

CMS experimental status on hh production search

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for the CMS collaboration

HH-2018, Fermilab
September 4th 2018

After finding the Higgs boson in 2012,



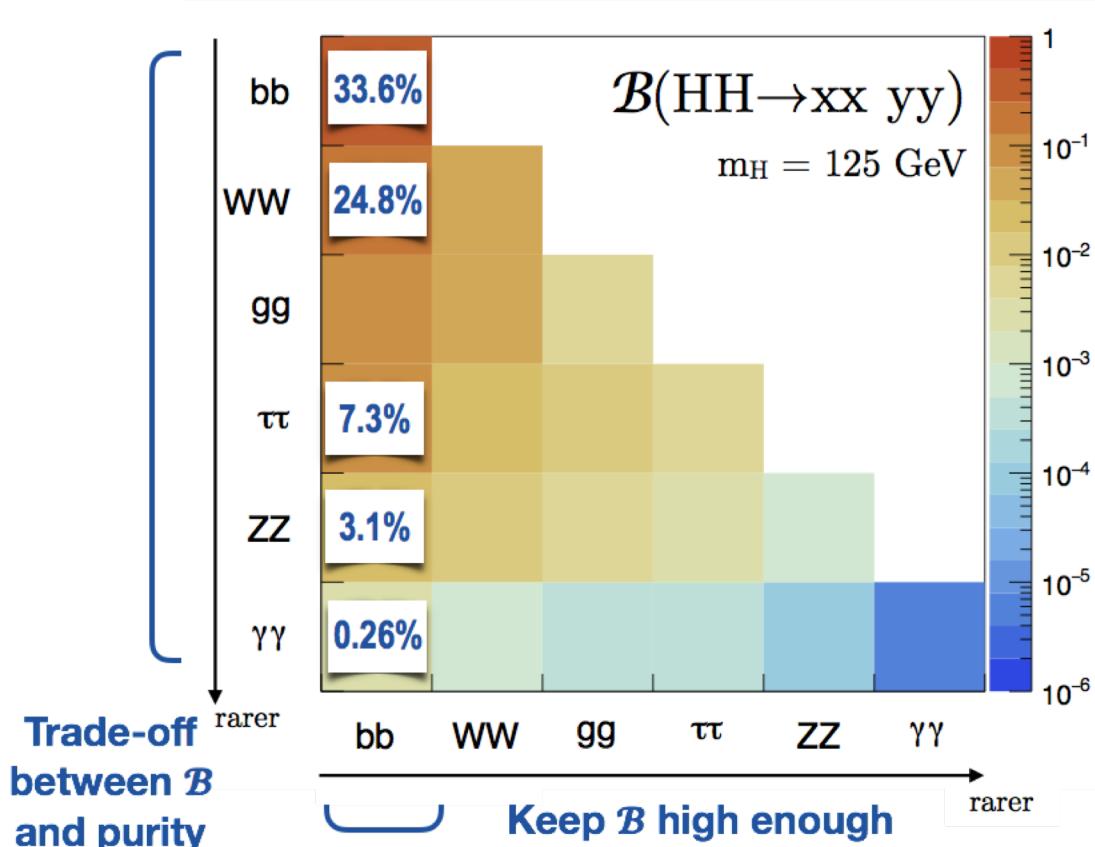
the next challenge is ...

...to find 2 Higgs's



Content

- Theoretical motivations
- Current resonant and non-resonant public results:
 - ✓ **bbbb:**
 - ✓ Resolved
 - ✓ Boosted
 - ✓ Semi-boosted
 - ✓ **bbττ**
 - ✓ Resolved
 - ✓ Boosted
 - ✓ **bbℓ⁺ℓvv**
 - ✓ **bbγγ**
- Run II combination
- New analyses
- Summary



CMS public results references

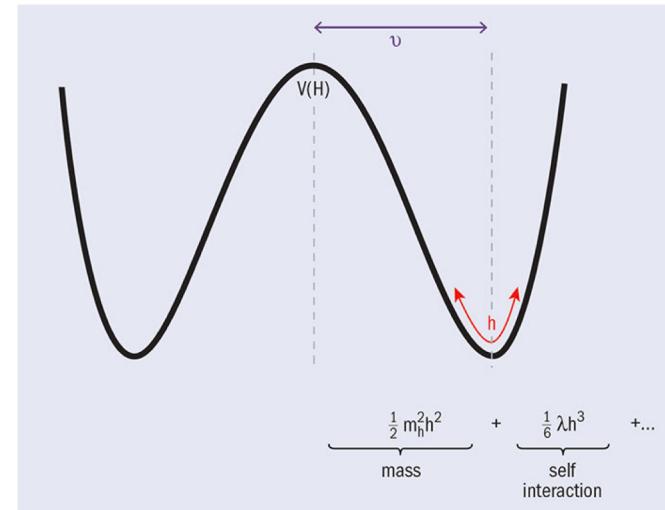
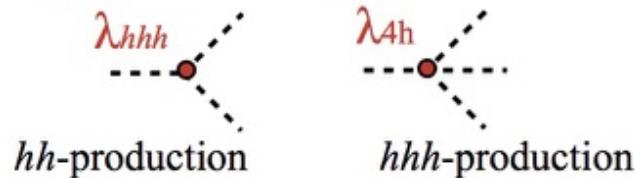
Final state	Targeted search	Documentation
4b	Low mass resonance	HIG-17-009 JHEP 08 (2018) 152
	High mass resonance	B2G-16-026 PLB 781 (2018) 244
	Intermediate mass resonance and non-resonant HH	CMS-PAS-B2G-17-019 arXiv:1808.01473
	Non-resonant HH	CMS-PAS-HIG-17-017
bb $\tau\tau$	Low mass resonance and non-resonant HH	HIG-17-002 PLB 788 (2018) 101
	High mass resonance	CMS-PAS-B2G-17-006 arXiv:1808.01365
bb $\ell^+\ell^-vv$	Low mass resonance and non-resonant HH	CMS-PAS-HIG-17-006 JHEP 01 (2018) 054
bb $\gamma\gamma$	Low mass resonance and non-resonant HH	CMS-PAS-HIG-17-008 arXiv:1806.00408
Combination	Resonant and non-resonant HH	CMS-PAS-HIG-17-030

HH in Standard Model

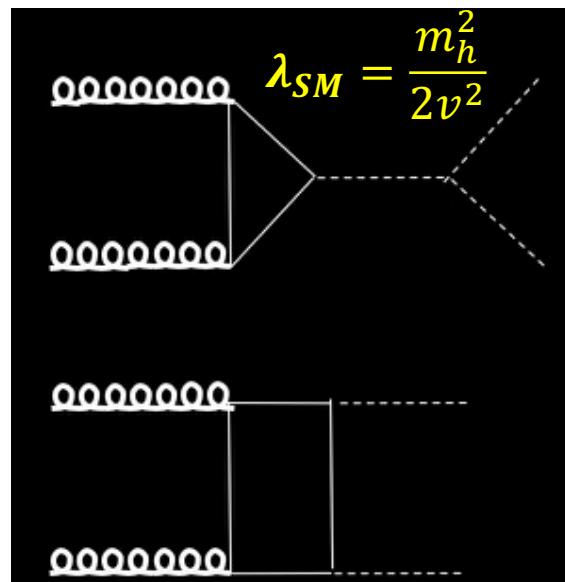
Start with Higgs potential:

$$V(\phi) = -\mu^2 \phi^2 + \lambda^2 \phi^4 \text{ (expand about minimum)}$$

$$= V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4} \frac{m_h^2}{2v^2} h^4$$



Shape of potential gives relationship between λ_{hhh} , m_h , v



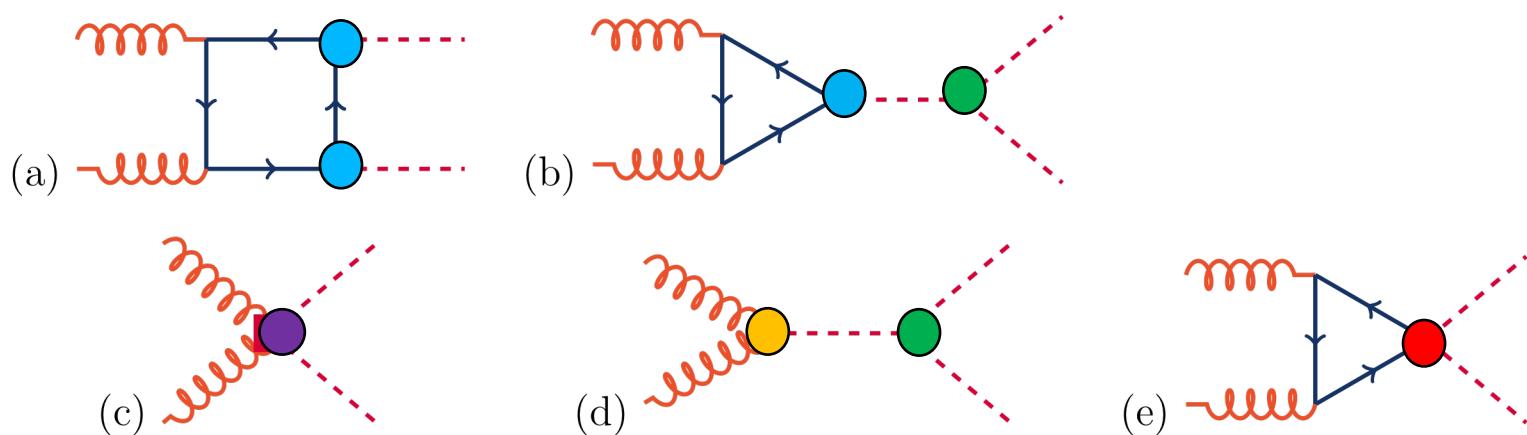
- Destructive interference among two diagrams leads to a small cross section
 - $\sigma(gg \rightarrow HH)_{SM} = 33.53 \text{ fb}^{+4.3\%}_{-6.0\%} (\text{scale}) \pm 5.9\% (\text{PDF})$
 - $\sigma(VBF \text{ HH})_{SM} = 1.64^{+0.05}_{-0.06} \text{ fb}$
- BSM contribution can modify the Higgs boson coupling parameters and enhance the HH cross section

$\sim 1000 \times$ less than H

Di-Higgs non-resonant with BSM contribution

- Extend the SM Lagrangian with dimension 4 and 6 operators in the framework of the EFT:

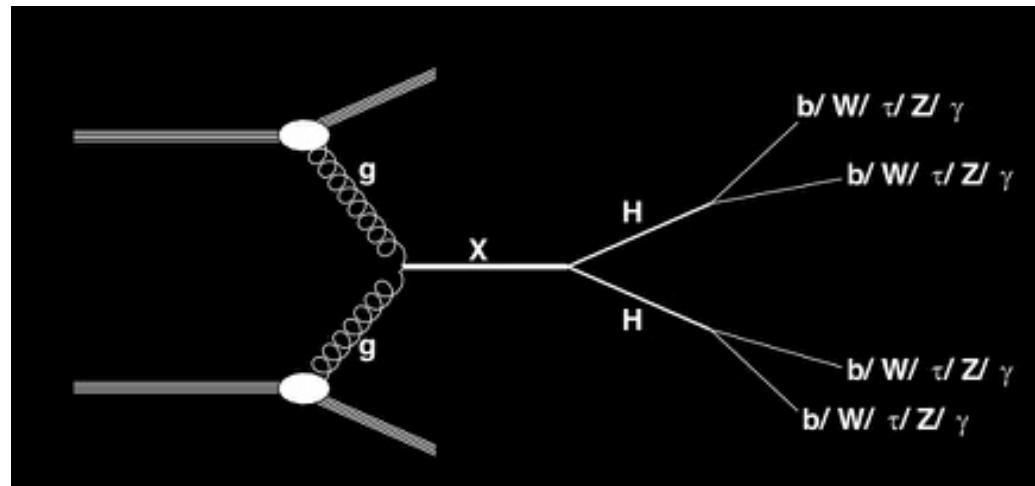
$$\begin{aligned} L_{hh} = & \frac{1}{2} \partial_\mu \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \textcolor{teal}{k}_2 \lambda_{SM} v h^3 \\ & - \frac{m_t}{v} \left(v + \textcolor{red}{k}_t h + \frac{\textcolor{red}{c}_2}{v} h h \right) (\bar{t}_L t_R + h.c.) \\ & + \frac{\alpha_S}{12} \left(\textcolor{blue}{c}_{1g} h - \frac{\textcolor{blue}{c}_{2g}}{2v} h h \right) G_{\mu\nu}^A G^{A\mu\nu} \end{aligned}$$

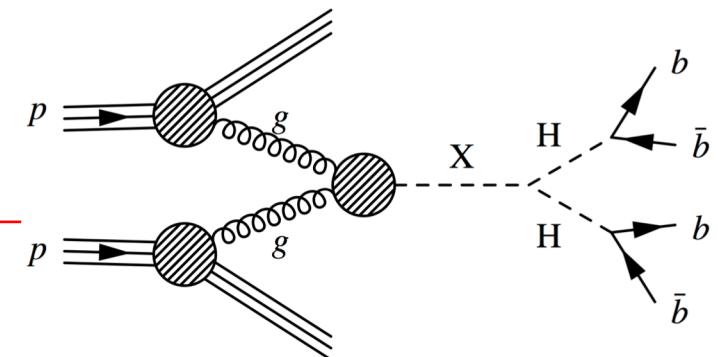


- Constraints on the range of 5 parameters from:
 - single H boson at the LHC and other theoretical considerations
- 13 benchmarks proposed for various anomalous coupling parameters

Di-Higgs resonant production

- Looking for a narrow resonance X with a mass m_X using the invariant mass spectrum m_{HH} .
 - One extra constraint w.r.t non-resonant
- Well-motivated signatures according to several scenarios:
 - Randall-Sundrum warped extra dimension → spin-0 radion or spin-2 KK graviton
- Cross section is significantly enhanced on resonances (up to pb)





$\mathcal{H}\mathcal{H} \rightarrow 4b$

3 analyses for different resonance mass ranges:

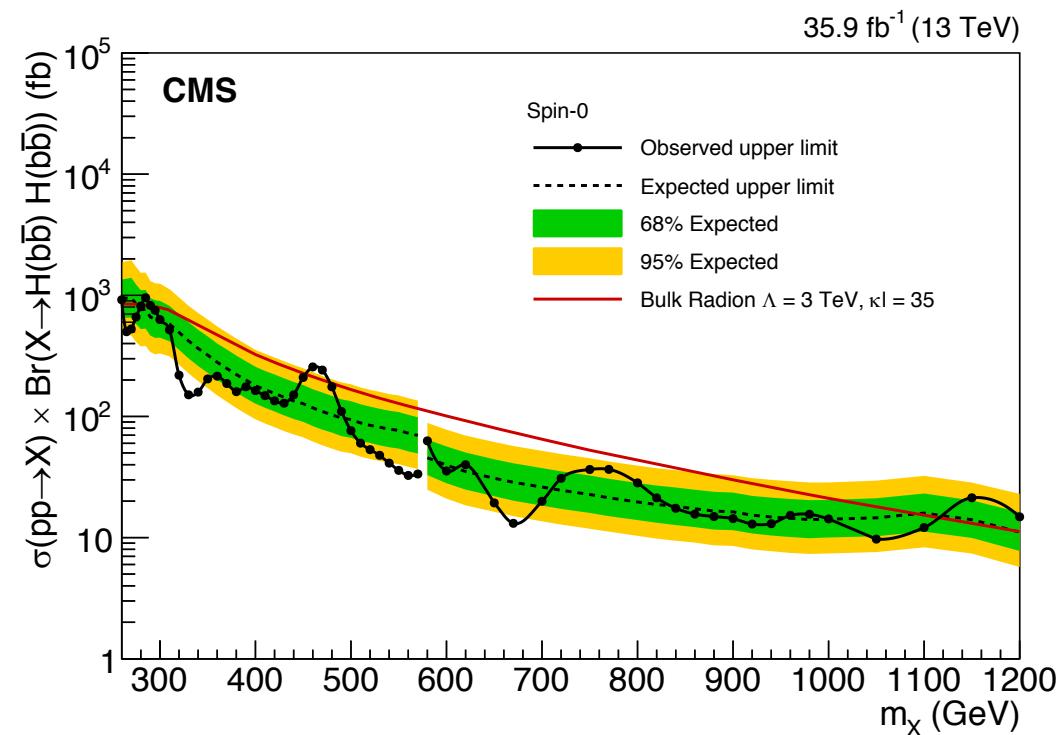
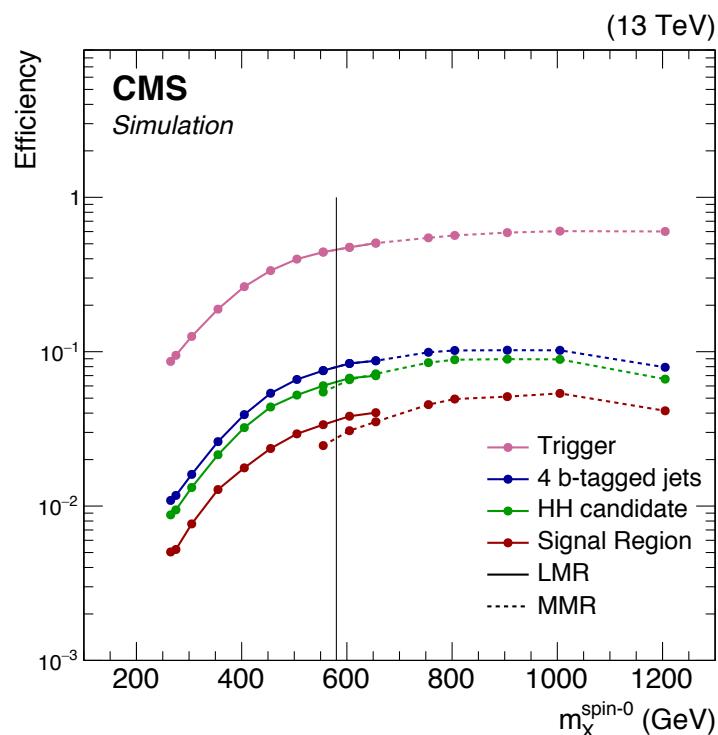
Resolved: 4 b jets used to reconstruct the $\mathcal{H}\mathcal{H} \rightarrow 4b$

Fully-merged: 2 large-area jets each identifying a boosted $H \rightarrow bb$

Semi-resolved: 1 large-area jet and 2 b jets

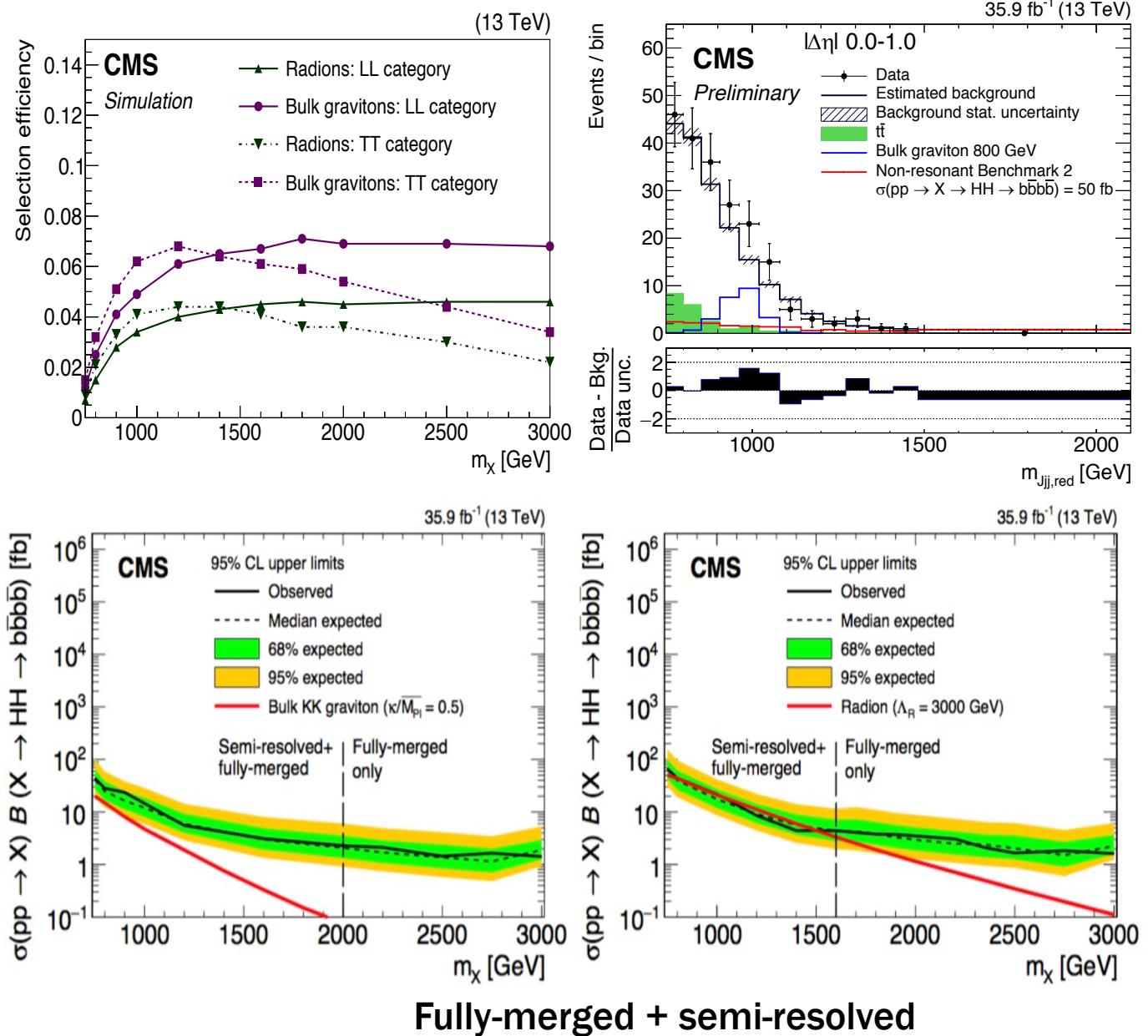
Detailed talk by
Andres Tiko

- The search covers low and medium mass regions
- Trigger the events using 4 jets (at least 3 should be b-tagged)
- Background estimation from sidebands of Higgs candidate masses.
- Upper limits set on the cross section of bulk gravitons and Radions in the warped extradimensional models

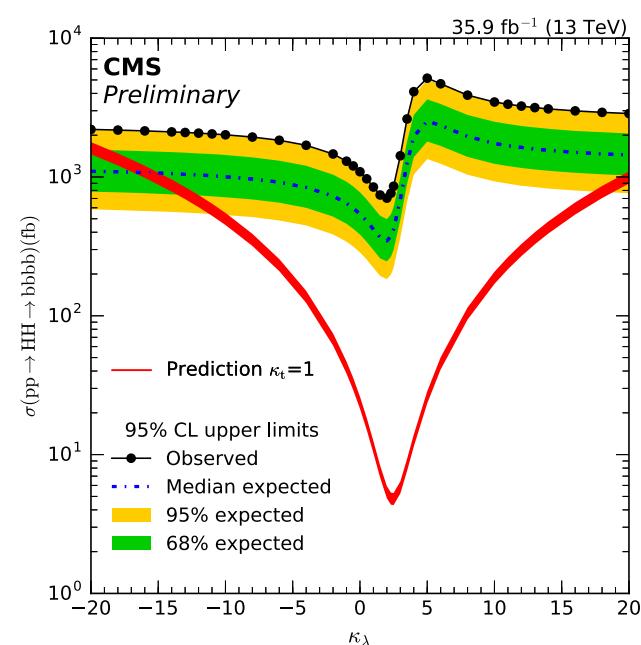
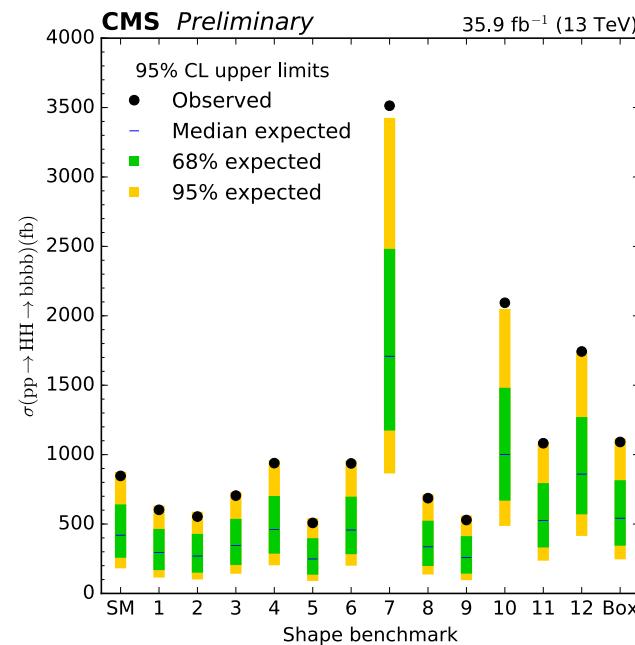
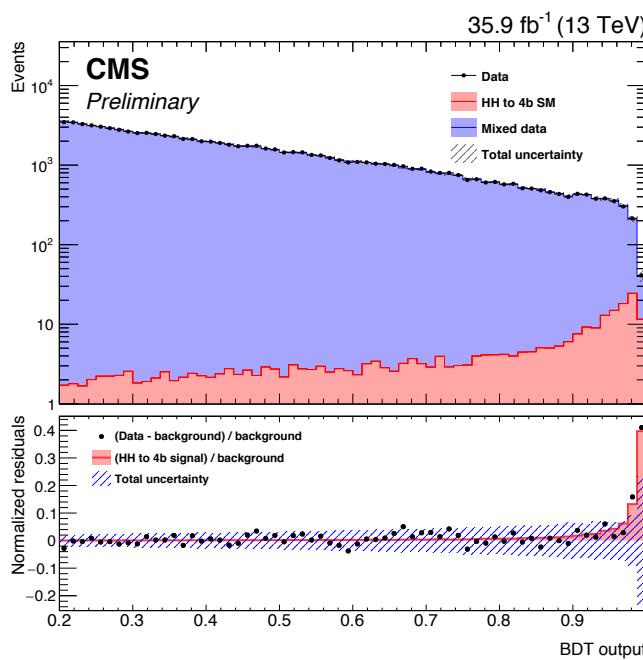


$\text{HH} \rightarrow 4\text{b}$ resonant (fully- and semi-merged)

- Switch to boosted techniques for high masses
- Background estimated from sideband regions using misidentification rate of Higgs jets in QCD background.
- Including semi-resolved events improve limits between 55-8% for the Radion in the mass range 750-1600 GeV.
- Similar search for non-resonant
 - Limit on SM XS 174 (obs) 119 (exp)



- Analysis optimized to be sensitive to the SM gg \rightarrow HH \rightarrow 4b process.
- Main background: QCD multijets. Reduced requiring 4 b jets and a BDT classifier.
- A hemisphere mixing technique is used to provide samples for BDT training and for predicting the background BDT shape.
- BDT modelling checked using data sidebands which exclude m(bb) around the Higgs boson mass.
- Limits set on different shape benchmarks: SM, 12 BSM benchmarks, $\kappa_\lambda = 0$



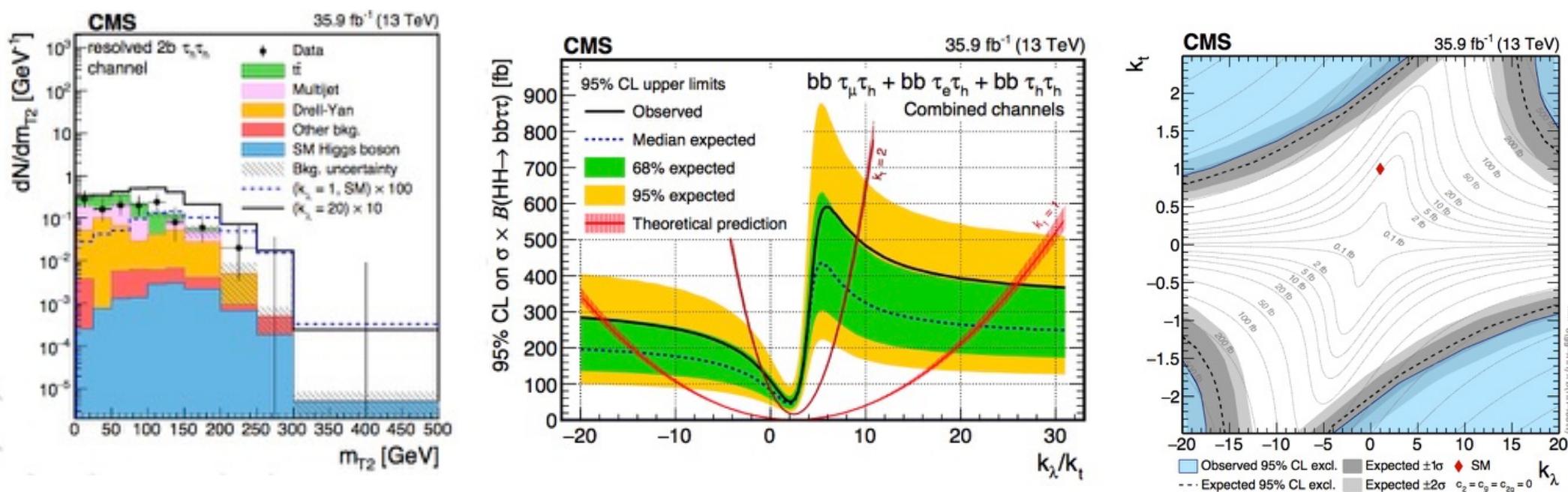
$$\mathcal{H}\mathcal{H} \rightarrow b\bar{b}\tau\tau$$

Analyses for both resonant and non-resonant in 3 categories:

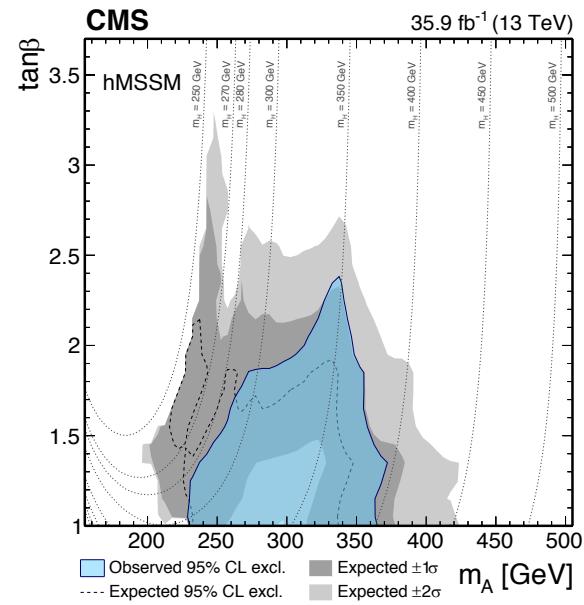
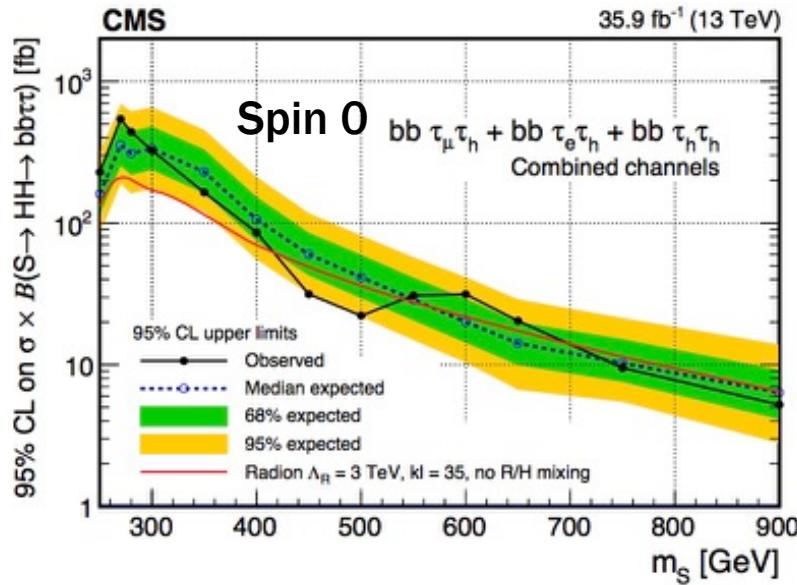
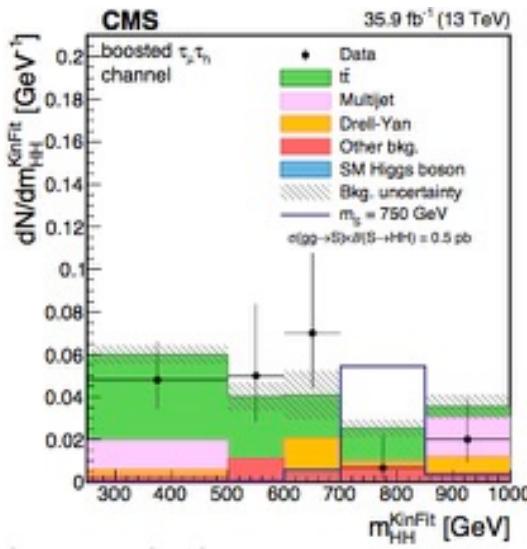
resolved 1 btag & 2 btag, and boosted

Detailed talks by
Arnaud Ferrari
Francesco Brivio
Chiara Amendola

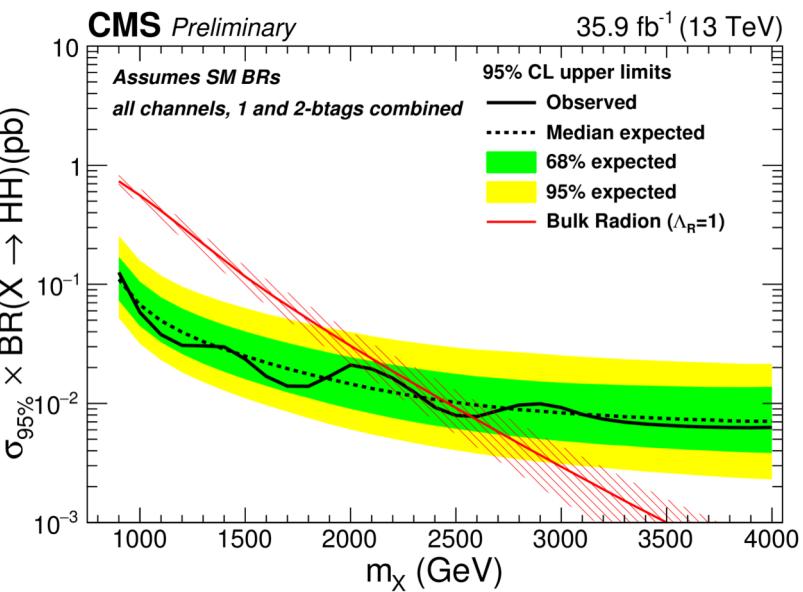
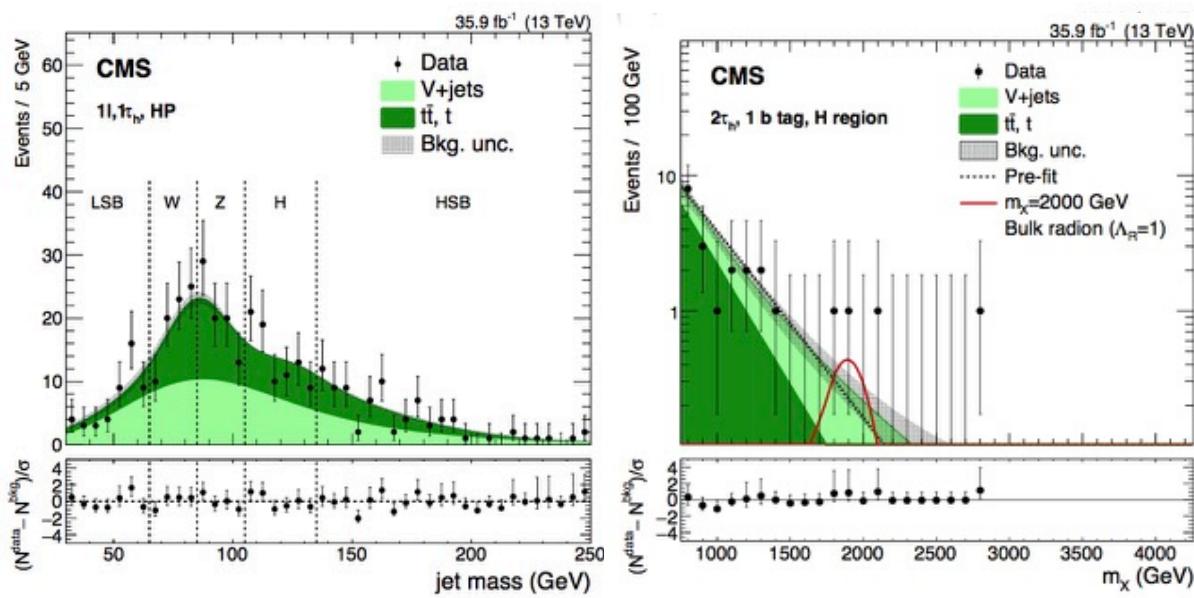
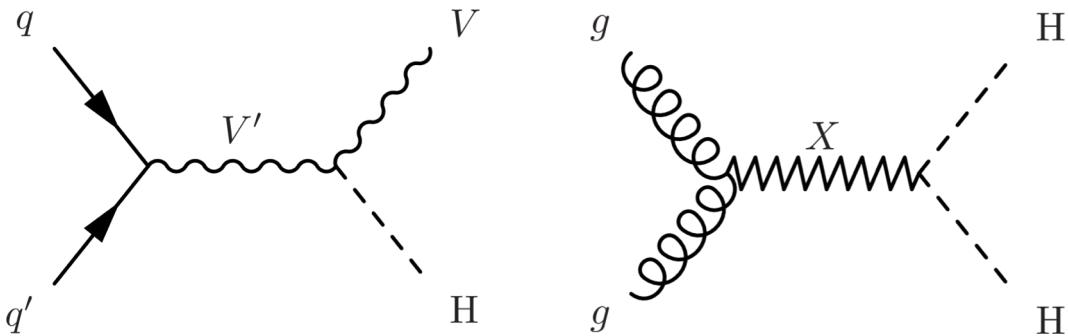
- Three different final states: $\text{bb}\tau_h\tau_h$, $\text{bb}\mu\tau_h$, $\text{bbe}\tau_h$
- The search also includes the cases where two b-jets are merged as a fat-jet as well
- Using m_{2T} as the observable
- The observed (expected) upper limit about 30 (25) times the prediction of the standard model



- The kin_fit variable is used for resonant searches
- Search include both low and high mass resonance analyses.
- The search also includes resolved and boosted bb system.
- Mass requirements:
$$\frac{(m_{\tau\tau} - 116 \text{ GeV})^2}{(35 \text{ GeV})^2} + \frac{(m_{\text{bb}} - 111 \text{ GeV})^2}{(45 \text{ GeV})^2} < 1$$
- Resonant HH search also sets limits in hMSSM parameter space in the low $\tan\beta$ region.



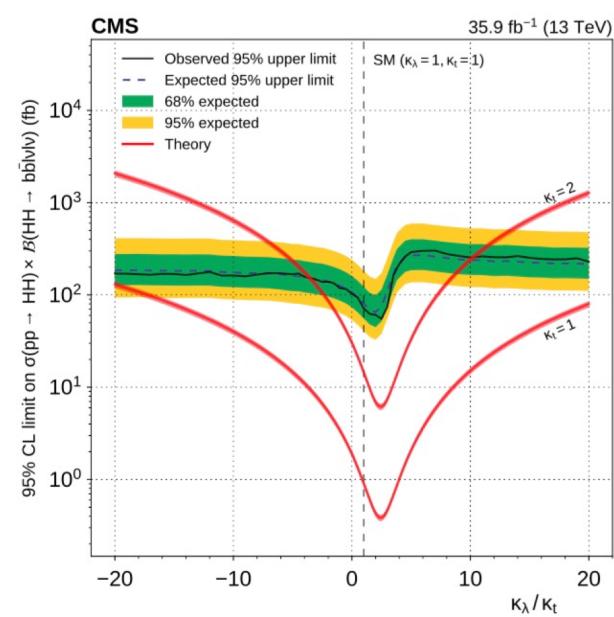
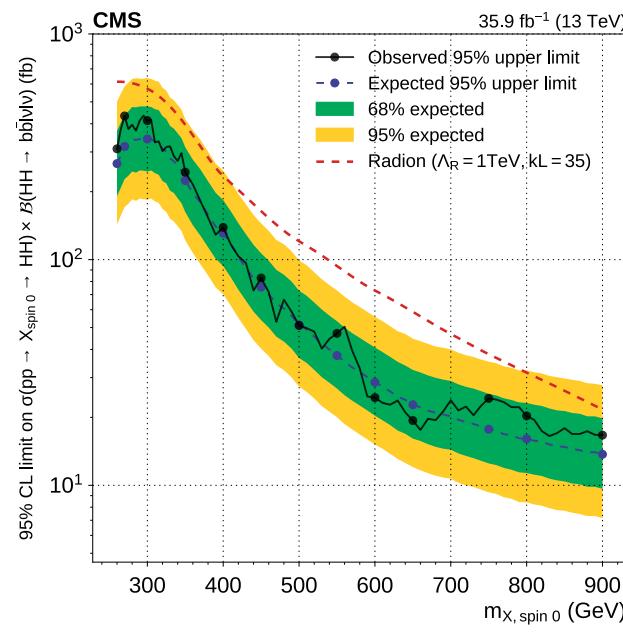
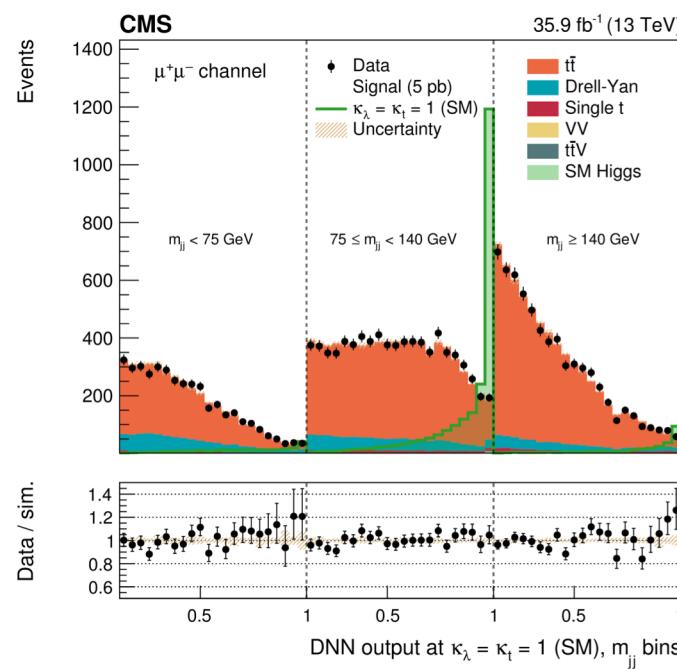
- Search for heavy resonances decaying to diHiggs or W/Z+H
- Boosted reconstruction for both ditau and bb
- Limit is set for mass greater than 1 TeV (both on spin0 and spin2 resonances)



$\mathcal{H}\mathcal{H} \rightarrow b\bar{b} l\bar{l} \nu\bar{\nu}$

Detailed talk by
Tao Huang

- Event categories: e^+e^- , $\mu^+\mu^-$, $e^\pm\mu^\mp$
- Exclude di-lepton events in case the mass is compatible with Z boson
- Neural network training used to improve signal-background separation.
- Upper limit on signal strength: $\text{obs(exp)} = 79(89) \times \text{SM}$
- Large ttbar background limits the exclusion power at low masses



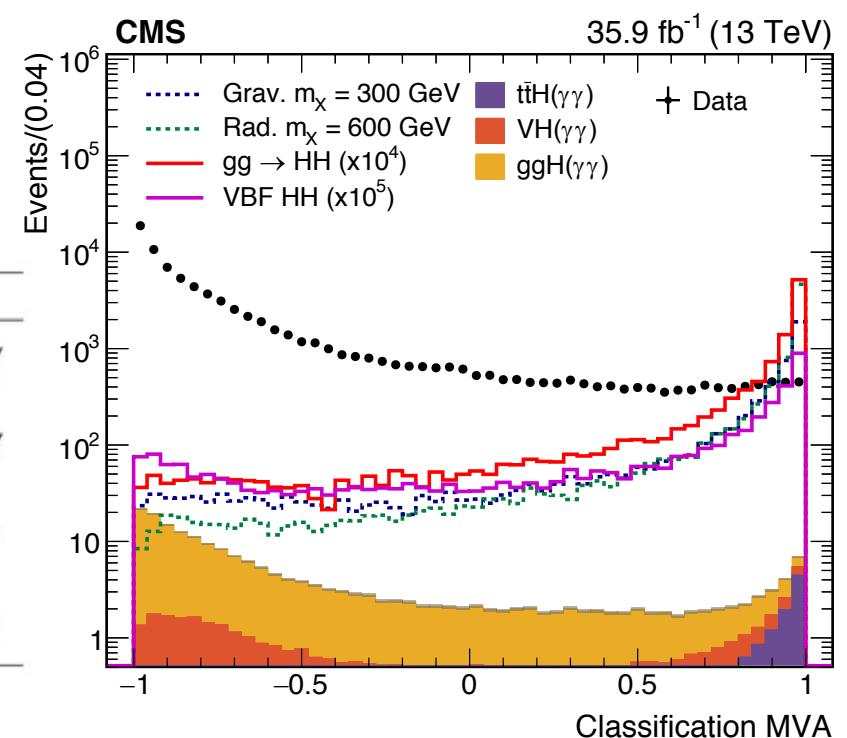
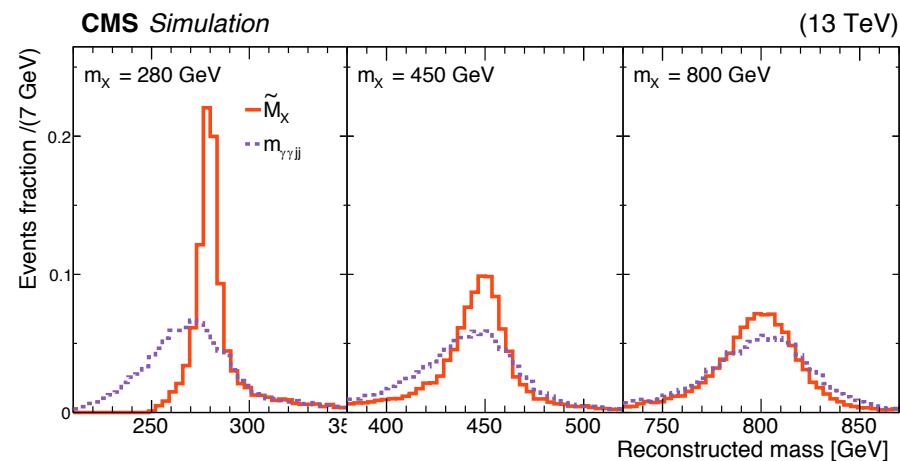
$$H\bar{H} \rightarrow b\bar{b}\gamma\gamma$$

Detailed talk by
Maxime Gouzevitch

$\text{HH} \rightarrow \text{bb}\gamma\gamma$

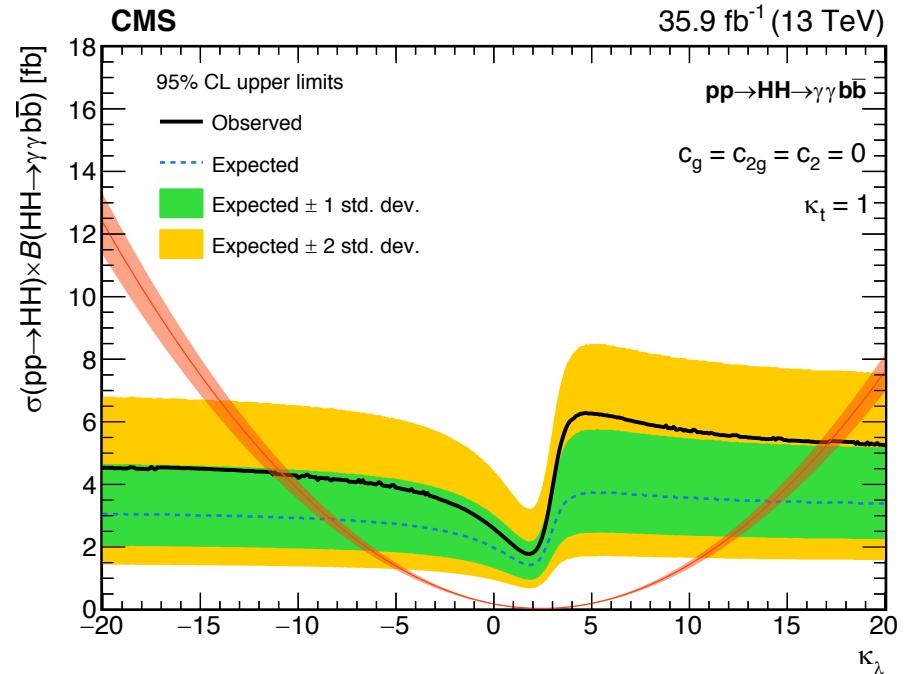
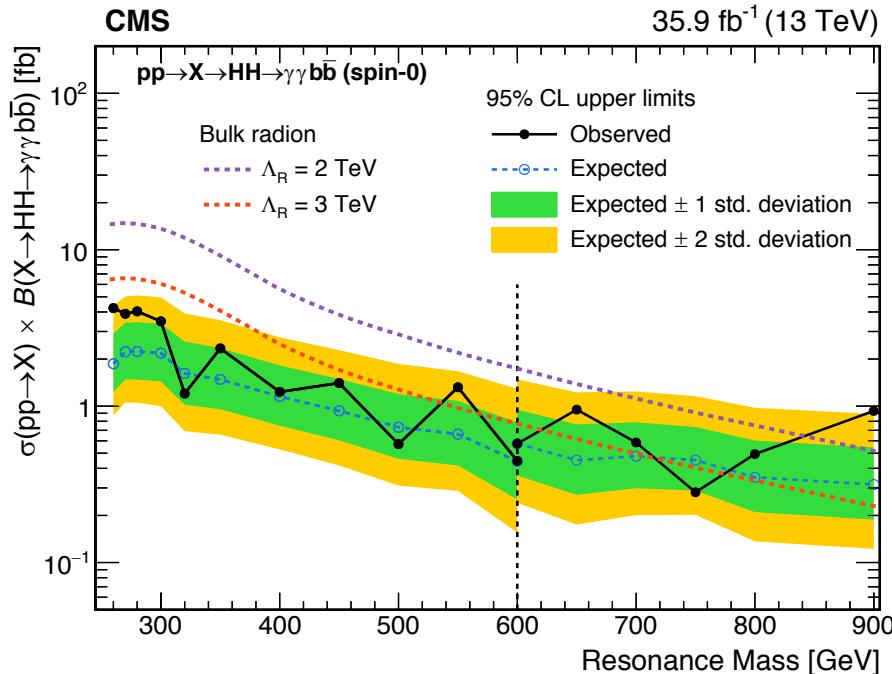
- Small BR (0.26%) but clean signature
- 2 photons+2 b-tagged jets (triggering using 2 photons)
- Resonant mass:

$$\tilde{M}_X = M(\text{jj}\gamma\gamma) - M(\text{jj}) - M(\gamma\gamma) + 250$$
- Categorization based on the MVA output and M_X mass
- Signal is searched for using a parametric fit to $M(\text{jj})$ and $M(\gamma\gamma)$



Analysis	Region	Classification MVA	\tilde{M}_X
Nonresonant	High-mass	HPC: MVA > 0.97 MPC: $0.6 < \text{MVA} < 0.97$	$\tilde{M}_X > 350 \text{ GeV}$
	Low-mass	HPC: MVA > 0.985 MPC: $0.6 < \text{MVA} < 0.985$	$\tilde{M}_X < 350 \text{ GeV}$
Resonant	$m_X > 600 \text{ GeV}$	HPC: MVA > 0.5 MPC: $0 < \text{MVA} < 0.5$	Mass window
	$m_X < 600 \text{ GeV}$	HPC: MVA > 0.96 MPC: $0.7 < \text{MVA} < 0.96$	Mass window

$\text{HH} \rightarrow \text{bb}\gamma\gamma$

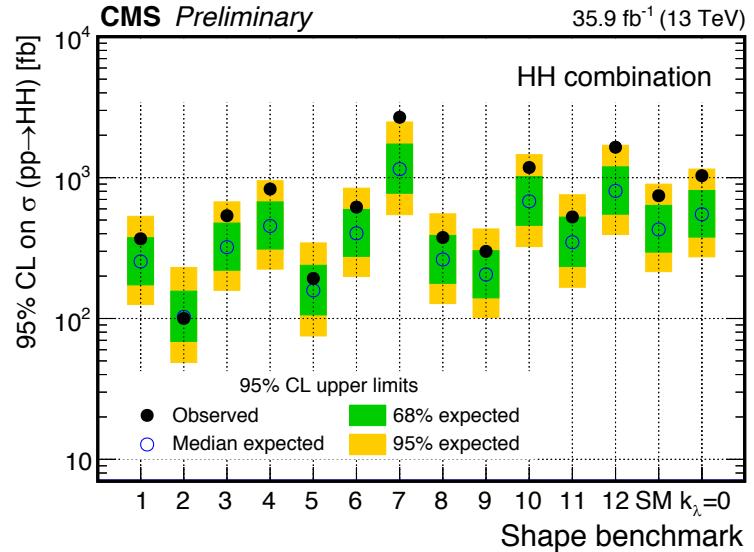
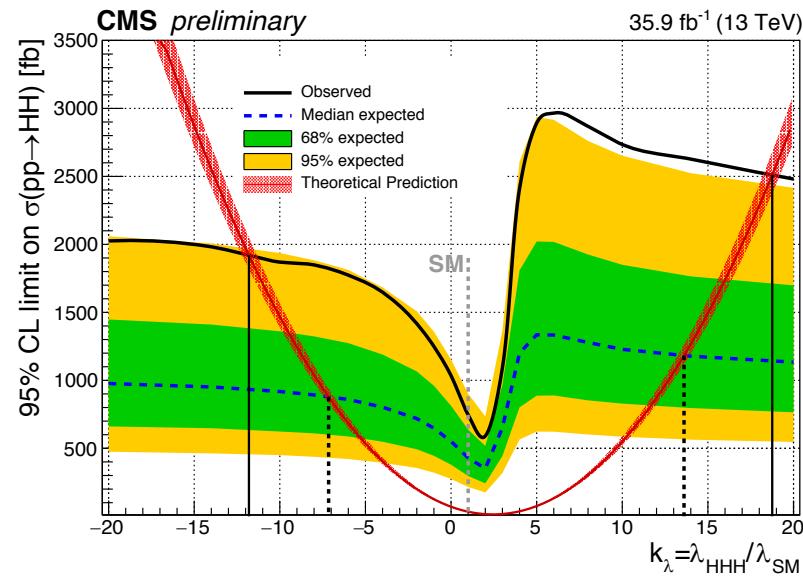


- Limits computed on the cross section of bulk gravitons and radions in the warped extradimensional models.
- Limit on SM cross section of $\text{gg} \rightarrow \text{HH} \rightarrow \text{bb}\gamma\gamma$: 2 fb (obs) 1.6 fb (exp)
 - Corresponds to 24 (obs) 19 (exp) times the SM expectations.
 - Including VBF HH production improves sensitivity by 1.3%
- Constraint on κ_λ between -11 and 17.

Combination

Detailed talk by
Luca Cadamuro

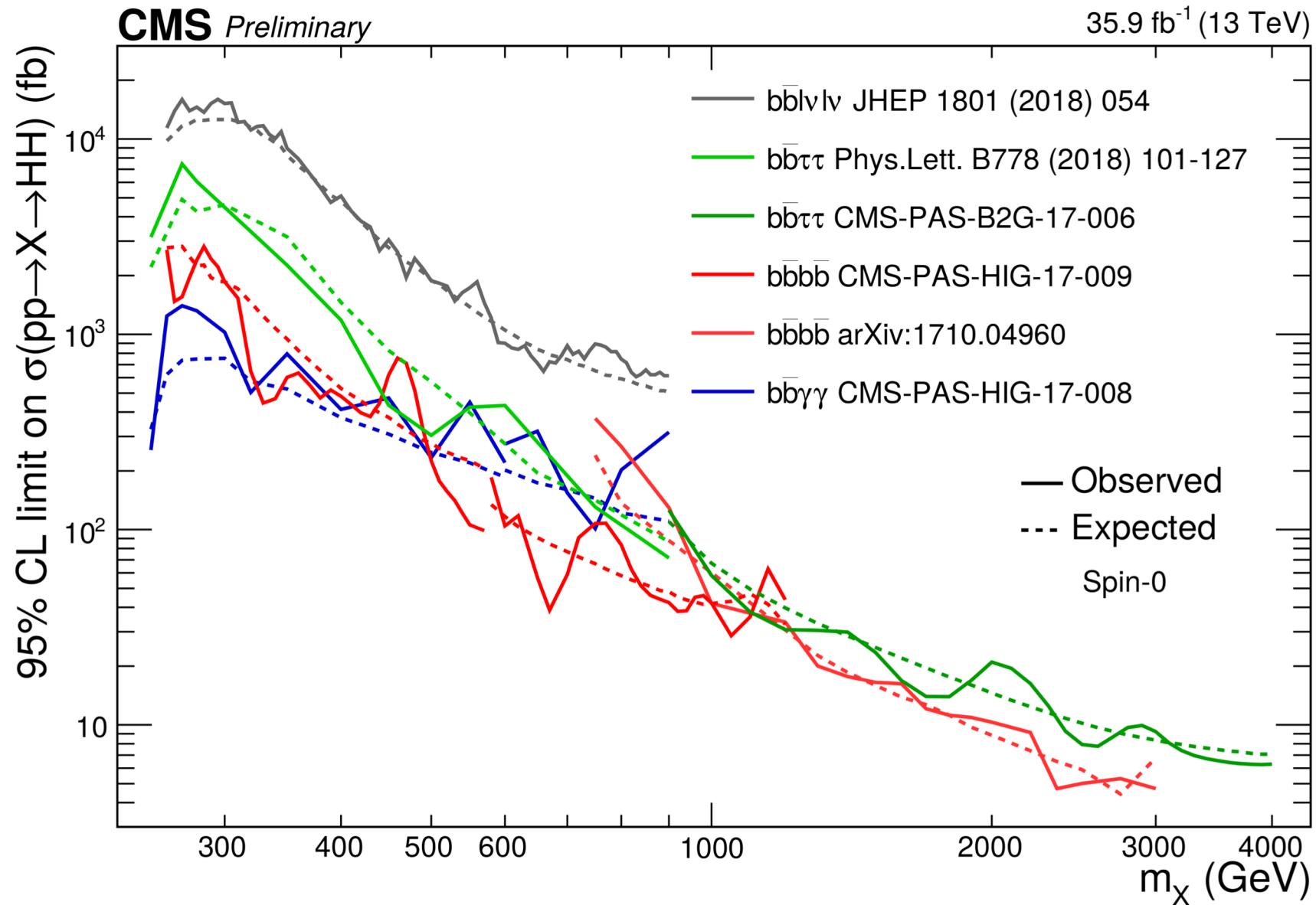
Combination of non-resonant



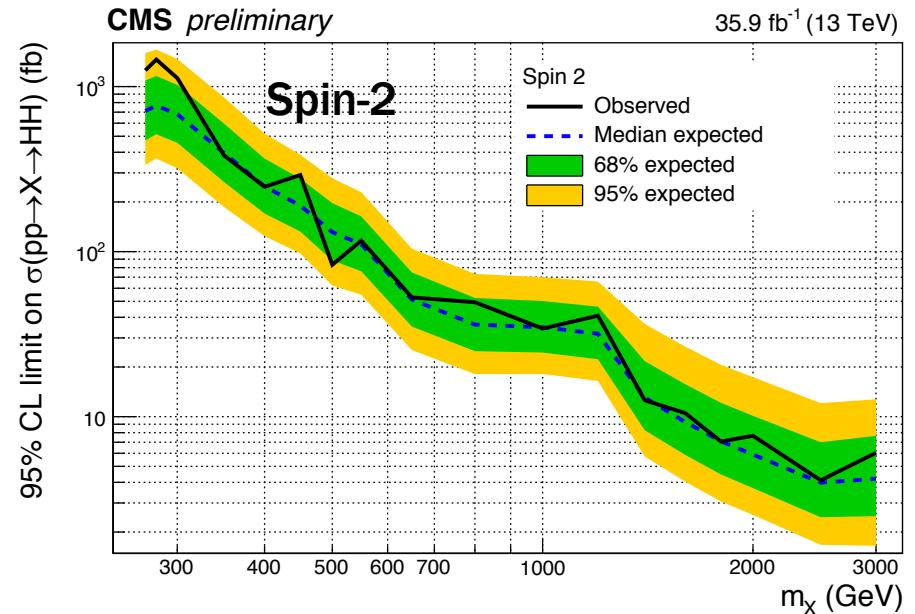
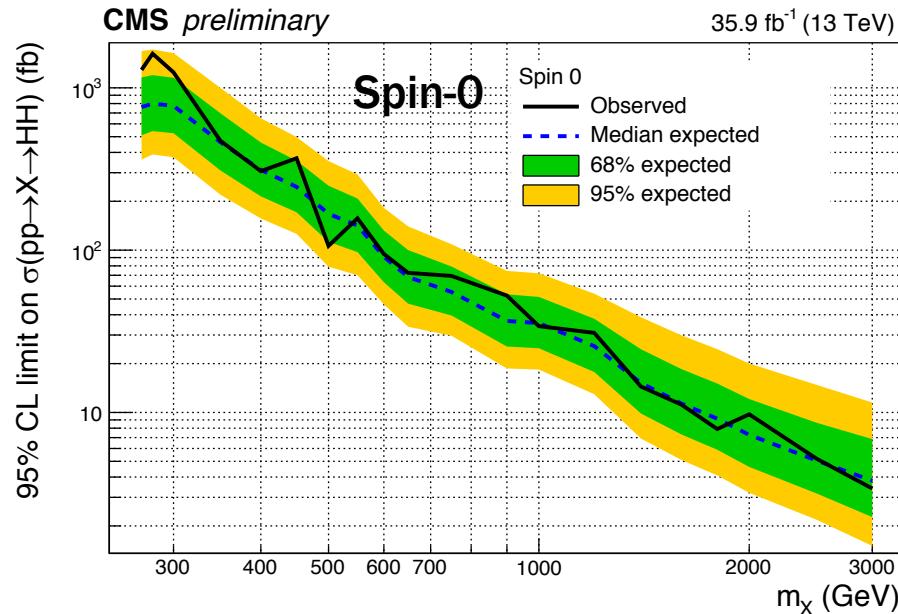
- Combined obs(exp) limit $\sim 22(13) \times SM$
- Limits set on 12 BSM shape benchmarks, SM, and $\kappa_\lambda=0$.
- Limit on κ_λ for $\kappa_t = 1$:
 - Observed: -11.8–18.8
 - Expected: -7.1–13.6
- Sensitivity to benchmarks with higher m_{HH} improved by including boosted topologies.

Final state	s/s _{SM} Obs(Exp)
bb $\gamma\gamma$	24 (19)
bb $\tau\tau$	31 (25)
bbl ⁺ l ⁻ $\nu\nu$	79 (89)
bbbb	75 (37)
Combined	22.2 (12.8)

Combination of resonant



Combination of Resonant



- Combination of several HH decay channels.
- Interpretation in terms of spin-0 (radion) and spin-2 (bulk graviton) production cross section times the branching fraction to HH.
- Narrow width approximation used.

New searches

Detailed talk by
Apichart Hortiangtham
Christian Veelken
Karl Ehataht
Saswati Nandan

New search channels

We have also started to explore new channels. [Less sensitive → more challenging]:

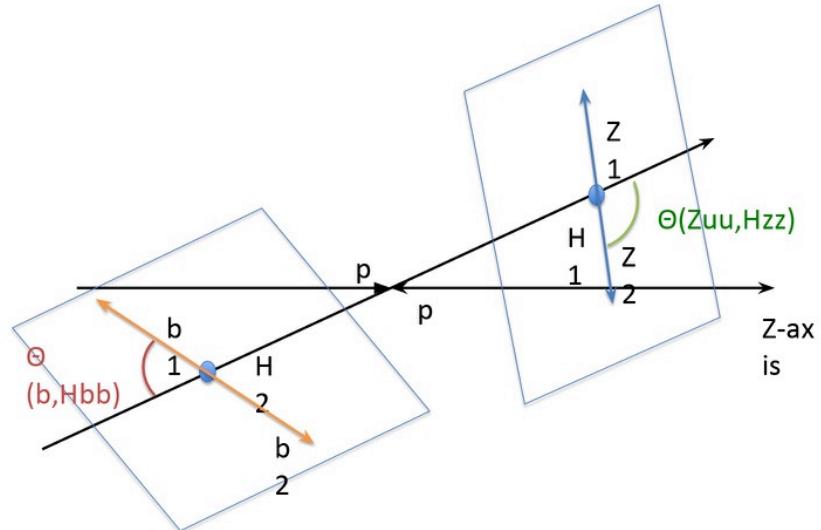
➤ $\text{HH} \rightarrow \text{bbZZ}$ (in 3 channels)

- $\text{bb}\ell^+\ell^-vv$
- $\text{bb}\ell^+\ell^-\ell^+\ell^-$
- $\text{bb}\ell^+\ell^-qq$

➤ Apart from kinematical distributions, some angular distributions are fed into the BDT

➤ $\text{HH} \rightarrow \tau\tau\tau\tau$

- Clean signatures with either 1, 2 or 3 leptons
- Dedicated effort to reconstruct ditau mass, consequently 4 tau system
- Non-negligible contribution from $\text{WW}\tau\tau$ and WWWW

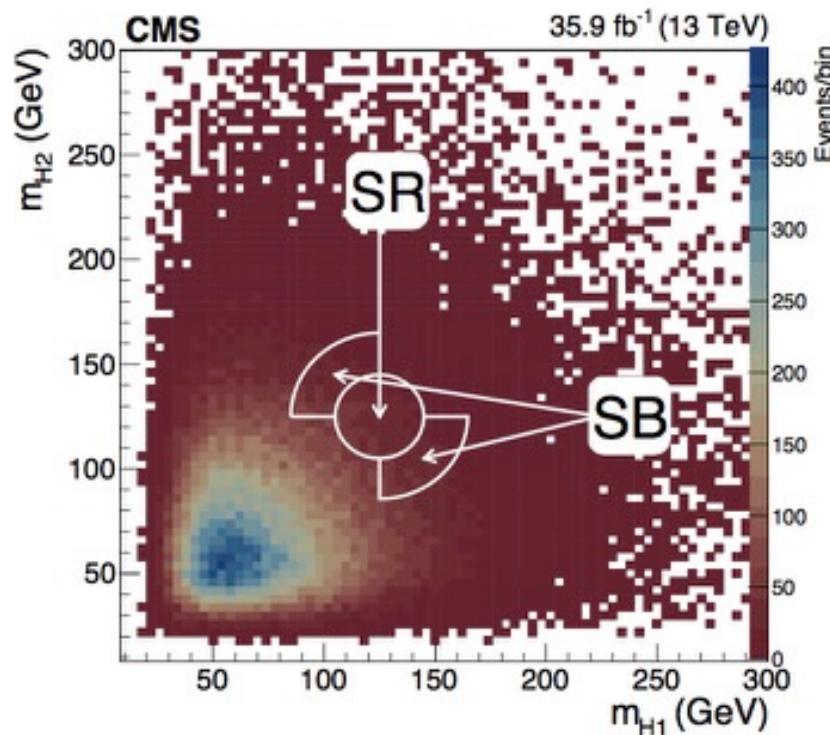


Summary

- CMS has conducted extensive searches for diHiggs production for all sensitive channels, in large mass ranges and for both resonant and non-resonant modes
- All results consistent with SM backgrounds so far
- Combined observed (expected) limit $\sim 22(13) \times \text{SM}$
- New search channels are being investigated
- We are now switching toward processing rest of run2 data (the next goal is run2 legacy analyses)
- More to come next year!

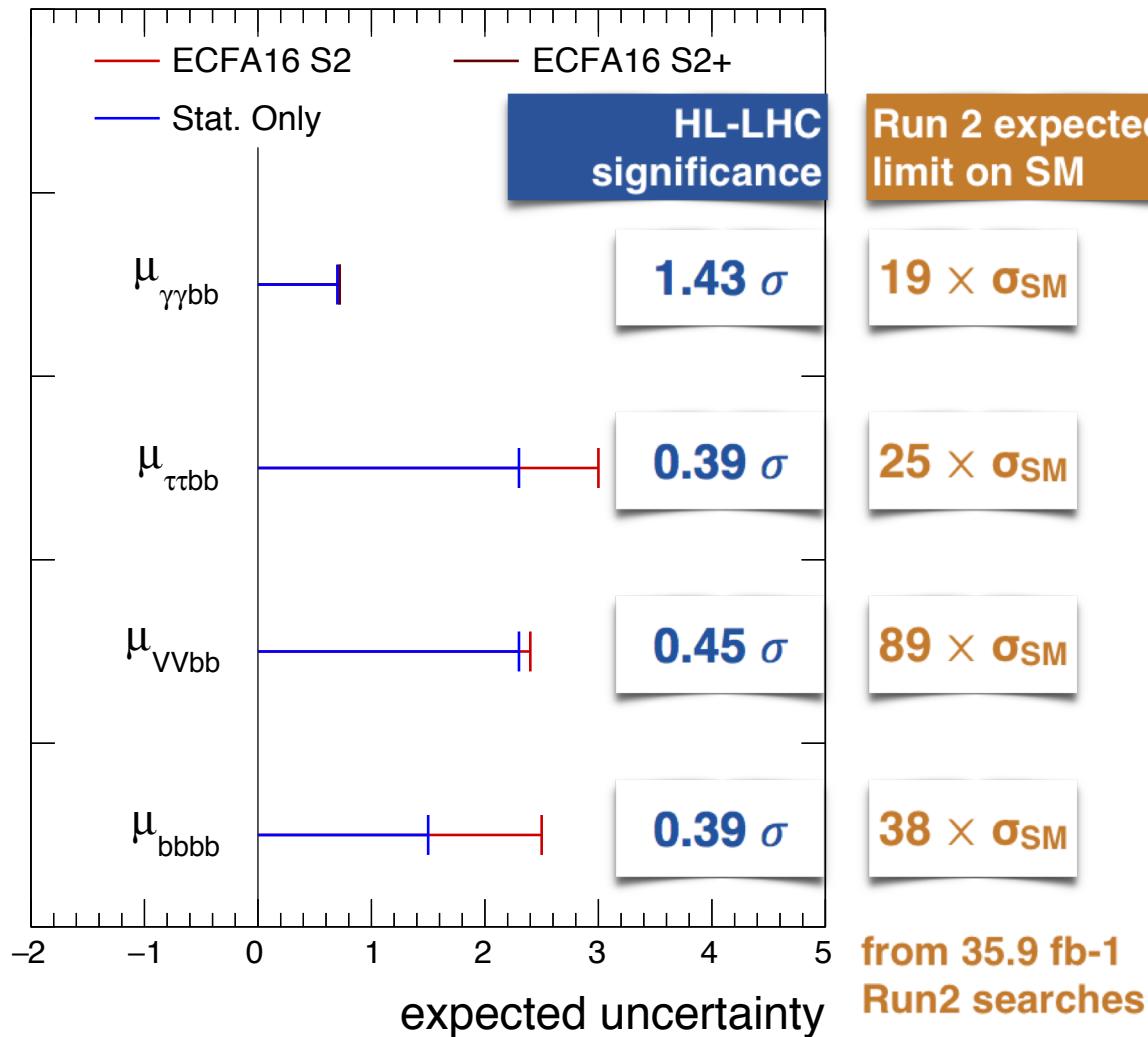
Backup

$\text{HH} \rightarrow \text{bb}$ low/medium mass signal region ($R < 1$)



Projection

CMS *Projection* $\sqrt{s} = 13 \text{ TeV}$ SM $gg \rightarrow HH$



Extrapolation of early Run II results (2.3/2.7 fb-1) to 3000 fb-1 superseded by more recent Run 2 results
Sensitivity limited by statistics
Sensitivities do not directly match the current Run 2 ones
different underlying assumptions, e.g. in analysis improvements