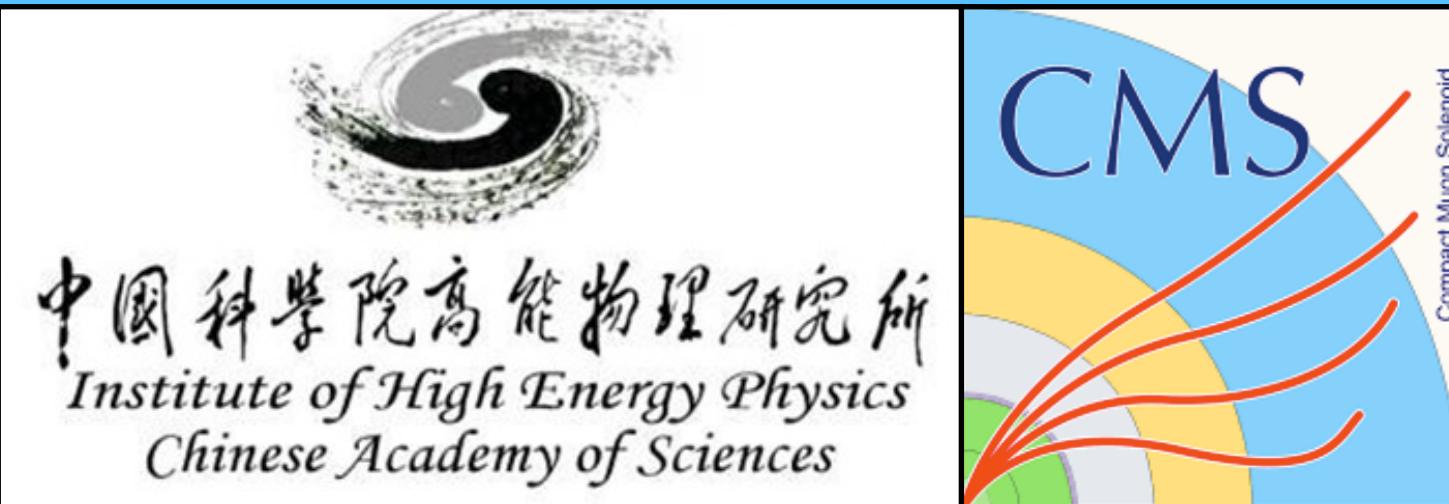




Search for Higgs boson pair production at CMS

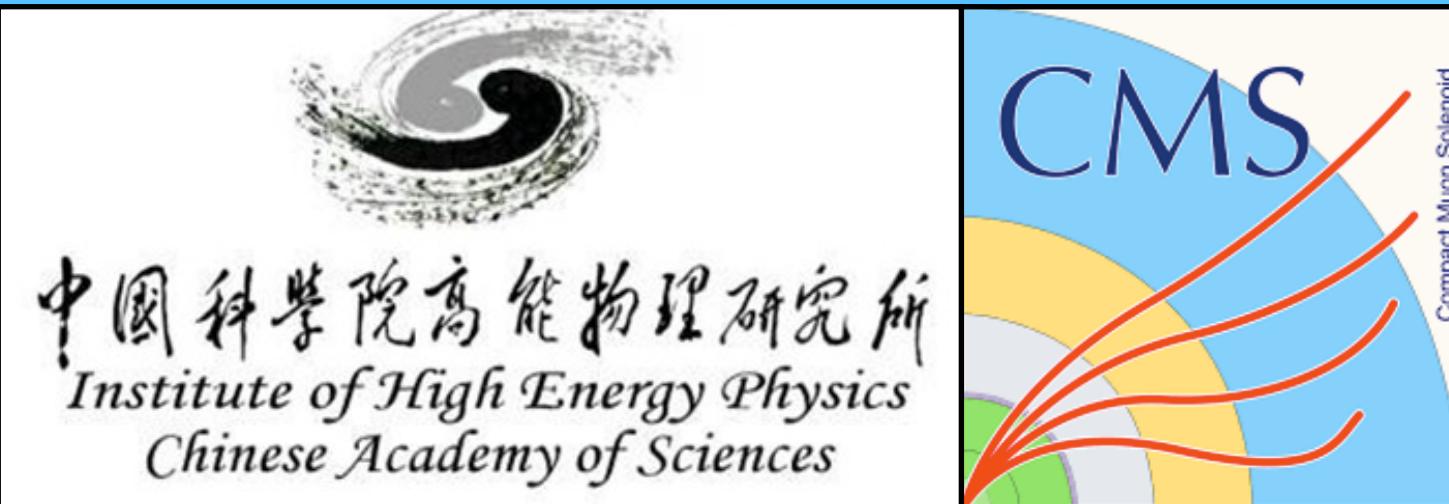
Chu Wang, Institute of High Energy Physics

Outline



- * Introduction
- * The HH analyses in CMS experiment
- * Overview of HH analyses
- * HH combination
- * Summary

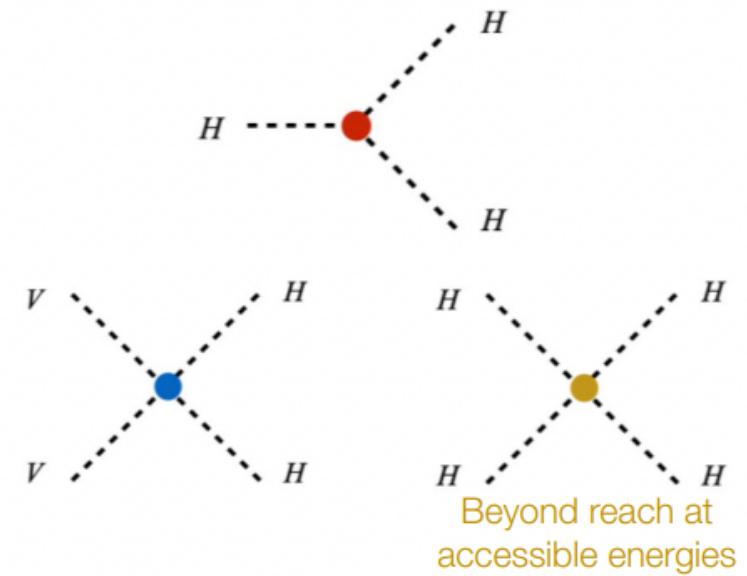
Introduction



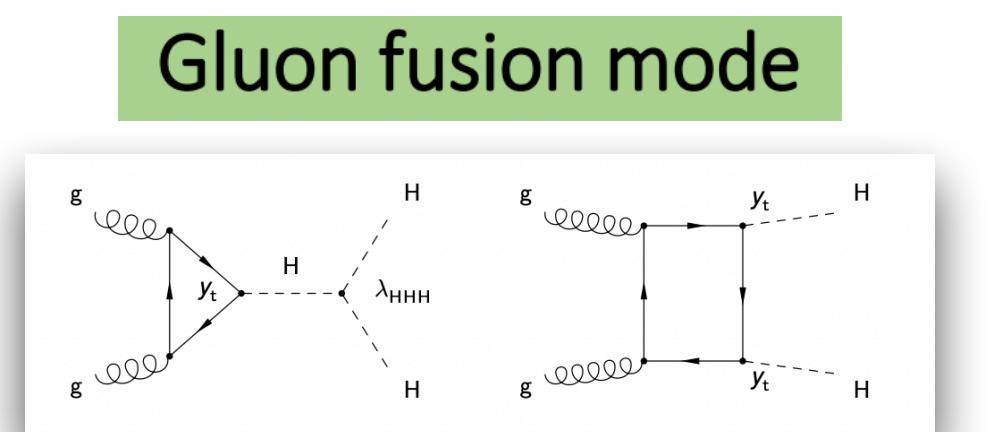
- The Higgs field potential:

$$V = \mu^2 H^2 + \frac{\mu^2}{\nu} H^3 + \frac{\mu^2}{4\nu^2} H^4 = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2\nu} H^3 + \frac{m_H^2}{8\nu^2} H^4$$

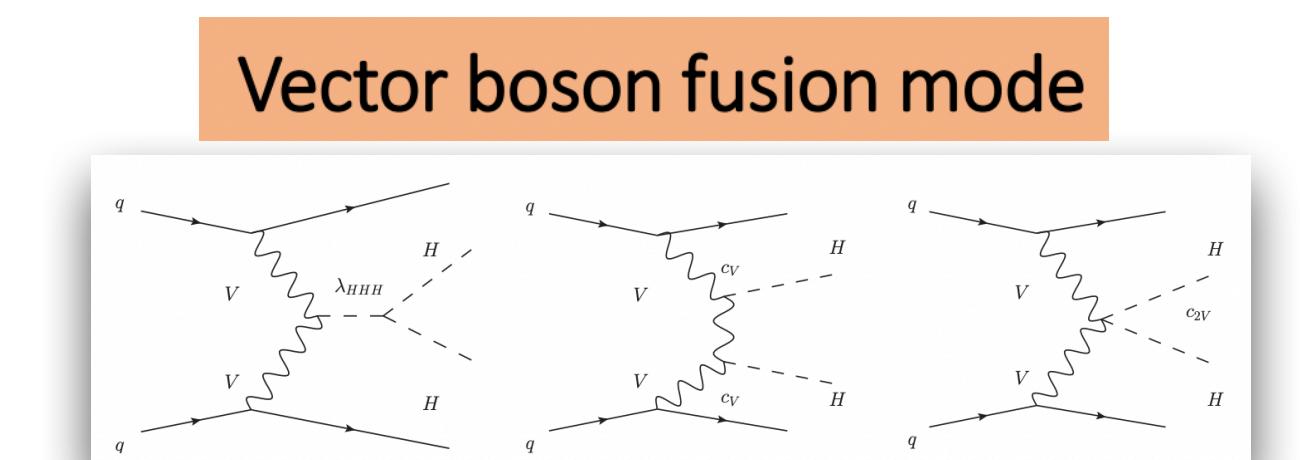
Mass-term λ_3 , trilinear self-coupling λ_4 , quartic self-coupling
 plus effect of cov.
 derivative on ϕ in \mathcal{L}_H
 C_{2V} , VVHH coupling



- Measurement of self-couplings λ_3 / λ_4 crucial for understanding the field potential
 - Mediates our understanding of how EWSB is realized

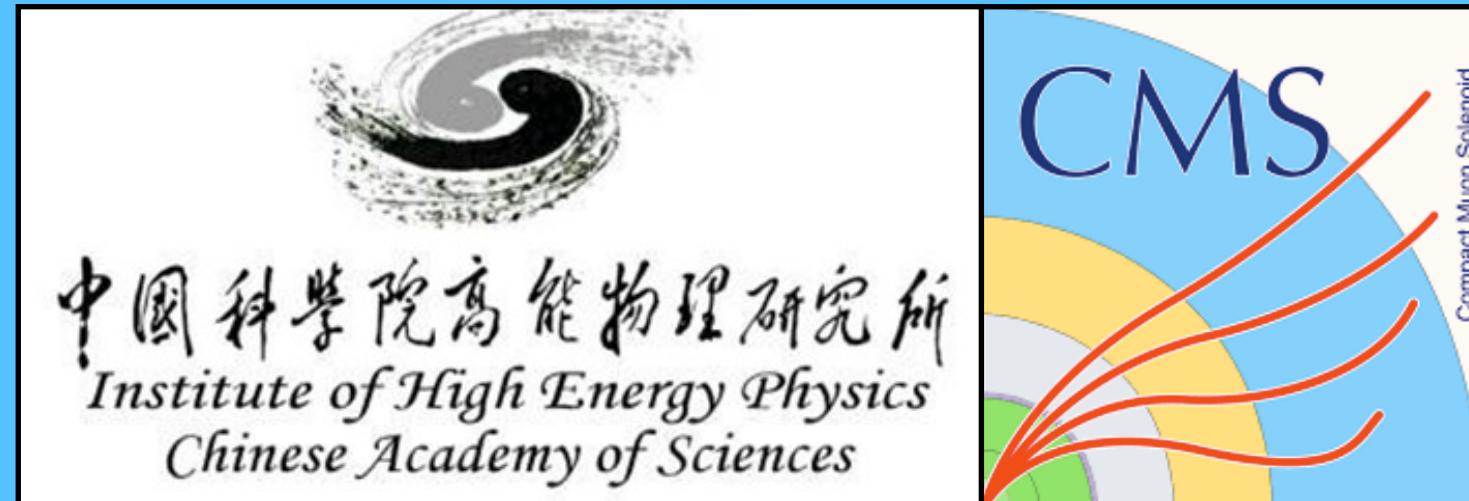


$\sigma = 31 \text{ fb}$
 largest cross section
 ⇒ provides the meaningful constraints in the Higgs boson self-coupling
 ⇒ The last piece of the Higgs mechanism to be measured



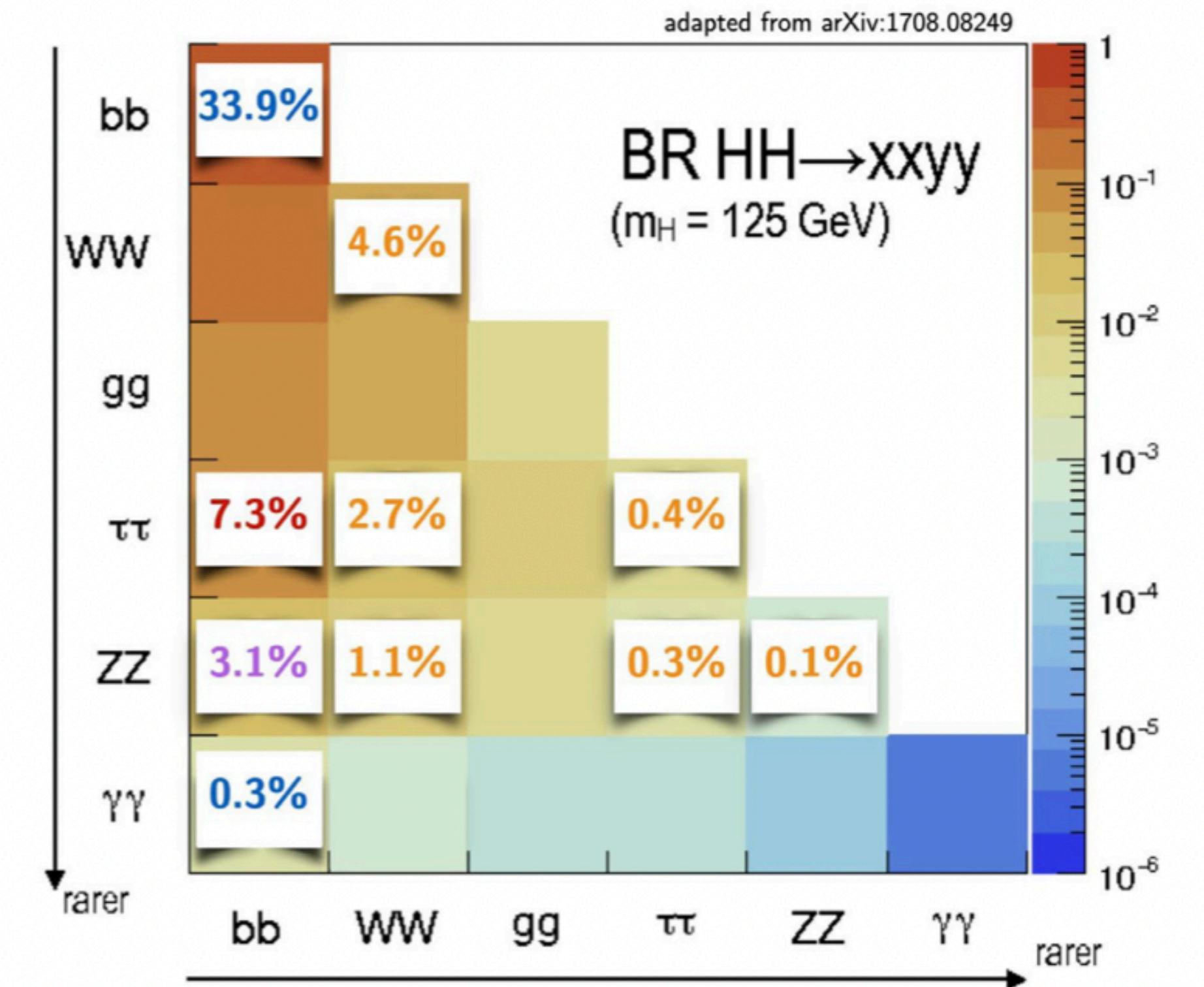
$\sigma = 1.7 \text{ fb}$
 Only process to approach the 4-linear coupling between two Higgs bosons and two vector bosons
 => A test of the doublet structure of the Higgs field

The HH analyses in CMS experiment

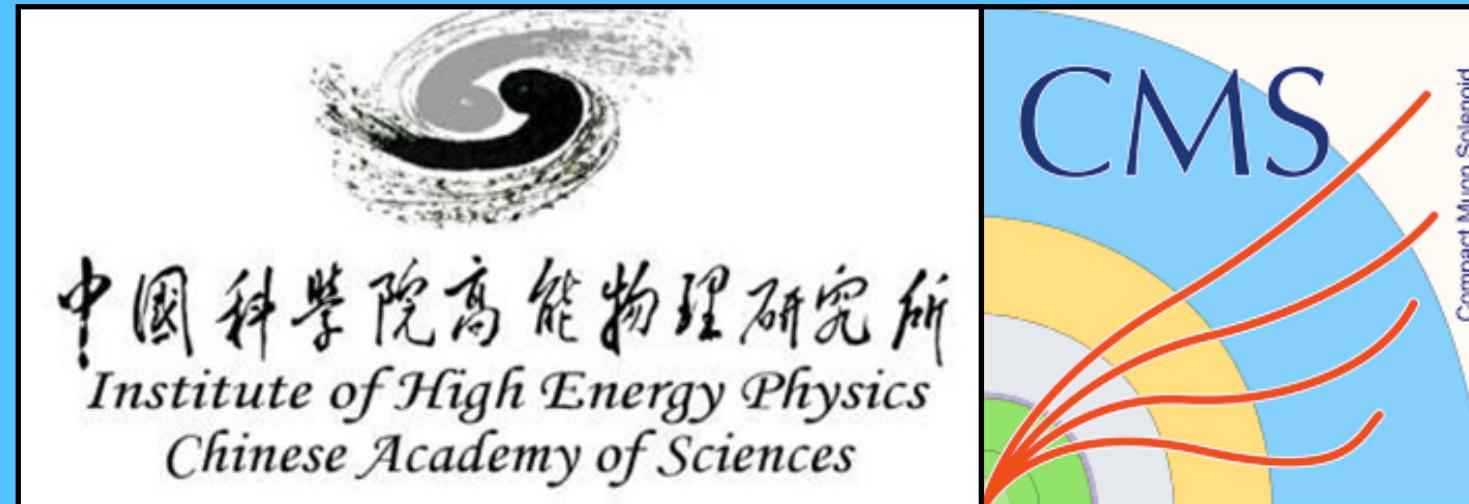


► Summary table of main HH analyses in CMS

| Channel | Publication | Include ggF? | Include VBF? |
|-------------------|----------------------------------|--------------|--------------|
| bb ZZ(4l) | arXiv:2206.10657 | Yes | No |
| bb $\gamma\gamma$ | JHEP (2021) | Yes | Yes |
| bb $\tau\tau$ | arXiv:2206.09401 | Yes | Yes |
| bb bb (resolved) | arXiv:2202.09617 | Yes | Yes |
| bb bb (boosted) | arXiv:2205.06667 | Yes | Yes |
| MultiLepton | arXiv:2206.10268 | Yes | Yes |
| WW $\gamma\gamma$ | Pre-approved | Yes | No |



Overview of HH analyses: bb $\gamma\gamma$



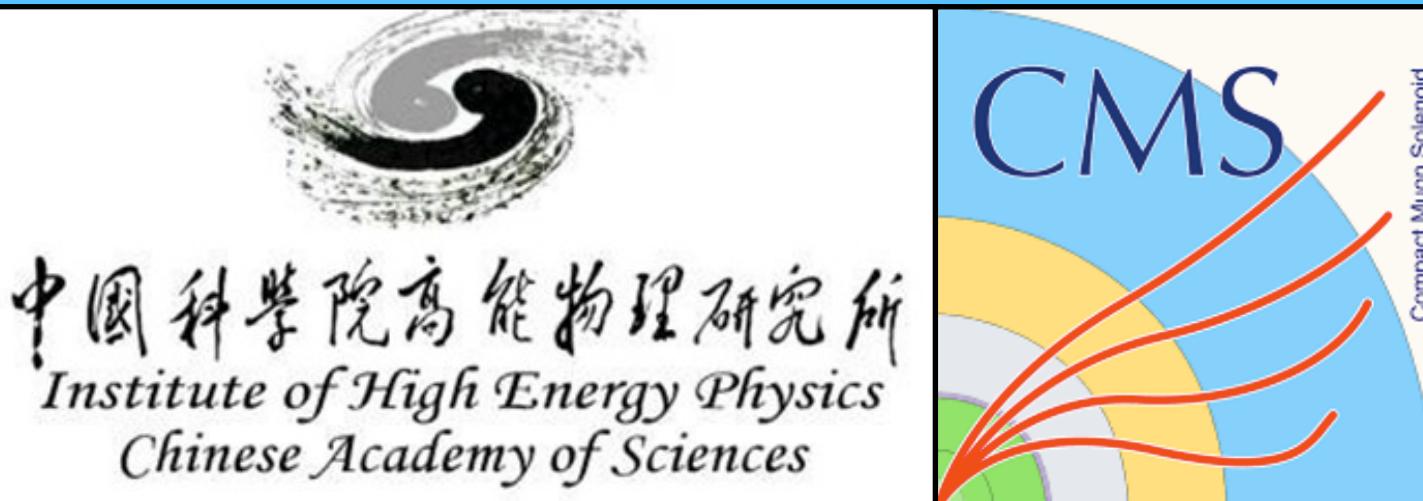
► Introduction to this analysis:

- In this analysis, we used Full-RunII data:
 - ggHH and VBF HH production modes are investigated
 - Small branch ratio, but clean signal extraction
 - Probing constrain the k_λ and k_{2v} , $k_\lambda = \lambda/\lambda_{SM}$ $k_{2v} = c_{2v}/c_{2v}^{SM}$
 - Considered Single-Higgs as backgrounds
 - Main non-resonant backgrounds: $\gamma\gamma + \text{Jets}$, $\gamma + \text{Jets}$, tth
 - Also investigated a range of EFT parameterised BSM interpretations

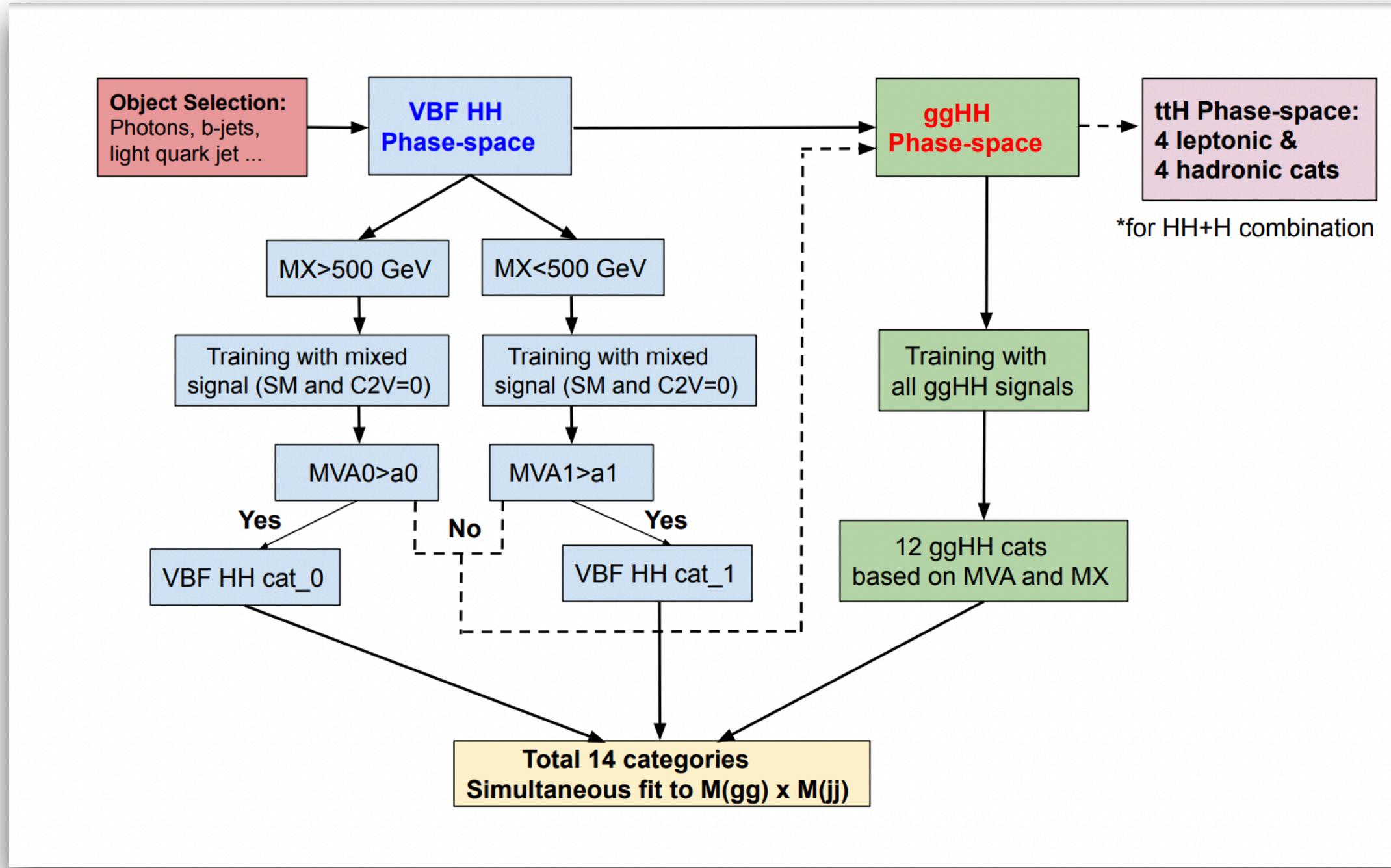
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | SM |
|------------------|------|------|------|------|------|------|------|------|------|------|------|------|-----|
| κ_λ | 7.5 | 1.0 | 1.0 | -3.5 | 1.0 | 2.4 | 5.0 | 15.0 | 1.0 | 10.0 | 2.4 | 15.0 | 1.0 |
| κ_t | 1.0 | 1.0 | 1.0 | 1.5 | 1.0 | 1.0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

EFT parameters

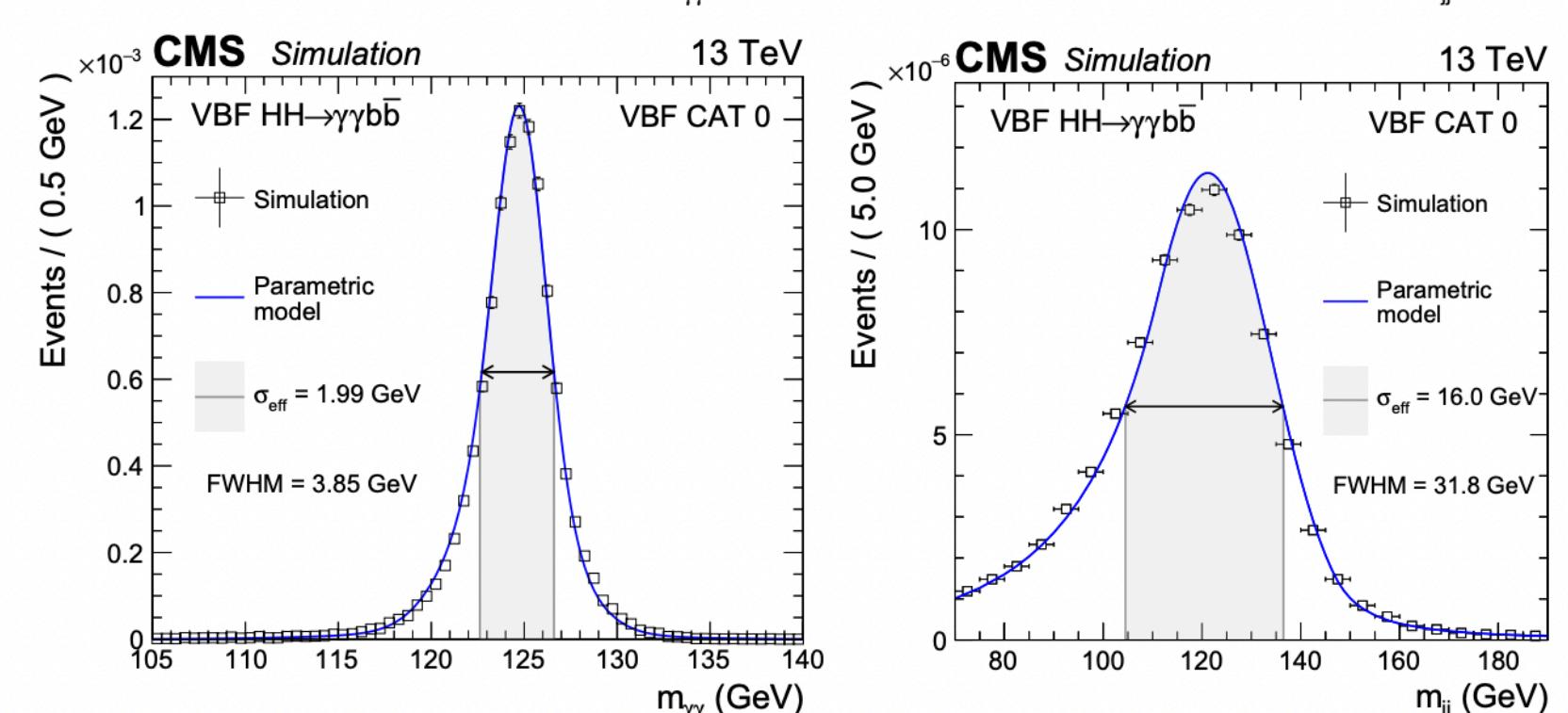
Overview of HH analyses: $b\bar{b}\gamma\gamma$



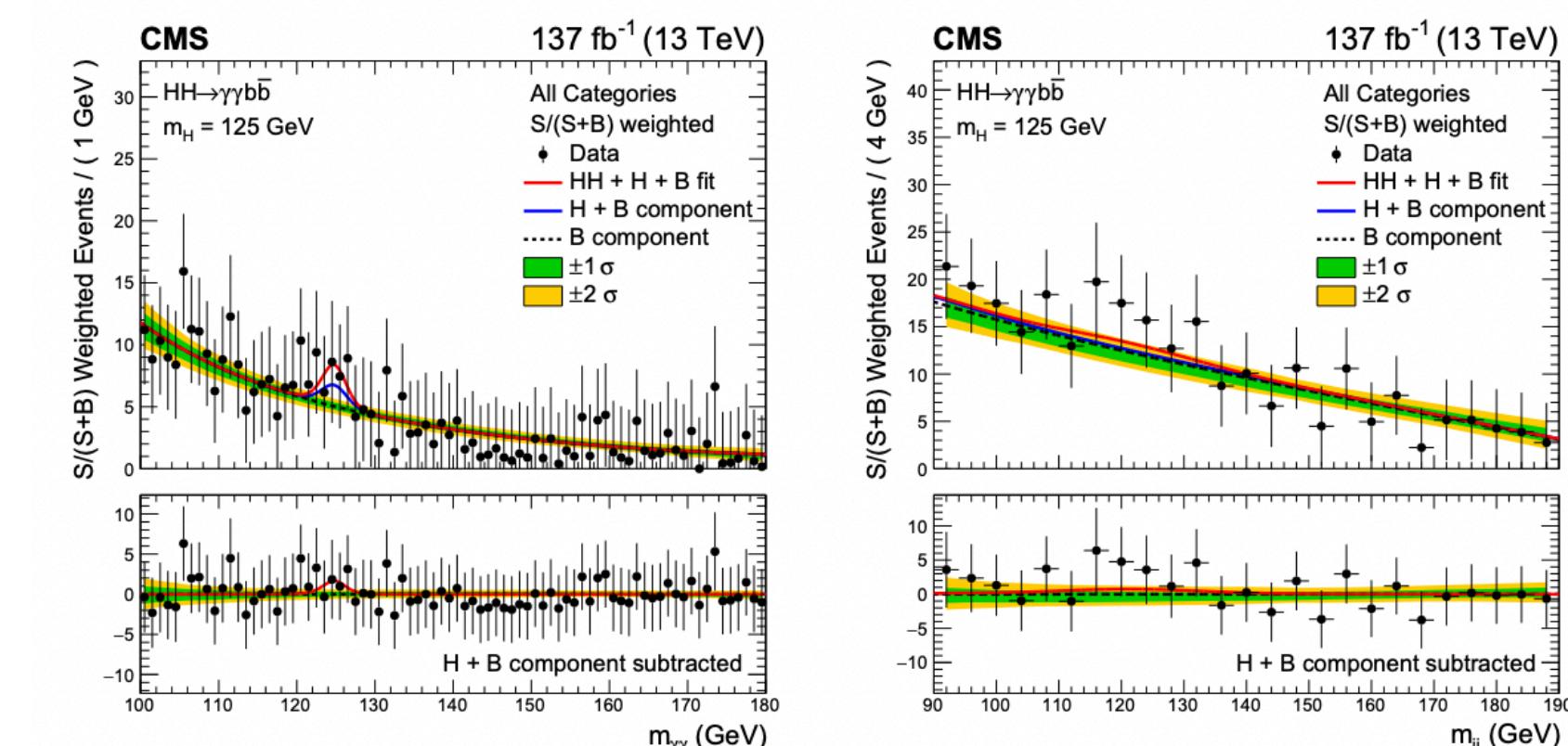
► Main analysis strategies



► Signal and background modeling

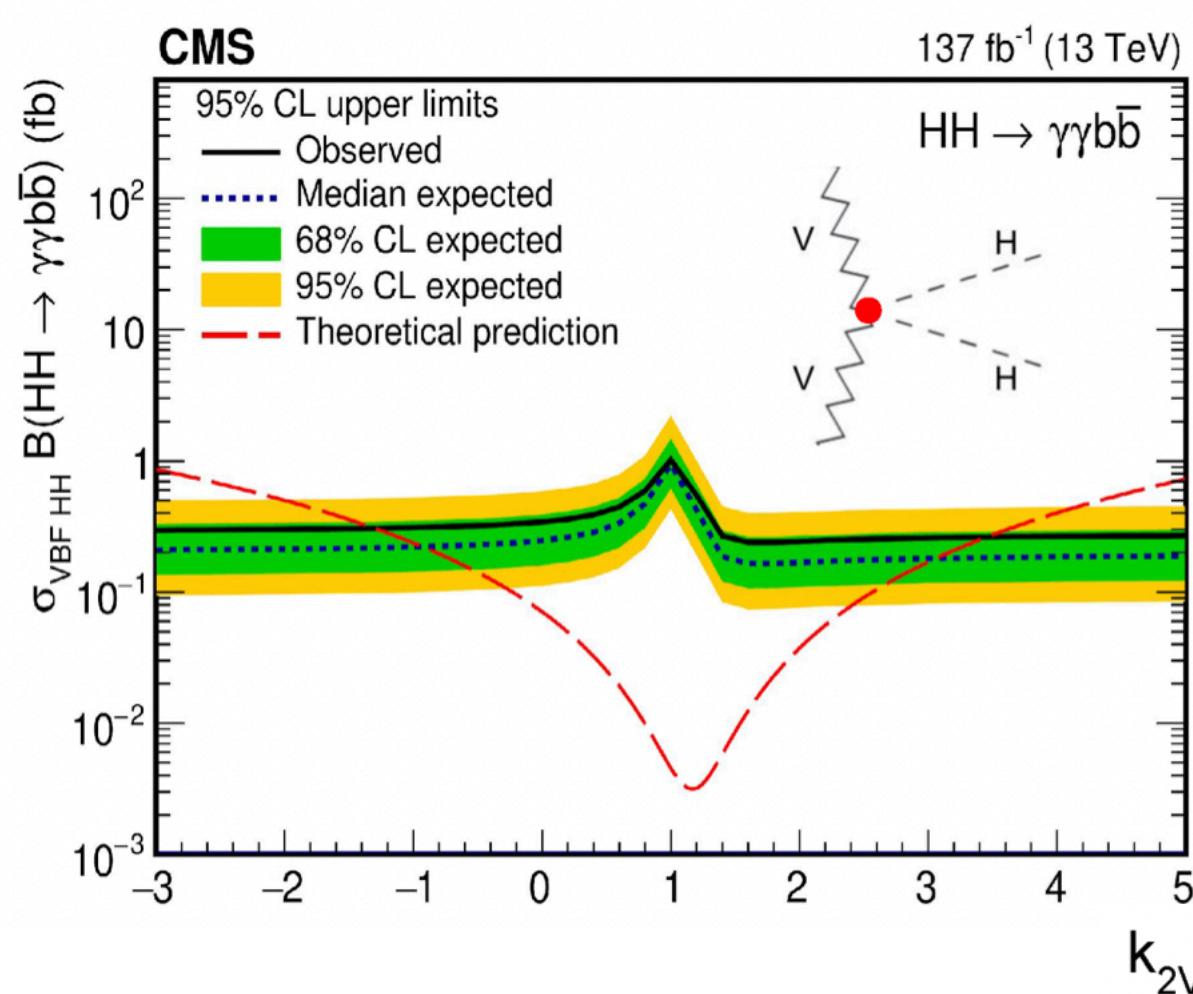
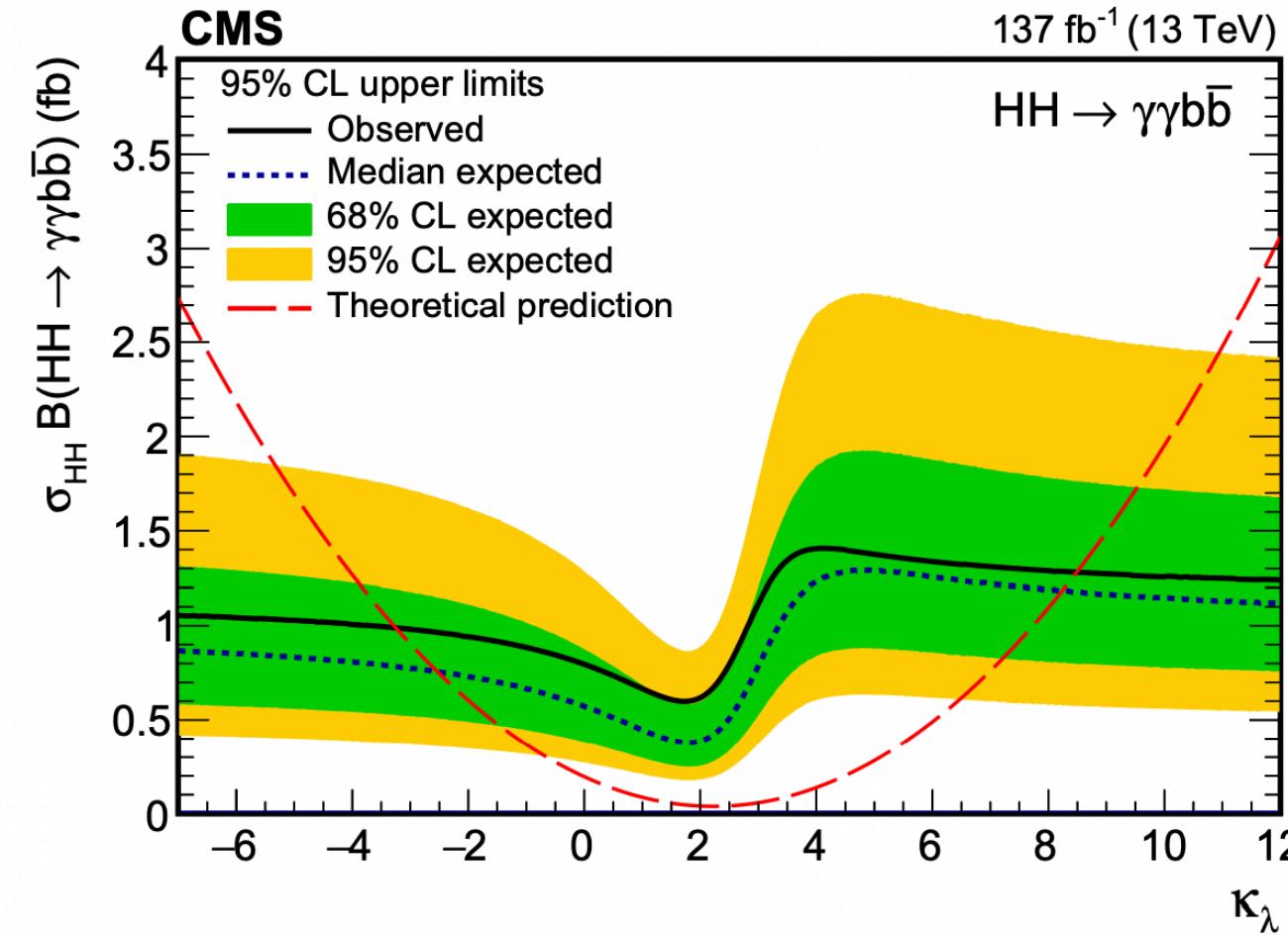
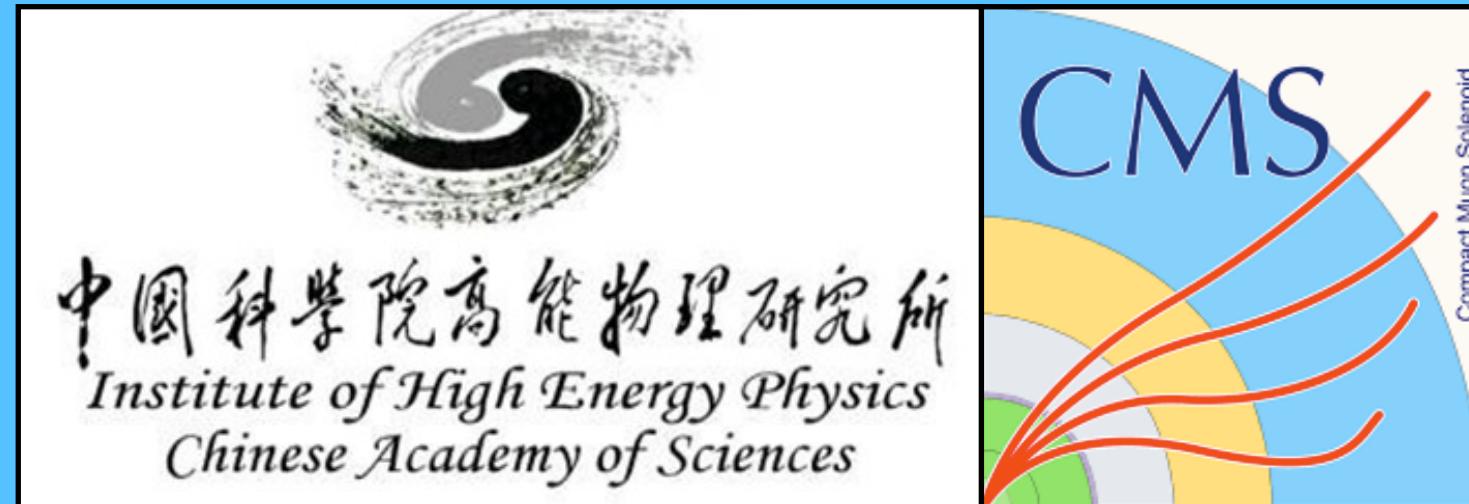


Used multi-Gaussians and DCB to modeling signal



The backgrounds derived from sideband events

Overview of HH analyses: $b\bar{b}\gamma\gamma$

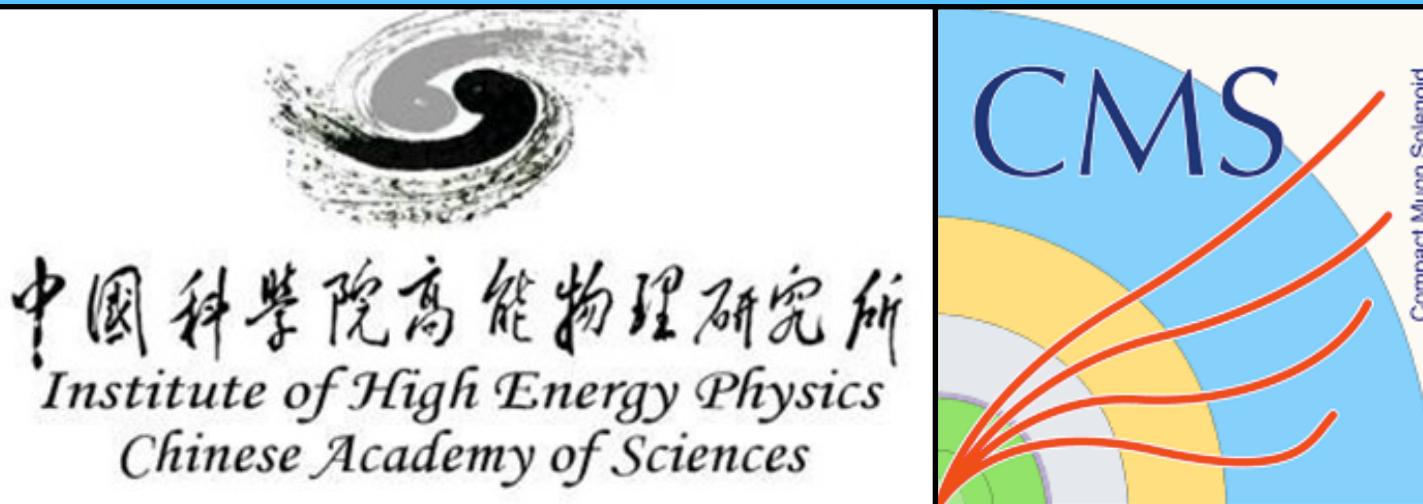


► Results:

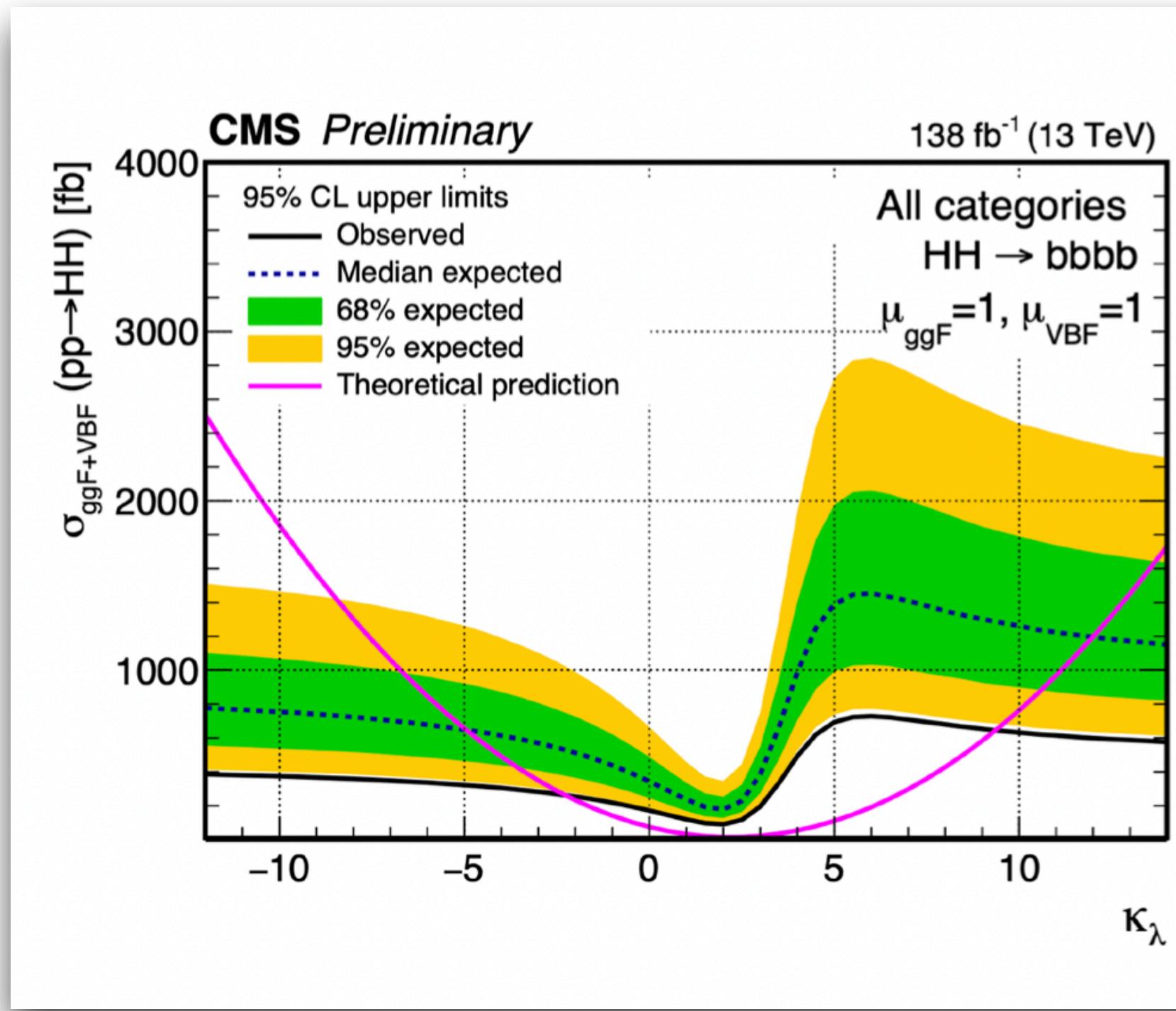
- Observed (expected) limits:
 - $\sigma^{HH} < 7.7$ (5.2) $\times \sigma_{SM}^{HH}$
- Observed (expected) k_λ interval:
 - -3.3 (-2.5) $< k_\lambda < 8.5$ (8.2)
- Observed (expected) k_{2V} interval:
 - -1.3 (0.9) $< k_{2V} < 3.5$ (3.0)

[JHEP 03 \(2021\) 257](#)

Overview of HH analyses: 4b (resolved)



- Final state with four b-jets, plus extra jet pair for VBF HH signal:
 - Highest branching ratio, but large multijet background
 - Used dedicated BDTs to separate different signals and backgrounds

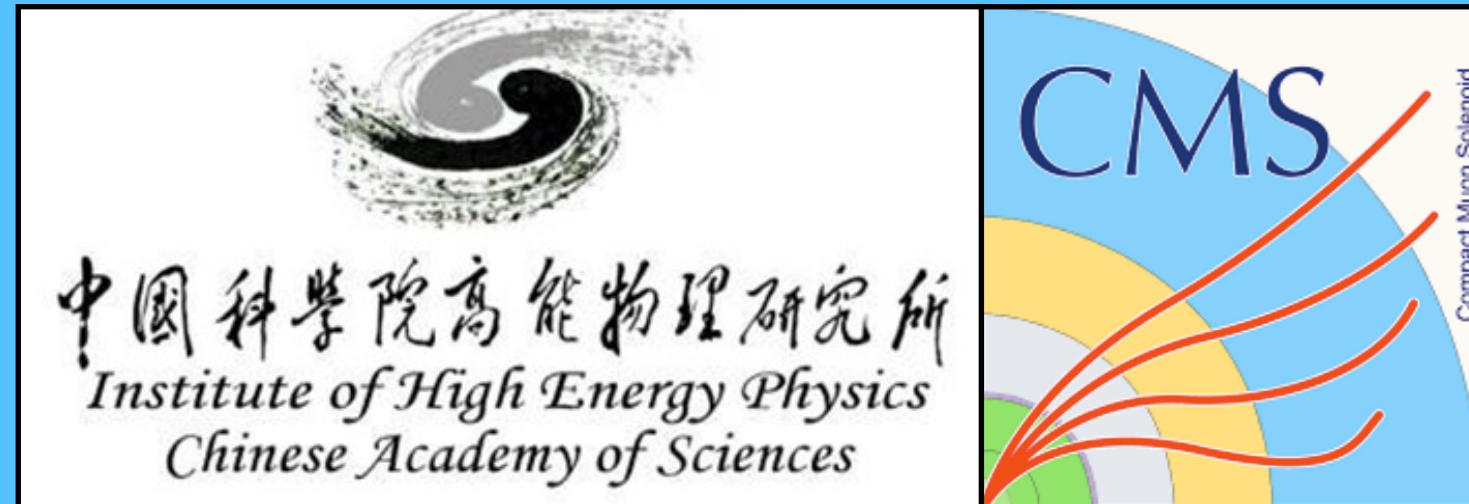


► Results:

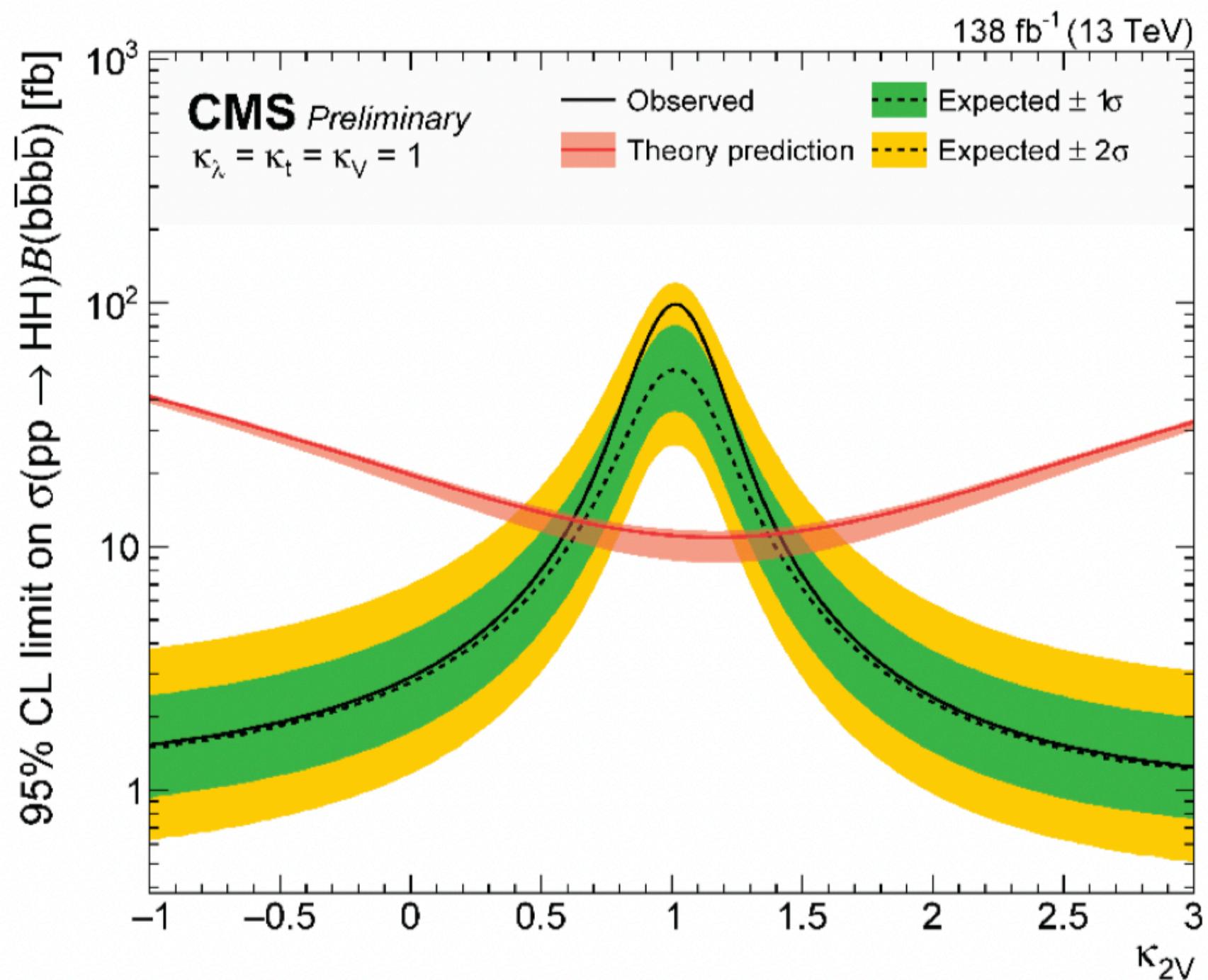
- Observed(expected) Limits:
 - $\sigma_{ggF+VBF}^{HH} < 3.9 (7.8) \times \sigma_{ggF+VBF}^{SM}$
- Observed(expected) k_λ interval:
 - $-2.3 (-5.0) < k_\lambda < 9.4 (12)$
- Observed(expected) $k_{2\nu}$ interval:
 - $-0.1 (-0.4) < k_{2\nu} < 2.2 (2.5)$

[arXiv:2202.09617](https://arxiv.org/abs/2202.09617)

Overview of HH analyses: 4b (boosted)



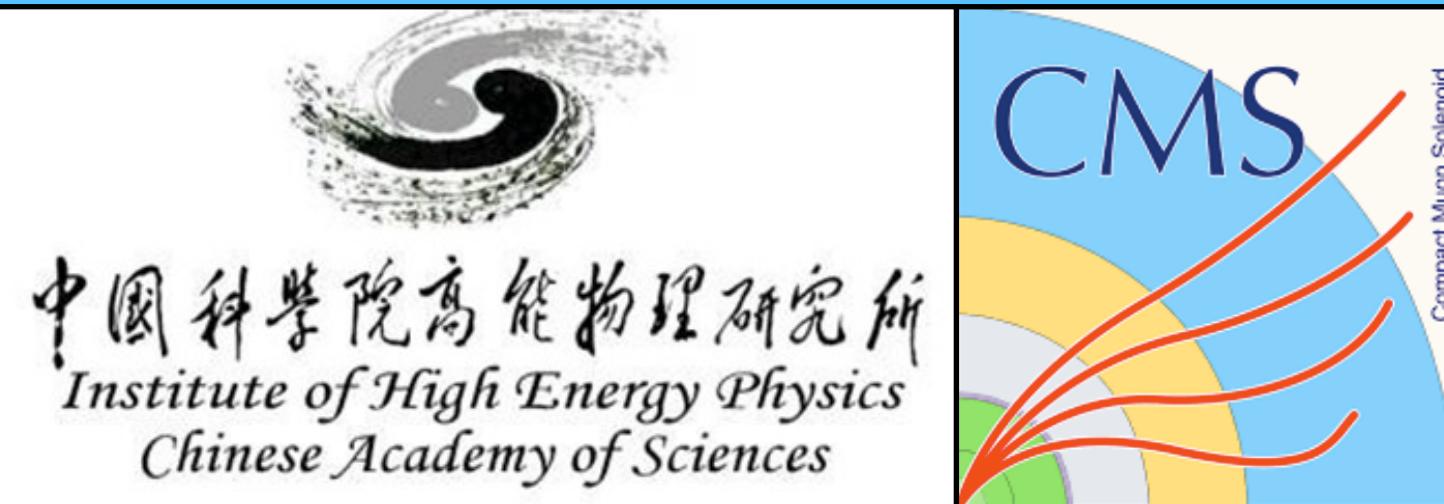
- ▶ Final state with two AK8 jets (+extra jet pair in VBF HH)
 - Main backgrounds coming from tt and QCD, used BDT to separation/categorisation



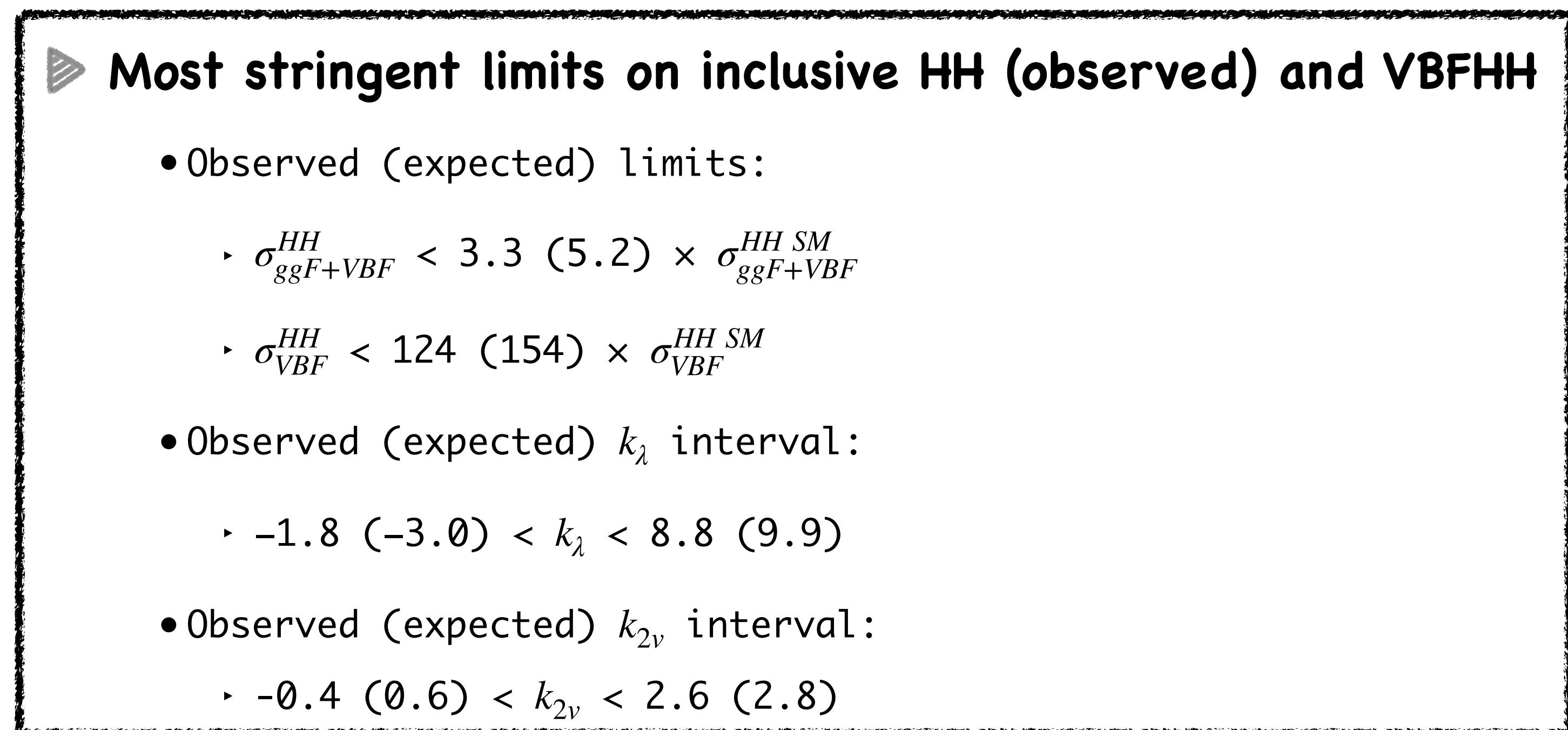
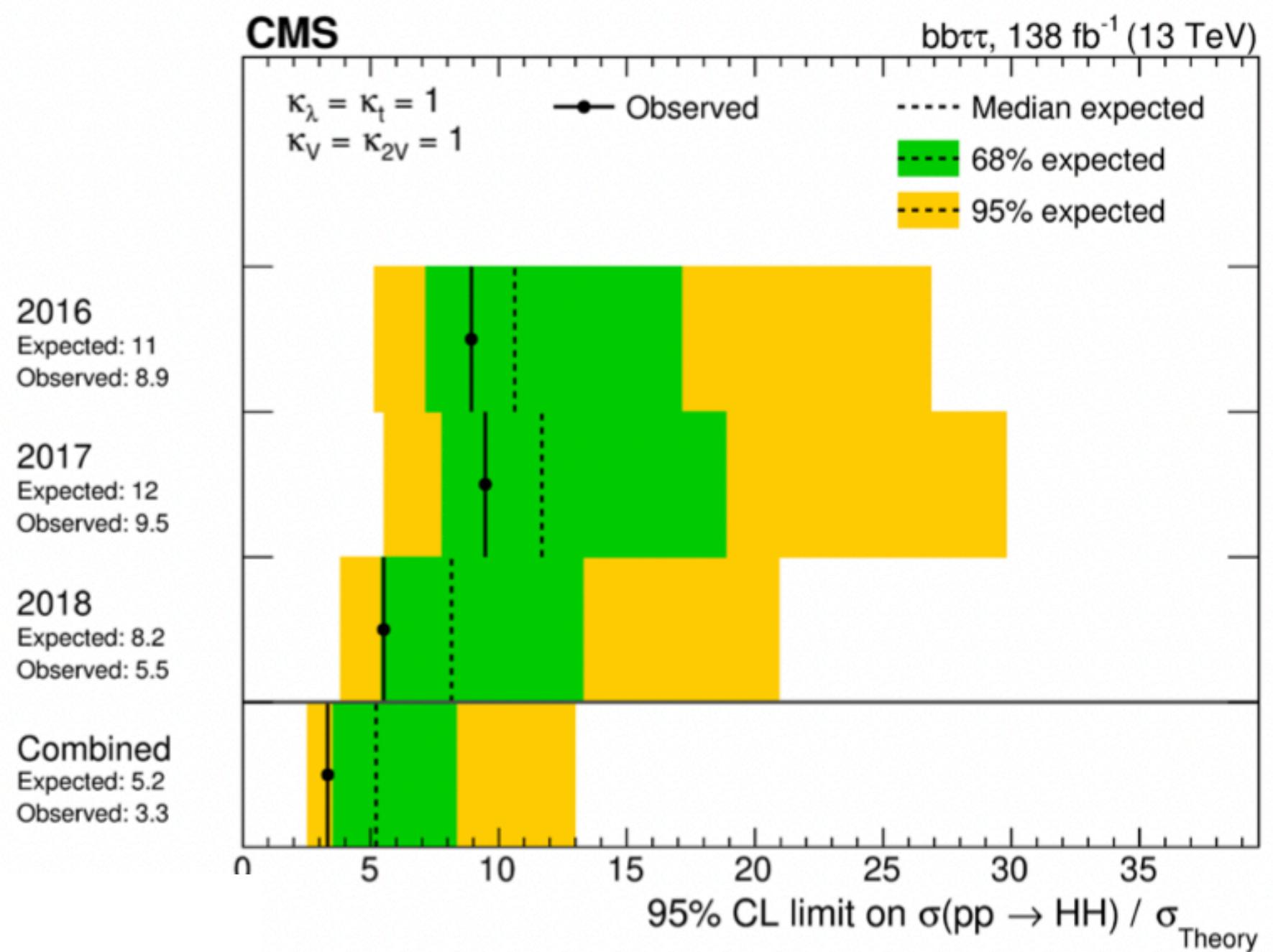
- ▶ Very good constraints on HH signal strength and $k\lambda$
 - Observed (expected) limits:
 - $\sigma_{ggF+VBF}^{HH} < 9.9 \text{ (5.1)} \times \sigma_{ggF+VBF}^{HH SM}$
 - Observed(expected) k_λ interval:
 - $-9.9 \text{ (-5.1)} < k_\lambda < 16.9 \text{ (12.2)}$
 - Observed(expected) $k_{2\nu}$ interval:
 - $0.62 \text{ (0.66)} < k_{2\nu} < 1.41 \text{ (1.37)}$

[arXiv:2205.06667](https://arxiv.org/abs/2205.06667)

Overview of HH analyses: $bb\tau\tau$

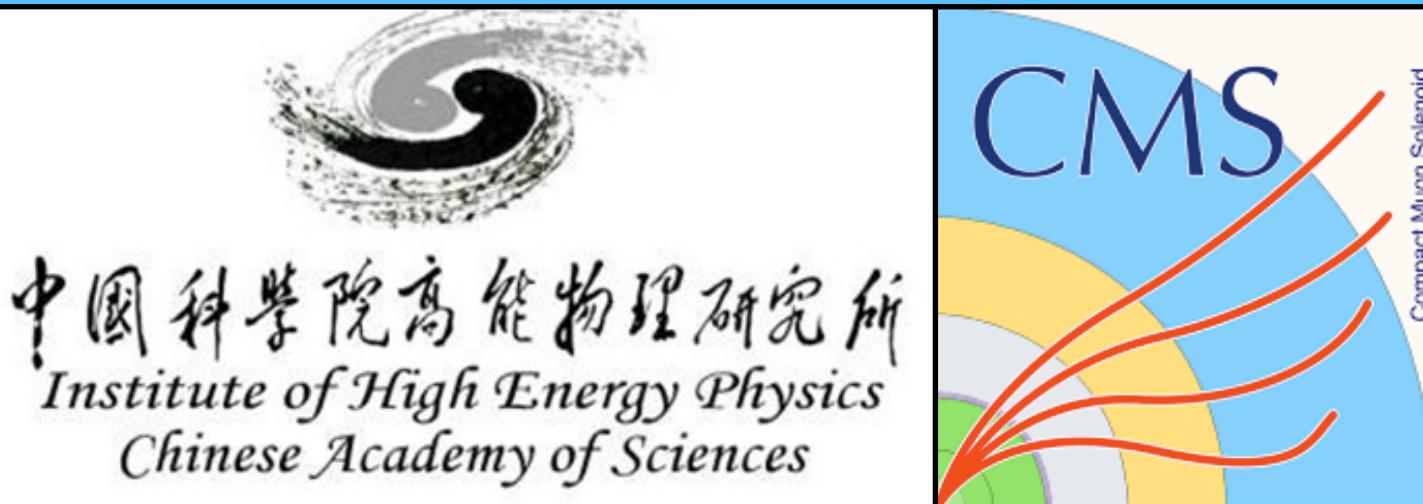


- ▶ Leading background from QCD, $t\bar{t}$ bar and DY events, DNN classifier used to separate background and signal



[arXiv:2206.09401](https://arxiv.org/abs/2206.09401)

Overview of all channels

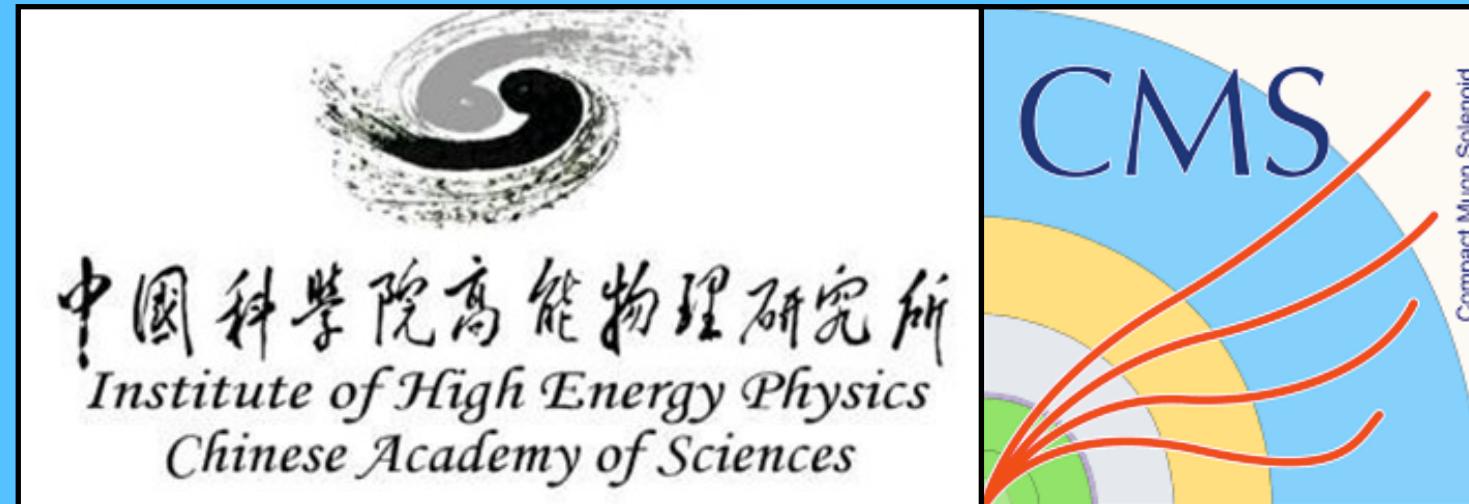


- ▶ Overview of all analyses which been included in latest HH combination
- ▶ Best sensitivity achieved by combine all channels

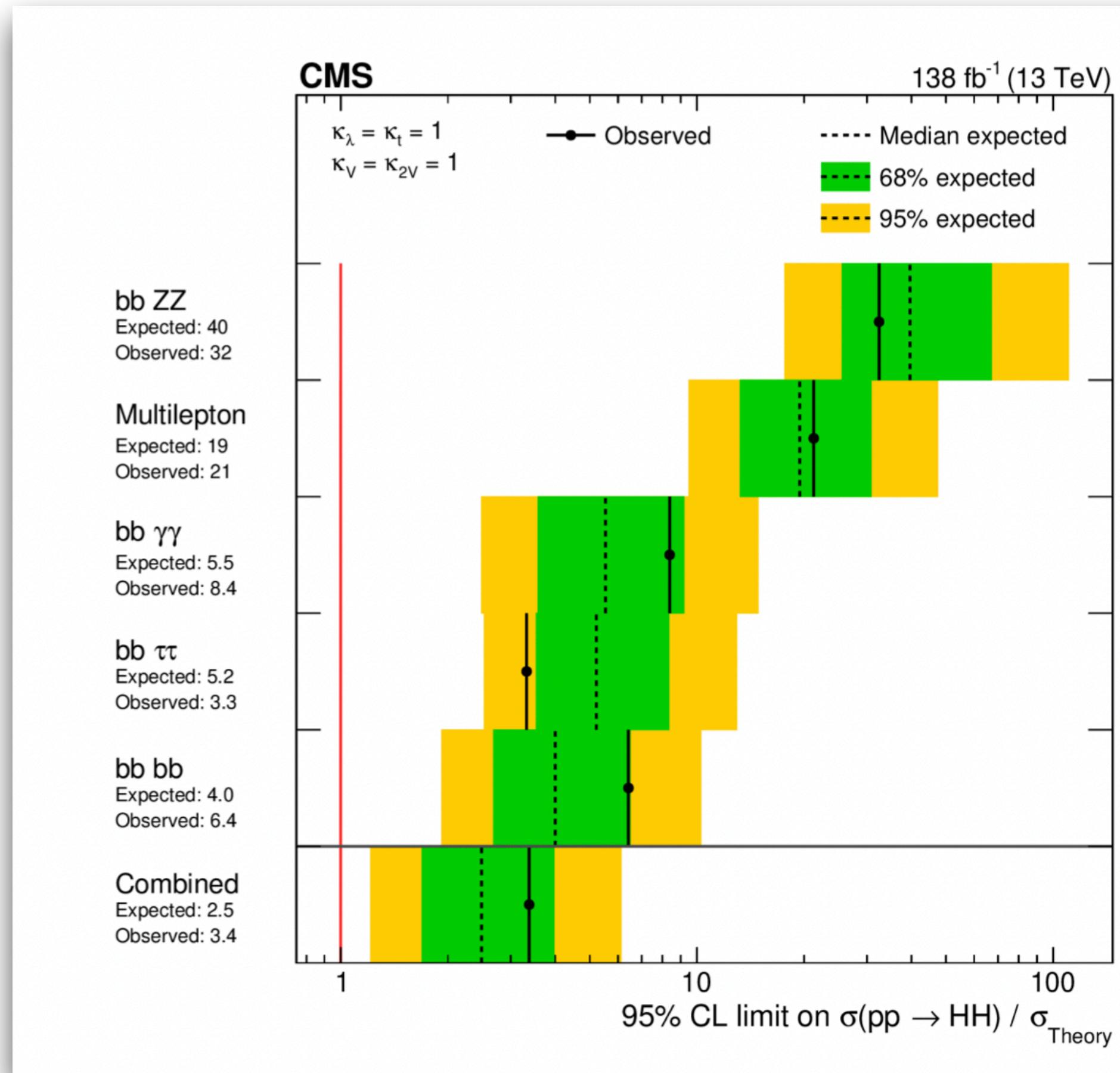
| Analysis | Description | Result (Limit) |
|---|---|----------------|
| bbZZ4l | <ul style="list-style-type: none">• BKG modelling mostly based on Monte Carlo• A few BKG components data-driven (e.g. fake leptons and DY)• Signal extraction made from an MVA | 32(40) XSM |
| bbττ | <ul style="list-style-type: none">• For bbττ a multi-classification DNN is used to better constrain the several BKG normalizations and separate the GGF and VBF components of the signal | 3.3(5.2) XSM |
| Multi-lepton (4V, 2V2τ, 4τ) | <ul style="list-style-type: none">• BKG is data-driven (apart from single H processes)• Several sub-categories are made to separate BKG and the GGF and VBF components of the signal• bbγγ: Signal is extracted from looking for a 125 GeV bump simultaneously in the reconstructed bb and γγ mass spectra• 4b: Depending on the category signal is extracted from an MVA output or from the HH mass spectra | 21(19) XSM |
| bbγγ | <ul style="list-style-type: none">• Data-driven BKG modelling of QCD and ttbar• Minor BKG components are taken from MC• Signal extraction made from the HH mass spectra / AK8 jet 2 mass | 8.4(5.5) XSM |
| 4b (resolved topology) | | 6.4(4.0) XSM |
| 4b (boosted topology, targeting VBF production) | | |
| 4b (boosted topology, targeting GGF production) | | |

Future combination will include WWgg and bbWW and other channels + more interpolation results

HH combination

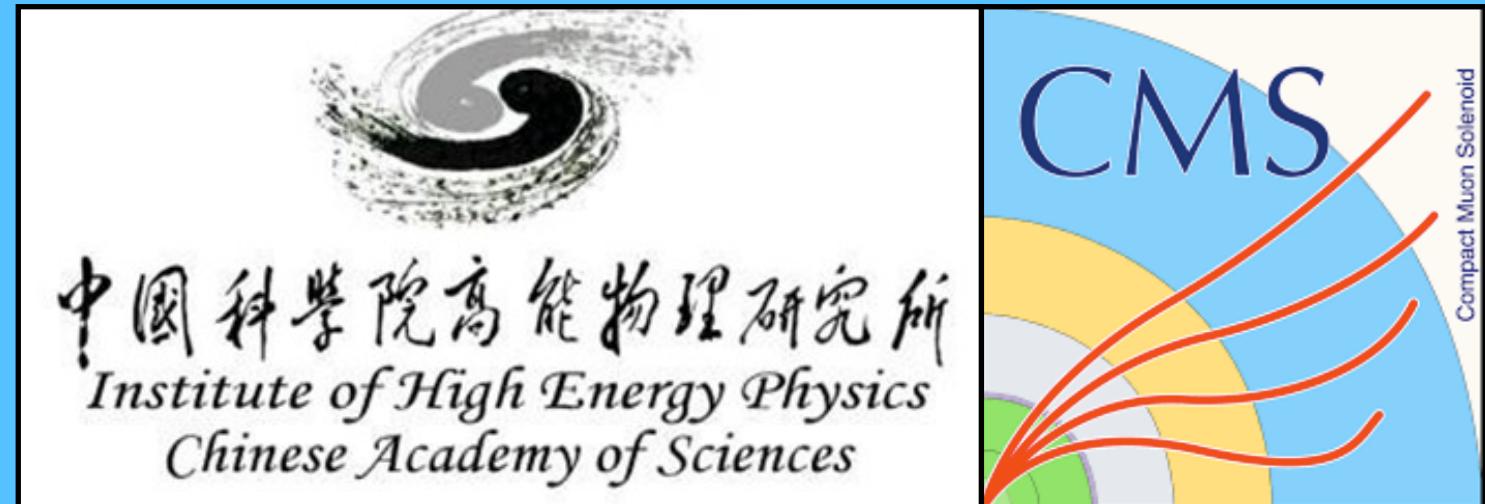


► Limits on the HH production



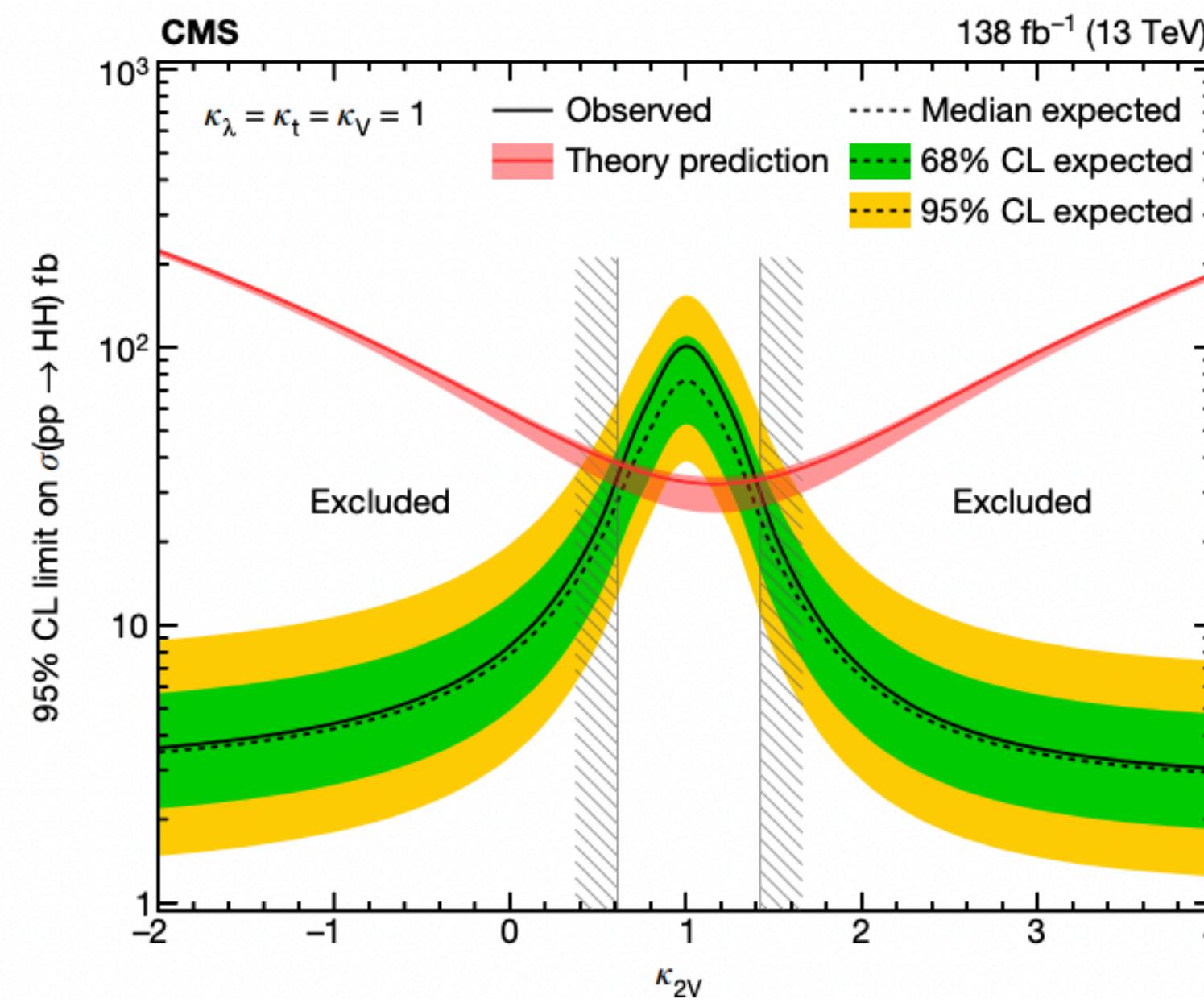
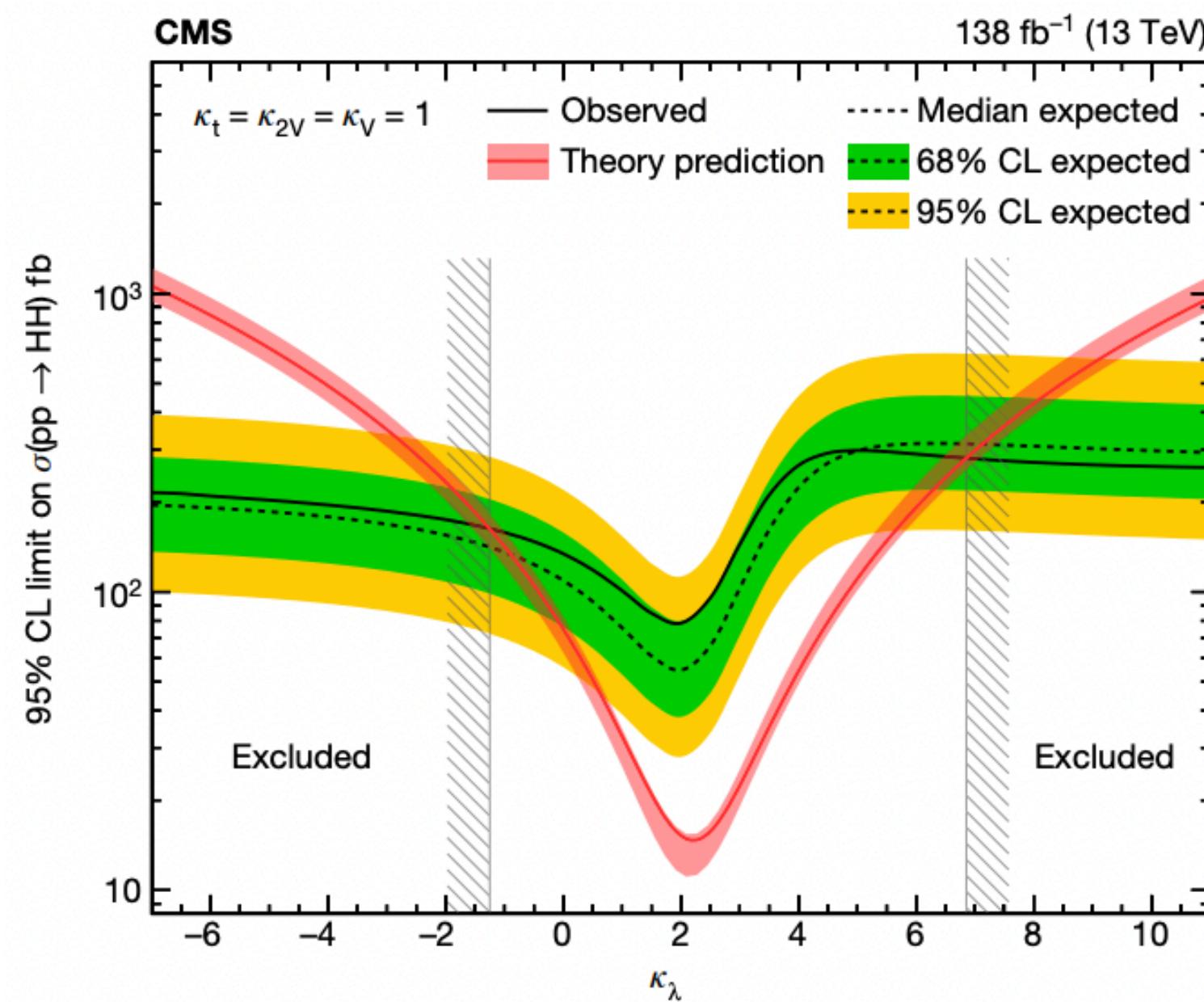
- The Full-Run2 combined 95% CL HH cross-section:
 - Observed(expected): **3.4 (2.5)X SM**
- Contribution sequence:
 - bb bb (resolved+boosted), bb $\tau\tau$, bb $\gamma\gamma$, multilepton, bbZZ(4l)
- HL-LHC sufficient to establish the existence of the SM HH production

HH combination

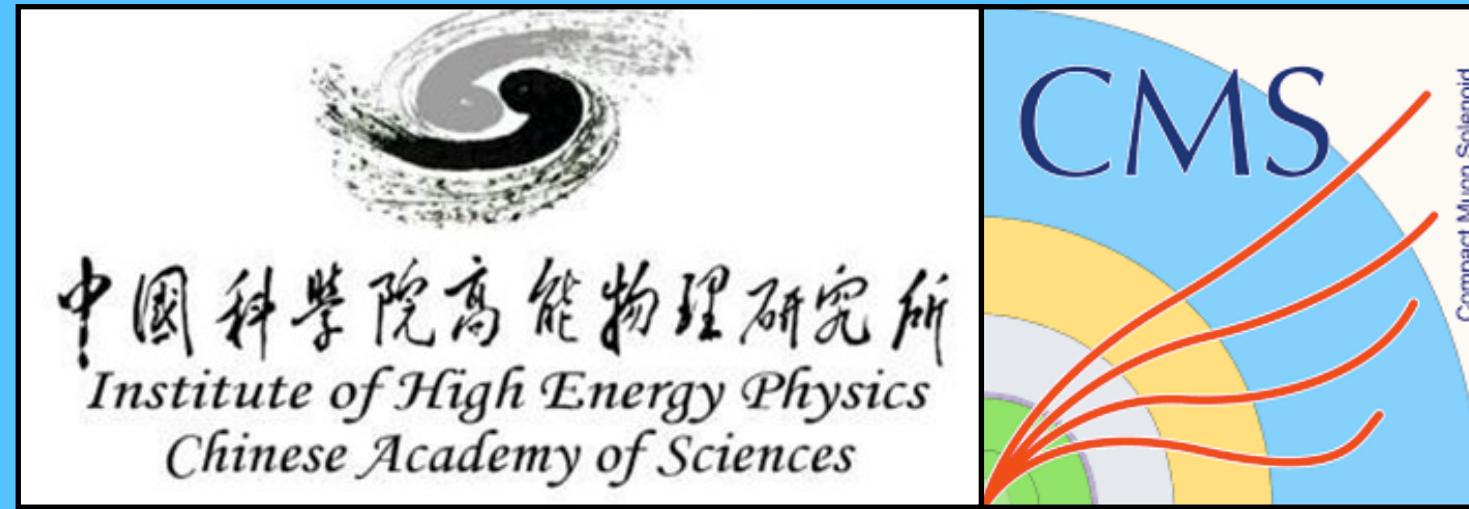


► Parameter scans

- 95% CL interval for Higgs boson self-interaction coupling modifier κ_λ : [-1.24, 6.49]
- 95% CL interval for 2 Higgs boson and 2 vector bosons coupling modifier k_{2V} : [0.67, 1.38]



Summary



- ▶ Introduced some HH analyses in CMS.
- ▶ The results of latest HH combination are shown:
 - SM combination: $3.4 \text{ (2.5)} \times \text{SM}$
 - Parameter scans: $k_\lambda \in [-1.24, 6.49]$, $k_{2\nu} \in [0.67, 1.38]$
- ▶ All results agree with SM prediction
- ▶ Expect more exciting results with more channels in Run2 as well as the H+HH, ATLAS+CMS combination in future.