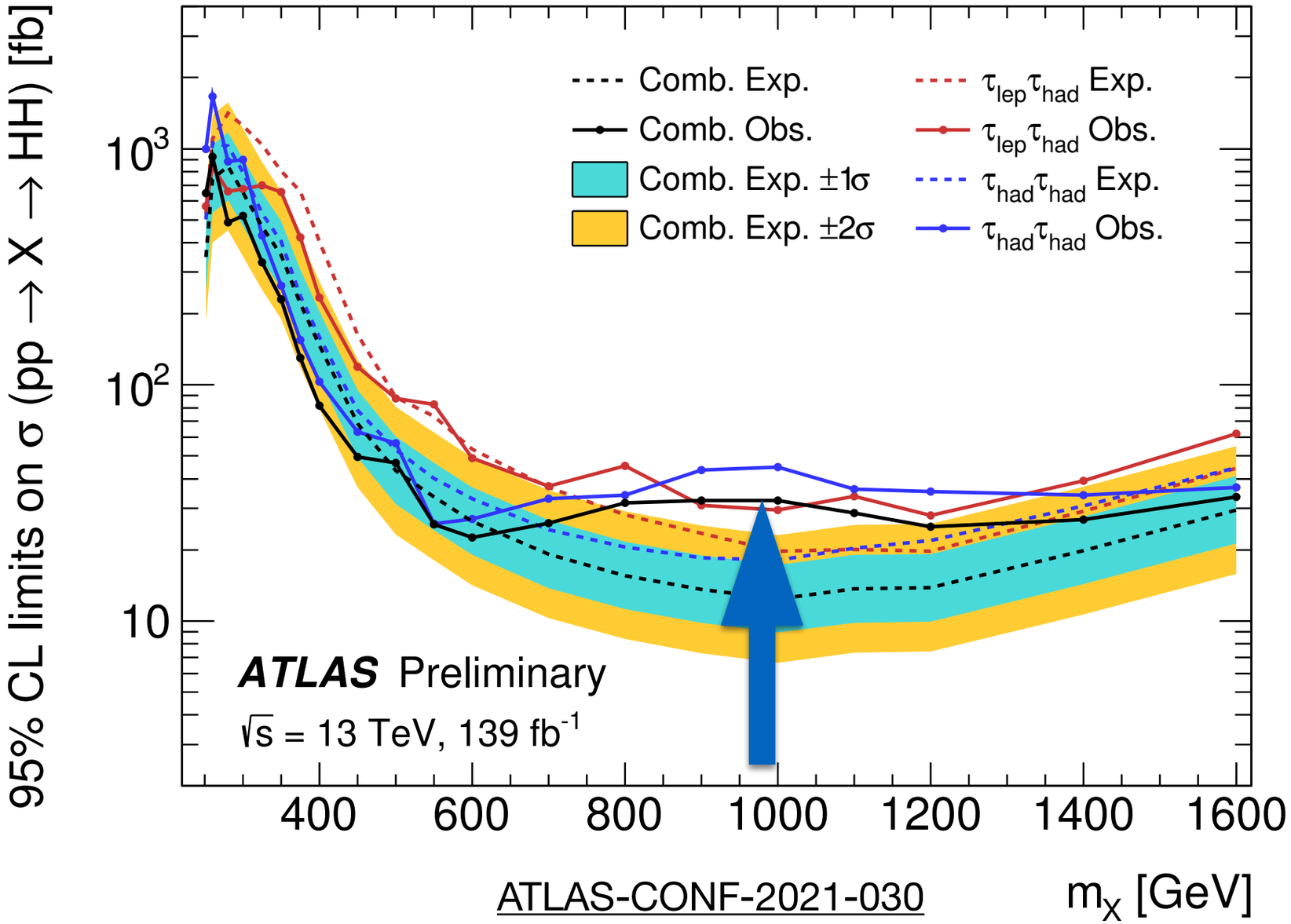




PNN used for the resonance search: automatically retrieve the optimized training response for different resonance mass points

ATLAS-CONF-2021-030

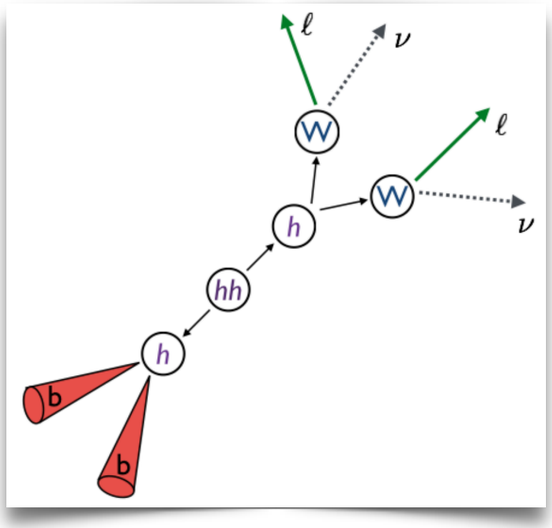
HH→bbττ @ ATLAS



- **Most significant excess $\tau_h\tau_h$ ($\tau_{lep}\tau_h$) for at 1TeV (1.1TeV)**
- **Combined results @ m_X = 1TeV:**
  - **a local significance of 3σ and a global significance of $2.0^{+0.4}_{-0.2}\sigma$**

HH→bblvlv @ ATLAS

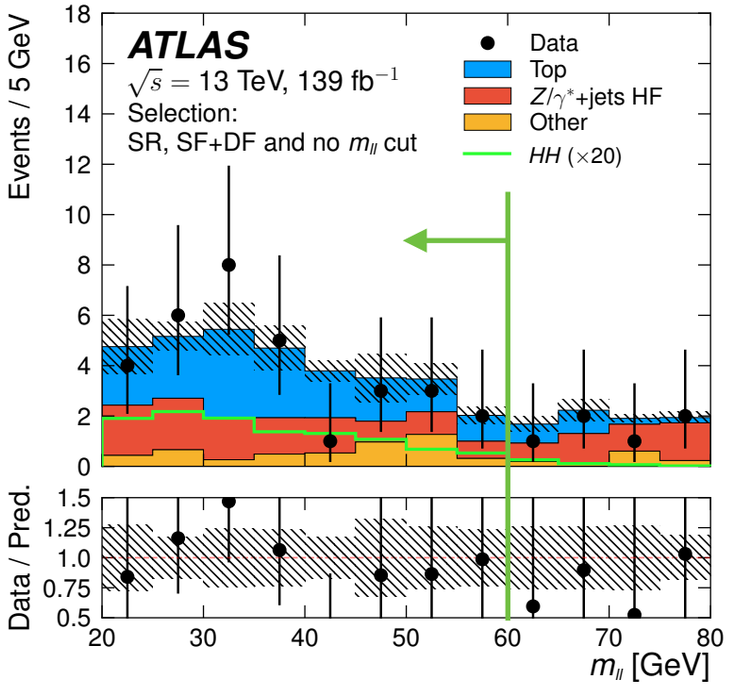
- Target for bblvlv final states, dominated by the bbWW* (only signal for the optimization)
- Most discriminate variable with DNN output: $d_{hh} = \ln(\frac{p_{HH}}{p_{Top} + p_{Zll} + p_{Z\tau\tau}})$

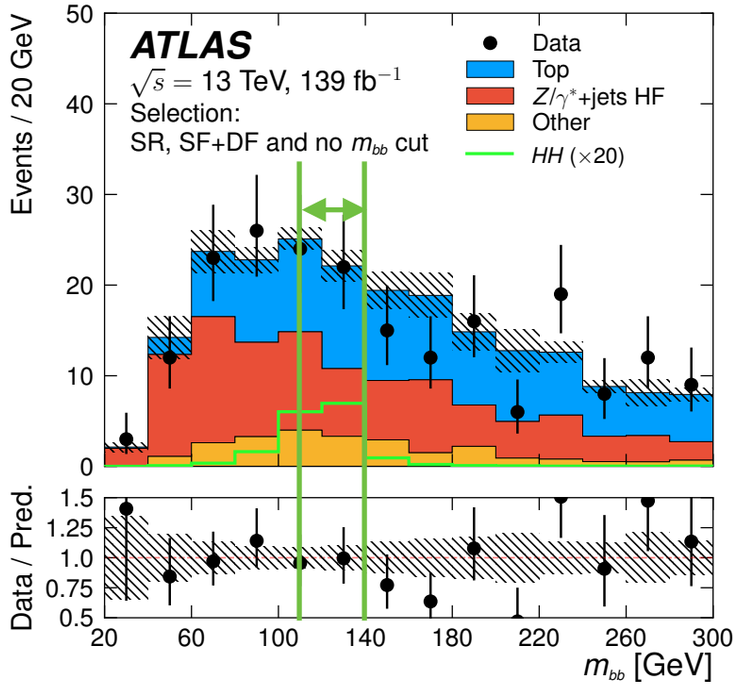


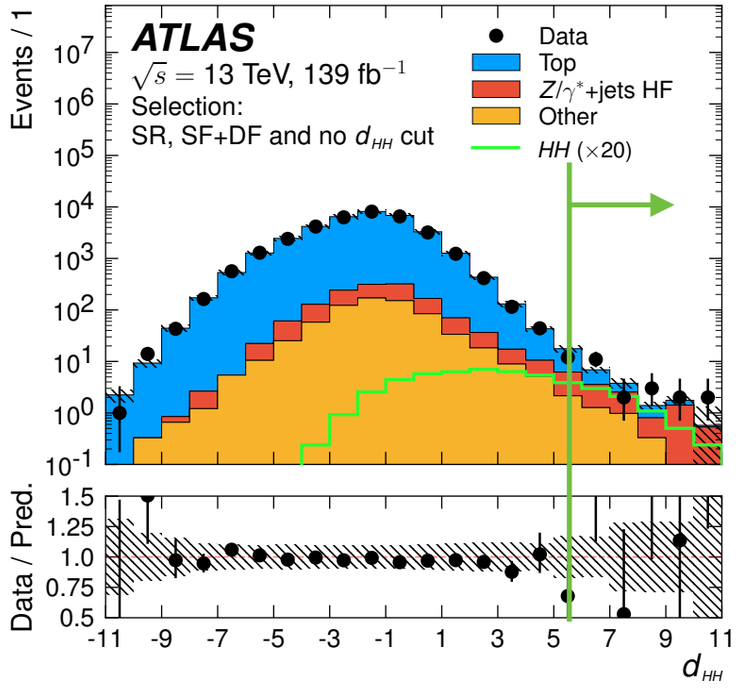
$hh \to bbWW^*,2\ell$	$hh \to bb\tau\tau,2\ell$	$hh \to bbZZ^*,2\ell$
0.027	0.009	0.003

Observable	SR-SF	SR-DF
Dilepton Flavour	SF	DF
$m_{\ell\ell}$ [GeV]	(20, 60)	(20, 60)
m_{bb} [GeV]	(110, 140)	(110, 140)
d_{HH}	> 5.45	> 5.55

	Region Definitions			
Observable	CR-Top	VR-1	CR-Z+HF	VR-2
Dilepton Flavour	DF	SF	DF or SF	SF
$m_{\ell\ell}$ [GeV]	(20, 60)	(20, 60)	(81.2, 101.2)	(71.2, 81.2) or (101.2, 115)
m_{bb} [GeV]	$\notin$ (100, 140)	> 140	(100, 140)	(100, 140)
d_{HH}	> 4.5	> 4.5	> 0	> 0

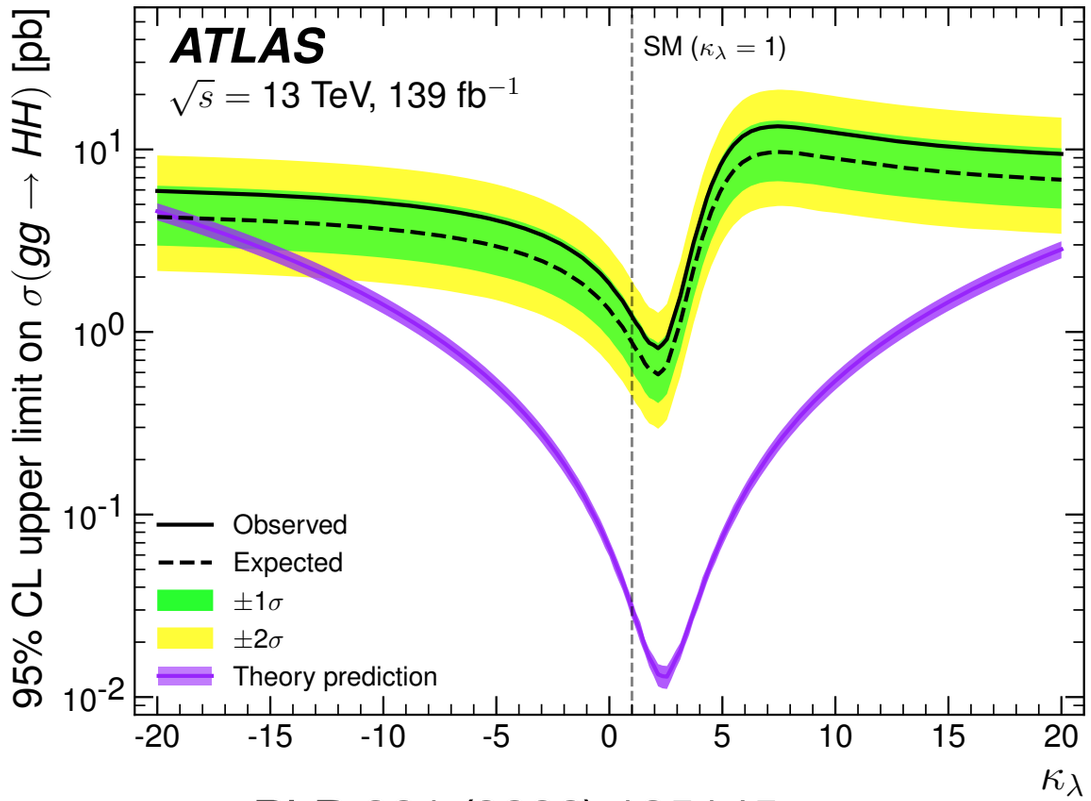






HH→bblvlv @ ATLAS

	-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

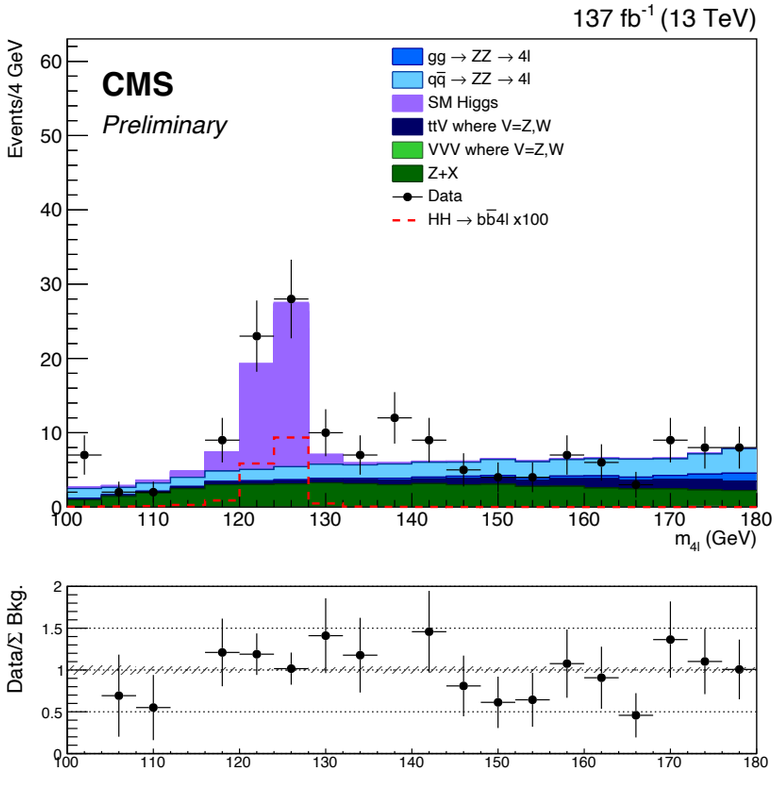


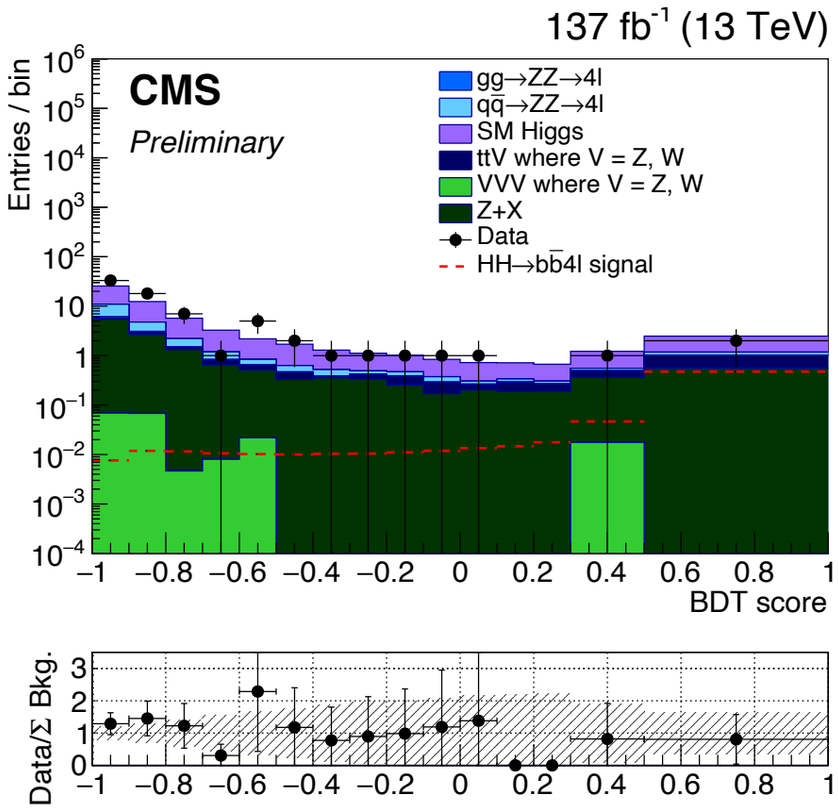
PLB 801 (2020) 135145

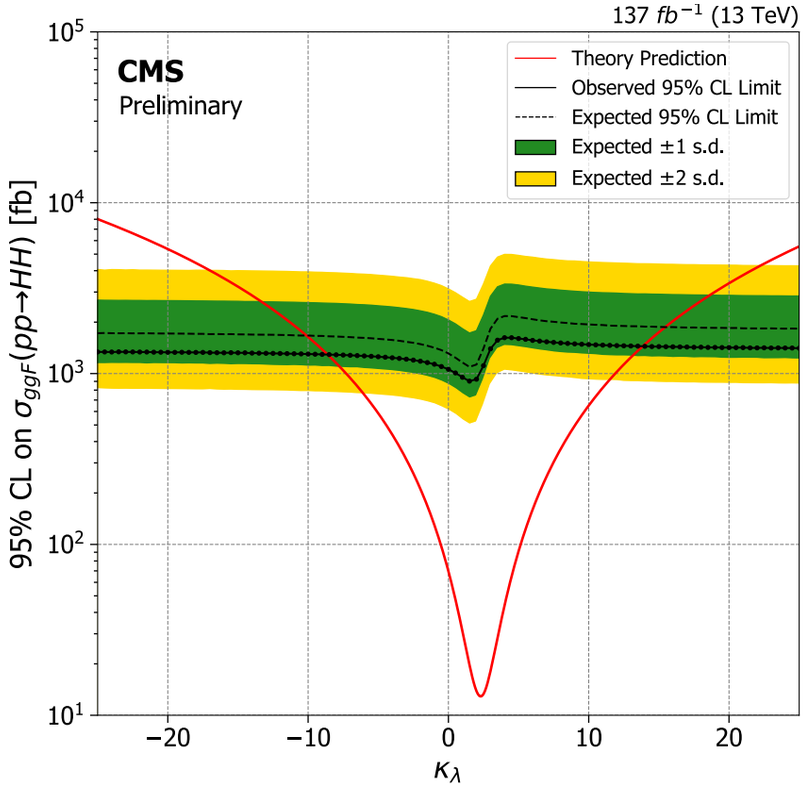
- A counting experiment is performed with a profile likelihood fit.
- No evidence of the HH production is observed
- Observed (expected) upper limit: σ_{HH} <40 (29) ×SM @ 95% CL

HH→bbZZ (4l) @ CMS

- Very rare BR (0.0145%) but very small background + clean H signature peaks
- Final fit to the BDT distribution in data





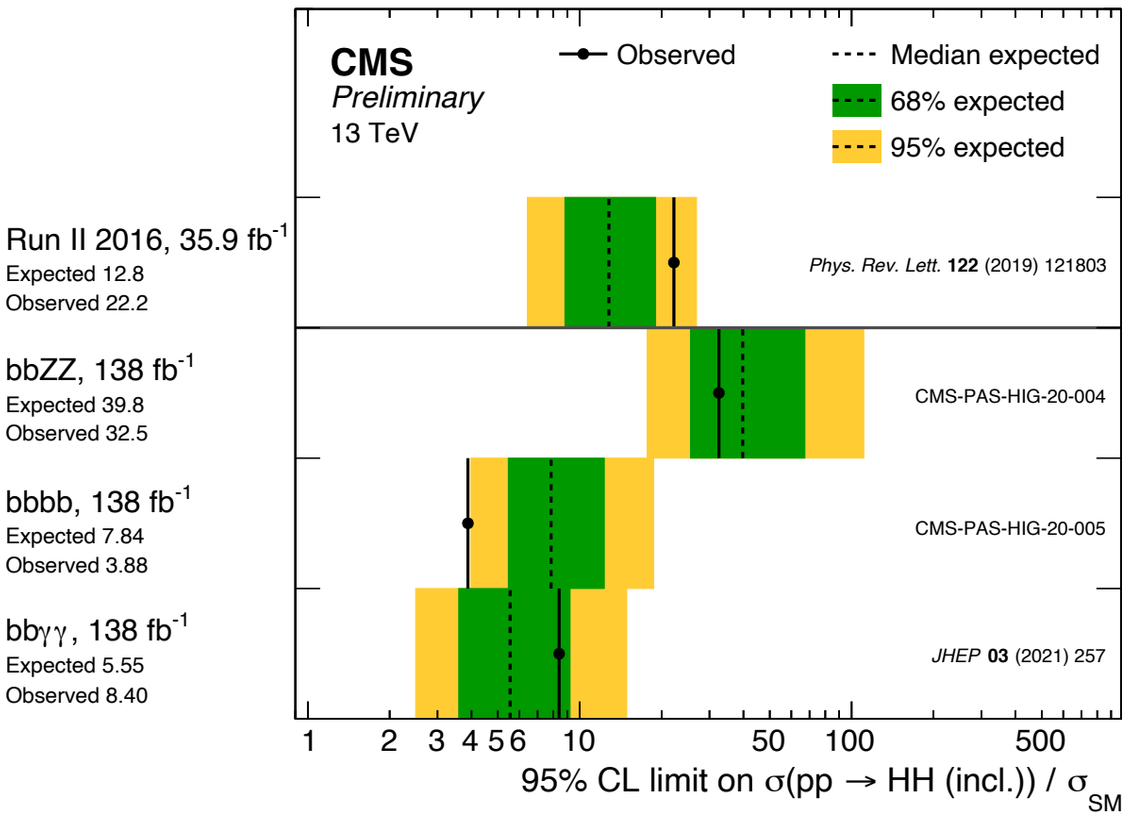


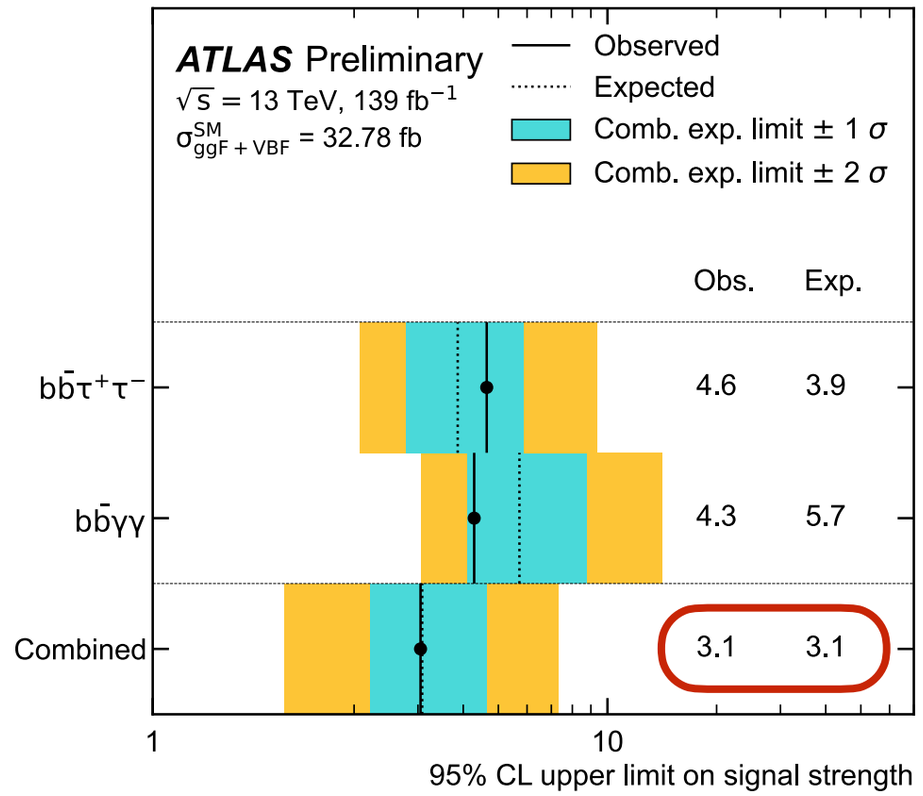
Observed (Expected) 95% CL < 30 (37)×SM

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

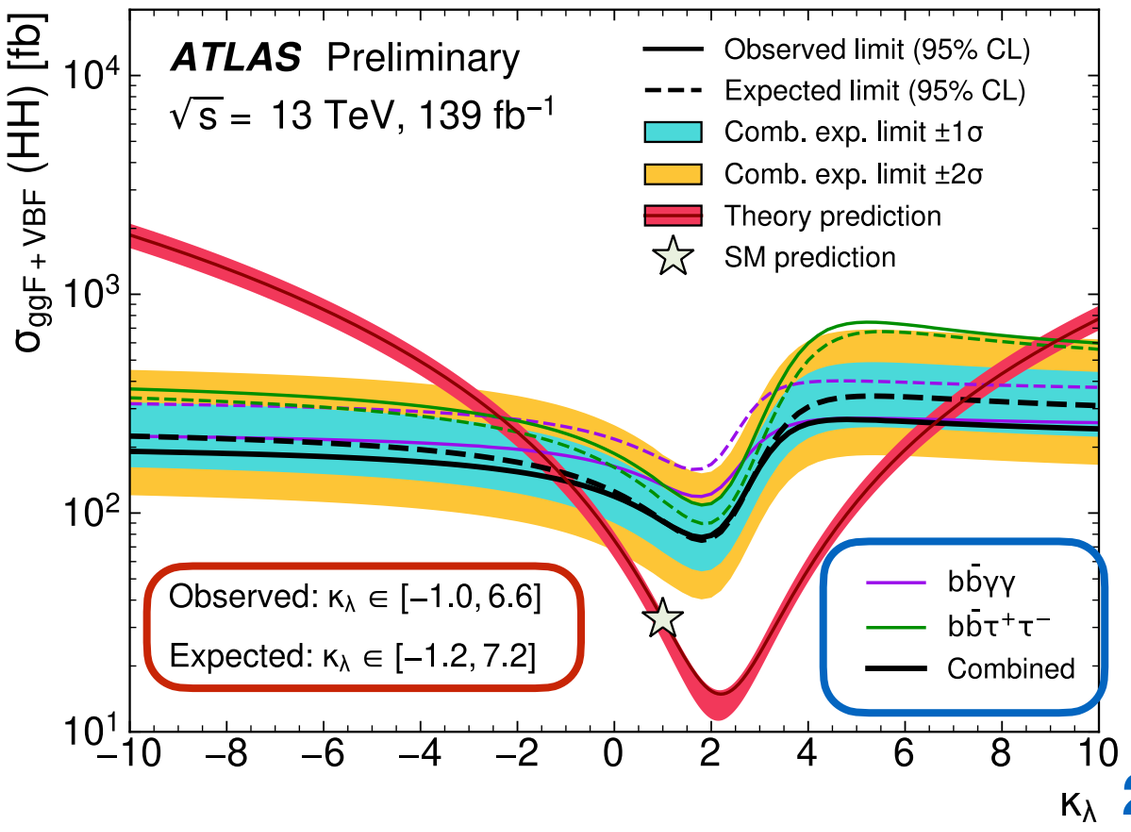
HIG-20-004-pas

HH combination of full Run2 data

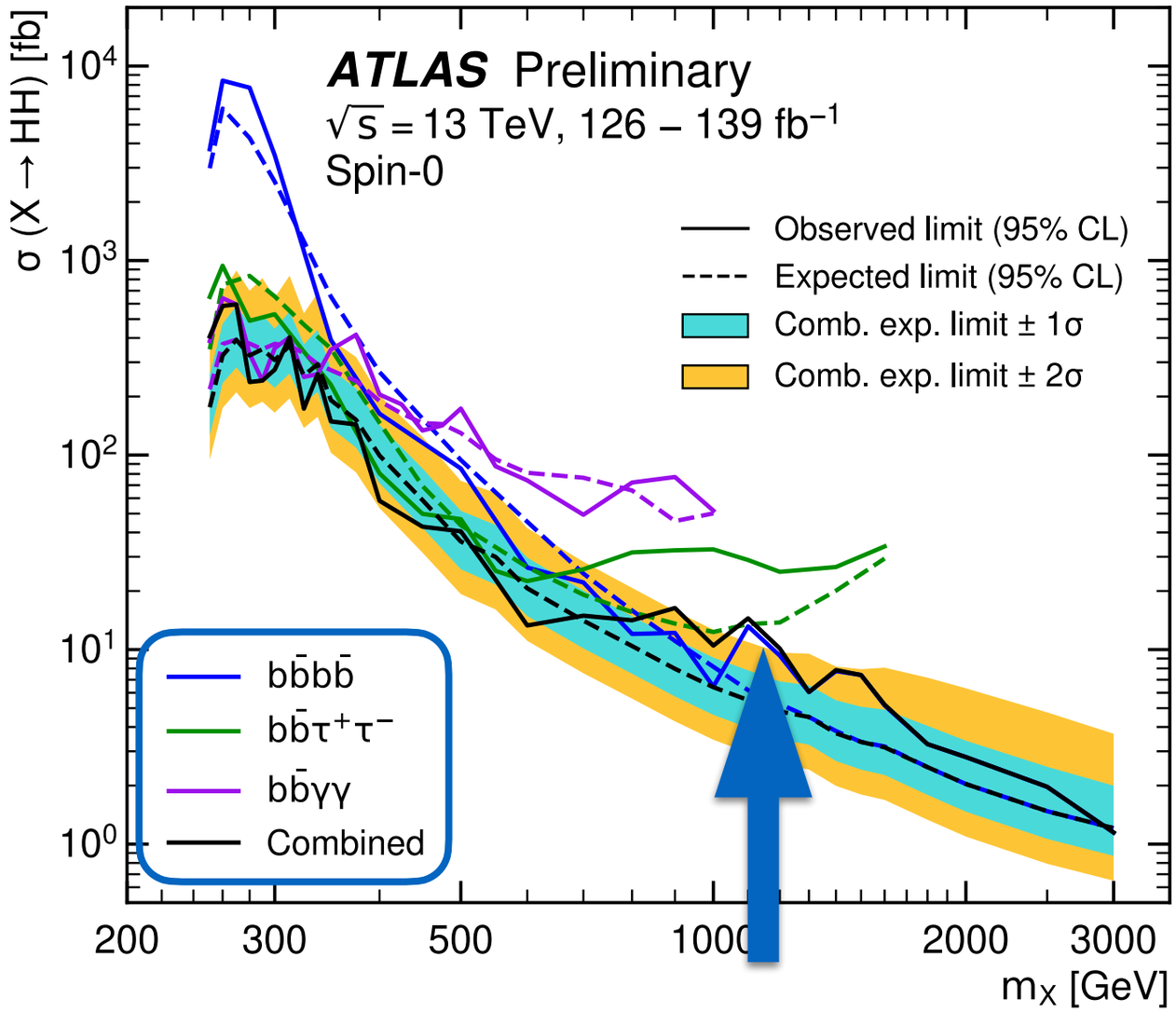




- Individual channel achieve 5-7×SM
  - more data, more sophisticated analysis method



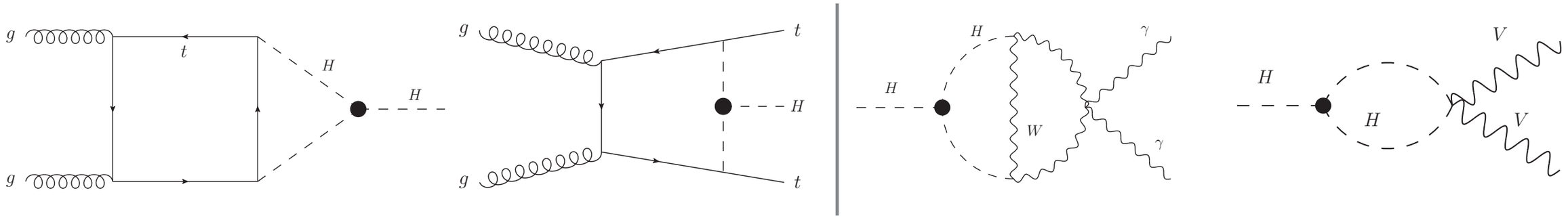
HH combination of full Run2 data



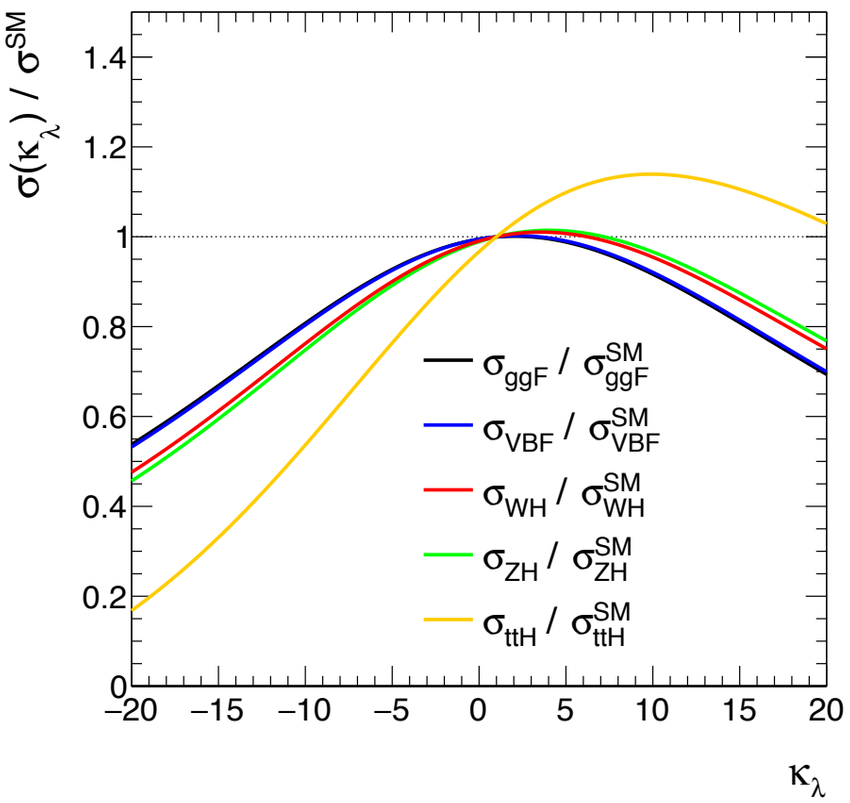
A local significance of 3.2σ and a global significance of 2.1σ @ mX = 1.1 TeV

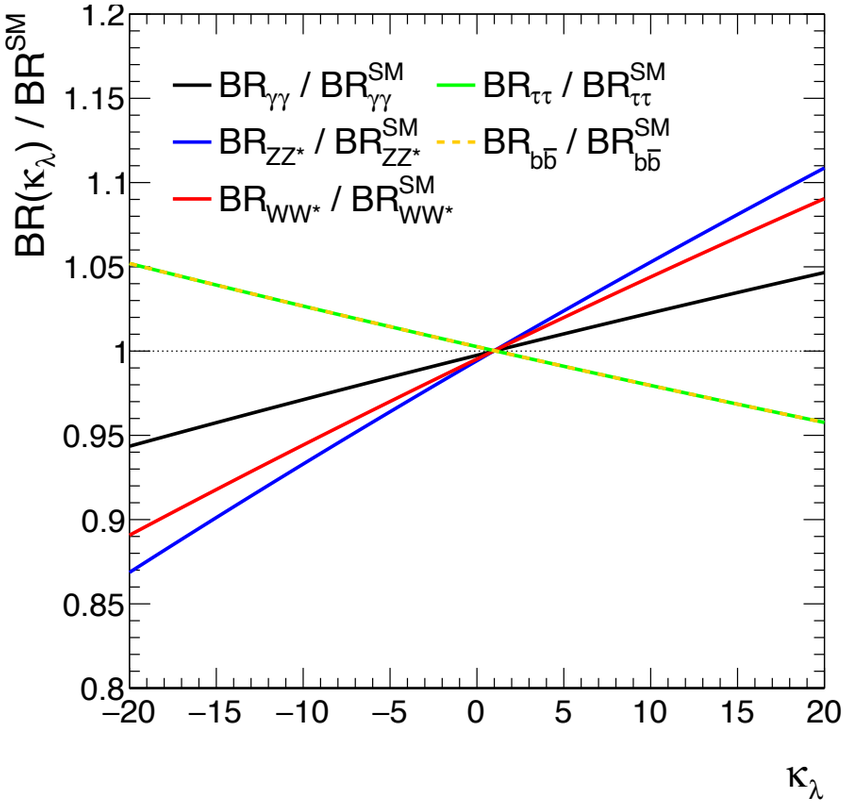
Self-coupling from single Higgs

All the single Higgs production and decay processes are affected by an anomalous trilinear (**not quartic**) Higgs self coupling, parametrized by κ_λ.

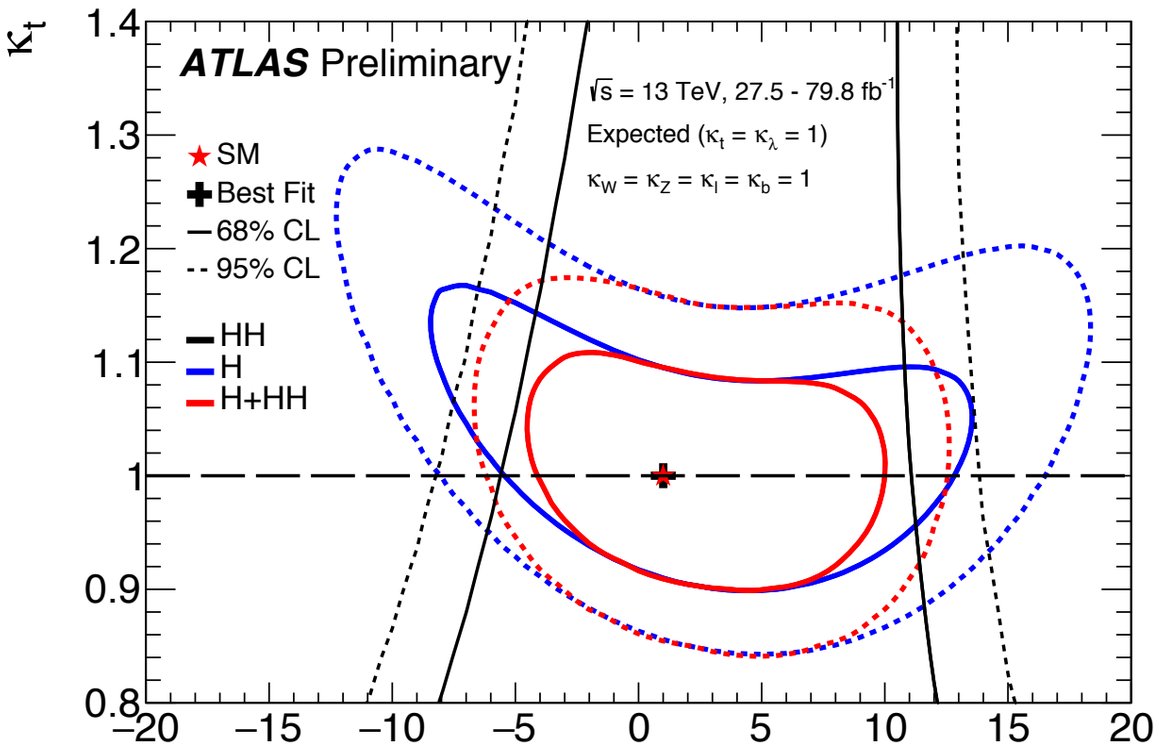


All the different signal strengths μ_i^f have a different dependence on a single parameter κ_λ, which can thus be constrained via a global fit.

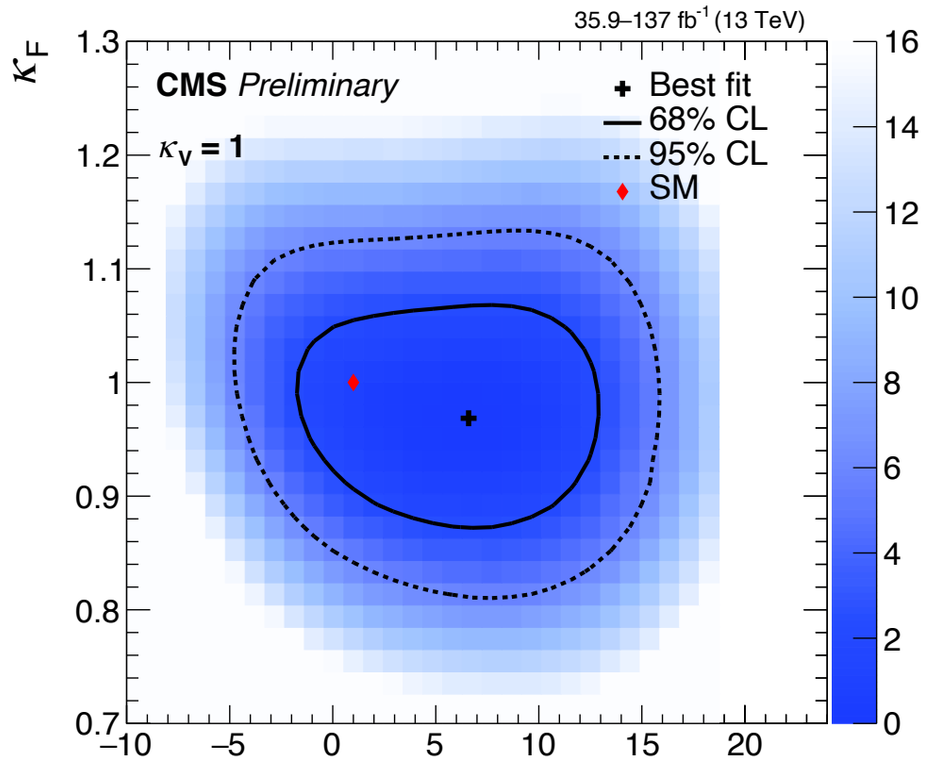




Self-coupling from single Higgs @ ATLAS



ATL-CONF-2019-012



HIG-19-005-pas

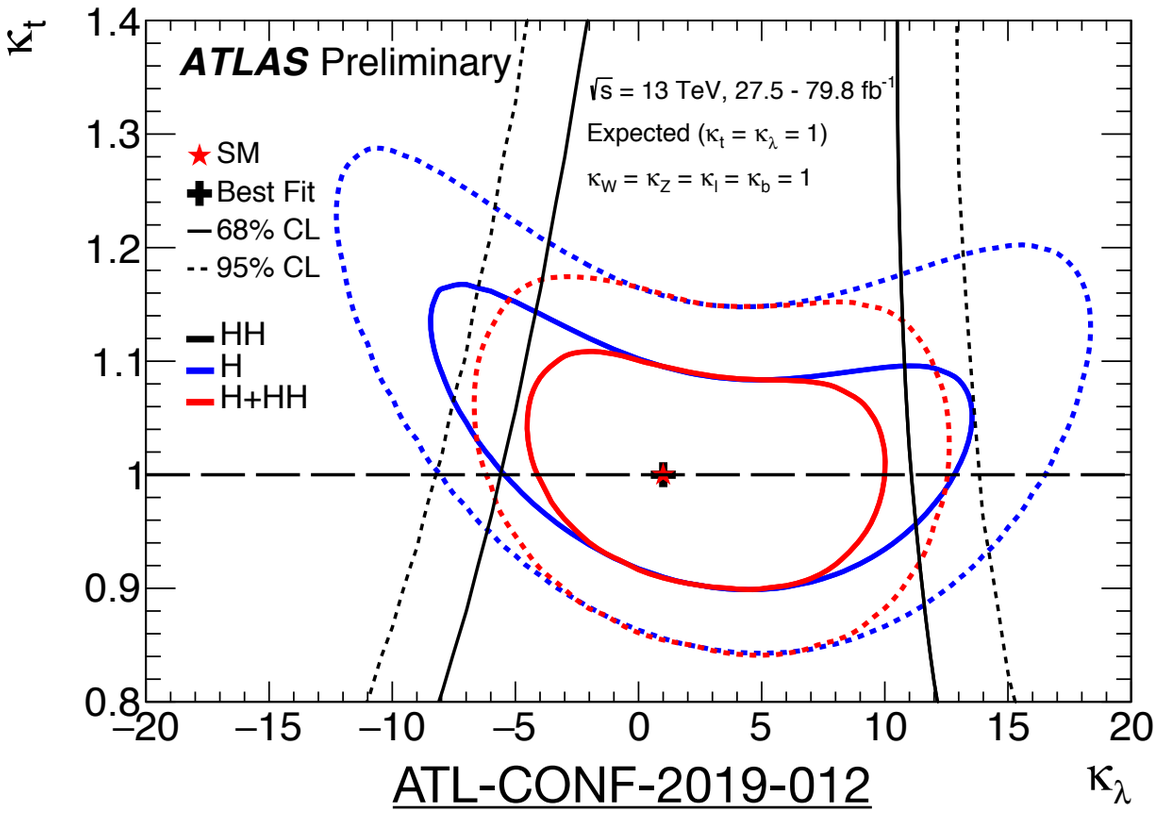
Constraint **(obs/exp) @ 95% CL:**

- **ATLAS (H): -3.2<κλ<11.9 / -6.2<κλ<14.4**
- **ATLAS (HH):** -5.0<κλ<12.0 / -5.8<κλ<12.0
- **ATLAS (H+HH): -2.3<κλ<10.3/-5.1<κλ<11.2**

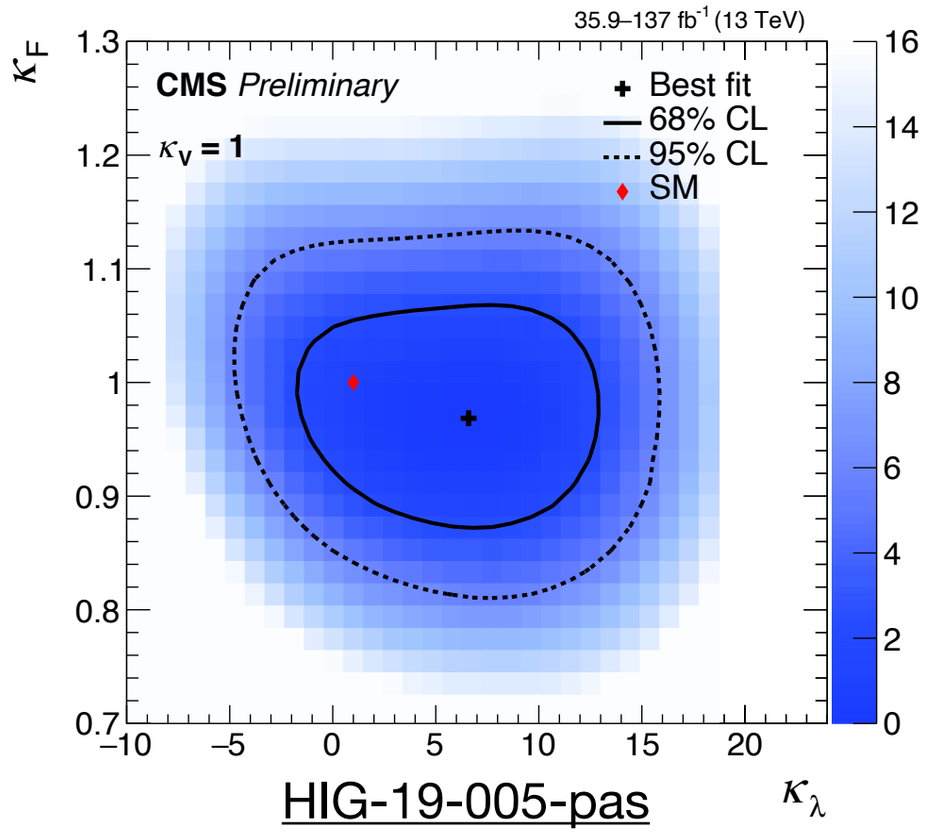
Assumption	Best fit κ_λ	95% CL interval
$\kappa_F = \kappa_V = 1$	$6.7^{+4.6}_{-6.6}$ $\left(^{+8.3}_{-3.8}\right)$	$[-3.5, 14.5]$ $\left([-5.1, 13.7]\right)$
$\kappa_F = 1$	$10.3^{+6.1}_{-10.0}$ $\left(^{+8.8}_{-5.0}\right)$	$[-5.5, 21.7]$ $\left([-7.4, 17.2]\right)$
$\kappa_V = 1$	$6.6^{+4.5}_{-6.1}$ $\left(^{+8.2}_{-4.0}\right)$	$[-3.3, 14.4]$ $\left([-5.5, 13.8]\right)$

Complement HH direct measurement and provide more stringent constraint.

Self-coupling from single Higgs @ ATLAS



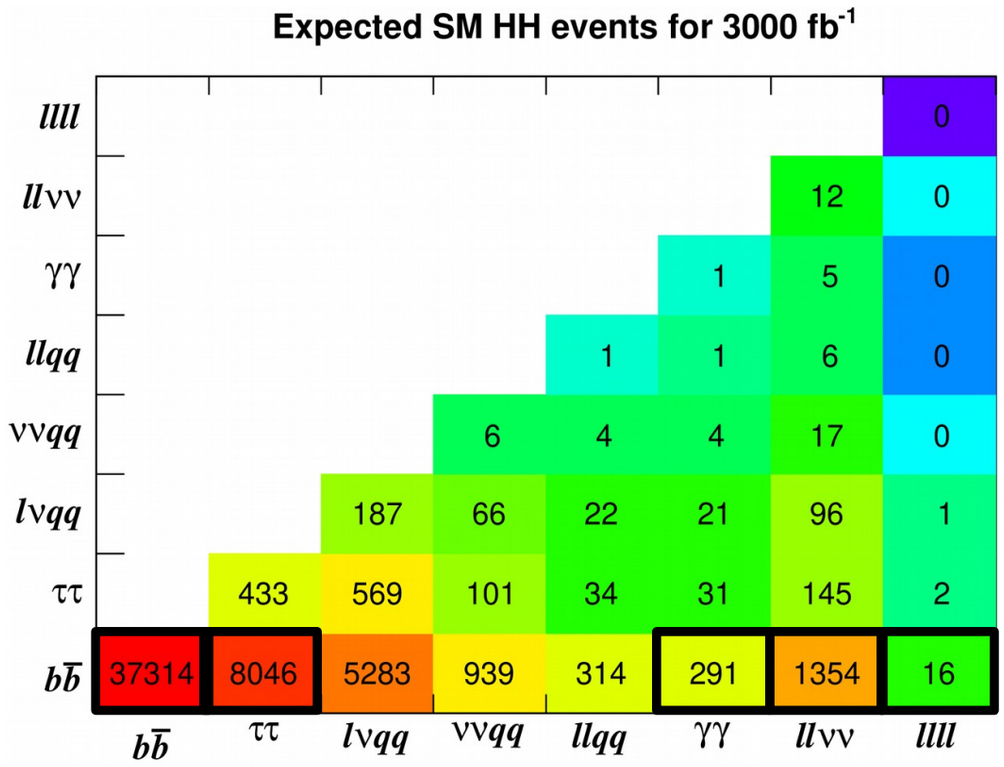
ATL-CONF-2019-012

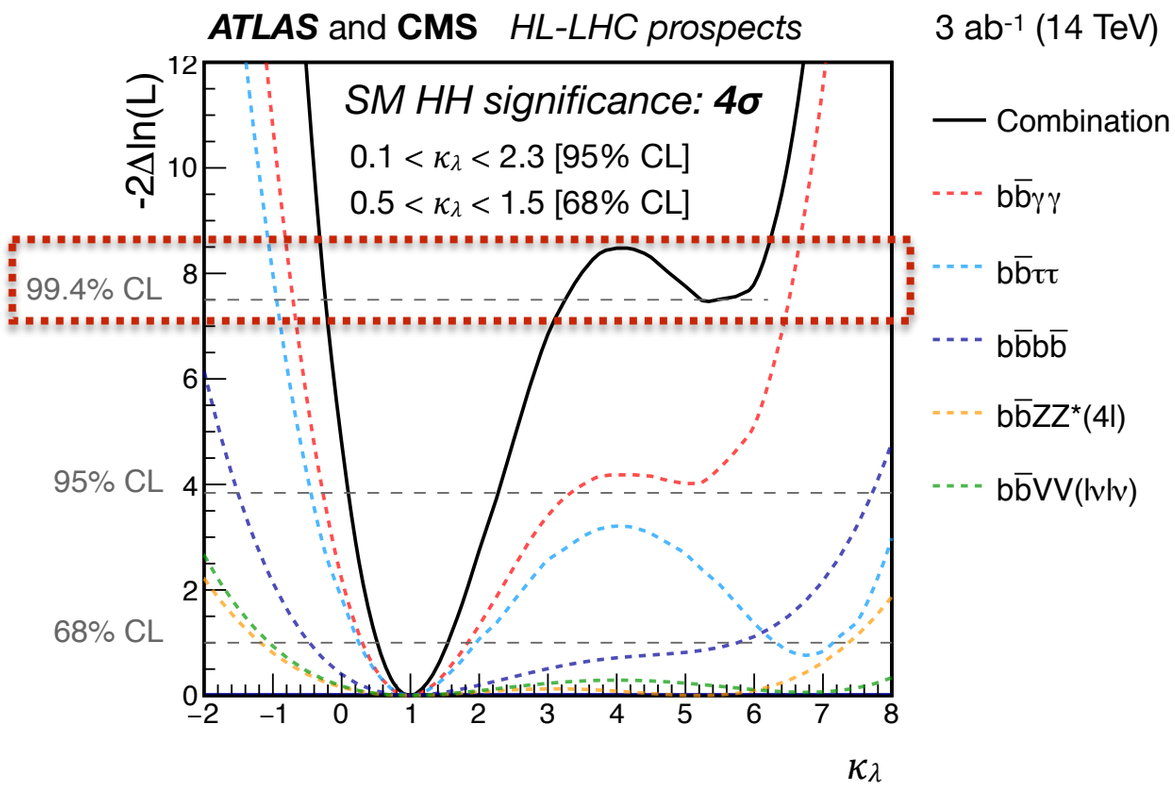


HIG-19-005-pas

- **Limited access to possible BSM effect**
  - No consideration of the kinematic dependence on kλ in the single Higgs process
  - No consistent EFT predicts only SM coupling variation without new interactions.
  - Combine LO and NLO effects in the two measurements with a k-framework

Prospect @ HL-LHC





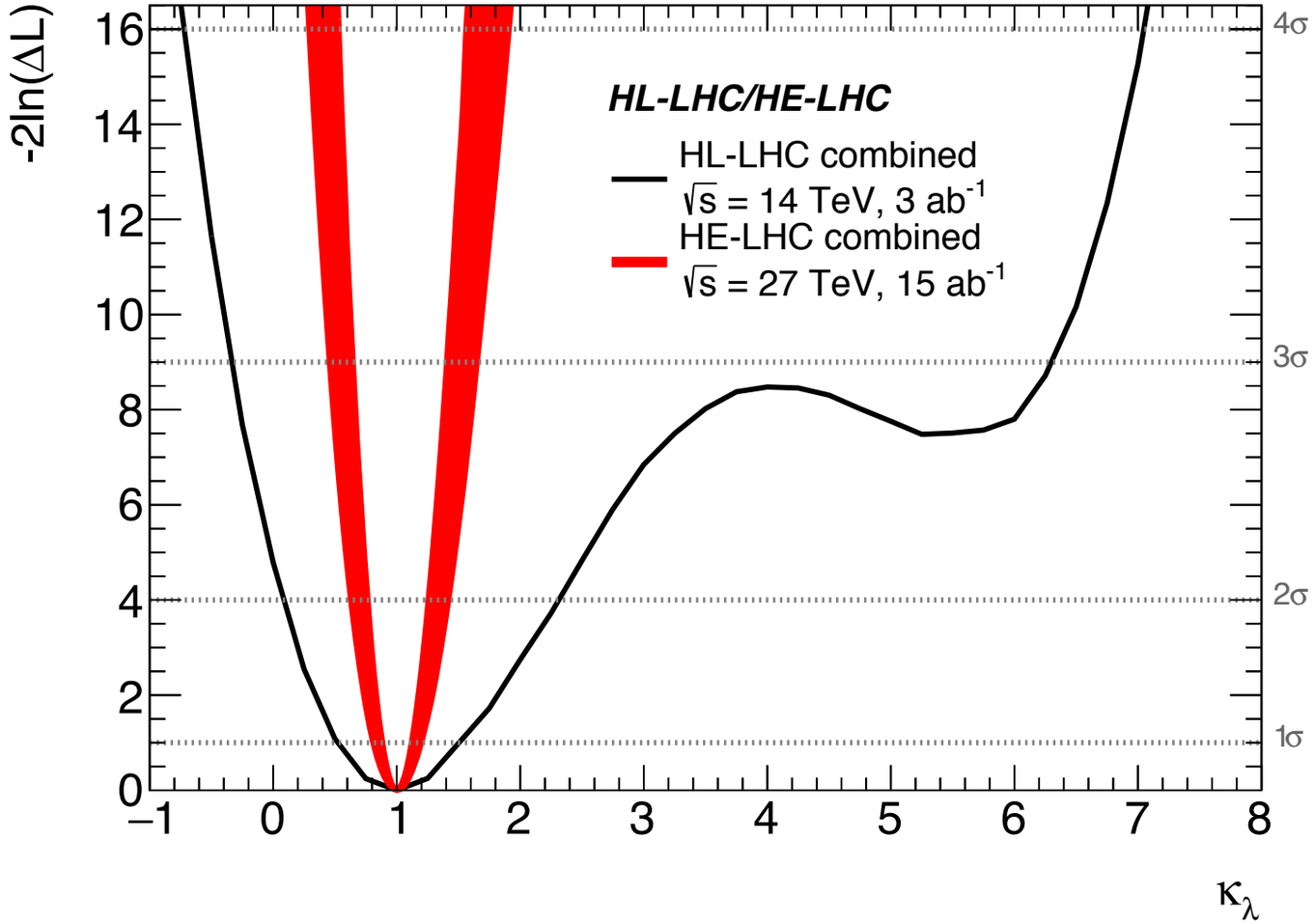
	ATLAS	CMS	
bbbb	extrapolation	parametric	Largest BR ☺ Large multijet and tt bkg ☹
bbττ	extrapolation	parametric	Sizeable BR ☺ Relatively small bkg ☺
bbγγ	smearing	parametric	Small BR ☹ Good diphoton resolution ☺ Relatively small bkg ☺
bbVV (→lνlν)		parametric	Large BR ☺ Large bkg ☹
bbZZ (→4l)		parametric	Very small BR ☹ Very small bkg ☺

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

Room with the exploration of the dependence on κ_λ

Prospect @ HE-LHC

- Extrapolate ATLAS HL-LHC results to HE-LHC:
  - scale **cross-section (*4)** from 14TeV to 27TeV and **luminosity (*5)** to 15ab-1
  - **bbγγ**：7.1σ with the precison on κ_λ of ~20%
  - **bbττ:** 10.7σ with the precision on κ_λ of ~40%
  - **Combination:** the precision on κ_λ of 10-20%



Summary

- Higgs self-coupling have been measured in most main HH channels with Run2 data, with the benefit from high statistics data, advanced MVA technique, and better reconstruction performance.

- Higgs self-coupling can be indirectly probed with single-Higgs process via NLO-EW correction, it can help to further constrain κ_λ

- HL-LHC: 4σ evidence of the HH process with ATLAS and CMS combination.

More promising results are coming soon.