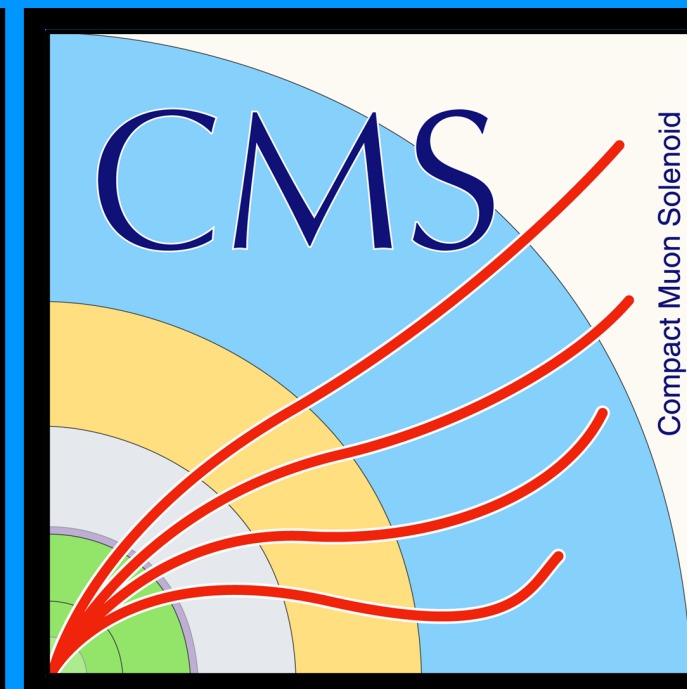
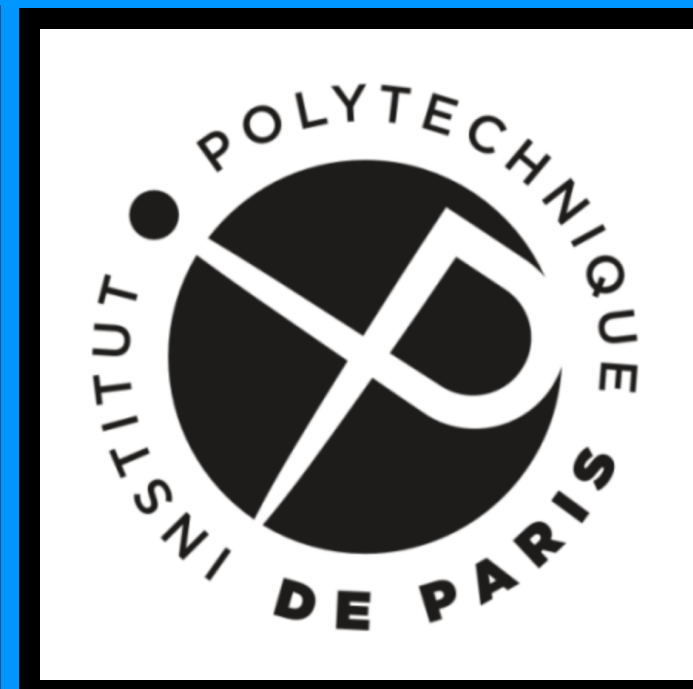


# HH searches: CMS Experimental Overview



**LHC Higgs WG  
20<sup>th</sup> Workshop**

**Bruno Alves, for the CMS Collaboration**



**14/11/2023**

**Indico**

# Motivation

**Resonant**

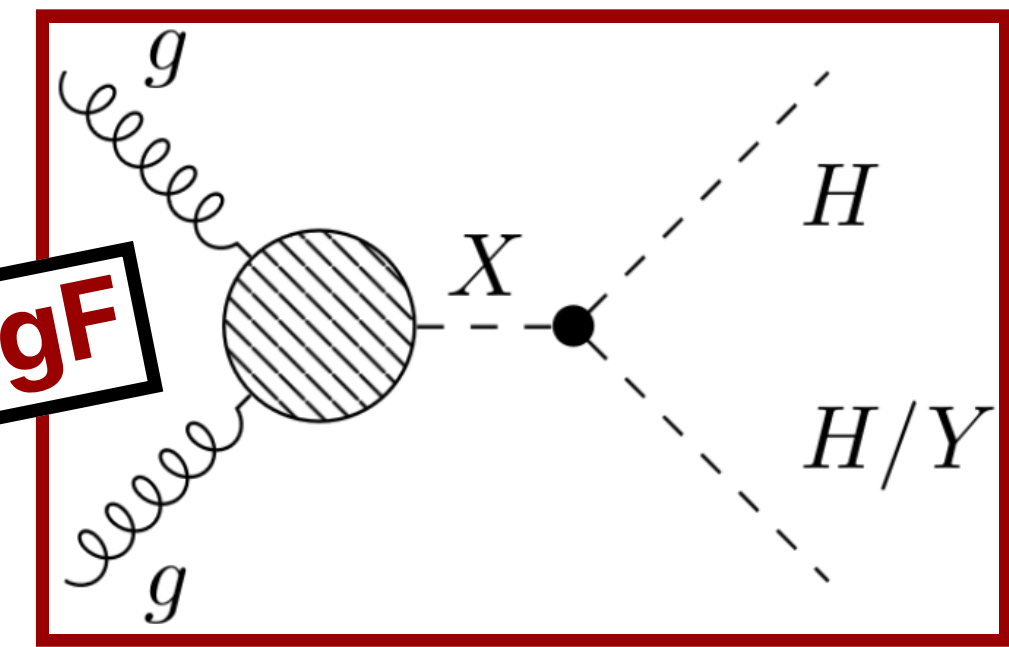
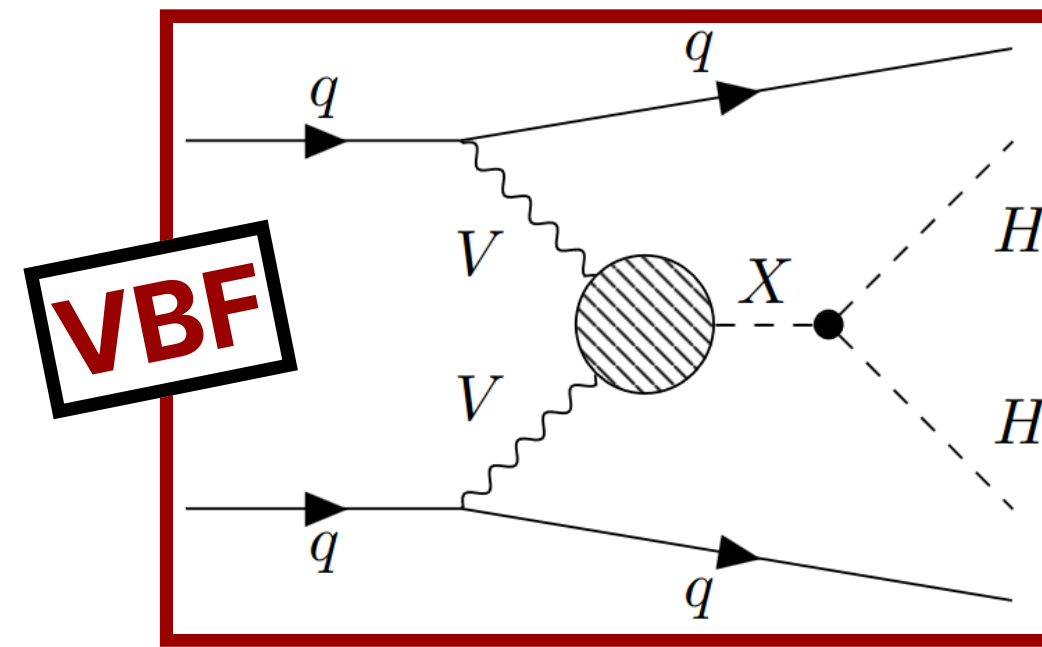
## Bump search: test resonant BSM

- Spin 0 and spin 2 hypotheses
- 2HDM, NMSSM, TRSM, WED...

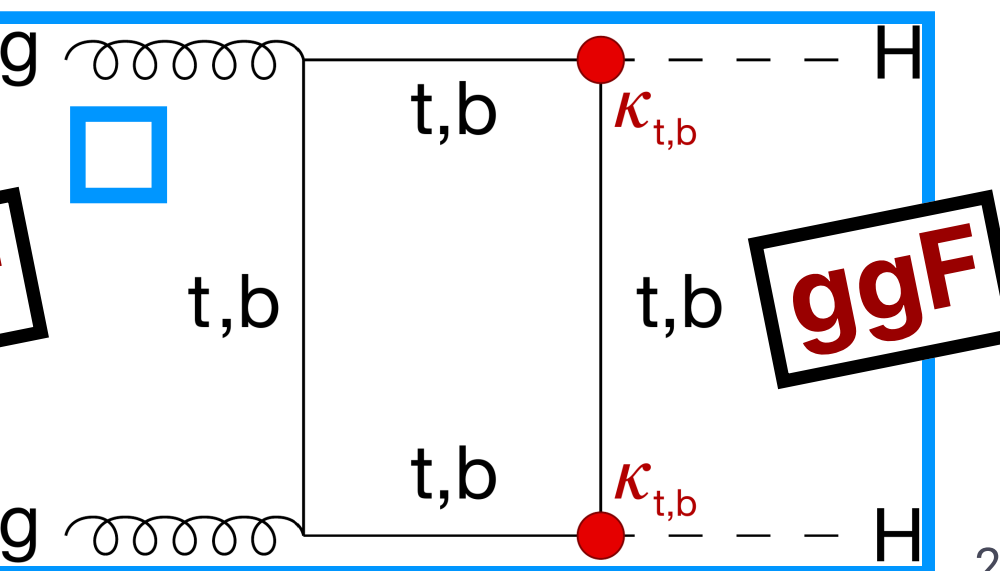
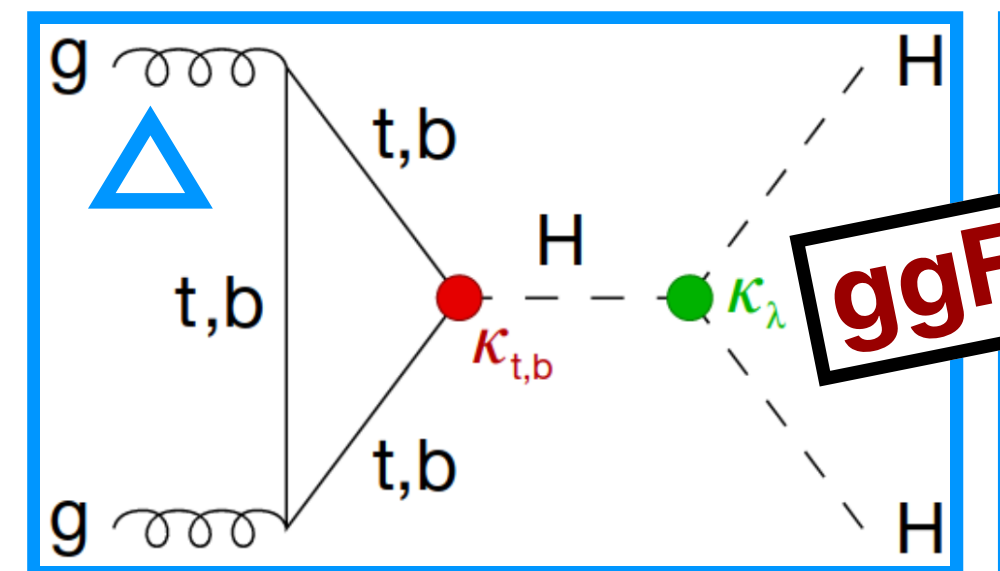
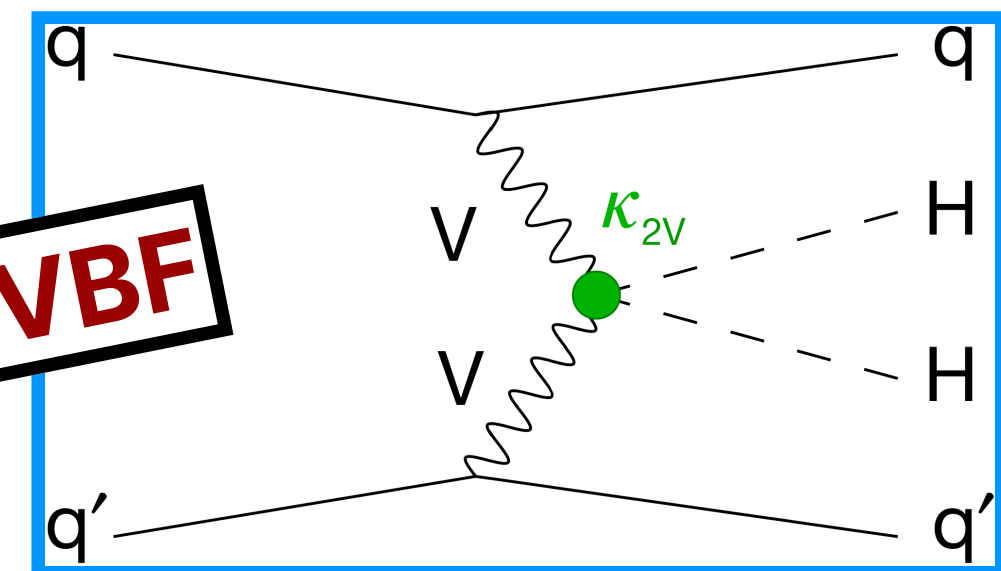
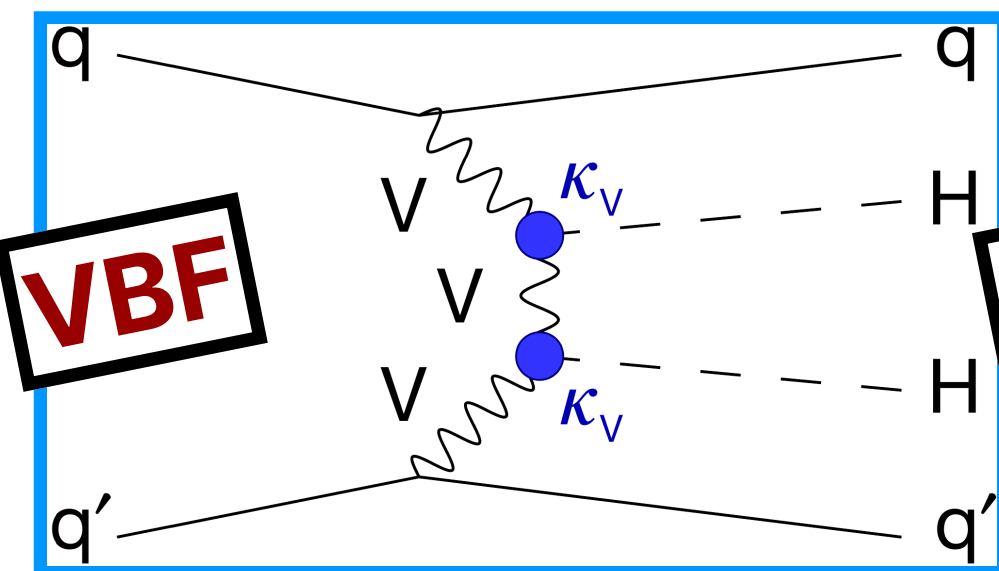
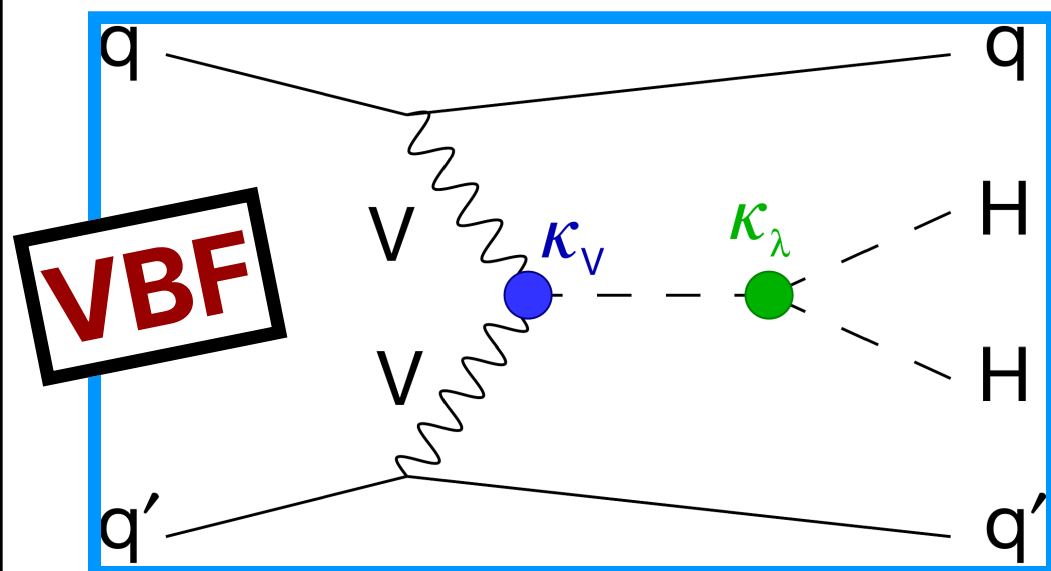
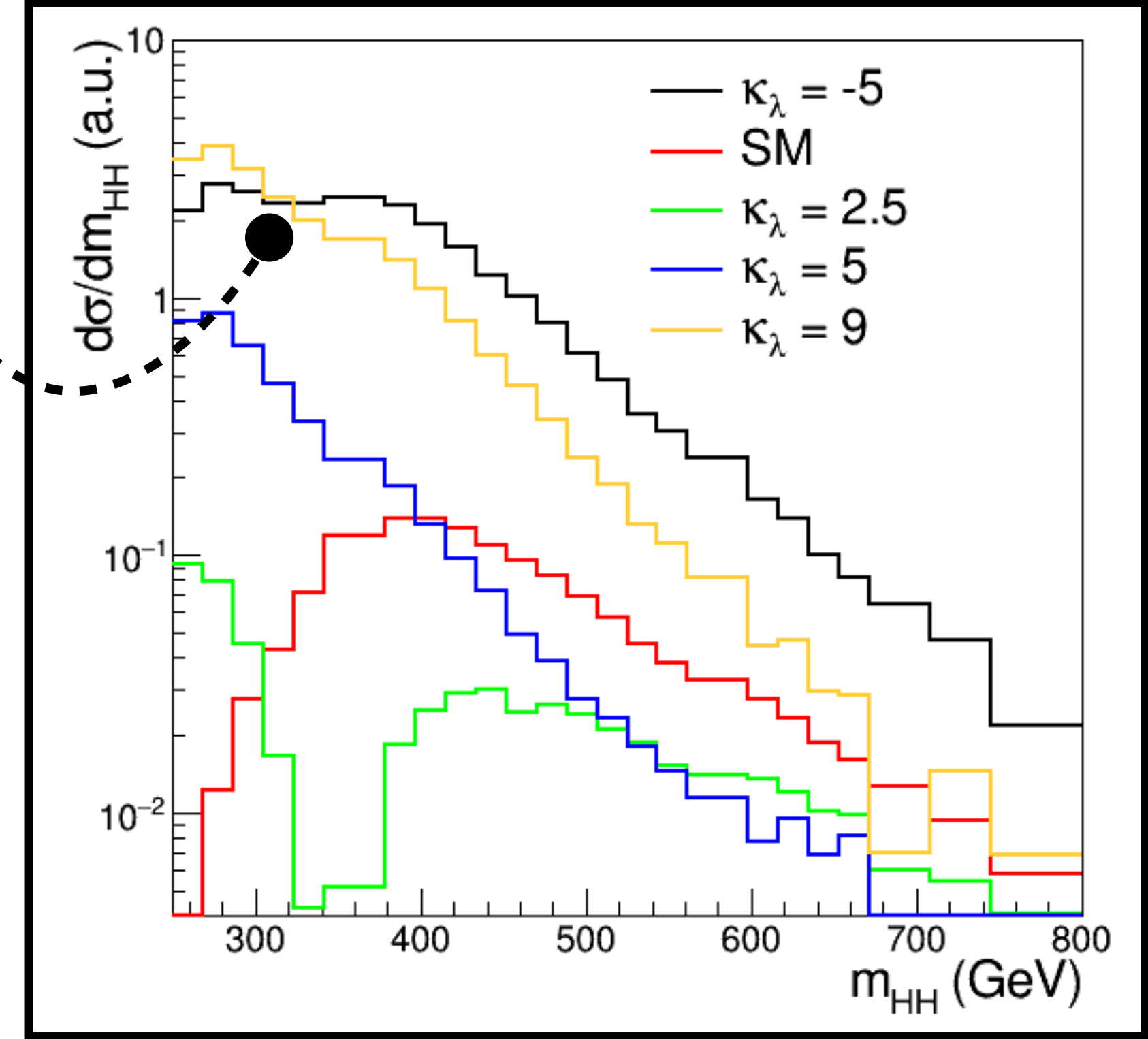
**Non-resonant**

## Test BSM w/ anomalous couplings: $k_\lambda$ , $k_t$ , $k_V$ , $k_{2V}$

- deviations may lead to diffs. in HH production rates and kinematics
- small SM HH cross-section because of  $\Delta$ - $\square$  interference

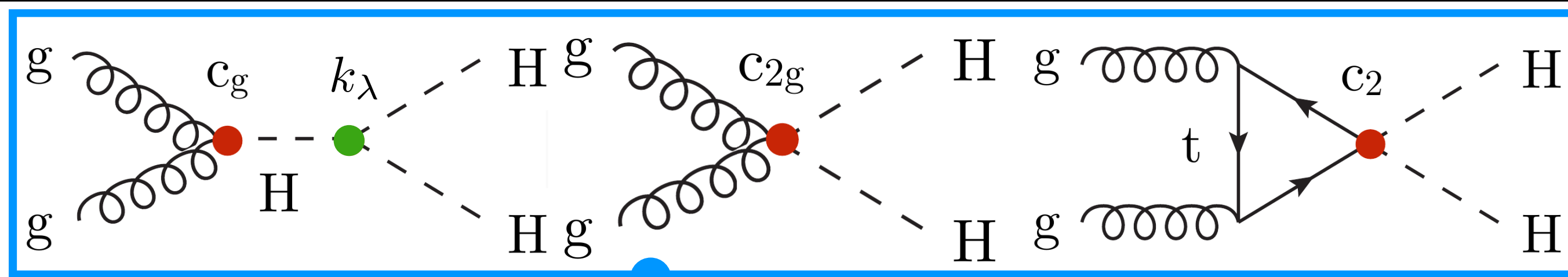


$\Delta$  dominates for large  $k_\lambda$



# Motivation: EFT

ggF



- Probe effects from resonances with very high mass at lower energy scales

- BSM effects on ggF HH production can be studied through EFT model with **three new couplings**

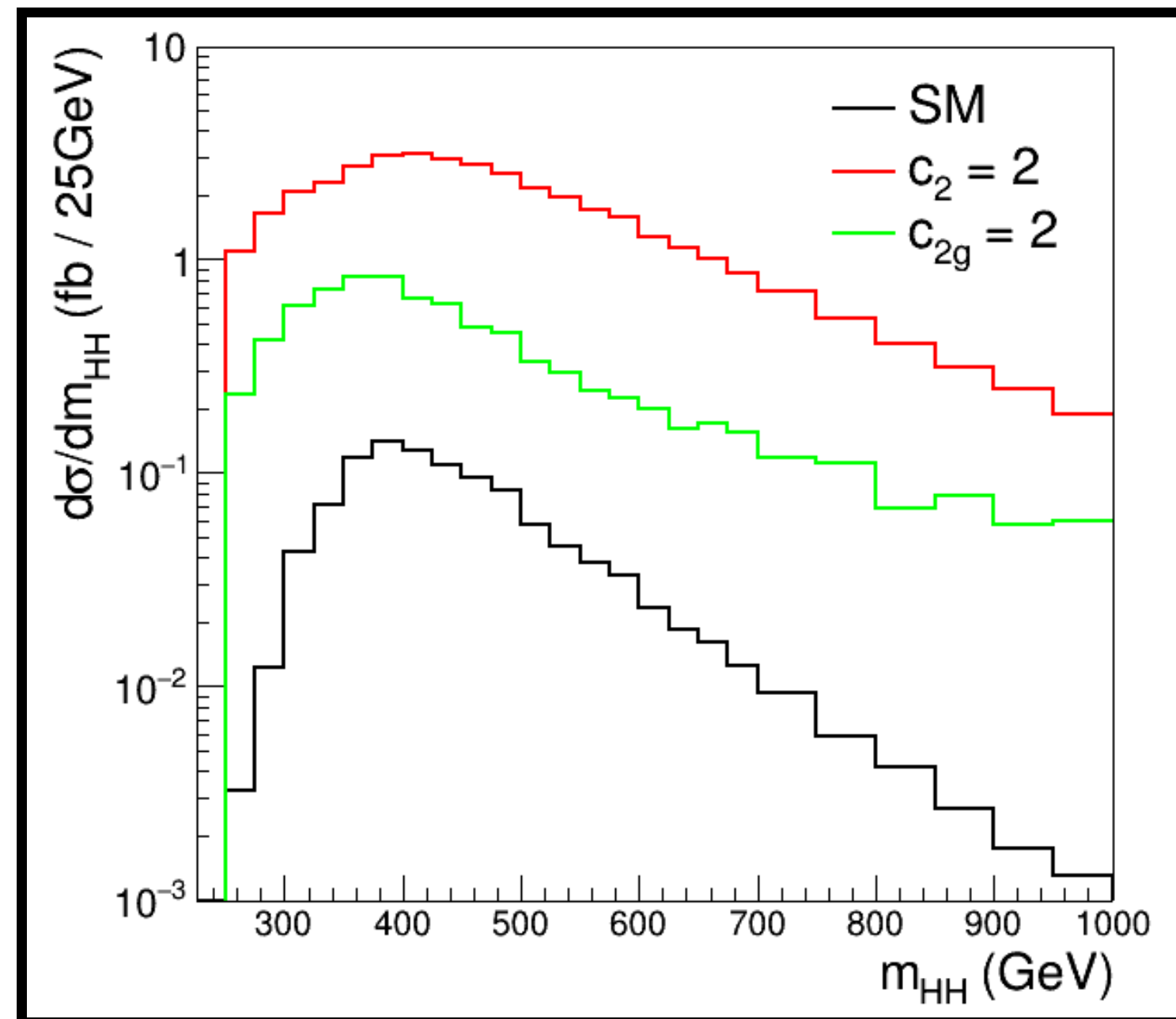
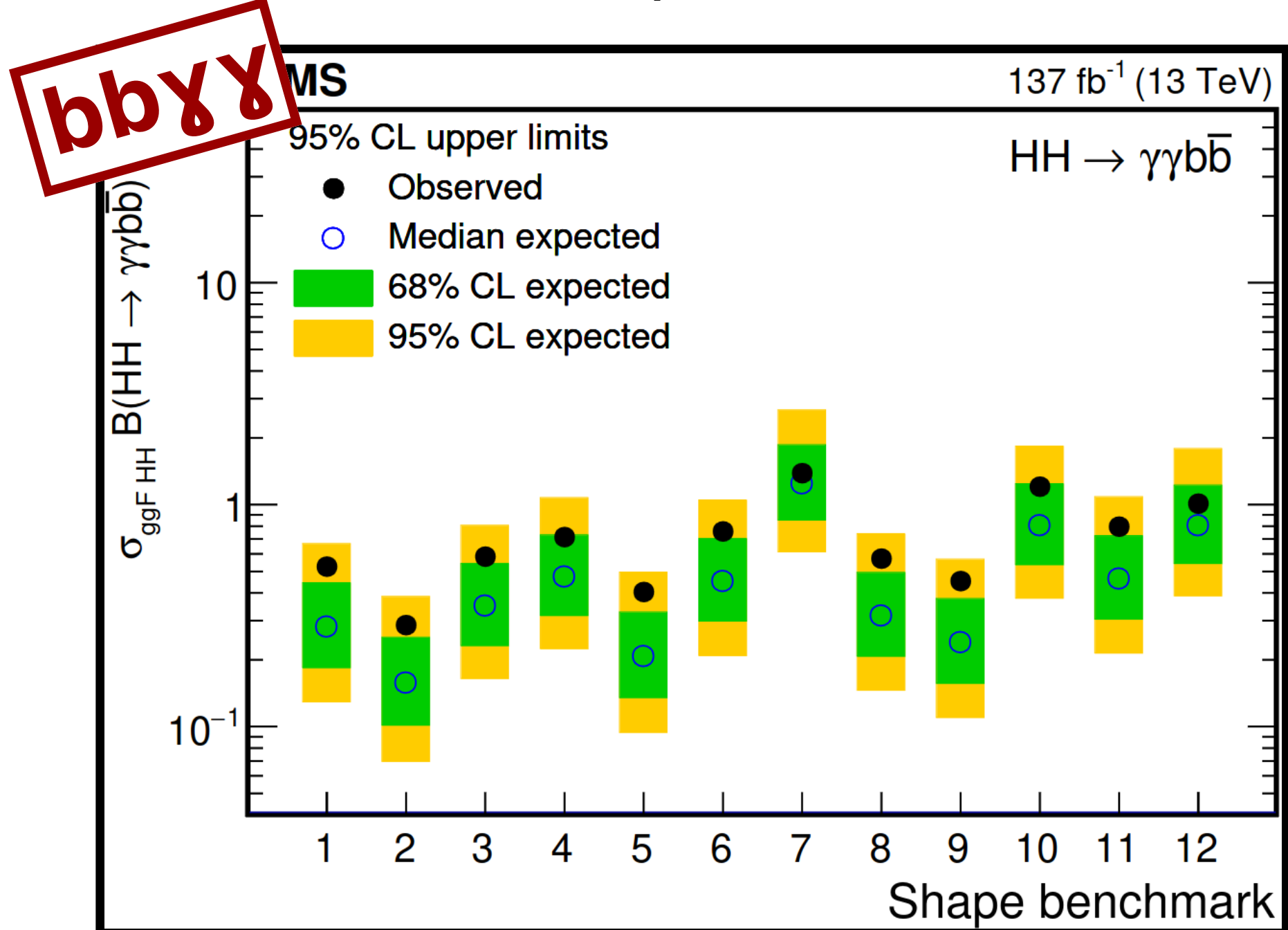
- Explore sensitivity to BSM EFT couplings with **EFT**

## benchmark points:

- based on test statistic measuring kinematics' similarity
  - allow extrapolation between different points

Benchmarks

	$\kappa_\lambda$	$\kappa_t$	$c_2$	$c_g$	$c_{2g}$
SM	1.0	1.0	0.0	0.0	0.0
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
8a	1.0	1.0	0.5	$\frac{0.8}{3}$	0.0
1b	3.94	0.94	$\frac{-1}{3}$	0.75	-1
2b	6.84	0.61	$\frac{1}{3}$	0.0	1.0
3b	2.21	1.05	$\frac{-1}{3}$	0.75	-1.5
4b	2.79	0.61	$\frac{1}{3}$	-0.75	-0.5
5b	3.95	1.17	$\frac{-1}{3}$	0.25	1.5
6b	5.68	0.83	$\frac{1}{3}$	-0.75	-1.0
7b	-0.10	0.94	1.0	0.25	0.5



A. Carvalho et al, Capozzi et al, Buchalla et al



# Production $\rightarrow$ HH $\rightarrow$ Decay

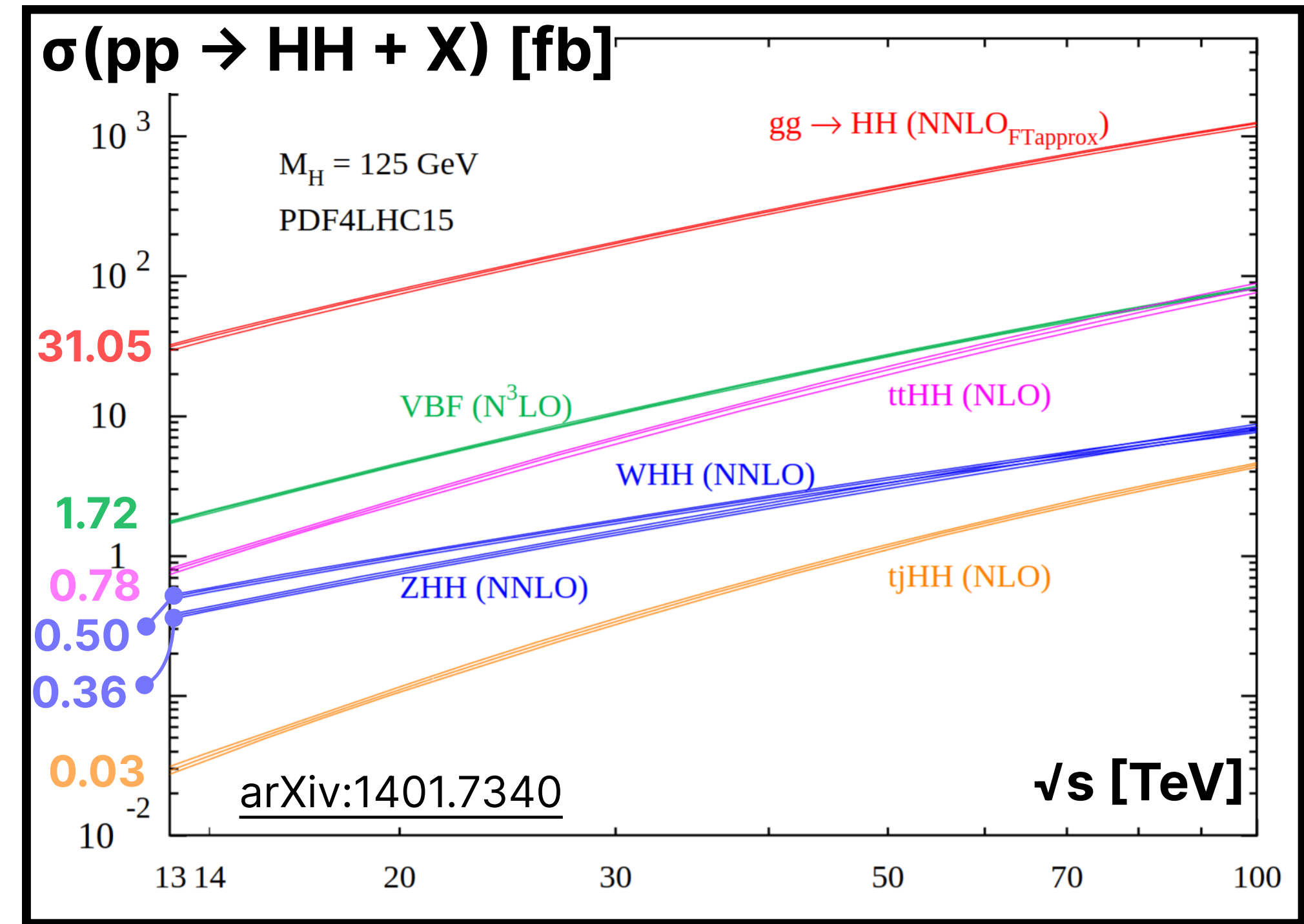
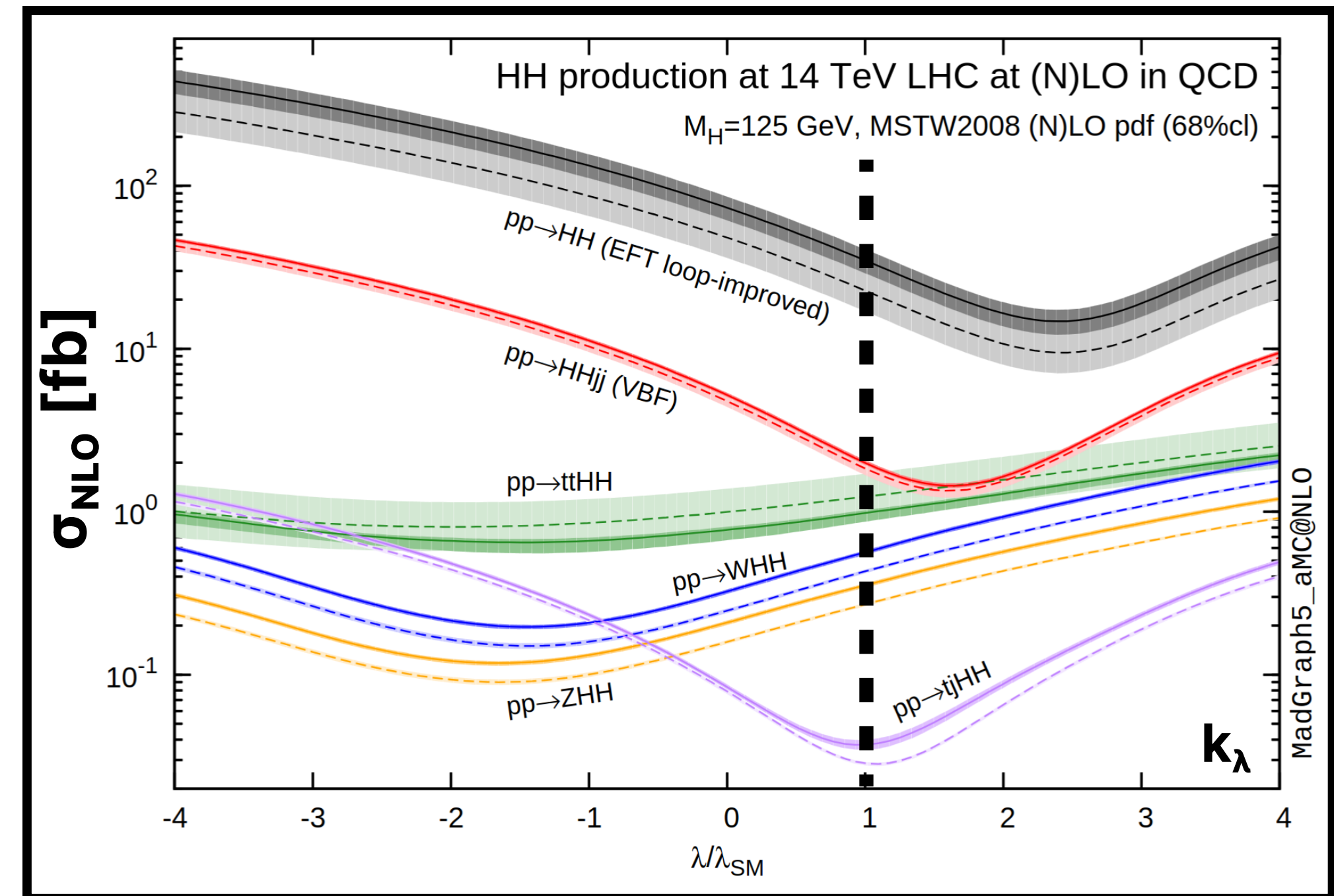
- **ggF**, **VBF** and **VHH** production
- Large variety of HH channels
  - trade-off between selection purity and branching ratio

**New!**

HH	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	 34%				
WW	 25%	 4.6%			
$\tau\tau$	 7.3%	 2.7%	 0.39%		
ZZ	 3.1%	 1.1%	 0.33%	 0.069%	
$\gamma\gamma$	 0.26%	 0.10%	 0.028%	 0.012%	 0.0005%

**No golden channel!**

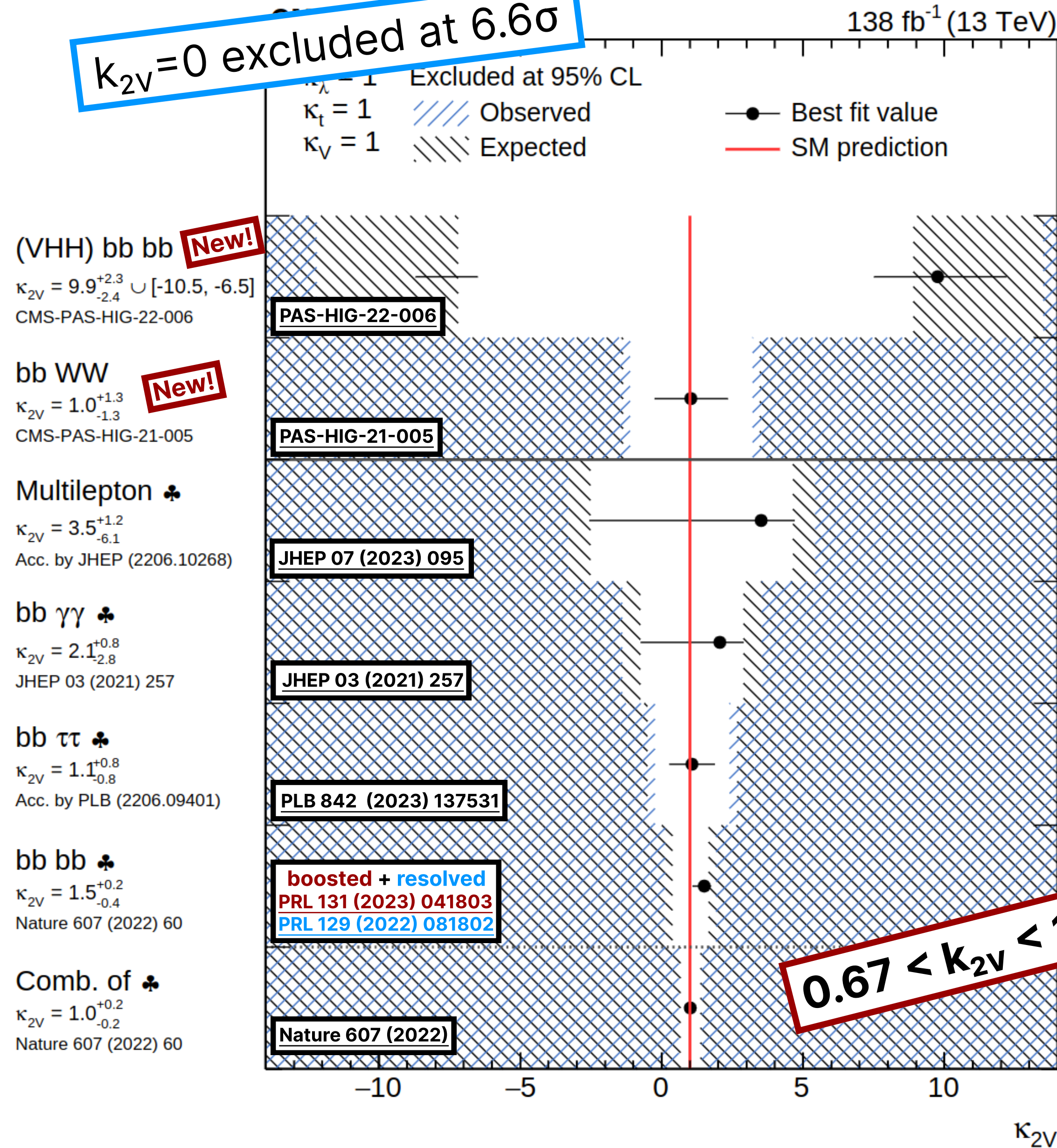
- ★ nonres VHH
- resonant
- nonres VBF
- nonres ggF





# Non-res. Run2 Combination

$k_{2V}=0$  excluded at  $6.6\sigma$



CMS Preliminary

138 fb<sup>-1</sup> (13 TeV)

(VHH) bb bb **New!**  
 $\kappa_\lambda = -25.1^{+6.8}_{-5.6}$   
 CMS-PAS-HIG-22-006

WW  $\gamma\gamma$   
 $\kappa_\lambda = 14.8^{+5.5}_{-13.3}$   
 CMS-PAS-HIG-21-014

bb WW **New!**  
 $\kappa_\lambda = 4.2^{+5.3}_{-5.7}$   
 CMS-PAS-HIG-21-005

bb ZZ ♣  
 $\kappa_\lambda = 2.3^{+5.6}_{-5.4}$   
 Acc. by JHEP (2206.10657)

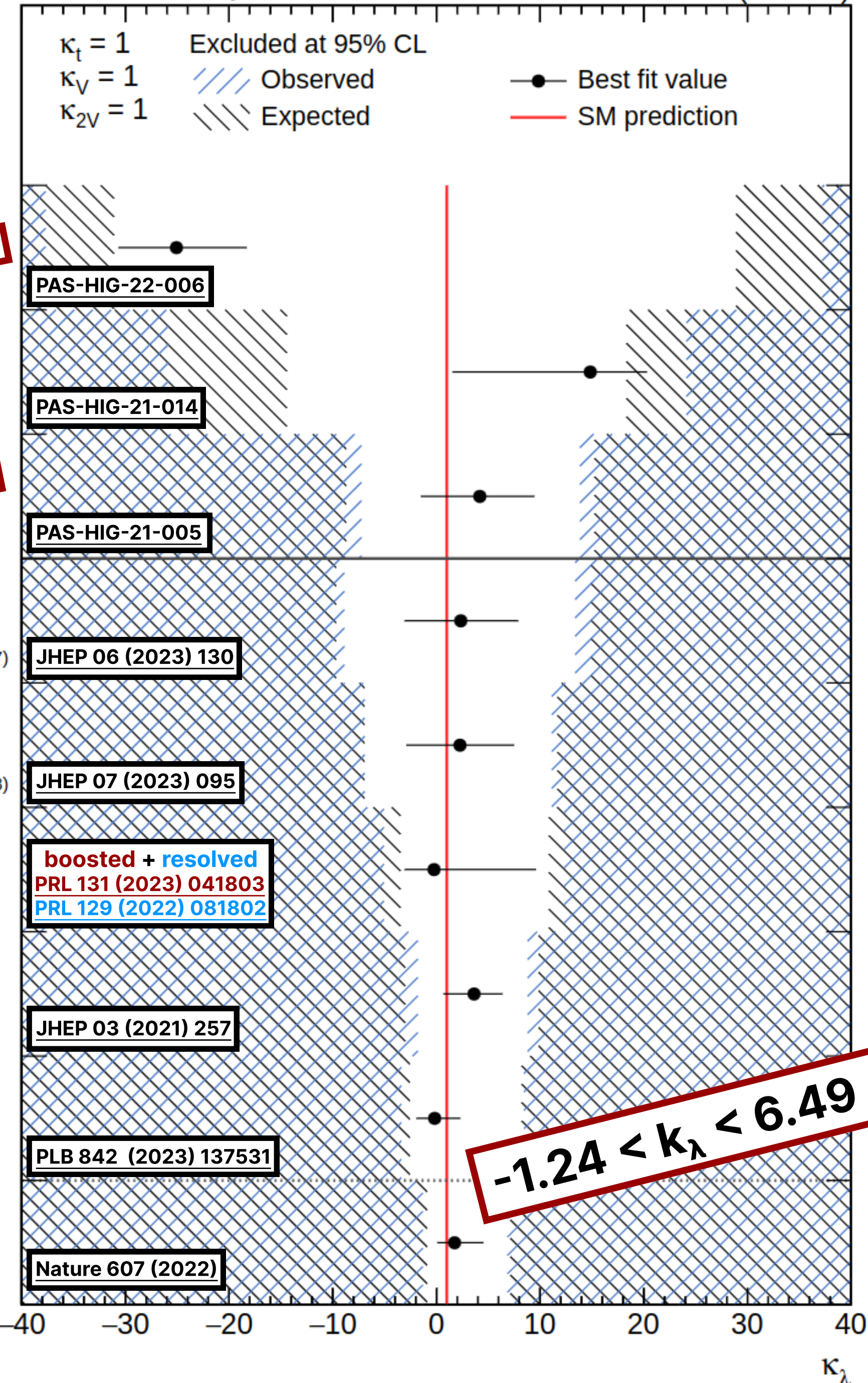
Multilepton ♣  
 $\kappa_\lambda = 2.3^{+5.2}_{-5.2}$   
 Acc. by JHEP (2206.10268)

bb bb ♣  
 $\kappa_\lambda = -0.2^{+9.9}_{-2.8}$   
 Nature 607 (2022) 60

bb  $\gamma\gamma$  ♣  
 $\kappa_\lambda = 3.6^{+2.8}_{-2.9}$   
 JHEP 03 (2021) 257

bb  $\tau\tau$  ♣  
 $\kappa_\lambda = -0.2^{+2.5}_{-1.7}$   
 Acc. by PLB (2206.09401)

Comb. of ♣  
 $\kappa_\lambda = 1.7^{+2.8}_{-1.7}$   
 Nature 607 (2022) 60



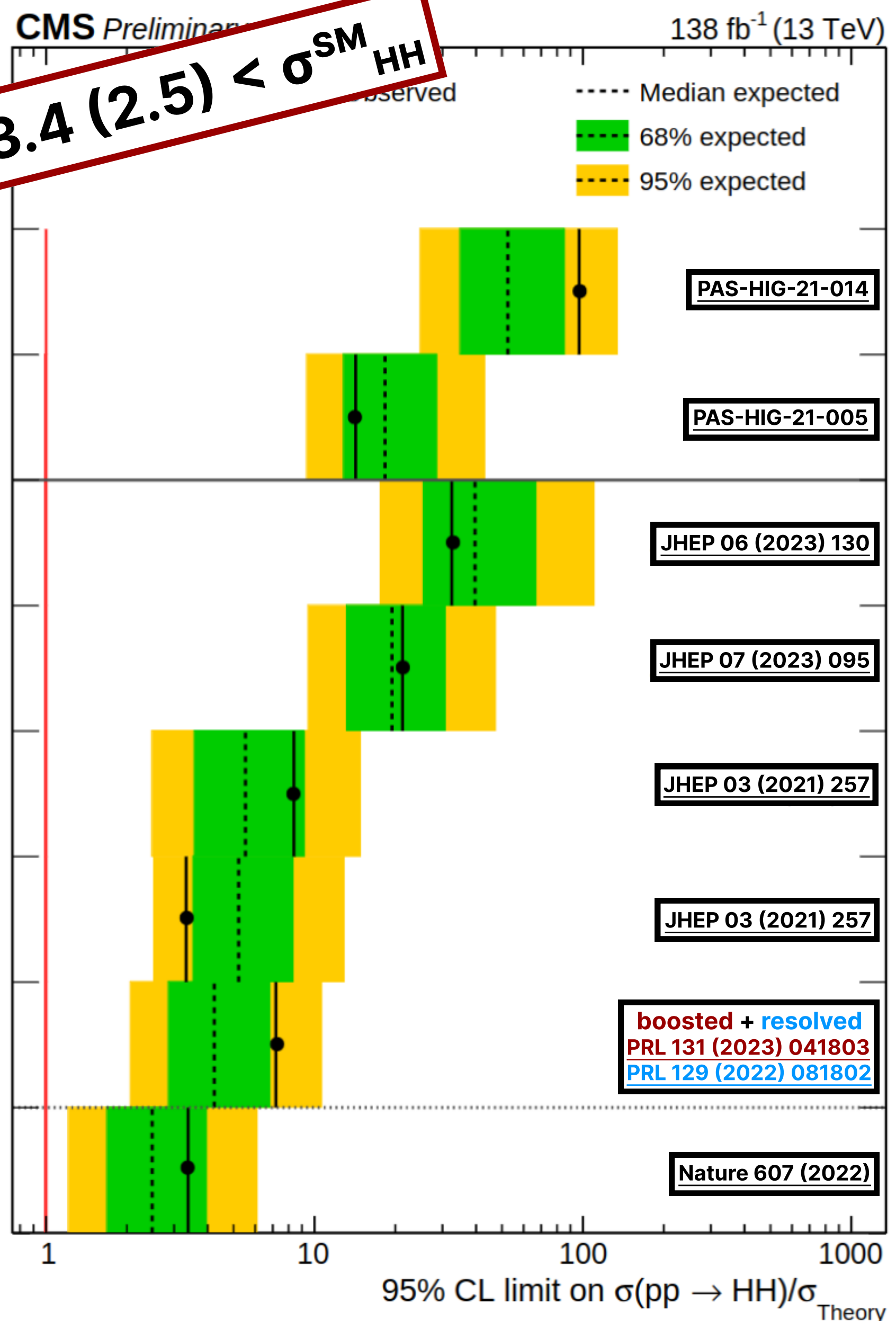


# Non-res. Run2 Combination

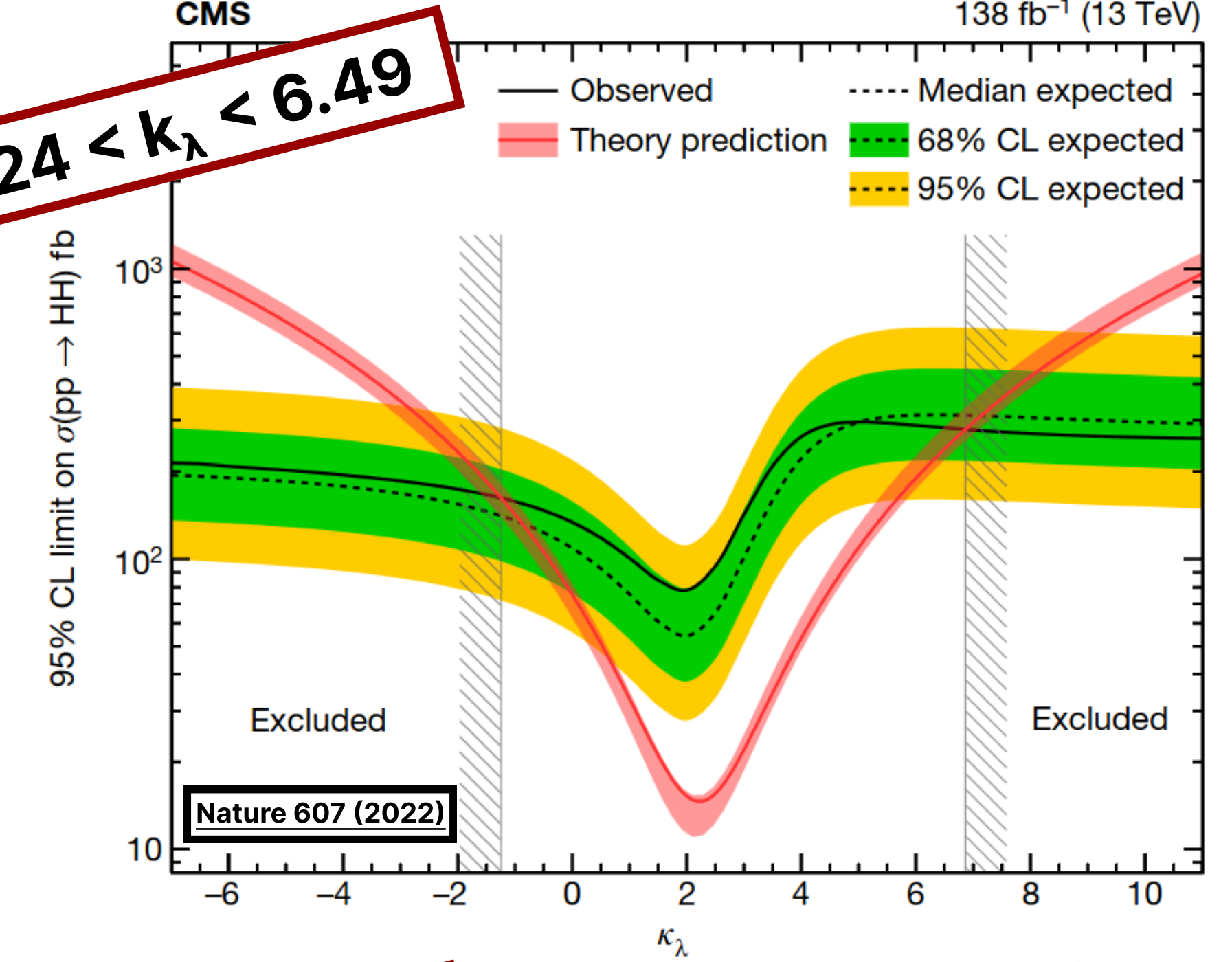
**$\sigma_{HH} < 3.4 (2.5) < \sigma_{HH}^{SM}$**

**New!**

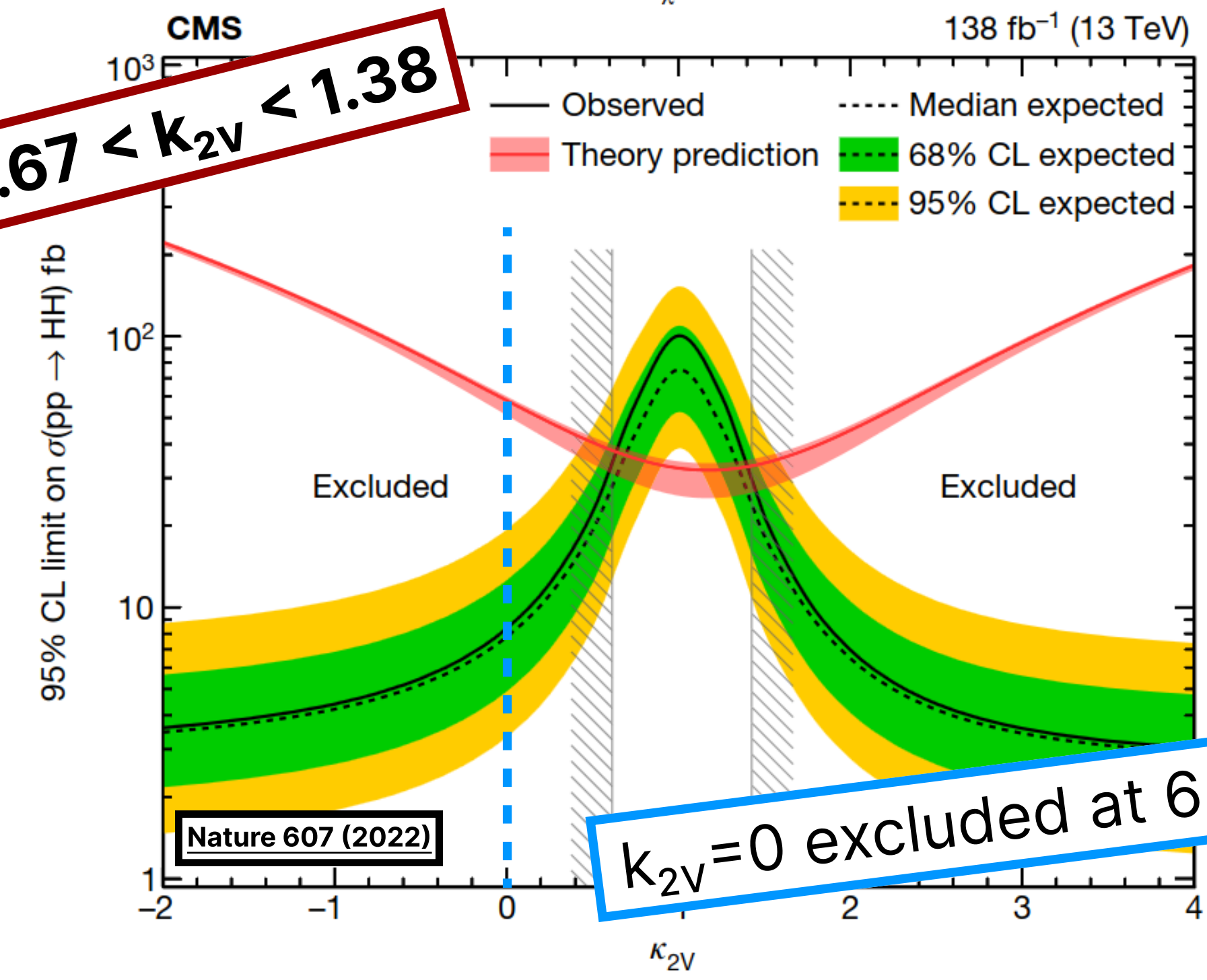
- WW  $\gamma\gamma$   
Expected: 52  
Observed: 97
- bb WW  
Expected: 18  
Observed: 14
- bb ZZ  $\clubsuit$   
Expected: 40  
Observed: 32
- Multilepton  $\clubsuit$   
Expected: 19  
Observed: 21
- bb  $\gamma\gamma$   $\clubsuit$   
Expected: 5.5  
Observed: 8.4
- bb  $\tau\tau$   $\clubsuit$   
Expected: 5.2  
Observed: 3.3
- bb bb  $\clubsuit$   
Expected: 4.2  
Observed: 7.2
- Comb. of  $\clubsuit$   
Expected: 2.5  
Observed: 3.4



**$-1.24 < \kappa_\lambda < 6.49$**



**$0.67 < \kappa_{2V} < 1.38$**





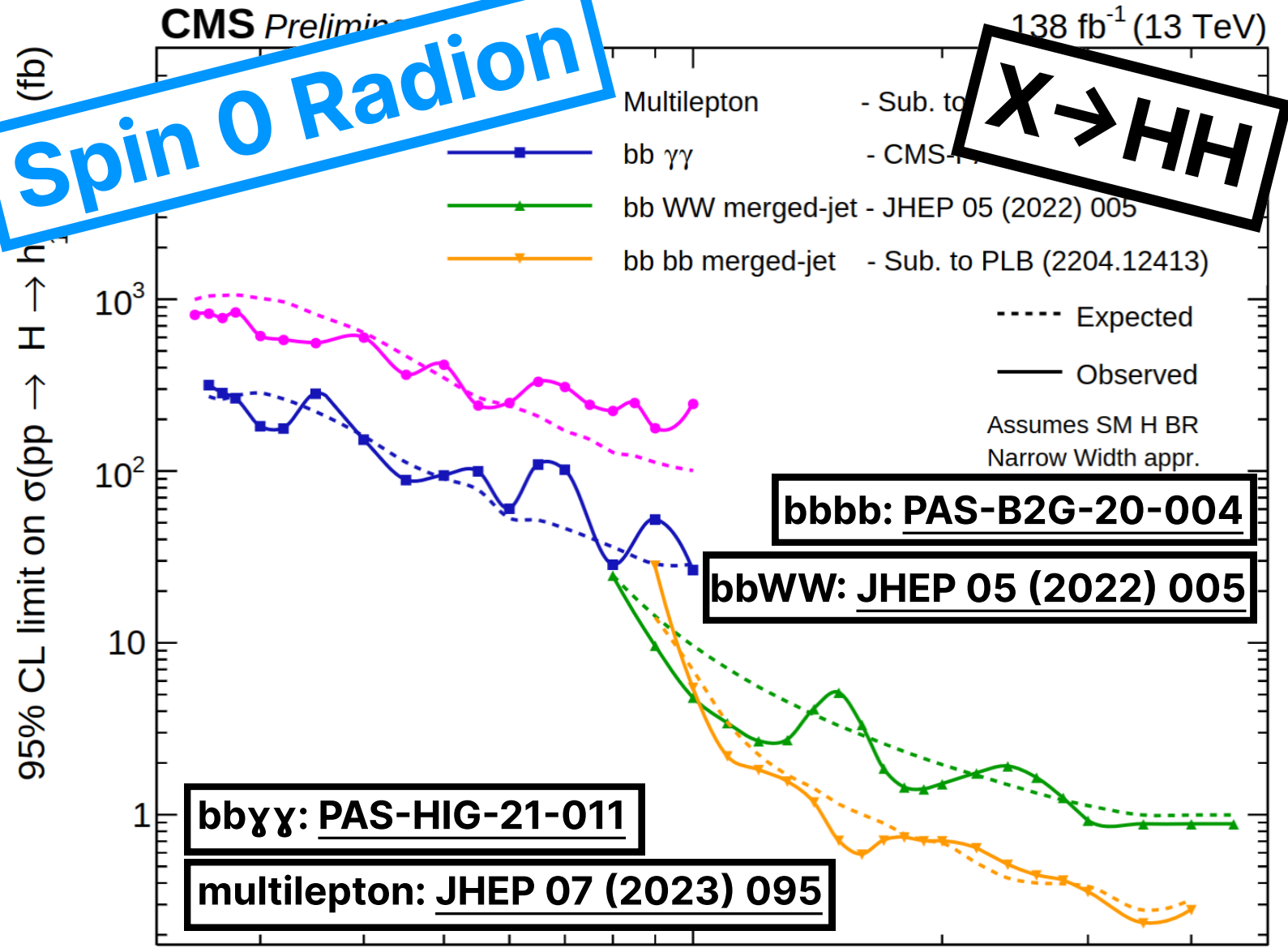
# Resonant Run2 Combination\* **ggF**

**bbγγ: PAS-HIG-21-011**

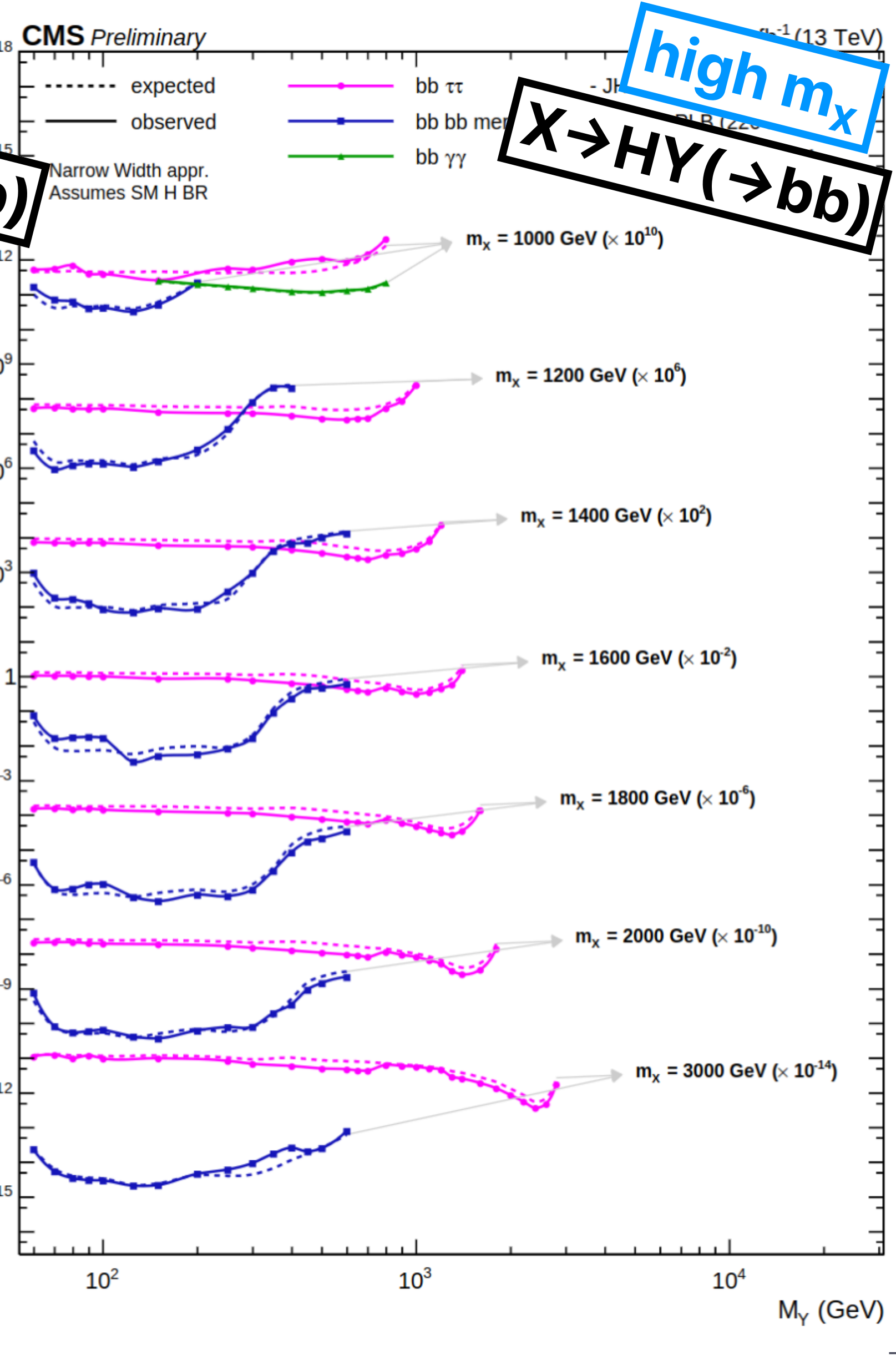
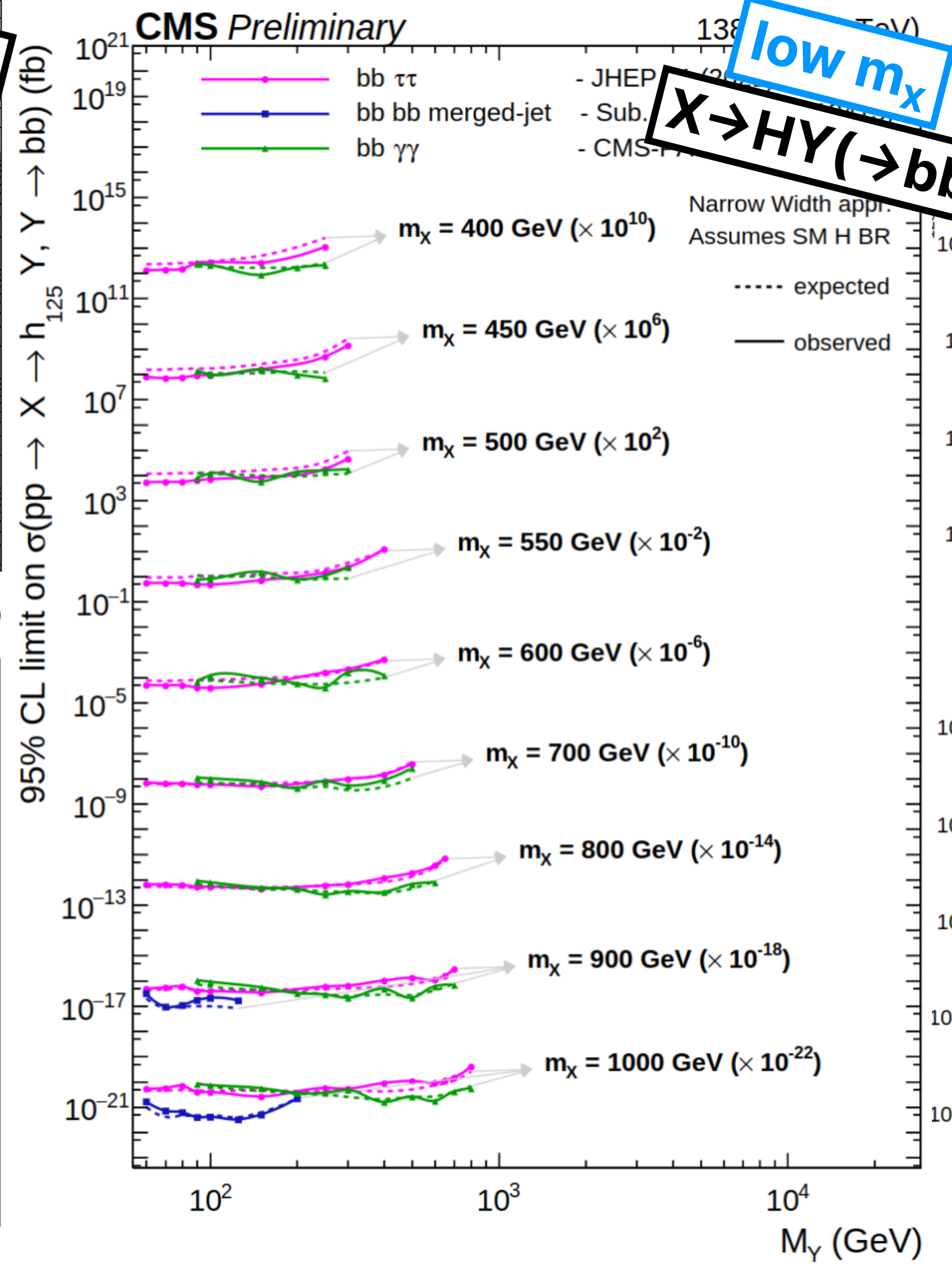
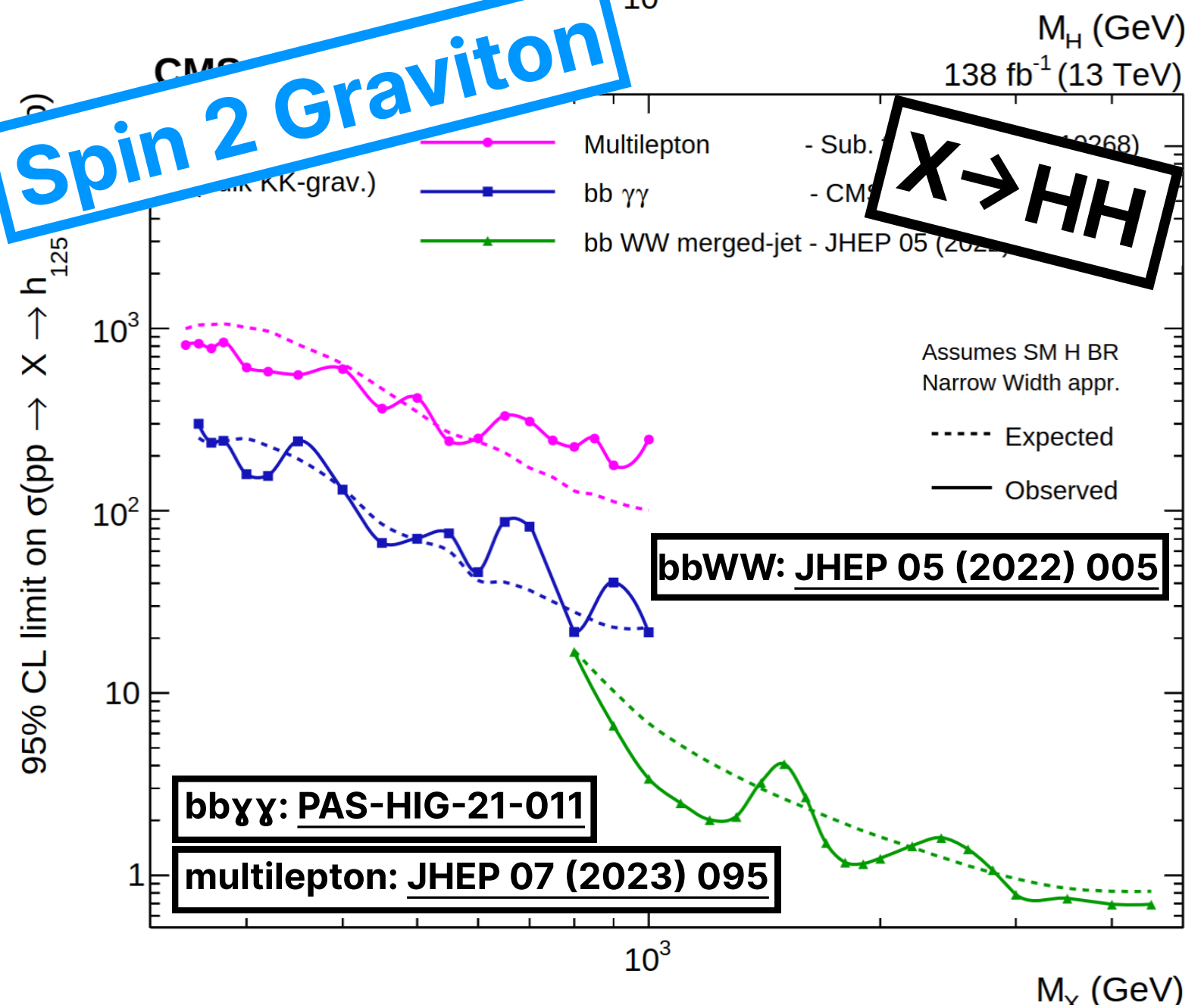
**bbττ: JHEP 11 (2021) 057**

**bbbb: PRB 842 (2023) 137392**

**Spin 0 Radion**



**Spin 2 Graviton**

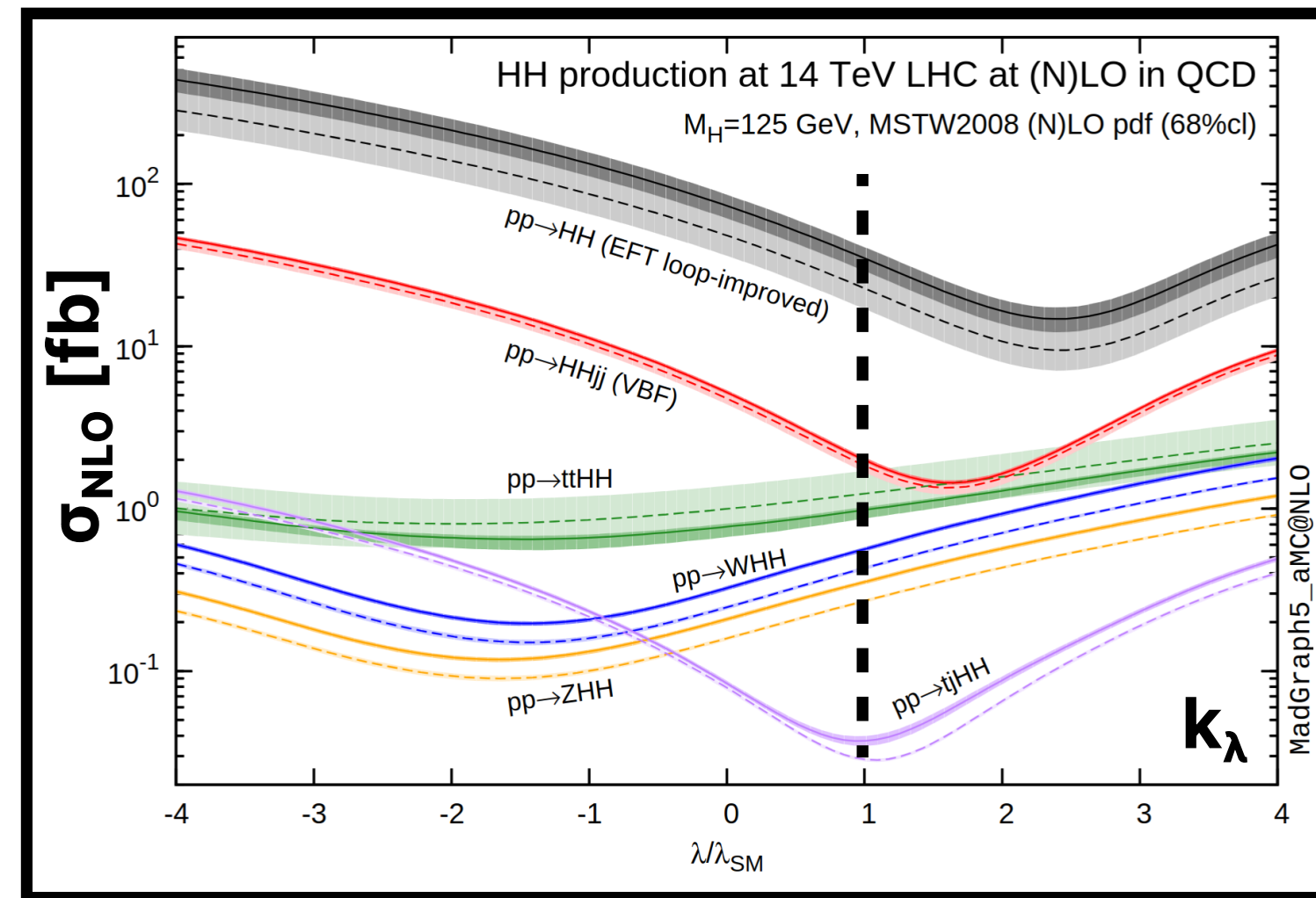
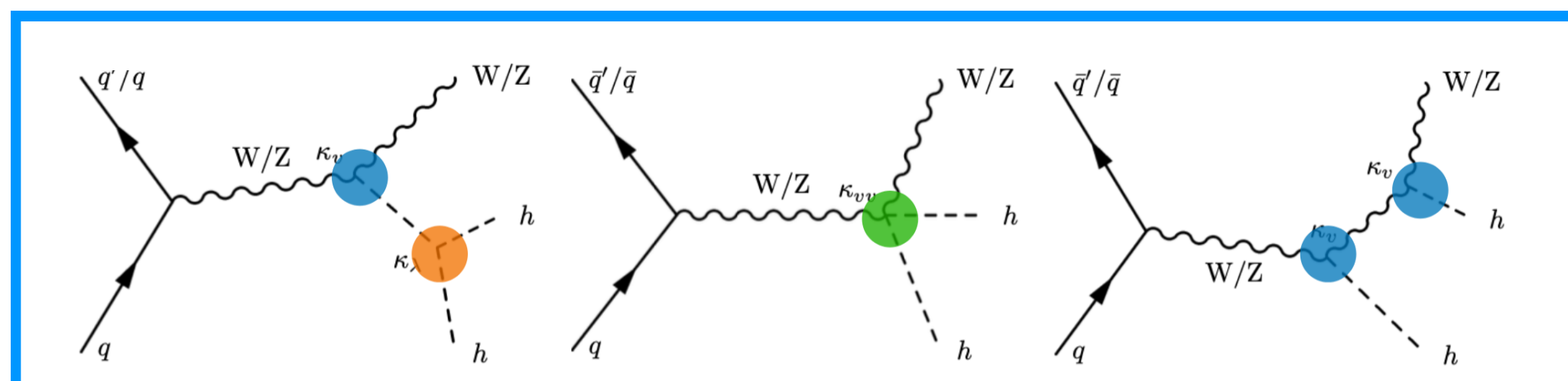




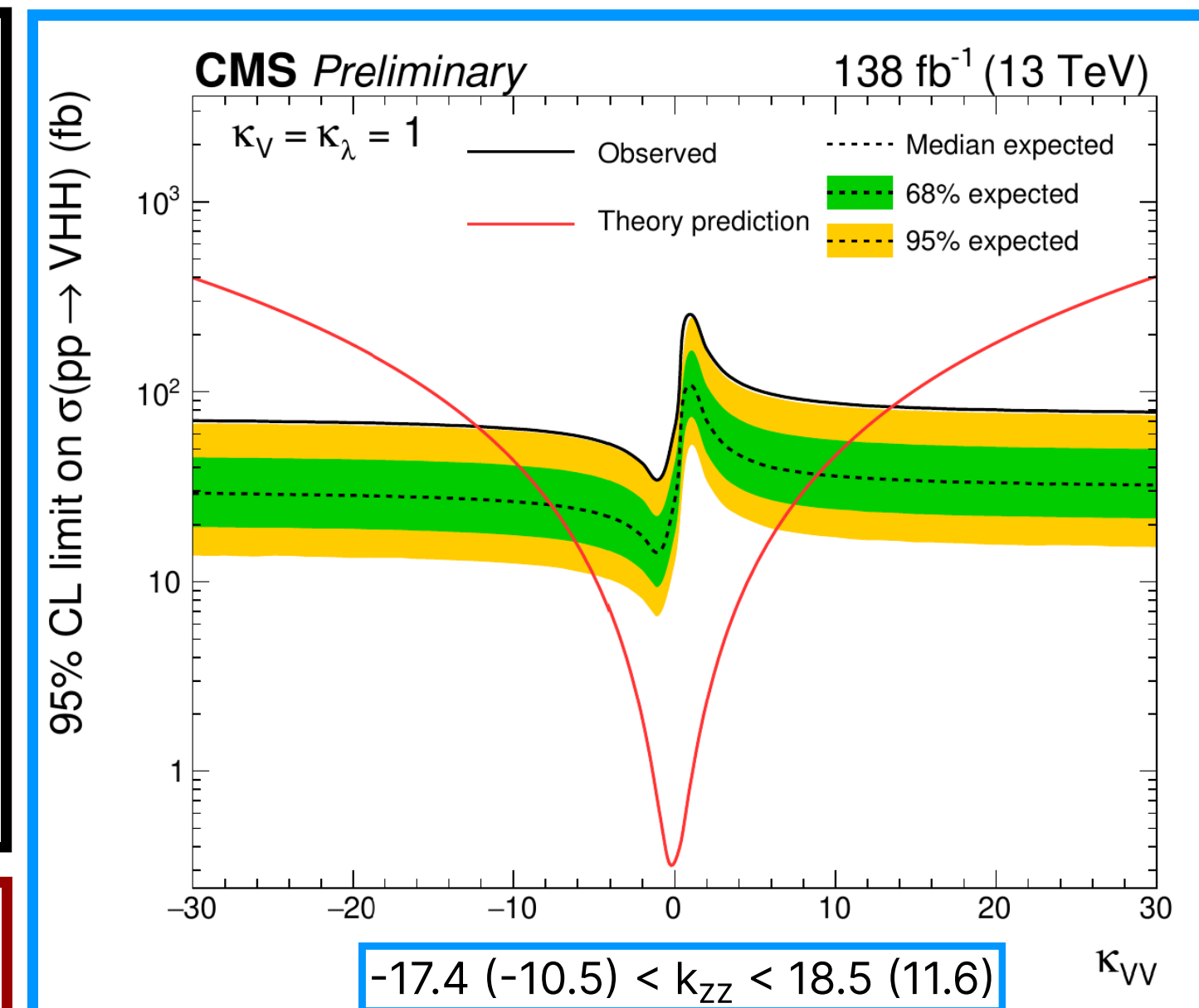
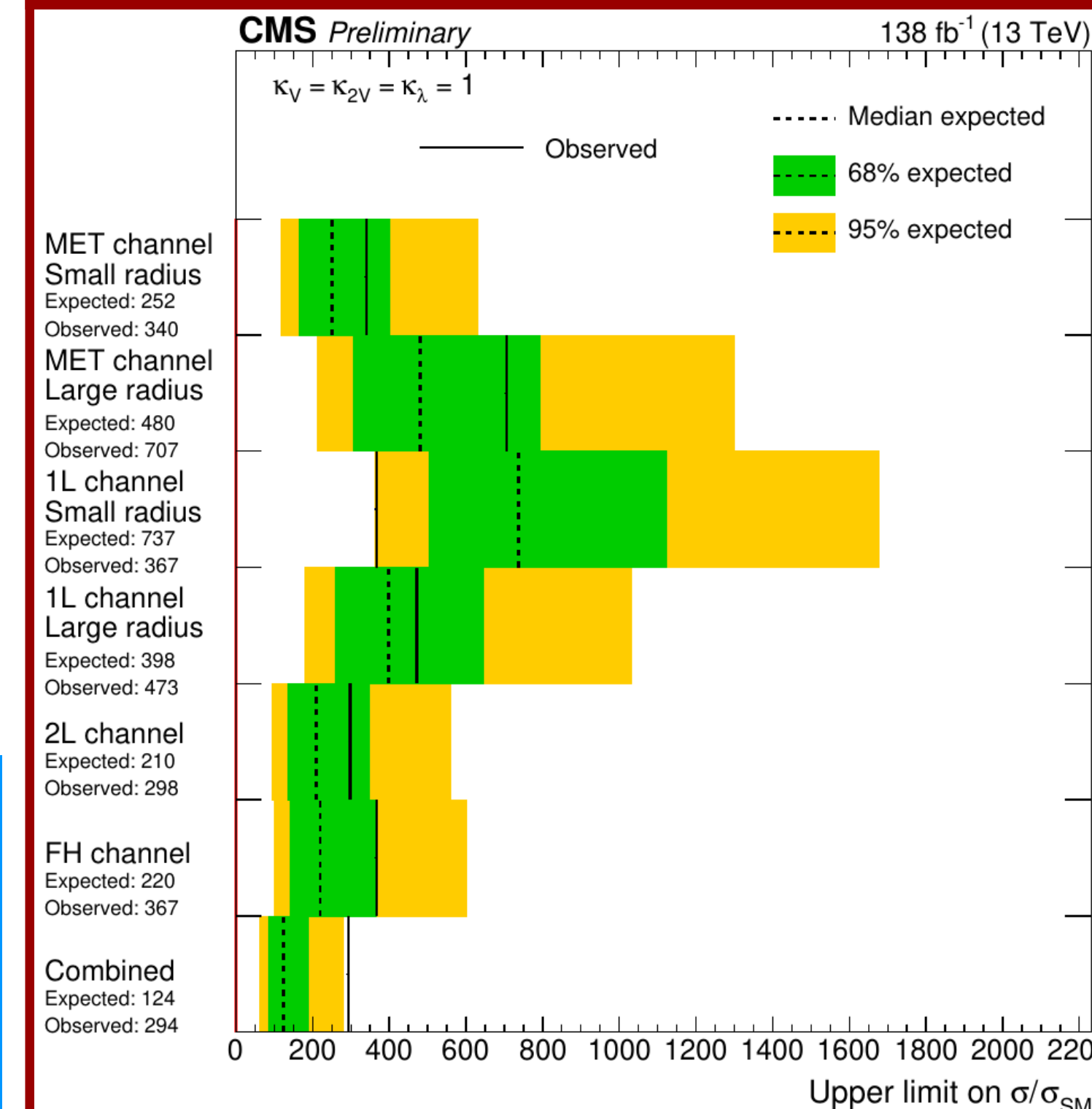
# VHH ( $\rightarrow 4b$ )

- **VHH for the 1<sup>st</sup> time at CMS**
  - **~110 events expected** (before H decay to b's, without selection)
- **Complementary to ggF and VBF!**
  - especially for  $4 < k_\lambda < 7$
  - because xsec comparable to ggF and VBF HH
- **4 channels:** 0/1/2 leptons and invis.
- **59 categories:** resolv./bosted,  $m_{HH}$ , #b-jets, signal- and tt-enhancement
- BDT and NN classifiers are used as signal vs bkg. discriminants
  - BDT defines regions sensitive to anomalous  $k_\lambda$  or  $k_{2V}$  hypoth.

## VHH LO

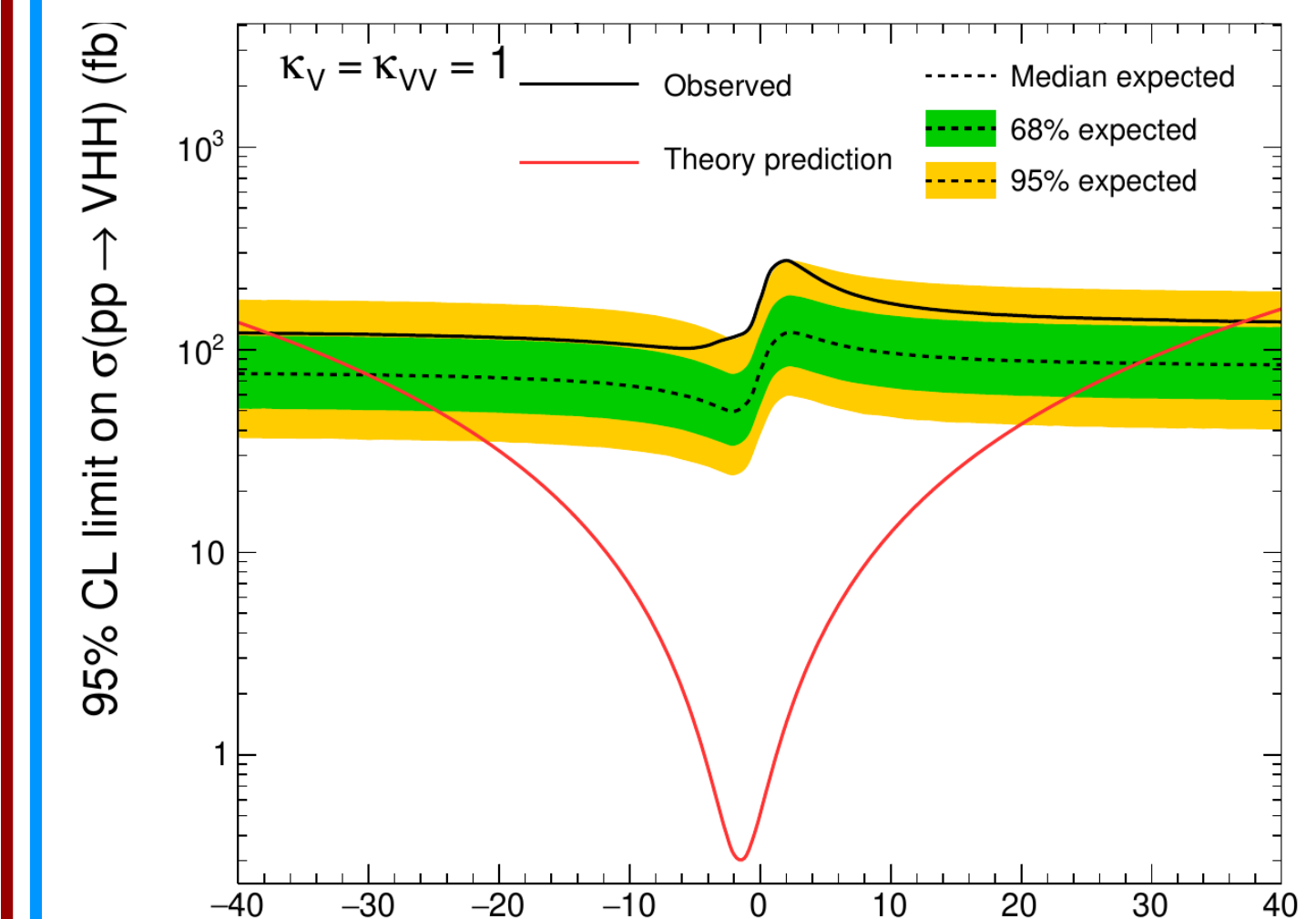


$$\sigma_{HH} < 294 (124) < \sigma_{HH}^{SM}$$



$$-12.2 (-7.2) < k_{2V} < 13.5 (8.9)$$

$$-14.0 (-10.2) < k_{WW} < 15.4 (11.6)$$



$$-37.7 (-30.1) < k_\lambda < 37.2 (28.9)$$



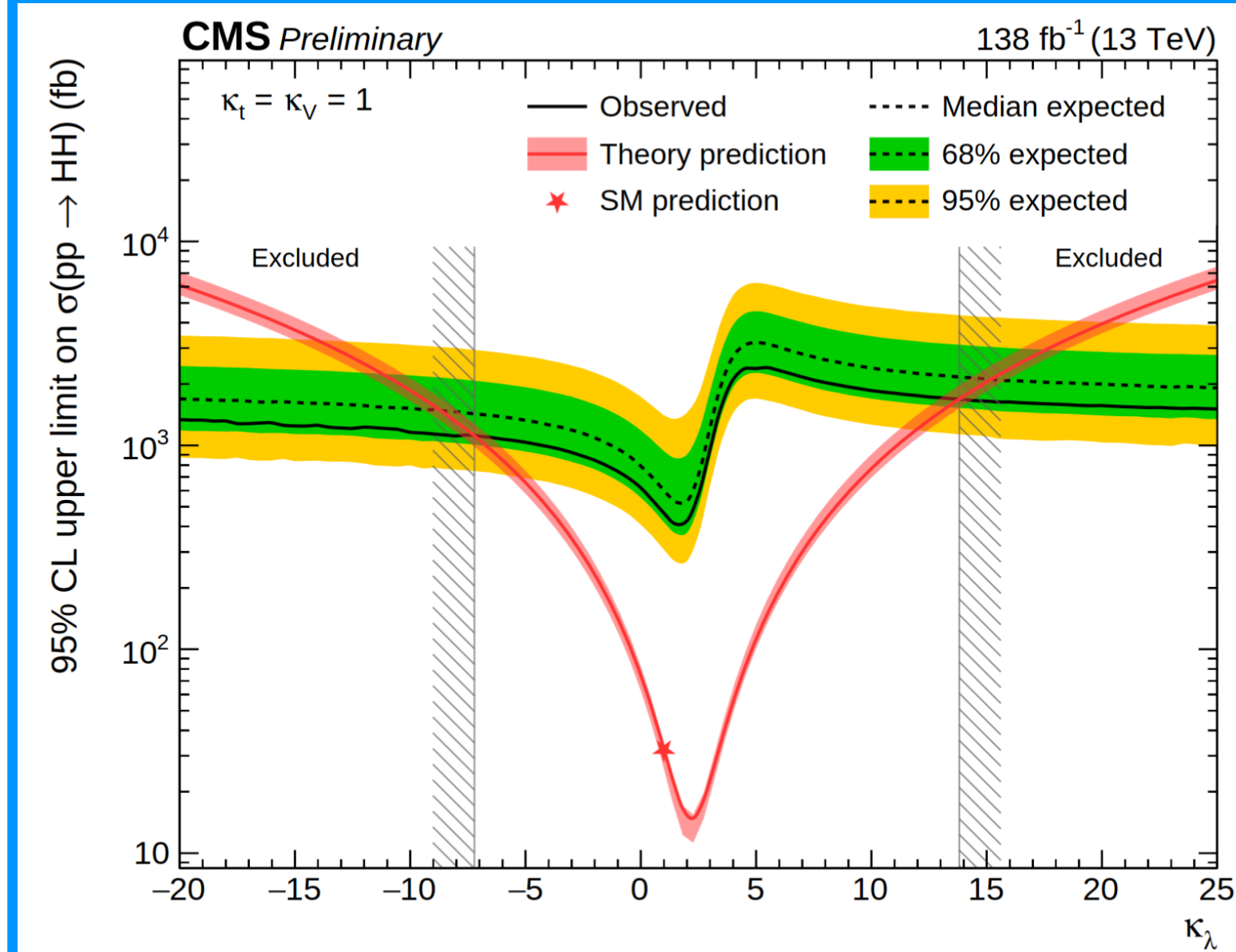
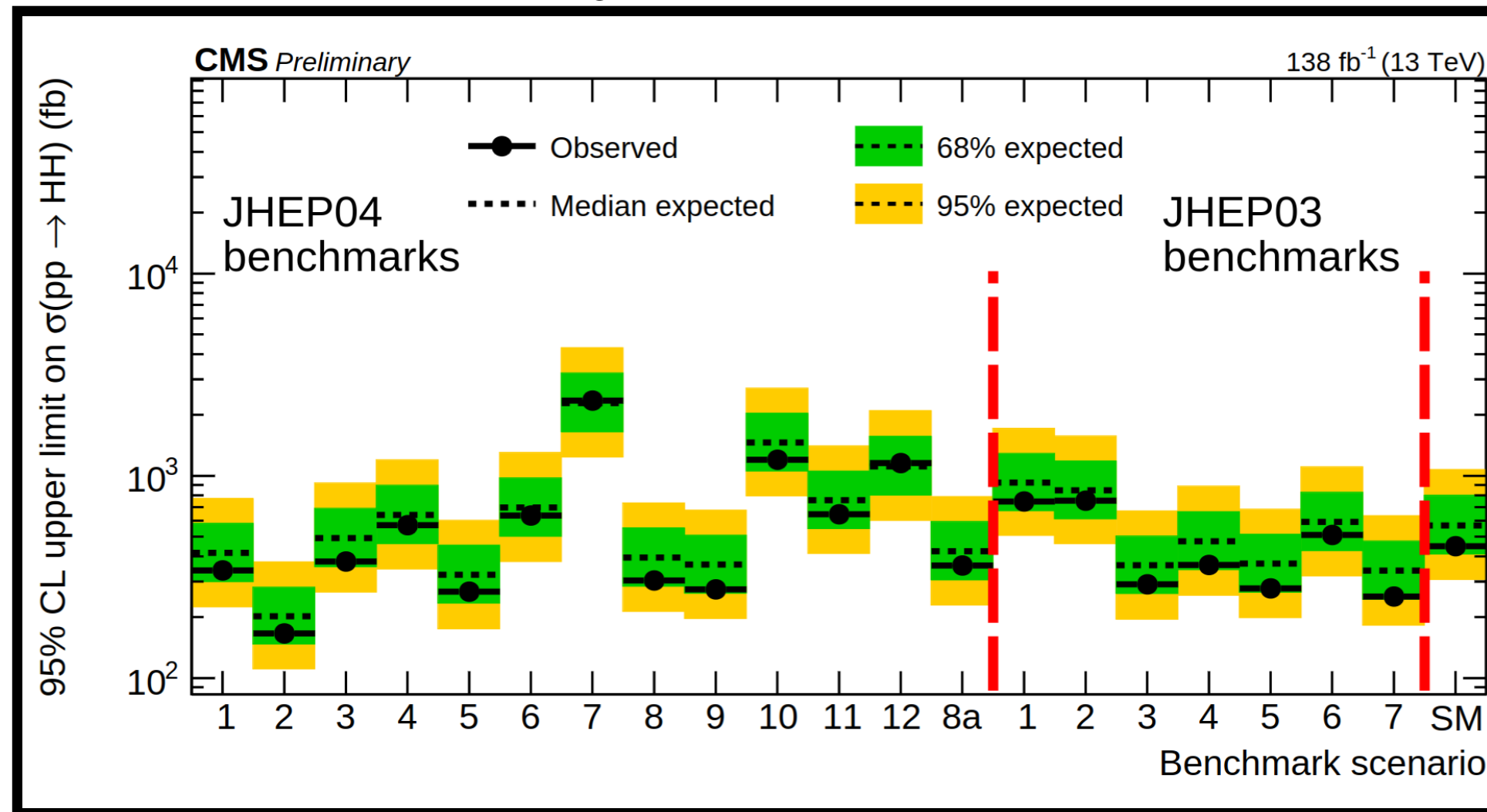
# $(X \rightarrow) HH \rightarrow bbWW$

VBF Res ggF

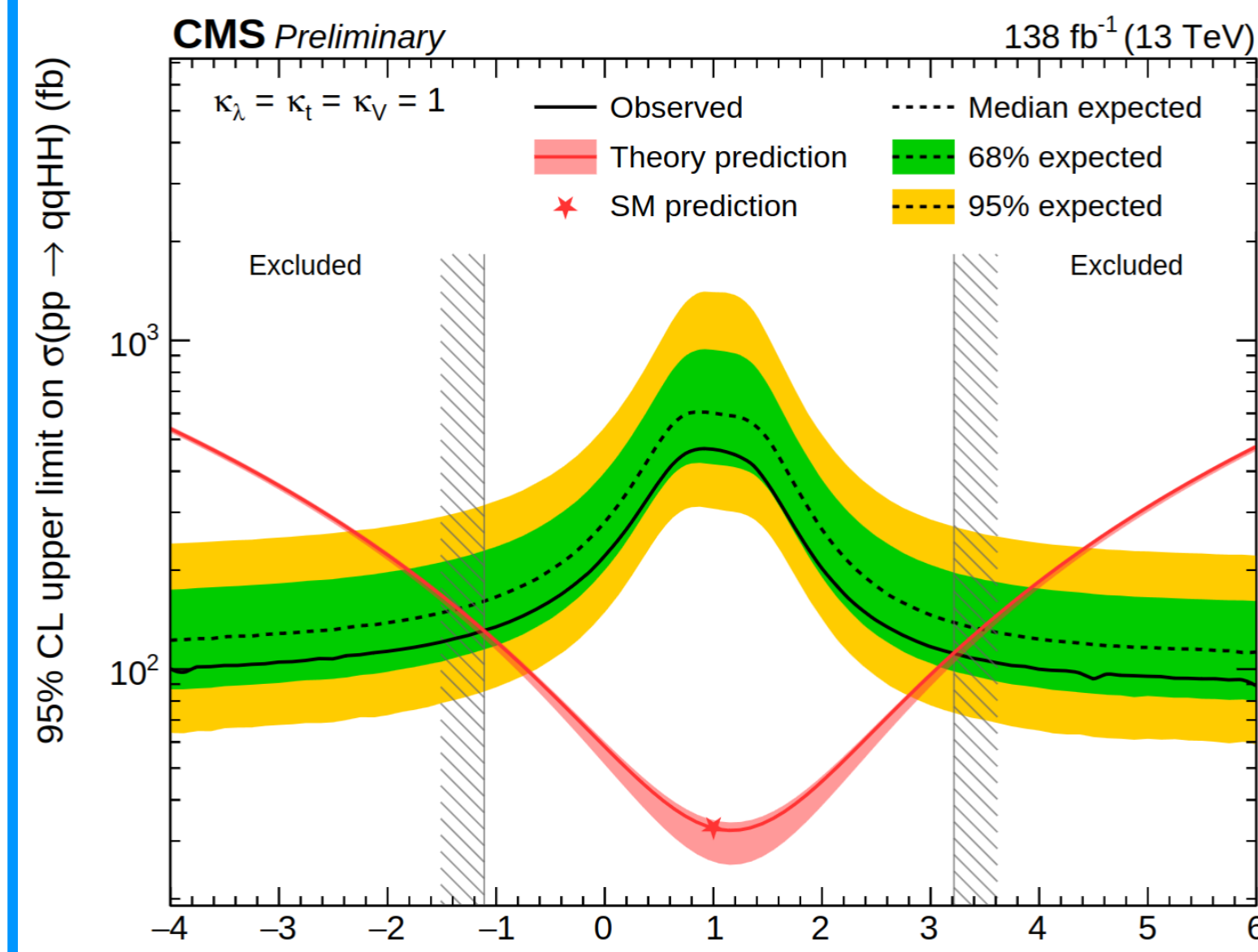
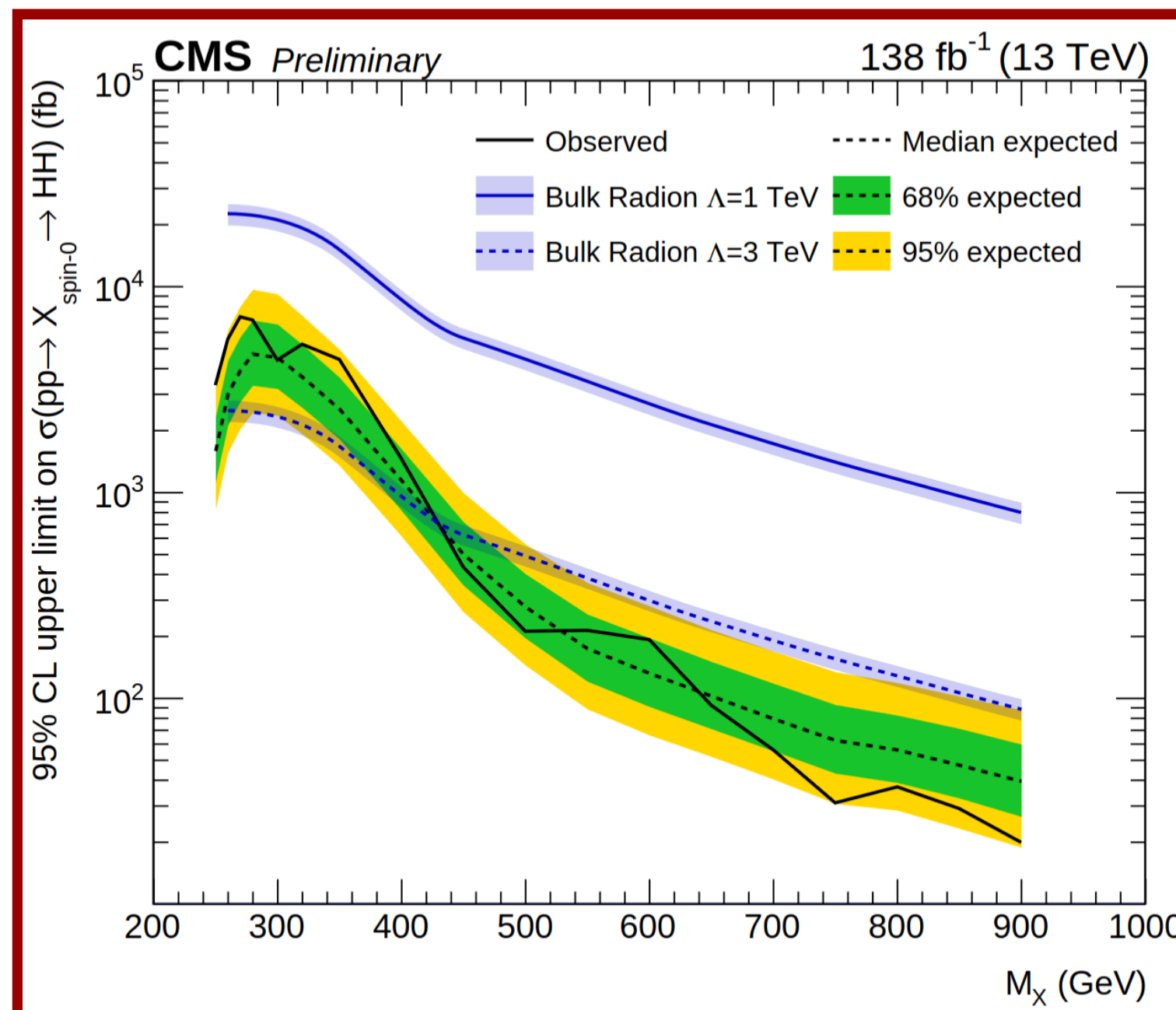
The analysis includes EFT limits +  $c_2$  scan

- 2 channels: 1 or 2  $\ell$ 's
- $\tau$  veto: orthogonality wrt.  $bb\tau\tau$
- data-driven DY estimated w/ dedicated CRs
- $t, tt$  and  $W$ +jets shape from MC, normalized w/ ML fit

- **DNN multi-classifier** to separate signals vs. main bkg components
  - the resonant analysis uses a parameterized DNN
- **Signal extraction from 1D fit of DNN score**
  - $2\ell$  channel in the resonant analysis uses instead a DNN vs. estimated\*  $m_{HH}$  2D fit (considering the 2 neutrinos)



$$-7.2(-8.7) < k_\lambda < 13.8 (15.2)$$



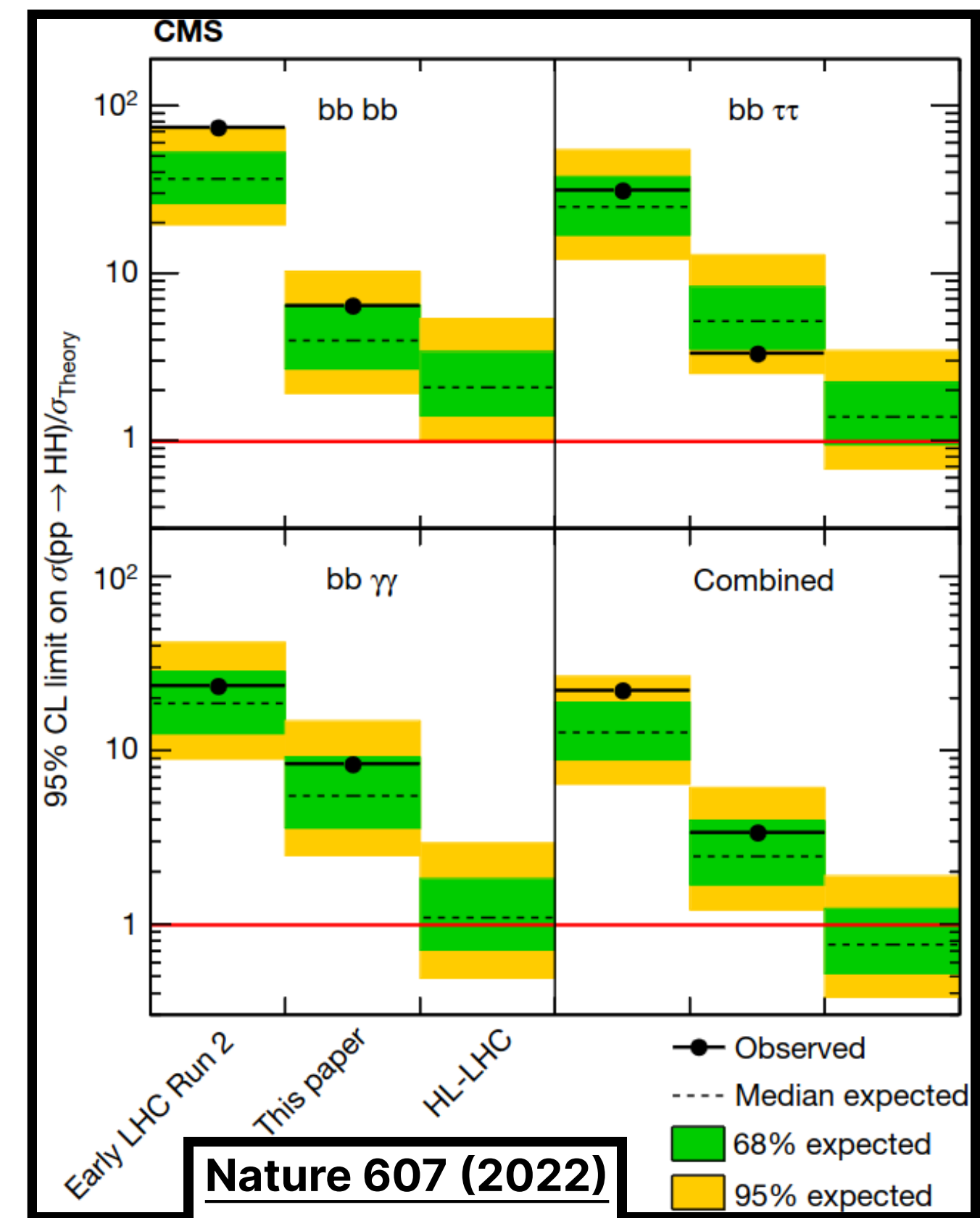
$$-1.1(-1.4) < k_{2V} < 3.2 (3.5)$$

\*Heavy Mass Estimator

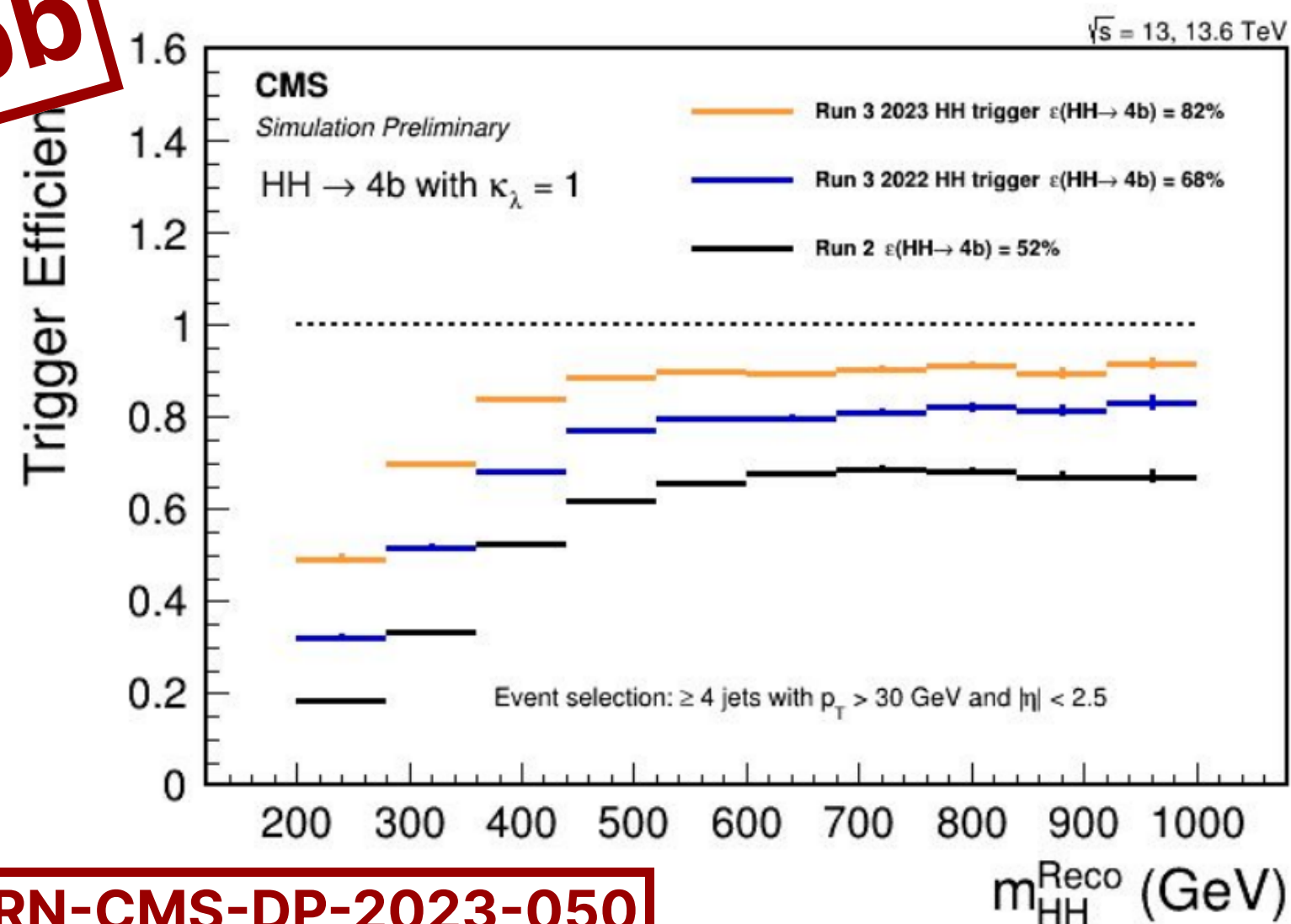


# Run3 and beyond

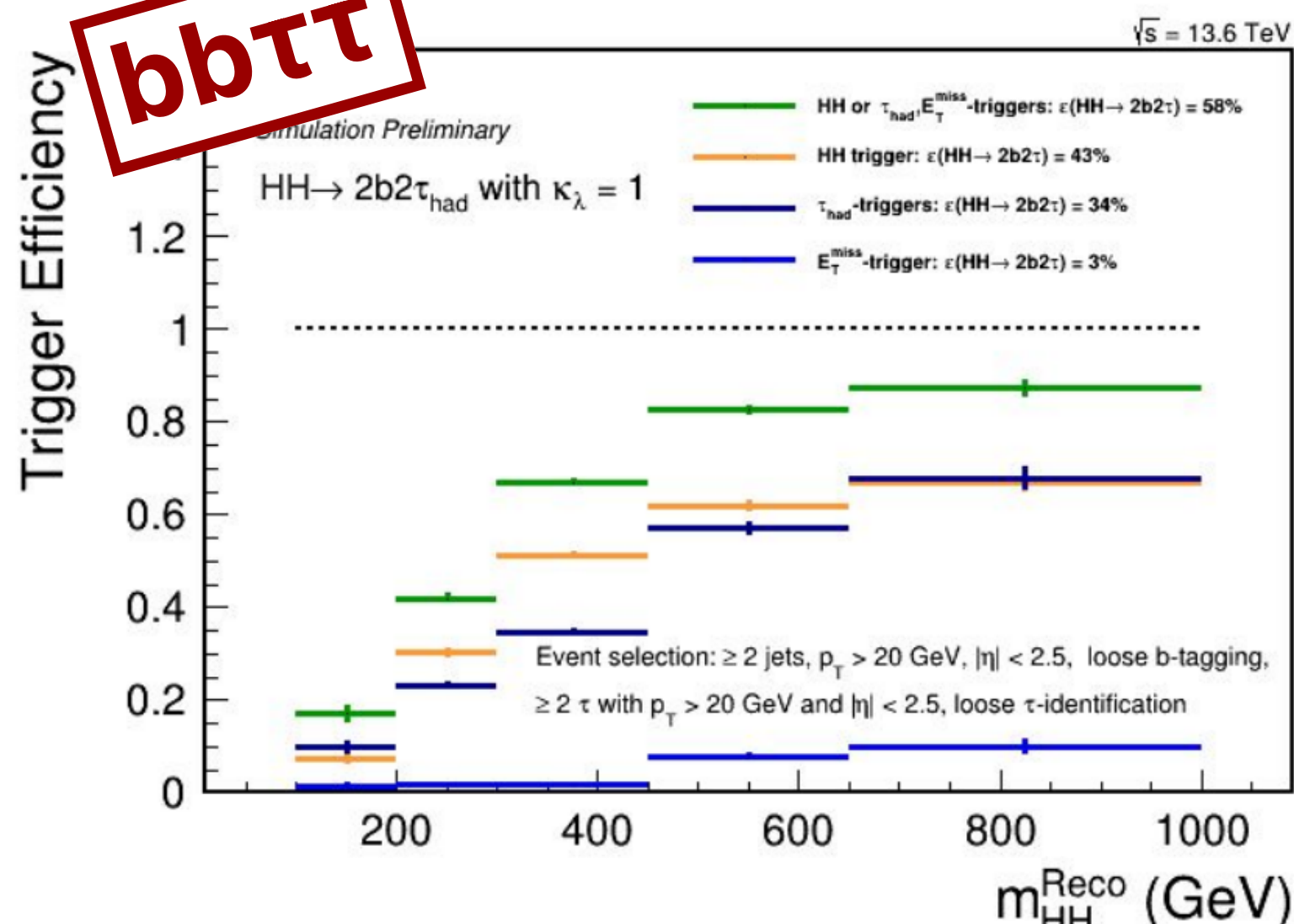
- $\kappa_\lambda$ ,  $X \rightarrow HH/Y$  and **EFT** will be further constrained in the near future
  - **new HH decay** channels are being explored
  - stats are still a limiting factor
    - but ggF theory uncert. may become important in the future
  - consider **H + HH combinations**†
  - we are **close to SM HH sensitivity** and  $\kappa_{2V}=0$  was excluded
- Run-3 is an opportunity for improvement before the HL-LHC
  - **improved trigger strategy** will boost HH searches
- We should consider going **beyond NWA**
  - interesting inputs from theorists on HH res/non-res interf. effects



**bbbb**

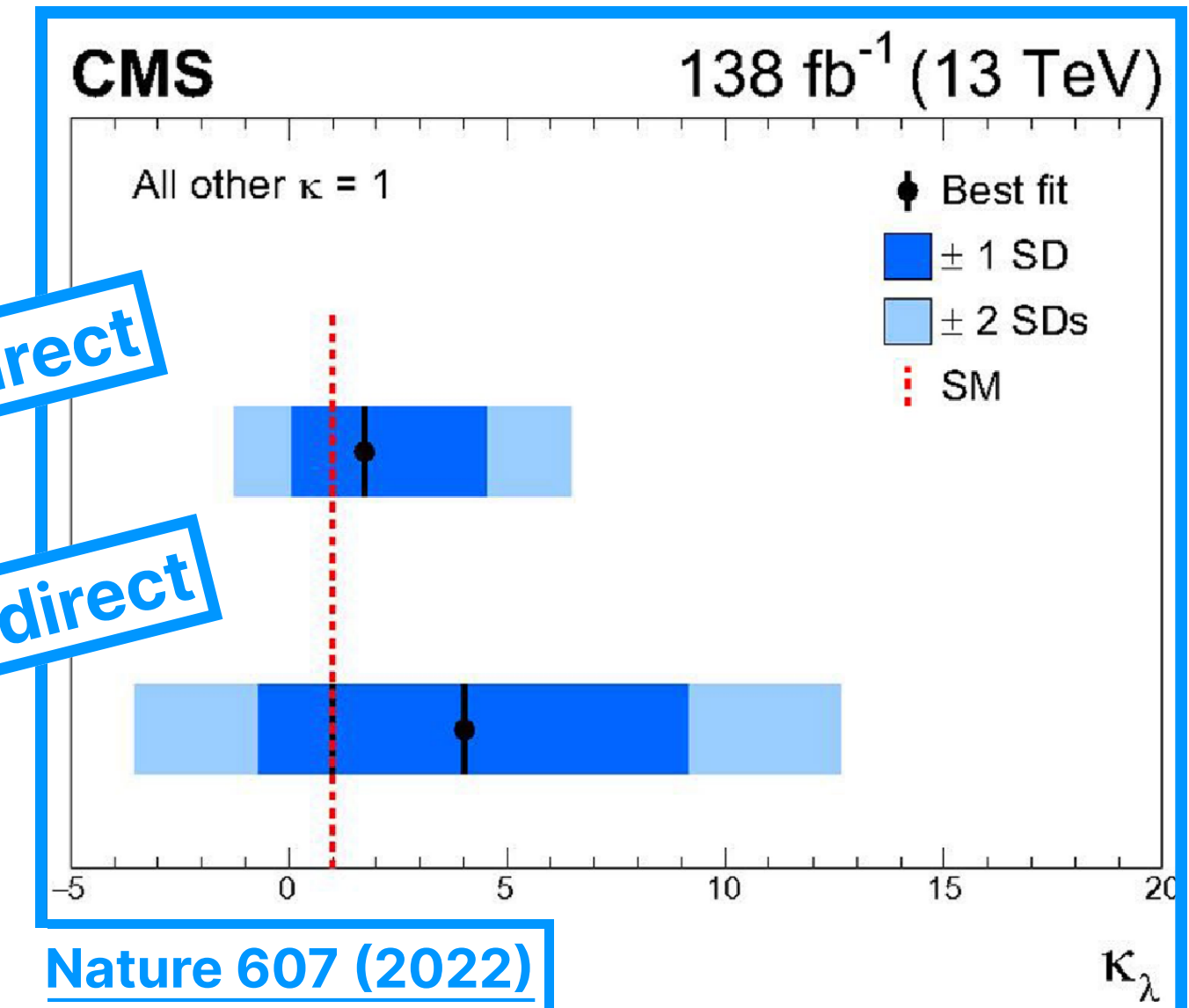


**bbTT**



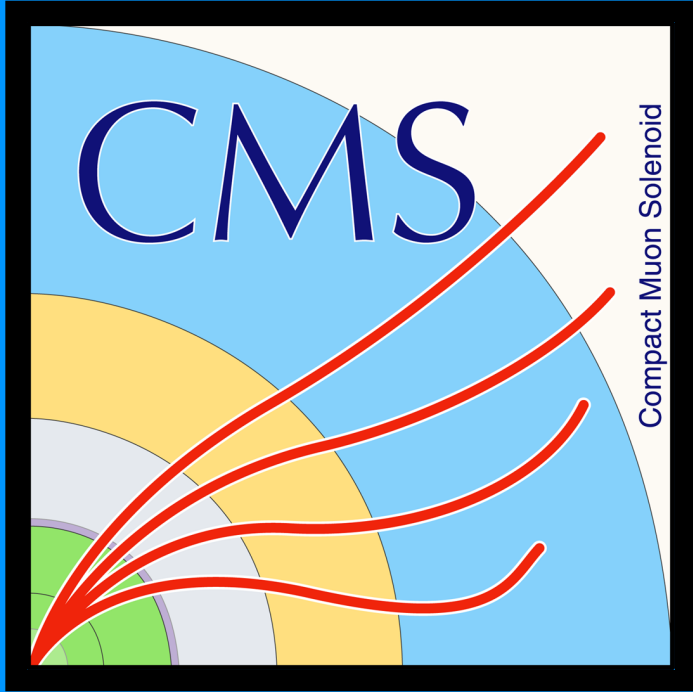
**Direct**

**Indirect**





# Backup



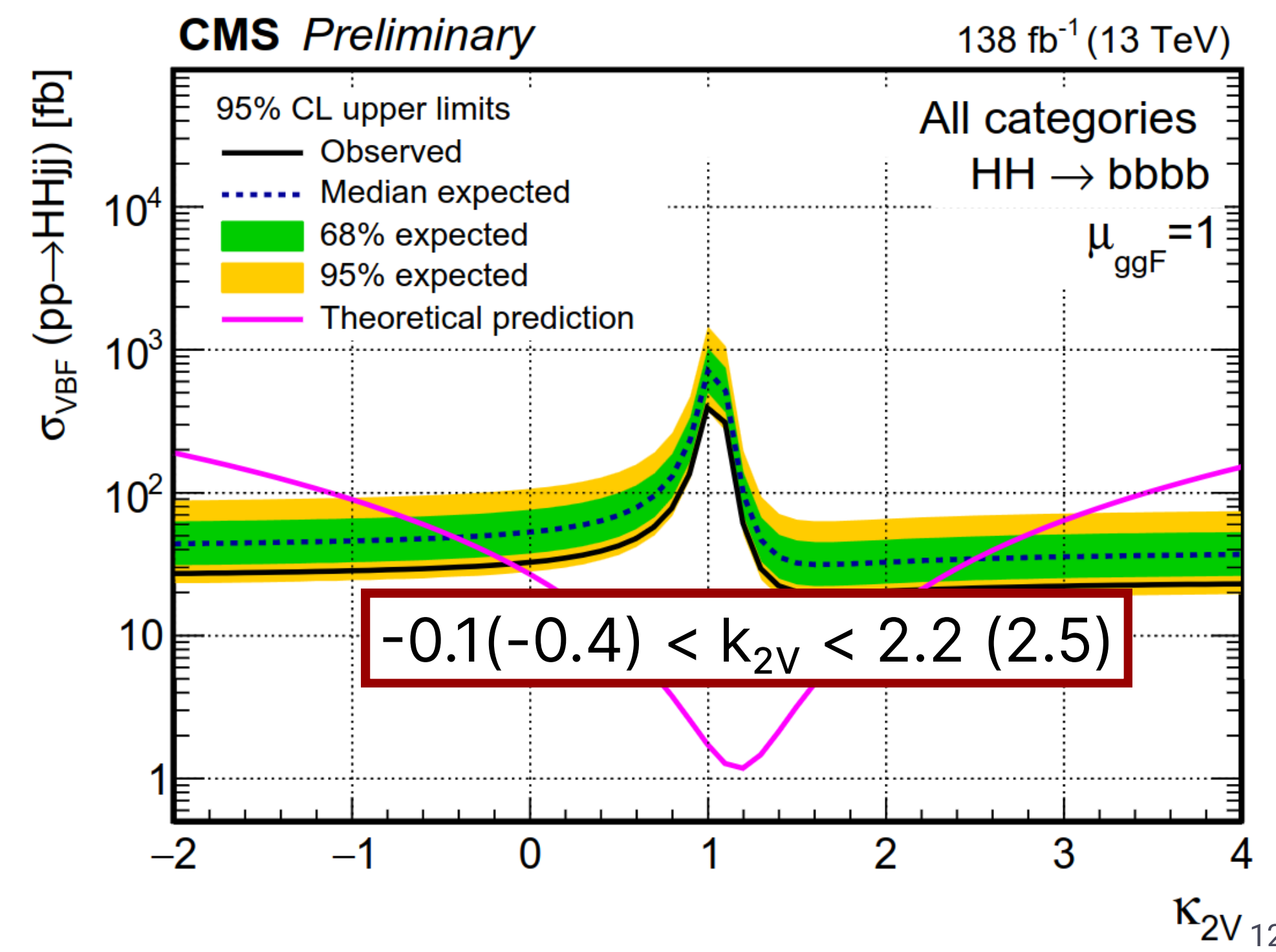
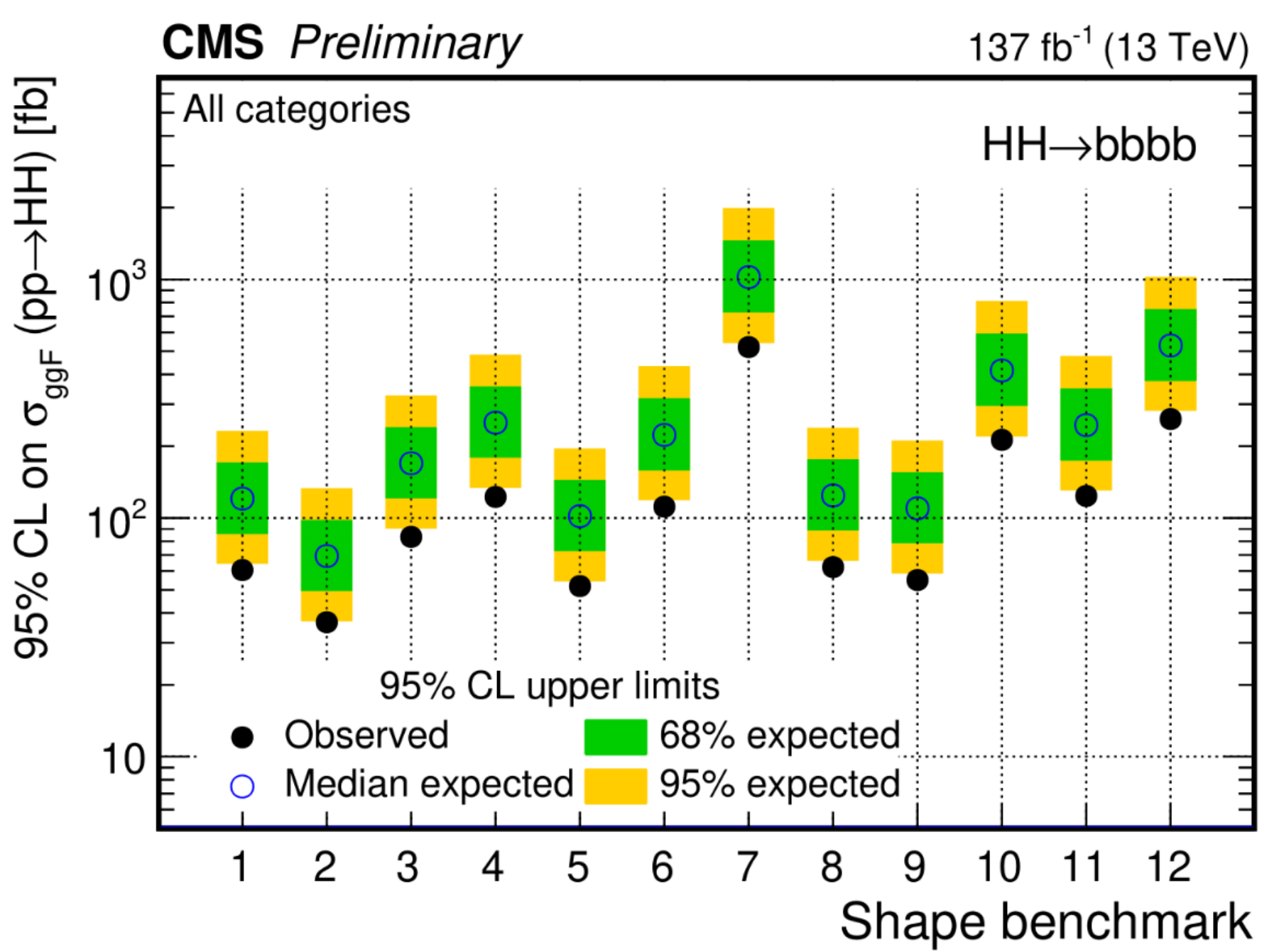
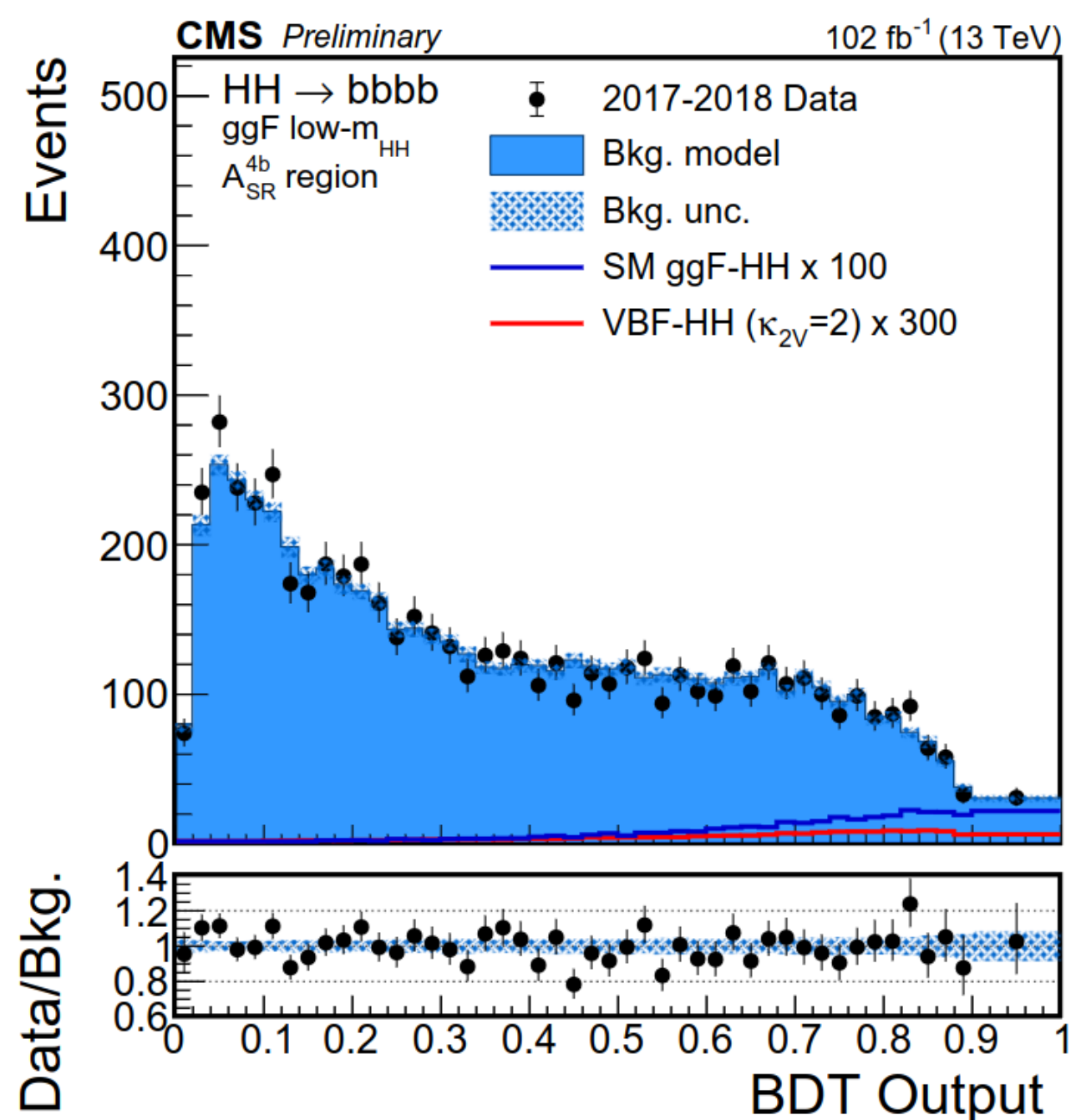
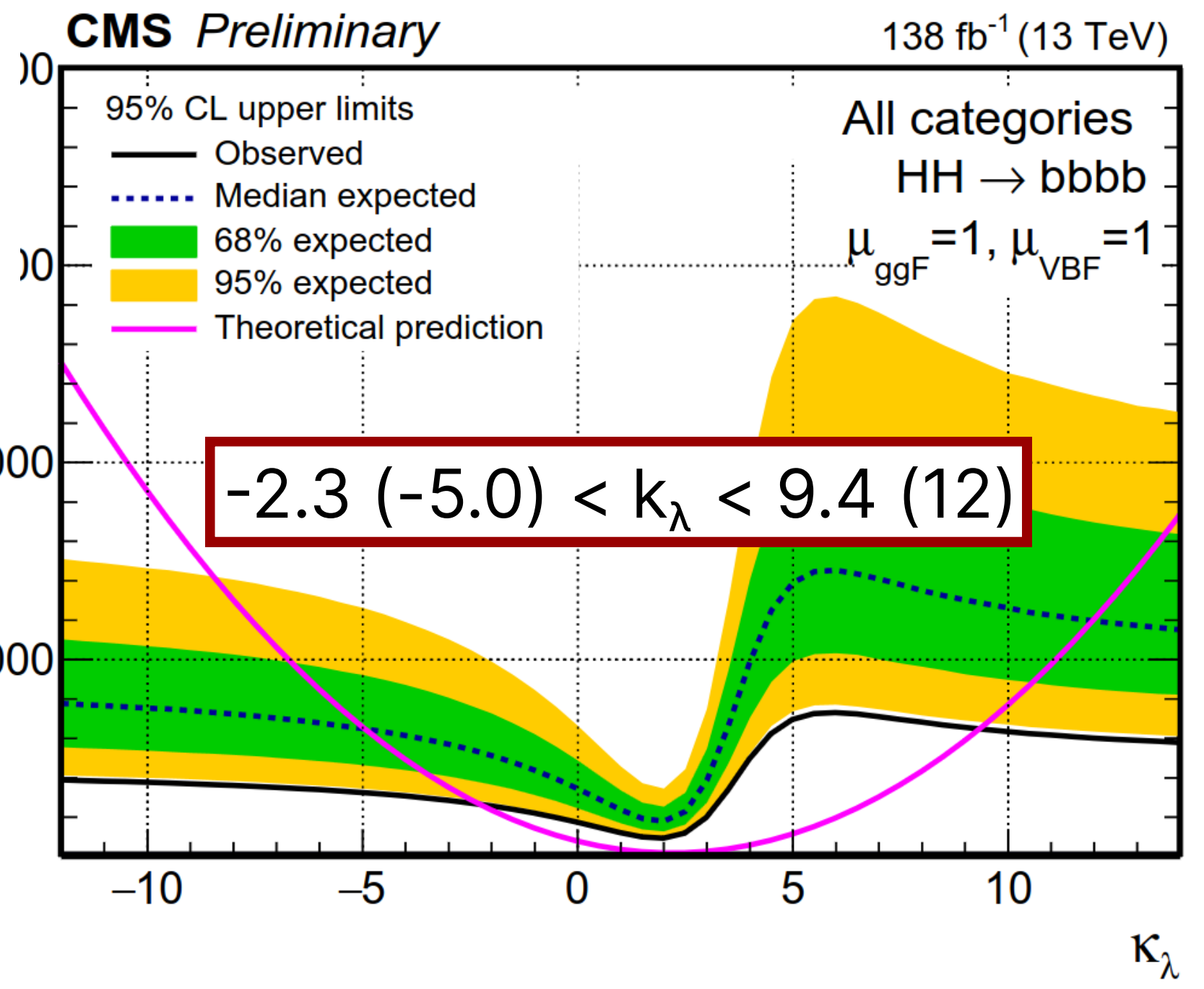
# HH → 4b resolved

ggF  
VBF

$$\sigma_{HH} < 3.9 \text{ (7.8)} < \sigma_{HH}^{SM}$$

$$\sigma_{VBF} < 226 \text{ (412)} < \sigma_{VBF}^{SM}$$

- Select jets with 4 highest DeepJet score
- 3 possible H pairs built w/  $m_{H1}$  vs.  $m_{H2}$  diagonal
- separate VBF and ggF categories
  - “ggF-killer” BDT increases purity in VBF category
  - additional low/high  $m_{HH}$  split for ggF
- QCD data-driven estimation using 3/4 b’s CRs
- Fit BDT ( $m_{HH}$ ) in ggF (VBF) categories



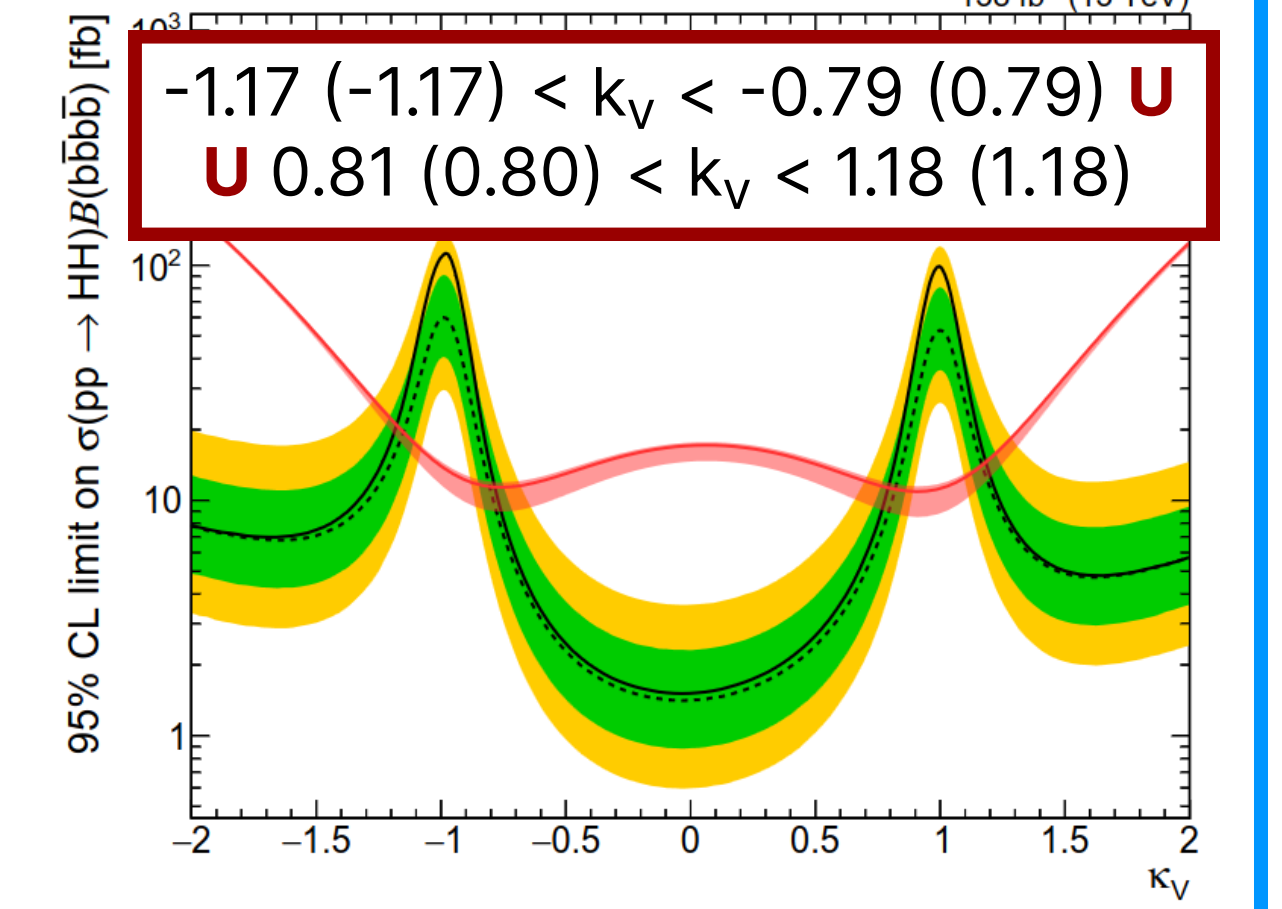
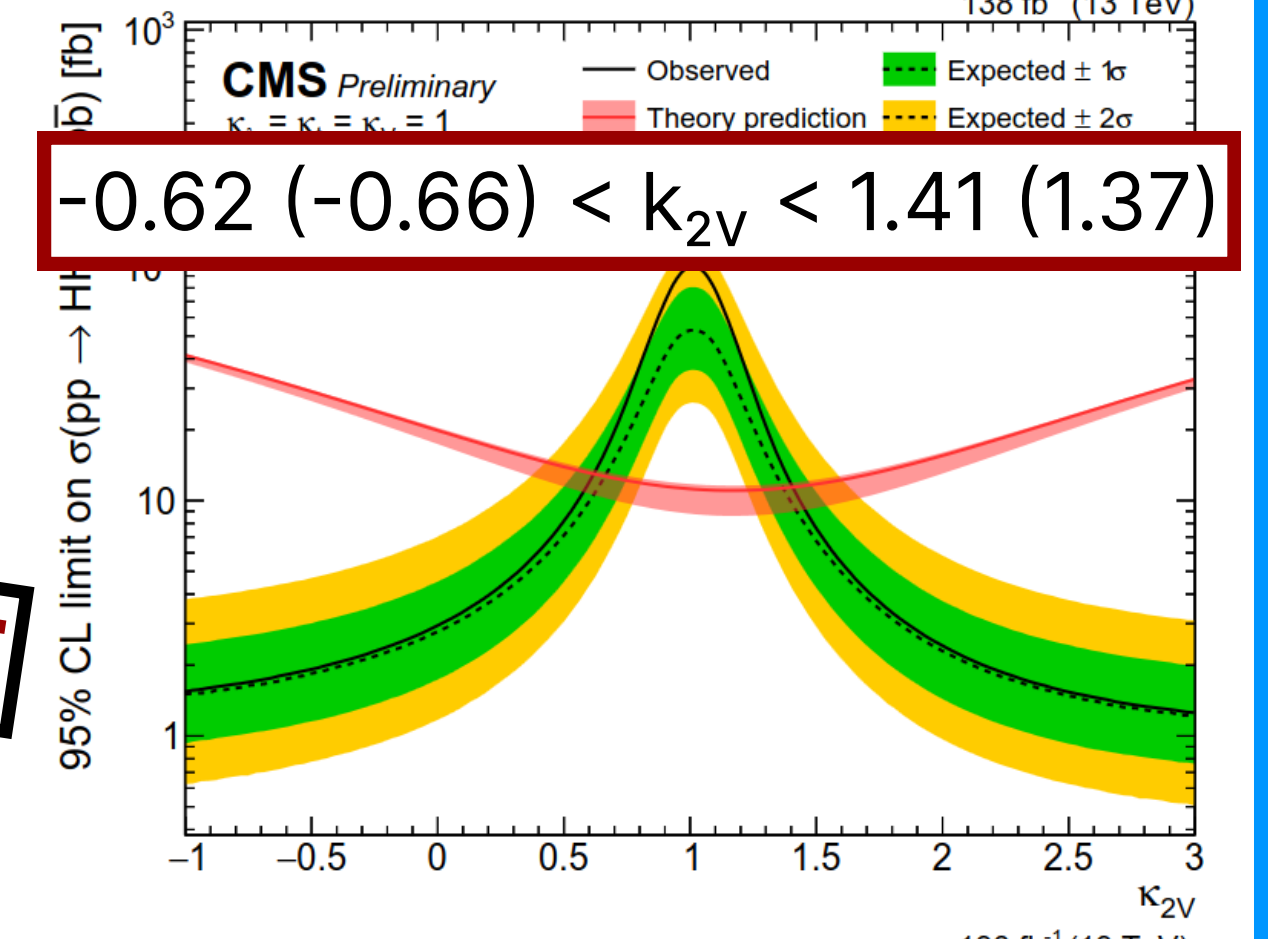
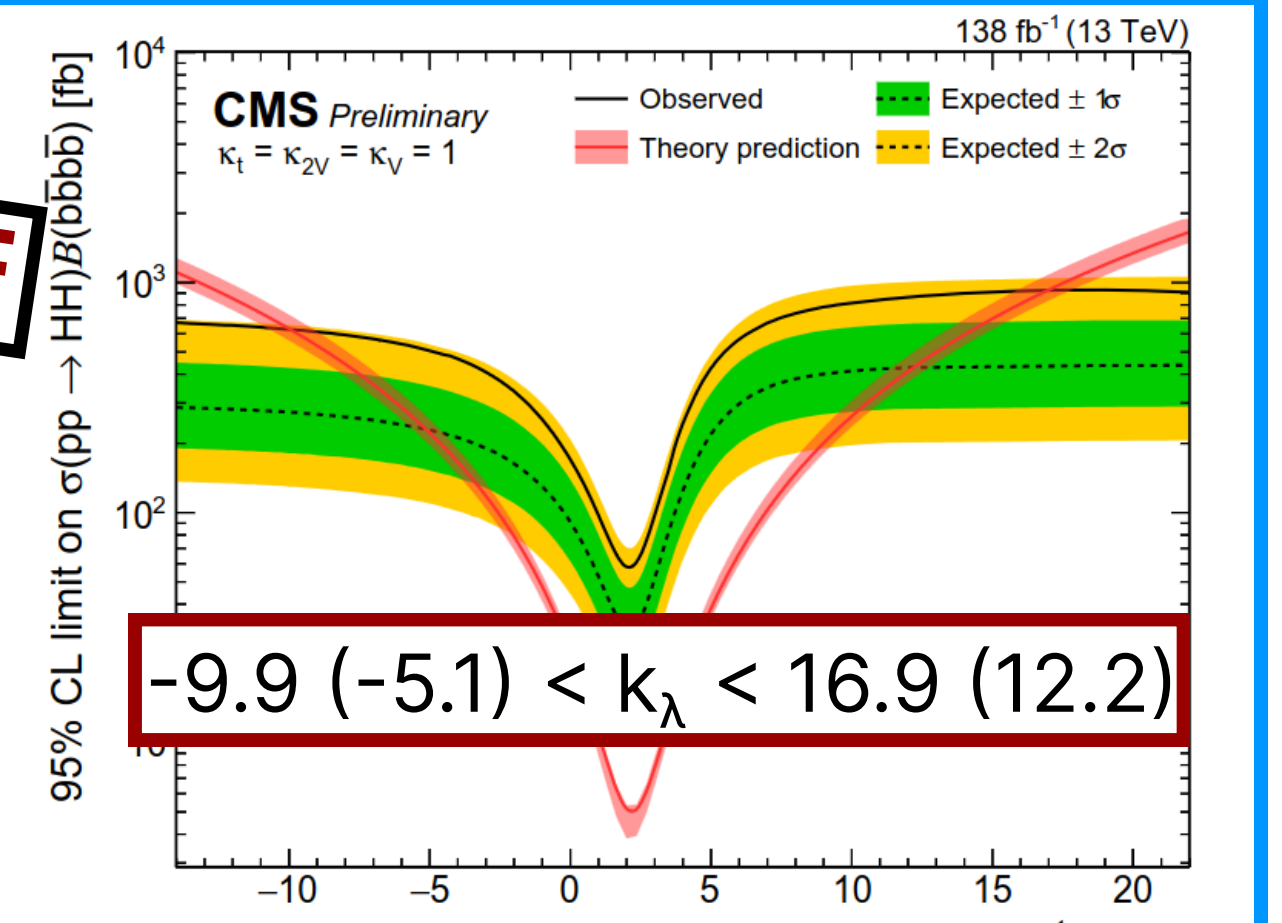
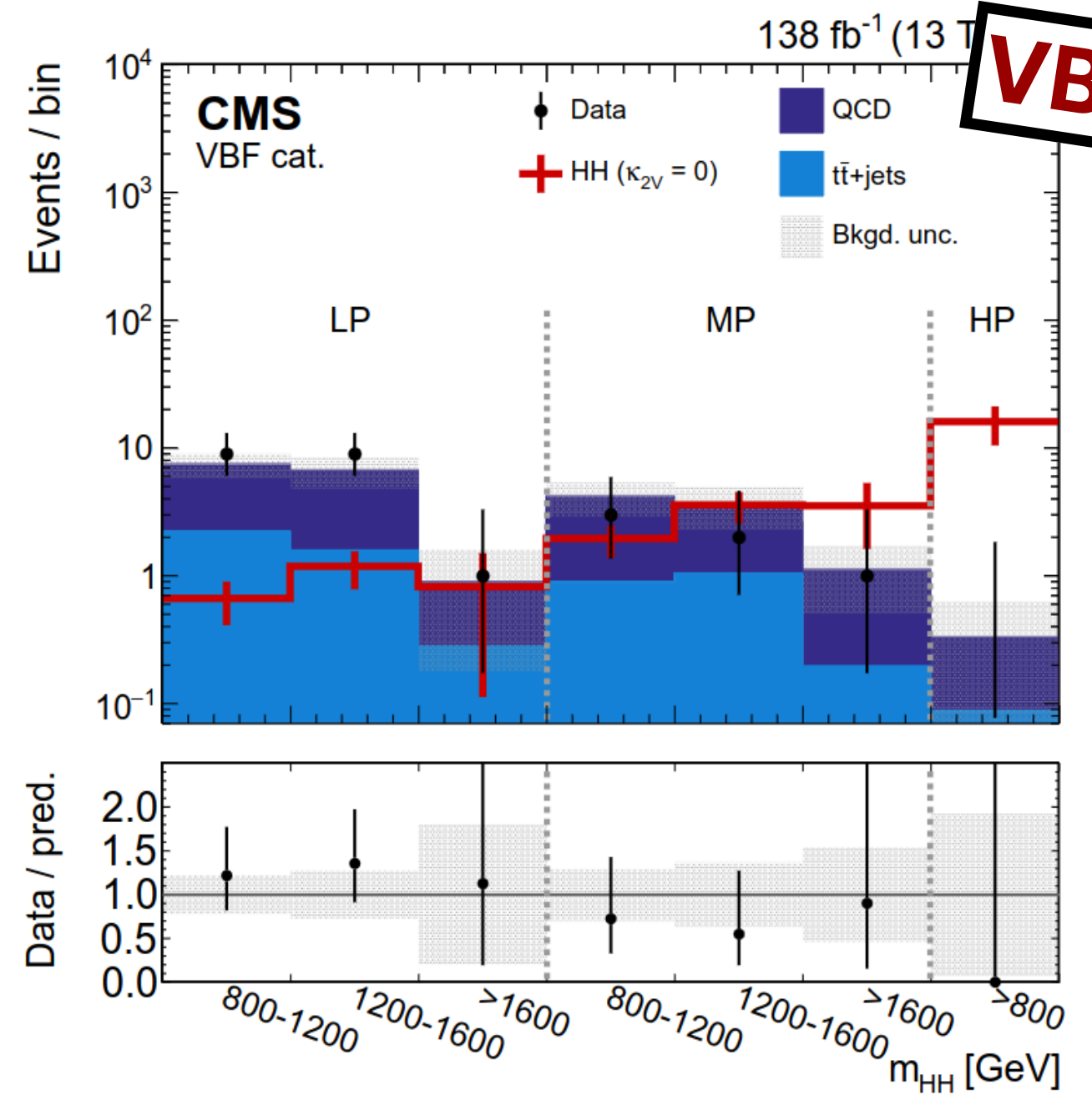
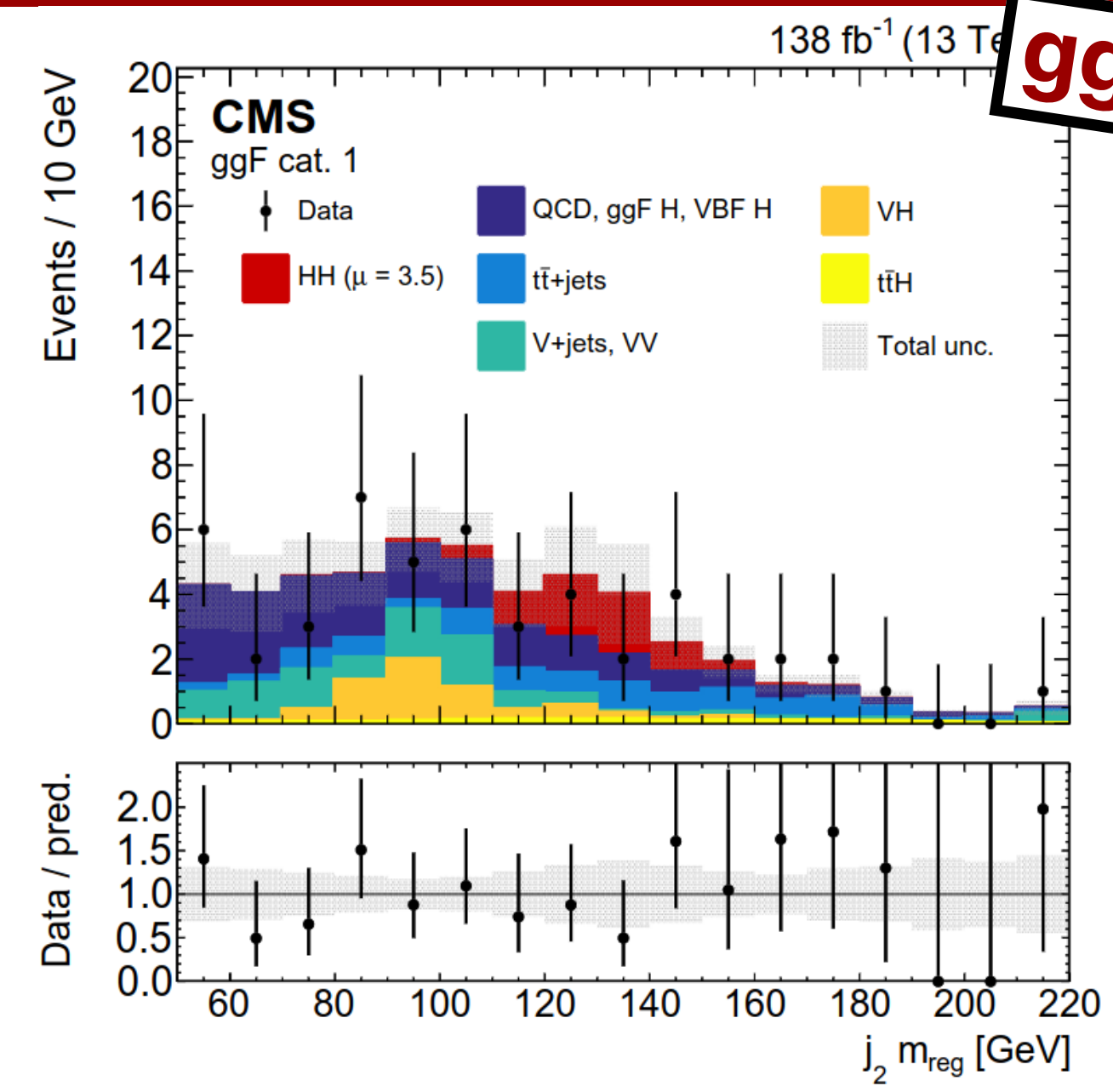


# HH → 4b boosted

**ggF** **VBF**

- 2 AK8 jets w/  $p_T(H) > 300\text{GeV}$
- Background: 85% QCD, 15% ttbar
- **PNet tagger for AK8 jets**
  - discriminate QCD vs. b-jets
  - provides 4x improvement in bkg. rejection over DeepAK8-MD
  - $p_T$ -dependent calibration performed w/ data and QCD-enriched MC
- **PNet regressed jet mass  $m_{\text{PNet}}$** 
  - improved bkg. rejection wrt  $m_{\text{SD}}$
- ggF and VBF categories use PNet tagger
  - ggF also uses BDT, which has 2x better bkg. rejection wrt. cuts
- Simultaneous ML fit in all ggF and VBF categories, plus CRs (QCD and tt)
  - ggF: **fit to PNet mass** of one bb cand.
  - VBF: **fit to  $m_{\text{HH}}$**

$$\sigma_{\text{HH}} < 9.9 \text{ (5.1)} < \sigma_{\text{HH}}^{\text{SM}}$$

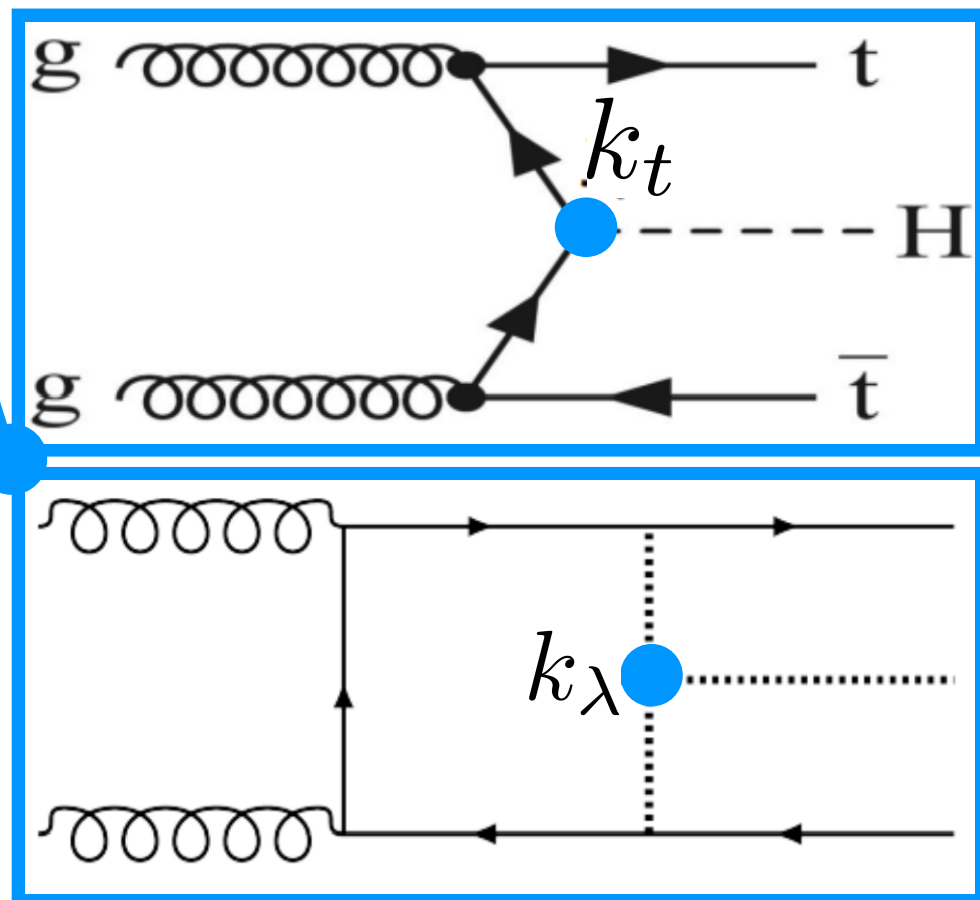




# HH → bbγγ

**ggF** **VBF**

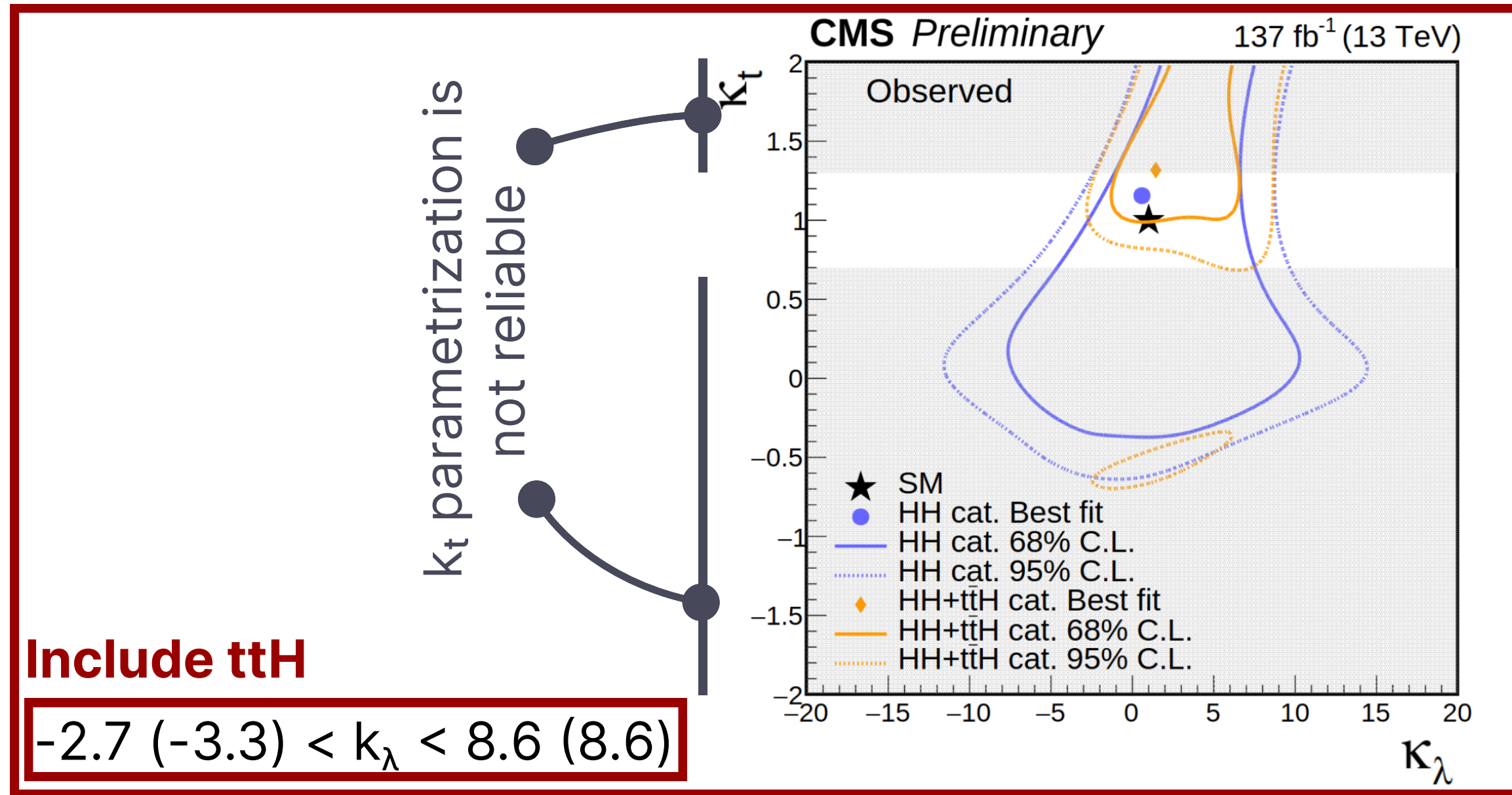
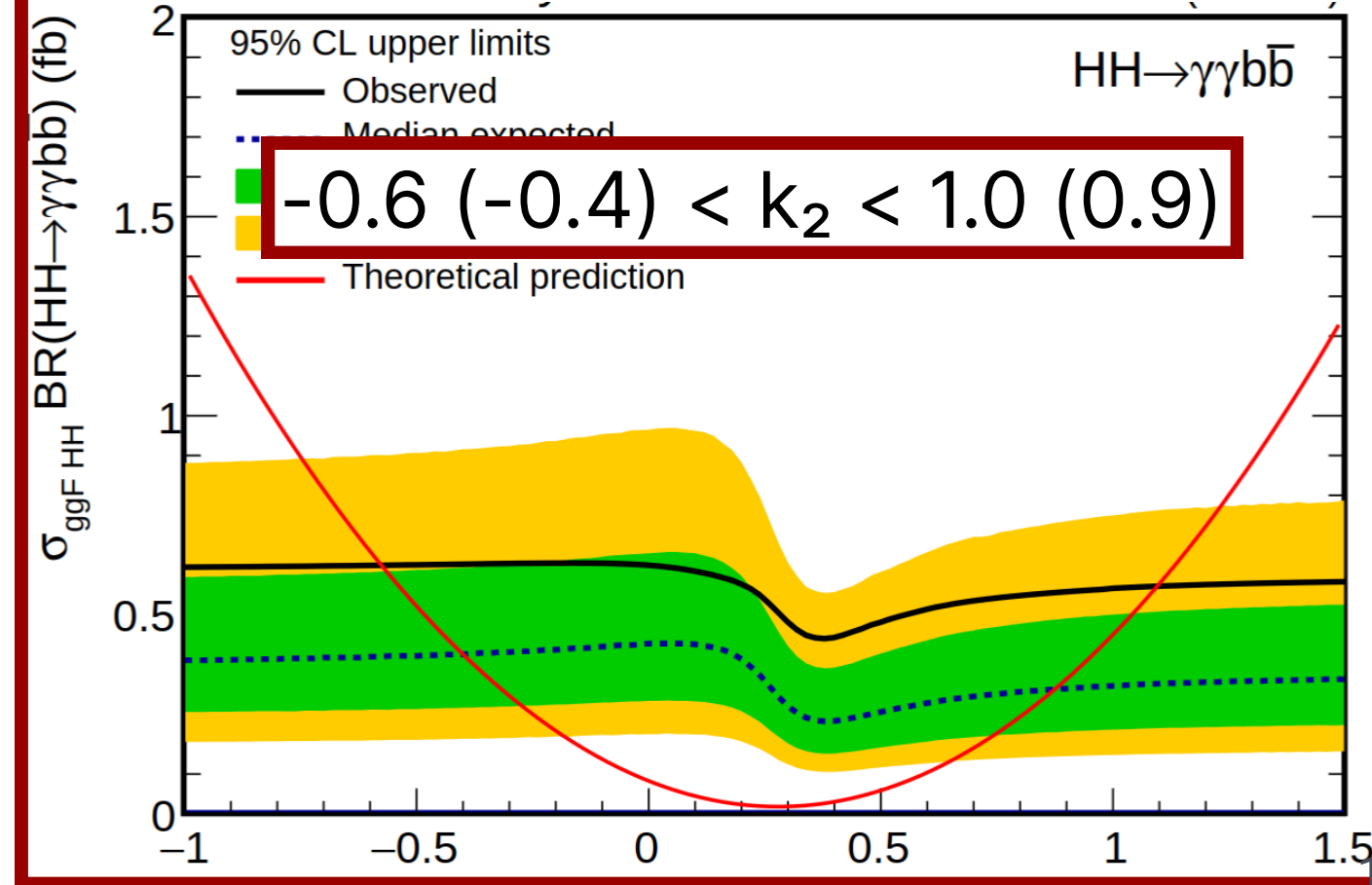
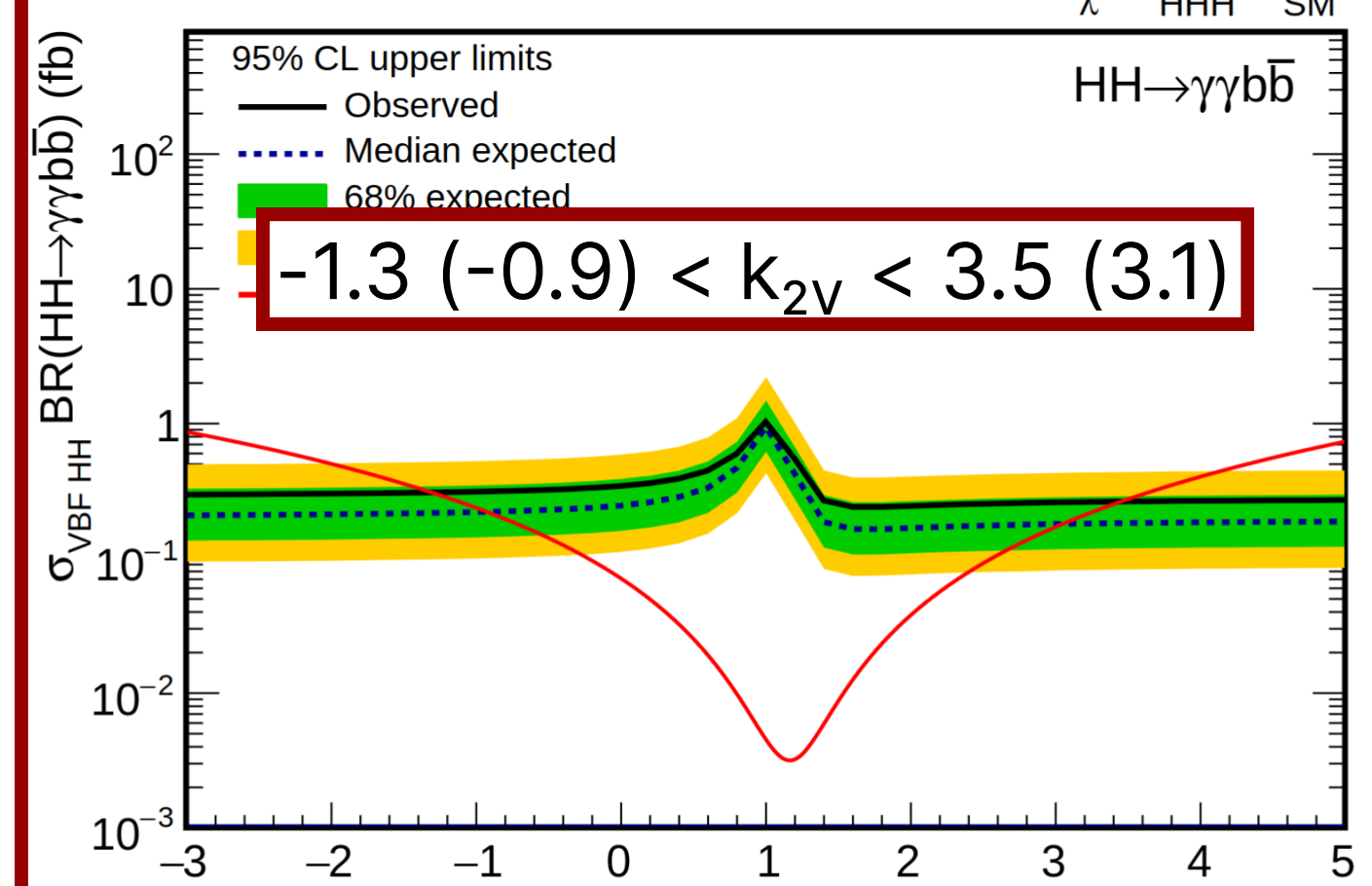
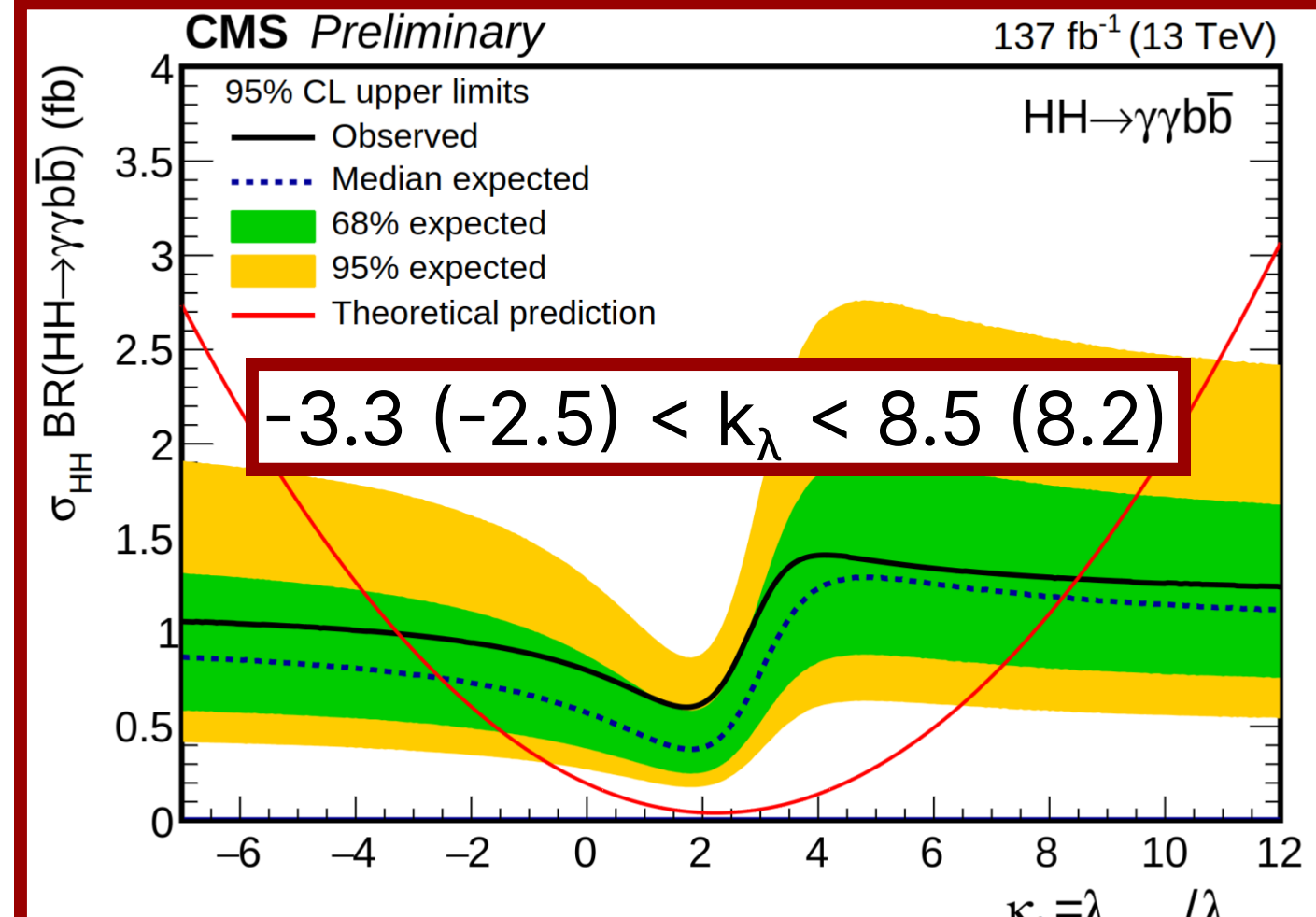
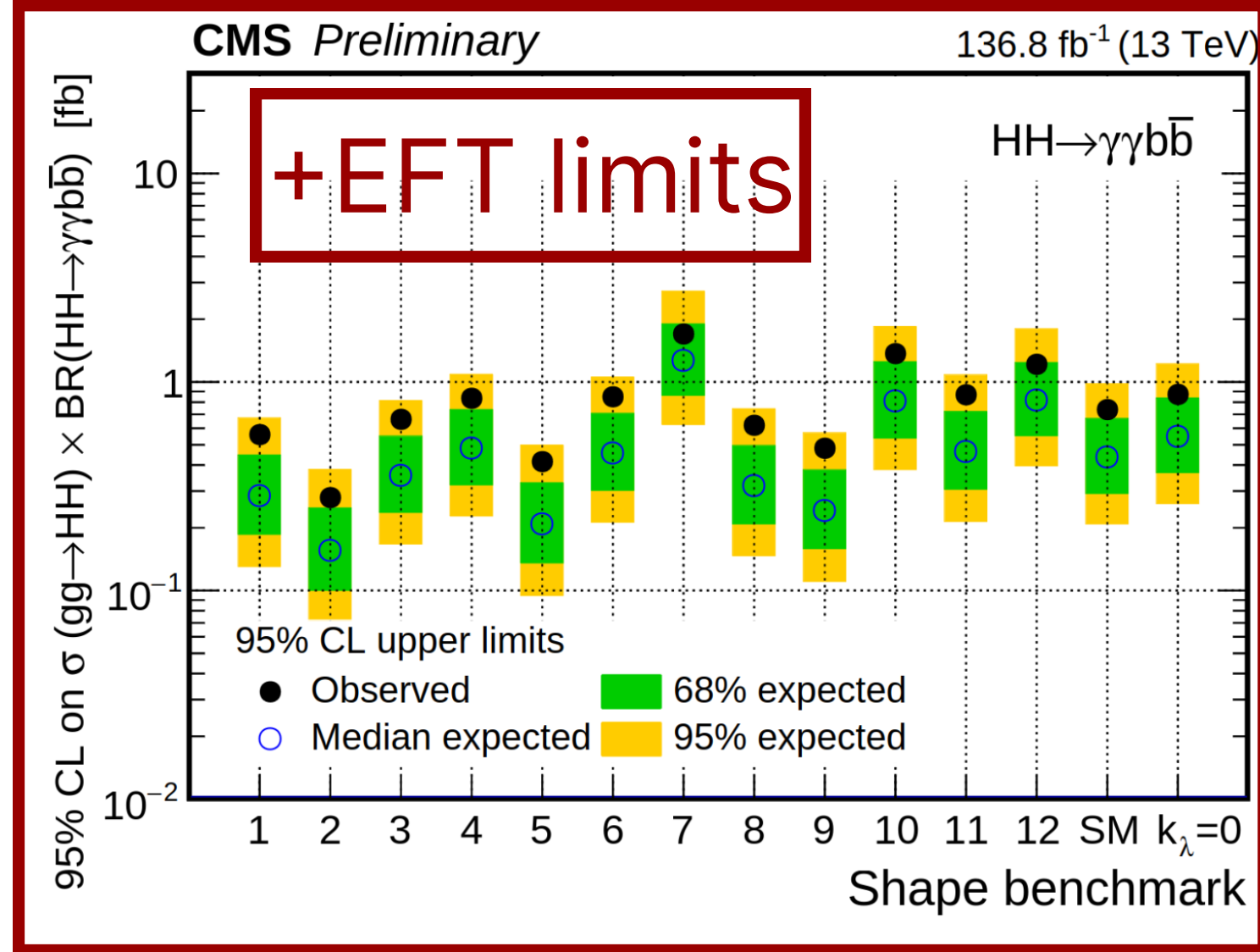
- optimized categories based on modified mass and ggF/VBF BDTs
- dedicated “ttH killer” DNN
- Signal extracted from unbinned 2D  $m_{\gamma\gamma}$  vs.  $m_{bb}$  parametric fit
  - $m_{\gamma\gamma}$ : sum of gaussians
  - $m_{jj}$ : double crystal-ball + gaus.
- HH+H combination: constrain  $\kappa_t$  w/ ttH phase-space



ttH analysis

$$\sigma_{HH} < 7.7 \text{ (5.2)} < \sigma_{HH}^{SM}$$

$$\sigma_{VBF} < 225 \text{ (208)} < \sigma_{HH}^{SM}$$

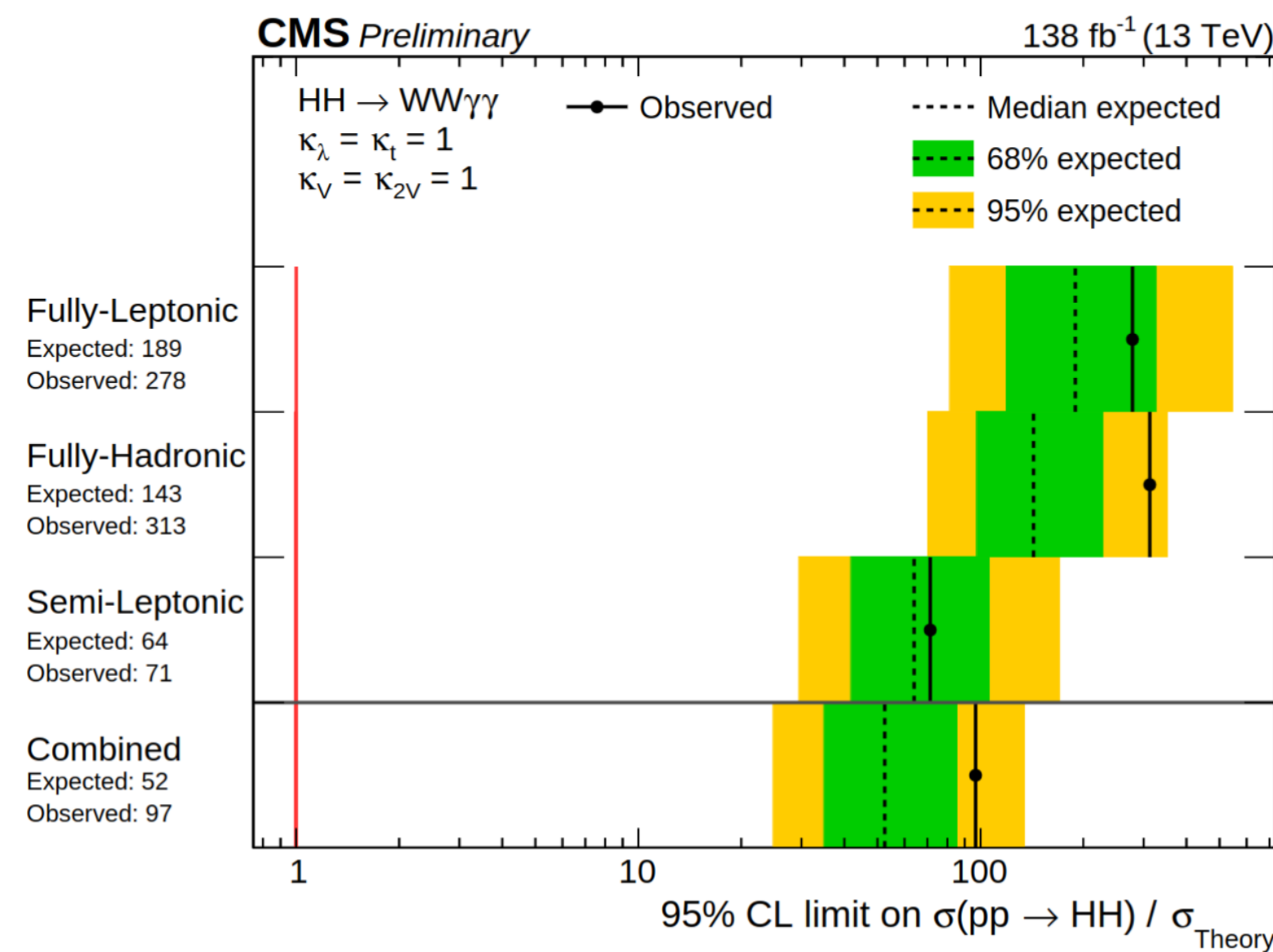
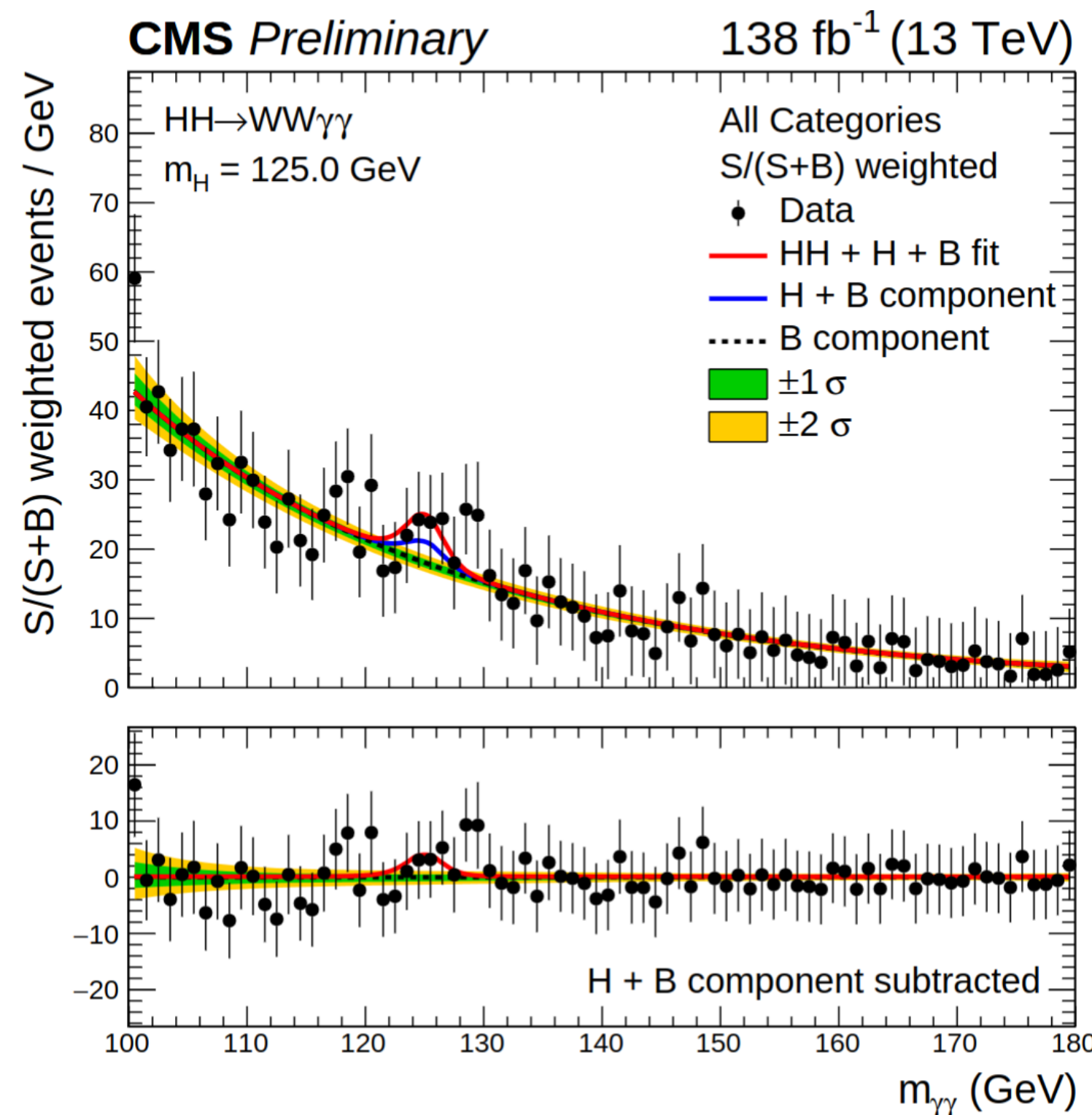


**Include ttH**  
 $-2.7 \text{ (-3.3)} < \kappa_\lambda < 8.6 \text{ (8.6)}$



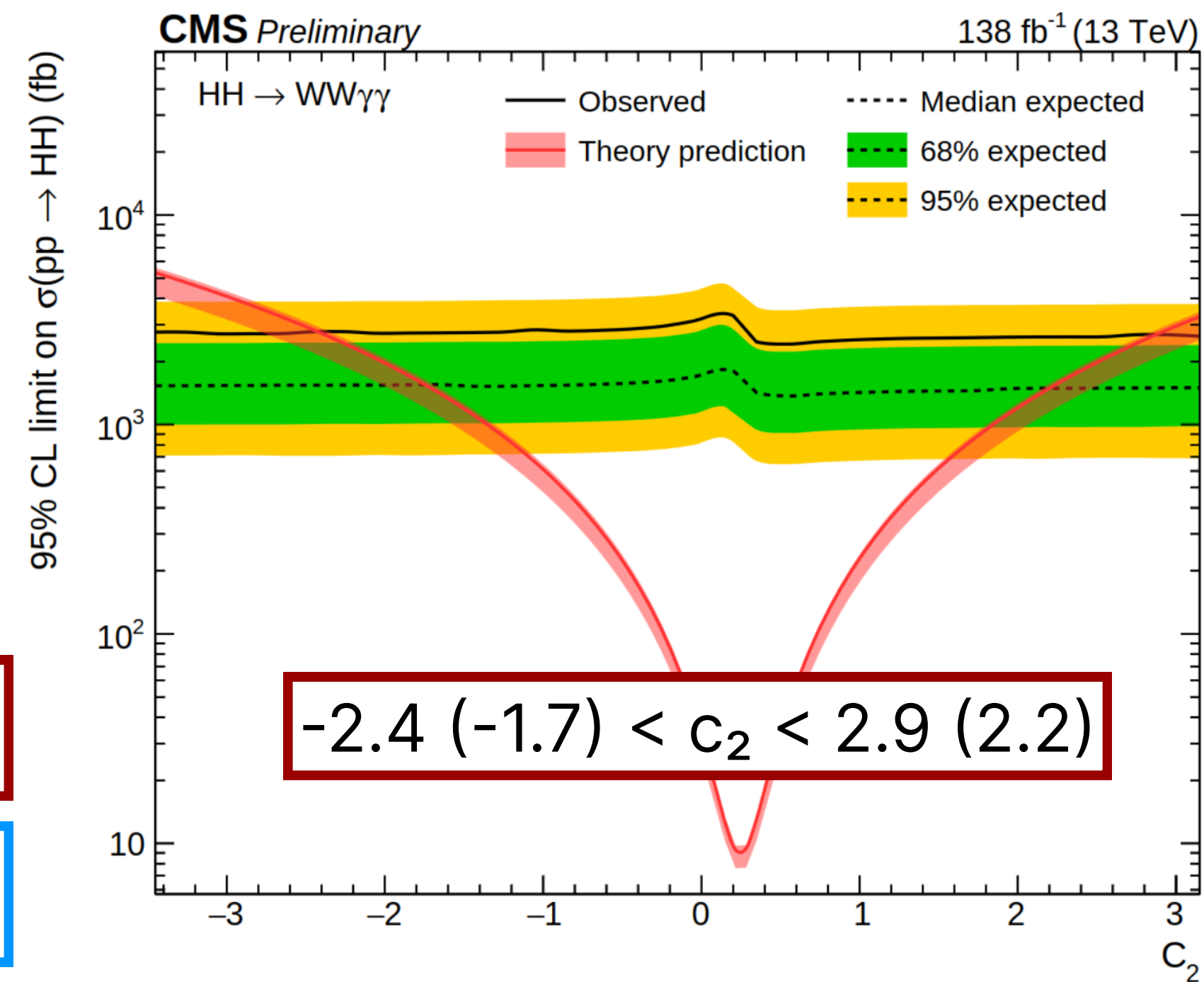
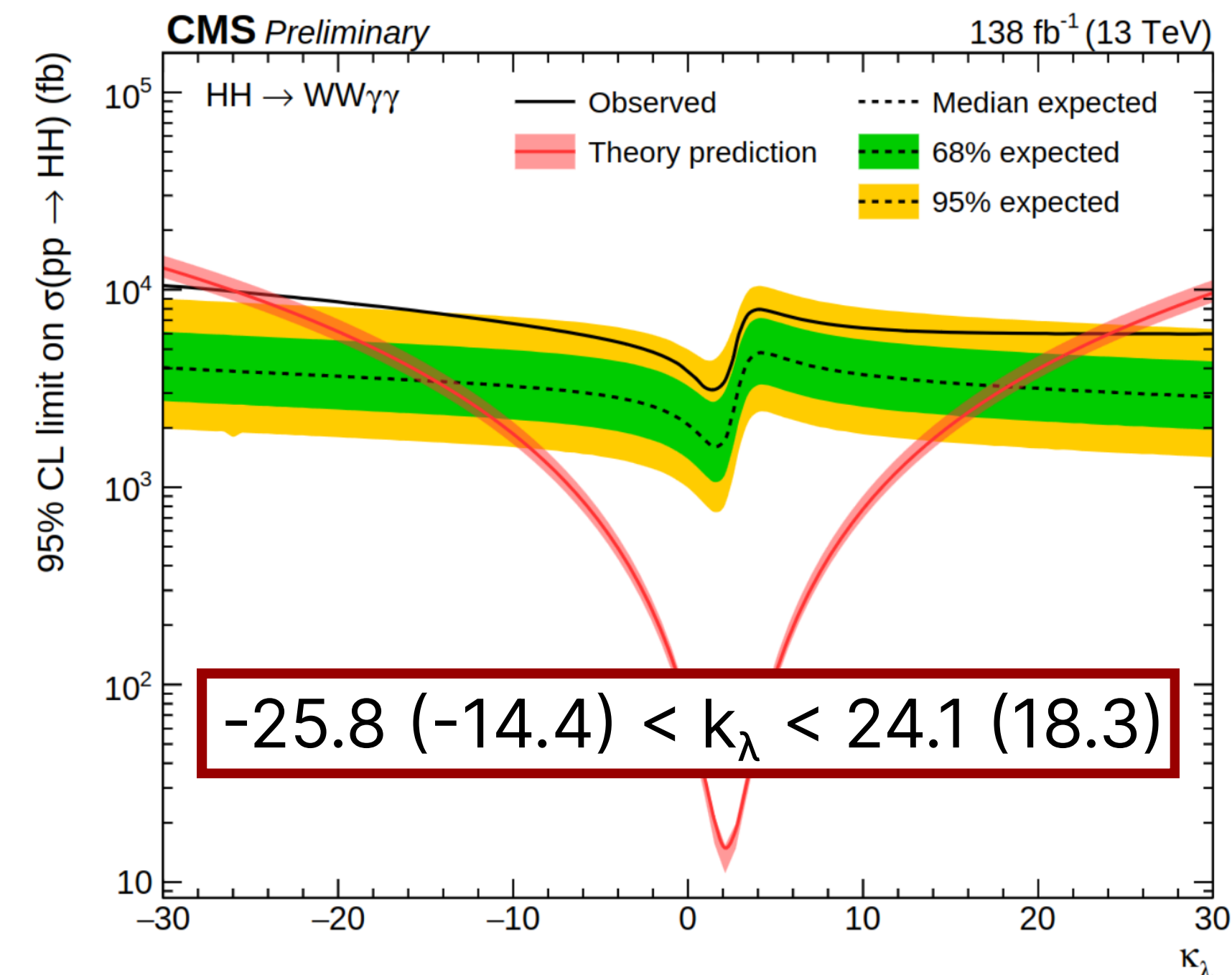
# HH → WWγγ ggF

- Signal extracted from  $m_{\gamma\gamma}$  parametric fit
- 3 channels based on #leptons
  - 0: multiclass DNN to remove H and  $\gamma$ /jets bkg. + binary DNN for EFT benchmarks
  - 1: WWγγ id and “bbyγ killer” binary DNNs
  - 2: cut based



$$\sigma_{\text{HH}} < 96.8 (52.5) < \sigma_{\text{HH}}^{\text{SM}}$$

$$\sigma_{\text{EFT}} < 1.7 - 6.2 (1.0 - 3.9)$$

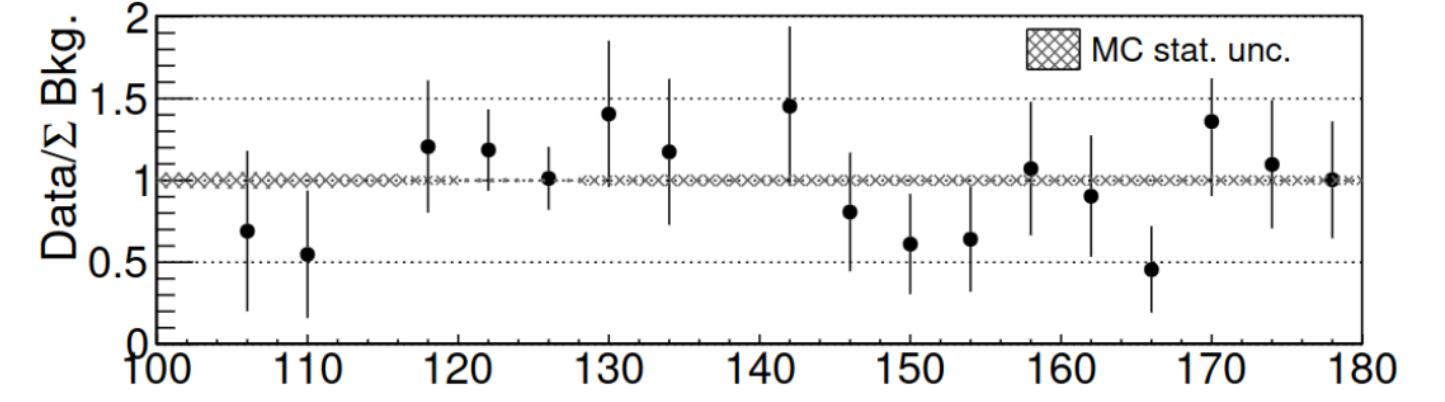
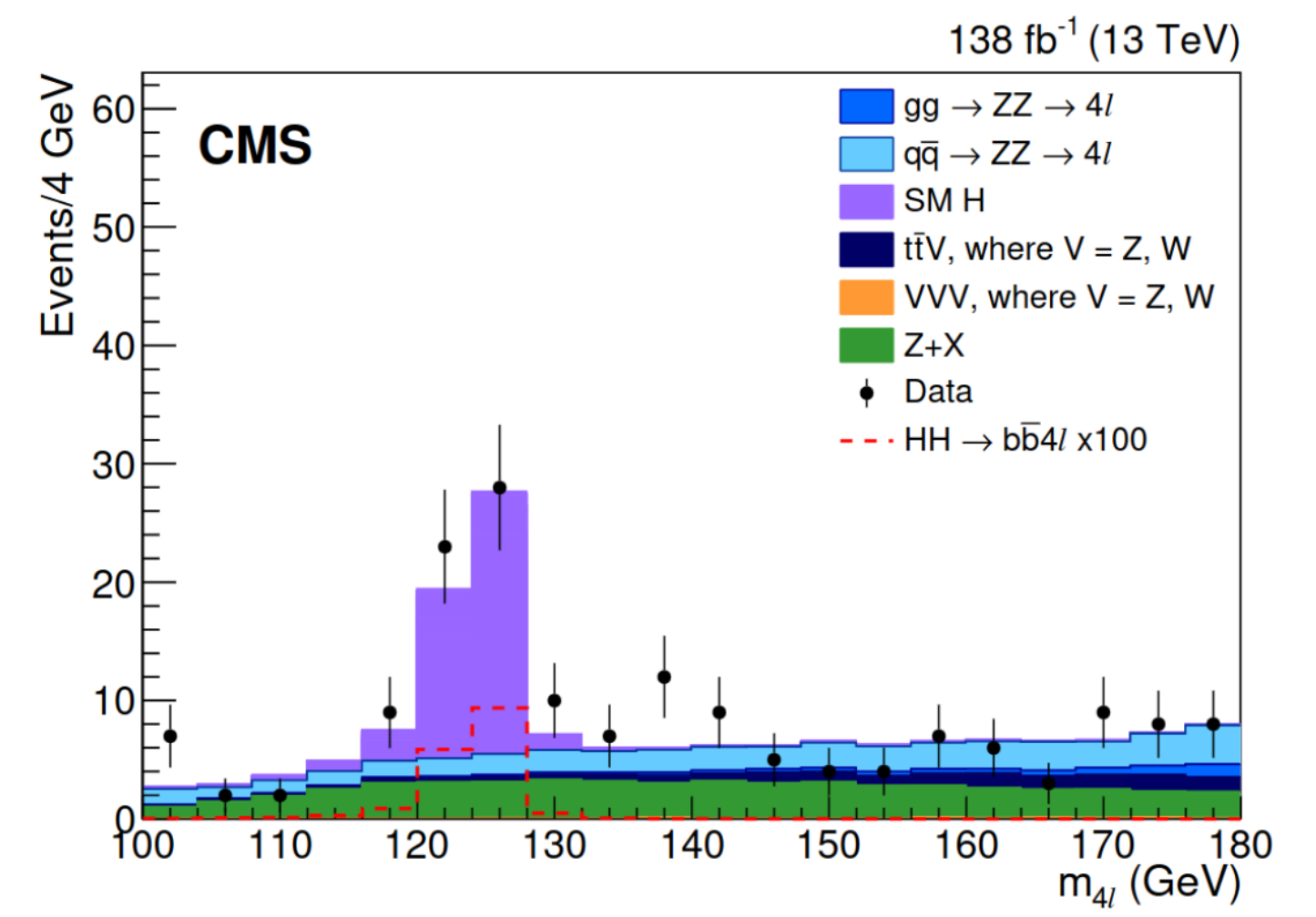
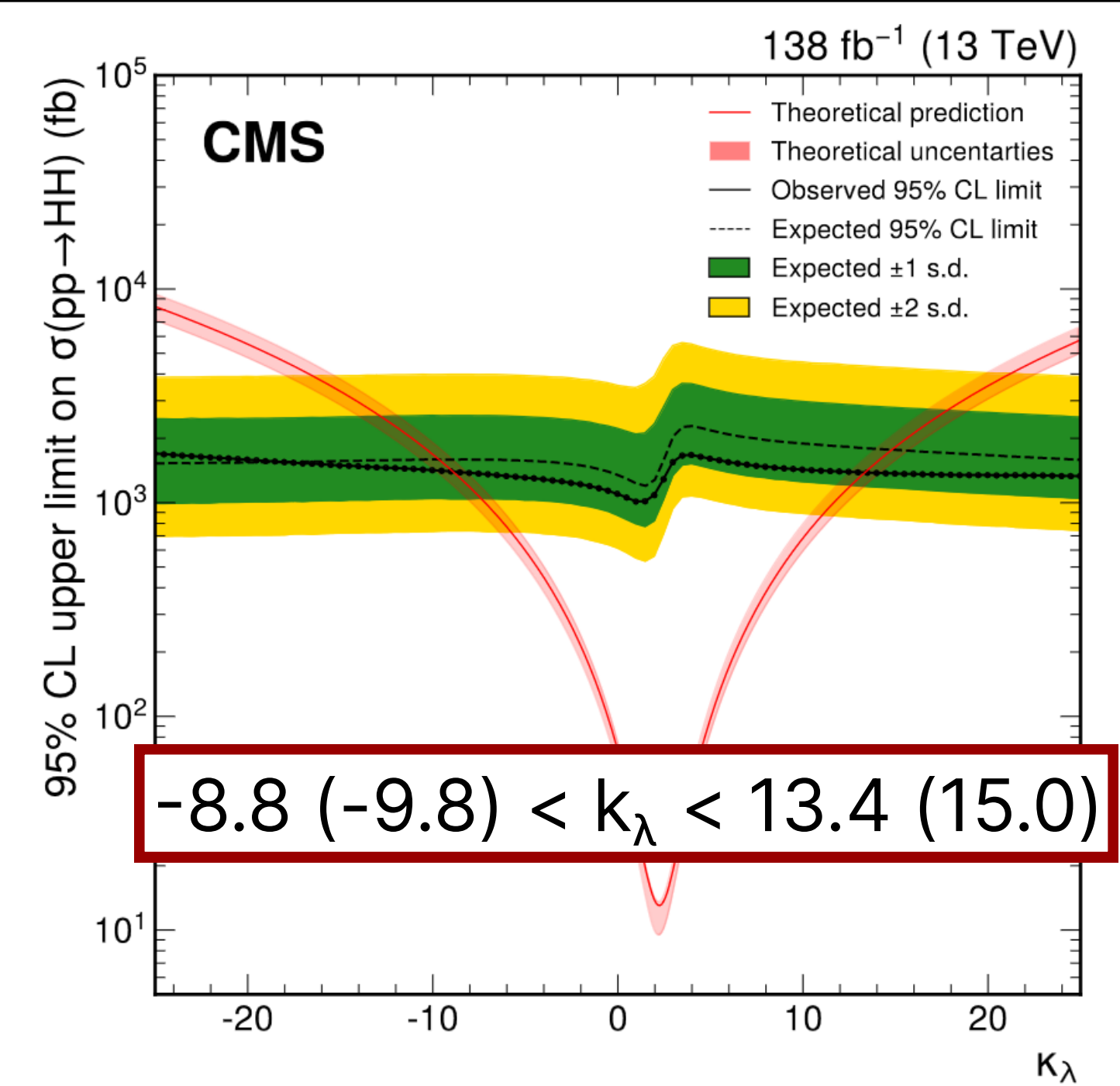
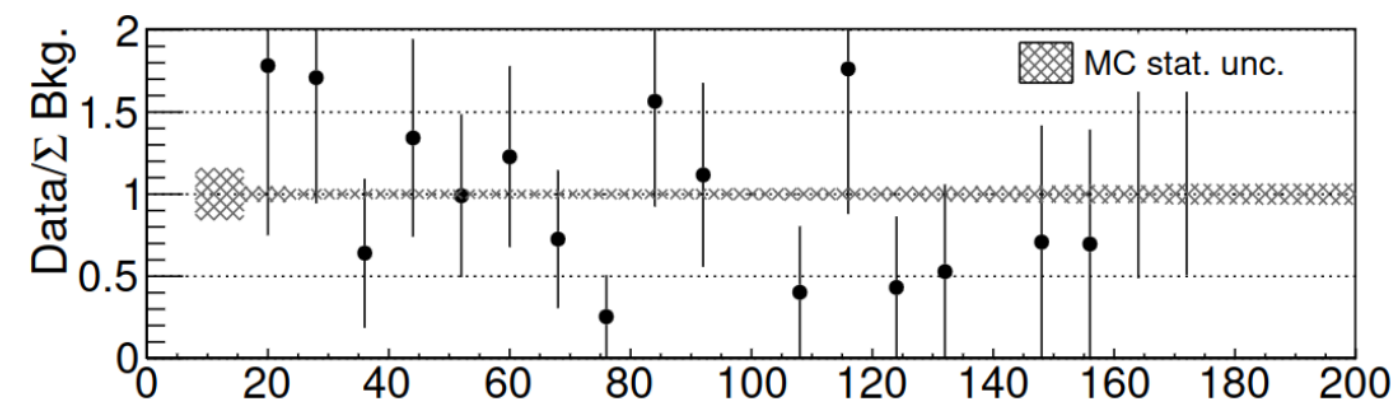
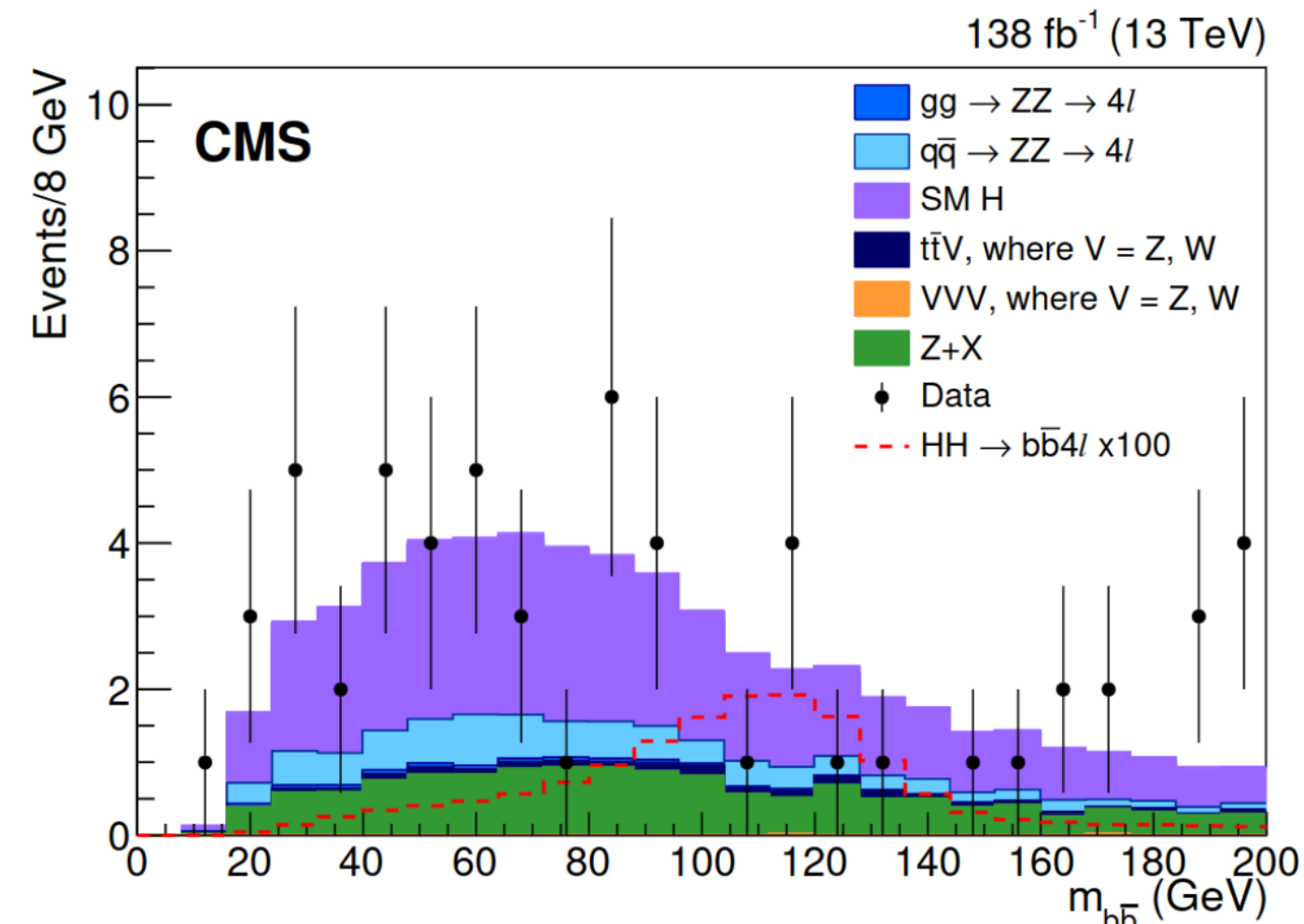
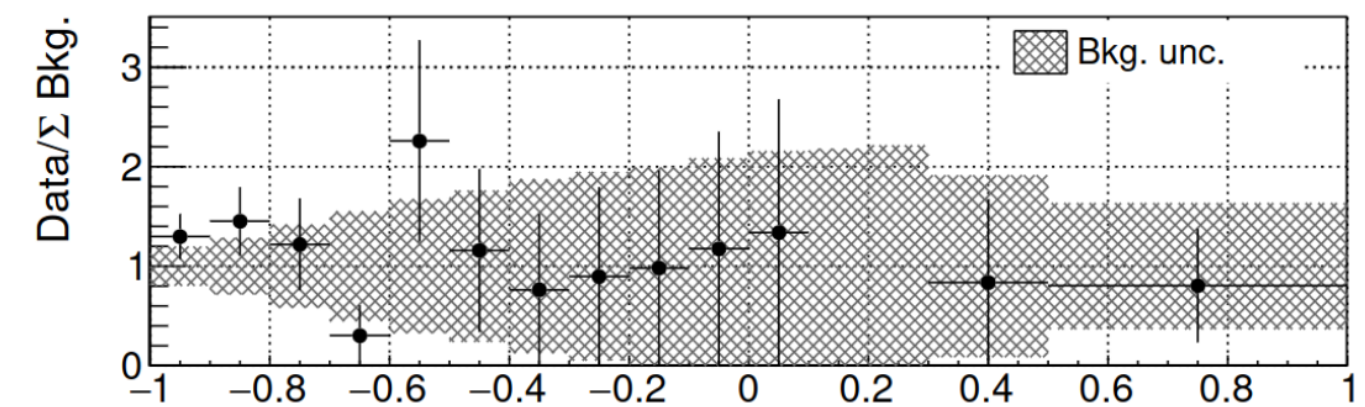
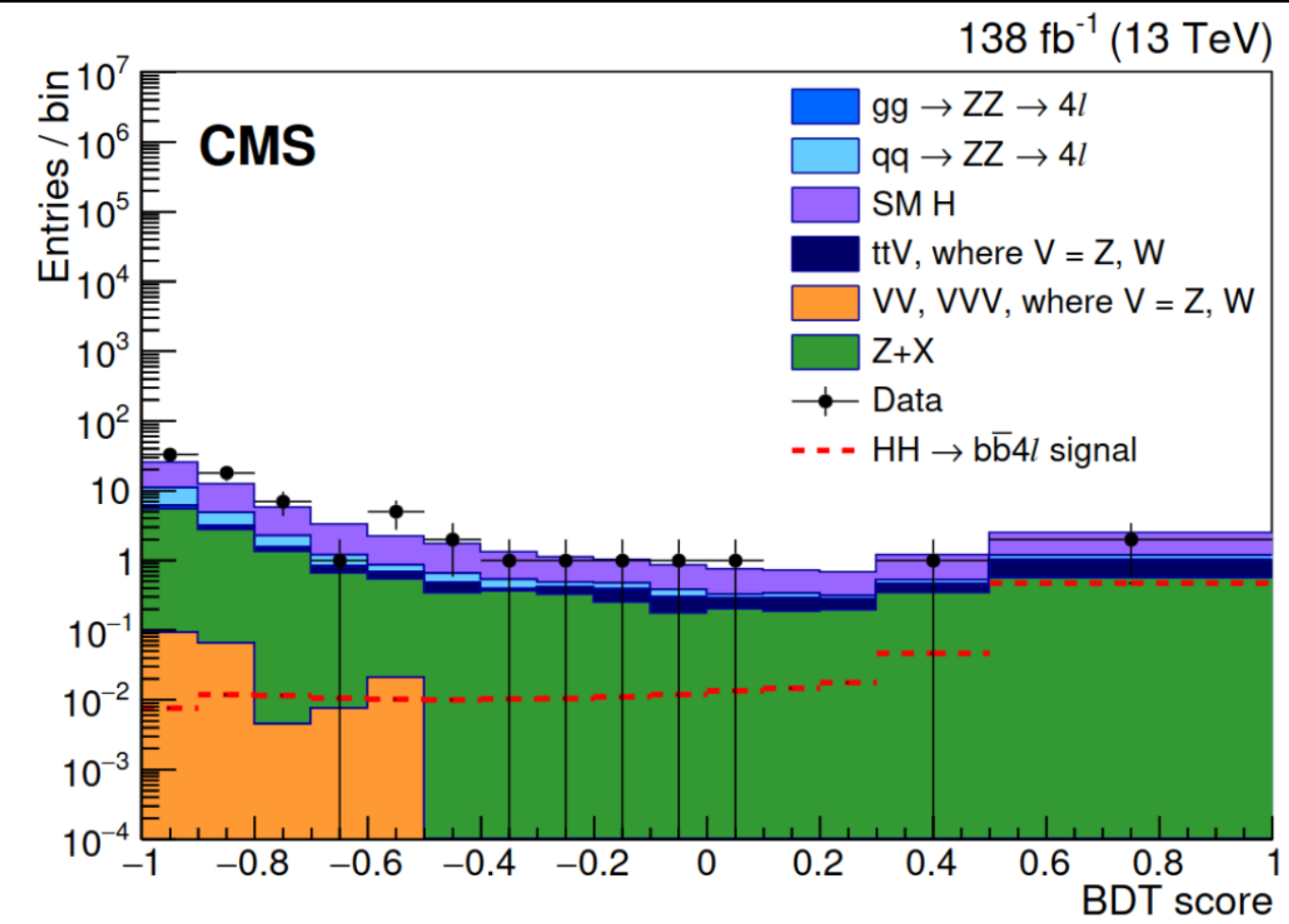




# HH → bbZZ **ggF**

- H → ZZ taken from HIG-19-001
- Select 2 extra jets w/ highest DeepCSV score
- “Fake” non-prompt leptons estimated from data
  - sources: e → γ conversion, misrec. jets, HF decays
  - measure fake rate in Z + 1l + 2jets region
  - apply fake rate in Z + 2l + 2jets region
- Signal vs bkg. discrimination w/ BDT being fed full b-tagger distribution of jets
  - year- and channel-dependent training

$$\sigma_{HH} < 32.4 \text{ (39.6)} < \sigma_{HH}^{\text{SM}}$$





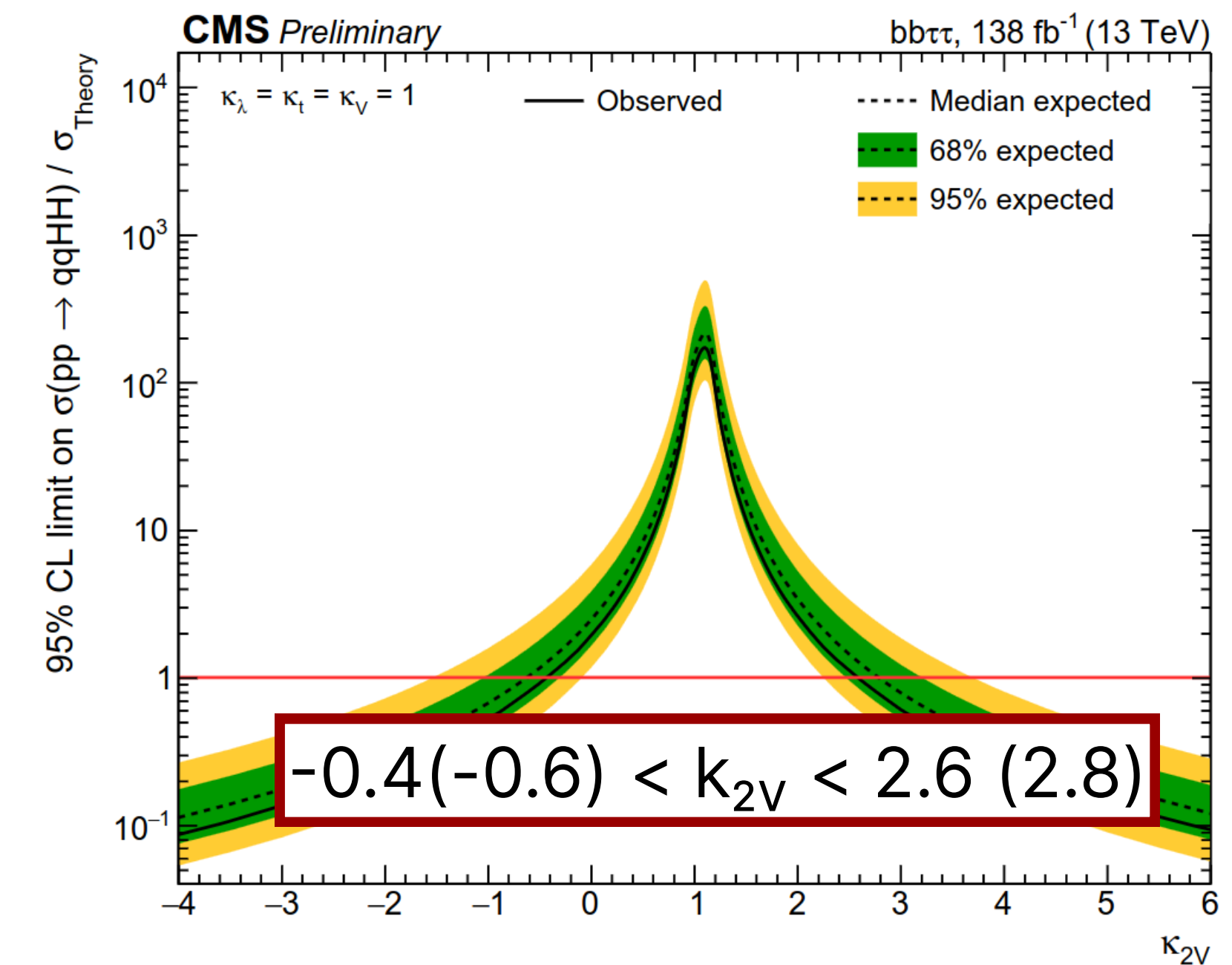
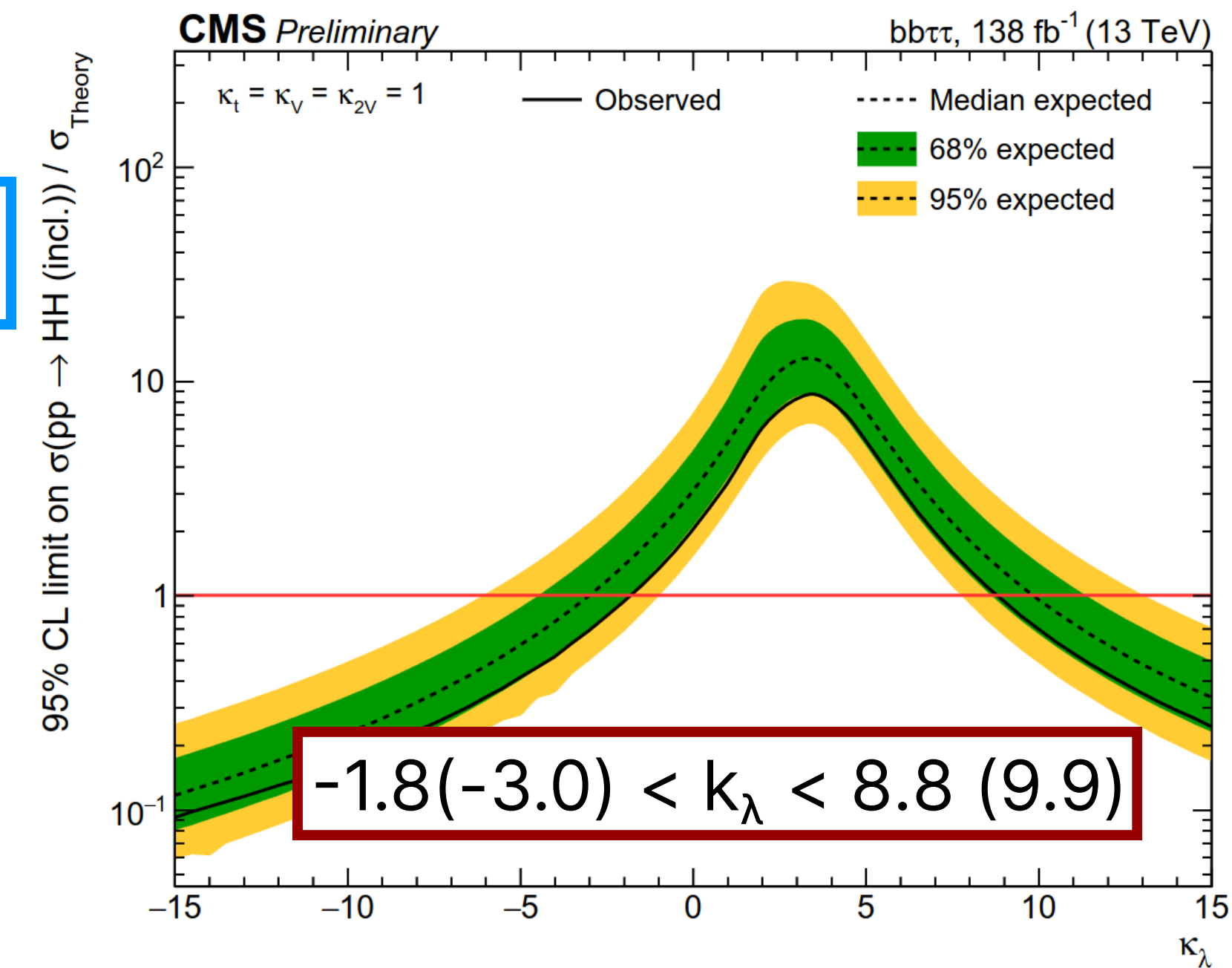
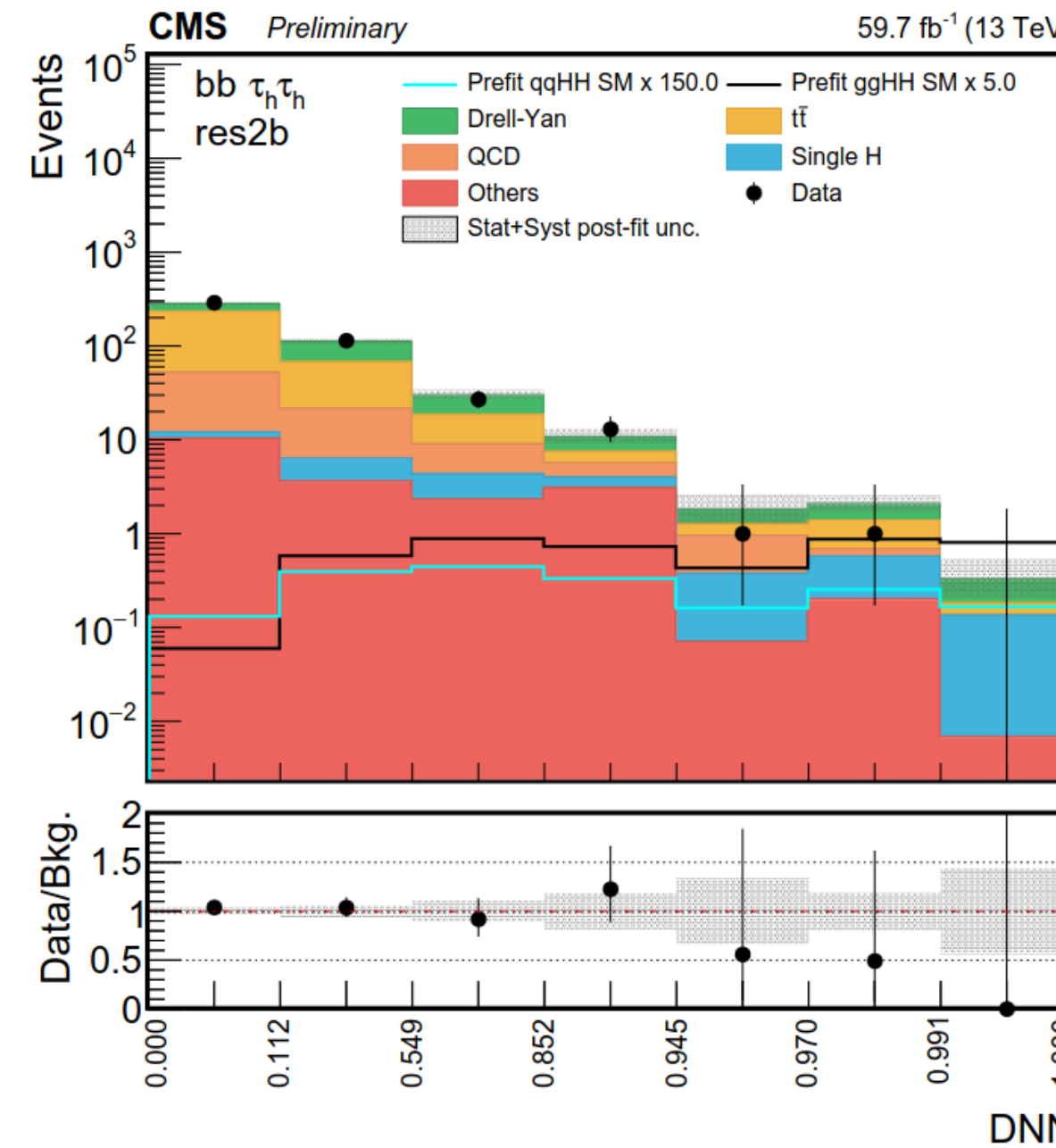
# HH → bbττ

**ggF** **VBF**

$$\sigma_{HH} < 3.3 \text{ (5.2)} < \sigma_{HH}^{SM}$$

$$\sigma_{VBF} < 124 \text{ (154)} < \sigma_{VBF}^{SM}$$

- ID with DeepJet and DeepTau
- 3 channels based on τ DM
- Categories: resolved, boosted and VBF-like
- Multi-classification approach to increase analysis sensitivity in the VBF category
  - 2 signal + 3 bkg. classes
- Fit the DNN score
  - most important features: DeepJet scores, inv. masses and many kinematic variables
  - two discriminators to enable inference on the entire dataset
  - ten networks per discriminator trained with 10-fold stratified cross-validation

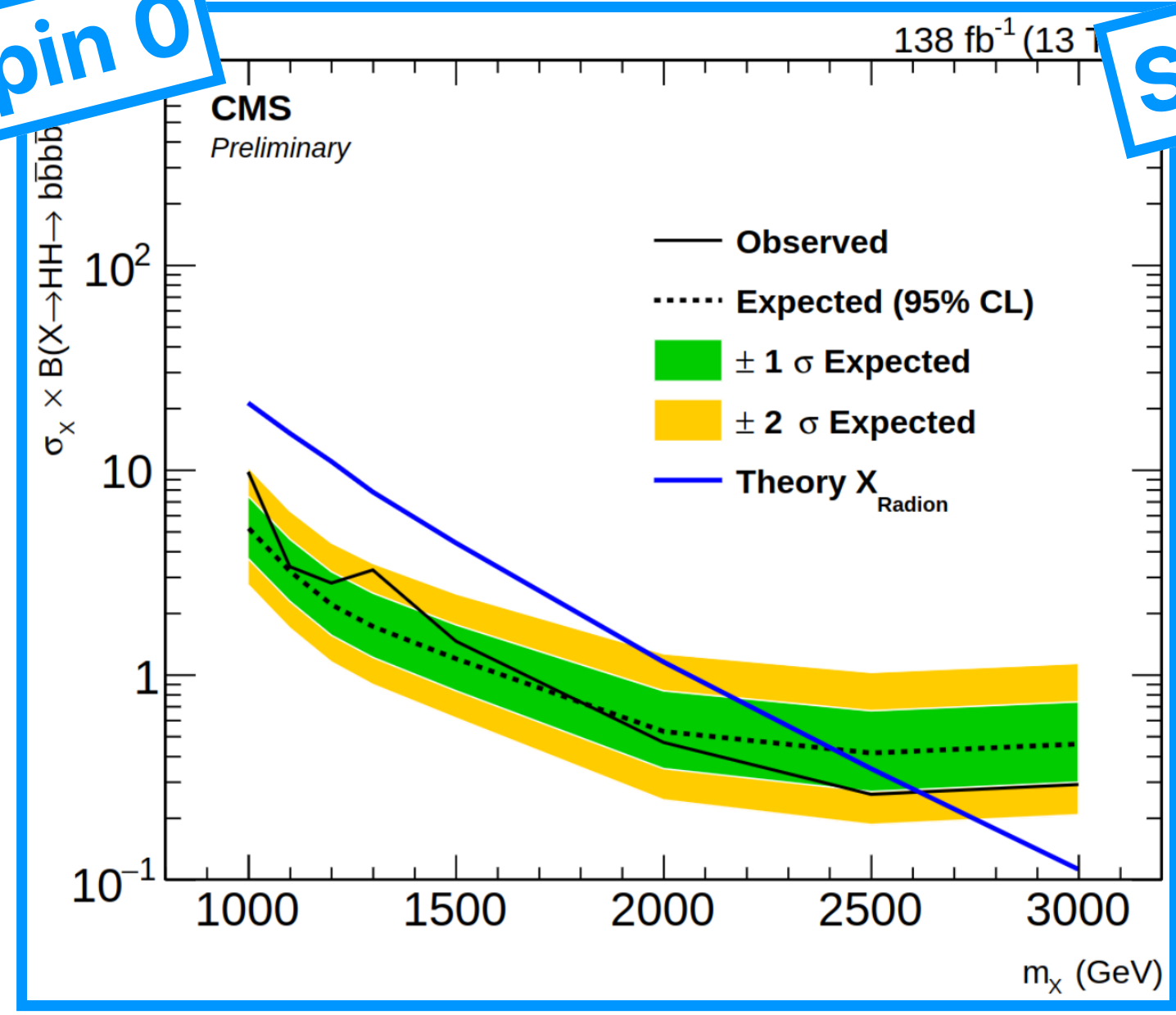


# $X \rightarrow HH \rightarrow 4b$

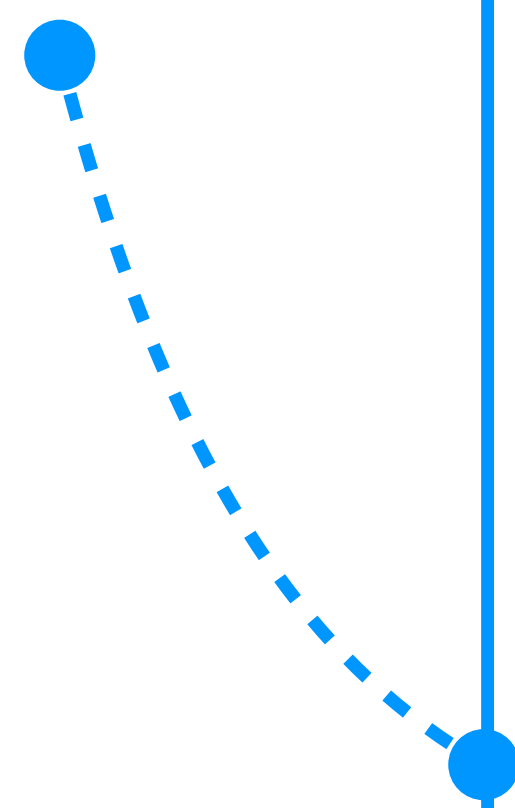
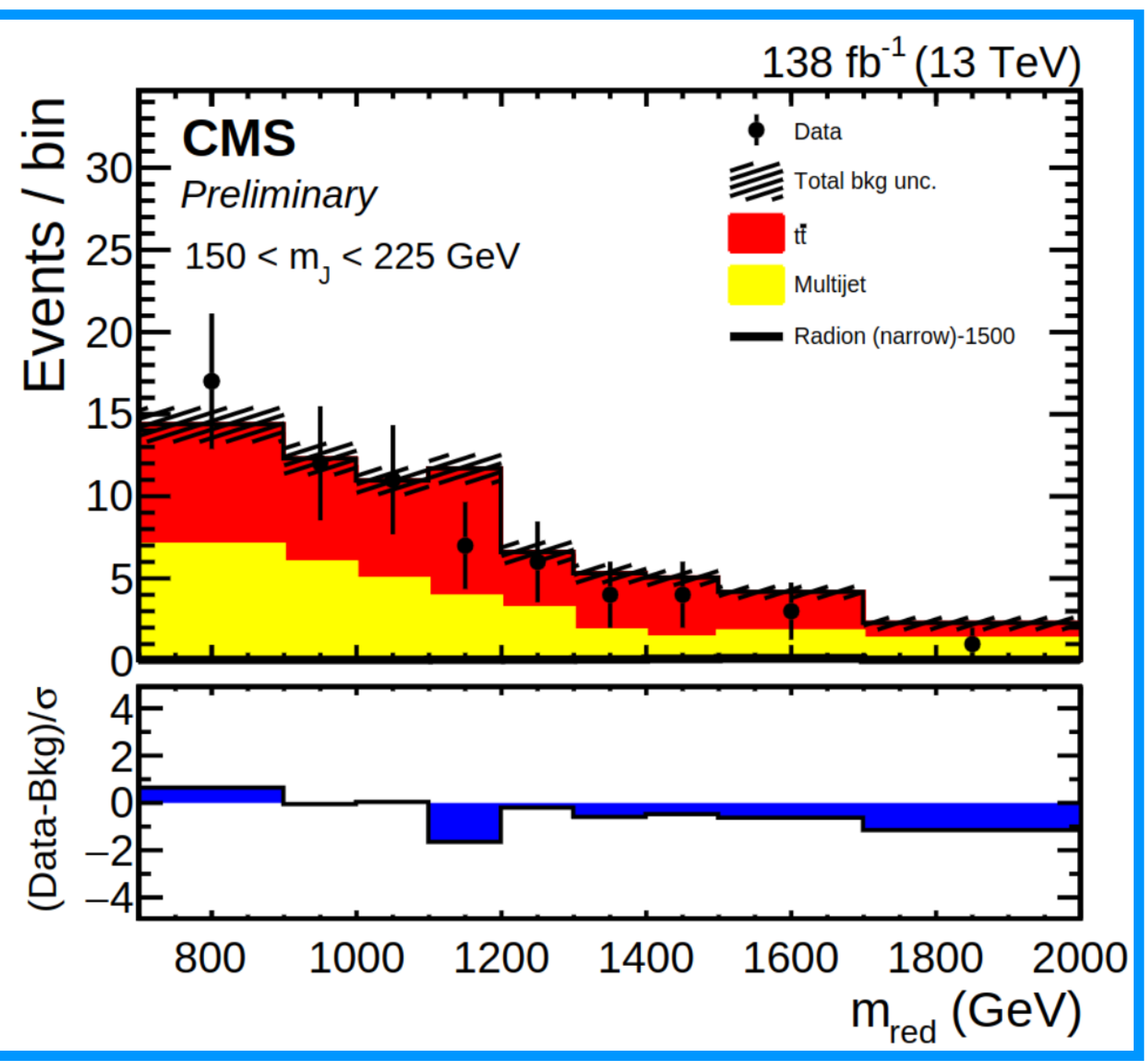
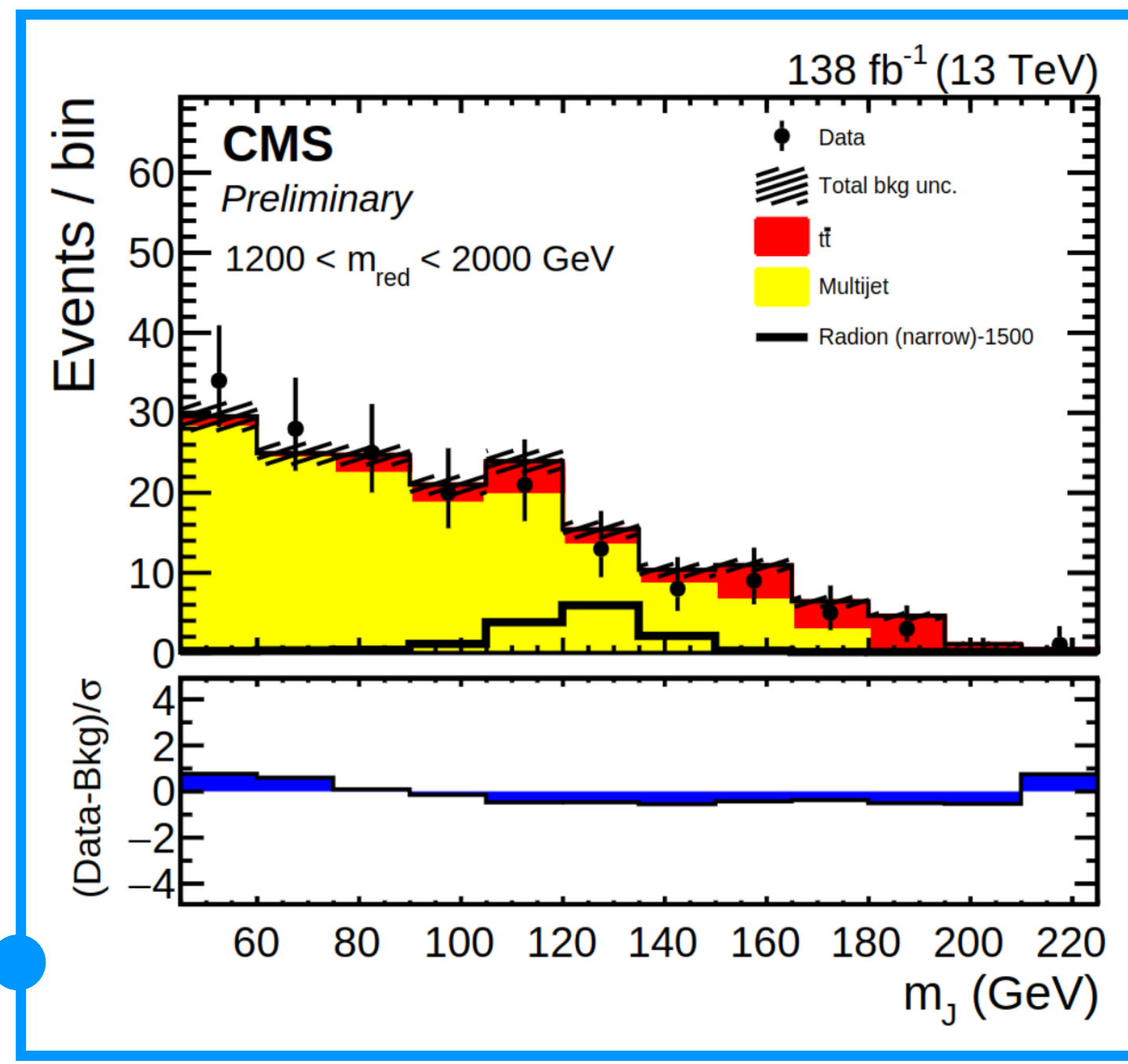
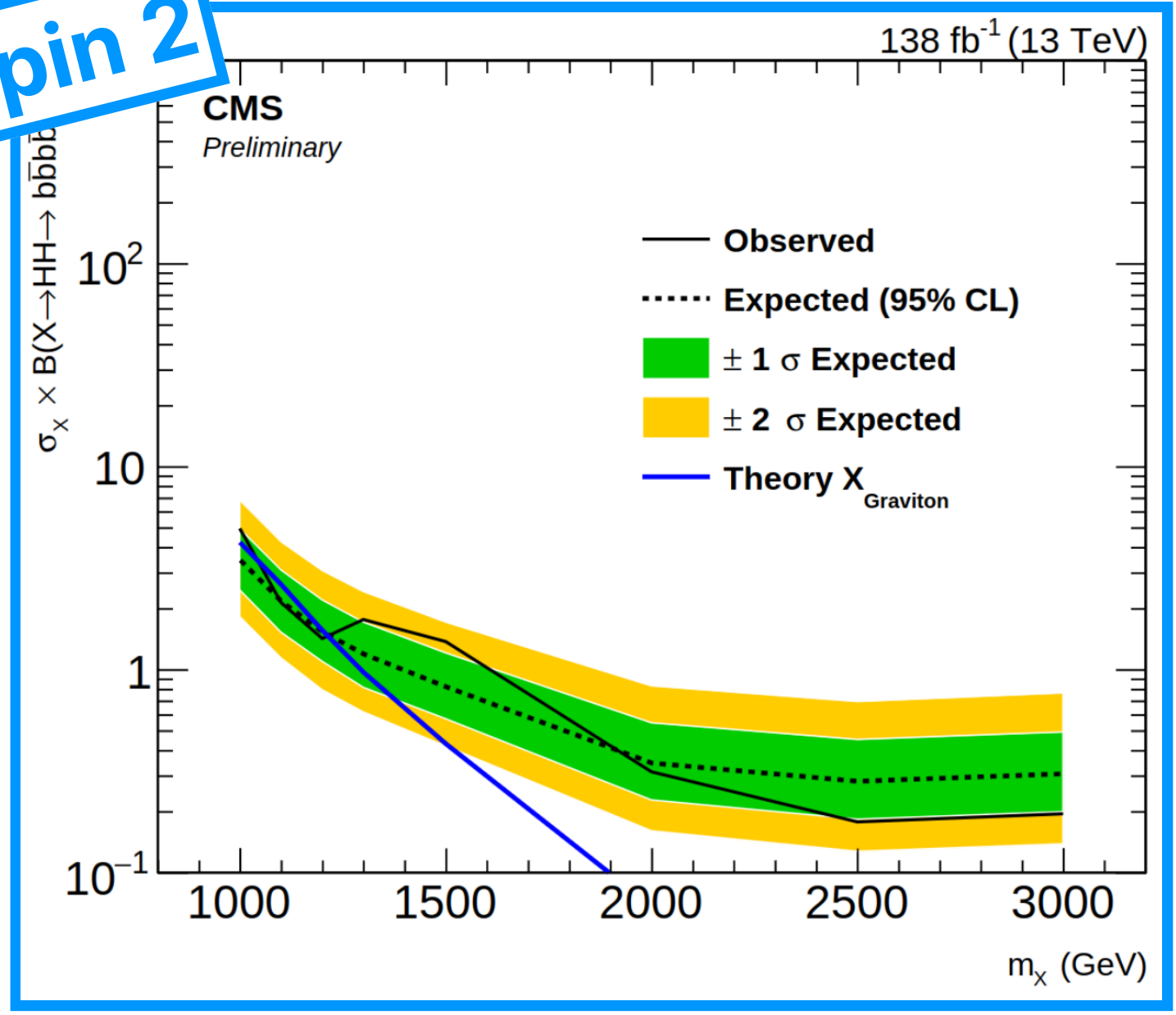
**Resonant**

- 3 categories: 2 Tight (DeepJet) AK8 tags, 2 Loose AK8 tags and semi-resolved (2 AK4 + 1 AK8)
- 2 control regions (orthogonal DeepJet tag)
- QCD and  $t\bar{t}$ +jets bkg. estimated from MC and data “reduced mass”  $m_{red}$  sidebands
  - $m_{red}$  mitigates fluctuations by JER and mass resolutions
- 2D binned fit to  $(m_{lead\ jet}, m_{red})$

**Spin 0**

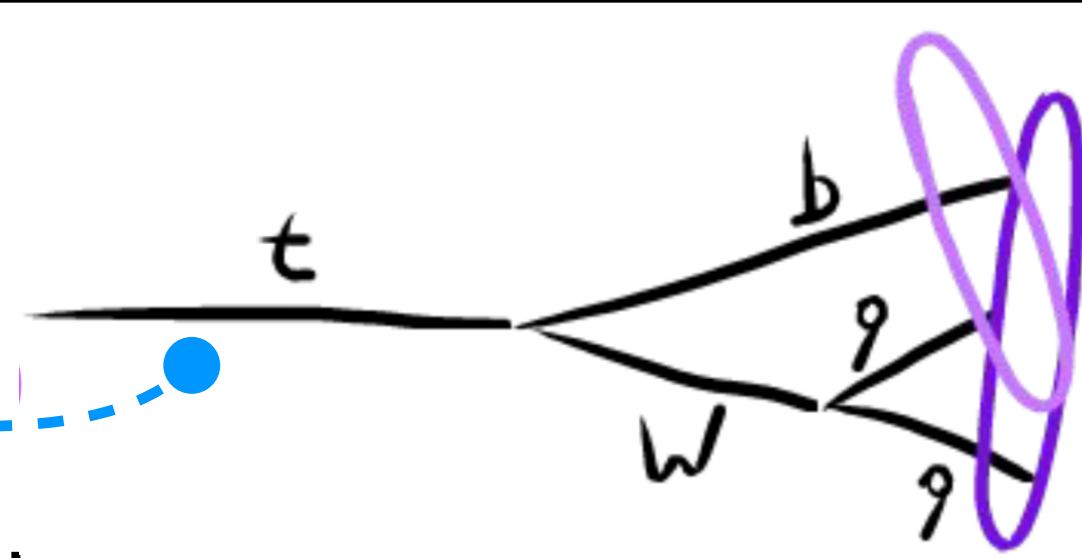


**Spin 2**

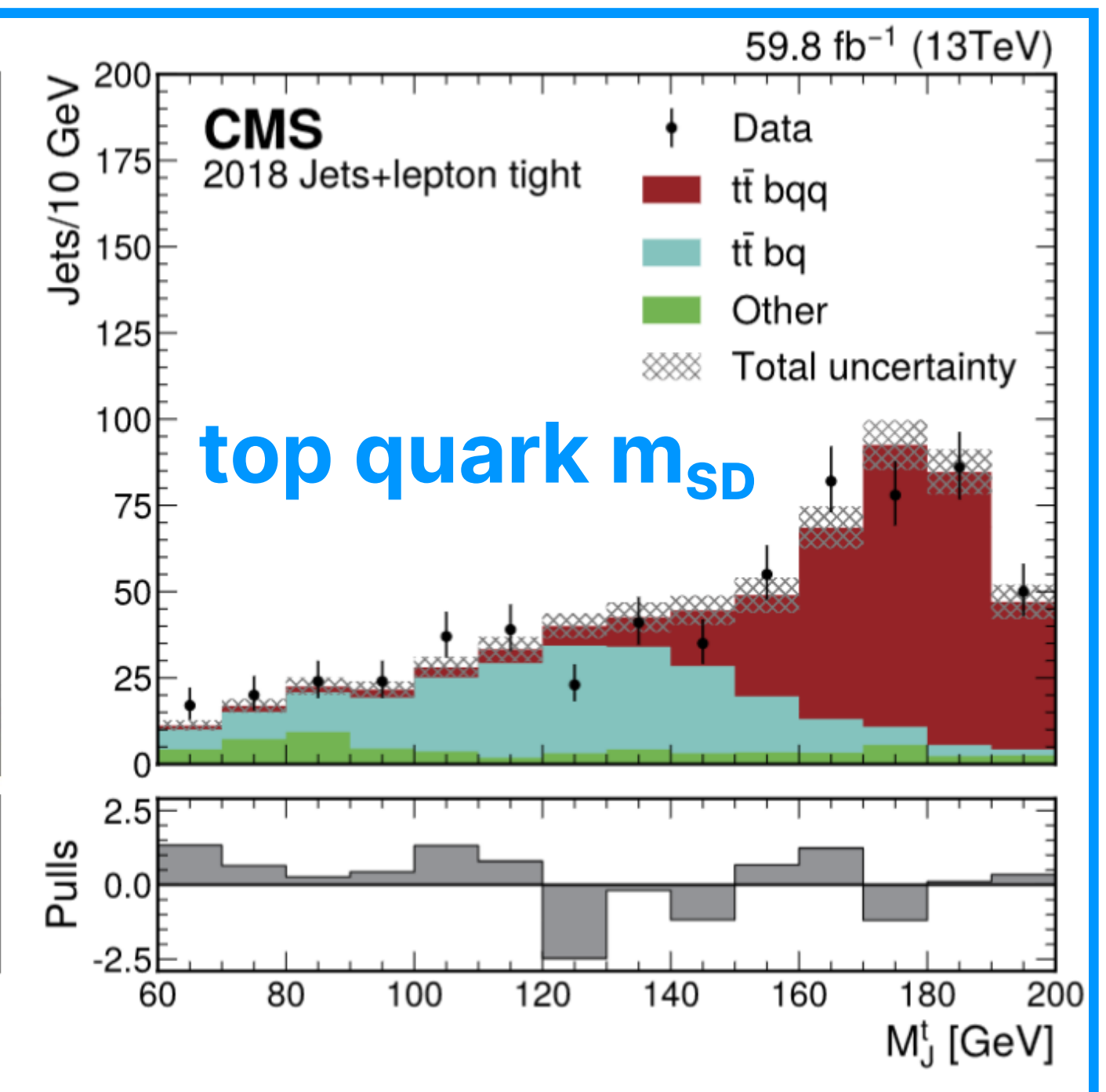
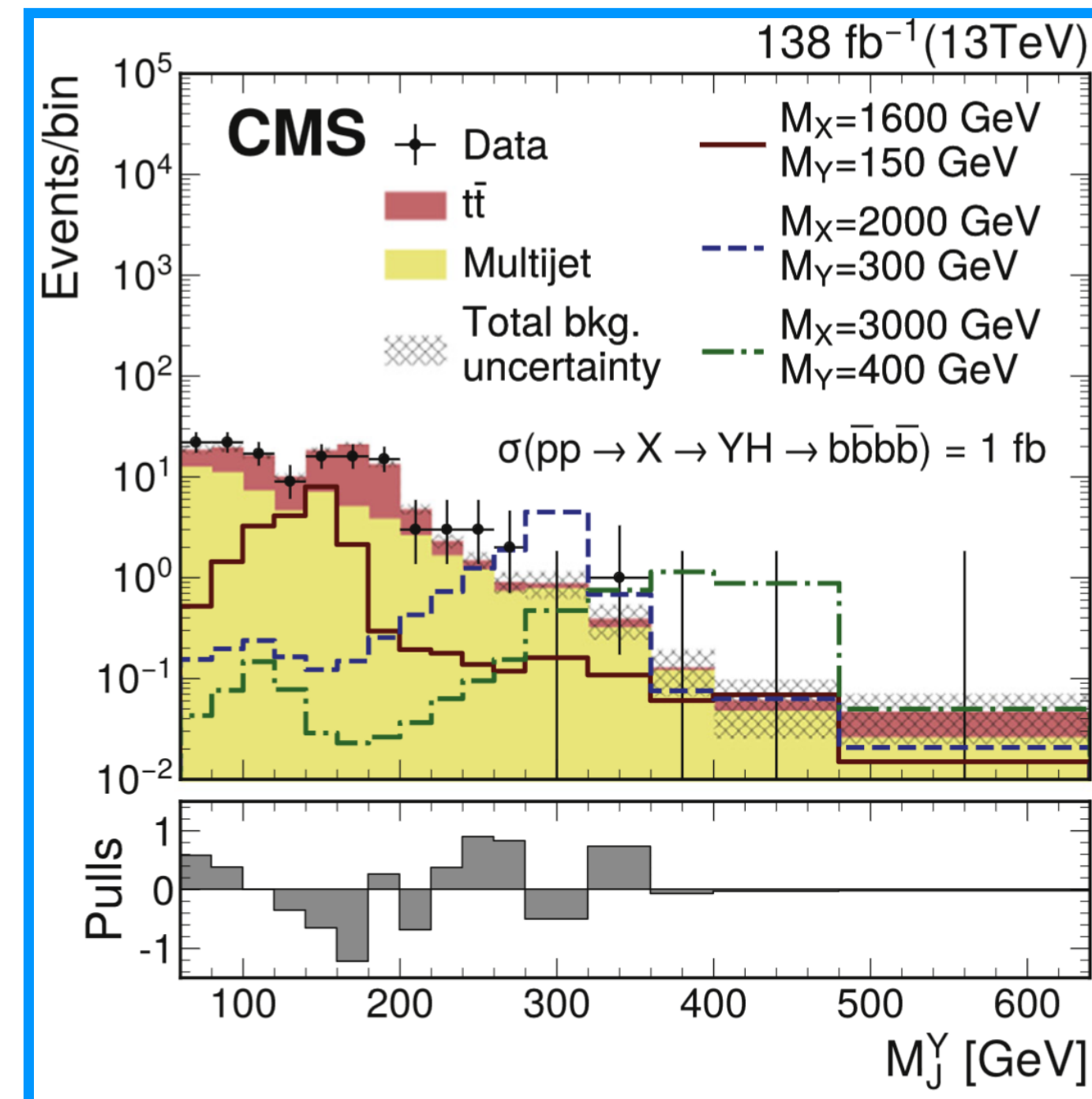
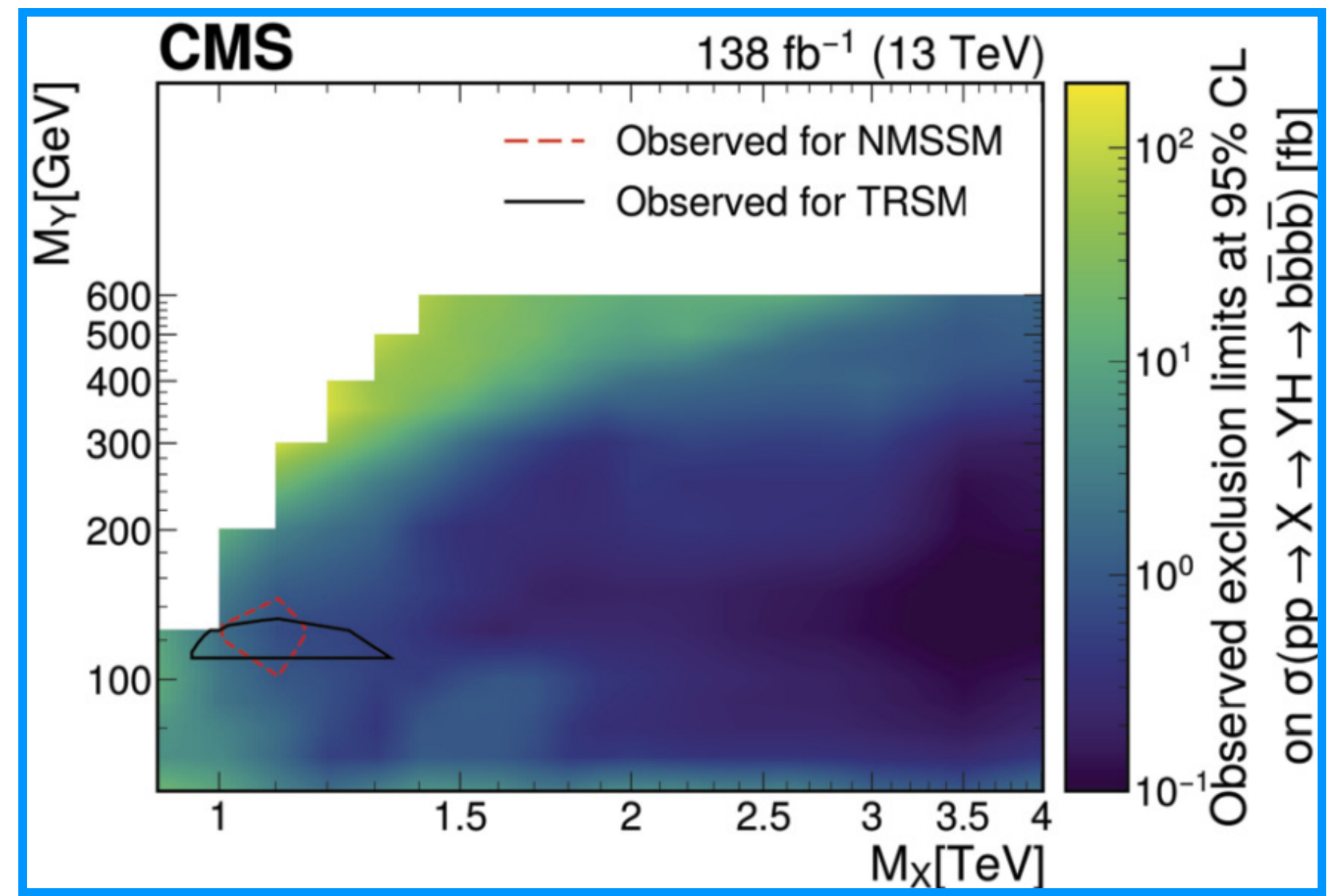




# $X \rightarrow HY \rightarrow 4b$ **Resonant**



- $t\bar{t}$  bkg. w/ 3 categories: fully-merged  $bqq$ , semi-merged  $bq$  and other
  - estimated from MC + corrections based on leptonic data regions
- QCD estimated in 2D regions of PNet score for  $H/Y \rightarrow bb$  candidates
  - not the same regions used for  $t\bar{t}$
  - PNet provides 4x improvement in bkg. rejection over DeepJet-MD
- Signal extraction via fit to inv. mass of two leading AK8 jets and soft drop mass of "Y-jet"

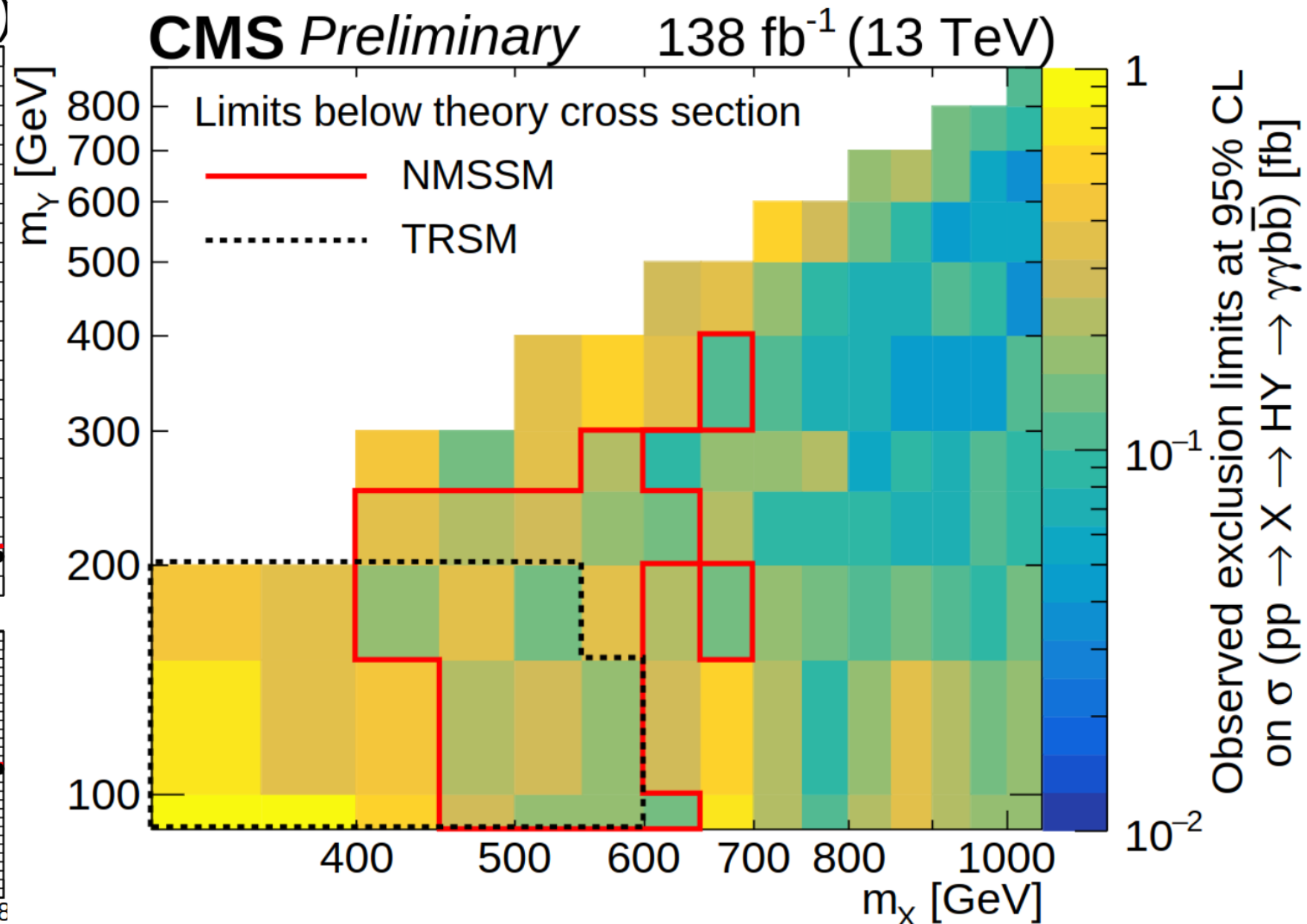
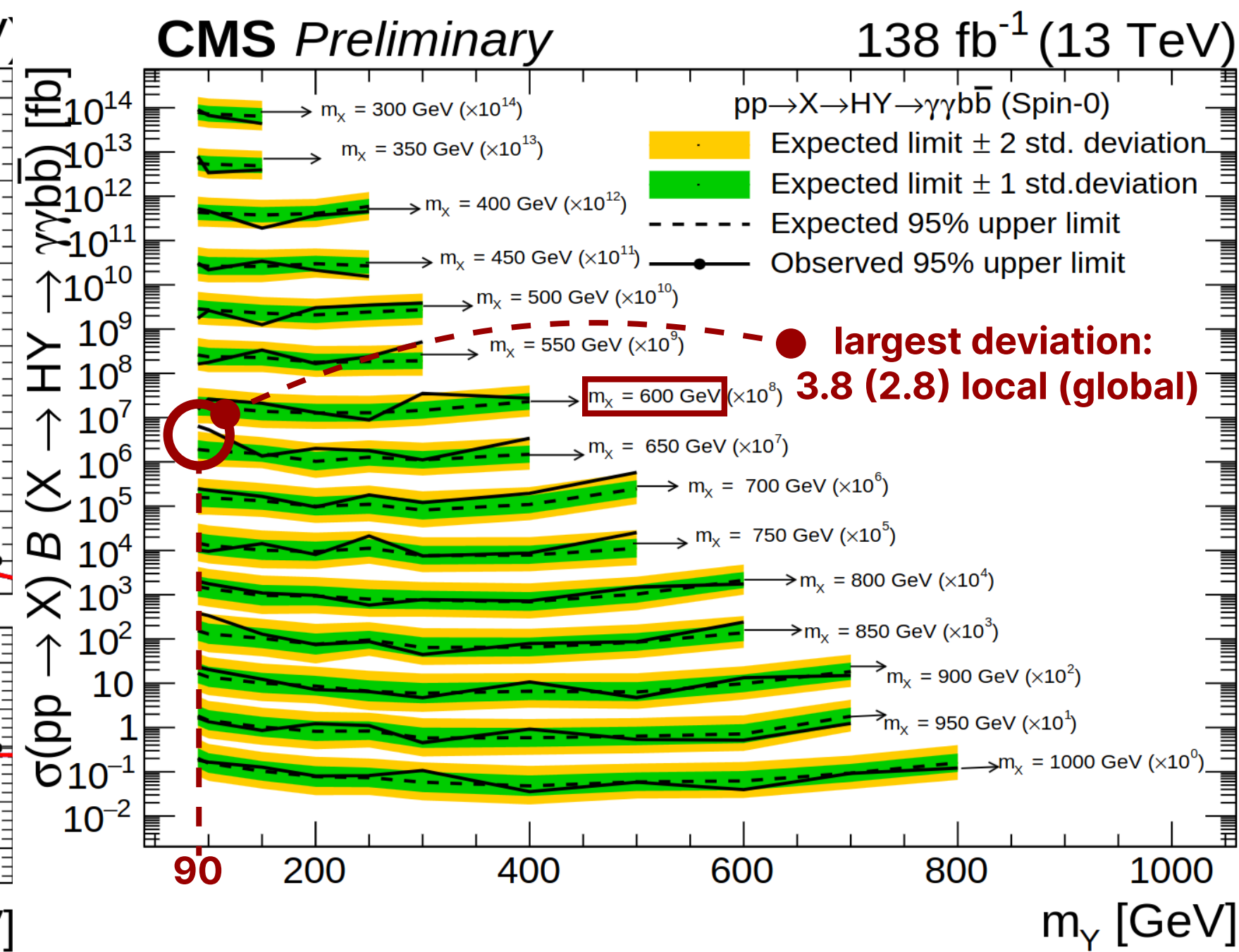
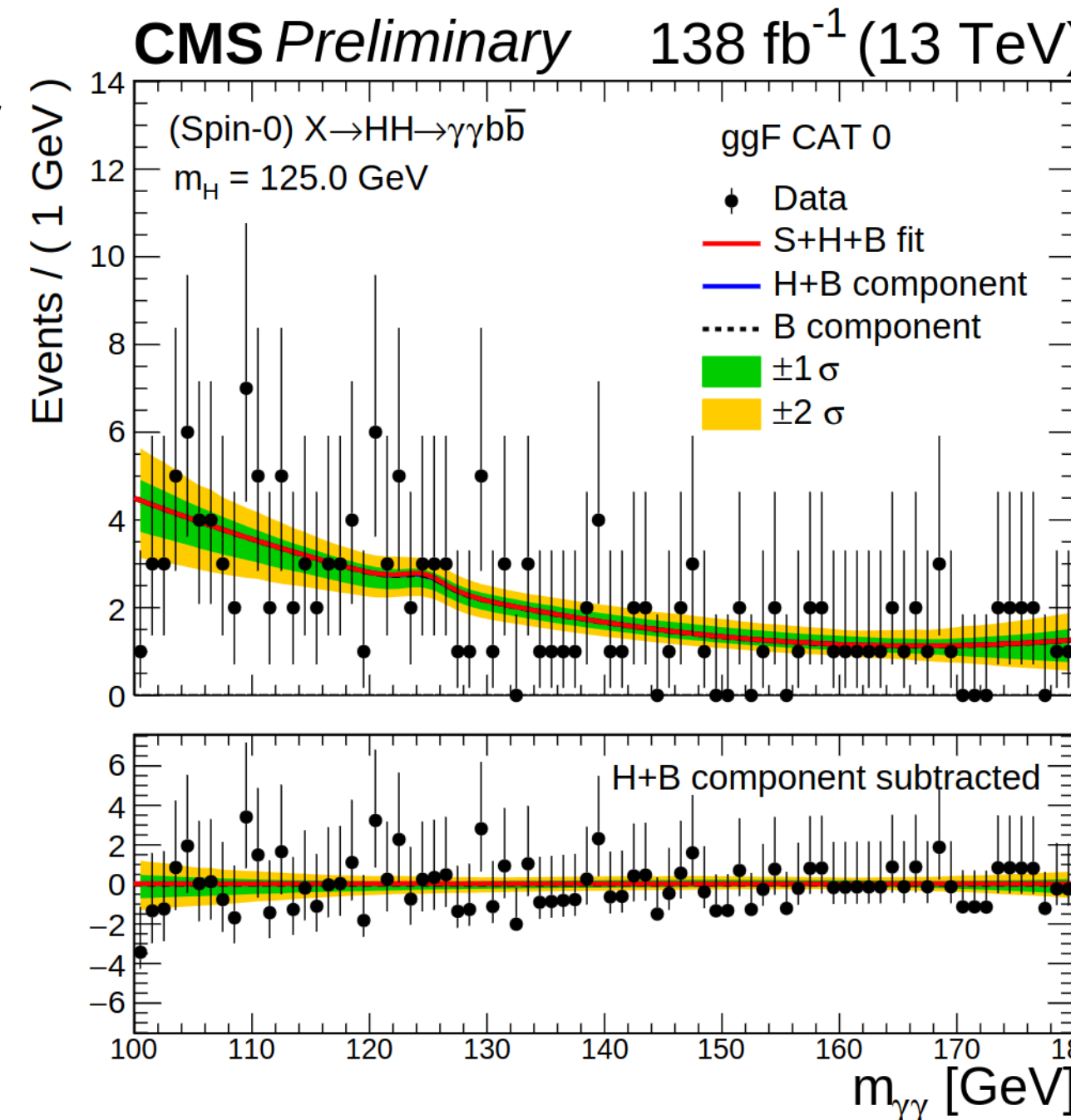
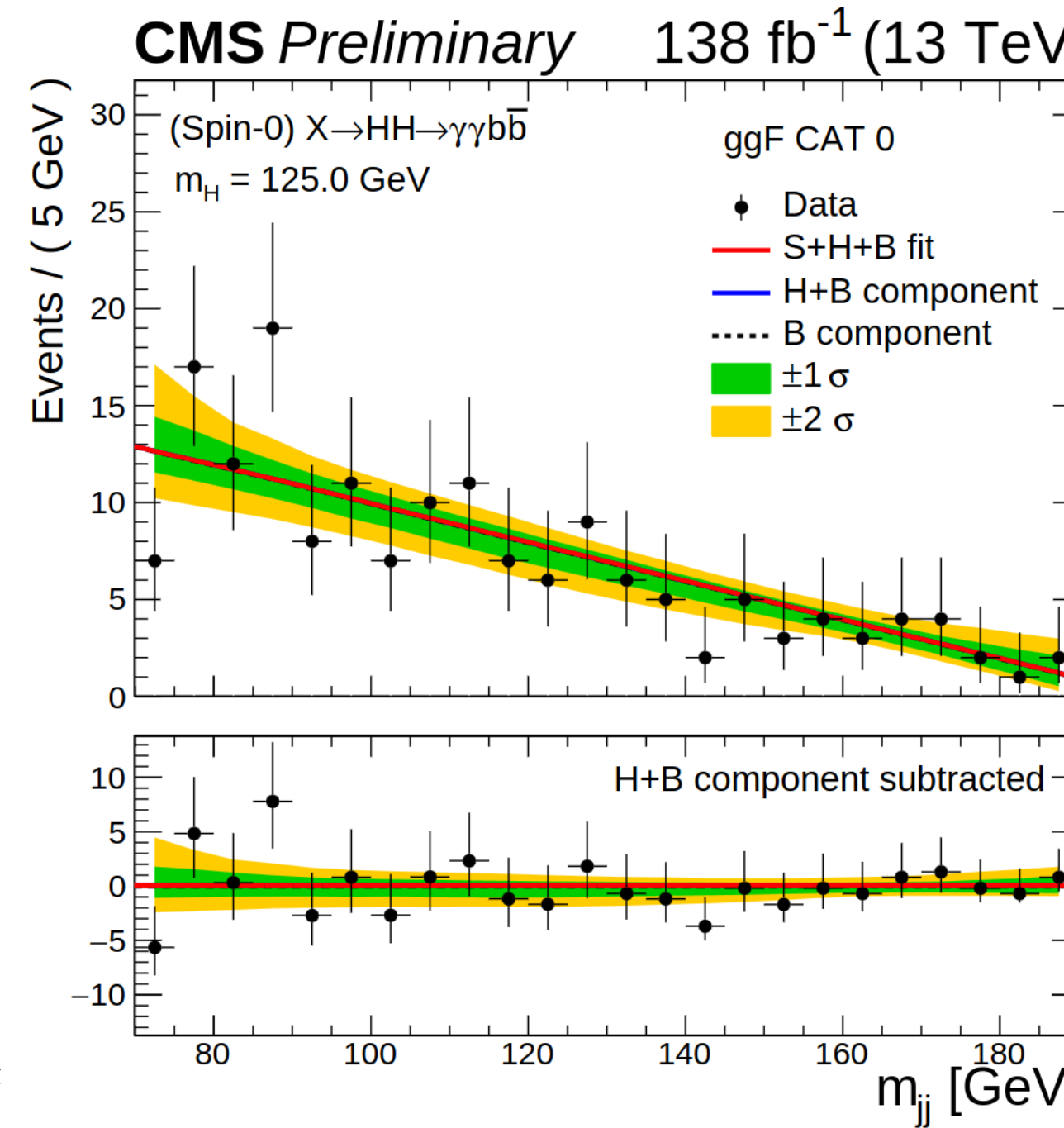




# $X \rightarrow HH / Y \rightarrow bb \gamma \gamma$

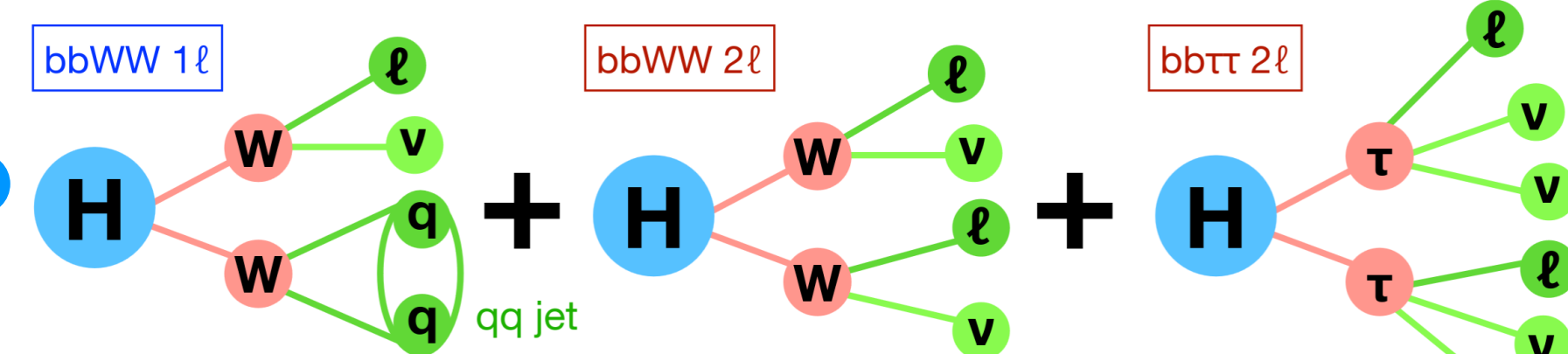
**Resonant**

- ttH-killer removes resonant background
- Use  $m_{jj\gamma\gamma} - m_{jj} - m_{\gamma\gamma}$  instead of  $m_{jj\gamma\gamma}$
- Multiclass BDT discriminates signal from non-res. bkg. in 6 different  $m_X / m_Y$  ranges
  - defined based on “boost factor”\*
- Categories are defined by maximizing the Punzi FOM on top of the BDT’s output
- Signal extracted from unbinned 2D  $m_{\gamma\gamma}$  vs.  $m_{bb}$  parametric fit
  - $m_{\gamma\gamma}$ : sum of gaussians
  - $m_{jj}$ : double crystal-ball + gaussian
  - polynomials, exp. or power law for background



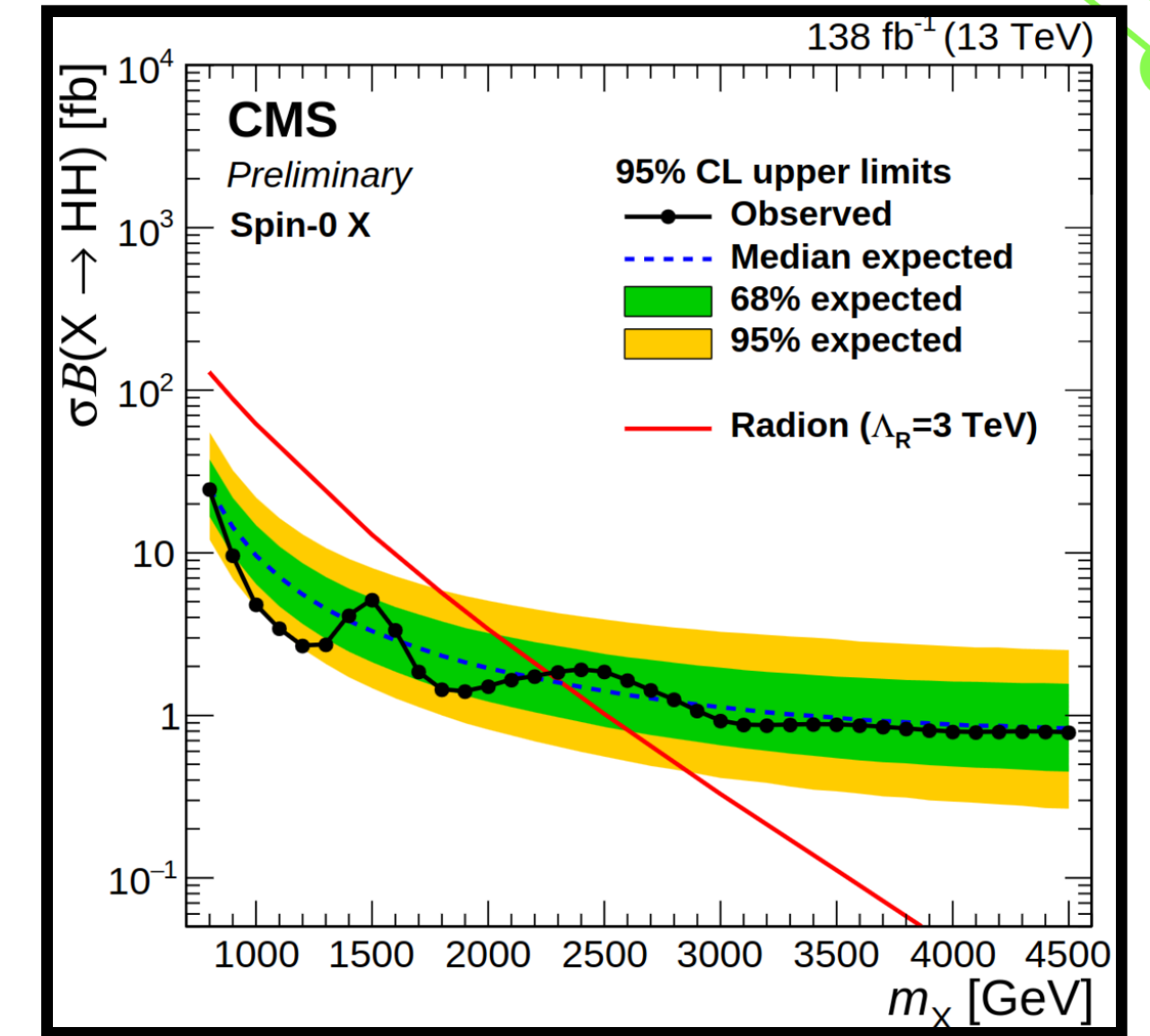
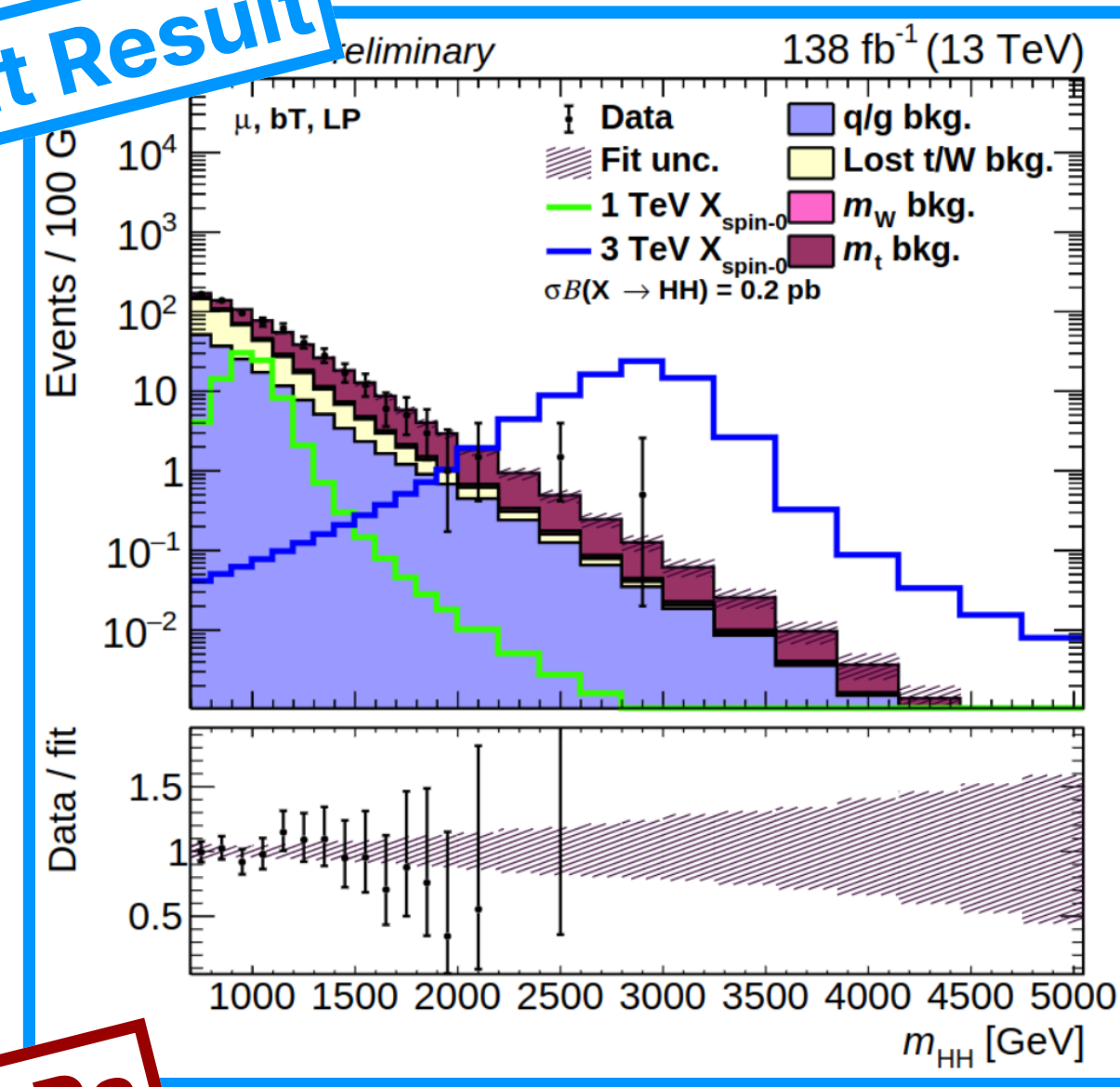


# $X \rightarrow HH \rightarrow bb + \text{leptons}$ (boosted) **Resonant**

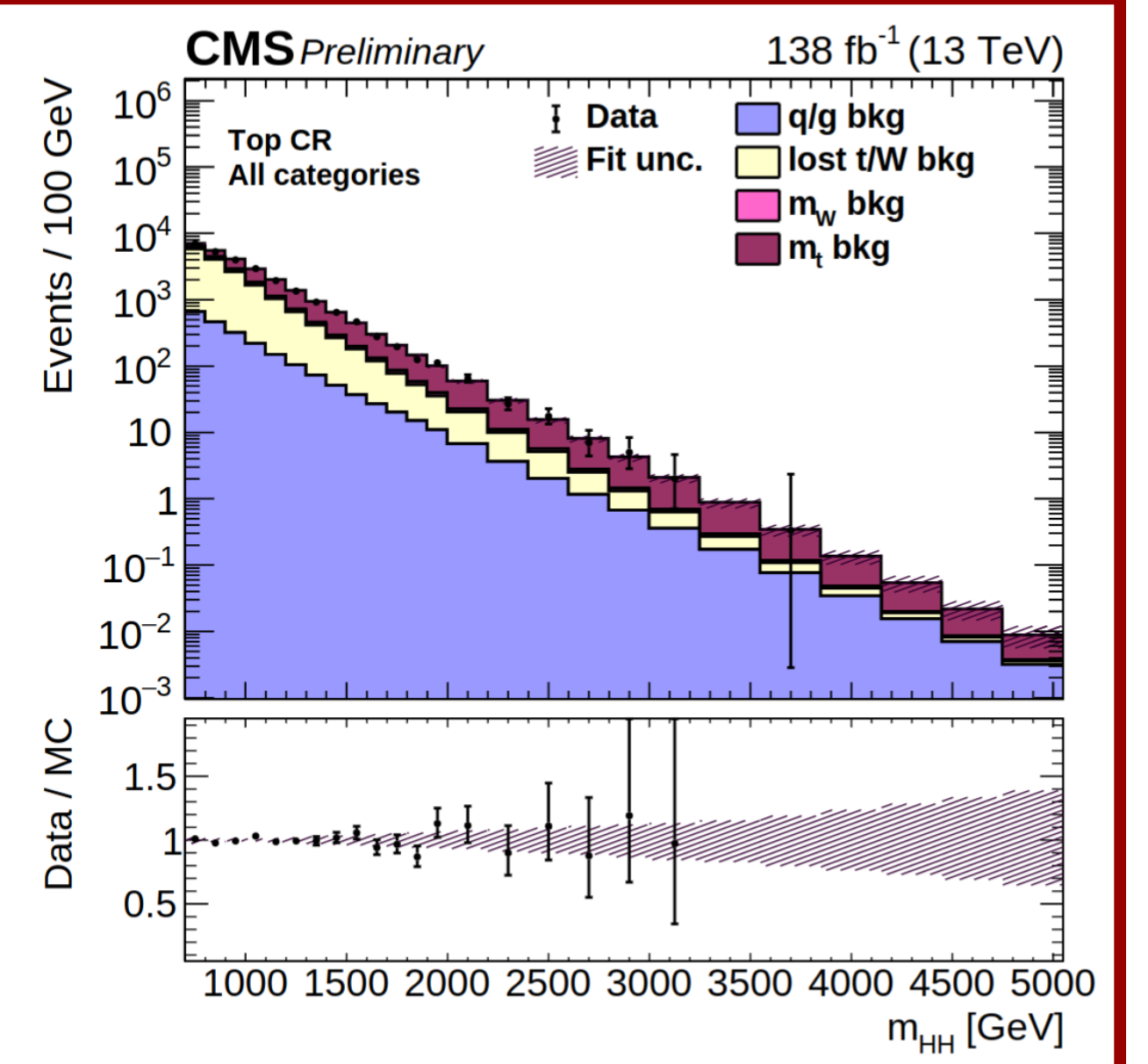
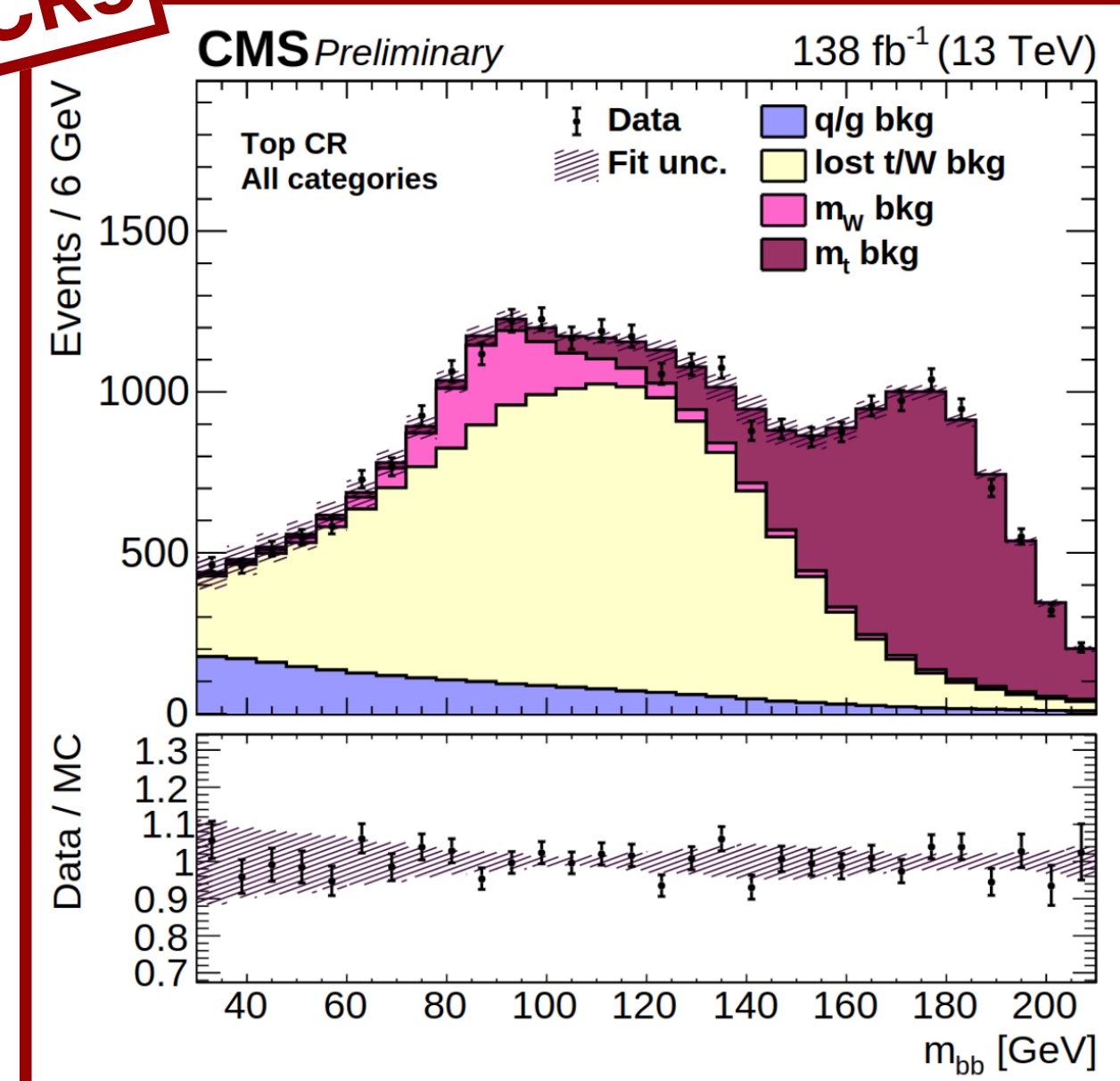


- Covers 2 final states:
  - bbWW\*  $\rightarrow$  bb $\ell\nu$ qq
  - bbWW and bb $\tau\tau \rightarrow$  bb $\ell\ell$  (cleaner)
- Bkgs.: ttbar, QCD, W/Z+jets
- H  $\rightarrow$  bb w/ AK8 jet + substructure
- No W\* mass constraints since it is off-shell
- Categorize based on DeepAK8-MD WPs
  - 1 $\ell$  channel: add N-subjetiness categ.
- 4 indep. bkg. component templates based on #gen quarks within  $\Delta R < 0.8$  of the bb jet:
  - $m_t$  bkg.: 3 quarks (from top decay)
  - $m_W$  bkg.: 2 quarks (from W/Z decay)
  - lost t/W bkg.: 1 quark
  - q/g bkg.: 0 quarks
- 2 CRs w/ and wo/ top contribution
- Simultaneous 2D fit in the  $m_{bb} - m_{HH}$  plane

**Fit Result**



**CRs**

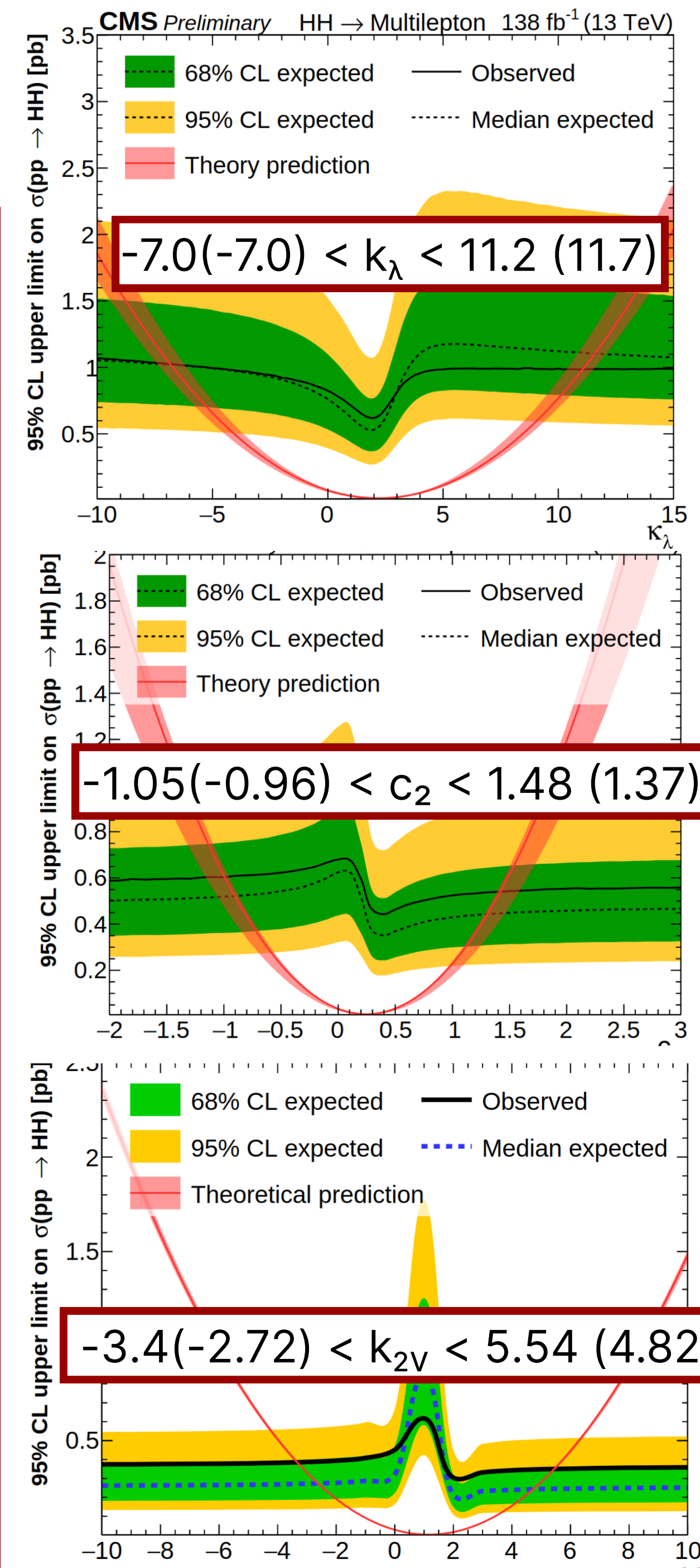
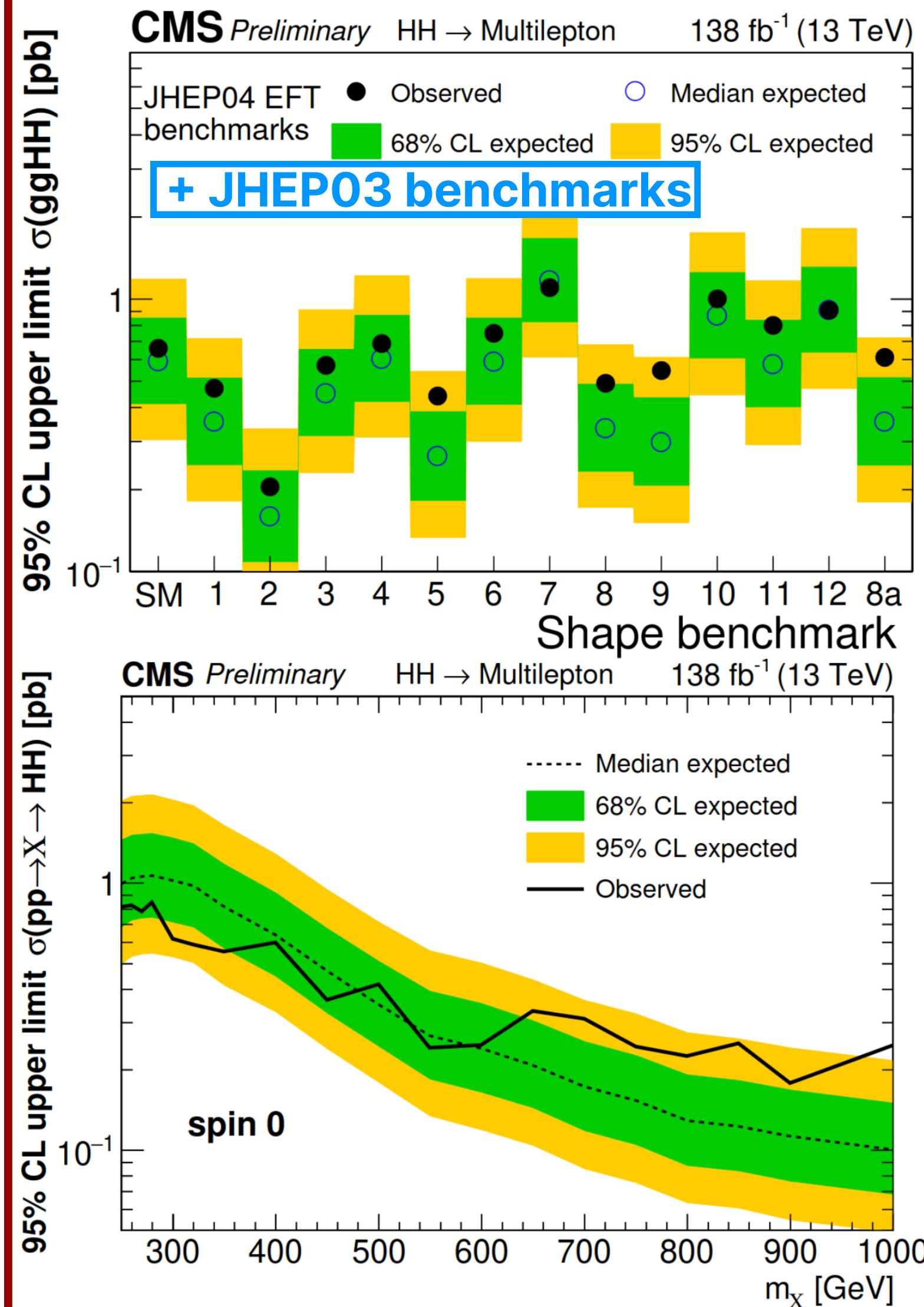




# HH → Multilepton (4V, 2V2τ, 4τ) ggF VBF Res

- 7.7% BR in total
- **7 channels**, depending on multipl. of hadronic τ, electrons and muons
- Train 3 BDTs (spin0/2, nonres) per channel, parameterized on EFT benchmarks and resonance mass
- Background estimation
  - fakes: **fake factor method**
  - **lepton charge flip**: from data
  - irred. + photon conversion: from MC
- ML fit inputs: **1 BDT / channel + 2 CRs**
  - full stats used for BDT training
- 2 CRs to constrain WZ and ZZ bkg.

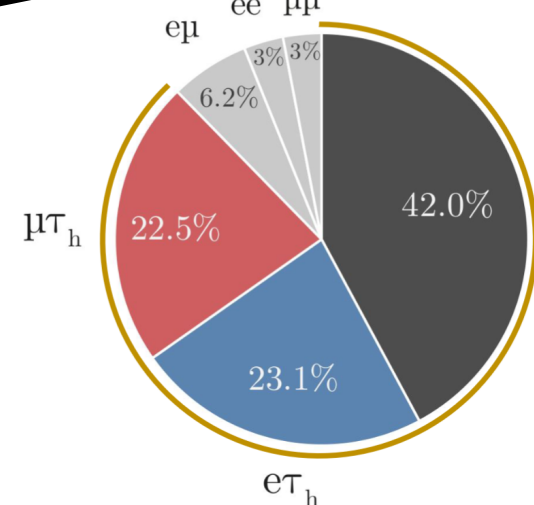
$$\sigma_{HH} < 21.8 \text{ (19.6)} < \sigma_{HH}^{\text{SM}}$$



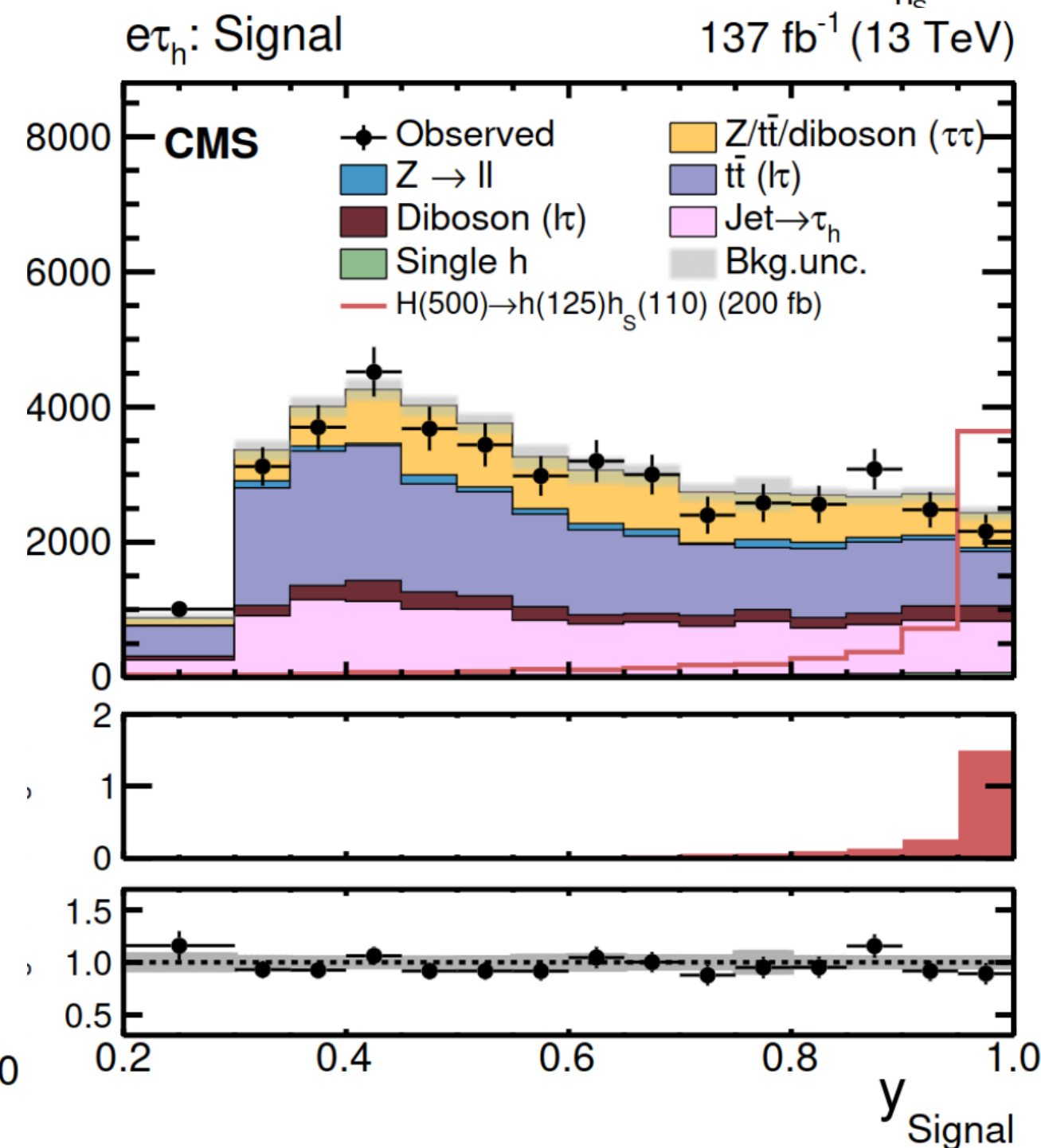
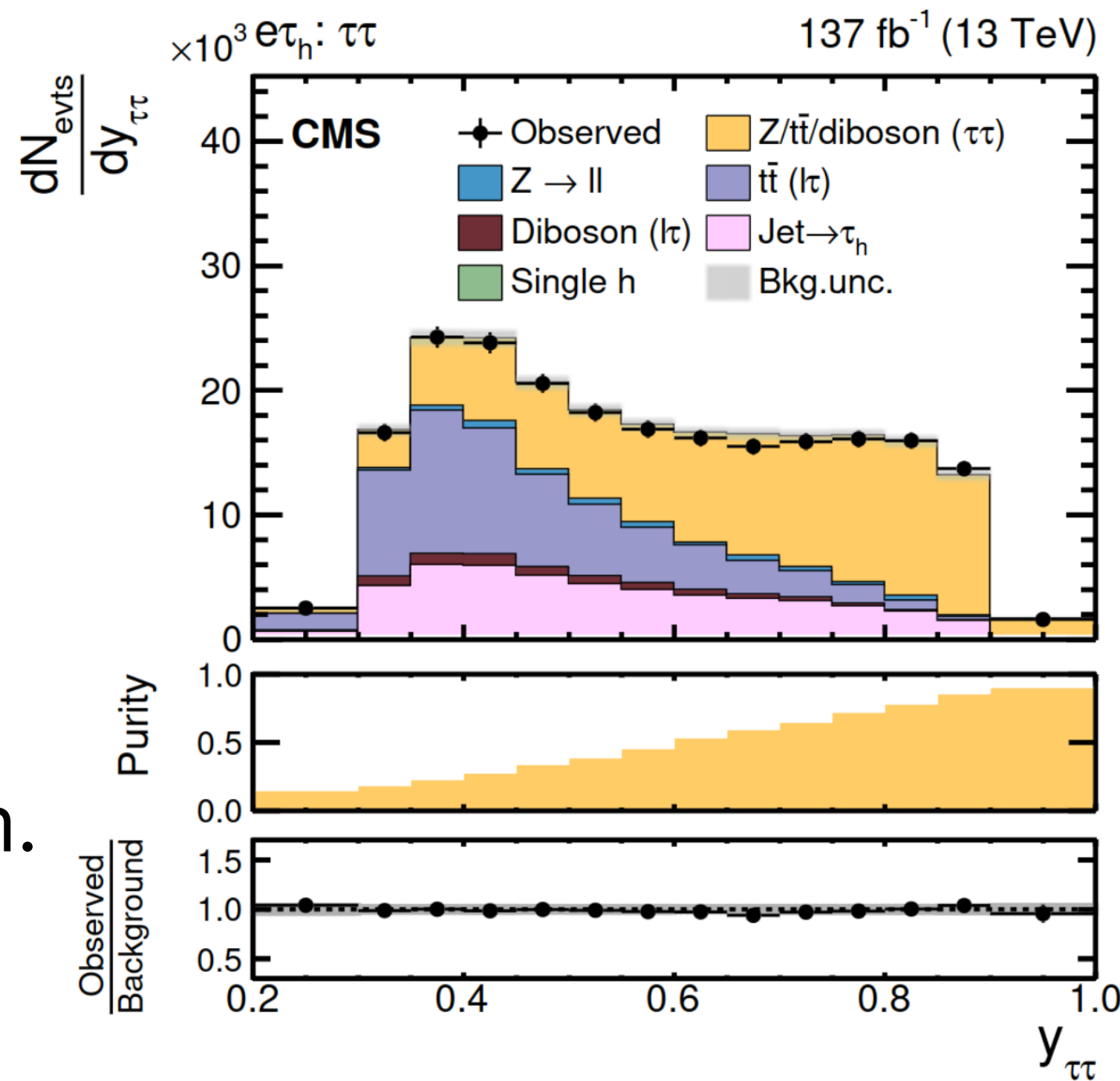
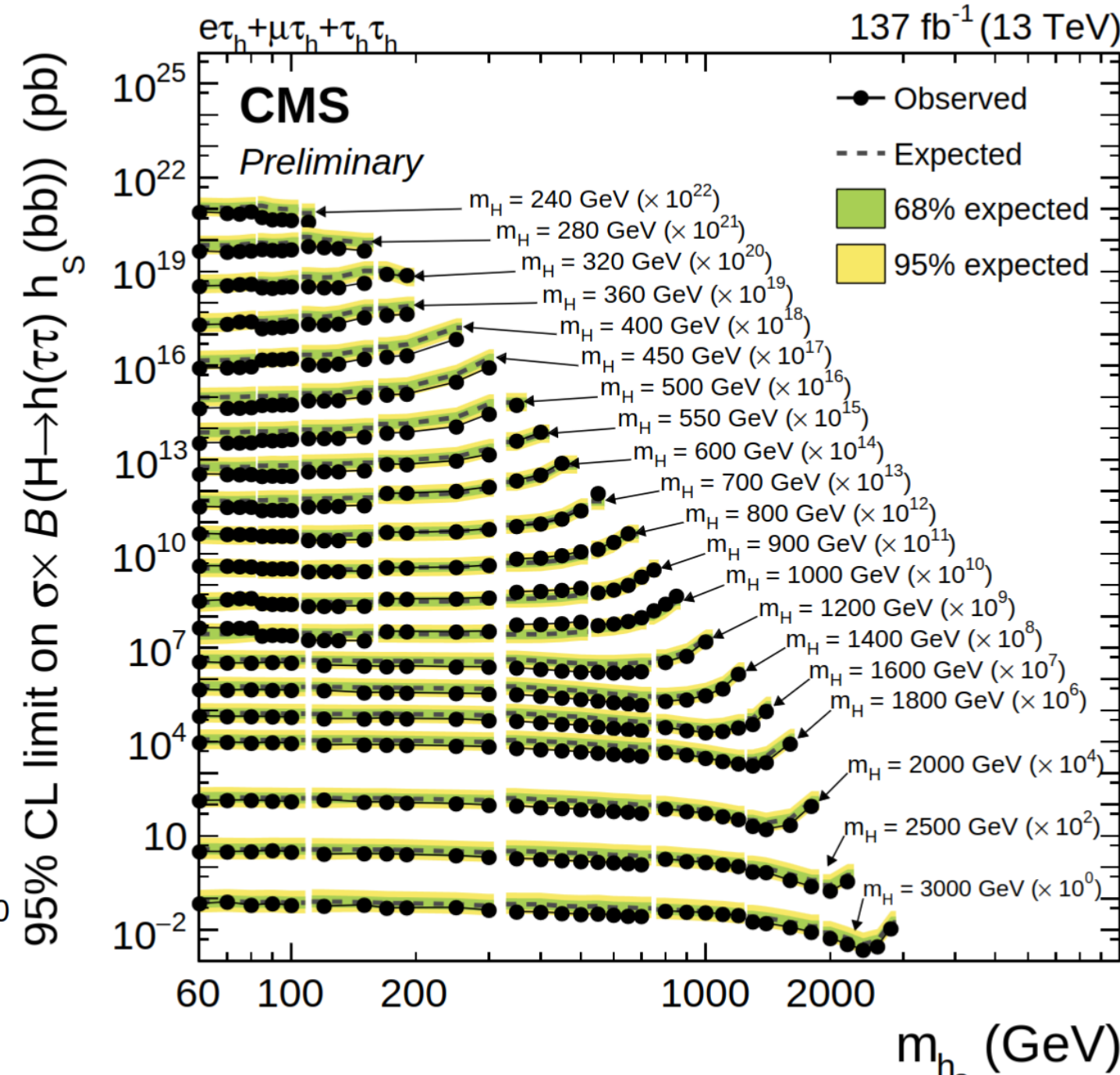
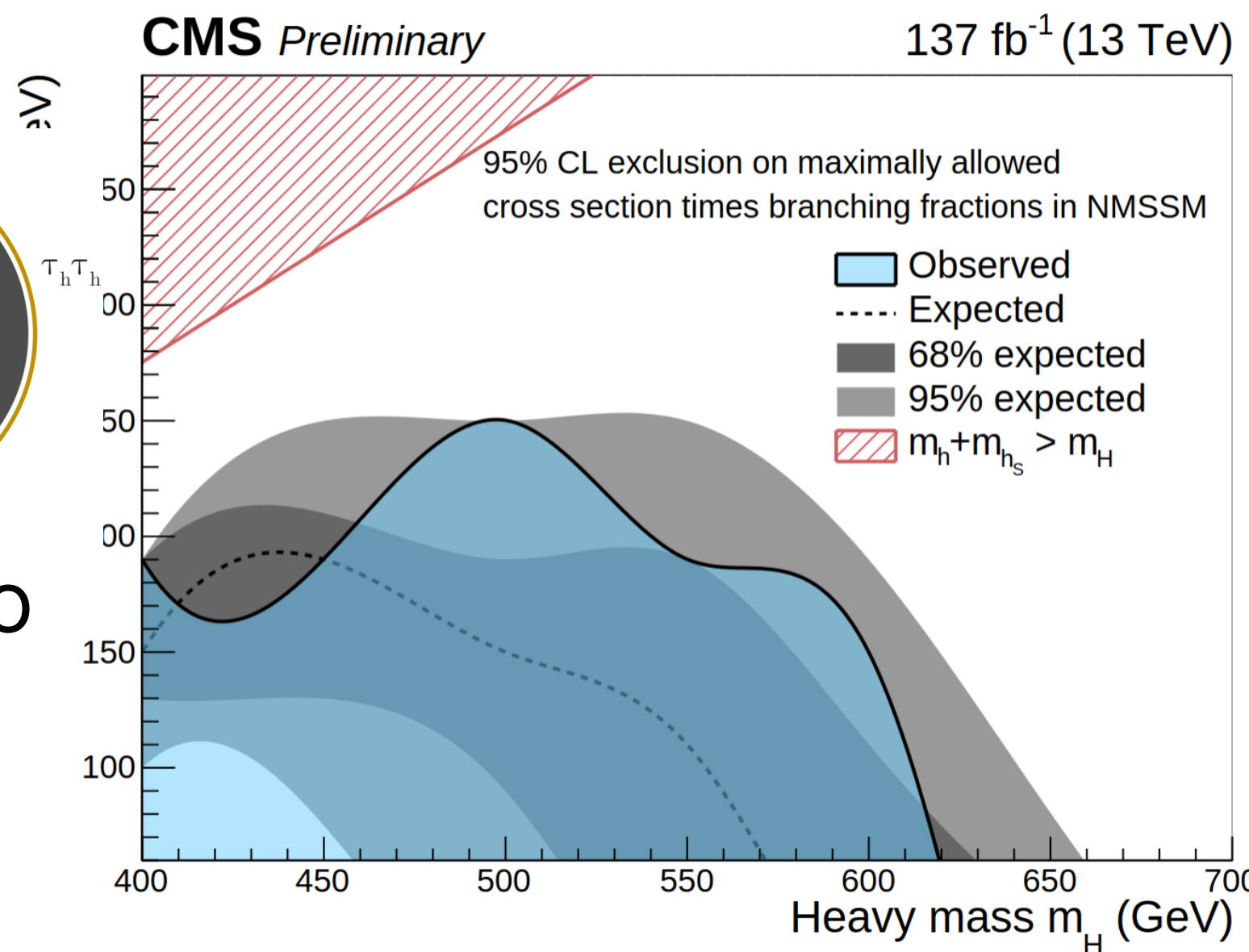


# $X \rightarrow HY \rightarrow bb\tau\tau$

**Resonant**



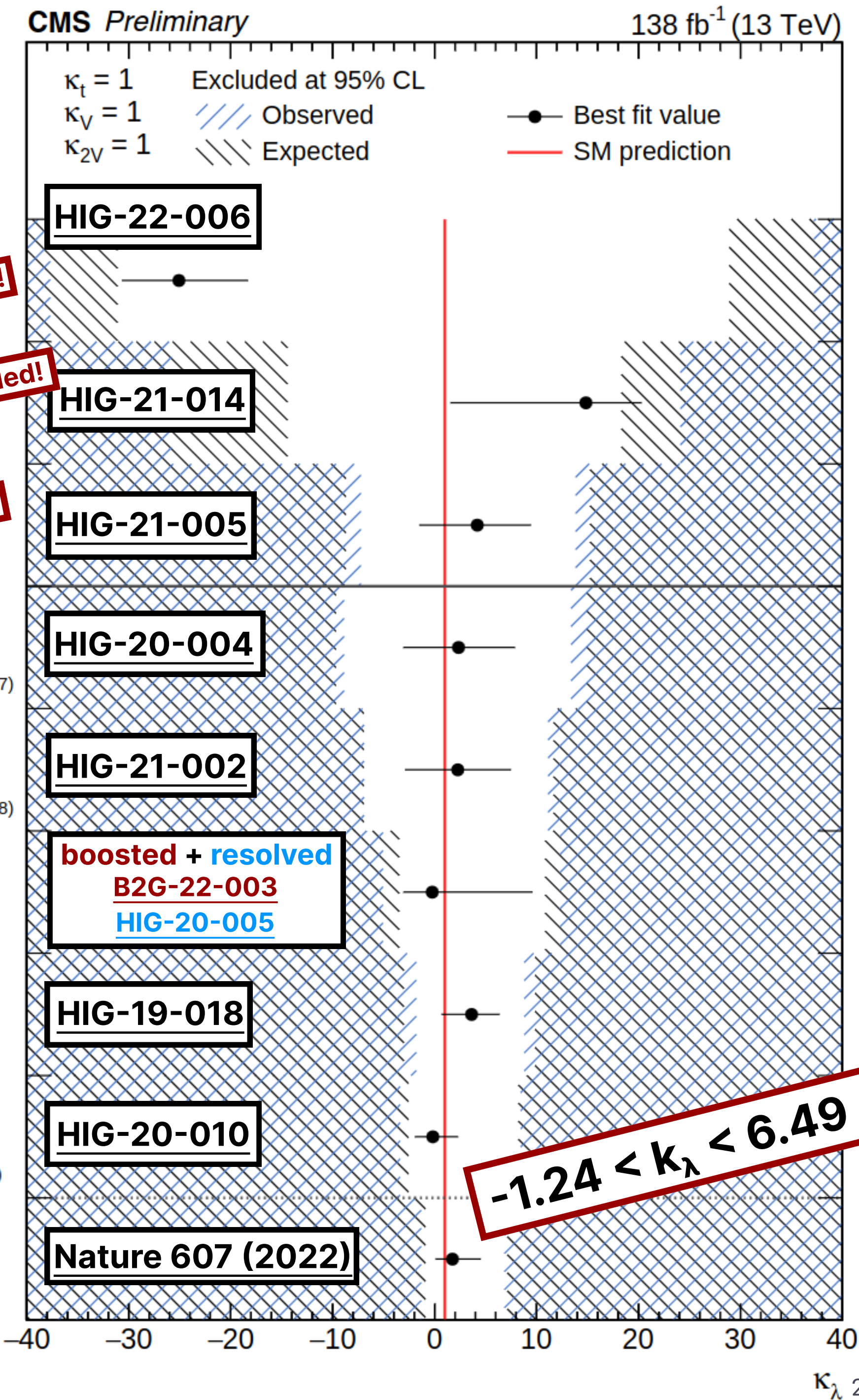
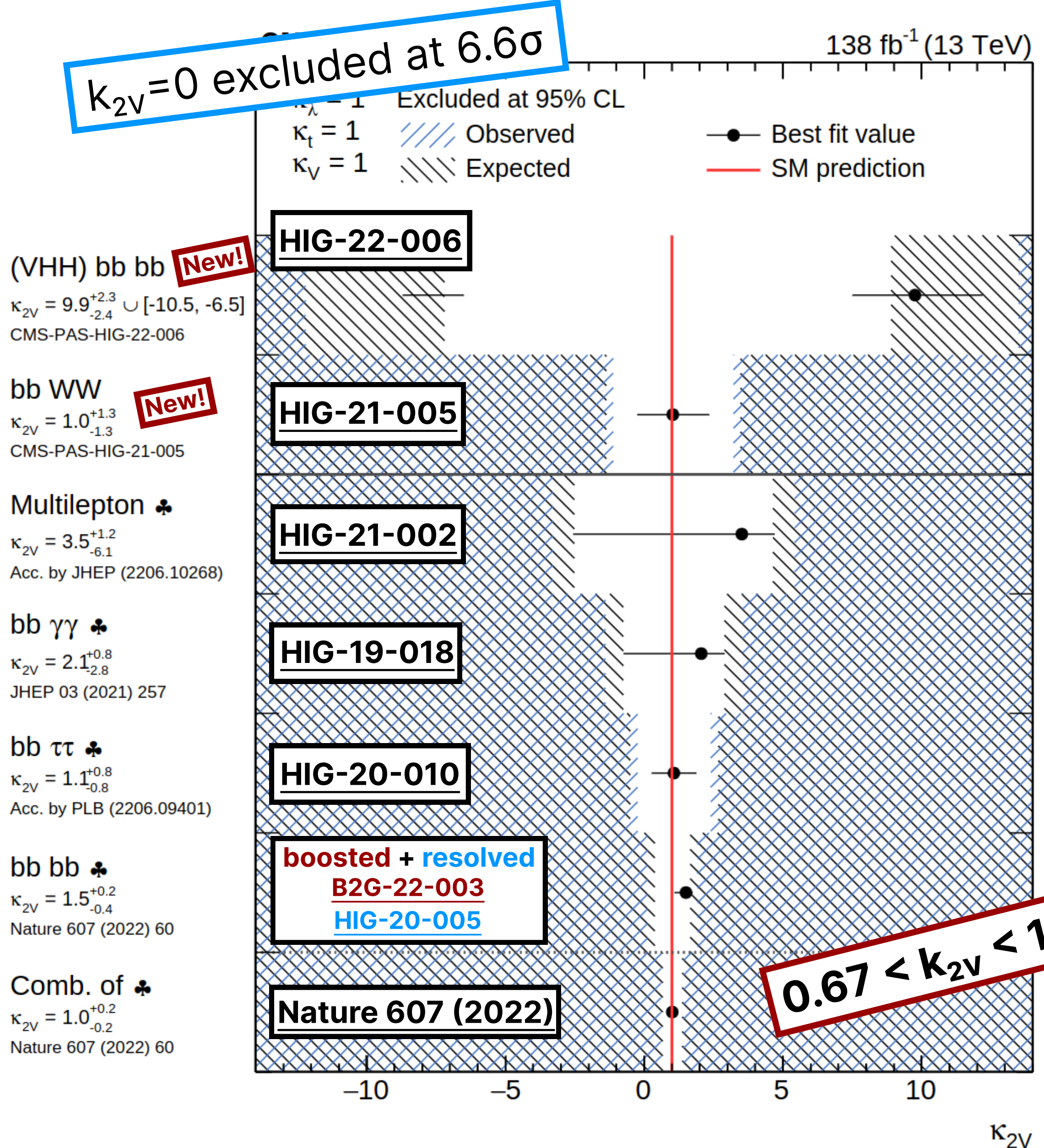
- $e\tau_h$ ,  $\mu\tau_h$  and  $\tau_h\tau_h$  channels
- At least one DeepJet b-jet
- $bb\tau\tau$  mass kin. fit\* w/  $m_{\tau\tau}=125$  GeV to estimate  $\tau$  energies before decay
  - improved reco  $m_{bb\tau\tau}$  resolution
- Background estimation:
  - **data-driven  $\tau$ -embedding<sup>†</sup>** for Z / tt / diboson  $\rightarrow \tau\tau$  (genuine  $\tau$ 's)
  - **transfer factors<sup>††</sup> for jet $\rightarrow\tau_h$  misid** (QCD, W+jets and tt) based on DeepTau WPs and MC for the rest (single H, Z / tt / diboson  $\rightarrow$  prompt e or  $\mu$ )
- Multiclass DNN as binned final discrim.
  - 5 categ.: signal,  $\tau\tau$ , tt, jet $\rightarrow\tau_h$ , other
  - **68 indep. trainings** to avoid perform. loss due to many mass hypothesis



\*adapted from [this](#) <sup>†</sup> $\tau$ -embedding <sup>††</sup>as described [here](#)

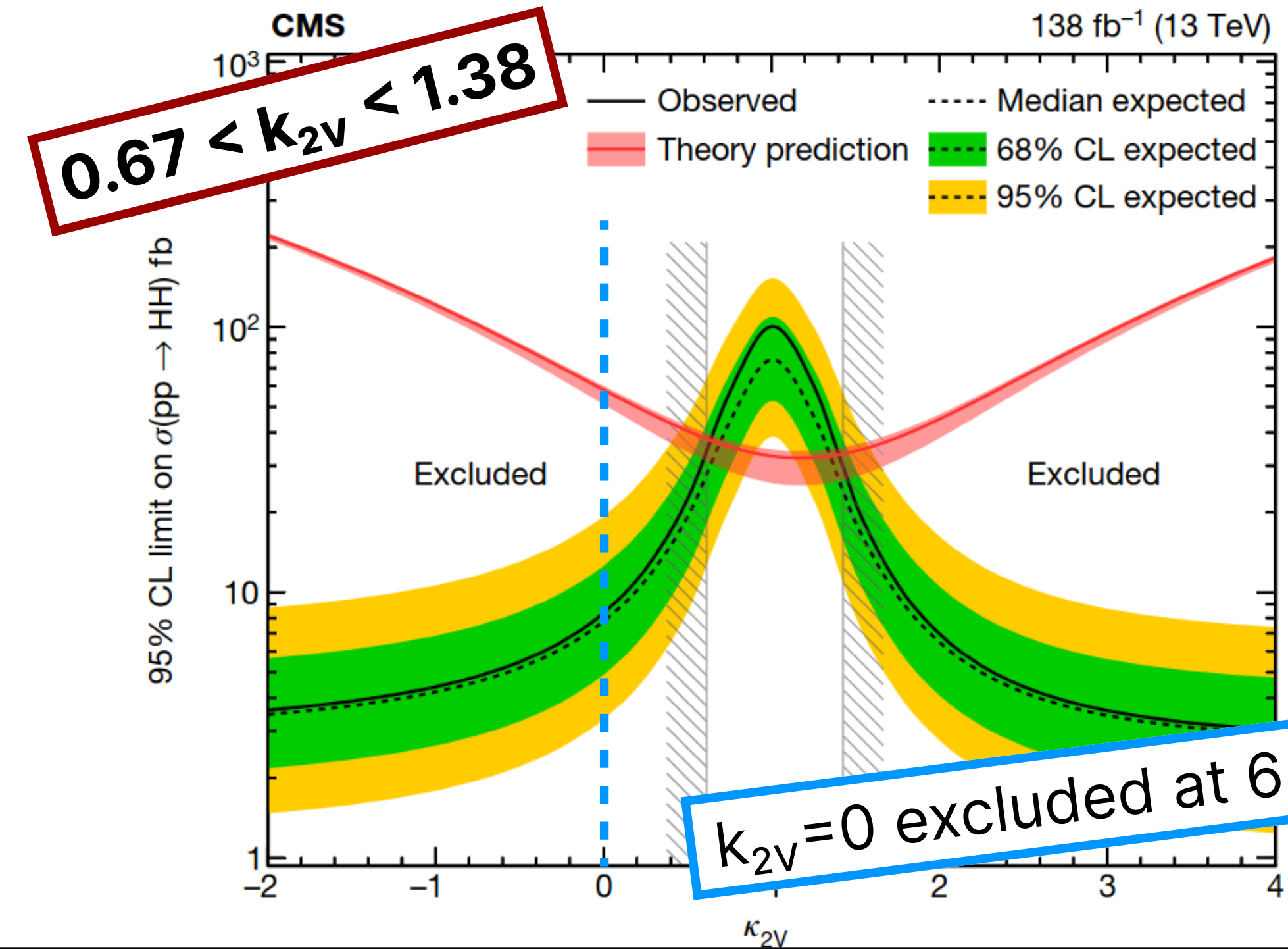
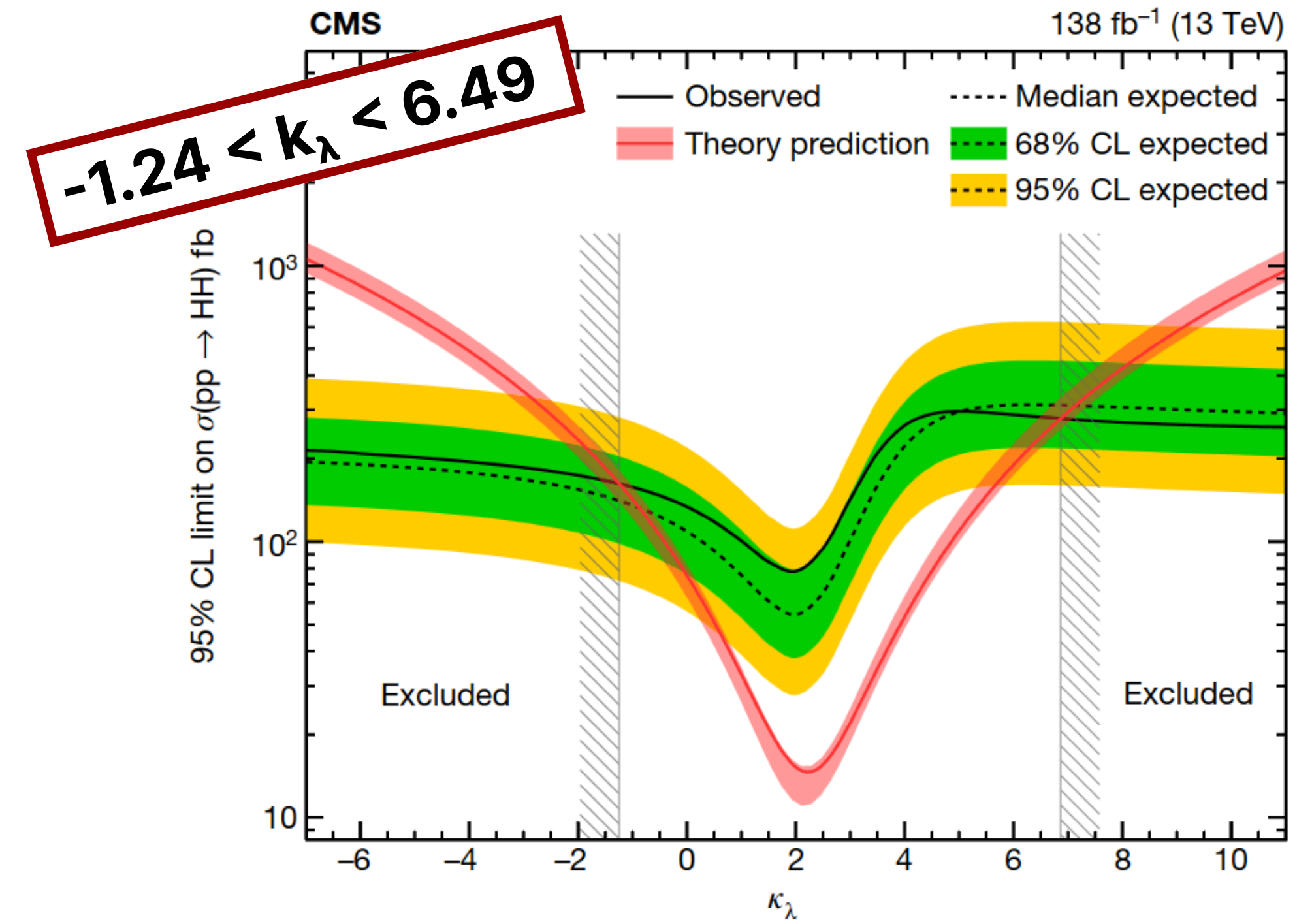
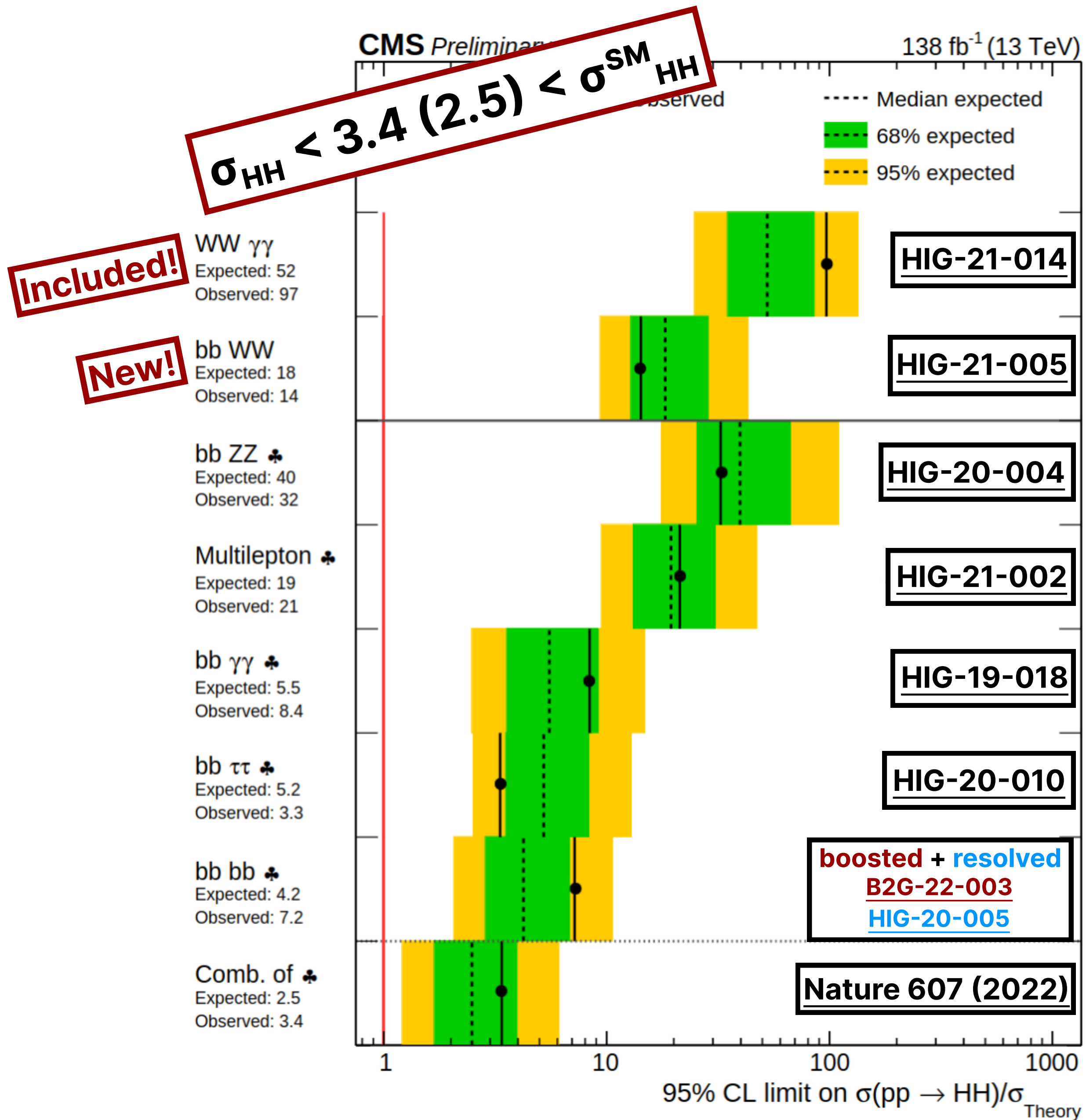


# CMS Internal links





# CMS Internal links





# CMS Internal links

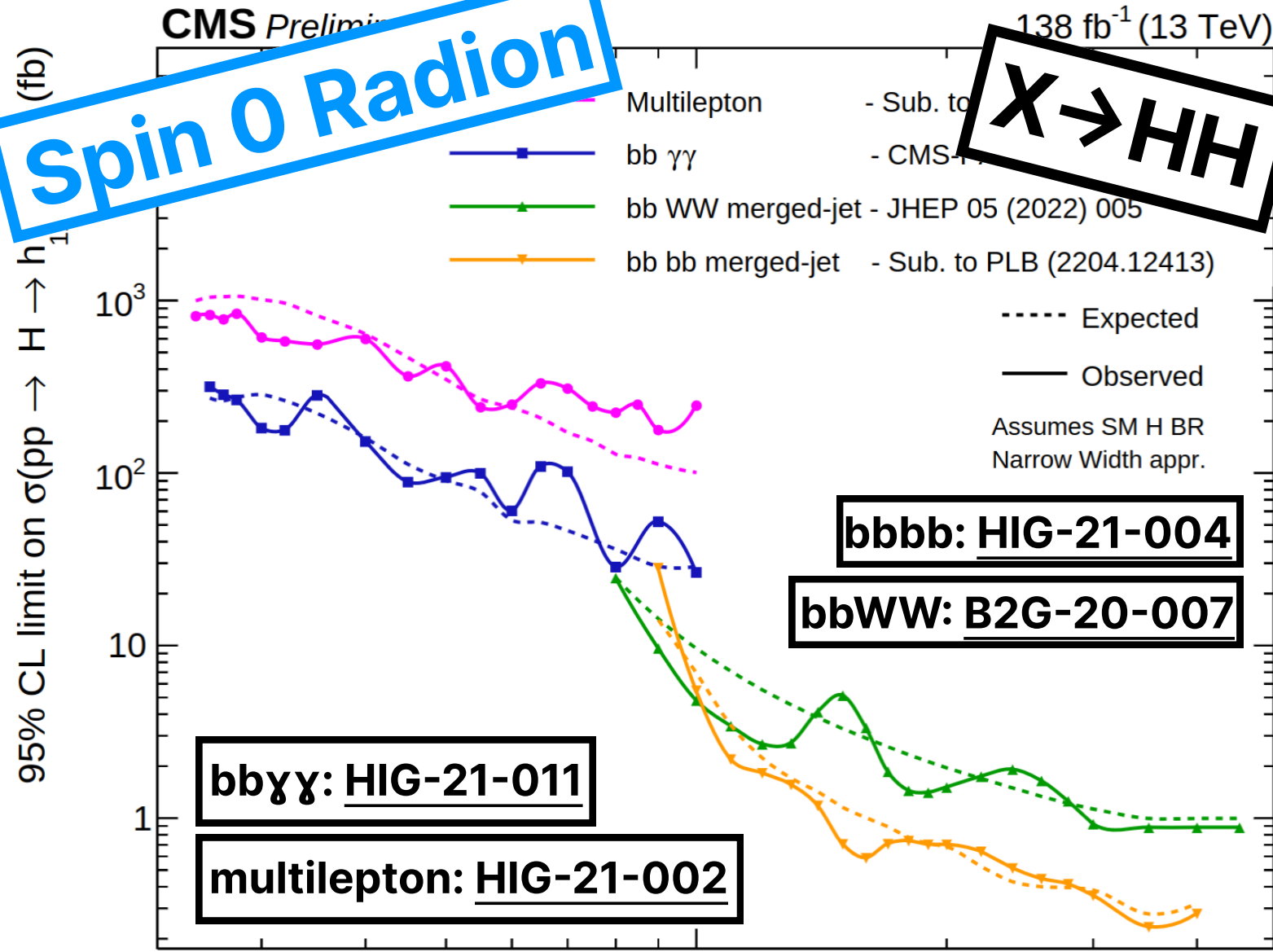
**ggF**

**bbγγ: HIG-21-011**

**bbττ: HIG-20-014**

**bbbb: B2G-21-003**

**Spin 0 Radion**



**Spin 2 Graviton**

