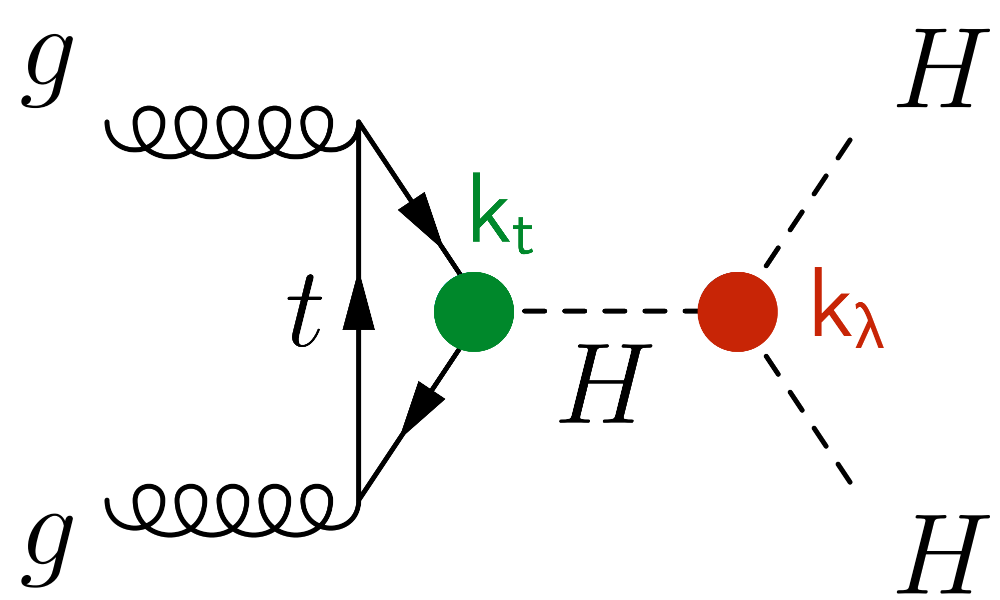

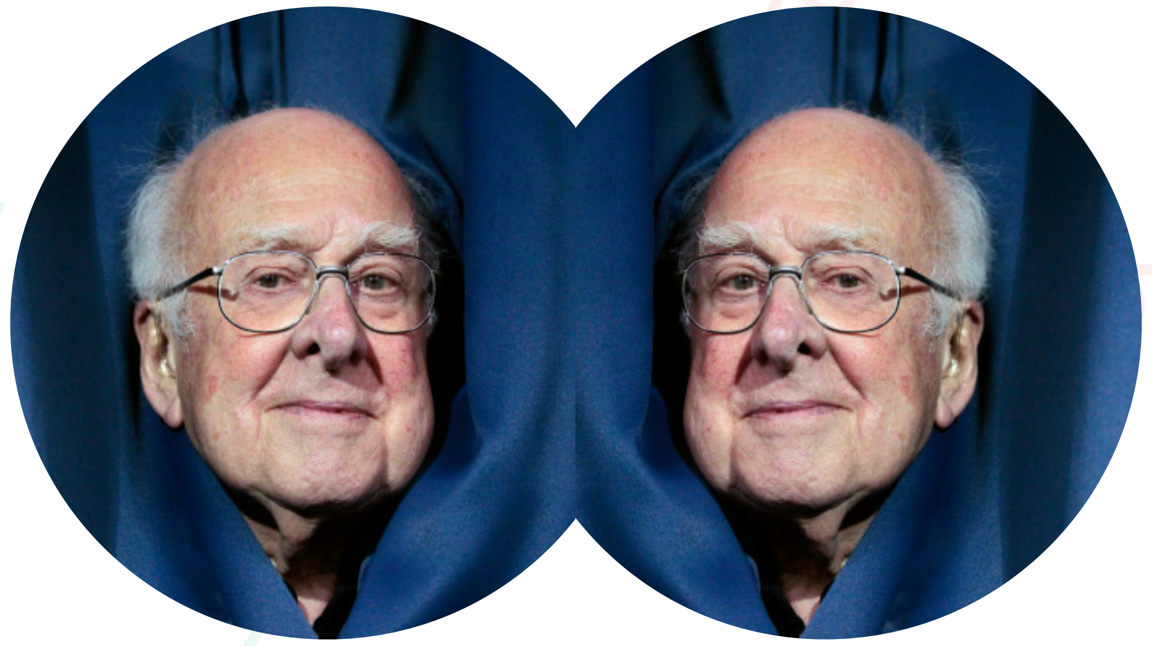

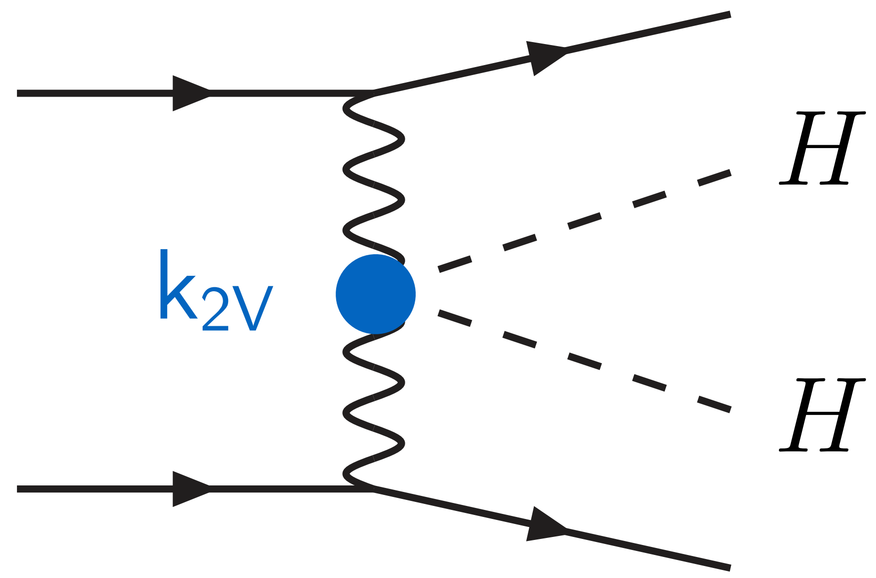

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CMS

Searches for non-resonant Higgs Boson Pair Production with CMS

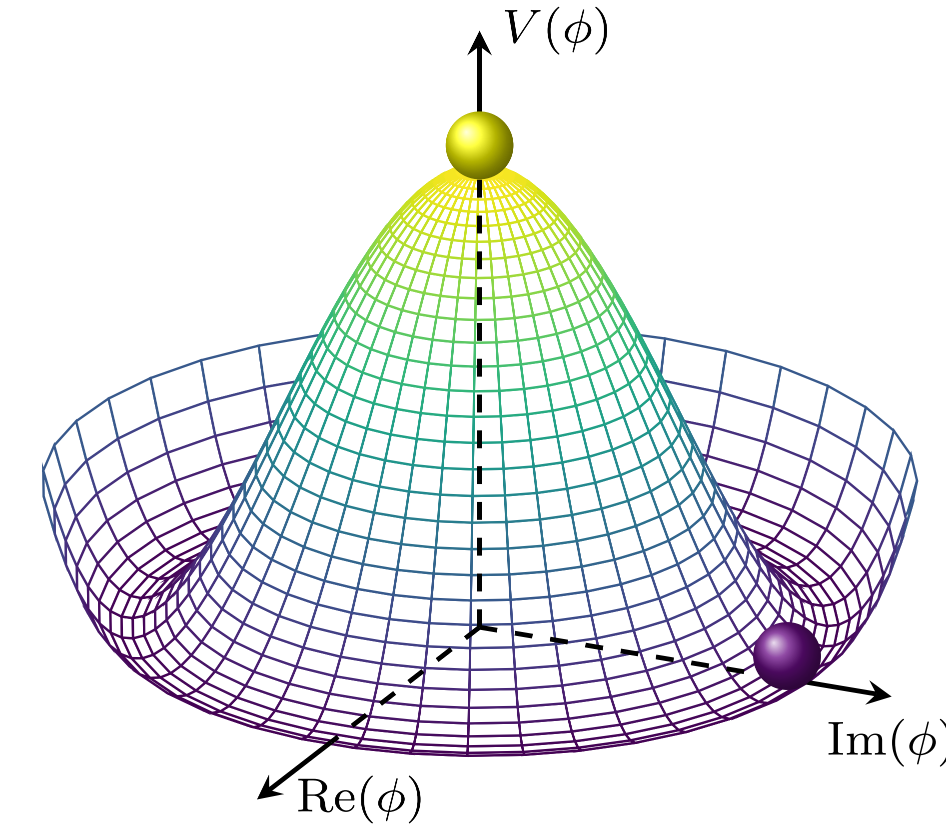
Marcel Rieger
on behalf of the CMS collaboration

Higgs Hunting 2022

13.09.2022

- **Search for HH production**
  1. Allows to probe parameters describing the Higgs field potential
     - ▻ $V = \boxed{\frac{m_H^2}{2} H^2} + \boxed{\frac{m_H^2}{2\nu} H^3} + \frac{m_H^2}{8\nu^2} H^4$

       Higgs discovery (2012) **Higgs self-coupling** (20??)

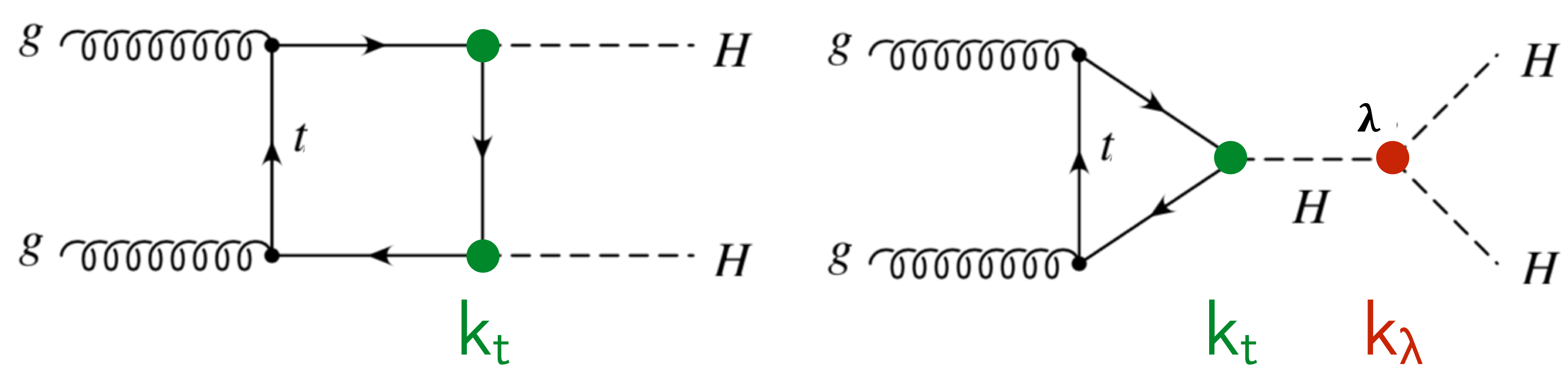


$$V(\phi) = -\mu^2 \left(\phi^\dagger \phi\right) + \lambda \left(\phi^\dagger \phi\right)^2$$

  2. Effect of cov. derivative D_μ on ϕ in $\mathscr{L}_H$
     - ▻ Yields additional quartic **VVHH coupling**

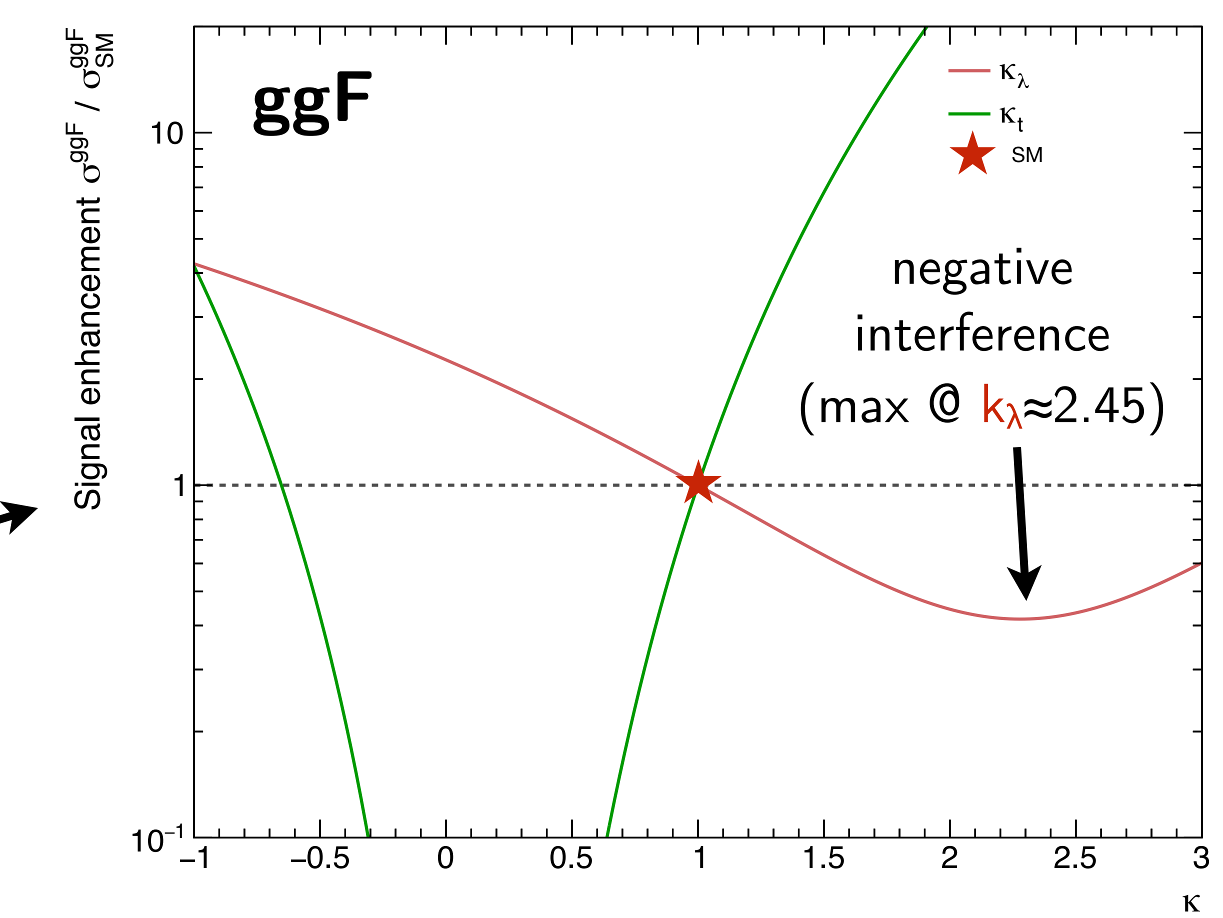
- Focus on **non-resonant SM production** in the talk

ggF

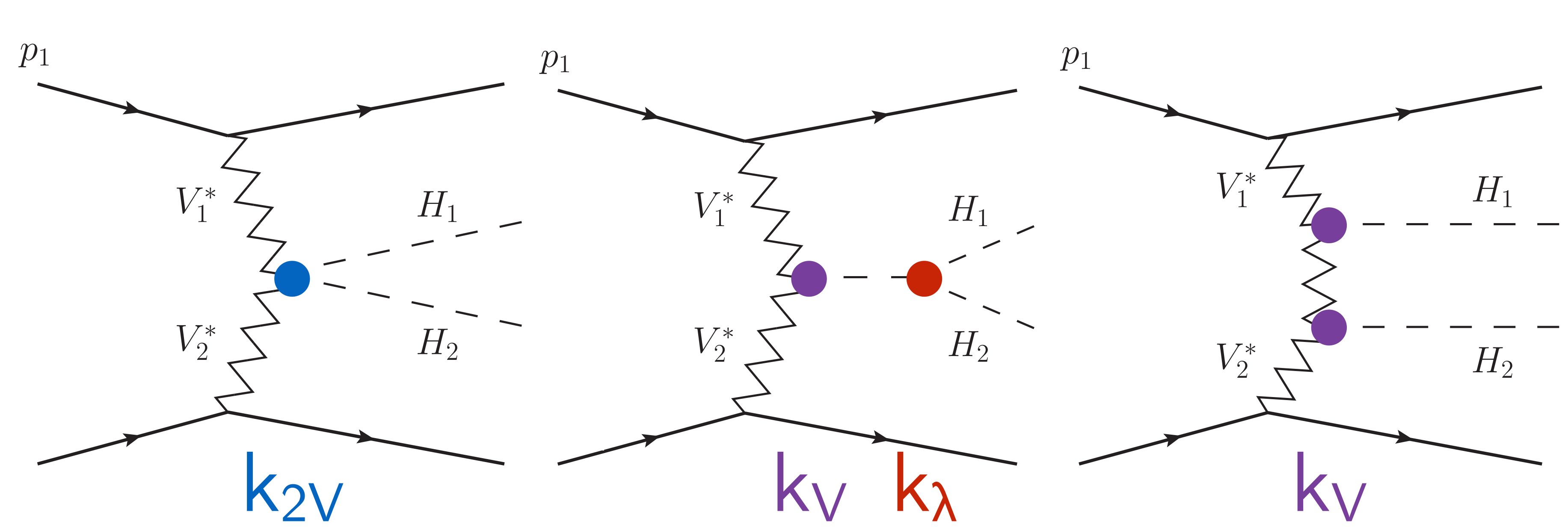


$\sigma_{\mathrm{ggF}} = 31.05$ fb (13 TeV)

dependence on **k**'s

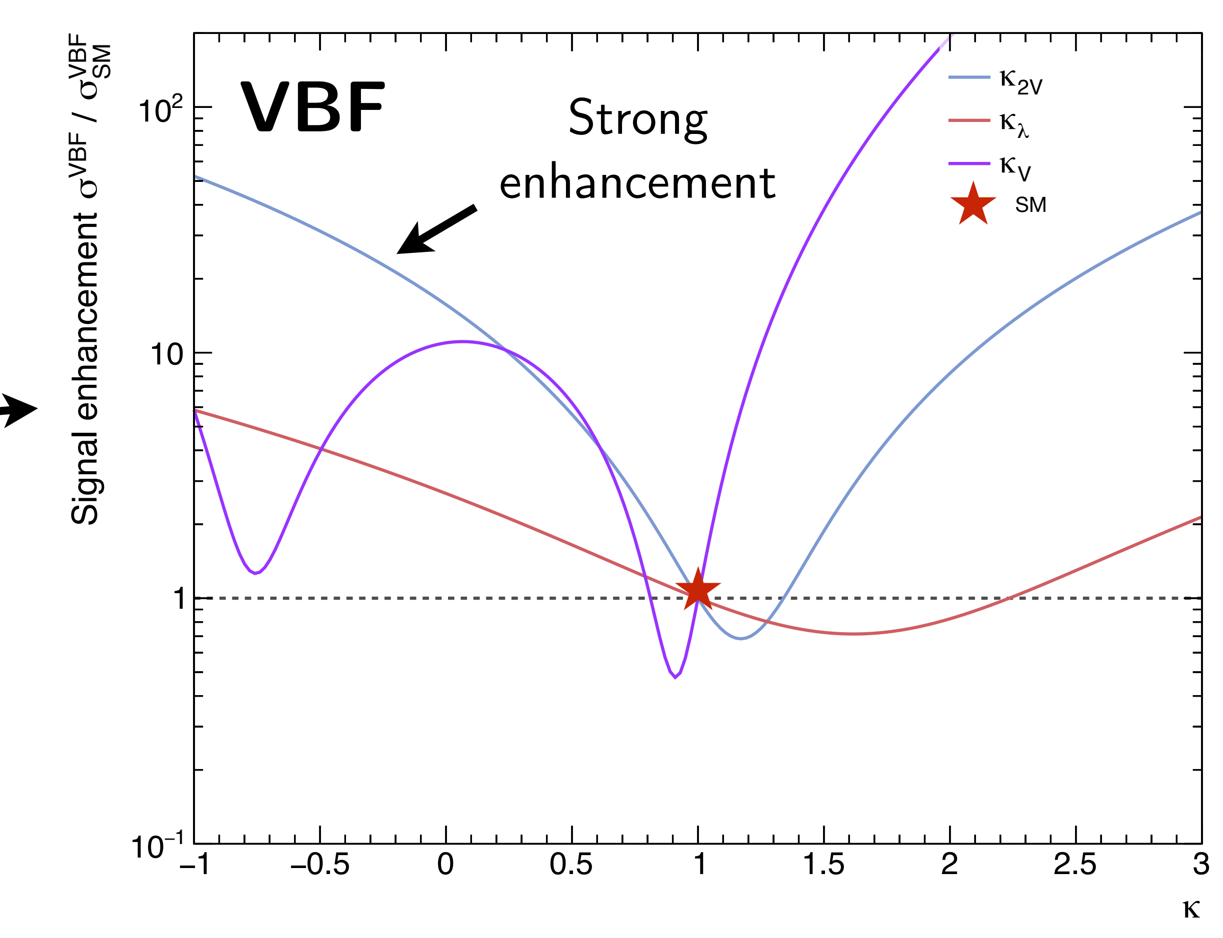


VBF



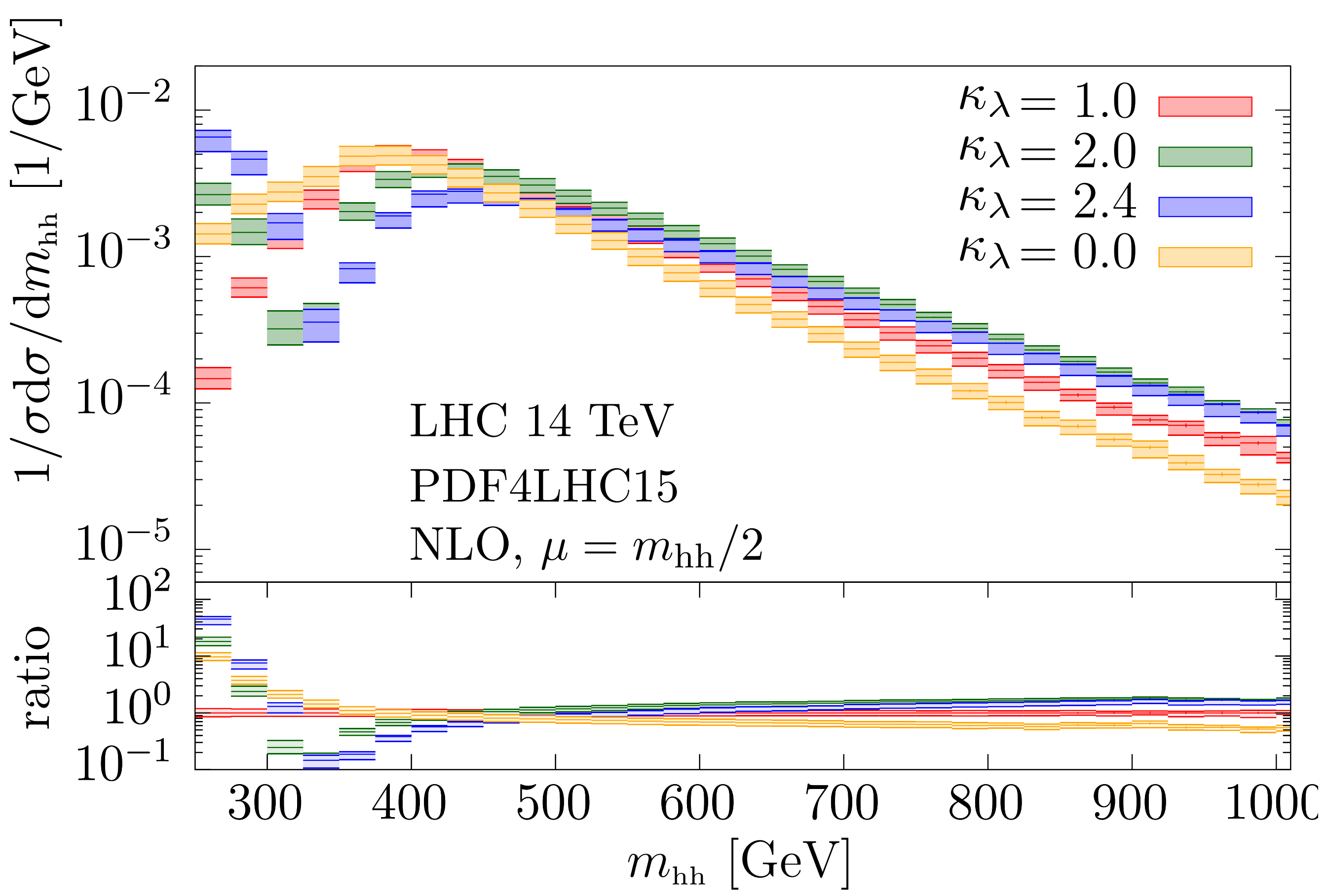
$\sigma_{\mathrm{VBF}} = 1.73$ fb (13 TeV)

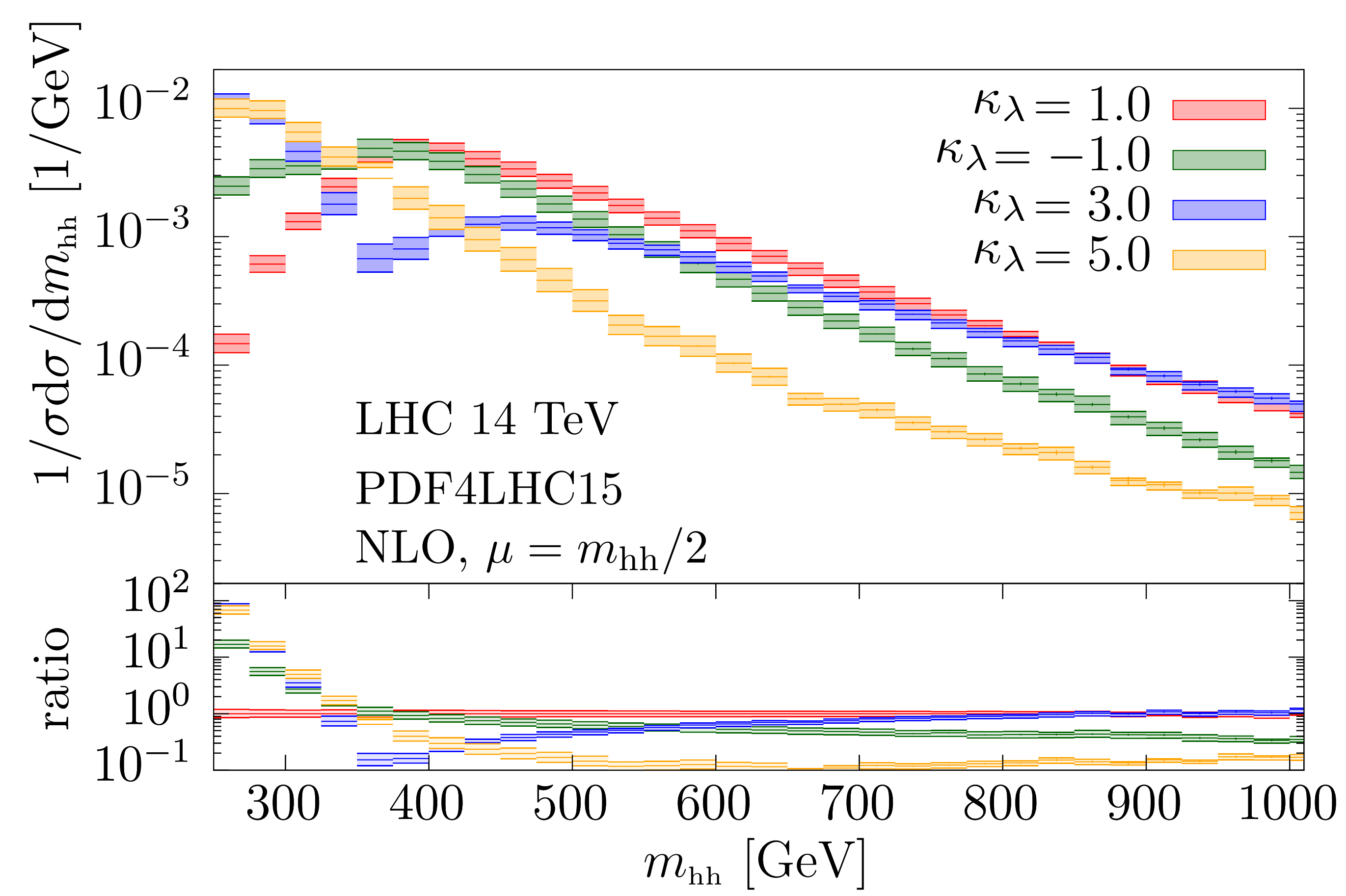
dependence on **k**'s

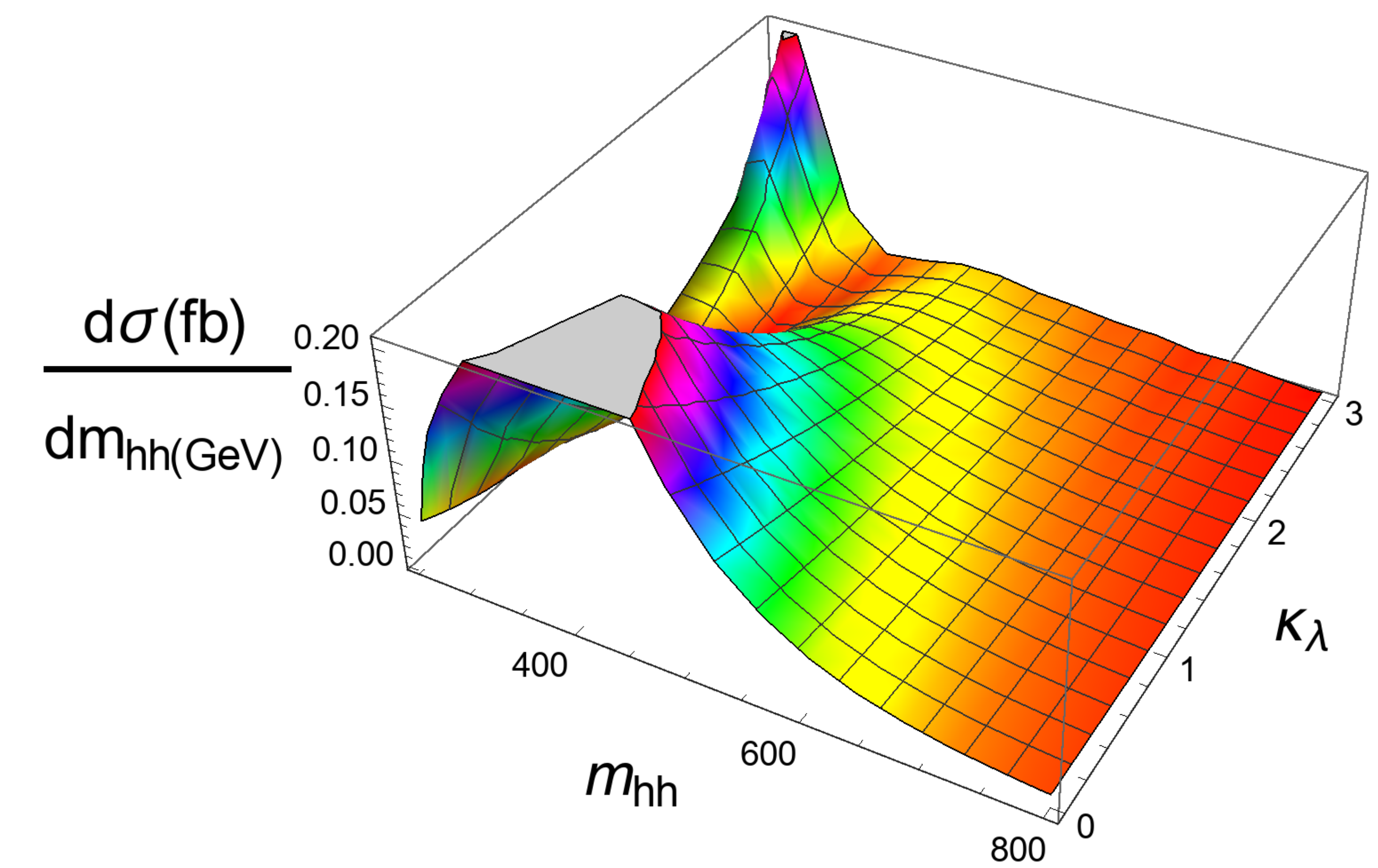


Event kinematics & effect on analyses

- **m_{HH} spectrum depends on k$_\lambda$**
  - Softer for large | k$_\lambda$ |
  - Hardest close to max. interference + double structure



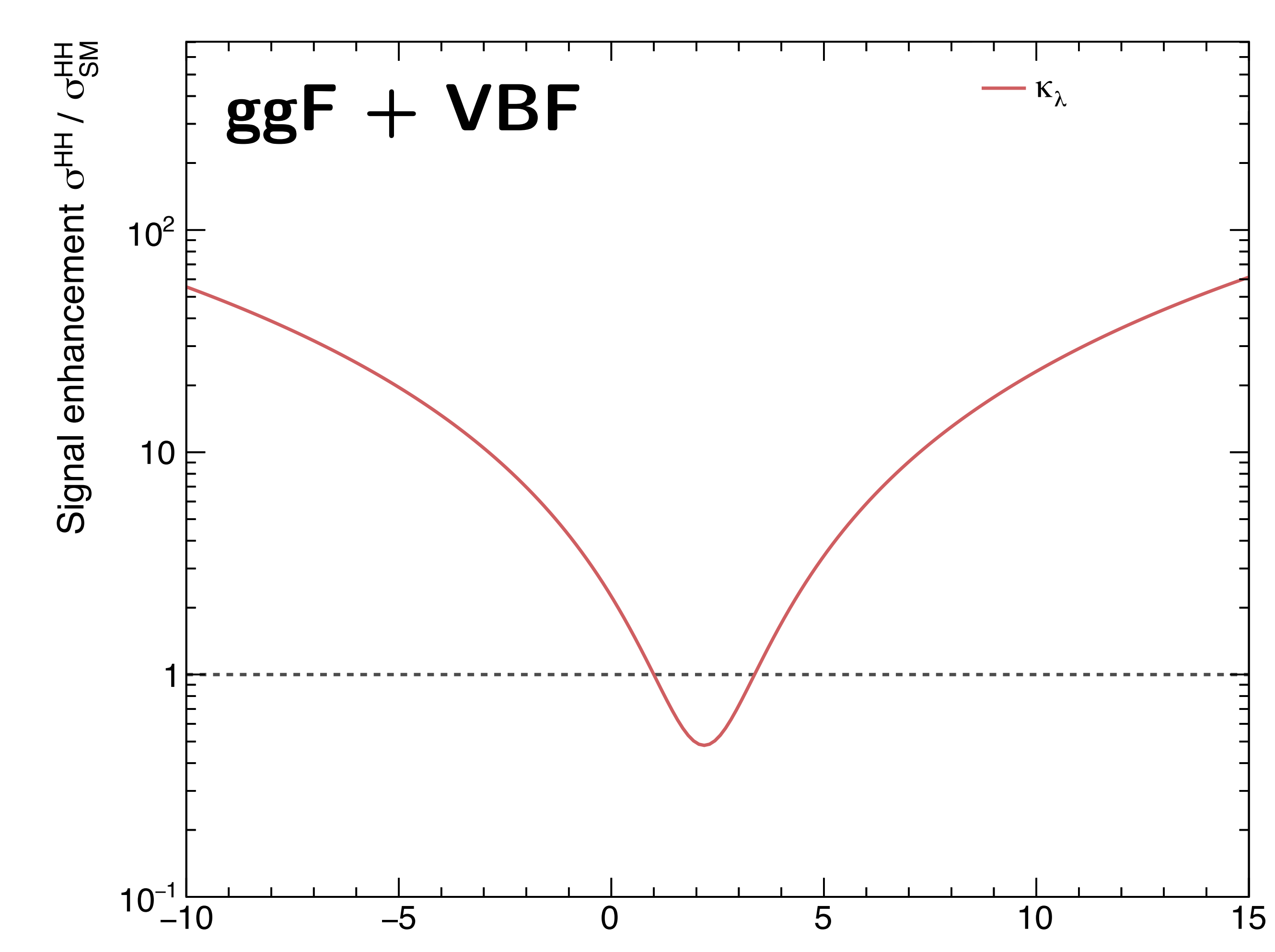




arXi:1910.00012

- **Effect on analyses**
  1. Large |**k$_\lambda$**|
     - ✓ Sensitivity due to enhanced cross section
     - ✗ Soft m_{HH} spectrum reduces selection efficiency
  2. Medium **k$_\lambda$**
     - ✓ Hard m_{HH} spectrum leads to clear (possibly boosted) signatures
     - ✗ Enhancement low or even negative

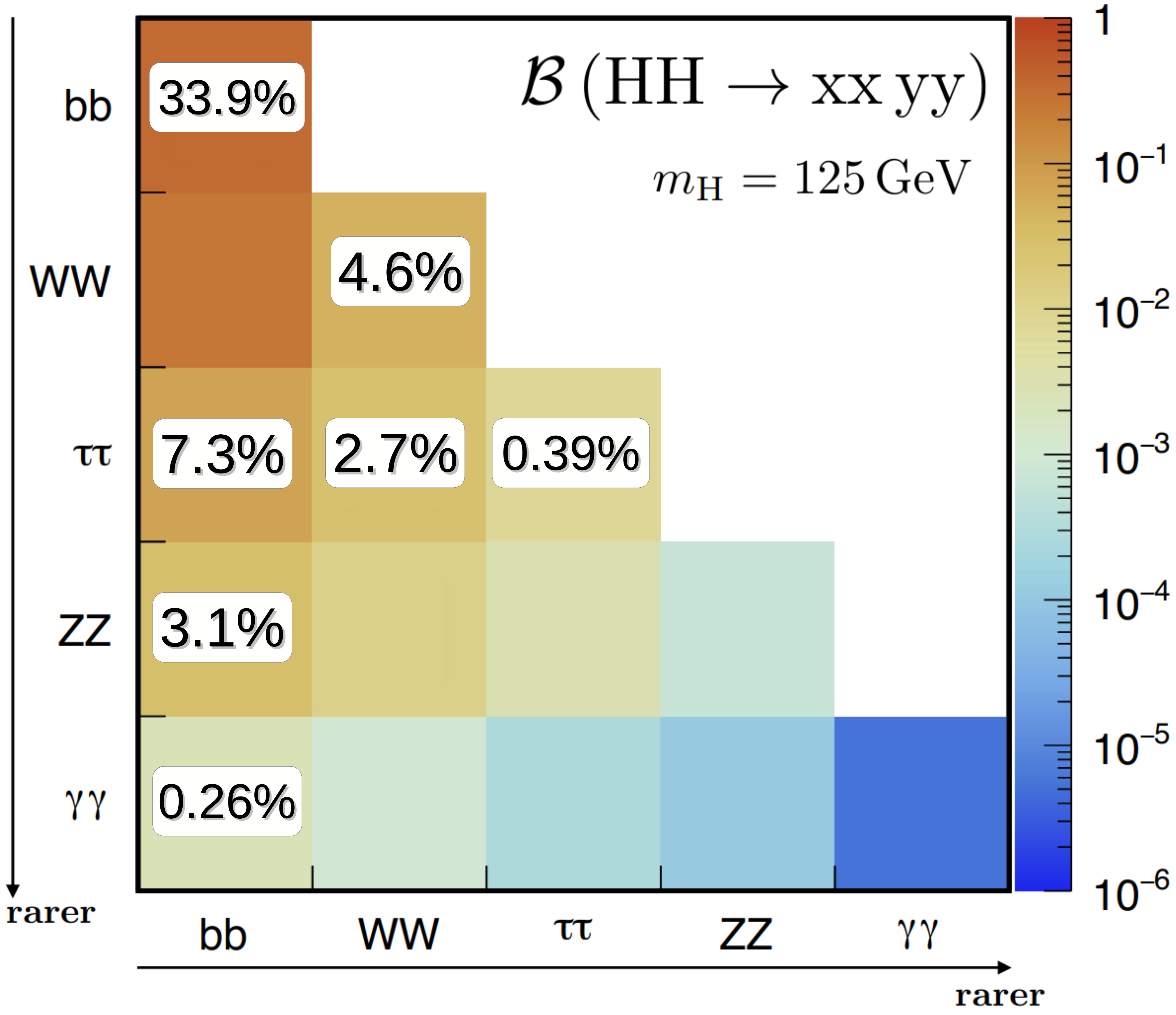
Cross section enhancement



- Modeling of HH (and single H) depending on (k$_\lambda$, k$_t$, k$_t$, k$_V$) in backup

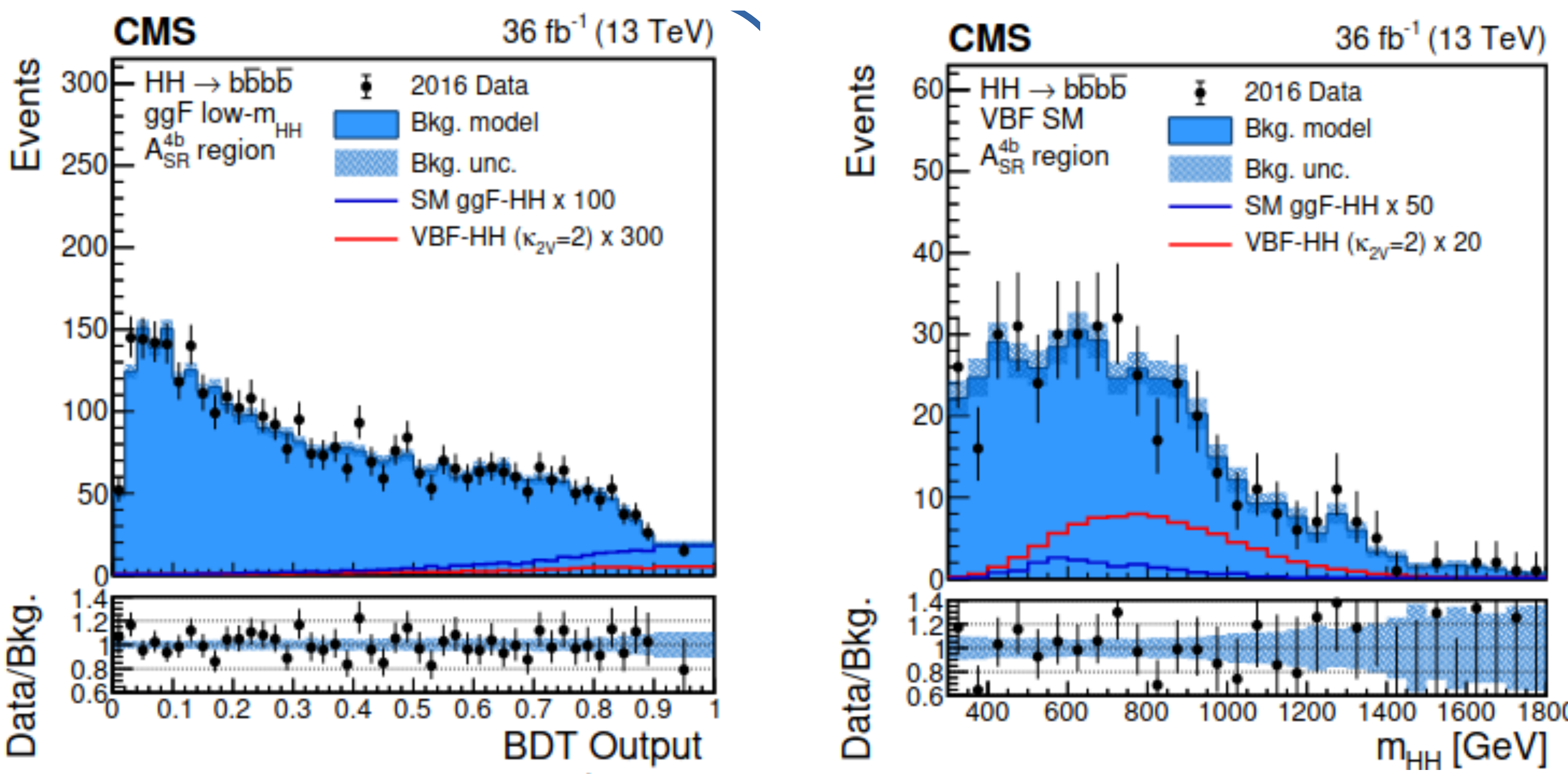
Results in particular
HH decay channels

Published HH searches at CMS

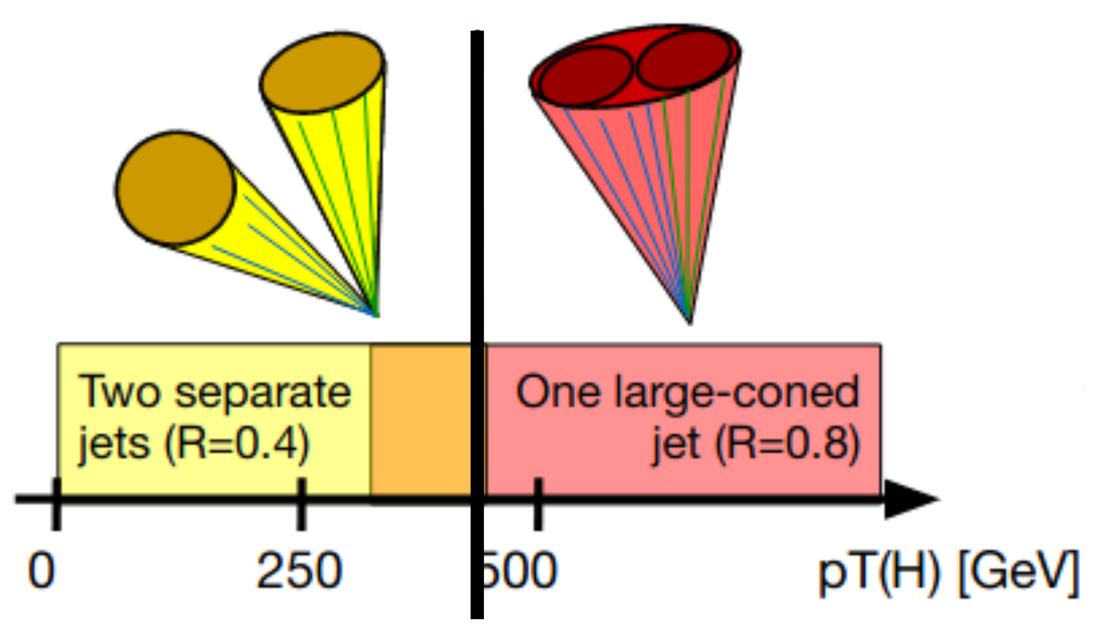


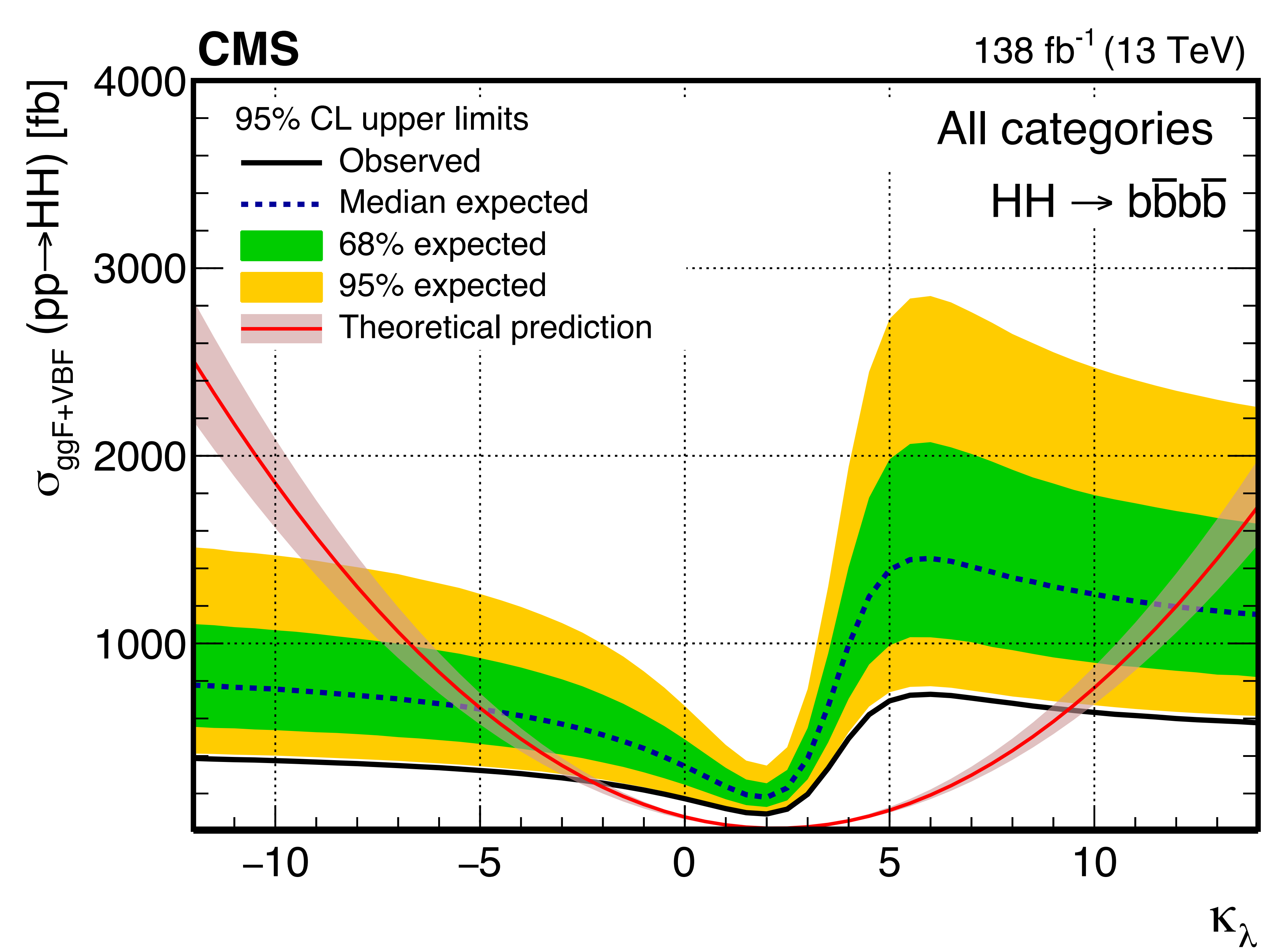
- $HH \rightarrow bbbb$ resolved (Phys. Rev. Lett. 129, 081802)
  - Large BR, large backgrounds
- $HH \rightarrow bbbb$ boosted (arXiv:2205.06667)
  - Merged jets topology
- $HH \rightarrow bb\tau\tau$ (arXiv:2206.09401)
  - Sizable BR, small backgrounds
- $HH \rightarrow bbZZ(4l)$ (arXiv:2206.10657)
  - Small BR, moderate backgrounds
- $HH \rightarrow bb\gamma\gamma$ (JHEP03(2021)257)
  - Small BR, very clean mass resolution
- $HH \rightarrow WWWW + WW\tau\tau + \tau\tau\tau\tau$ (arXiv:2206.10268)
  - Multiple small BRs, various final states

- Phys. Rev. Lett. 129, 081802



- **Strategy**
  - Select events with resolved b jets
  - Rely on CMS *DeepJet* efficiency (~75%) and b-jet energy regression
  - Simultaneous fit on distributions
    - ▻ BDT in **ggF**-like categories
    - ▻ m_{HH} in **VBF**-like categories



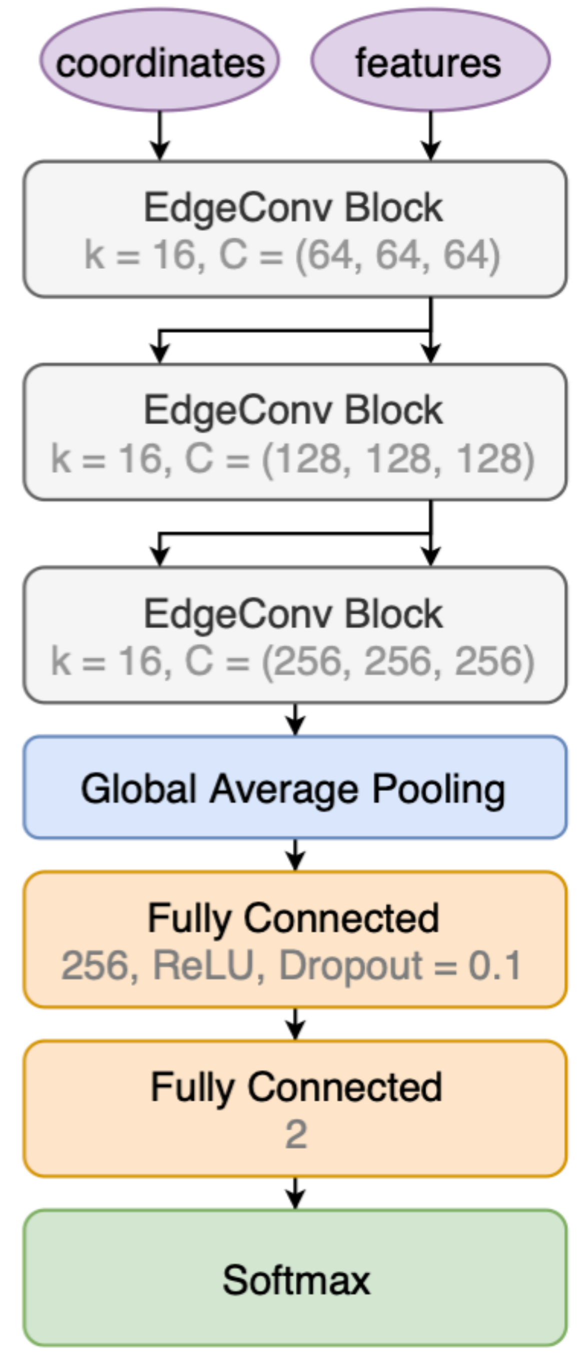


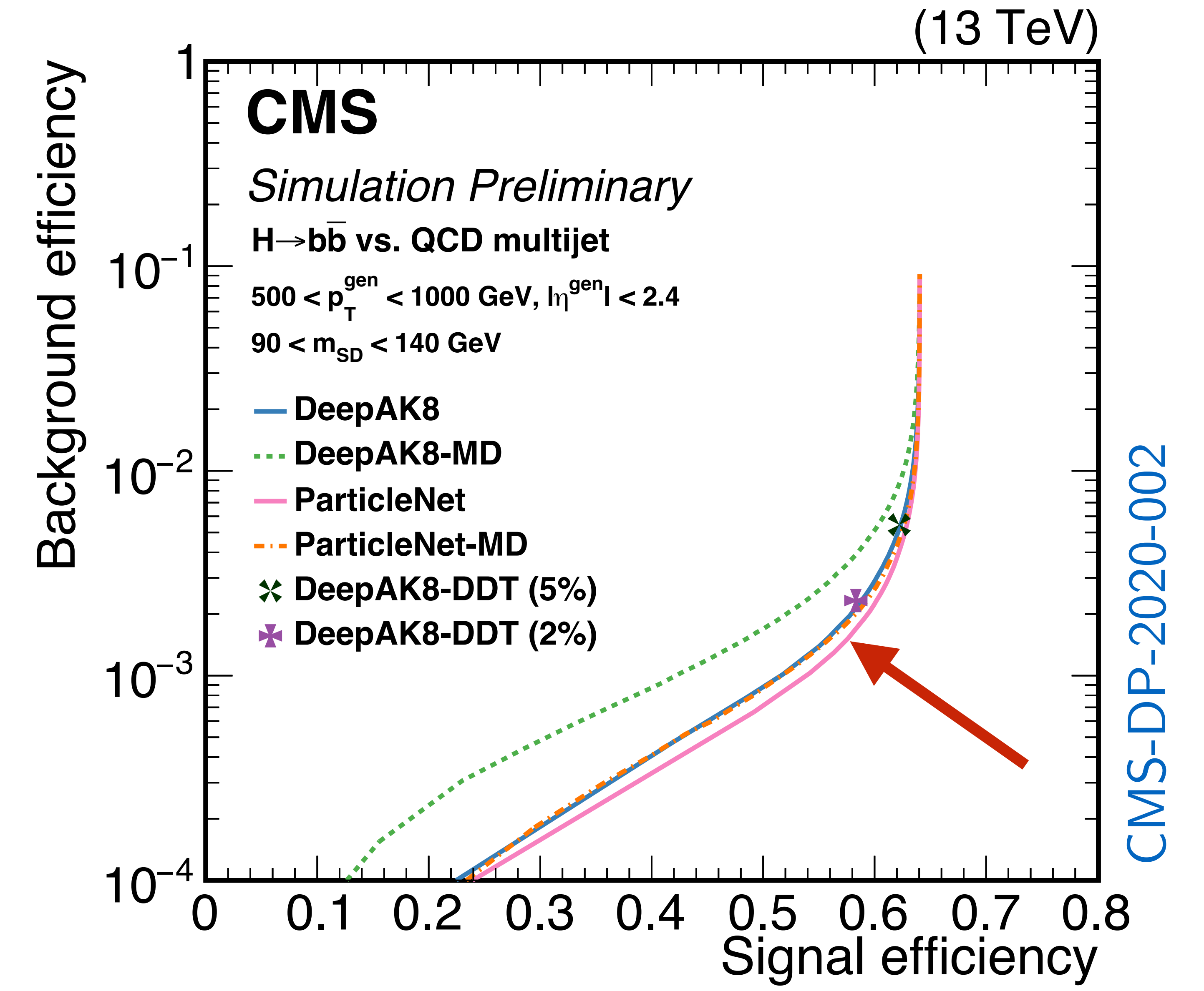
- **Results**
  - Upper limit on σ_{HH}/σ_{SM} of **3.9** (**7.9**)
  - Upper limit on σ_{VBF}/σ_{SM} of **226** (**412**)
  - Constraints $k_\lambda \in [-2.3, +9.4]$, $k_{2V} \in [-0.1, +2.2]$

$HH \rightarrow bbbb$ boosted

- arXiv:2205.06667

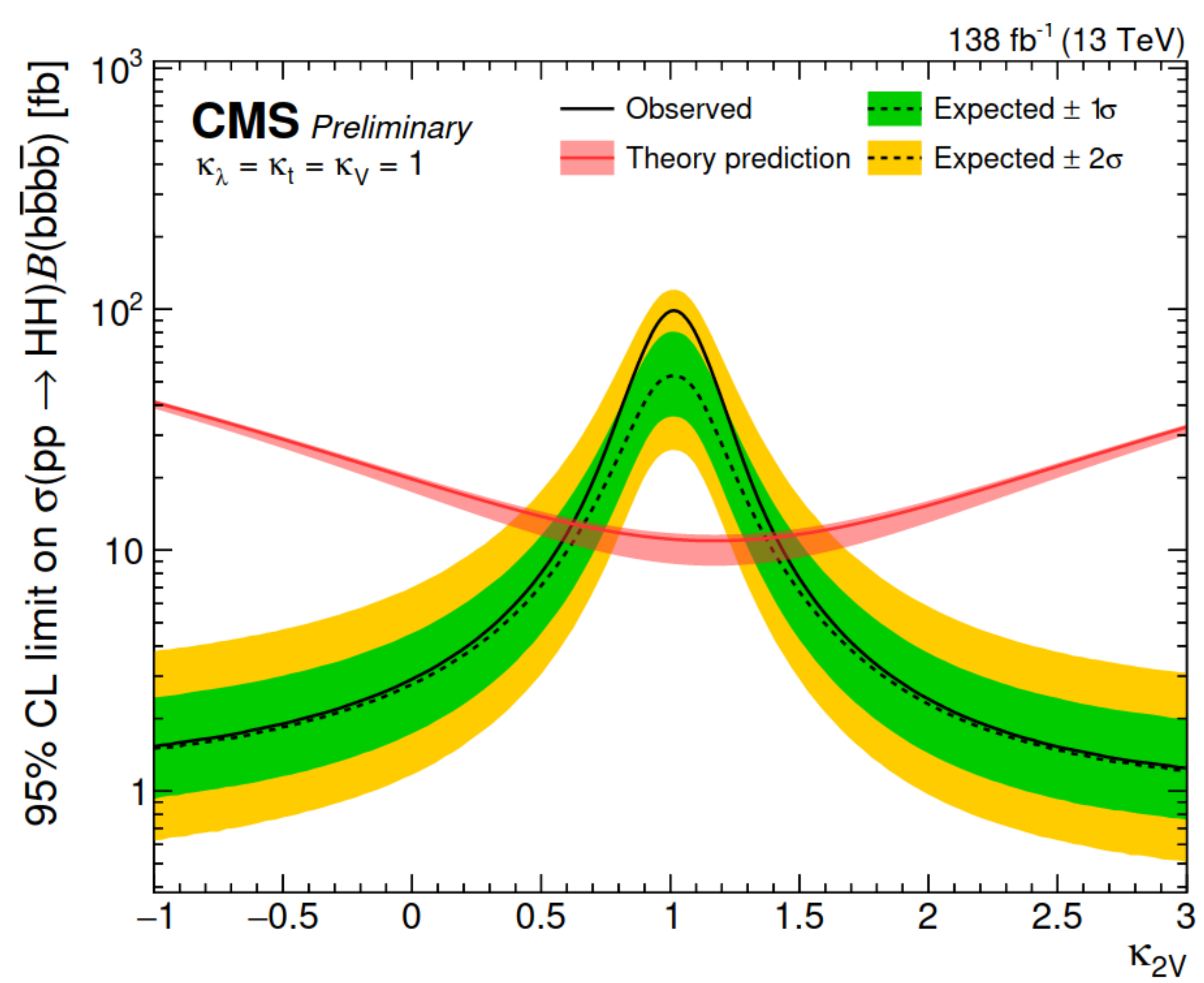
- **Strategy**
  - Exploit boosted topology for **k_λ**, **k_{2V}** ≠ 1
  - Select events with two large-cone jets
    - $p_T > 300$ GeV
    - $|\eta| < 2.4$
  - Distinguish between large-cone $H \rightarrow bb$ and QCD jets using GNN (ParticleNet)

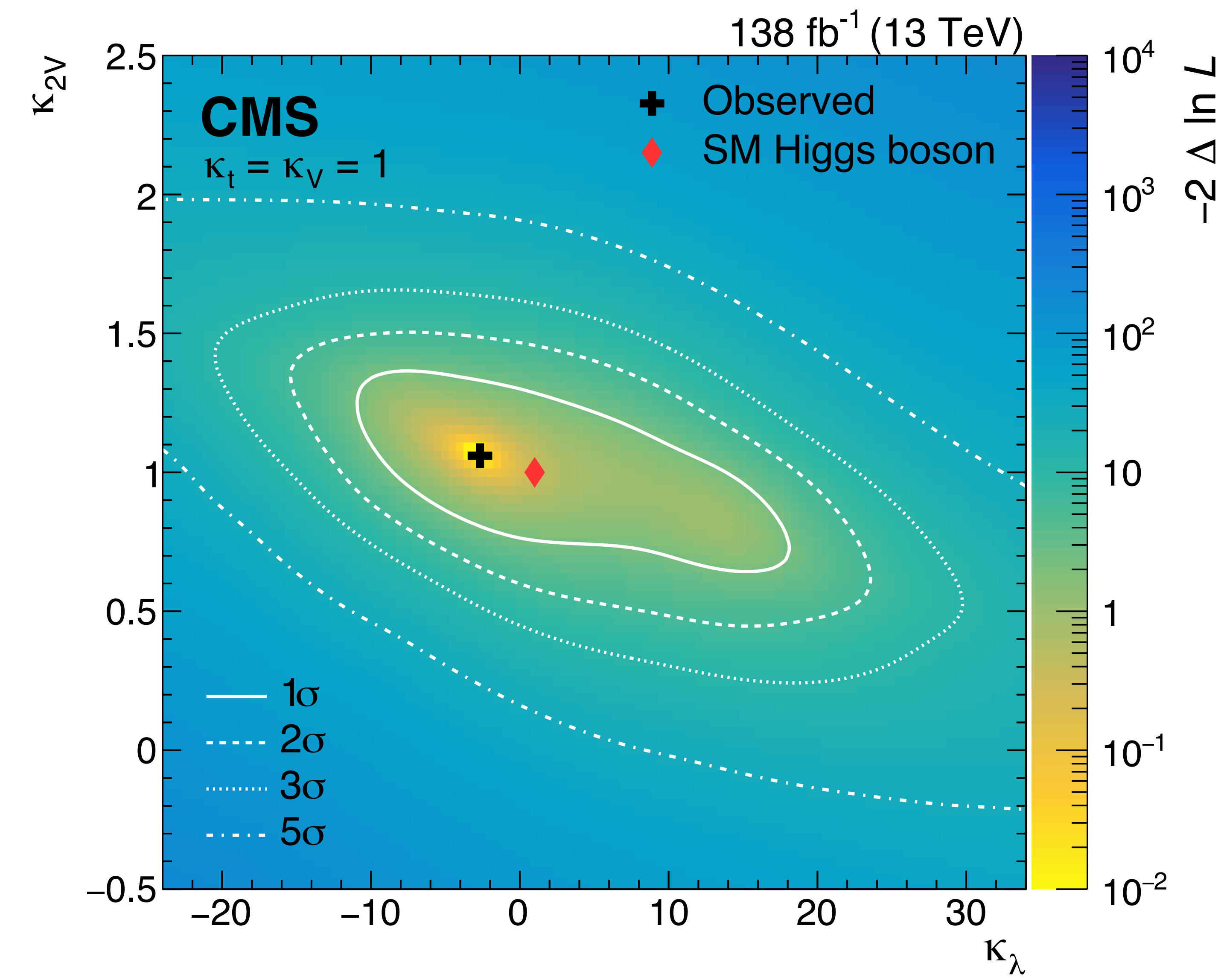




- **Results**
  - Upper limit on σ_{HH}/σ_{SM} of **9.9** (**5.1**)
  - Constraints **k_λ** ∈ [-9.9, +16.9], and **k_{2V}** ∈ [+0.62, +1.41]
  - First analysis to exclude **k_{2V}** ≤ 0

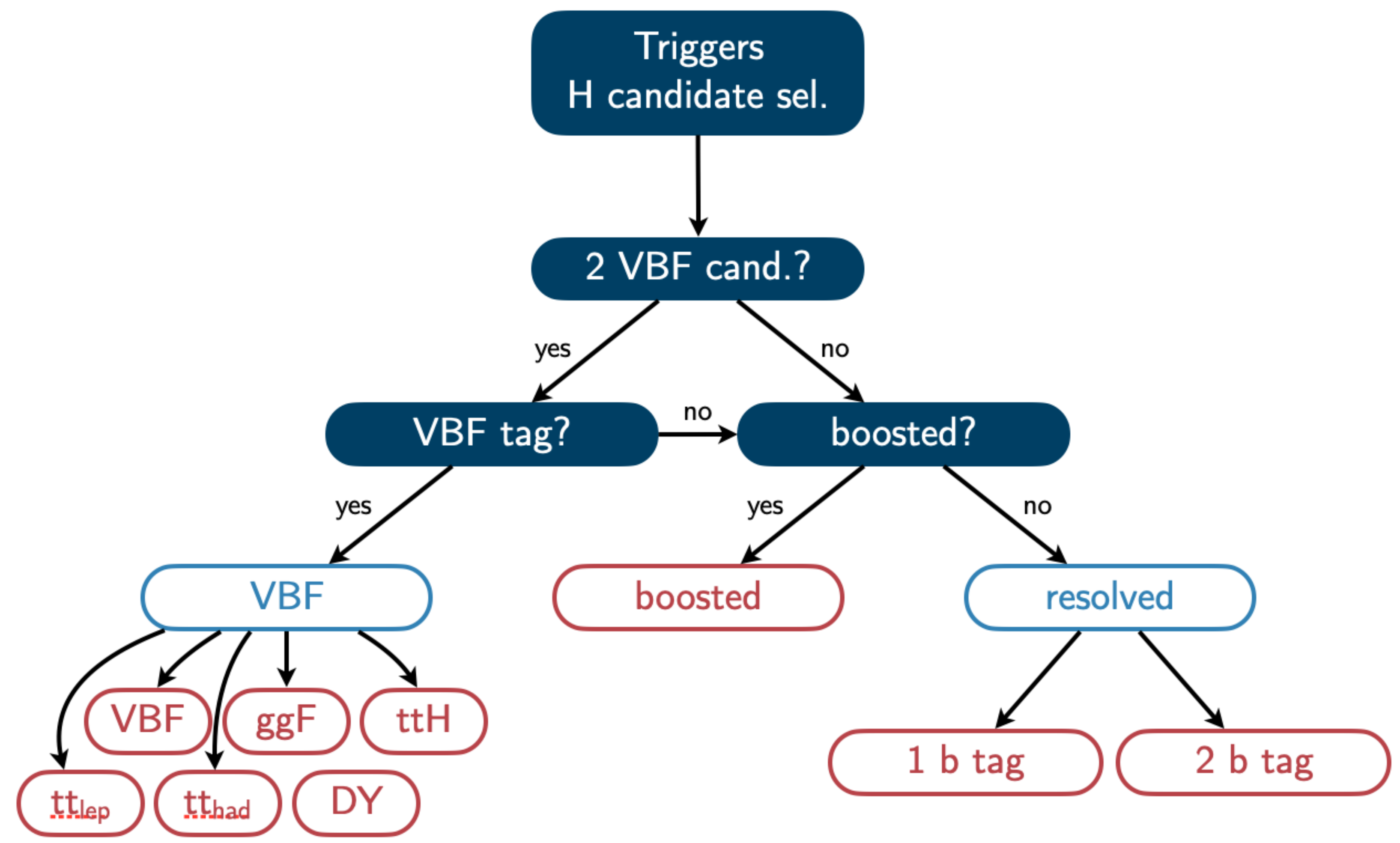
- More in Irene's talk after the break





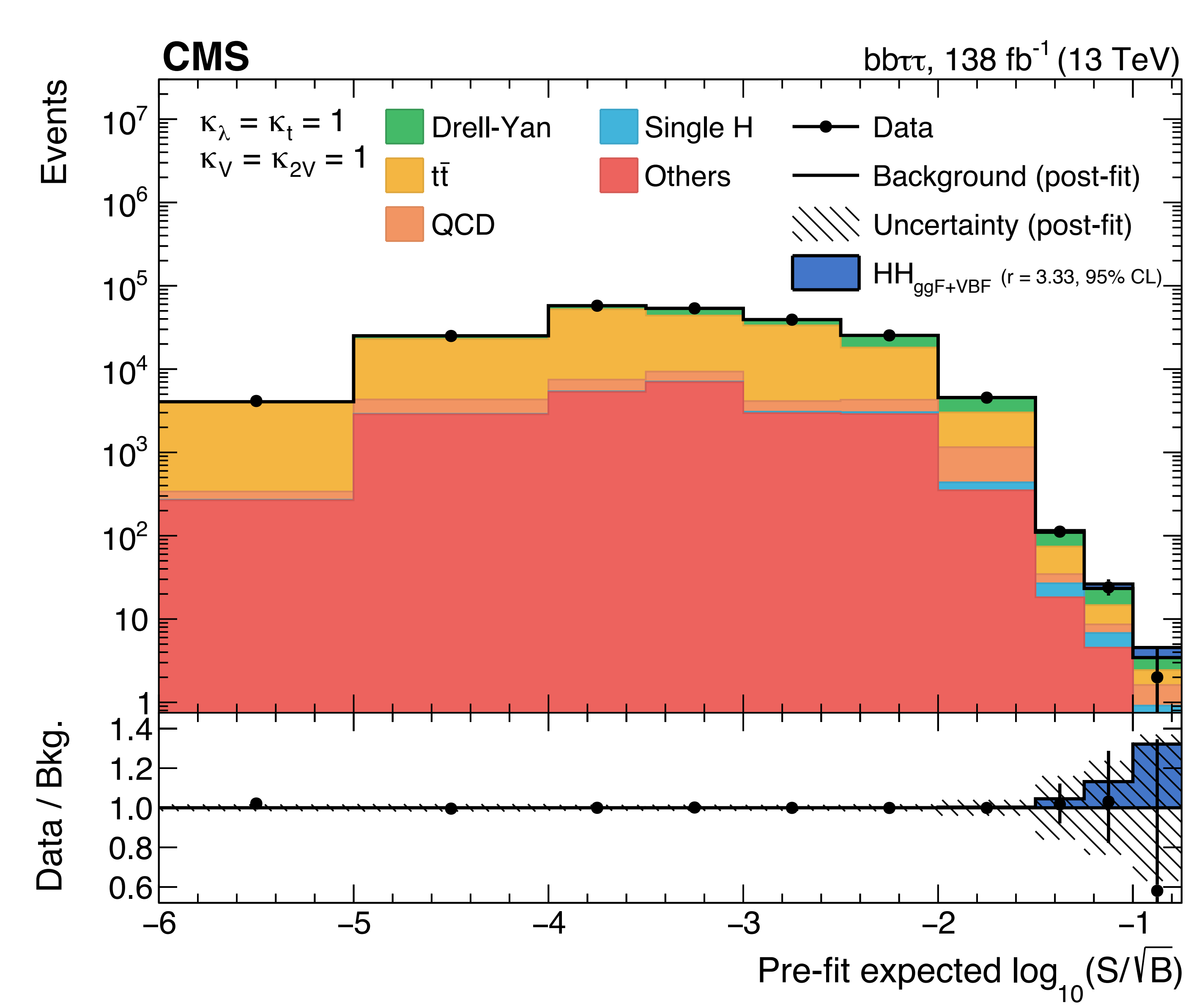
- arXiv:2206.09401

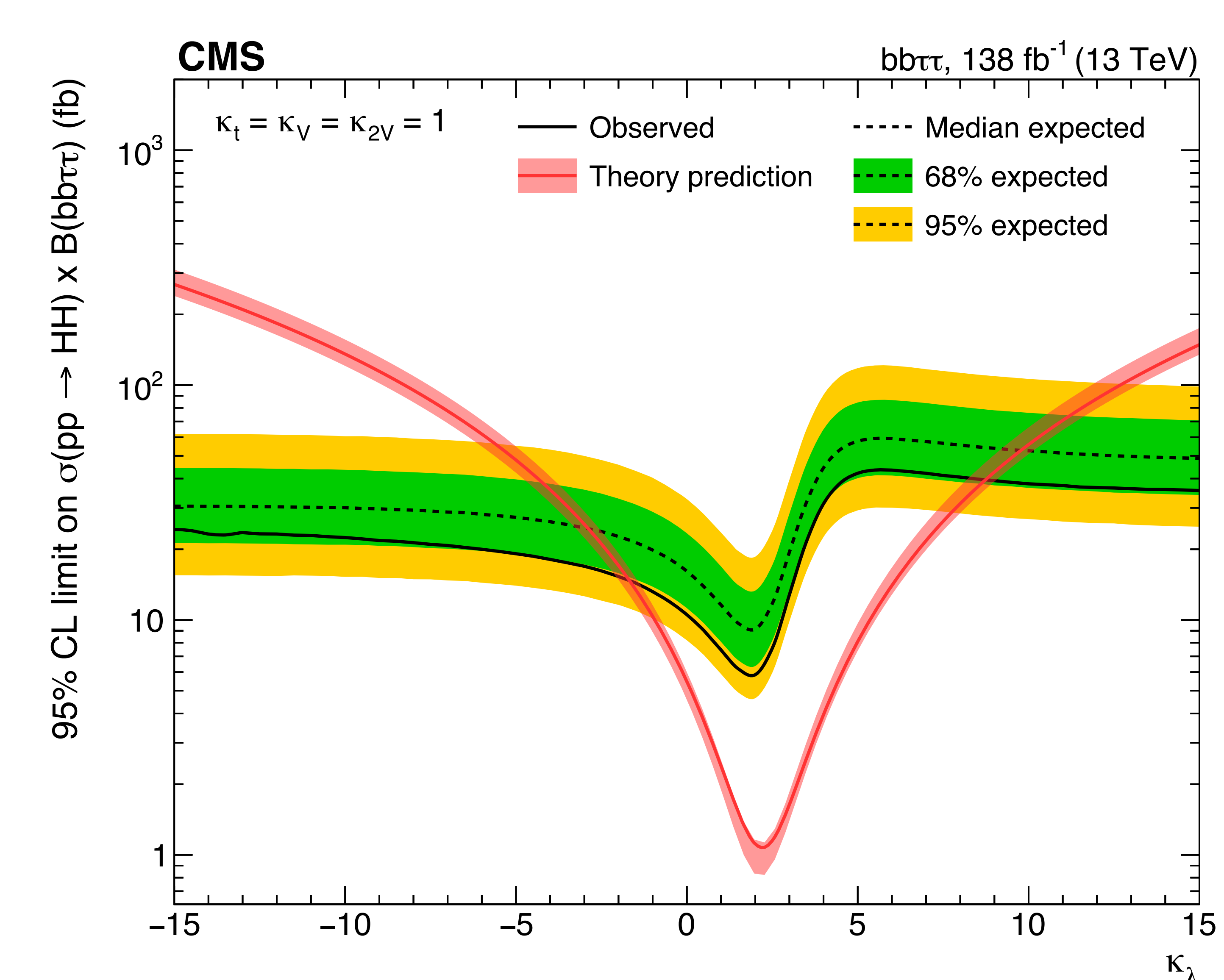
- **Strategy**
  - Target both **ggF** and **VBF** modes
  - Profit from CMS *DeepJet* and *DeepTau* object taggers
  - Split into resolved, boosted and VBF phase spaces
  - Further divide VBF phase space using multi-class classifier
  - Fit DNN in 72 resulting categories



- **Results**
  - Upper limit on σ_{HH}/σ_{SM} of **3.3** (**5.2**)
  - Upper limit on σ_{VBF}/σ_{SM} of **124** (**154**)
    - Best expected HH VBF limit at CMS
  - Constraints $\boldsymbol{k_\lambda} \in [-1.7, +8.7]$
  - Constraints $\boldsymbol{k_{2V}} \in [-0.4, +2.6]$

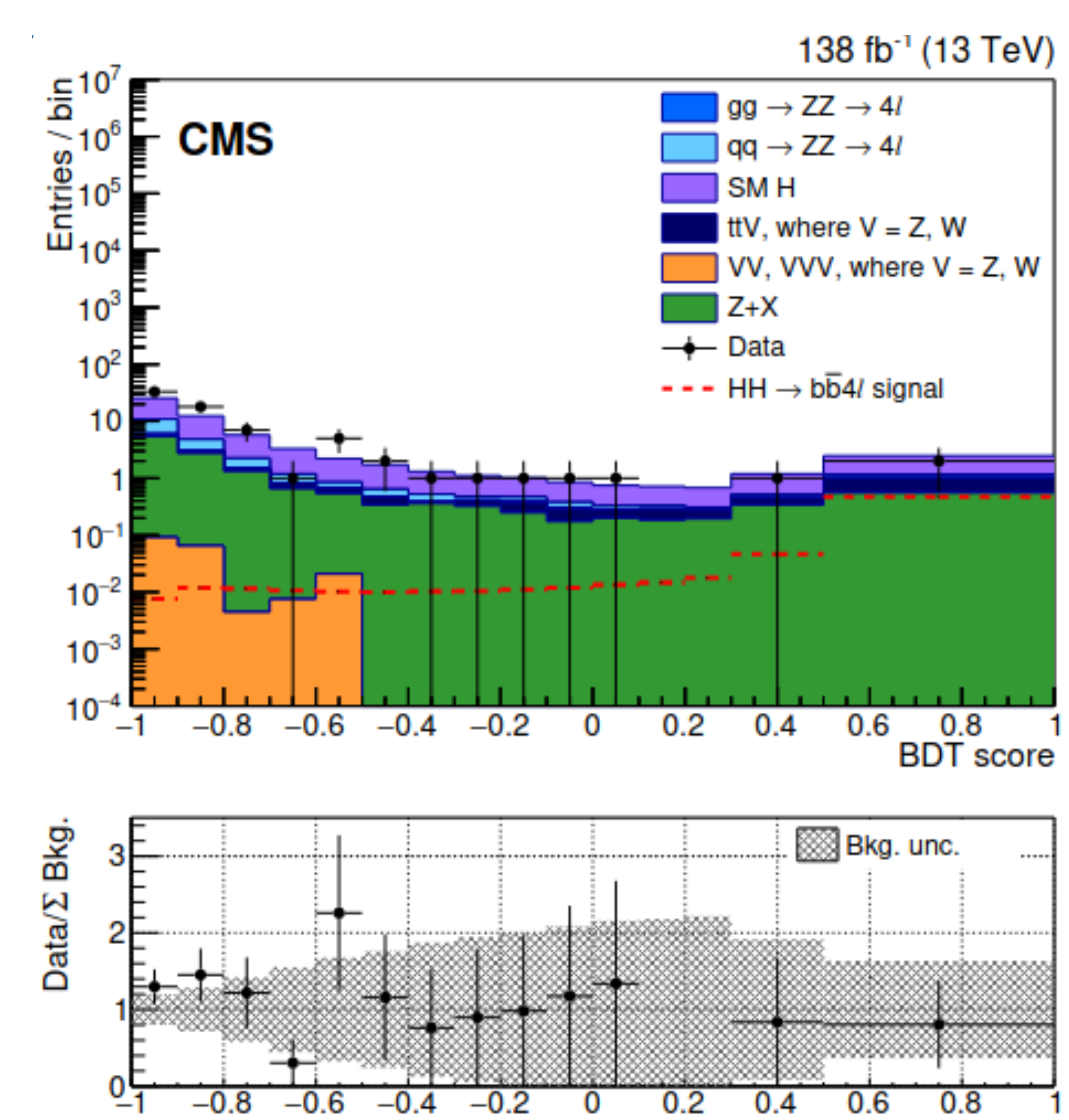
- More details in Valeria's talk

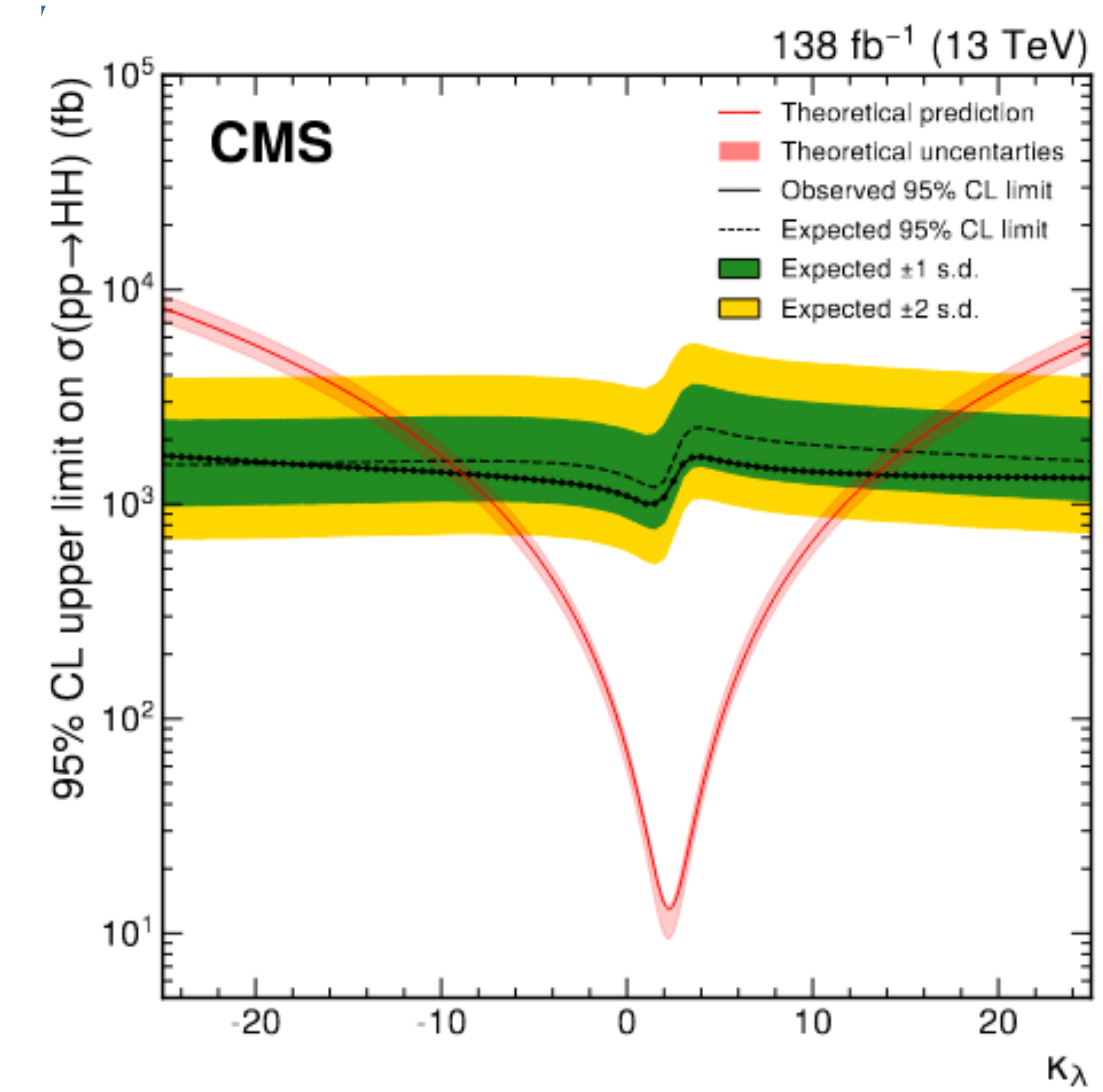




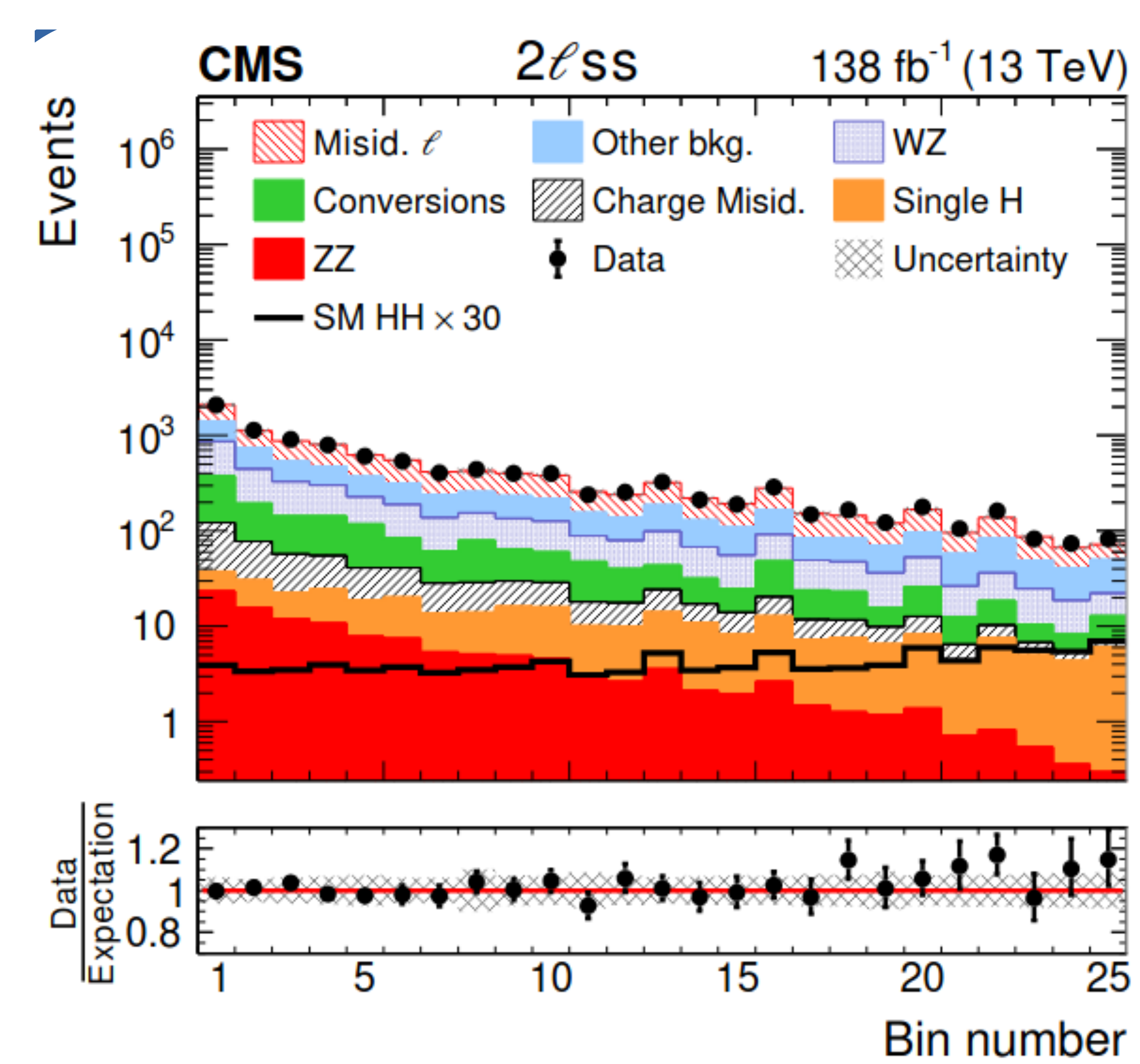
$HH \to bbZZ(4l)$ and $HH \to$ multilepton

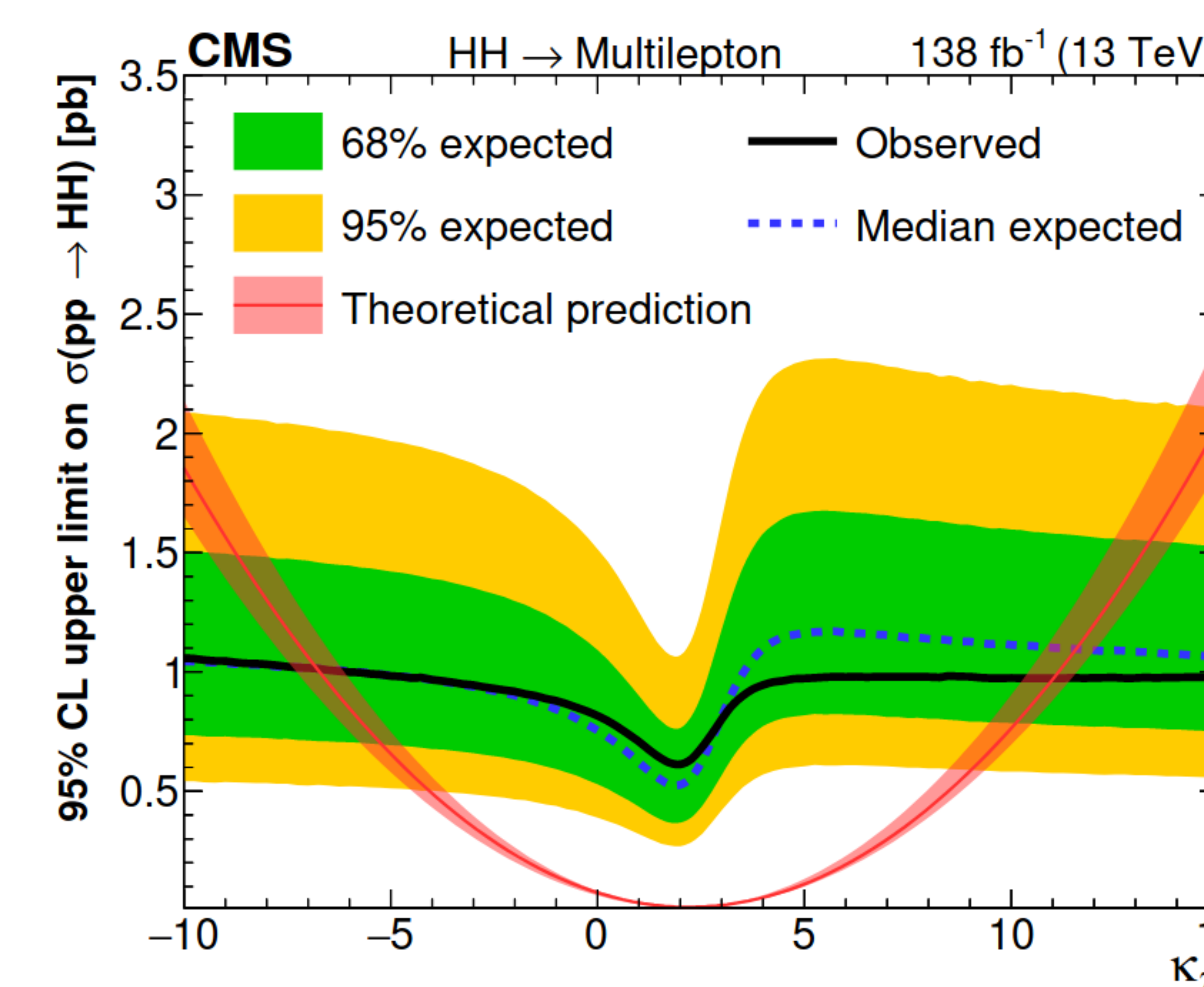
- bbZZ(4l) (arXiv:2206.10657)
  - **Strategy**
    - Select 2 pairs of OS leptons
      - $40\ (12) < m_{Z_1}\ (m_{Z_2}) < 120$ GeV
      - $115 < m_{4l} < 135$ GeV
    - Select 2 b-jets with highest score (DeepJet)
    - Fit BDT distributions
  - **Results**
    - Upper limit on σ_{HH}/σ_{SM} of **32** (**40**)
    - Constraints $\kappa_\lambda \in [-8.8, +13.4]$





- multilepton (arXiv:2206.10268)
  - **Strategy**
    - Combination of 7 categories involving leptons
      - $HH \to WWWW,\ WW\tau\tau,\ \tau\tau\tau\tau$ decay channels
    - Lower lepton thresholds beneficial at high $|\kappa_\lambda|$
    - BDTs fit in all categories
  - **Results**
    - Upper limit on σ_{HH}/σ_{SM} of **21.3** (**19.4**)
    - Constraints $\kappa_\lambda \in [-6.9, +11.1]$

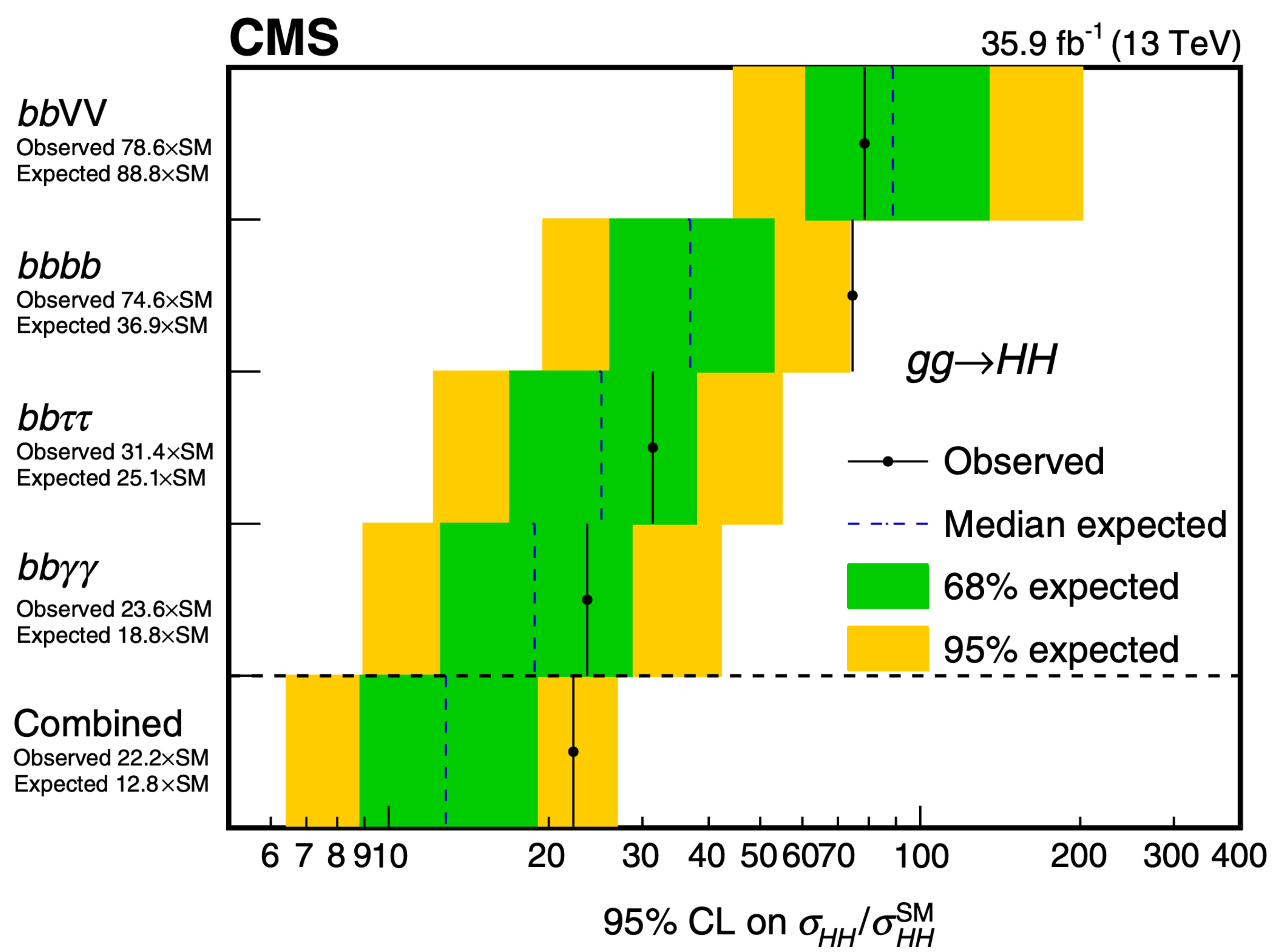




Combination results

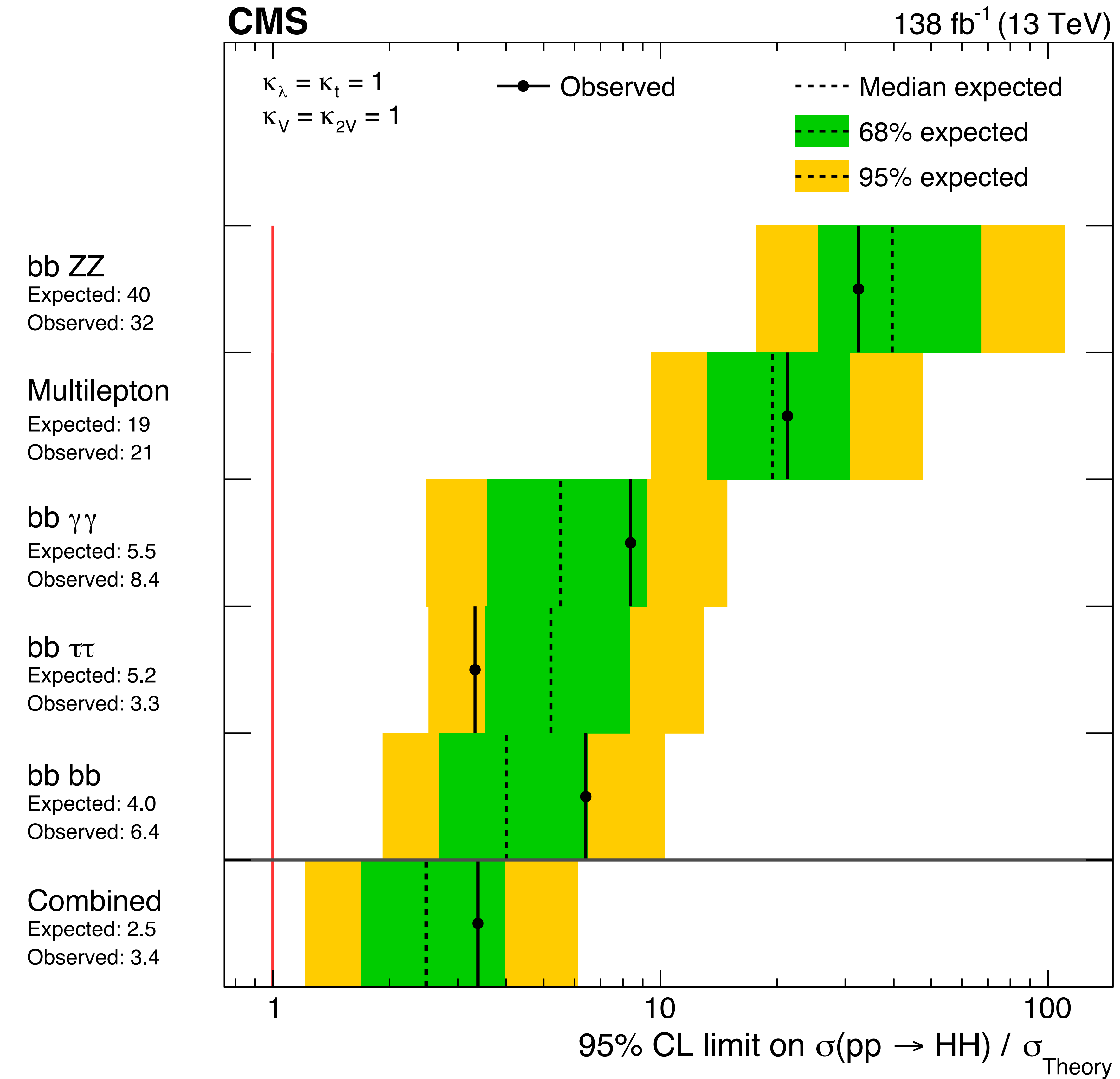
2016 data

Phys. Rev. Lett. 122 (2019) 121803



Run 2 combination

Nature 607 (2022) 60



new

new

x **3** improvement

x **5** improvement

x **5** improvement
(x **30** in boosted ch.)

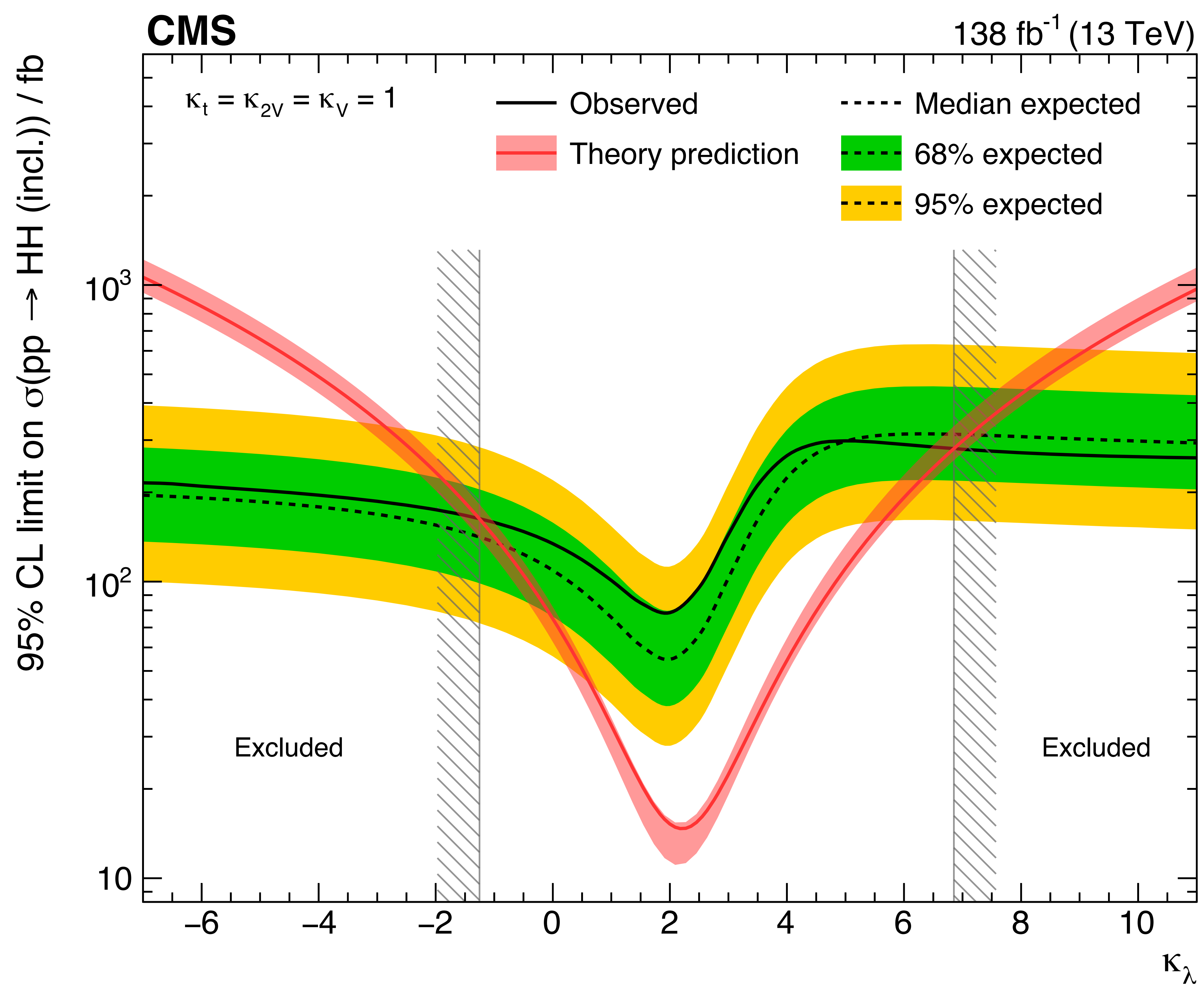
- **Run 2 combination**
  - Observed (expected) limit at 95% CL on σ/σ_{SM} measured as **3.4 (2.5)**
- **2016 data**
  - Scaling expected 95% CL limit of **12.8** to Run 2 luminosity would imply a limit of **6.5**

Major improvements due to

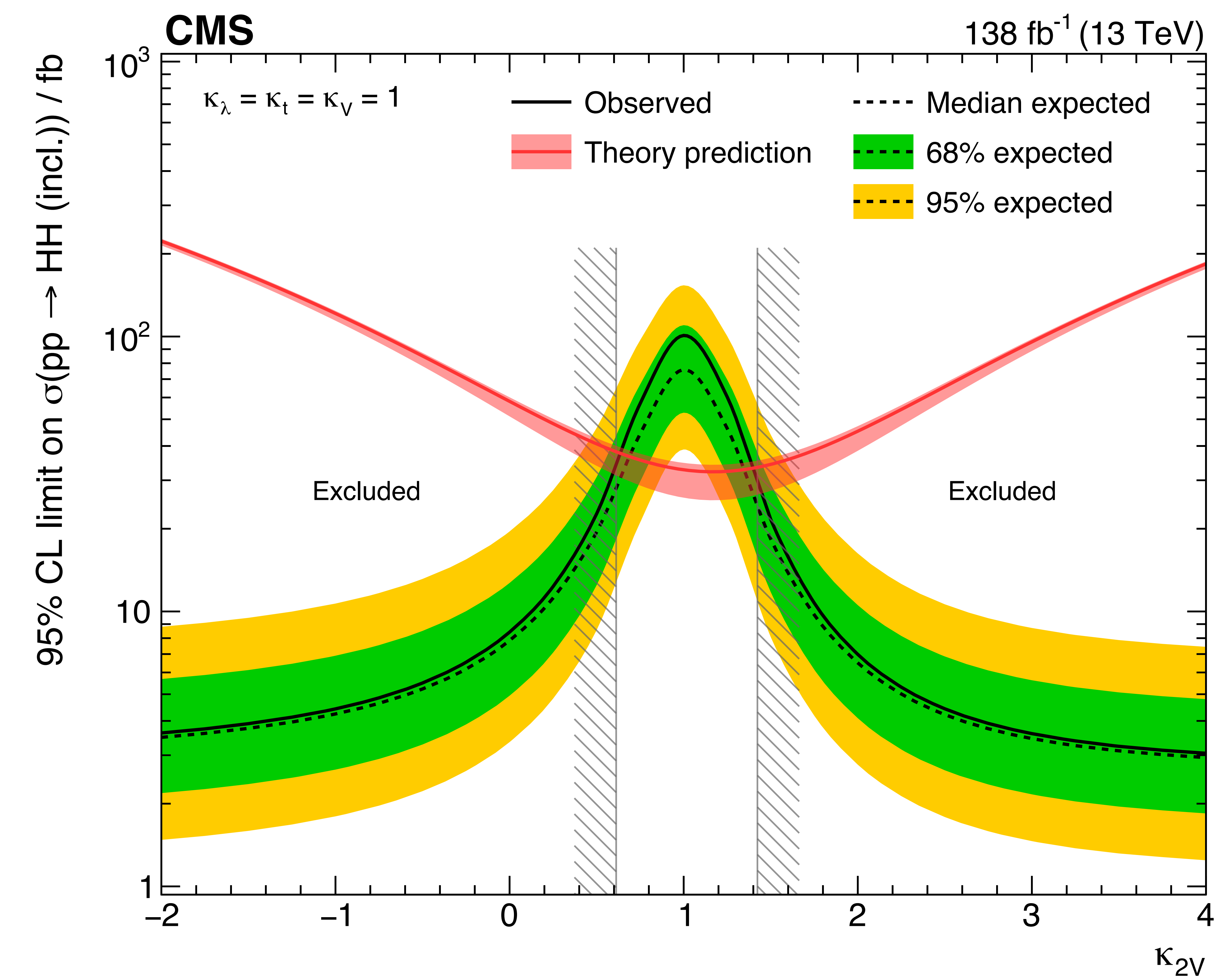
➜ Detector upgrades & trigger development
➜ CMS reconstruction & object tagging
➜ Improved analysis techniques
➜ Additional decay channels

Nature 607 (2022) 60

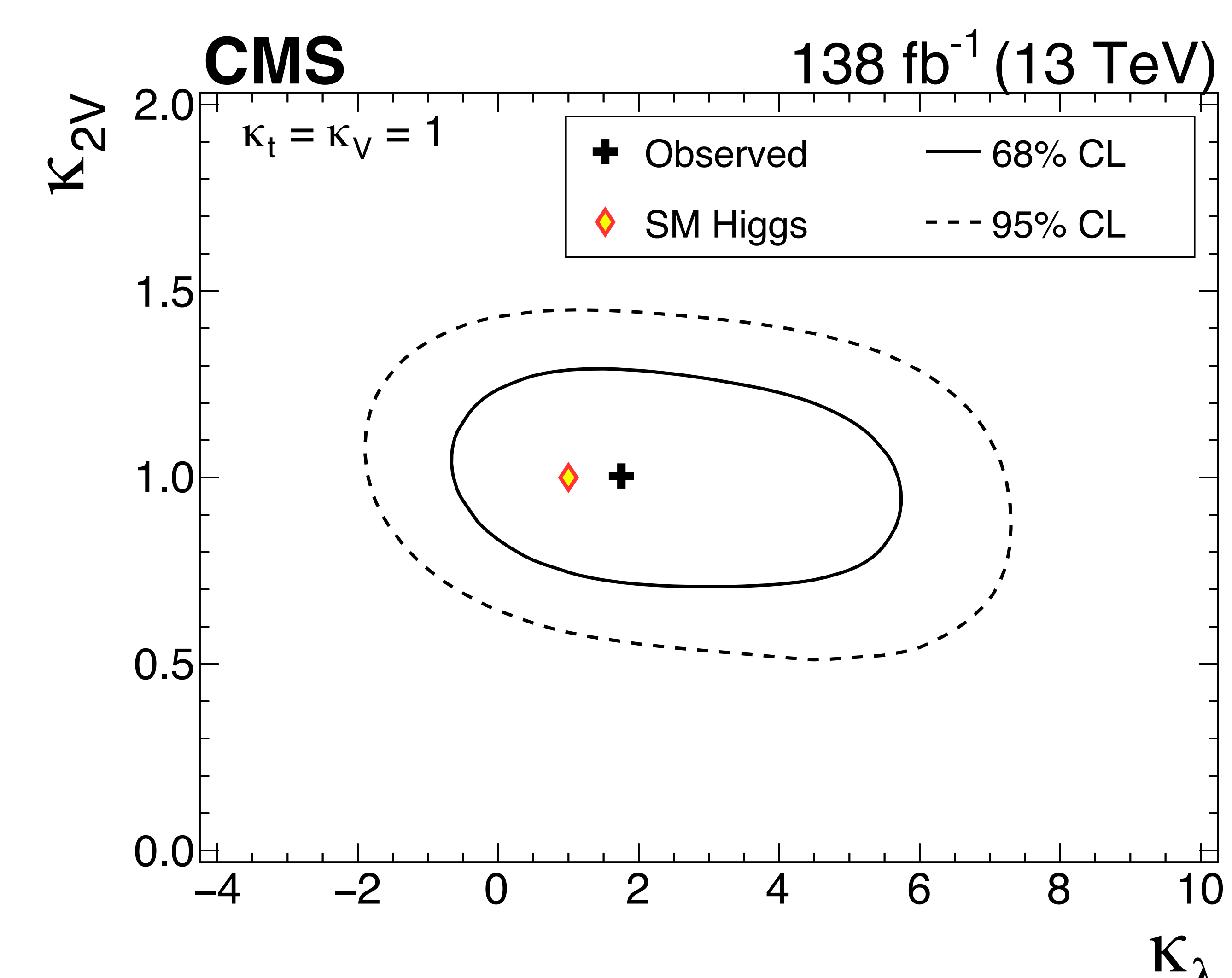
$\mathbf{k}_\lambda$



$\mathbf{k}_{2V}$



- $\mathbf{k}_\lambda$
  - Observed constraint at 95% CL to [**-1.24, +6.49**]
- $\mathbf{k}_{2V}$
  - Observed constraint at 95% CL to [**+0.67, +1.38**]
  - $\mathbf{k}_{2V}$ **= 0** excluded with **6.6σ** (assuming SM values of other **k**'s)
    - ▻ Establishes **quartic VVHH coupling** for the first time

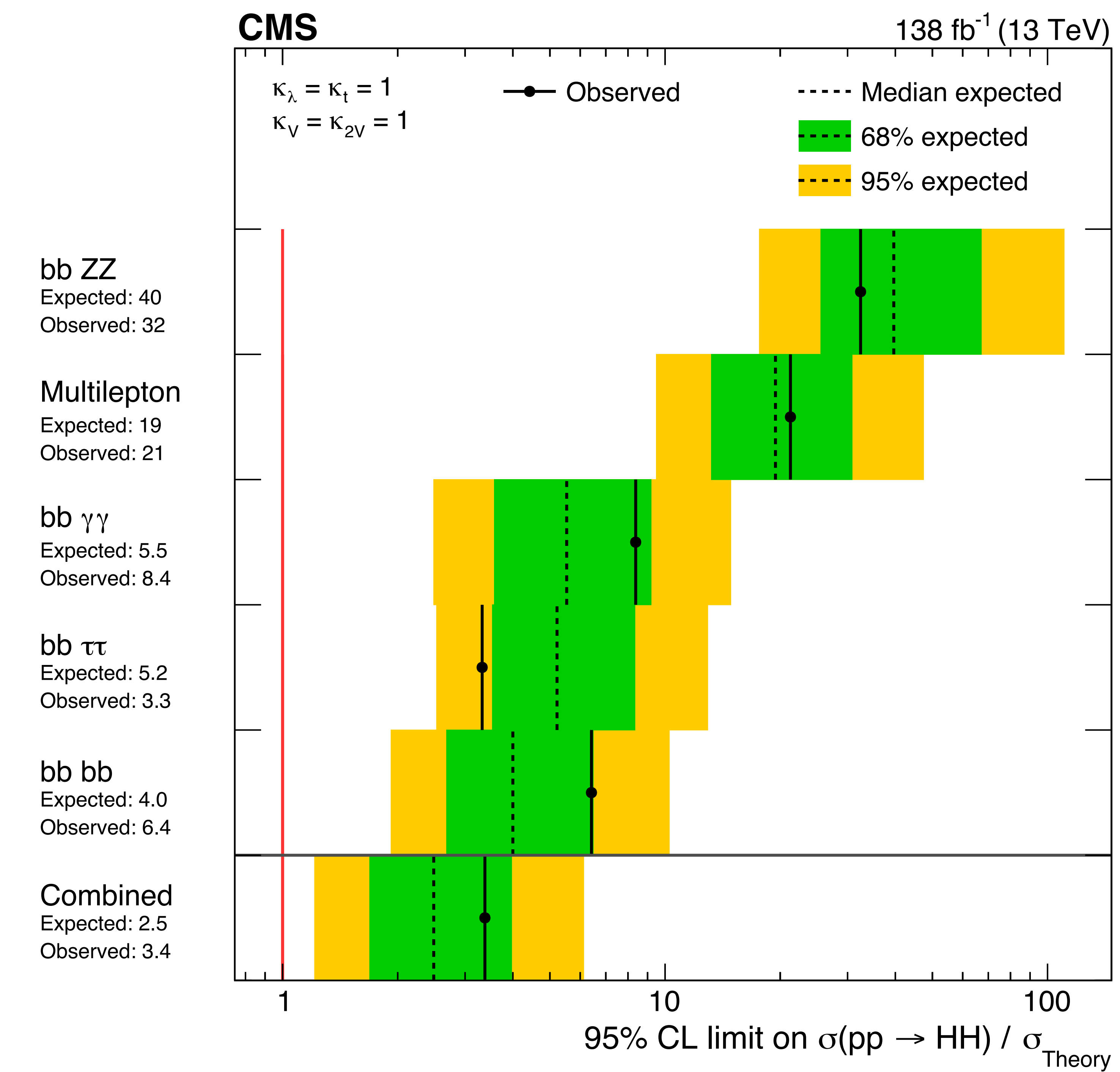


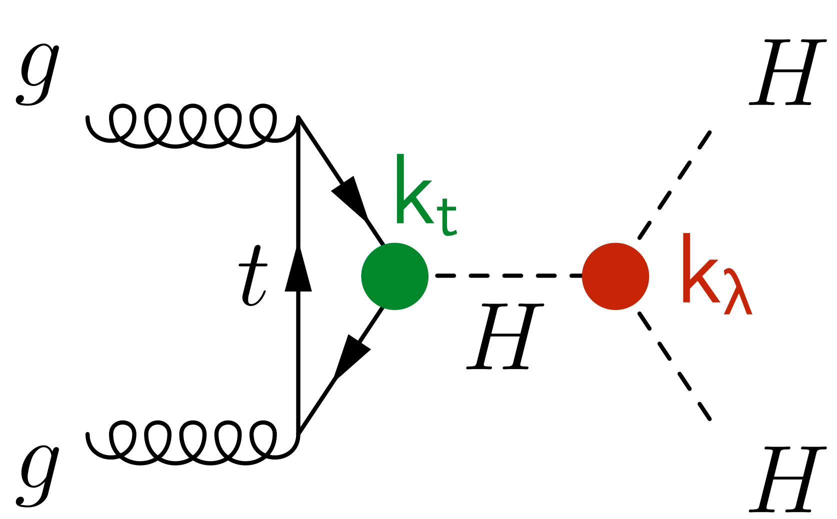
Nature 607 (2022) 60

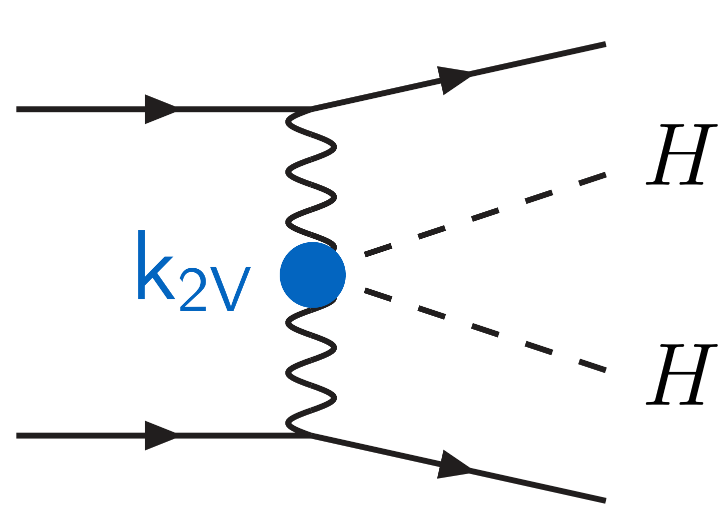
- Searches of HH production at CMS aim to investigate both **tri-H** and quartic **VVHH** couplings
  - → Five decay channels published and combined
  - → Ongoing efforts to include more decay channels and production modes

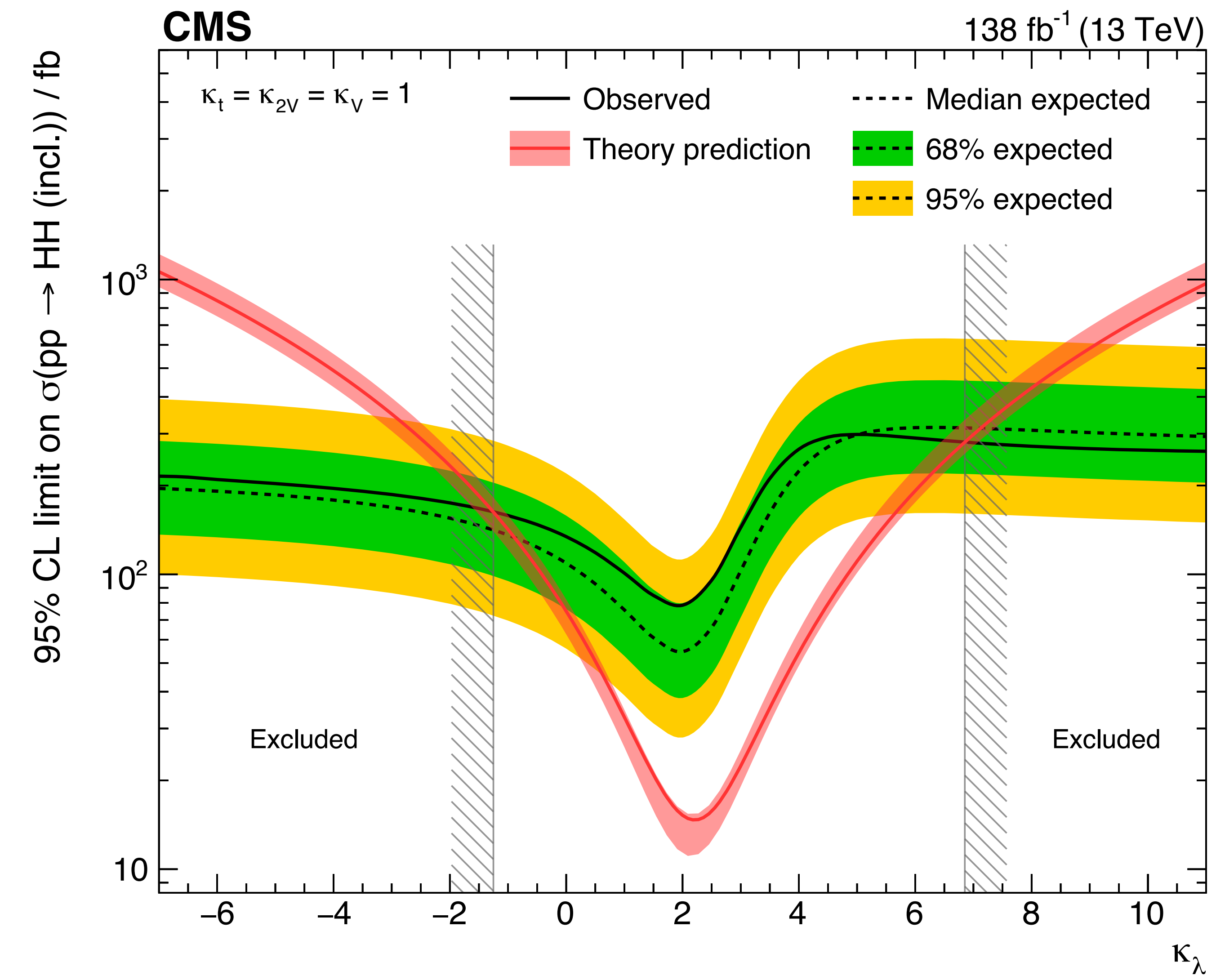
- k_λ constrained to [**-1.24**, **+6.49**], k_{2V} to [**+0.67**, **+1.38**]
- $k_{2V} \leq 0$ excluded with **6.6σ** assuming otherwise SM couplings
- Combined upper limit on inclusive HH production observed as **3.4 x SM**
  - → Run 2 expectation exceeded

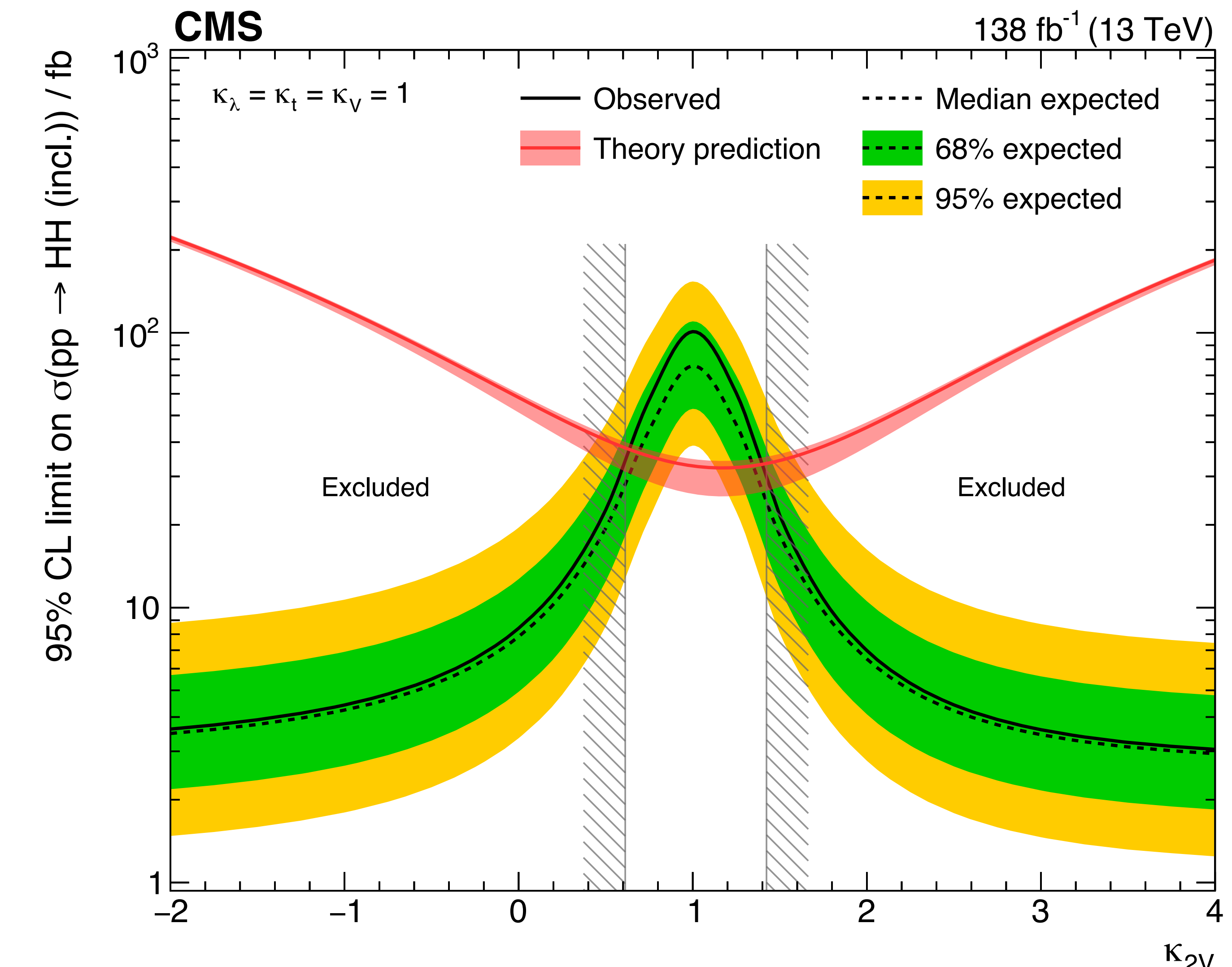
- EFT interpretations and resonant HH searches on the horizon
- Exciting years ahead!











Backup

HH signal modeling

- Morphing between shapes produced at discrete (**k_λ**, **k_t**, **k_t**, **k_V**) points used for template fits continuous in all **k**'s

$$D_{gghh}(k_\lambda, k_t) = r \cdot r_{gghh} \cdot \sum_{i}^{3} f^i_{gghh}(k_\lambda, k_t) \cdot D^i_{gghh}$$

$$D_{qqhh}(k_{2V}, k_V, k_\lambda) = r \cdot r_{qqhh} \cdot \sum_{i}^{6} f^i_{qqhh}(k_{2V}, k_V, k_\lambda) \cdot D^i_{qqhh}$$

(morphed shape) (coupling strengths) (morphing fractions) (discrete shapes)

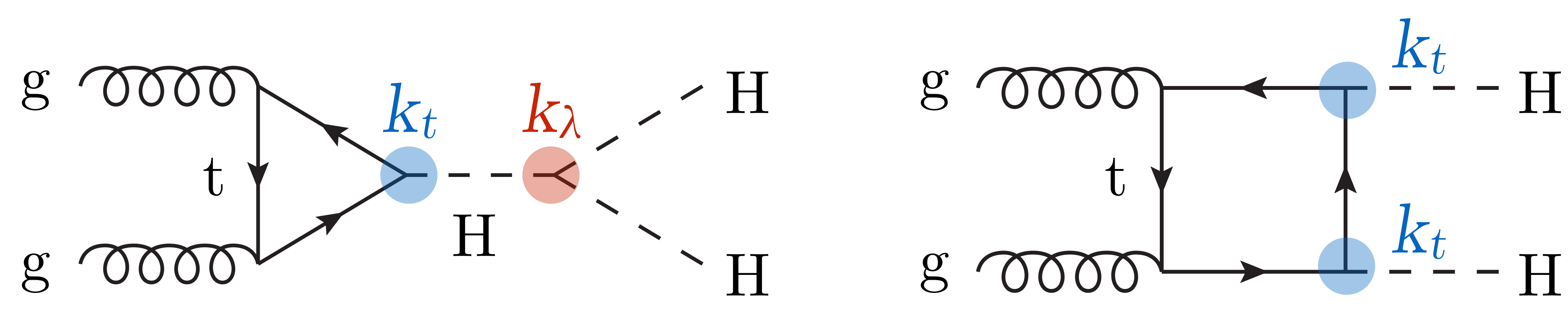
Morphing fractions $f^i_{gghh,qqhh}$ from parameterization of amplitudes at guidance points (backup)

  - Additional effects modelled (backup)
    - **k_λ** dependent QCD scale + m_{top} uncertainty on HH_{ggF}
    - Scaling of single Higgs background cross sections with **k**'s
    - Scaling of Higgs branching fractions with **k**'s

Same effects as presented in Alkaid's talk on ATLAS H+HH

- Signal model available publicly (based on CMS "combine" tool / RooFit)
  - Basis for all Run 2 HH analyses at CMS
  - Also used by some FCC projections (non-CMS)

HH ggF modeling



$$A = k_t\, k_\lambda\, T + k_t{}^2\, B$$

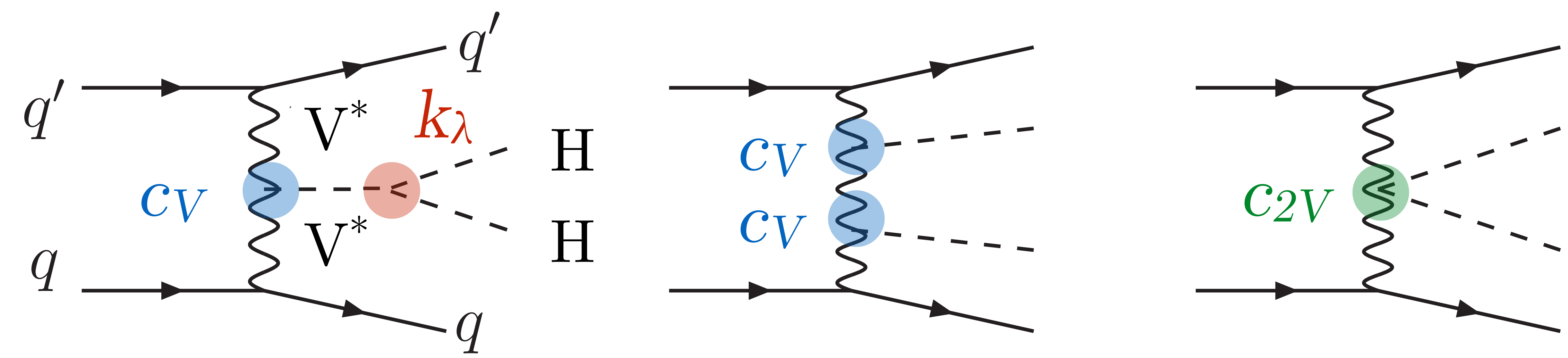
$$\sigma(k_t, k_\lambda) \sim |A|^2 = k_t{}^2\, k_\lambda{}^2\, |T|^2 + k_t{}^4\, |B|^2 + k_t{}^3\, k_\lambda\, |T^* B + B^* T|$$

$$= k_t{}^2\, k_\lambda{}^2\, t + k_t{}^4\, b + k_t{}^3\, k_\lambda\, i$$

triangle *box* *interference*

- Vectorized: $\sigma = c(\kappa_\lambda, \kappa_t) \cdot v$ with $c = (\kappa_\lambda^2 \kappa_t^2, \kappa_t^4, \kappa_\lambda \kappa_t^3)$ and $v = (t, b, i)$
- For three $(\kappa_\lambda, \kappa_t)$ guidance points: $\boldsymbol{\sigma} = \mathbf{c} \cdot \mathbf{v}$ $\quad \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{pmatrix} = \begin{pmatrix} c_1^1 & c_1^2 & c_1^3 \\ c_2^1 & c_2^2 & c_2^3 \\ c_3^1 & c_3^2 & c_3^3 \end{pmatrix} \begin{pmatrix} t \\ b \\ i \end{pmatrix}$
- Invert to obtain morphing fractions: $\underbrace{\sigma(\kappa_\lambda, \kappa_t)}_{\text{cross sections at } \kappa_\lambda, \kappa_t} = \underbrace{\mathbf{c}^{\mathbf{T}}(\kappa_\lambda, \kappa_t) \cdot \mathbf{C}^{-1}}_{\text{vector of morphing fractions}} \cdot \underbrace{\boldsymbol{\sigma}}_{\text{cross sections at guidance points}}$

$$a = |A|^2\ ,\ b = |B|^2,\ c = |C|^2,$$
$$i_{ab} = |A^*B + B^*A|,\ i_{ac} = |A^*C\ + C^*A|,\ i_{bc} = |B^*C + C^*B|$$



$$\mathcal{A} = c_V\, k_\lambda\, A + c_V{}^2\, B + c_{2V}\, C$$

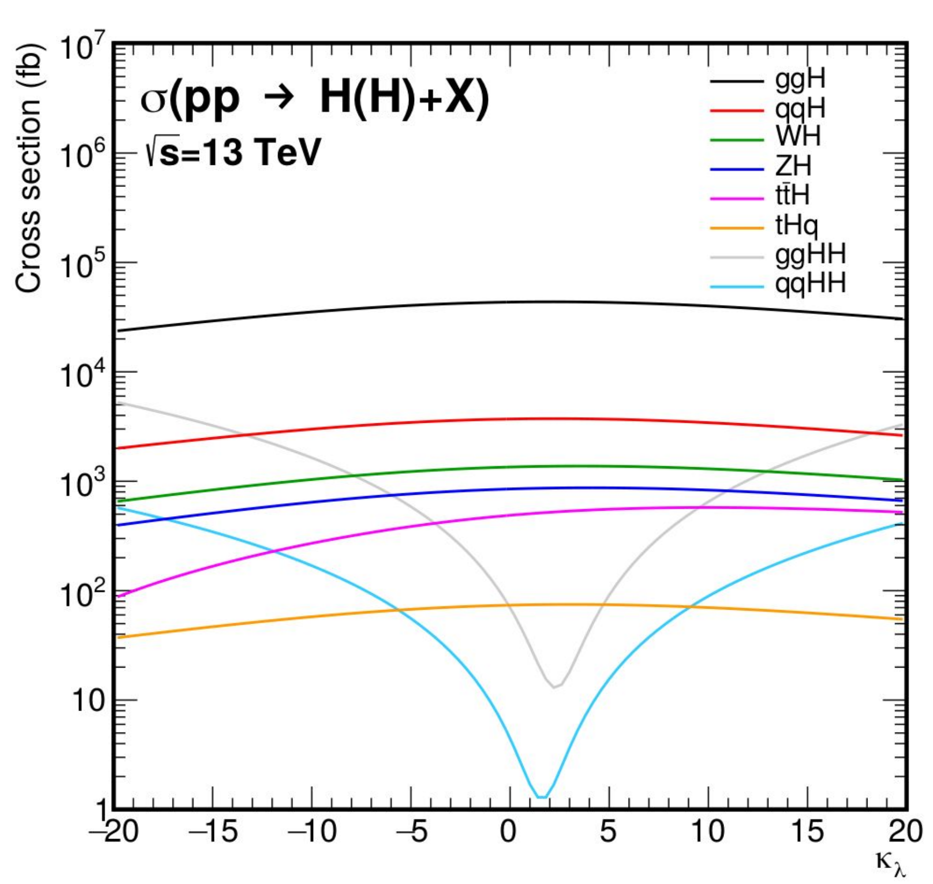
$$\sigma(k_\lambda,\ c_V,\ c_{2V}) \sim |\mathcal{A}|^2 = c_V{}^2\, k_\lambda{}^2\, a + c_V{}^4\ b + c_{2V}{}^2\ c + c_V{}^3\, k_\lambda\, i_{ab} + c_V\, c_{2V}\, k_\lambda\, i_{ac} + c_V{}^2\ c_{2V}\ i_{bc}$$

- Vectorized: $\sigma = c(c_V, c_{2V}, \kappa_\lambda) \cdot v$
- For three $(\kappa_\lambda, \kappa_t)$ guidance points: $\boldsymbol{\sigma} = \mathbf{c} \cdot \mathbf{v}$ $\quad \sigma(\kappa_\lambda, C_V, C_{2V}) = \begin{pmatrix} C_V^2 \kappa_\lambda^2 \\ C_V^4 \\ C_{2V}^2 \\ C_V^3 \kappa_\lambda \\ C_V \kappa_\lambda C_{2V} \\ C_V^2 C_{2V} \end{pmatrix} \cdot \begin{pmatrix} a \\ b \\ c \\ i_{ab} \\ i_{ac} \\ i_{bc} \end{pmatrix}$
- Invert to obtain morphing fractions: $\underbrace{\sigma(c_V, c_{2V}, \kappa_\lambda)}_{\text{cross sections at } \kappa_\lambda, \kappa_t} = \underbrace{\mathbf{c}^{\mathbf{T}}(c_V, c_{2V}, \kappa_\lambda) \cdot \mathbf{C}^{-1}}_{\text{vector of morphing fractions}} \cdot \underbrace{\boldsymbol{\sigma}}_{\text{cross sections at guidance points}}$

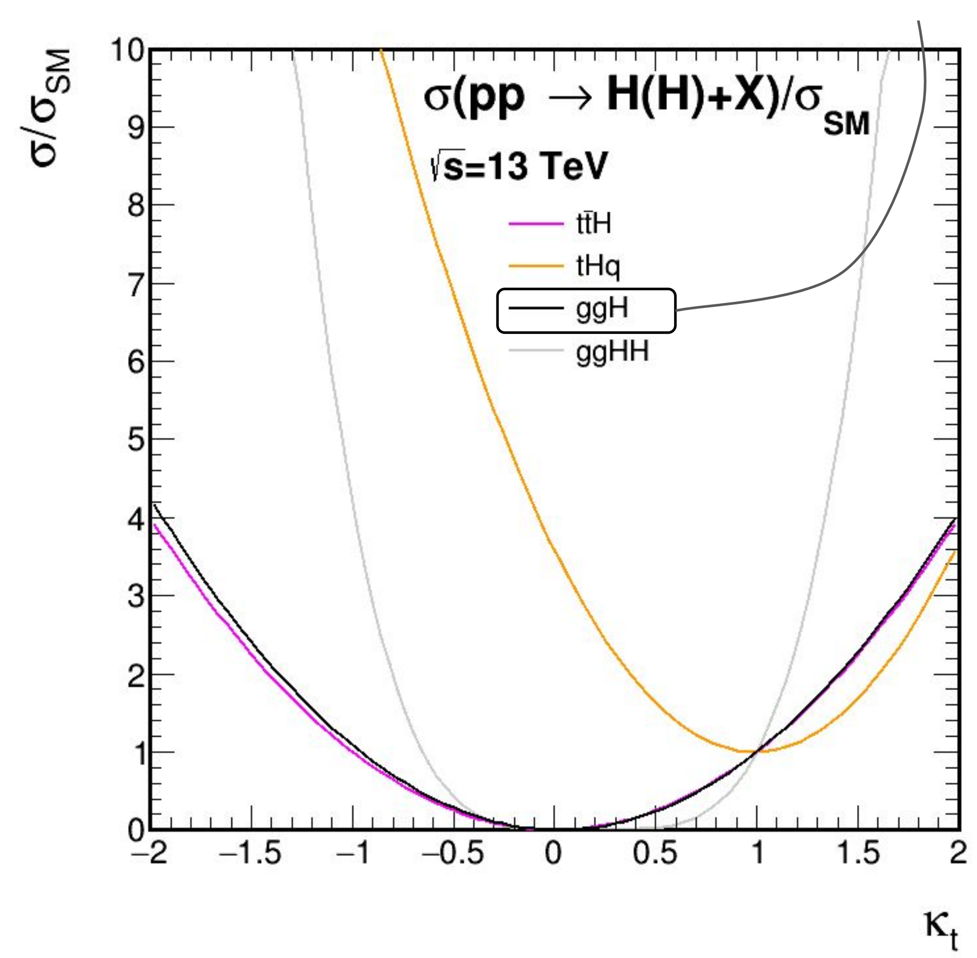
Modeling of Higgs contributions

- Single Higgs background cross sections **and** Higgs BRs also depend on (**k_λ**, **k_t**, **k_V**)

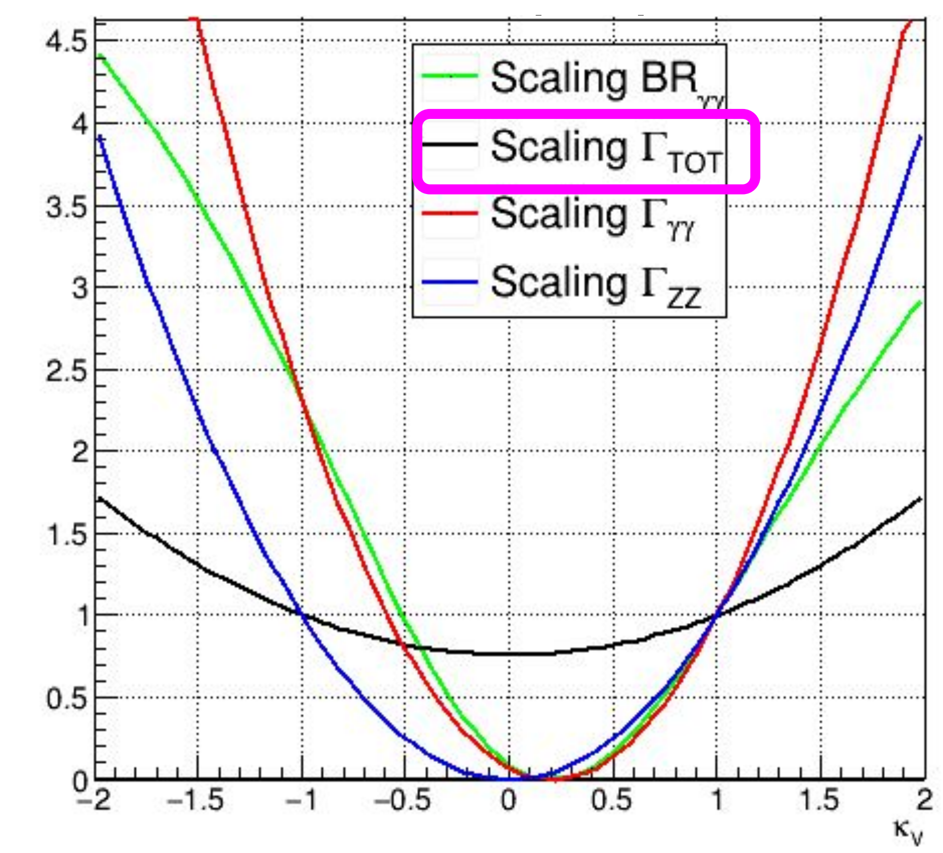
σ vs. k_λ
(arxiv:1709.08649)



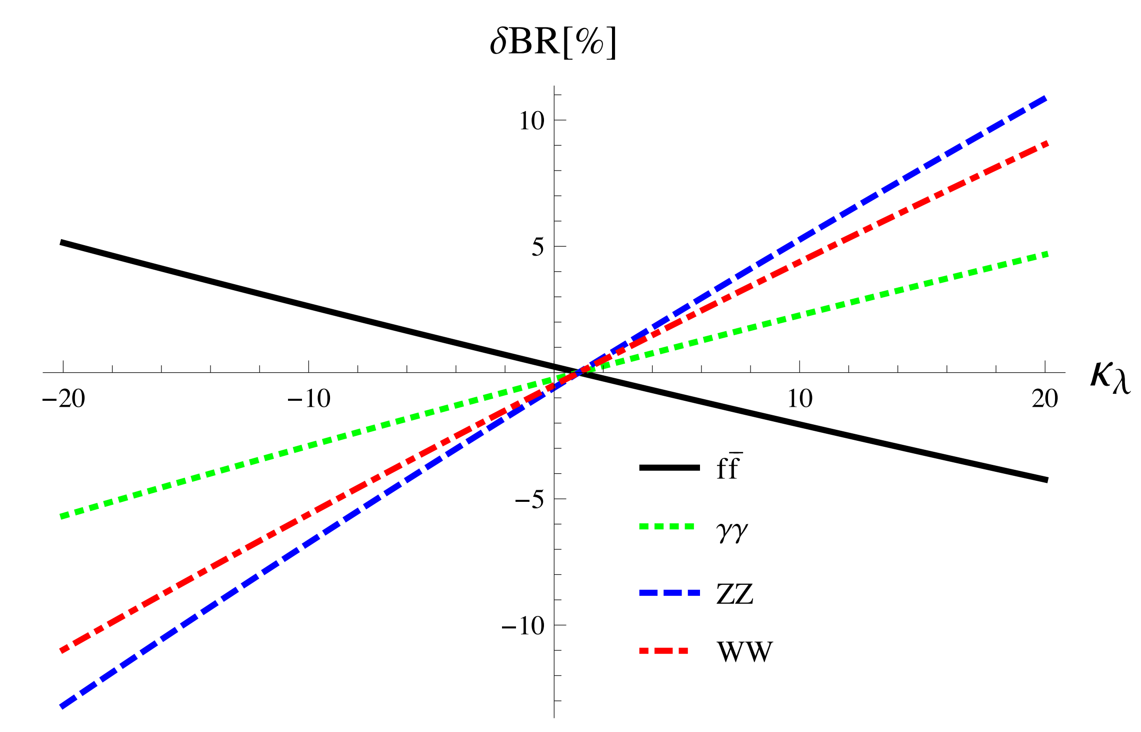
σ vs. k_t
(arxiv:1307.1347)



$BR_{\gamma\gamma}$ and Γs vs. k_V
(arxiv:1307.1347)



BRs vs. k_λ
(arxiv:1607.04251)



- Both scalings implemented in our physics model for cases where
  - different non-SM combinations of (**k_λ**, **k_t**, **k_V**) are tested, or
  - (**k_λ**, **k_t**, **k_V**) are allowed to float during fit

$HH \rightarrow bb\gamma\gamma$

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- **Strategy**
  - $\gamma\gamma$ selection
    - p_{T1} $(p_{T2}) > 0.33$ $(0.25) \cdot m_{\gamma\gamma}$
    - $100 < m_{\gamma\gamma} < 180$
    - $m_{\gamma\gamma}$ resolution of 1.4 - 2.0 GeV
  - bb selection
    - 2 jets with highest b-tag score (CMS *DeepJet*)
    - $70 < m_{bb} < 190$ GeV
    - b-jet energy regression
  - 2D maximum likelihood fit on m_{jj} and $m_{\gamma\gamma}$
- **Results**
  - Upper limit on σ_{HH}/σ_{SM} of **7.7** (**5.2**)
  - Upper limit on σ_{VBF}/σ_{SM} of **225** (**208**)
  - Constraints $\mathbf{k_\lambda}$ to [-3.3, +8.5]
  - Constraints $\mathbf{k_{2V}}$ to [-1.3, +3.5]