HiggsHiggs Hunting at LHC

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HiggsDiscovery@10
Symposium for the 10 years
from the Higgs boson observation

University of Birmingham

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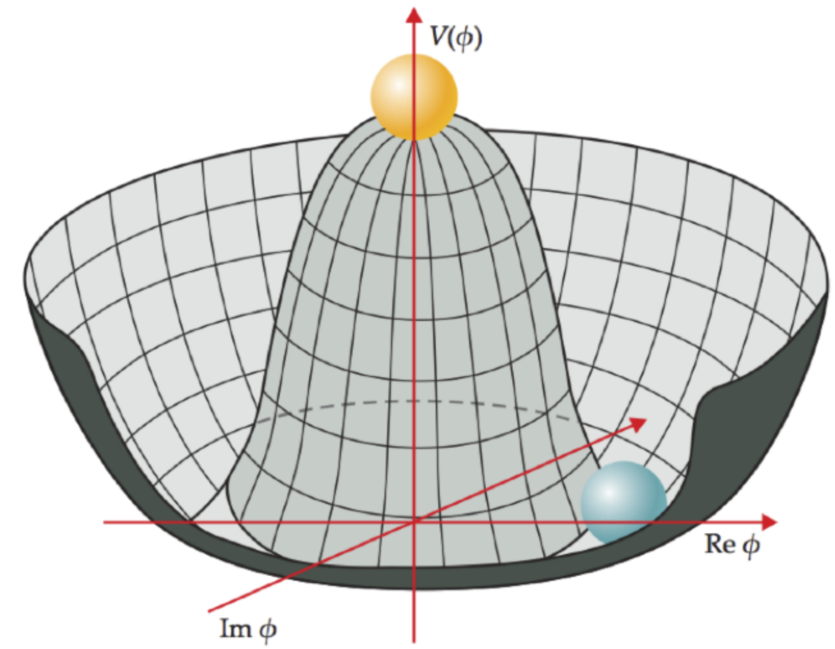
Higgs potential

- Ultimative probe of the scalar sector
  - Its properties are determined by the shape of the Higgs potential
  - Shape controlled by μ^2 and λ



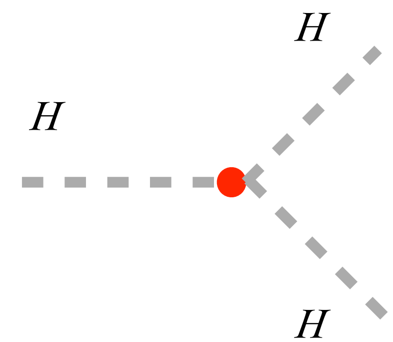
$$V^{\mathrm{SM}}(\phi) = \mu^2\phi^2 + \lambda\phi^4 \xrightarrow{\phi\to v+H} \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

$$\langle\phi_0\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}, \quad v = \sqrt{\mu^2/\lambda}$$

mass term

$$m_{\mathrm{H}} = \sqrt{2\lambda}v$$

\+



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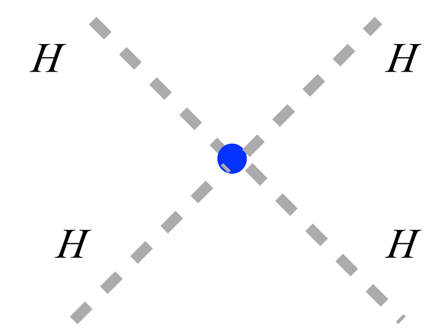


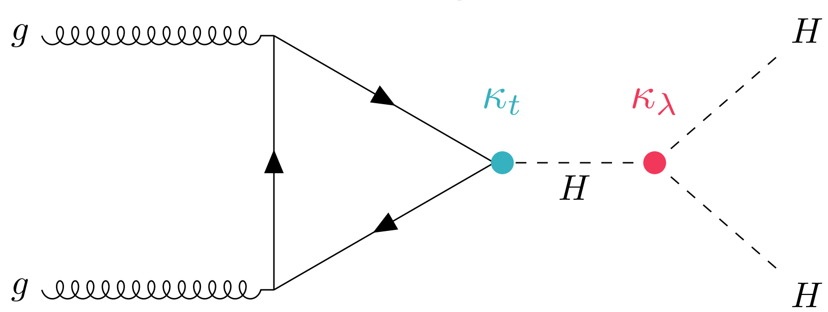
Measure Higgs self-coupling λ via di-Higgs production

Main HH production modes

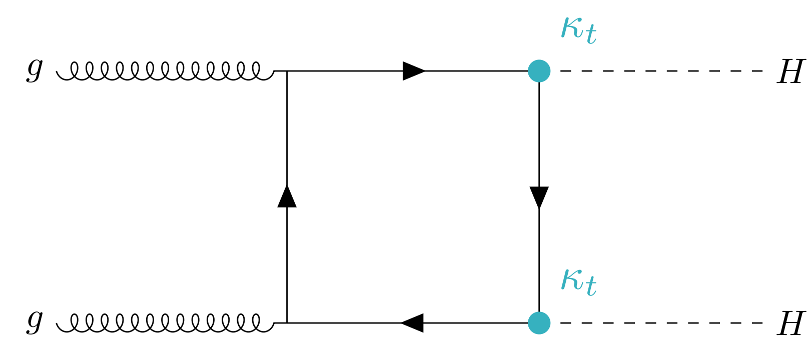
- **Gluon - gluon fusion:**

$\sigma_{\mathrm{ggF}}^{\mathrm{SM}} = 31\,\mathrm{fb} \pm 3\,\%\,(\mathrm{PDF} + \alpha_S)^{+6\%}_{-23\%}(\mathrm{scale} + m_t)$ at 13 TeV

"triangle"

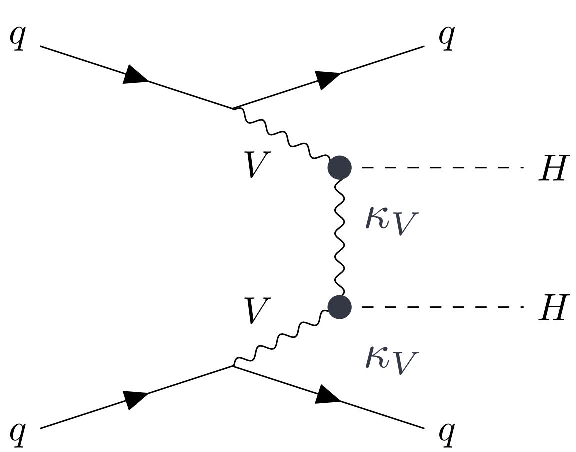


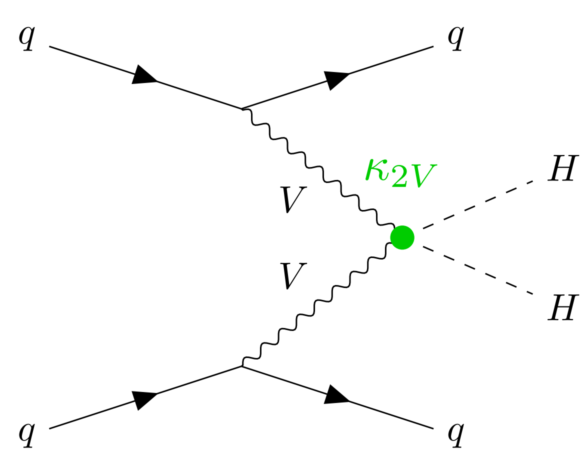
"box"

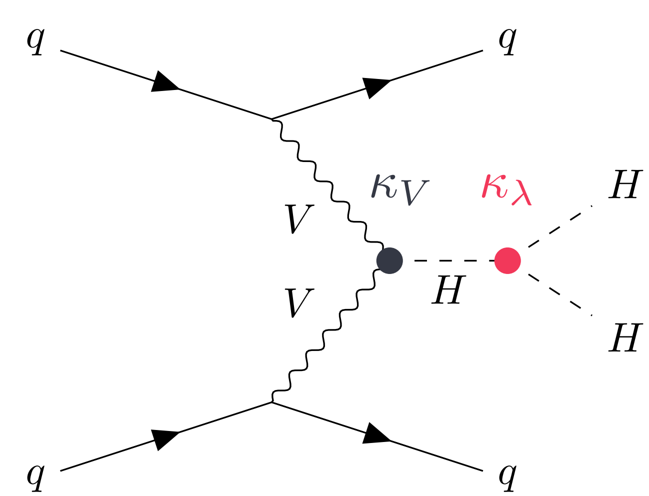


- **Vector - boson fusion:**

$\sigma_{\mathrm{VBF}}^{\mathrm{SM}} = 1.7\,\mathrm{fb} \pm 2.1\,\%\,(\mathrm{PDF} + \alpha_S)^{+0.03\%}_{-0.04\%}(\mathrm{scale})$ at 13 TeV







remark: κ_X is a coupling modifier, $\kappa_X = c_X / c_X^{\mathrm{SM}}$

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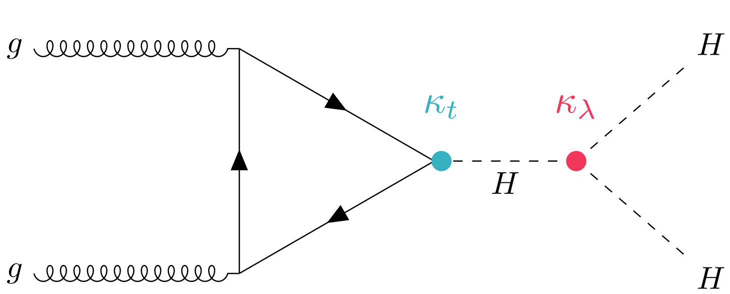
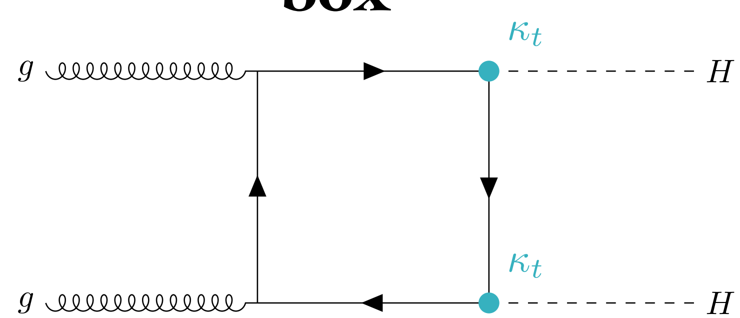
Inv. mass m_{HH} is the key

triangle



+

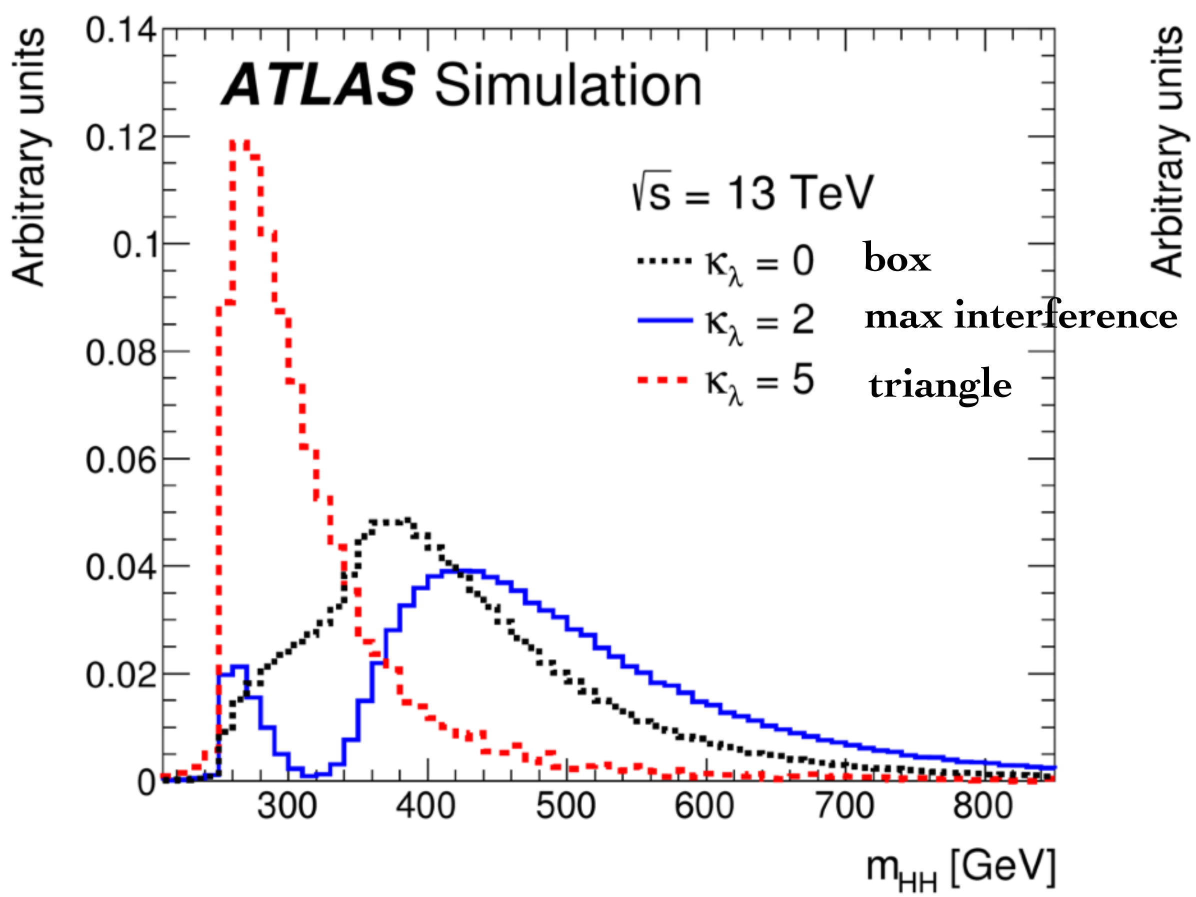
box

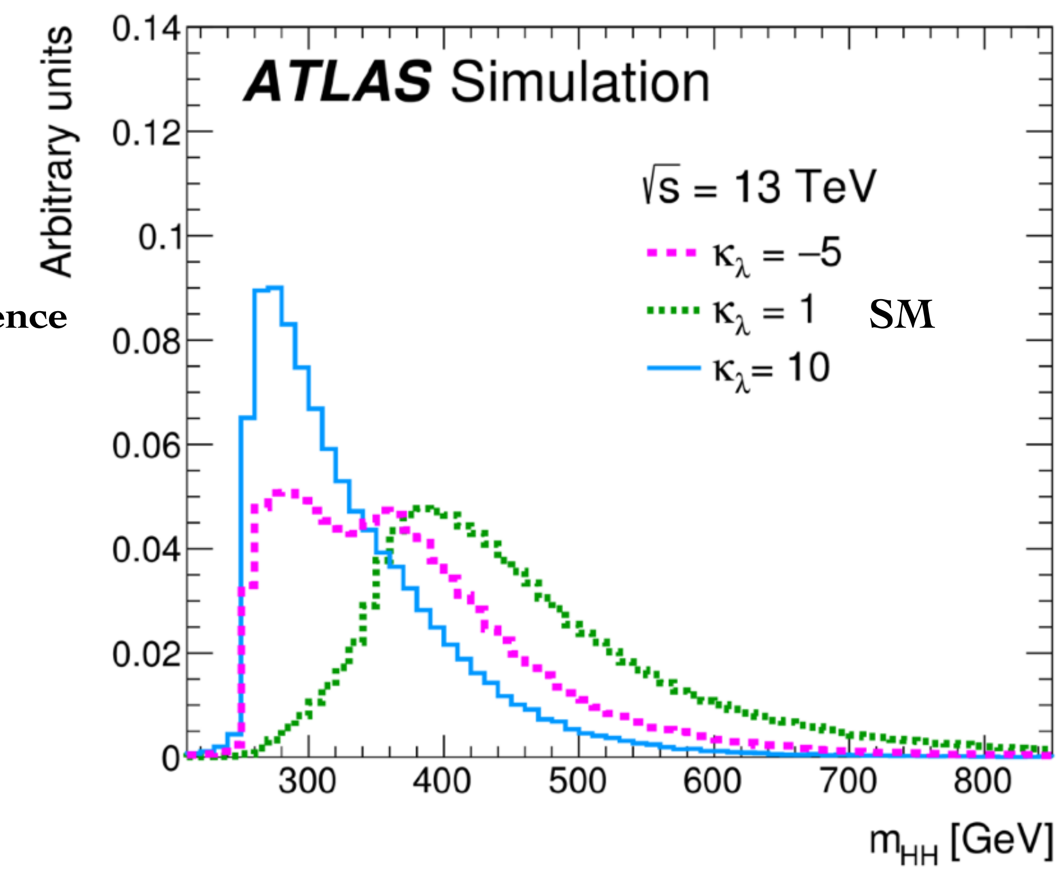


destructive interference

$$\mathscr{A}(\kappa_t,\kappa_\lambda) = \mathscr{A}_\square(\kappa_t) + \mathscr{A}_\triangle(\kappa_t,\kappa_\lambda) = \kappa_t^2\mathscr{A}_\square + \kappa_t\kappa_\lambda\cdot\mathscr{A}_\triangle$$

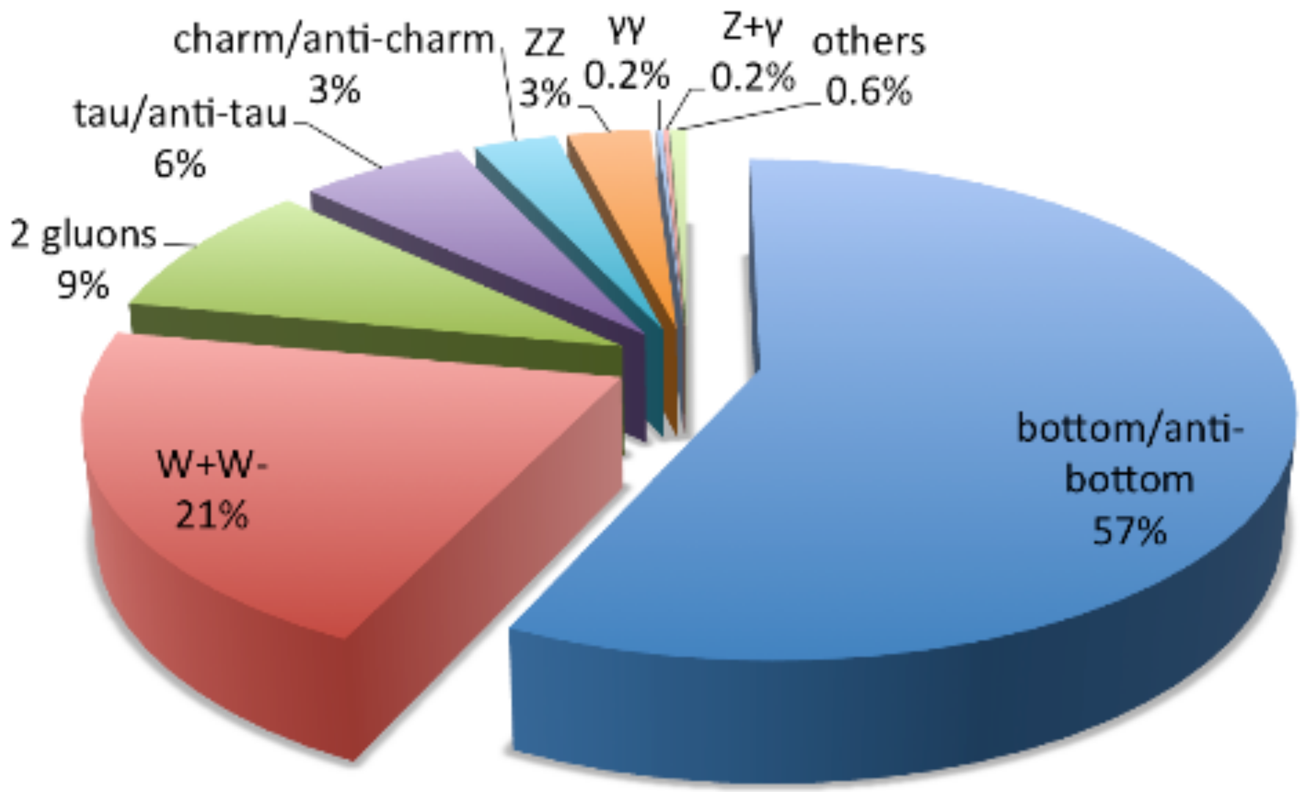
$$\left|\mathscr{A}(\kappa_t,\kappa_\lambda)\right|^2 = \kappa_t^4\mathscr{A}_\square^2 + \kappa_t^2\kappa_\lambda^2\cdot\mathscr{A}_\triangle^2 + 2\kappa_t^3\kappa_\lambda\Re(\mathscr{A}_\square\mathscr{A}_\triangle)$$





Main HH decay modes

$H \to XX$



$HH \to XX$

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

multilepton

Most promising channels at LHC: 4b, bbττ and bbγγ

✓ : public Run 2 results

Search Channels

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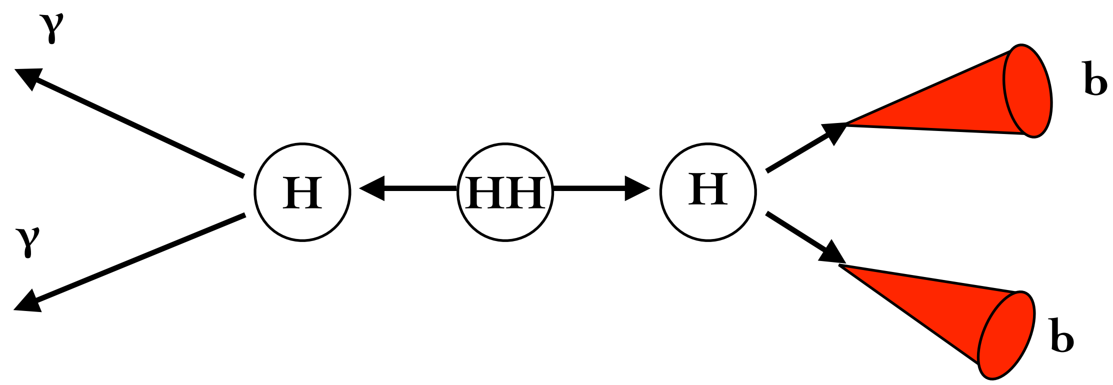
HH bbγγ



Pros:

- ➡ Low background
- ➡ Excellent $m_{\gamma\gamma}$ resolution
- Probes mostly the lower end of the m_{HH} spectrum
  - sensitive to the Higgs self-coupling
- Recent results:
  - ATLAS: arXiv:2112.11876
  - CMS: JHEP03 (2021) 257

Contras:

- ➡ Low branching ratio (0.26%)

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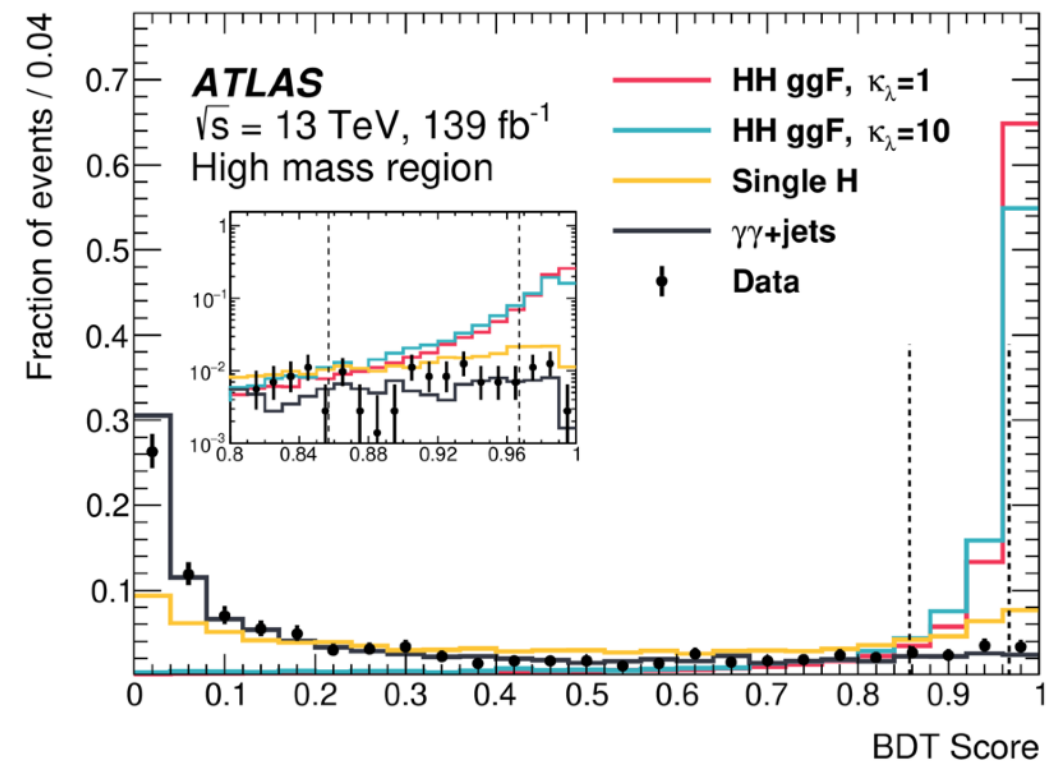
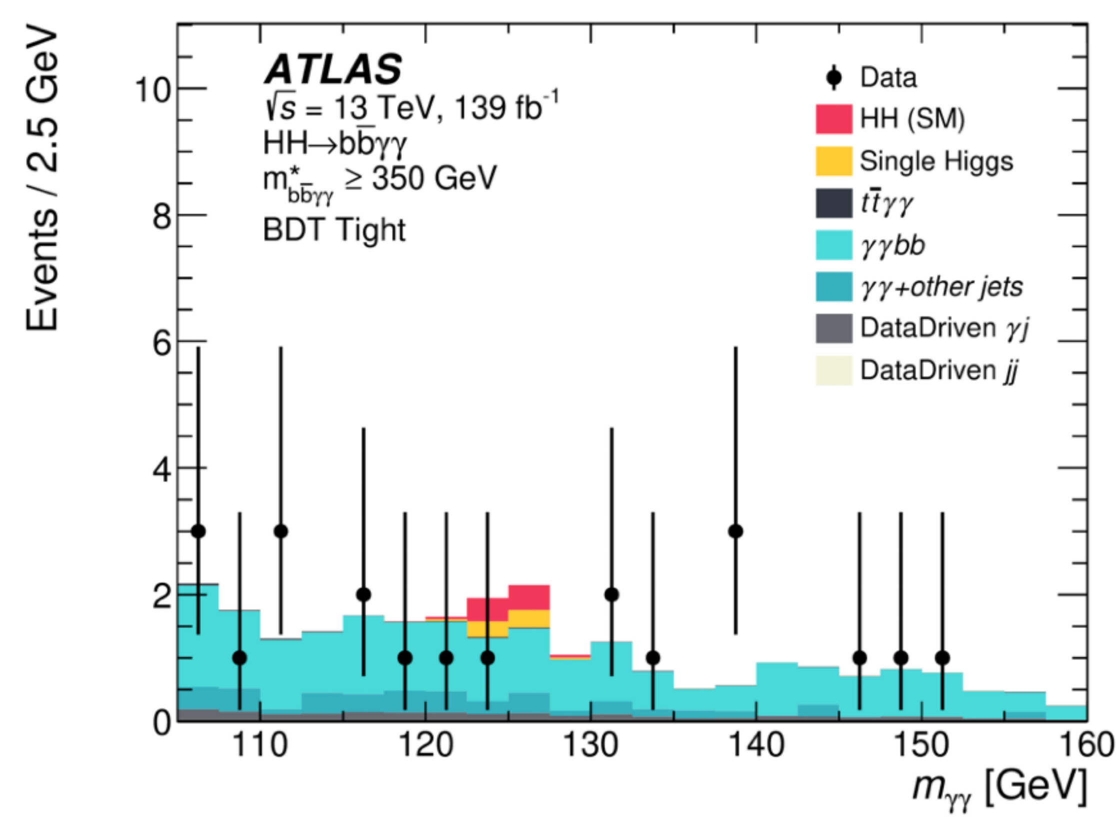
HH bbγγ at ATLAS

- Di-photon triggers
- Events with **2 photons** and **2 b-tagged jets**
- Events are divided into
  - **high mass** → SM-like signals
  - **low mass** → non SM-like signals

  regions based on
  $m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250\,\text{GeV}$
  - no specific VBF category
- **BDT** trained in each mass region
  - kinematic variables such as m_{bb}, $p_T^{\gamma}/m_{\gamma\gamma}$
- **Fit** to $m_{\gamma\gamma}$
  - HH and H: double-sided Crystal Ball
  - continuous bkg: exp. function normalised to sidebands in data

Obs. (exp.) limit on $\sigma^{HH}_{ggF+VBF}$
4.2 (5.7) x SM at 95% CL





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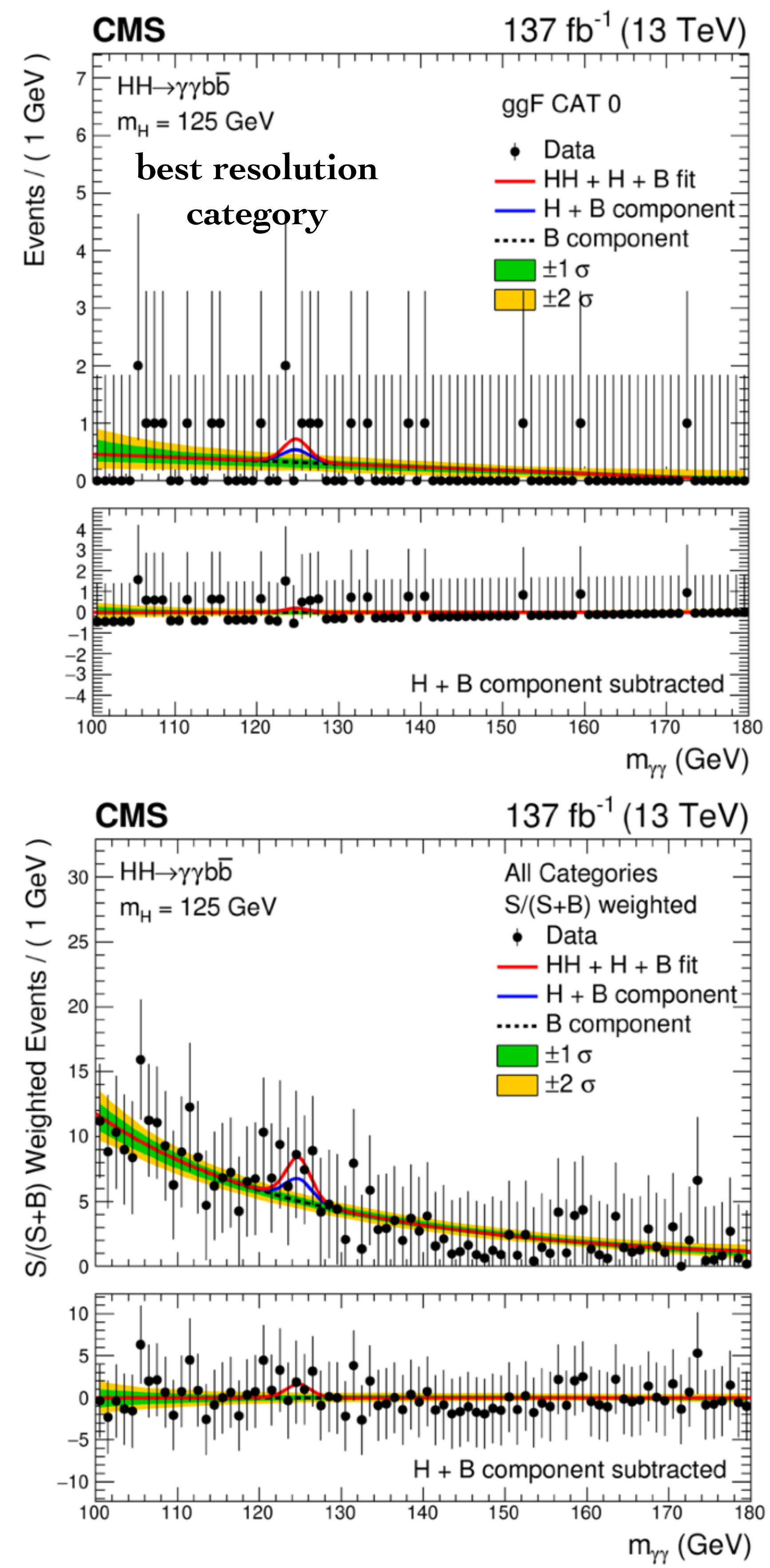
HH bbγγ at CMS

- Similar analysis strategy as ATLAS with a few differences listed below
- **12 ggF-like** and **2 VBF-like** SRs based on
  - DNN score to separate HH and ttH
  - ggF- and VBF-specific BDT scores to separate HH from $\gamma\gamma$ and $\gamma + \text{jets}$
- **Parametric fit** in the $(m_{\gamma\gamma}; m_{bb})$-plane in the SRs
  - HH and H shapes from simulation
  - other bkgs from data using discrete profiling

Obs. (exp.) limit on $\sigma^{\text{HH}}_{\text{ggF+VBF}}$
7.7 (5.2) x SM at 95% CL



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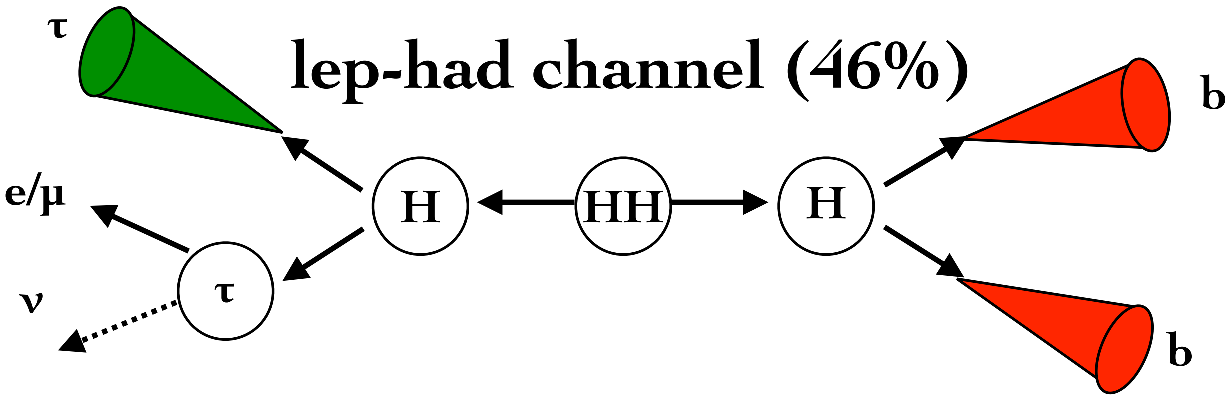
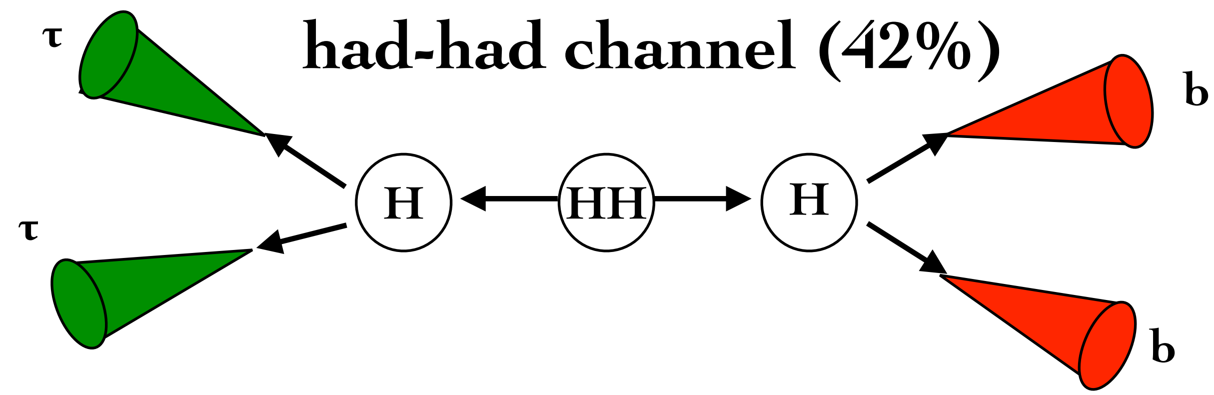
HH bbττ





Pros:

- ➡ Sizeable branching ratio (7%)
- ➡ Moderate bkg contamination

Contras:

- ➡ Neutrinos in τ decays
- ➡ Challenging had. τ reco and triggering

- Probes the intermediate m_{HH} spectrum
  - broad range of κ_λ hypotheses
- Recent results:
  - ATLAS: ATLAS-CONF-2021-030
  - CMS: arXiv:2206.09401

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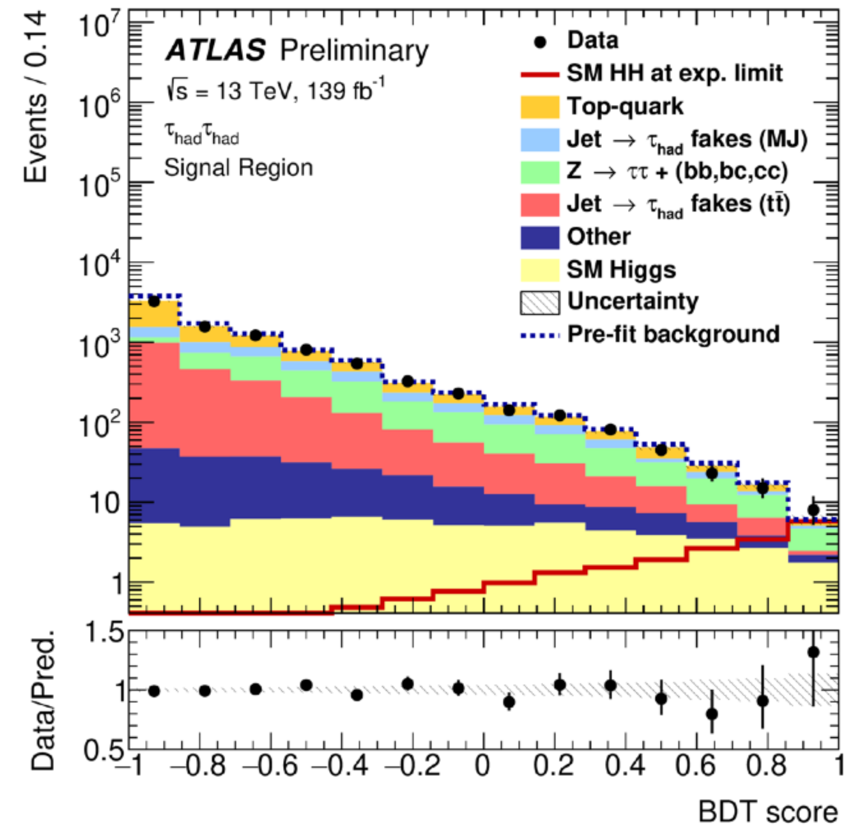
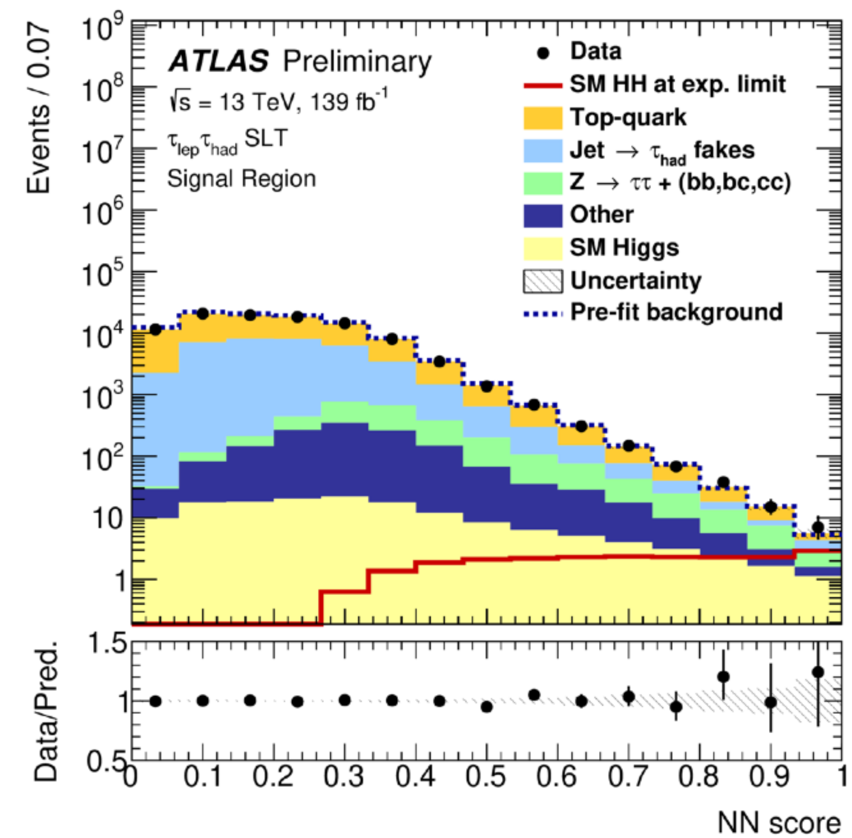
HH bbττ at ATLAS

- Electron/muon and τ-triggers
- Events with **at least one** τ and **2 b-jets**
- Events split into **3 categories**: single-lepton-trigger, lepton-tau-trigger and $bb\tau_h\tau_h$
  - no specific VBF category, resolved only
- **Background estimate**:
  - $t\bar{t}$ with real τ's and Z+jets from simulation; a dedicated Z + jets CR to constrain the normalisation in data
  - multijet and $t\bar{t}$ with mis-identified τ's from data in regions with inverted τ-ID (charge or isolation)
- Dedicated **multivariate classifier** in each category: BDT in $bb\tau_h\tau_h$ and NN in $bb\tau_\ell\tau_\ell$

Obs. (exp.) limit on $\sigma^{HH}_{ggF+VBF}$
4.6 (3.9) x SM at 95% CL





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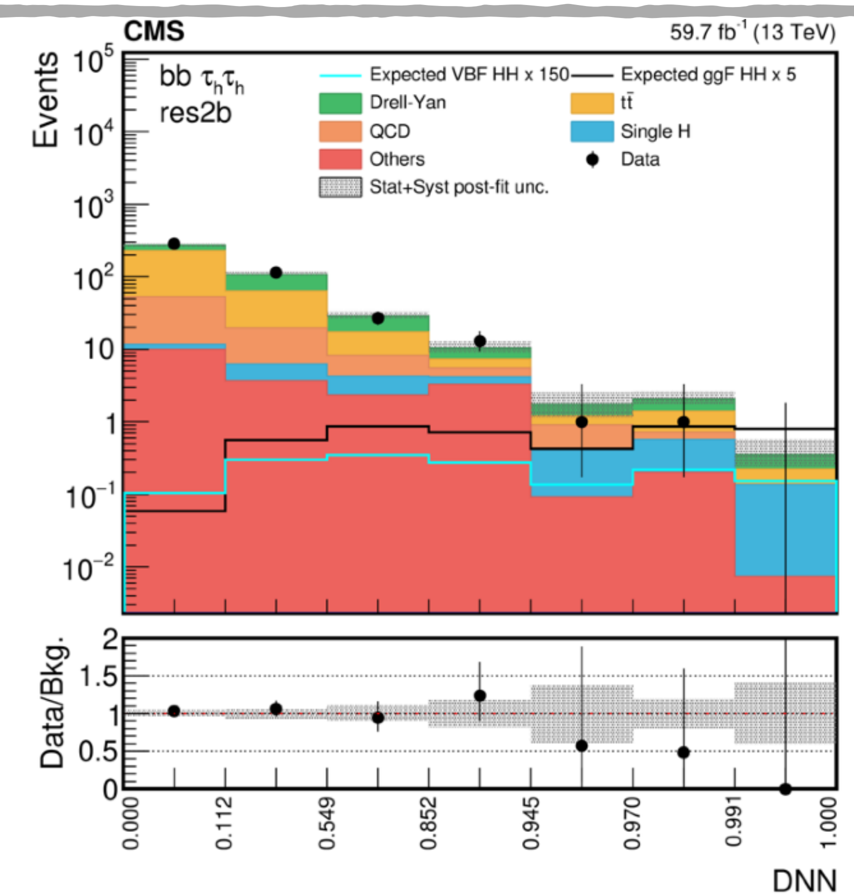
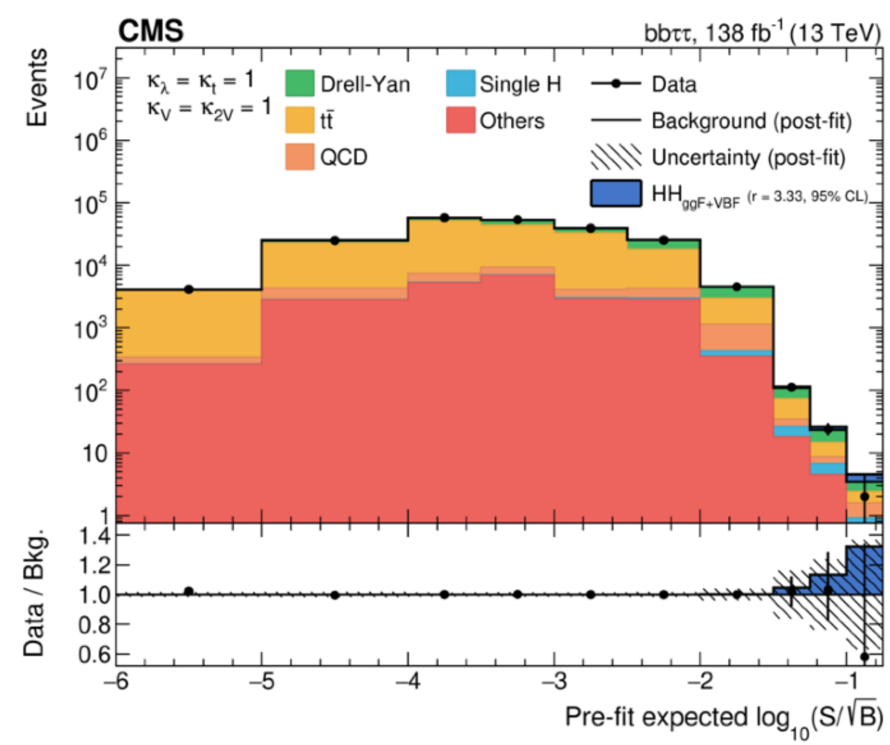
HH bbττ at CMS

- Electron/muon and τ-triggers
- Events split into $bb\tau_h\tau_e$, $bb\tau_h\tau_\mu$ and $bb\tau_h\tau_h$ final states
- **8 signal categories** per final state and year:
  - resolved 2b, resolved 1b and boosted
  - 5 VBF multiclass categories: VBF, ggF, $t\bar{t}H$, $t\bar{t}$ and DY
- **Background estimate**:
  - $t\bar{t}$ and Z+jets from simulation normalised to data in CRs
  - multijet from data in regions with inverted τ-ID (charge or isolation)
- single **DNN** training to extract signal

Obs. (exp.) limit on $\sigma^{HH}_{ggF+VBF}$
3.3 (5.2) x SM at 95% CL





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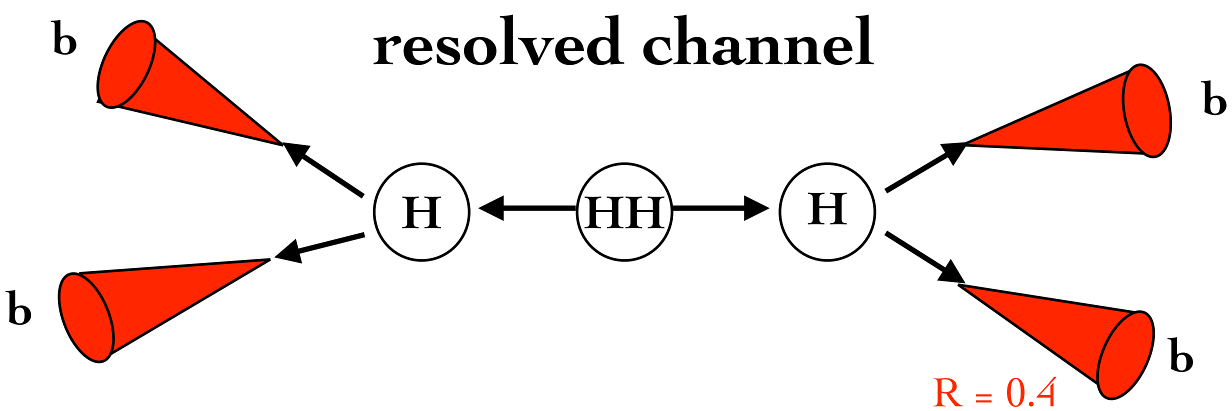
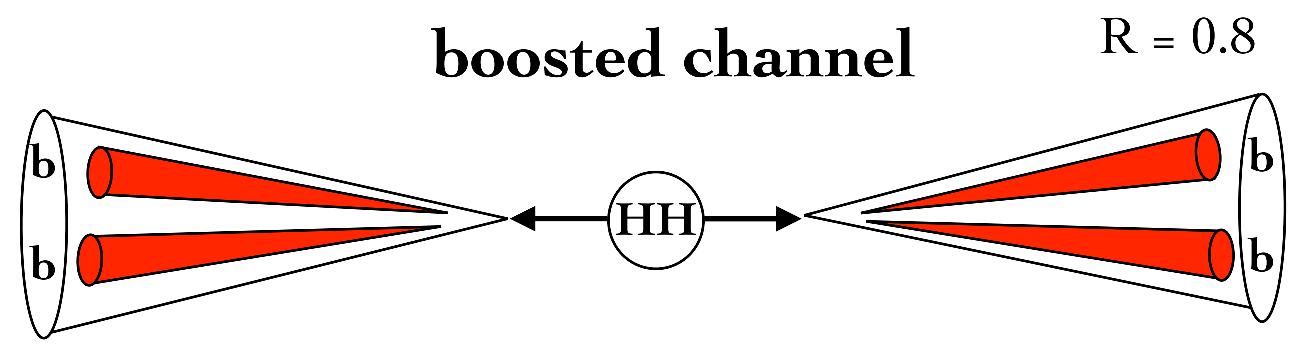
HH 4b





Pros:

➡ highest branching ratio (34%)

Contras:

➡ high multijet background

- probes mostly the higher end of the m_{HH} spectrum
  - sensitive to New Physics at high $p_{\mathrm{T,HH}}$
- Recent results resolved channel:
  - ATLAS: ATLAS -CONF-2022-035
  - CMS: arXiv:2202.09617
- Recent results boosted channel:
  - CMS: arXiv:2205.06667

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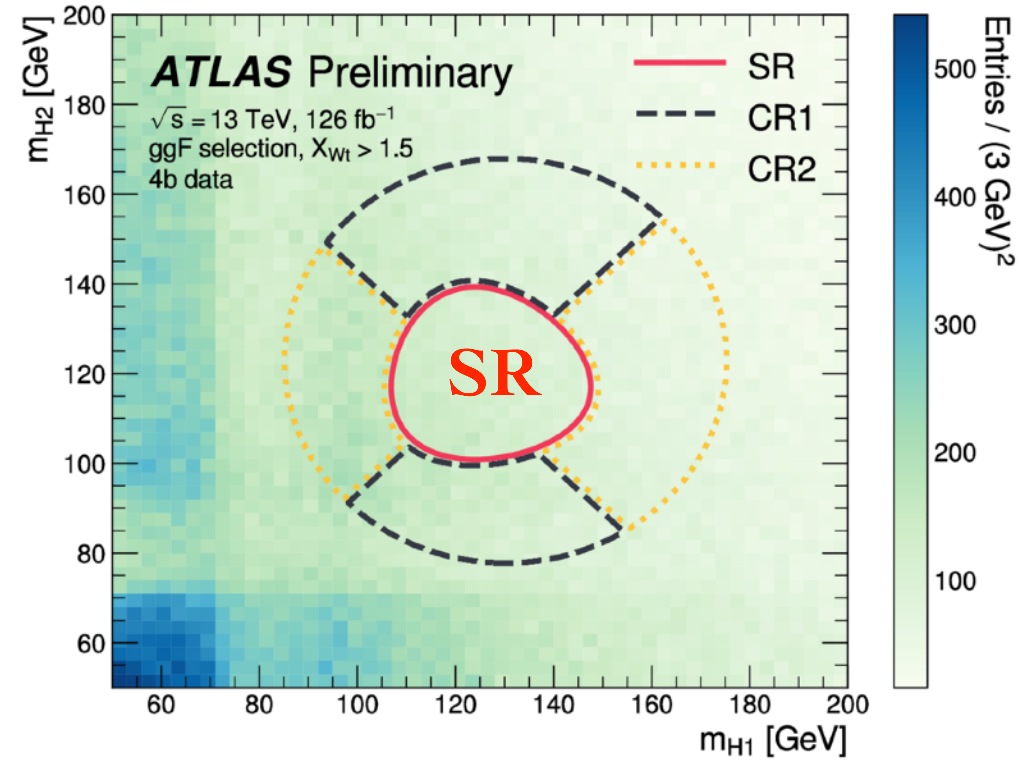
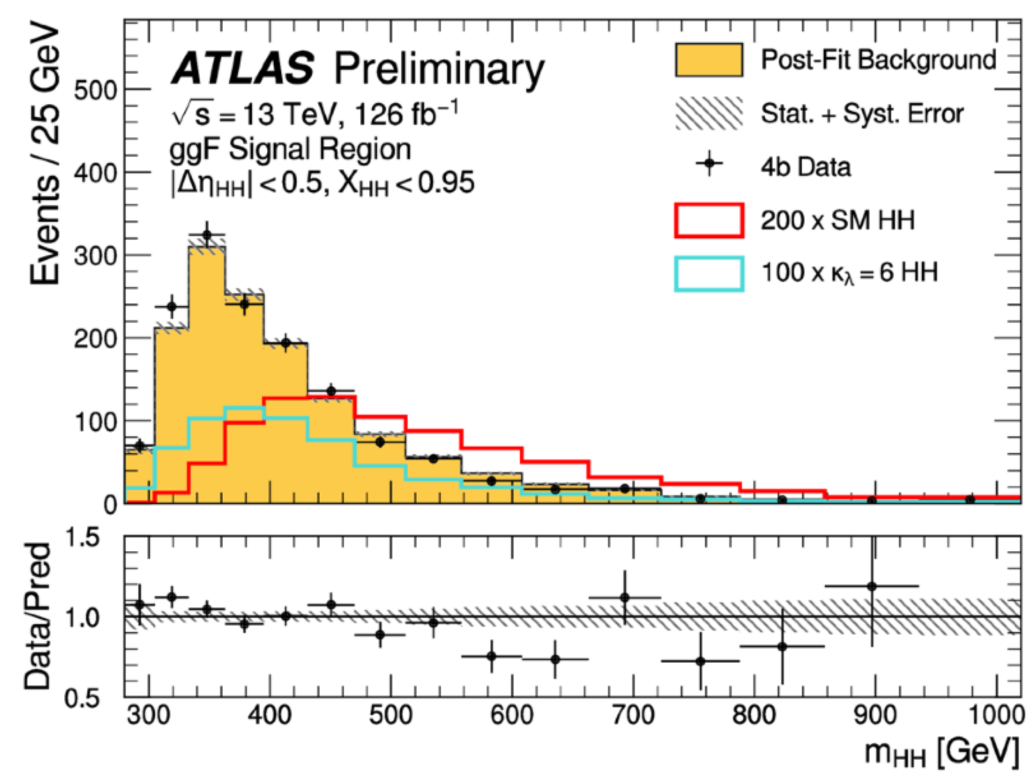
HH 4b at ATLAS

- **2b1j** or **2b2j** triggers
- **18 ggF-like** and **2 VBF-like** event categories based on forward jets and event kinematics
- **Data-driven background**:
  - SR $2b \rightarrow 4b$ event reweighting
  - NN-based reweighting function derived in CRs around SR
  - validated in signal-depleted data
- **Fit** m_{HH}

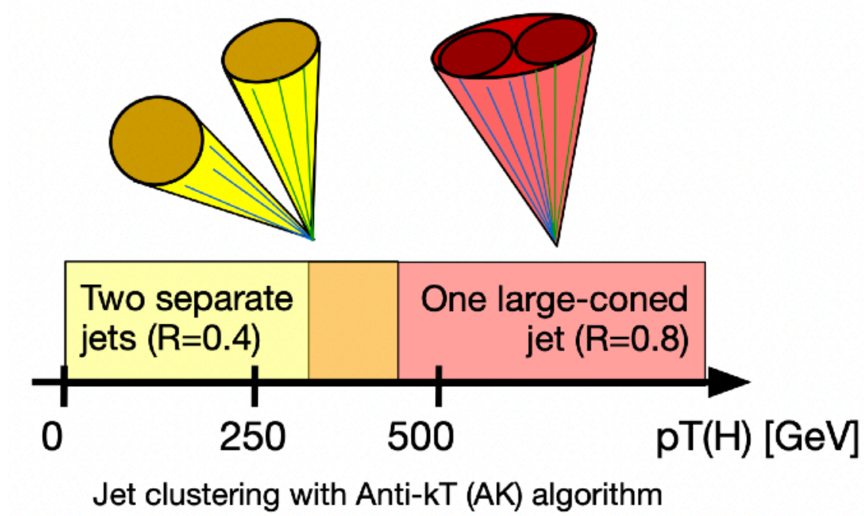
Obs. (exp.) limit on $\sigma^{\mathrm{HH}}_{\mathrm{ggF+VBF}}$
5.4 (8.1) x SM at 95% CL

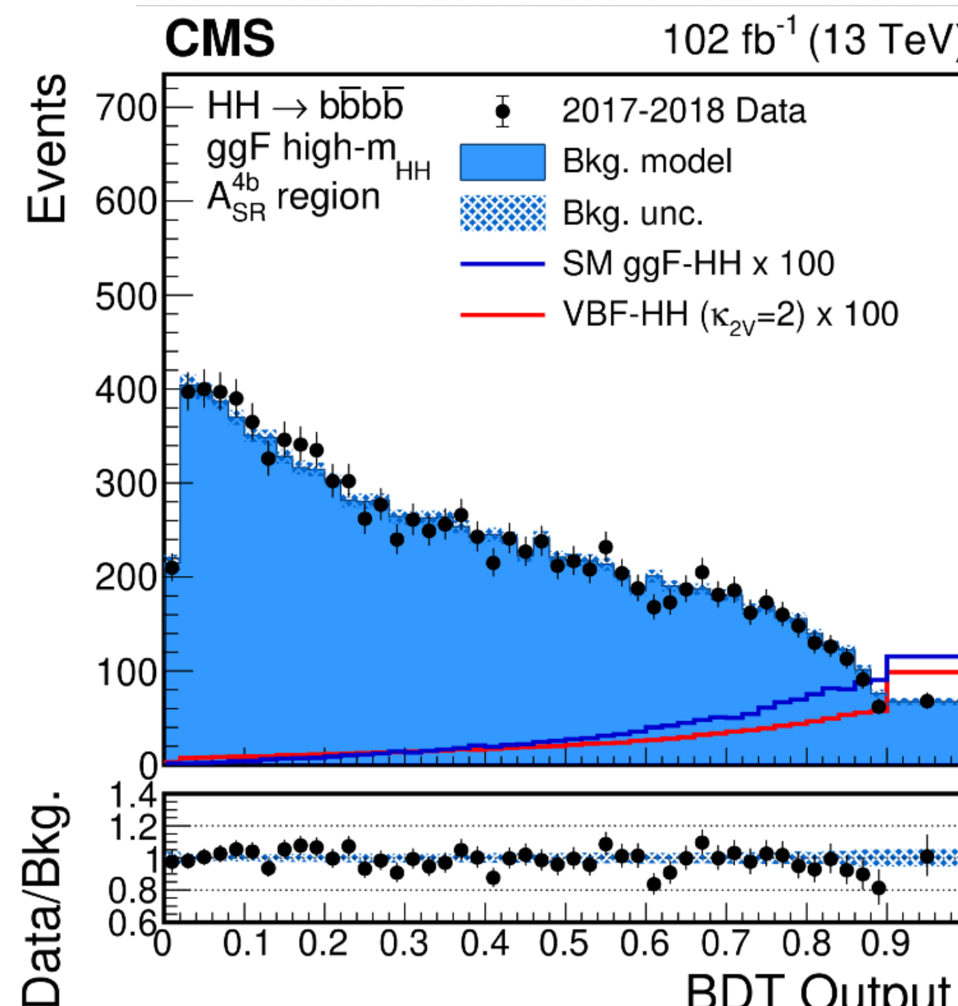




HH 4b resolved at CMS

- trigger with at least 3 jets
- Event categorisation based on the $BDT_{ggF-VBF}$ classifier:
  - 2 ggF-like SR: signal vs bkg trained BDT classifier
  - 2 VBF-like SRs: m_{HH} or single bin classifier
- data-driven background:
  - BDT-based $3b \rightarrow 4b$ reweighting





Obs. (exp.) limit on $\sigma^{HH}_{ggF+VBF}$
3.9 (7.8) x SM at 95% CL

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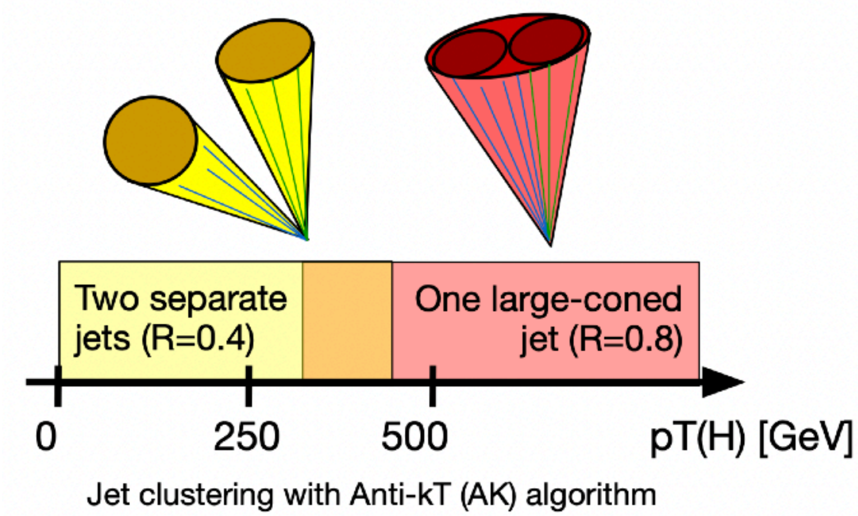
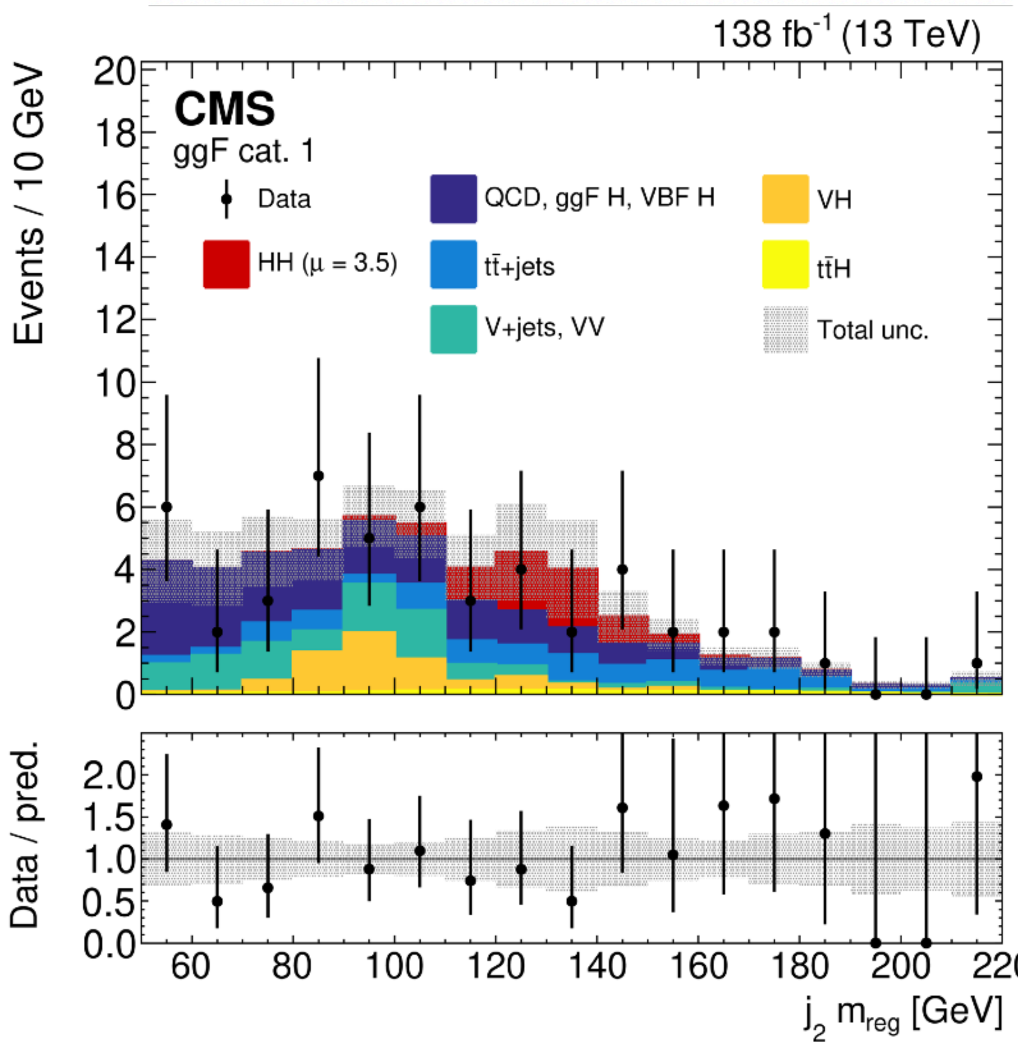
HH 4b boosted at CMS

- **High p_T jet** and H_T triggers
- Large-R jet as proxy for Higgs; **sophisticated tagger** to identify $H \to bb$ candidates
- **Event categorisation:**
  - **3 ggF-like** SRs: jet regressed mass as discriminant
  - **3 VBF-like** SRs: m_{HH}





Obs. (exp.) limit on $\sigma^{HH}_{ggF+VBF}$ 9.9 (5.1) x SM at 95% CL

Results

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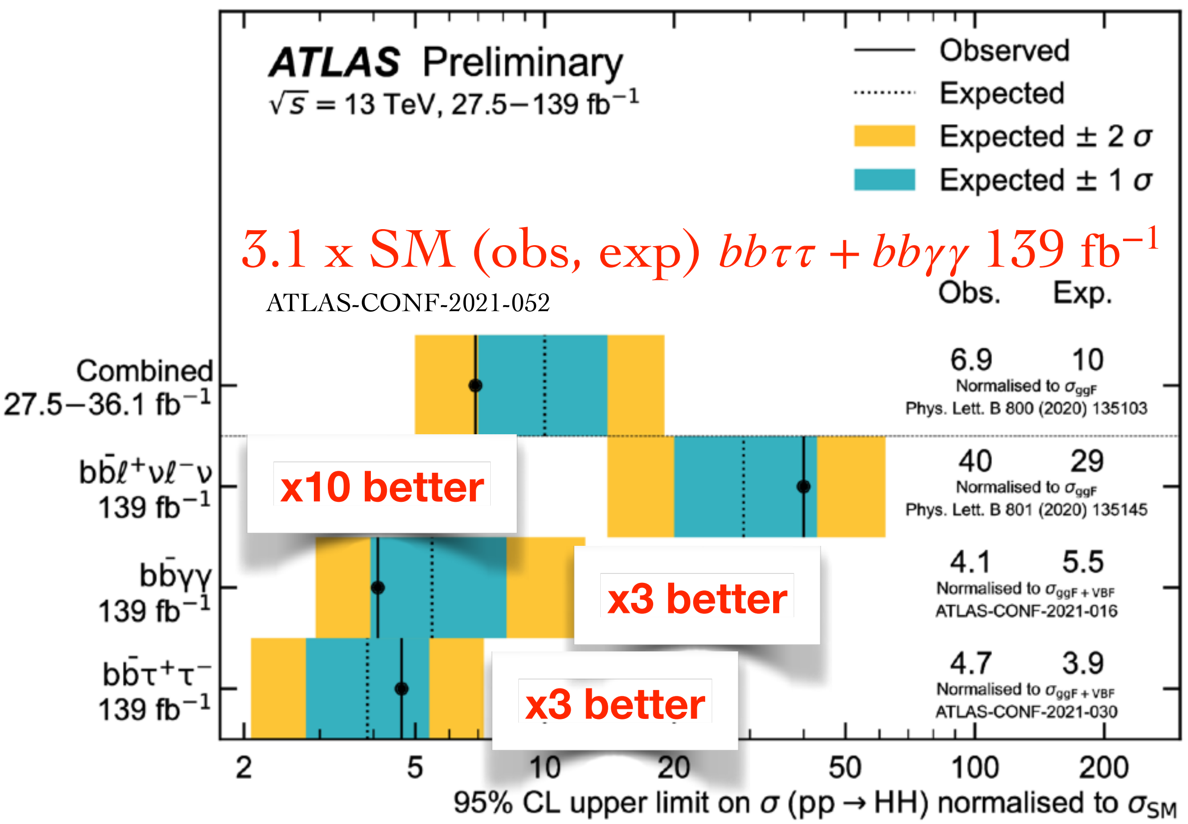
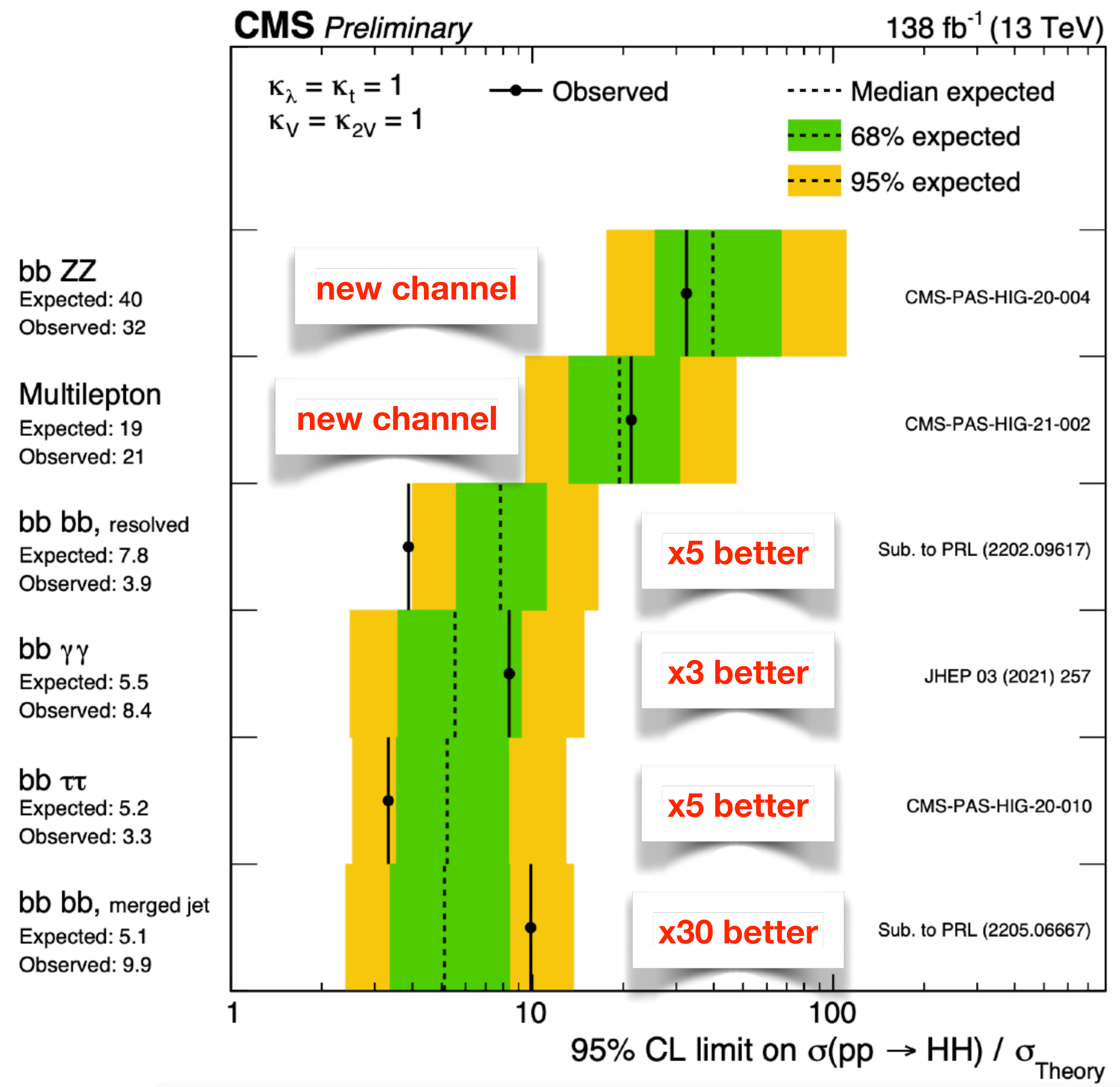
HH Non-Resonant Production





improvements quoted with respect to the 2015+2016 dataset

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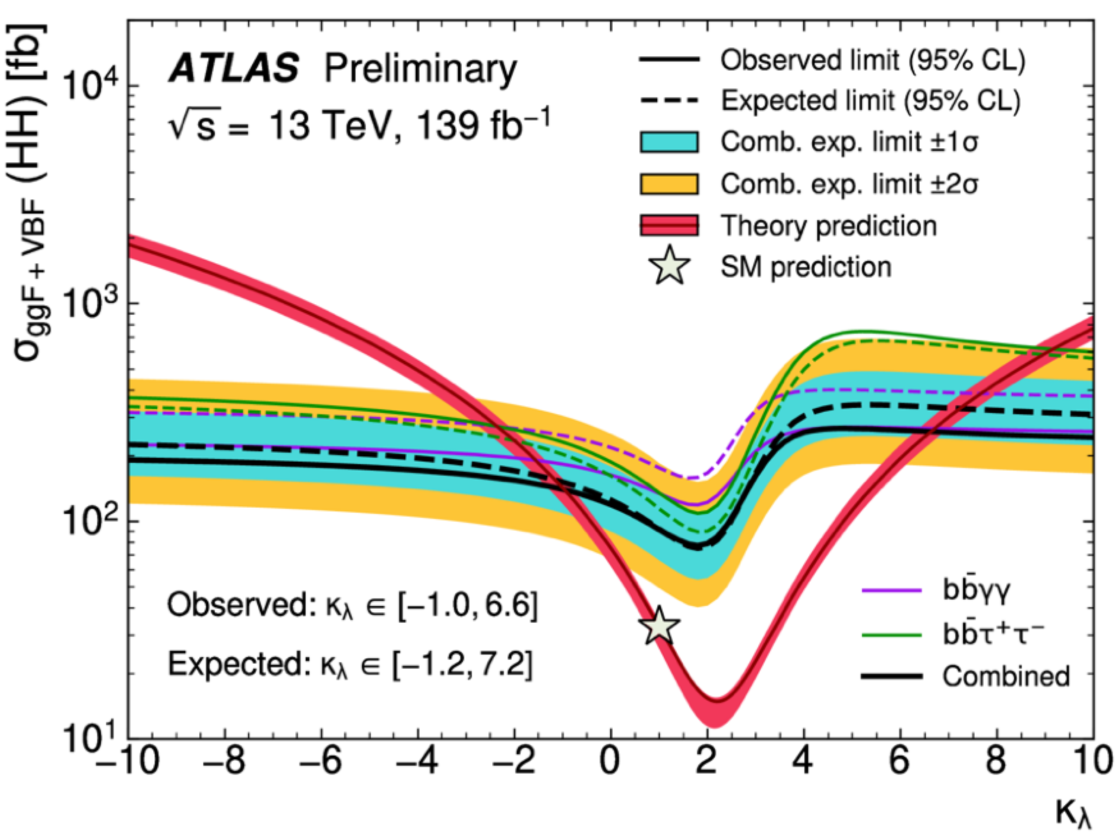
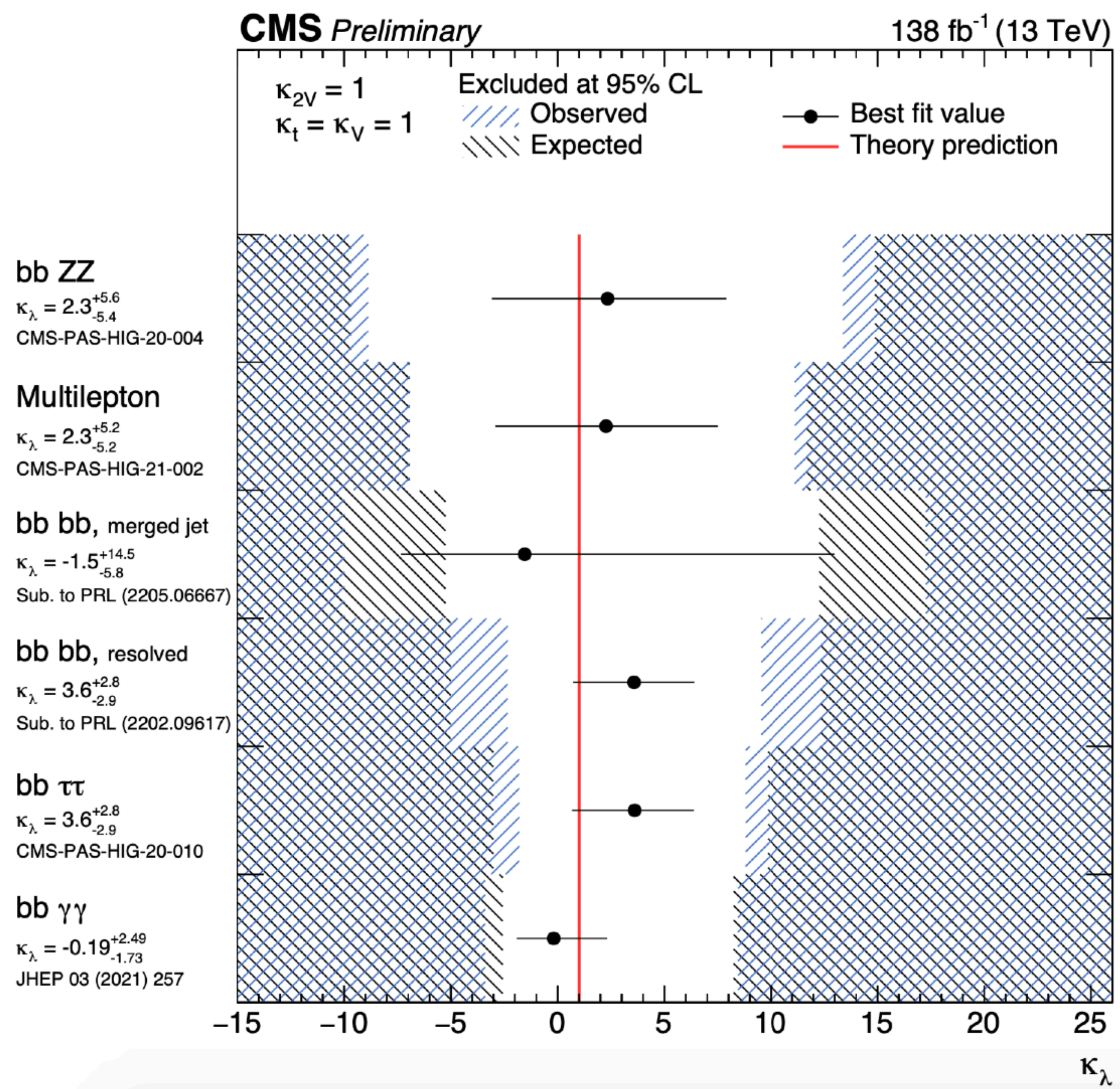
Higgs Self-Coupling





HHVV Coupling

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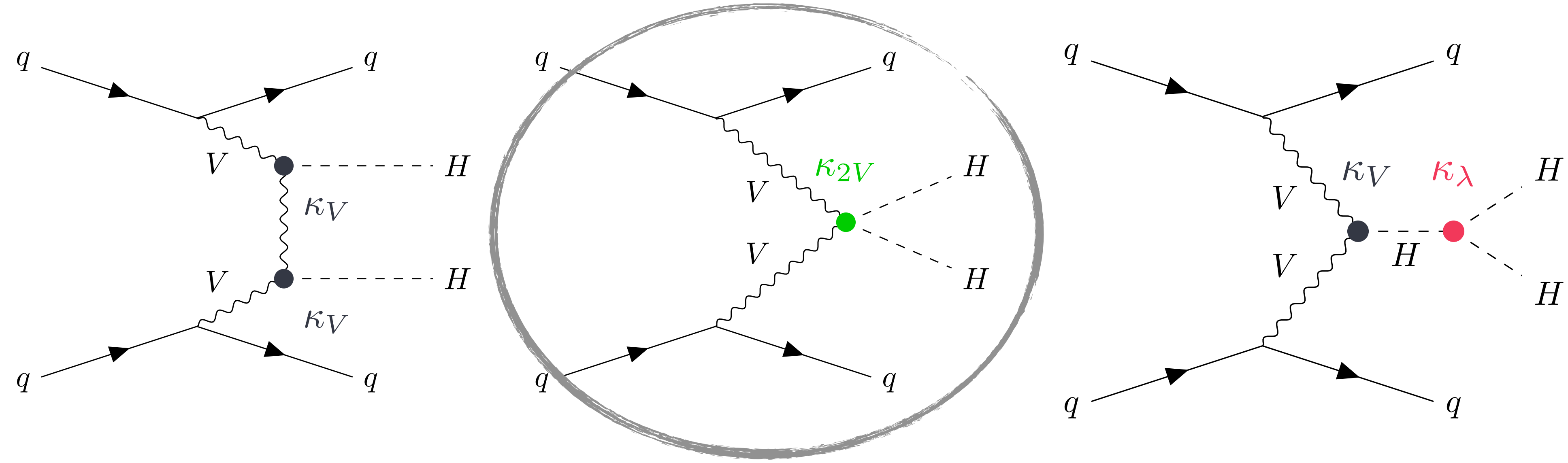
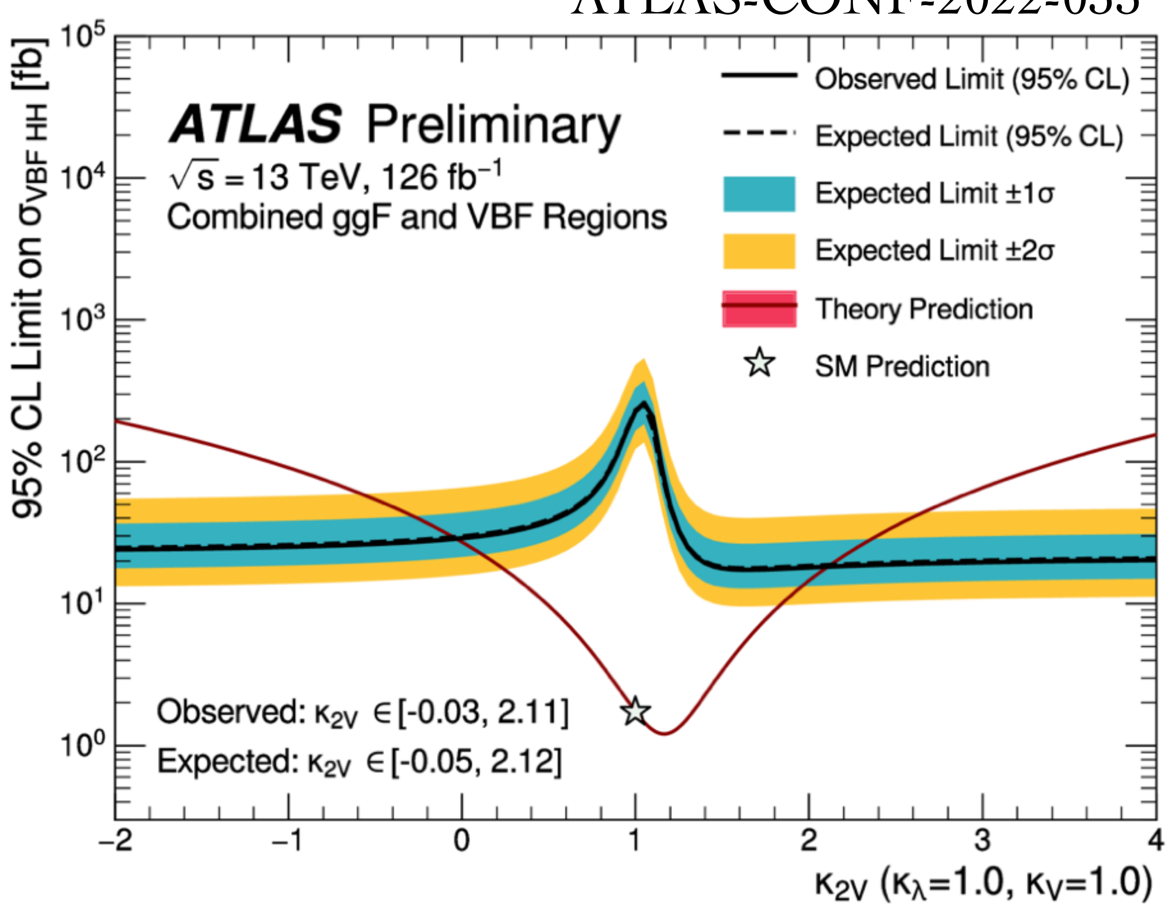
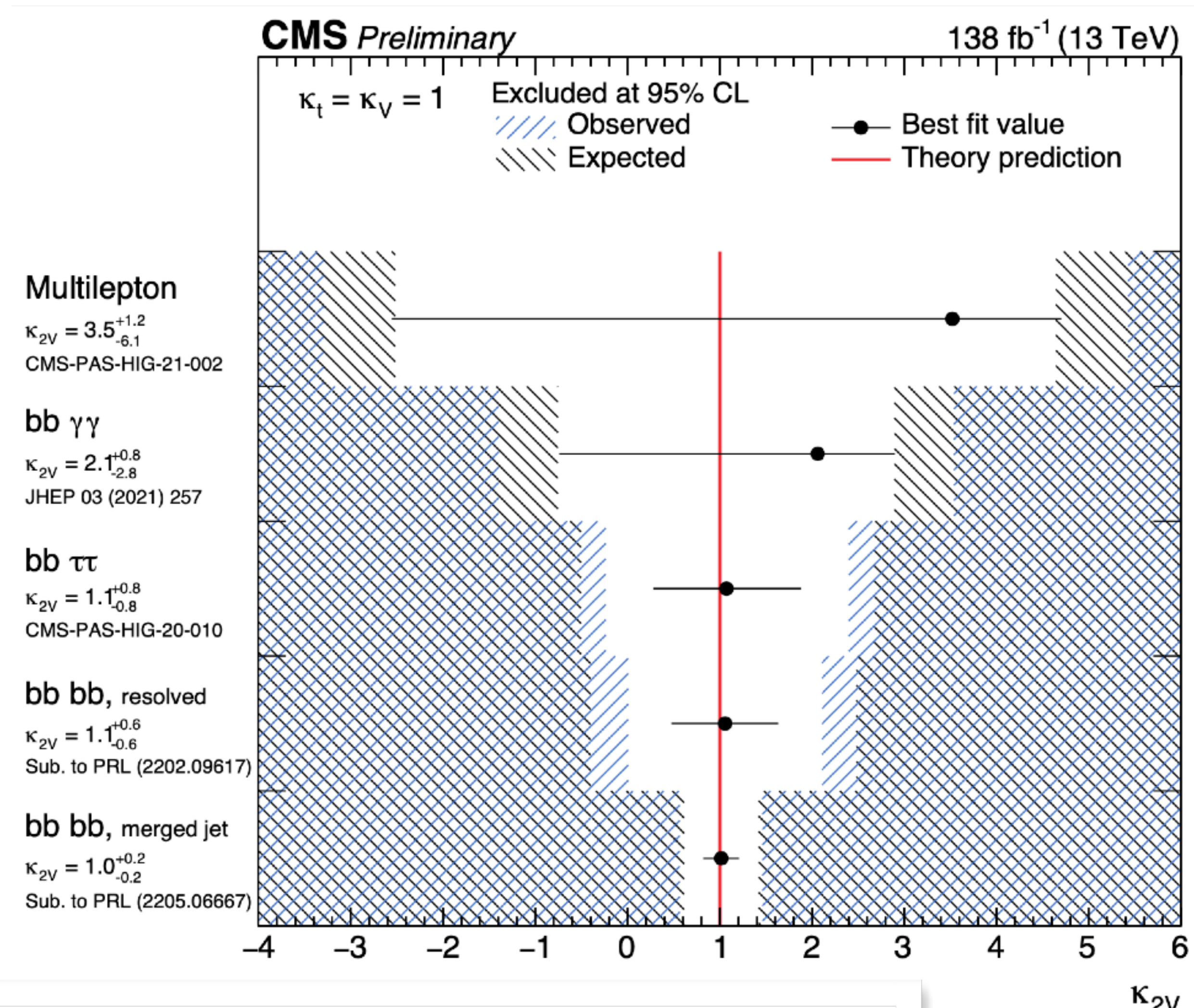
HHVV Coupling



ATLAS-CONF-2022-035





κ_{2V} = 0 excluded with 6.3σ in the boosted 4b CMS channel

HH + H

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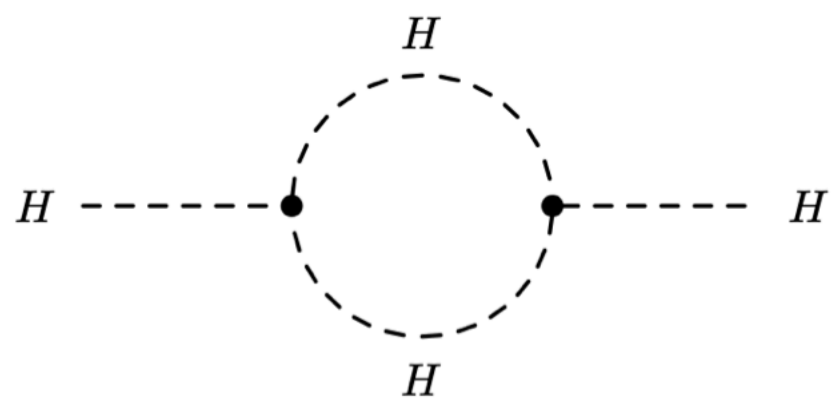
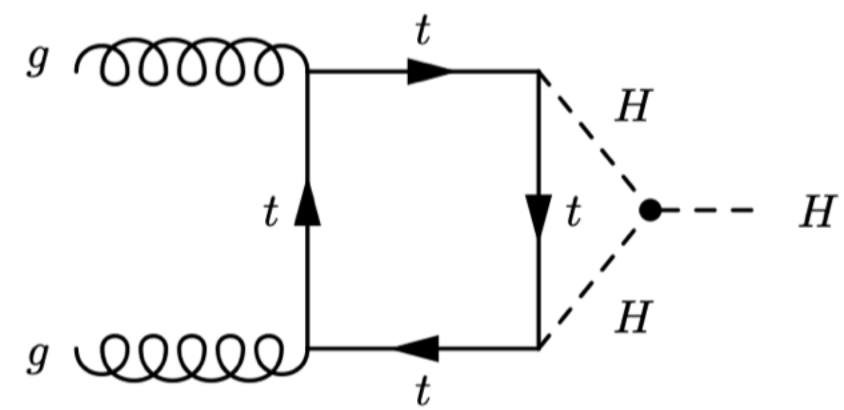
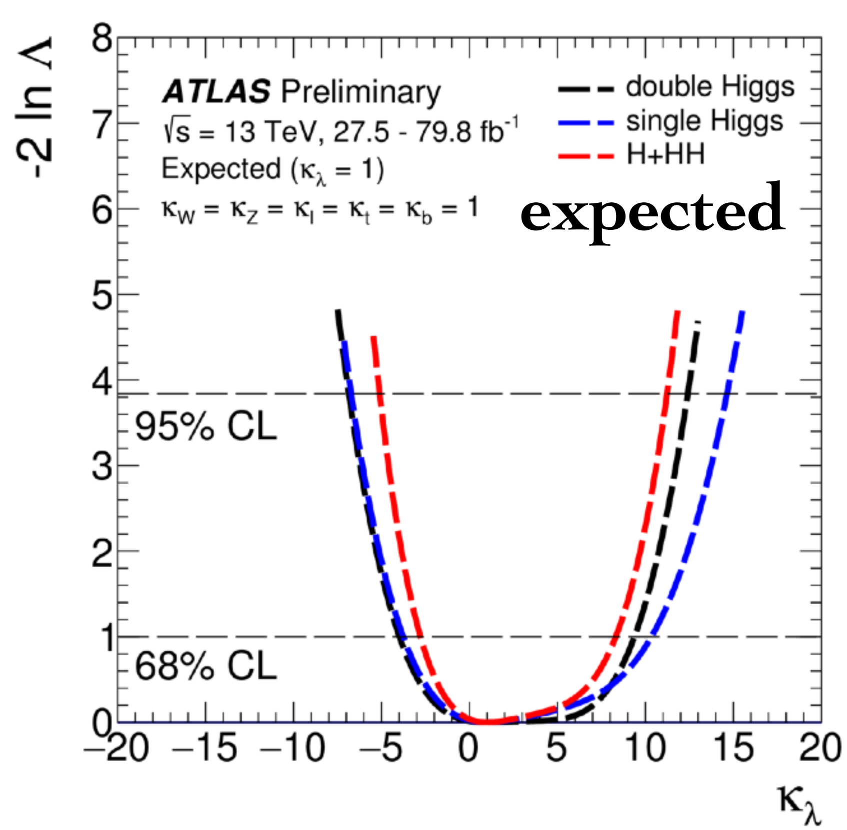
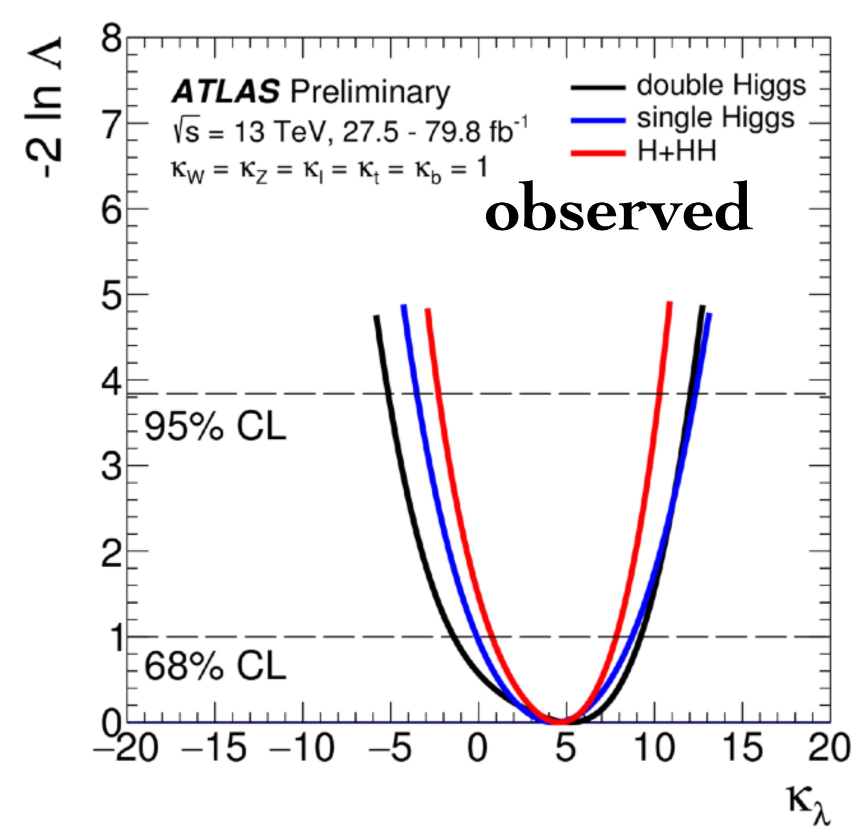
Triple-Higgs in Single-Higgs Final State





- Single Higgs production is sensitive to Higgs self-coupling via next-to-leading order electroweak corrections
- Combine H and HH analyses
- Last publication: ATLAS-CONF-2019-049





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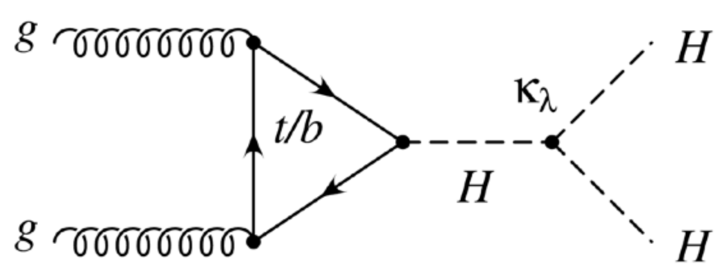
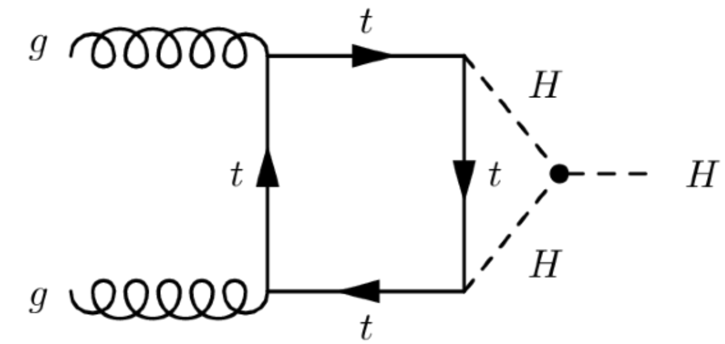
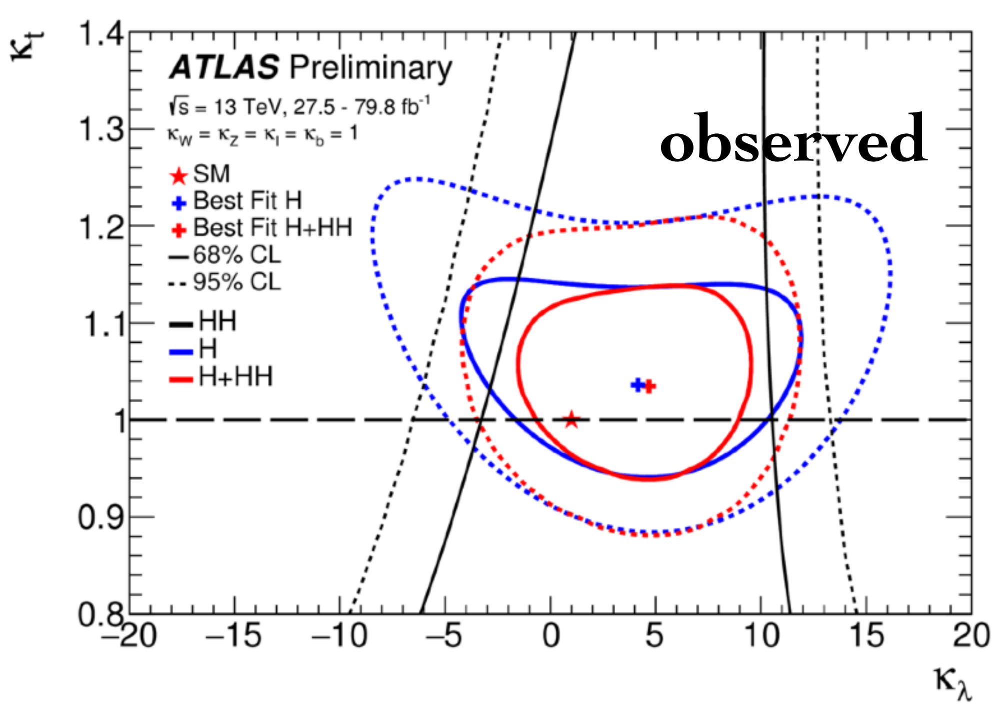
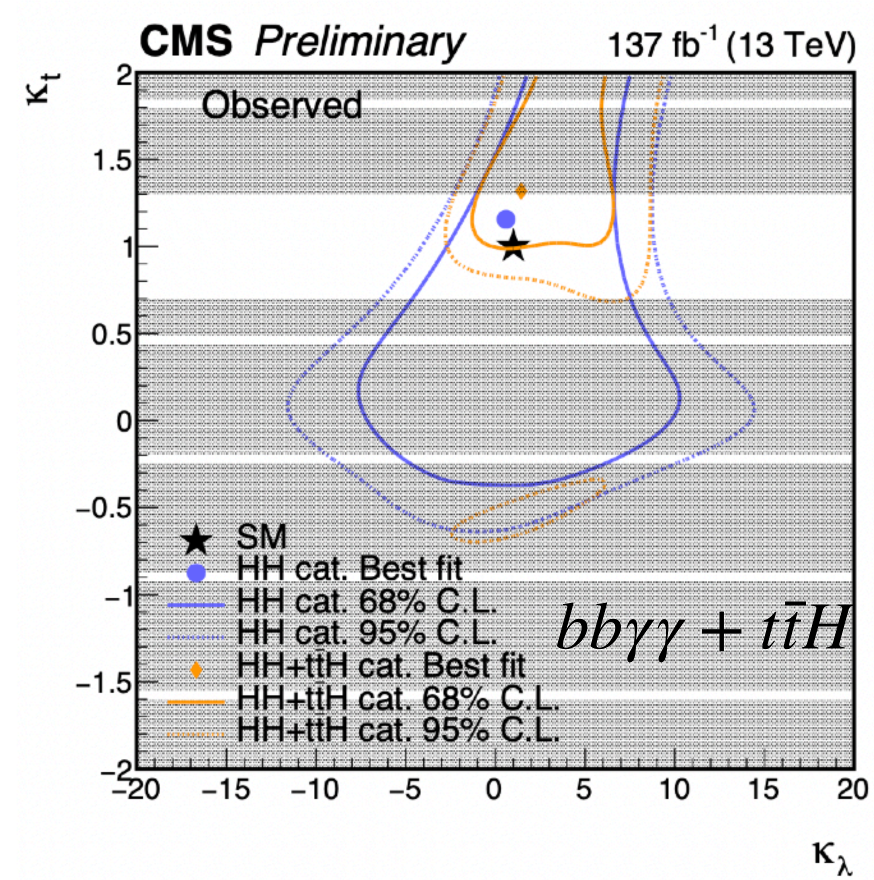
Higgs Self-Coupling H + HH









- Top quark appears in loops
- Simultaneous fit of top-Higgs and H self-couplings

Conclusions

- **Strong program** of searches for non-resonant HH production and determination of Higgs self-coupling
  - innovative analysis techniques enables sensitivities well beyond the expectations
  - most results published with the full Run 2 data set
  - combinations to follow
- Limits on the HH production cross-section: 3.1xSM
- Higgs self-coupling constrained to [−1,6.6] (expected [−1.2,7.2])
- Absence of VVHH interaction excluded > 6σ

bbbb

γγbb

bbττ

bbℓℓ

bbVV

multi-lepton