Searches for non-resonant HH production at CMS

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On behalf of CMS Collaboration

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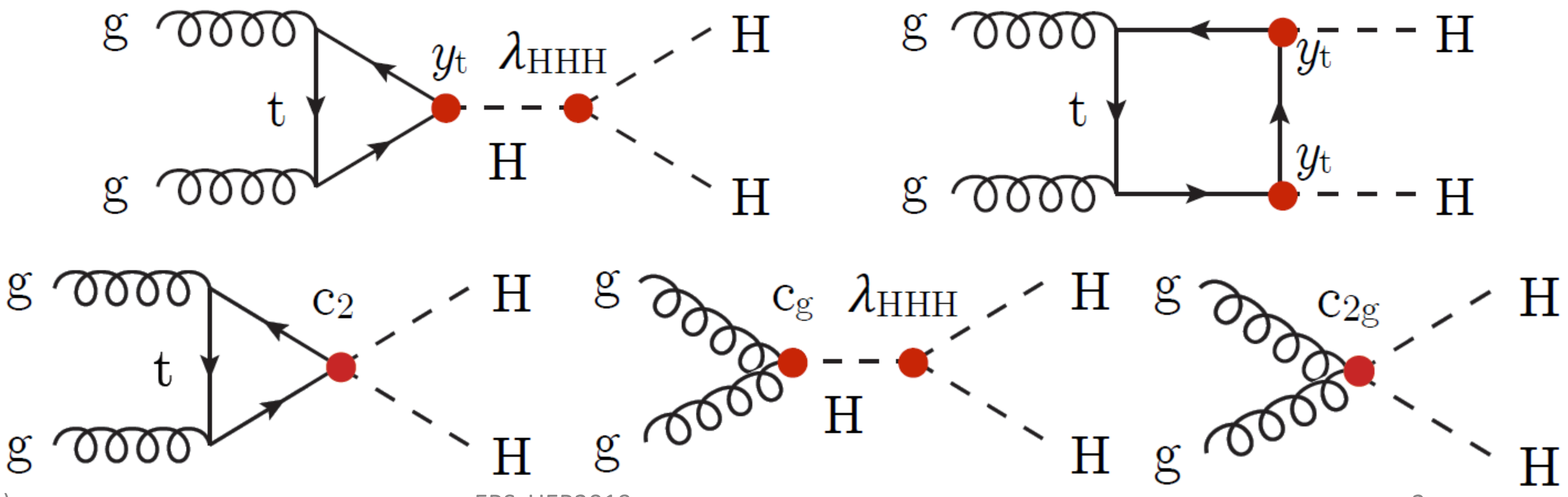
non-resonant HH production

- Can be used to directly study the **Higgs boson self-coupling**
- At CERN LHC is mainly produced through gluon fusion via fermion loop
- In Standard Model **destructive interference** of box and triangle contributions → tiny cross section (33.49 fb *)
- BSM processes can modify the cross-section and kinematic properties → EFT approach → results in **5 parameters** controlling tree-level interactions (k_λ, k_t, c_g, c_{2g}, c_2)

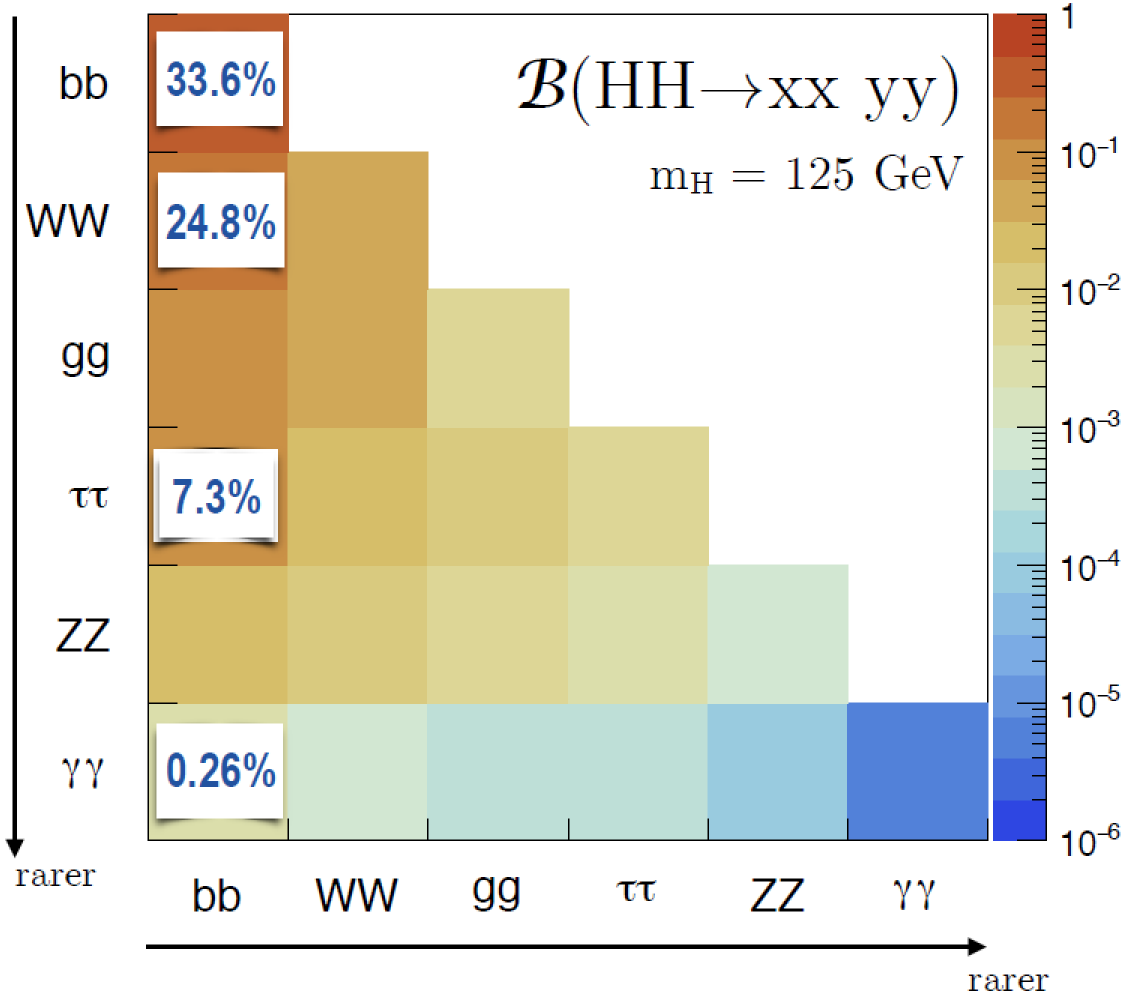
*old value used in the presented analyses, the most recent prediction is 31.05fb

$$\boldsymbol{k_\lambda = \lambda_{HHH}/\lambda_{SM}}$$
$$\boldsymbol{k_t = y_t/y_{SM}}$$

12 benchmarks chosen to study different possible modification of SM HH signal (JHEP 04 (2016) 126)



HH decay channels

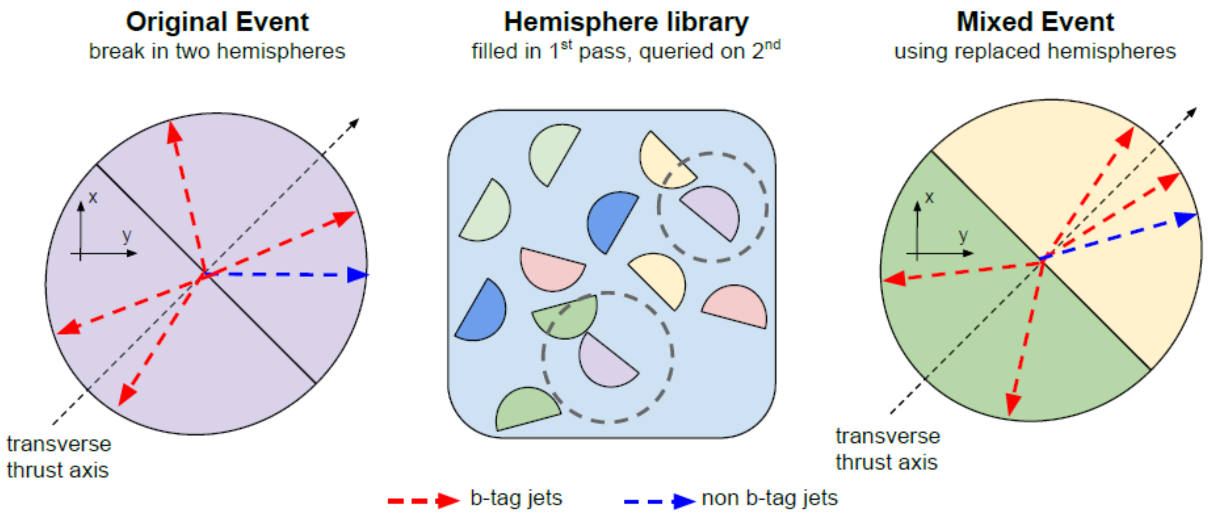


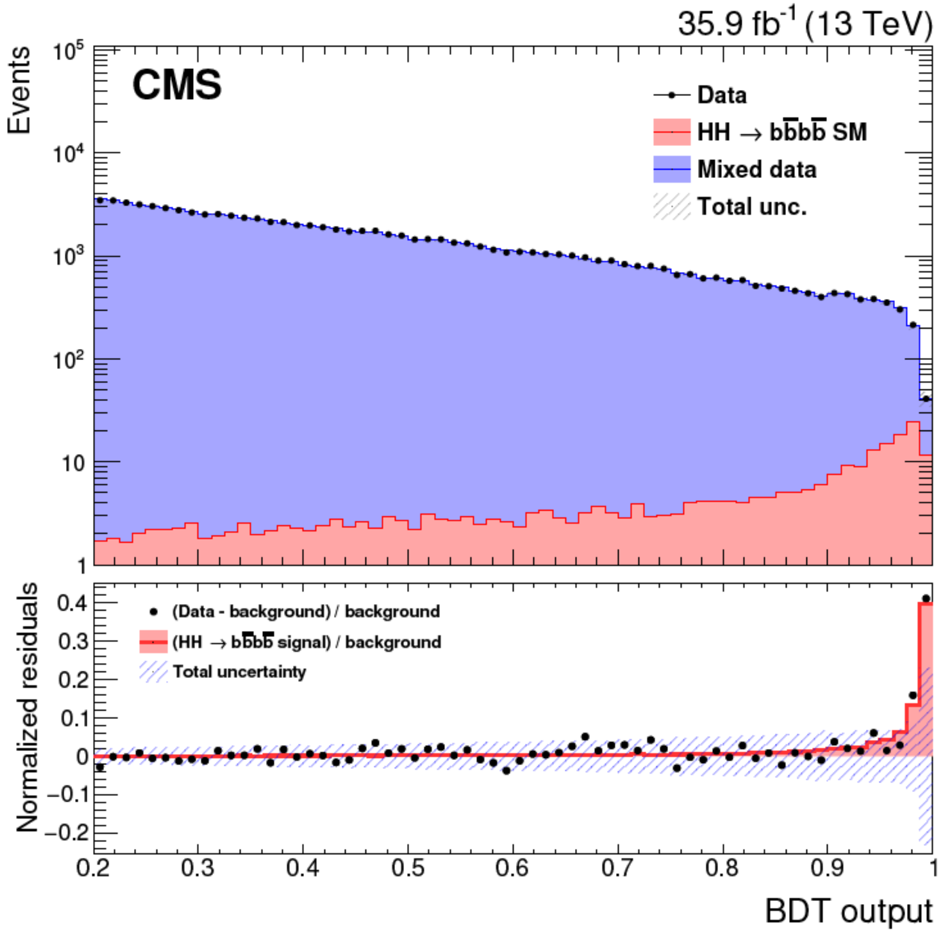
- Rich phenomenology with many final states accessible at LHC
- **Run 1**: CMS performed searches in **bb$\gamma\gamma$** and **bb$\tau\tau$** final states → combined upper limit on HH cross section: 43 times SM expectation
- **Run 2**: opportunity for HH because of increase in the cross section
- **4 final states explored** by CMS at 13 TeV with 35.9fb^{-1} (2016 data)
  → **Combination** performed

HH→4b

JHEP04(2019)112

- Final state with **4 identified b-jets**, paired into Higgs boson candidates
- BDT trained on HH-decay kinematics to enhance the sensitivity
- Background model created with **hemisphere mixing technique** applied to signal region events and validated in data control regions
- Dominant bkg: QCD multi-jet events





HH→4b

JHEP04(2019)112

- BDT discriminant values > 0.2 for extracting the limits
- Two component likelihood fit performed on the binned BDT output distribution

SM

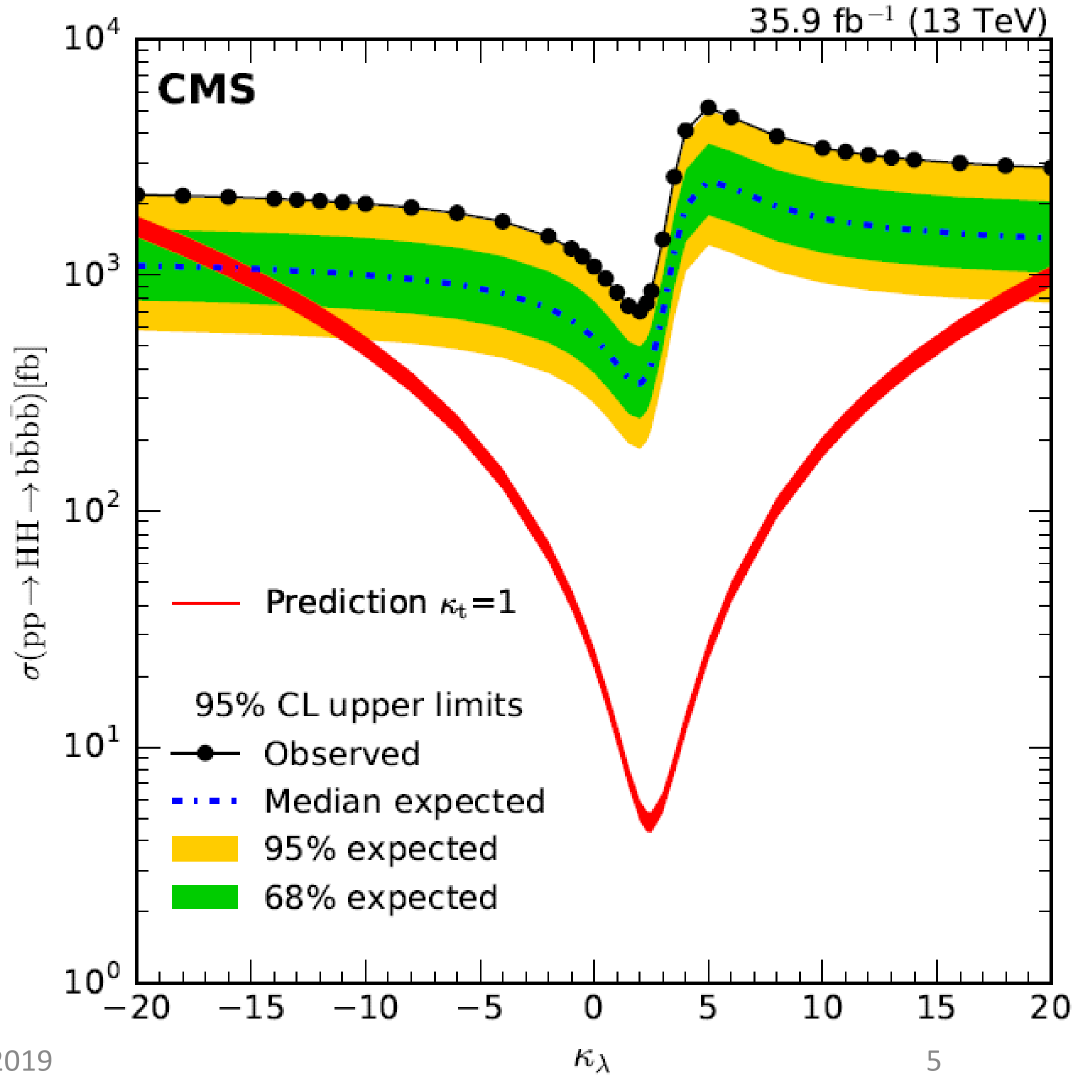
- Observed (Exp.) 95% CL upper limit:

$$\boldsymbol{\sigma(pp \rightarrow HH \rightarrow b\bar{b}b\bar{b}) = 847\ (419)\ \text{fb}}$$

- Corresponds to 75 (37) × SM expectation

BSM

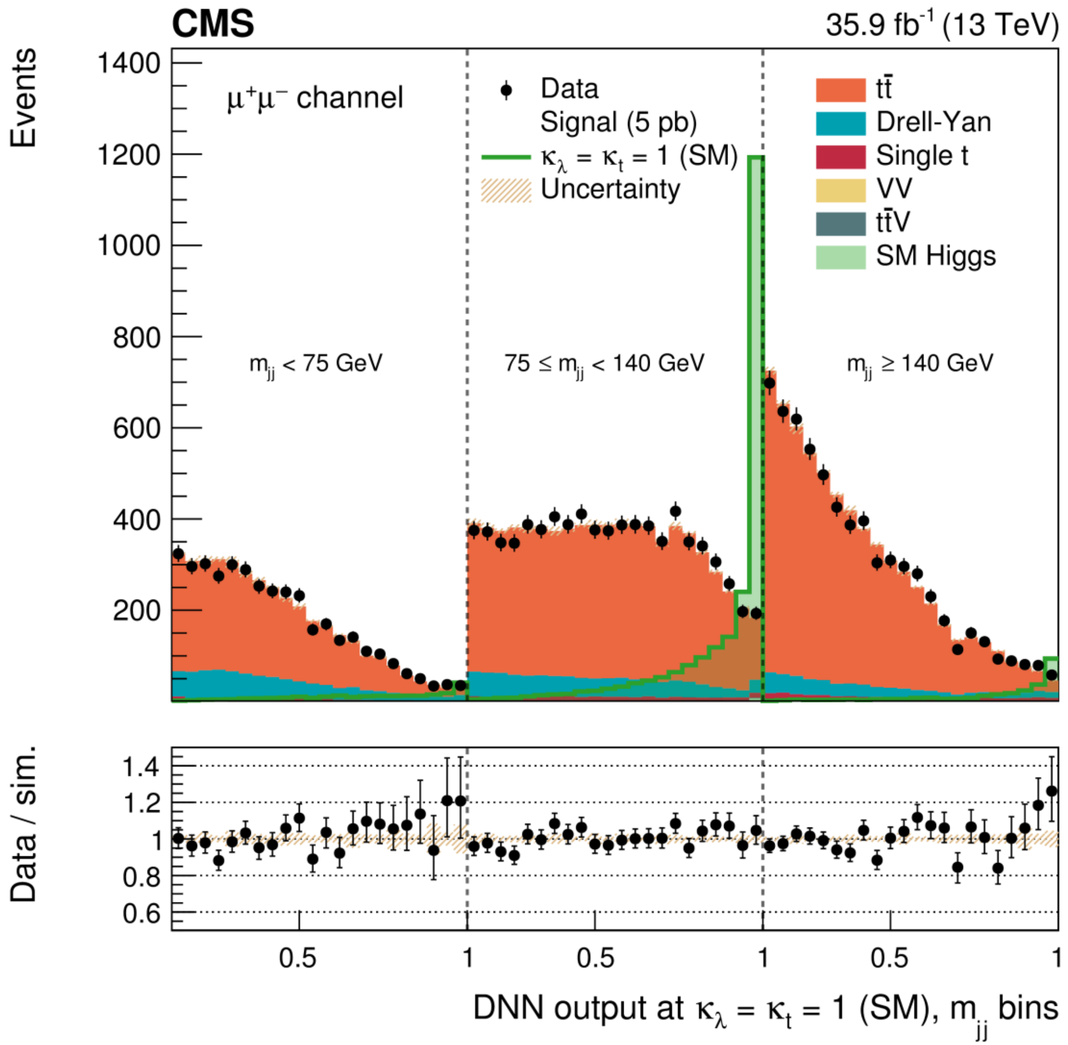
- HH production with k_λ values in range [-20,20] (k_t=1) → **no $\boldsymbol{k_\lambda}$ values excluded**



HH→bblνlν

JHEP01(2018)054

- Events selected if **2 opposite charge leptons** $(e^+e^-, \mu^+\mu^-, e^\pm\mu^\pm)$ and **2 b-jets**
- Events come from $\underline{HH \rightarrow bbWW \rightarrow bbl\nu l\nu}$ and $\underline{HH \rightarrow bbZZ^* \rightarrow bb\nu\nu ll}$ processes
- **mass requirement** $(12 < m_{\ell\ell} < m_Z - 15\ GeV)$ to suppress quarkonia resonances and Z boson background
- Large irreducible background from $t\bar{t}$ and Drell-Yan processes → **DNN** to discriminate signal from background



$HH \to bbl\nu l\nu$

JHEP01(2018)054

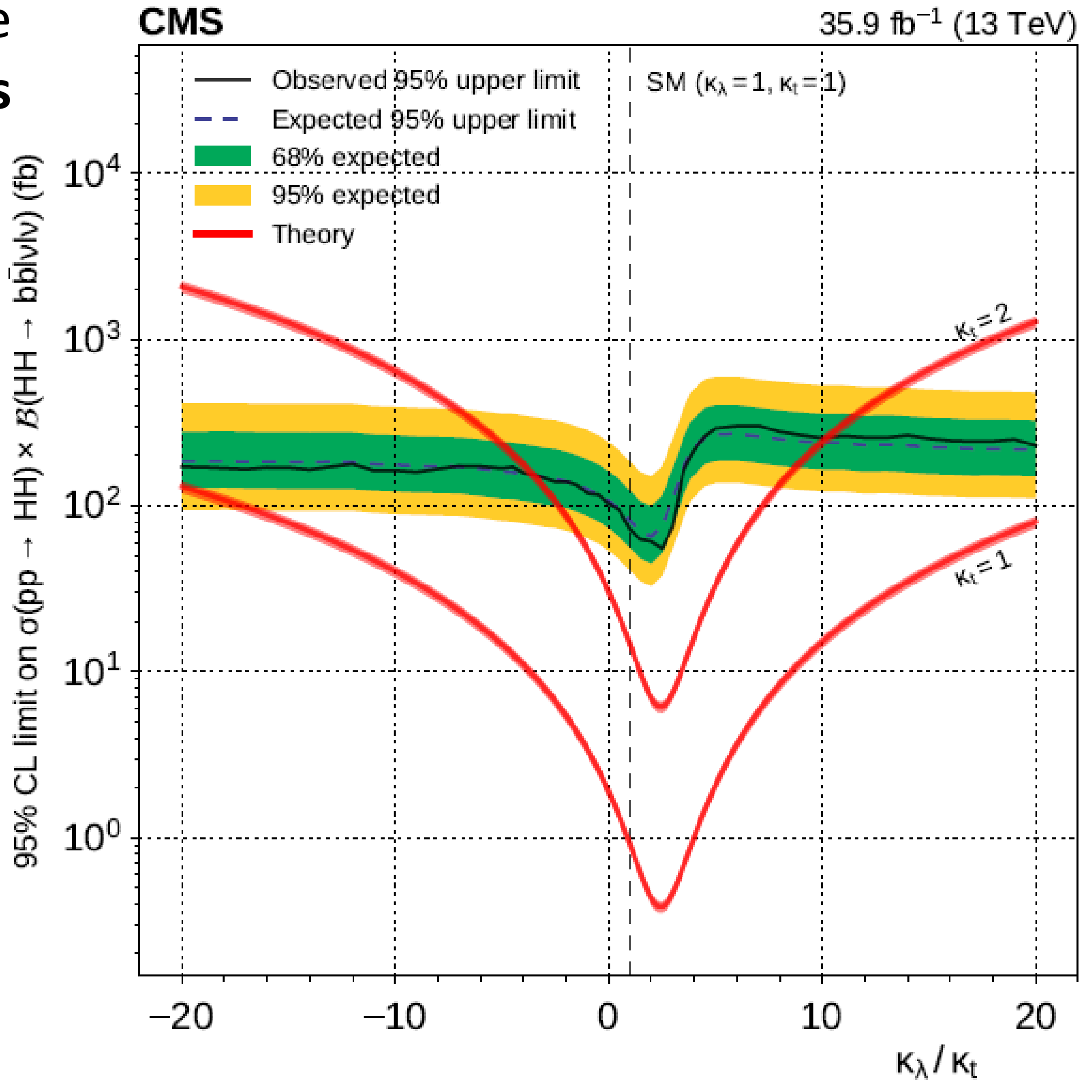
- Binned Maximum Likelihood fit performed over the DNN output distributions in **3 different m_{jj} regions** and **3 channels** $(e^+e^-, \mu^+\mu^-, e^\pm\mu^\pm)$

SM

- Observed (Exp.) 95% CL upper limit
  $$\sigma(pp \to HH \to b\bar{b}\ell\nu\ell\nu) = 72\ (81^{+42}_{-25})\ \text{fb}$$
- Corresponds to 79 (89) × SM expectation

BSM

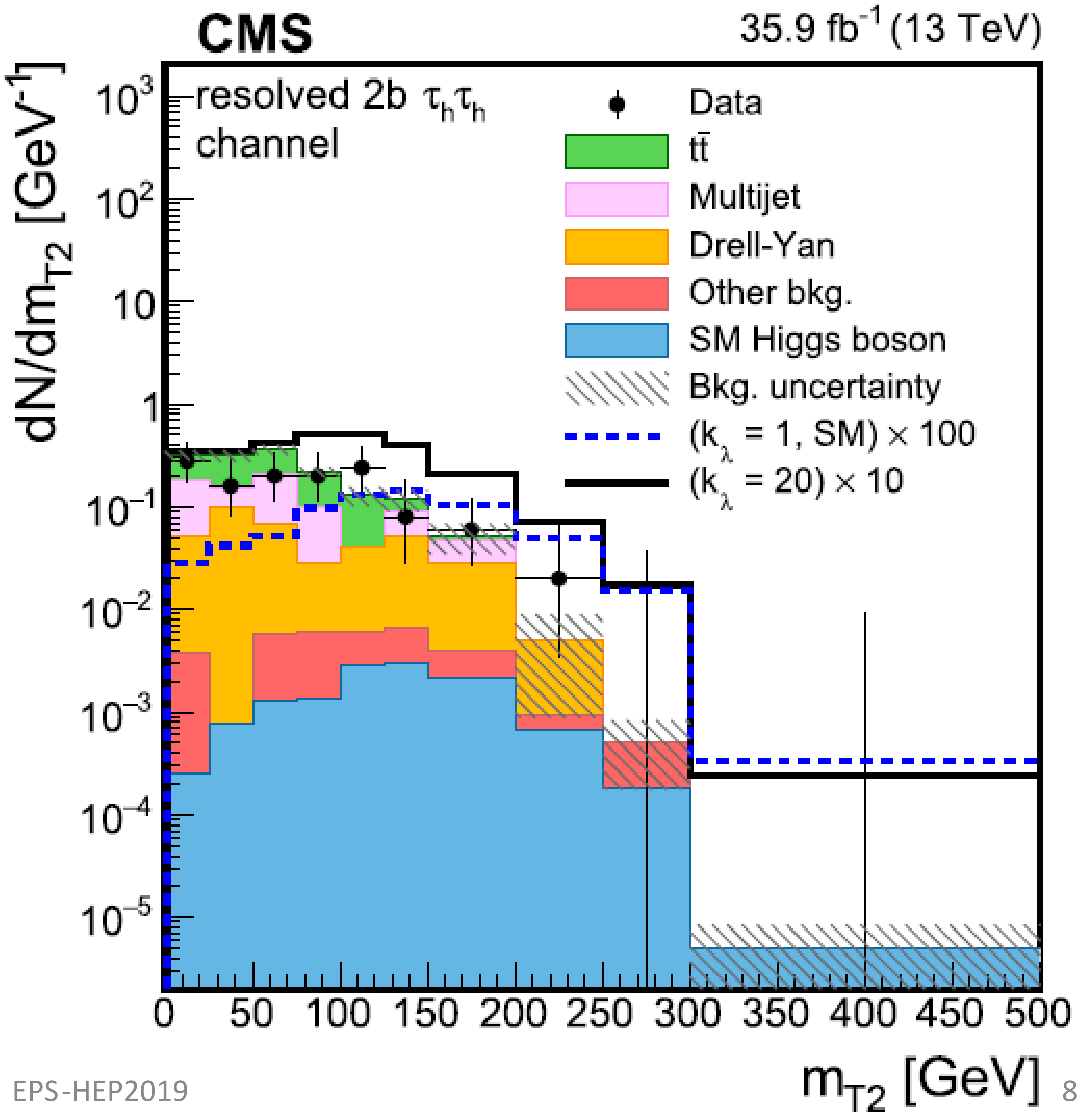
- Upper limits set as a function of k_λ / k_t



$HH \to bb\tau\tau$

PLB 778 (2018) 101

- Select events with **1 isolated $\boldsymbol{\tau_{had}}$** with a **second lepton of opposite charge** (e, μ or τ_{had})
- Events categorized according to number of b-jets
- Main background sources: $t\bar{t}$, $Z/\gamma^* \to \ell\ell$, QCD multi-jets (data-driven estimate)
- **BDT** discriminant trained on kinematic variables used to reduce $t\bar{t}$ background
- **Stranverse mass $\boldsymbol{m_{T2}}$** provide best separation between HH signal and background



$HH \rightarrow bb\tau\tau$

PLB 778 (2018) 101

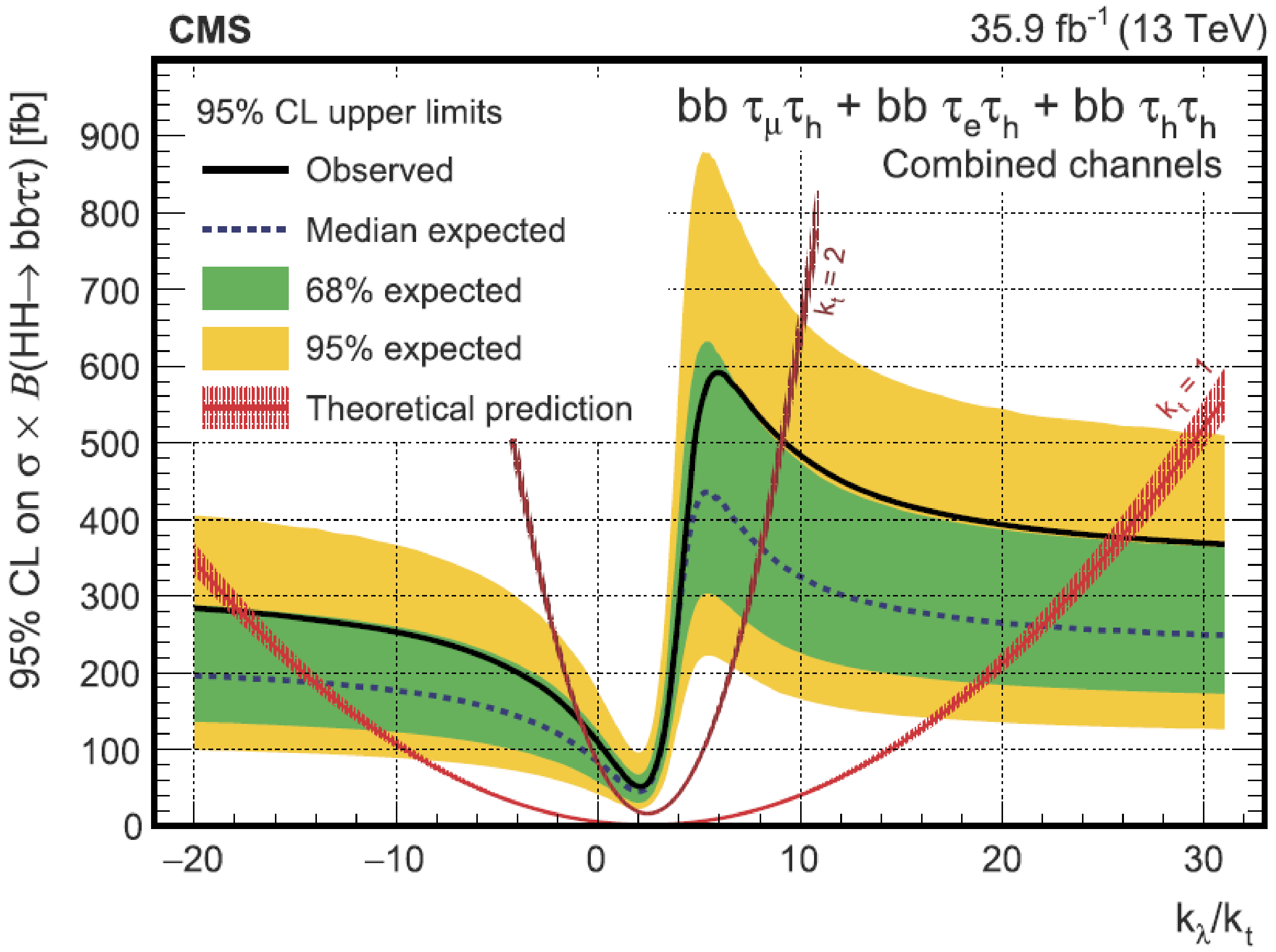
- Binned Maximum Likelihood fit performed on the m_{T2} distributions, in the 3 final states

SM

- Observed (Exp.) 95% CL upper limit $\boldsymbol{\sigma(pp \rightarrow HH \rightarrow b\bar{b}\tau\tau) = 75.4\ (61.0)\ \mathrm{fb}}$
- Corresponds to 30 (25) × SM expectation

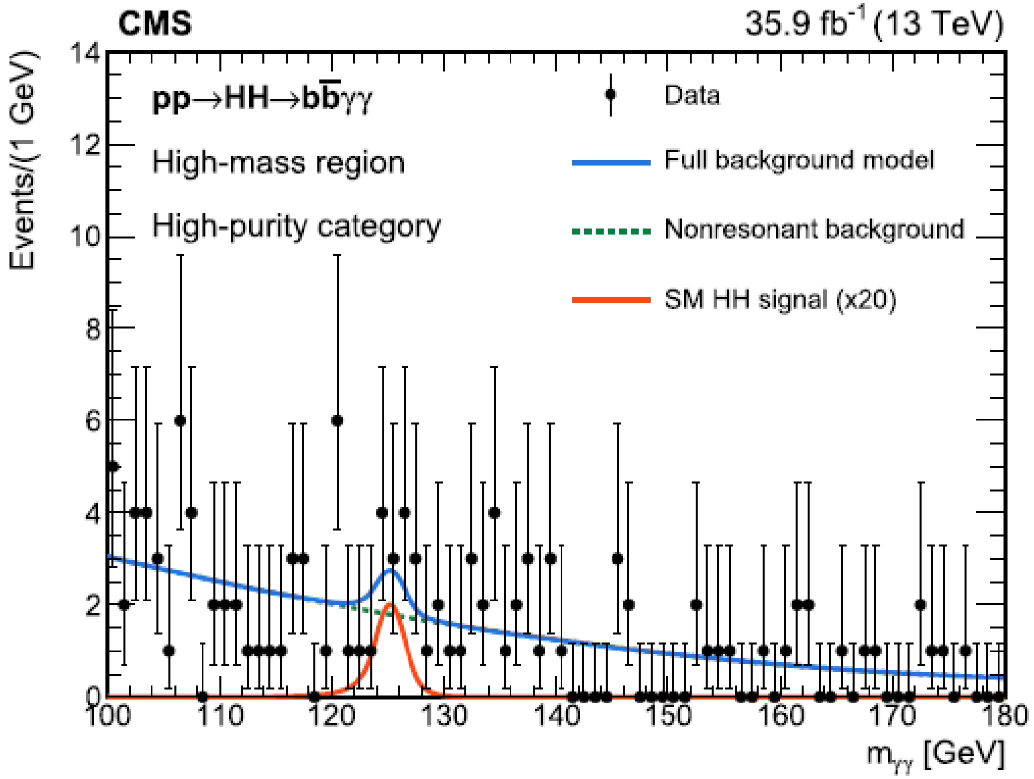
BSM

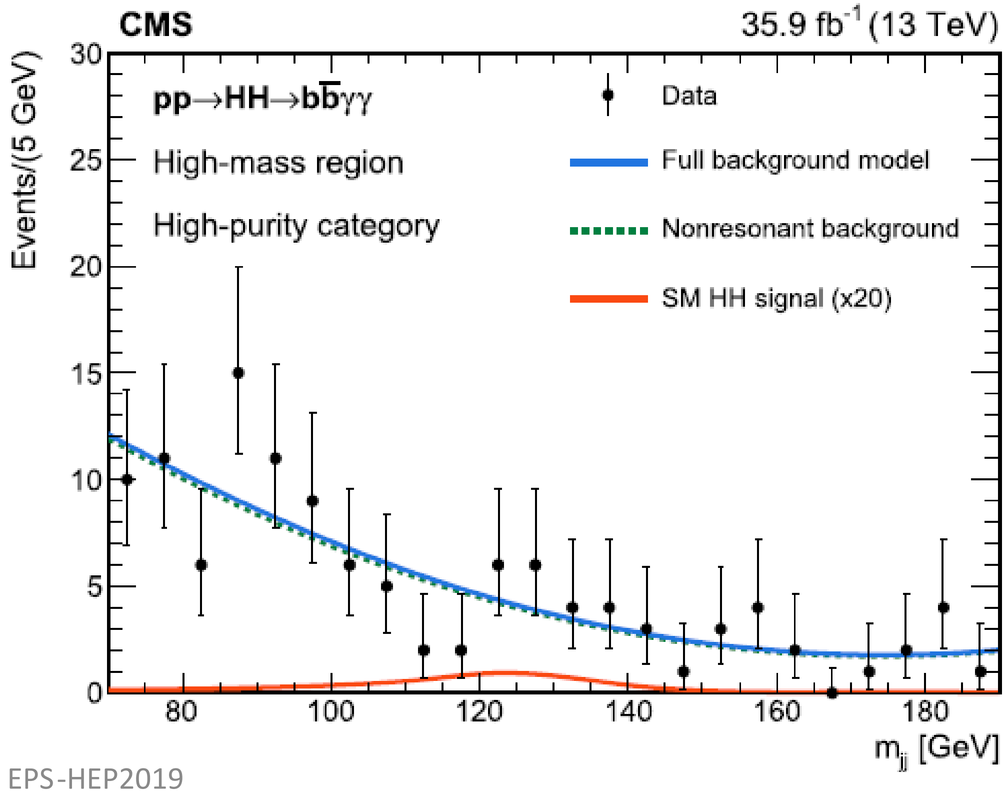
- Upper limits set as a function of k_λ / k_t



[Phys. Lett. B 788, 7 (2019)]

- Select events with **2 identified photons** and **2 b-jets**
- Main background: $\gamma(\gamma) + jets$ (estimated from mass sidebands)
- Events classified into categories according to **HH reduced mass** ($M_x = m_{jj\gamma\gamma} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)$) and **purity** of the event (applied using BDT discriminants)





$HH \to bb\gamma\gamma$

[Phys. Lett. B 788, 7 (2019)](#)

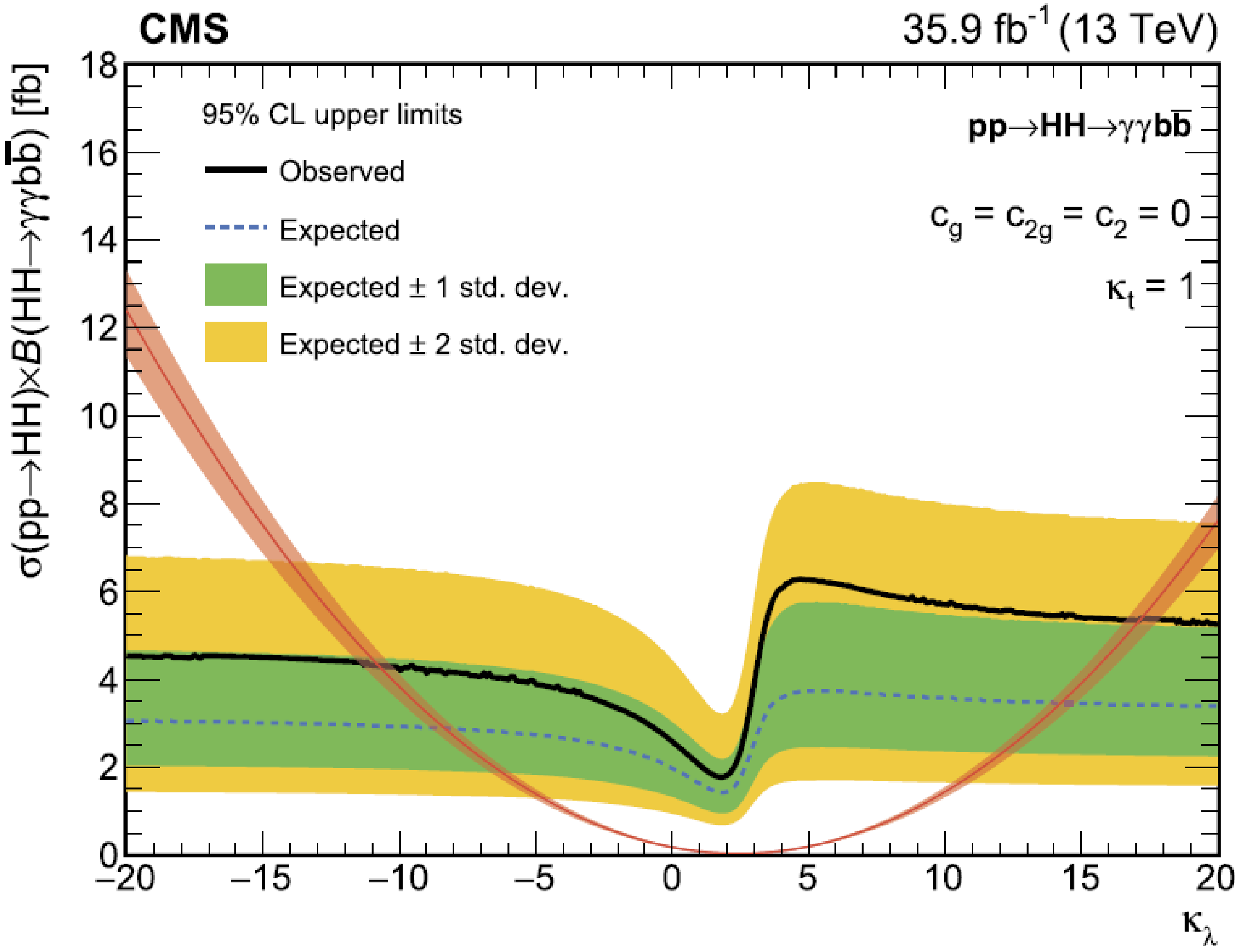
- 2D fit on the di-photon and di-(b)jet invariant mass distributions to extract the results

SM

- Observed (Exp.) 95% CL upper limit $\boldsymbol{\sigma(pp \to HH \to b\bar{b}\gamma\gamma) = 2.0\ (1.6)\ \mathrm{fb}}$
- Corresponds to 24 (19) × SM expectation

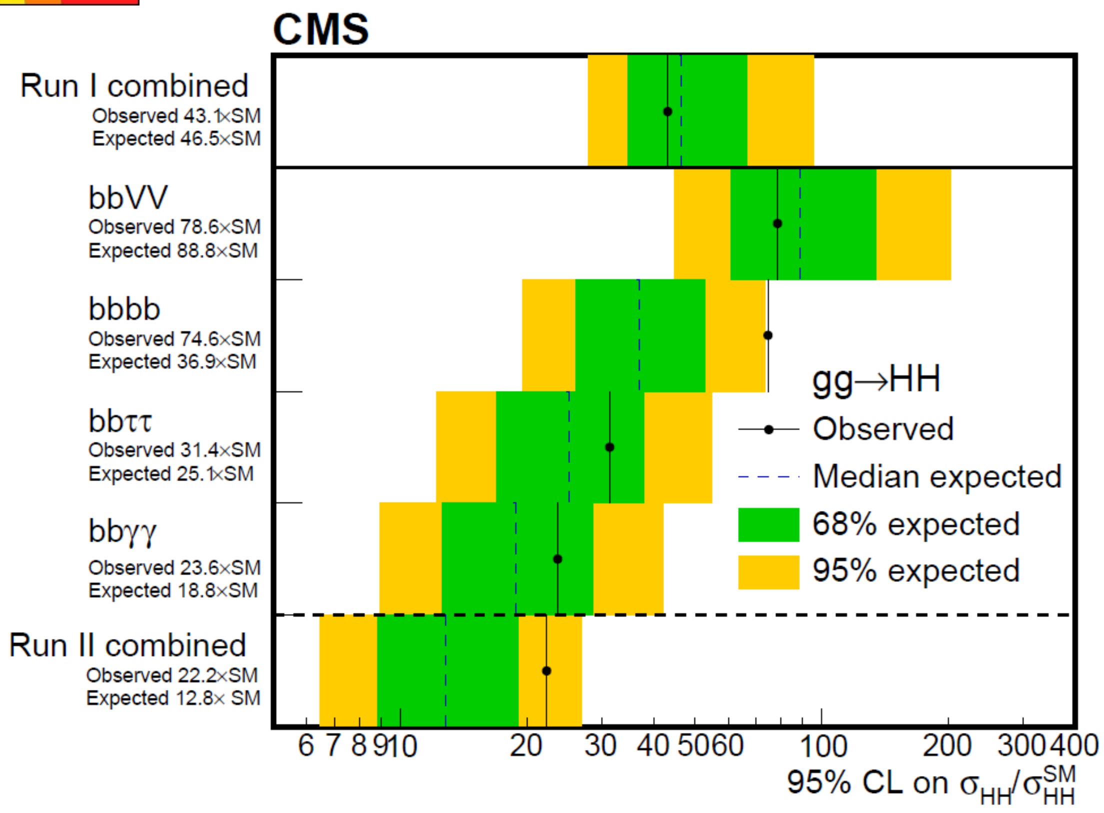
BSM

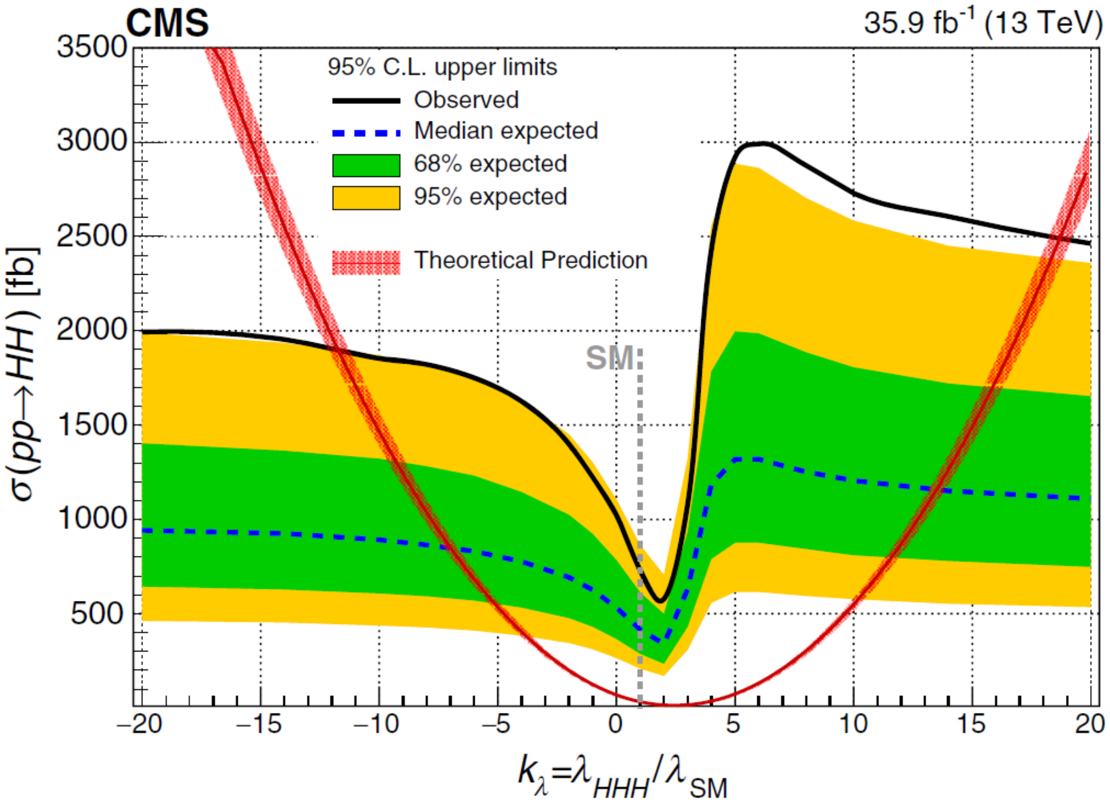
- k_λ scan in range [-20,20] (k_t=1) → 95% CL limit on coupling: $\boldsymbol{-11 < k_\lambda < 17}$



Combination

Phys. Rev. Lett. 122, 121803





95% CL limit on non-resonant HH production signal strength:

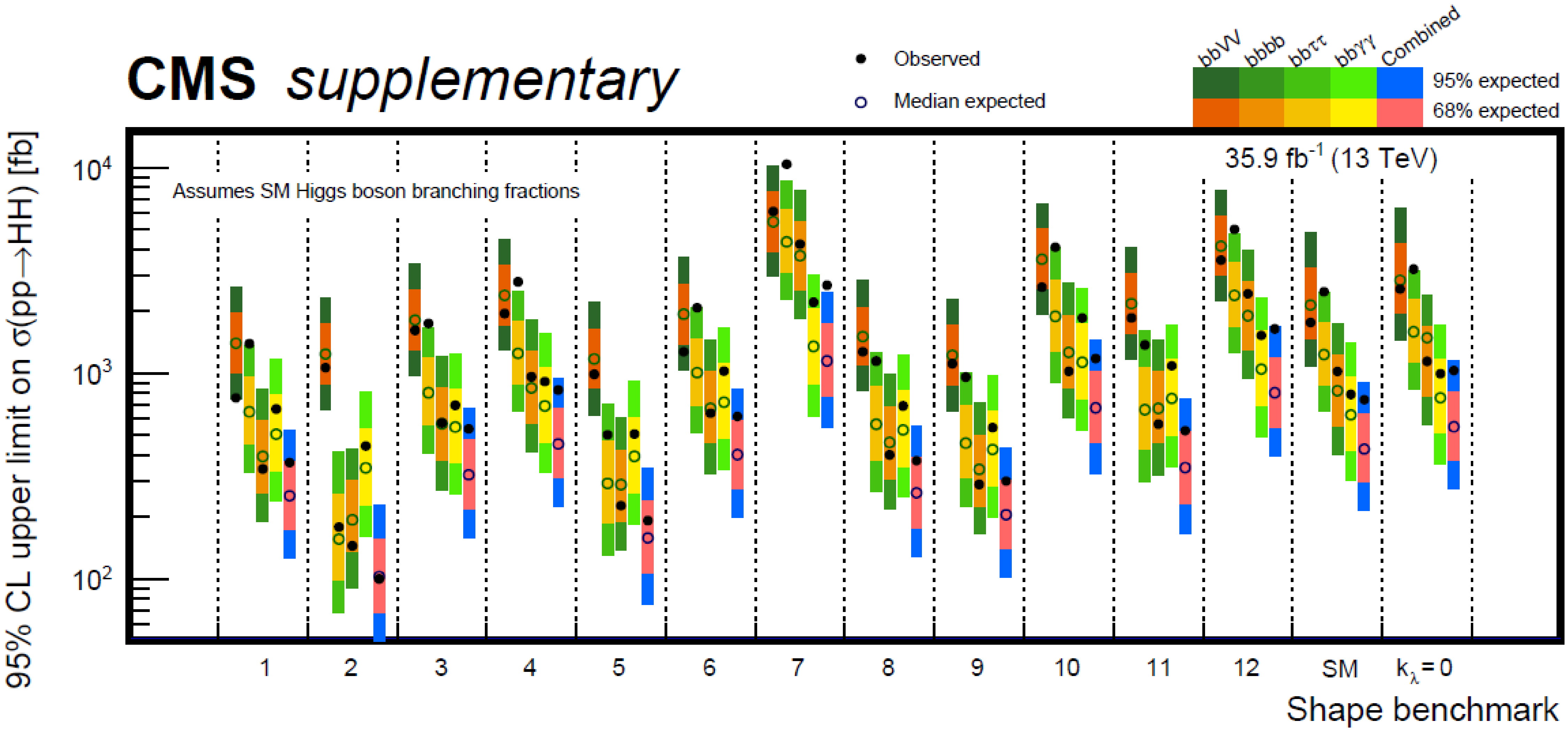
- Observed: **22.2**
- Expected: **12.8**

Constraint on k_λ parameter:

- Observed: $-11.8 < k_\lambda < 18.8$
- Expected: $-7.1 < k_\lambda < 13.6$

Combination - benchmarks

http://link.aps.org/supplemental/10.1103/PhysRevLett.122.121803



Conclusions and prospects

- Various double-Higgs boson searches performed in CMS
- **4 different decay channels** explored up to now
- Wide range of results available using **13 TeV data collected in 2016** (35.9 fb^{-1})
- Searches not yet sensitive to SM production, but limits from combinations increasingly stringent
- Various BSM scenarios tested

Much more to come in the future!

- **New searches channels** are being investigated
- 2017 and 2018 13 TeV data are being analysed → $\mathbf{150\ fb^{-1}}$ recorded from LHC Run 2
- New data will be collected in **Run 3** and **HL-LHC** (see Sylvie's talk)

Many powerful results to come!

Back-up

Benchmark shapes

JHEP 04 (2016) 126

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

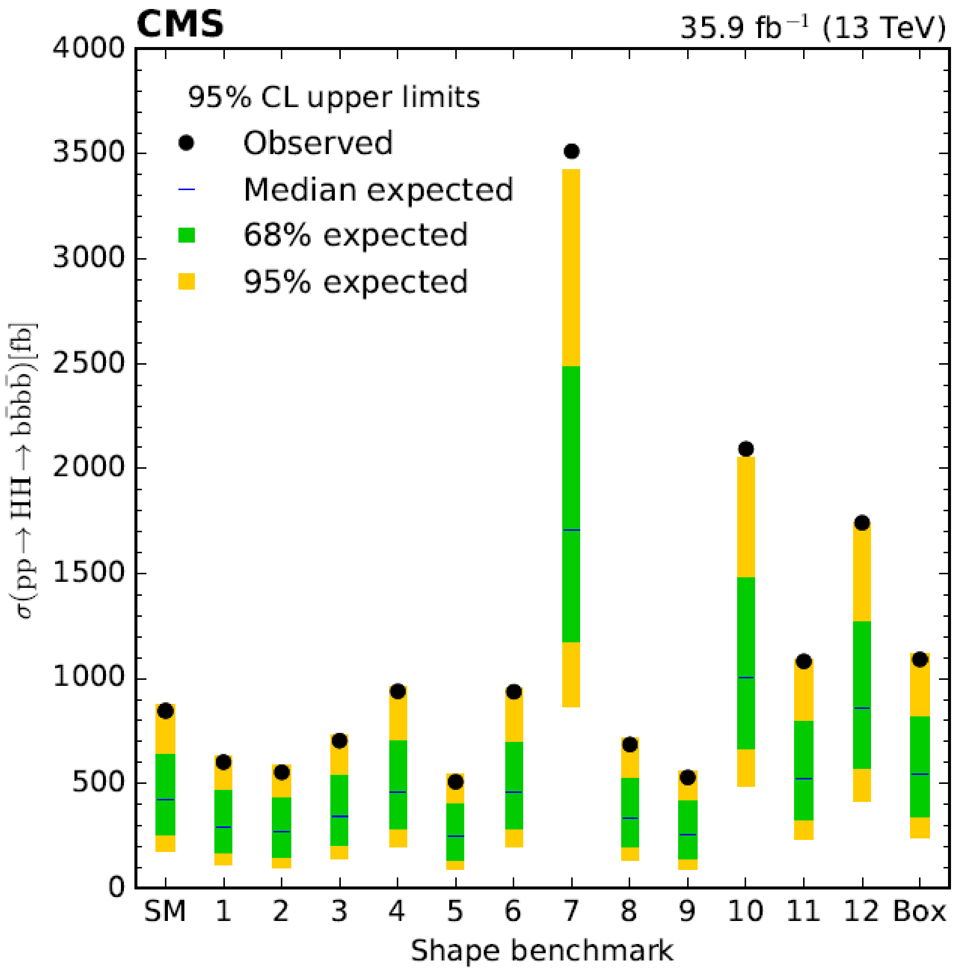
HH→4b - systematics

JHEP04(2019)112

Source	Affects	Exp. limit variation
Bkg. shape	bkg.	30%
Bkg. norm.	bkg.	8.6%
b tagging eff.	sig	2.8%
Pileup	sig	<0.01%
Jet energy res.	sig	<0.01%
Jet energy scale	sig	<0.01%
Int. luminosity	sig	<0.01%
Trigger eff.	sig	<0.01%
μ_F and μ_R scales	sig	<0.01%
PDF	sig	<0.01%

HH→4b – results

JHEP04(2019)112



Category	Observed	Expected	-2 s.d.	-1 s.d.	+1 s.d.	+2 s.d.
SM HH → $b\bar{b}b\bar{b}$	847	419	221	297	601	834

Benchmark point	Observed	Expected	-2 s.d.	-1 s.d.	+1 s.d.	+2 s.d.
1	602	295	155	209	424	592
2	554	269	141	190	389	548
3	705	346	182	245	497	691
4	939	461	244	327	662	920
5	508	248	131	176	357	501
6	937	457	240	323	657	916
7	3510	1710	905	1210	2440	3390
8	686	336	177	238	483	674
9	529	259	136	183	373	520
10	2090	1000	527	709	1440	2010
11	1080	525	277	372	755	1050
12	1744	859	455	611	1230	1710
Box	1090	542	286	384	775	1080

HH→bblνlν - systematics

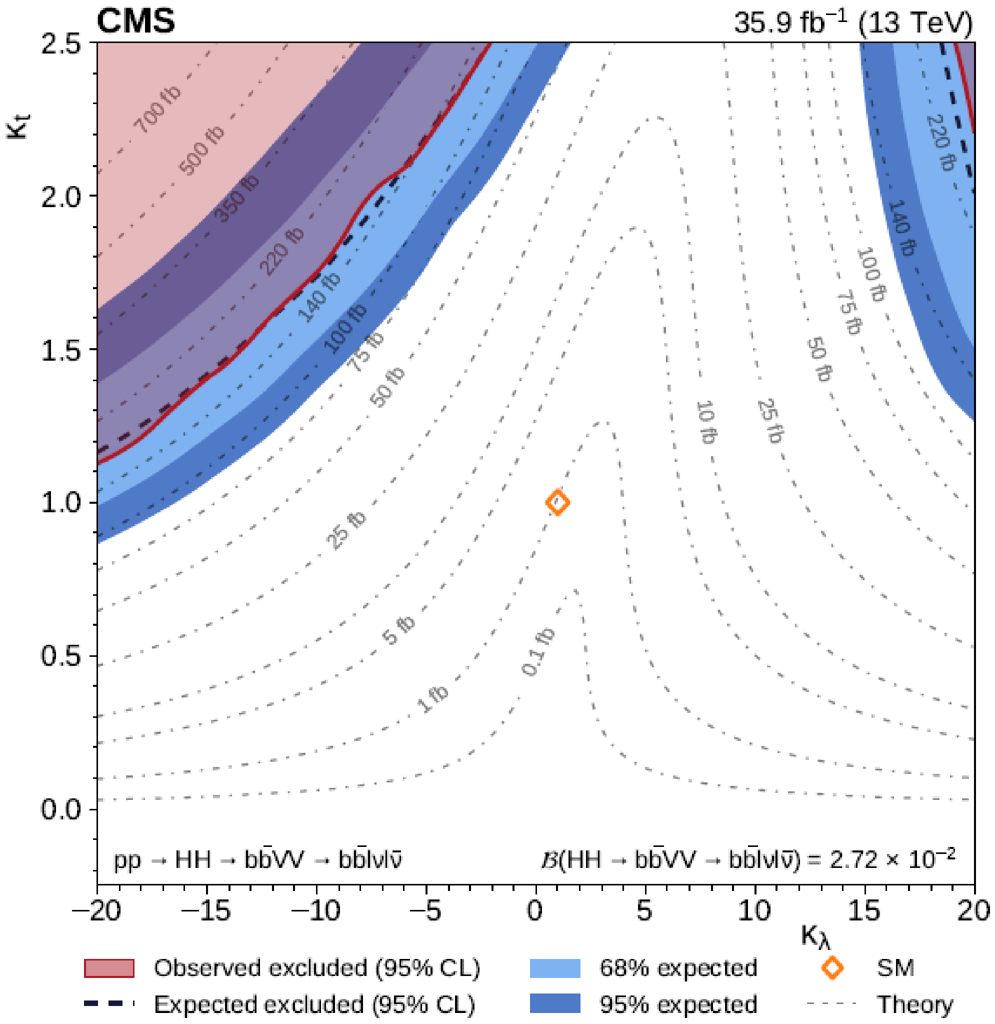
JHEP01(2018)054

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	$m_X = 400\,\text{GeV}$
μ_R and μ_F scales	24.2%	4.6–4.7%
Simulated sample size	<0.1%	<0.1%

HH→bblνlν

JHEP01(2018)054



$HH \to bb\tau\tau$ - systematics

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Systematic uncertainties affecting the normalization of the different processes.

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

$HH \to bb\tau\tau$ - m_{T2}

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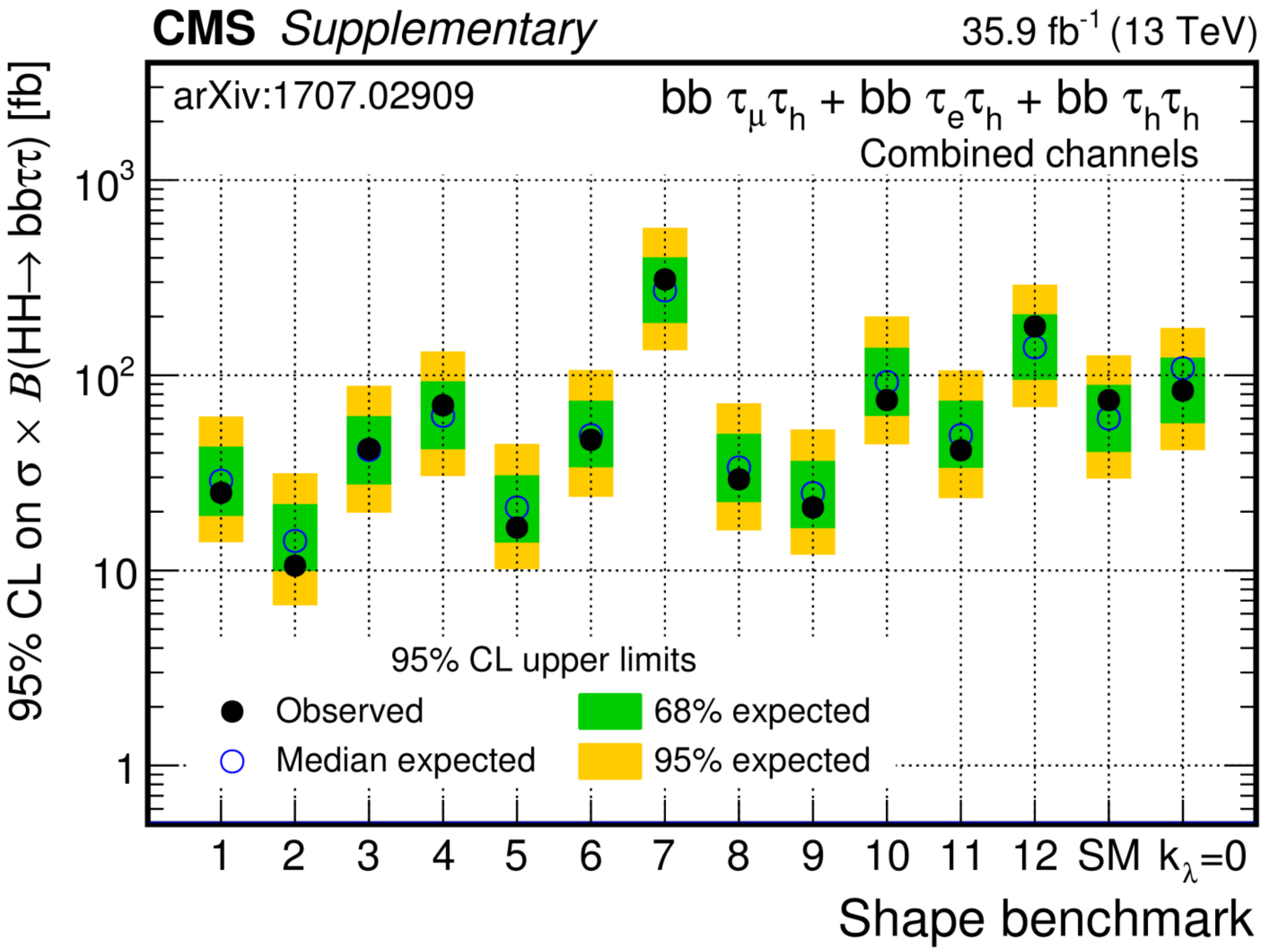
- Defined as the largest mass of the parent particle that is compatible with the kinematic constraints of the event
- In case of $bb\tau\tau$ decay, where the dominant bkg is $t\bar{t}$ production, the parent particle is interpreted as $t \to Wb$
- If
  - $\vec{b}, \vec{b}'$ momenta of selected b-jets
  - m_b , $m_{b'}$ invariant mass of selected b-jets
  - $\vec{c}, \vec{c}'$ momenta of other particles produced in top decay
  - m_c , $m_{c'}$ invariant mass of other particles produced in top decay
  - $m_T\left(\vec{b}_T, \vec{c}_T, m_b, m_c\right) = \sqrt{m_b^2 + m_c^2 + 2(e_b e_c - \vec{b}_T \cdot \vec{c}_T)}$, transverse mass
  - $e = \sqrt{m^2 + p_T^2}$, transverse energy of a particle of mass m and transverse momentum p_T

Then

$$\boldsymbol{m_{T2}\left(m_b, m_{b'}, \vec{b}_T, \vec{b}_T{}', \vec{p}_T^{\Sigma}, m_c, m_{c'}\right) = \min_{\vec{c}_T + \vec{c}'_T = \vec{p}_T^{\Sigma}} \{\max(m_T, m_T{}')\}}$$

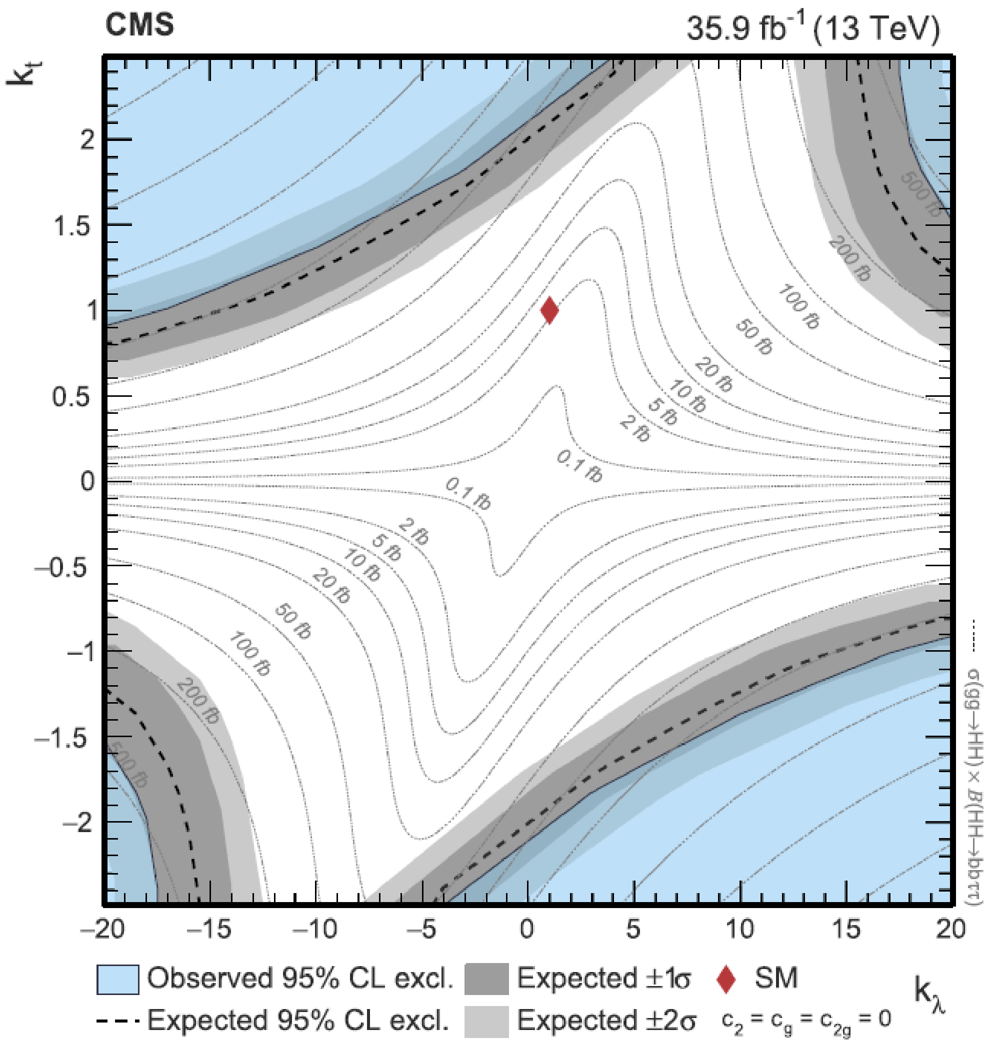
$HH \to bb\tau\tau$

[PLB 778 (2018) 101]



HH→bbττ

[PLB 778 (2018) 101]



HH→bbγγ - systematics

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Summary of systematic uncertainties.

Sources of systematic uncertainties	Type	Value (%)
Integrated luminosity	Normalization	2.5
Photon related uncertainties		
Diphoton selection (with trigger uncertainties and PES)	Normalization	2.0
Photon identification	Normalization	1.0
PES ($\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}}$)	Shape	0.5
PER ($\frac{\Delta \sigma_{\gamma\gamma}}{\sigma_{\gamma\gamma}}$)	Shape	5.0
Jet related uncertainties		
Dijet selection (JES+JER)	Normalization	0.5
JES ($\frac{\Delta m_{jj}}{m_{jj}}$)	Shape	1.0
JER ($\frac{\Delta \sigma_{jj}}{\sigma_{jj}}$)	Shape	5.0
Resonant analysis specific uncertainties		
Mass window selection (JES+JER)	Normalization	3.0
Classification MVA – b tagging (HPC)	Normalization	10–19
Classification MVA – b tagging (MPC)	Normalization	3–9
Nonresonant analysis specific uncertainties		
$\widetilde{M}_X$ Classification	Normalization	0.5
Classification MVA – b tagging (HPC)	Normalization	10–19
Classification MVA – b tagging (MPC)	Normalization	3–9
Theoretical uncertainties in the SM single-Higgs boson production		
QCD missing orders (ggH, VBF H, VH, $t\bar{t}$H)	Normalization	0.4–5.8
PDF and α_S uncertainties (ggH, VBF H, VH, $t\bar{t}$H)	Normalization	1.6–3.6
Theoretical uncertainty $b\bar{b}$H	Normalization	20
Theoretical uncertainties in the SM HH boson production		
QCD missing orders	Normalization	4.3–6
PDF and α_S uncertainties	Normalization	3.1
m_t effects	Normalization	5

HH→bbγγ

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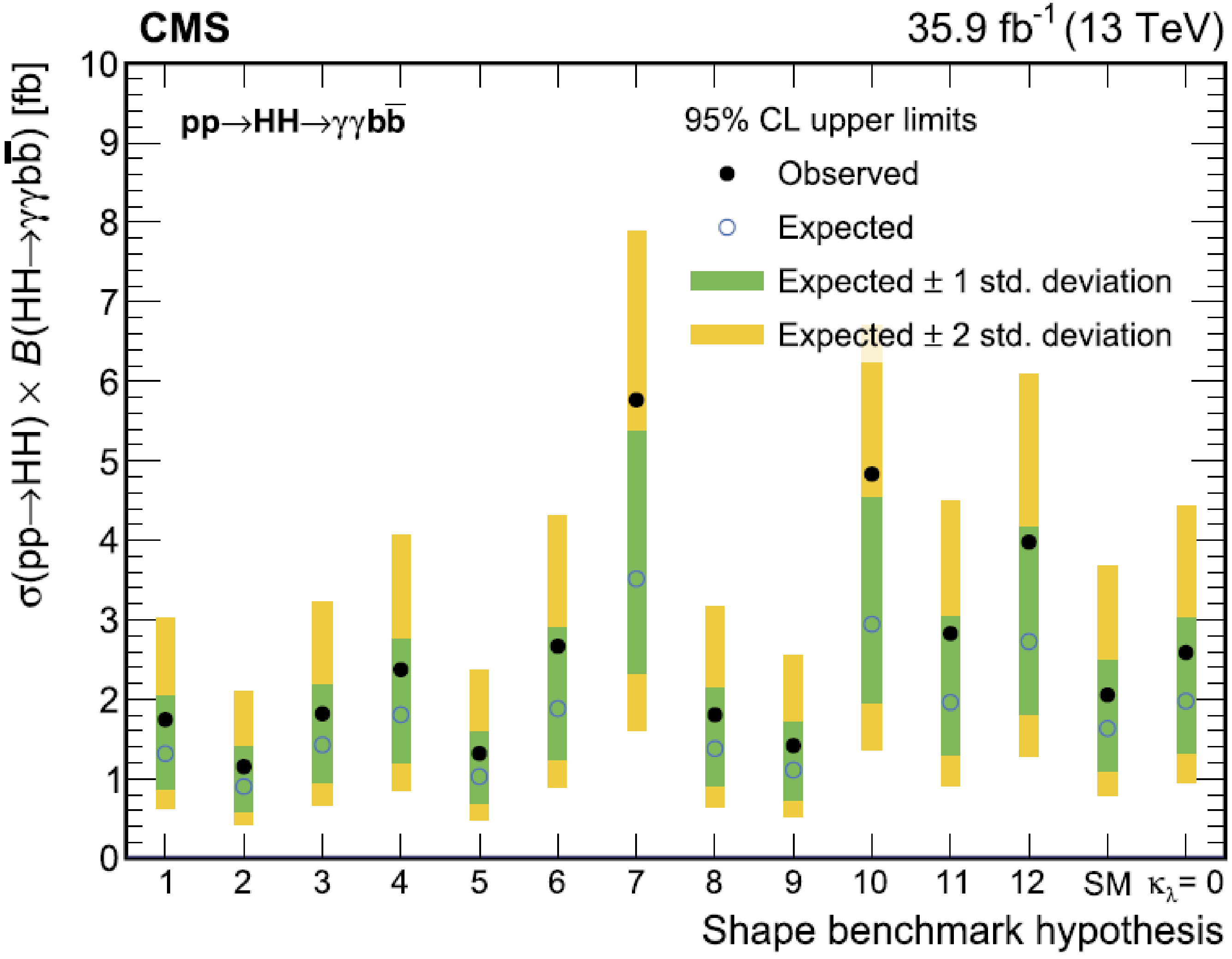

Combination

http://link.aps.org/supplemental/10.1103/PhysRevLett.122.121803