Di-Higgs Searches @ CMS

Bruno Alves, for the CMS Collaboration

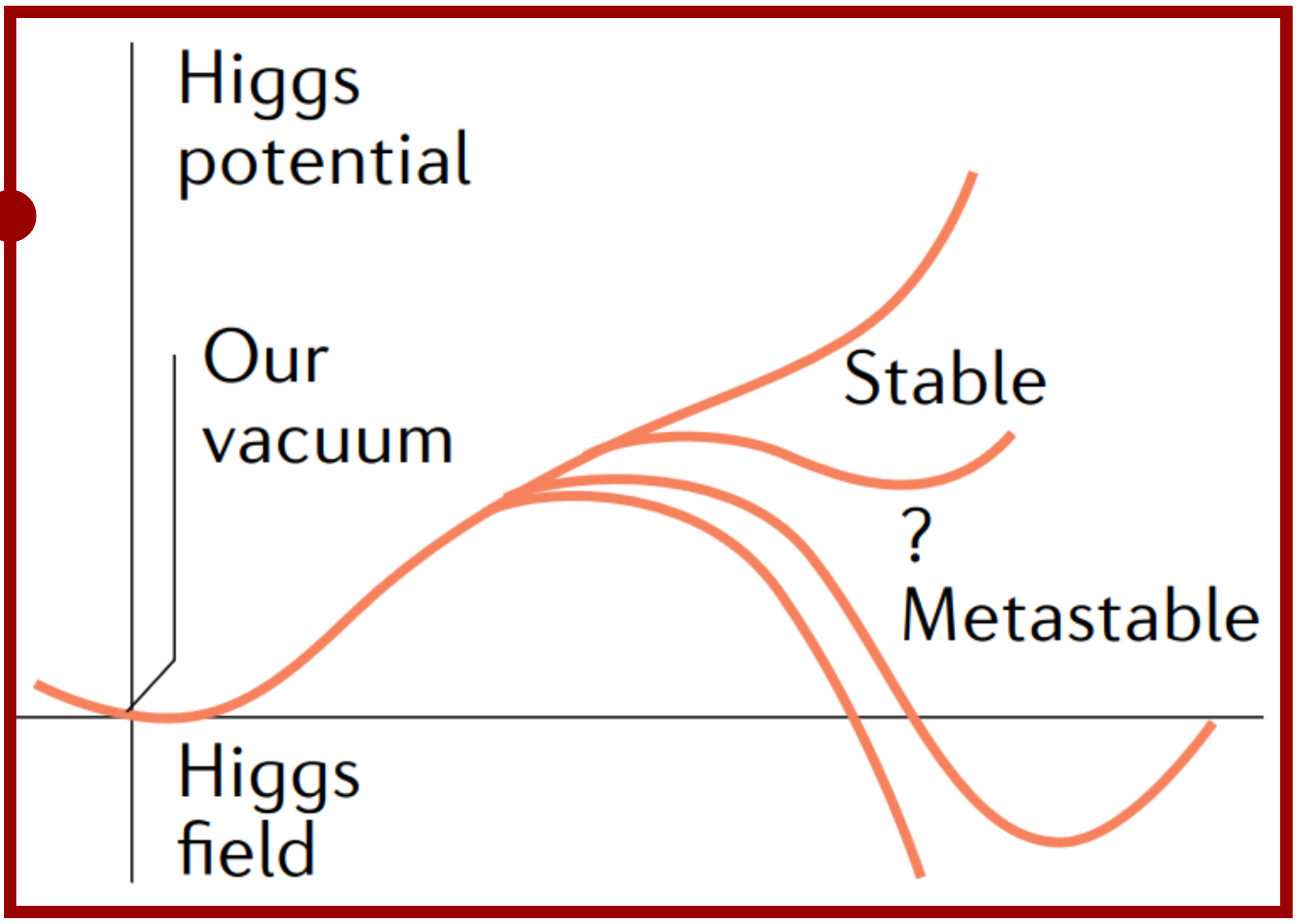
Indico

9/04/2024

DIS Grenoble

Motivation: HH non-res. searches

Nature Reviews Physics, volume 3, pages 608–624 (2021)



Measurement of the Higgs boson self-interaction

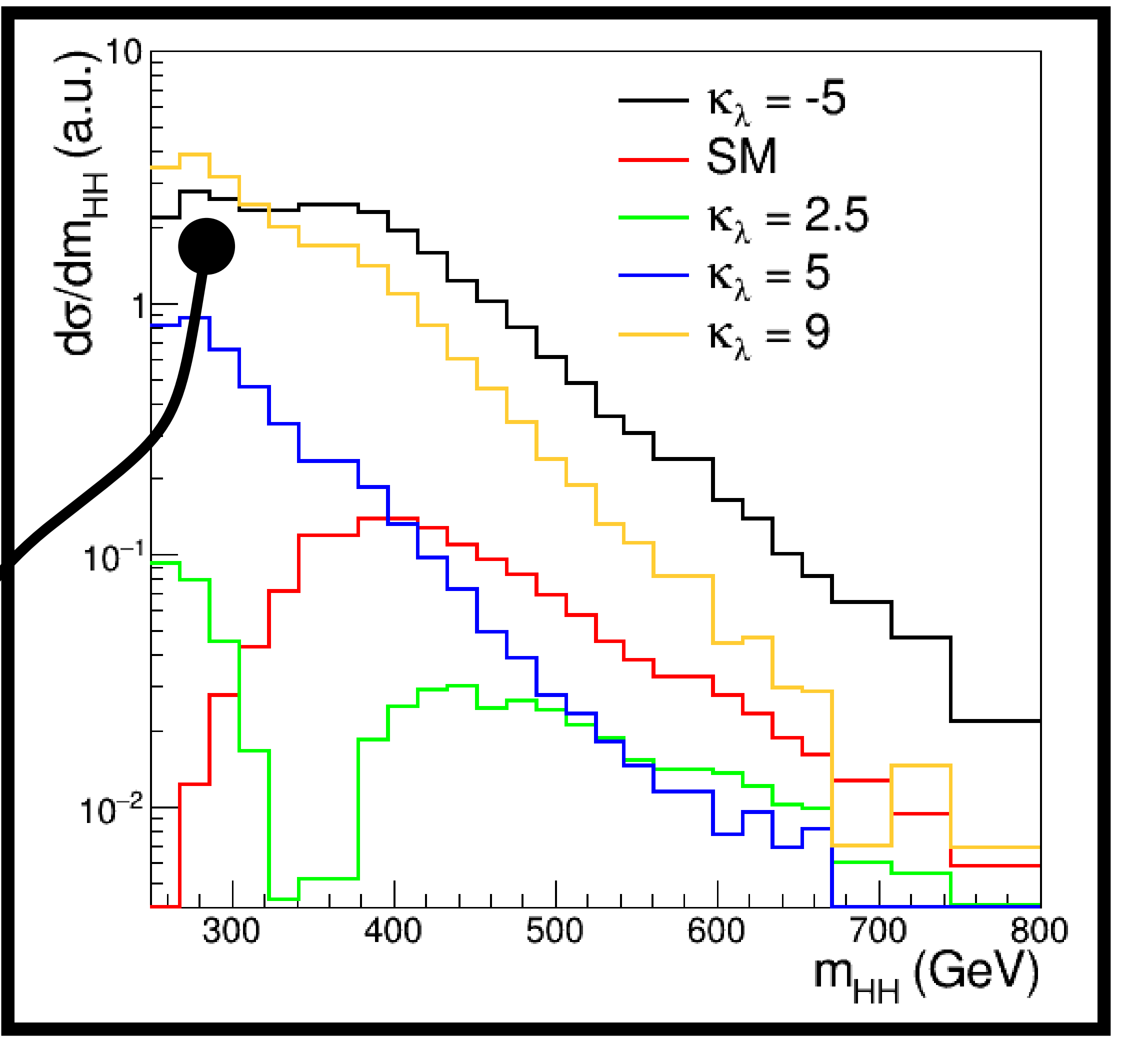
- test vacuum stability
- SM closure: λ_{HHH} is not free!
- deviations can explain baryogenesis

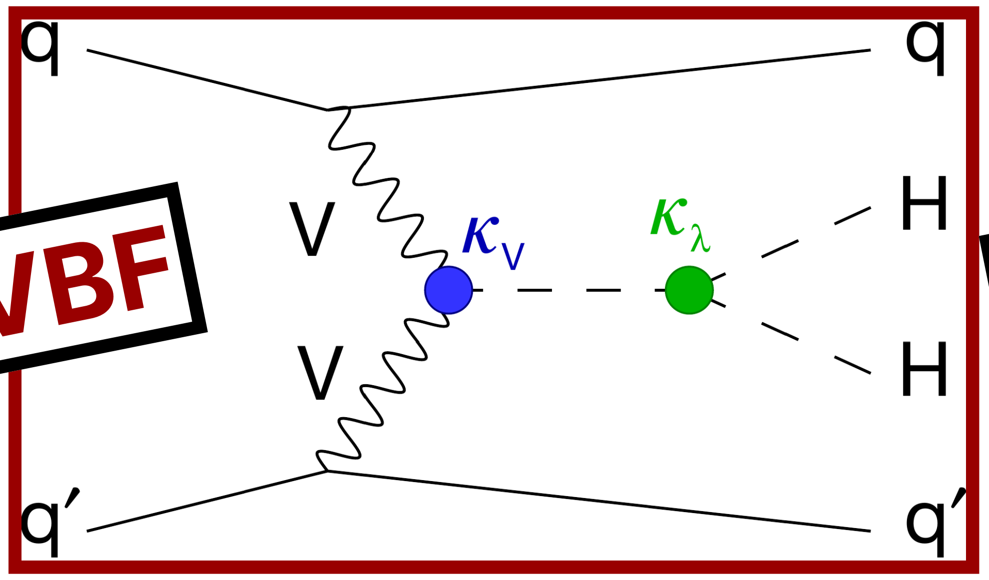
$$\lambda_{HHH}^{SM} = \frac{m_H^2}{2v^2} \simeq 0.13$$

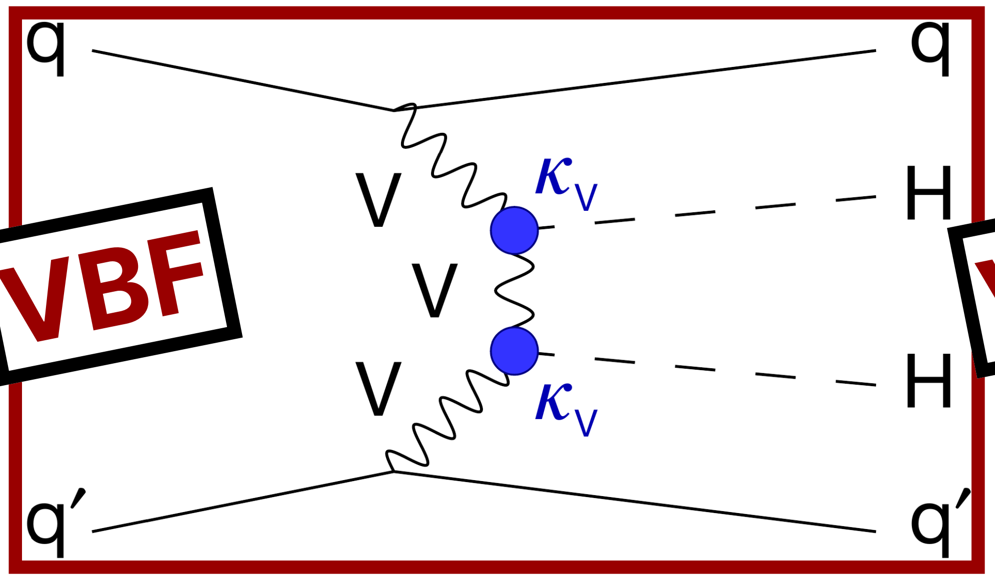
Test BSM w/ anomalous couplings: k_λ, k_t, k_V, k_{2V}

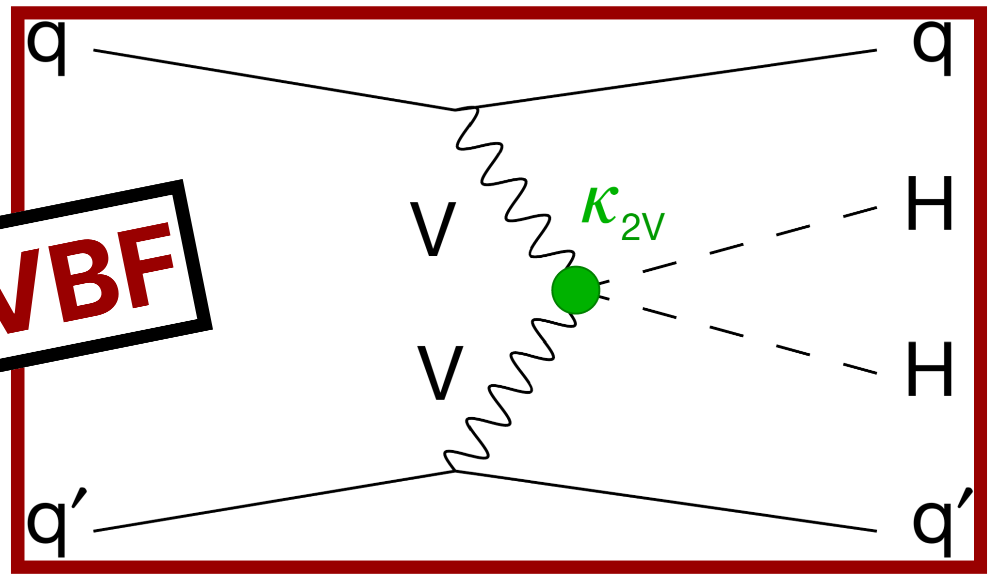
- deviations may lead to diffs. in HH production rates and kinematics
- small SM HH cross-section because of △-□ interference

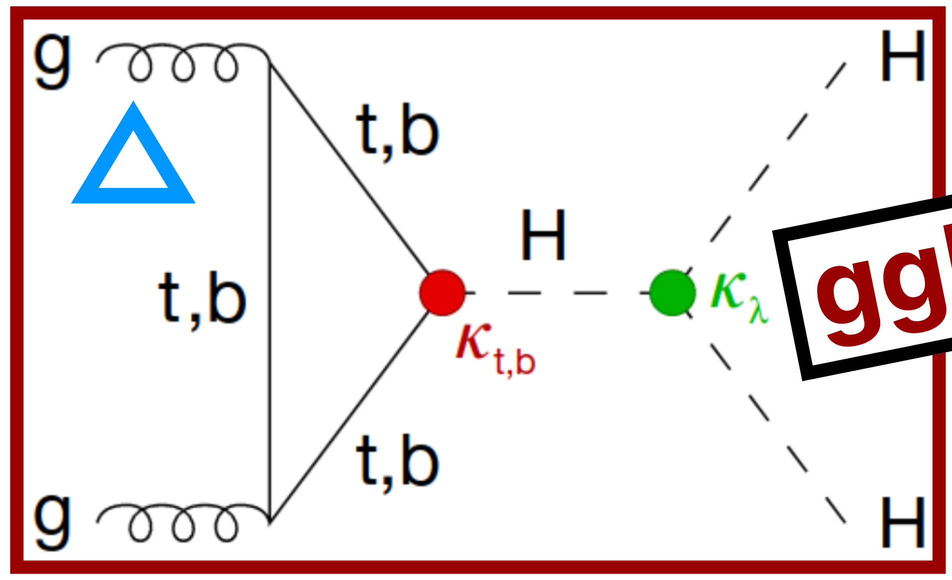
△ dominates for large $|k_\lambda|$

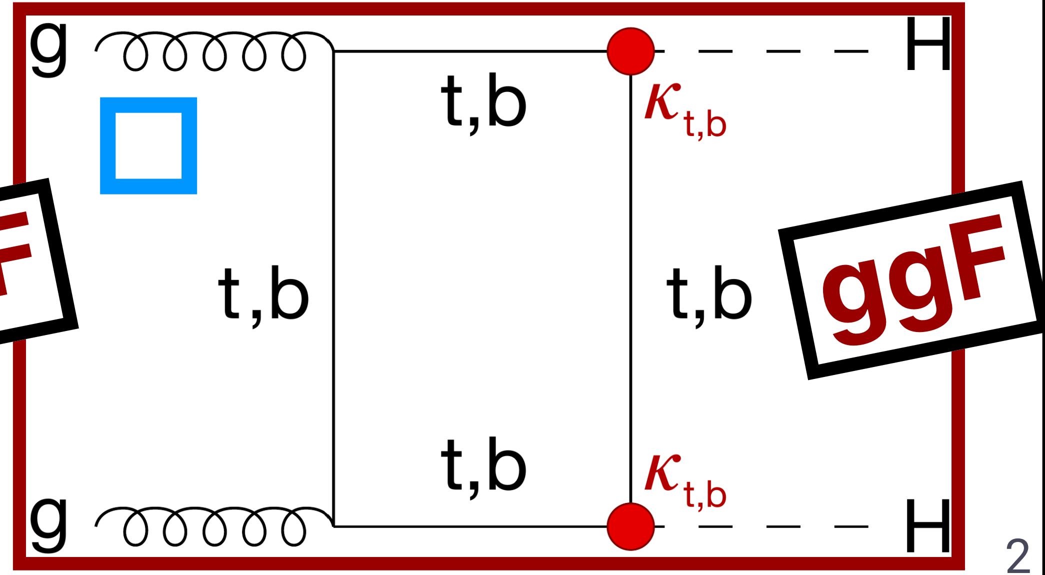




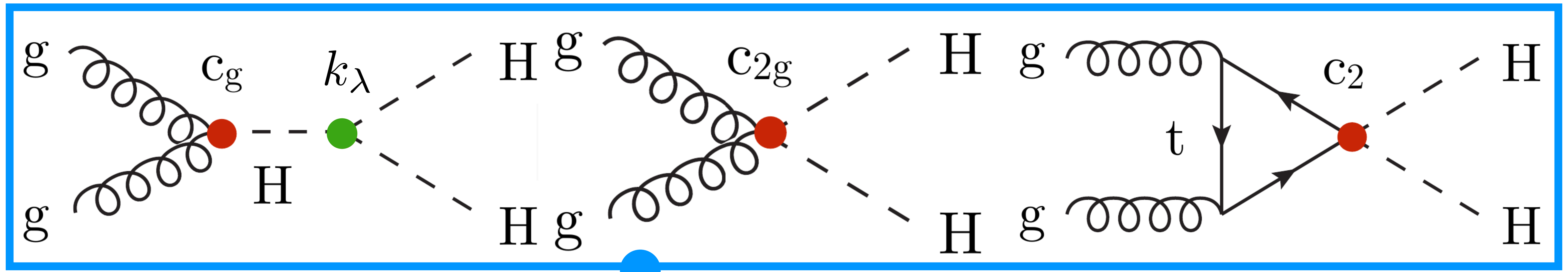








Motivation: EFT ggF



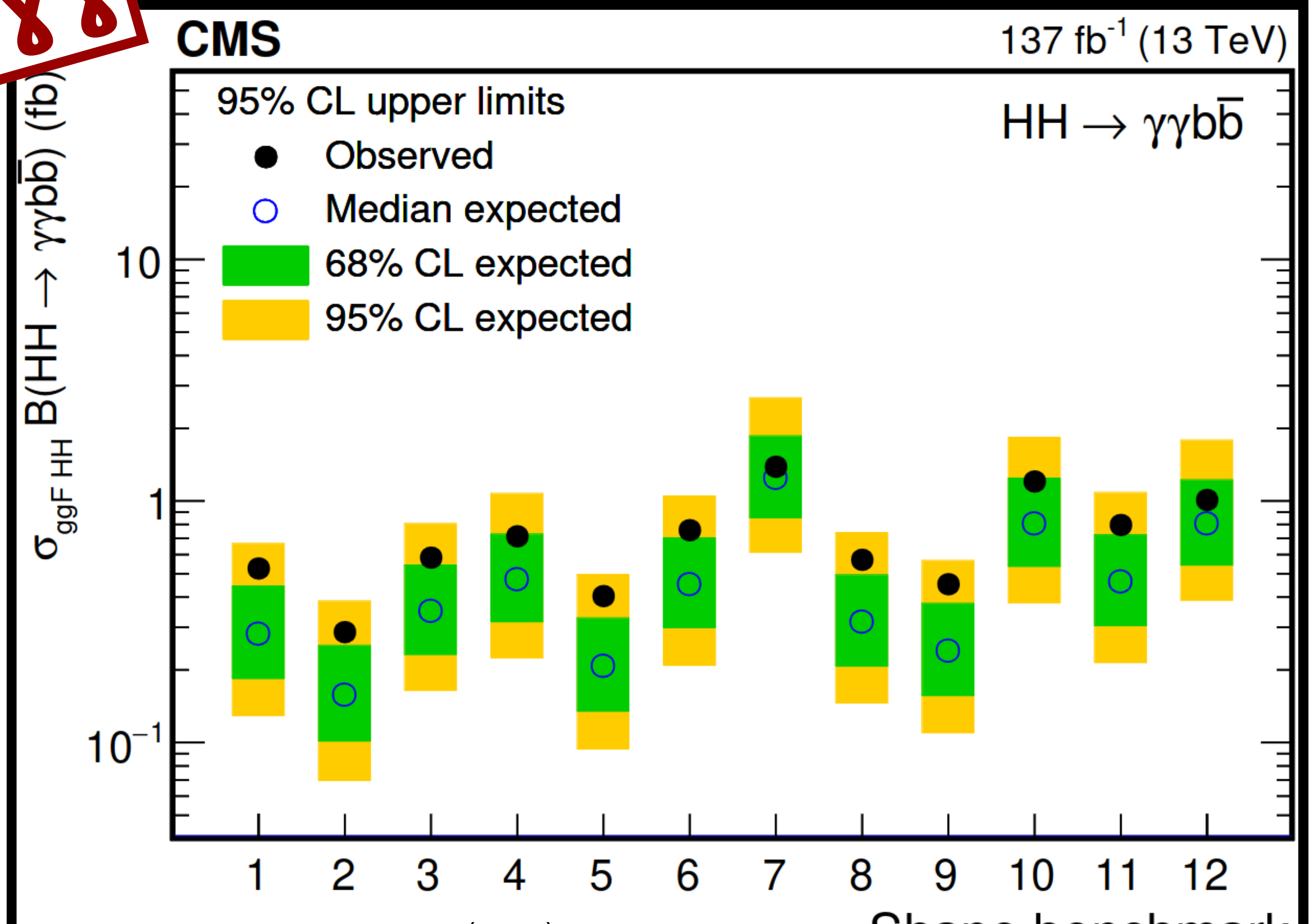
- **Probe effects from resonances with very high mass at lower energy scales**
  - BSM effects on ggF HH production can be studied through EFT model with **three new couplings**
- Explore sensitivity to BSM EFT couplings with **EFT benchmark points**:
  - based on test statistic measuring kinematics' similarity
  - allow extrapolation between different points

Benchmarks

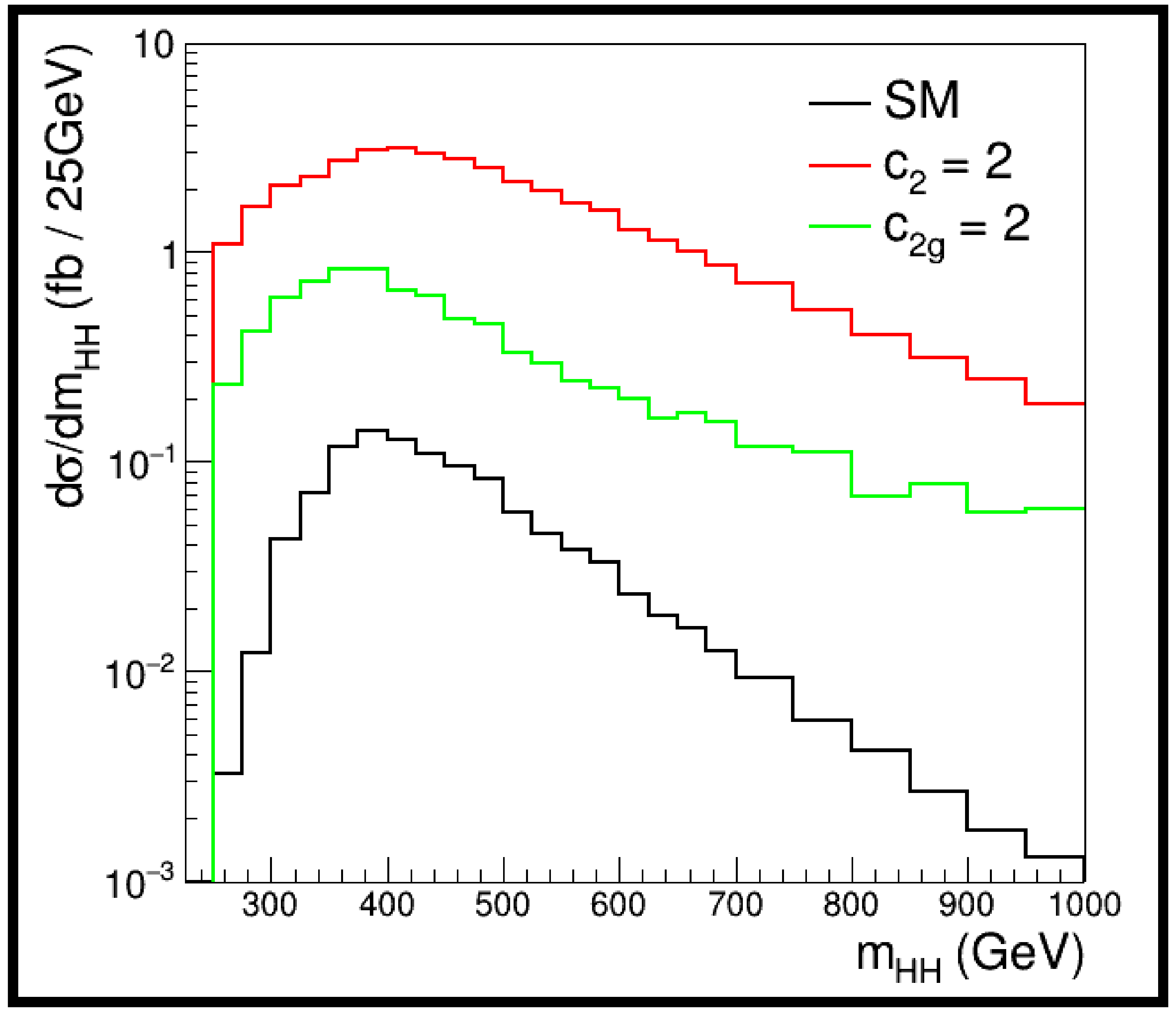
	κ_λ	κ_t	c_2	c_g	c_{2g}
SM	1.0	1.0	0.0	0.0	0.0
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0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

bbγγ



J. High Energ. Phys. 2021, 257 (2021)



Production → HH → Decay

- **ggF**, **VBF** and **VHH** production
  - ~1000x rarer than single-H production
- Large variety of HH channels
  - trade-off between selection purity and branching ratio
- **New:** HH→γγττ, ZZ/ZH→4b, H+HH

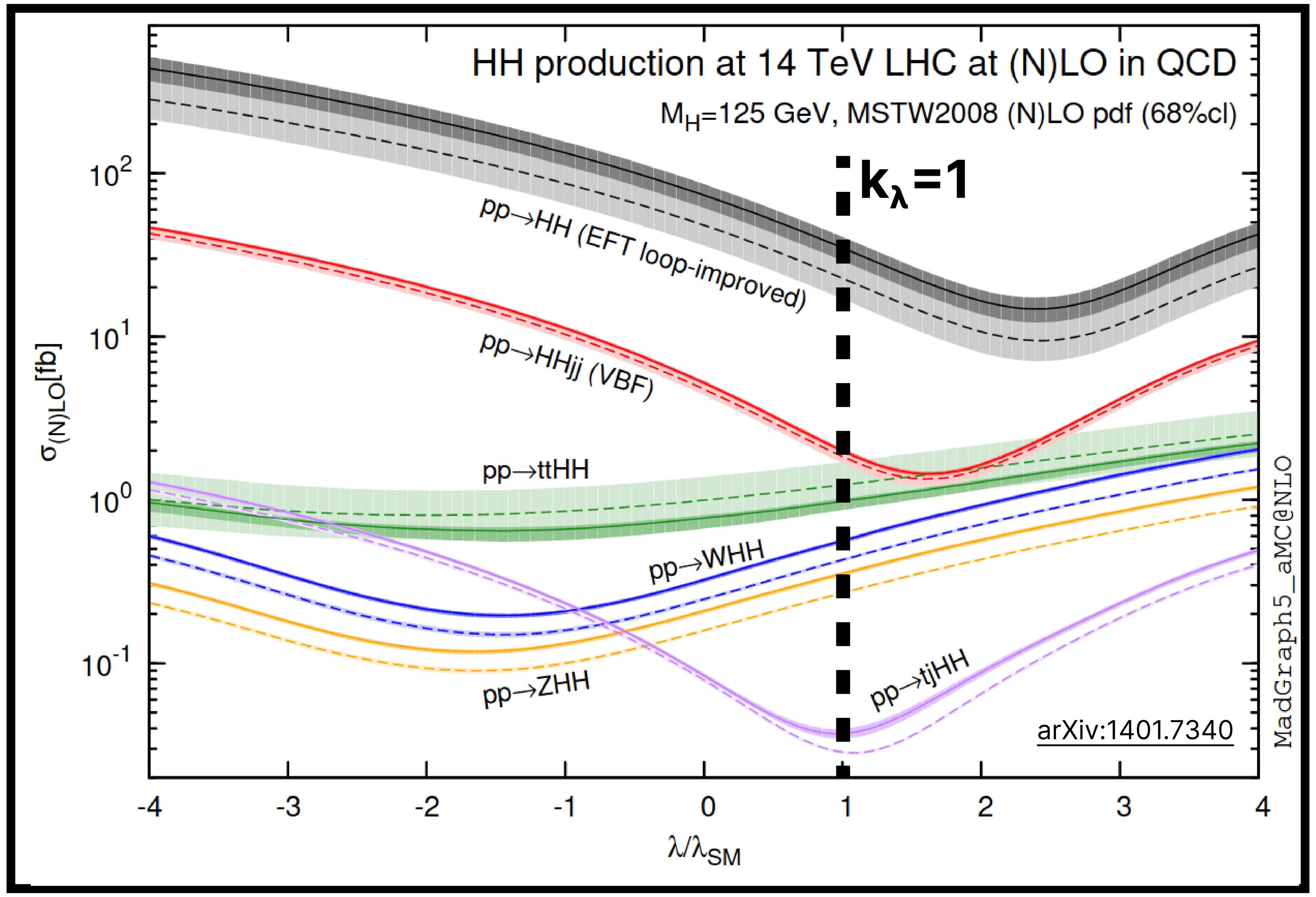
applicable to HH→4b

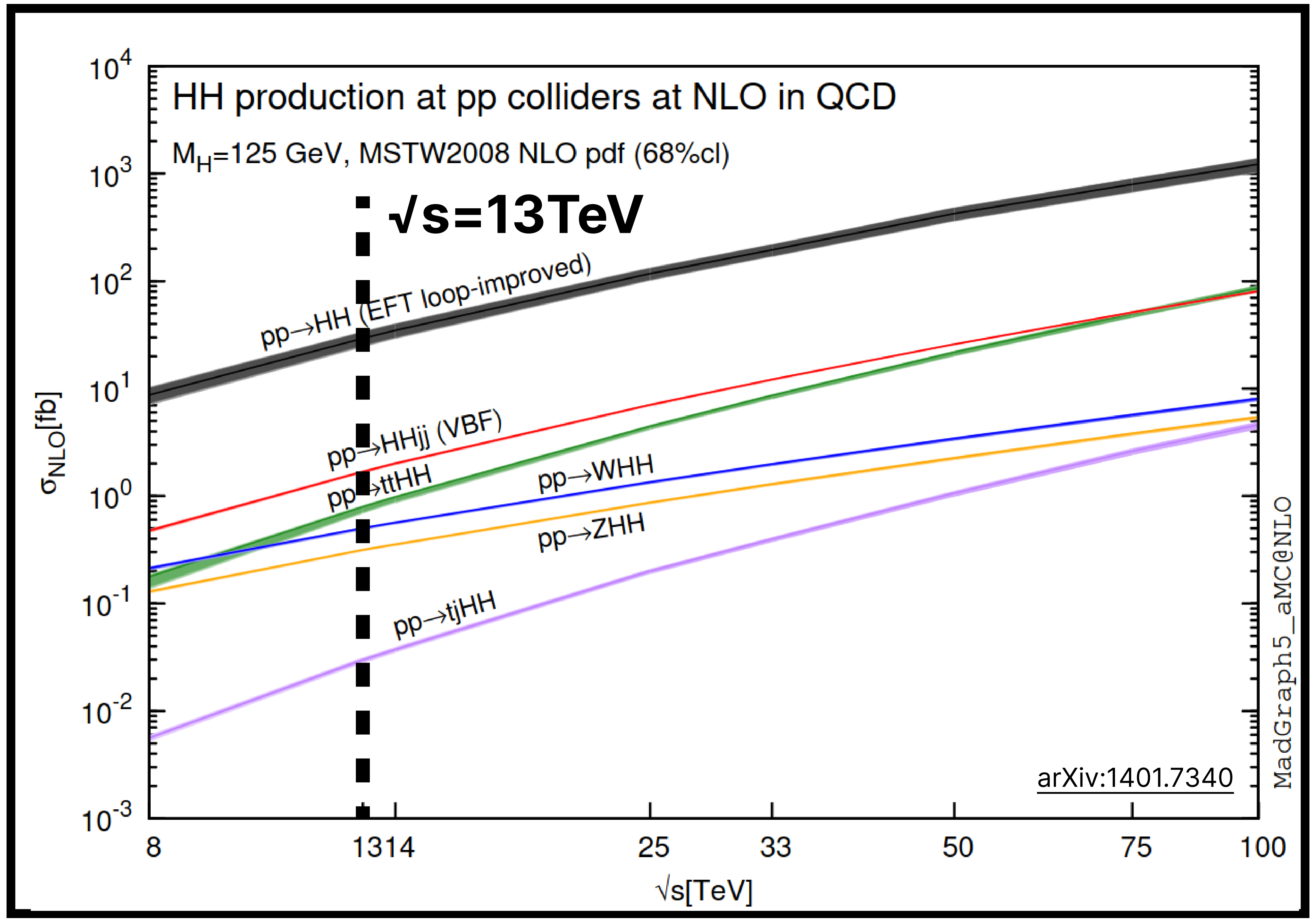
HH	**bb**	**WW**	**ττ**	**ZZ**	**γγ**
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

"Silver bullets"

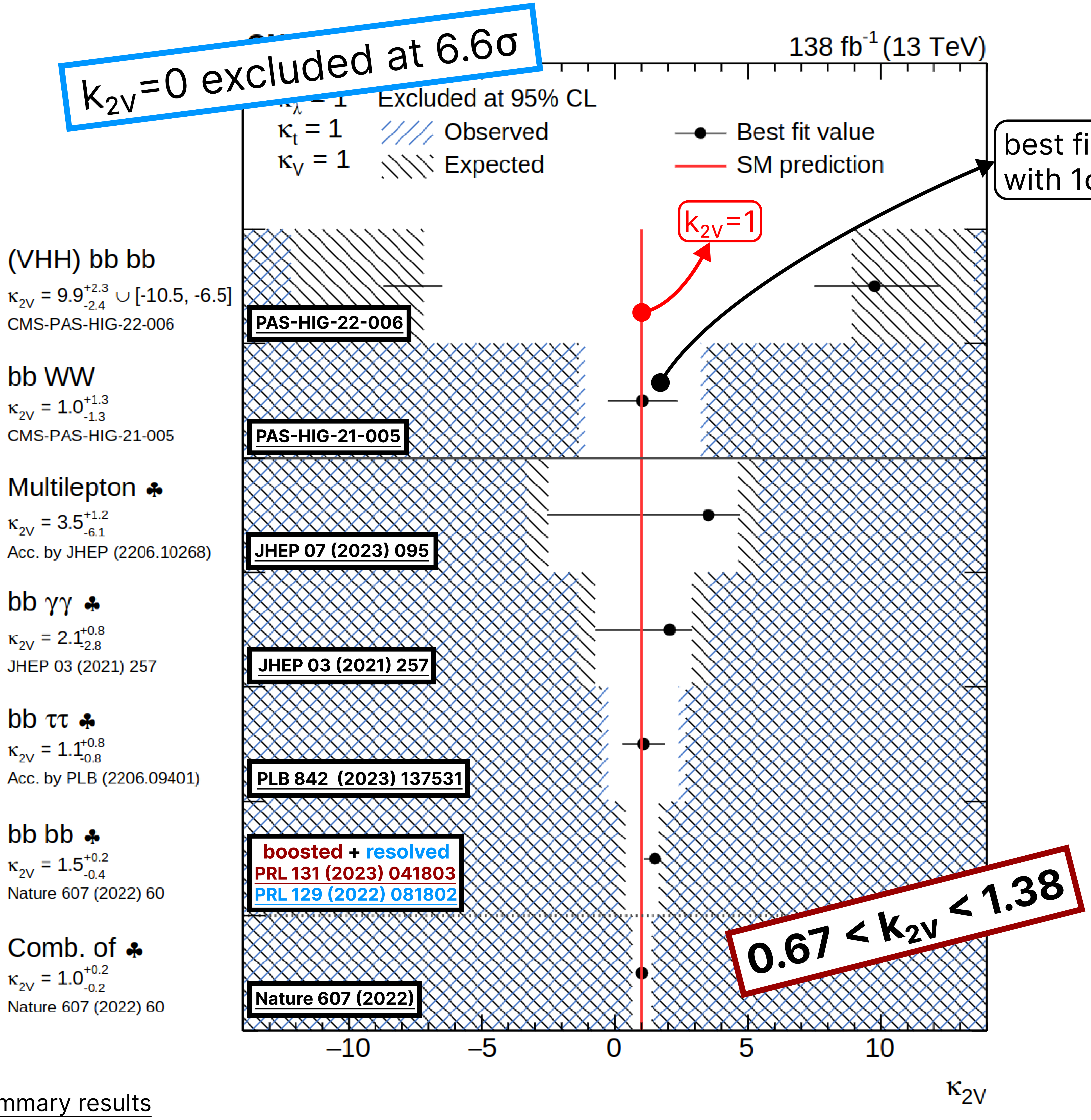
No golden channel!

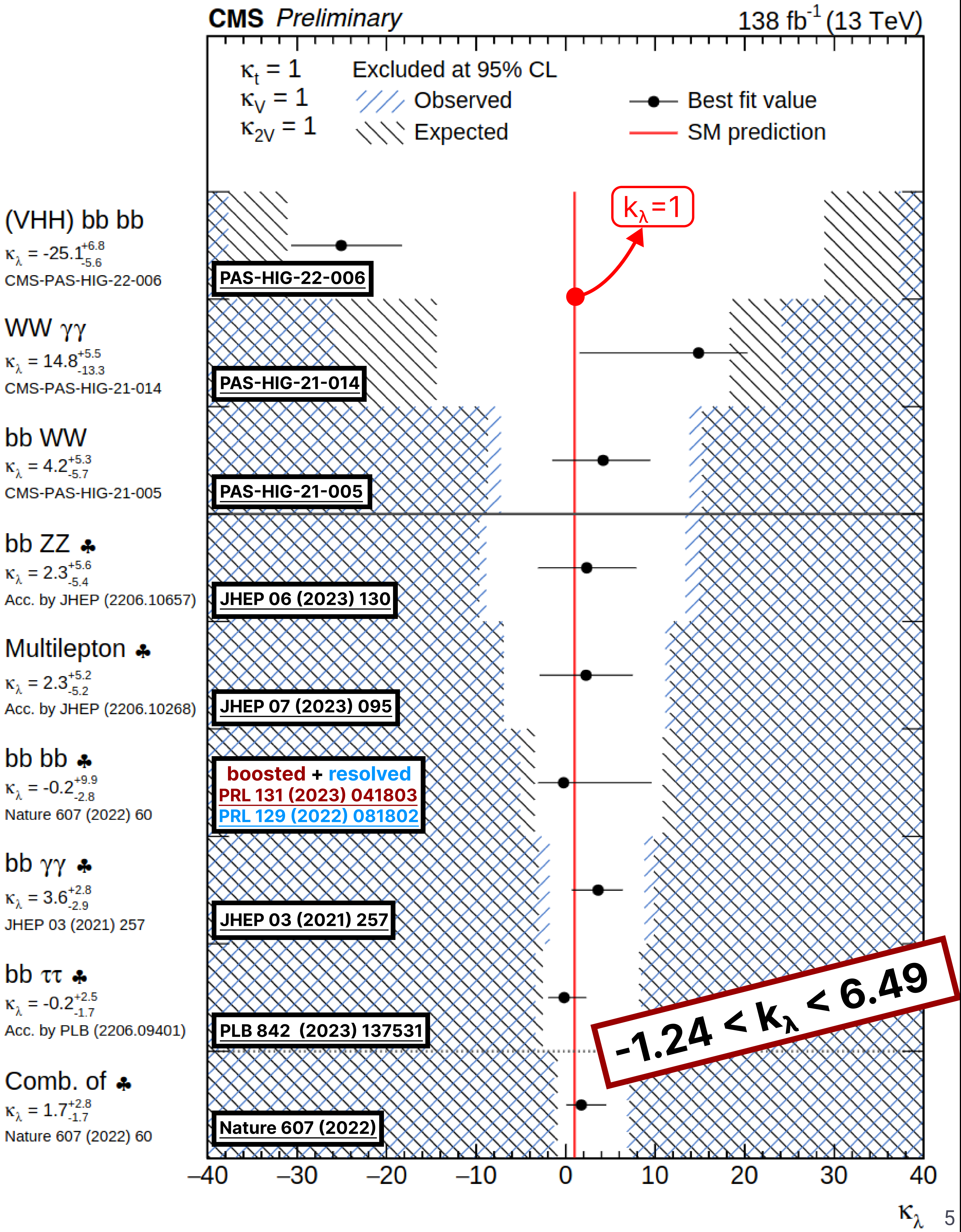
- ★ **nonres VHH**
- **resonant**
- **nonres VBF**
- **nonres ggF**





Run2 Combination





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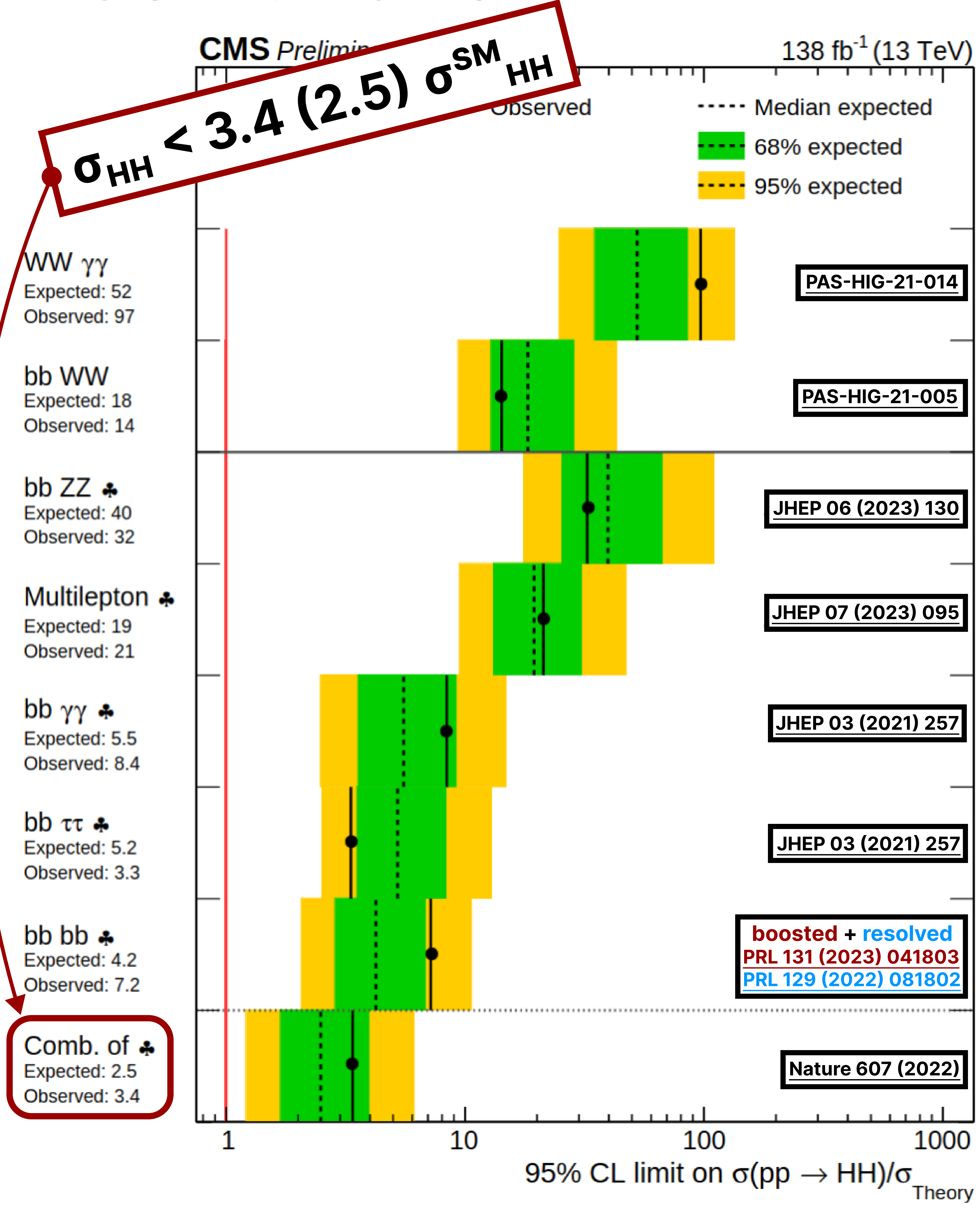
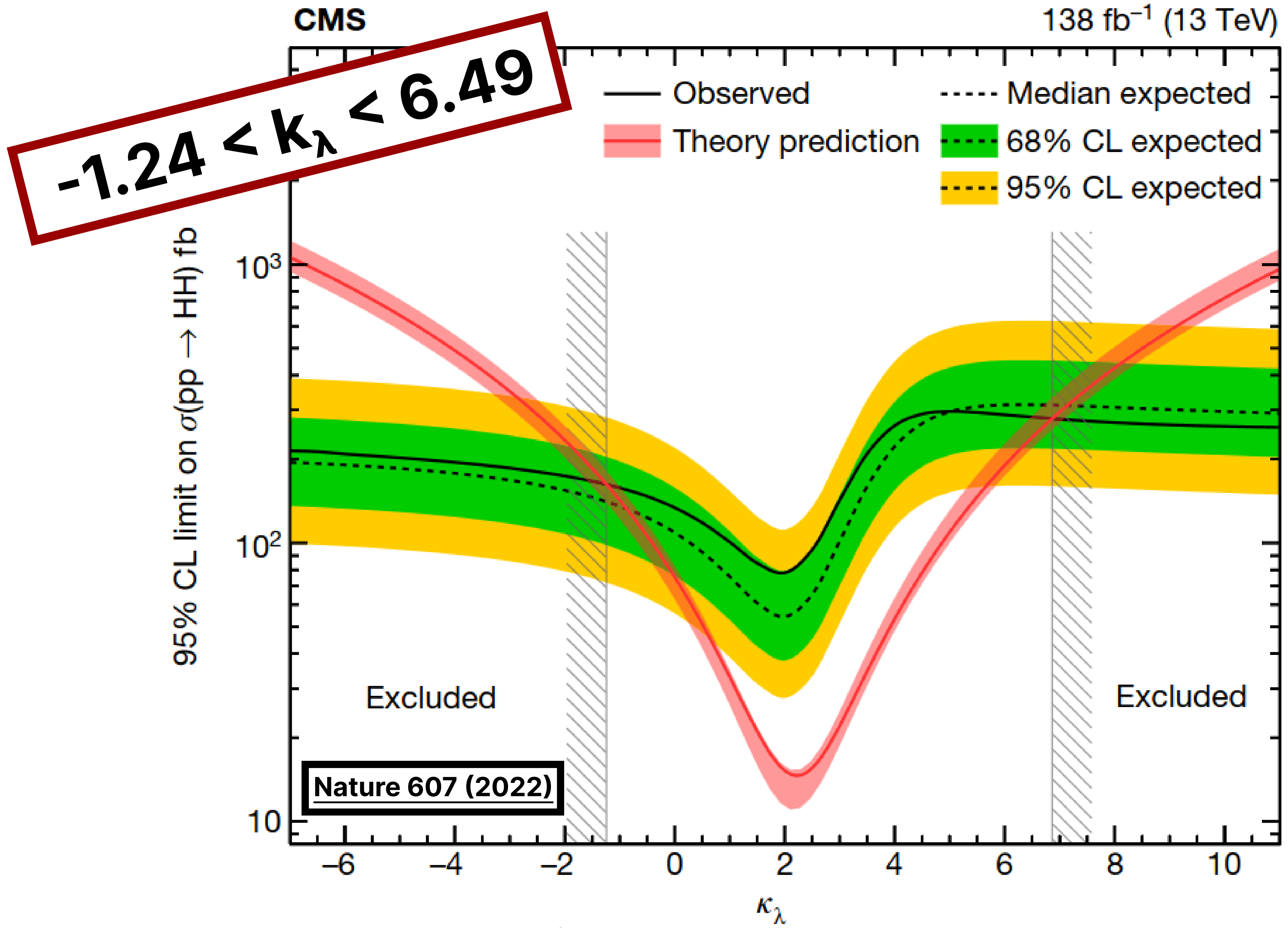
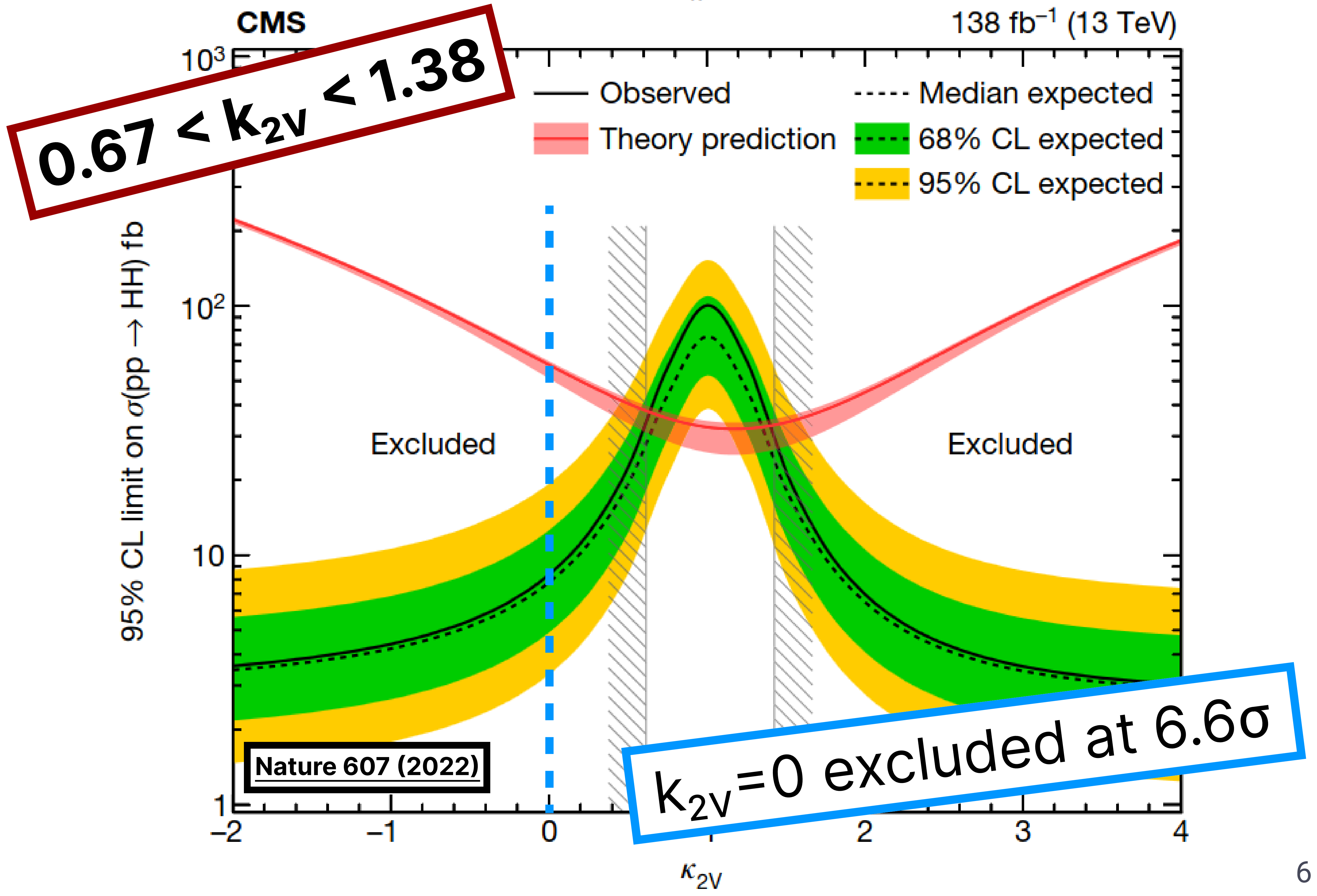
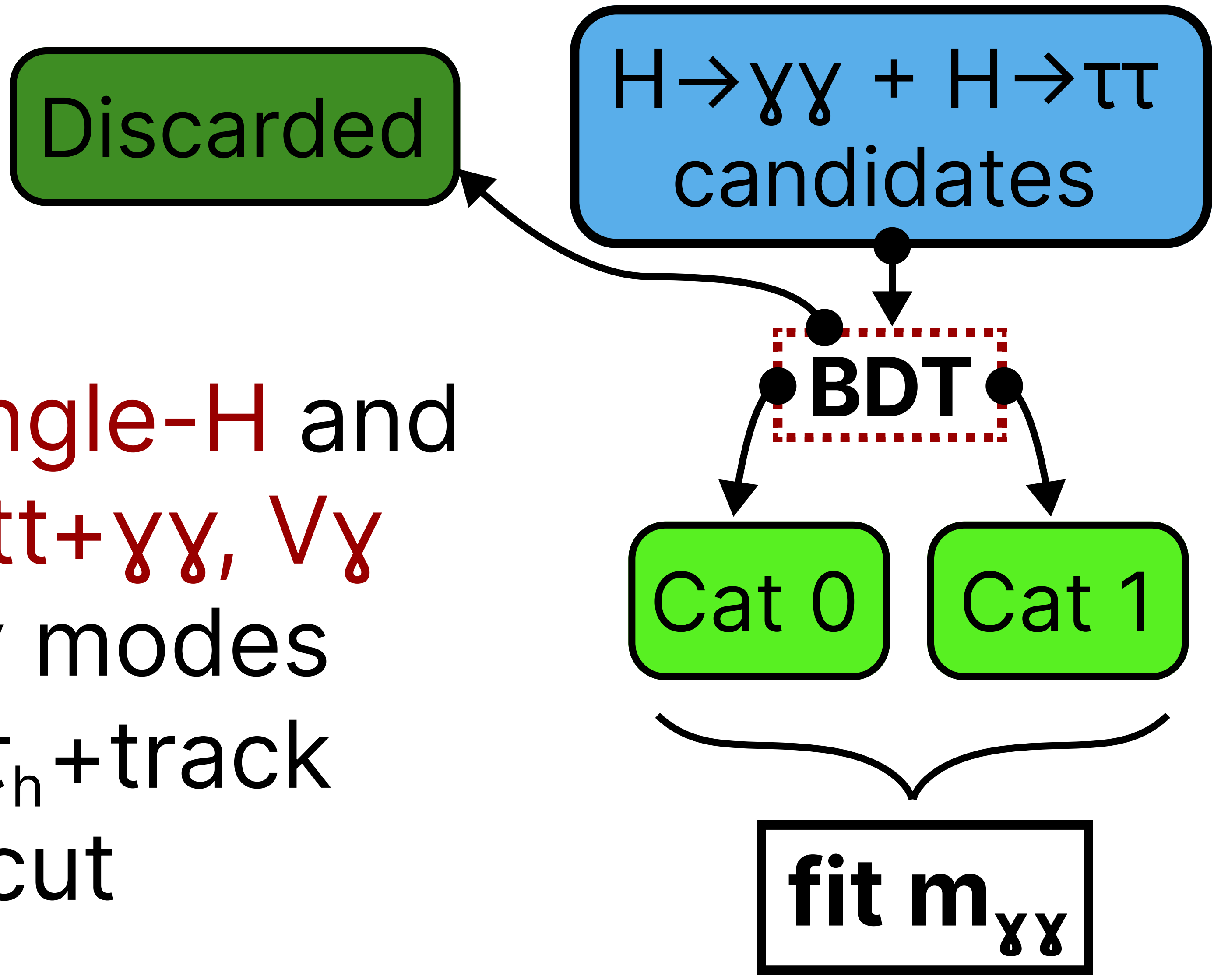


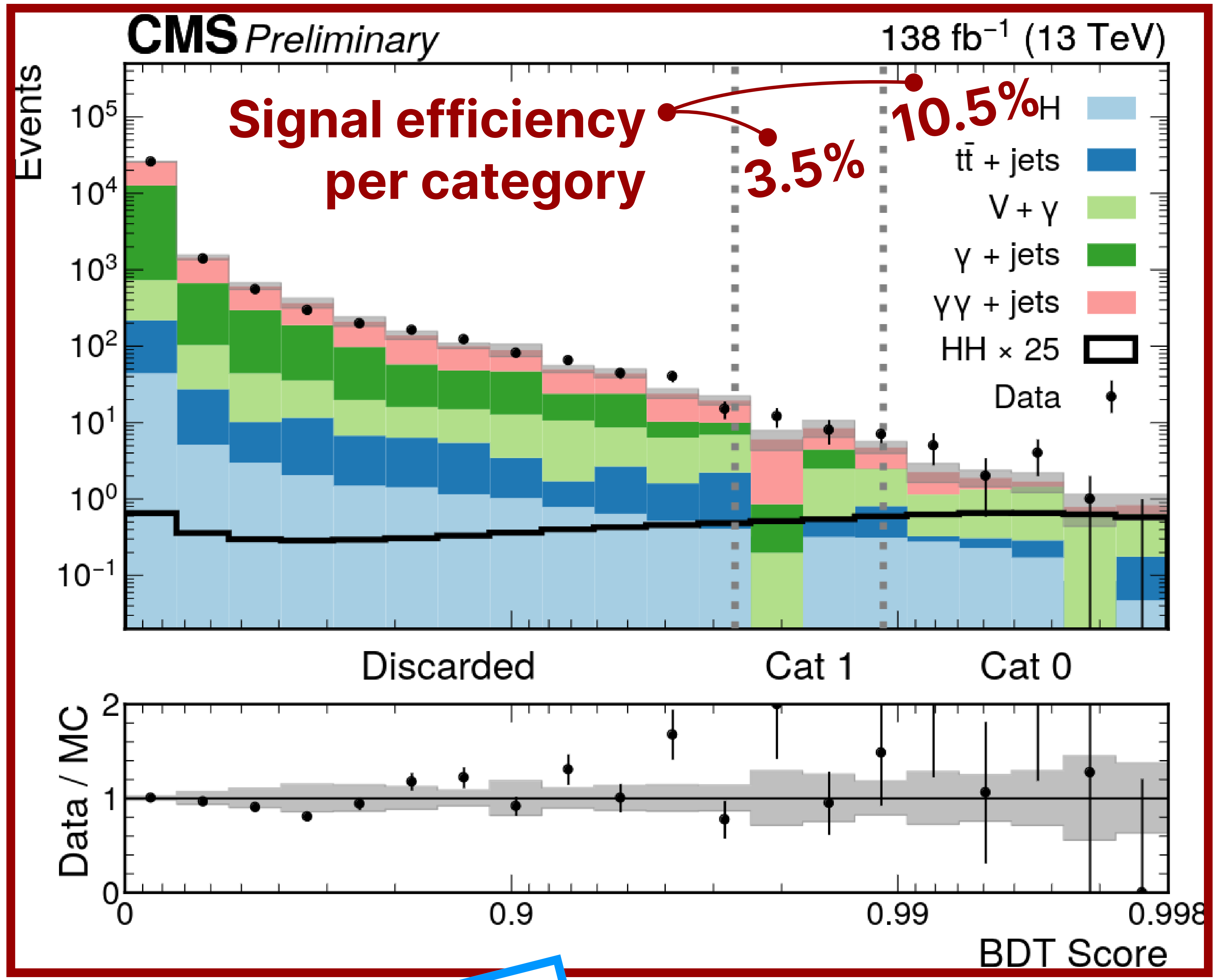




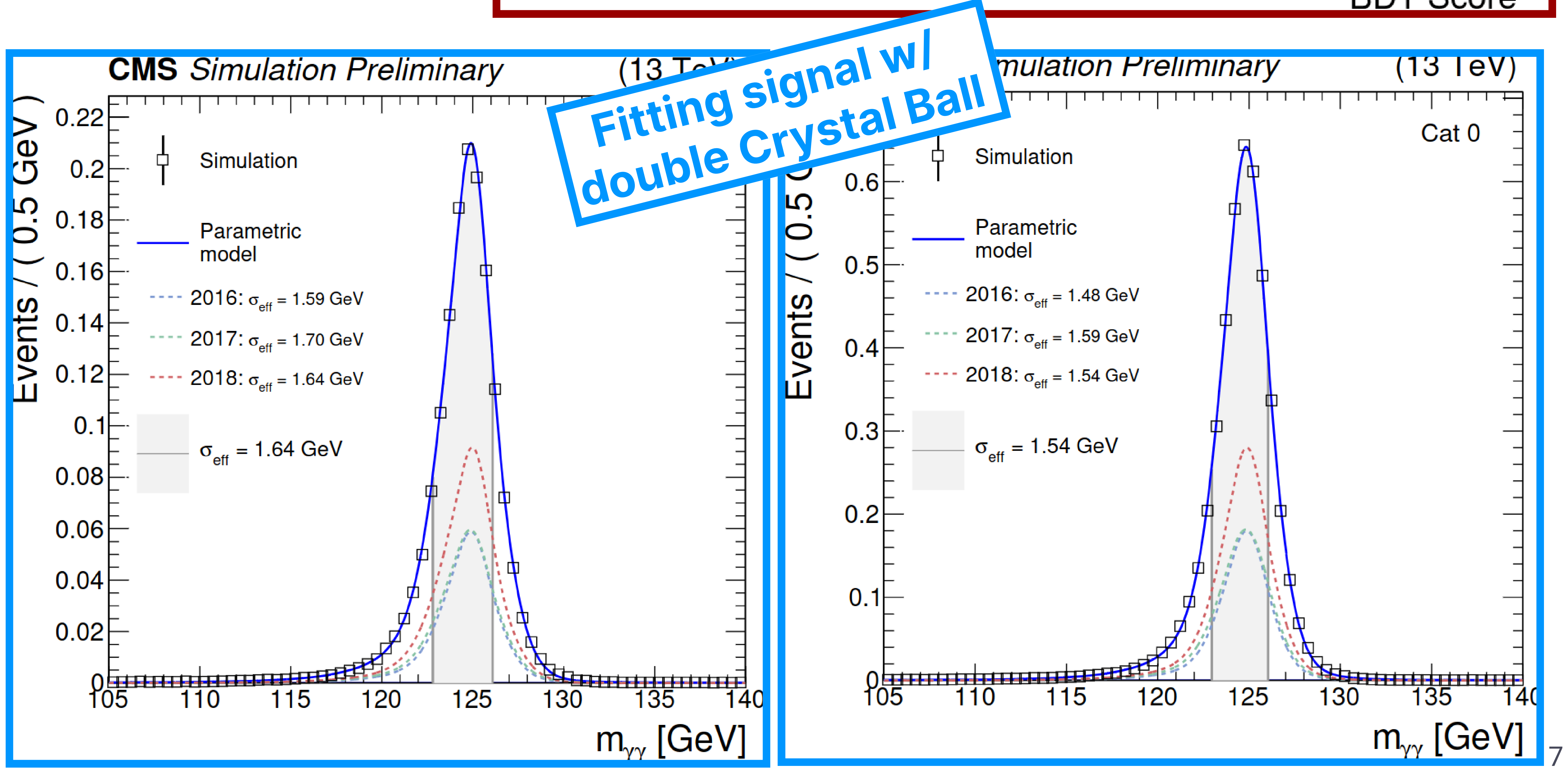
$HH \to \gamma\gamma\tau\tau$ ggF



- Dominant bkgs. are peaking single-H and non-res. γ+jets, $\gamma\gamma$+jets, tt+γ, tt+$\gamma\gamma$, Vγ
- τ's reconstructed in all 6 decay modes
  - and consider single τ_h and τ_h+track
  - apply DY veto with a mass cut
- A BDT uses kinematic features
  - enforces $m_{\gamma\gamma}$ independence at 1st order



- Fit $m_{\gamma\gamma}$ in signal-enriched categories
  - signal and $H\to\gamma\gamma$ bkgd. from simulation
  - bkgd. continuum using the discrete profiling method
    - take the minimum likelihood of many analytic functions vs. signal strength: the envelope
    - penalize functions w/ more params



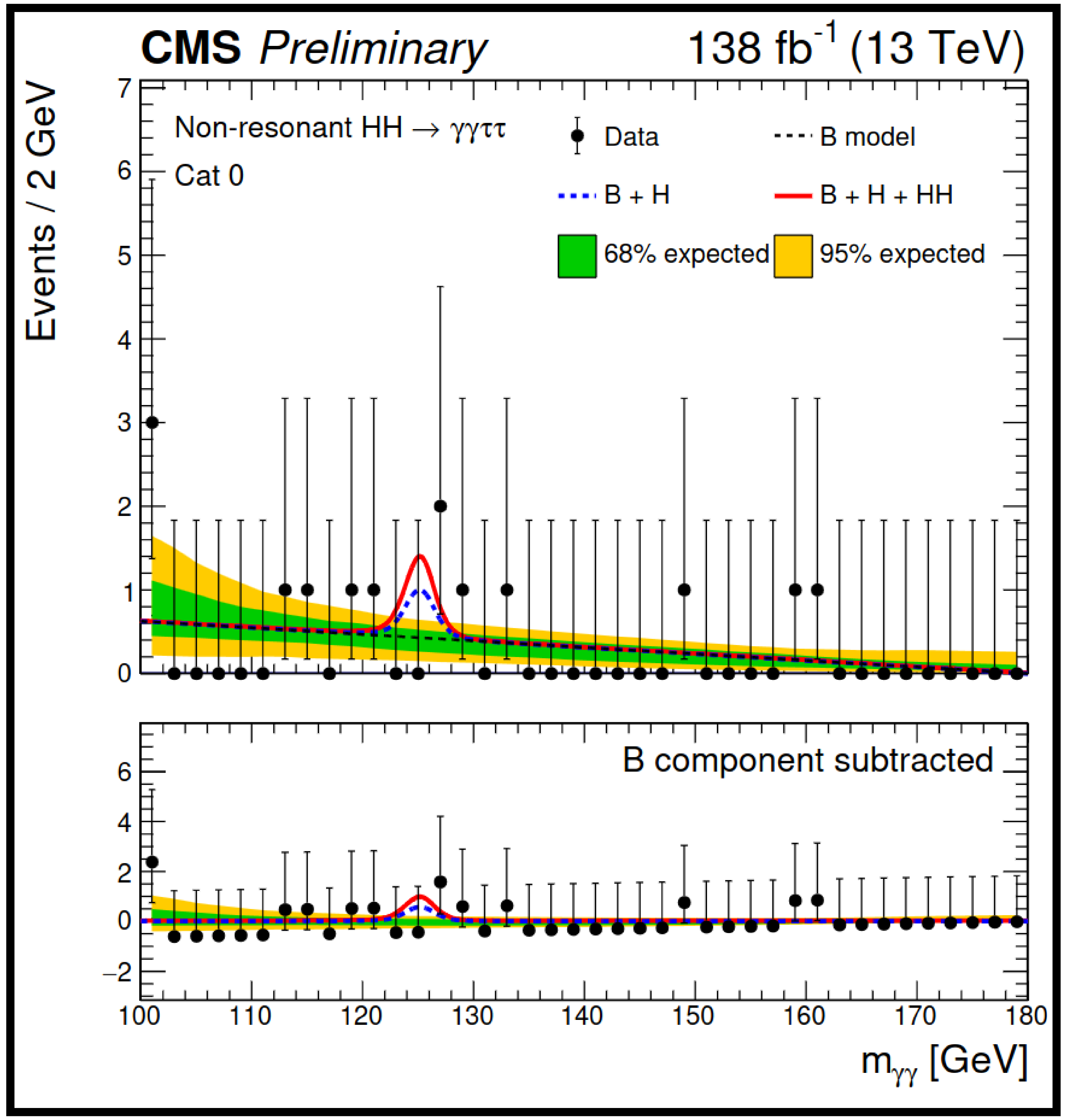
CMS-PAS-HIG-22-012

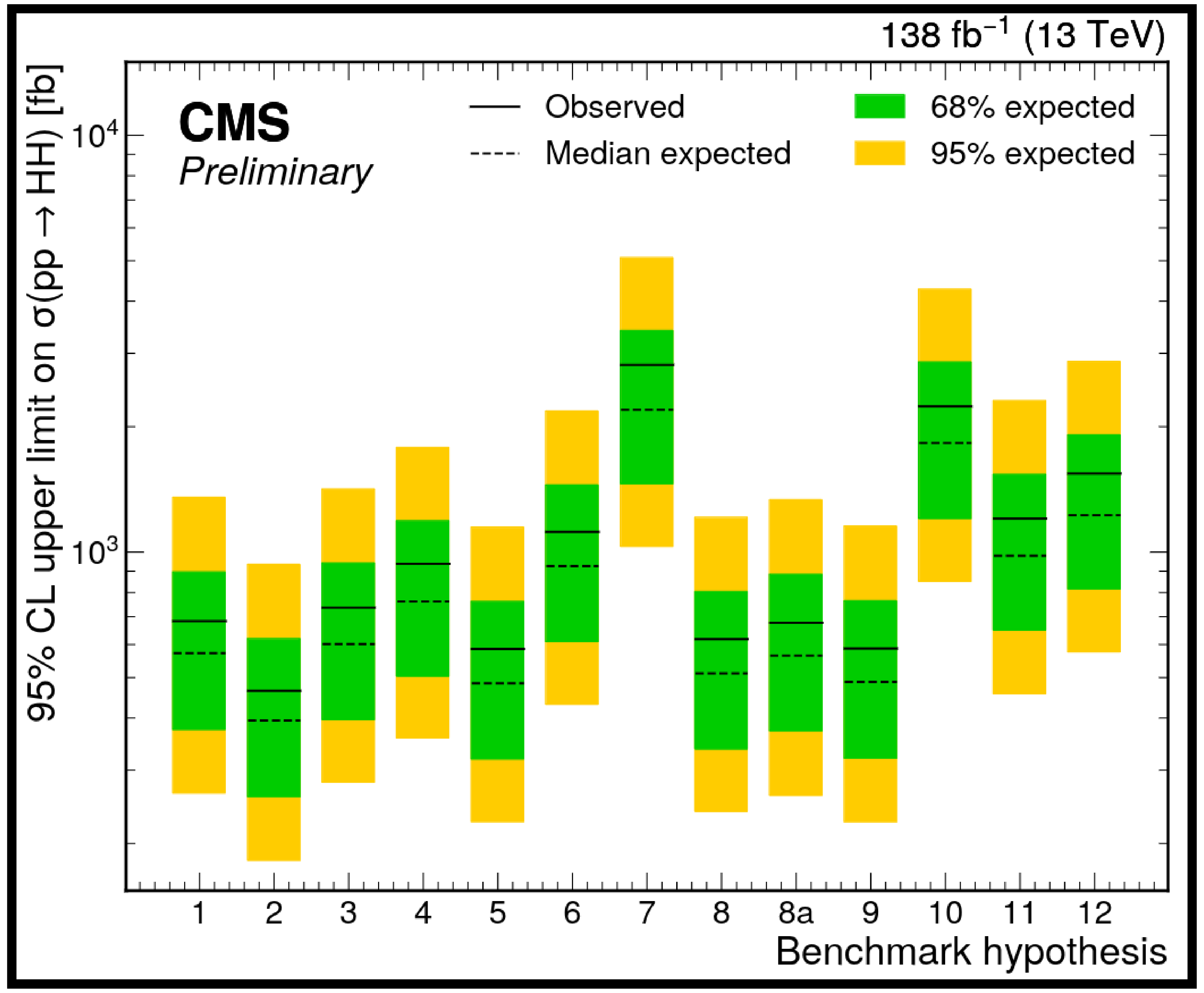
$HH \to \gamma\gamma\tau\tau$ ggF

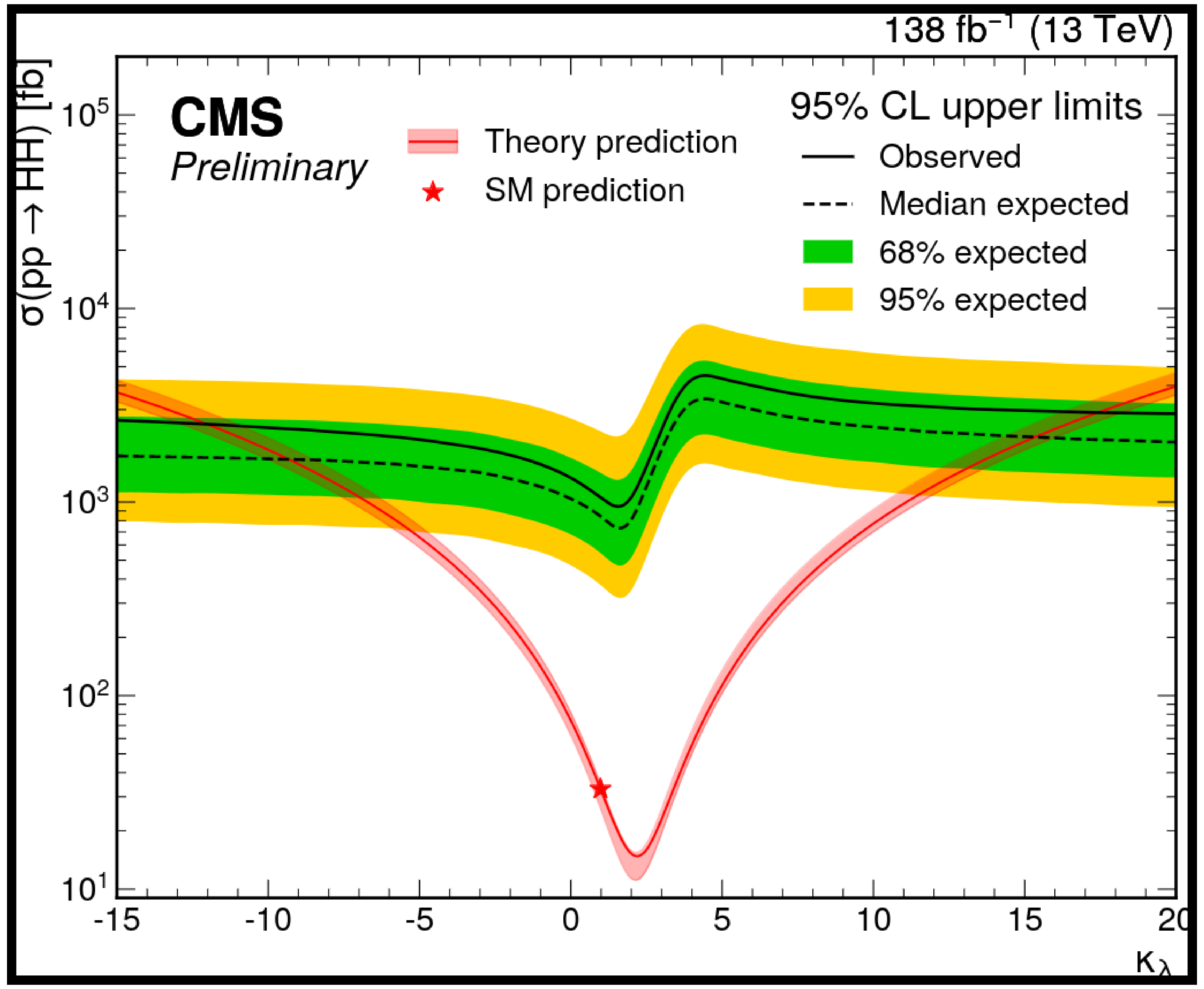
- Results expected to be added to a future HH combination
- The work also covers many resonant channels (not discussed here)

$\sigma_{HH} < 33\ (26)\ \sigma^{SM}_{HH}$

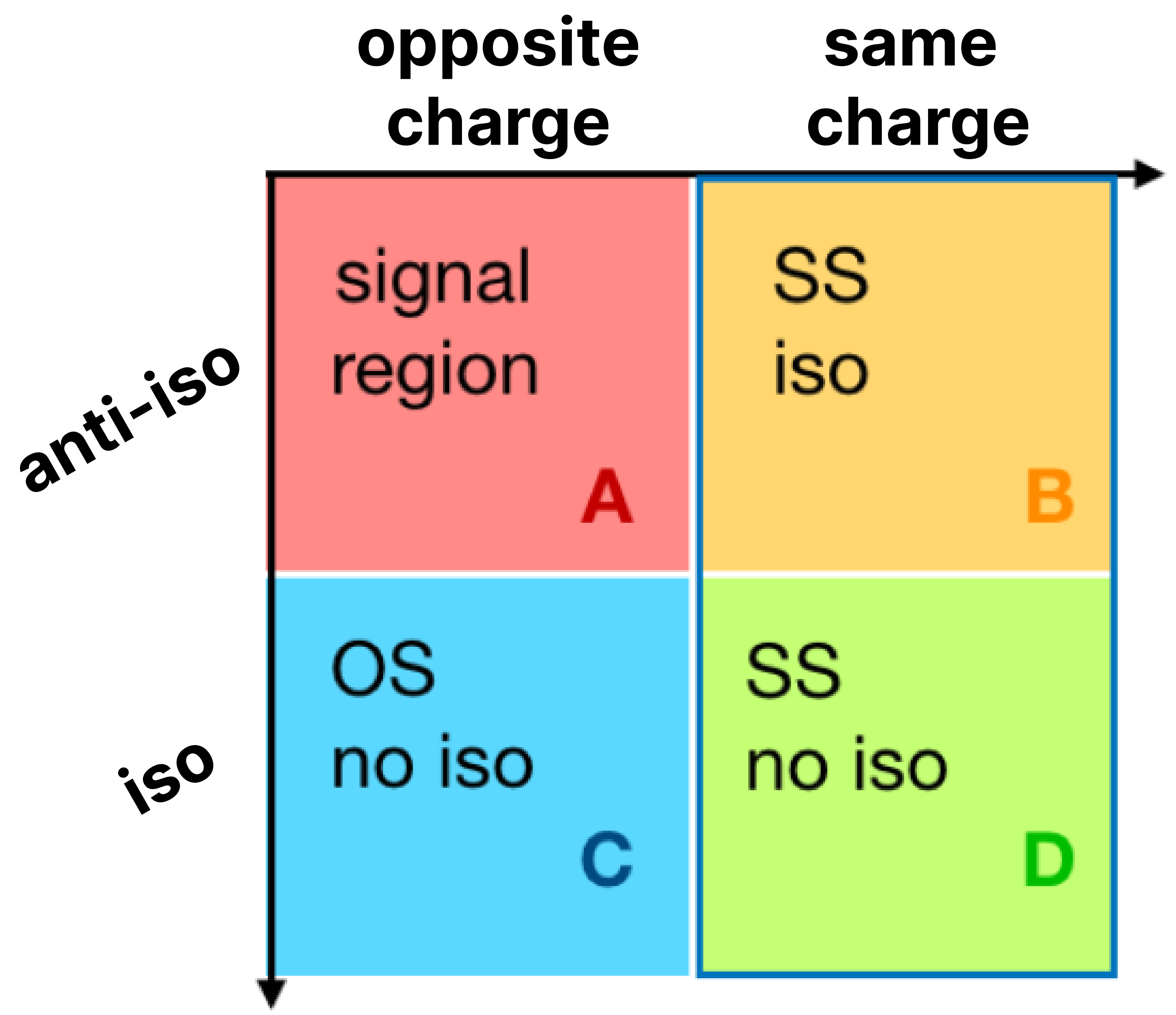
$-13\ (-11) < \kappa_\lambda < 18\ (16)$







Modelling the QCD background



shape | yield correction

A = C * B/D

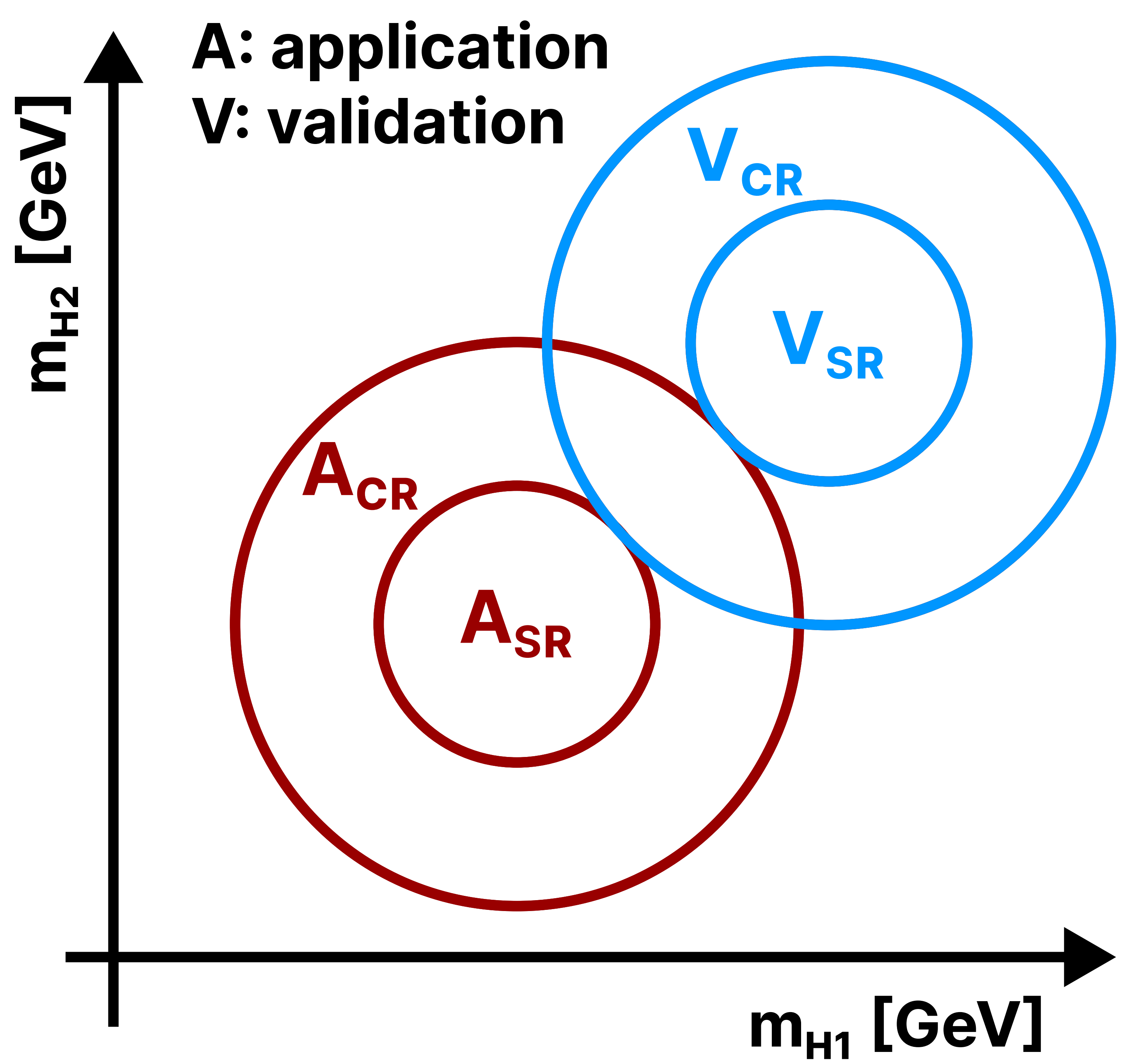
A = B * C/D

HH→bbττ

Phys. Lett. B, 842, 137531

- QCD data-driven estimation using tau charge and isolation
- ABCD-like method
  - The shape uncertainty dominates (QCD dominates in the most sensitive ττ channel)

$$N^{4b}_{SR} = \sum_{ibin} \left(\frac{N^{4b}_{CR}}{N^{3b}_{CR}} \right)_{ibin} \left(N^{3b}_{SR} \right)_{ibin}$$



HH→4b (resolved)

Phys. Rev. Lett. 129, 081802

- QCD data-driven estimation using 3/4 b's CRs
  - BDT reweighting fixes remaining diffs. in the 3b's SR
- ABCD-like method
  - Largest systematics come from the background model

Modelling the QCD background

shape | yield correction

$A = C * B/D$

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HH→bbττ

Phys. Lett. B, 842, 137531

- QCD data-driven estimation using tau charge and isolation
- ABCD-like method
  - The shape uncertainty dominates

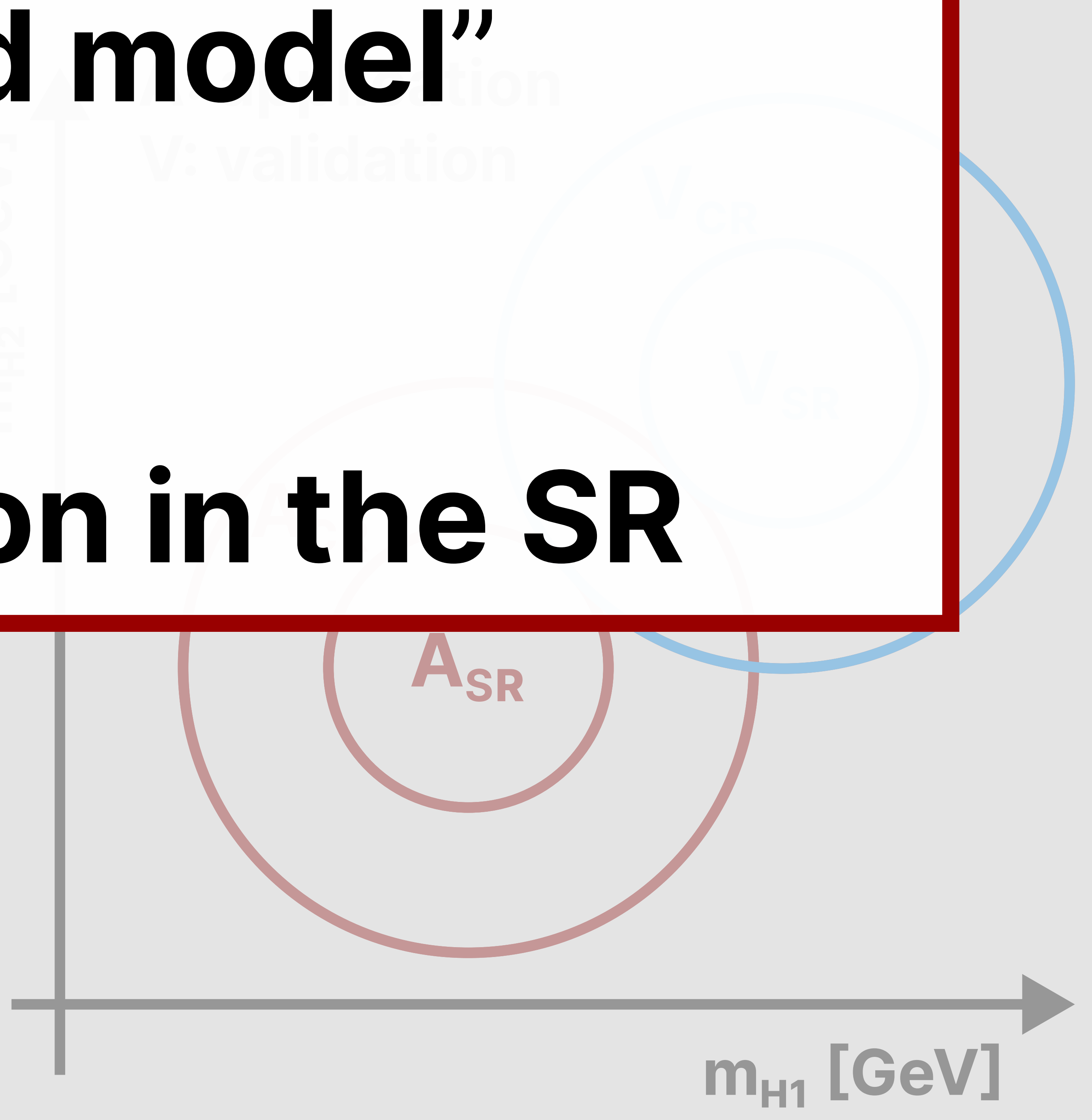
Finite data in VRs imply an

“Inherent limitation on the capability to validate the performance of the background model”

We would also like to

directly test the ABCD extrapolation in the SR

HH→4b



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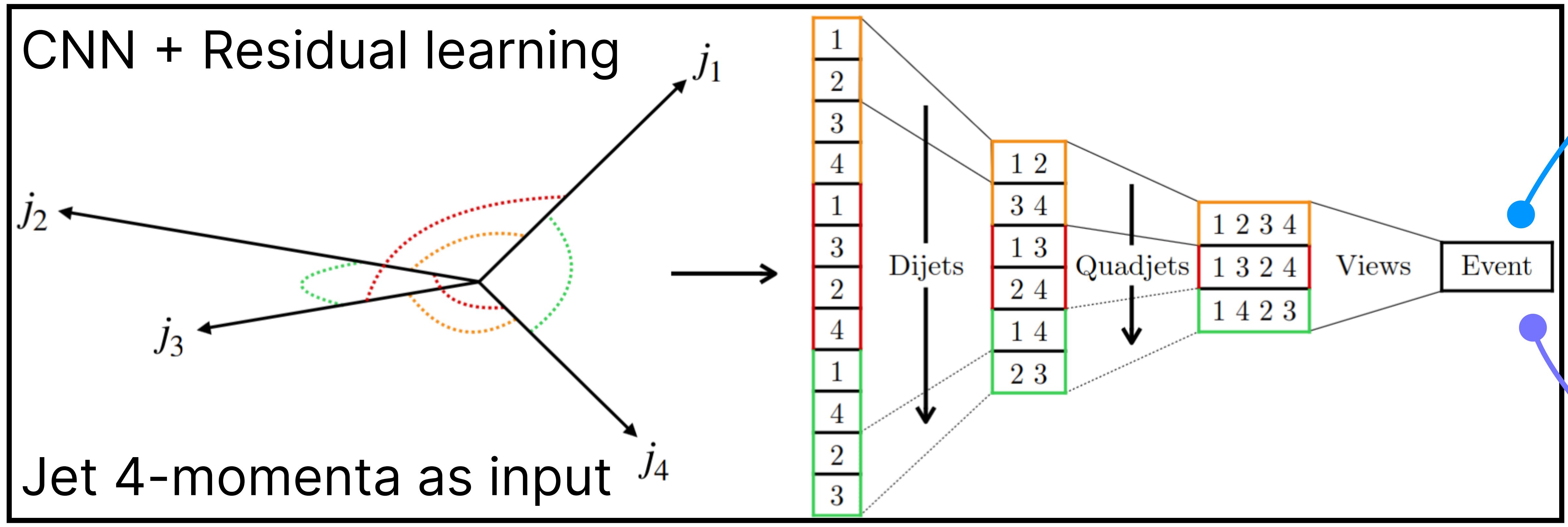
ZZ/ZH→4b: Techniques for HH→4b

- The same DNN multiclassifier architecture is used for:
  a. signal vs bkgd. discrimination
  b. kinematic correction of the background model
  c. remove ttbar from synthetic dataset



P_{Data}, P_{Bkgd}

$P_{tt,4b}$, $P_{Data,4b}$, $P_{tt,3b}$, $P_{Data,3b}$

P_{Data}, P_{tt}

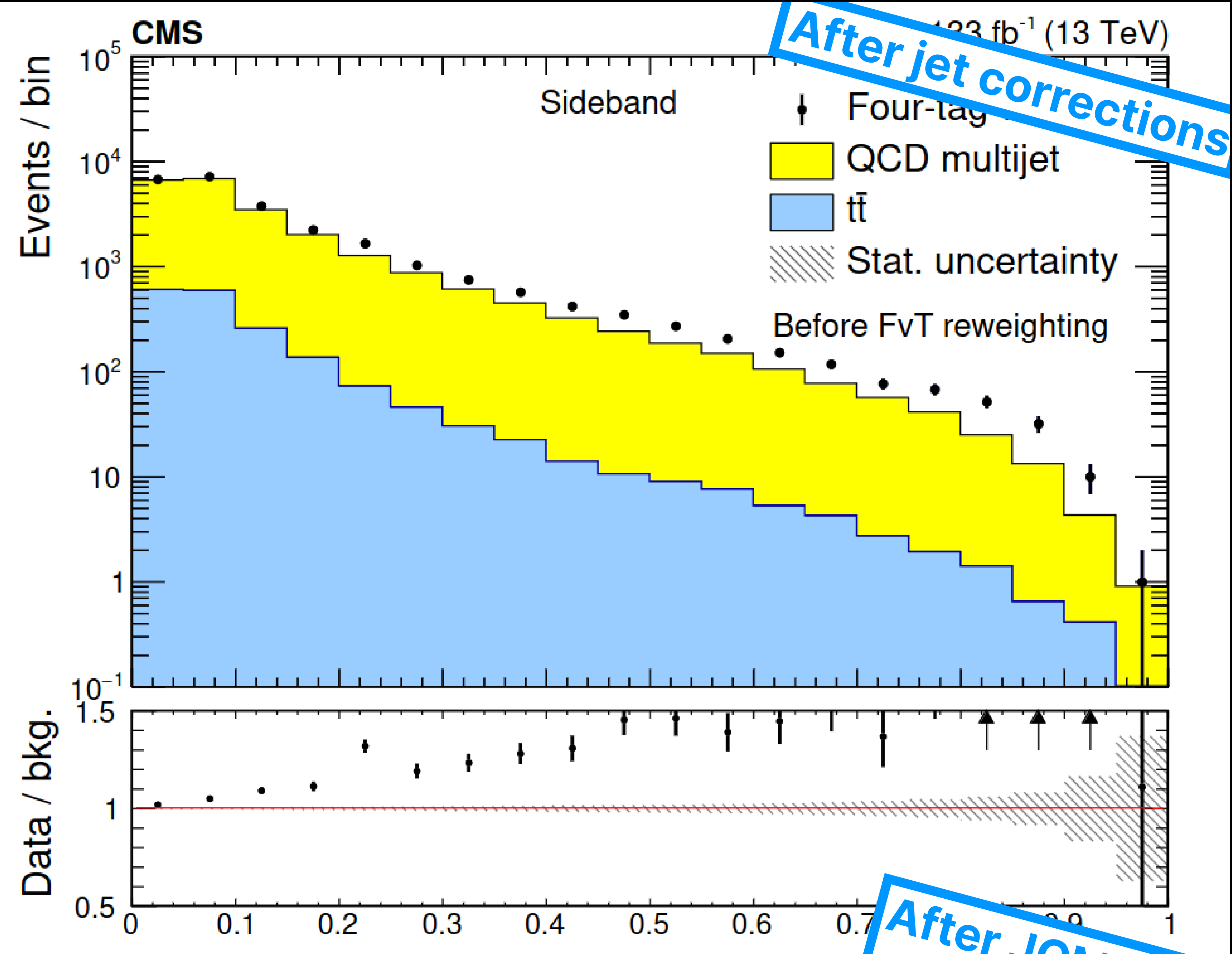
- QCD is modeled w/ events having 3 b-tagged jets
  - 17x more stats. (also loosening the b-tag requirement)
  - two sets of weights to describe the analysis 4b's bkgd.
    i. account for additional jet activity
    ii. correct kinematic differences

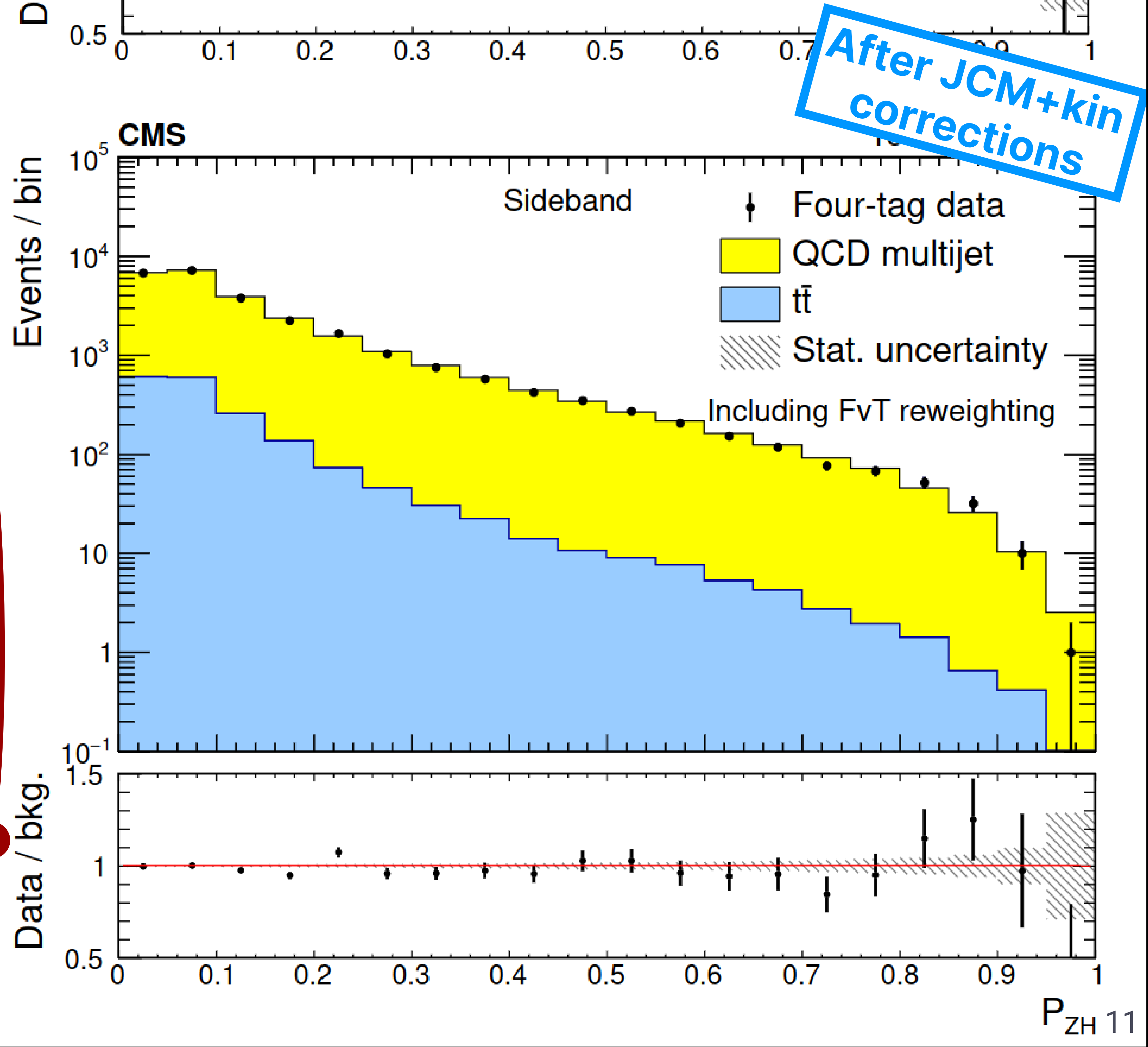
"ABCD-like"

$$w_{\mathrm{JCM}} = \begin{cases} t\sum_{i=1}^{n}\binom{n}{i} f^i (1-f)^{n-i}(1+e/n^d) & (3+i)\ \text{even} \\ t\sum_{i=1}^{n}\binom{n}{i} f^i (1-f)^{n-i} & (3+i)\ \text{odd,} \end{cases}$$

see backup for explanation

$$w_{\mathrm{FvT}} = \frac{P(M_{4b})}{P(D_{3b})} \equiv \frac{P(D_{4b}) - P(t\bar{t}_{4b})}{P(D_{3b})}$$





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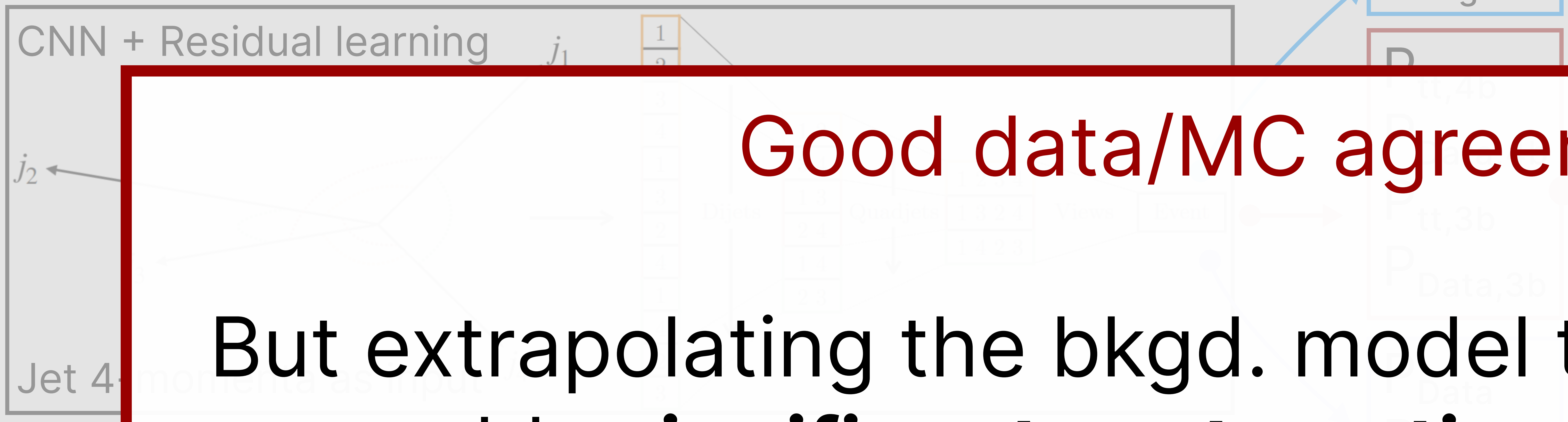

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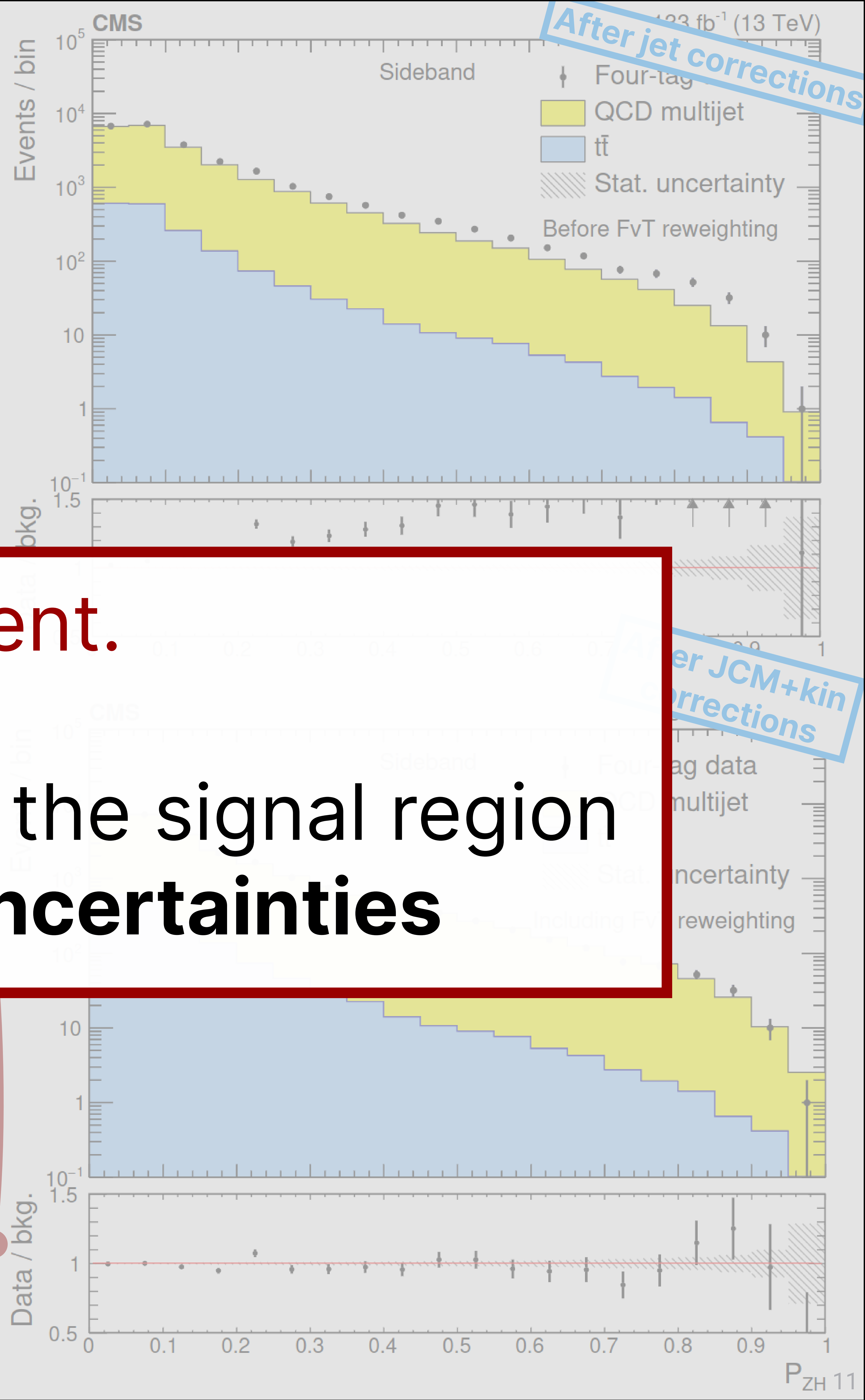


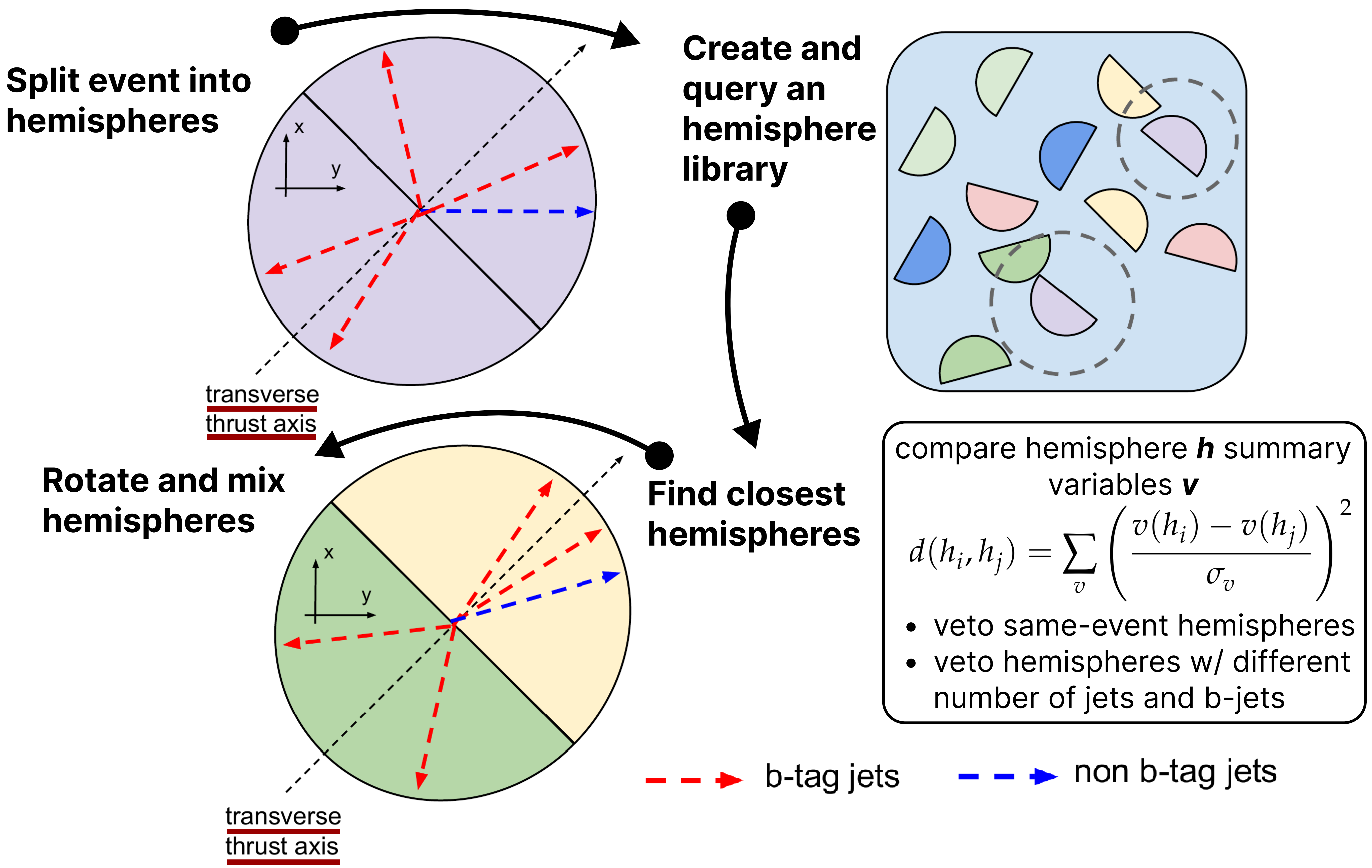
Good data/MC agreement.

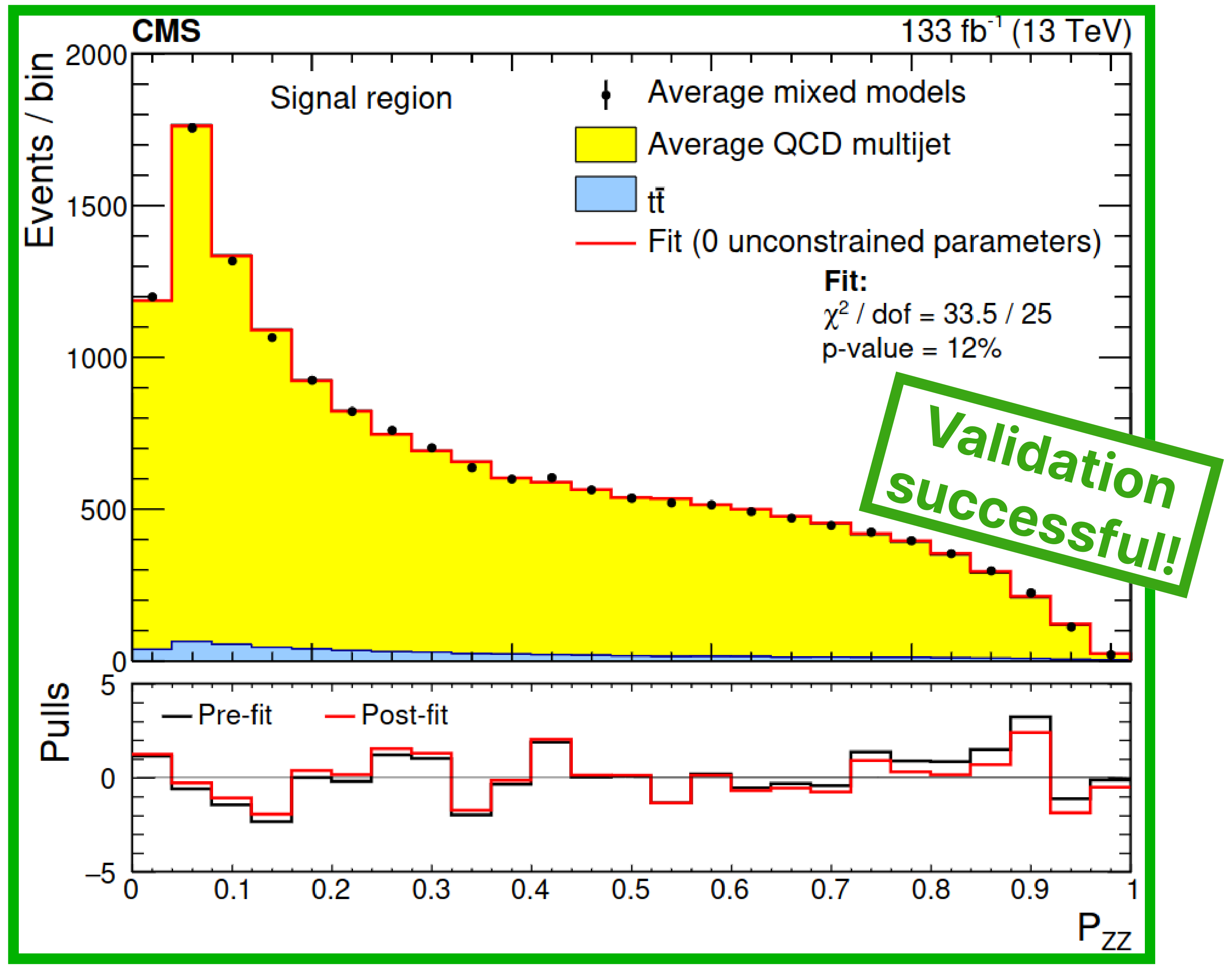
But extrapolating the bkgd. model to the signal region adds **significant systematics uncertainties**

Hemisphere Mixing

- Generate instead synthetic data
  - use it for bkgd. validation
  - technique introduced in an older CMS HH→4b analysis
- **HM improvements (new!)**
  a. use 3-tagged data in the mixing: more stats, less signal contam.
  b. Avoid mixing QCD hemispheres with ttbar hemispheres

Thrust axis: the axis where the sum of the absolute values of the projections of the p_T of the jets is maximal





each mixed model is a subsample of the mixed data to match the stats of the 4-tagged SR

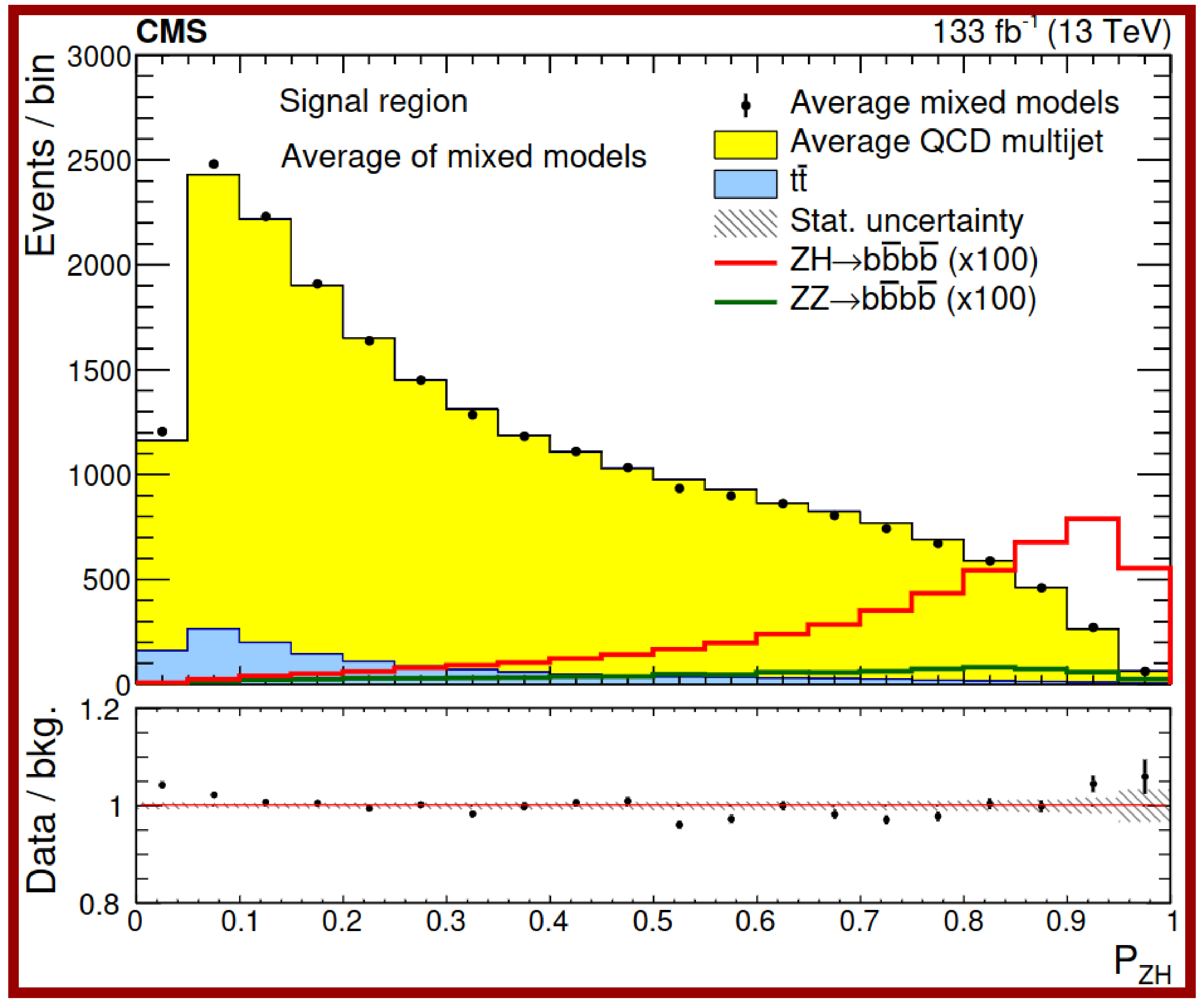
Systematics

1. diffs. btw. mixed models and their averages
2. diffs. btw. bkgd. model and mixed models
3. check fit robustness against the addition of an unconstrained signal template

Not suffering from low stats!

ZZ/ZH→4b: Results and Prospects

- Fit validated using a mixed model replacing the 4-tag dataset
- Combined fit in ZZ and ZH
  - Similar sensitivities despite different xsecs
  - ZH has more efficiency and less background



	ZZ	ZH
μ(exp.)	$1^{+1.9}_{-1.7}$ $(1^{+1.4}_{-1.3})$	$1^{+1.5}_{-1.4}$ $(1^{+1.1}_{-1.1})$
μ(obs.)	$0.0^{+2.0}_{-1.7}$	$2.2^{+0.9}_{-0.8}$
Limit(exp.)	3.8 (2.8)	2.9 (2.3)
Limit(obs.)	3.8	5.0

ZH will likely be observed first!

Importantly: We now have a principled and precise way of measuring the most important systematics directly in the SR.

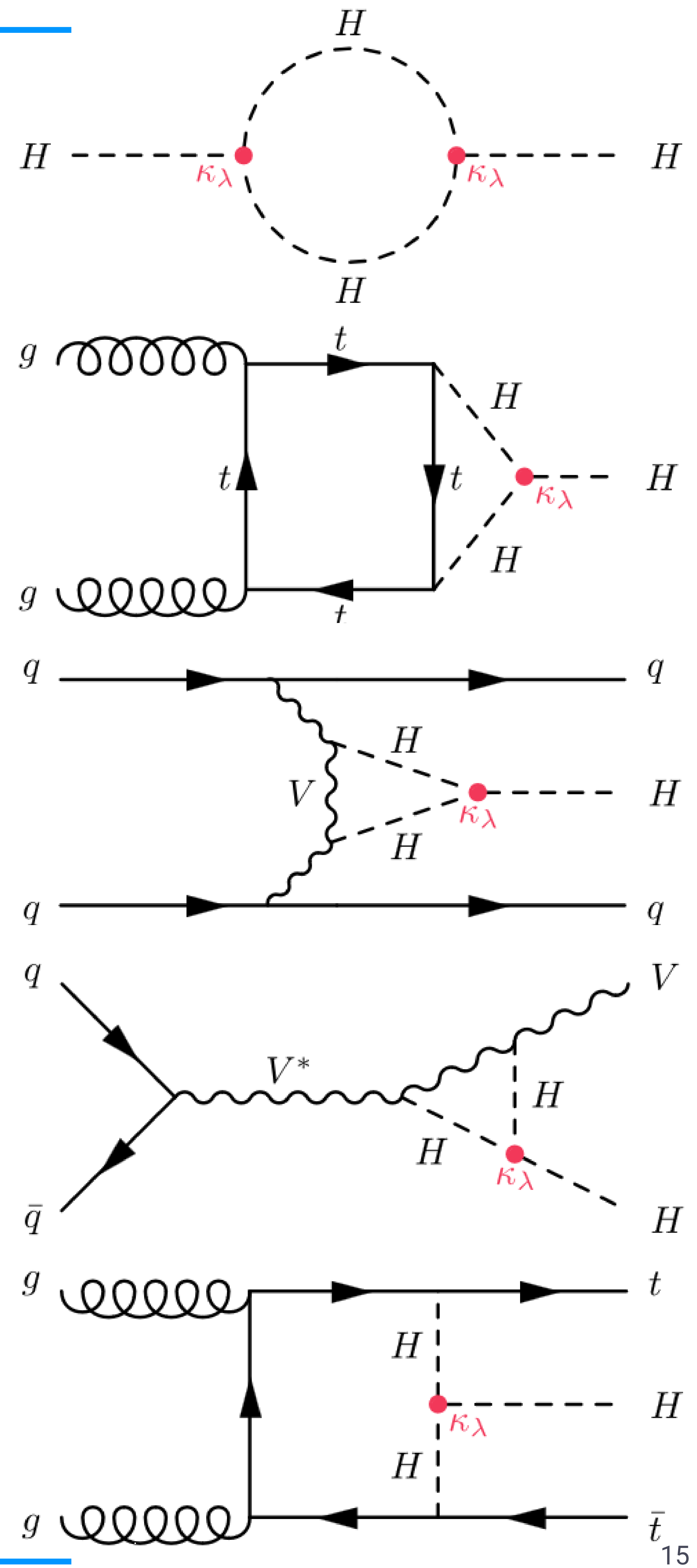
Combination H+HH

- We can exploit NLO corrections to single-H which depend on k_λ
  - largest sensitivity is present in VH and ttH processes (up to 10%)

- **Complementarity**
  - Single-H provides stronger constraints on H couplings to fermions and vector bosons
  - HH is more sensitive to $\mathbf{k_\lambda}$

- Main challenge: estimate and efficiently remove overlaps between signal region of different analysis
  - additional selections are applied and/or
  - the least sensitive category/analysis is removed
  - example: HH→bbZZ is removed in favour of H→ZZ→4l

- The modelling of systematics in HH processes is generally simpler due to their limited statistics



CMS-PAS-HIG-23-006

Combination H+HH

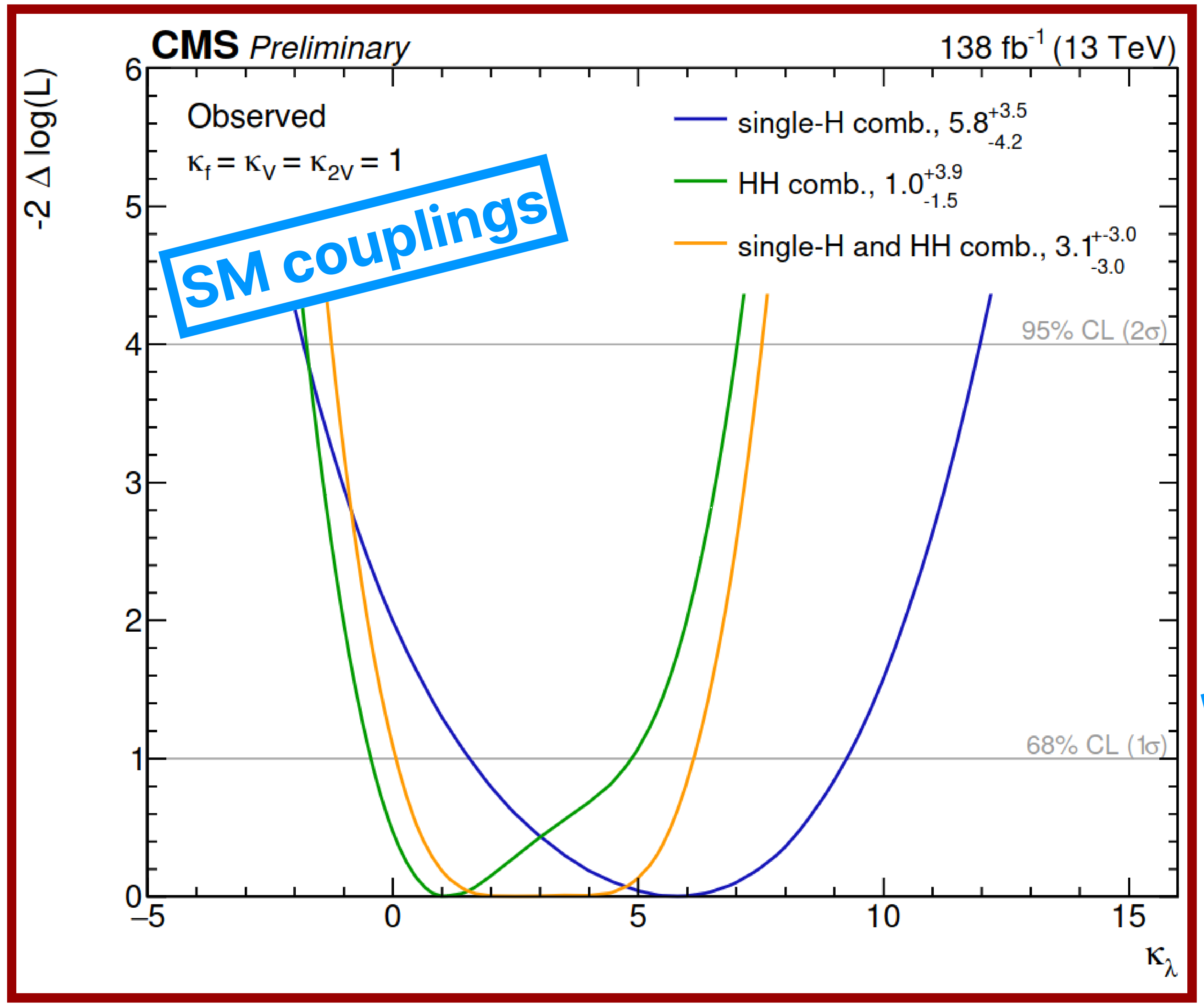
Setting couplings to SM

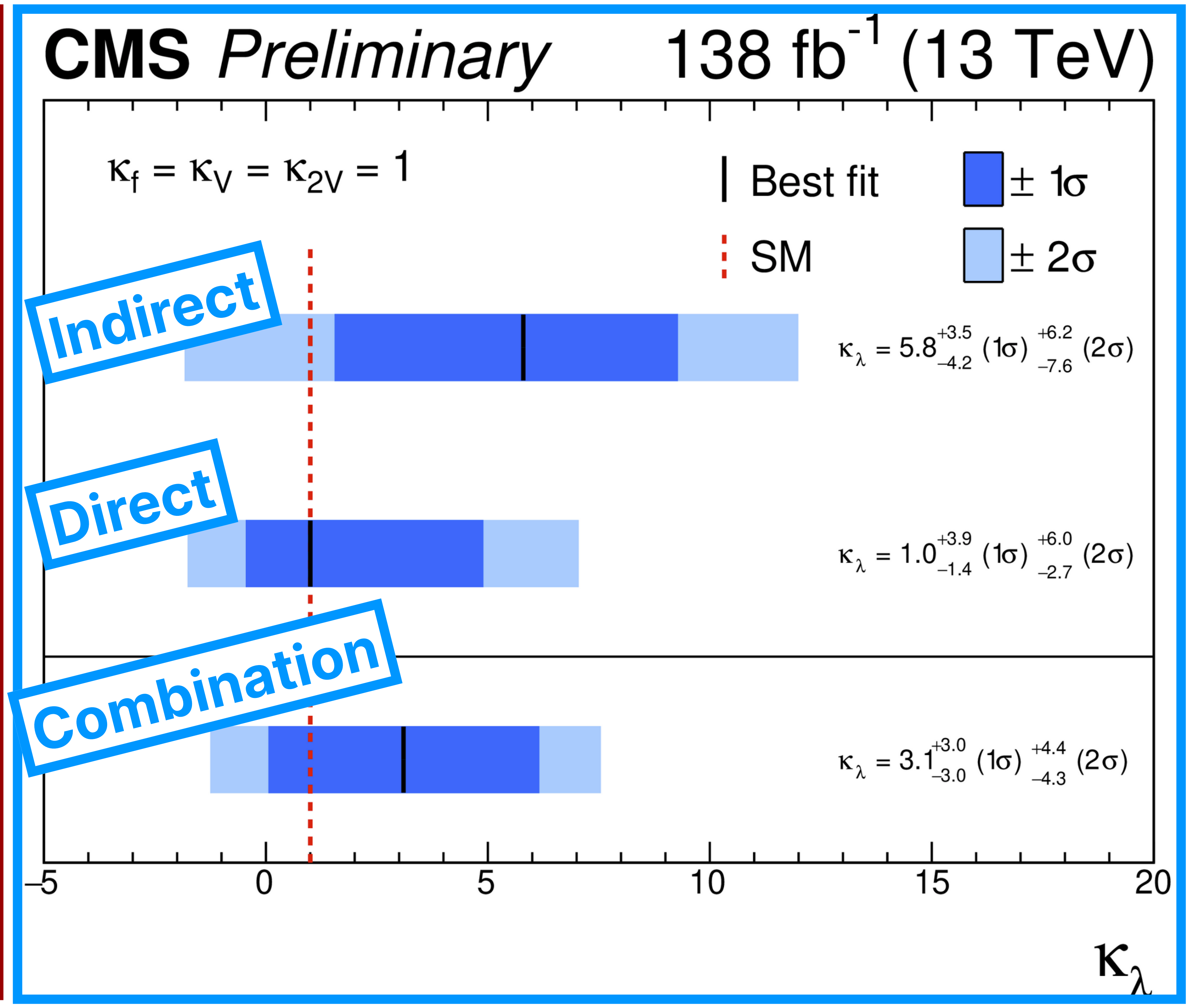
- $-1.2(-2.0) < k_{\lambda} < 7.5\ (7.7)$

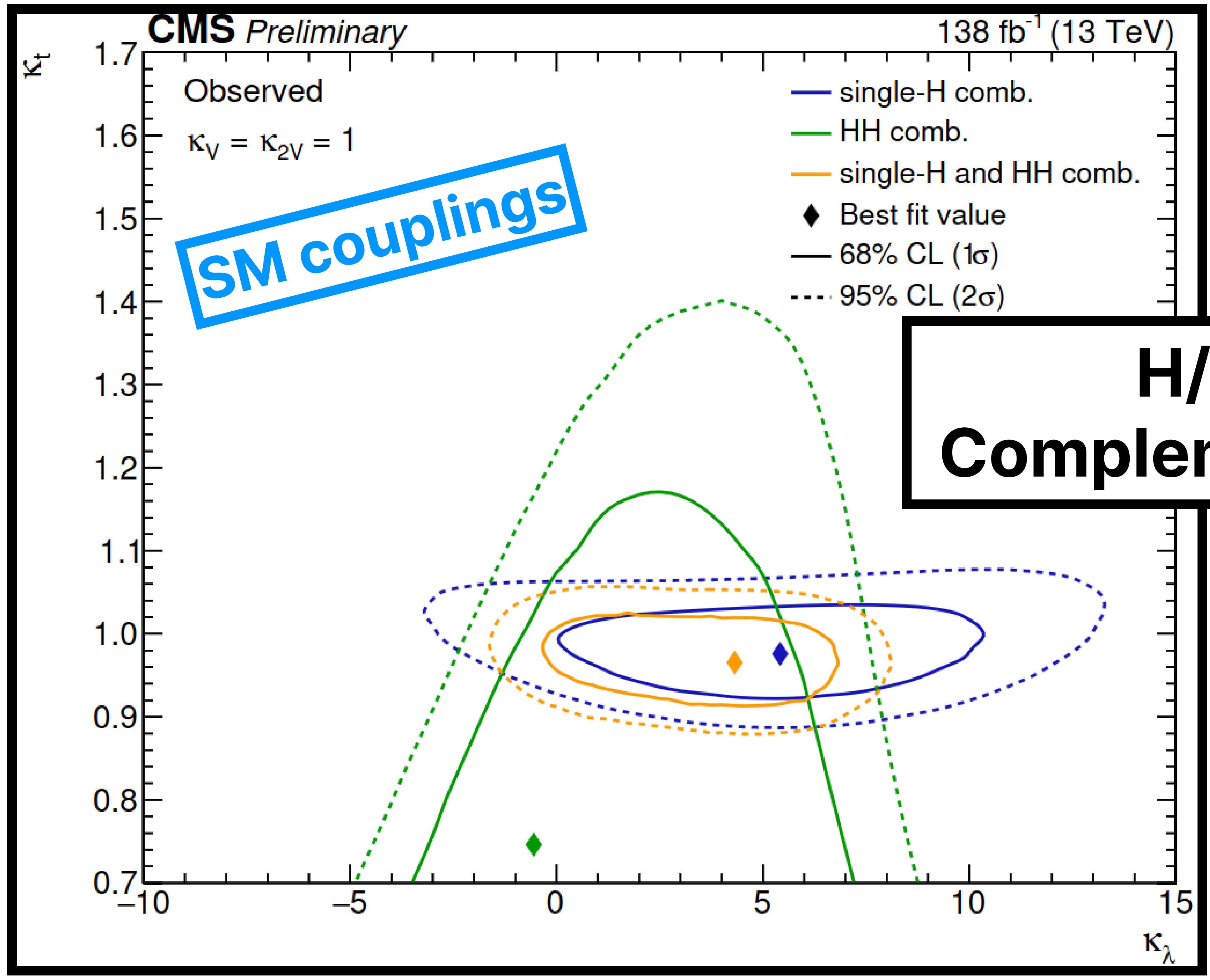
Let couplings free in the fit

- $-1.4(-2.3) < k_{\lambda} < 7.8\ (7.8)$

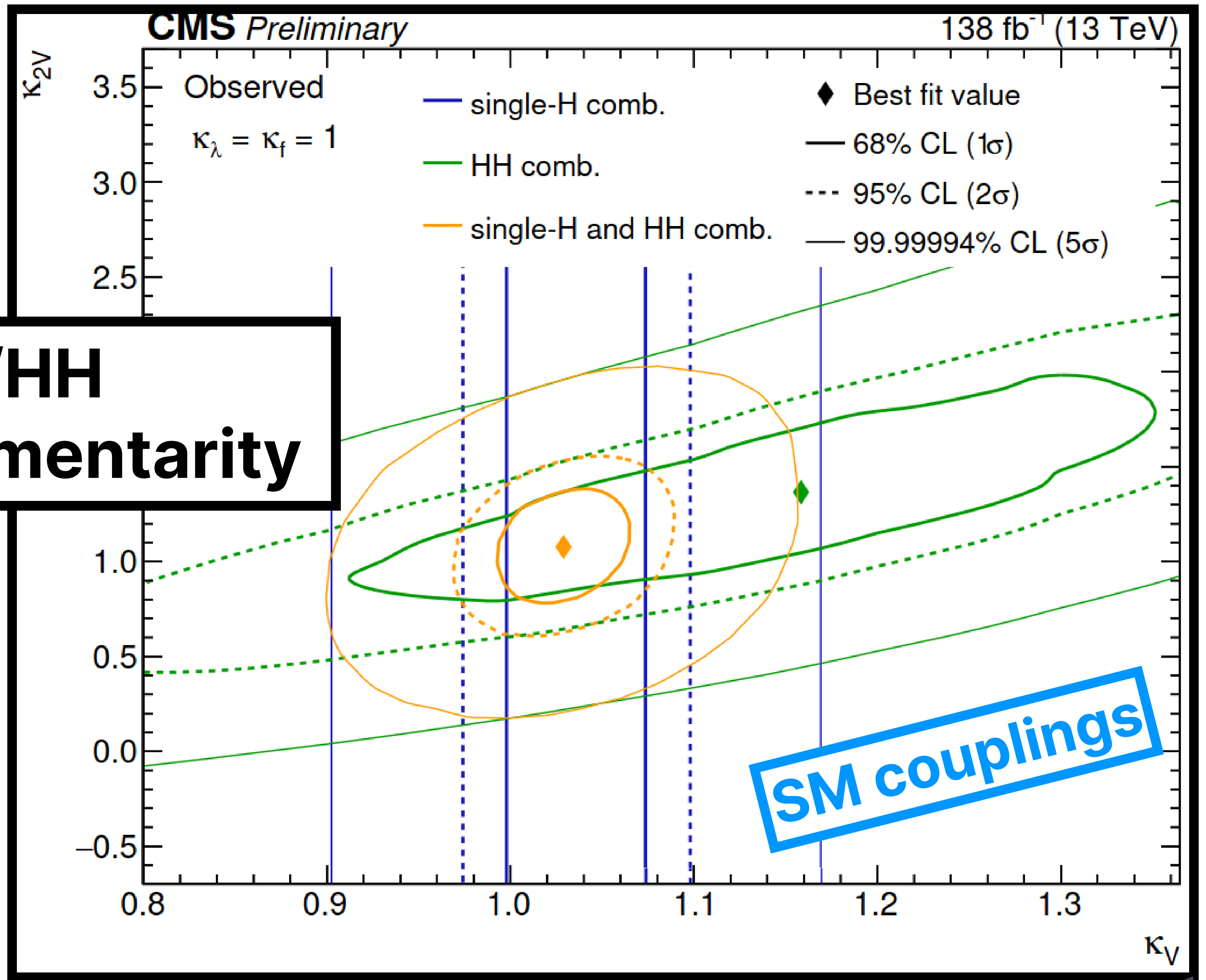
- Similar sensitivity to k_{λ} as in the ATLAS H+HH comb.
- **k_{2V}=0** excluded at **>5σ**







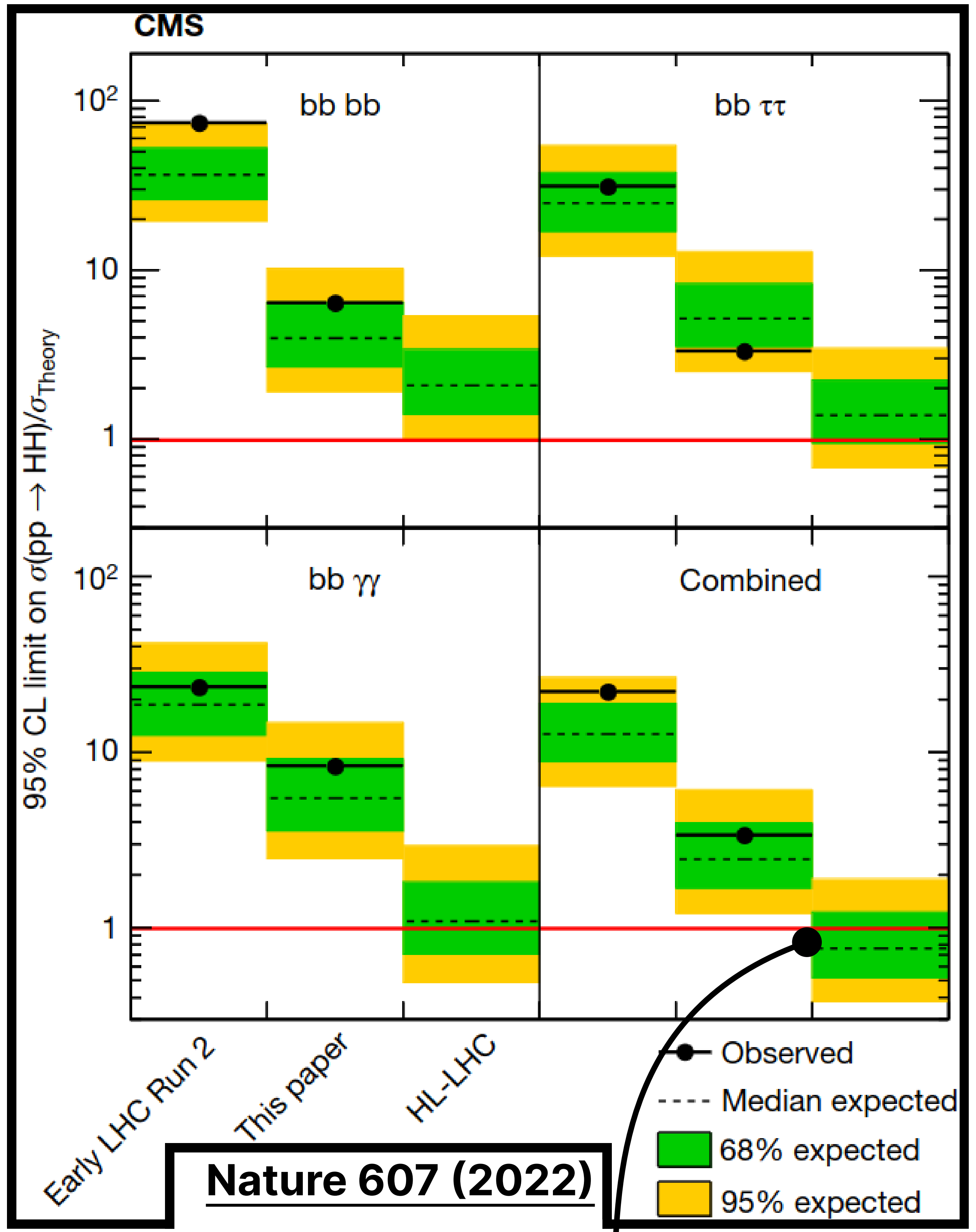
H/HH Complementarity



CMS-PAS-HIG-23-006 + additional figure

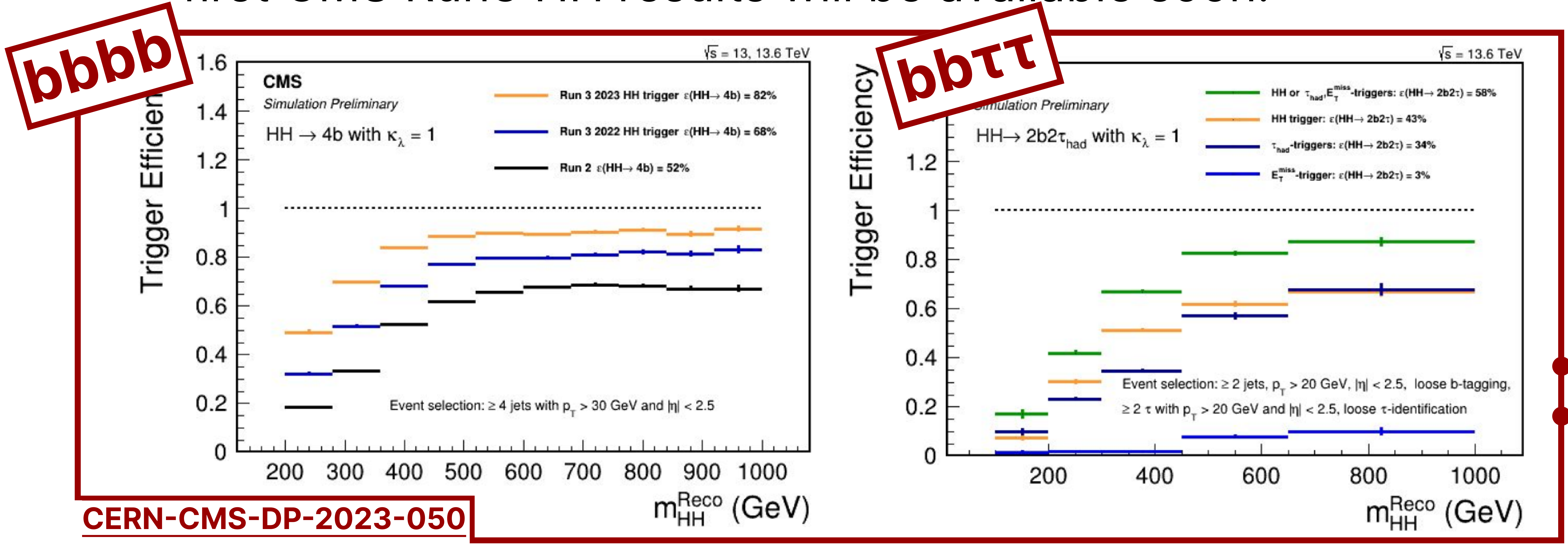
Run 3 and beyond

- **k_λ** 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
  - we are **close to SM HH sensitivity and k_{2V}=0 was excluded**
- Run 3 is an opportunity for improvement before the HL-LHC
  - **improved trigger strategy** will boost HH searches
  - **improved taggers**: transformers, PNet for τ-jets, ...
  - several analysis might benefit from synthetic datasets
  - first CMS Run3 HH results will be available soon!



Nature 607 (2022)

We are getting close...



CERN-CMS-DP-2023-050

PNet b-tagging at trigger level

Data parking allows lower HT thresholds

Backup

Indico

9/04/2024

DIS Grenoble

ZZ/ZH→4b: Weight for additional jet activity

- Requiring 3 b-tagged jets biases the SR (which has 4)
- A "Jet Combinatorial Model" weight is introduced to improve the background description of the four-tag sample
  - introduce "anti-b-tagged" jets: jets not passing the looser b-tagging requirement
  - considers all combinations of anti-b-tagged jets where at least one is treated like a real b-jet (so 3+1 b-jets, or 3+2, or 3+3, or 3+...)

number of anti-b-tagged jets

"pair-enhancement" factor

$$w_{\mathrm{JCM}} = \begin{cases} t\sum_{i=1}^{n} \binom{n}{i} f^i (1-f)^{n-i} (1 + e/n^d) & (3+i) \text{ even} \\ t\sum_{i=1}^{n} \binom{n}{i} f^i (1-f)^{n-i} & (3+i) \text{ odd}, \end{cases}$$

normalization to account for the looser b-tag requirement of the 3-tag sample

constant per-jet "transfer factor"

dilution of "pair-enhancement" with increasing jet multiplicity

number of b-tagged jets in the event

The parameters ***t***, ***f***, ***e*** and ***d*** are obtained with a fit to the distributions of jet and b-jet multiplicities

Technique introduced in the ATLAS HH→4b result

Motivation: EFT

- Given the absence of clear NP signals: EFTs!
- Look for effects from an unknown high-energy theory in a model independent way

Taylor expanding the SM in (E,vev)/Λ:

violate L,
some violate B,
high suppression

further suppressed

19 parameters

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda_i} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} \mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda_i^3} \mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda_i^4} \mathcal{O}_i^{(8)} + \dots$$

1 operator type
(Weinberg operator)

Majorana ν masses
(m_ν small -> Λ_i high)

2499 parameters with ΔL=ΔB=0
+ O(300) with ΔL=ΔB=1 ⟶ proton decay -> Λ_i high

76 assuming $U(3)^5$ flavor symmetry

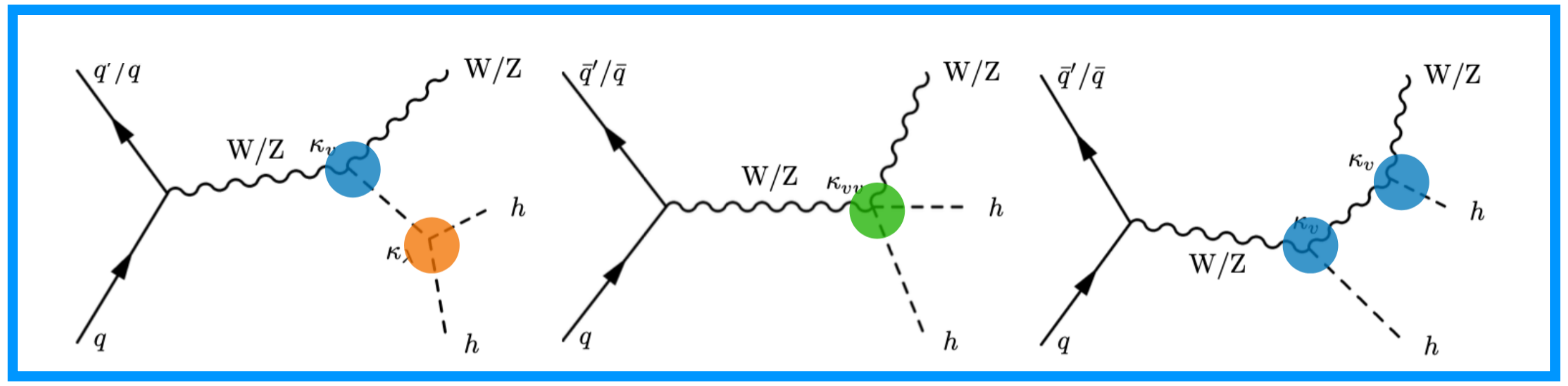
Credit: B. Moser

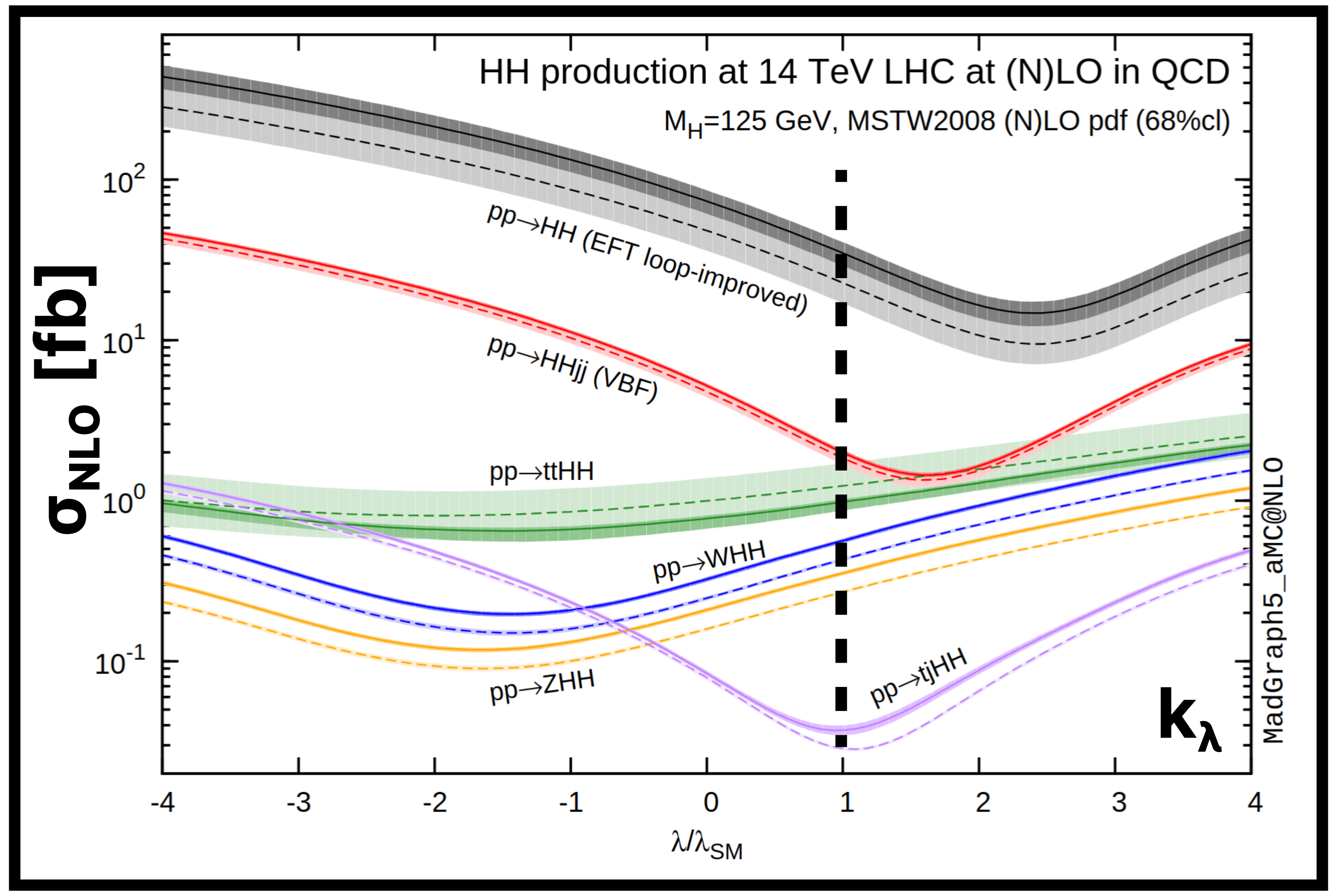
The first two quark families and all three lepton families are taken to be massless

VHH (→4b)

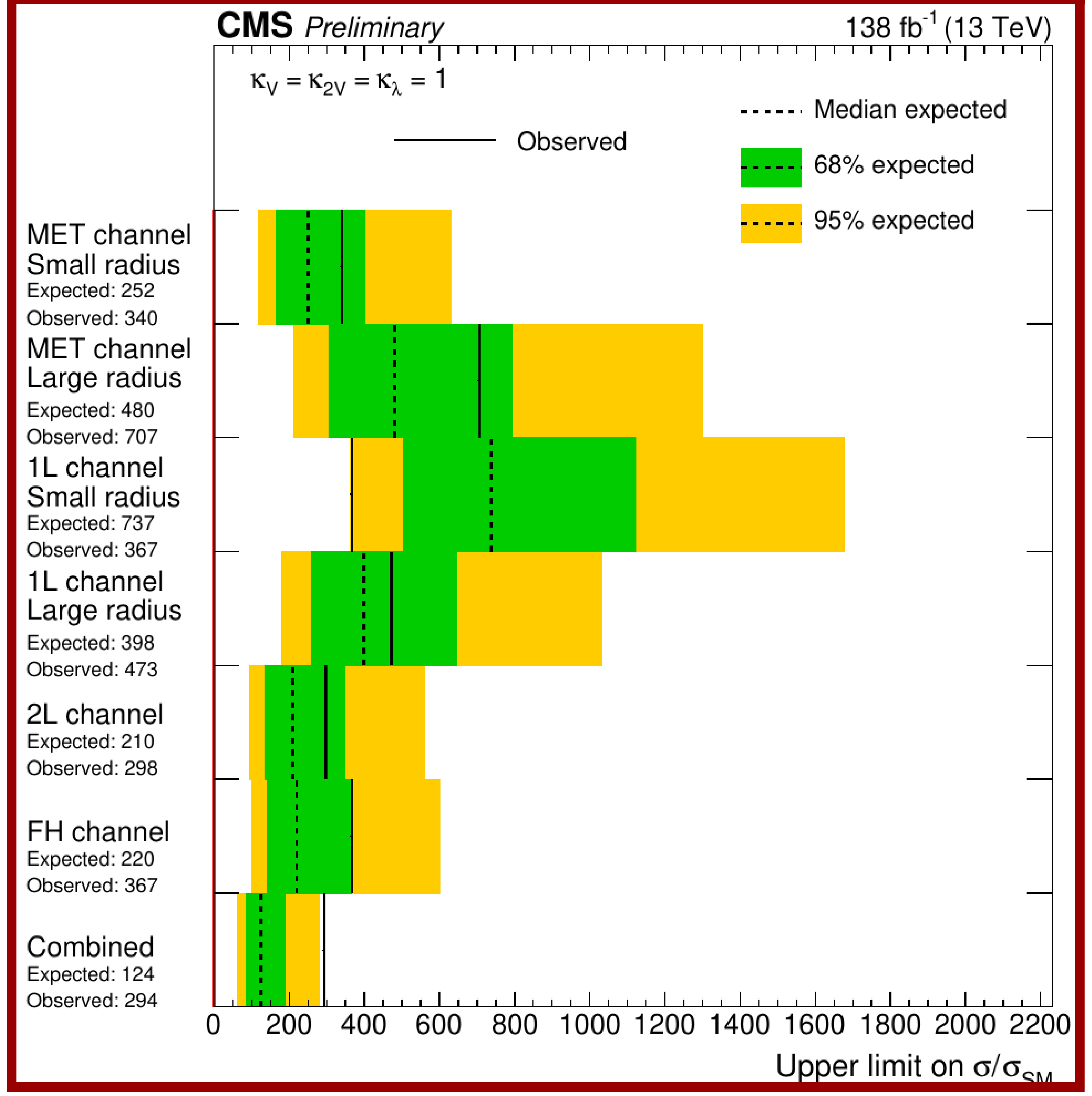
- **VHH for the 1st time at CMS**
  - **~110 events expected** (before H decay to b's, without selection)
- **Complementary to ggF and VBF!**
  - especially for $4 < k_\lambda < 7$
  - because xsec comparable to ggF and VBF HH
- **4 channels**: 0/1/2 leptons and invis.
- **59 categories**: resolv./bosted, 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_λ or k_{2V} hypoth.

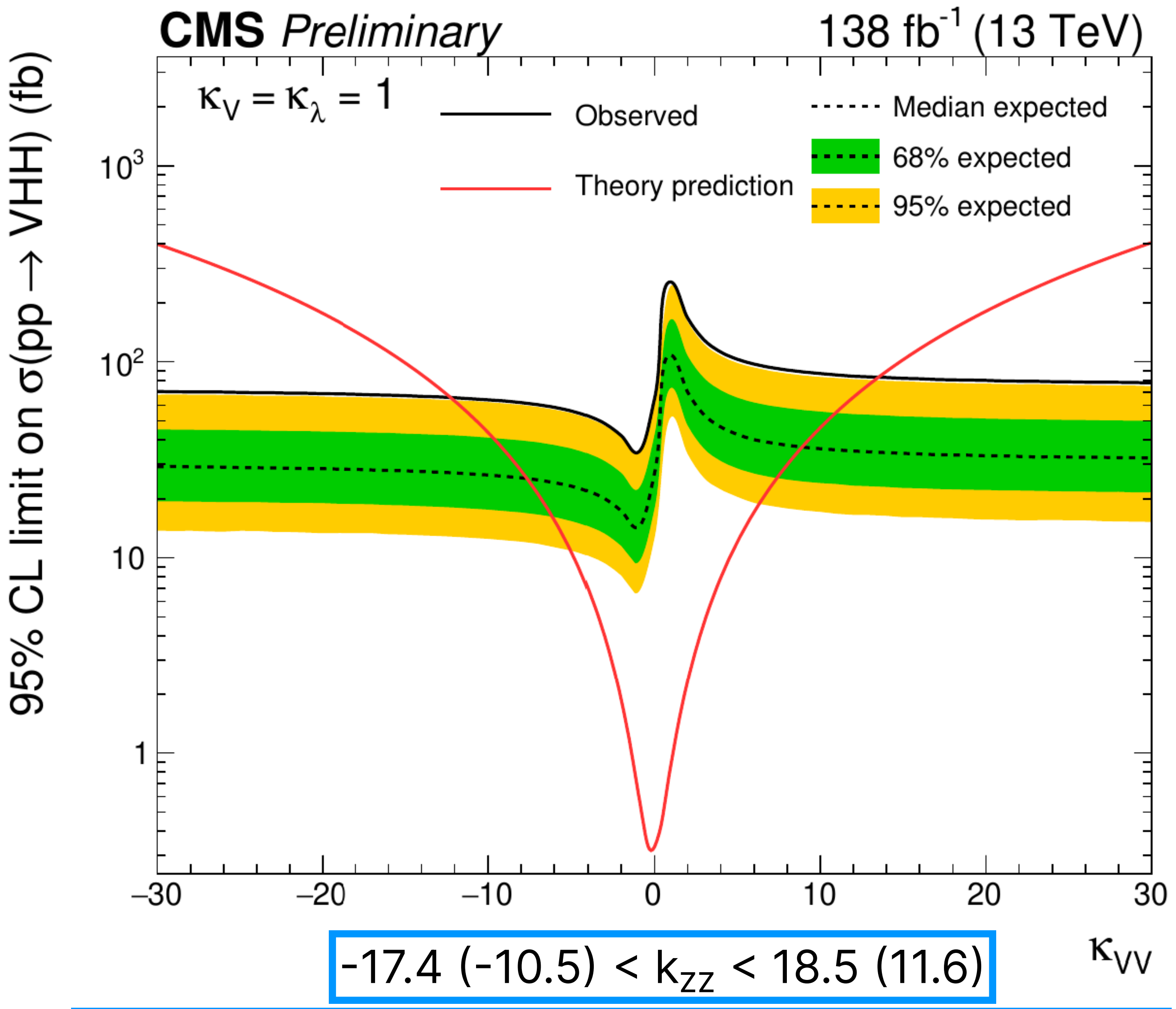
VHH LO





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

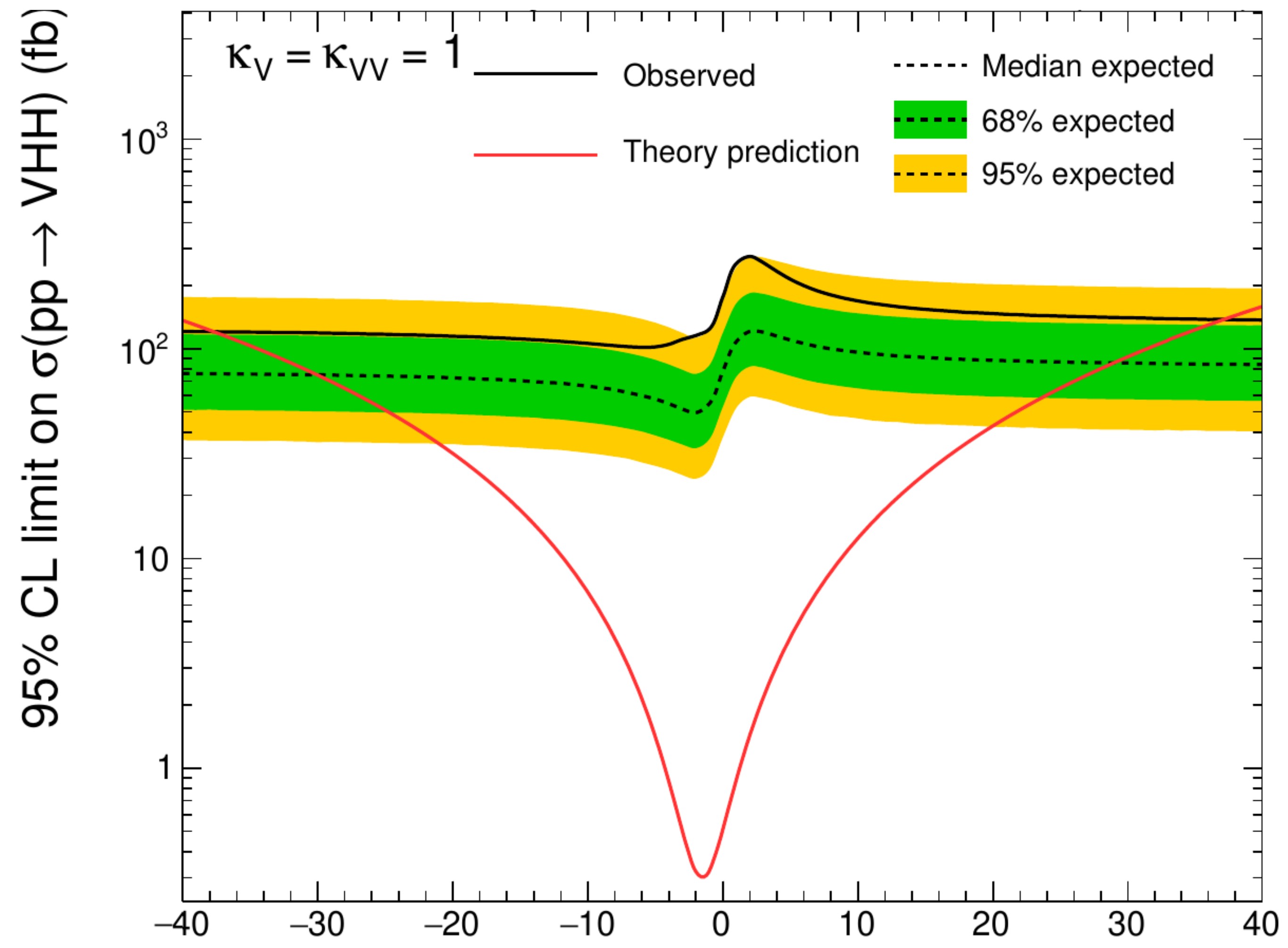




$-17.4\ (-10.5) < k_{ZZ} < 18.5\ (11.6)$

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

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

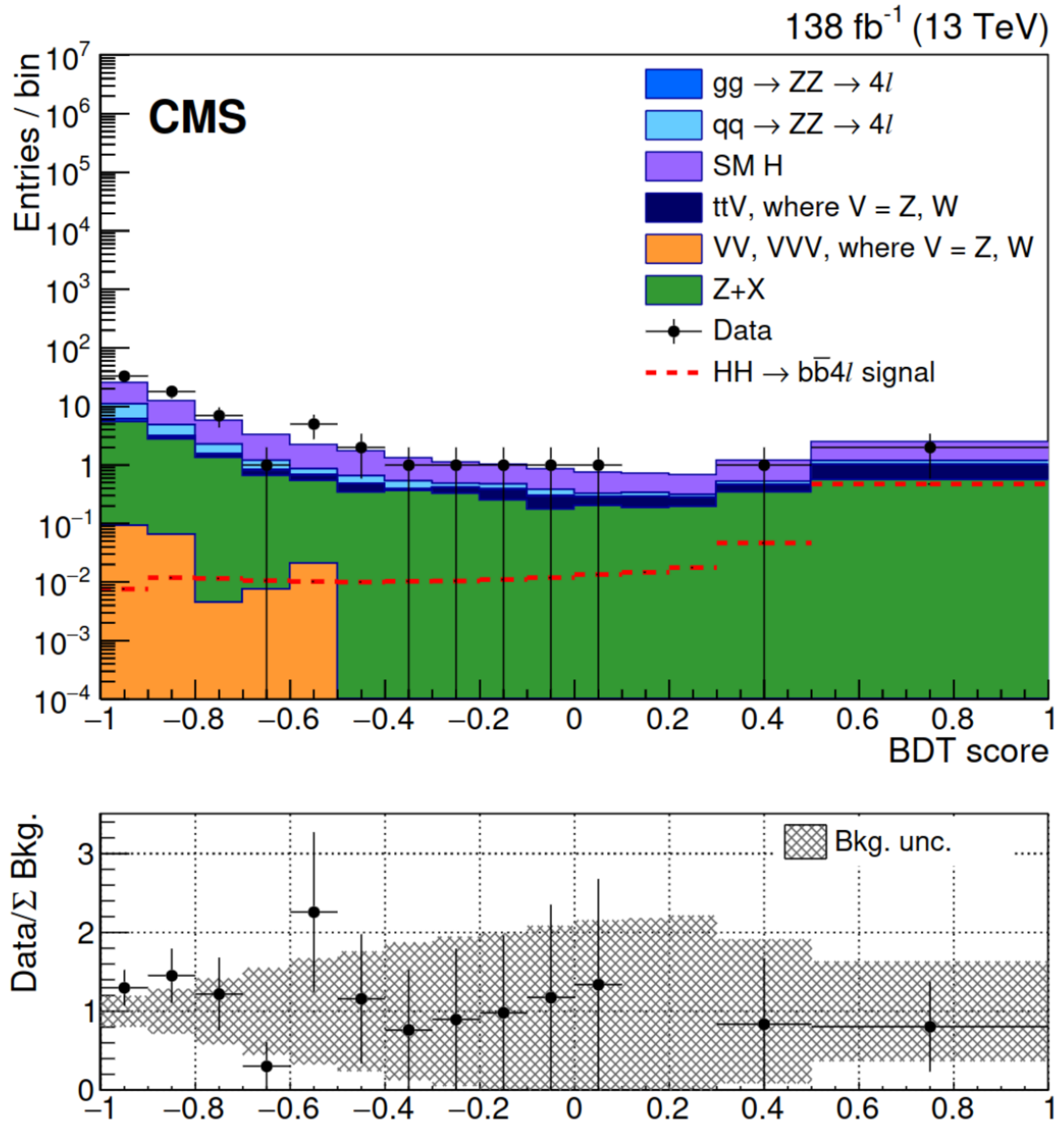


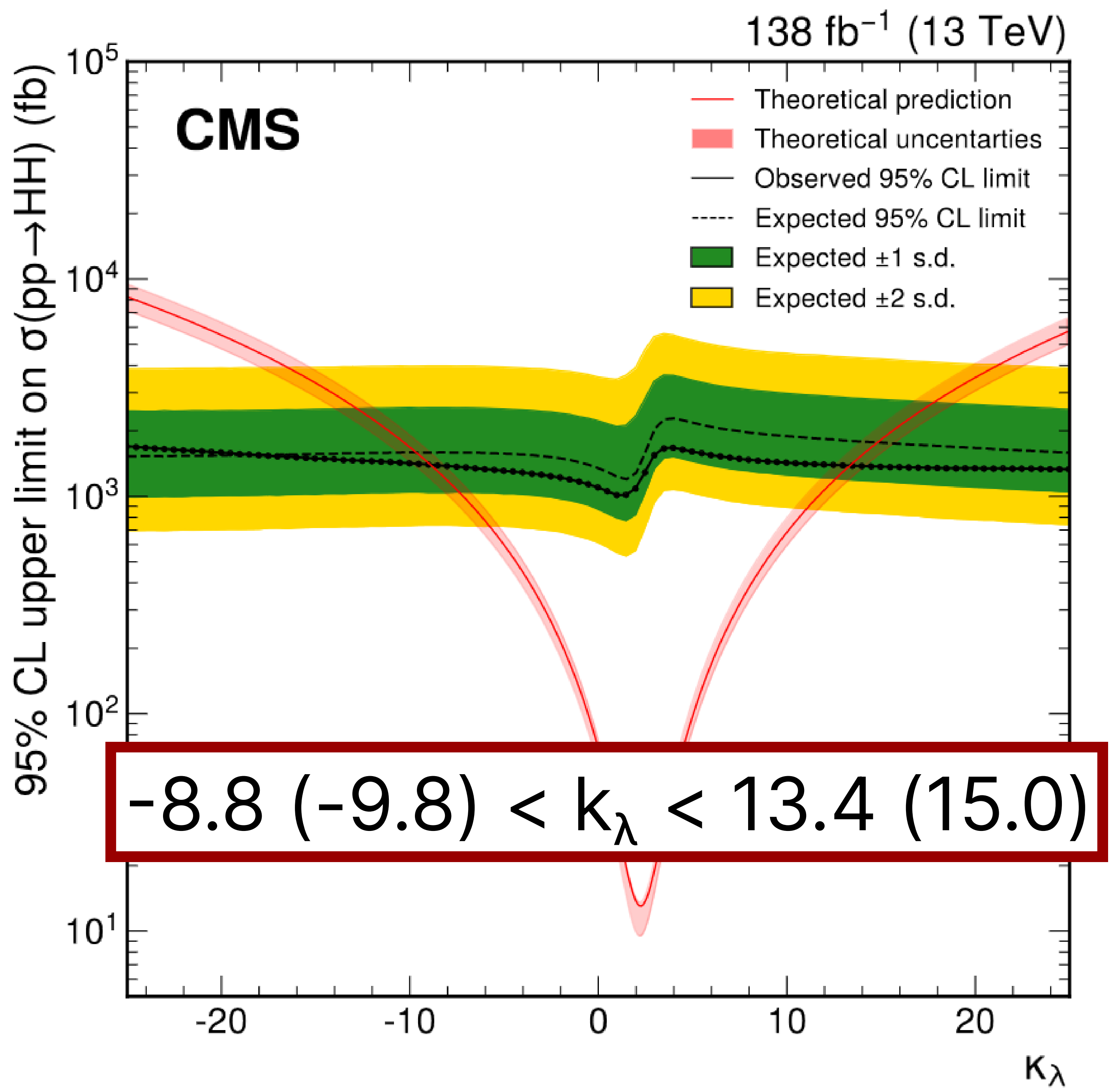
$-37.7\ (-30.1) < k_\lambda < 37.2\ (28.9)$

HH→bbZZ ggF

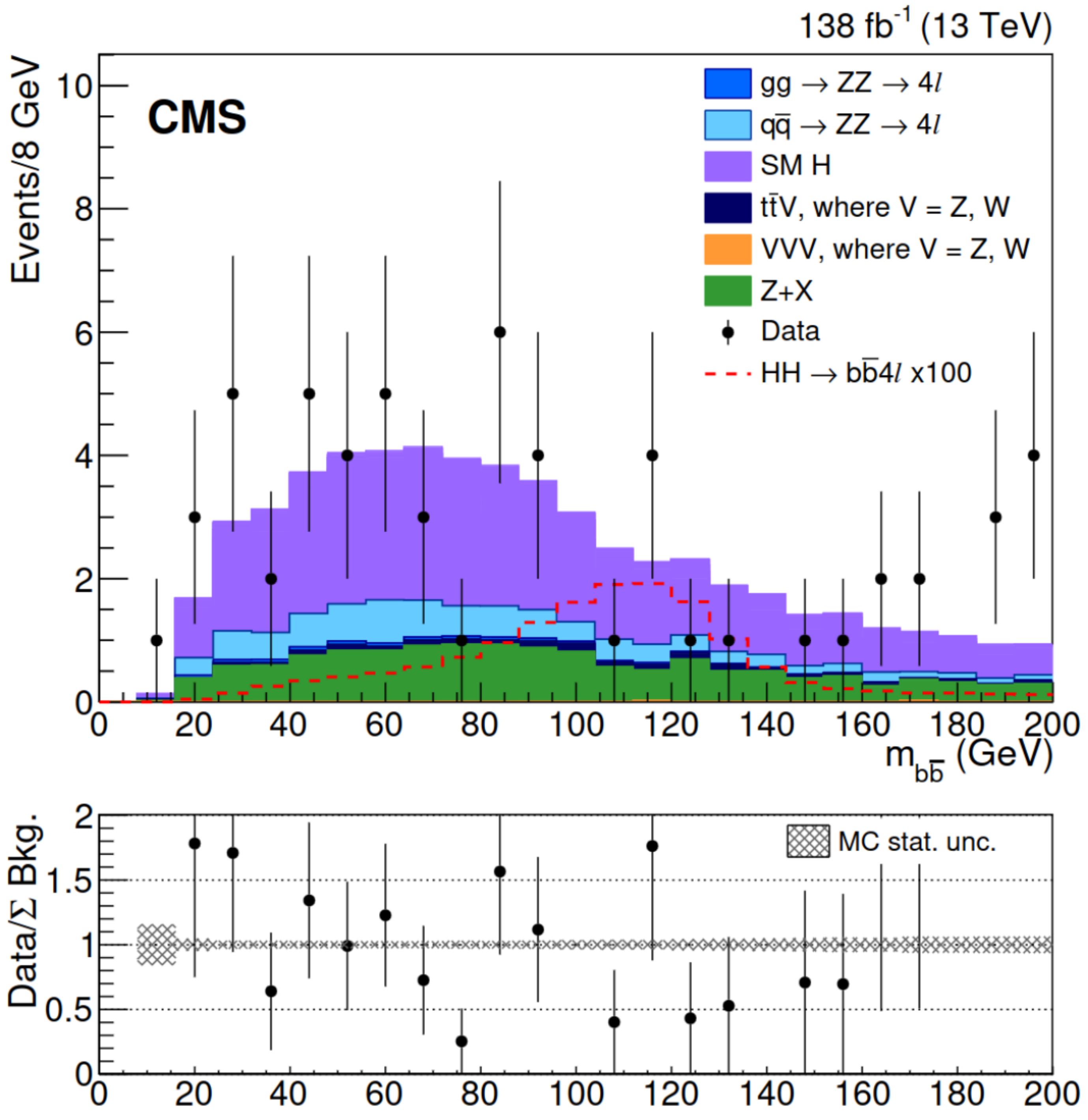
- H→ZZ taken from HIG-19-001
- Select 2 extra jets w/ highest DeepCSV score
- "Fake" non-prompt leptons estimated from data
  - sources: e→ɣ conversion, misrec. jets, HF decays
  - measure fake rate in Z + 1l + 2jets region
  - apply fake rate in Z + 2l + 2jets region
- Signal vs bkg. discrimination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

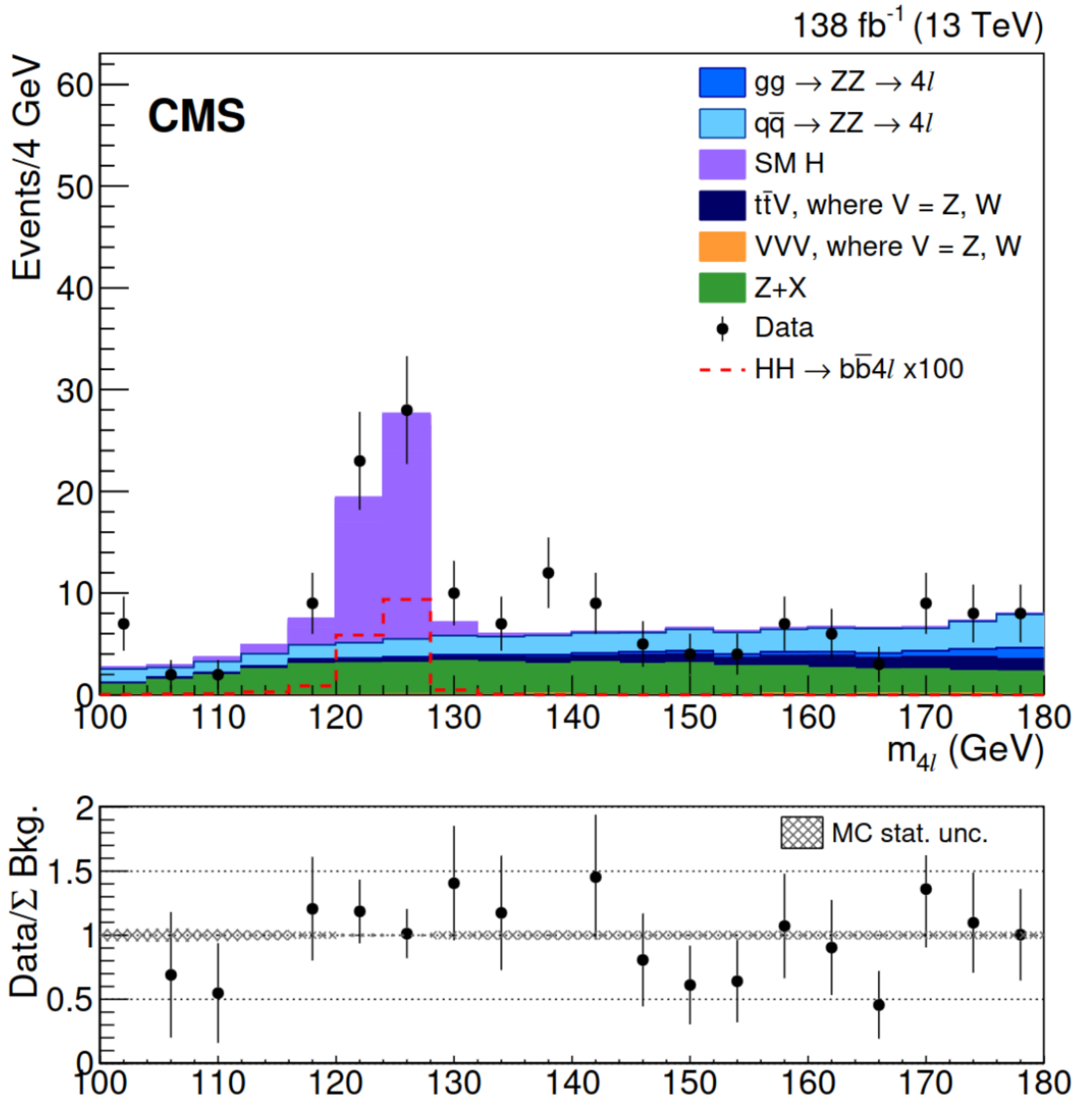
σ_{HH} < 32.4 (39.6) < σ^{SM}_{HH}





-8.8 (-9.8) < k_λ < 13.4 (15.0)





Phys. Lett. B, 842, 137531 (2023)

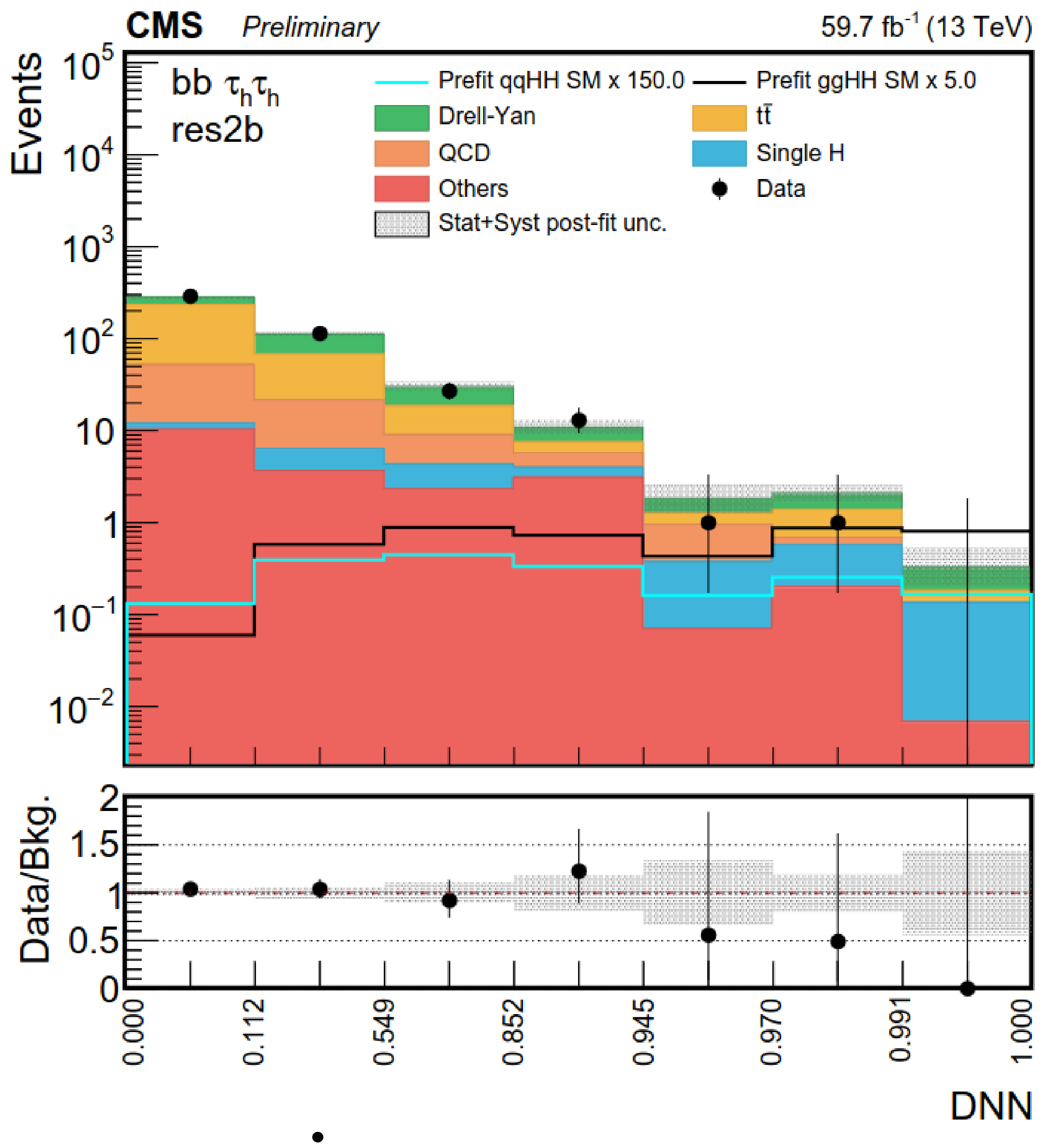
HH→bbττ

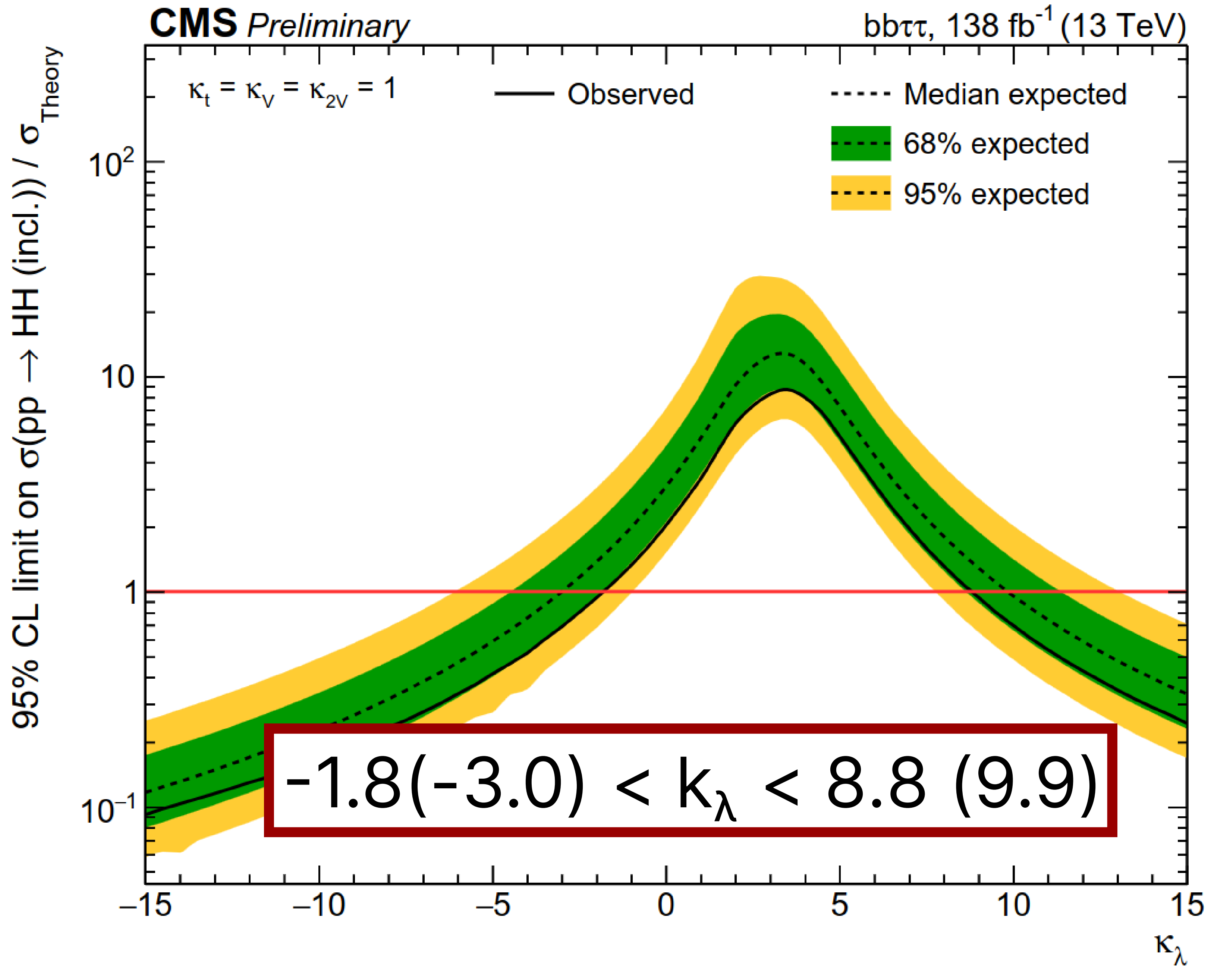
ggF VBF

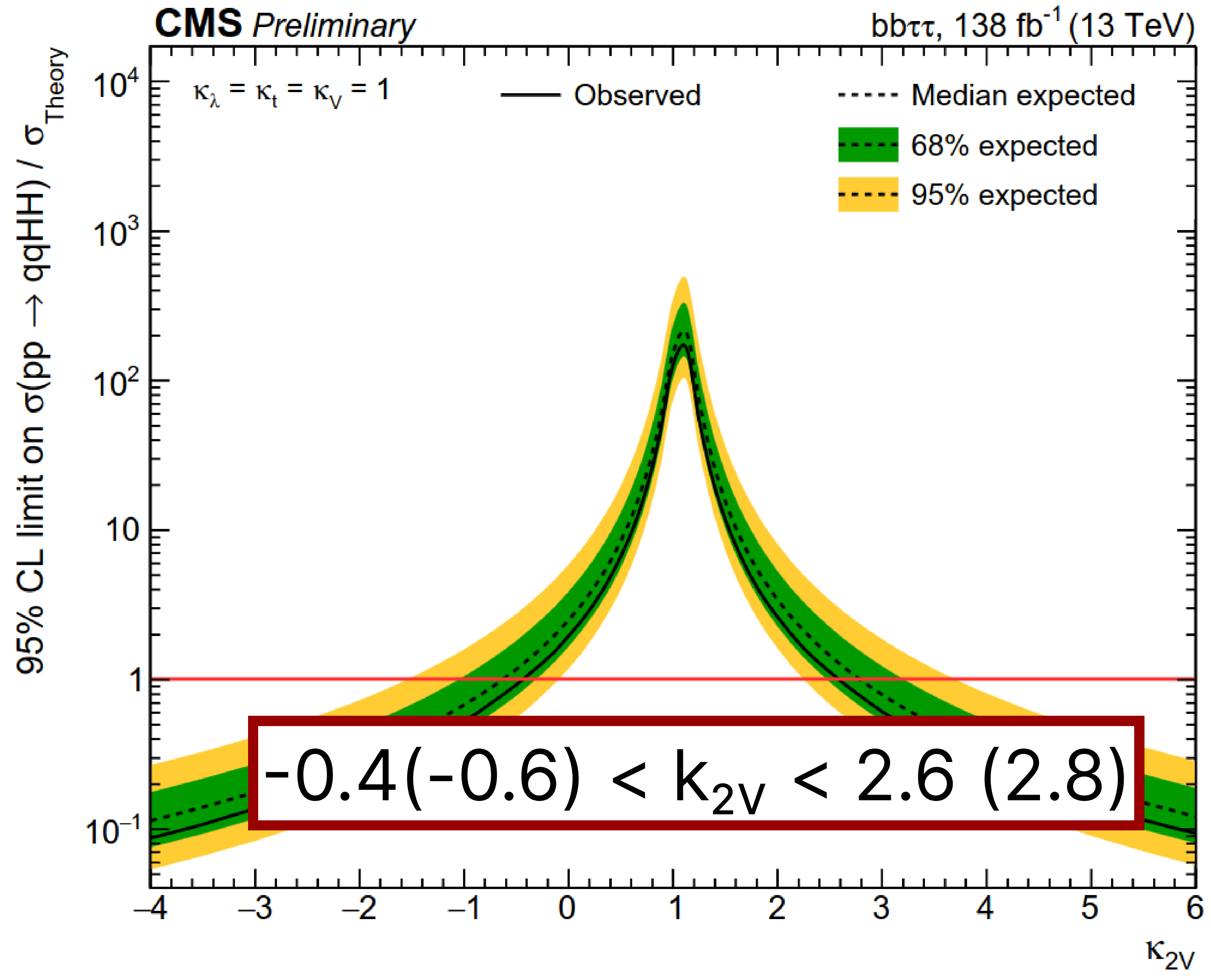
$\sigma_{HH} < 3.3\ (5.2) < \sigma^{SM}_{HH}$

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

- 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

Phys. Rev. Lett. 131, 041803 (2023)

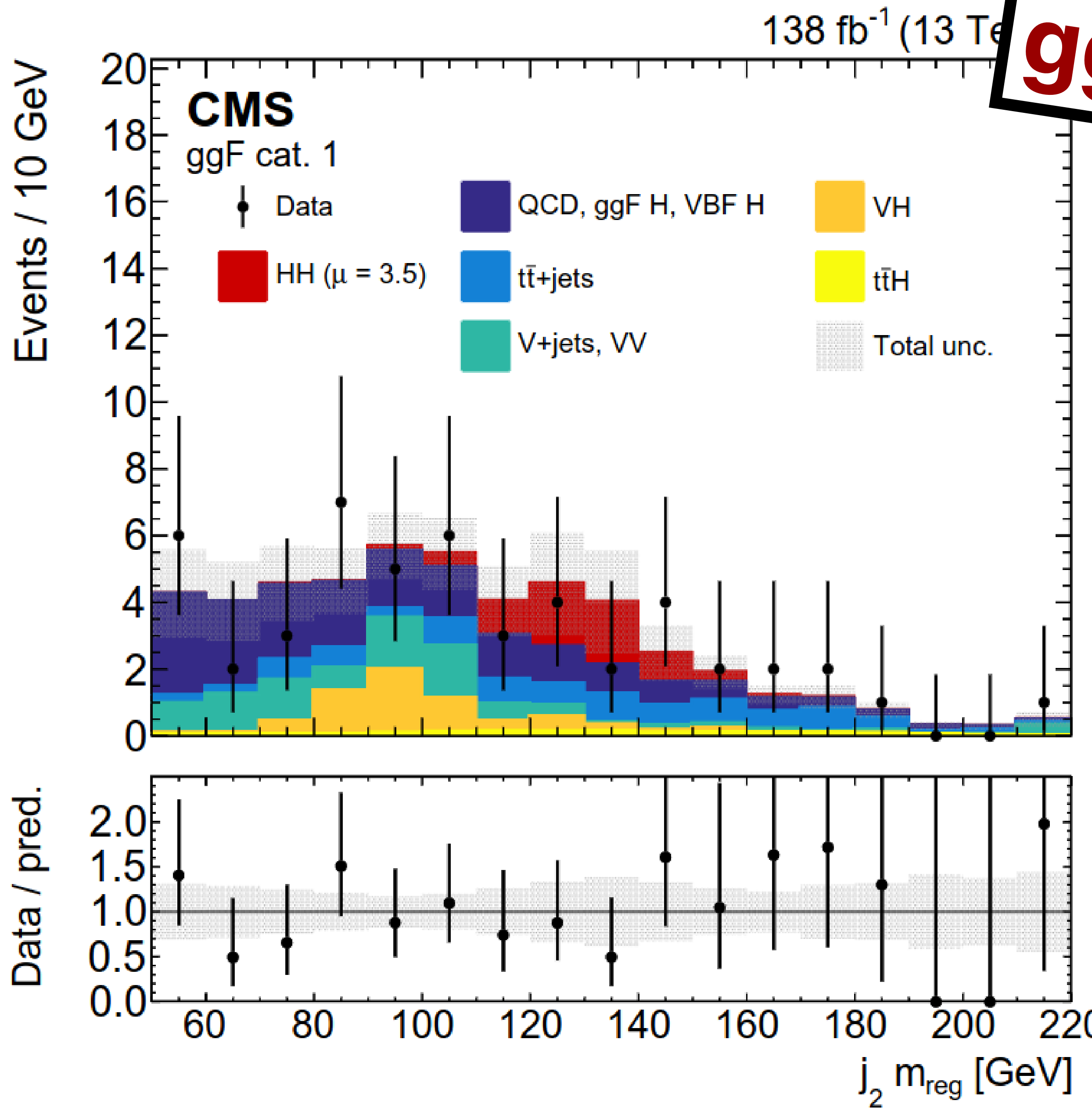
HH→4b boosted

ggF VBF

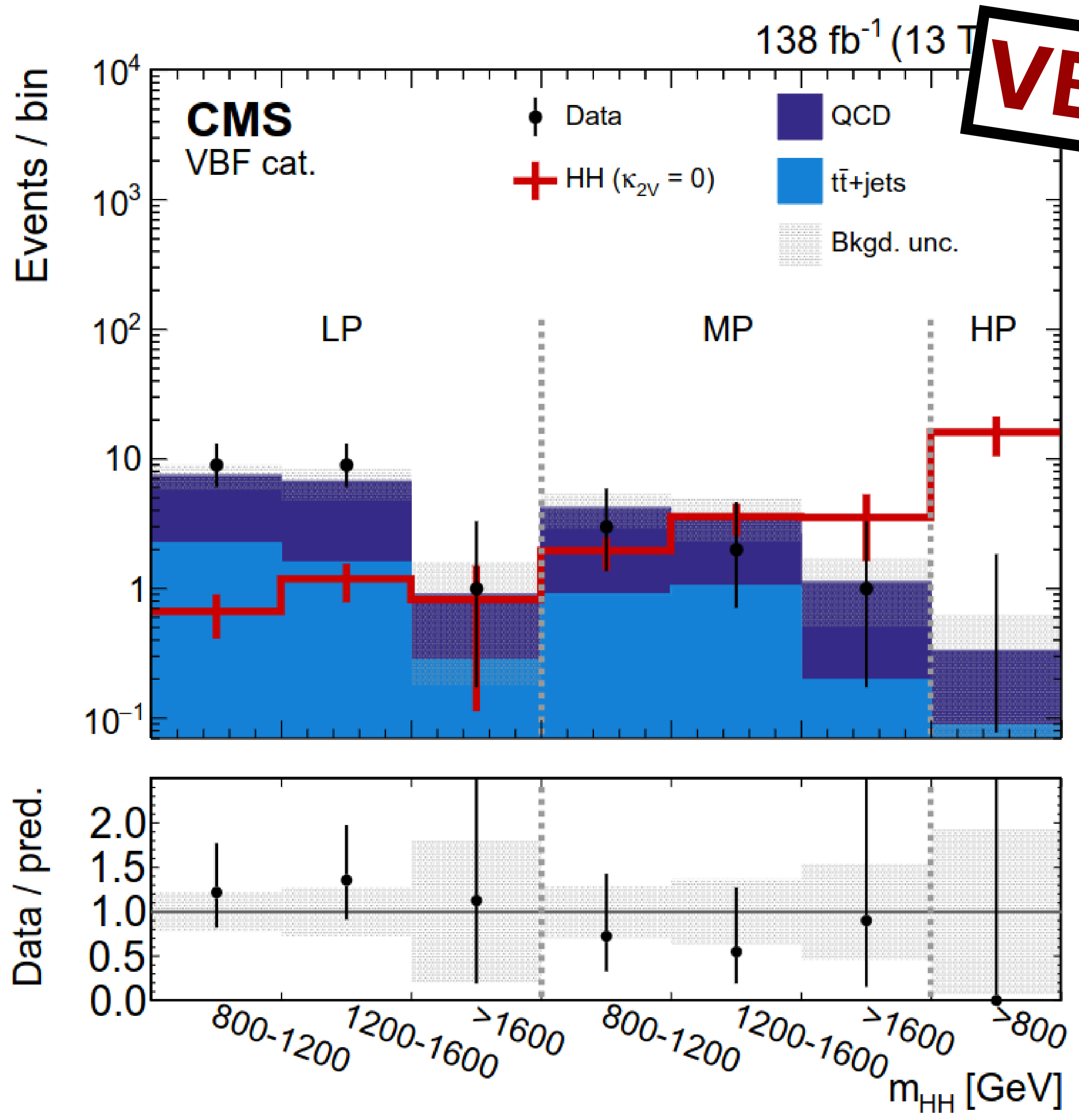
- 2 AK8 jets w/ $p_T(H)$ > 300GeV
- Background: 85% QCD, 15% ttbar
- **PNet tagger for AK8 jets**
  - discriminate QCD vs. b-jets
  - provides 4x improvement in bkg. rejection over DeepAK8-MD
  - p_T-dependent calibration performed w/ data and QCD-enriched MC
- **PNet regressed jet mass m_{PNet}**
  - improved bkg. rejection wrt m_{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_{HH}**

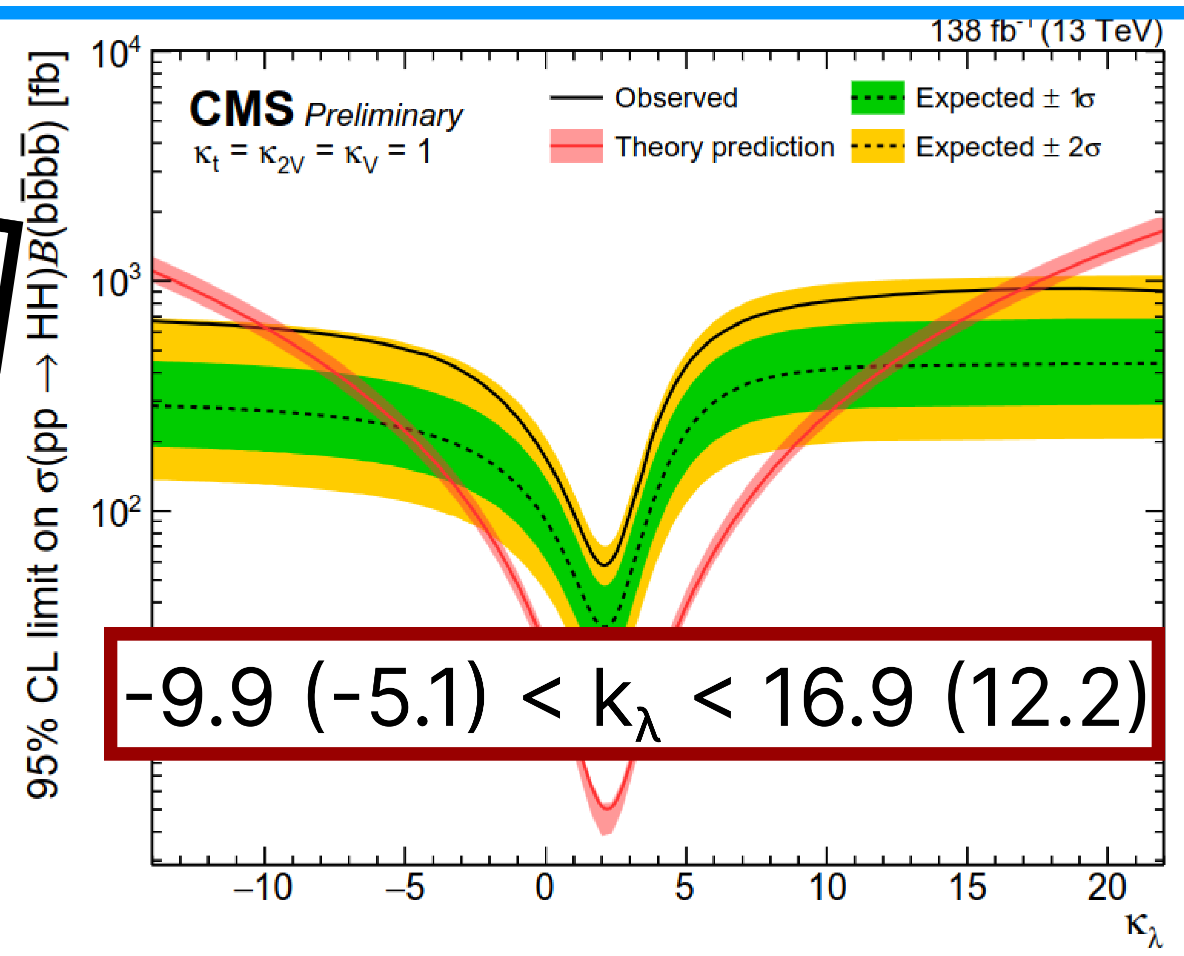
σ_{HH} < 9.9 (5.1) < σ^{SM}_{HH}

ggF

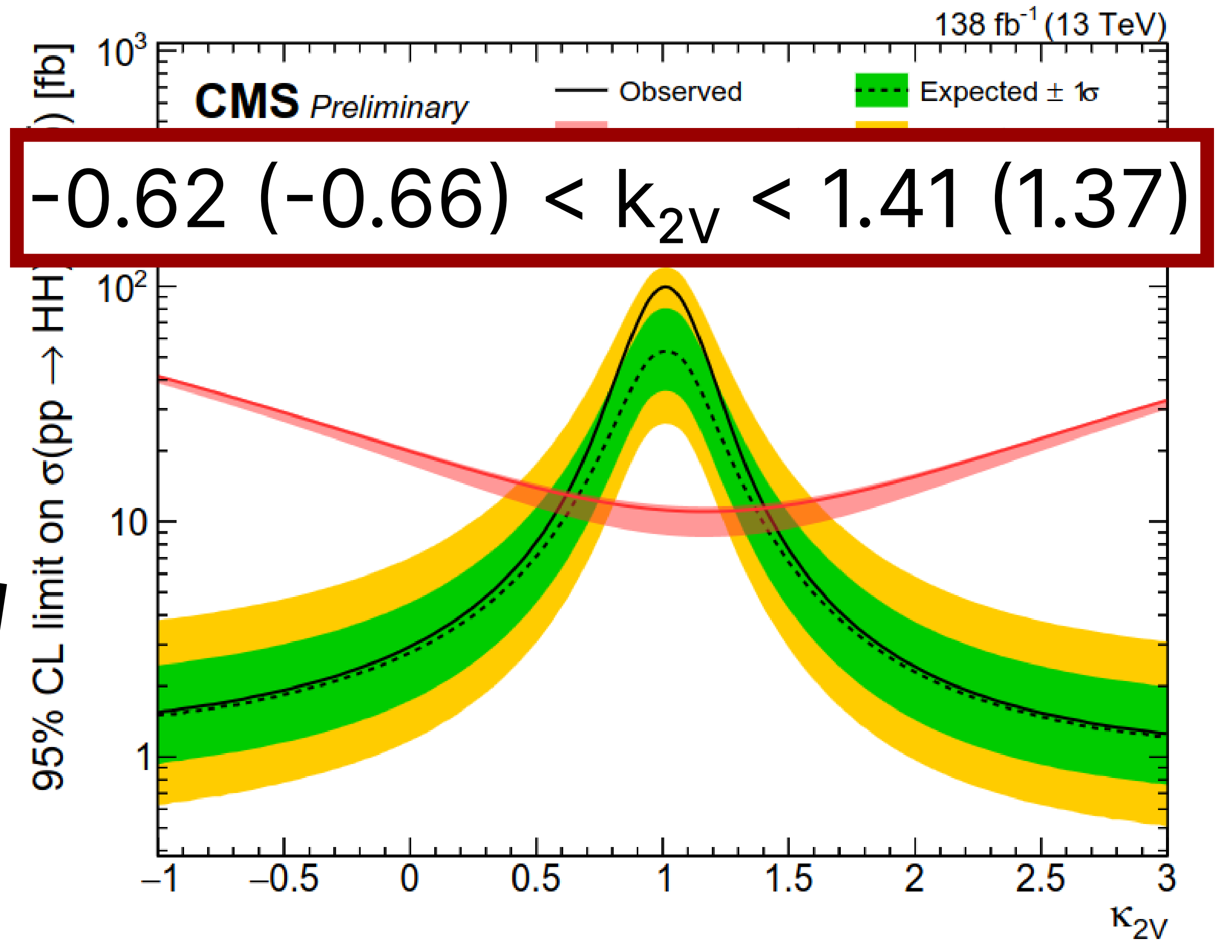


VBF

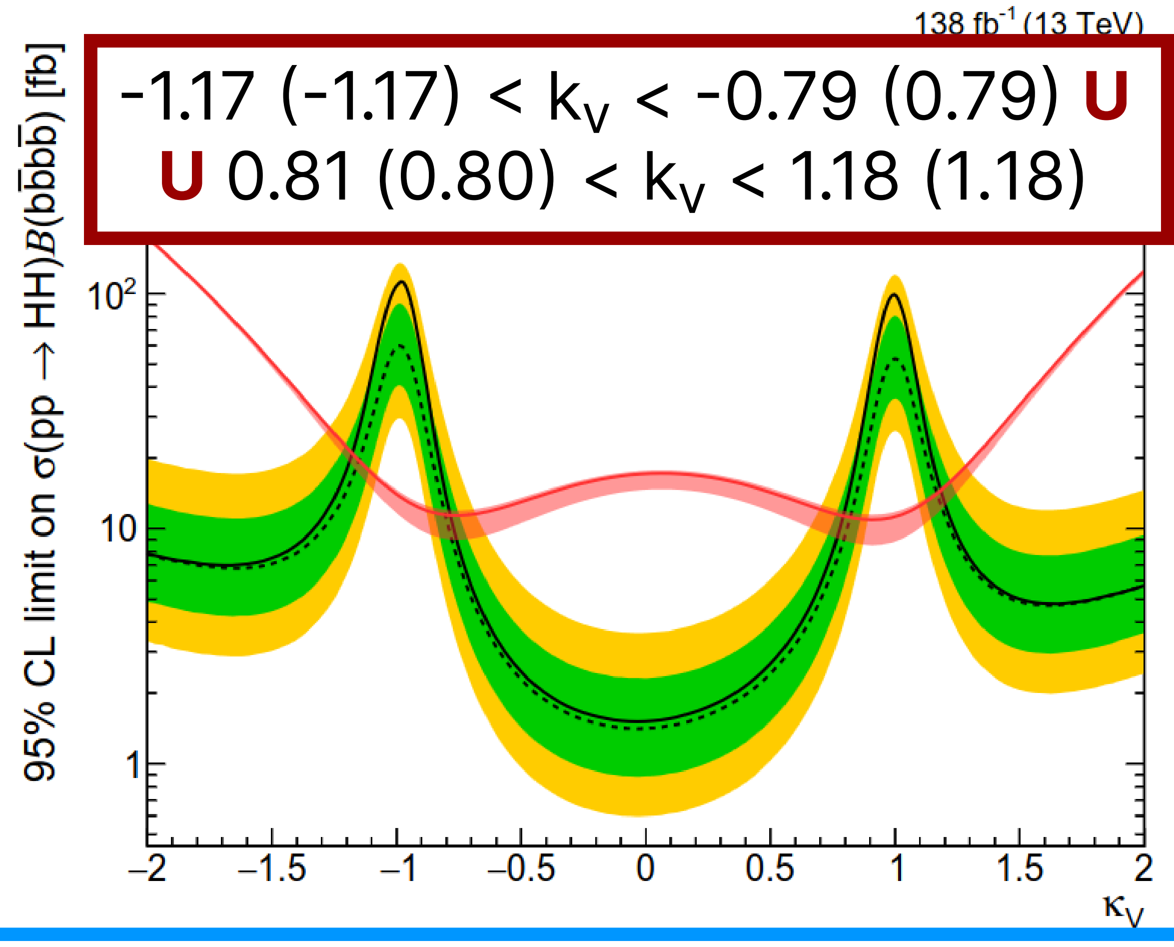




$-9.9\ (-5.1) < k_\lambda < 16.9\ (12.2)$



$-0.62\ (-0.66) < k_{2V} < 1.41\ (1.37)$



$-1.17\ (-1.17) < k_V < -0.79\ (0.79)$ **U**
U $0.81\ (0.80) < k_V < 1.18\ (1.18)$

Phys. Rev. Lett. 129, 081802

HH→4b resolved

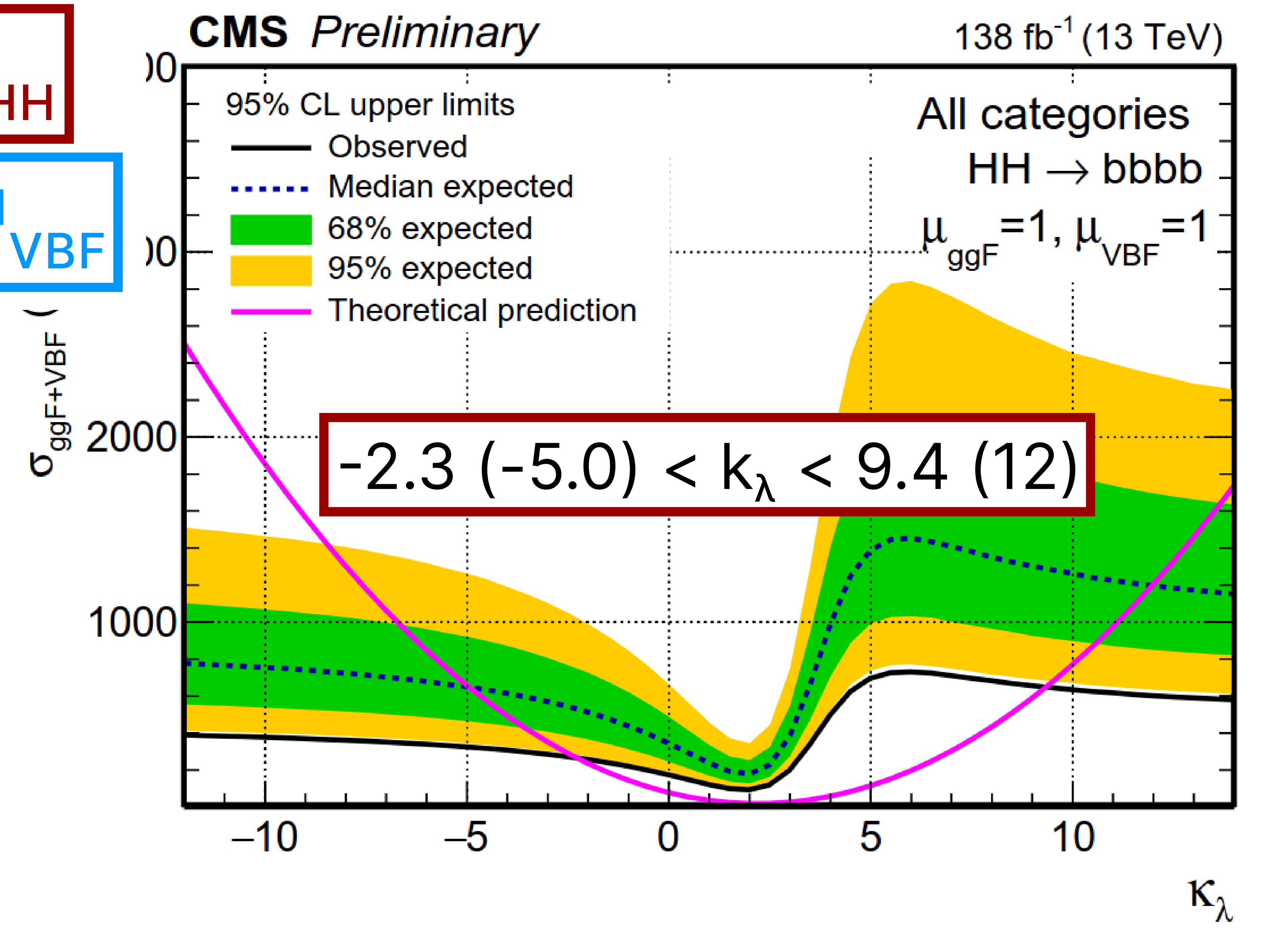
ggF

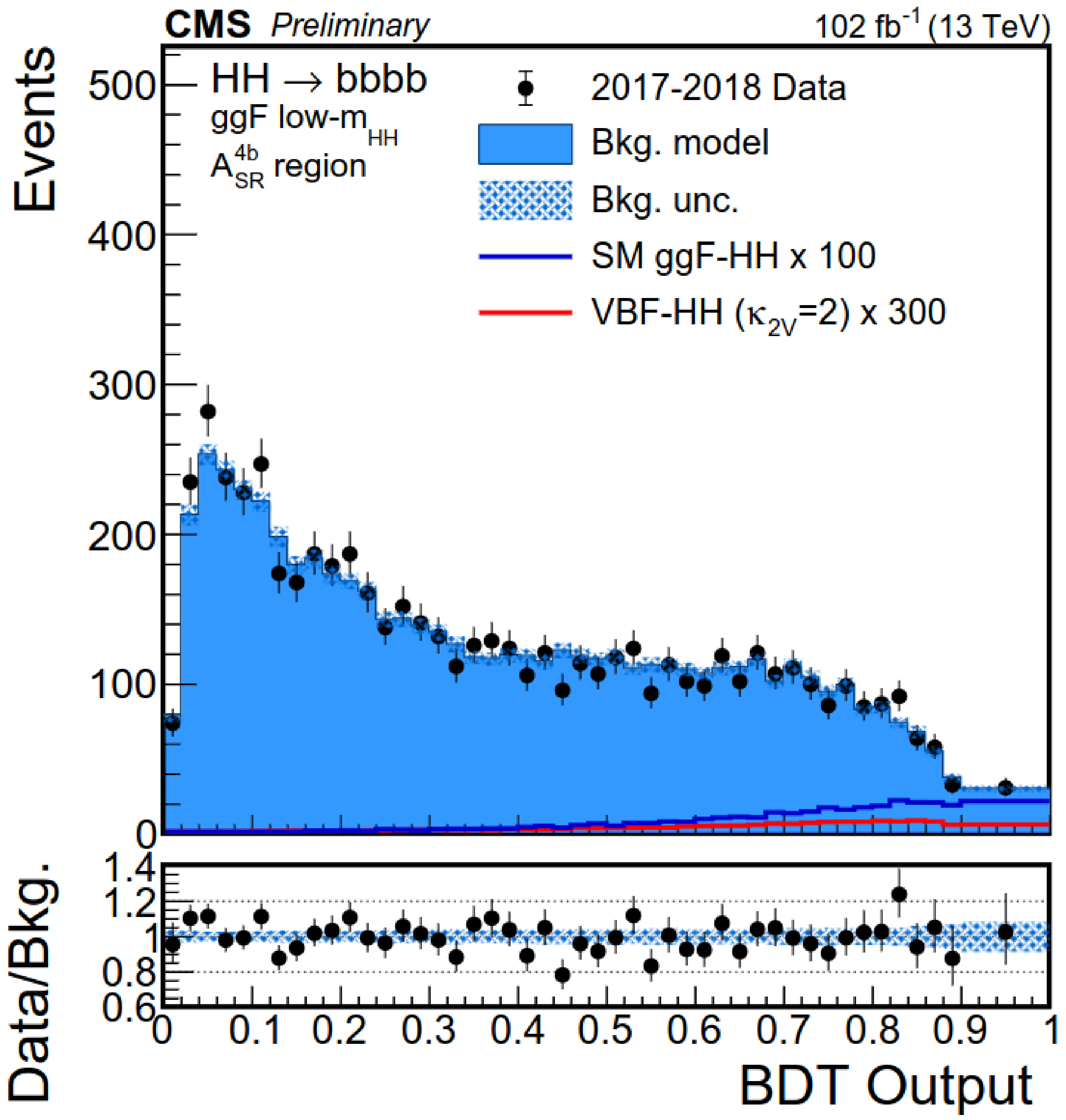
VBF

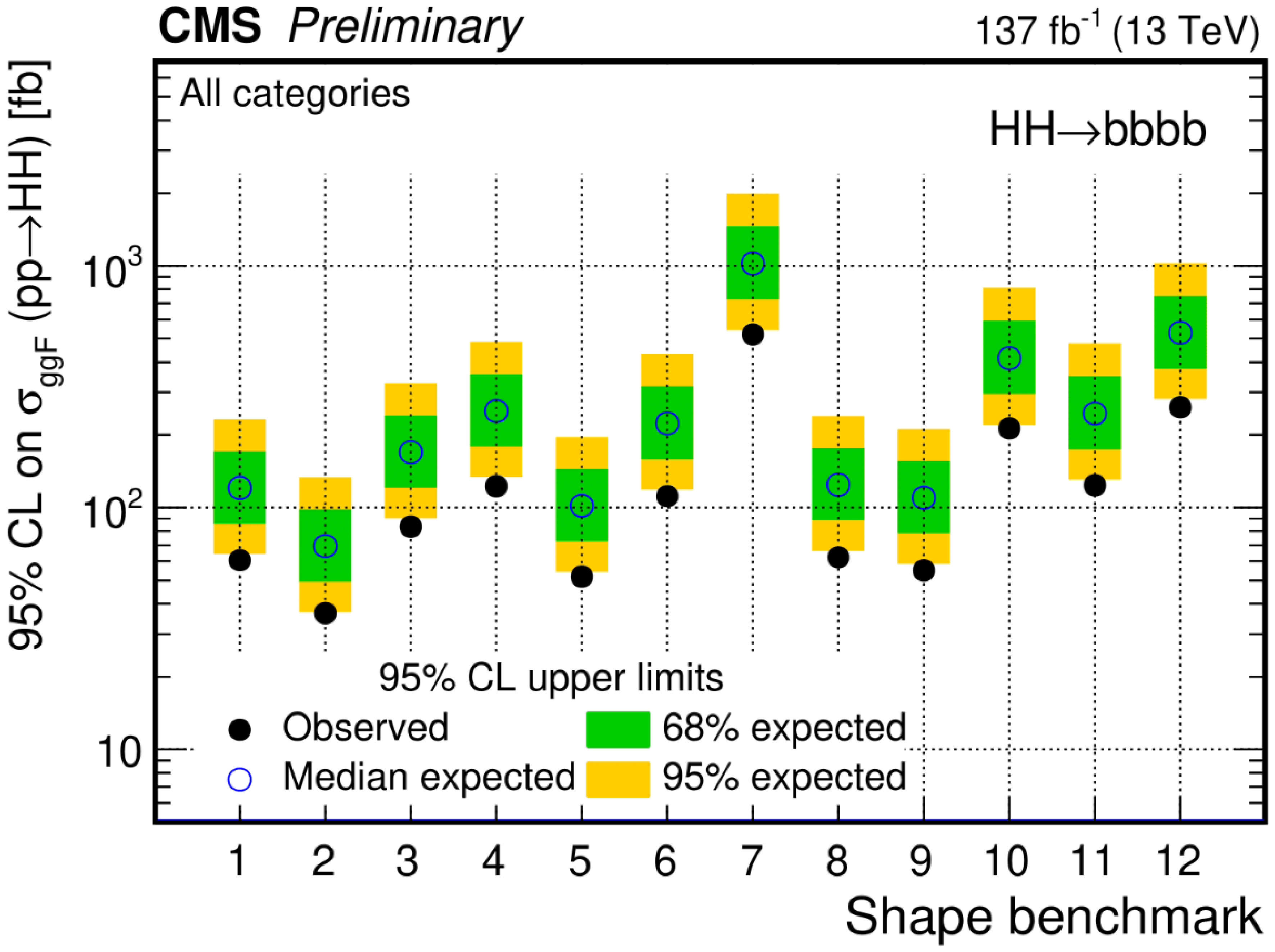
$\sigma_{HH} < 3.9\ (7.8) < \sigma^{SM}_{HH}$

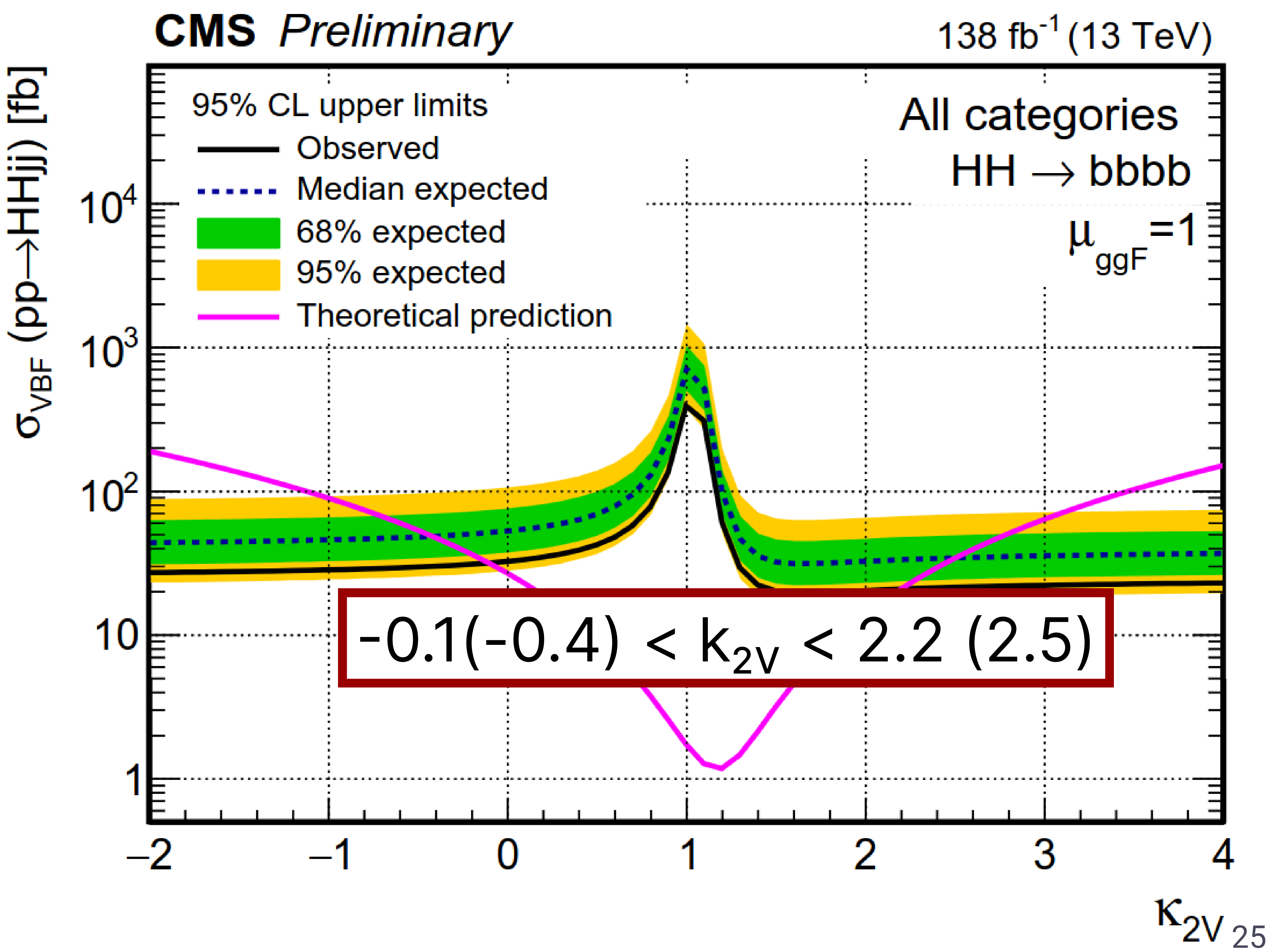
$\sigma_{VBF} < 226\ (412) < \sigma^{SM}_{VBF}$

- 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









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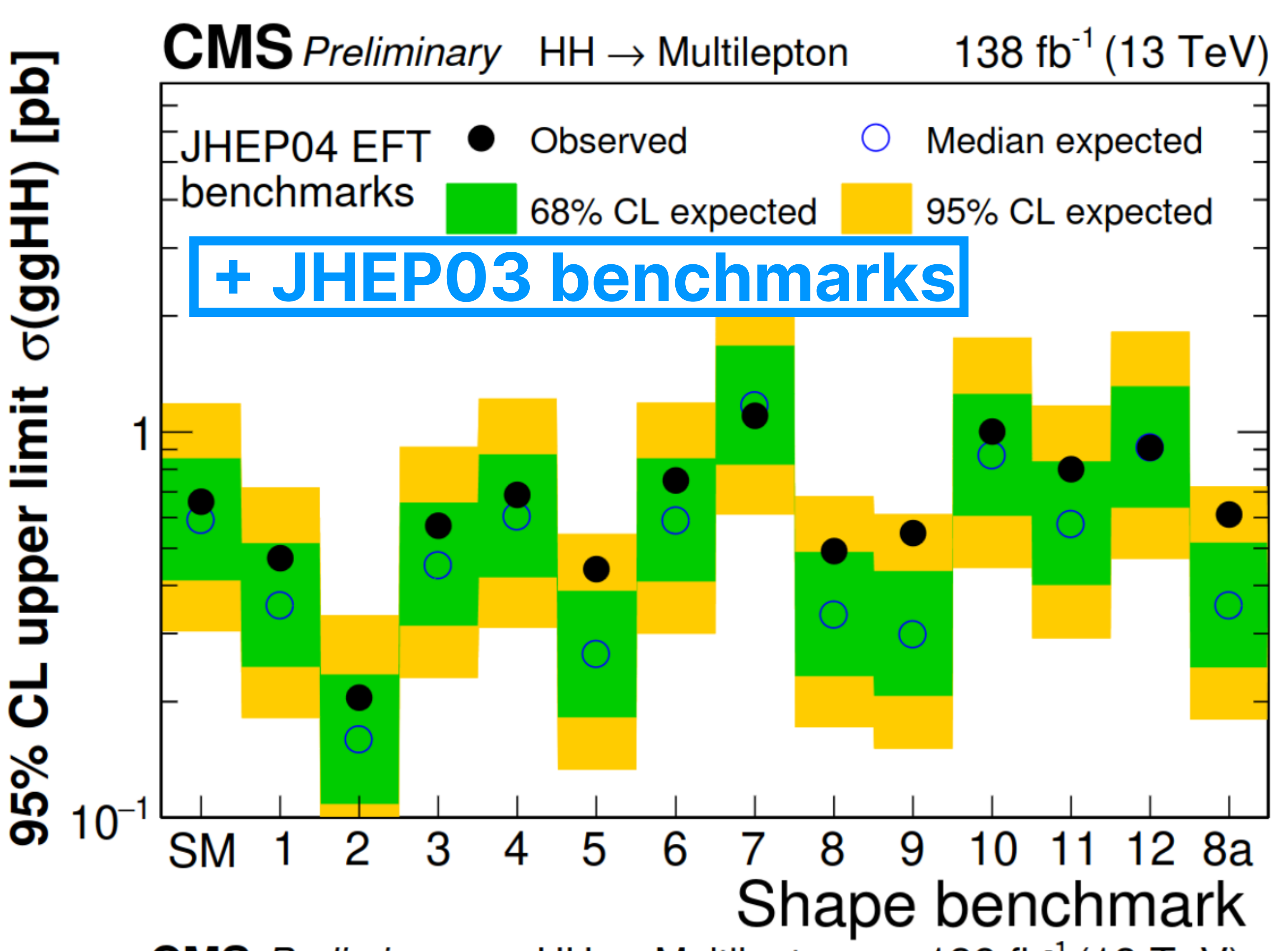
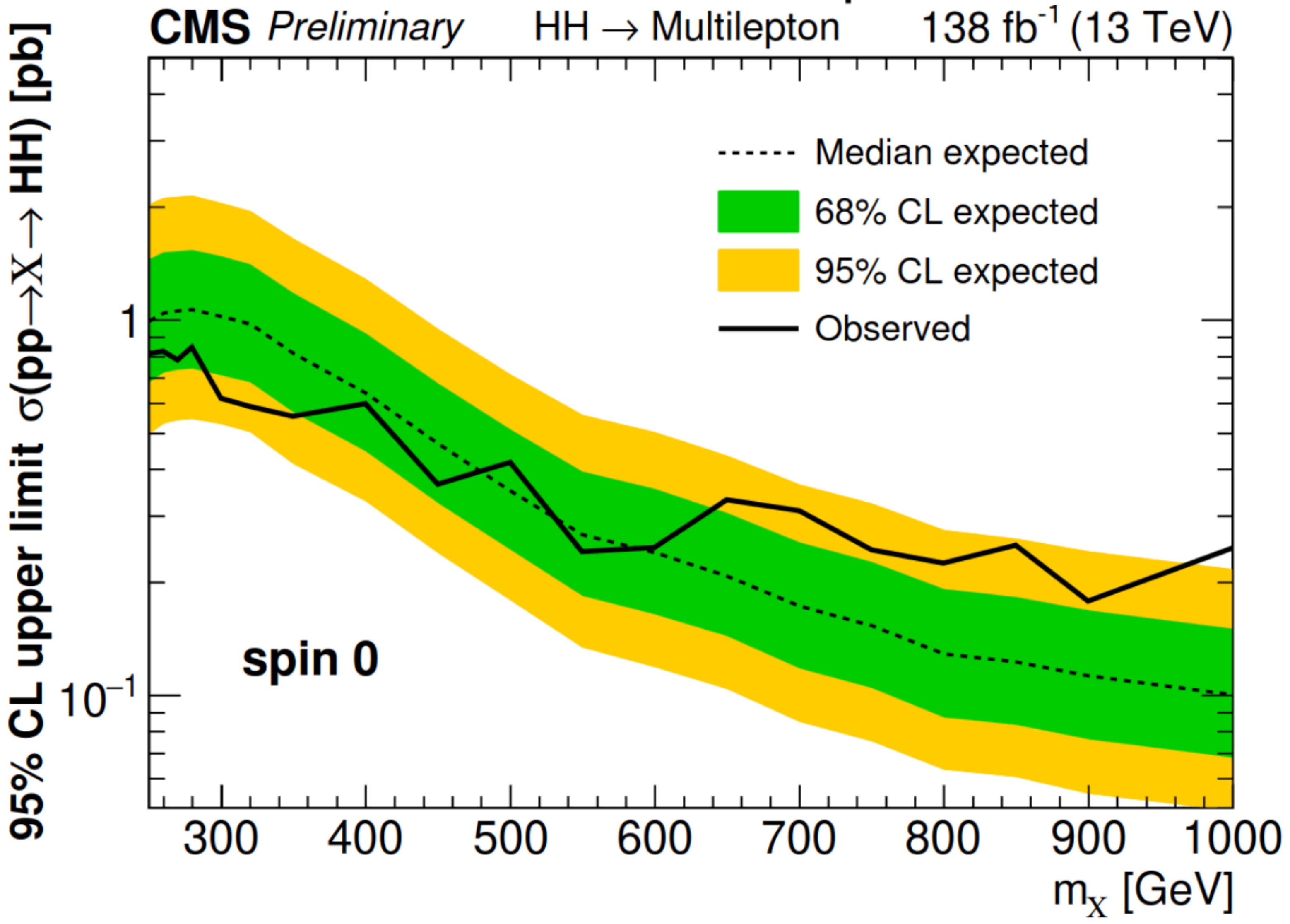
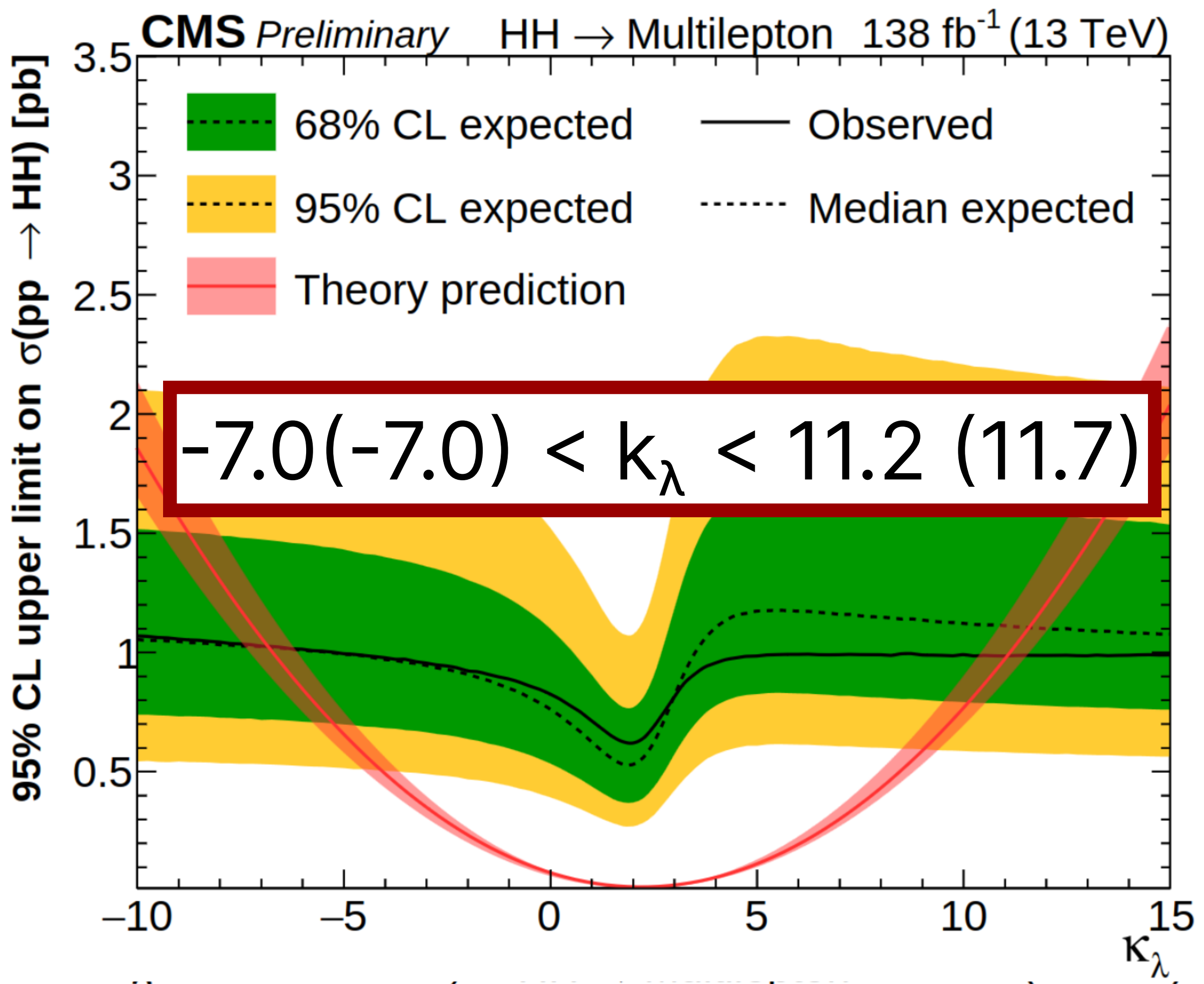
HH→Multilepton (4V, 2V2τ, 4τ) ggF VBF Res

- 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 bkgs.

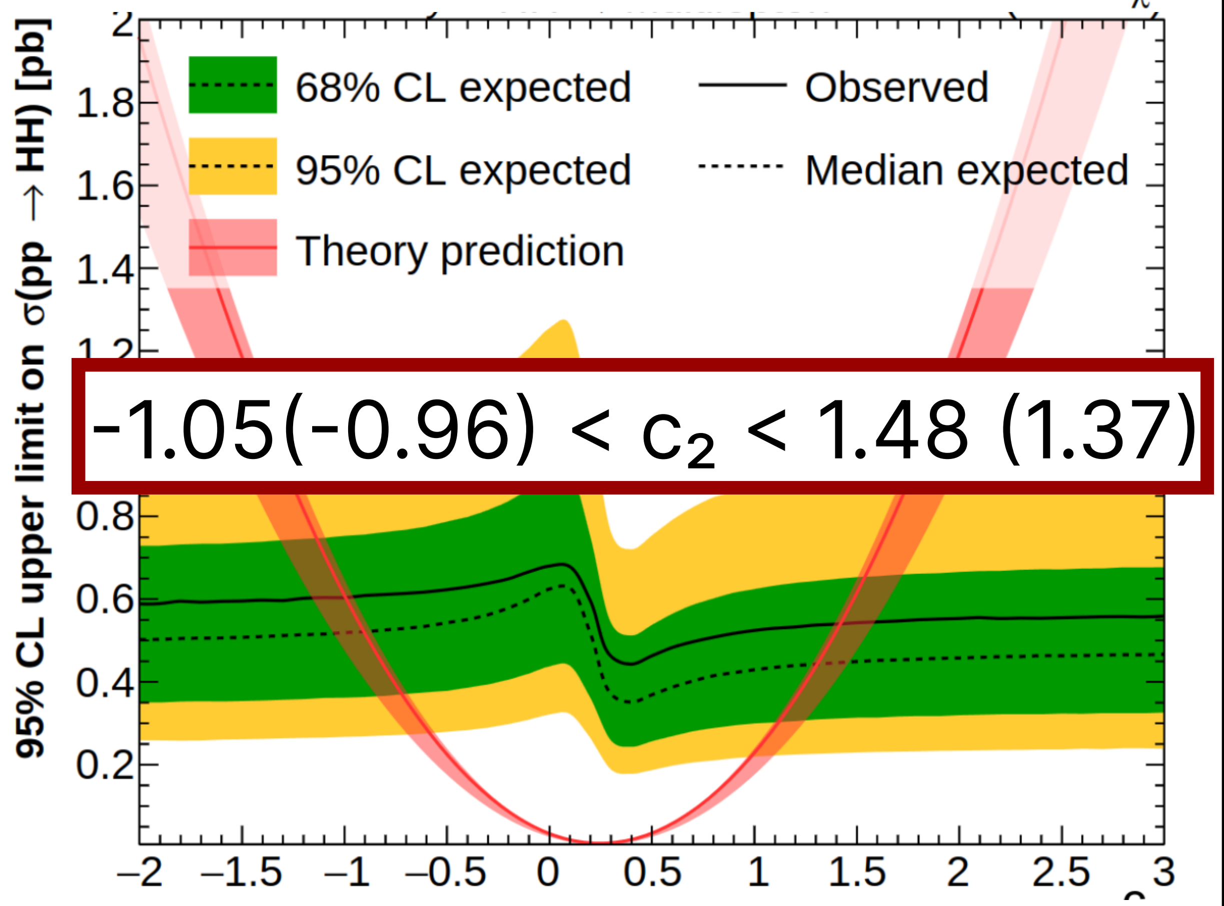
$\sigma_{HH} < 21.8\ (19.6) < \sigma^{SM}_{HH}$



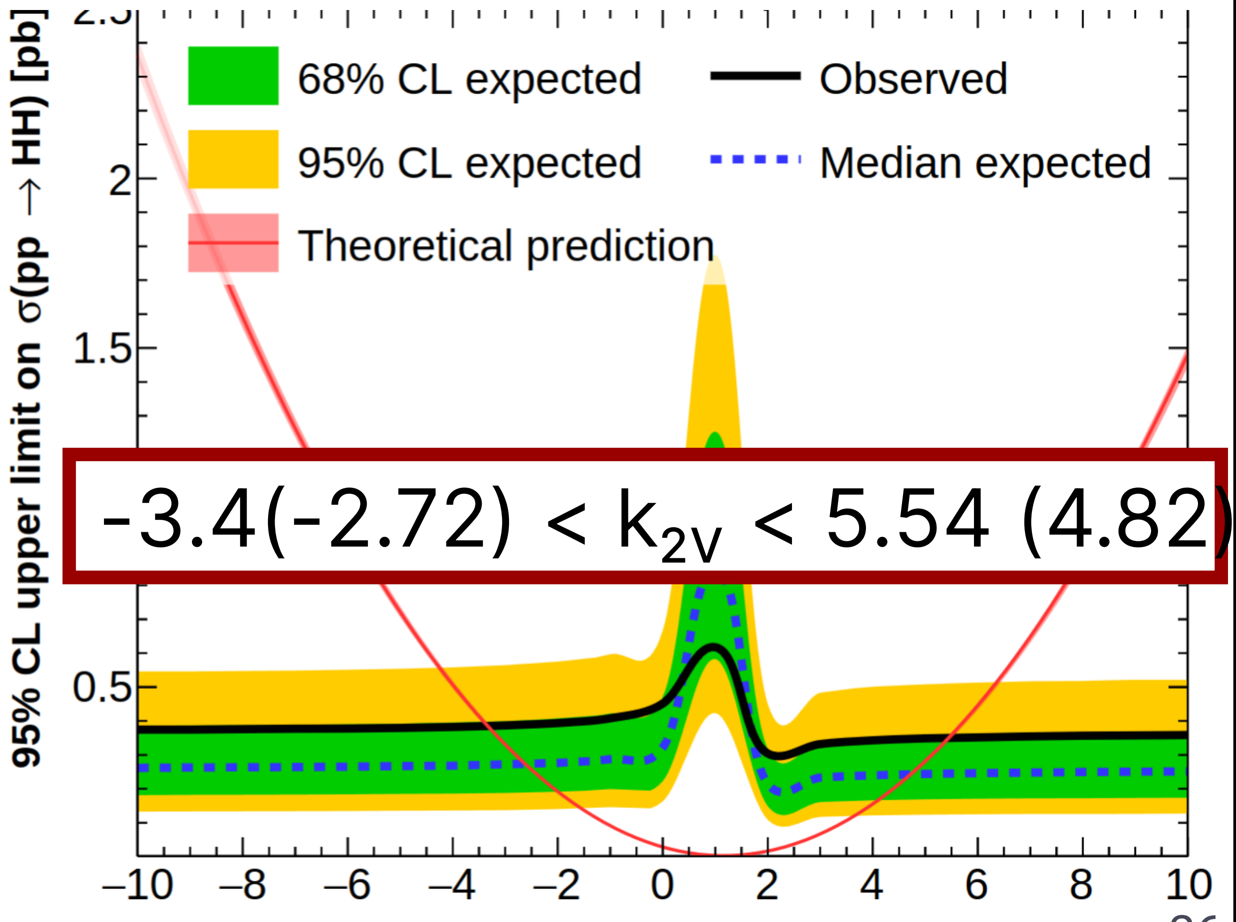




$-7.0(-7.0) < k_{\lambda} < 11.2\ (11.7)$



$-1.05(-0.96) < c_2 < 1.48\ (1.37)$



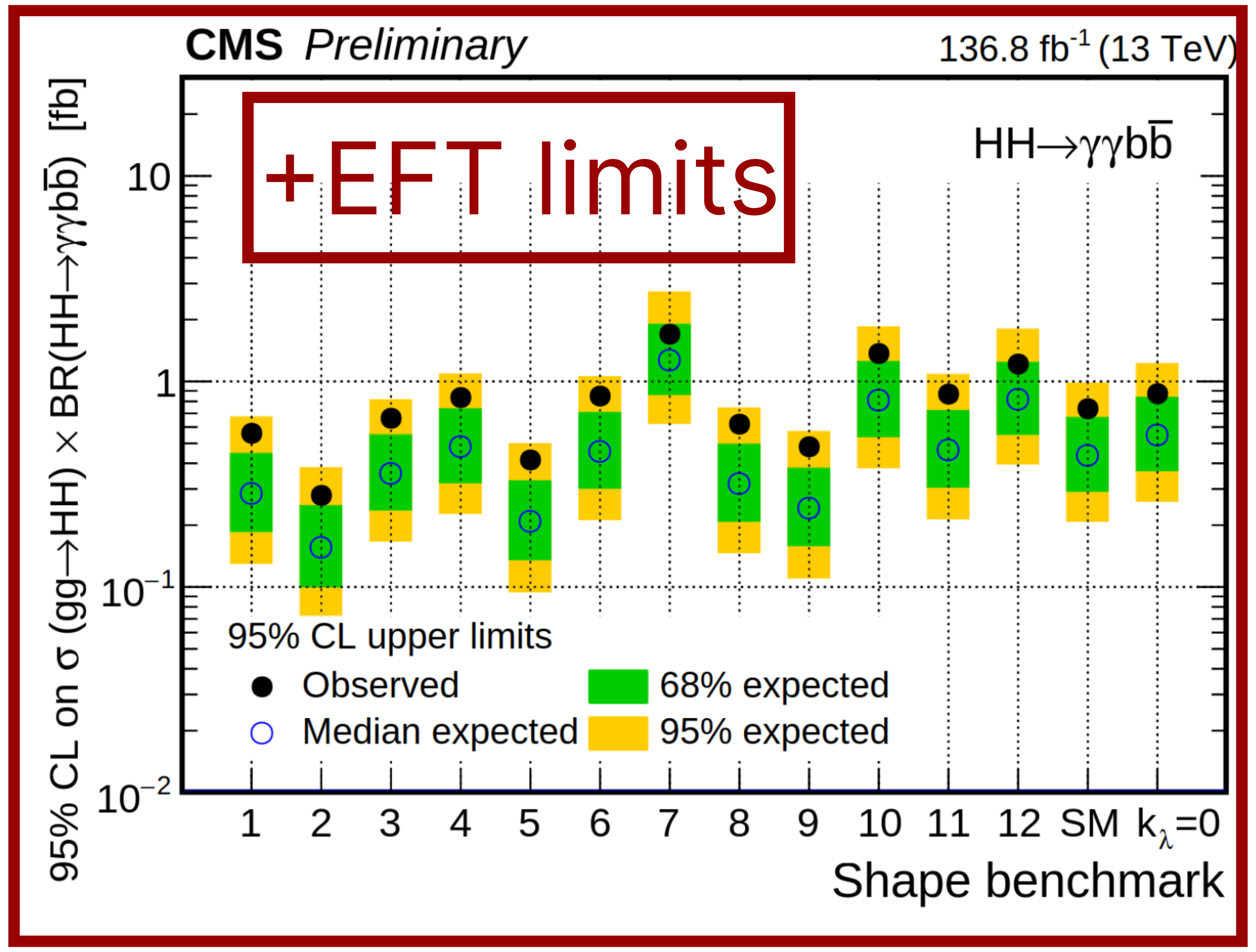
$-3.4(-2.72) < k_{2V} < 5.54\ (4.82)$

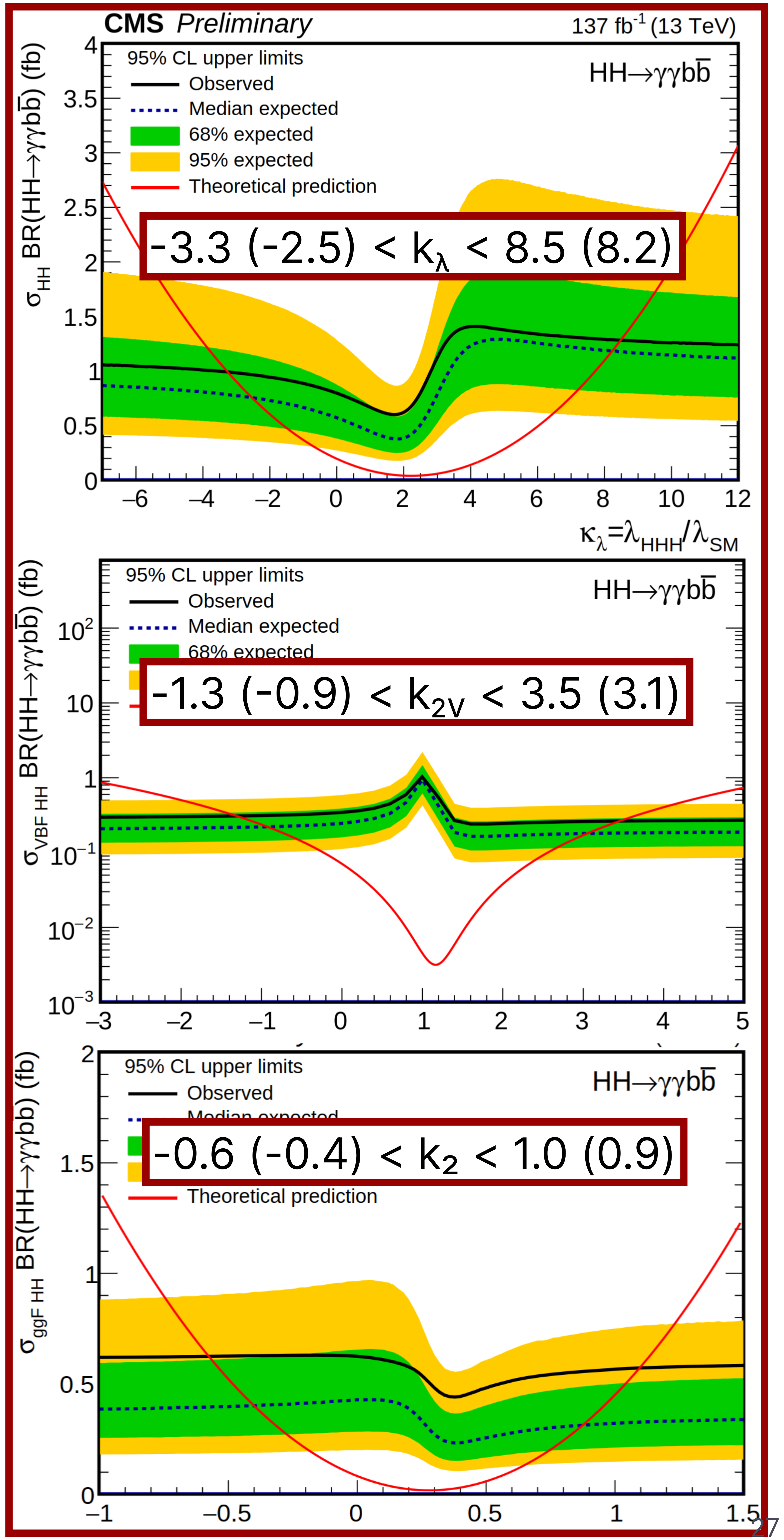
$HH \to bb\gamma\gamma$ ggF VBF

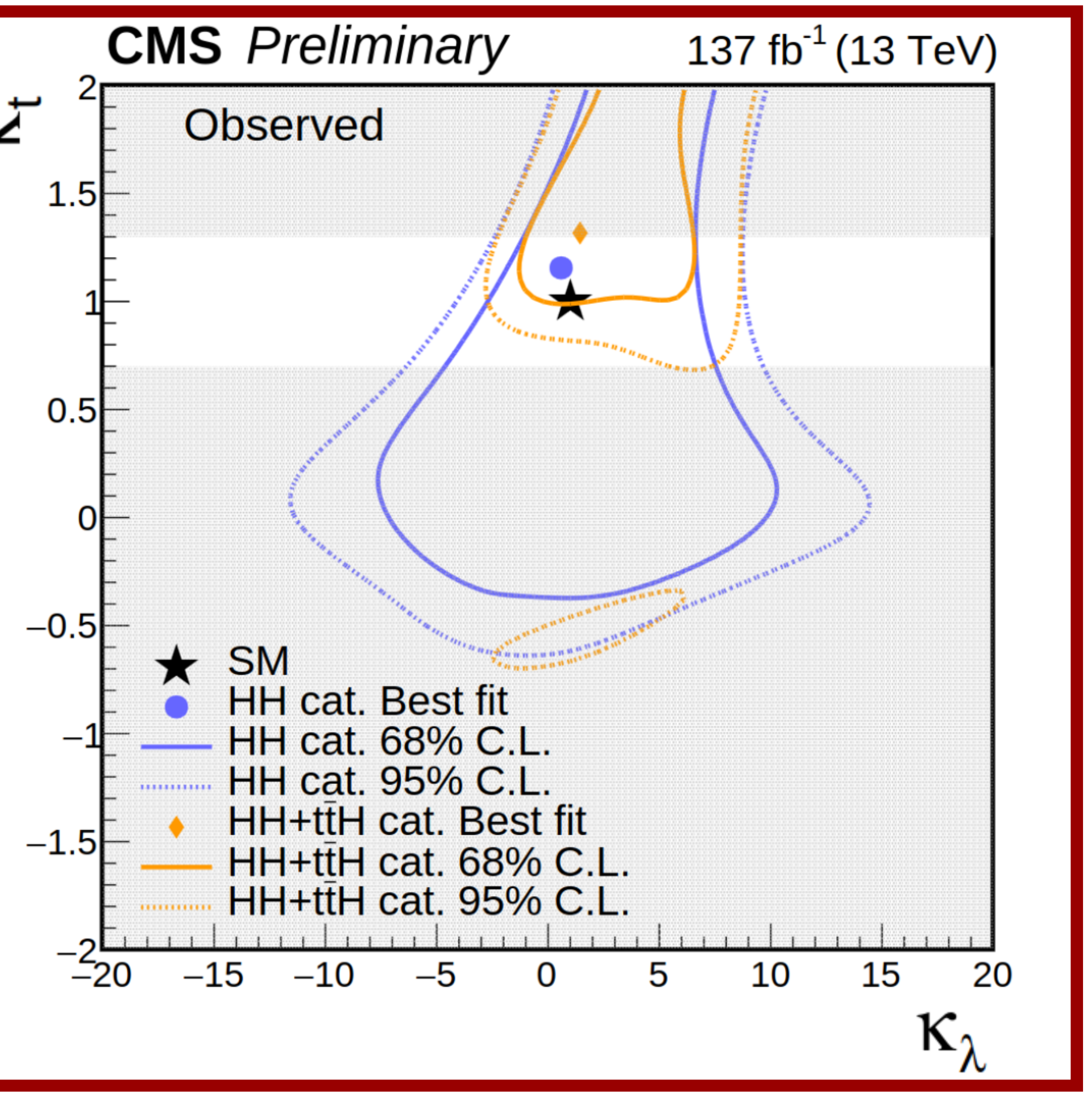
- optimized categories based on modified mass and ggF/VBF BDTs
- dedicated "ttH killer" DNN
- Signal extracted from unbinned 2D $m_{\gamma\gamma}$ vs. m_{bb} parametric fit
  - $m_{\gamma\gamma}$: sum of gaussians
  - m_{jj}: double crystal-ball + gaus.
- HH+H combination: constrain κ_t w/ ttH phase-space

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

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

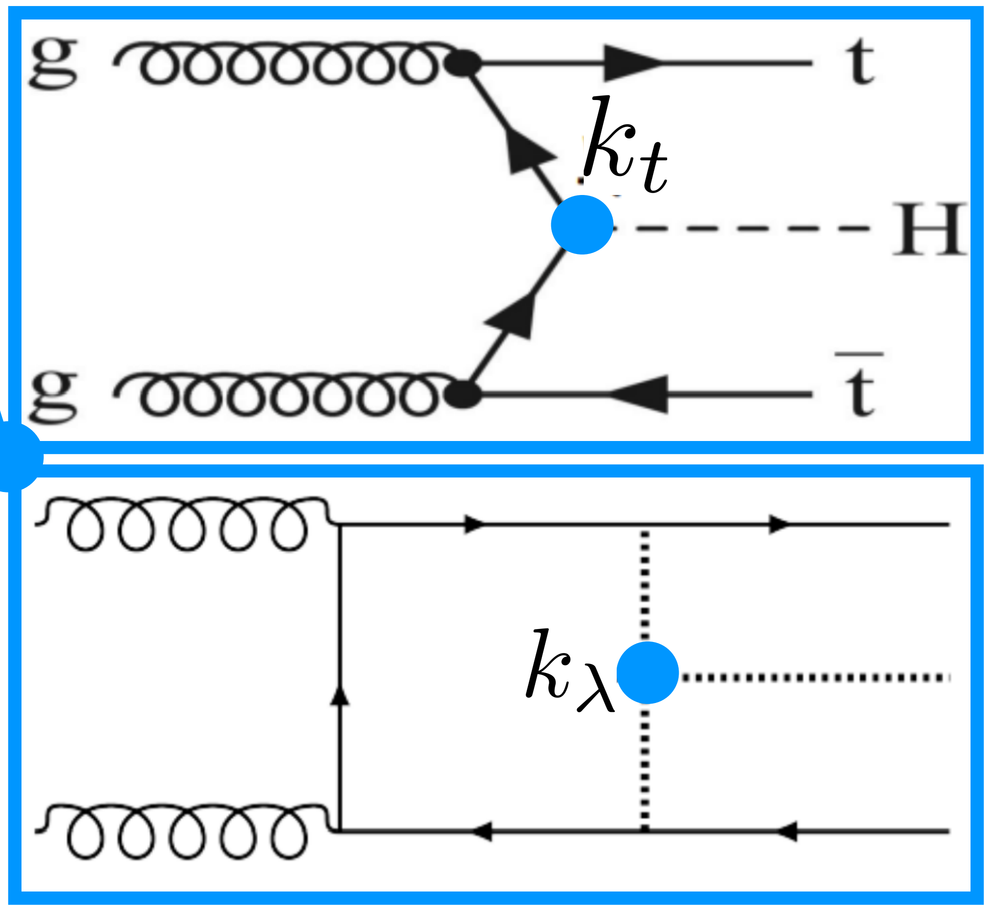






Include ttH

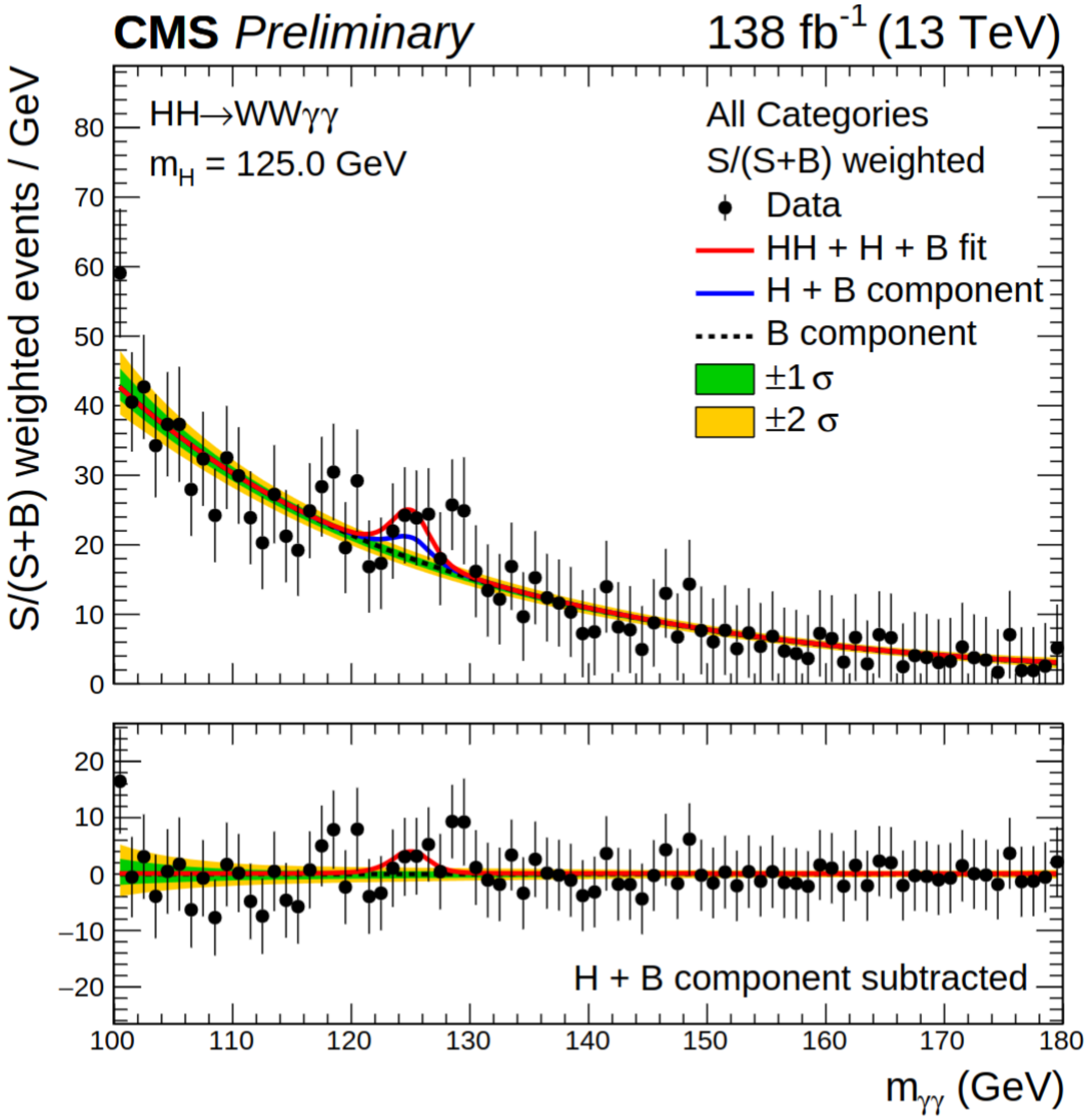
$-2.7\ (-3.3) < k_\lambda < 8.6\ (8.6)$

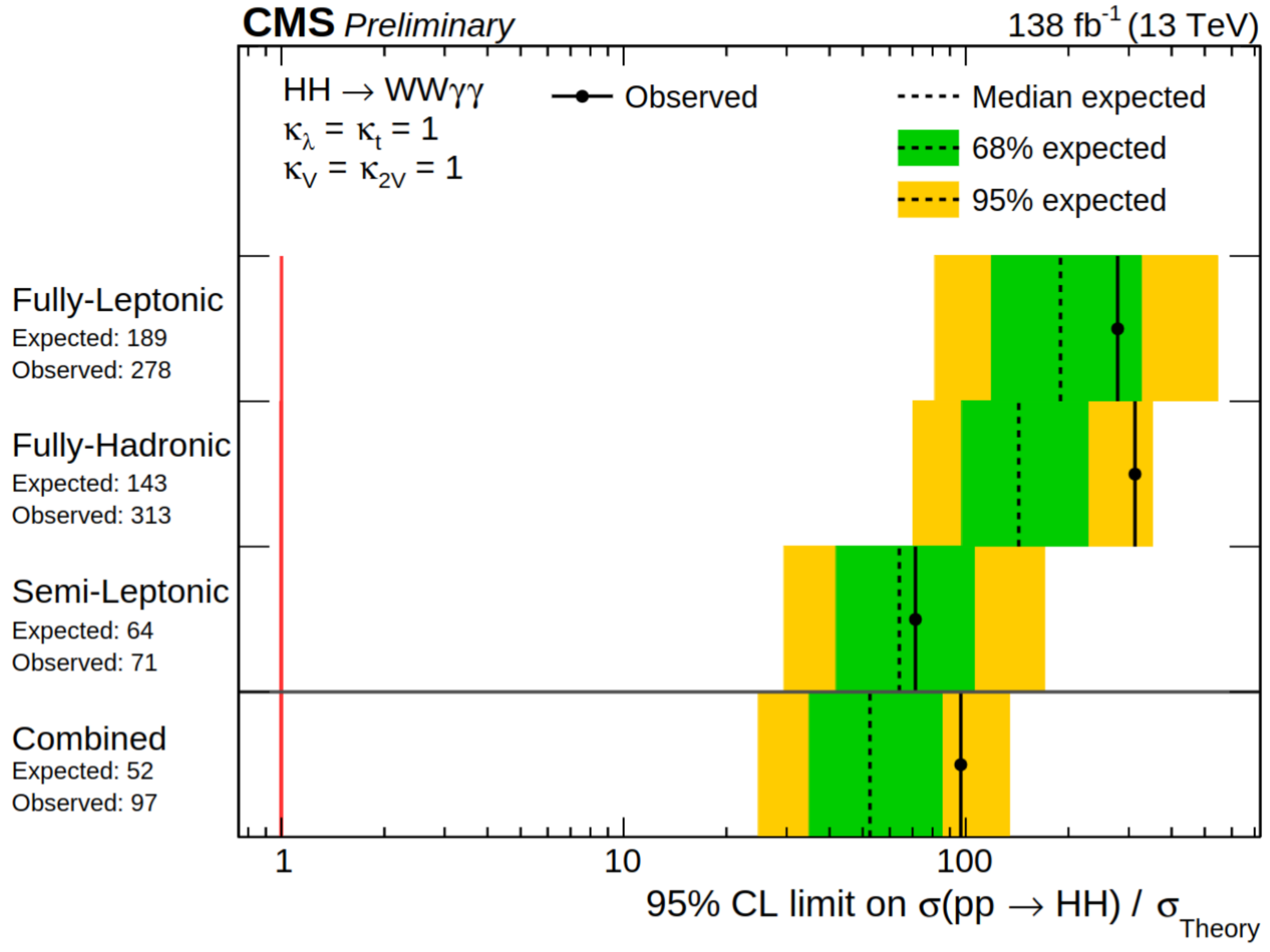


ttH analysis

HH→WWγγ **ggF**

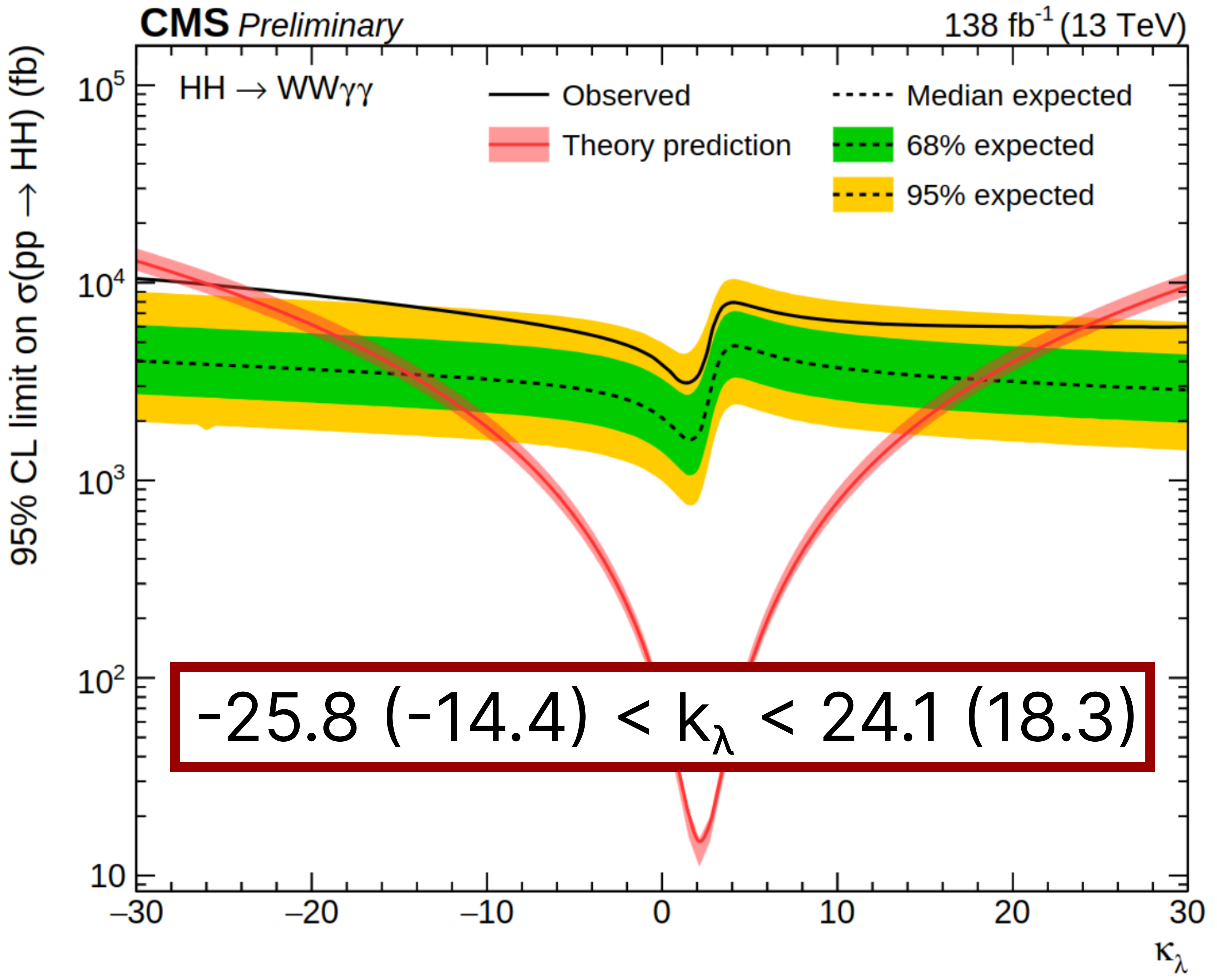
- Signal extracted from $m_{\gamma\gamma}$ parametric fit
- 3 channels based on #leptons
  - 0: multiclass DNN to remove H and γ/jets bkgs. + binary DNN for EFT benchmarks
  - 1: WWγγ id and "bbγγ killer" binary DNNs
  - 2: cut based



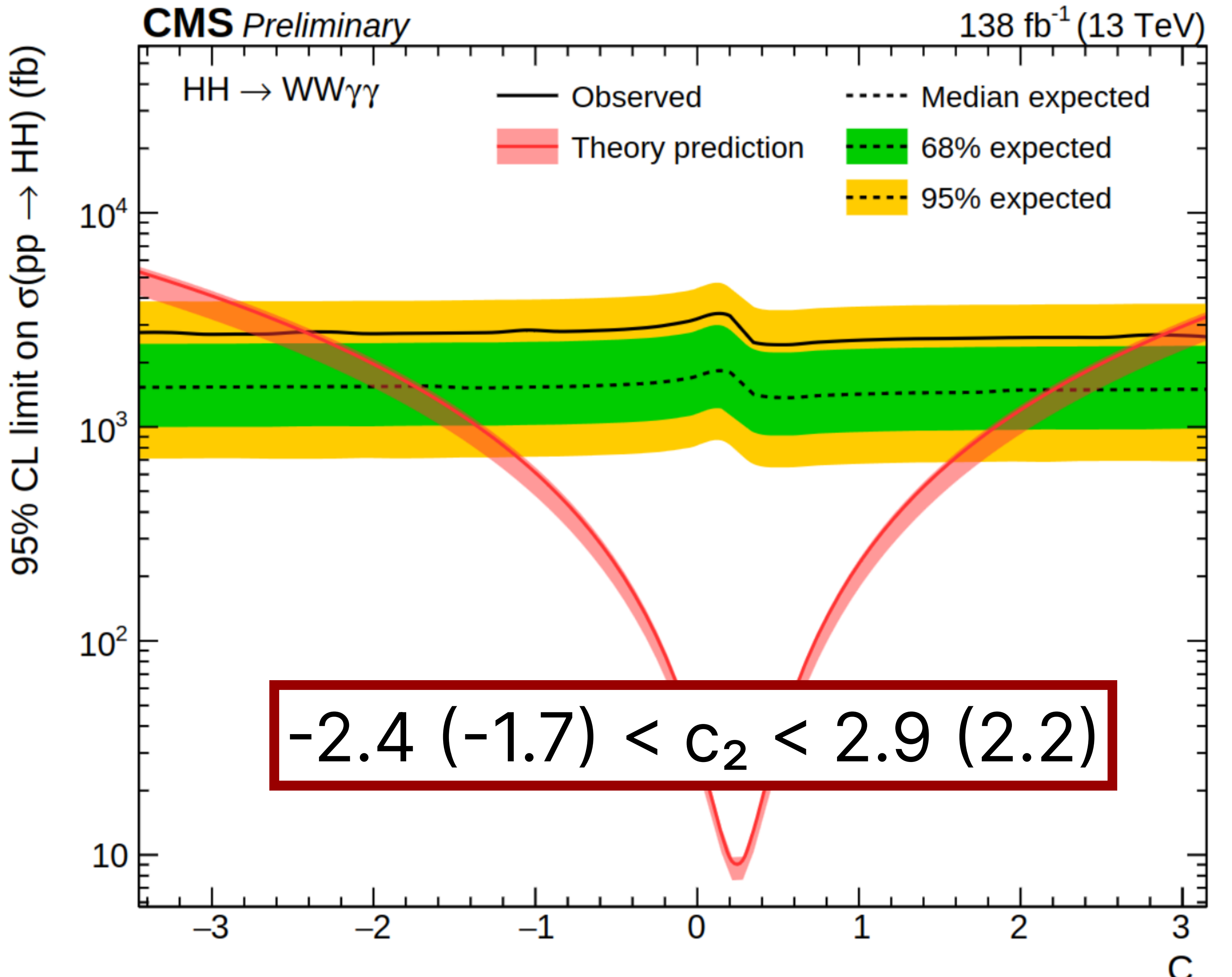


$\sigma_{HH} < 96.8\ (52.5) < \sigma^{SM}_{HH}$

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

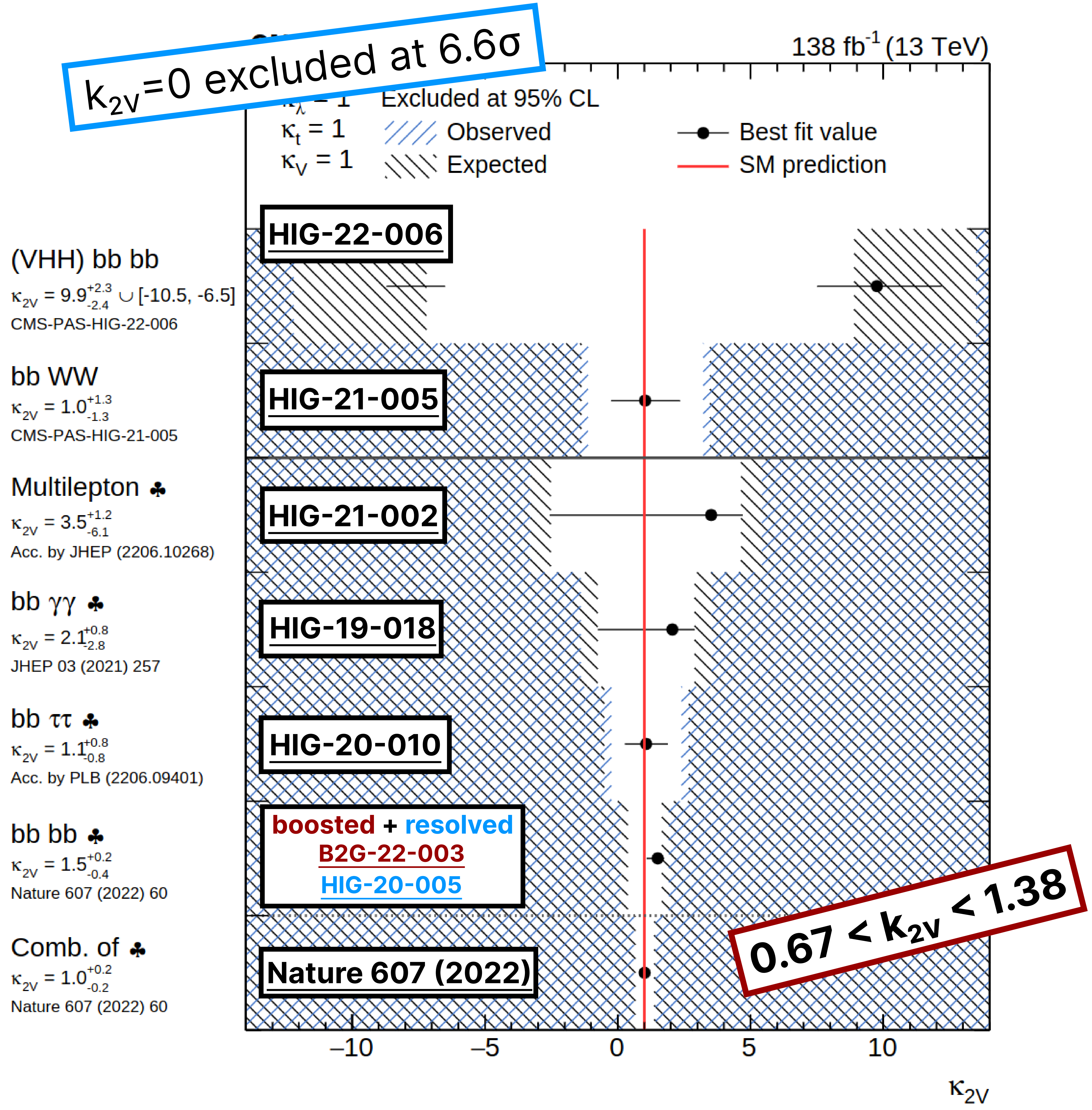


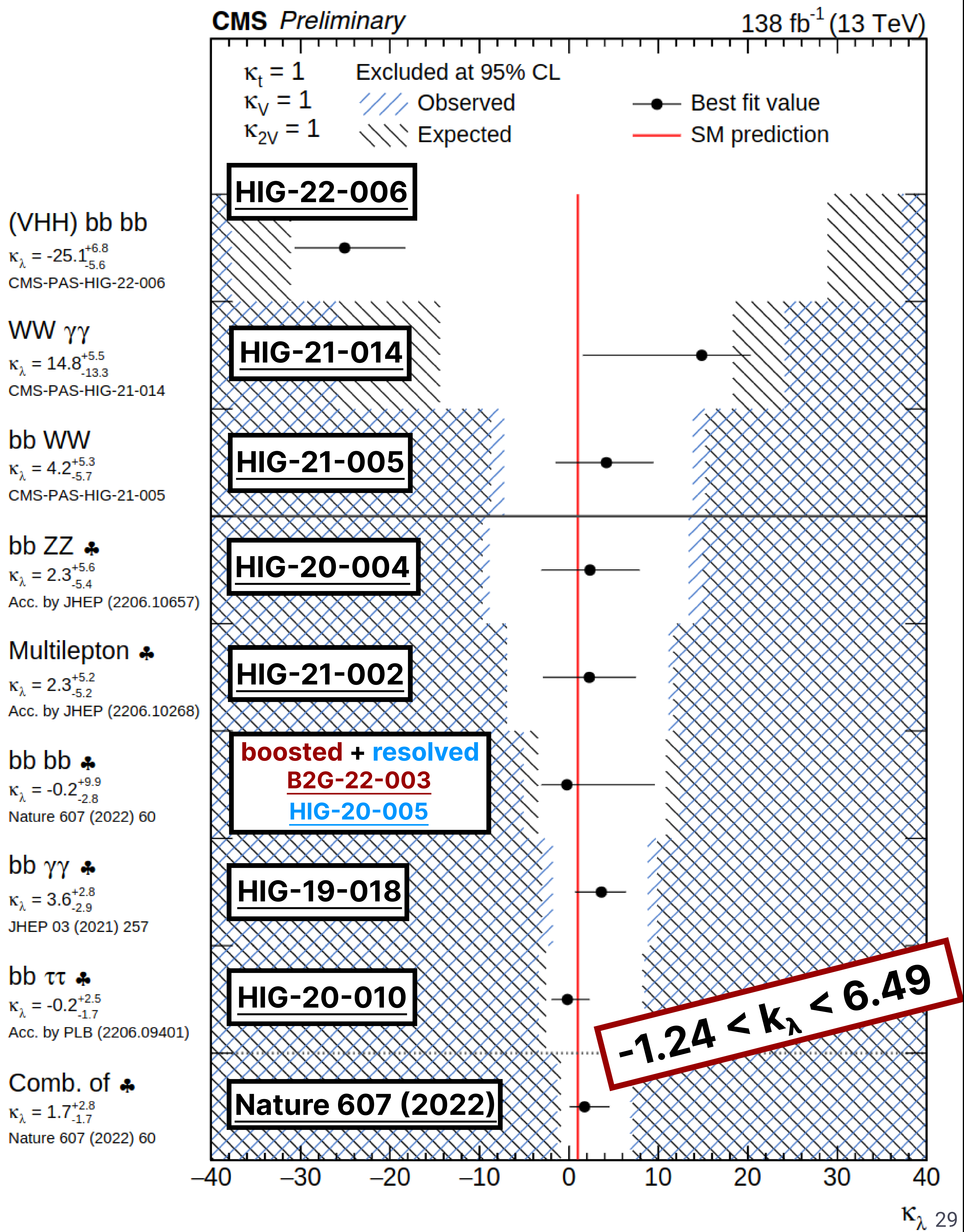
$-25.8\ (-14.4) < k_{\lambda} < 24.1\ (18.3)$



$-2.4\ (-1.7) < c_2 < 2.9\ (2.2)$

CMS Internal links





CMS Internal links