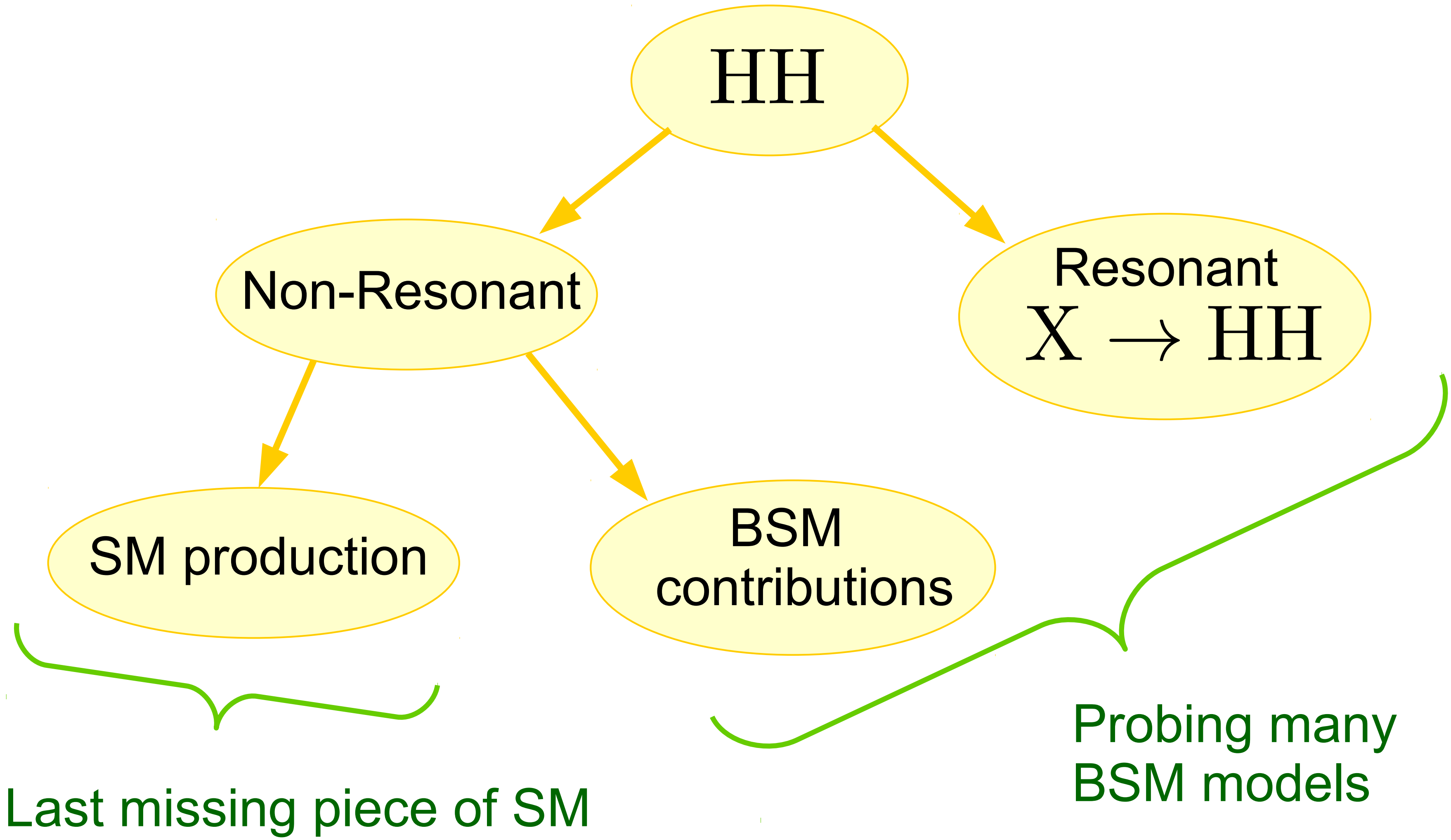
Searches for HH production at CMS

Petar Maksimovic,
Johns Hopkins
on behalf of the CMS collaboration

PHENO 2018

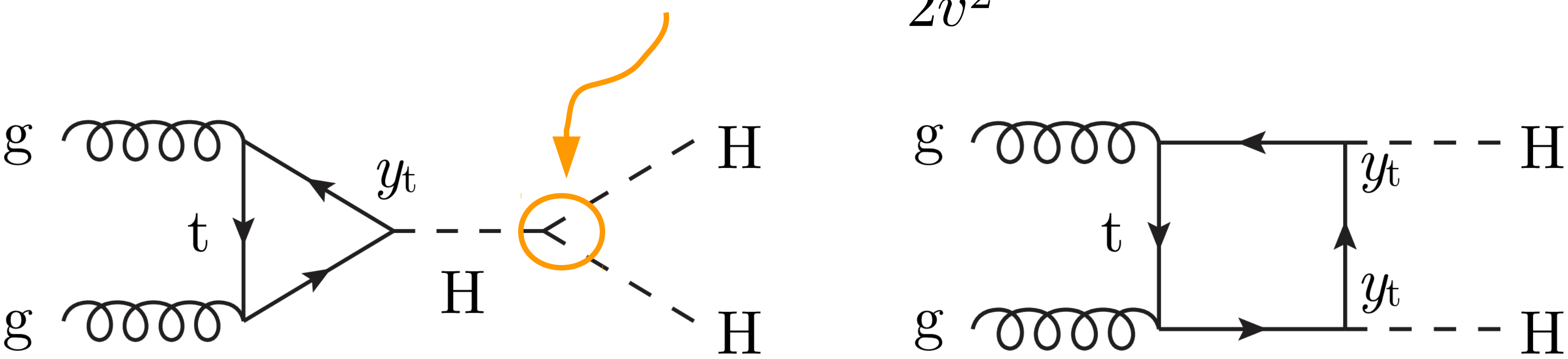
The layout of this talk



HH in the SM

- Measurement of Higgs boson self-coupling = a fundamental test of SM!
- SM predicts extremely small cross-section for HH prod.
  - 33.5 fb @ 13 TeV

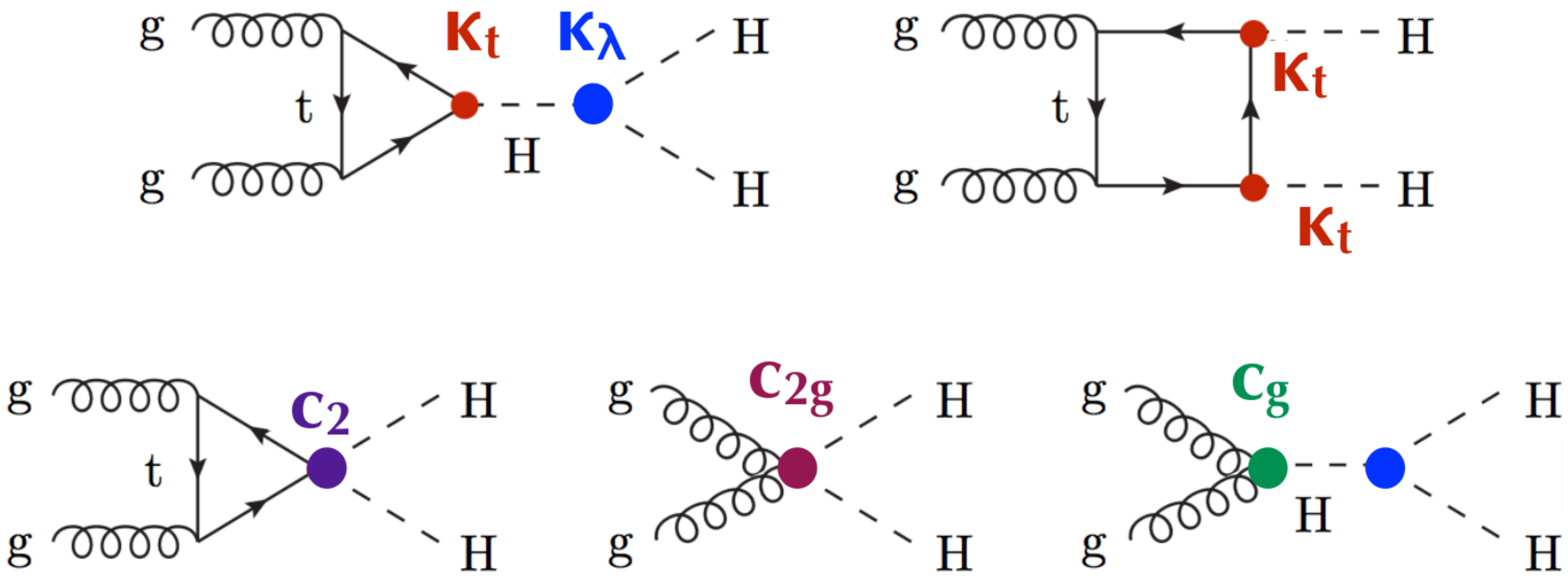
$$\lambda_{\mathrm{HHH}} = \frac{m_H^2}{2v^2}$$



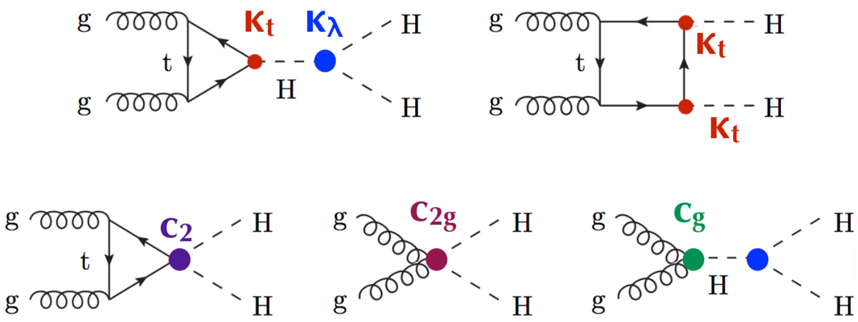
- HHH probes the shape of the Higgs potential!

HH in BSM (non-resonant)

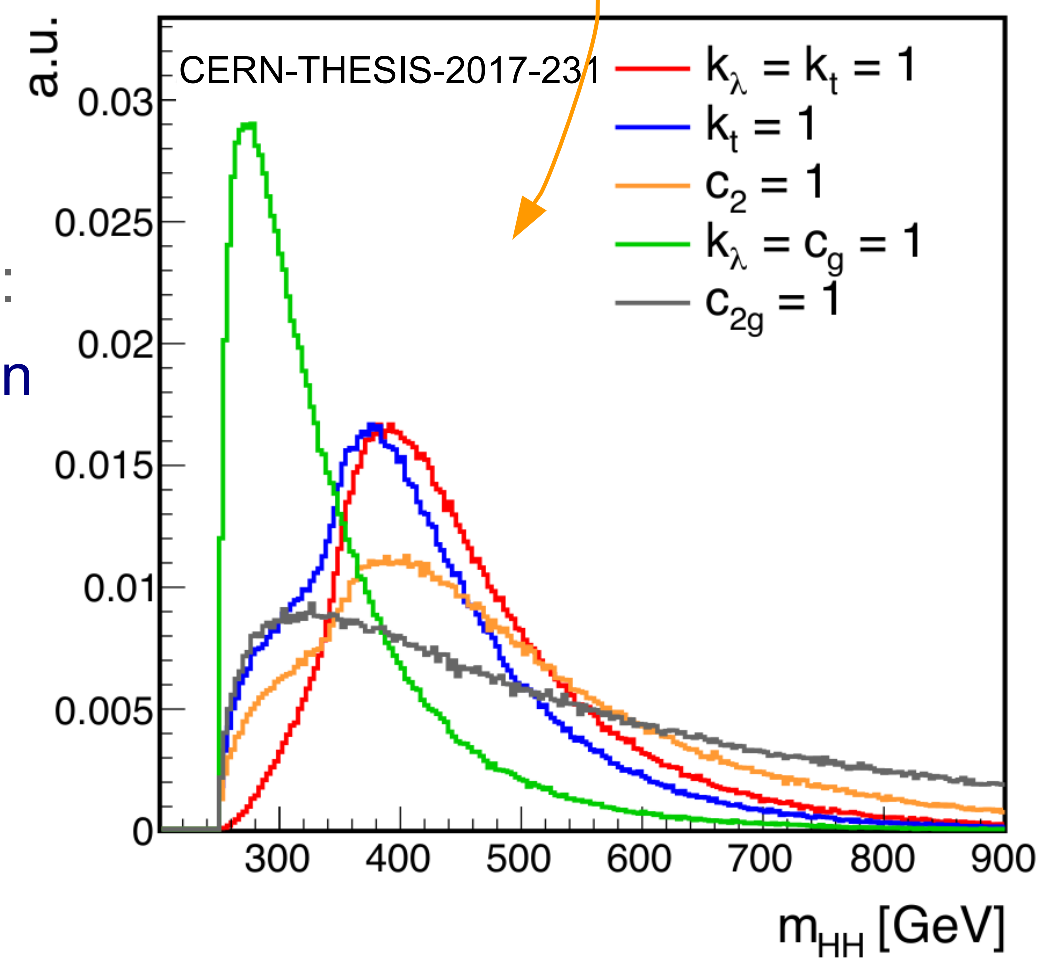
- BSM: dimension 6 operators. Parameterize using EFT approach:
  - modifications to $\kappa_\lambda = \lambda/\lambda_{SM}$ and $\kappa_t = y_t/y_{t,SM}$
  - three new interactions: c_2, c_{2g}, c_g



HH in BSM (non-resonant)



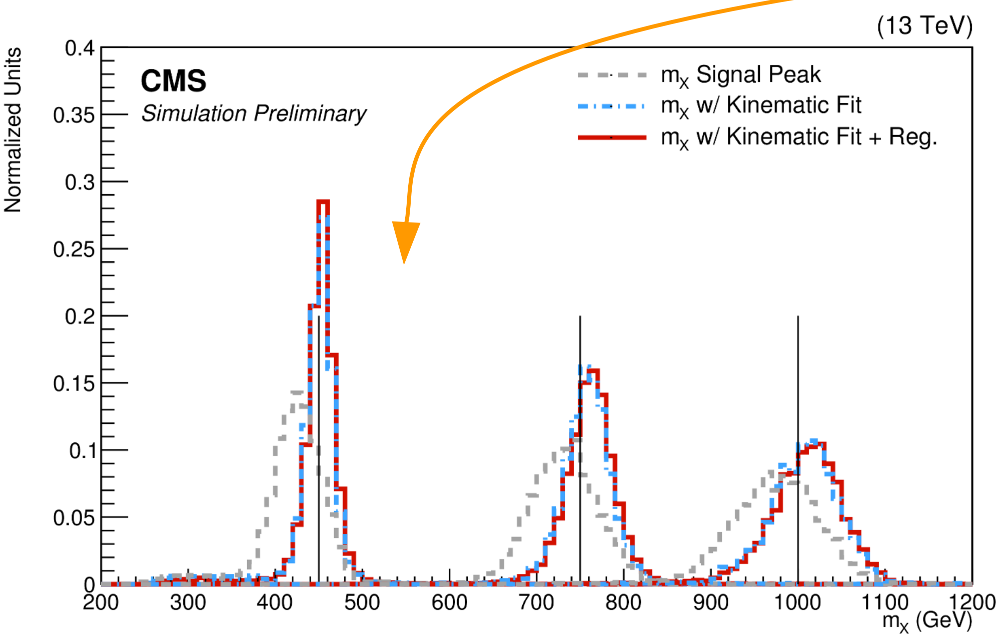
- Strong effects on cross-section and m_{HH} shape!



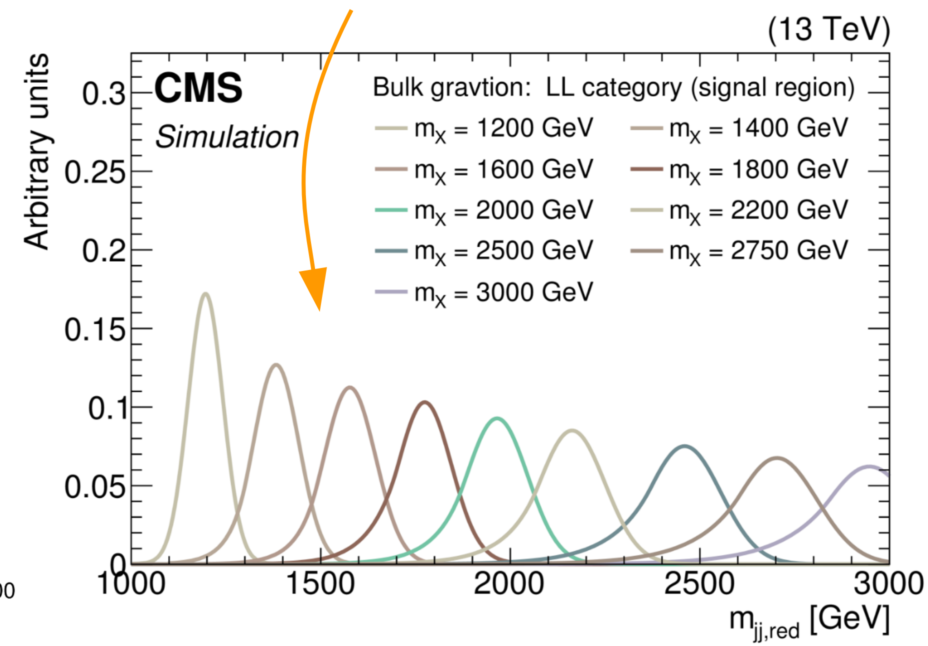
- To see deviation from SM:
  - Better than 20% precision on λ_{HHH}
  - [1305.6397]
- Less for NMSSM
  - [1505.05488]

HH in BSM (resonant)

- HH resonances from warped extra dimensions models:
  - Radion (spin = 0)
    - gg production
    - higher cross-section
  - First KK excitation of the graviton (spin = 2)
    - gg production
    - lower-cross section

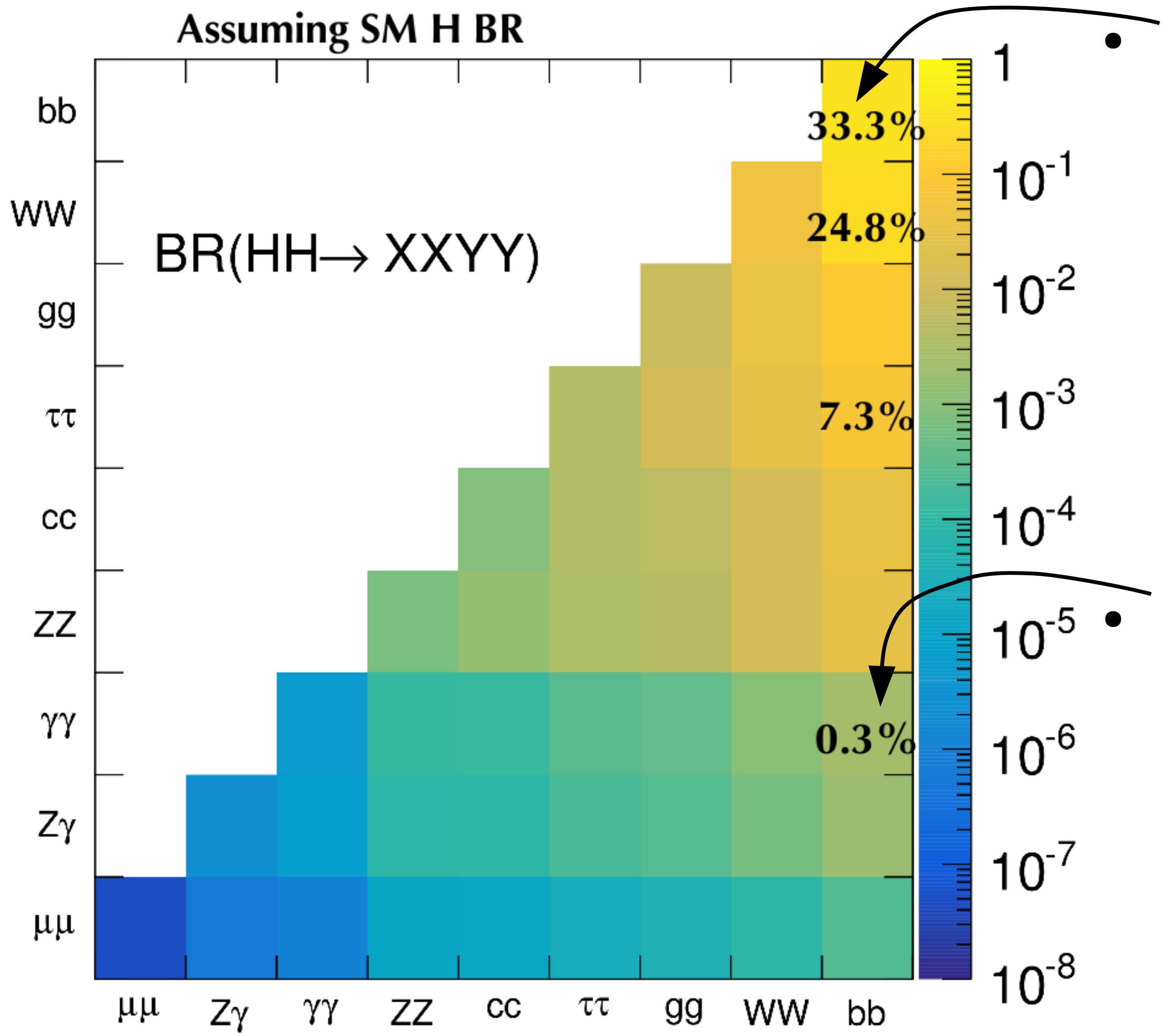


(resolved 4b channel)



(boosted 4b = higher masses)

Complementarity of HH channels

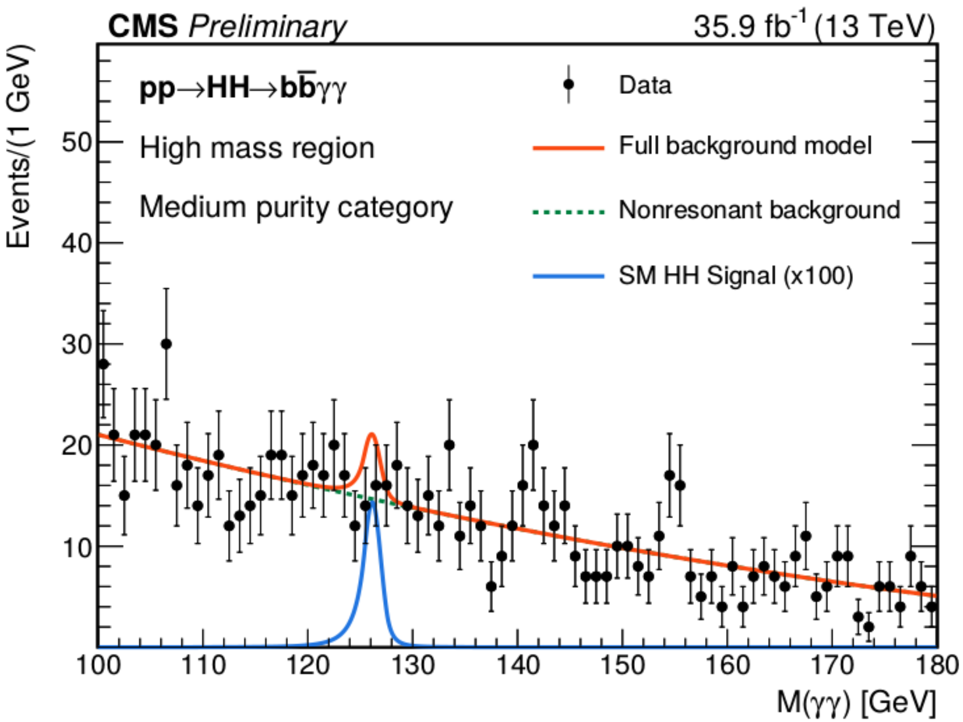


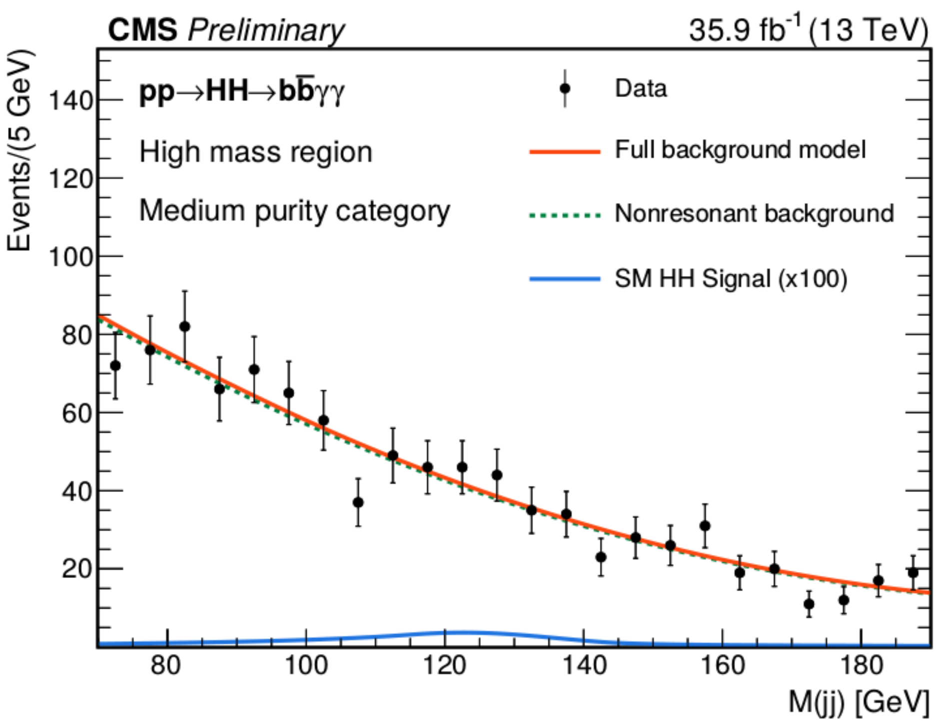
- H(bb)
  - largest BR
  - high ϵ_b, low fake rate suppress light QCD background
  - but, bb QCD still high
- H(γγ)
  - low BR, but
  - low backgrounds
  - excellent mass resolution

$\mathrm{H}(\gamma\gamma)\mathrm{H}(b\bar{b})$

CMS-HIG-17-008

- 2 photons, 2 b-jets
- nonresonant + resonant
- b-jet energy regression to improve $m_{b\bar{b}}$ resolution
- 2D fit of $m_{b\bar{b}}$ vs. $m_{\gamma\gamma}$
- main background: γ+jets
  - smooth 2D surface in the fit
- SM single Higgs (from MC)
  - ridge in the fit

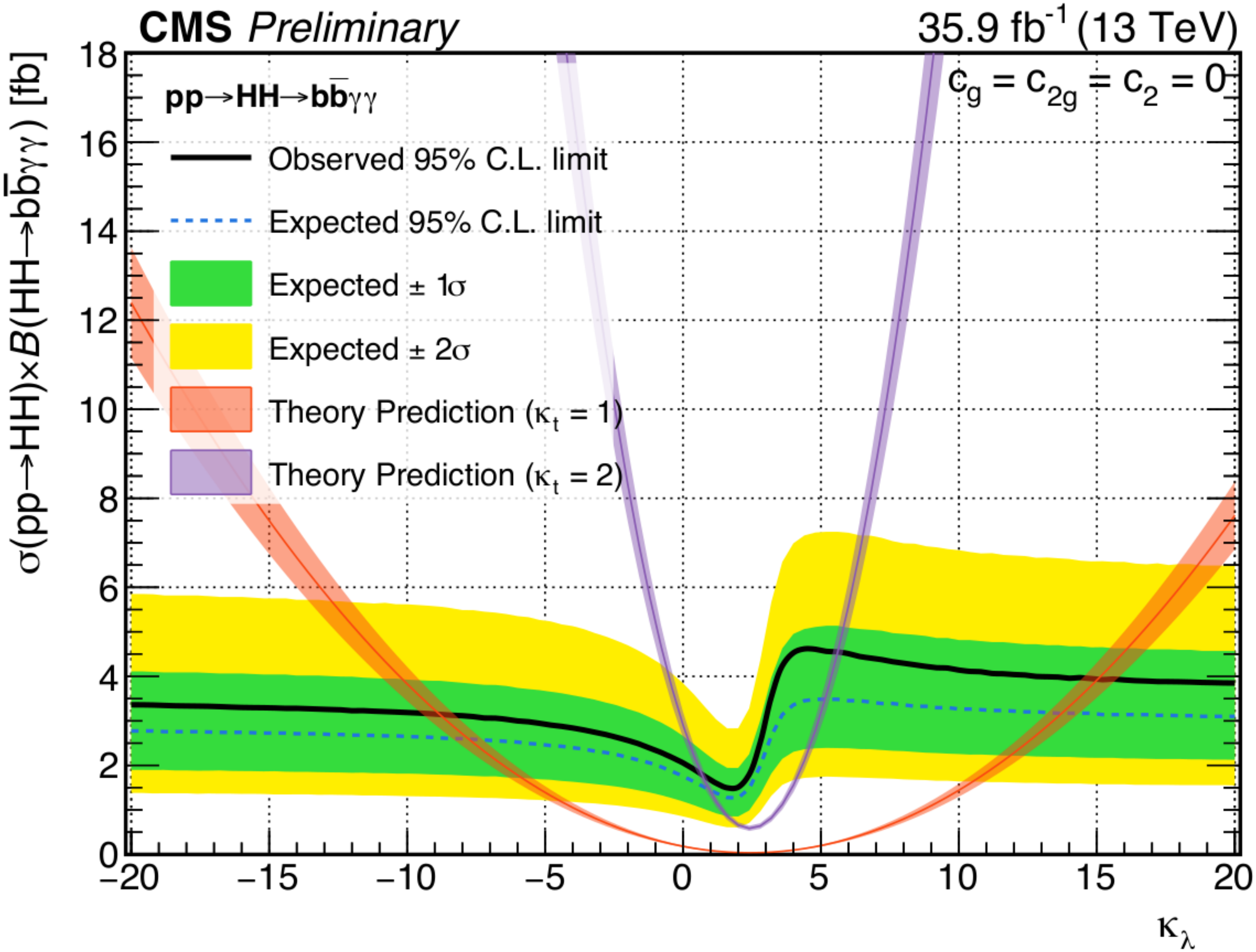




$\mathrm{H}(\gamma\gamma)\mathrm{H}(b\bar{b})$

CMS-HIG-17-008

- Likelihood: joint probability $m_{\gamma\gamma}$ vs. $m_{b\bar{b}}$

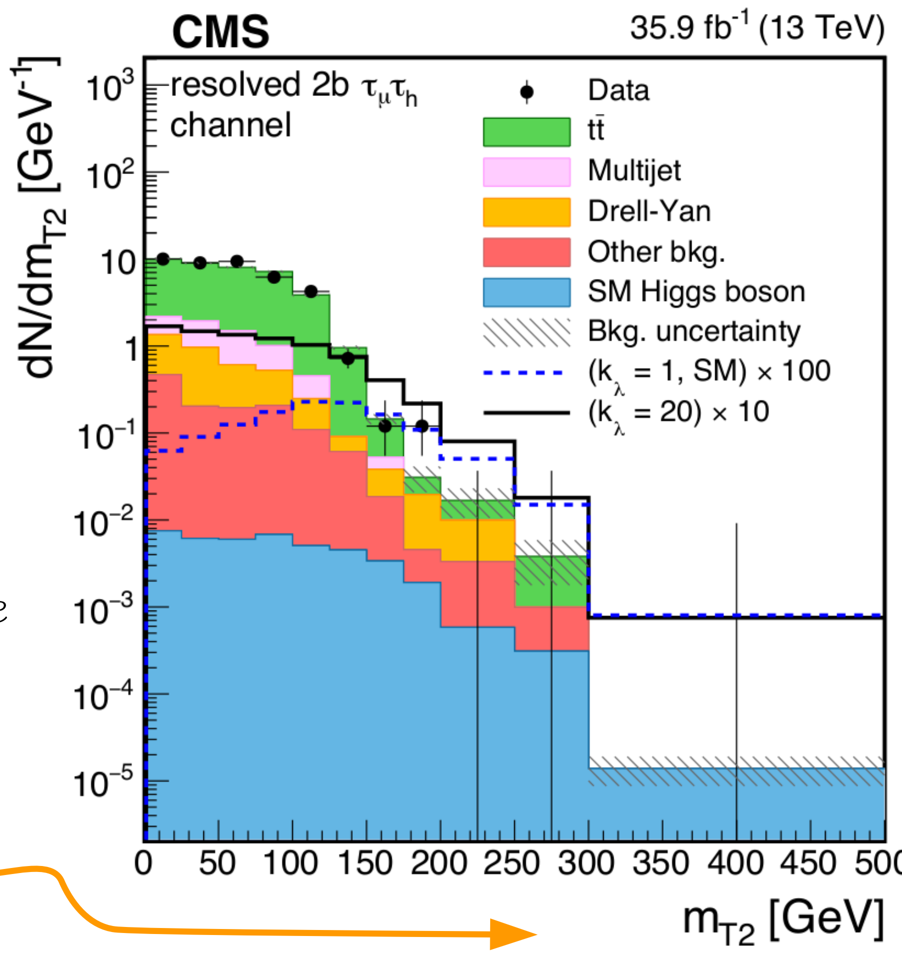


- obs. (exp) limit corresponds to ~ 19 (16) x SM
- anomalous k_λ coupling probed

$\mathrm{H}(\tau\tau)\mathrm{H}(b\bar{b})$

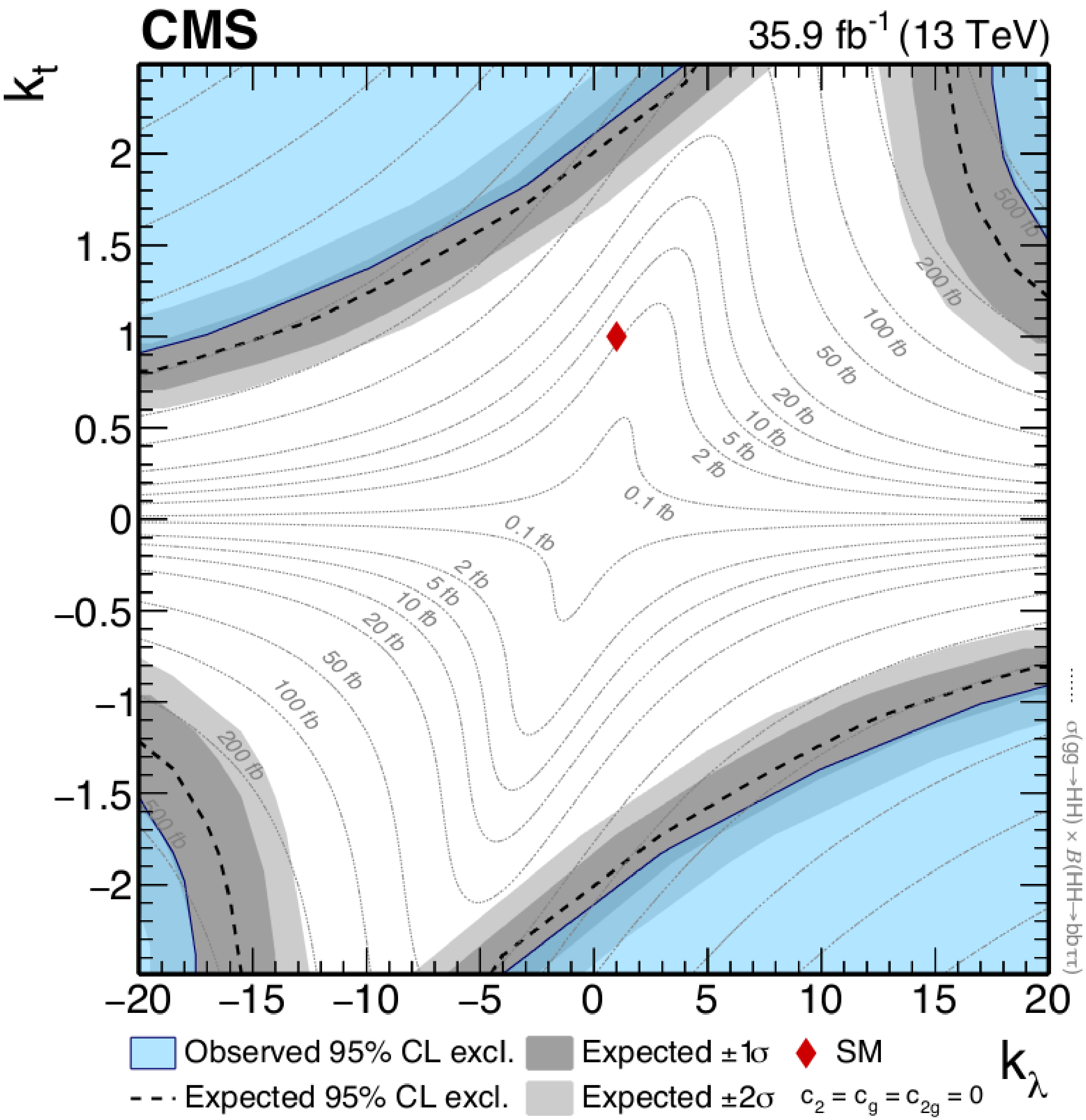
Phys. Lett. B 778 (2018) 101

- $\tau_h\tau_\mu + \tau_h\tau_e + \tau_h\tau_h \quad (88\%)$
- 2 jets (resolved) or 1 large-R jet (boosted)
- Likelihood fit to estimate $m_{\tau\tau}$ (despite $p_{\mathrm{T}}^{\mathrm{miss}}$)
- $m_{b\bar{b}}, m_{\tau\tau}$ compatible with m_H
- Events categorized by N_b
- Main backgrounds:
  - $t\bar{t}$, Z/γ*+jets (from MC)
  - multijet (from data)
- BDT to reject $t\bar{t}$ in $\tau_h\tau_\mu + \tau_h\tau_e$
  - based on angular separation of leptons and visible mass
- m_{T2} used to extract the signal



$\mathrm{H}(\tau\tau)\mathrm{H}(b\bar{b})$

Phys. Lett. B 778 (2018) 101



- Obs. (exp.) limit
  ~ 30 (25) x SM

- Anomalous k_λ and k_t couplings tested
  - Sensitive to sign of k_t

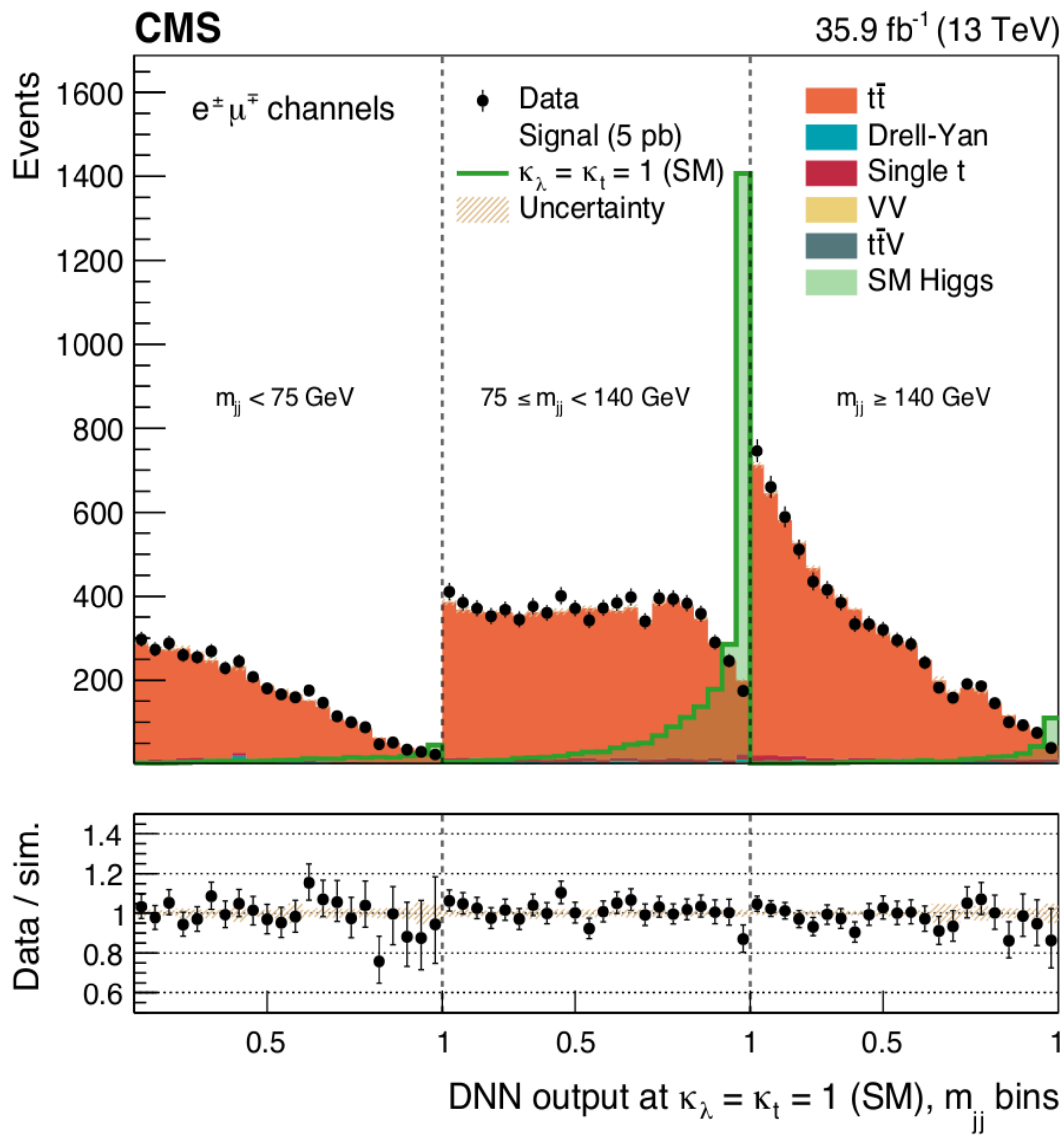
$\mathrm{H}(VV^* \to \ell\nu\ell\nu)\mathrm{H}(b\bar{b})$

JHEP 01 (2018) 054

- 2 OS leptons
  - (ee, μμ and eμ+μe)
- 2 b-jets

- Main backgrounds:
  - $t\bar{t}$ (from MC)
  - Z+jets (from 0 b-jets data)

- DNN to separate signal from $t\bar{t}$
  - Parametrized as function of k_λ and k_t
- m_{jj} and DNN classifier used to categorize events



$\mathrm{H}(VV^* \to \ell\nu\ell\nu)\mathrm{H}(b\bar{b})$

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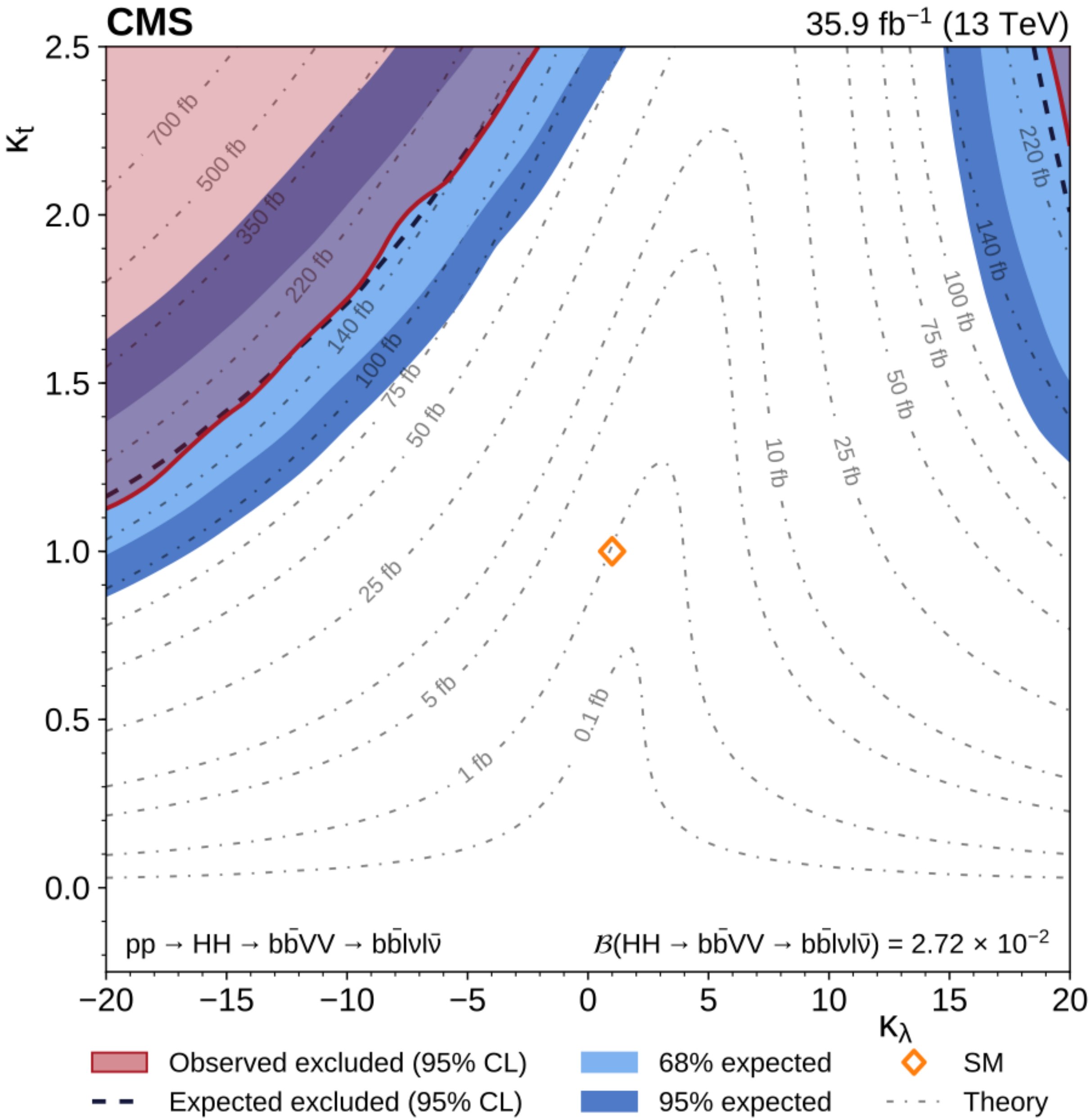
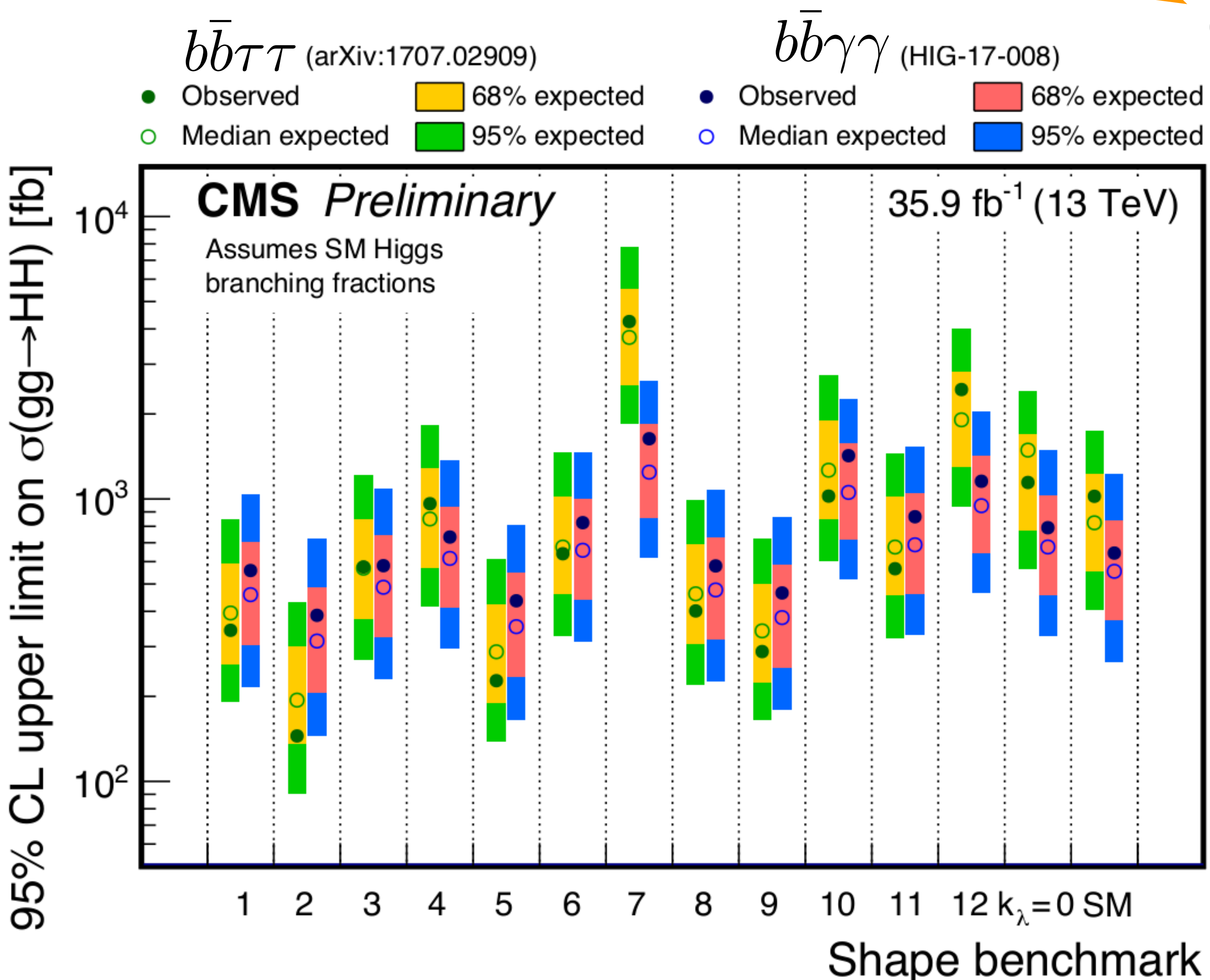
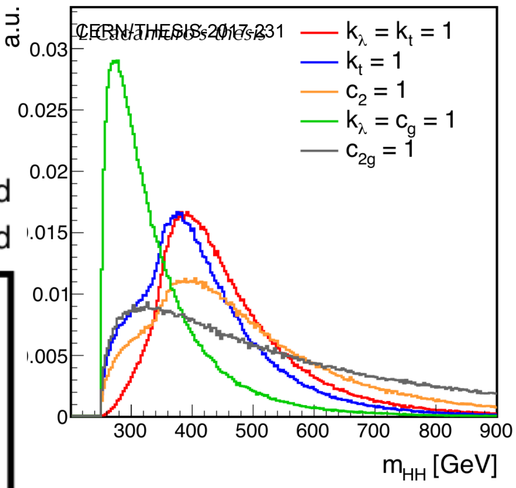


- The final DNN discriminant is used in three $m_{b\bar{b}}$ regions
- Obs. (exp.) limit ~ 79 (89) x SM
- Anomalous k_λ and k_t couplings tested

BSM limits for $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$

- BSM: 12 "benchmark points"

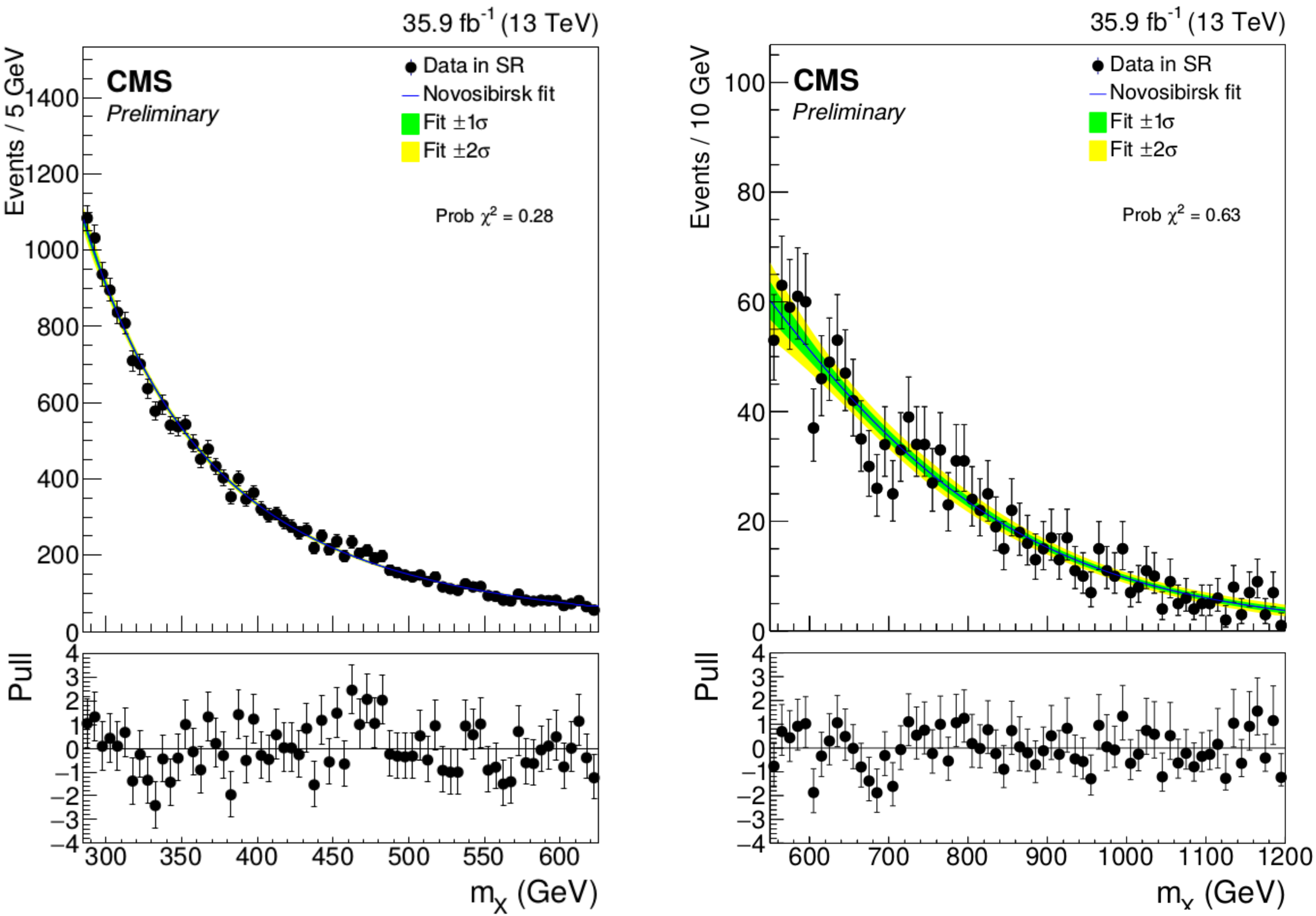




$X \to H(b\bar{b})H(b\bar{b})$ "resolved"

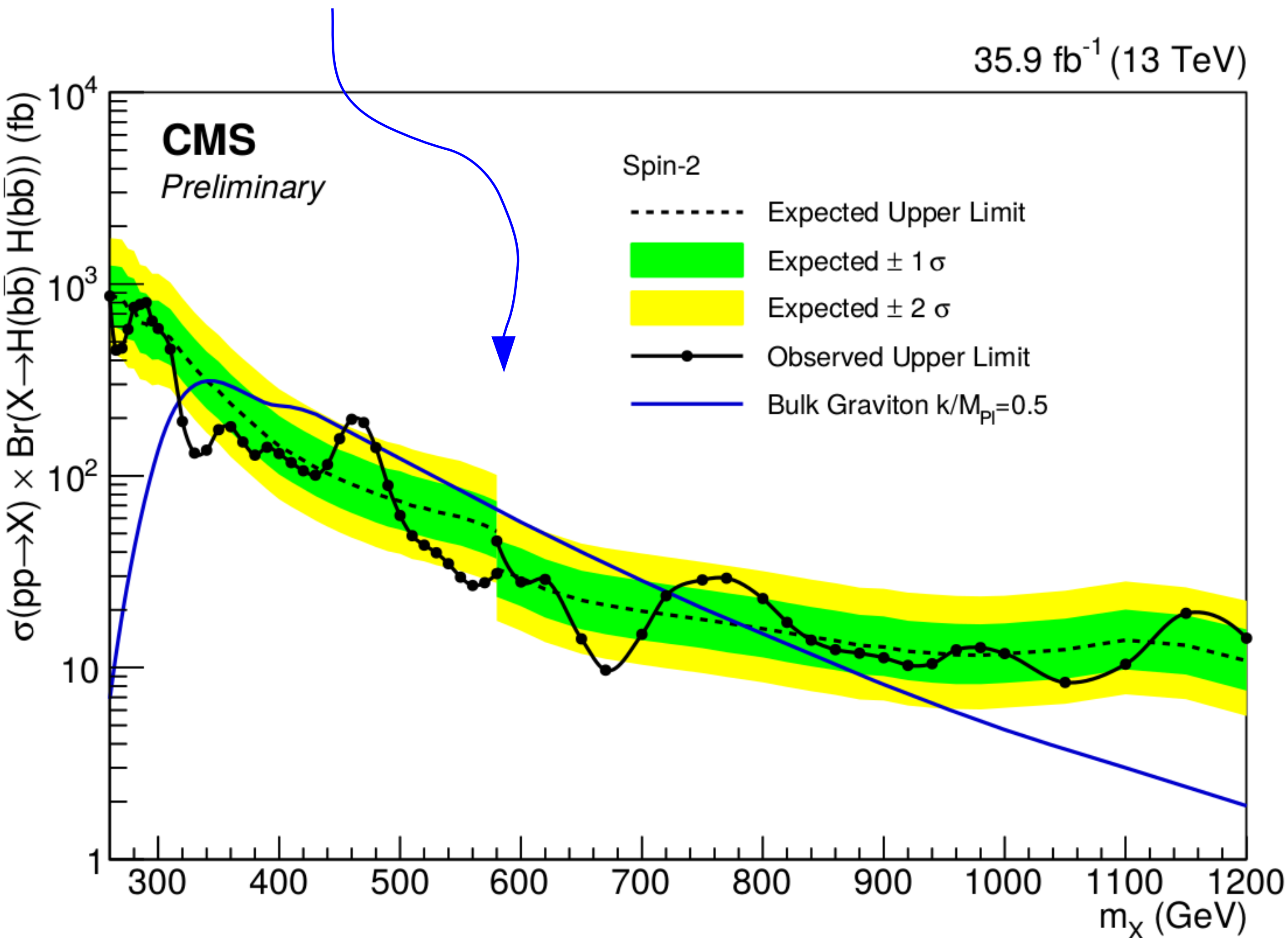
HIG-17-009

- 4 b-tagged jets, kinematic fit
- Main background: multijet (QCD + ttbar) (from data)



$X \to H(b\bar{b})H(b\bar{b})$ "resolved"

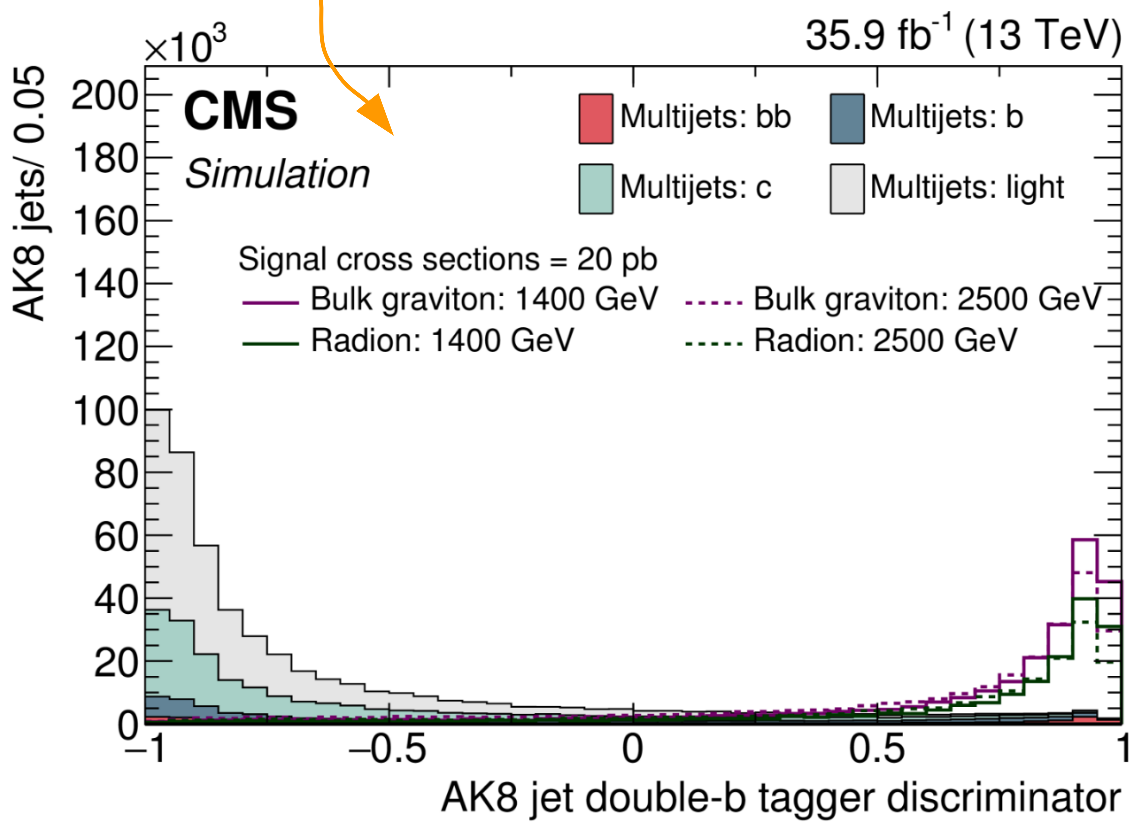
- Bulk graviton limit
- Discontinuity where two strategies change



$X \rightarrow H(b\bar{b})H(b\bar{b})$ "boosted"

PLB 781 (2018) 244

- Large $p_T(H) \rightarrow$ hadronizations of form a single "fat" jet!
  - BDT using both displaced vertices and hadronization information
  - Calibrated on data



$X \rightarrow H(b\bar{b})H(b\bar{b})$ "boosted"

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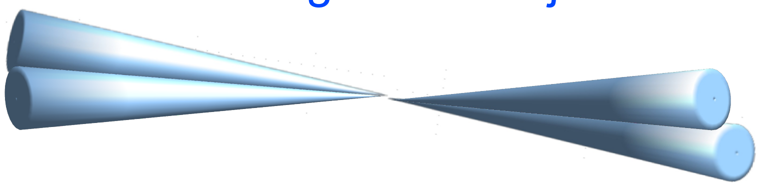
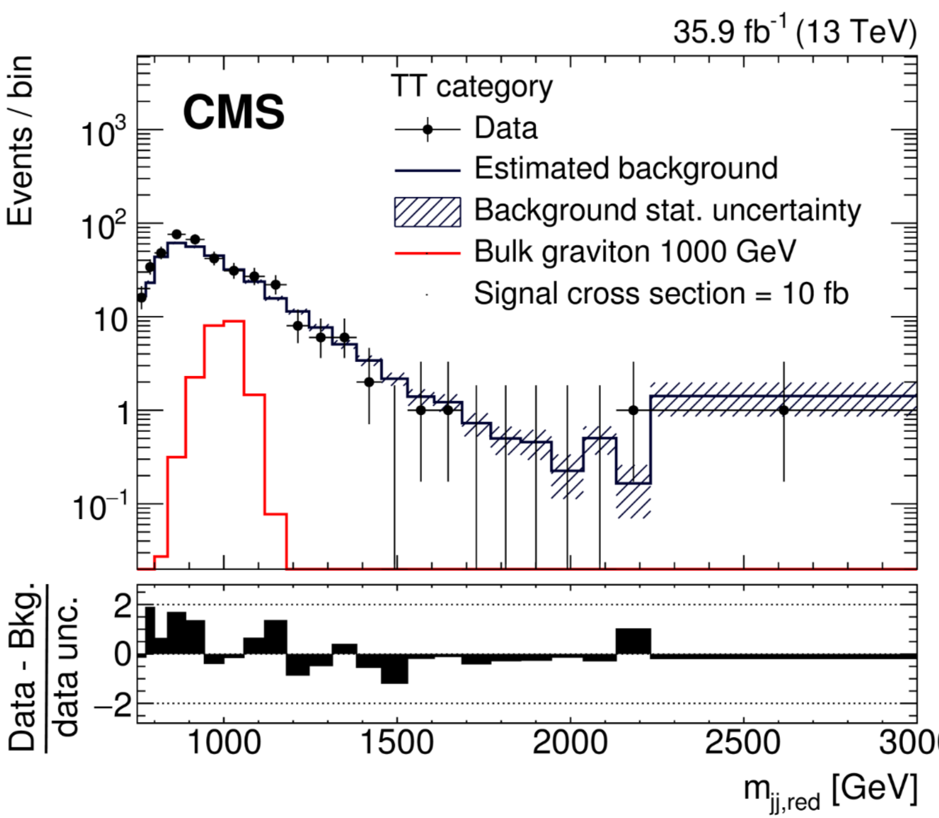
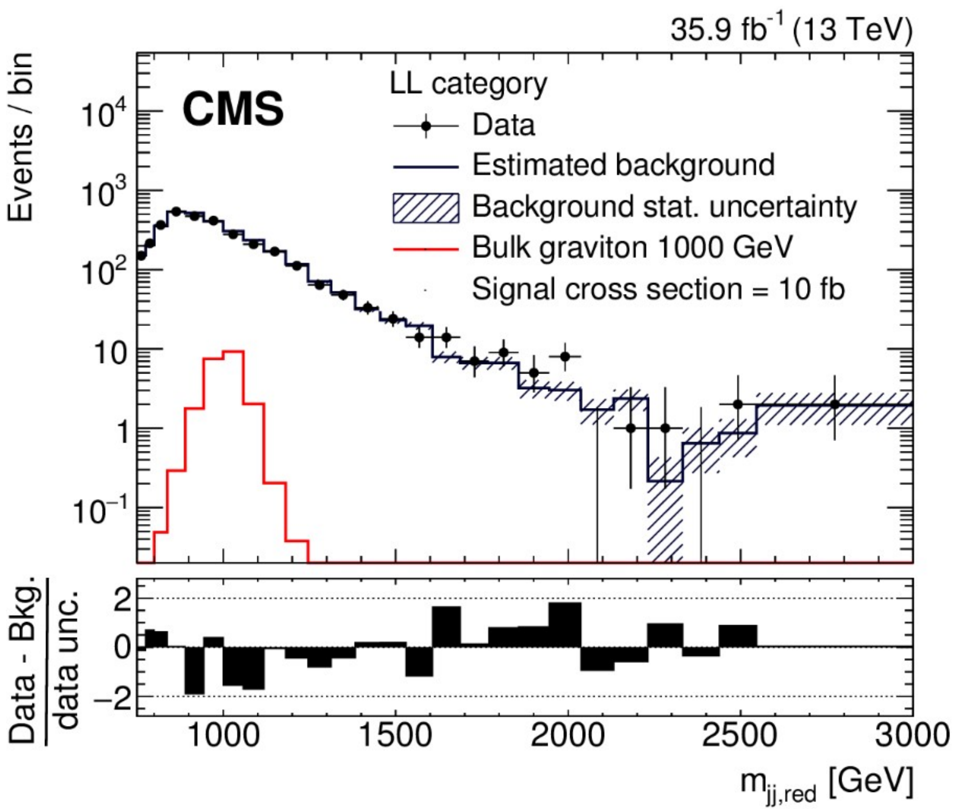
- Improve access to large m_{HH}

Two merged H→bb jets



- Main bkg: QCD
- Estimated from data





$X \to H(b\bar{b})H(b\bar{b})$ "boosted"

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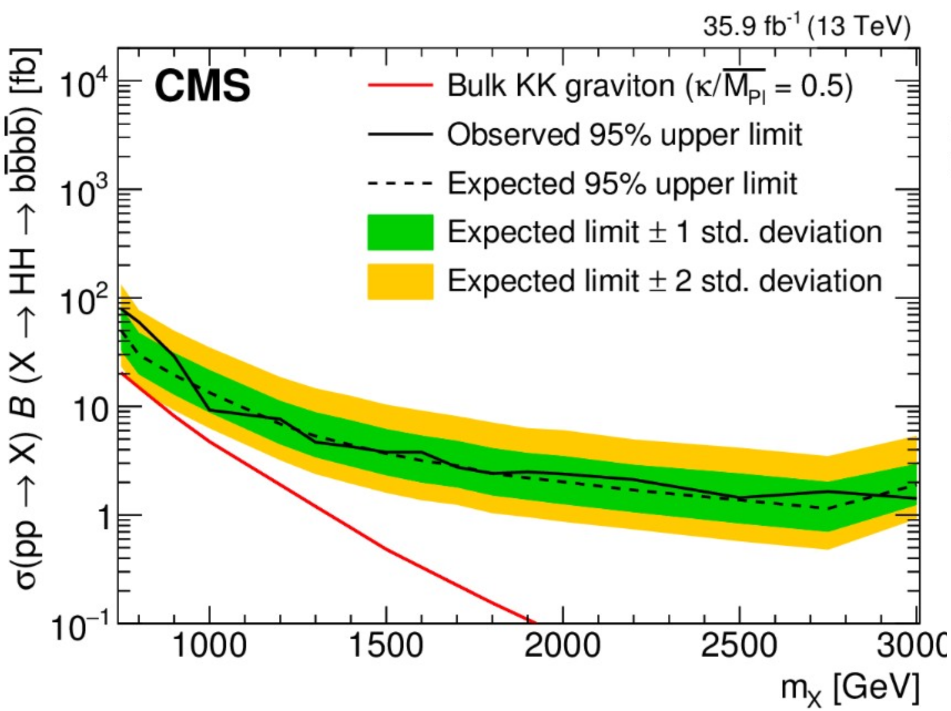
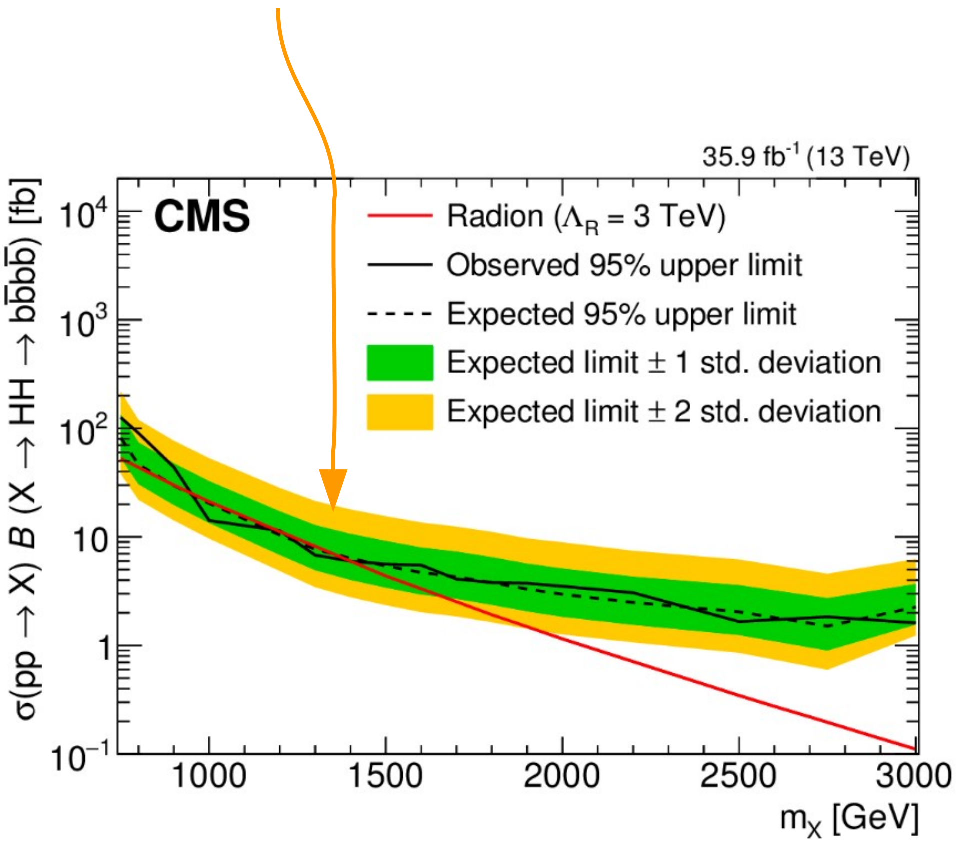
- Improved limits for high masses (esp. radion)





Conclusions

- CMS has a broad (and still expanding) program of searches for HH production
  - both resonant and non-resonant
- New searches:
  - boosted channels, non-resonant...
- Keep improving and adding new channels
- Try to reach sensitivity of SM HH production
  - but keep an eye on BSM as well!
- Still a lot of Run 2 data to analyze!

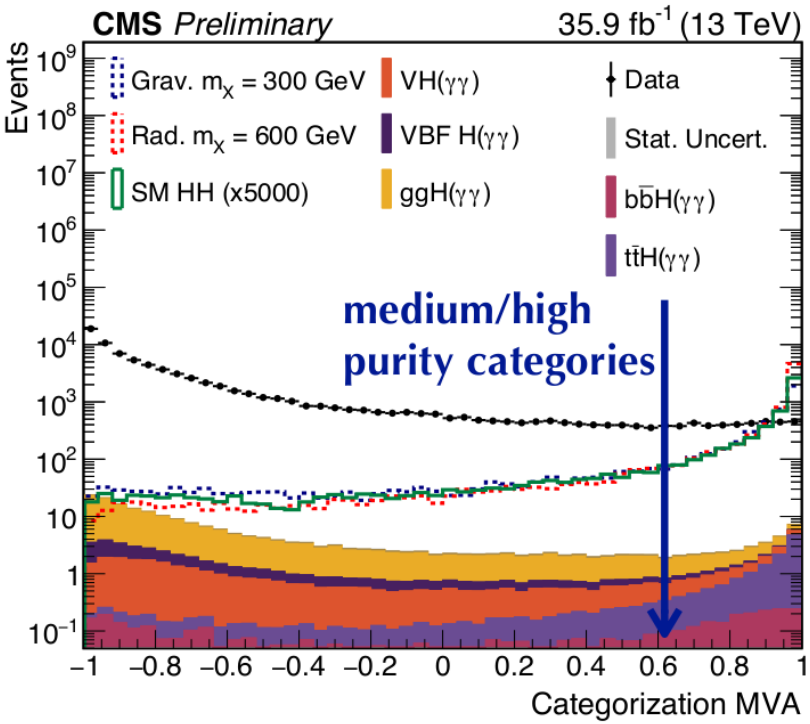
BACKUP MATERIAL

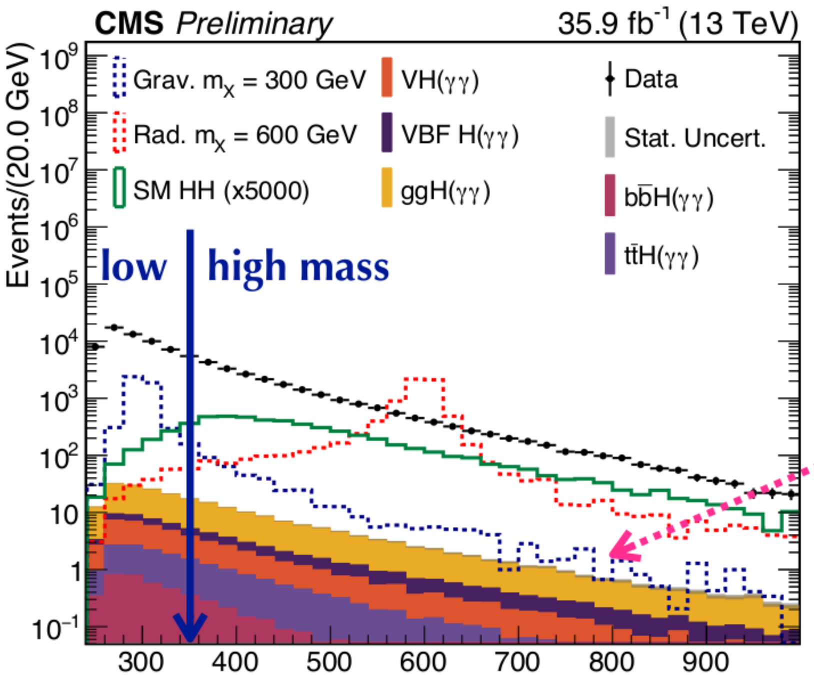
$H(\gamma\gamma)H(b\bar{b})$

CMS-HIG-17-008

- 2 photons, 100< $m_{\gamma\gamma}$<180 GeV
- 2 b jets, 70< $m_{b\bar{b}}$<190 GeV
- b-jet energy regression to improve $m_{b\bar{b}}$ resolution

- Mx and BDT (including angular correlations) used to categorize events
- γ+jets (from data)
- SM single Higgs (from MC)





$$M_X = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - m_H) - (m_{\gamma\gamma} - m_H)$$

$\mathrm{H}(\gamma\gamma)\mathrm{H}(b\bar{b})$

Sources of Systematical Uncertainties	Type	Value
General uncertainties		
Integrated luminosity	Normalization	2.5%
Photon related uncertainties		
Photon energy scale ($\frac{\Delta M(\gamma\gamma)}{M(\gamma\gamma)}$)	Shape	1.0%
Photon energy resolution ($\frac{\Delta\sigma_{\gamma\gamma}}{\sigma_{\gamma\gamma}}$)	Shape	1.0%
Diphoton selection (with trigger uncertainties and PES)	Normalization	2.0%
Photon Identification	Normalization	1.0%
Jet related uncertainties		
Jet energy scale ($\frac{\Delta M(jj)}{M(jj)}$)	Shape	1.0%
Jet energy resolution ($\frac{\Delta\sigma_{jj}}{\sigma_{jj}}$)	Shape	5.0%
Dijet selection (JES)	Normalization	0.5%
Nonresonant specific uncertainties		
$\tilde{M}_X$ Classification	Normalization	0.5%
Classification MVA (high purity)	Normalization	5%
Classification MVA (medium purity)	Normalization	2.0%

$\mathrm{H}(\tau\tau)\mathrm{H}(b\bar{b})$

Phys. Lett. B 778 (2018) 101

Systematic uncertainty	Value	Processes
Luminosity	2.5%	all but multijet, $Z/\gamma^* \to \ell\ell$
Lepton trigger and reconstruction	2–6%	all but multijet
τ energy scale	3–10%	all but multijet
Jet energy scale	2–4%	all but multijet
b tag efficiency	2–6%	all but multijet
Background cross section	1–10%	all but multijet, $Z/\gamma^* \to \ell\ell$
$Z/\gamma^* \to \ell\ell$ SF uncertainty	0.1–2.5%	$Z/\gamma^* \to \ell\ell$
Multijet normalization	5–30%	multijet
Scale unc.	+4.3%/−6.0%	signals
Theory unc.	5.9%	signals

$\mathrm{H}(VV^* \to \ell\nu\ell\nu)\mathrm{H}(b\bar{b})$

JHEP 01 (2018) 054

Source	Background yield variation	Signal yield variation
Electron identification and isolation	2.0–3.2%	1.9–2.9%
Jet b tagging (heavy-flavour jets)	2.5%	2.5–2.7%
Integrated luminosity	2.5%	2.5%
Trigger efficiency	0.5–1.4%	0.4–1.4%
Pileup	0.3–1.4%	0.3–1.5%
Muon identification	0.4–0.8%	0.4–0.7%
PDFs	0.6–0.7%	1.0–1.4%
Jet b tagging (light-flavour jets)	0.3%	0.3–0.4%
Muon isolation	0.2–0.3%	0.1–0.2%
Jet energy scale	<0.1–0.3%	0.7–1.0%
Jet energy resolution	0.1%	<0.1%
Affecting only $t\bar{t}$ (85.1–95.7% of the total bkg.)		
μ_R and μ_F scales	12.8–12.9%	
$t\bar{t}$ cross section	5.2%	
Simulated sample size	<0.1%	
Affecting only DY in $e^{\pm}\mu^{\mp}$ channel (0.9% of the total bkg.)		
μ_R and μ_F scales	24.6–24.7%	
Simulated sample size	7.7–11.6%	
DY cross section	4.9%	
Affecting only DY estimate from data in same-flavour events (7.1–10.7% of the total bkg.)		
Simulated sample size	18.8–19.0%	
Normalisation	5.0%	
Affecting only single top quark (2.5–2.9% of the total bkg.)		
Single t cross section	7.0%	
Simulated sample size	<0.1–1.0%	
μ_R and μ_F scales	<0.1–0.2%	
Affecting only signal	SM signal	$m_X = 400\,\mathrm{GeV}$
μ_R and μ_F scales	24.2%	4.6–4.7%
Simulated sample size	<0.1%	<0.1%