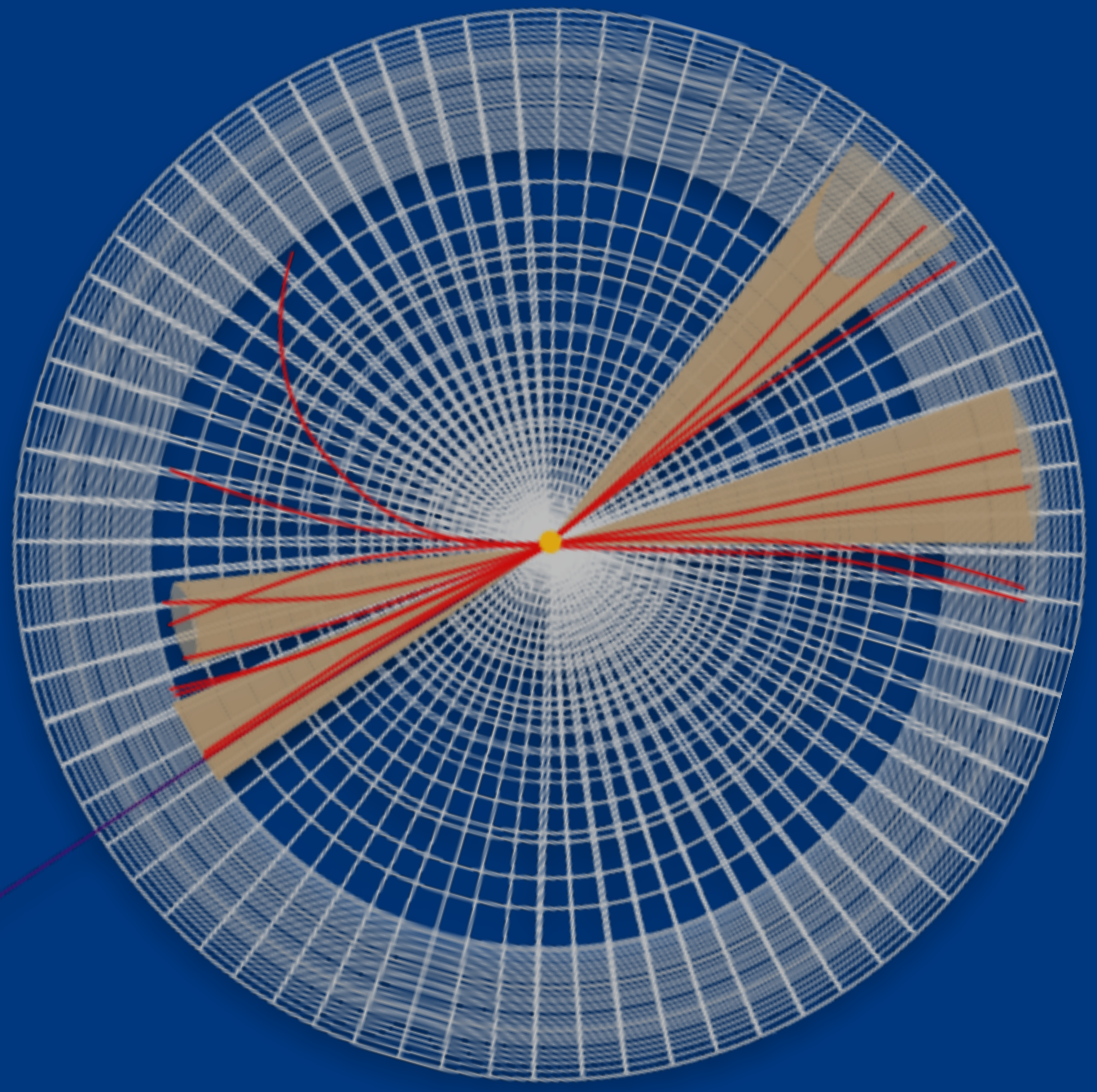
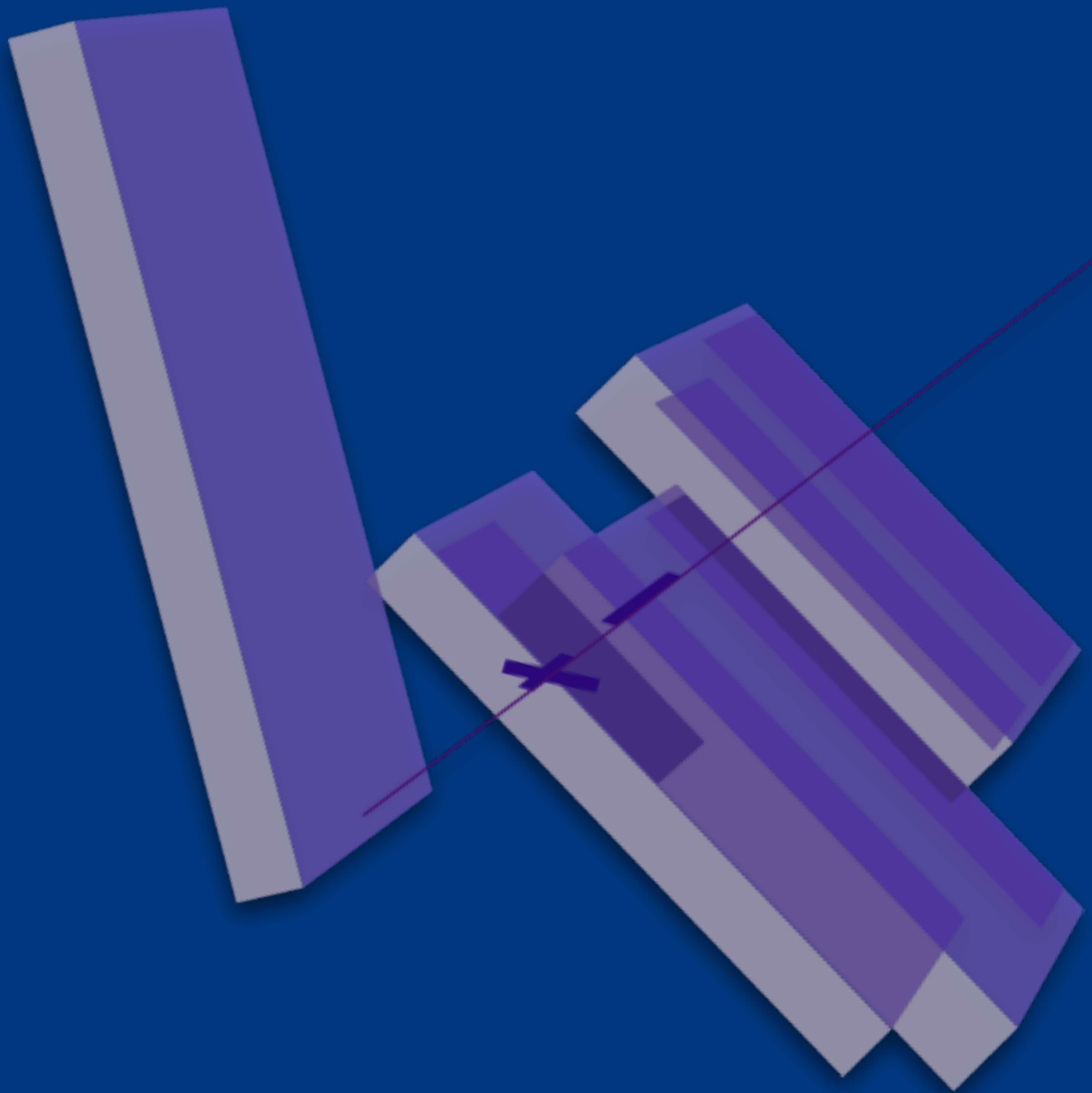
DiHiggs with CMS





Caterina Vernieri (FNAL)
on behalf of the CMS Collaboration

April 4, 2018
HL/HE LHC Meeting, Fermilab

di-Higgs in the SM

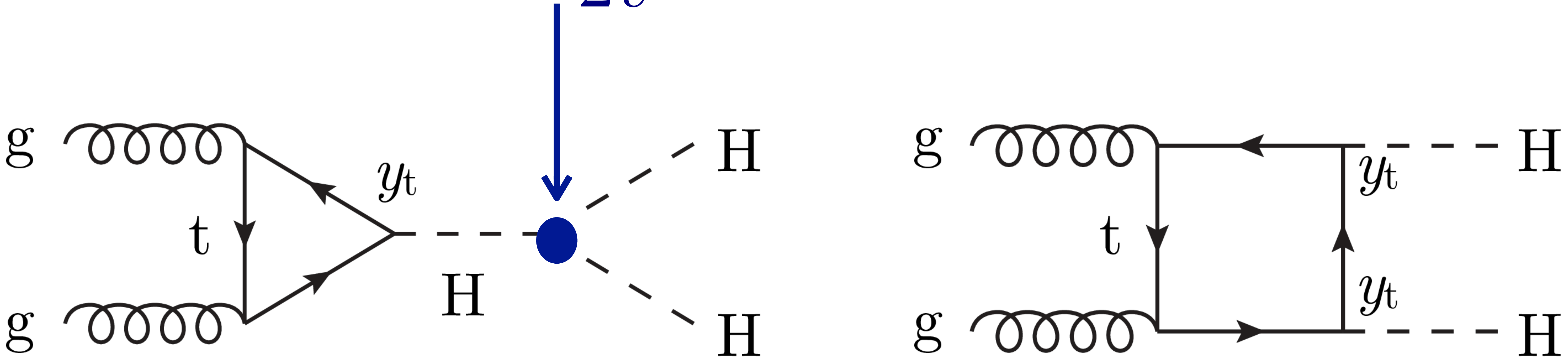
The measurement of the Higgs boson **self coupling** is a **fundamental** test of the SM

SM predicts a **extremely small cross section** for HH production (33.5 fb at 13 TeV)

Main production mode is gluon fusion

In the SM:

$$\lambda_{\mathrm{HHH}} = \frac{m_{\mathrm{H}}^2}{2v^2} = 0.13$$



ArXiv:1610.07922
JHEP04(2016)126

di-Higgs in BSM

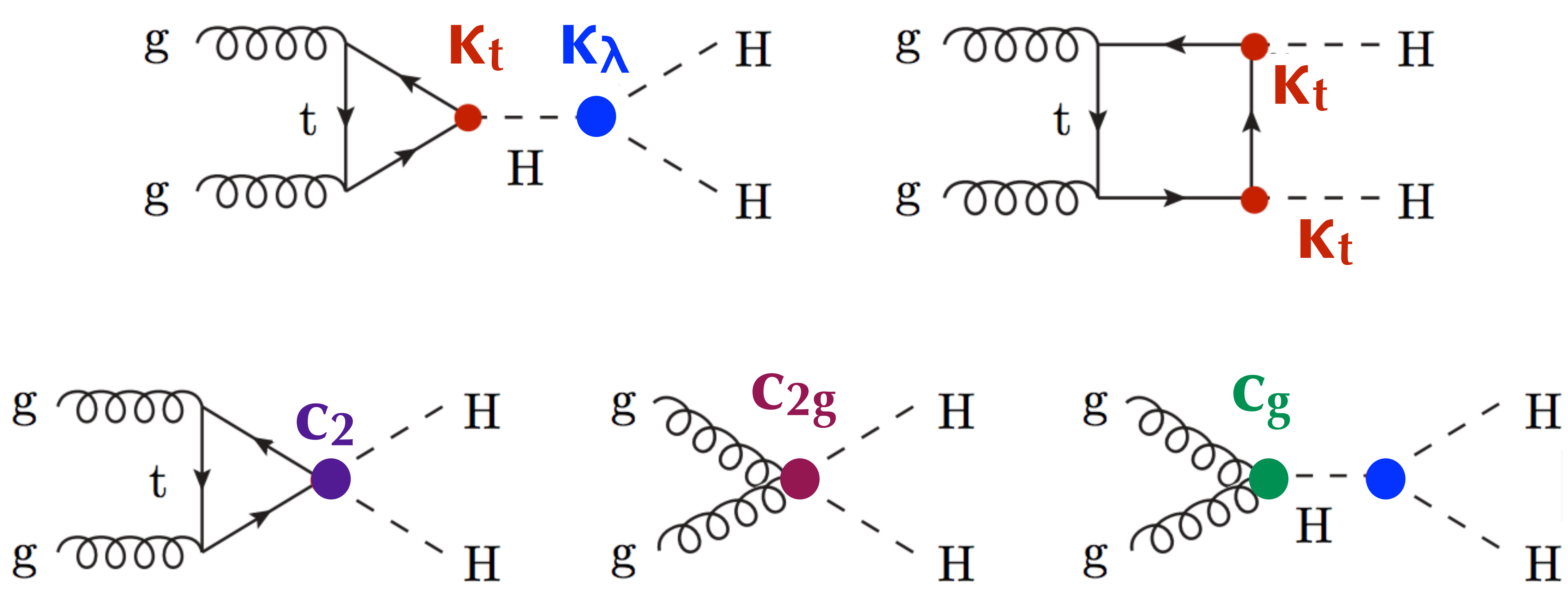
Anomalous Higgs boson couplings

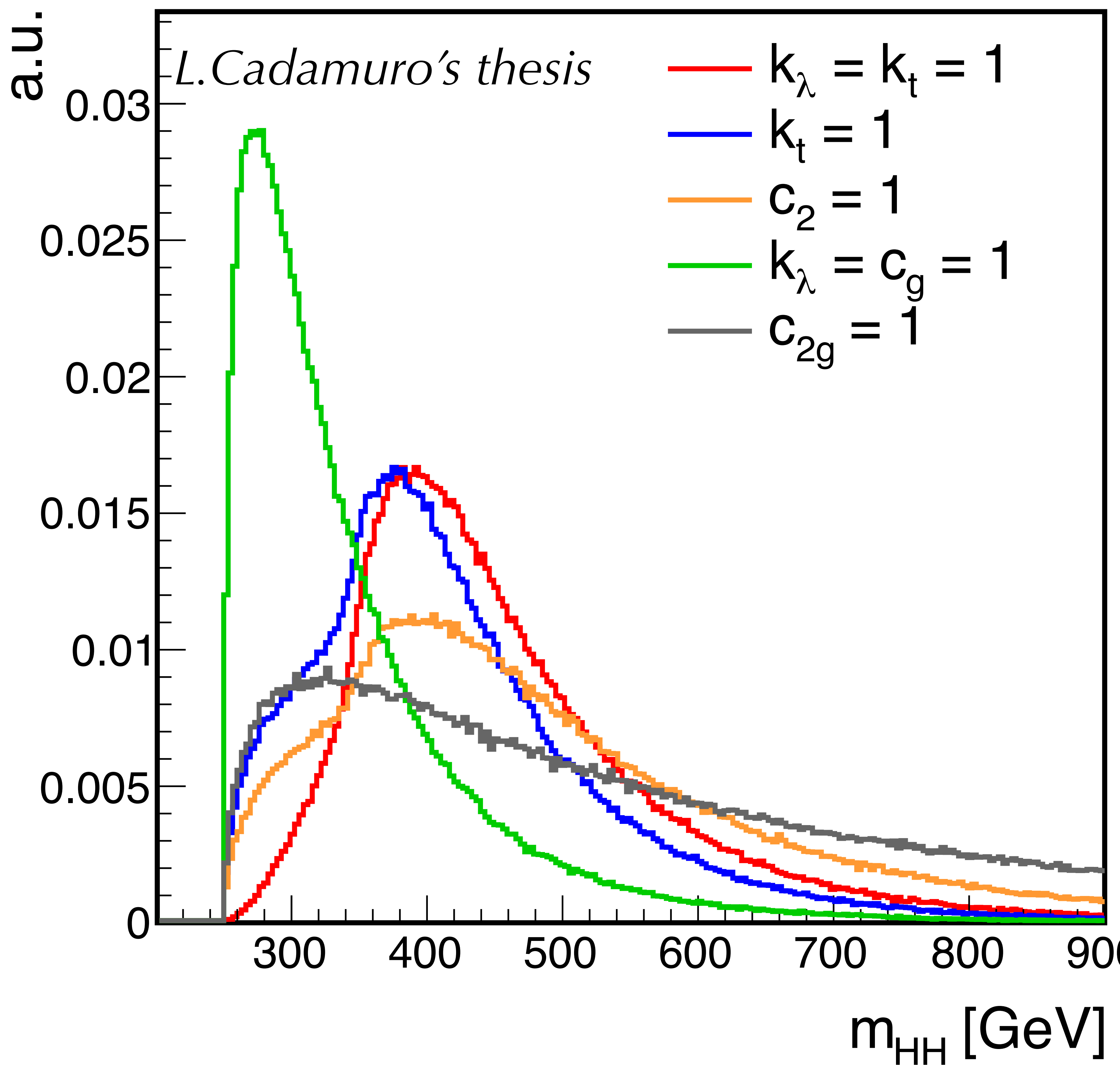
Strong effect on cross-section and m(hh) shape

EFT approach parametrizes new physics (dim 6 operators)

modifications to $\kappa_\lambda = \lambda / \lambda_{SM}$ and $\kappa_t = y_t / y_{t,SM}$

three new interactions: c_2, c_{2g}, c_g





ArXiv:1610.07922
JHEP04(2016)126

di-Higgs in BSM

Modified in many BSM scenarios

Better than 20% precision on λ_{HHH} [1305.6397] to see a deviation from SM (or less [1505.05488] in NMSSM)

Anomalous Higgs boson couplings

Strong effect on cross-section and m(hh) shape

EFT approach parametrizes new physics (dim 6 operators)

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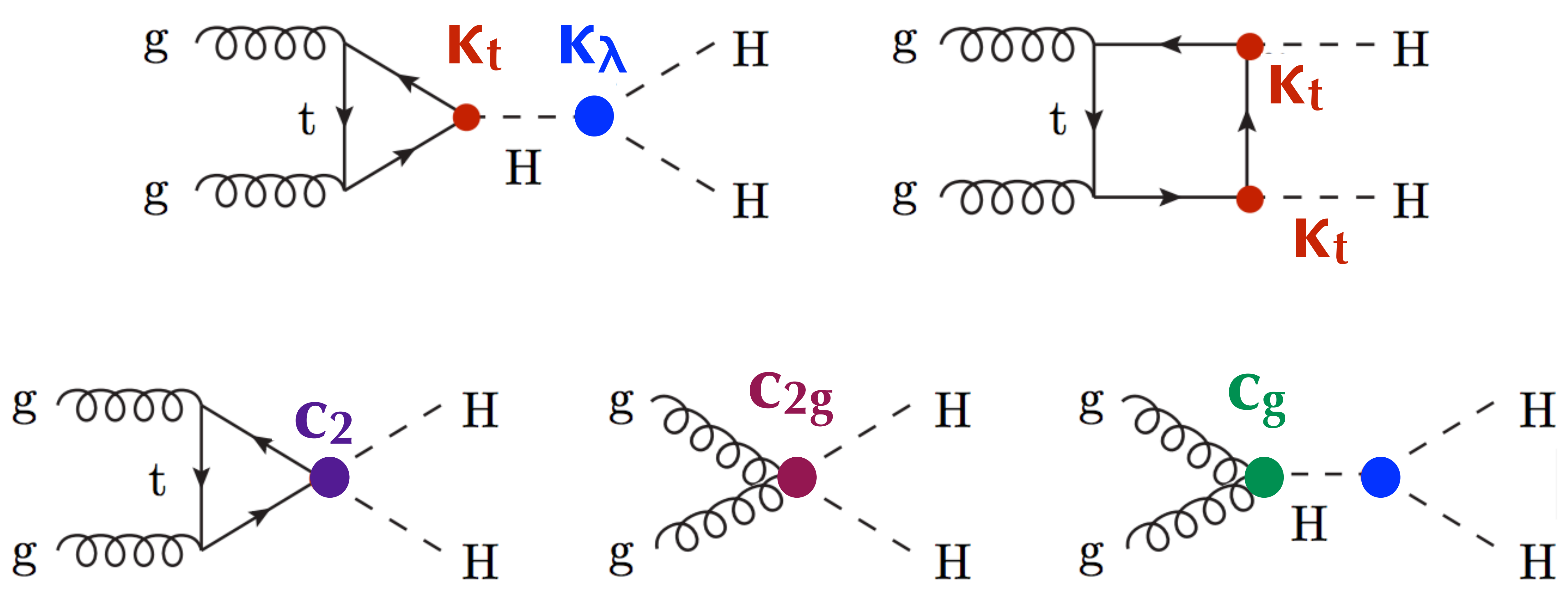
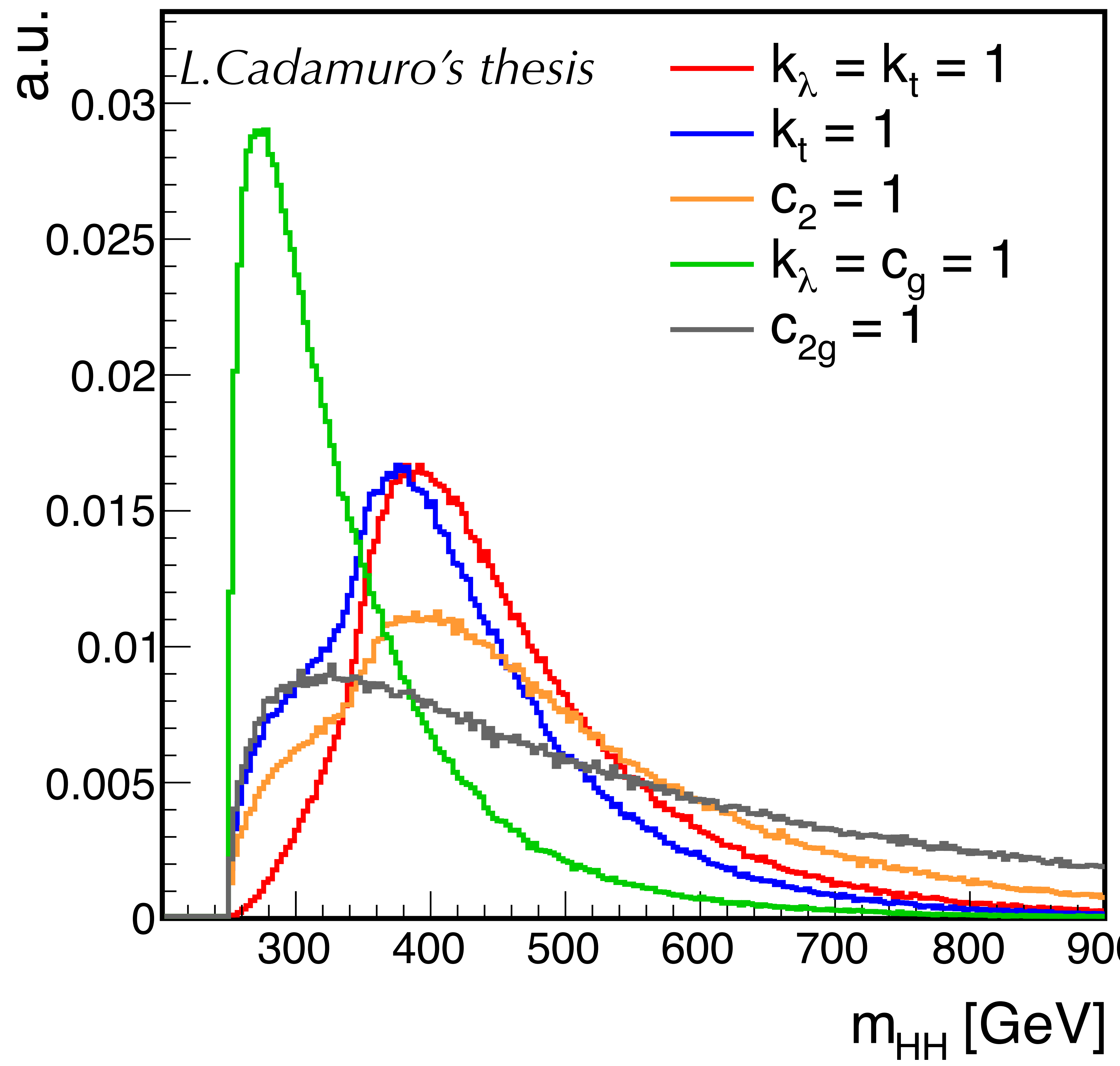
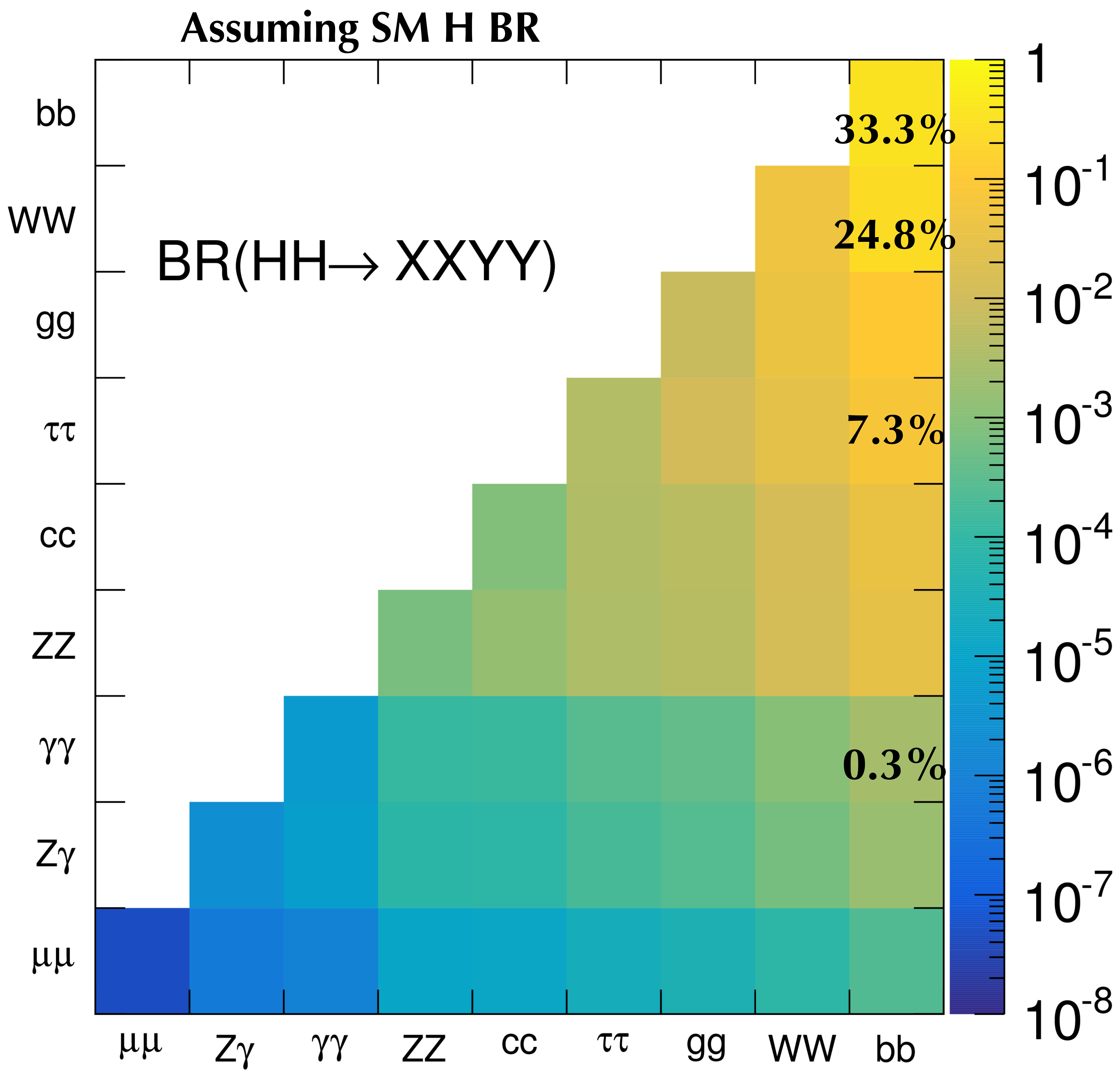




HH, a variety of final states



Complementarity of the channels

H($b\bar{b}$)

highest BR: larger statistics

high b-tag efficiency and low fake rate

multi-light jets background is highly reduced

H(γγ)

simple topology

excellent mass resolution

Limited by small BR

HH CMS results

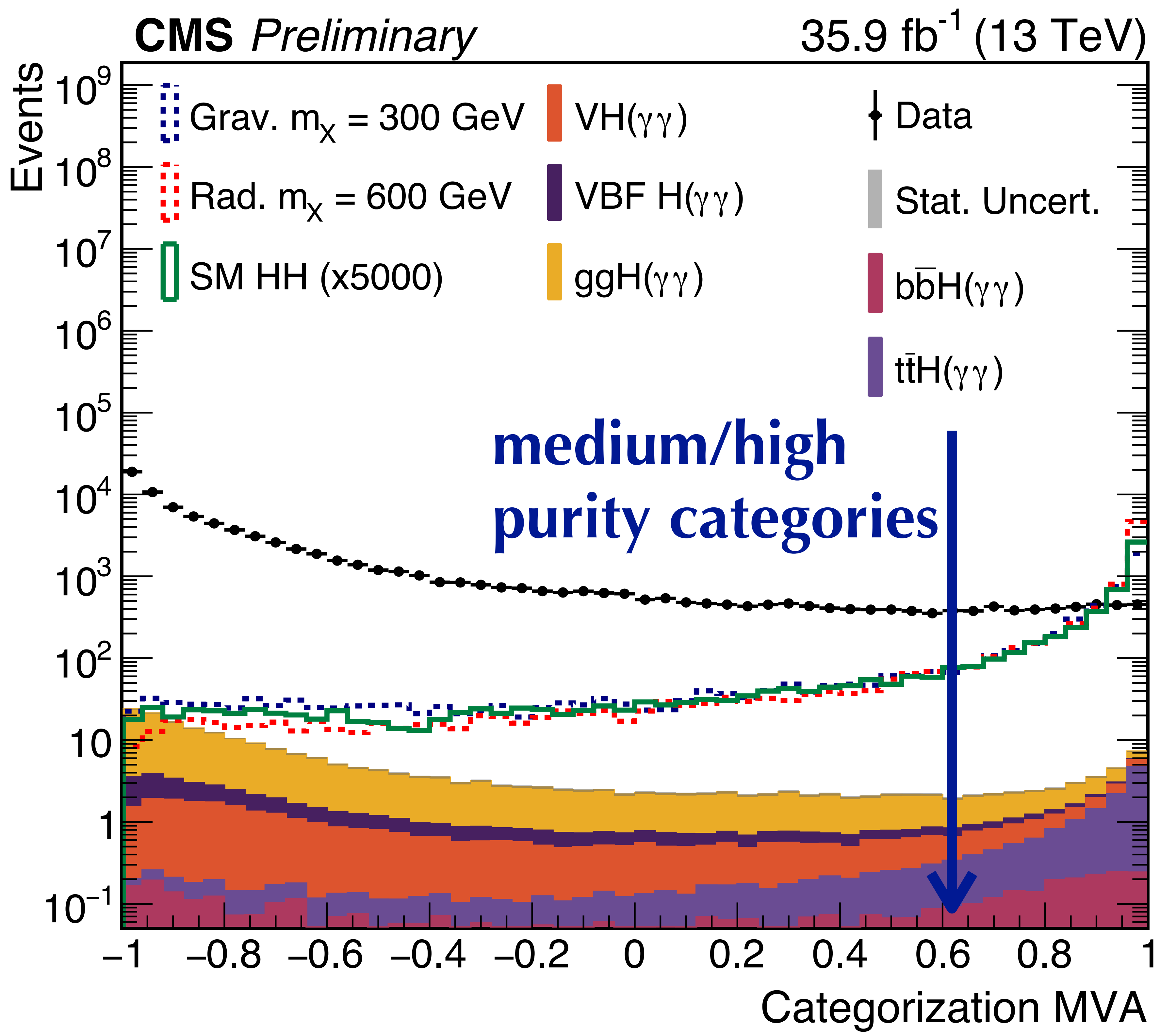
- **Run I**
  - $b\bar{b}\tau\tau$ + $b\bar{b}\gamma\gamma$ combination 43 (47) x SM observed (expected) *Phys. Rev. D 96, 072004 (2017)*
  - Dominant systematic uncertainties from background modeling and b-tagging
- **Run II**
  - $b\bar{b}\gamma\gamma$ *CMS-HIG-17-008*
  - $b\bar{b}\tau\tau$ *Phys. Lett. B 778 (2018) 101*
  - $b\bar{b}VV^{*}(\rightarrow l\nu l\nu)$ *JHEP 01 (2018) 054*
  - $b\bar{b}b\bar{b}$ *CMS-HIG-16-026* (based on L= 2.3 fb^{-1} only)

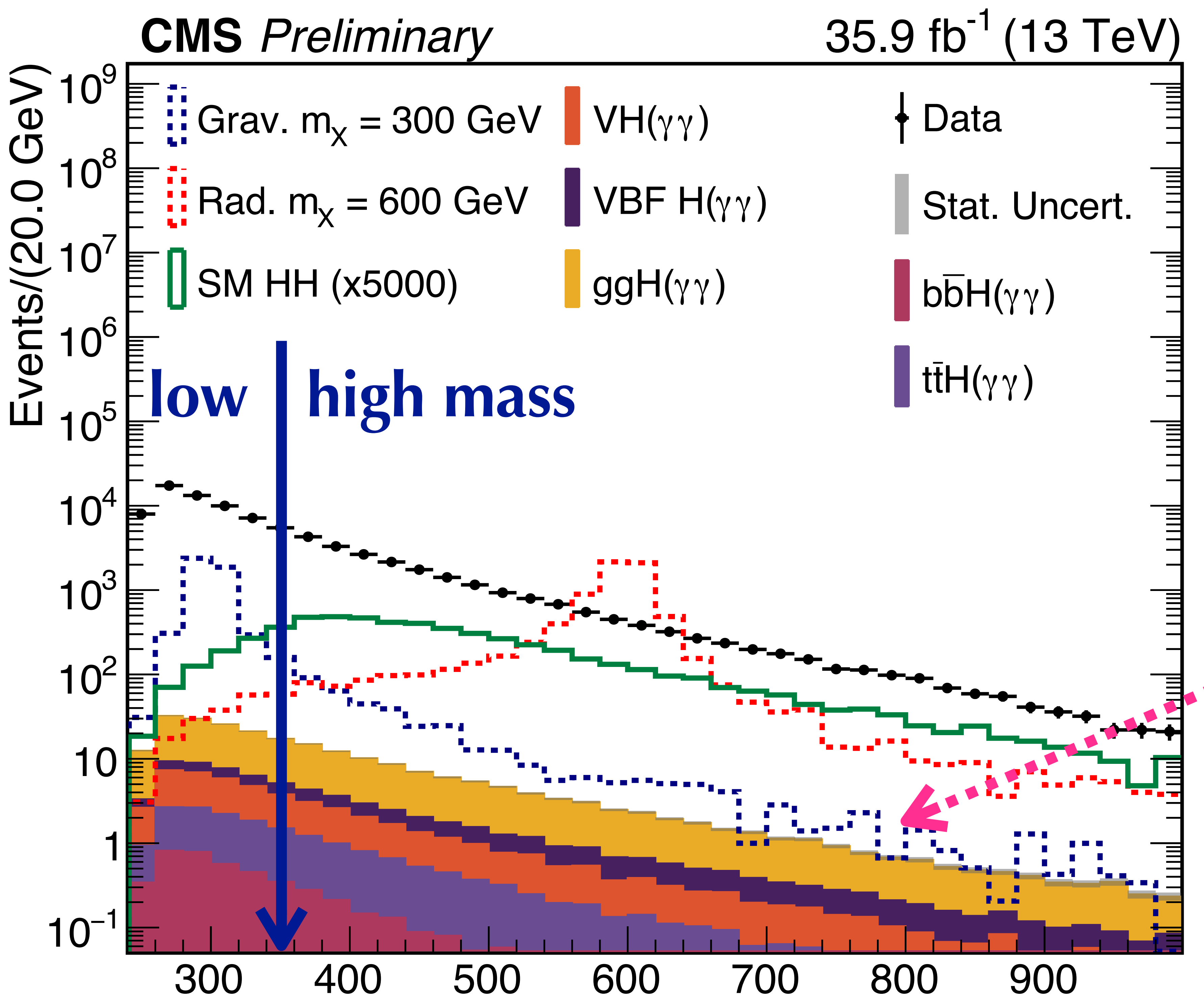
HH searches need:

- good **b-jets identification** efficiency
- best possible **resolution on $m_H/m_{b\bar{b}}$**
- exploit all possible information from the event to **improve S/B**

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

- 2 photons, $100 < m_{\gamma\gamma} < 180$ GeV
- 2 jets, $70 < m_{jj} < 190$ GeV
- b-jet energy regression to improve $m(b\bar{b})$ resolution
- **Mx** and **BDT (including angular correlations)** classifier used to categorize events





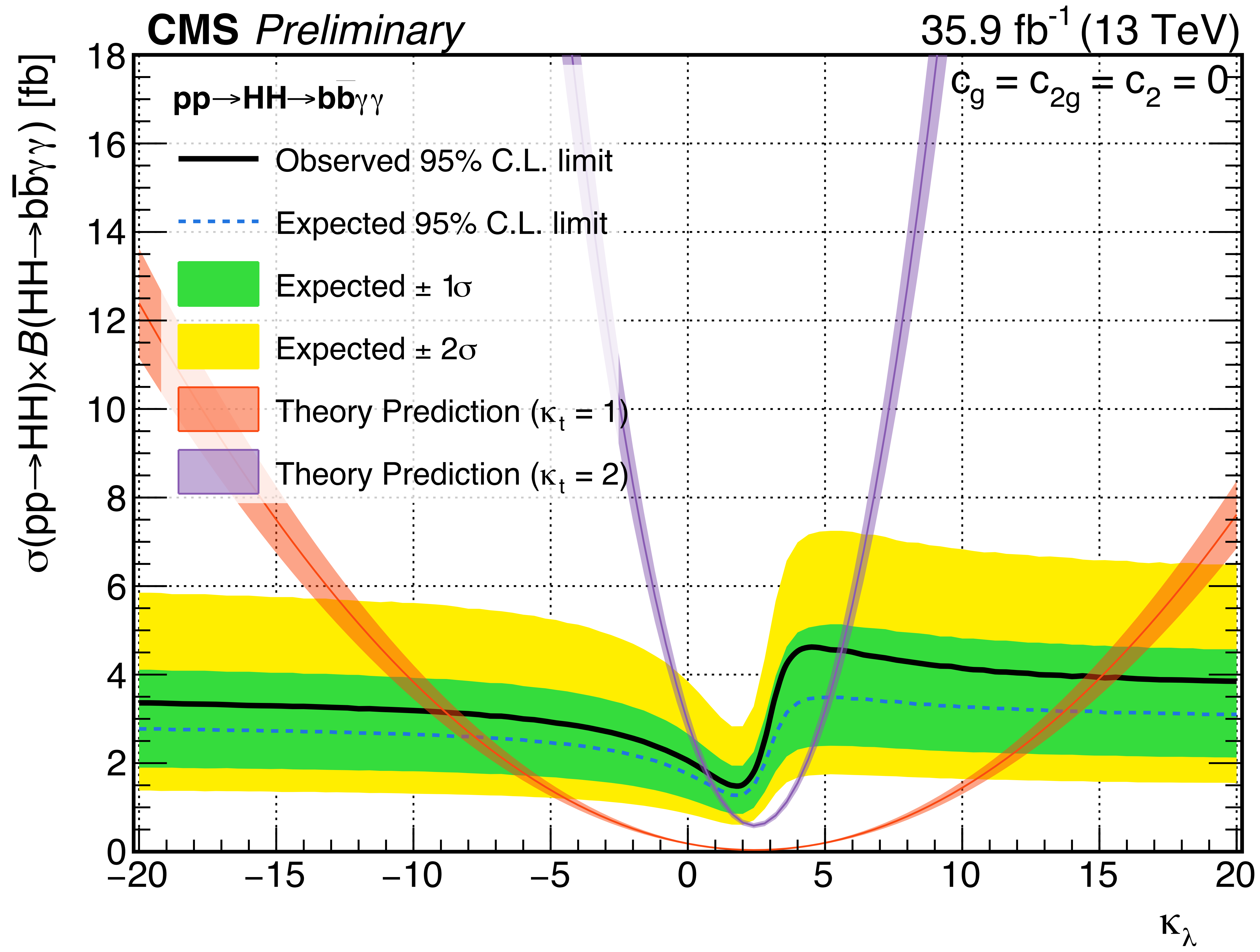
$$M_X = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - m_H) - (m_{\gamma\gamma} - m_H)$$

- photon+jets (prompt photons or jets misidentified as photon) **from data**
- **SM single Higgs** from simulation

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

- Likelihood fits simultaneous to $m(b\bar{b})$ and $m(\gamma\gamma)$
  - single Higgs background constrained as no resonant structure is expected in the $m(b\bar{b})$ distribution
- The observed (expected) upper limit at 95% CL corresponds to about **19 (16) x SM**
- Anomalous κ_λ coupling tested

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%

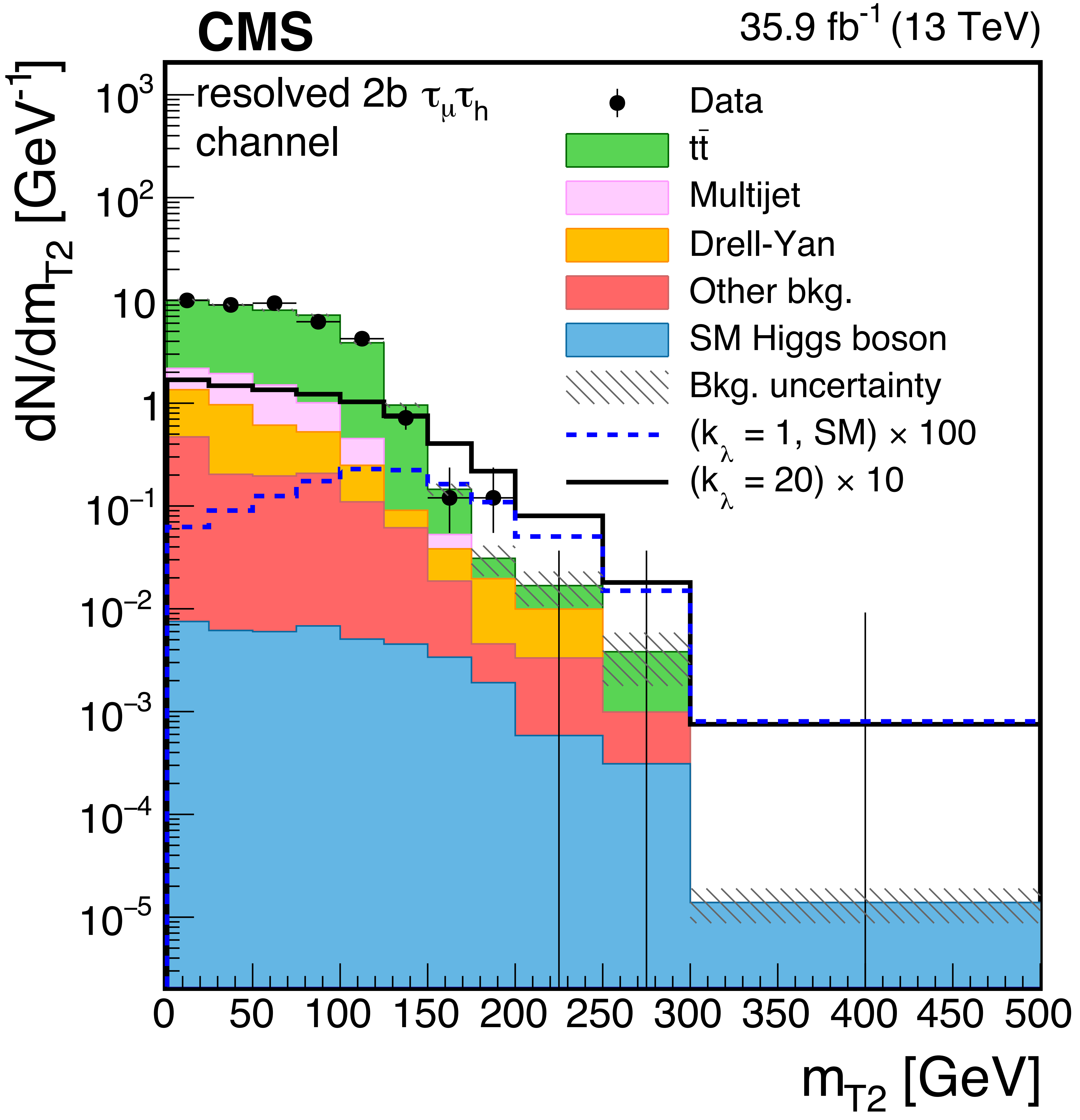


Phys. Lett. B 778 (2018) 101

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

- $\tau_h\tau_\mu+\tau_h\tau_e+\tau_h\tau_h$ (88%)
- 2 jets (resolved) or 1 large-R jet (boosted)
- Likelihood fit to estimate m($\tau\tau$) (despite the missing energy)
- m($b\bar{b}$) and m($\tau\tau$) compatible with m_H
- Events are then categorized by number of b-tags
- **Main backgrounds**:
  - top, Z/γ*+jets (from MC)
  - multijet (from data)
- **BDT** to reject top background in $\tau_h\tau_\mu+\tau_h\tau_e$
  - based on angular separation of leptons and visible mass
- **stranverse mass** (m_{T2}) used to extract the signal

$$\mathrm{m_{T2}} = \min_{p_{T1}+p_{T2}=p_T^{\tau\tau}} \{\max(\mathrm{m_T}, \mathrm{m'_T})\}$$

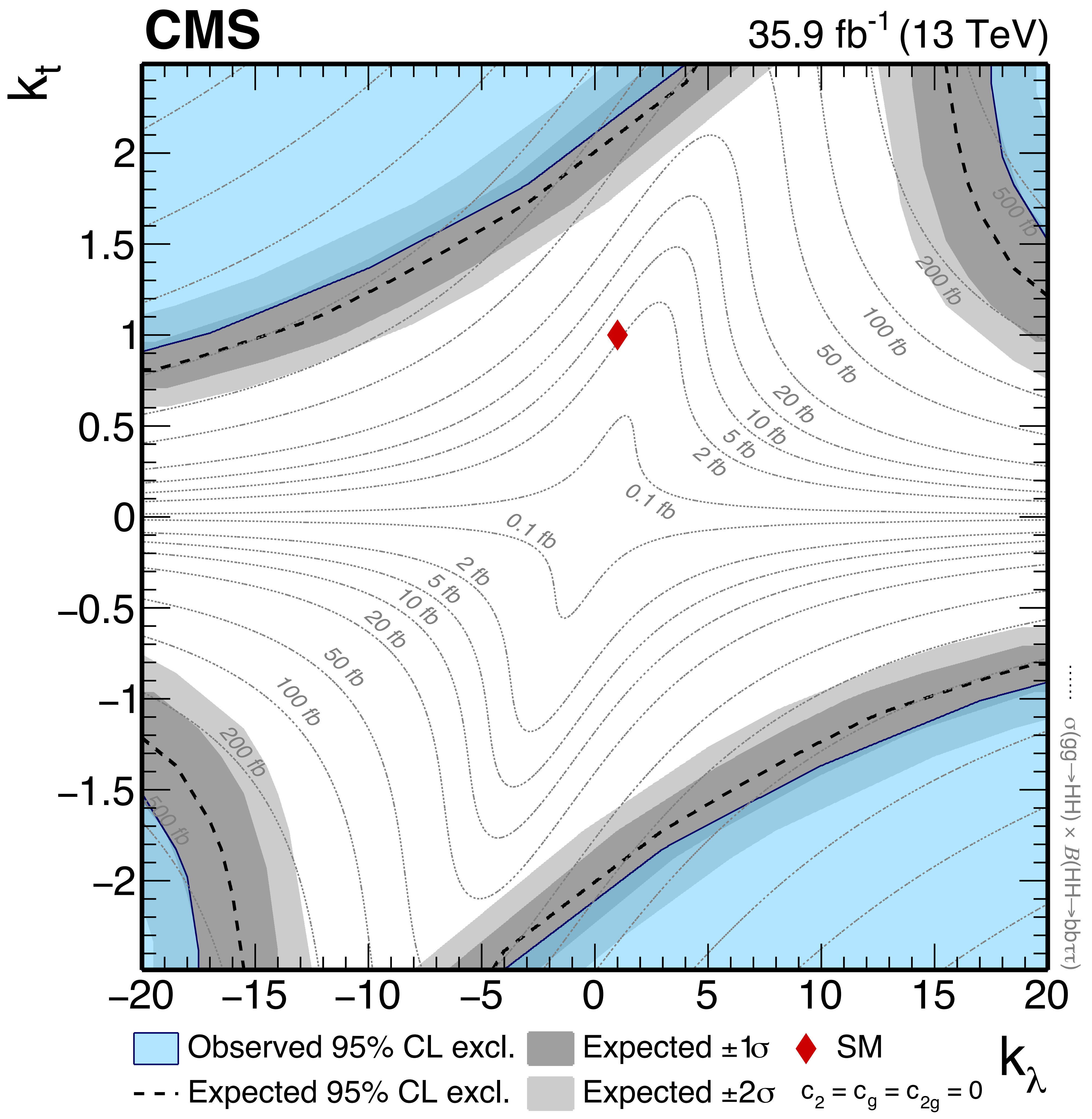


Phys. Lett. B 778 (2018) 101

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

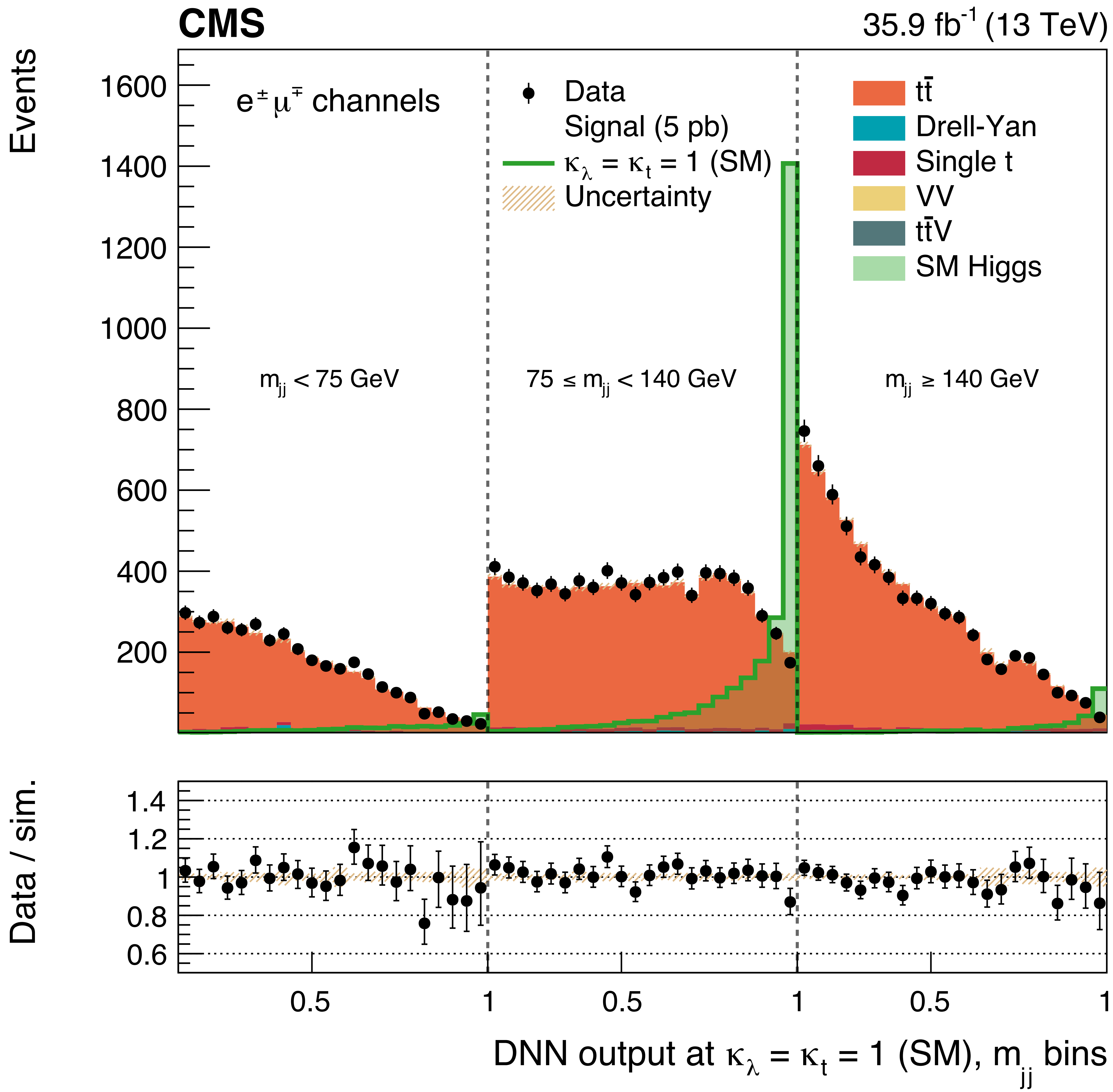
- The observed (expected) upper limit at 95% CL corresponds to about 30 (25) x SM
- Anomalous κ_λ and κ_t couplings tested
  - Sensitive to the sign of κ_t

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



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

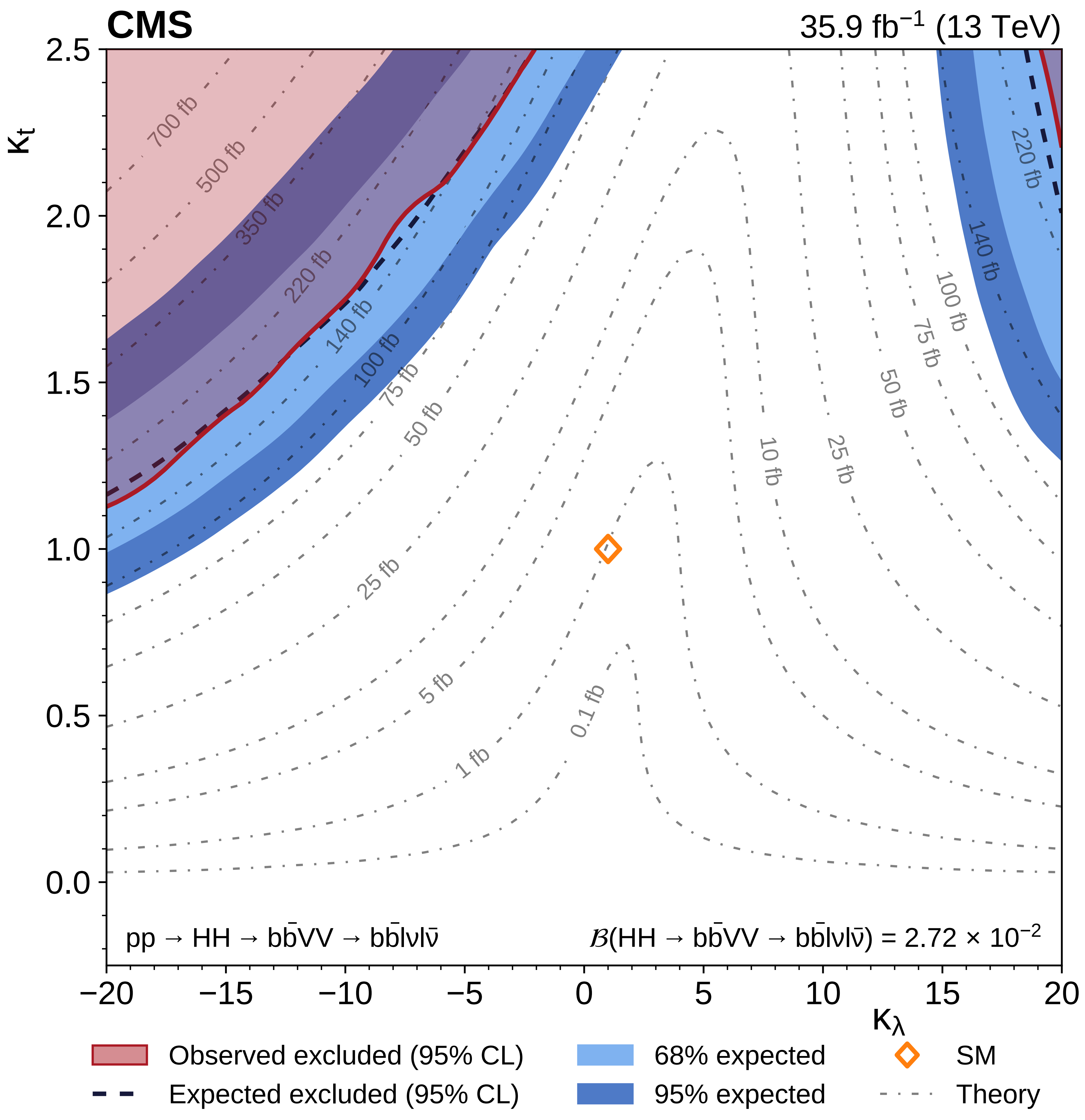
- 2 opposite sign leptons (ee, μμ and eμ+μe) and 2 b-jets
- **Backgrounds**:
  - top (from MC)
  - Z+jets (from 0 b-jets data)
- **DNN** based on the event kinematic to separate signal and top background
  - Parametrized DNN as function of κ_λ and κ_t
- **m_{jj}** and **DNN** classifier used to categorize events



H(VV*→lνlν)H(bb̄)

- The final DNN discriminant is used in three m(bb̄) regions
- The observed (expected) upper limit at 95% CL corresponds to about **79 (89) x SM**
- Anomalous κ_λ and κ_t couplings tested

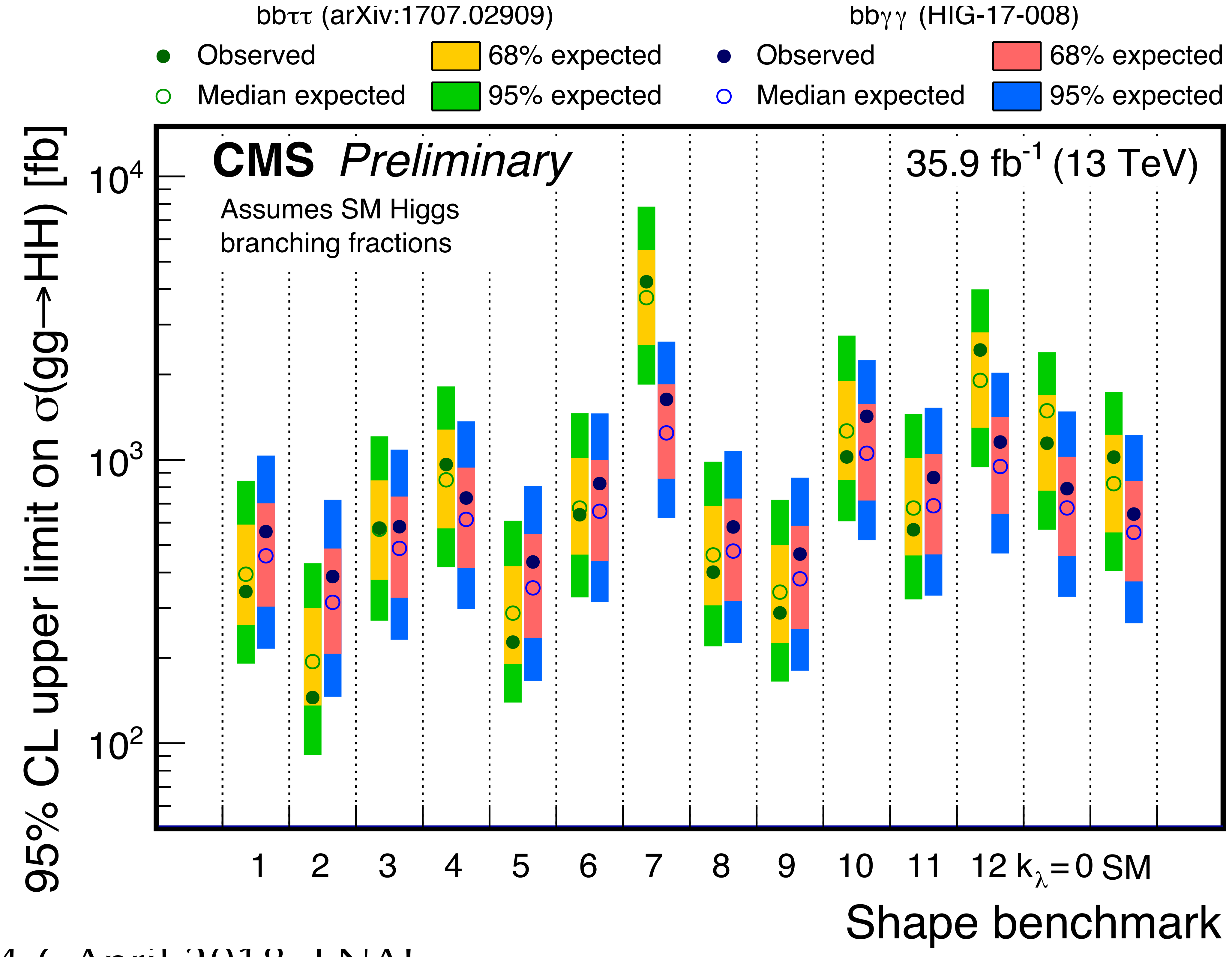
Source	Background yield variation	Signal yield variation
Electron identification and isolation	2.0–3.2%	1.9–2.9%
Jet b tagging (heavy-flavour jets)	2.5%	2.5–2.7%
Integrated luminosity	2.5%	2.5%
Trigger efficiency	0.5–1.4%	0.4–1.4%
Pileup	0.3–1.4%	0.3–1.5%
Muon identification	0.4–0.8%	0.4–0.7%
PDFs	0.6–0.7%	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	$m_X = 400$ GeV
μ_R and μ_F scales	24.2%	4.6–4.7%
Simulated sample size	<0.1%	<0.1%



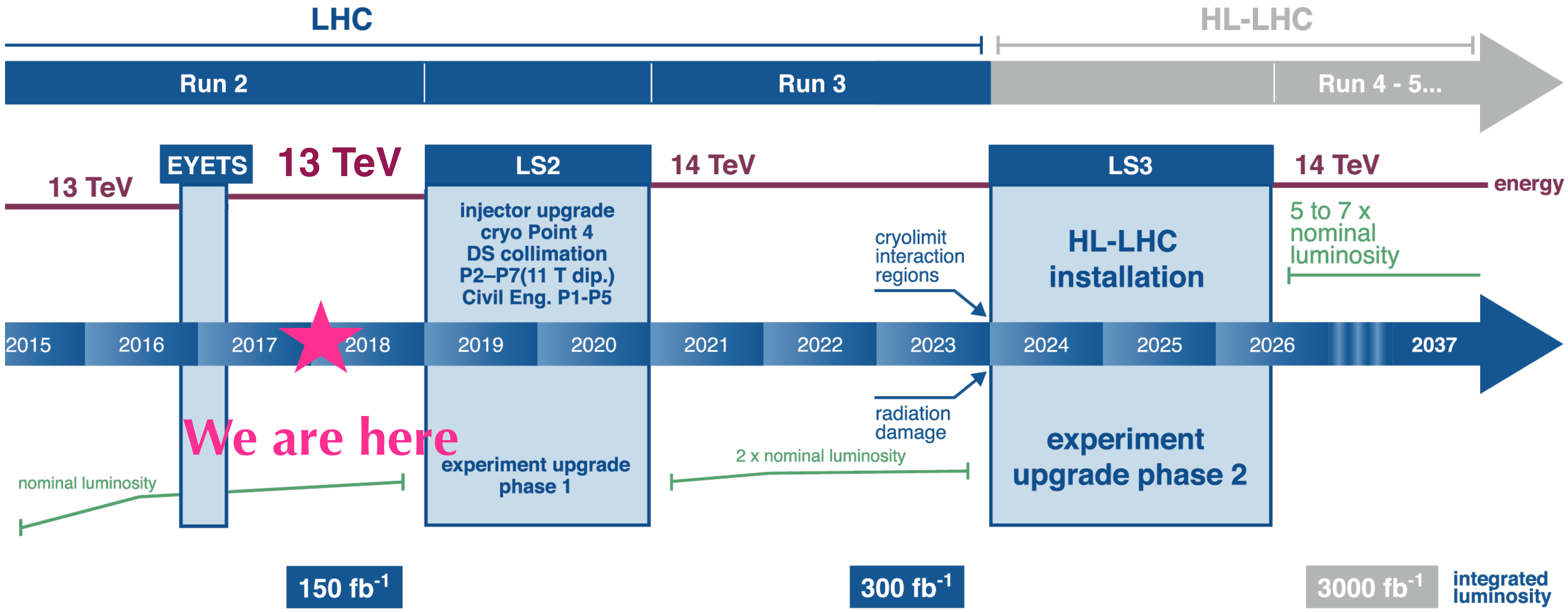
Summary of CMS HH results

- Similar sensitivity from several channels to SM HH production
  - SM production limits reach **~20xSM**
  - Best channel ($b\bar{b}\gamma\gamma$) limits on anomalous trilinear coupling: **$\kappa_\lambda \in$[-9, 15] assuming SM top-H coupling**
- Constraints set on anomalous Higgs boson couplings
  - 12 benchmarks of representative shapes
  - The different final states are complementary in different regions of BSM topologies

Channel	Obs (exp) 95% CL limit on σ/σ_{SM}
$b\bar{b}VV^*(\rightarrow l\nu l\nu)$	79(89)
$b\bar{b}\tau\tau$	31(25)
$b\bar{b}\gamma\gamma$	**19(16)**



LHC → HL-LHC



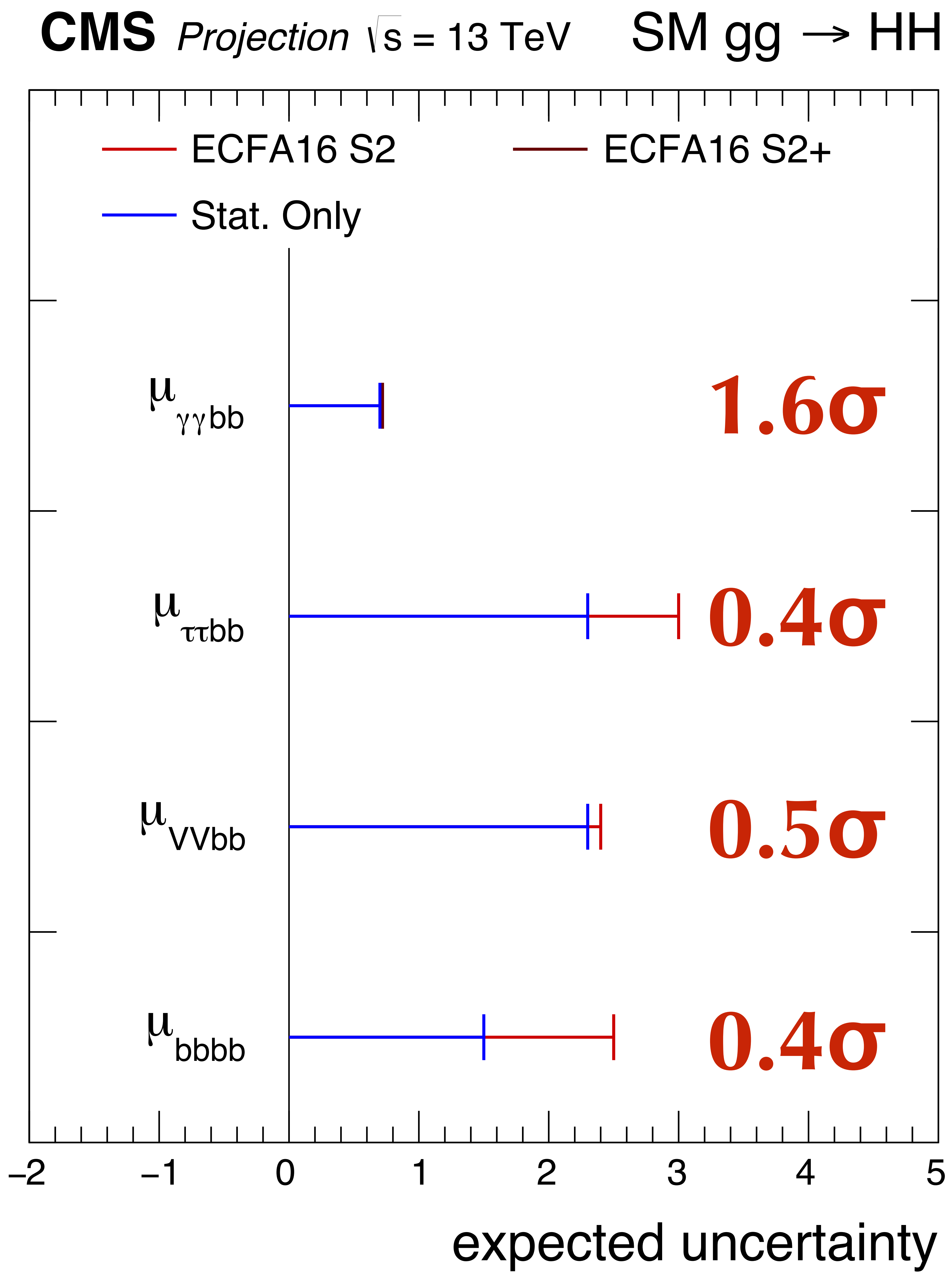
HL-LHC will enable precision measurements of H properties (couplings, self-couplings,…) and to probe the existence of very rare new physics processes

CMS-FTR-16-002
CMS-TDR-17-001

Projections for HL-LHC

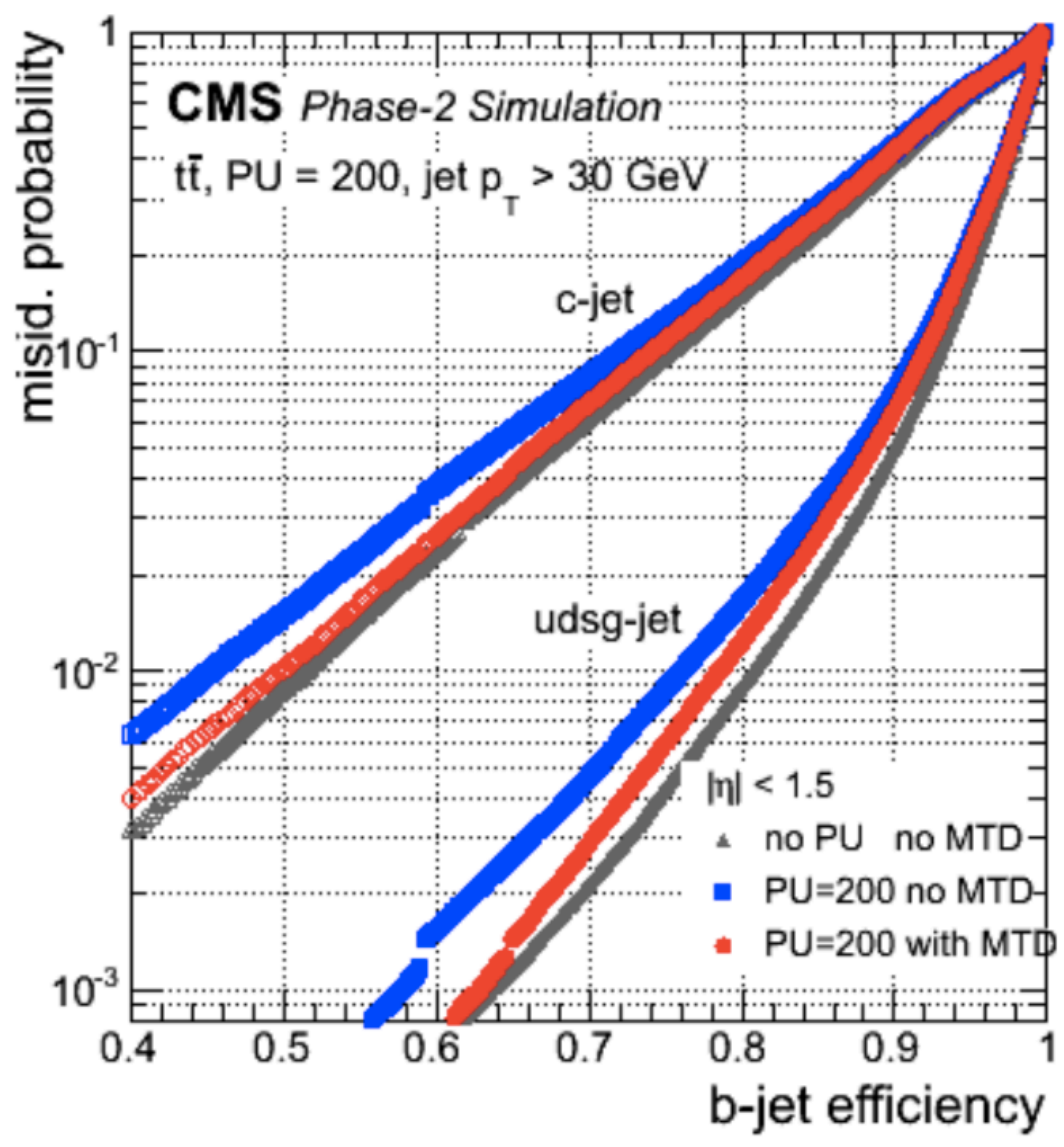
Extrapolation from Run II to HL-LHC (3000 fb^{-1})

- based on 2015 data, about 2.3-2.7fb^{-1}
- Different scenarios:
  - **No systematics**
  - **ECFA16 S2** reduced theory uncertainties and reduced systematics
  - **ECFA16 S2 +** including future detector performance



Considerations about HL-LHC

- ***SM HH discovery is challenging*** but analysis improvements thus far are faster than only luminosity gains
- We will have a **new tracker detector at HL-LHC…**
  - *10% improvement in signal acceptance* for H(b$\bar{b}$)H(b$\bar{b}$) from extended tracker acceptance up to $|\eta| = 4$
  - *10-15% increase for the VBF* process
  - b-tagging performance will benefit from a more granular detector
- We will have a **timing detector at HL-LHC…**
  - *~ 30% improvement in light-jet discrimination* by removing spurious tracks entering into secondary vertex reconstructing
  - *~20% increase in effective integrated luminosity for HH*
- **Better background discrimination** from selection optimization with the large dataset



Mip Timing Detector

Channel	Signal increase (%)
HH→ $bb\gamma\gamma$	22
HH→ $b\bar{b}b\bar{b}$	18

On going studies for HL-LHC (towards YR5)

CMS-TDR-17-001
CMS-TDR-17-007
arXiv:1704.01953
arXiv:1709.08649

- ***Dedicated analysis for Phase II*** shows that SM HH production can be measured by CMS with approximately **50% precision** using 3000 fb^{-1}
  - $H(b\bar{b})H(b\bar{b})$ not included but a promising channel
- Studies based on **full-sim/Delphes** are on going:
  - $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}VV$, $\mathbf{b\bar{b}\tau\tau}$, and VBF for VVHH
- **Combination** of all channels
  - projections from CMS HH 13 TeV combination as reference
  - possible combination with ATLAS
- Possibility to constrain λ_{HHH} further from:
  - **single** H measurement [currently interest in $H(\gamma\gamma)$]
  - $\mathbf{m_{HH}}$ **differential information**

Category	σ_{HH}/σ_{SM}	$\sigma_{ggHH}/\sigma_{SM}$	σ_{VBF}/σ_{SM}
2b0j	1.8	3.0	72.6
VBF	3.9	5.4	86.6
Combined	1.6	2.8	52.2

$b\bar{b}\tau_h\tau_h$ ~ 1.5xSM
(2-3xSM from Run II projections)

Conclusions & Outlook

- Similar sensitivity from several channels to SM HH production
  - SM production limits reach ~20xSM
  - best channel (bb$\gamma\gamma$) limits on anomalous trilinear coupling: $\kappa_\lambda \in [-9, 15]$
- Run III and HL-LHC will be crucial to test SM HH and BSM contributions
- HL-LHC projections show a challenging road ahead
  - We will have new tracker and timing detectors
    - improved tracking and b-tagging performance
  - Analysis techniques improves fast

Additional Material

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

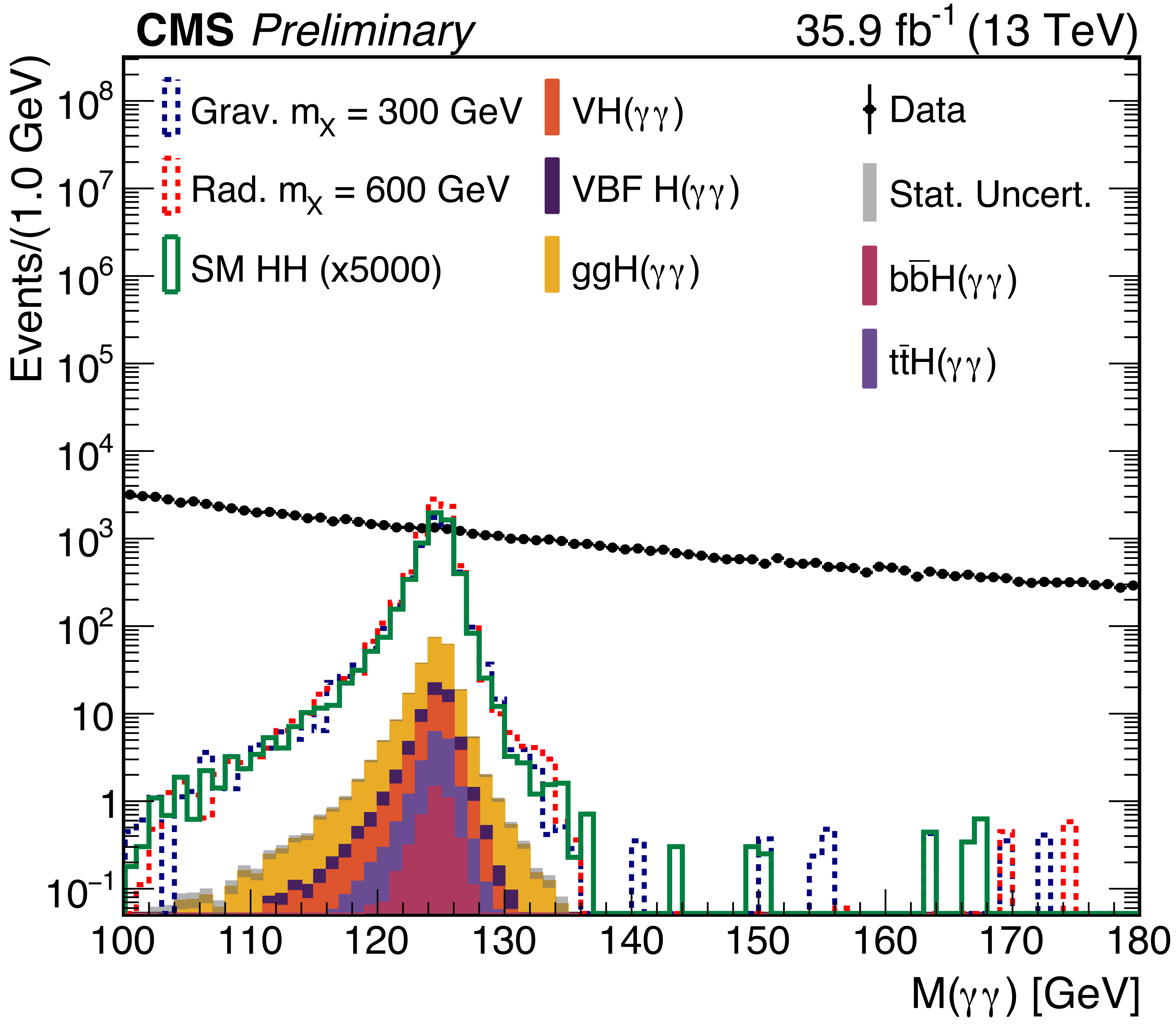
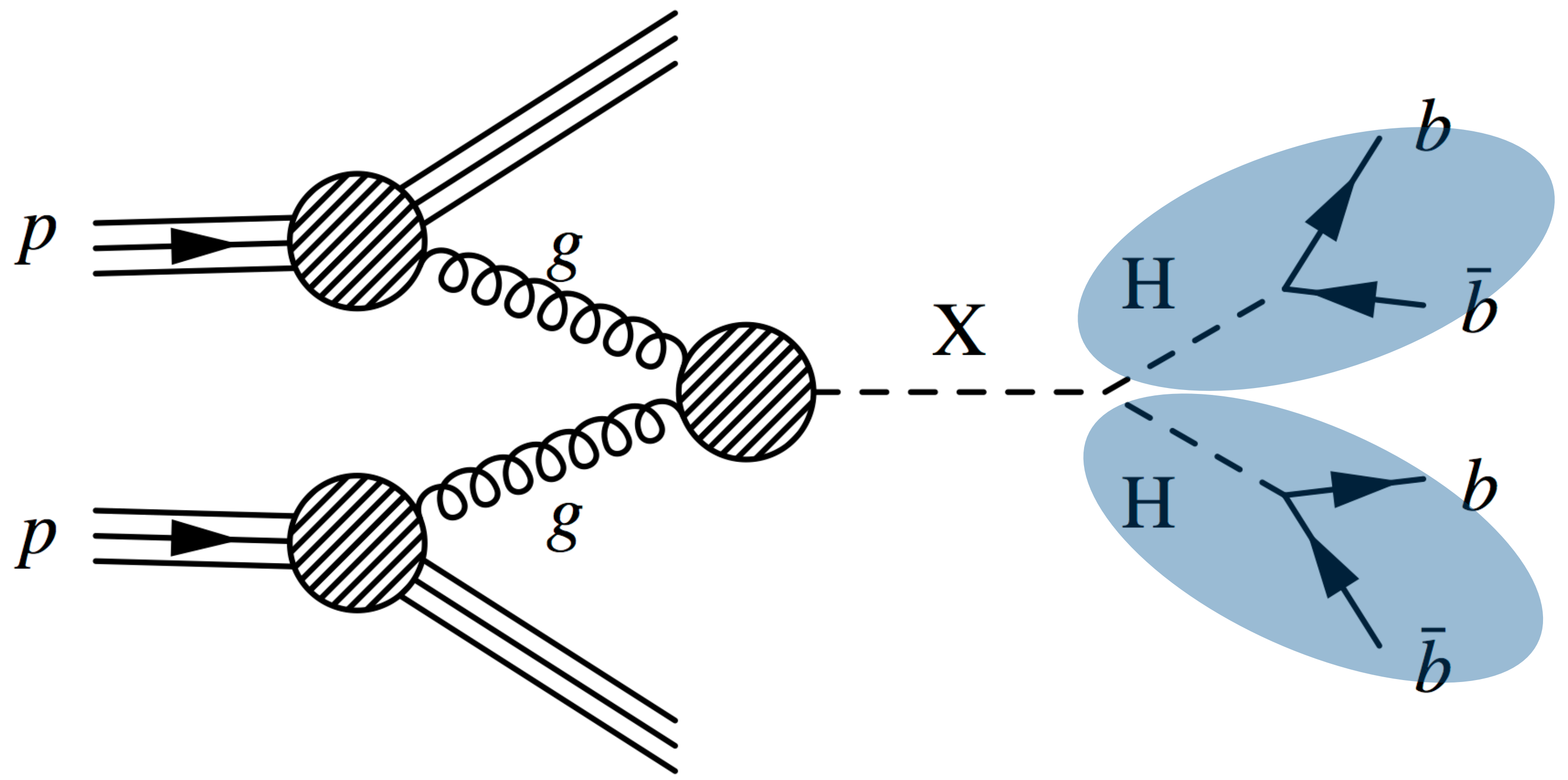
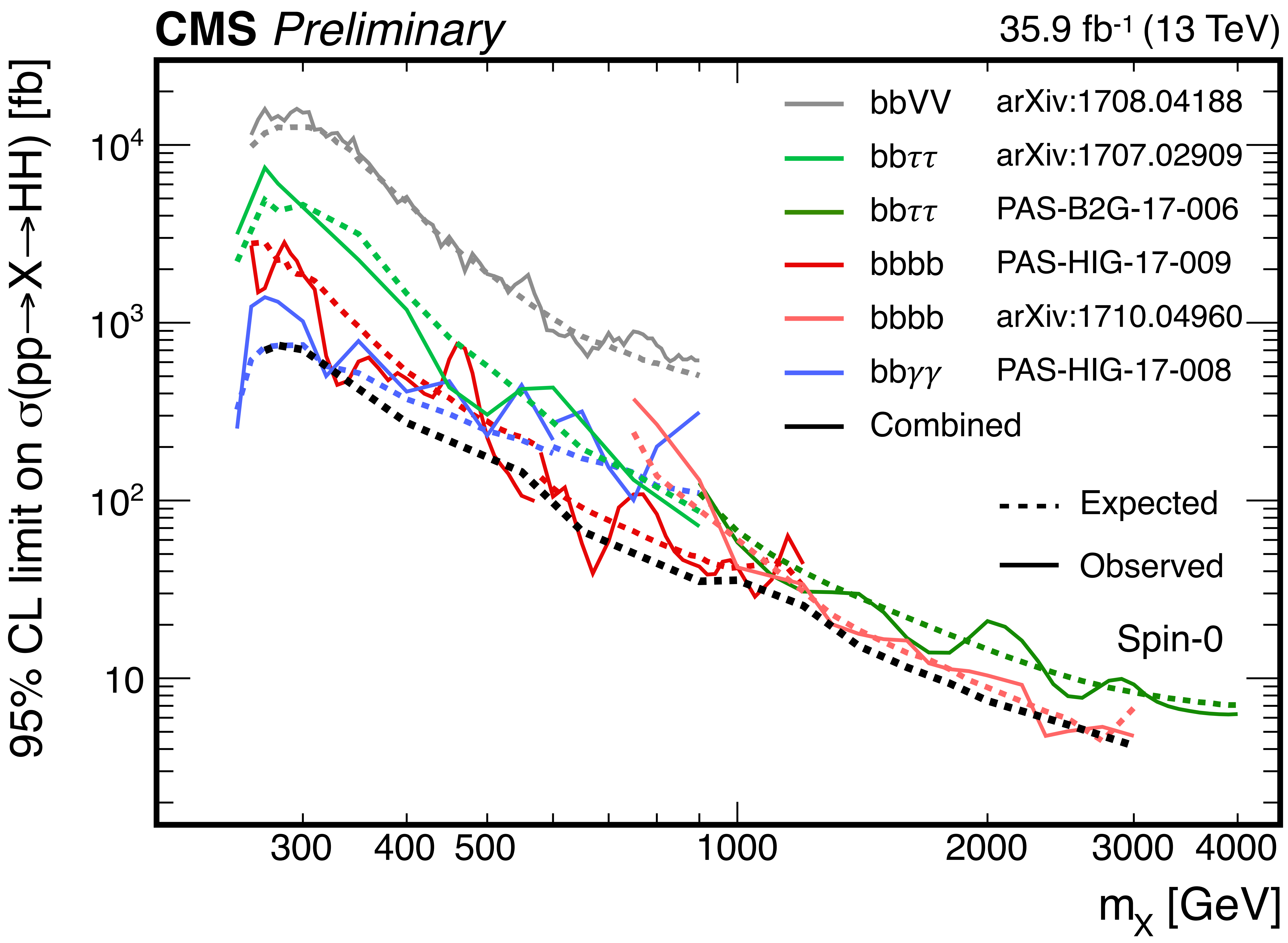


Table 1: Summary of the analysis baseline selection criteria.

Photons		Jets	
Variable	Selection	Variable	Selection
$E_T(\gamma_1)$	> 30 GeV and $> M(\gamma\gamma)/3$	p_T [GeV]	> 25
$E_T(\gamma_2)$	> 20 GeV and $> M(\gamma\gamma)/4$	$\Delta R(j,\gamma)$	> 0.4
$\lvert\eta(\gamma)\rvert$	< 2.5	$\lvert\eta(j)\rvert$	< 2.4
$M(\gamma\gamma)$ [GeV]	$[100, 180]$	$M(jj)$ [GeV]	$[70, 190]$

Run II HH resonant searches





- **H($b\bar{b}$)H($b\bar{b}$) is the best final state** to search for a new HH heavy state
- boosted topology helps to reduce multi-jet background

HH to 4b is also a preliminary step towards Higgs self-coupling measurement

Timing for leptons

~7% efficiency gain for each muon or electron (taking 2% bkg. eff WP)