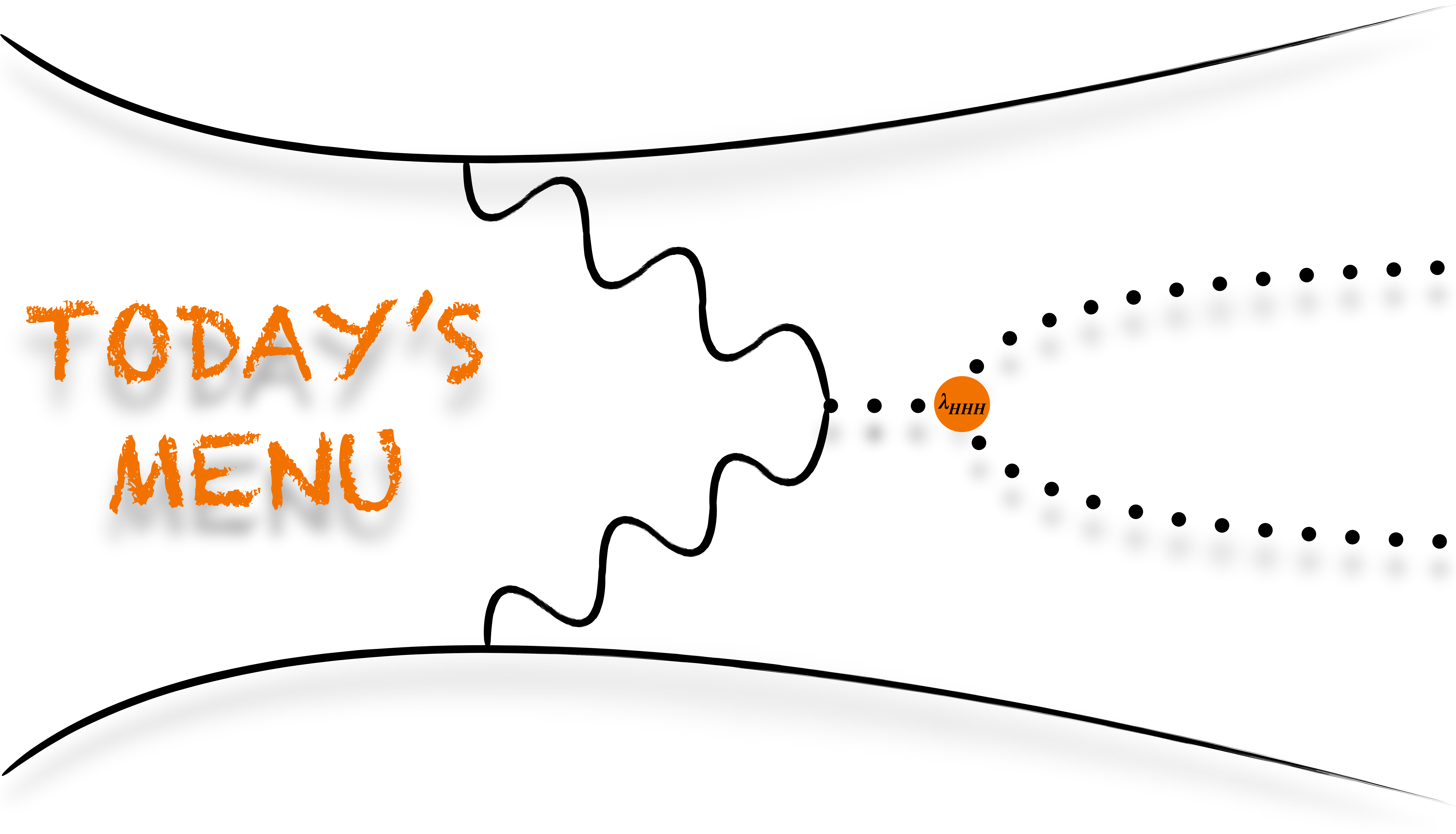
Higgs-self coupling

highlights from CMS

Jona Motta (LLR, École Polytechnique)
on behalf of the CMS Collaboration



λ_{HHH} : what, why, and where?

Direct HH searches

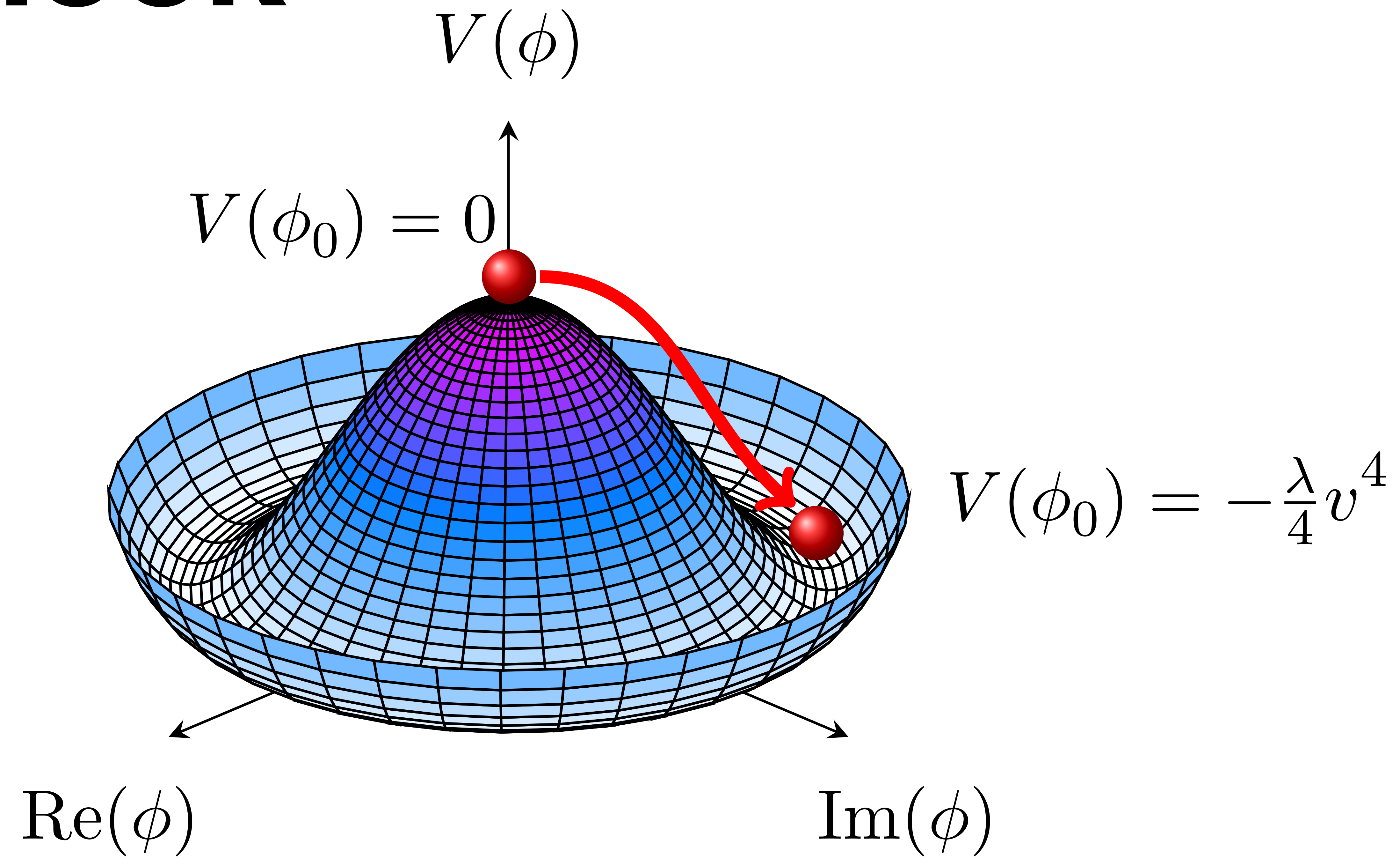
Indirect λ_{HHH} effects

Outlook and conclusions

What, why, and where to look

The Higgs mechanism is the most economical way to endow fundamental particles with mass while keeping the SM gauge invariant and predictive

The **Higgs field** is responsible for the spontaneous breaking of electroweak symmetry



$$V_H = \mu^2 + \frac{\mu^2}{v}H^3 + \frac{\mu^2}{4v}H^4 - \frac{1}{4}\mu^2 v^2$$
$$= \frac{1}{2}m_H^2 + \lambda_{HHH} v H^3 + \lambda_{HHHH} H^4 - \frac{1}{8}m_H^2 v^2$$

→

$$\lambda_{HHH} = 4\lambda_{HHHH} = \frac{m_H^2}{v^2}$$

only parameter regulating field's shape
+
predicted by the SM once m_H is measured

What, why, and where to look

Check out
Raffaele's and Lisa's
talks later

1. λ_{HHH} is not a free parameter → closure test of SM
2. λ_{HHH} only parameter regulating H potential shape → EWSB and vacuum stability test
3. Deviation of λ_{HHH} from SM can allow first-order EW transition → 3rd Sakharov condition for matter-antimatter asymmetry

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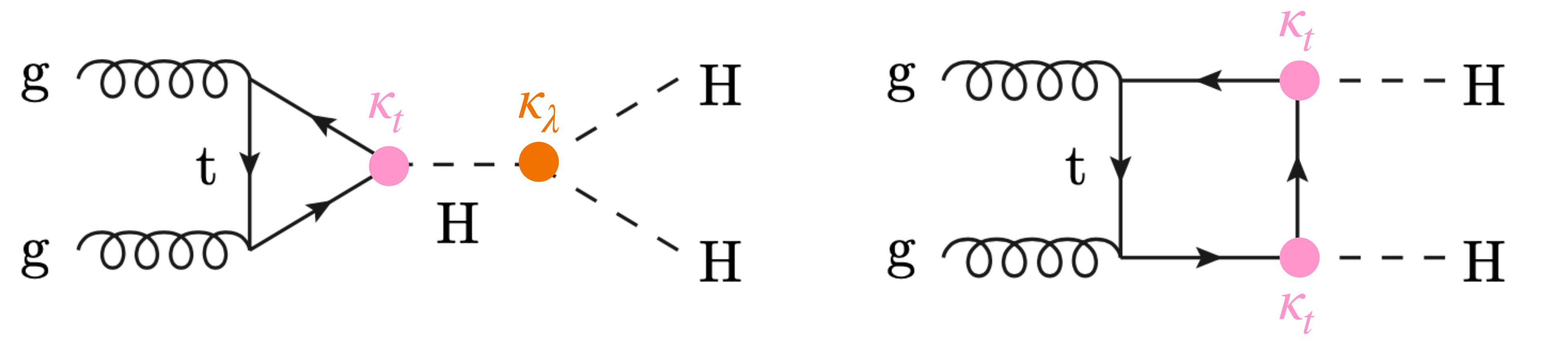
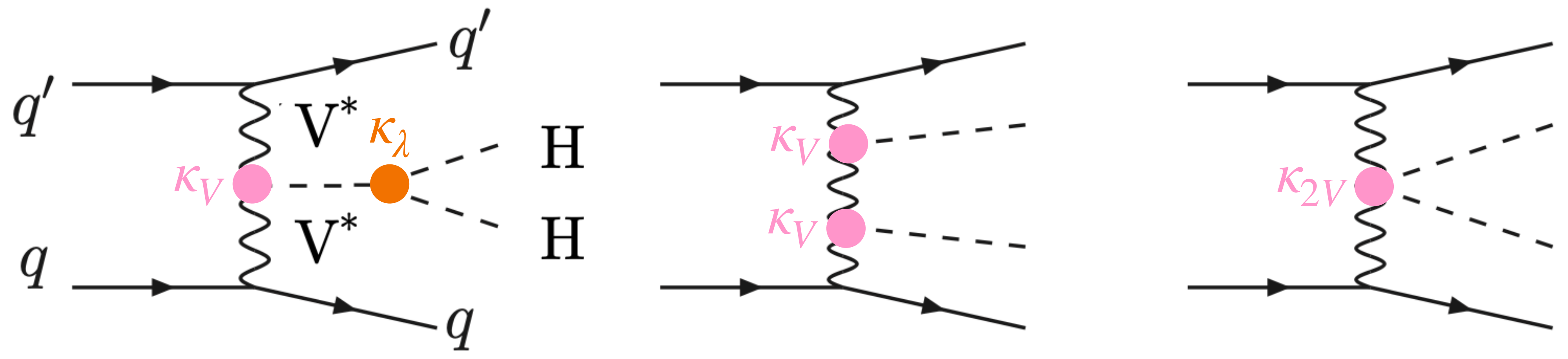
NON-RESONANT HH PRODUCTION

1. Test BSM effective models with anomalous couplings: κ_λ , κ_t , κ_V , κ_{2V}
2. Test model-independent non-resonant EFT benchmarks



DESTRUCTIVE INTERFERENCE
↓

$\sigma^{\mathrm{ggHH}}_{\mathrm{NNLO\text{-}FTapprox}}(\sqrt{s} = 13\mathrm{TeV}, m_{\mathrm{H}} = 125\mathrm{GeV}) \approx 31\mathrm{fb}$



$\sigma^{\mathrm{qqHH}}_{\mathrm{N3LO}}(\sqrt{s} = 13\mathrm{TeV}, m_{\mathrm{H}} = 125\mathrm{GeV}) \approx 1.7\mathrm{fb}$

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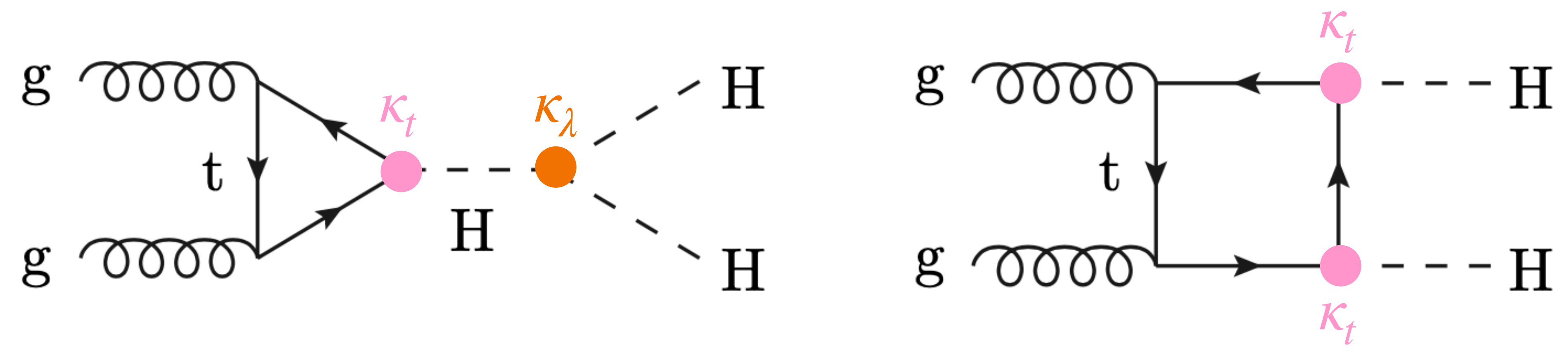

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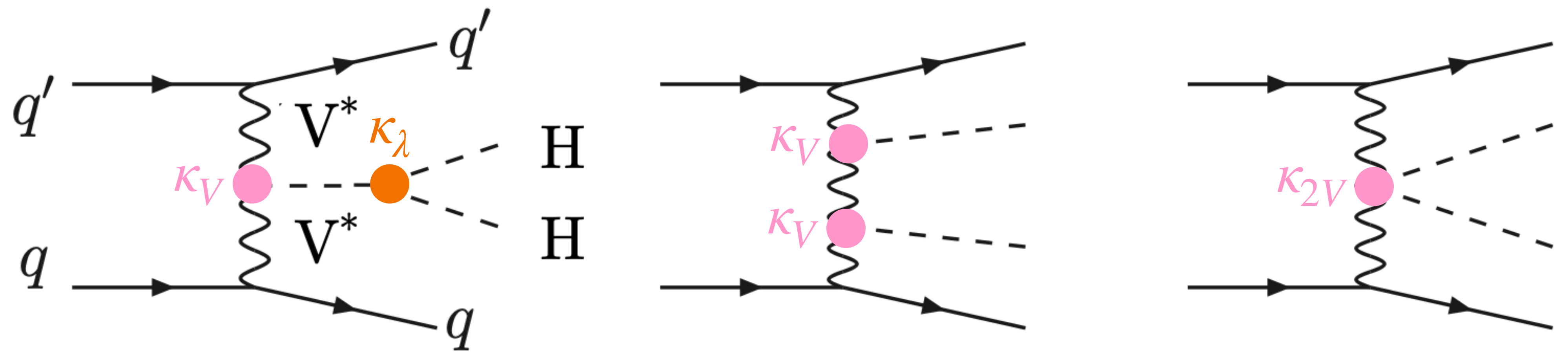

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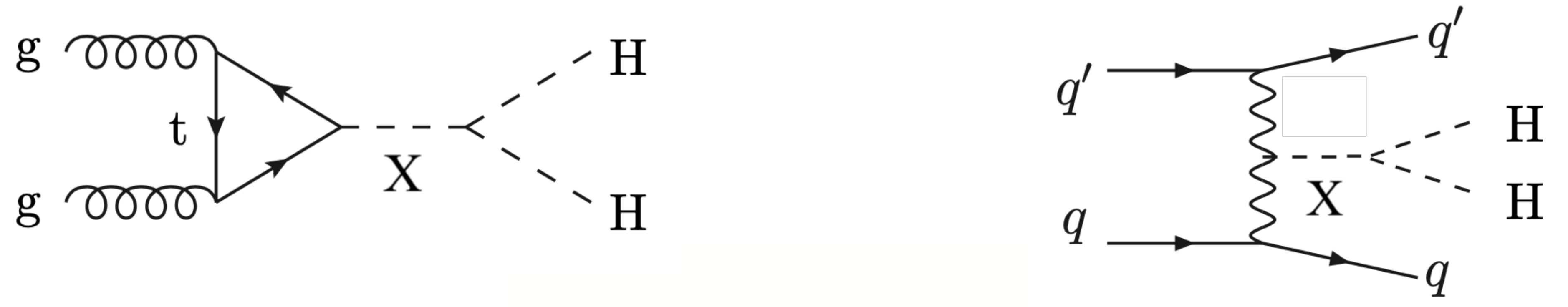
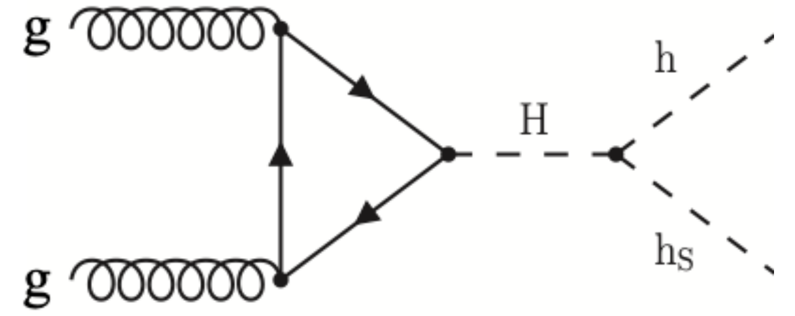
⊕

RESONANT HH PRODUCTION

Check out Chayanit's talk later





Test **resonant BSM models**

i. Minimal Supersymmetric Standard Model (**MSSM**)

→ **2 h± + 3 h0** (scalar and pseudoscalar zoo)

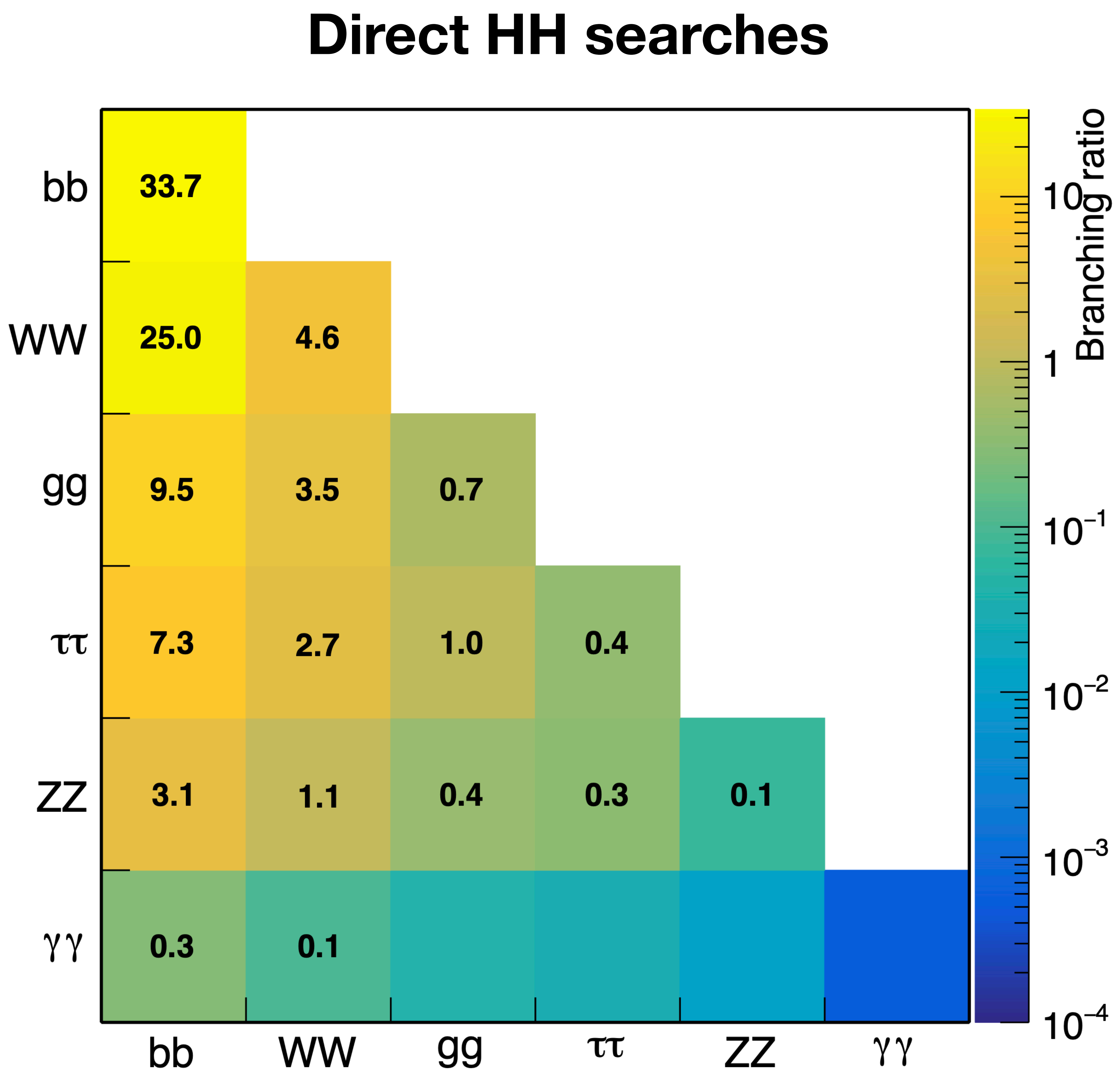
ii. Next to MSSM (**NMSSM**) or any two Higgs doublet plus singlet models (**2HDM+S**)

→ **2 h± + 5 h0** (scalar and pseudoscalar zoo)

iii. **Extra Dimensions**

→ **spin-0 radion / spin-2 graviton**

What, why, and where to look



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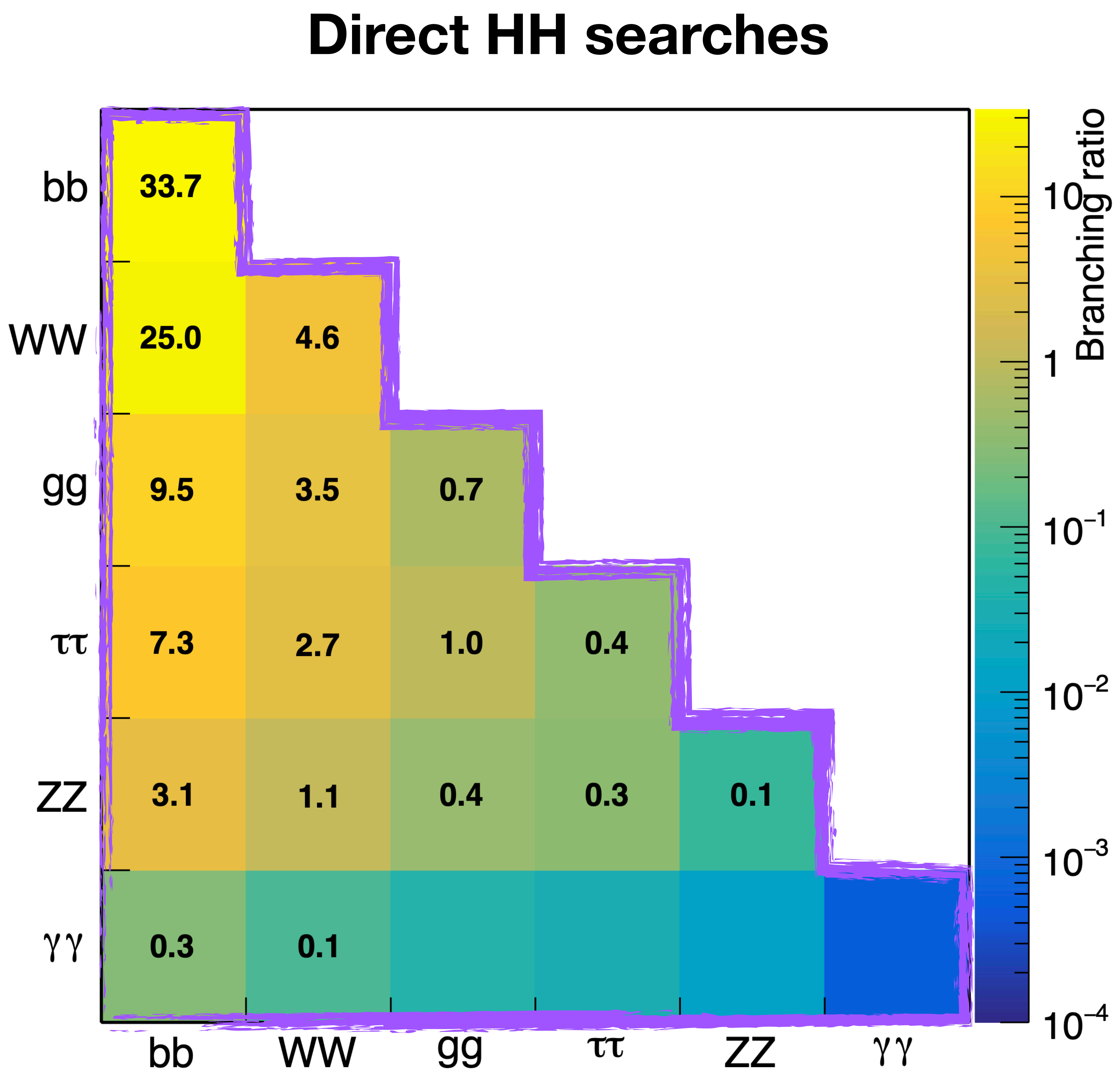

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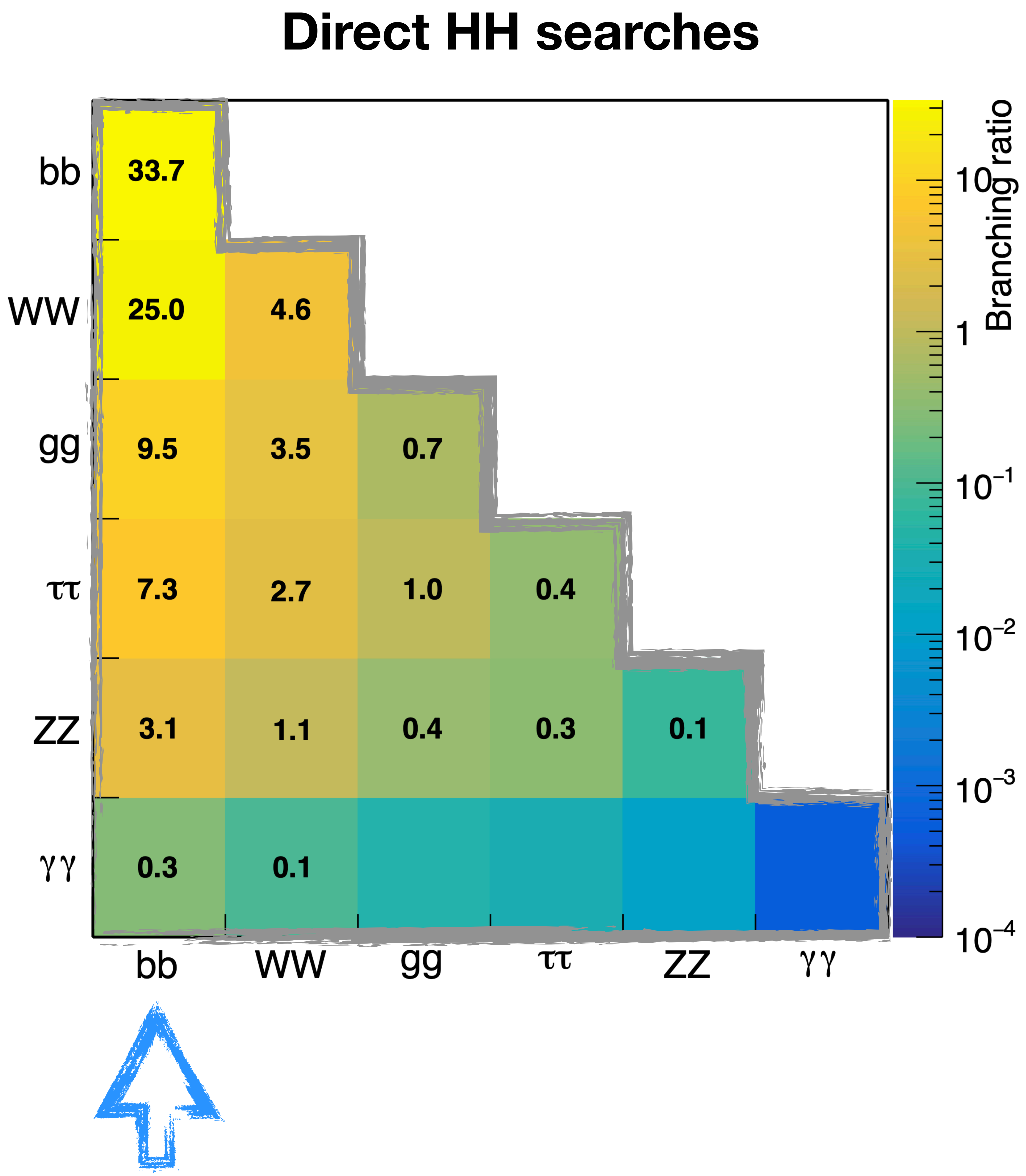
What, why, and where to look



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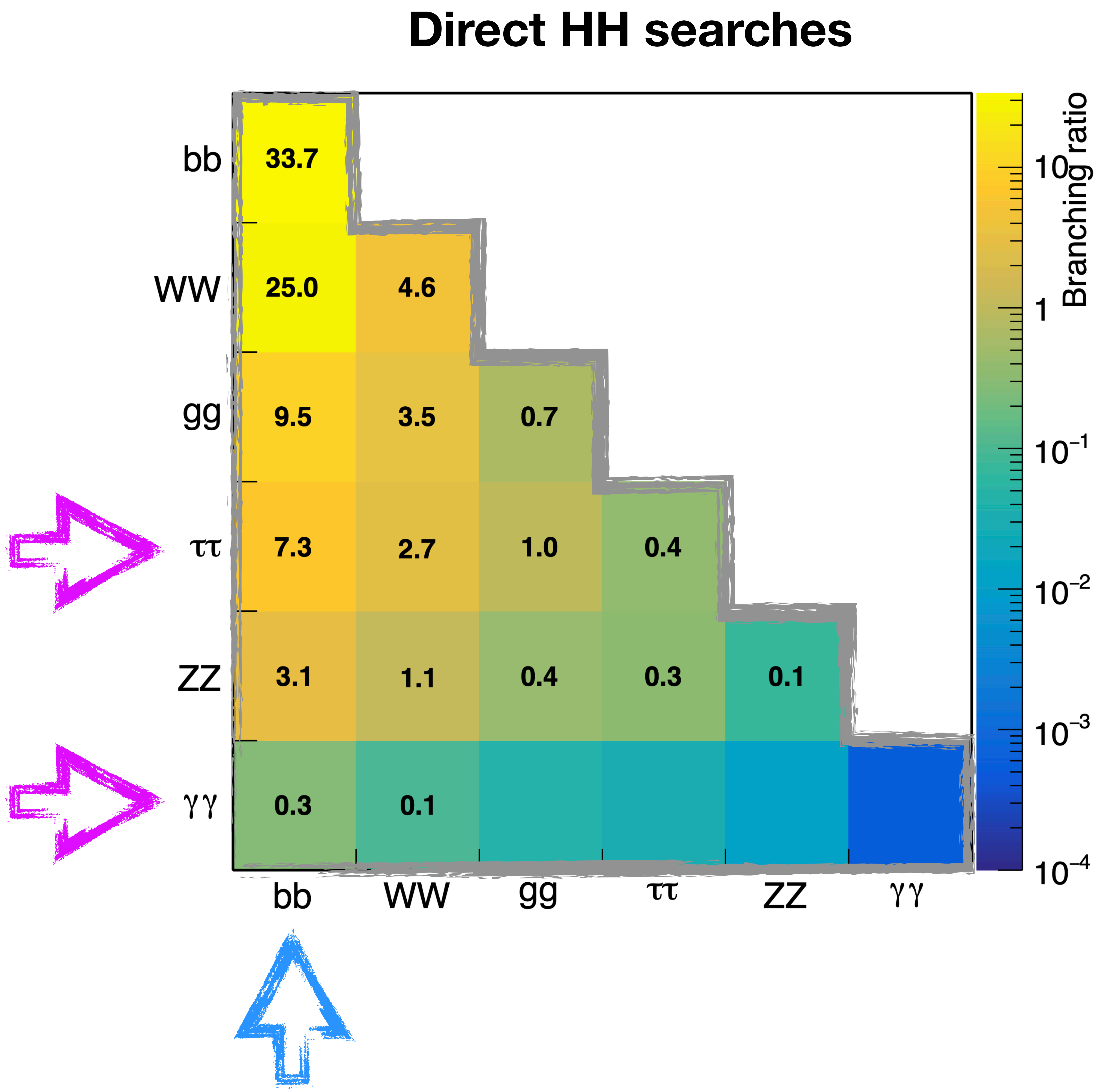
1. **Either large branching ratio**

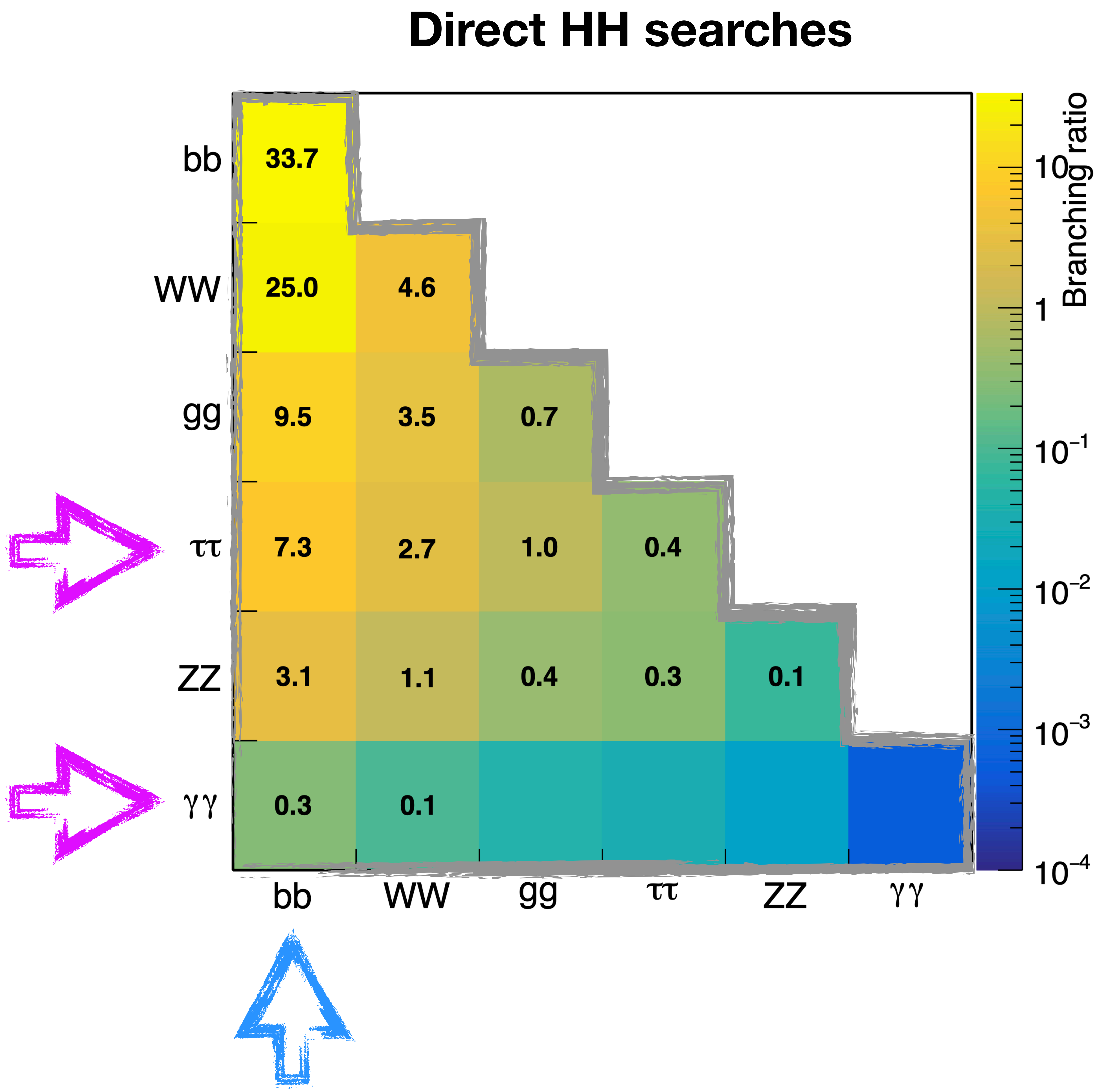
What, why, and where to look



Ideally we would like to investigate all the possible decay modes of HH but given the current luminosity and the harsh experimental conditions, to achieve good sensitivity, we need:

1. **Either large branching ratio**
2. **Or very good selection purity**

What, why, and where to look



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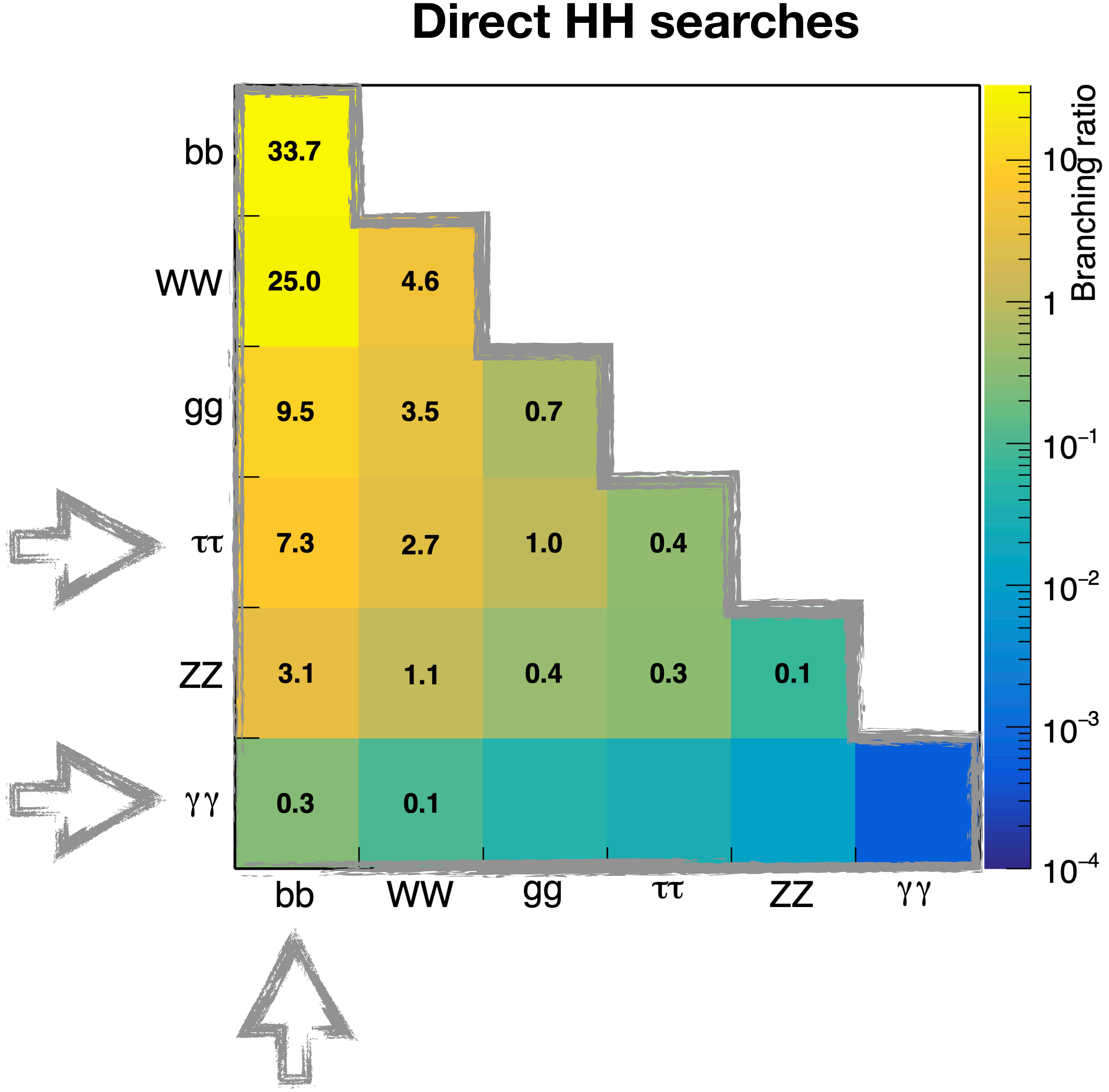
What, why, and where to look



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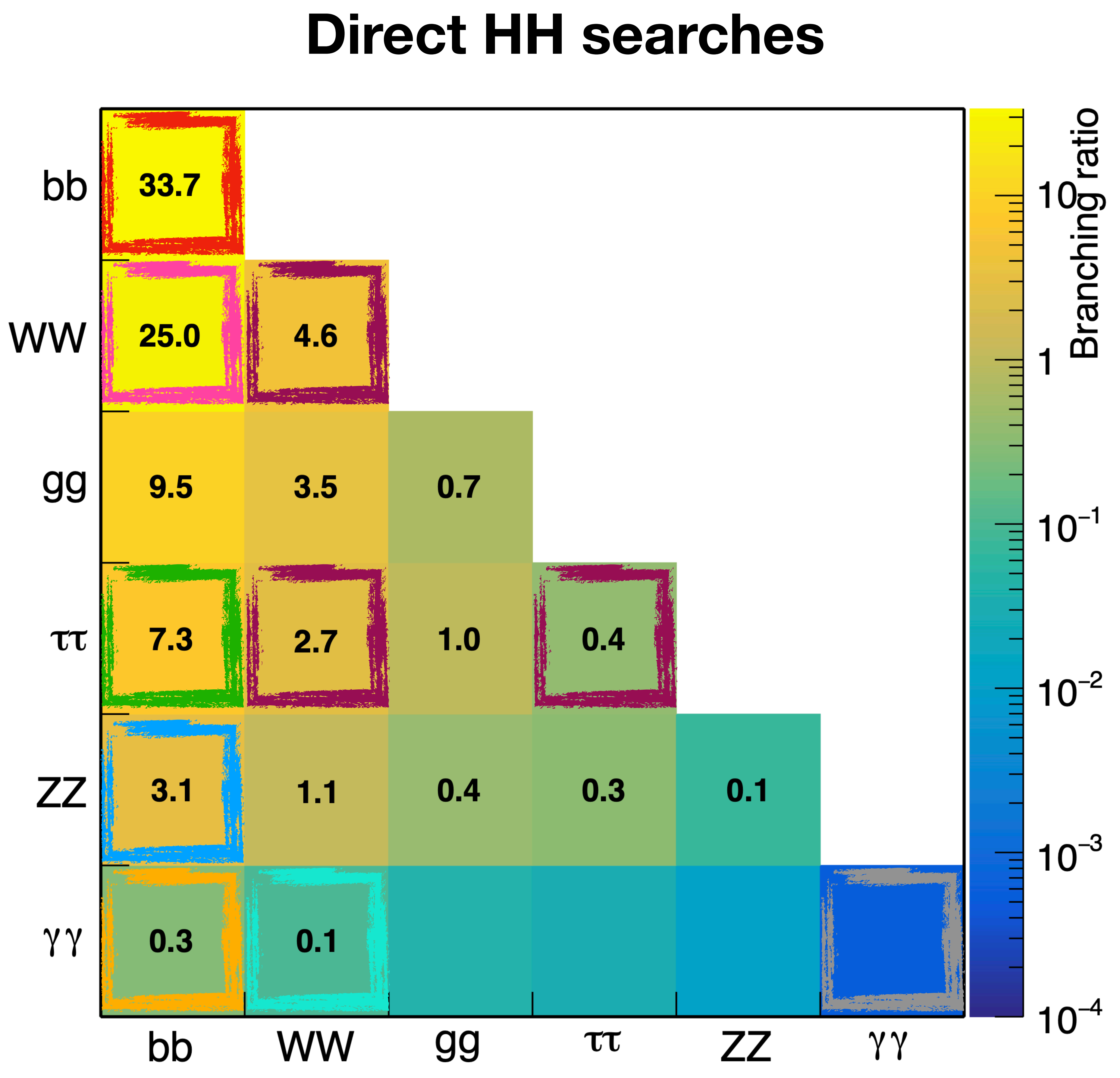
BUT

Thanks to ever-improving reconstruction techniques and identification methods **we are gradually escaping these two constraints!**

What, why, and where to look



Complementary searches to constrain BSM models:

- H→aa→$\gamma\gamma\gamma\gamma$ [JHEP07 (2023) 148] [arXiv:2209.06197v1]
- H→aa→bb$\tau\tau$ + bb$\mu\mu$ [CMS-PAS-HIG-21-021] [CMS-PAS-HIG-22-007]

Check out Stephanie's talk tomorrow morning

HH → bbbb * Non-resonant, resolved topology Phys. Rev. Lett. 129.081802
Non-resonant, boosted topology Phys. Rev. Lett. 131.041803
Non-resonant, VHH production CMS-PAS-HIG-22-006
Resonant X→YH Phys. Lett. B 842.137392

HH → bb$\tau\tau$ * Non-resonant Phys. Lett. B 842.137531
Resonant X→YH JHEP 11 (2021) 057

HH → bb$\gamma\gamma$ * Non-resonant JHEP 03 (2021) 257
Resonant X→YH CMS-PAS-HIG-21-011

HH → bbZZ * Non-resonant JHEP 06 (2023) 130
Resonant Phys. Rev. D. 102.032003

HH → bbWW Non-resonant + Resonant CMS-PAS-HIG-21-005
Resonant JHEP 05 (2022) 005

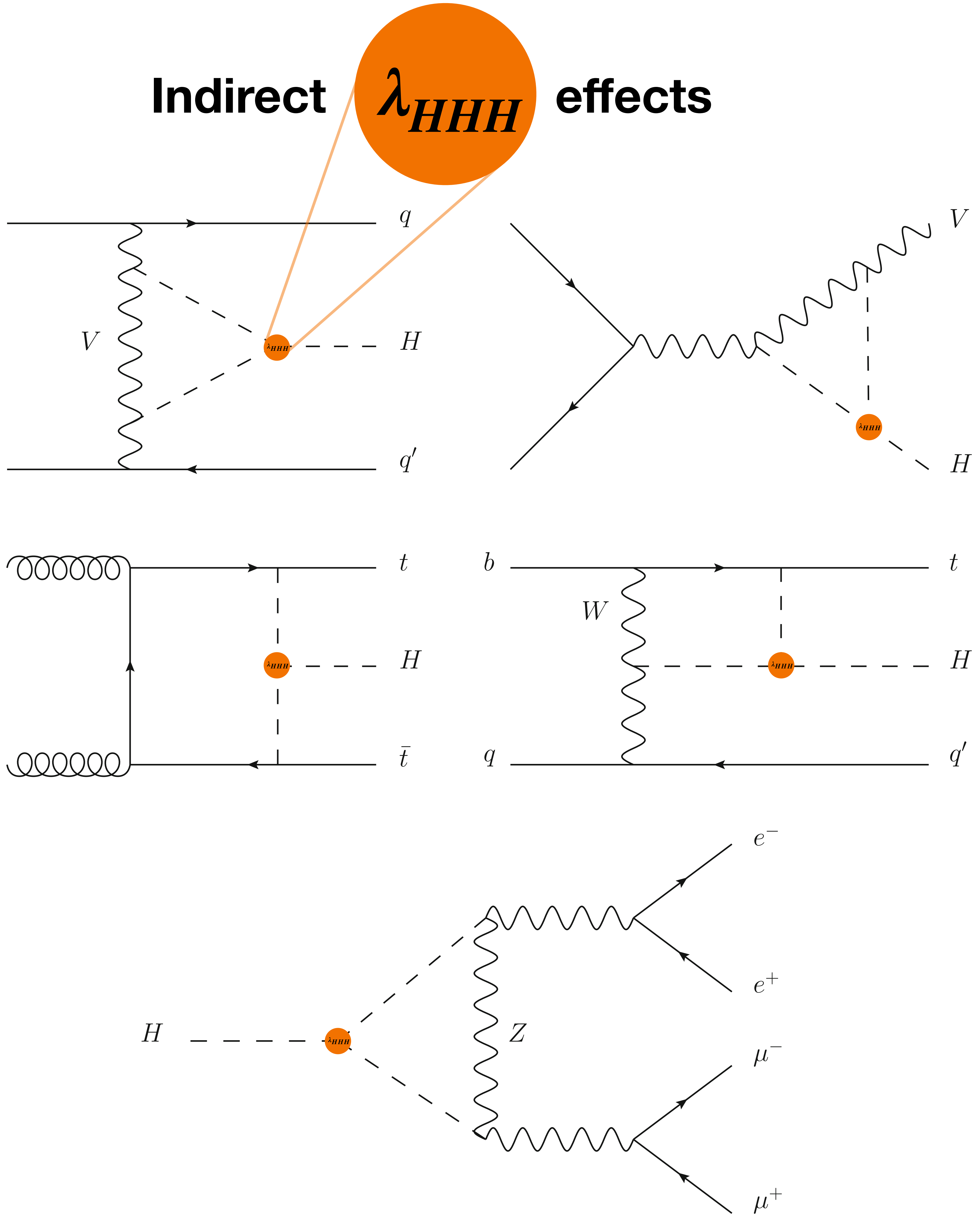
HH → WW$\gamma\gamma$ Non-resonant CMS-PAS-HIG-21-014

HH → WWWW + WW$\tau\tau$ + $\tau\tau\tau\tau$ * Non-resonant + Resonant JHEP 07 (2023) 095

HH combination Nature 607 (2022) 60 (uses only starred * final states)

What, why, and **where to look**

Indirect λ_{HHH} effects



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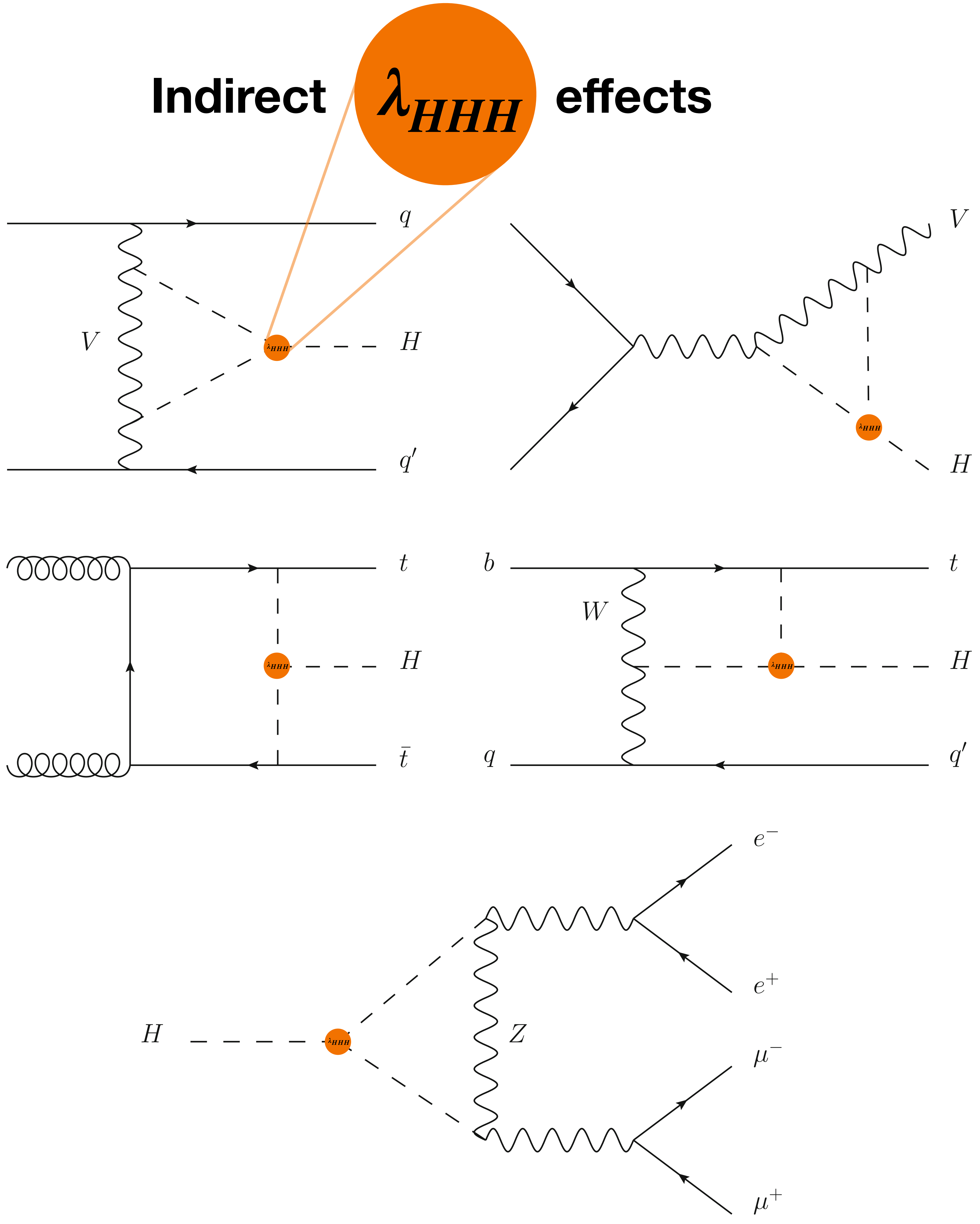


- **At NLO EW correction H boson production includes processes sensitive to λ_{HHH}**
- **ttH, tH, and VH have the largest sensitivity owing to large t/V masses**

- Independently targeted only by one analysis H→ZZ→$\ell\ell\ell\ell$
- Combined result obtained in Nature H combination
- One future projection in $\gamma\gamma$ final state

Differential H→ZZ→$\ell\ell\ell\ell$ JHEP 08 (2023) 040

H combination Nature 607 (2022) 60

Projections ttH+tH, H → $\gamma\gamma$ CMS-PAS-FTR-18-020

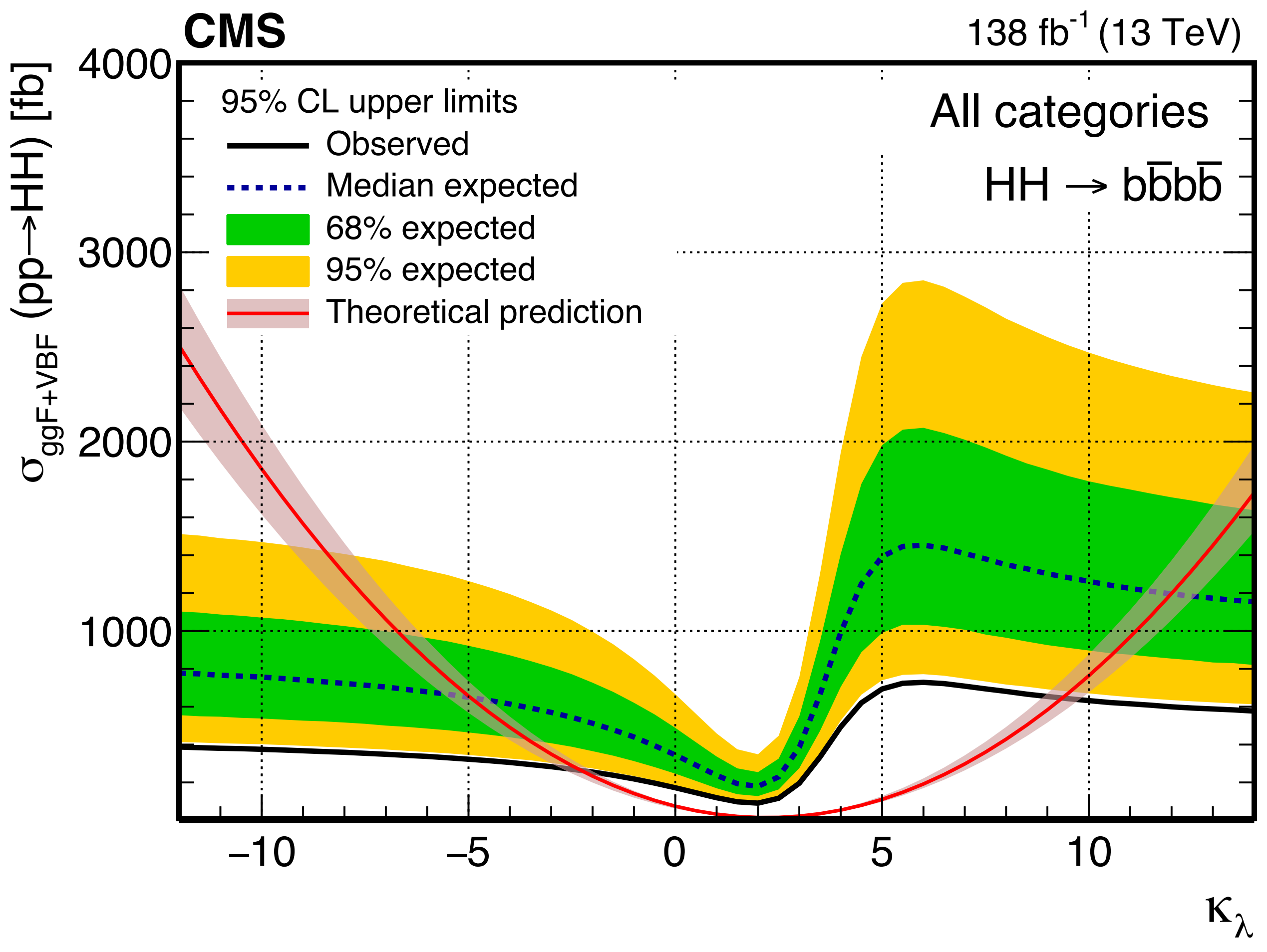
Direct HH searches : the historic three*

Direct HH searches : the historic three*

HH→bbbb resolved

Phys. Rev. Lett. 129.081802

- **Largest Br = 34%**
- **ID with DeepJet**
- Large QCD bkg
- Simultaneous fit of distributions : BDT for ggF and m_{HH} for VBF
- **95% CL upper limit on** $\sigma_{HH}/\sigma_{HH}^{SM} = 3.9(7.9)$
- **95% CL upper limit on** $\sigma_{VBF}/\sigma_{VBF}^{SM} = 226(412)$
- $\kappa_\lambda \in [-2.3, +9.4]$



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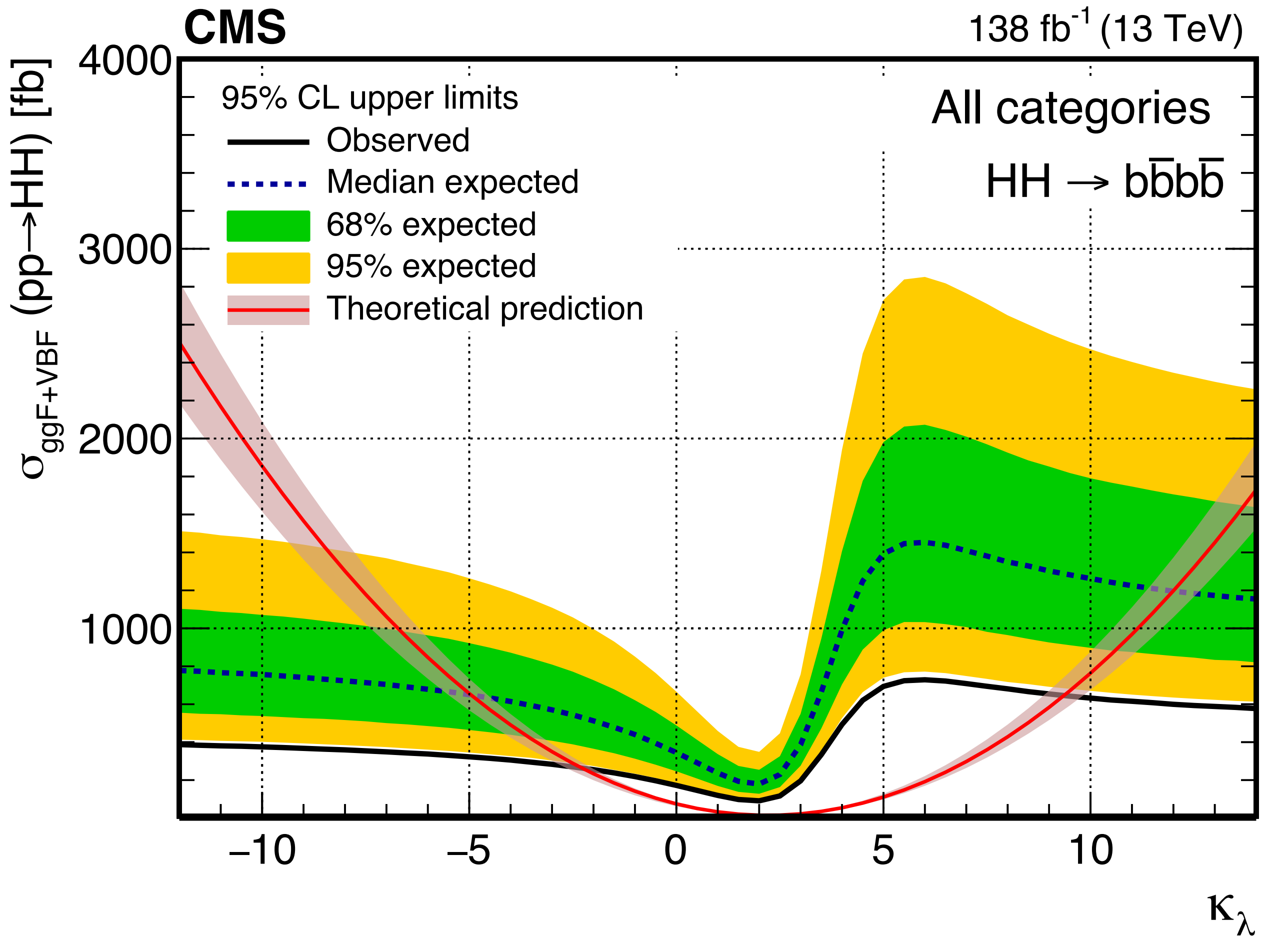

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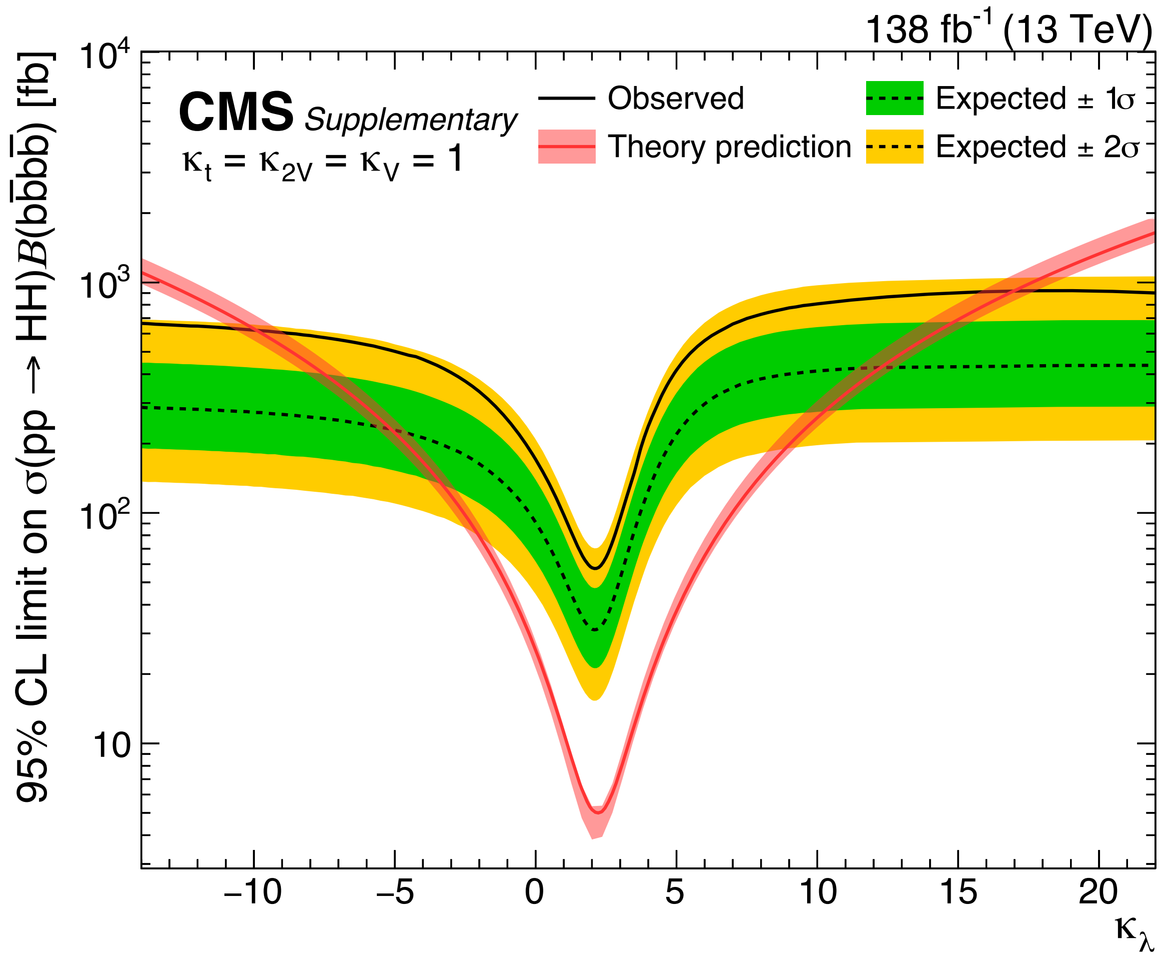
- $\kappa_\lambda \in [-9.9, +16.9]$
- $\kappa_{2V} \in [0.62, +1.41]$



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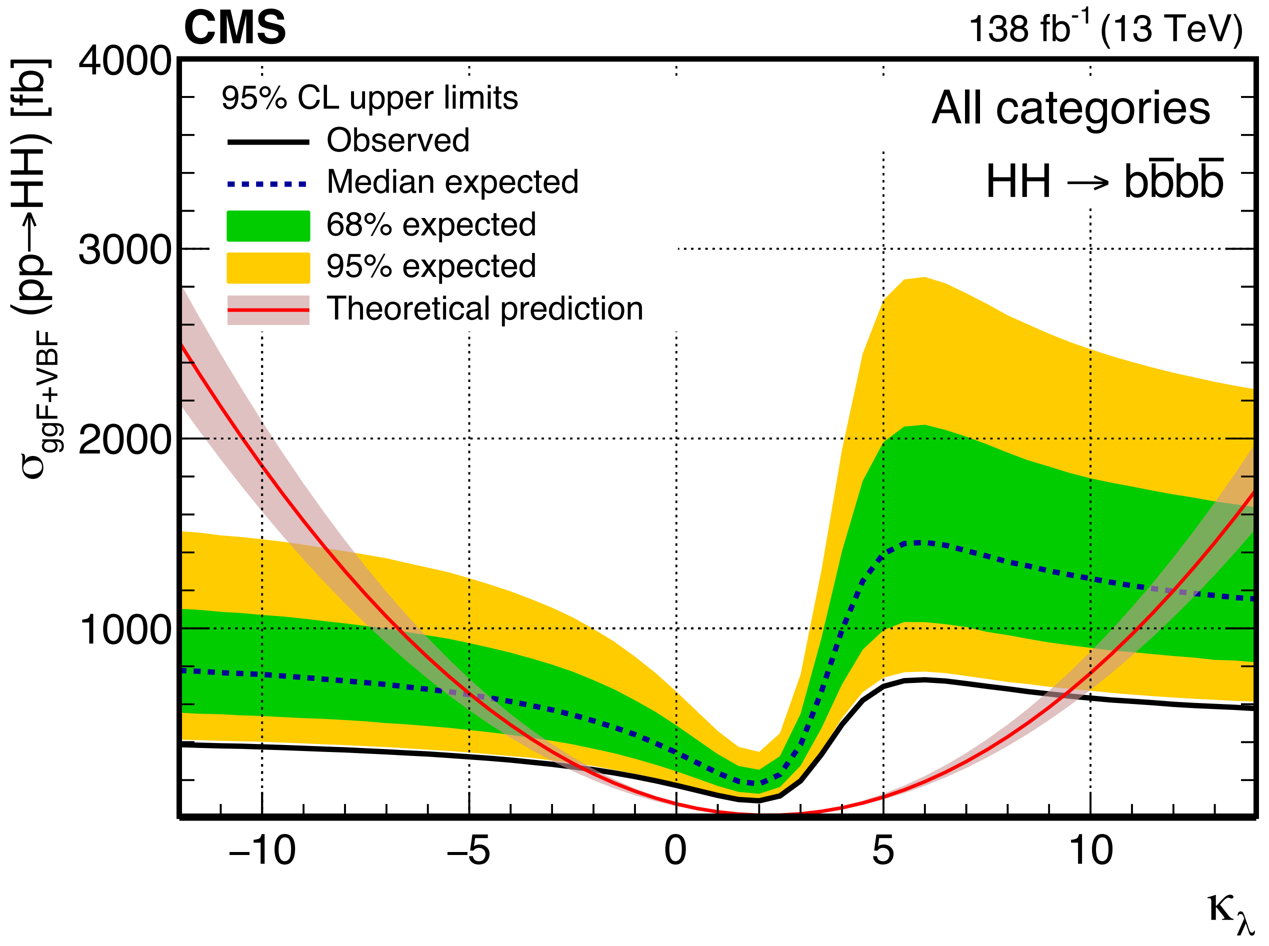
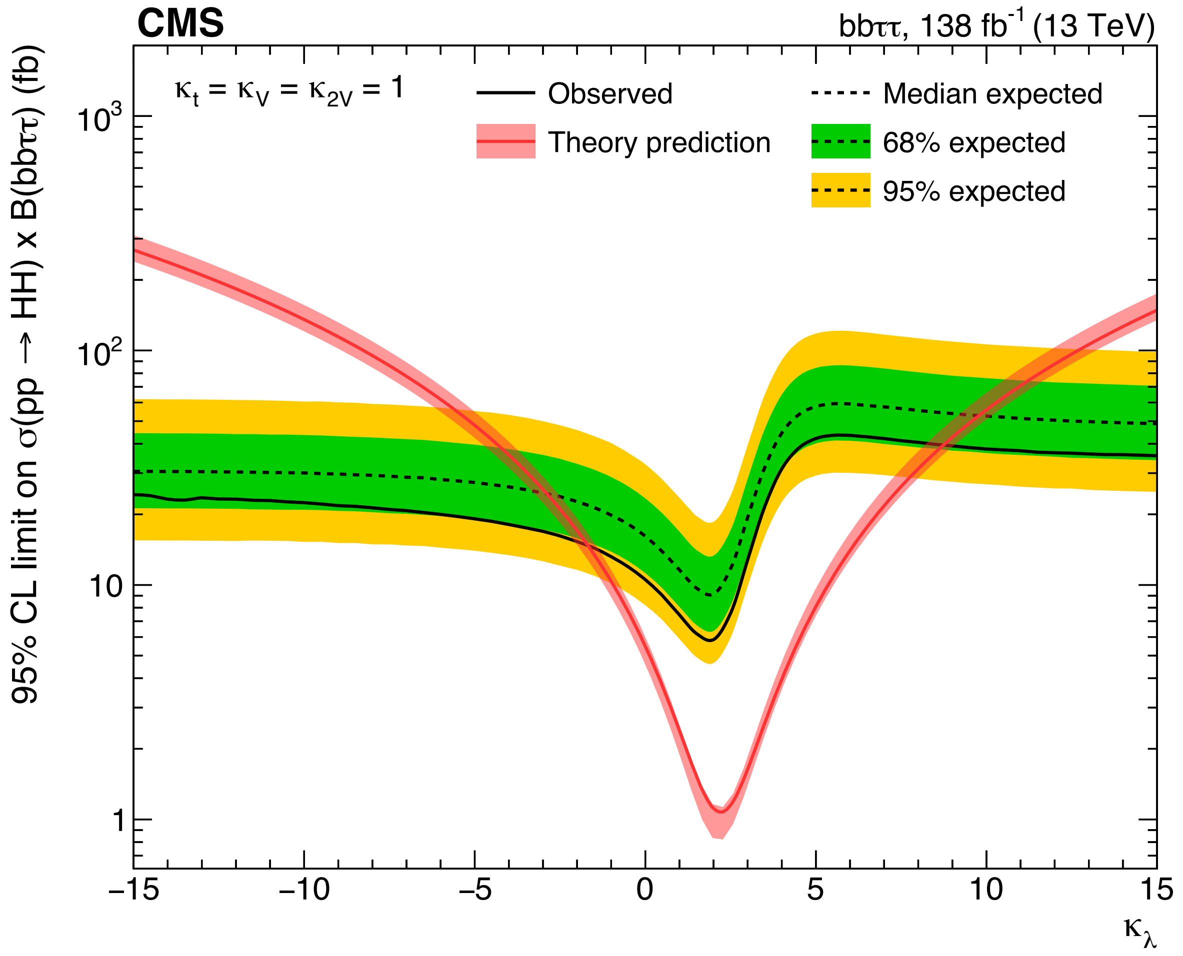


HH→bbττ

Phys. Lett. B 842.137531

- **Sizeable Br = 7.3%**
- **ID with DeepJet and DeepTau**
- Large tt̄ and DY bkg
- Simultaneous fit of single DNN output 72 signal regions
- **95% CL upper limit on** $\sigma_{HH}/\sigma_{HH}^{SM} = 3.3(5.2)$
- **95% CL upper limit on** $\sigma_{VBF}/\sigma_{VBF}^{SM} = 124(154)$
- $\kappa_\lambda \in [-1.7, +8.7]$



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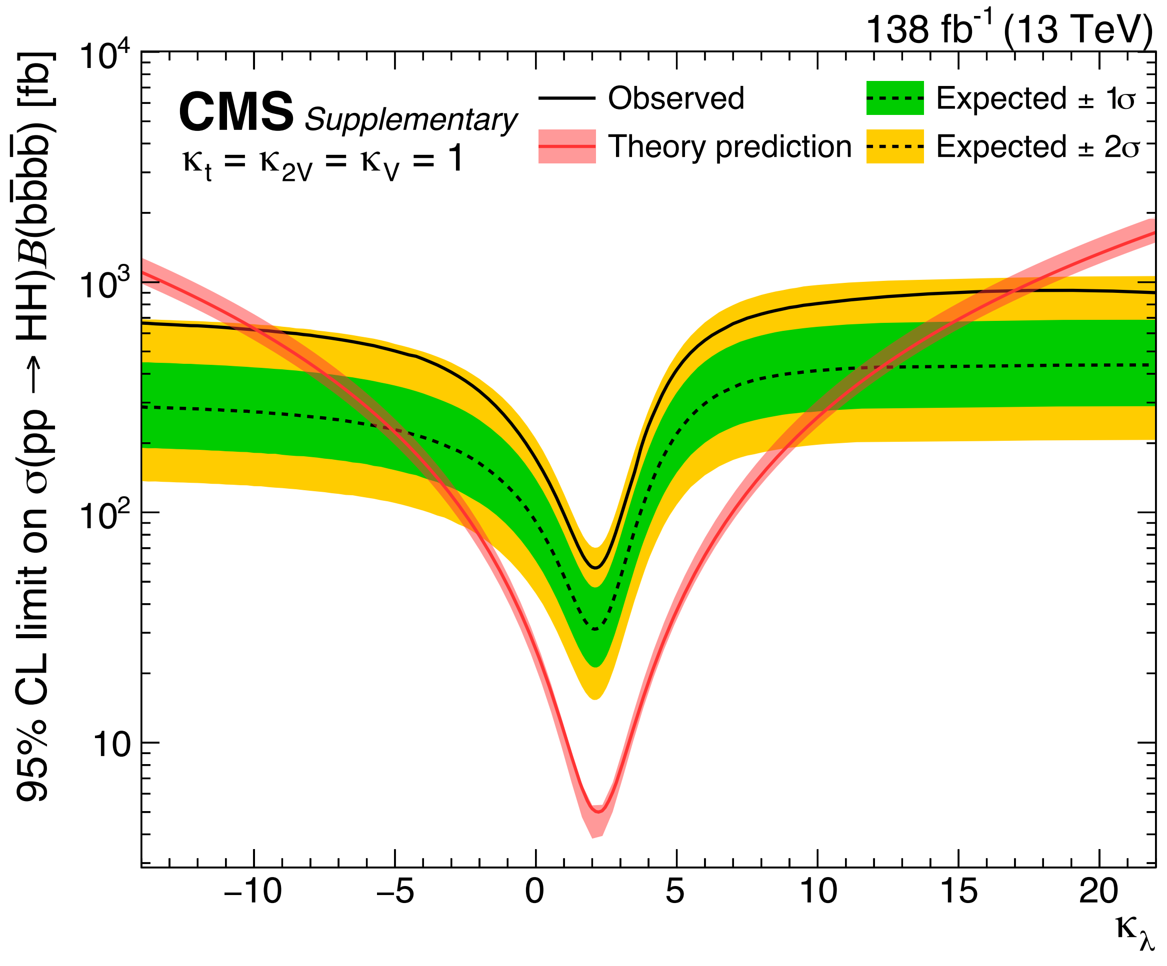

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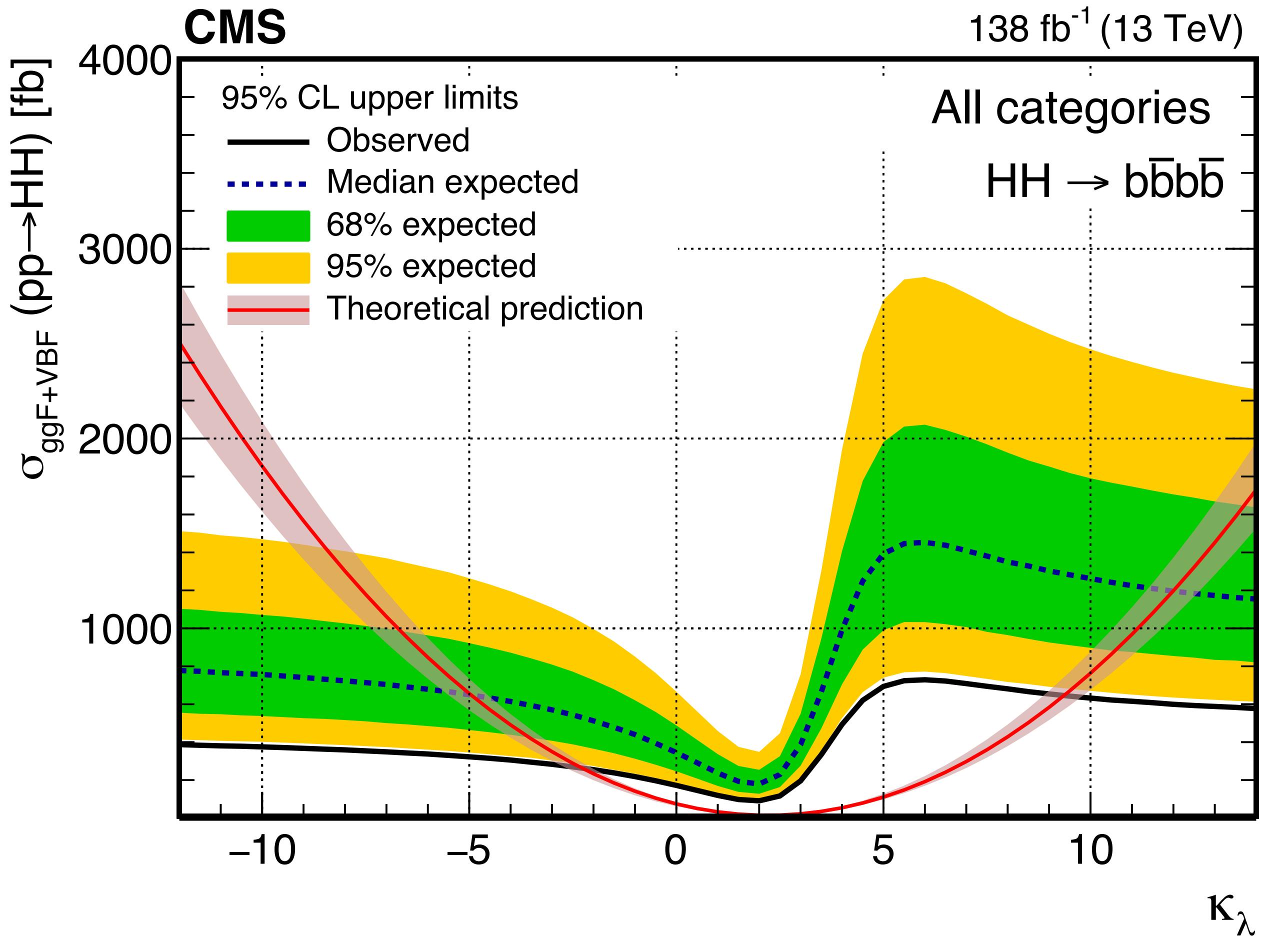

HH→bb$\tau\tau$

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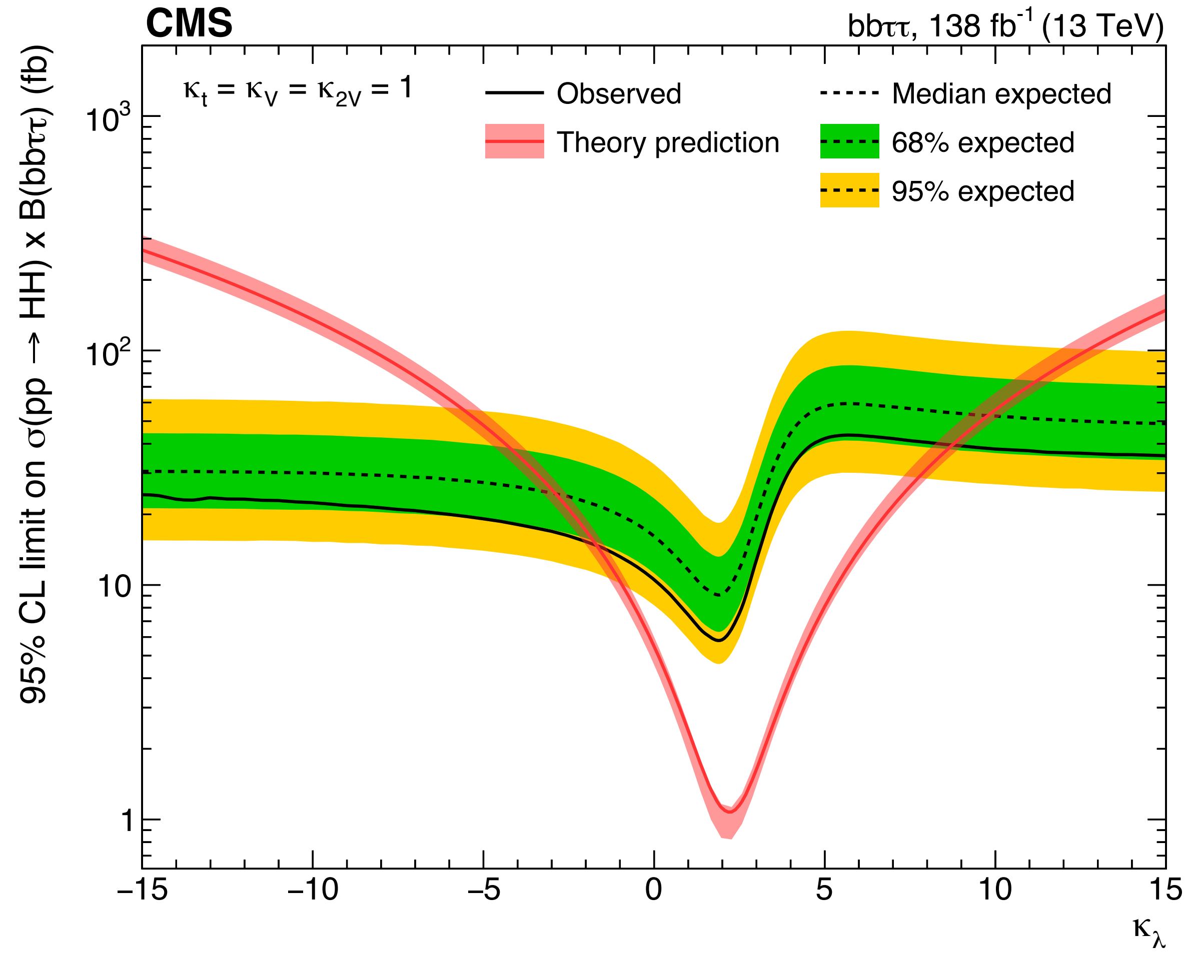

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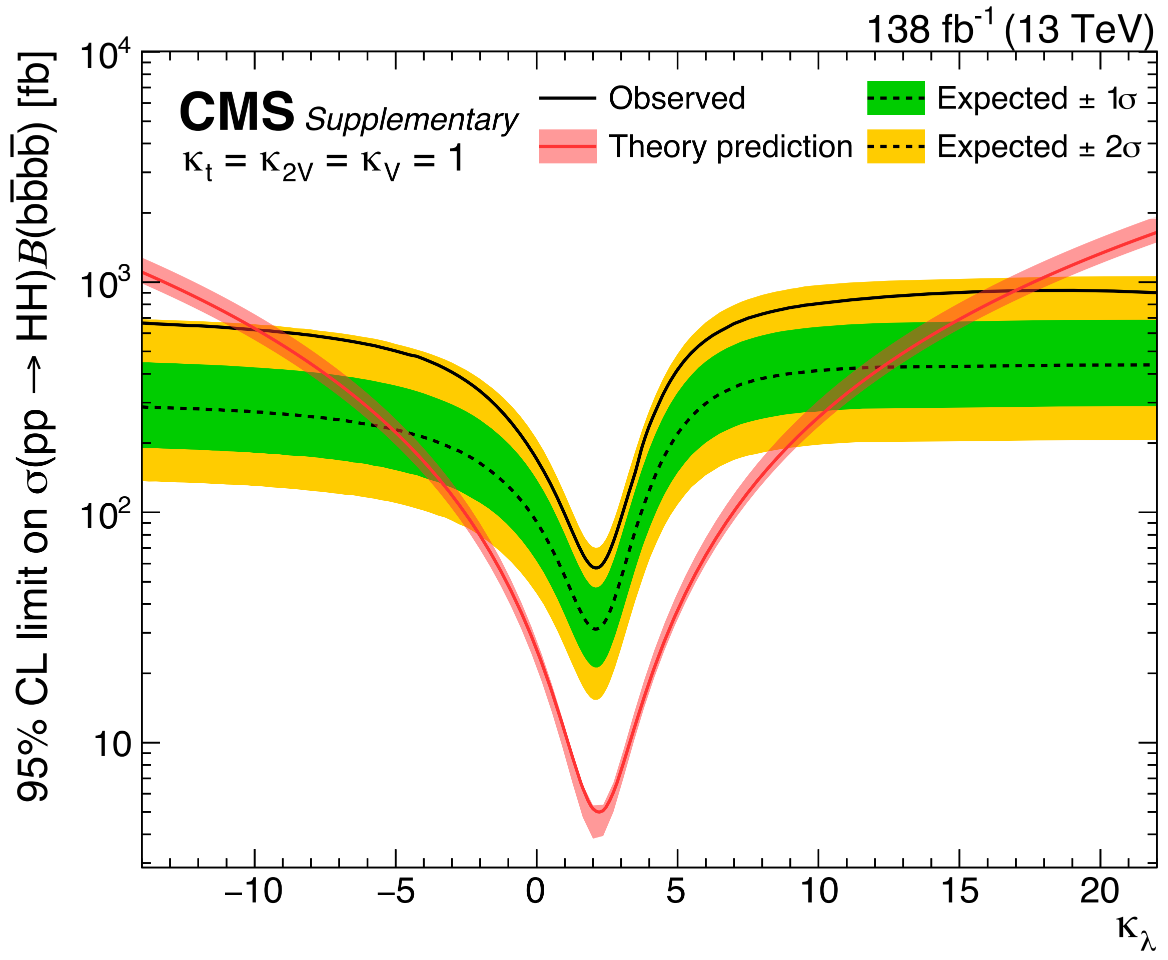
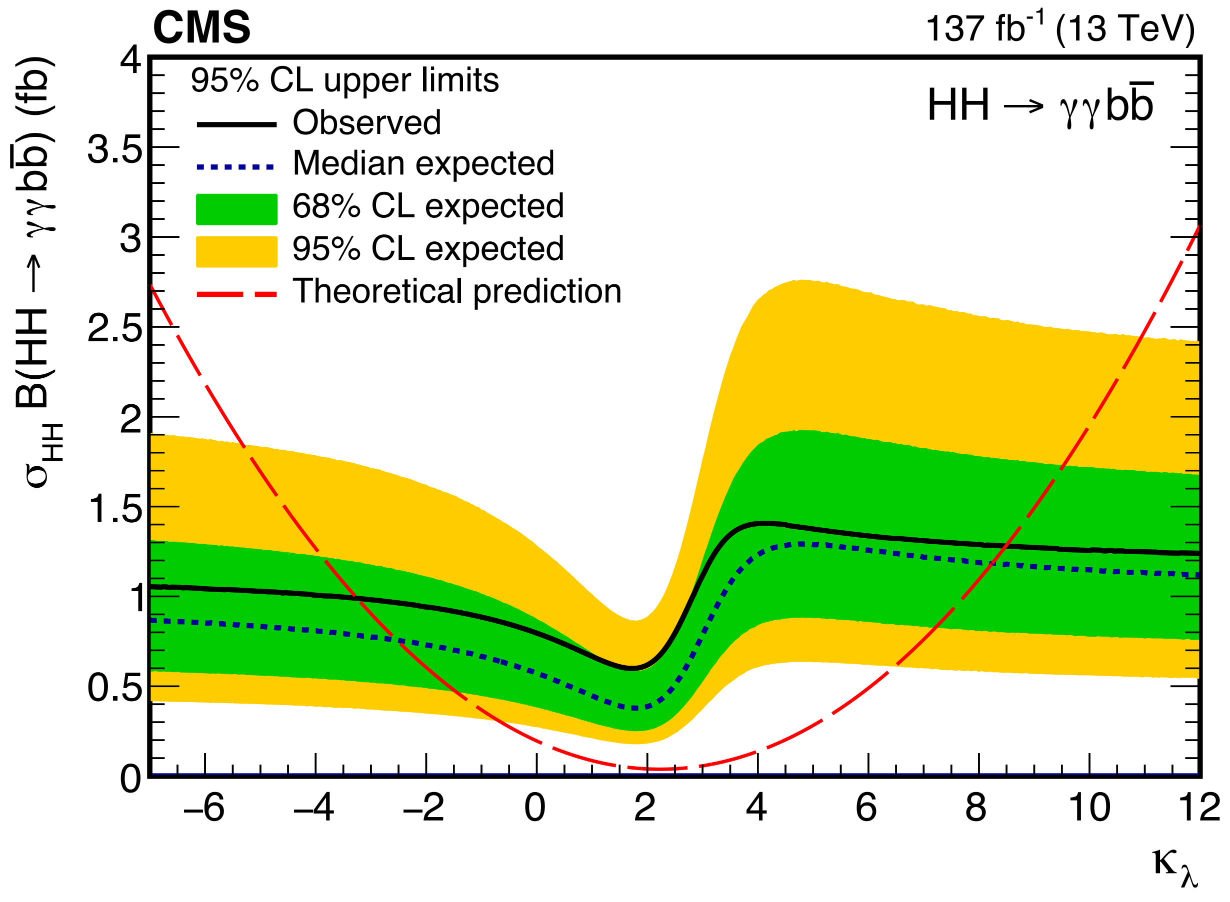


HH→bb$\gamma\gamma$

JHEP 03 (2021) 257

- **Tiny Br = 0.3% + very good purity**
- B-jets ID with DeepJet
- Purely kinematical signal region definition
- $(m_{bb}, m_{\gamma\gamma})$ 2D maximum likelihood fit
- **95% CL upper limit on** $\sigma_{HH}/\sigma_{HH}^{SM} = 7.7(5.2)$
- **95% CL upper limit on** $\sigma_{VBF}/\sigma_{VBF}^{SM} = 225(208)$
- $\kappa_\lambda \in [-3.3, +8.5]$



Direct HH searches : the additional two

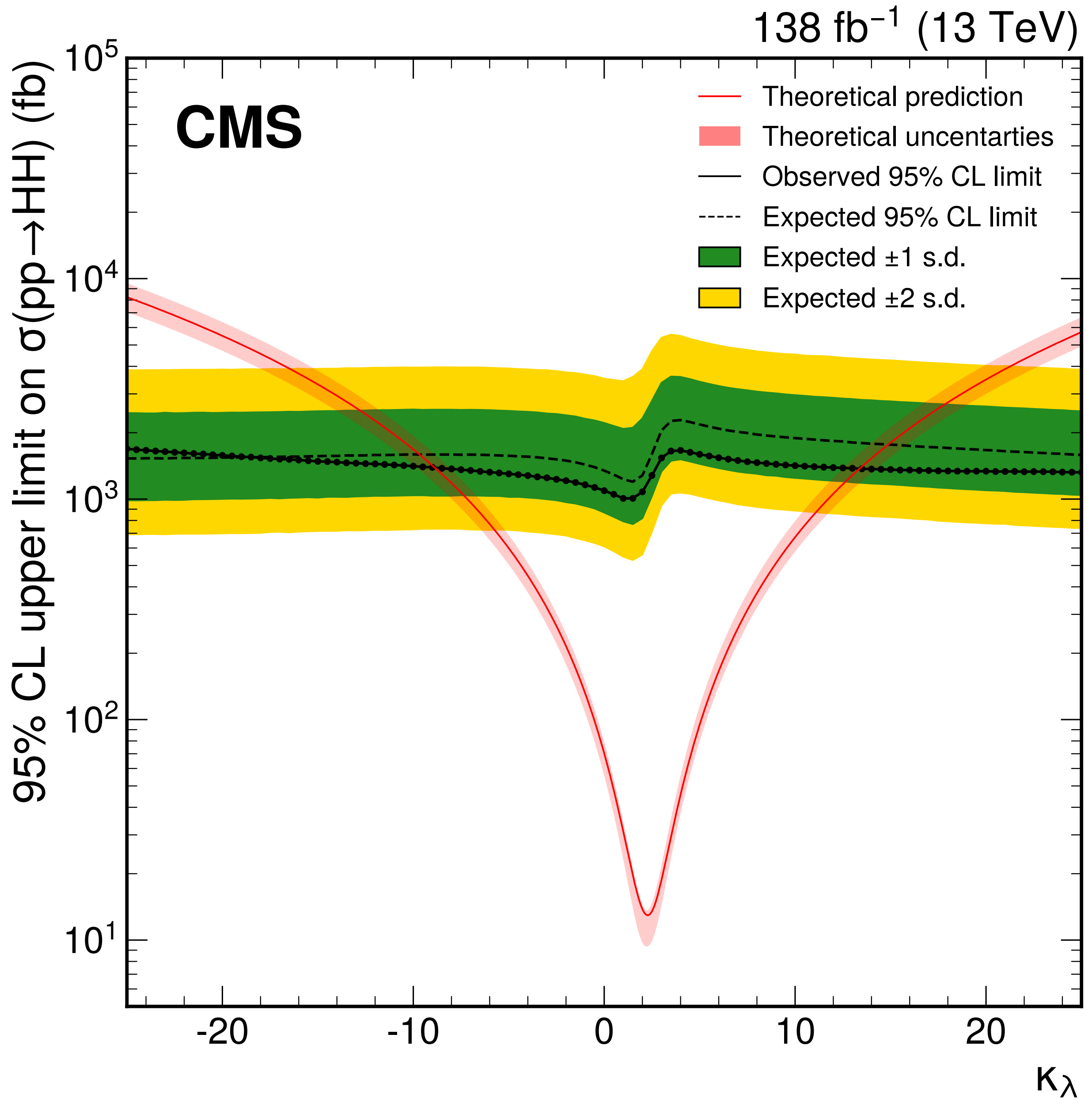
Direct HH searches : the additional two

HH → bbZZ

JHEP 06 (2023) 130

- **Very small Br = 3.1% → Br = 0.014% when including Z →** $\ell\ell$
- **B-jets ID with DeepJet**
- Single H and ZZ bkg
- BDT used for signal extraction
- **95% CL upper limit on** $\sigma_{HH}/\sigma_{HH}^{SM} = 32(40)$
- $\kappa_\lambda \in [-8.8, +13.4]$

Only result in this channel at the LHC



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JHEP 06 (2023) 130

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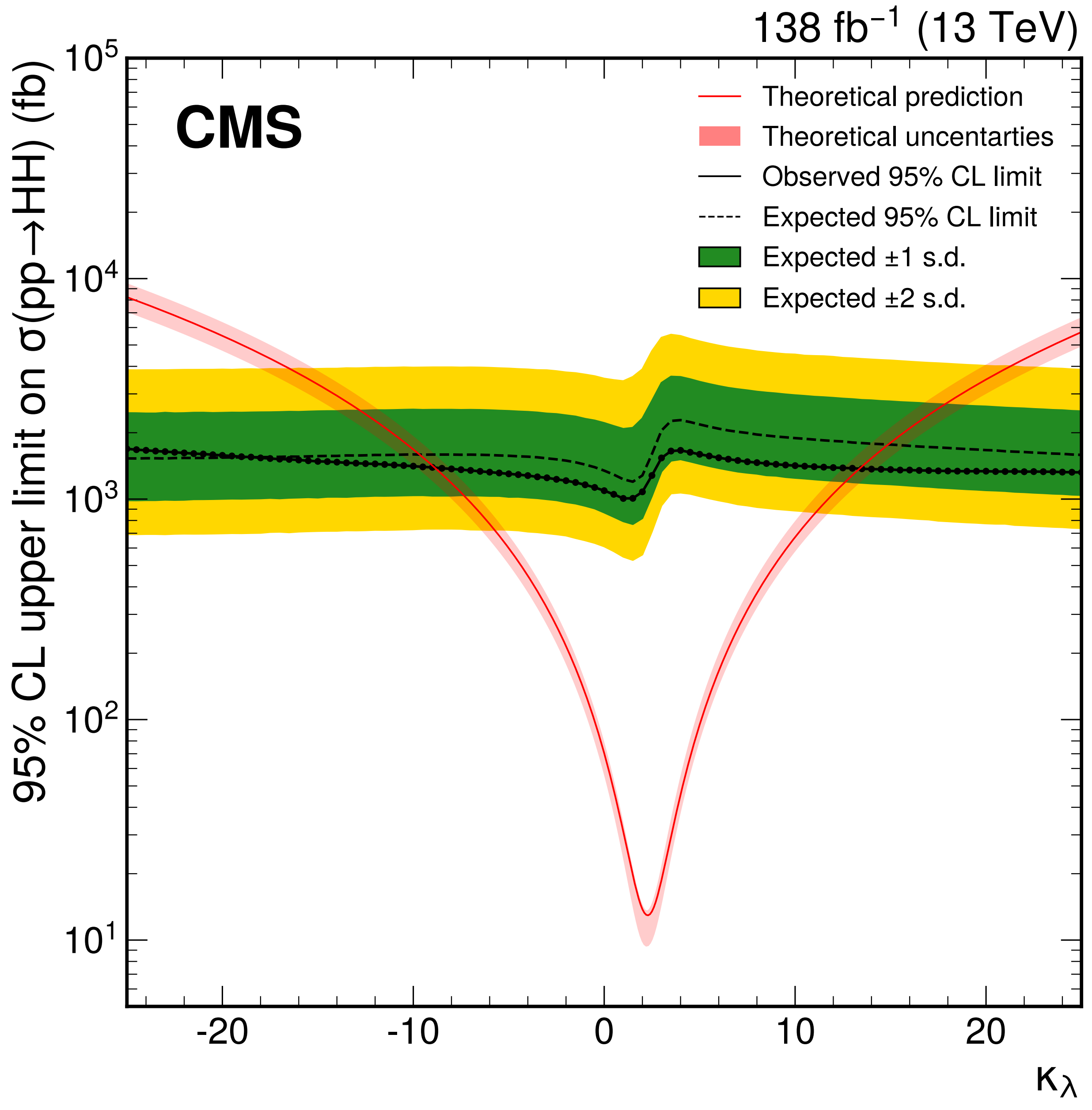
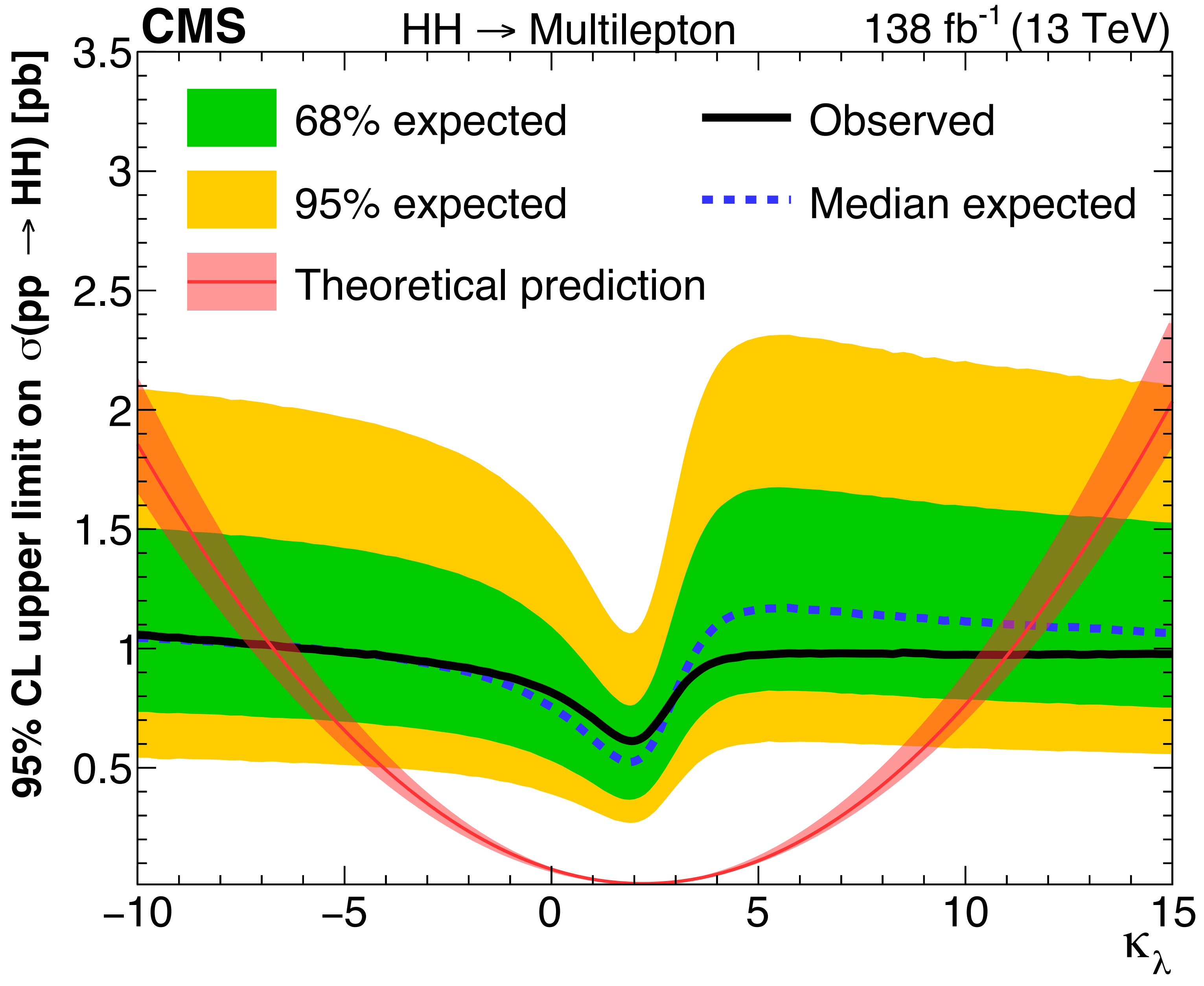


HH → WWWW + WW$\tau\tau$ + $\tau\tau\tau\tau$

JHEP 07 (2023) 095

- **Small Br(4W) = 4.6%, Br(2W2τ) = 2.7%, Br(4τ) = 0.4%**
- **7 categories of ℓ-multiplicity**
- Large QCD, V, VV, and $t\bar{t}$ bkg
- BDT used for signal extraction
- **95% CL upper limit on $\sigma_{HH}/\sigma_{HH}^{SM} = 21.3(40)$**
- $\kappa_\lambda \in [-6.9, +11.1]$

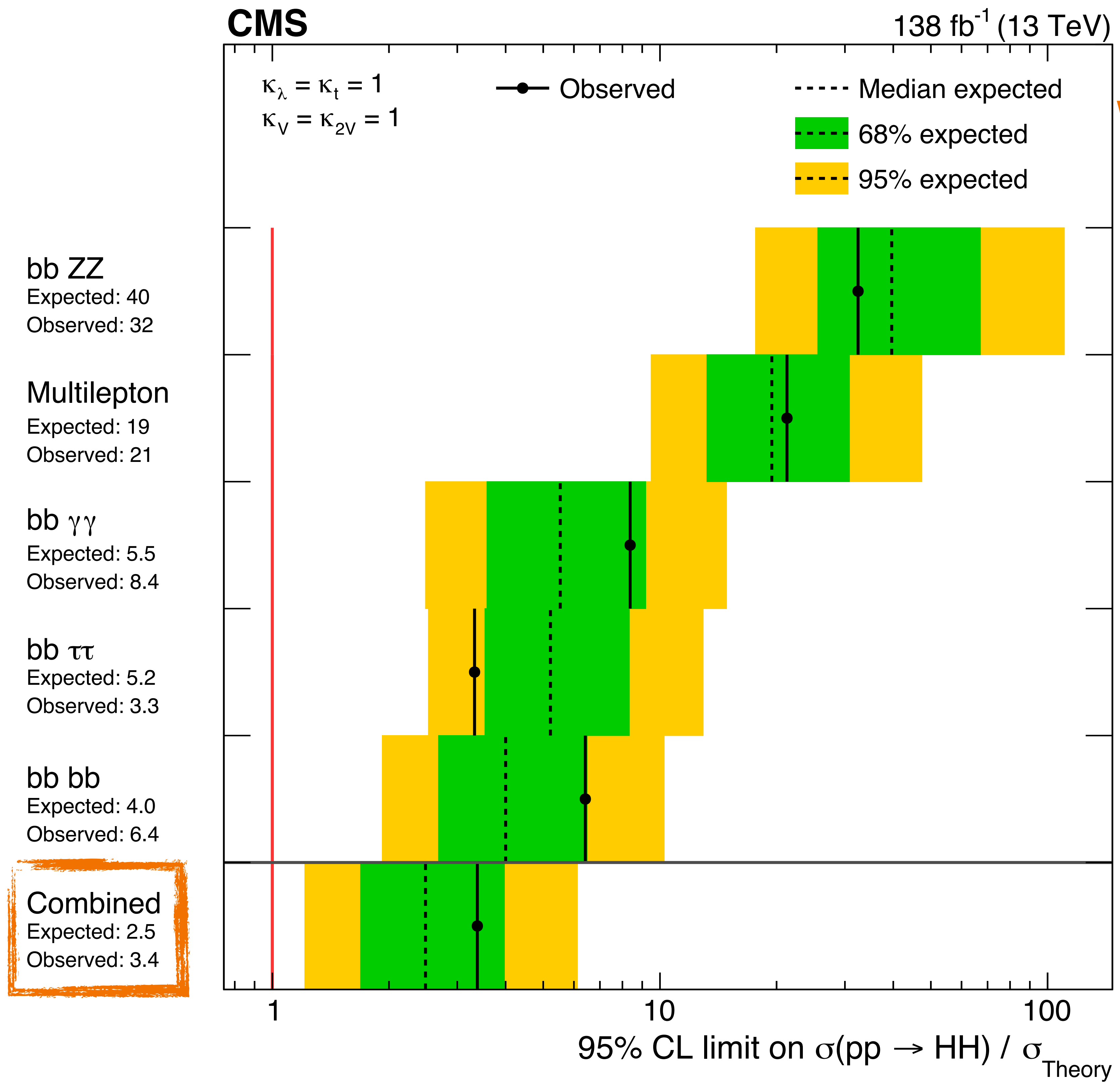
Only result in this channels with full Run-2 dataset



Direct HH searches : the combination

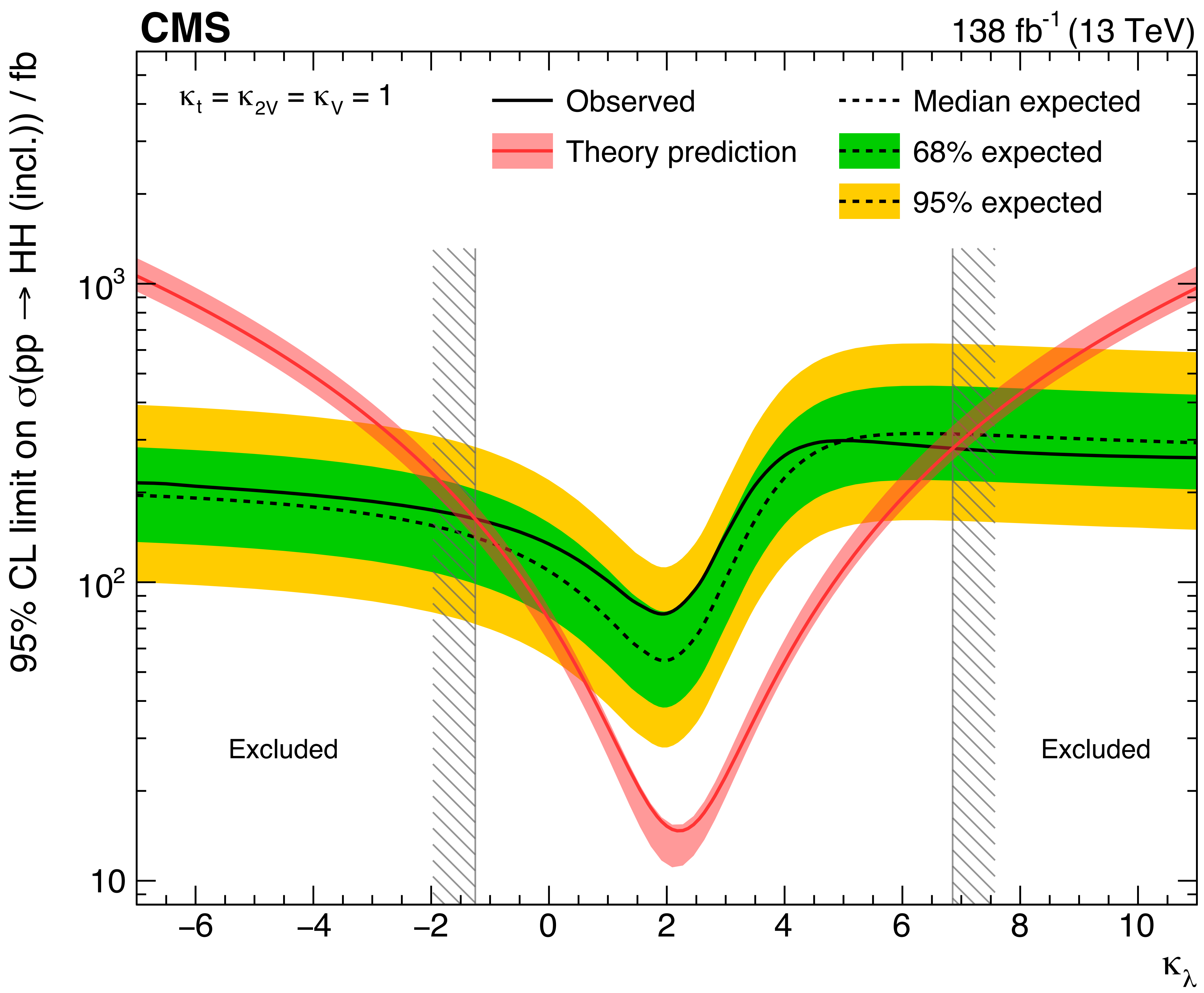
Nature 607 (2022) 60

- Early Run-2 95% CL upper limit was $12.8 \times \sigma_{HH}^{SM}$ → simple luminosity scaling would predict $6.5 \times \sigma_{HH}^{SM}$ with full Run-2 dataset
- **Combined Run-2 result is $2.5 \times \sigma_{HH}^{SM}$**
- **Much better than simple lumi scaling** owing to:
  - **DeepJet, DeepTau, ParticleNet**
  - **Improved L1 and HLT triggers**
  - **Detector upgrades** (happened in 2016 YETS)
  - **Improved analysis with extensive use of ML**



WRT EARLY RUN-2 (2016) RESULTS

- bb ZZ: **NEW**
- Multilepton: **NEW**
- bb γγ: **× 3 BETTER**
- bb ττ: **× 5 BETTER**
- bb bb: **× 6 BETTER**, **× 30 in boosted analysis**
- Combined: **× 5 BETTER**



- $\kappa_\lambda \in [-1.24, +6.49]$
- $\kappa_{2V} \in [0.67, +1.38]$

Both results obtained with all other couplings set to SM prediction, i.e. $\kappa = 1$

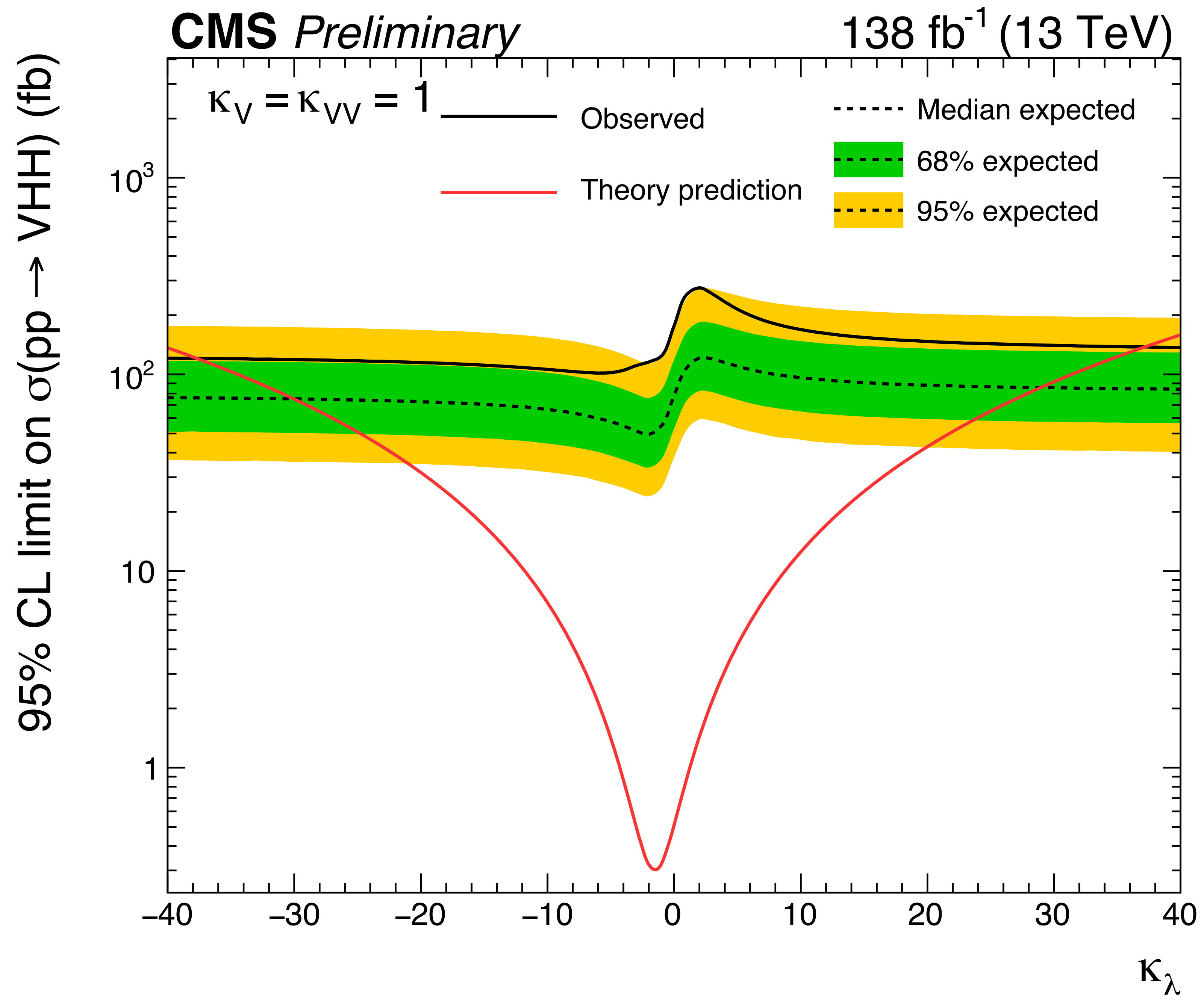
VVHH coupling established at 6.6σ significance level

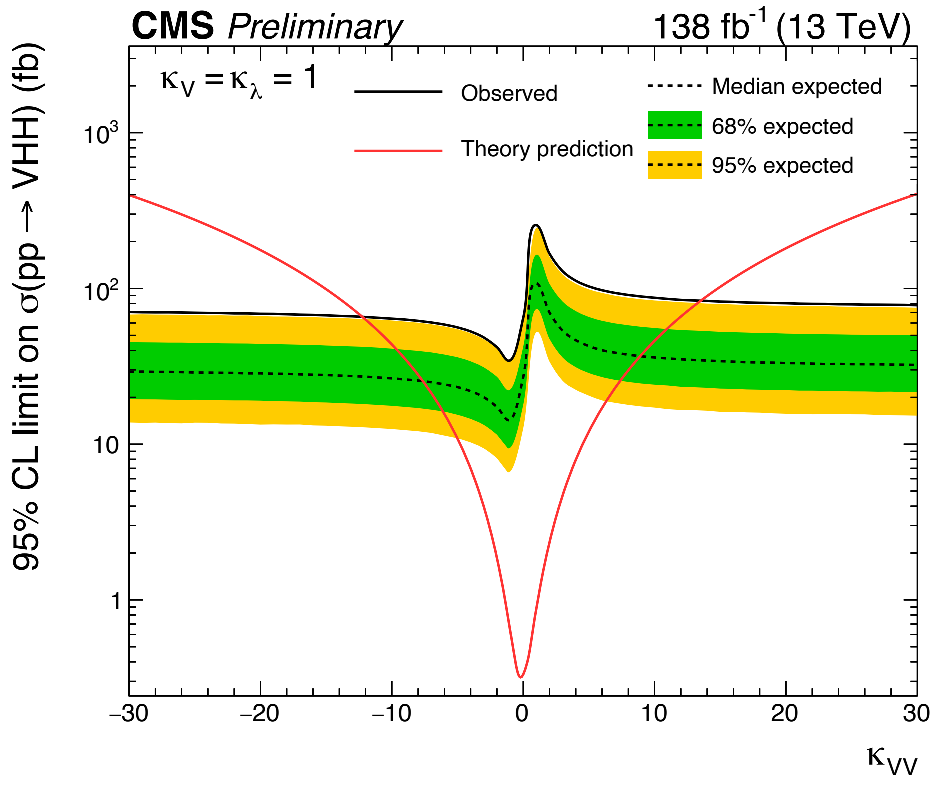
Direct HH searches : the new-comers

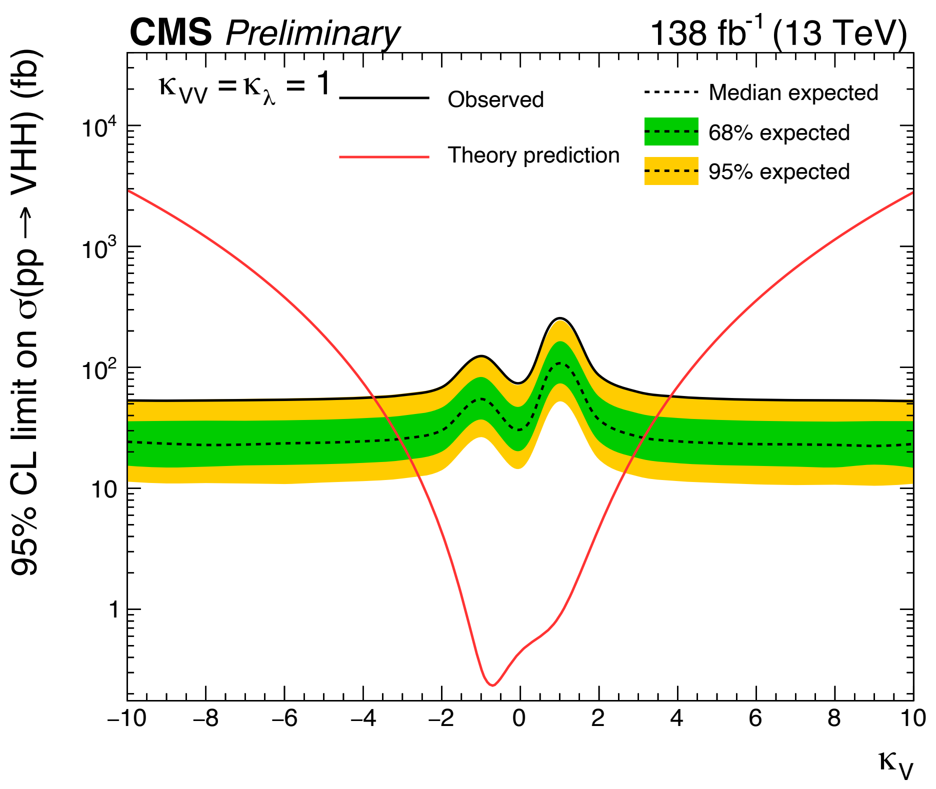
VHH | HH → bbbb

CMS-PAS-HIG-22-006

- **First ever analysis at CMS to target a production mechanism other than ggF and VBF**
- **Tiny event yield : SM predicts 110 VHH events in Run-2**
- 4 channels based on V decay:
  - (MET) Z → $\nu\nu$, (1L) W → $\ell\nu$
  - (2L) Z → $\ell\ell$, (FH) W/Z→qq
- Signal regions (SRs), control regions, and sidebands defined on one-dimensional distance from where both H masses are 125 GeV
- SRs further categorised base on number of b-jets, and based on BDT selection to enhance κ sensitivity
- **BDT and DNN used for signal extraction in 2L+1L and FH channels,** respectively
- **95% CL upper limit** $\sigma_{VHH}/\sigma_{VHH}^{SM} = 294\ (124)$
- $\kappa_\lambda \in [-37.7, 37.2]([-30.1, 28.9])$ - $\kappa_{2V} \in [-12.2, 13.5]([-7.2, 8.9])$
- $\kappa_{2Z} \in [-17.4, 18.5]([-10.5, 11.6])$ - $\kappa_{2W} \in [-14.0, 15.4]([-10.2, 11.6])$





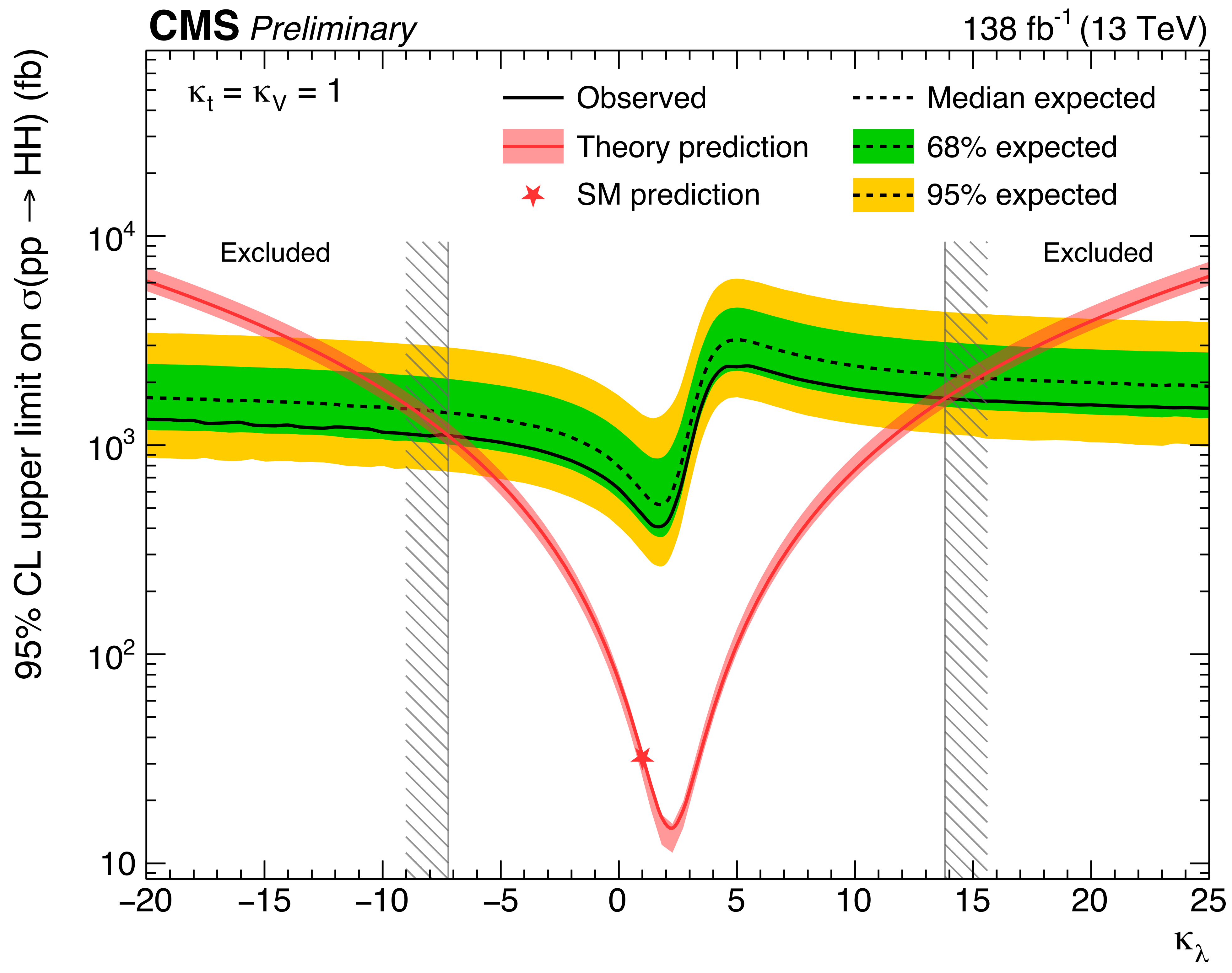


Direct HH searches : the new-comers

HH → bbWW

CMS-PAS-HIG-21-005

- **Second largest Br = 25%**
- Multijet, $t\bar{t}$, t, and DY backgrounds
- 2 channels based on W decay: single- or double-lepton
- Final categorisation based on **DNN multi-classifier with boosted and resolved categories**
- **All categories simultaneously fitted**
- $\sigma_{HH}/\sigma_{HH}^{SM} = 18\ (14)$ - $\sigma_{VBF}/\sigma_{VBF}^{SM} = 277\ (301)$
- $\kappa_\lambda \in [-7.2, 13.8]([-8.7, 15.2])$
- $\kappa_{2V} \in [-1.1, 3.2]([-0.9, 3.0])$ → **Interval comparable to bb$\gamma\gamma$ analysis**

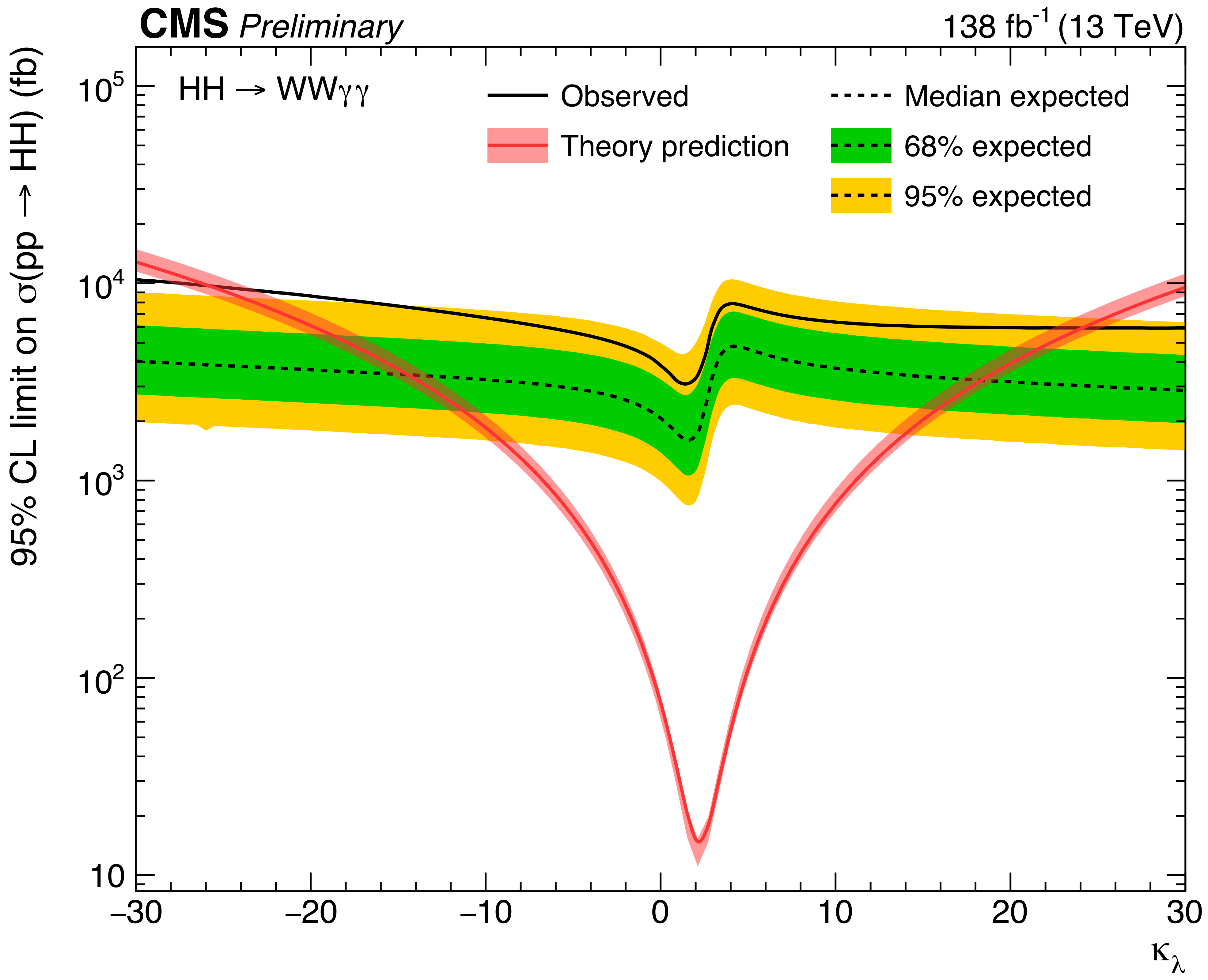


Direct HH searches : the new-comers

HH → WW$\gamma\gamma$

CMS-PAS-HIG-21-014

- **Very small Br = 0.1% + good $\gamma\gamma$ selection**
- $t\bar{t}\gamma$, $\gamma/\gamma\gamma$+jets, DY, and single-H backgrounds
- 3 channels based on W decay: fully hadronic (FH), one lepton (SL), two leptons (FL)
- Final categorisation based on **DNN multi-classifier in FH and SL, fully cut based in FL channel**
- **All categories simultaneously fitted**
- $\sigma_{HH}/\sigma_{HH}^{SM} = 97\ (52)$
- $\kappa_\lambda \in [-25.8, 24.1]([-14.4, 18.3])$



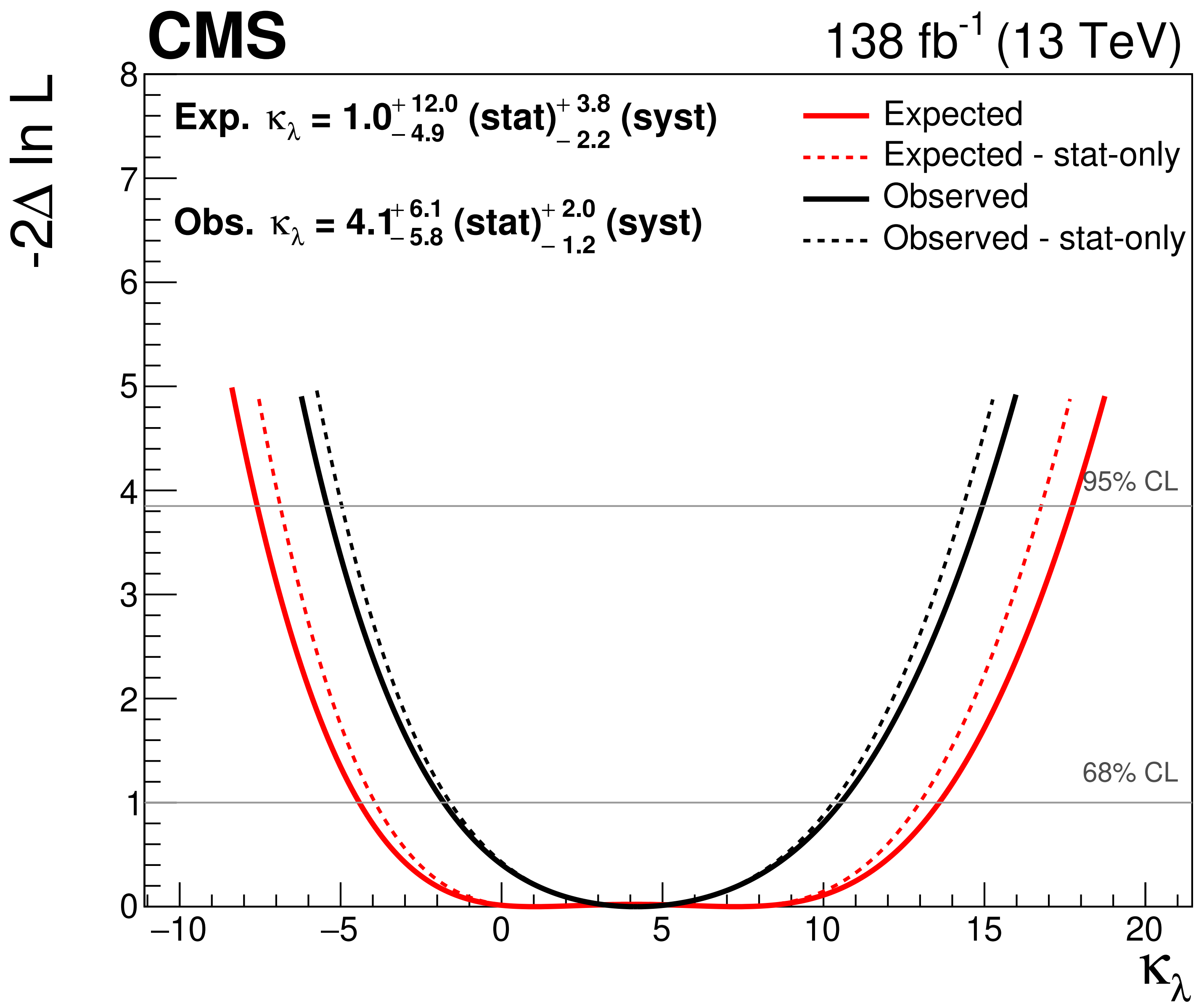
Indirect λ_{HHH} effects

Indirect λ_{HHH} effects

H → ZZ → $\ell\ell\ell\ell$

[JHEP 08 (2023) 040]

- **H → ZZ → $\ell\ell\ell\ell$ inclusive and differential σ measurement**
- **Parametric maximum likelihood of $m_{4\ell}$ invariant mass in fiducial phase space, using a matrix element approach to categorisation**
- **At present, only single H analysis at the LHC to perform κ_λ scan**
- $\kappa_\lambda = 4.1^{+6.1}_{-5.8}\,(stat.)\,^{+2.0}_{-1.2}\,(syst.)$ observed
- $\kappa_\lambda \in [-5.4, 14.9]\ ([-7.6, 17.7])$



Indirect λ_{HHH} effects

$H \to ZZ \to \ell\ell\ell\ell$

JHEP 08 (2023) 040

- $H \to ZZ \to \ell\ell\ell\ell$ inclusive and differential σ measurement
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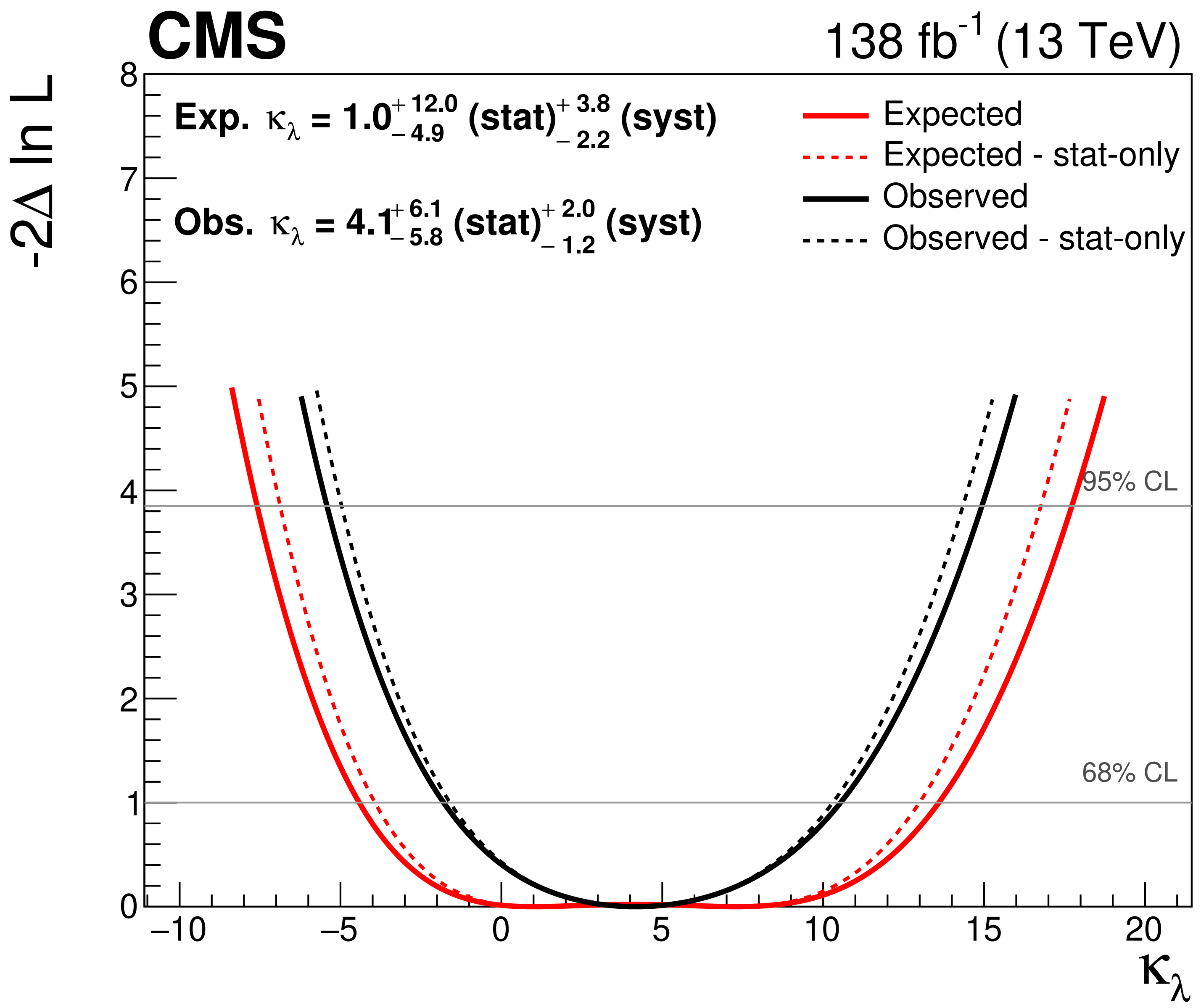

H combination

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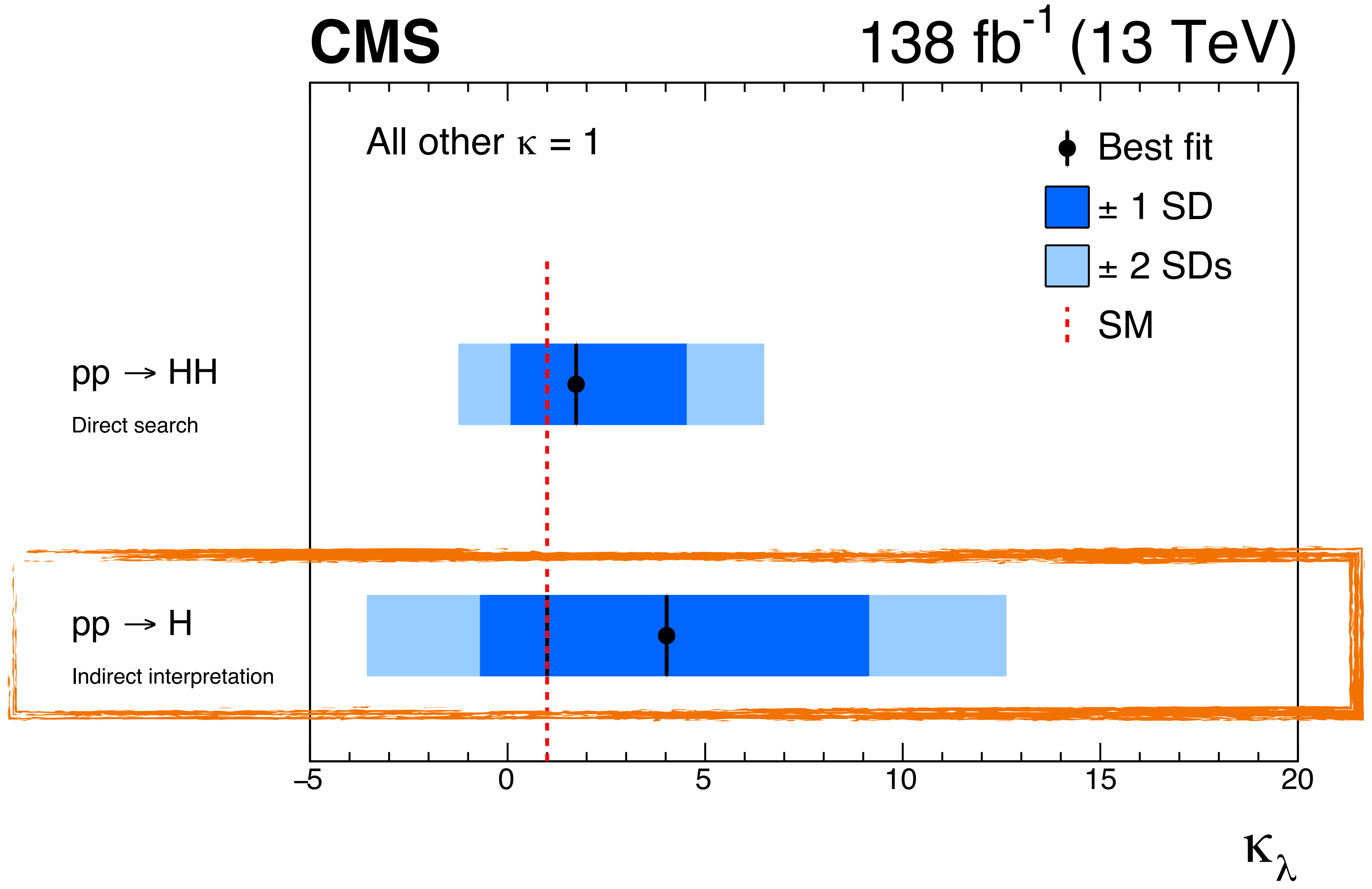
- Combination of single H channels:
  $H \to \gamma\gamma$, $H \to ZZ \to \ell\ell\ell\ell$, $H \to WW \to \ell\nu\ell\nu$, $H \to Z\gamma$, $H \to \tau\tau$, $H \to bb$, $H \to \mu\mu$, $H \to$ inv., ttH | $H \to$ leptons
- Likelihood scan performed with κ_λ as only free parameter
- $\kappa_\lambda \in [-1.24, 6.49]$ ($[-1.23, 7.2]$)

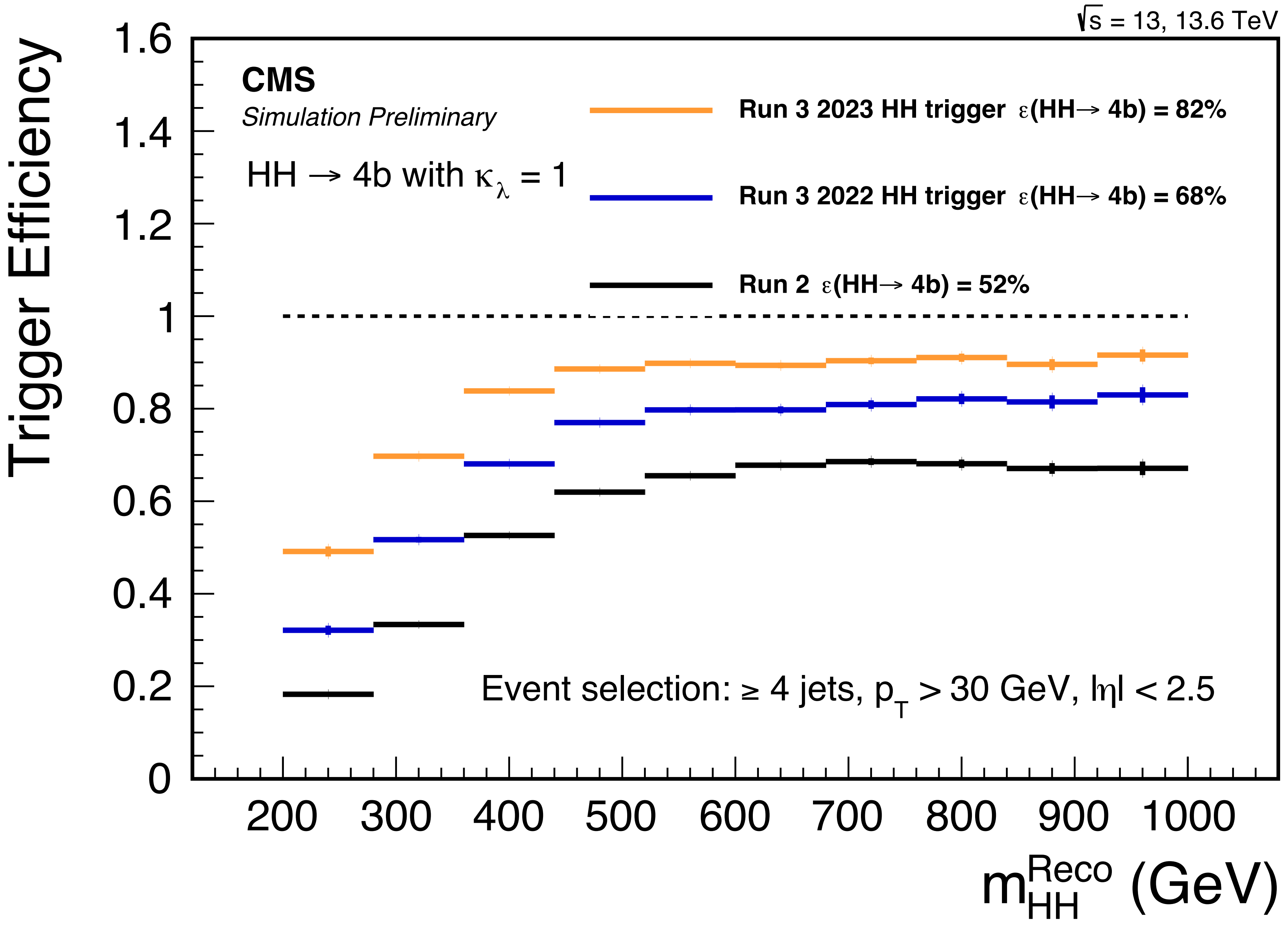


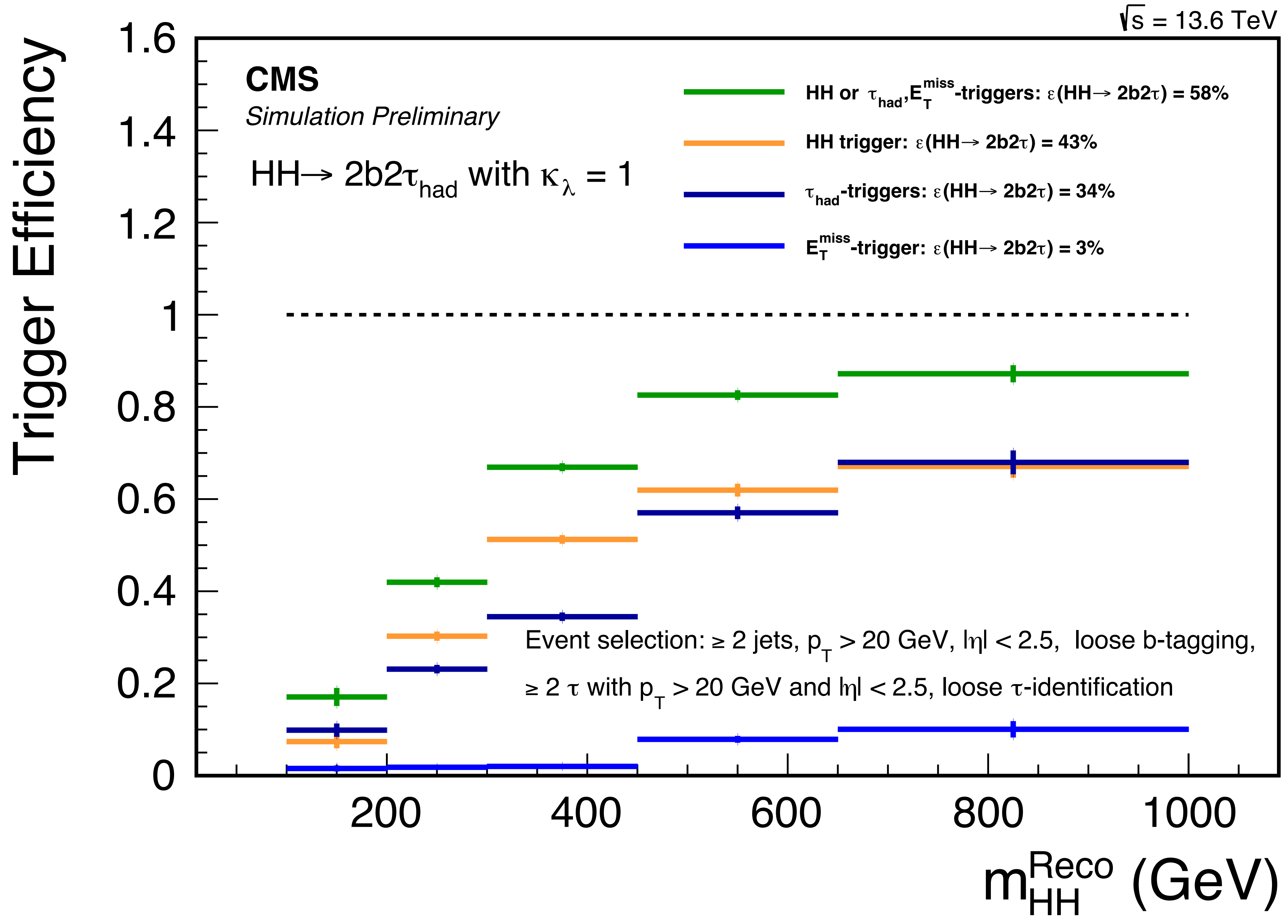
Outlook : Run-3 trigger improvements

CERN-CMS-DP-2023-050

Direct HH searches

- **New trigger :** $N > 4$ jets with $p_T > 30$ GeV and $|\eta| < 2.4 \wedge \sum_N p_T > 280$ GeV $\wedge$ ⟨ParticleNet b-tag score⟩$_{jets} > 0.55$
- **Data parking :** allows a higher rate and acceptance at the cost of delayed reconstruction, this new HLT trigger records events at 180 Hz at an instantaneous luminosity of 2.0×10^{34} cm^{-2}s^{-1}
- Considerable improvement in HH→bbbb and HH→bb$\tau\tau$ channels: **up to 57% improvement in efficiency** → **Run-3 for CMS means higher integrated luminosity at higher selection efficiency!**



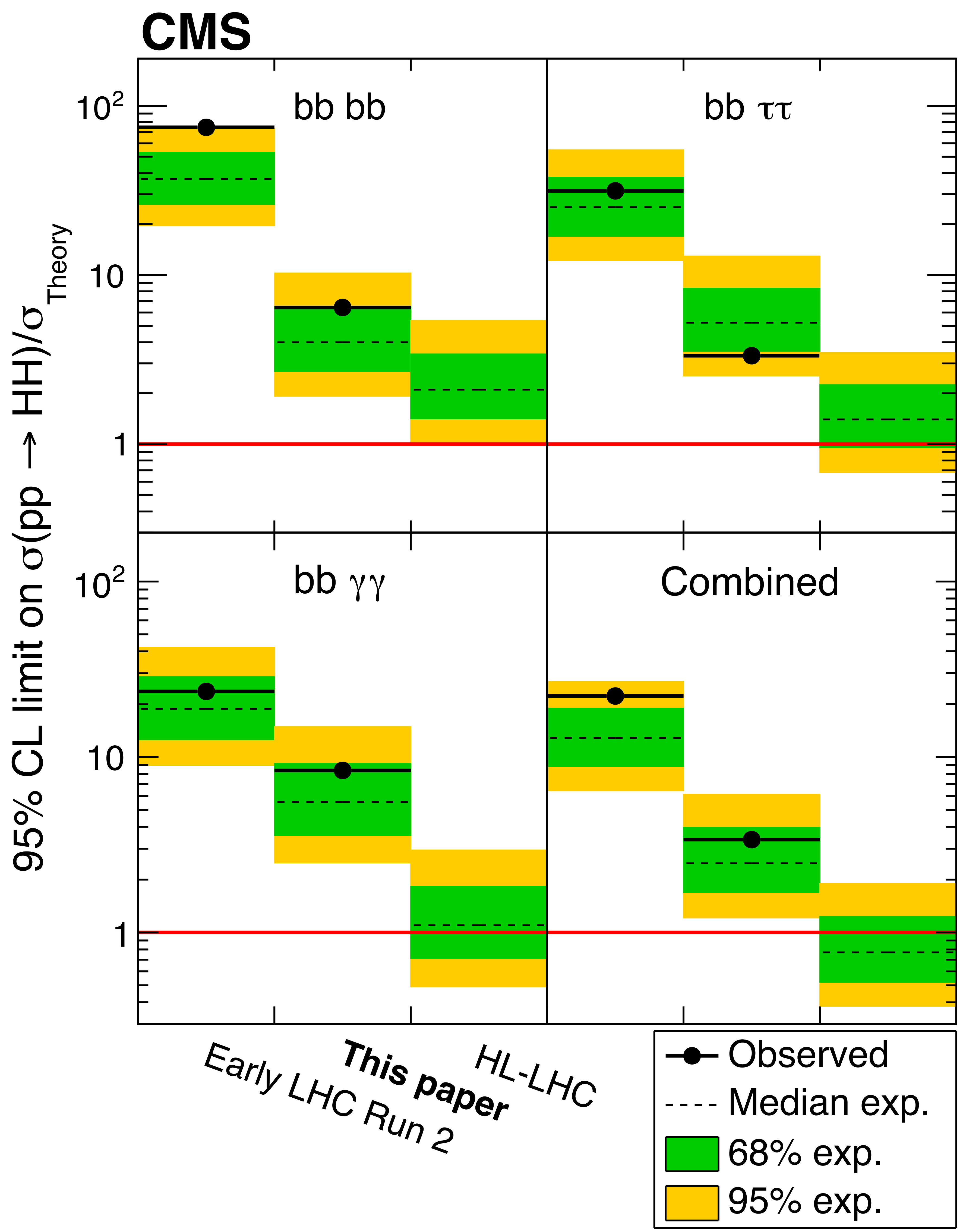


Outlook : the HL-LHC prospects

Nature 607 (2022) 60

Direct HH searches

- **Projection to the HL-LHC performed for the three most sensitive channels and their combination**
- Early Run-2 results compared to full Run-2 and full HL-LHC dataset (3000 fb^{-1})
- **Results expressed in the hypothesis of HH not existing → combined limit <1 shows that sensitivity is sufficient to establish HH existence**



Conclusions

- **Probing λ_{HHH} is one of the main goals we have for the coming years**
- **Run-2 analyses showcased an impressive improvement over the previous expectation**
    - $\kappa_\lambda \in [-1.24, +6.49]$ **current tightest constraint at CMS**
- HH and H+HH combinations are being performed and will become public soon
- **Run-3 is underway and constitutes a huge opportunity to further improve the results we have from Run-2, possibly reaching unexpected goals**
- **Important trigger improvements have already been introduced for HH searches in Run-3**
- Run-3 also constitutes an important test-bench for new ideas that will ultimately be deployed at the HL-LHC