Latest combined Higgs boson measurements from CMS

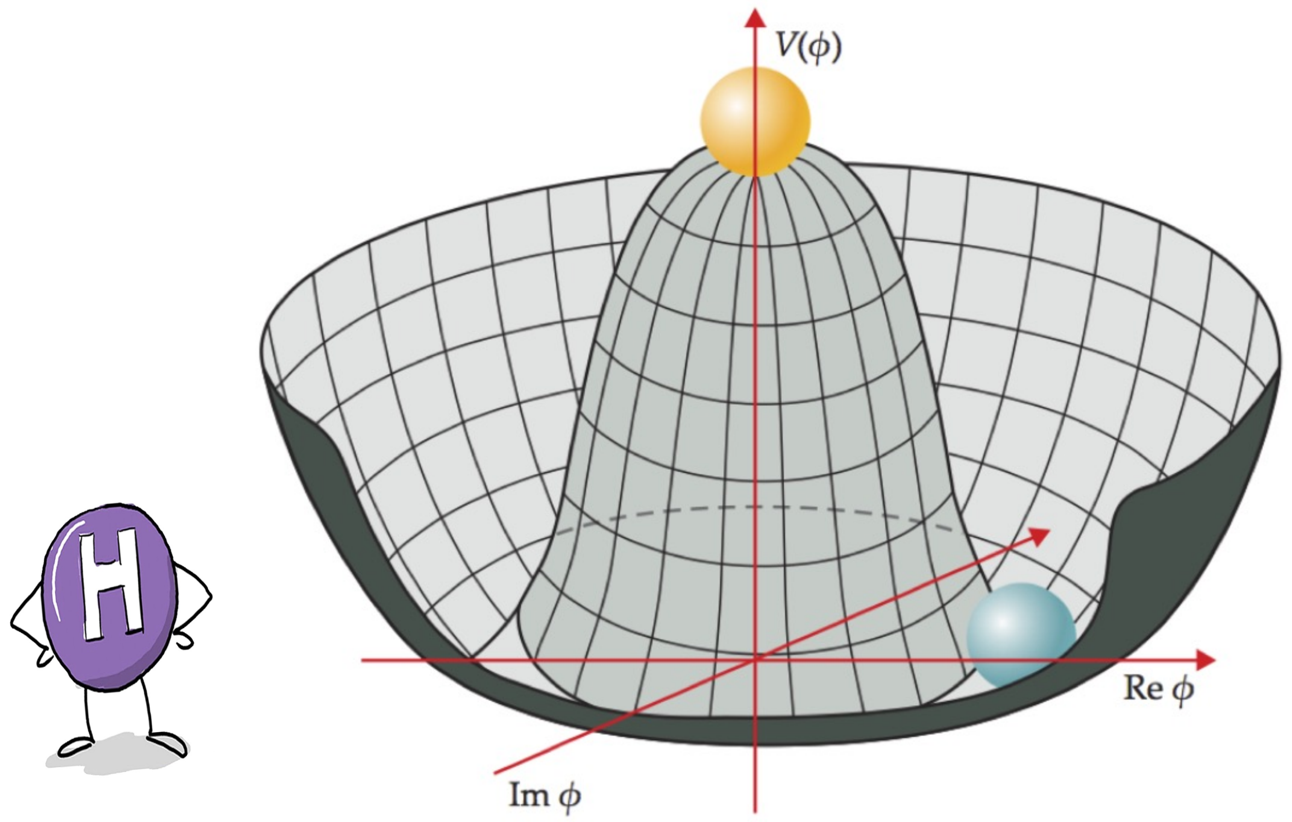
(Higgs boson pair + single Higgs production)

Yihui Lai (University of Maryland)
on behalf of the CMS collaboration

Higgs 2023 conference, IHEP CAS, Beijing
November 27, 2023

Introduction

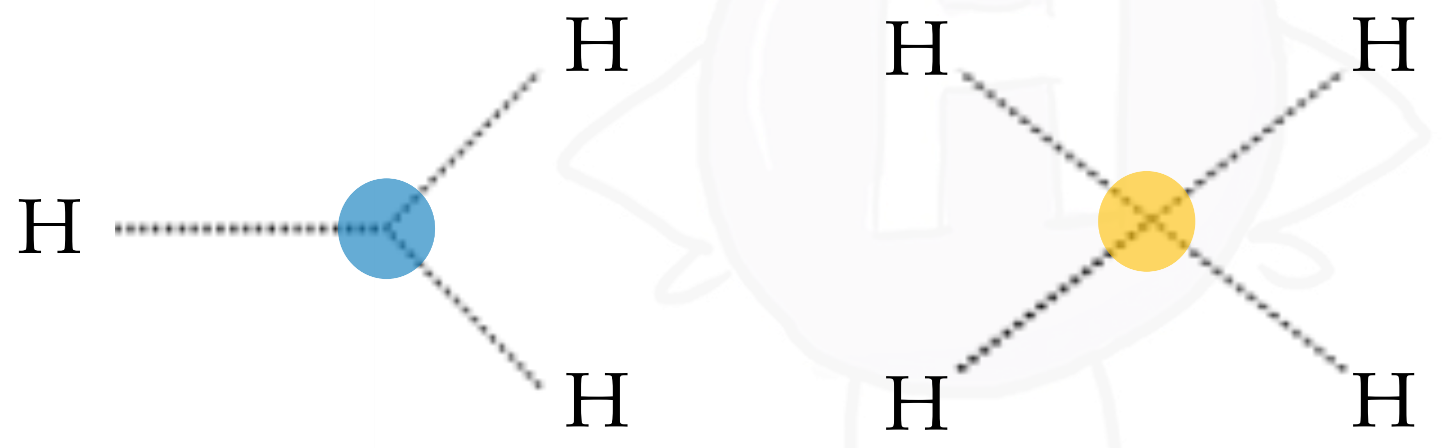
- Higgs boson couplings to fermions and vector bosons compatible with SM
- **Self-coupling (λ)** is a crucial missing element
  - a probe of the **Higgs field potential $V(h)$**
  - a fundamental test of SM
- Significant efforts to better constrain the **trilinear coupling λ_3**
- Deviation of λ_3 from SM is characterized by $\boldsymbol{\kappa_\lambda = \lambda_3/\lambda_{SM}}$



Self-coupling arises from Higgs field potential expansion around its v.e.v.

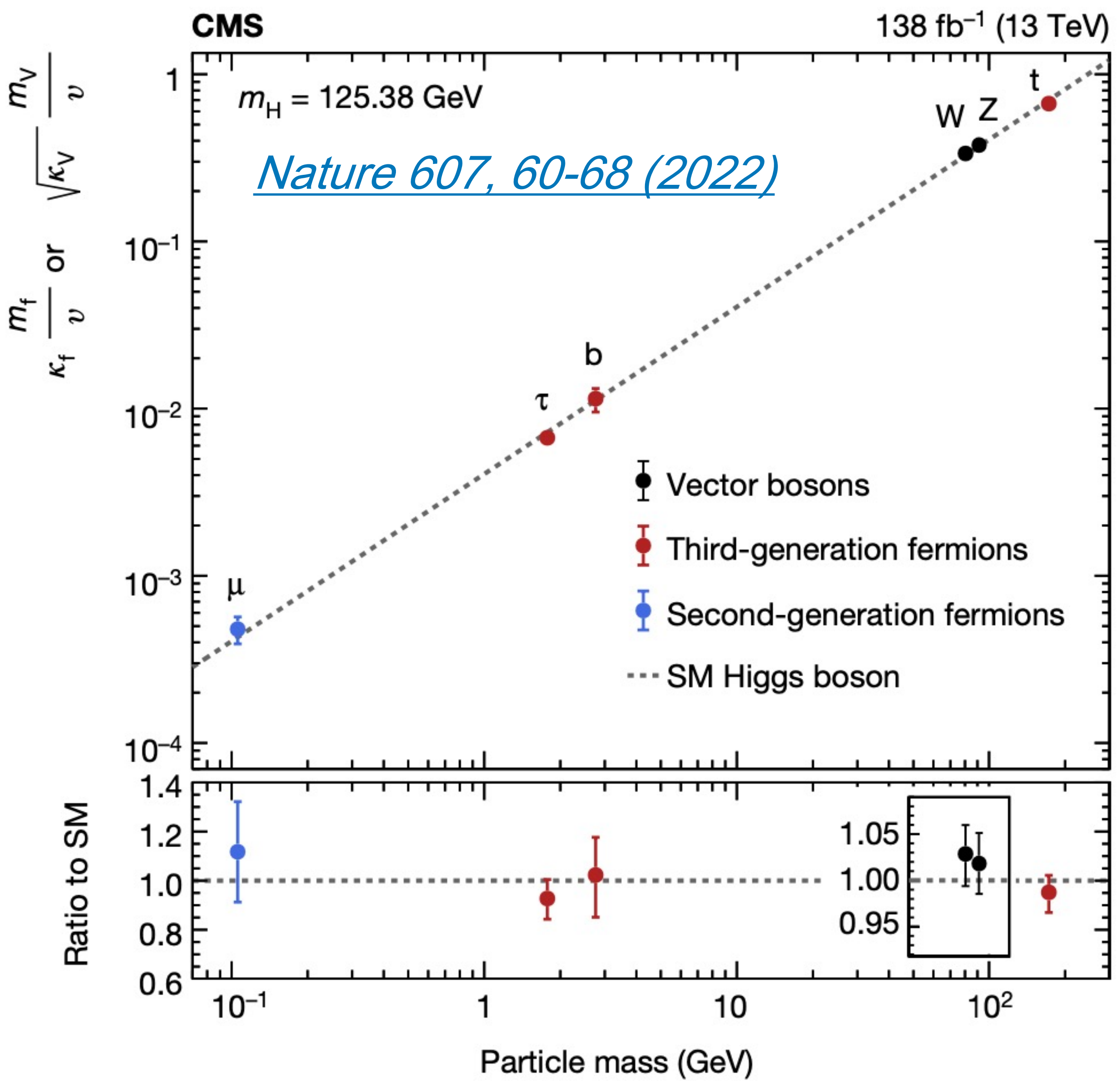
$$V(h) = \frac{1}{2}m_h^2h^2 + \boxed{\lambda_3 v h^3} + \boxed{\frac{1}{4}\lambda_4 h^4} + \ldots$$

We focus on the trilinear coupling !



Higgs trilinear coupling in SM: $\lambda_{SM} = m_h^2/2v^2$

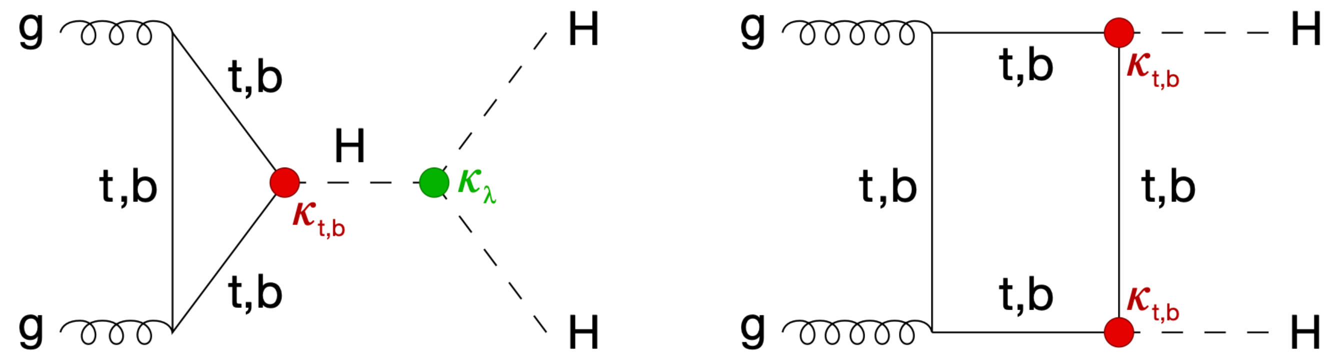
with v = Higgs boson v.e.v.



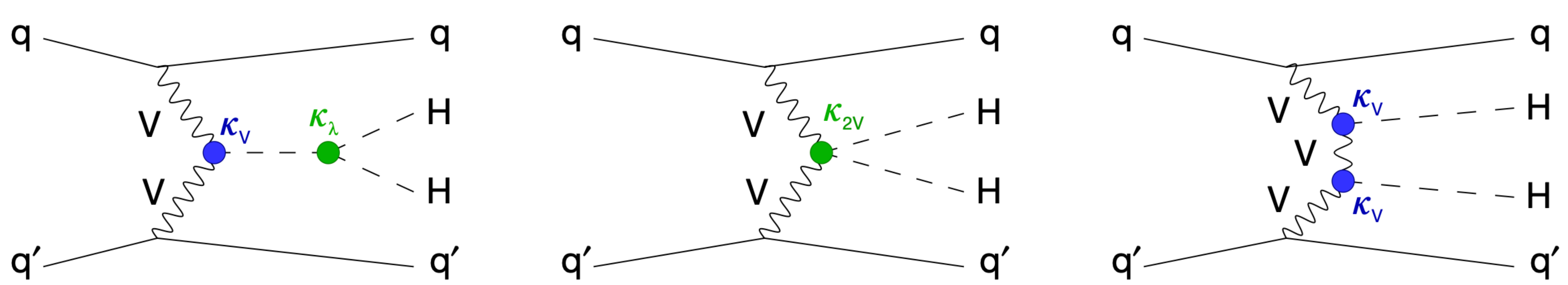
How to probe the Higgs boson self-coupling (λ)?

- HH: λ_3 can be directly accessed through the production of Higgs boson pair (HH)
- Single-H: Additional contributions also come from single Higgs (H) production via NLO EW corrections

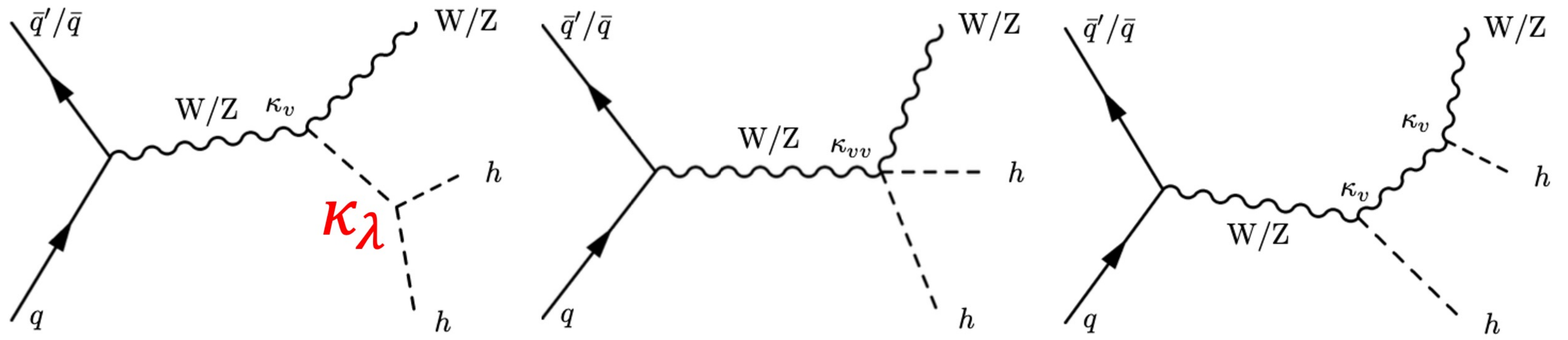
ggF production (ggHH) diagrams at LO 31 fb @13TeV @ NNLO

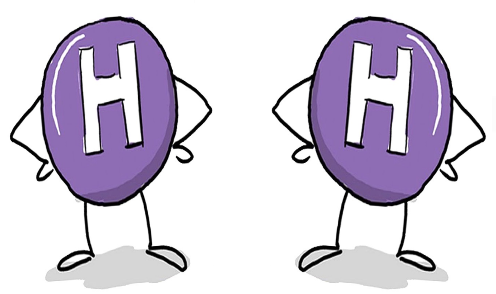


VBF production (qqHH) diagrams at LO 1.72 fb @13TeV @ N3LO



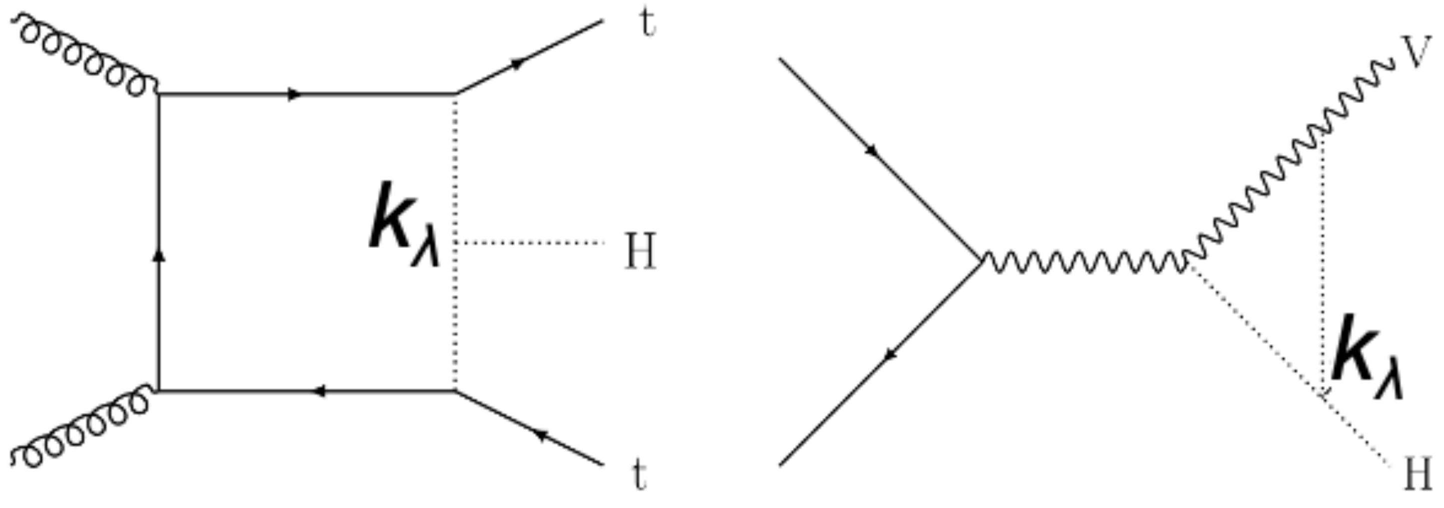
VHH production diagrams at LO 0.86 fb @13TeV @ NNLO

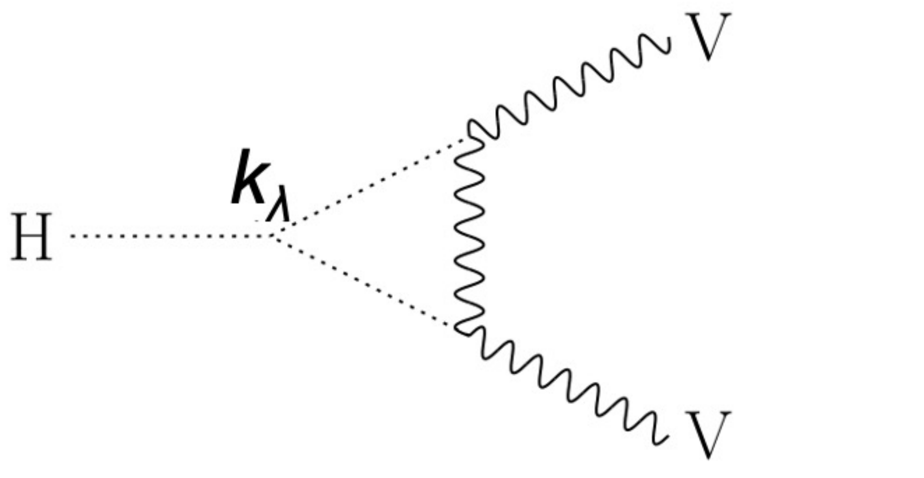


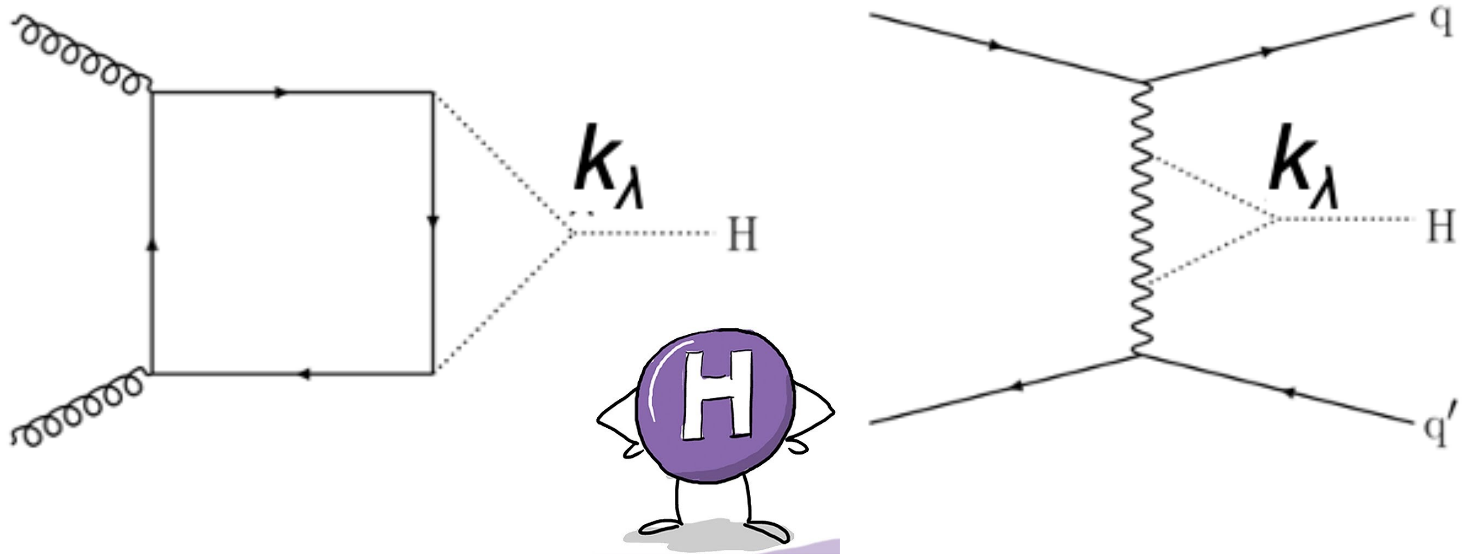


Examples of κ_λ-dependent diagrams for single-H prod. mechanisms O(κ_λ)

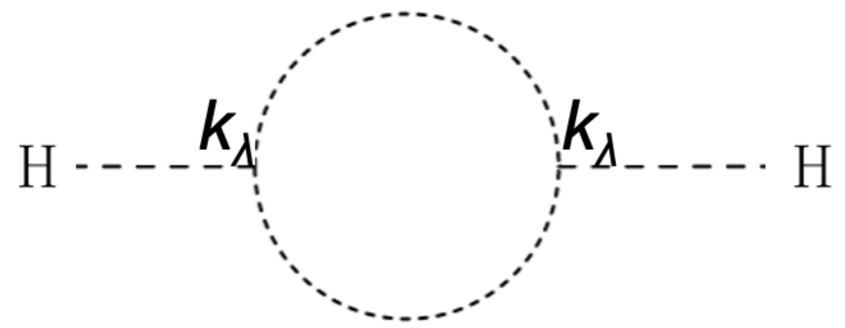
Example of κ_λ-dependent diagrams for Higgs decay O(κ_λ)







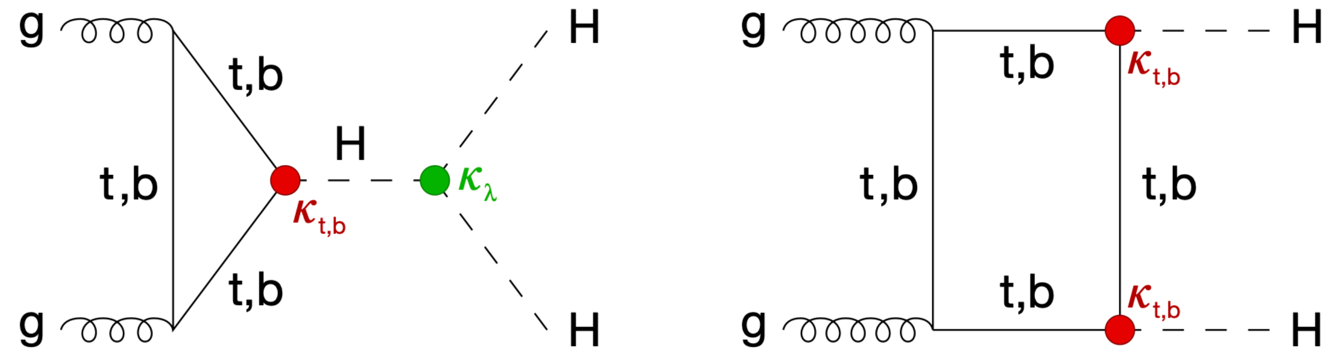
Higgs boson self-energy O(κ_λ^2)



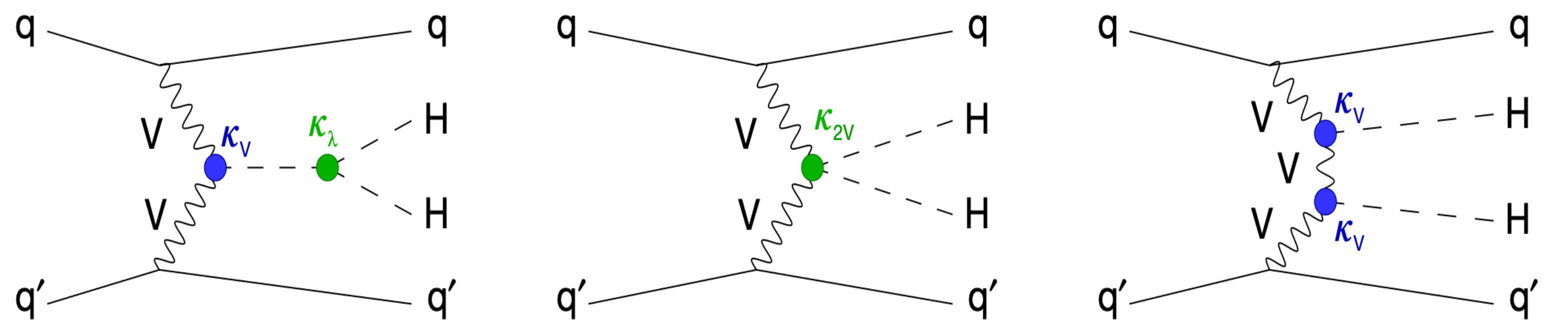
Trilinear self-coupling in Higgs boson pair (HH) production

- The SM HH production is **extremely rare**, with only ~4000 events expected at Run 2
- Modification of Higgs coupling affect both total and differential cross section (XS)
  - Total XS changes significantly with non-SM κ_λ
  - The m_{HH} spectrum also depends on κ_λ

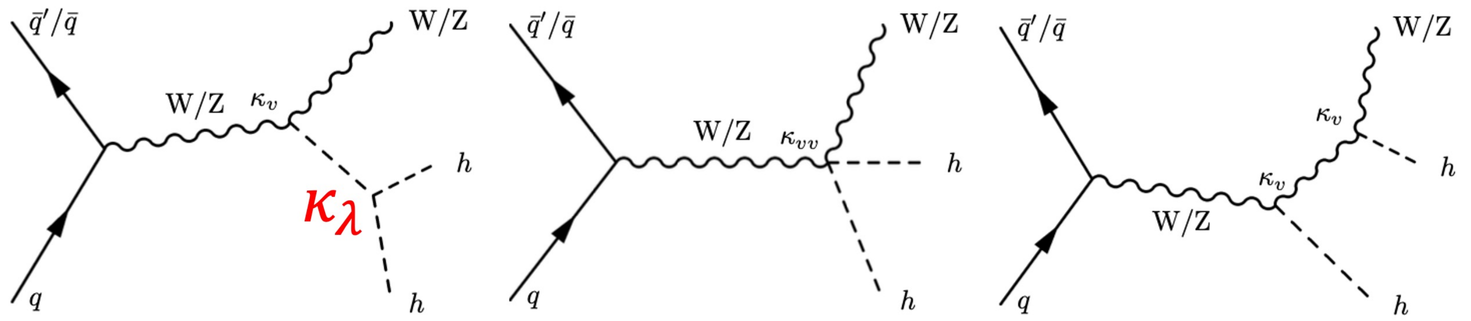
ggF production (ggHH) diagrams at LO

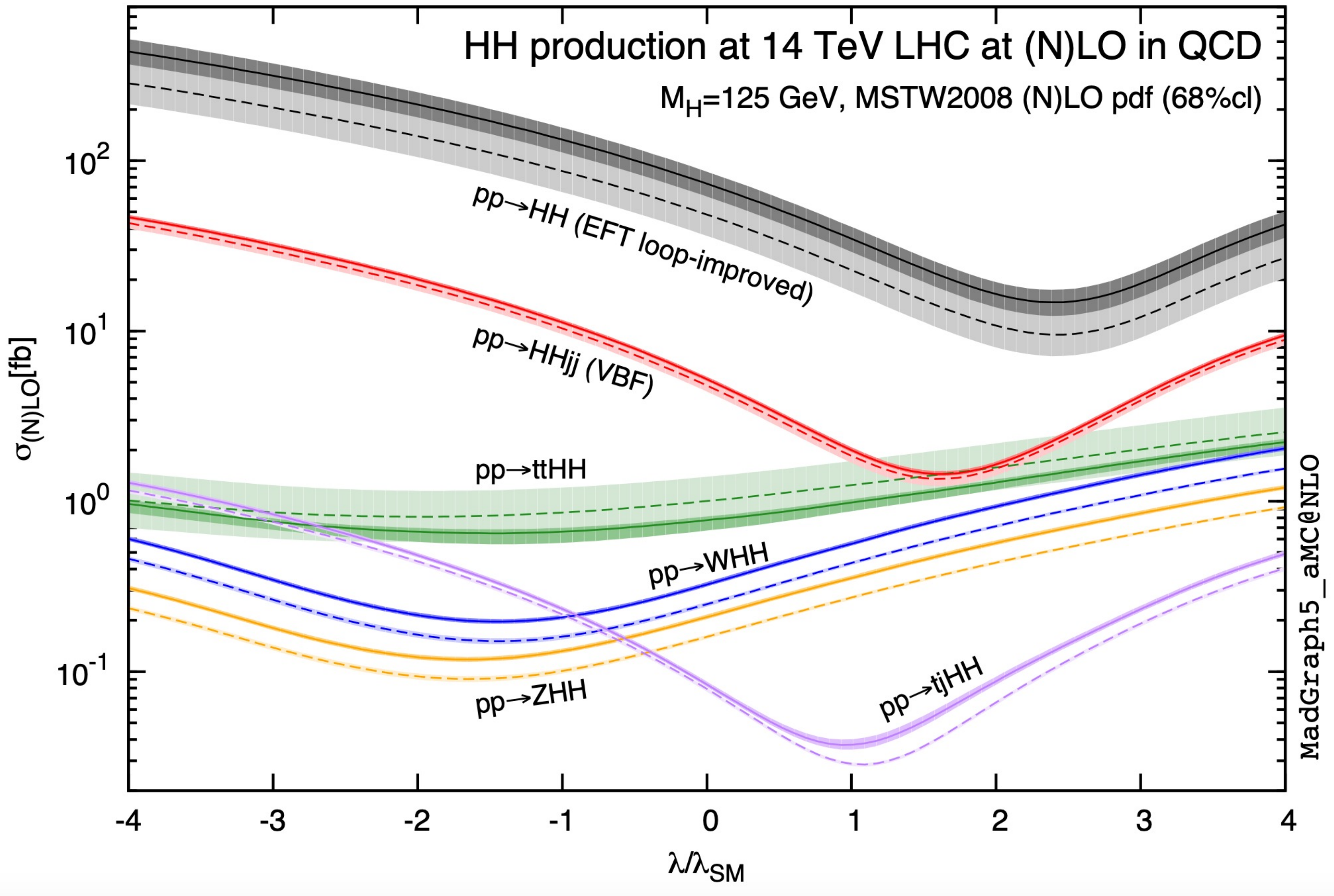


VBF production (qqHH) diagrams at LO



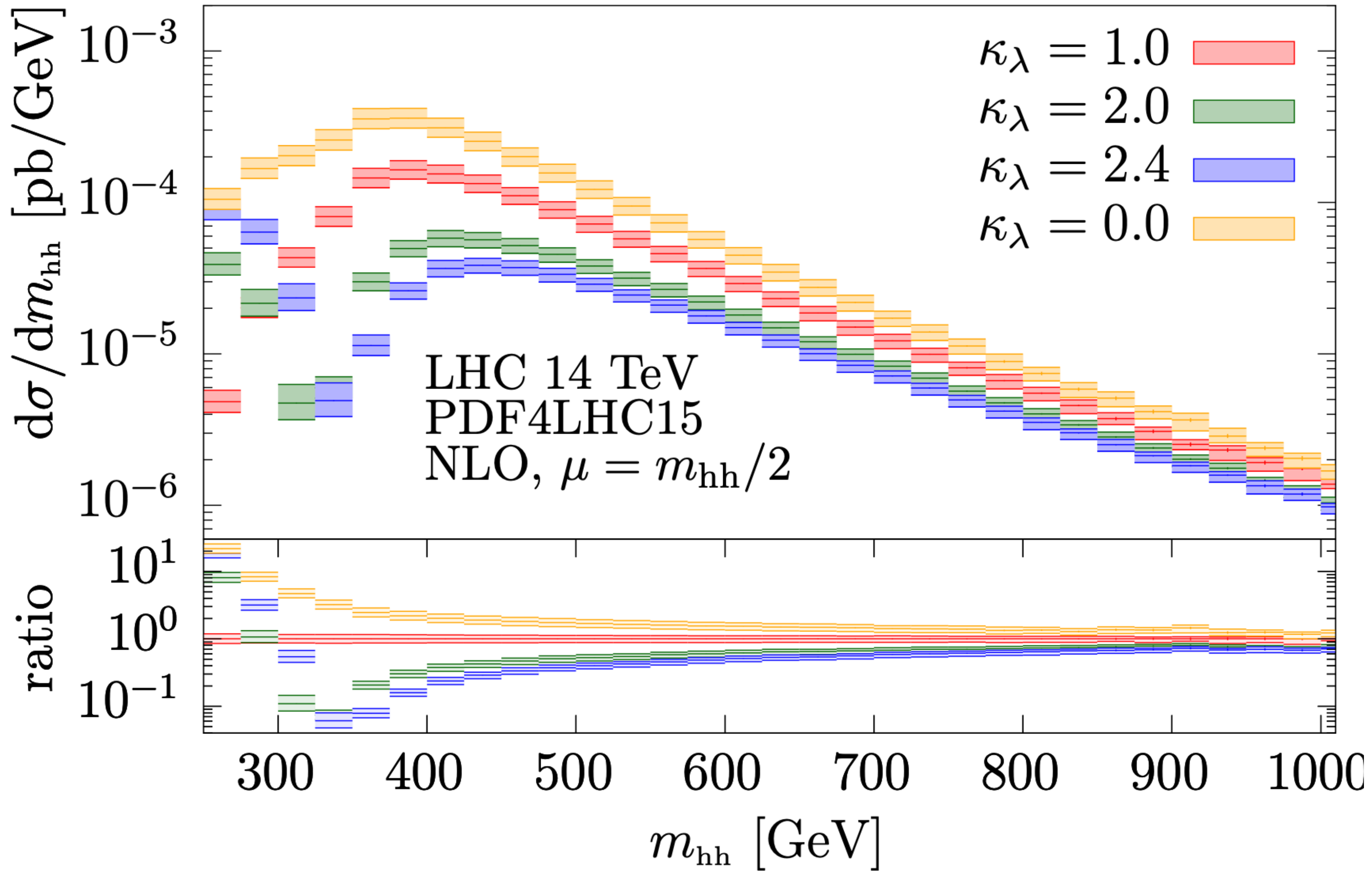
VHH production diagrams at LO





[Phys.Lett. B732 (2014) 142-149](https://)

Differential ggHH XS in m_{HH} for several values of κ_λ

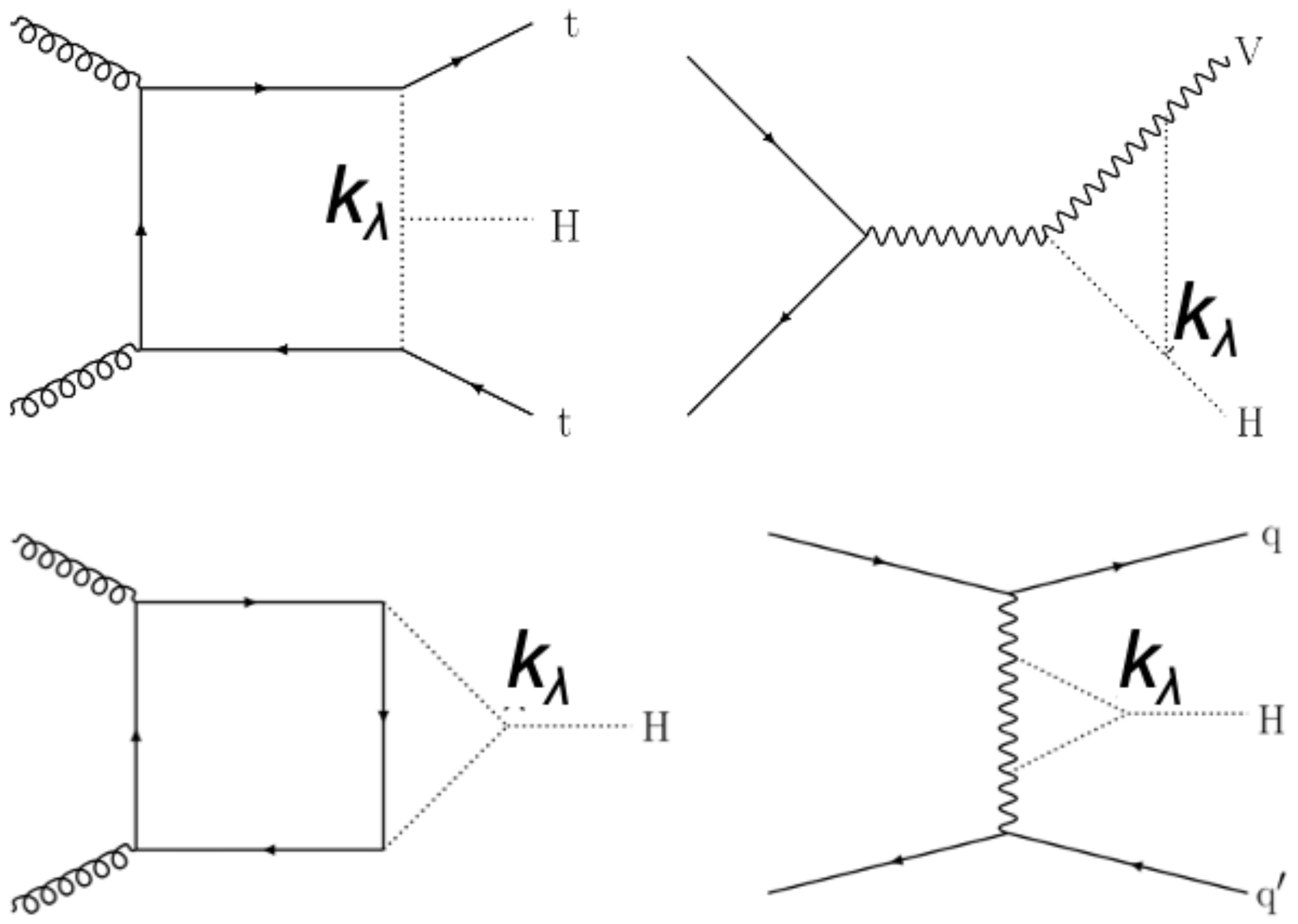


J. High Energ. Phys. (2019) 66

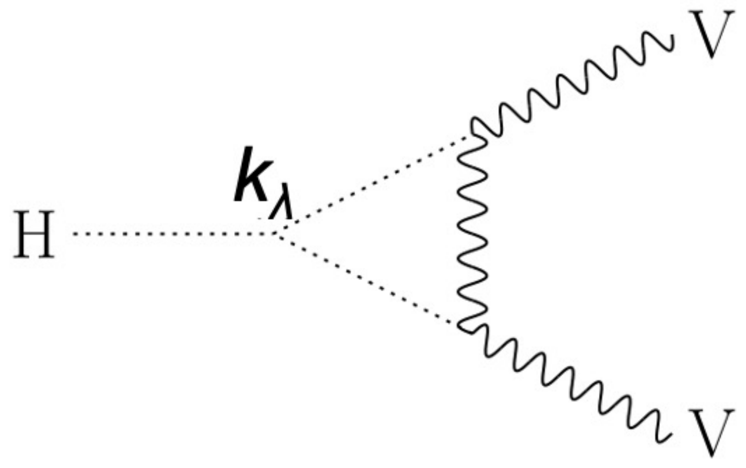
Trilinear self-coupling in single Higgs (H) production

- At NLO EW correction, the single-H production includes processes sensitive to κ_λ
- Both Higgs production and decay are dependent on κ_λ

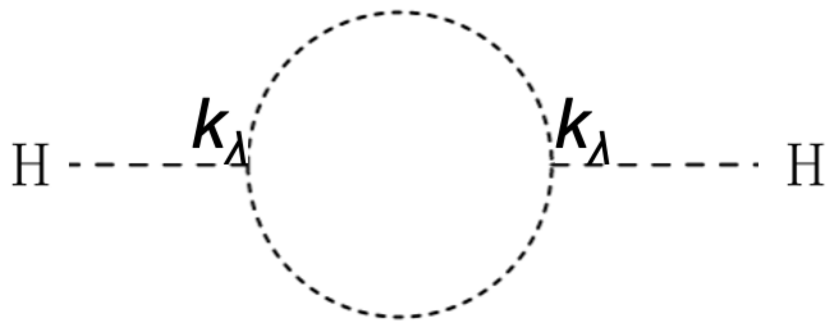
Examples of κ_λ-dependent diagrams for single-H prod. mechanisms $O(\kappa_\lambda)$



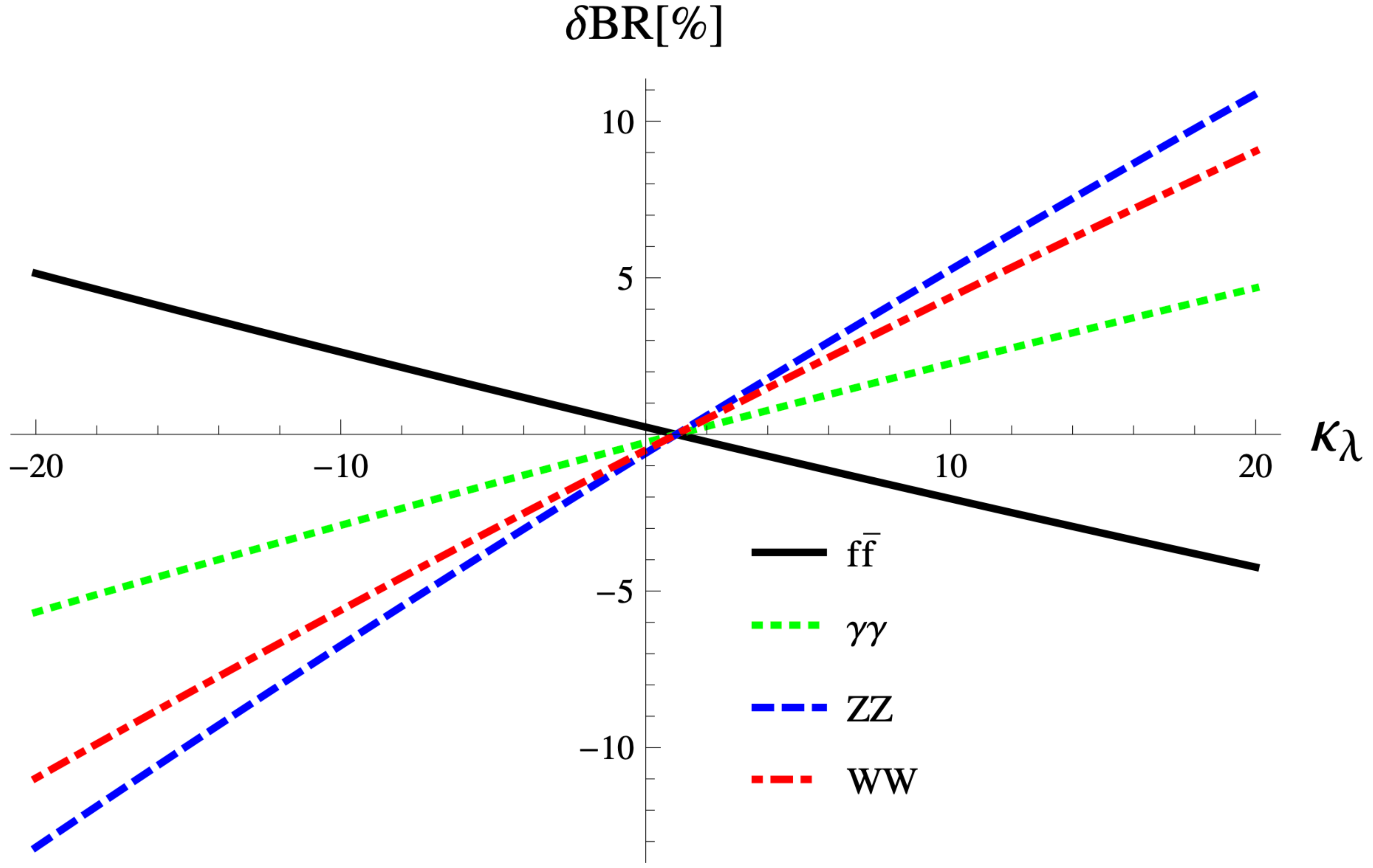
Example of κ_λ-dependent diagrams for Higgs decay $O(\kappa_\lambda)$



Higgs boson self-energy $O(\kappa_\lambda^2)$



Modification of Higgs BR vs κ_λ

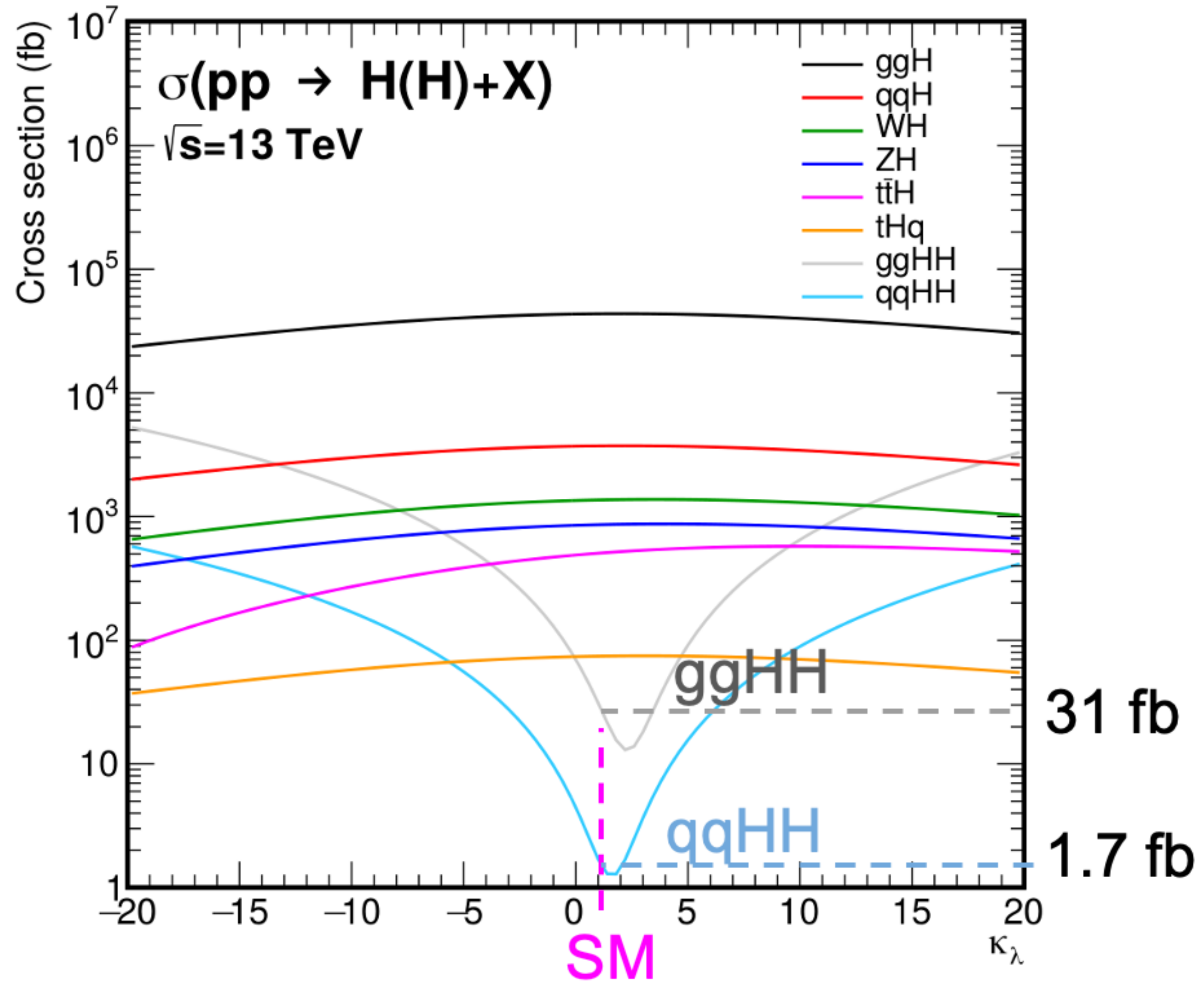


[J. High Energ. Phys. 12(2016)080]

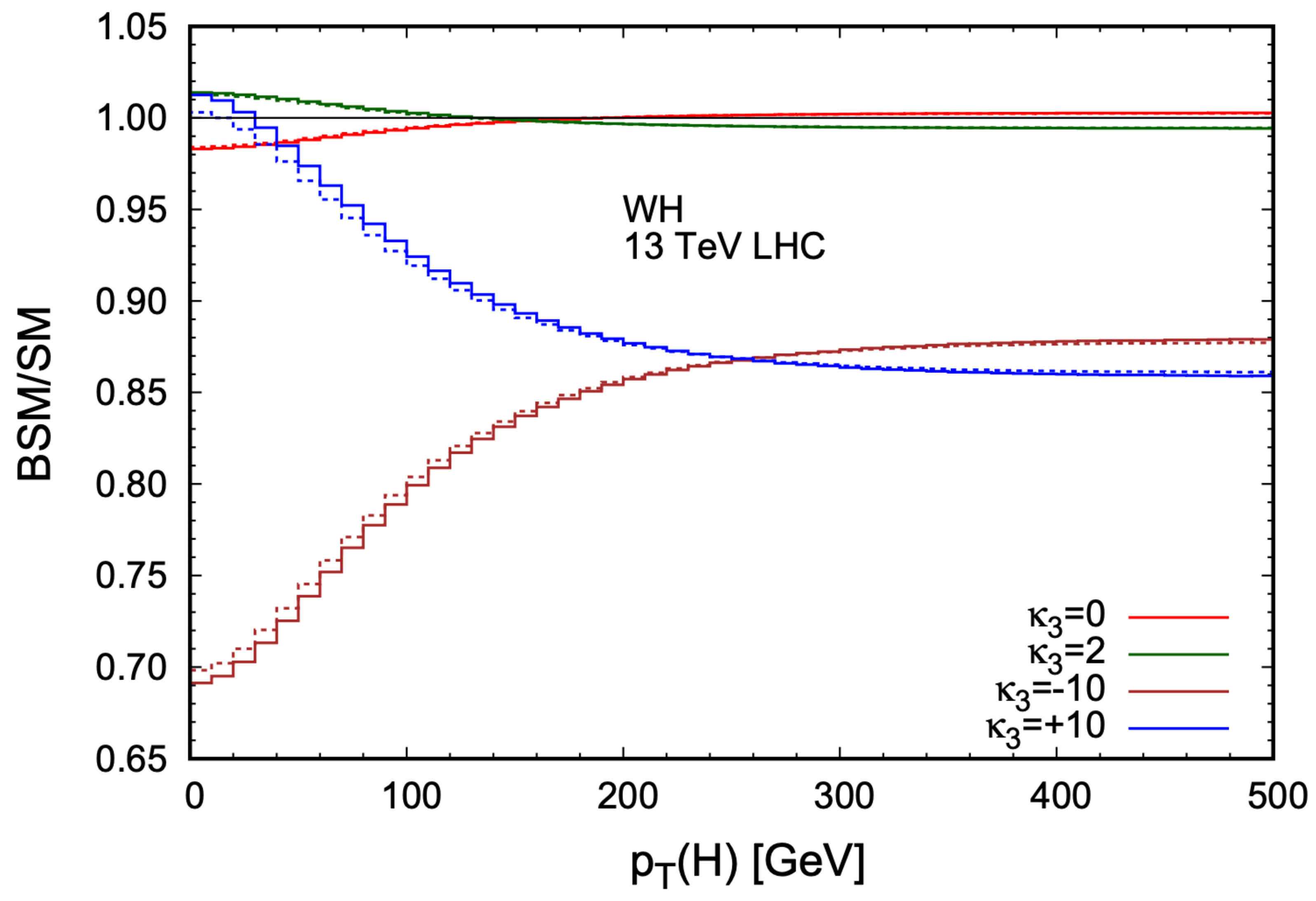
Trilinear self-coupling in single Higgs (H) production

- Additional sensitivity from kinematic dependence on κ_λ, VH and $t\bar{t}H$ have the largest effect!
- For analyses with Simplified Template Cross Section (STXS) binning , the dependency on κ_λ is taken differentially

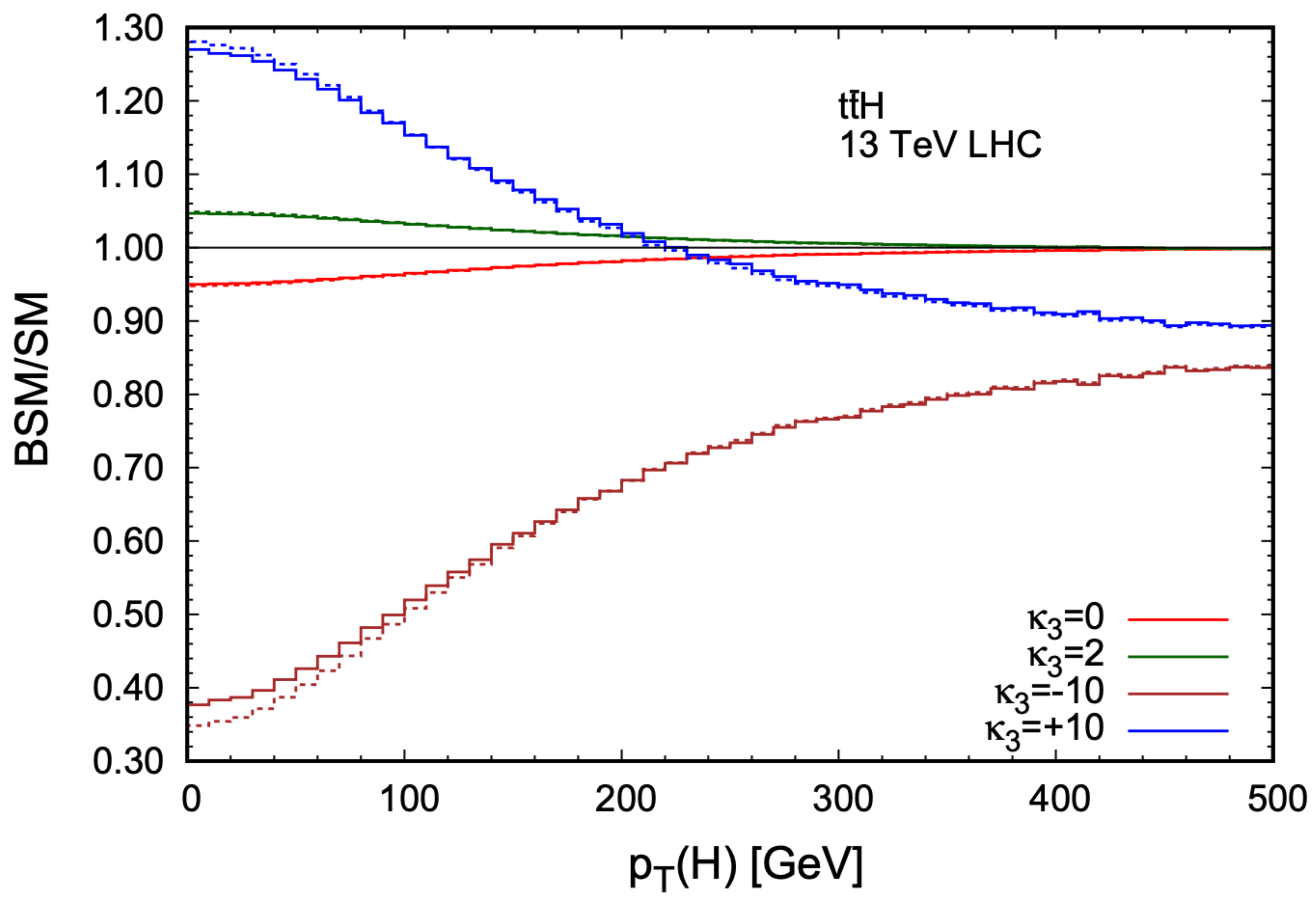
Modification of total XS vs κ_λ



Modification of differential XS for WH



Modification of differential XS for $t\bar{t}H$



Phys. Rev. D 98, 114016 (2018)
arXiv:2003.01700

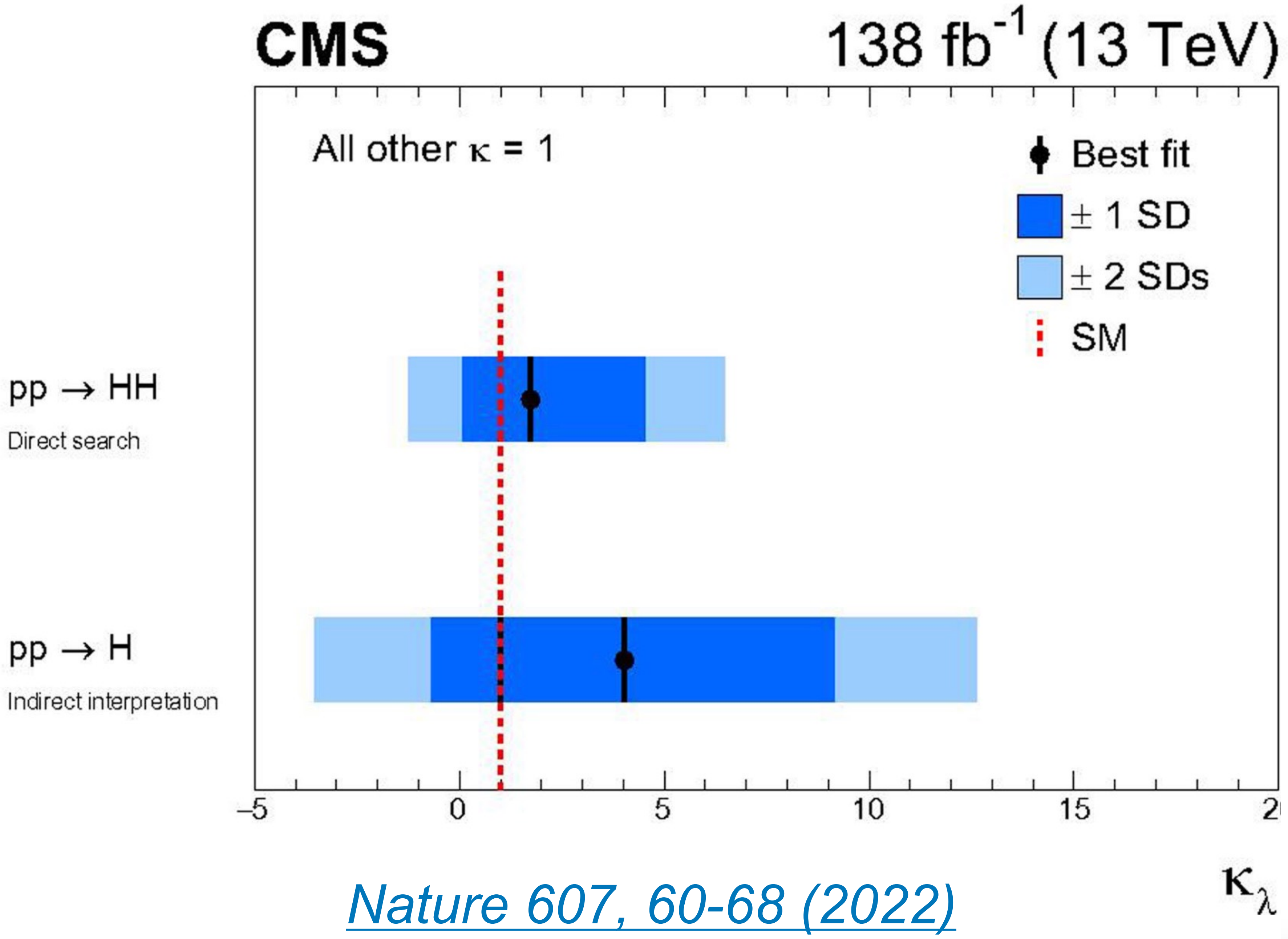
Eur. Phys. J. C (2017) 77: 887
LHCHWG-2022-002

Why HH+H combination ?

- Ultimate precision on κ_λ with the Run 2 data
- Simultaneous fit of κ_λ and Higgs couplings to fermions and vector bosons
  - $\kappa_{2V} = 0$ excluded at 6.6 s.d. in the HH combination (Nature 607, 60-68 (2022)) with the assumption that other couplings are SM value → this HH+H combination allows more general statements!
  - BSM phenomena affecting κ_λ should reasonably introduce deviations in other H couplings

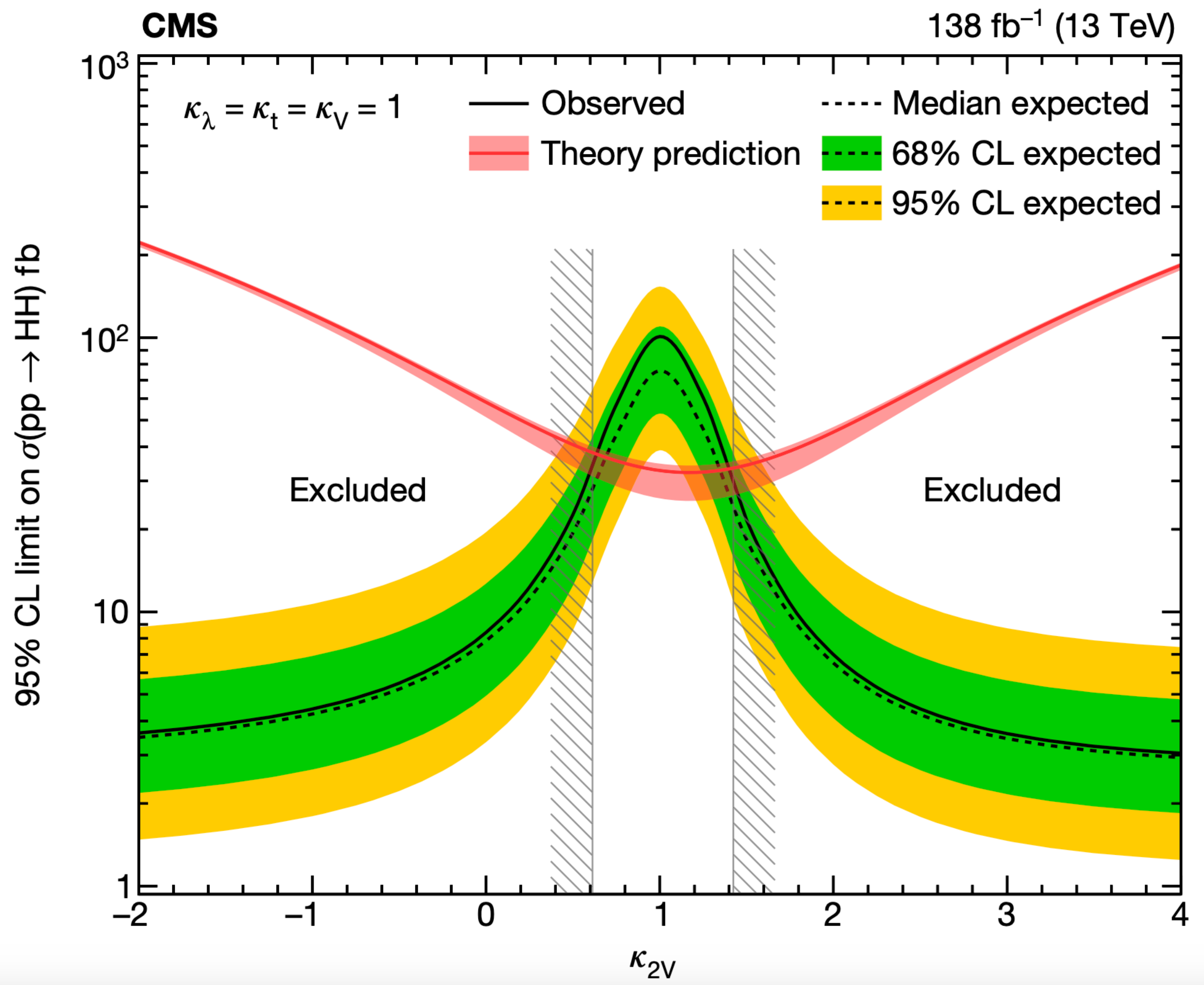
To combine HH and single-H :

- Overlaps removed
- Uncertainties across channels are correlated when relevant



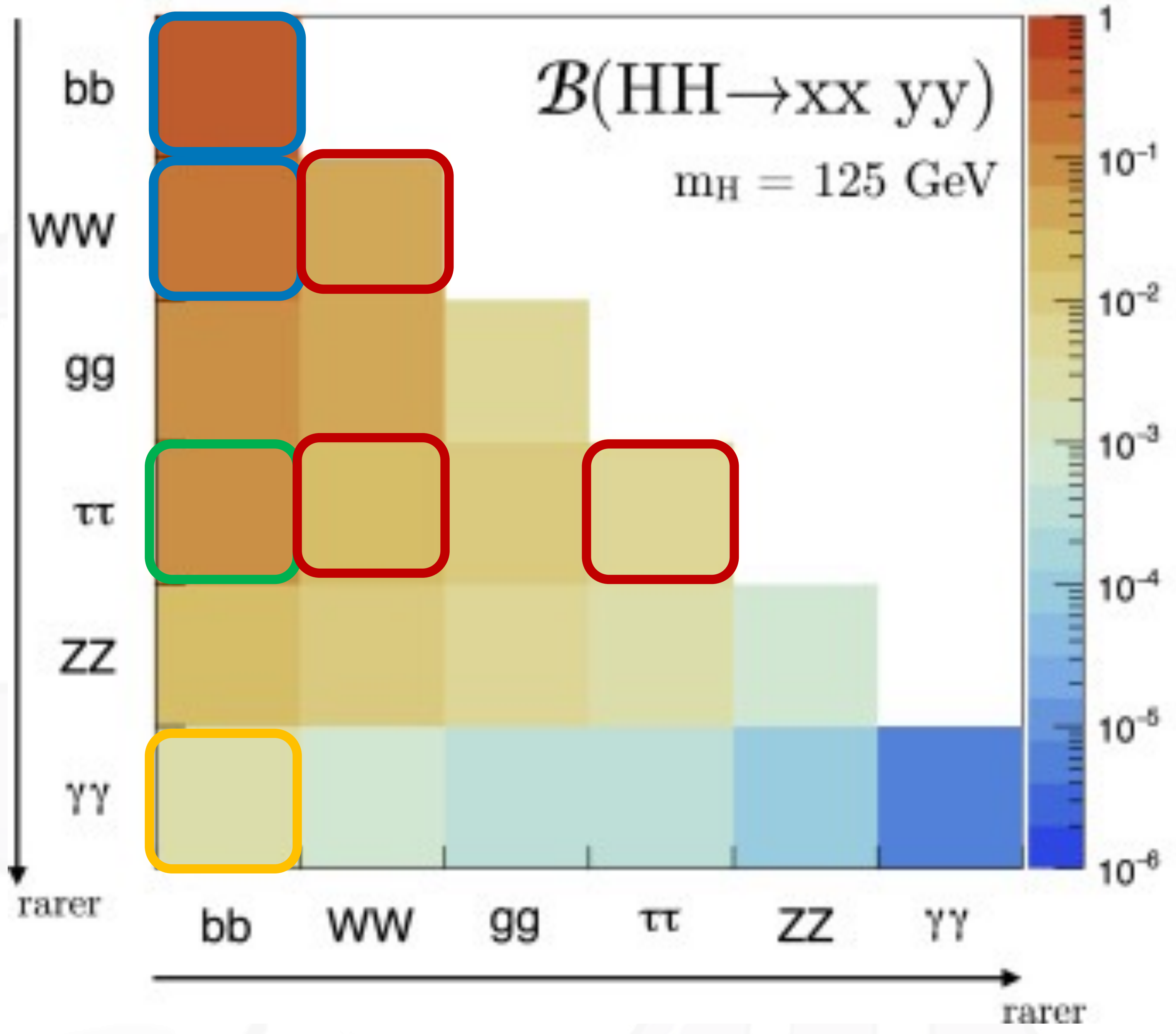
Nature 607, 60-68 (2022)

$\kappa_{2V} = 0$ is excluded with other couplings fixed @SM



Combination input analyses

- Cover main single-H production channels and decay modes
- Analyses for HH production targeting ggF, VBF and VHH
- Comparing to combination in [Nature 607, 60-68 (2022)]
  - Update to STXS: $H \to WW$
  - Newcomers: $VHH(4b), HH \to b\bar{b}WW$
  - Not included: $H \to Z\gamma, H \to invisible$ (weak constraint on κ_λ) and $HH \to b\bar{b}ZZ(4l)$ (large overlaps with $H \to ZZ(4l)$)
- Thorough study about the possible overlaps between single-H and HH analyses



Single-H analyses

Analysis	Int. luminosity (fb^{-1})	Max. granularity	References
$H \to ZZ \to 4l$	138	STXS 1.2	Eur. Phys. J. C 81 (2021) 488
$ggH(b\bar{b})$	138	Inclusive	JHEP 12 (2020) 085
$VH \to b\bar{b}$	77	Inclusive	Phys. Rev. Lett. 121 121801
$t\bar{t}H(b\bar{b})$	36	Inclusive	JHEP 03 (2019) 026
$t\bar{t}H$ multilepton	138	Inclusive	Eur. Phys. J. C 81 (2021) 378
$H \to \mu\mu$	138	Inclusive	JHEP 01 (2021) 148
$H \to \gamma\gamma$	138	STXS 1.2	JHEP 07 (2021) 027 JHEP 03 (2021) 257
$H \to \tau\tau$	138	STXS 1.2	Eur. Phys. J. C 83 (2023) 562
$H \to WW$	138	STXS 1.2	Eur. Phys. J. C 83 (2023) 667

HH analyses

Analysis	Int. luminosity (fb^{-1})	Targeted production modes	References
$HH \to b\bar{b}\gamma\gamma$	138	ggHH and qqHH	JHEP 03 (2021) 257
$HH \to b\bar{b}\tau\tau$	138	ggHH and qqHH	Phys. Lett. B 842 (2023) 137531
$HH \to b\bar{b}b\bar{b}$ (resolved)	138	ggHH and qqHH	Phys. Rev. Lett. 129 081802
$HH \to b\bar{b}b\bar{b}$ (boosted)	138	ggHH and qqHH	Phys. Rev. Lett. 131 041803
HH(leptons)	138	ggHH	JHEP 2307 (2023) 095
$HH \to b\bar{b}WW$	138	ggHH and qqHH	CMS-PAS-HIG-21-005
$VHH \to b\bar{b}b\bar{b}$	138	VHH	CMS-PAS-HIG-22-006

Overlap removal

- The single-H analyses orthogonal from each other based on the definition of signal regions
- Overlap study performed in Nature 607, 60-68 (2022) for the HH analyses
  - Exceptions: $VHH(4b), HH \rightarrow b\bar{b}WW$
- Possible overlaps between single-H and HH analyses. Some overlaps excluded by orthogonal requirements on multiplicity of leptons, photons, jets, b-jets, ….
  - If that is not sufficient, comparisons are done event-by-event
    Overlap(A, B) = events in (A & B) / max(events in A, events in B) $\rightarrow$ negligible if < 1%
- Optimized to maximize the expected sensitivity on κ_λ, κ_f and κ_V!

single-H / HH analysis	$HH \rightarrow b\bar{b}\gamma\gamma$	$HH \rightarrow b\bar{b}\tau\tau$	$HH \rightarrow 4b$	HH(leptons)	$HH \rightarrow b\bar{b}WW$
$H \rightarrow \gamma\gamma$	✗	✓	✓	✓	✓
$H \rightarrow WW$	✓	✓	✓	✗	✗
$t\bar{t}H$ multi-leptons	✓	✗	✓	✓	✗
$H \rightarrow \mu\mu$	✓	✓	✓	✓	✓
$H \rightarrow ZZ \rightarrow 4l$	✓	✓	✓	✓	✓
$H \rightarrow b\bar{b}(ggH, VH, t\bar{t}H)$	✓	✗	✗	✓	✗
$H \rightarrow \tau\tau$	✓	✗	✓	✓	✓
$VHH \rightarrow b\bar{b}b\bar{b}$	✓	✓	✗	✓	✓

✓: Non overlapping analysis
✗: Overlaps removable with negligible impacts on the combination

Overlap removal – highlights by H decays

$H \rightarrow \gamma\gamma$

- A dedicated $t\bar{t}H(\gamma\gamma)$ enriched region in $HH \rightarrow b\bar{b}\gamma\gamma$, so the $t\bar{t}H$ category in $H \rightarrow \gamma\gamma$ is removed
  - Orthogonal selections by construction
- Some sub-leading STXS categories are removed from $H \rightarrow \gamma\gamma$ (high p_T ggH and VH hadronic events)

single-H / HH analysis	$HH \rightarrow b\bar{b}\gamma\gamma$	$HH \rightarrow b\bar{b}\tau\tau$	$HH \rightarrow 4b$	HH(leptons)	$HH \rightarrow b\bar{b}WW$
$H \rightarrow \gamma\gamma$	✗	✓	✓	✓	✓
$H \rightarrow WW$	✓	✓	✓	✗	✗
$t\bar{t}H$ multi-leptons	✓	✗	✓	✓	✗
$H \rightarrow \mu\mu$	✓	✓	✓	✓	✓
$H \rightarrow ZZ \rightarrow 4l$	✓	✓	✓	✓	✓
$H \rightarrow b\bar{b}(ggH, VH, t\bar{t}H)$	✓	✗	✗	✓	✗
$H \rightarrow \tau\tau$	✓	✗	✓	✓	✓
$VHH \rightarrow b\bar{b}b\bar{b}$	✓	✓	✗	✓	✓

Overlap removal – highlights by H decays

$H \rightarrow \gamma\gamma$

- A dedicated $t\bar{t}H(\gamma\gamma)$ enriched region in $HH \rightarrow b\bar{b}\gamma\gamma$, so the $t\bar{t}H$ category in $H \rightarrow \gamma\gamma$ is removed
  - Orthogonal selections by construction
- Some sub-leading STXS categories are removed from $H \rightarrow \gamma\gamma$ (high p_T ggH and VH hadronic events)

$H \rightarrow b\bar{b}$

- Lepton veto used in $HH \rightarrow 4b$, only potential overlap with $t\bar{t}H(b\bar{b})$ and $VHH(4b)$ fully hadronic categories. These fully hadronic categories are removed
- The $t\bar{t}$ CR (1 lepton) in $HH \rightarrow b\bar{b}WW$ and $VH(b\bar{b})$ cover similar phase space, the one from $VH(b\bar{b})$ is removed

single-H / HH analysis	$HH \rightarrow b\bar{b}\gamma\gamma$	$HH \rightarrow b\bar{b}\tau\tau$	$HH \rightarrow 4b$	HH(leptons)	$HH \rightarrow b\bar{b}WW$
$H \rightarrow \gamma\gamma$	✗	✓	✓	✓	✓
$H \rightarrow WW$	✓	✓	✓	✗	✗
$t\bar{t}H$ multi-leptons	✓	✗	✓	✓	✗
$H \rightarrow \mu\mu$	✓	✓	✓	✓	✓
$H \rightarrow ZZ \rightarrow 4l$	✓	✓	✓	✓	✓
$H \rightarrow b\bar{b}(ggH, VH, t\bar{t}H)$	✓	✗	✗	✓	✗
$H \rightarrow \tau\tau$	✓	✗	✓	✓	✓
$VHH \rightarrow b\bar{b}b\bar{b}$	✓	✓	✗	✓	✓

Overlap removal – highlights by H decays

$H \to \tau\tau$

- Both $t\bar{t}H$ *multi-leptons* and $HH \to b\bar{b}\tau\tau$ have 2 leptons categories: $1l + 1\tau_h$ and $0l + 2\tau_h$. The one from $t\bar{t}H$ *multi-leptons* is removed
- Sub-leading STXS bins targeting ggH/VH events with >2 additional jets are also removed from $H \to \tau\tau$

single-H / HH analysis	$HH \to b\bar{b}\gamma\gamma$	$HH \to b\bar{b}\tau\tau$	$HH \to 4b$	HH(leptons)	$HH \to b\bar{b}WW$
$H \to \gamma\gamma$	✗	✓	✓	✓	✓
$H \to WW$	✓	✓	✓	✗	✗
$t\bar{t}H$ multi-leptons	✓	✗	✓	✓	✗
$H \to \mu\mu$	✓	✓	✓	✓	✓
$H \to ZZ \to 4l$	✓	✓	✓	✓	✓
$H \to b\bar{b}(ggH, VH, t\bar{t}H)$	✓	✗	✗	✓	✗
$H \to \tau\tau$	✓	✗	✓	✓	✓
$VHH \to b\bar{b}b\bar{b}$	✓	✓	✗	✓	✓

Overlap removal – highlights by H decays

$H \to \tau\tau$

- Both $t\bar{t}H$ *multi-leptons* and $HH \to b\bar{b}\tau\tau$ have 2 leptons categories: $1l + 1\tau_h$ and $0l + 2\tau_h$. The one from $t\bar{t}H$ *multi-leptons* is removed
- Sub-leading STXS bins targeting ggH/VH events with >2 additional jets are also removed from $H \to \tau\tau$

$H \to WW$

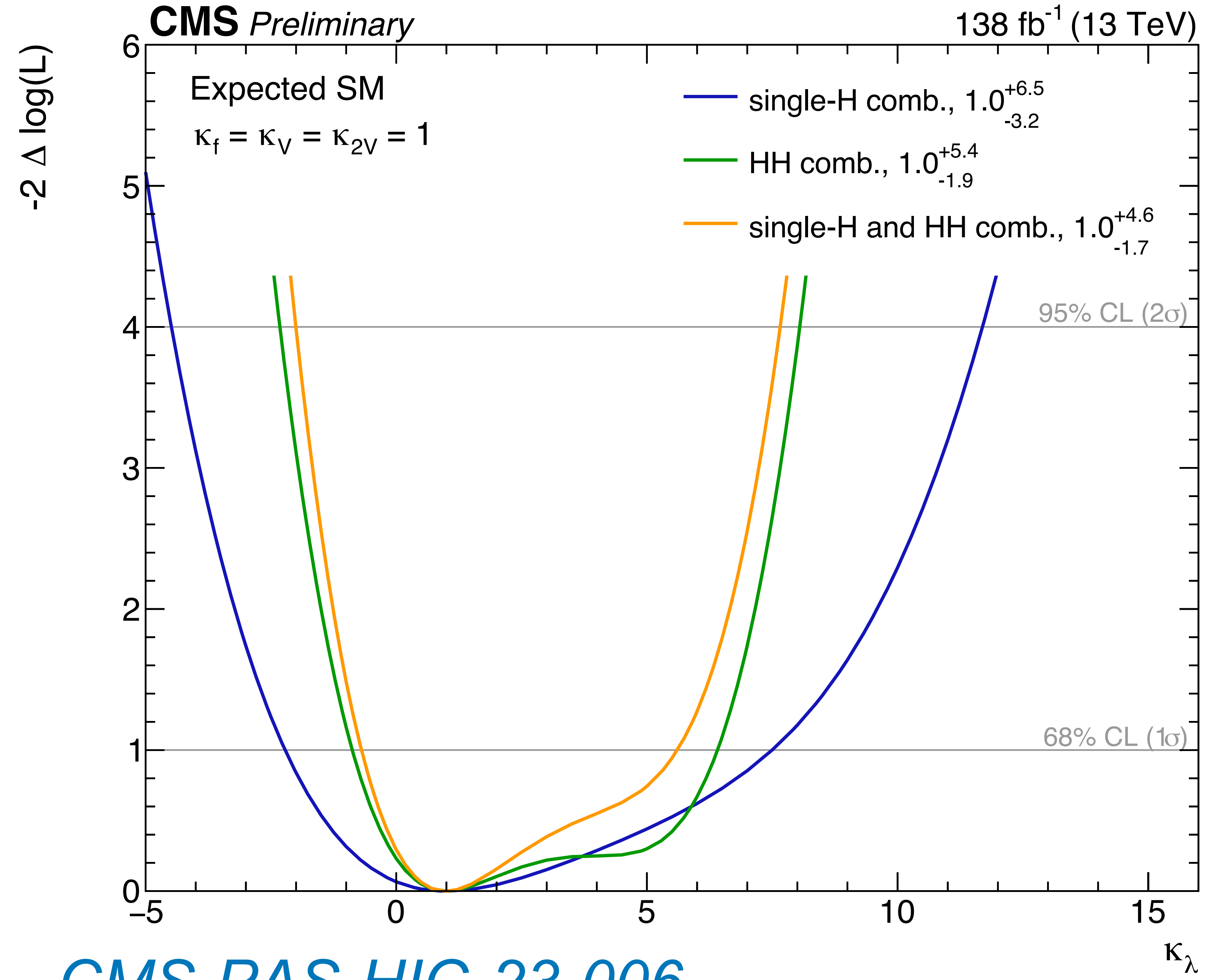
- Both VH channel of $H \to WW$ and HH *multi-leptons* have 2 leptons and 3 leptons categories
  - The $2l$ category of HH *multi-leptons* and $3l$ category of $H \to WW$ are removed
- Categories with 2 opposite-sign leptons + $1\tau_h$ from $t\bar{t}H$ *multi-leptons* are removed due to overlaps with $2l$ category of $HH \to b\bar{b}WW$

single-H / HH analysis	$HH \to b\bar{b}\gamma\gamma$	$HH \to b\bar{b}\tau\tau$	$HH \to 4b$	HH(leptons)	$HH \to b\bar{b}WW$
$H \to \gamma\gamma$	✗	✓	✓	✓	✓
$H \to WW$	✓	✓	✓	✗	✗
$t\bar{t}H$ multi-leptons	✓	✗	✓	✓	✗
$H \to \mu\mu$	✓	✓	✓	✓	✓
$H \to ZZ \to 4l$	✓	✓	✓	✓	✓
$H \to b\bar{b}(ggH, VH, t\bar{t}H)$	✓	✗	✗	✓	✗
$H \to \tau\tau$	✓	✗	✓	✓	✓
$VHH \to b\bar{b}b\bar{b}$	✓	✓	✗	✓	✓

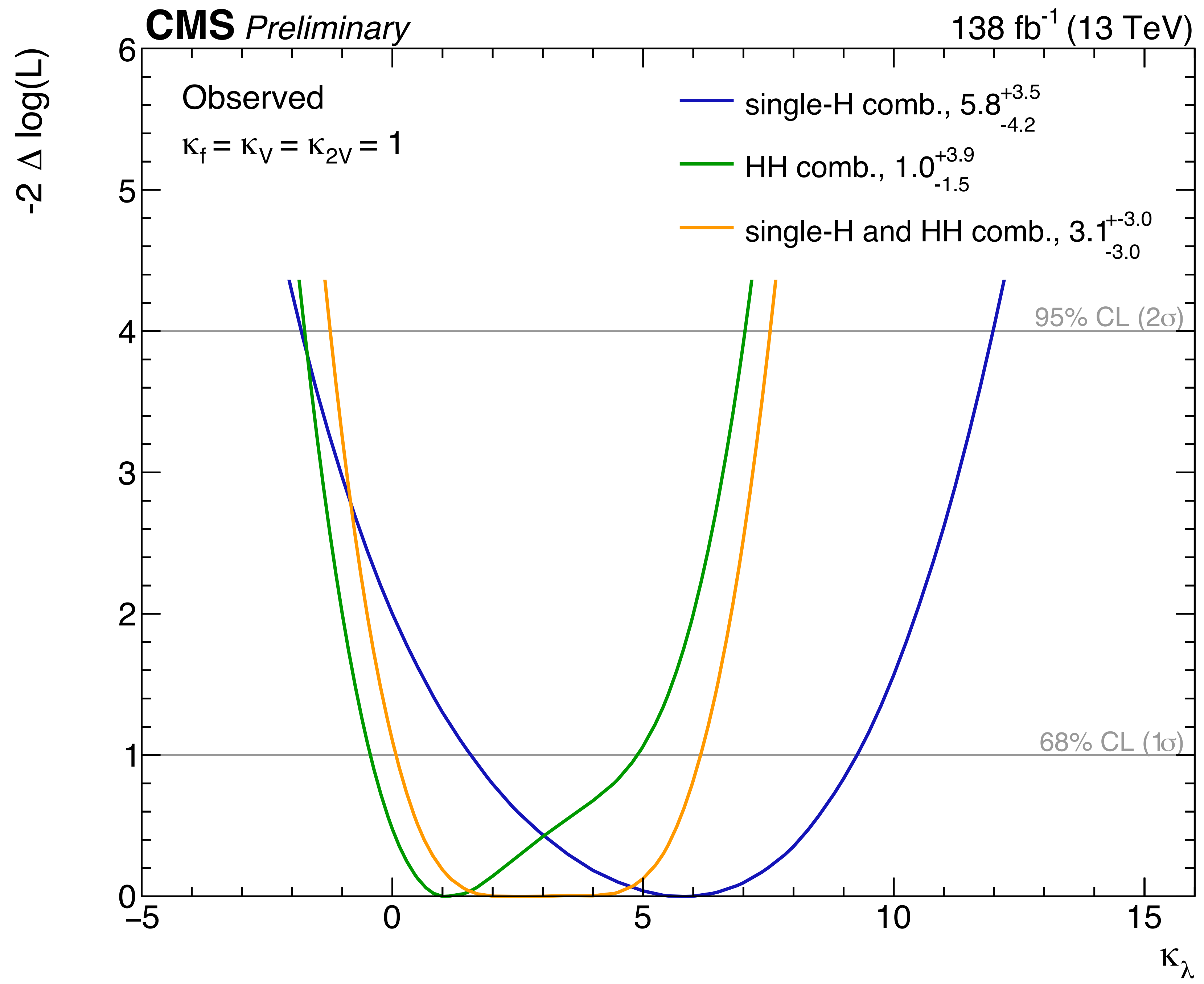
Combination results: κ_λ constraint

- Assuming BSM only affect κ_λ and all the other Higgs couplings are set to be SM values
- Sensitivity on κ_λ is driven by HH categories
- The single-H expected to improve sensitivity around $\kappa_\lambda = 5$
- Individual results consistent with previous combination [Nature 607, 60-68 (2022)]

Expected 95% C.L. : $-2.0 < \kappa_\lambda < 7.7$



Observed 95% C.L. : $-1.2 < \kappa_\lambda < 7.5$

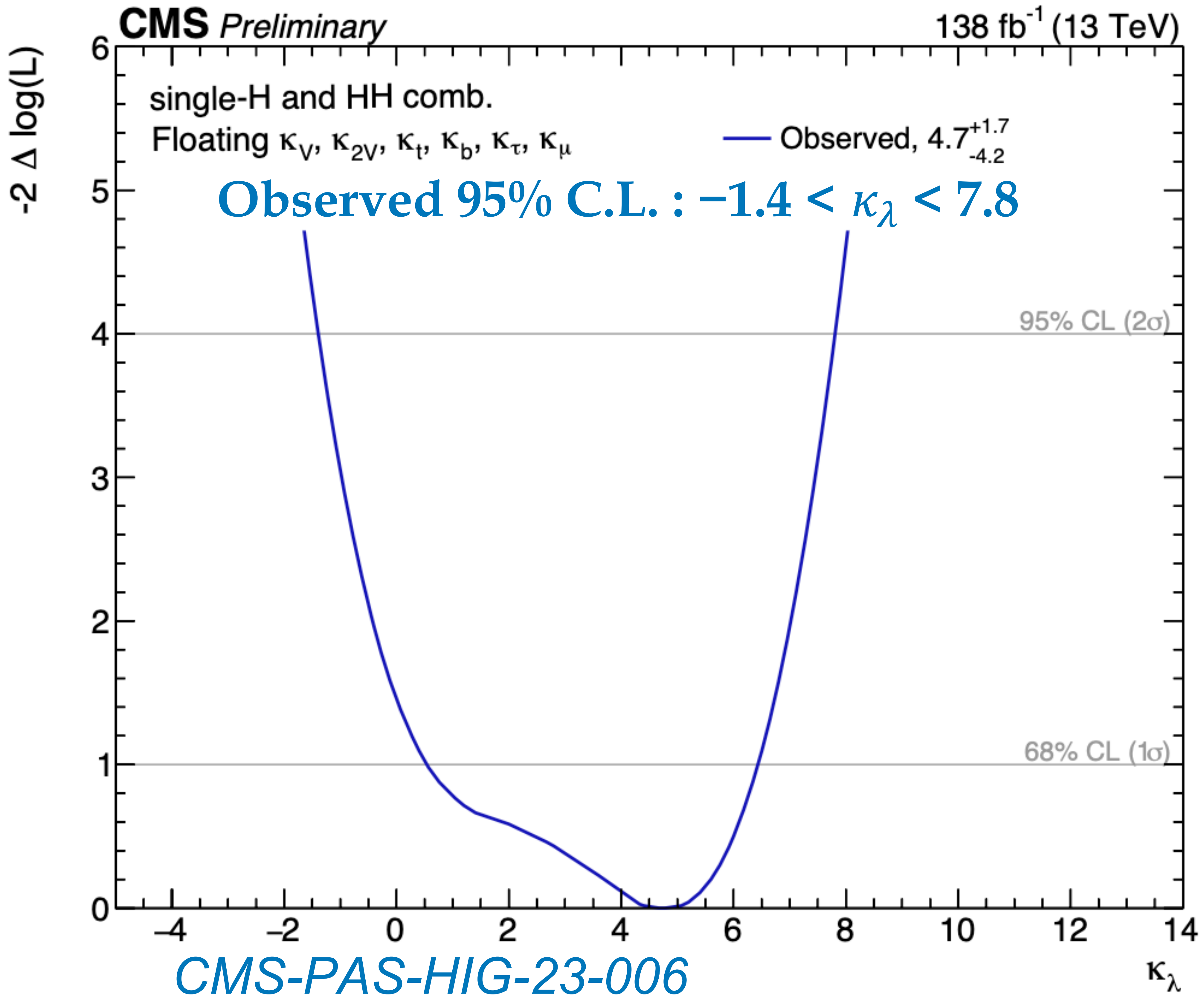


CMS-PAS-HIG-23-006

- The observed κ_λ from HH comb. is very close to 1
- The observed κ_λ from single-H comb. > 1
- HH+H combined likelihood is flat around minima

Combination results: κ_λ generic constraint

- Alternatively, other Higgs coupling modifiers can be floating
- The constraint on κ_λ is still strong
- Very consistent constraint compared to ATLAS combination results



CMS-PAS-HIG-23-006

CMS constraint on κ_λ

Only κ_λ floating

$\kappa_\lambda, \kappa_V, \kappa_t, \kappa_b, \kappa_\tau$ floating

Hypothesis	Obs. 95% CL (2σ)	Exp. 95% CL (2σ)
Single-H combination	$[-1.8, +12.0]$	$[-4.5, +11.7]$
HH combination	$[-1.7, +7.0]$	$[-2.3, +8.0]$
HH+H, Other couplings fixed to SM	$[-1.2, +7.5]$	$[-2.0, +7.7]$
HH+H, Floating (κ_V, κ_{2V}, κ_F)	$[-1.7, +7.7]$	$[-2.2, +7.8]$
HH+H, Floating (κ_V, κ_t, κ_b, κ_τ)	$[-1.4, +7.8]$	$[-2.3, +7.7]$
HH+H, Floating (κ_V, κ_{2V}, κ_t, κ_b, κ_τ, κ_μ)	$[-1.4, +7.8]$	$[-2.3, +7.8]$

ATLAS constraint on κ_λ

Only κ_λ floating

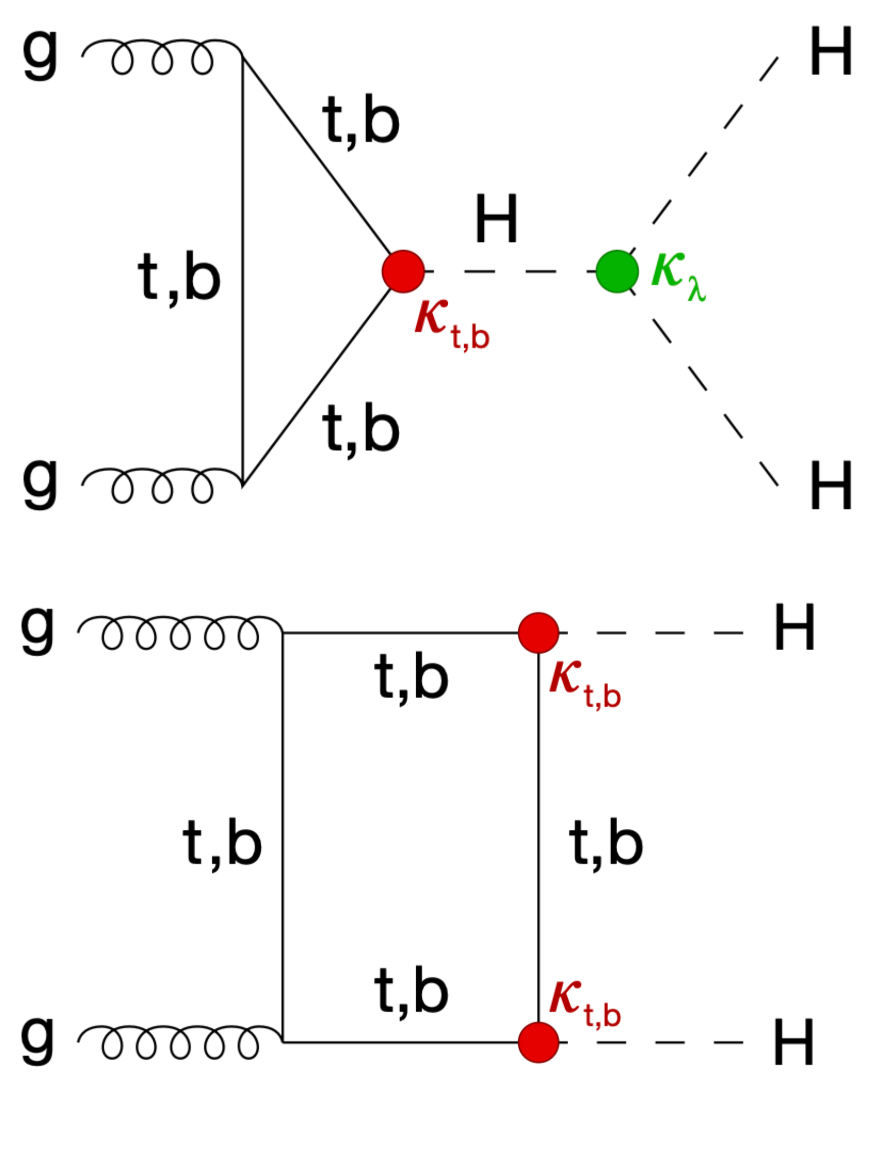
$\kappa_\lambda, \kappa_V, \kappa_t, \kappa_b, \kappa_\tau$ floating

Combination assumption	Obs. 95% CL	Exp. 95% CL
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$
Single-*H* combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$
HH+*H* combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.5$
HH+*H* combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$
HH+*H* combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$

Phys. Lett. B 843 (2023) 137745

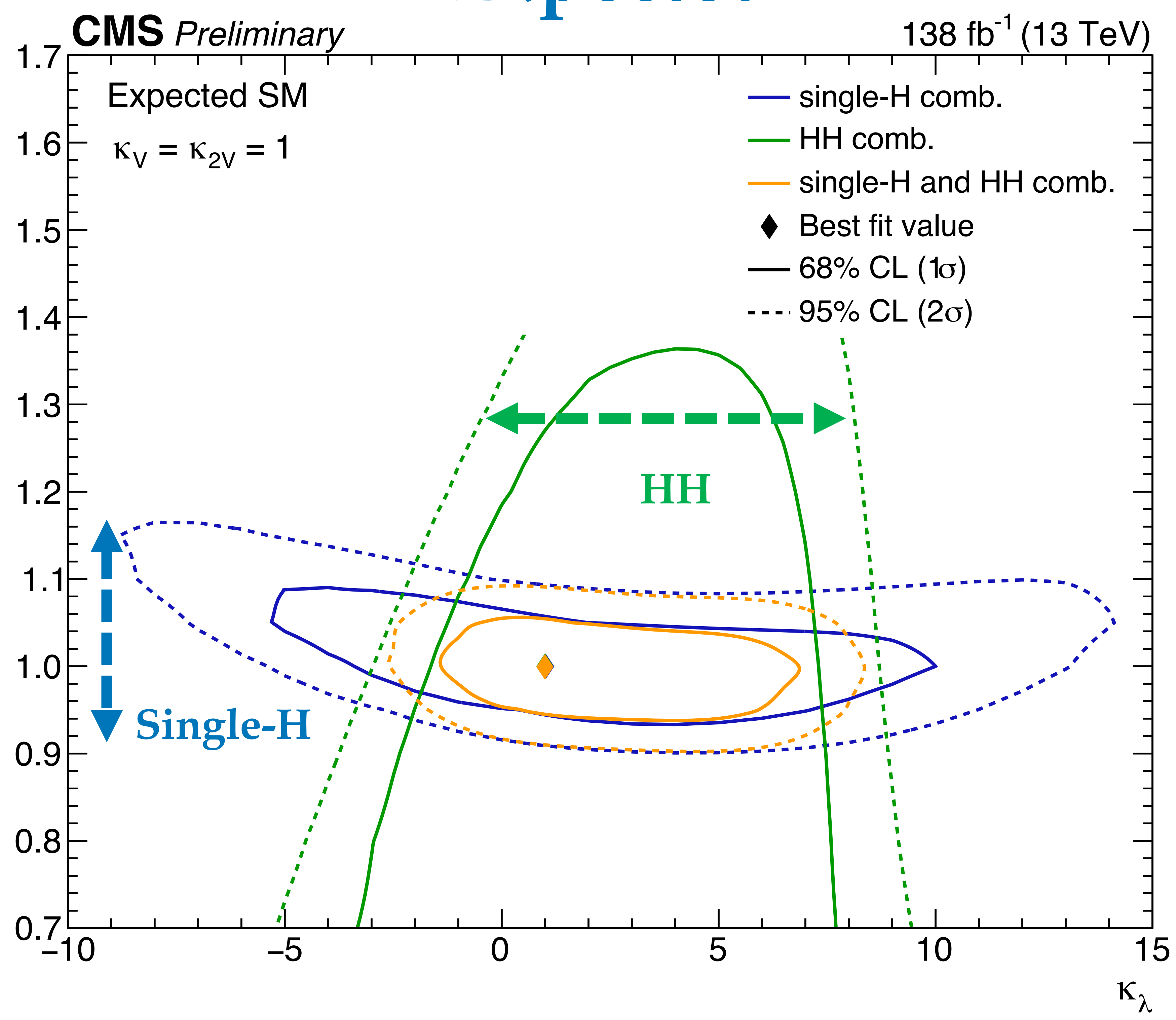
2D likelihood scan (κ_λ, κ_t)

- Large degeneracy of the ggHH XS with respect to $\kappa_\lambda, \kappa_t \rightarrow$ weak constraint on κ_t
- Excellent constraint on κ_t from Single-H combination (e.g. ggH)
- Complementarity of HH and single-H fully exploited

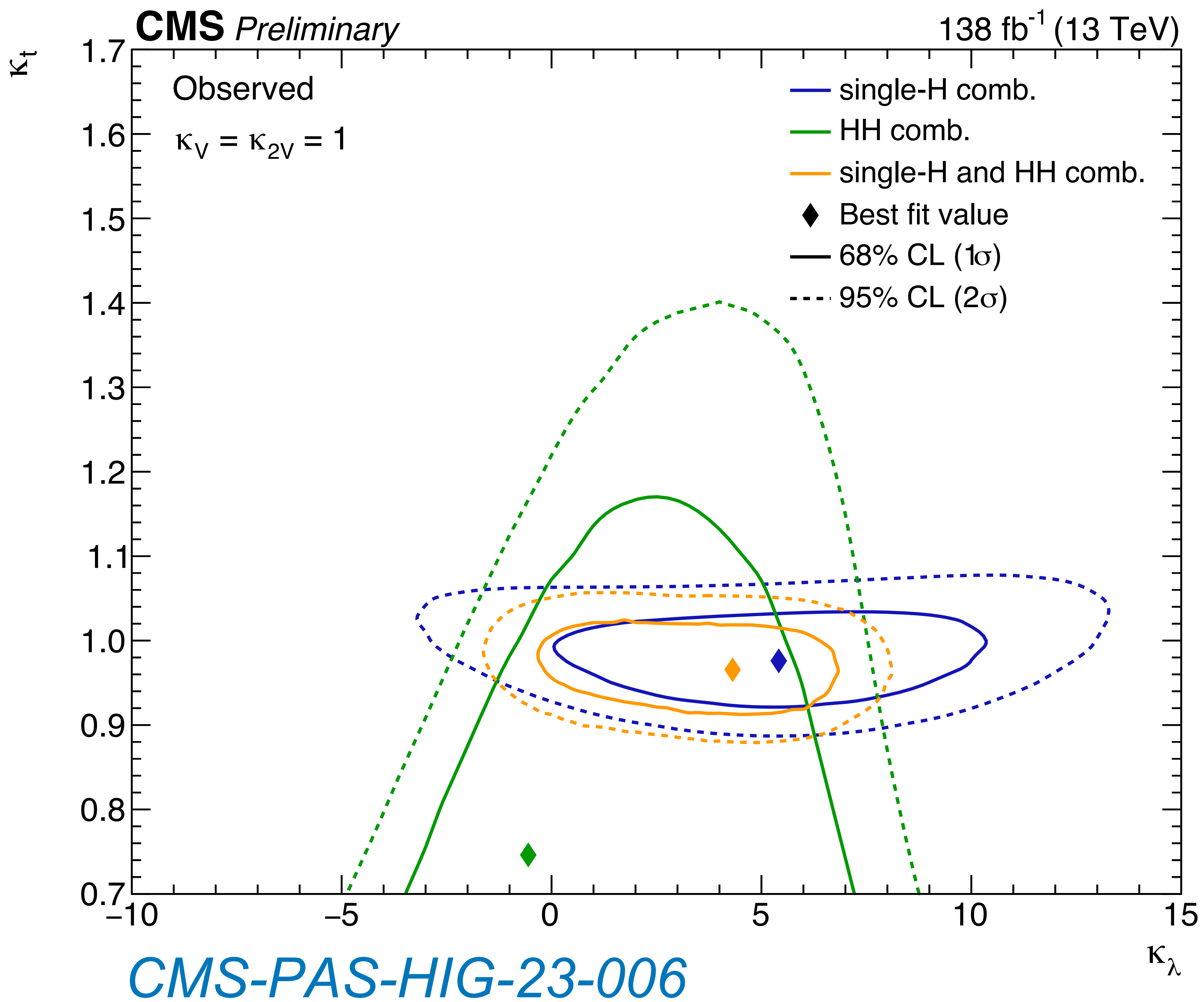


ggHH production diagrams

Expected



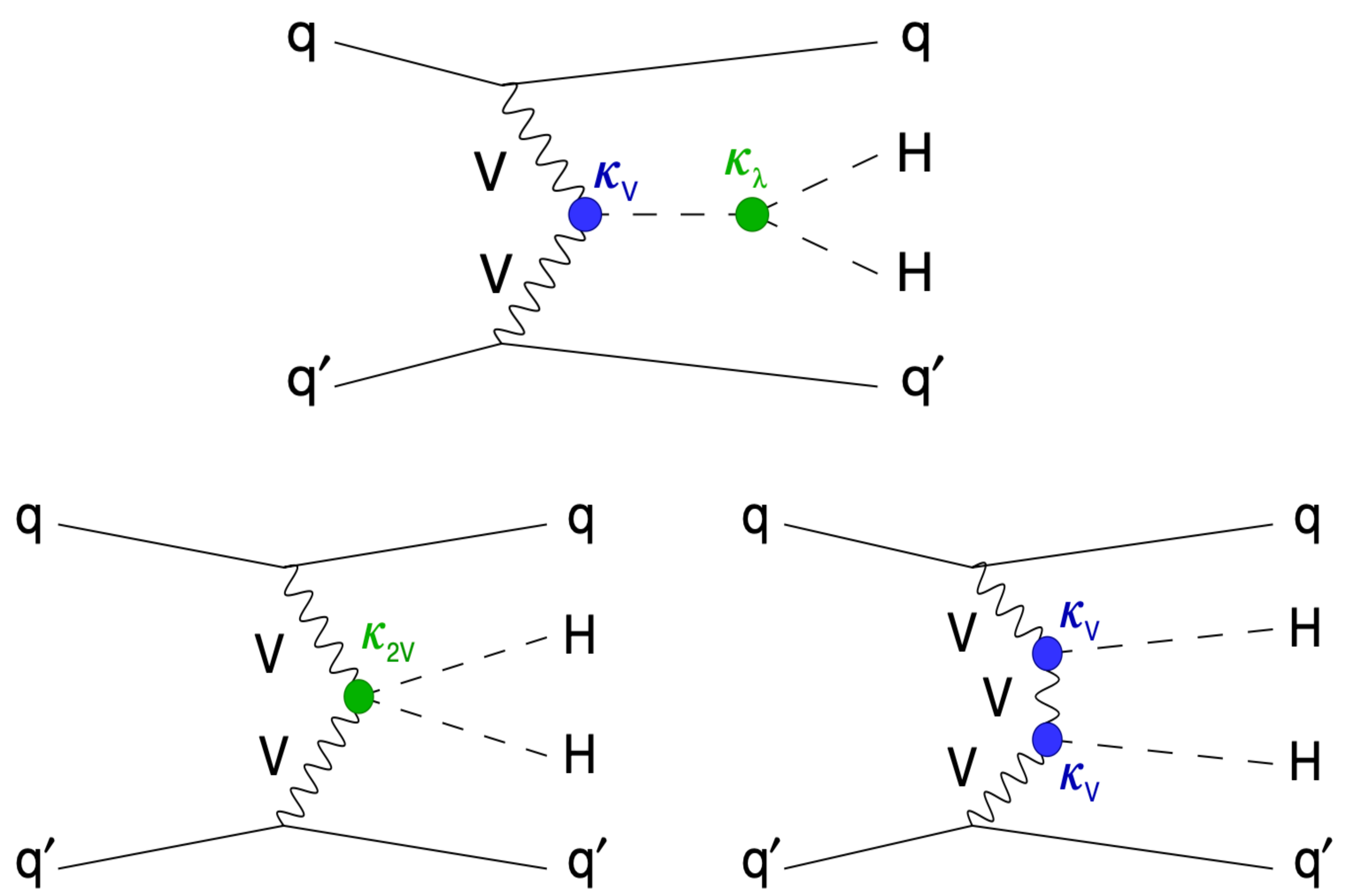
Observed



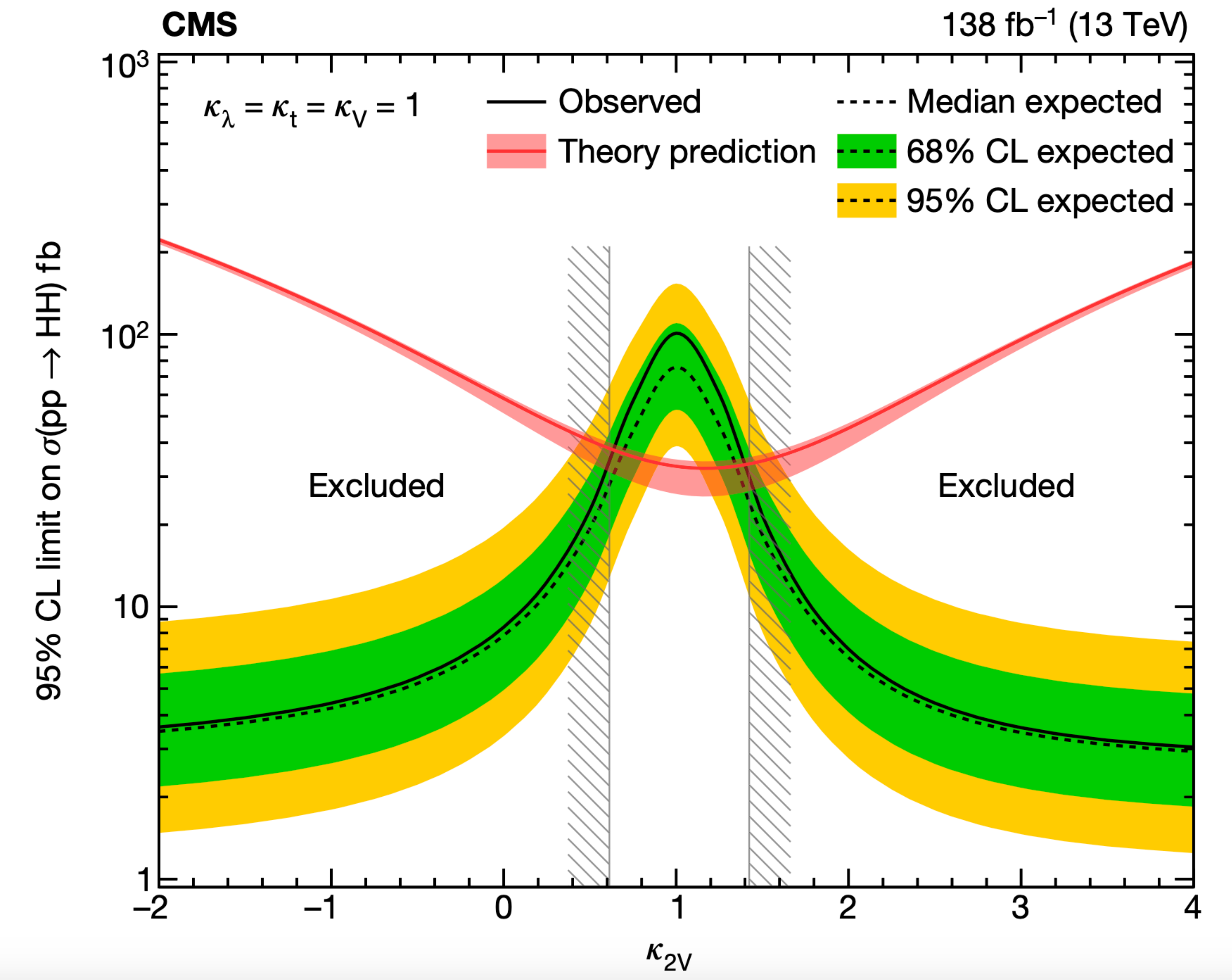
[CMS-PAS-HIG-23-006](CMS-PAS-HIG-23-006)

2D likelihood scan (κ_V, κ_{2V})

- Constraint on κ_{2V} is driven by the qqHH production
- No sensitivity to κ_{2V} from single-H, but strong constraint on κ_V

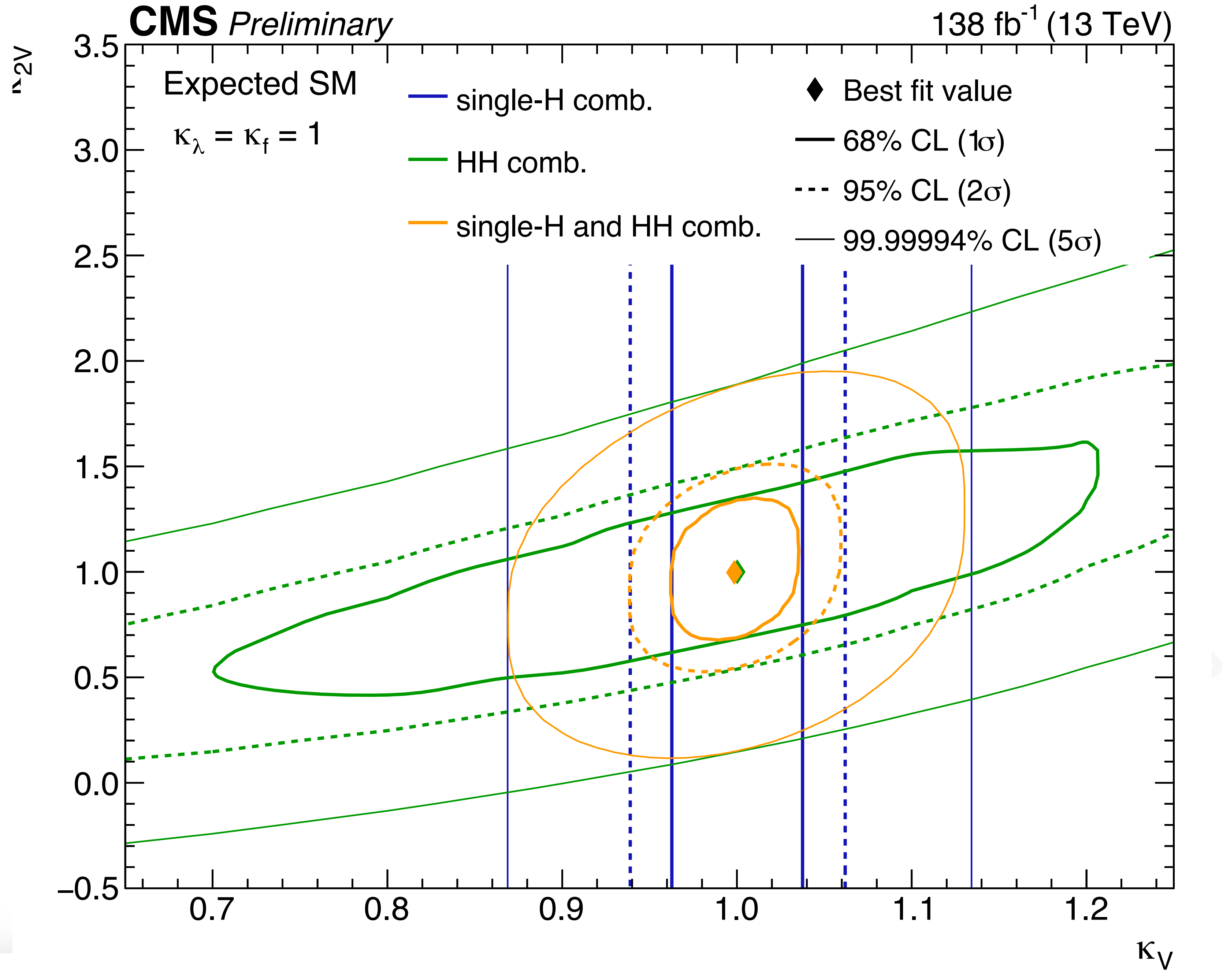


qqHH production diagrams



Nature 607, 60-68 (2022)

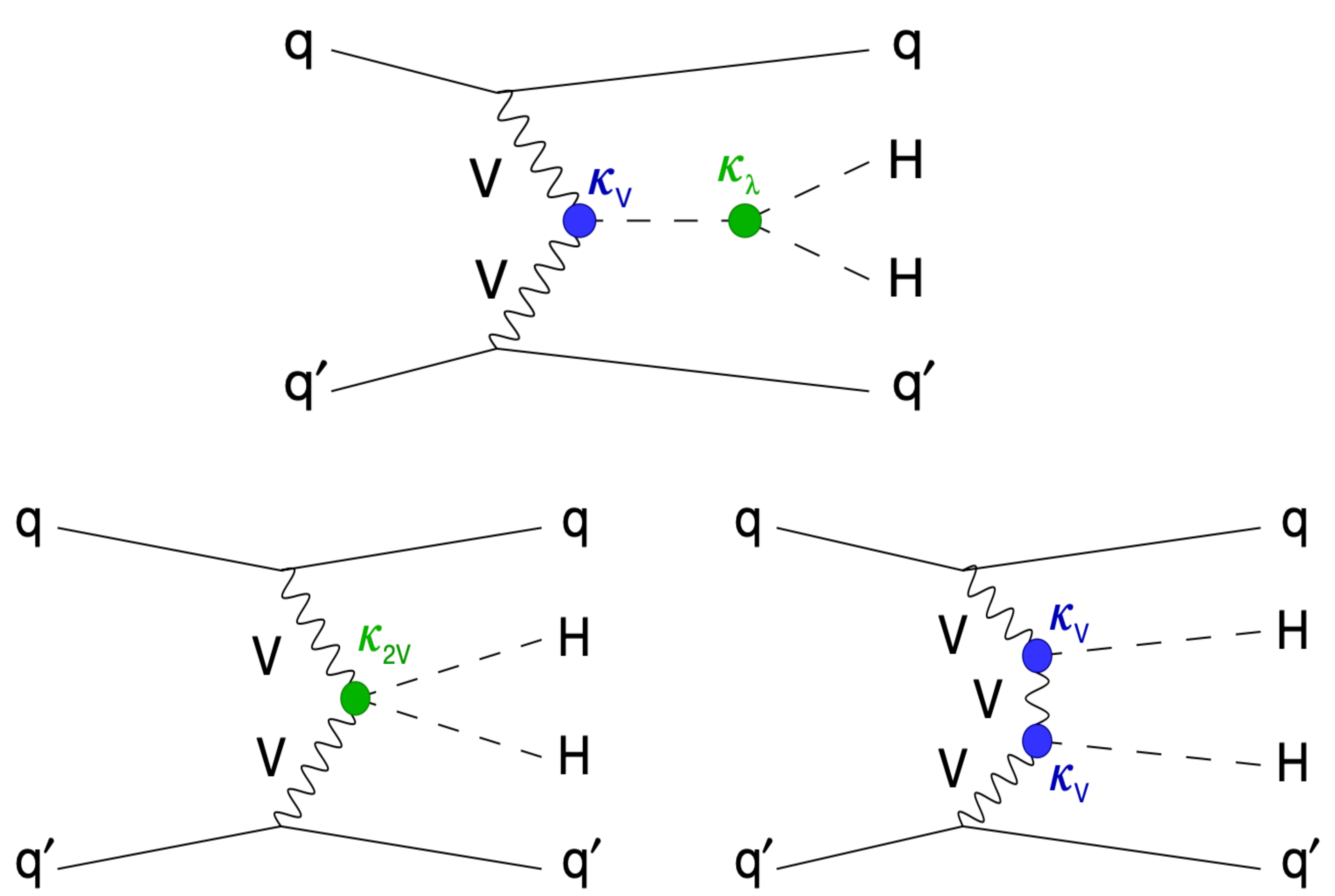
Expected



CMS-PAS-HIG-23-006

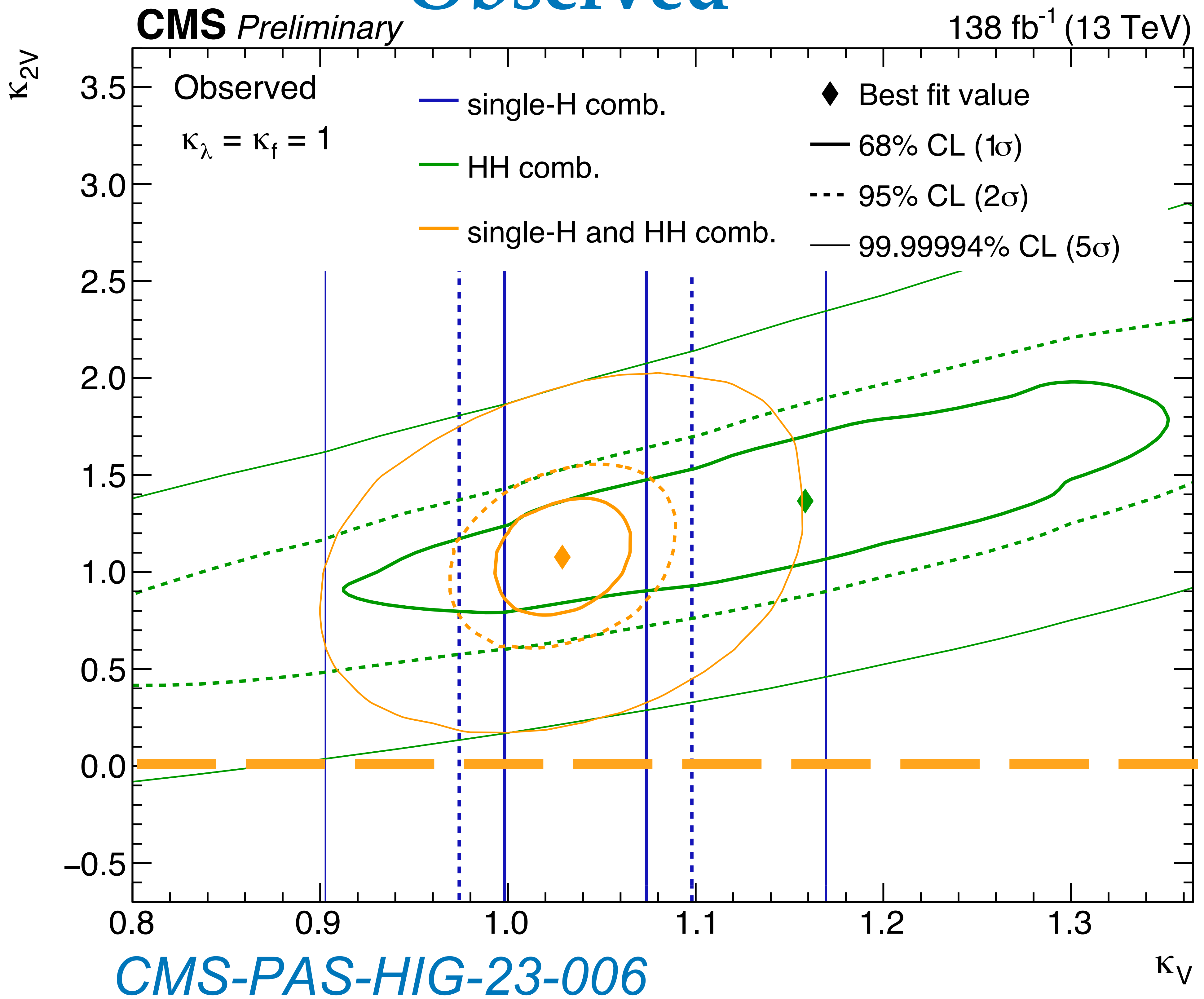
2D likelihood scan (κ_V, κ_{2V})

- Constraint on κ_{2V} is driven by the qqHH production
- No sensitivity to κ_{2V} from single-H, but strong constraint on κ_V
- **First exclusion of $\boldsymbol{\kappa_{2V} = 0}$ for any value of $\boldsymbol{\kappa_V}$ at $\boldsymbol{5\sigma}$!**



qqHH production diagrams

Observed



[CMS-PAS-HIG-23-006](CMS-PAS-HIG-23-006)

$\kappa_{2V} = 0$ excluded more than 5σ

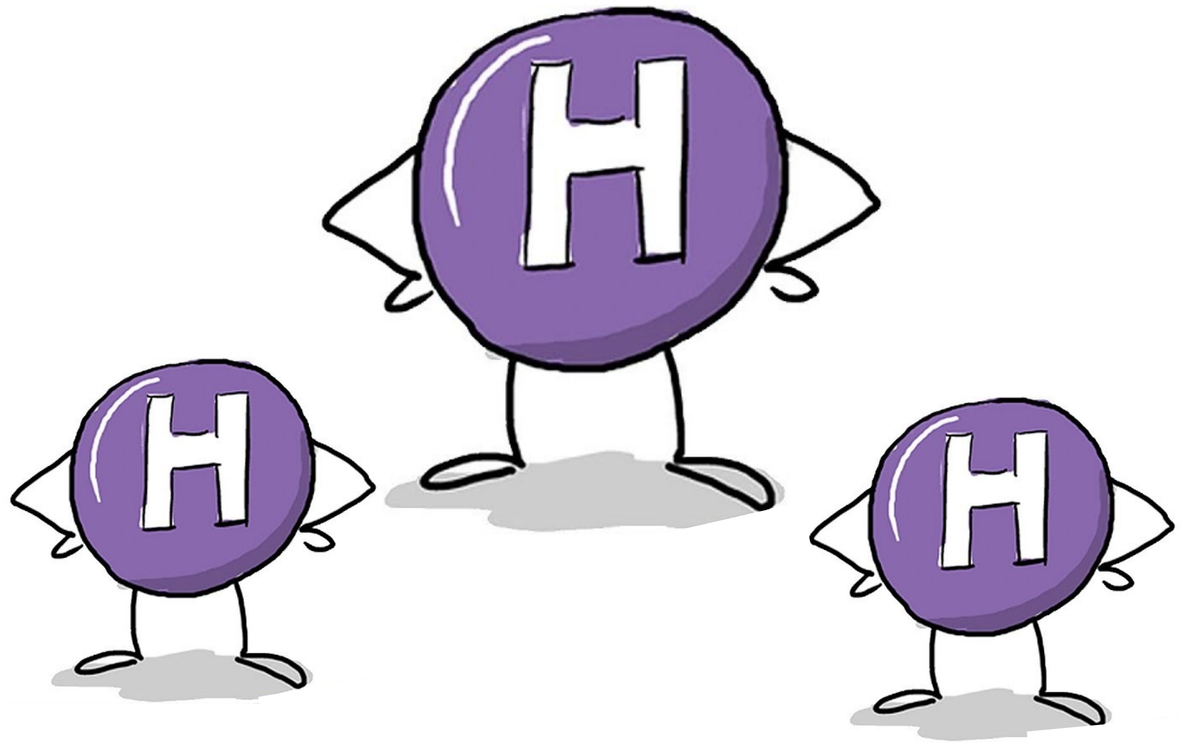
Summary

- **First combination of HH and single-H production** at CMS with full Run 2 dataset !
- Most stringent constraint on the κ_λ exclusion with general assumptions from the CMS experiment
  - Exclusion of $\kappa_{2V} = 0$ for any value of κ_V at 5σ for the first time!
  - Constraints on κ_λ:

    κ_λ-only: $-1.2 < \kappa_\lambda < 7.5$ (Observed 95% C.L.)

    κ_λ-generic ($\kappa_V, \kappa_{2V}, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$ floating): $-1.4 < \kappa_\lambda < 7.8$ (Observed 95% C.L.)

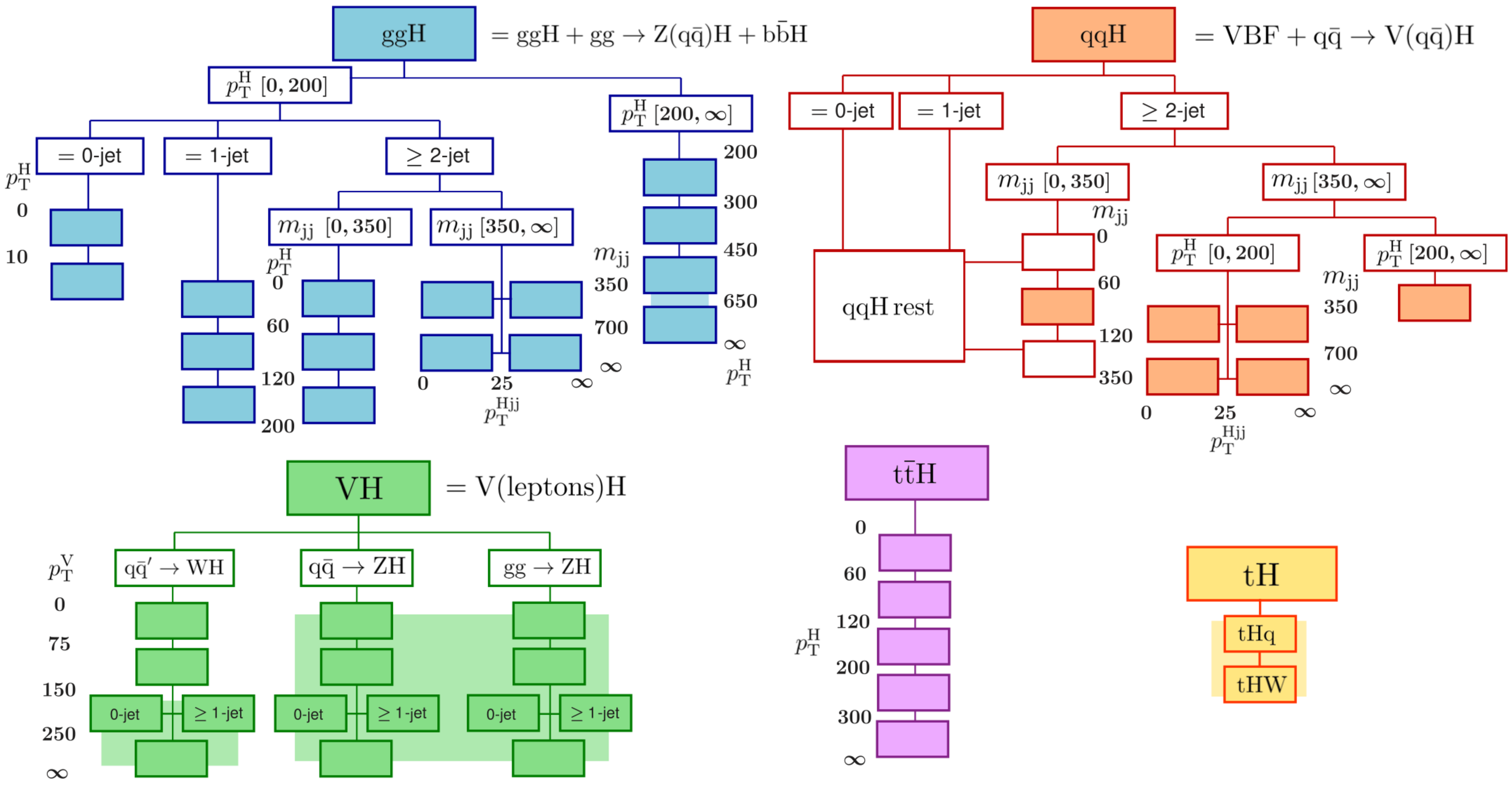
- Run 3 is underway and significant opportunity for further improvements. Stay tuned for more exciting developments!



Thank you

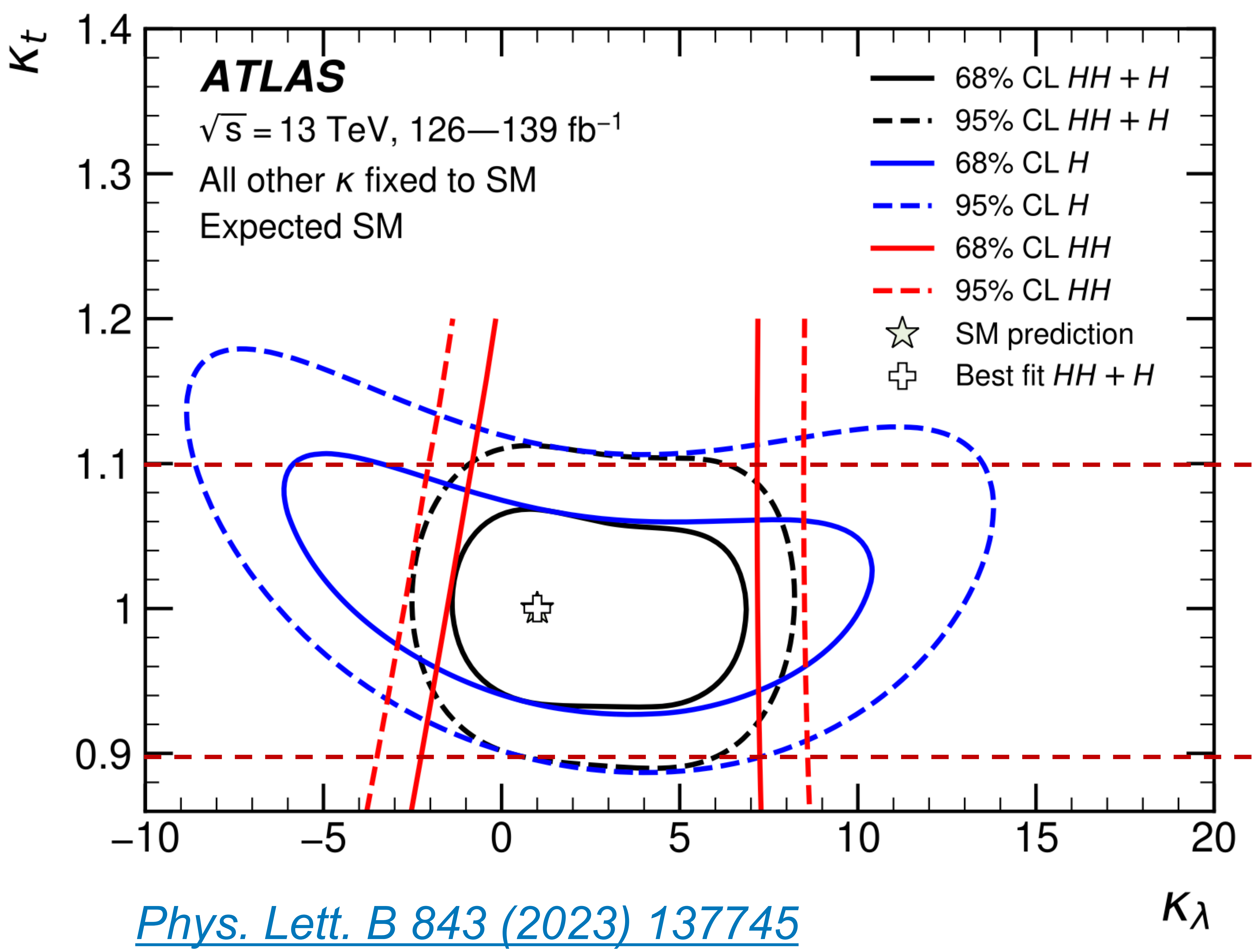
Backup

- The Simplified Template Cross Section (STXS) framework

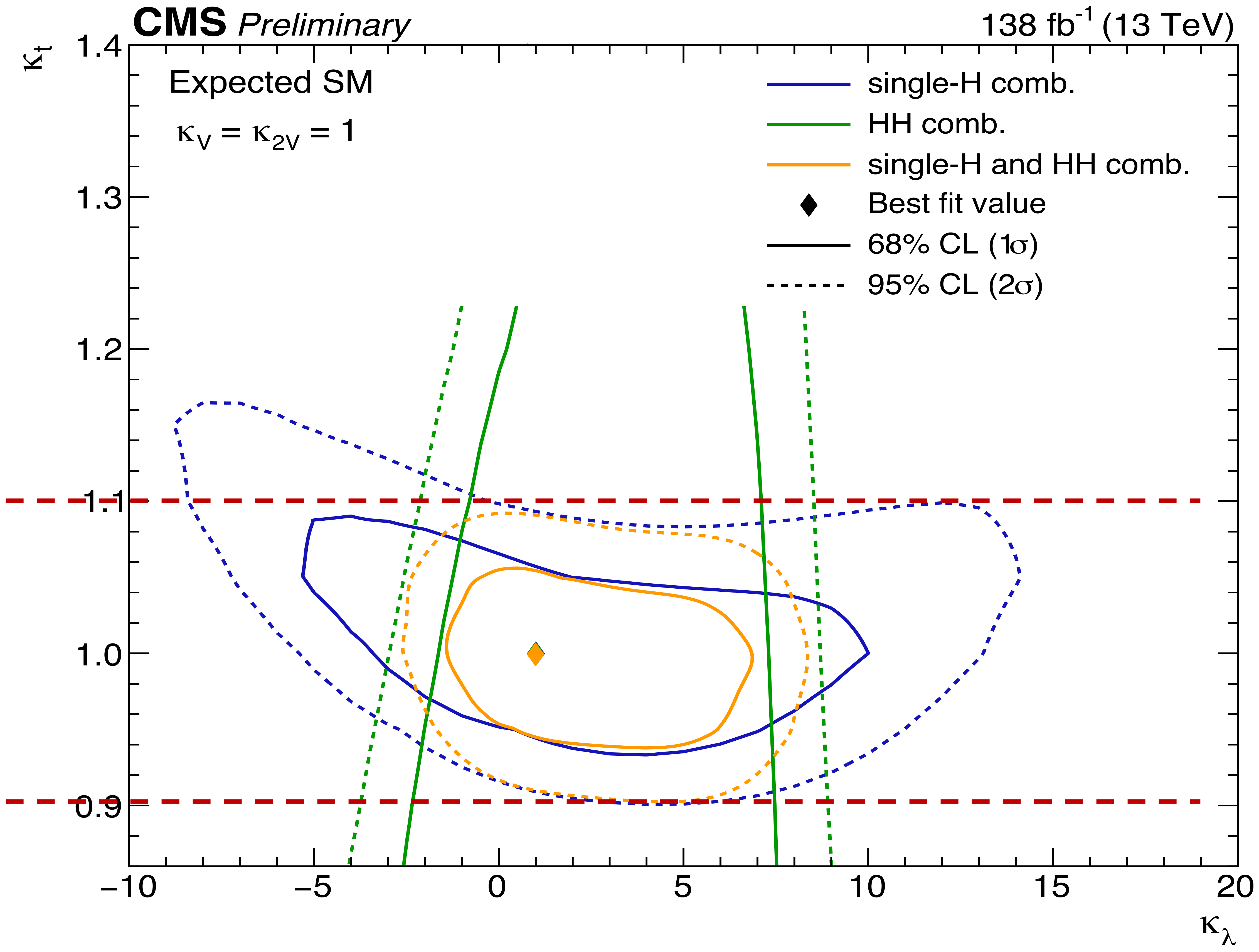


$(\kappa_\lambda, \kappa_t)$ likelihood scan comparison

- ATLAS $(\kappa_\lambda, \kappa_t)$ 2D likelihood scan
- CMS $(\kappa_\lambda, \kappa_t)$ 2D likelihood scan



Phys. Lett. B 843 (2023) 137745

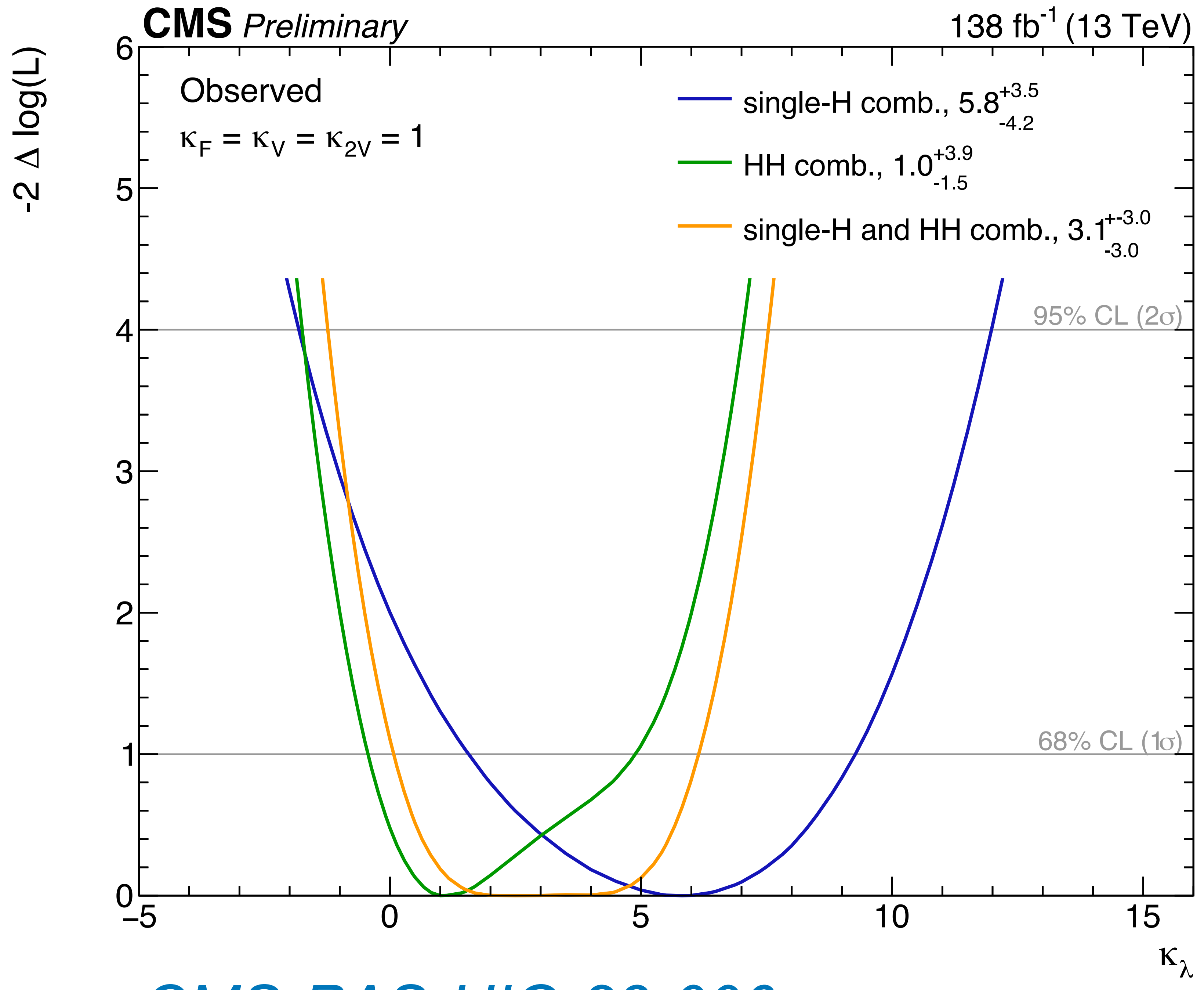


CMS-PAS-HIG-23-006

Compare to ATLAS

CMS HH+H comb.

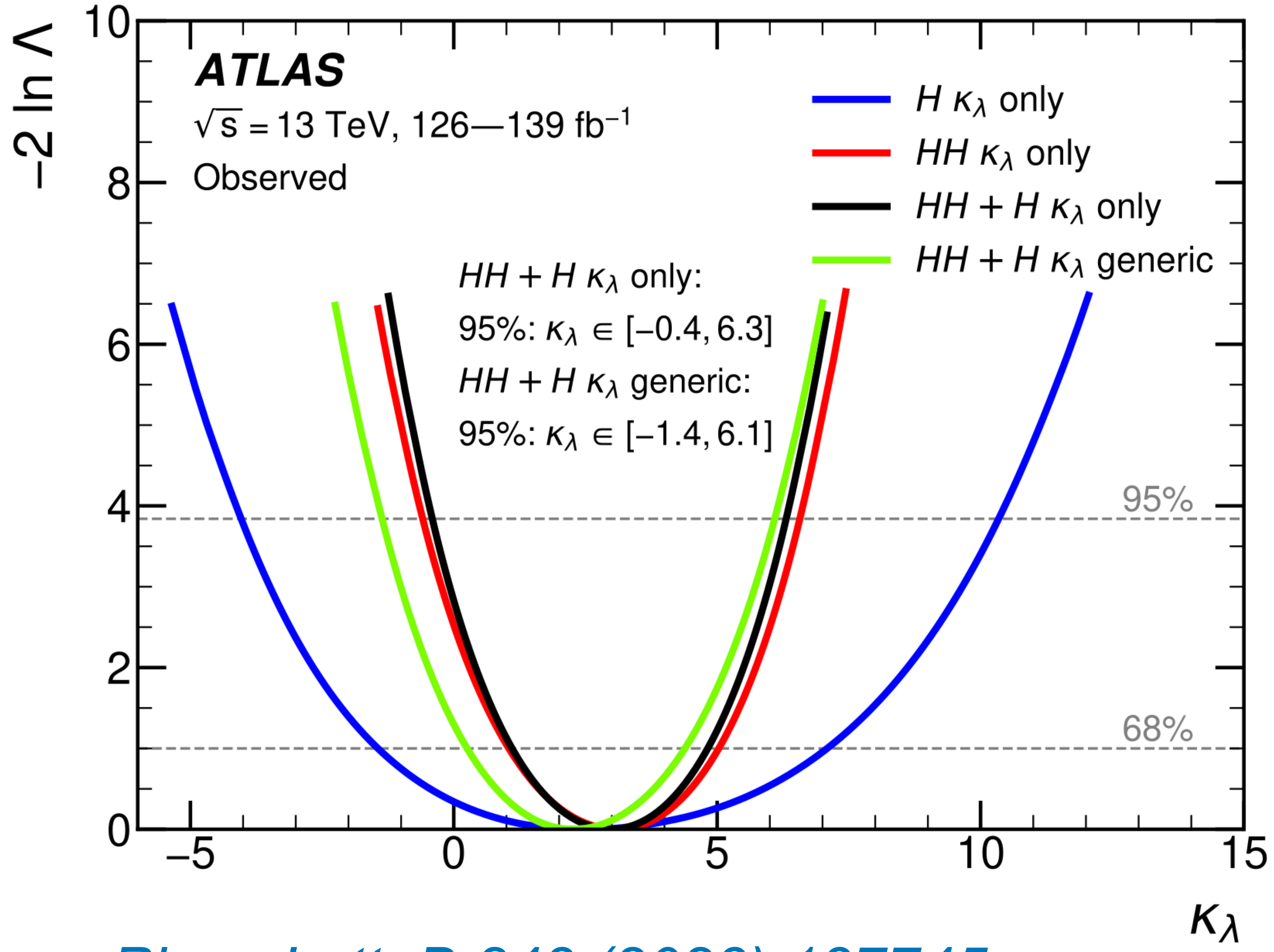
Observed 95% C.L. : $-1.2 < \kappa_\lambda < 7.5$



[CMS-PAS-HIG-23-006](CMS-PAS-HIG-23-006)

ATLAS HH+H comb.

Observed 95% C.L. : $-0.4 < \kappa_\lambda < 6.3$



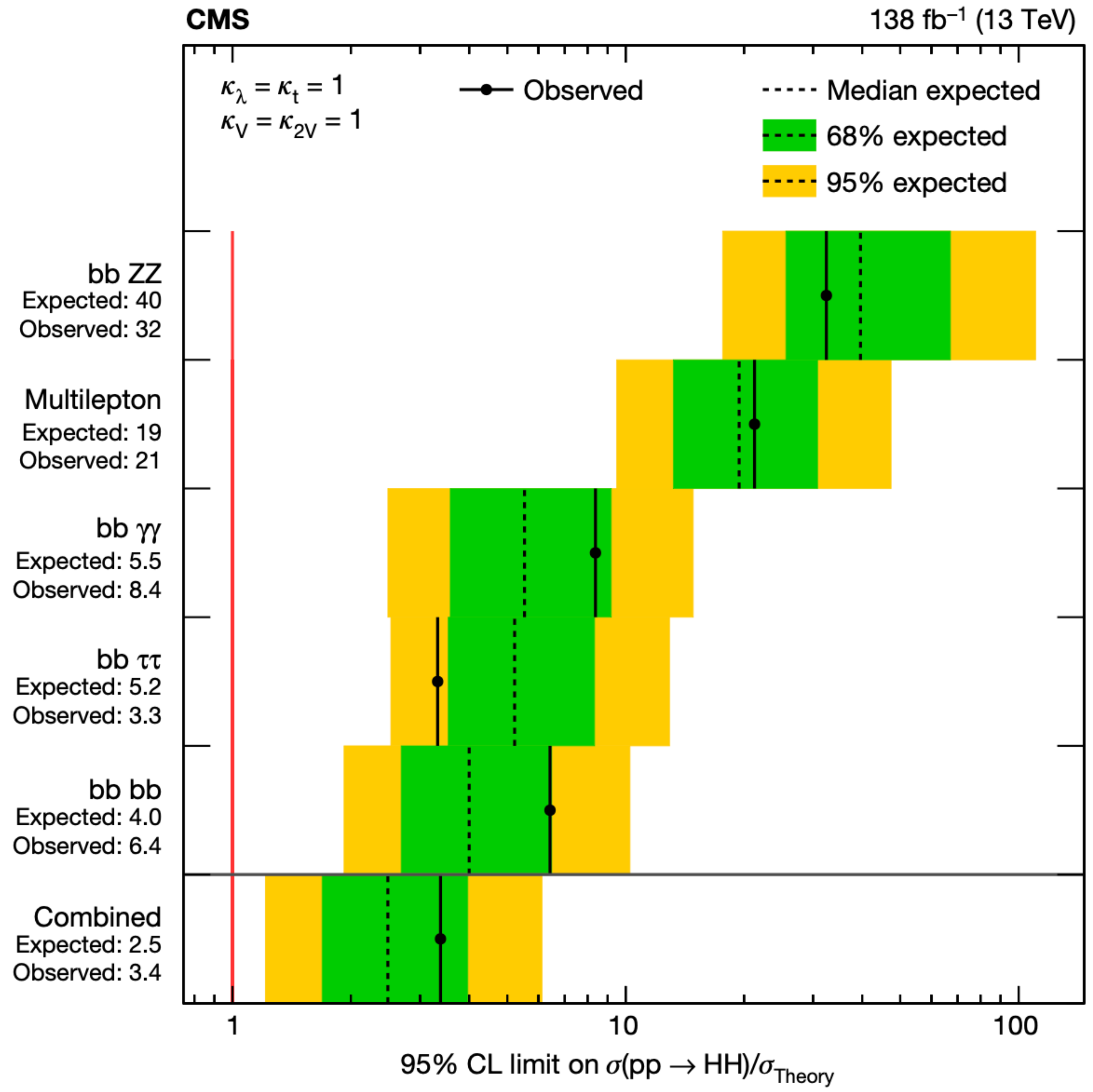
Phys. Lett. B 843 (2023) 137745

Previous CMS combination

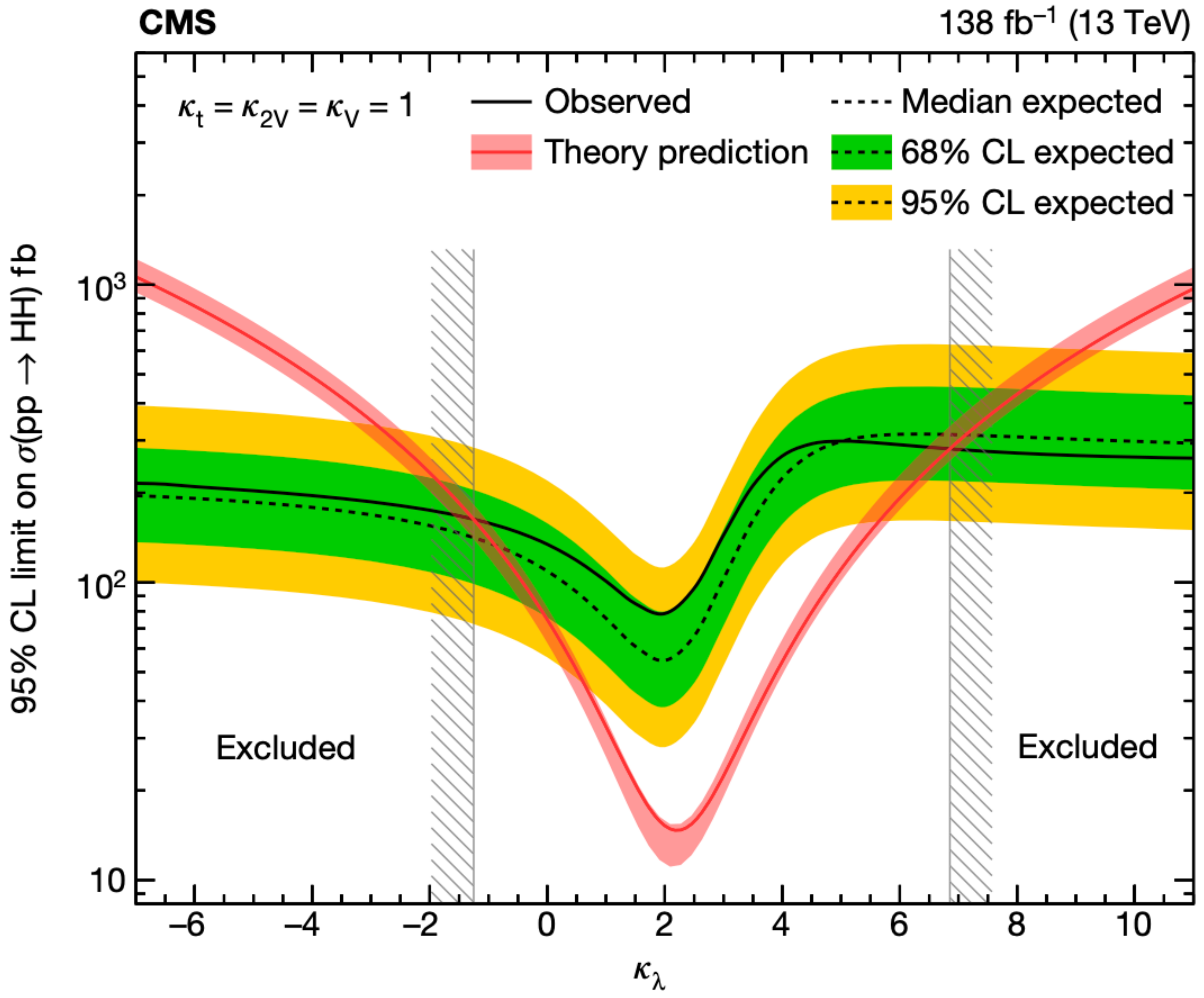
- Caveat: constraint based on upper limit scan, not directly comparable to constraint from likelihood scan

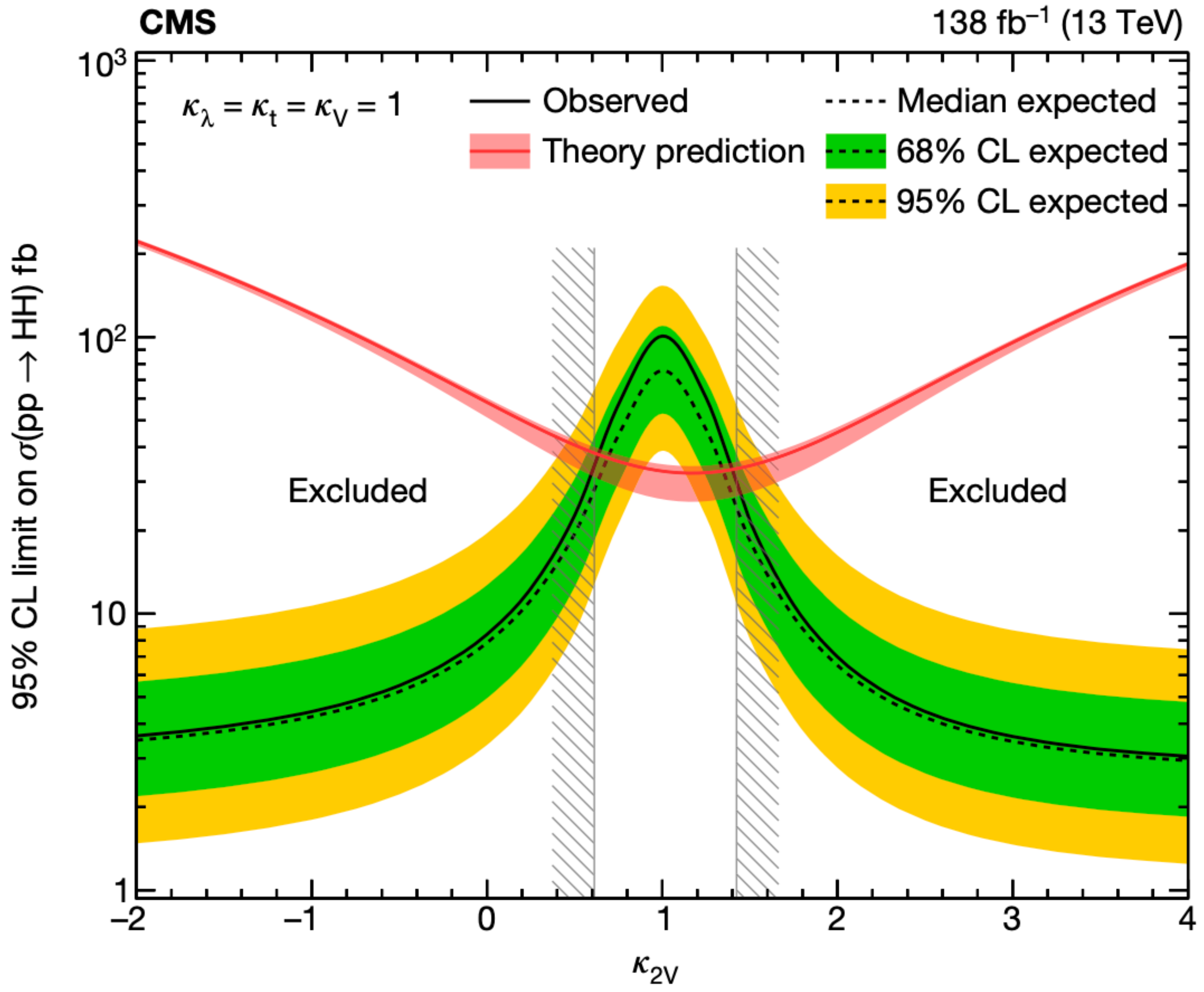
$-1.24 < \kappa_\lambda < 6.49$ (Observed 95% C.L.)

$0.67 < \kappa_{2V} < 1.38$ (Observed 95% C.L.)



[Nature 607, 60-68 (2022)]



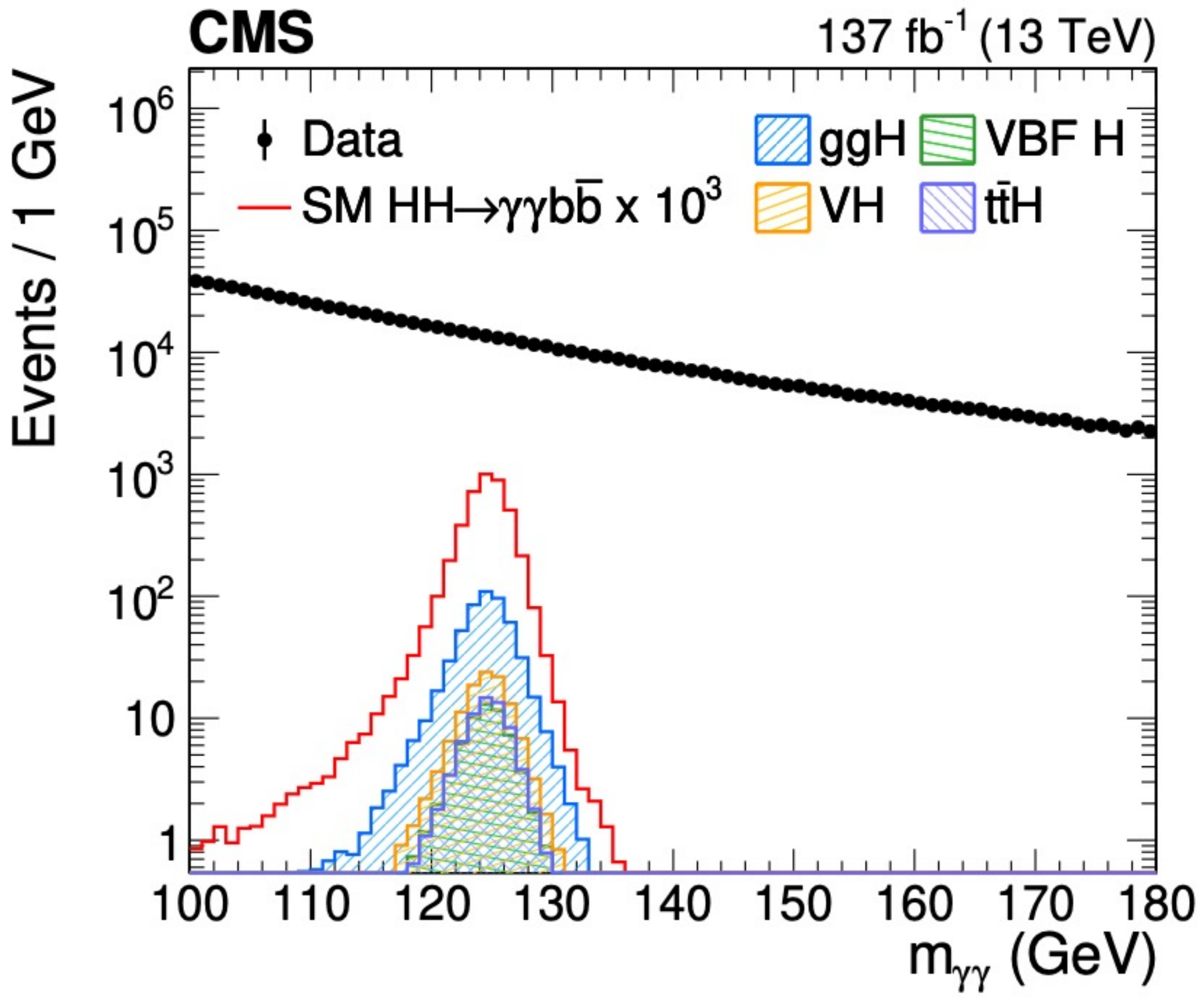


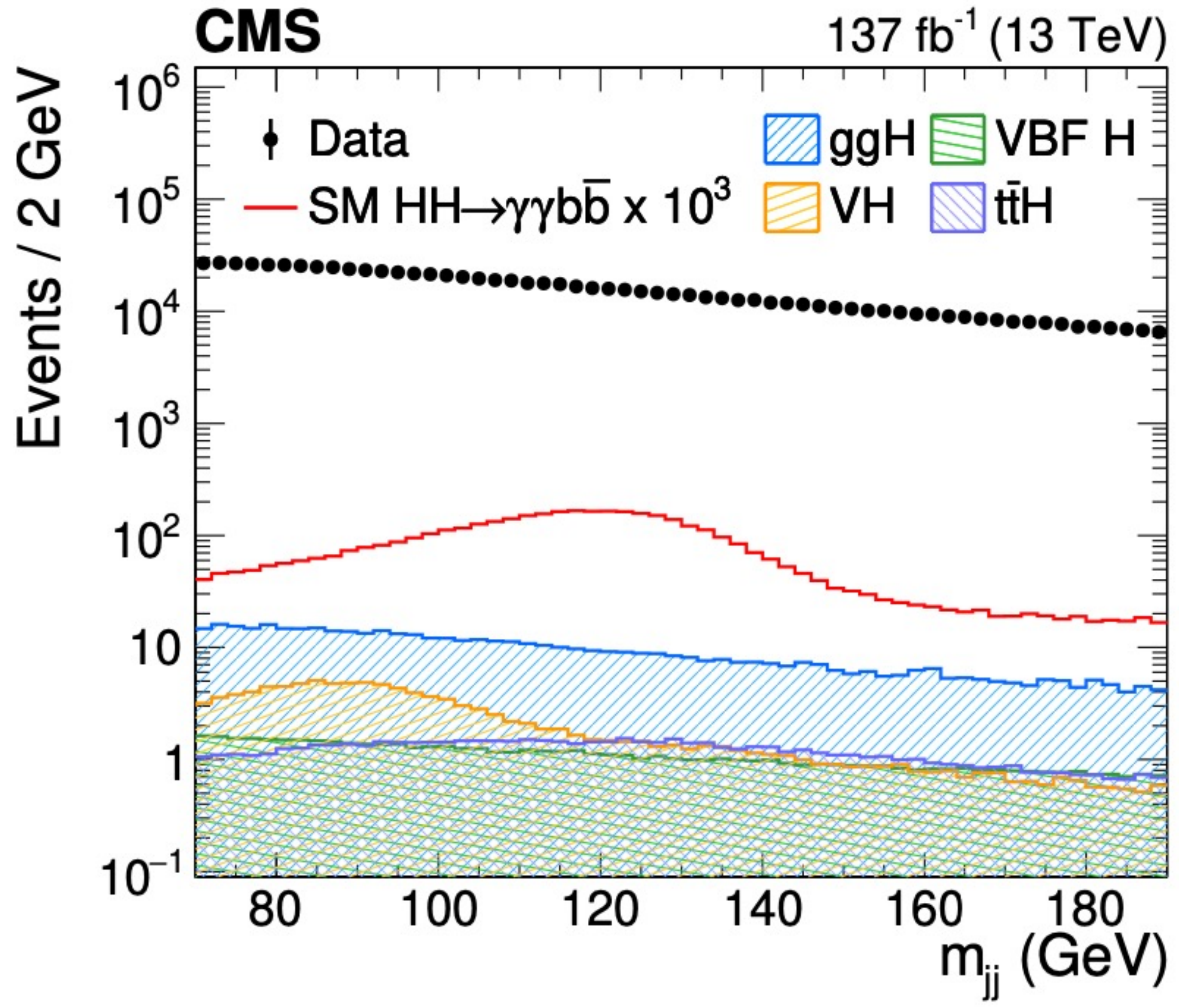
Backup

- $HH \rightarrow b\bar{b}\gamma\gamma$

[JHEP 03 (2021) 257](https://doi.org/10.1007/JHEP03(2021)257)

- $100 < m_{\gamma\gamma} < 180$ GeV
- $p_T^{\gamma 1}/m_{\gamma\gamma} > 1/3$ and $p_T^{\gamma 2}/m_{\gamma\gamma} > 1/4$
- $70 < m_{bb} < 190$ GeV
- Jet pT > 25 GeV





- Additional orthogonal categories targeting the $t\bar{t}H(\gamma\gamma)$ process are included in the analysis: $t\bar{t}H$ leptonic and $t\bar{t}H$ hadronic
- $t\bar{t}H$ leptonic: at least one isolated electron (muon) with $|\eta| < 2.4$ and pT > 10 (5) GeV, and at least one jet with pT > 25 GeV are required
- $t\bar{t}H$ hadronic: at least three jets are required, one of which must be b tagged, and a lepton veto is imposed

Backup

- $HH \rightarrow b\bar{b}b\bar{b}$ resolved

Phys. Rev. Lett. 129, 081802

- At least 4 Jets are required and the four Jets with the largest DEEPJET output are selected
- At least 3 of the selected jets are required to satisfy the medium WP of the DEEPJET discriminant
- **Events are rejected if they contain an electron or a muon with pT > 15 and 10 GeV**

Lepton veto! Only possible overlaps with $t\bar{t}H(b\bar{b})$ and $VHH(4b)$ fully hadronic channels

- $HH \rightarrow b\bar{b}WW$

CMS-PAS-HIG-21-005

- Single lepton channel: only a lepton satisfying tight selection criteria and have pT > 32 GeV. Either ≥ 3 small-radius jets or ≥ 1 large-radius jet + ≥ 1 small-radius which is separated from the large-radius jet by ΔR > 1.2.
- Dilepton channel: two leptons that pass the tight selection criteria and have opposite charges. Either ≥ 1 large-radius jet or ≥ 1 small-radius jet, that is b-tagged.

Categories	Sub-Categories		
HH(GGF)	Resolved 1b	Resolved 2b	Boosted
HH(VBF)	Resolved 1b	Resolved 2b	Boosted
Top + Higgs	Resolved		Boosted
WJets + Other	Inclusive		

Table 1: The summary of the categories of events according to the DNN based multiclassification and $H \rightarrow b\bar{b}$ topology for the single lepton channel.

Categories	Sub-Categories		
HH(GGF)	Resolved 1b	Resolved 2b	Boosted
HH(VBF)	Resolved 1b	Resolved 2b	Boosted
Top + Other	Resolved		Boosted
DY + Multi-boson	Inclusive		

Table 2: The summary of the categories of events according to the DNN based multiclassification and $H \rightarrow b\bar{b}$ topology for the dilepton channel.

Backup

- $VH(b\bar{b})$

  [Physics Letters B 780 (2018) 501–532]

Table 1
Selection criteria that define the signal region. Entries marked with "–" indicate that the variable is not used in the given channel. Where selections differ for different $p_T(V)$ regions, there are comma separated entries of thresholds or square brackets with a range that indicate each region's selection as defined in the first row of the table. The values listed for kinematic variables are in units of GeV, and for angles in units of radians. Where selection differs between lepton flavors, the selection is listed as (muon, electron).

Variable	0-lepton	1-lepton	2-lepton
$p_T(V)$	>170	>100	[50, 150], >150
$M(\ell\ell)$	–	–	[75, 105]
p_T^{ℓ}	–	(> 25, > 30)	>20
$p_T(j_1)$	>60	>25	>20
$p_T(j_2)$	>35	>25	>20
$p_T(jj)$	>120	>100	–
$M(jj)$	[60, 160]	[90, 150]	[90, 150]
$\Delta\phi(V, jj)$	>2.0	>2.5	>2.5
$CMVA_{max}$	>$CMVA_T$	>$CMVA_T$	>$CMVA_L$
$CMVA_{min}$	>$CMVA_L$	>$CMVA_L$	>$CMVA_L$
N_{aj}	<2	<2	–
$N_{a\ell}$	=0	=0	–
p_T^{miss}	>170	–	–
$\Delta\phi(\vec{p}_T^{miss}, j)$	>0.5	–	–
$\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{miss}(trk))$	<0.5	–	–
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	–	<2.0	–
Lepton isolation	–	<0.06	(< 0.25, < 0.15)
Event BDT	>−0.8	>0.3	>−0.8

Table 4
Definition of the control regions for the 1-lepton channels. The HF control region is divided into low- and high-mass ranges as shown in the table. The significance of p_T^{miss}, $\sigma(p_T^{miss})$, is p_T^{miss} divided by the square root of the scalar sum of jet p_T where jet $p_T > 30$ GeV. The values listed for kinematic variables are in units of GeV, except for $\sigma(p_T^{miss})$ whose units are $\sqrt{\text{GeV}}$. For angles units are radians. Entries marked with "–" indicate that the variable is not used in that region.

Variable	$t\bar{t}$	W+LF	W+HF
$p_T(j_1)$	>25	>25	>25
$p_T(j_2)$	>25	>25	>25
$p_T(jj)$	>100	>100	>100
$p_T(V)$	>100	>100	>100
$CMVA_{max}$	>$CMVA_T$	[$CMVA_L$,$CMVA_M$]	>$CMVA_T$
N_{aj}	>1	–	=0
$N_{a\ell}$	=0	=0	=0
$\sigma(p_T^{miss})$	–	>2.0	>2.0
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	<2	<2	<2
$M(jj)$	<250	<250	<90, [150, 250]

Backup

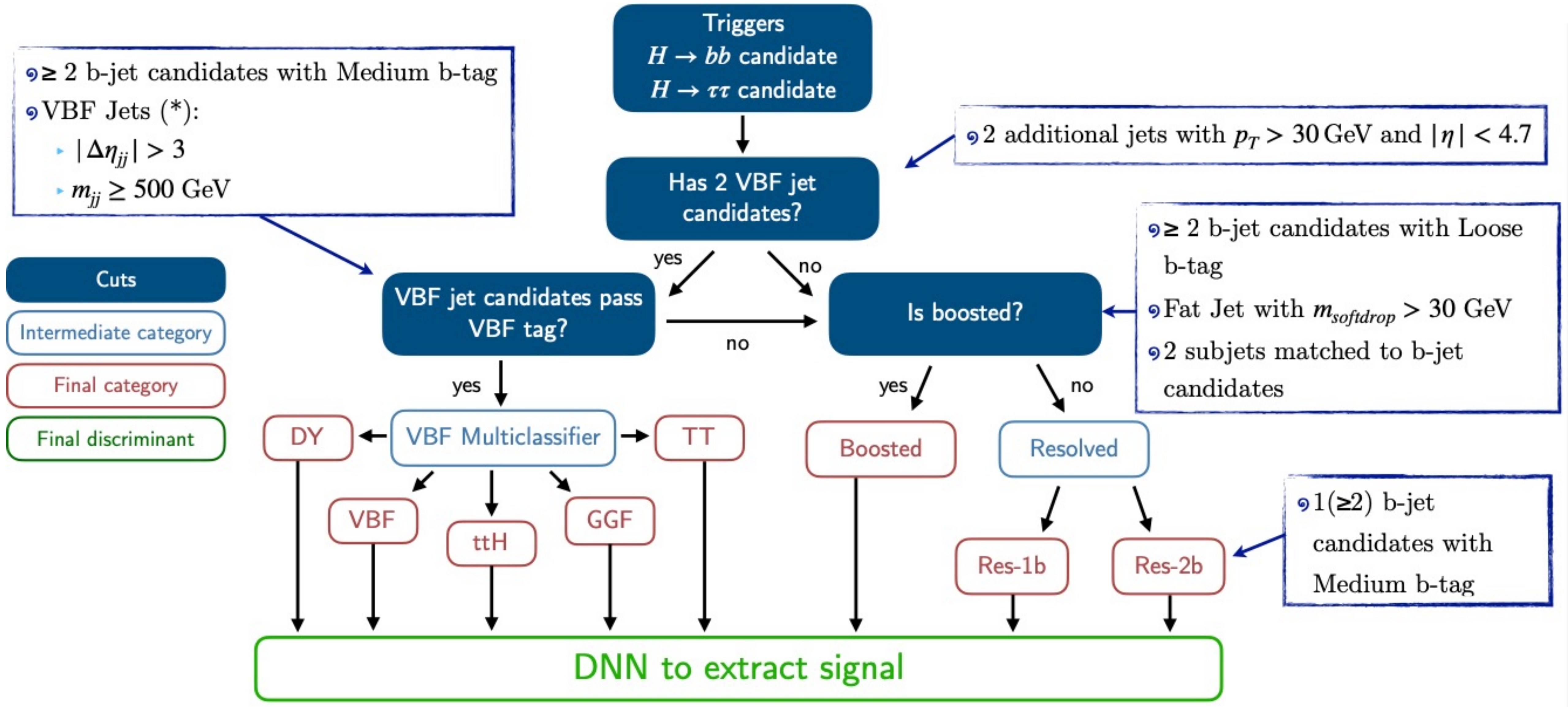
- $t\bar{t}H$ *multi-leptons*

  [Eur. Phys. J. C 81 (2021) 378]

Table 3: Event selections applied in the $0\ell + 2\tau_h$, $1\ell + 1\tau_h$, $1\ell + 2\tau_h$, and $2\ell + 2\tau_h$ channels. The p_T thresholds applied to the lepton and to the τ_h of highest and second-highest p_T are separated by slashes. The symbol "—" indicates that no requirement is applied.

Selection step	$0\ell + 2\tau_h$	$1\ell + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \to bqq'$, $t \to bqq'$ with $H \to \tau\tau \to \tau_h\nu\tau_h\nu$	$t \to bqq'$, $t \to bqq'$ with $H \to \tau\tau \to \ell\nu\nu\tau_h\nu$
Trigger	Double-τ_h trigger	Single-lepton and lepton+τ_h triggers
Lepton p_T	—	$p_T > 30$ (e) or 25 GeV (μ)
Lepton η	—	$\lvert\eta\rvert < 2.1$
τ_h p_T	$p_T > 40$ GeV	$p_T > 30$ GeV
τ_h η	$\lvert\eta\rvert < 2.1$	
τ_h identification	loose	medium
Charge requirements	$\sum_{\tau_h} q = 0$	$\sum_{\ell,\tau_h} q = 0$
Multiplicity of central jets	$\geq$4 jets	
b tagging requirements	$\geq$1 tight b-tagged jet or $\geq$2 loose b-tagged jets	
Dilepton invariant mass	$m_{\ell\ell} > 12$ GeV	

- $HH \to b\bar{b}\tau\tau$



Borrow from Valeria's [slides]

- Some overlaps are found between the $HH \to b\bar{b}\tau\tau$ analysis and two sub-dominant categories of $t\bar{t}H$ *multi-leptons* analysis targeting final states with $1l + 1\tau_h$ or $0l + 2\tau_h$. These two categories are removed from $t\bar{t}H$ *multi-leptons* without any significant impact on the combination.

Backup

- *HH multi-leptons*

  JHEP 07 (2023) 095

  - 7 channels according to lepton multiplicity: $4\tau_h$, $1l + 3\tau_h$, $2l + 2\tau_h$, $3l + 1\tau_h$, $\boldsymbol{3l}$, $\boldsymbol{2lss}$, $4l$

Category	2ℓss	3ℓ
Targeted HH decays	WW^*WW^*	WW^*WW^*
Trigger	Single- and double-lepton	Single-, double- and triple-lepton
Lepton p_T	>25 / 15 GeV	>25 / 15 / 10 GeV
Lepton charge sum	±2, with charge quality requirements applied	±1
Dilepton invariant mass	$\lvert m_{\ell\ell} - m_Z \rvert > 10\,\mathrm{GeV}$ †	$\lvert m_{\ell\ell} - m_Z \rvert > 10\,\mathrm{GeV}$ ‡
Jets	≥2 small-radius jets or ≥1 large-radius jet	≥1 small-radius jet or ≥1 large-radius jet
Missing p_T	$p_T^{miss,LD} > 30\,\mathrm{GeV}$ §	$p_T^{miss,LD} > 30\,\mathrm{GeV}$ ‖

- $H \to$ WW

  Eur. Phys. J. C 83 (2023) 667

Category	Number of leptons	Number of jets	Subcategorization
ggH	2	—	(DF, SF) × (0 jets, 1 jet, ≥2 jets)
VBF	2	≥2	(DF, SF)
VH2j	2	≥2	(DF, SF)
WHSS	2	≥1	(DF, SF) × (1 jet, 2 jets)
WH3ℓ	3	0	SF lepton pair with opposite or same sign
ZH3ℓ	3	≥1	(1 jet, 2 jets)
ZH4ℓ	4	—	(DF, SF)

- The $\boldsymbol{3l}$ category, is the dominant category of the *HH multi-leptons* analysis and hence is
- Similarly, the $\boldsymbol{2lss}$ category plays a sub-dominant role in *HH multi-leptons* and is dropped in favor of the corresponding categories in $H \to$ WW. The removal of these categories does not impact significantly the sensitivity of this combination

Statistical procedure

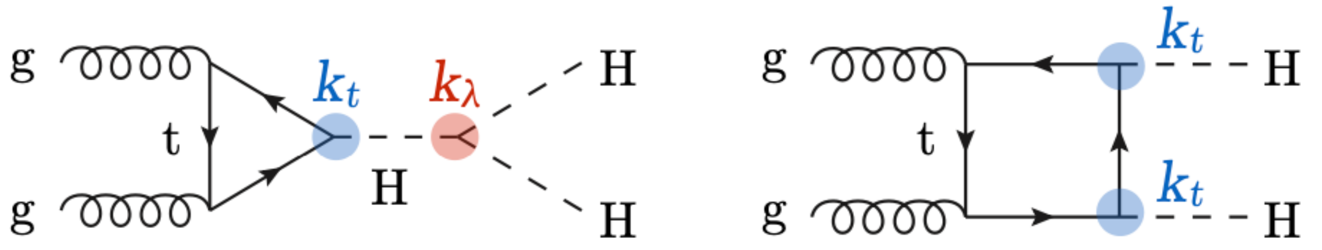
- A profiled likelihood ratio q is used as test statistics to estimate the parameters of interest (POIs) $\vec{\alpha}$ of the model and their associated confidence interval, taking into account the systematic uncertainties as individual nuisance parameters $\vec{\theta}$:

$$q(\vec{\alpha}) = -2\log\left(\frac{L(\vec{\alpha},\hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}},\hat{\vec{\theta}})}\right)$$

- L is the likelihood function, which is built as the product of the likelihoods of the respective input analyses, multiplied by constraint terms on the nuisance parameters
- The POIs and nuisance parameter values maximizing the likelihood function are given by $(\hat{\vec{\alpha}},\hat{\vec{\theta}})$, while $\hat{\hat{\vec{\theta}}}(\vec{\alpha})$ is the set of nuisance parameter values which maximize the likelihood function for a given set of POI values
- The $\hat{\vec{\alpha}}$ are taken as the best-fit values of the considered POIs. For the one-dimensional measurements, the intervals at 1σ and 2σ confidence levels are identified as the intervals of POI values for which q < 1 and q < 4, respectively. Instead, for two-dimensional measurements the 1σ and 2σ surfaces correspond to the regions of POI values which give q < 2.30 and q < 6.18, respectively

Physics model

- Combine model describe HH and single H XS's w.r.t κ_λ and Higgs coupling to fermions and vector bosons
- HH modeled at differential level w.r.t $\kappa_\lambda, \kappa_t, \kappa_V, \kappa_{2V}$

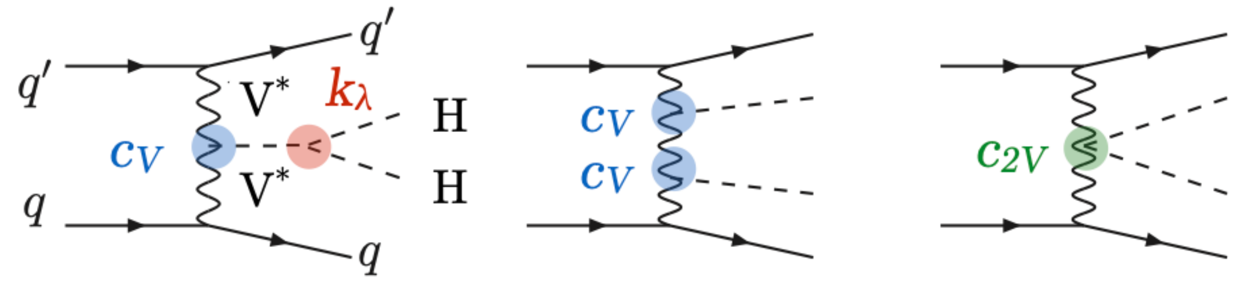


$$A = k_t\, k_\lambda\, T + k_t^2\, B$$

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

$$= \underbrace{k_t^2\, k_\lambda^2\, t}_{\textit{triangle}} + \underbrace{k_t^4\, b}_{\textit{box}} + \underbrace{k_t^3\, k_\lambda\, i}_{\textit{interference}}$$

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



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

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

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

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

Borrow from Marcel Rieger's slides: [Searches for non-resonant Higgs Boson Pair Production with CMS]

Physics model

- Combine model describe HH and single H XS's w.r.t κ_λ and Higgs coupling to fermions and vector bosons
- HH modeled at differential level w.r.t $\kappa_\lambda, \kappa_t, \kappa_V, \kappa_{2V}$
- SH modeled following the theory prescriptions
  - Differential effects of κ_λ up to STXS 1.2 granularity
  - H coupling effect on SH and HH BR also considered

Single H cross sections

κ_λ effect on single-H XS

$$\frac{\sigma^i}{\sigma^i_{SM}} = Z_{\mathrm{H}}^{BSM}\left[\frac{(\kappa_\lambda - 1)C_1^i}{K^i_{EW}} + F_i(\kappa_{\mathrm{V}}, \kappa_f)\right] \quad \text{with } Z_{\mathrm{H}}^{BSM} = \frac{1}{1-({\kappa_\lambda}^2 - 1)\delta Z_{\mathrm{H}}}$$

k-factor for NLO EW corrections not factorizing with κ_λ effects

κ_F, κ_V Scaling from k-framework

Wavefunction renormalization

Higgs branching ratios

$$\frac{BR^f}{BR^f_{SM}} = \frac{\kappa_f^2 + C_1^f(\kappa_\lambda - 1)}{\sum_j BR^j_{SM}\left[\kappa_f^2 + C_1^j(\kappa_\lambda - 1)\right]}$$

JHEP12(2016)080
Eur. Phys. J. C (2017) 77: 887