CMS searches for Higgs boson pair production

Alexandra Carvalho
On behalf of the CMS collaboration

CERN seminar, 12 November 2024

The Higgs mechanism

- The Standard Model of particle physics is a formidable description of known matter and the three of four elementary forces in Nature
- The Higgs mechanism is the simplest way to unify ElectroWeak interactions,

$$\Phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

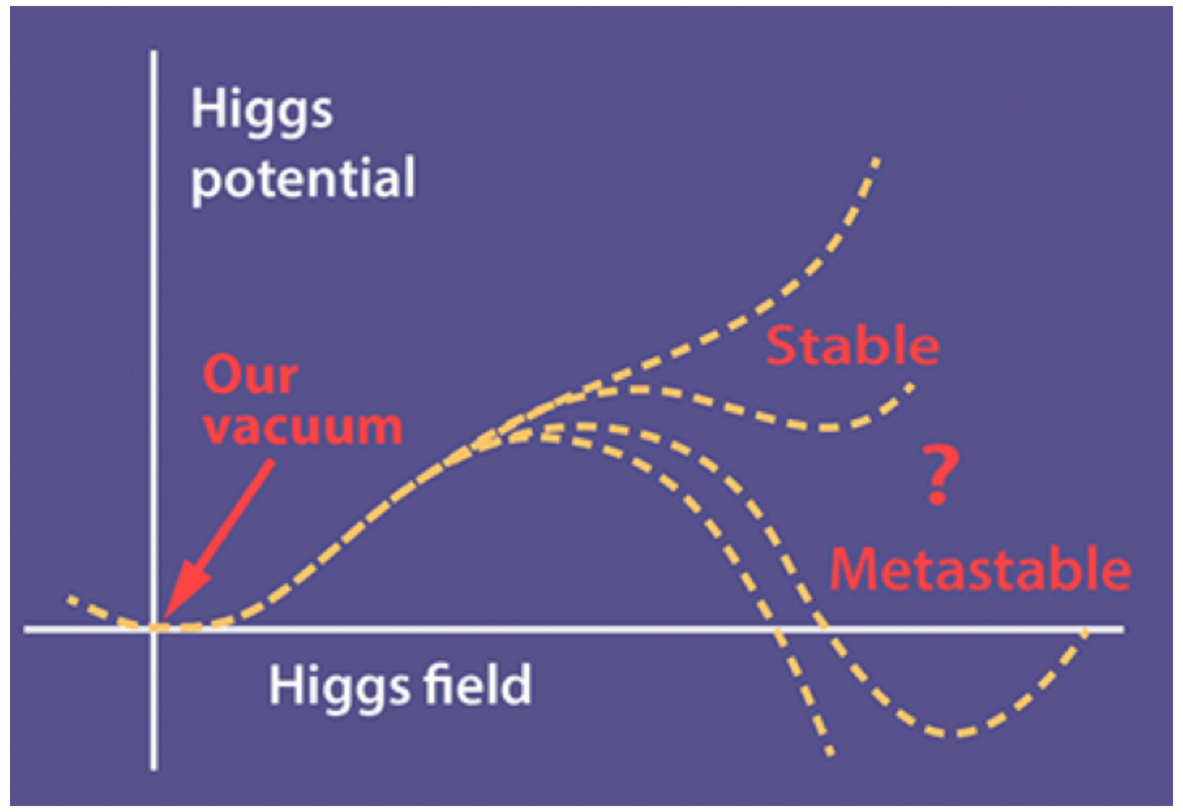
SU(2) doublet

$$V(\Phi^\dagger\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

One mass term, one self coupling

- Spontaneous breaking of the EW symmetry (EWSB) results in the mass properties of the Weak gauge bosons, plus a scalar particle: The Higgs Boson (H)

- Once its mass is known, many things are predicted:
  - Mass of all known matter is generated via the H couplings
  - The shape of the H potential is determined (value of it self coupling) ==> the fate of the vacuum of the universe

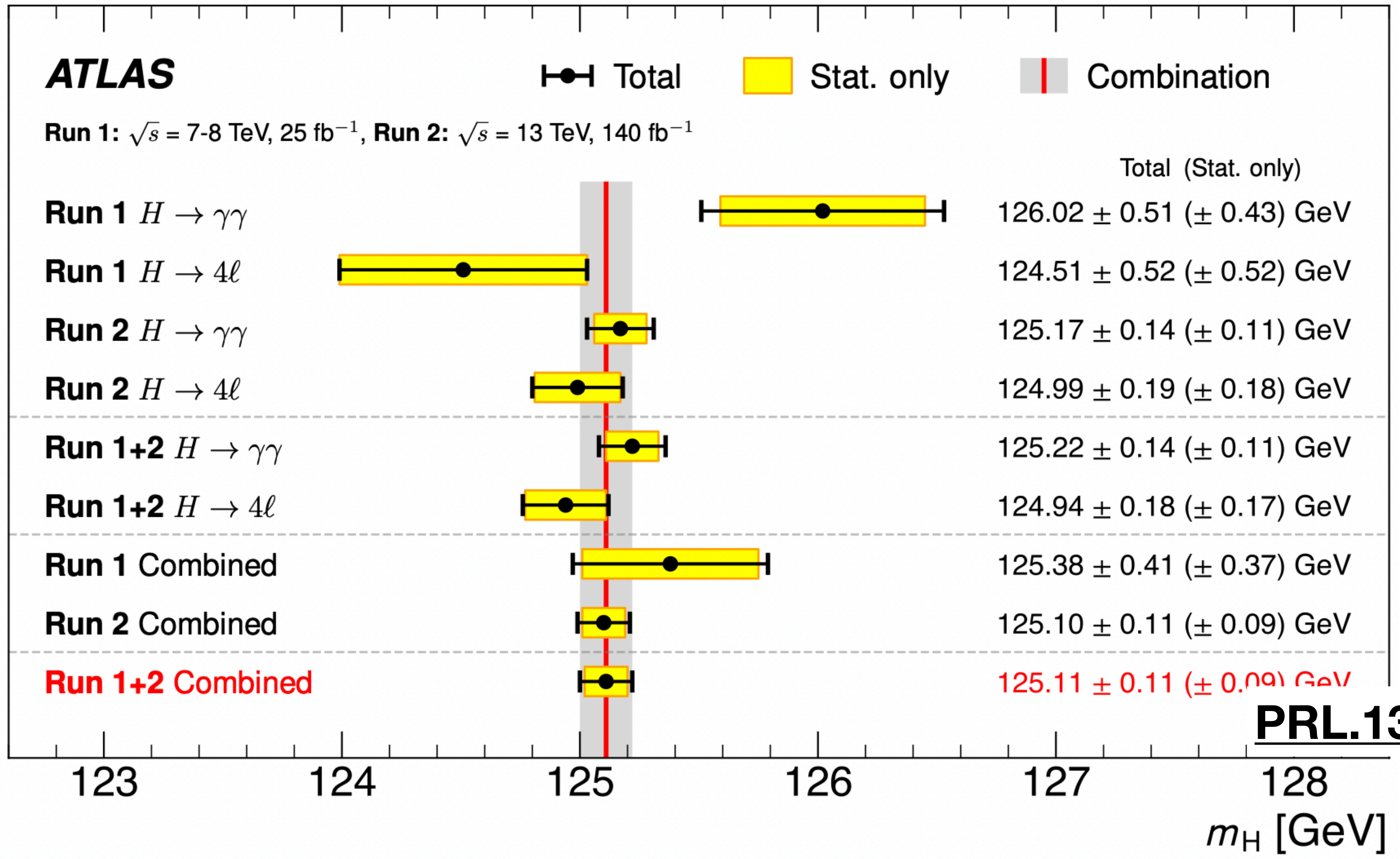


Deviations on the H potential disbalance all predictions and would be a clear sign on New Physics

The Higgs Boson

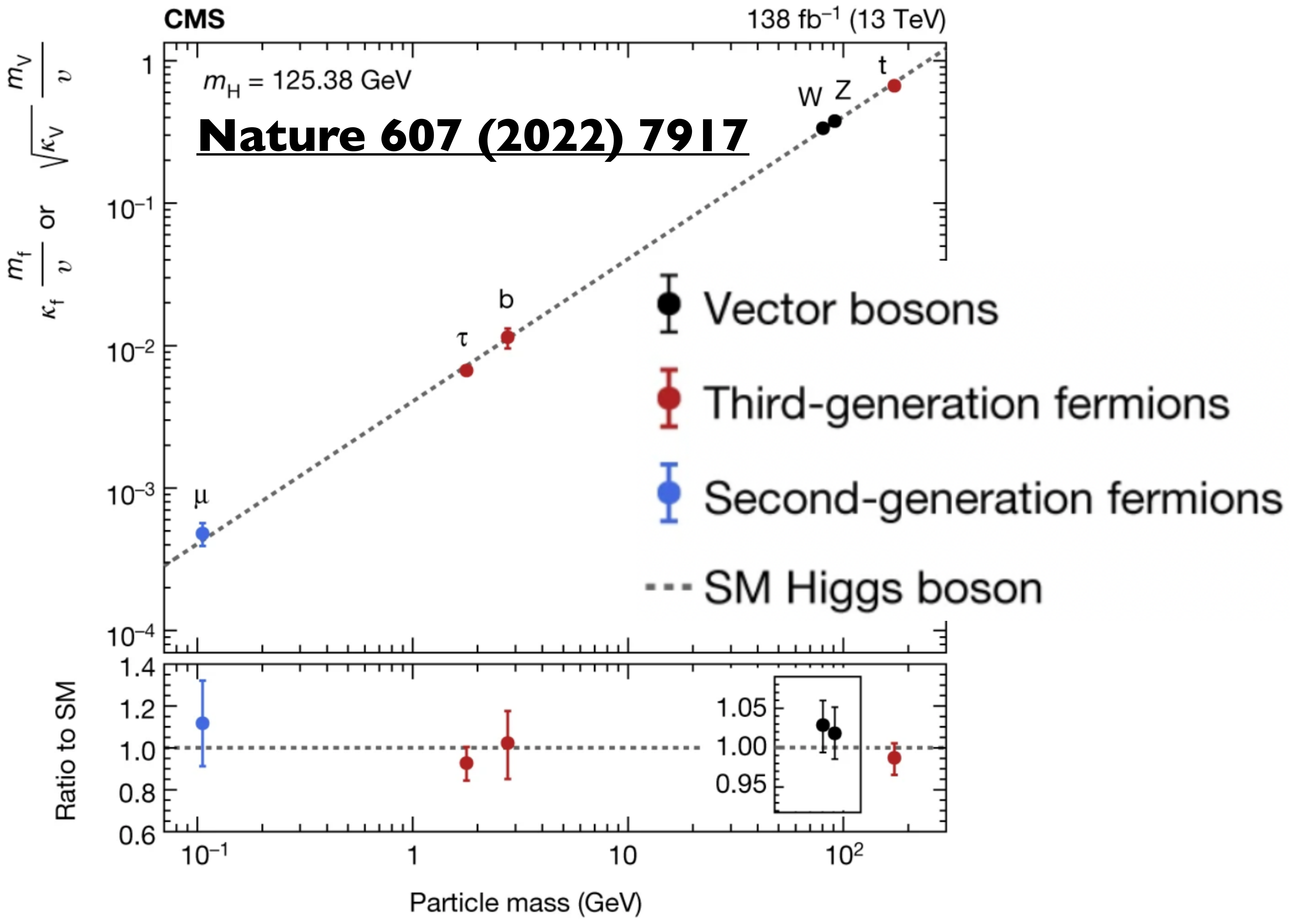
- The Higgs boson was discovered by the ATLAS and CMS experiments at the LHC in 2012
  - many studies of Higgs boson properties have been performed, in particular:

mH measured with astonishing precision



PRL.131.251802

Particle masses relations to their couplings to H follow the SM predictions



Nature 607 (2022) 7917

The H width and CP properties are well measured

What is missing?
The H potential !!!

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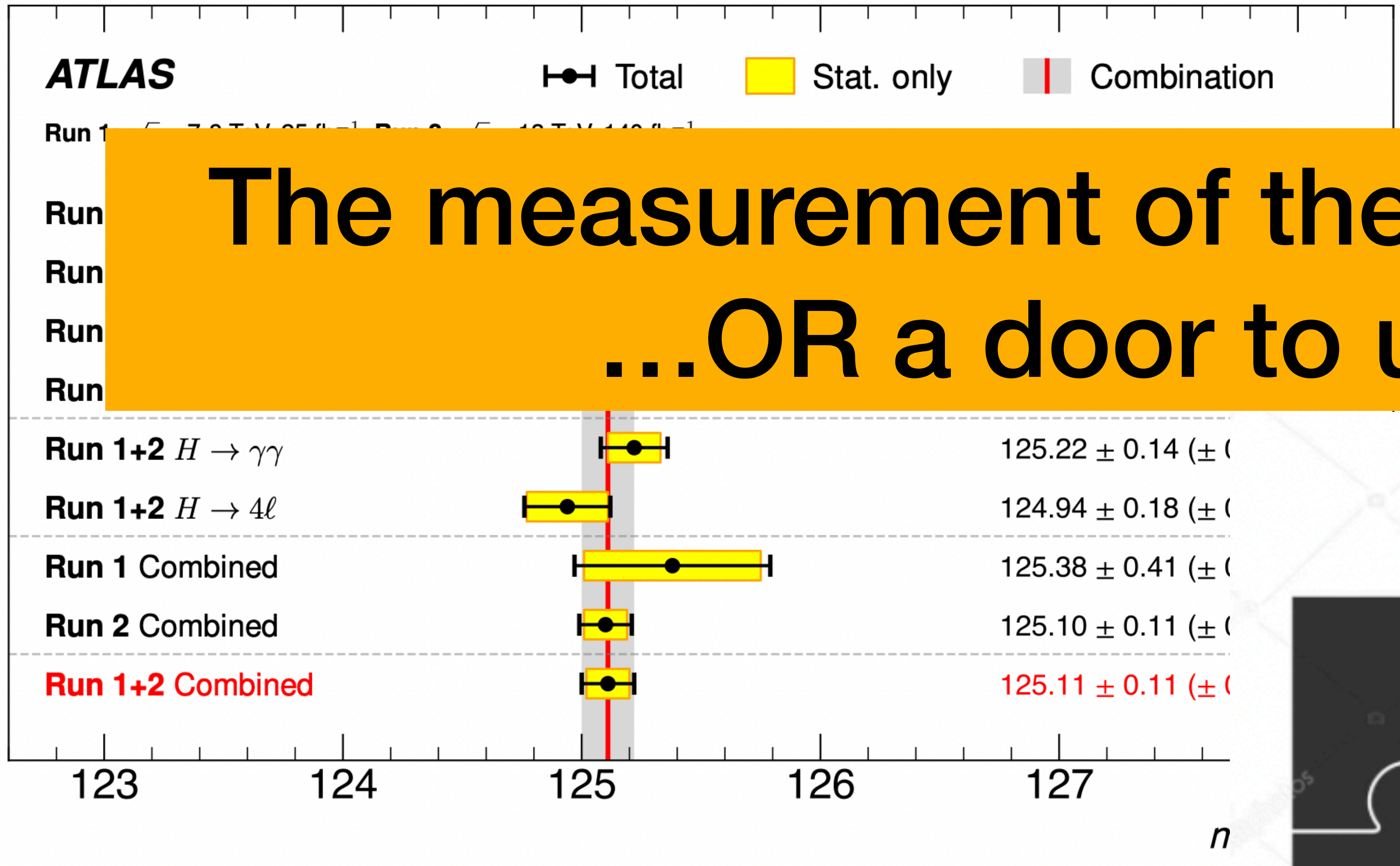
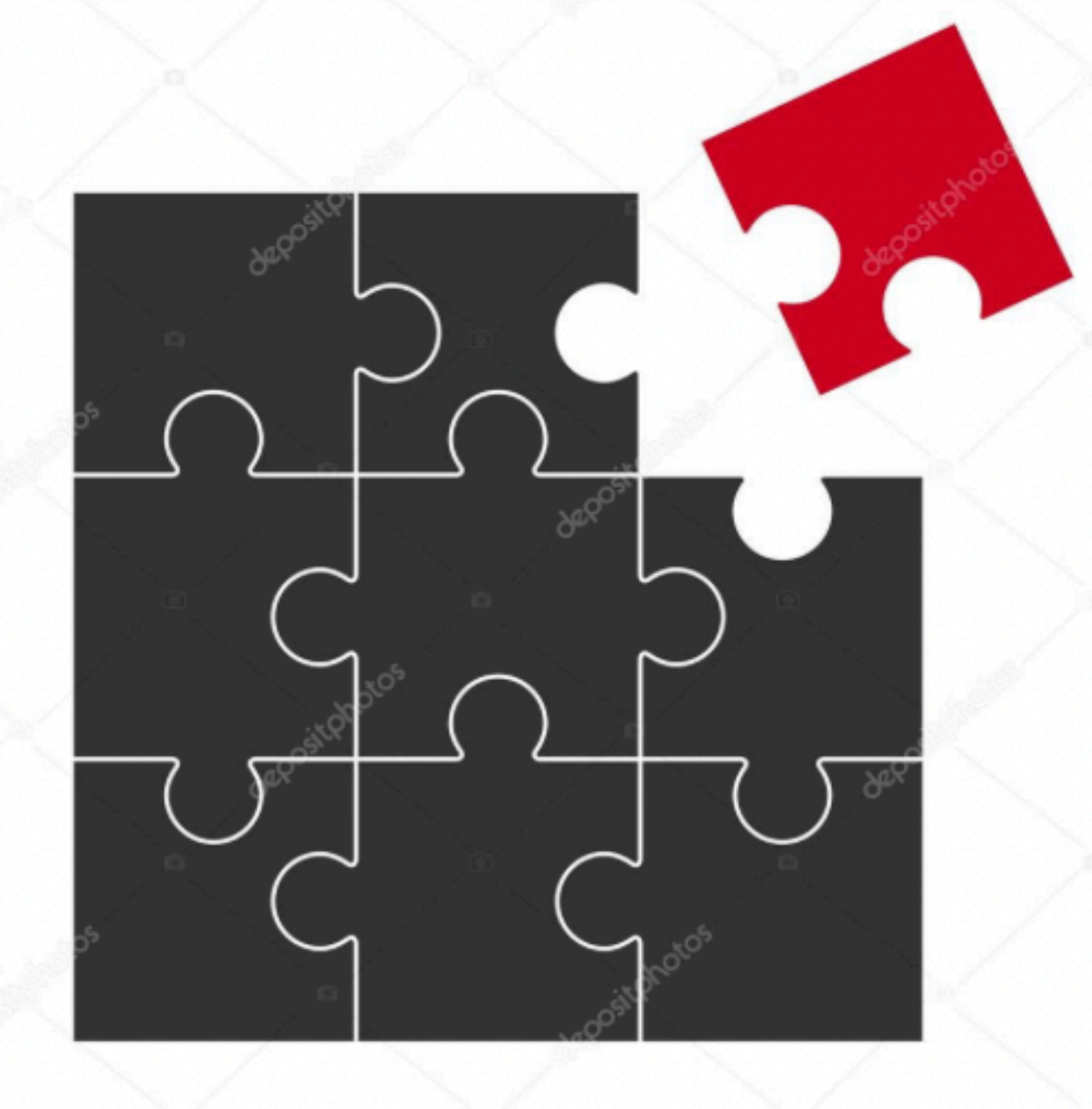


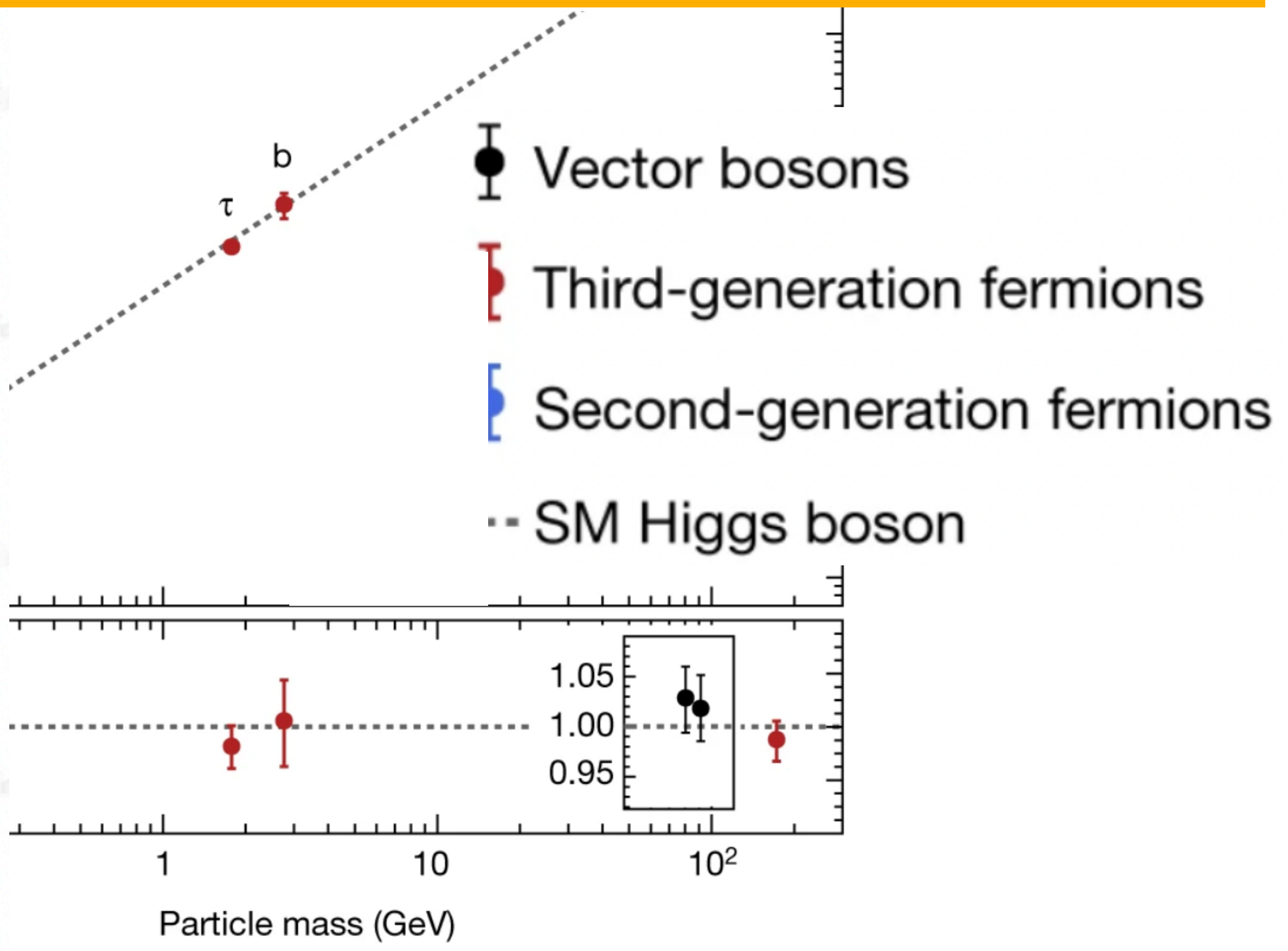
Particle masses relations to their couplings to H follow the SM predictions

The measurement of the H potential is a closure of the SM …
…OR a door to understand physics beyond it

The H width and CP properties are w

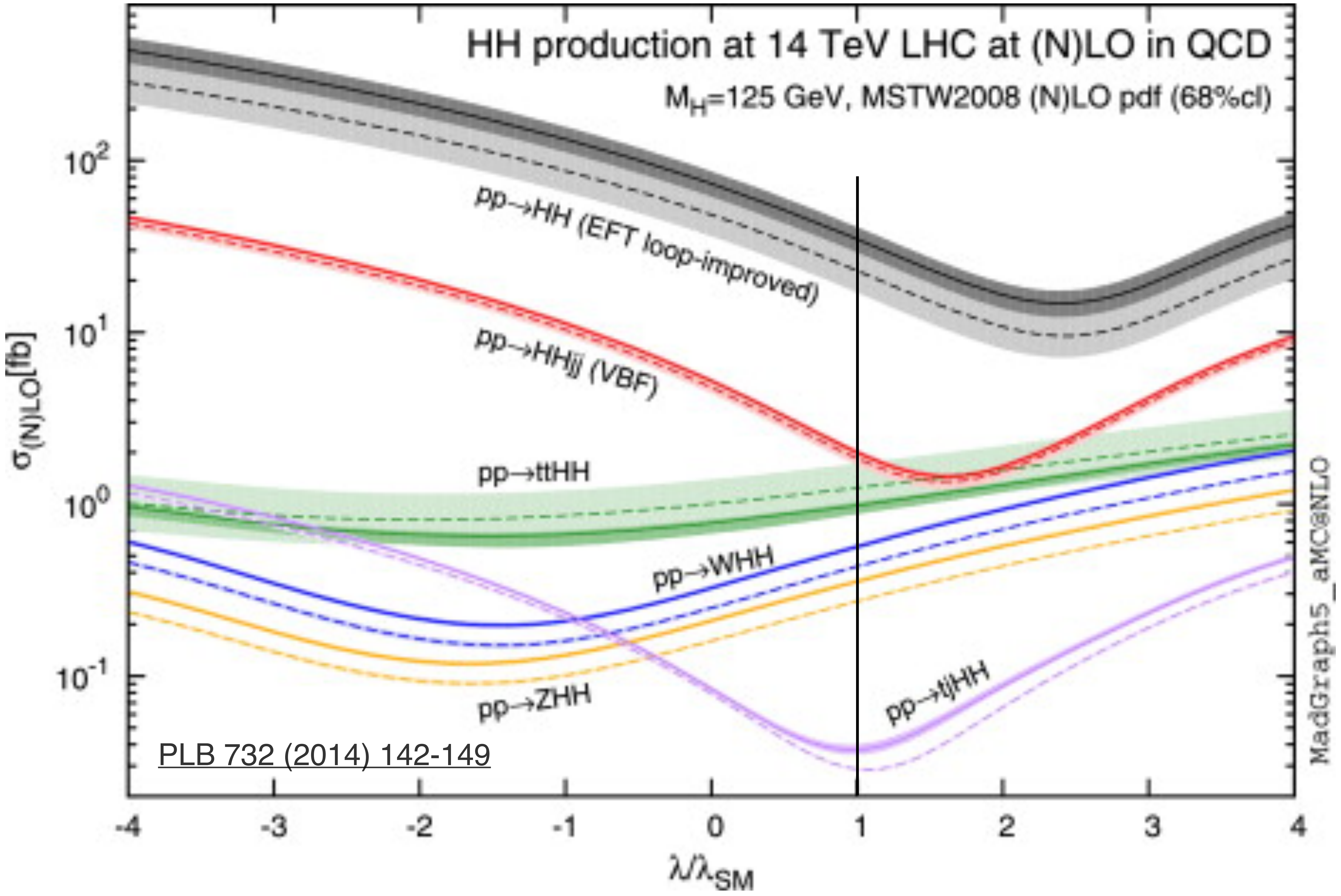
What is missing?
The H potential !





Higgs pairs in the Standard Model

The search for non-resonant H boson pair production is the only direct method to probe λ at LHC

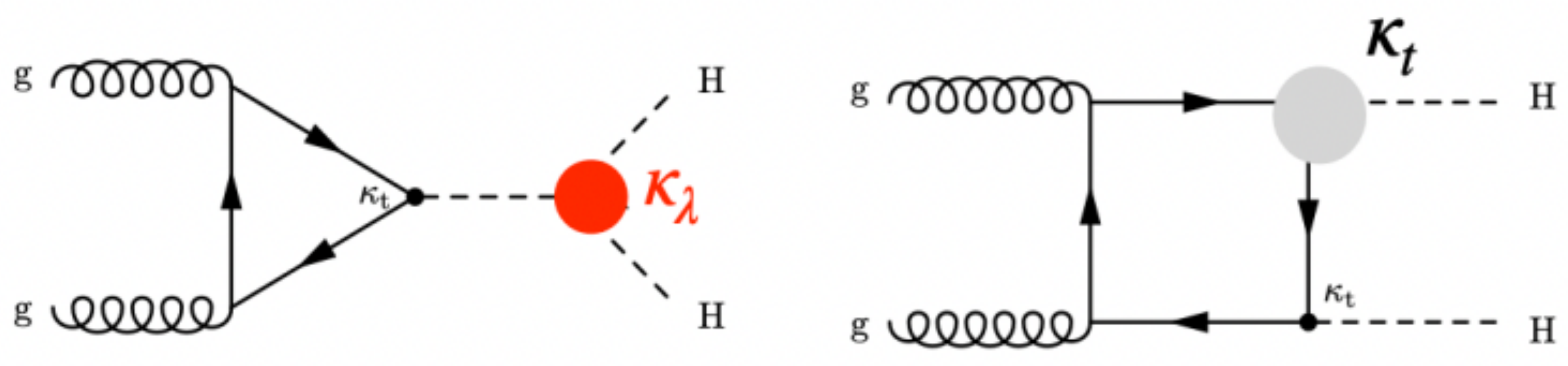


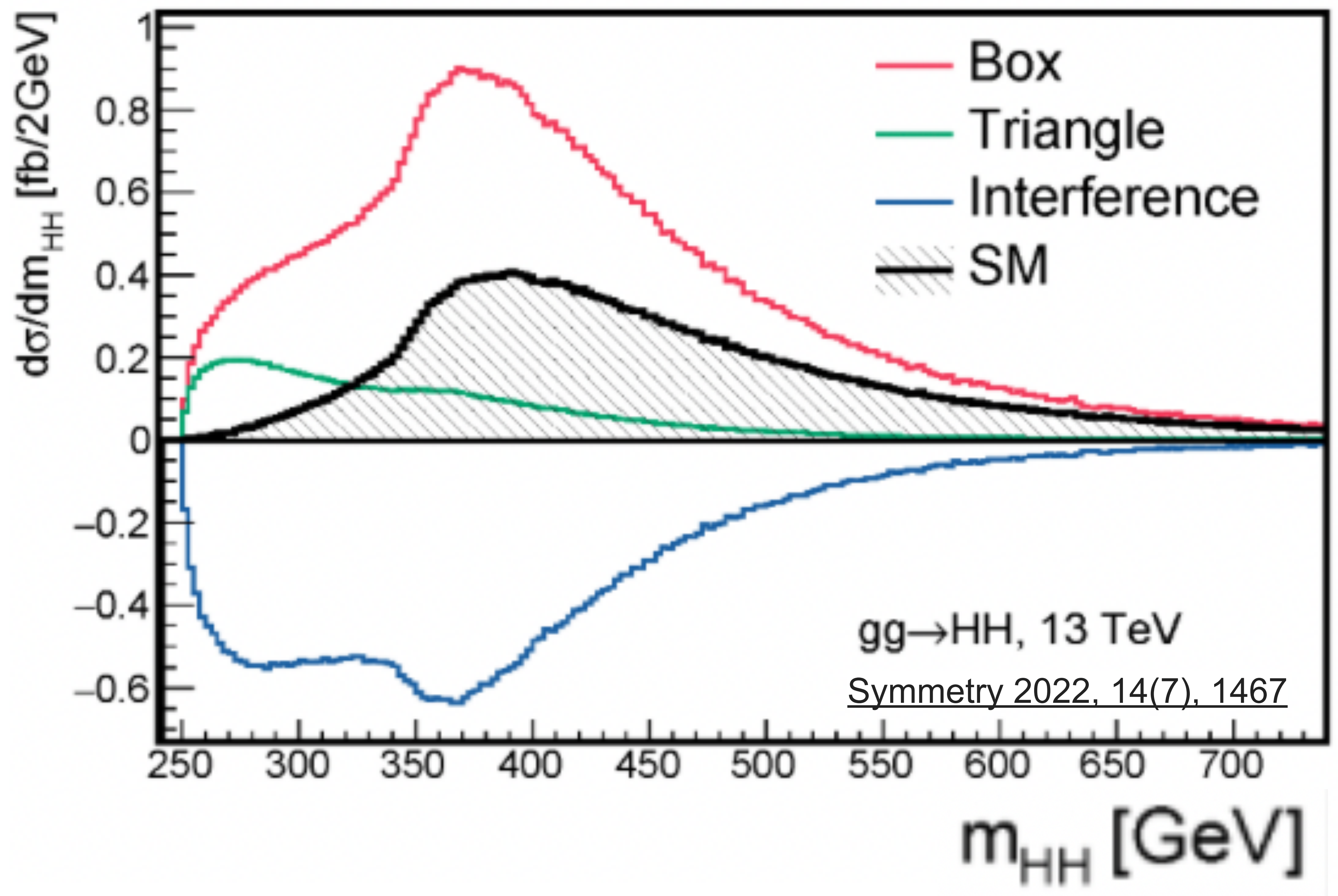
Main production mechanisms at the LHC are gluon fusion (ggF) and vector boson fusion (VBF)

Test deviation from the SM couplings with κ-framework: $\kappa_X = X / X_{SM}$

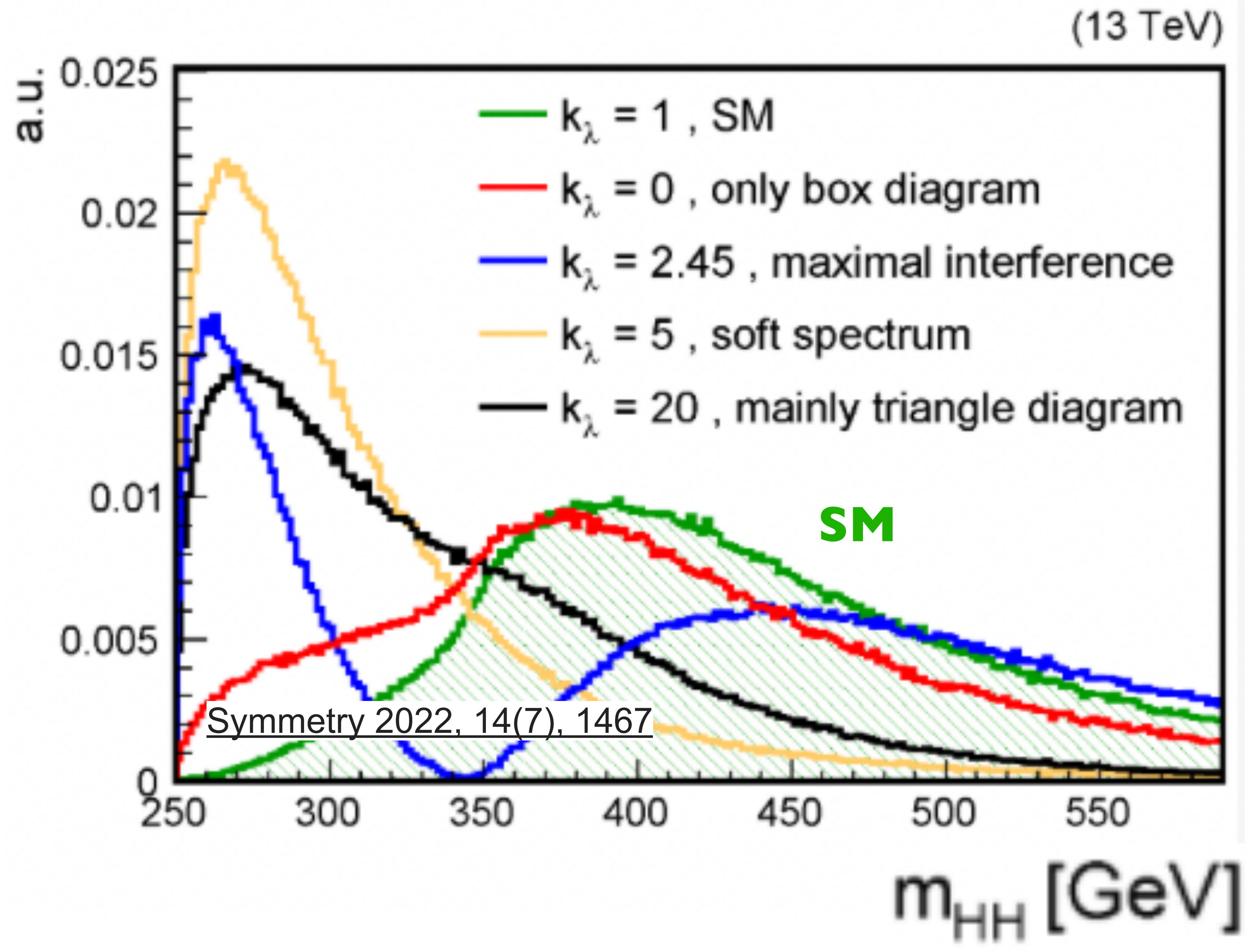
Higgs pairs in the SM: gluon fusion production

ggF: loop induced processes, destructive interference





σ_{ggF} **(SM) = 31.05 fb**

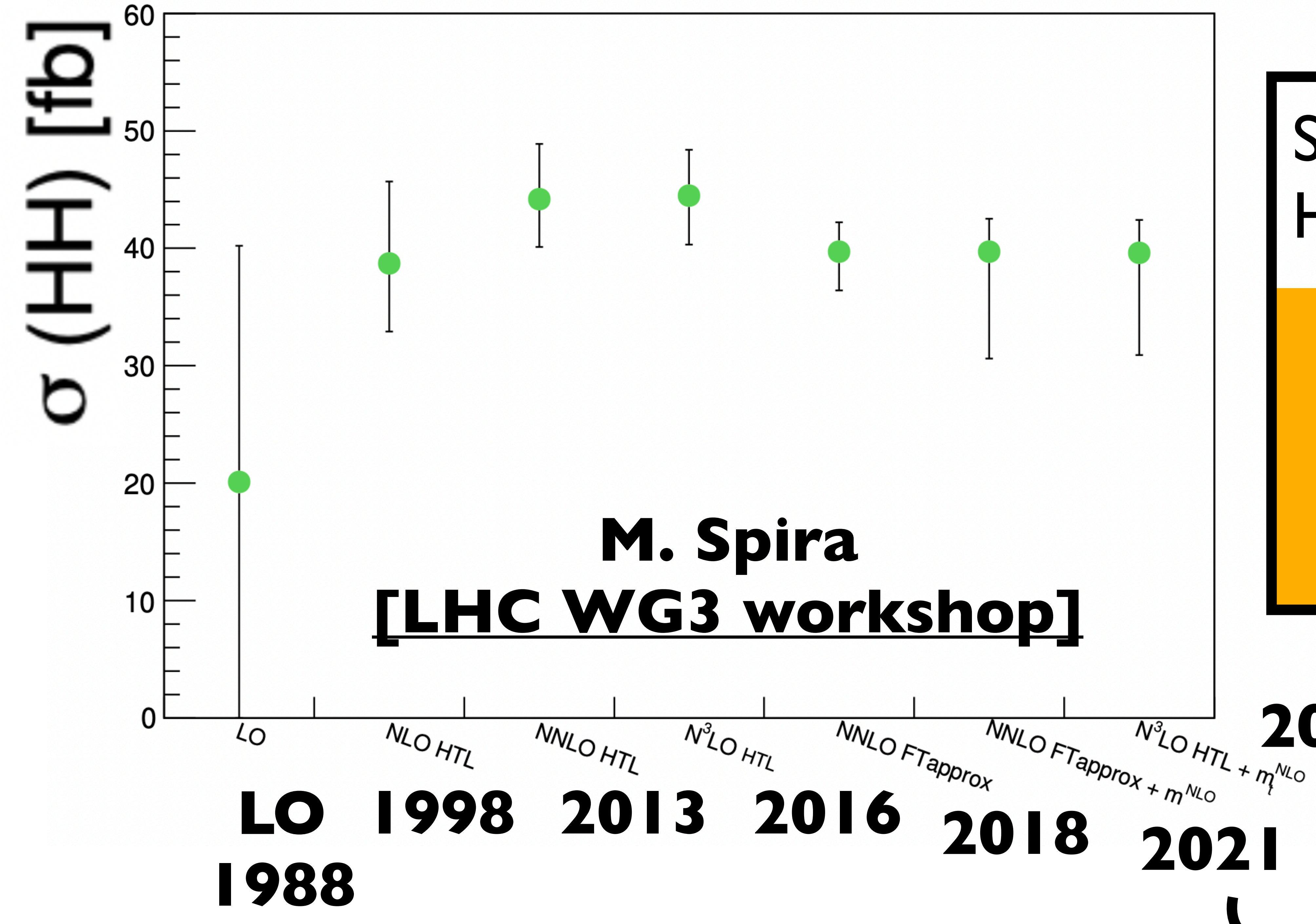


Deviations of κλ from the SM prediction
==> softer signal

The theory saga on ggF signal modelling

- ggF H pair production is an one loop process, making its simulation challenging
  - First modelled using form factors to emulate the loop [2014]
  - Full model at QCD NLO precisions to SM-like processes [2016]
    - Including BSM-like processes in HEFT [2020], and SMEFT [2022]

- Total cross-section computation had evolved considerably in the last years

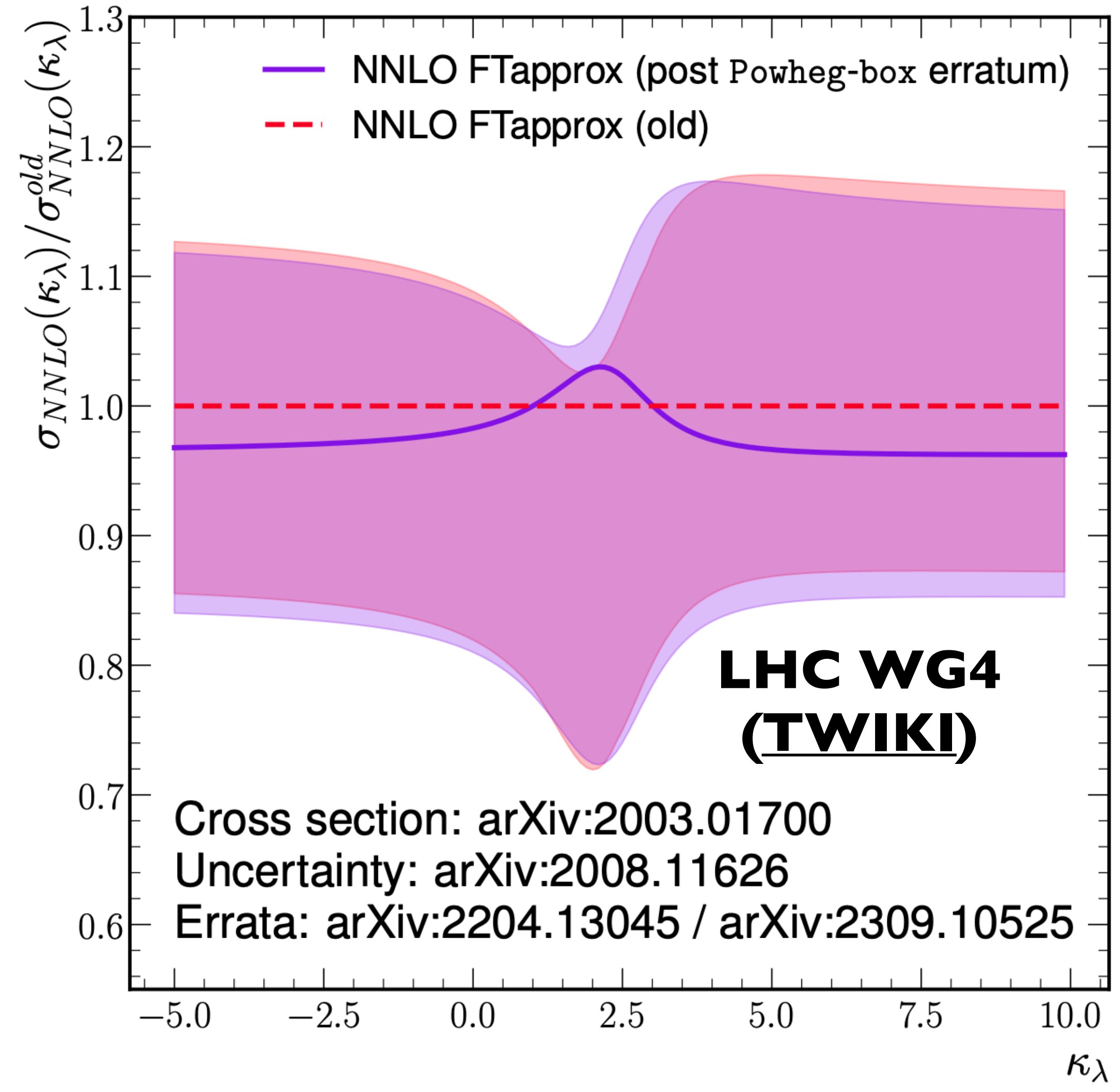


2022

State of art: N3LO w/ Heavy top mass approx.

Still needs progress: Uncertainties in top mass dominate the uncertainty

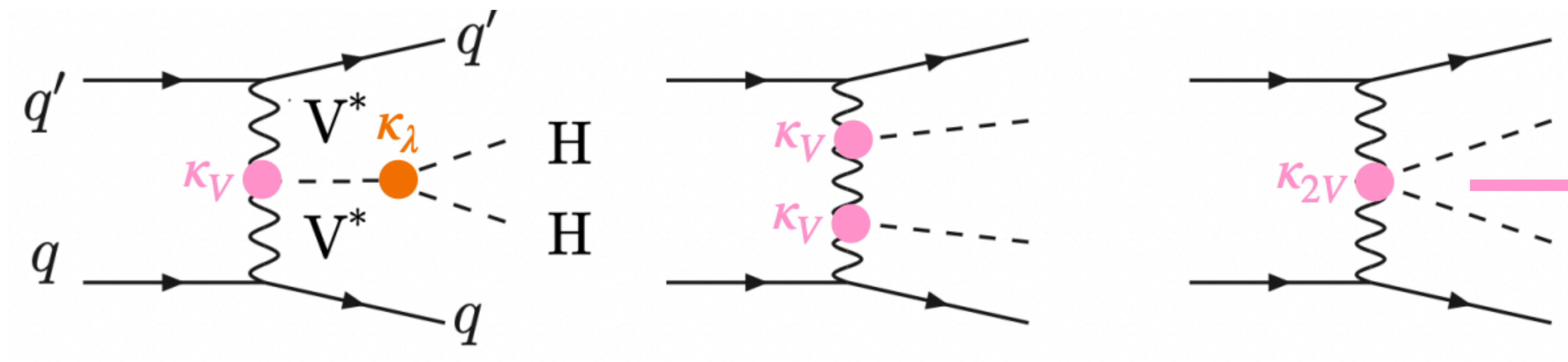
We use N3LO with top mass effects, That got sligtly updated since last comb.



Higgs pairs in the SM: Vector Boson fusion production

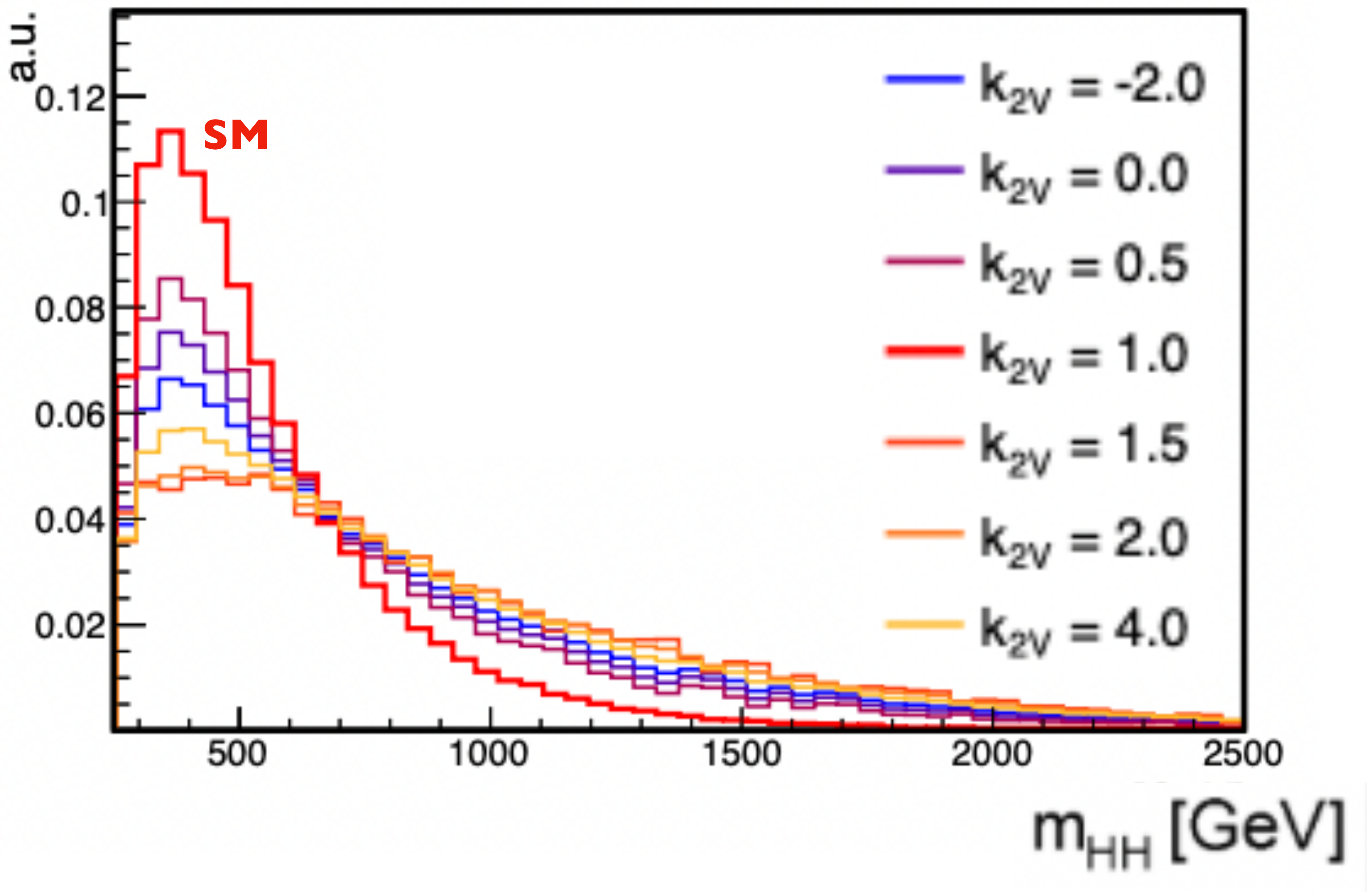
VBF: tree-level process

σ_{VBF} (SM) = 1.7 fb



The VVHH contact interaction is also probed

A test of the doublet structure of the H field !



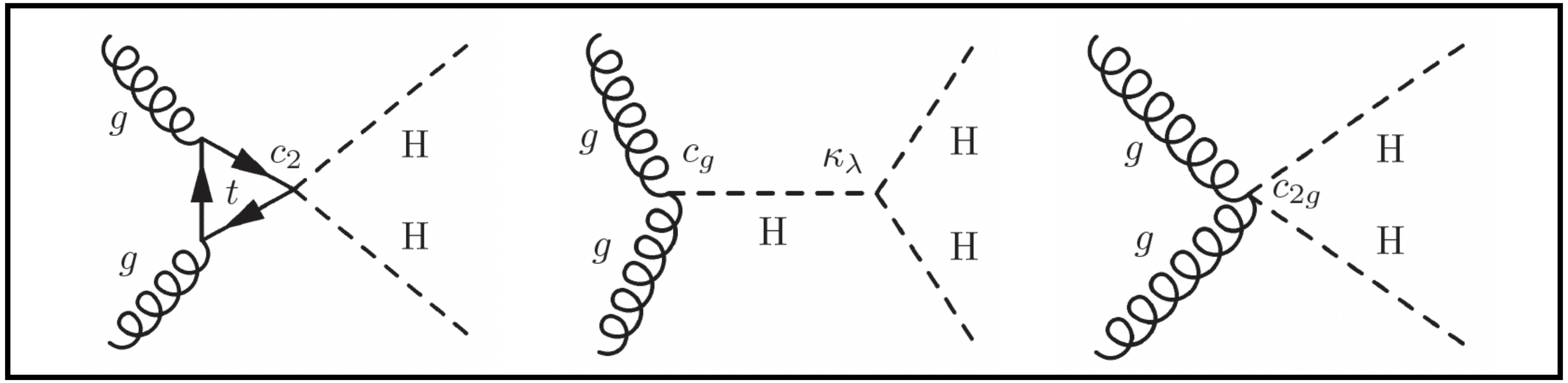
Deviations of κ_{2V} from the SM prediction ==> harder signal

κ_{2V} is also probed with V-associated production of H pairs (VHH)

What if there is more than the SM interactions

New symmetries and/or new (super) heavy particles induces additional effective terms into the H potential

- specially on ggF production (BSM-like couplings)



More violent variations in signal topology and cross section variations

- We assumed these in the Higgs EFT (HEFT) scenario
  => linear variation of couplings
    - Althernative approach, Standard Model EFT (SMEFT) the Symmetries existend on the SM are assumed to govern the new interactions, introducing correlations between couplings
- New physics influencing H pairs production can also manifest itself on the existence of resonances decaying to H pairs, accessible by the LHC (for a review of CMS results see arXiv:2405.17605, acc. by Physics Reports)
  - If the new particles are additional H bosons, the couplings of the 125 GeV are changed by mixing,
    - also, event topologies can be modified by interference terms

What if there is more than the SM interactions

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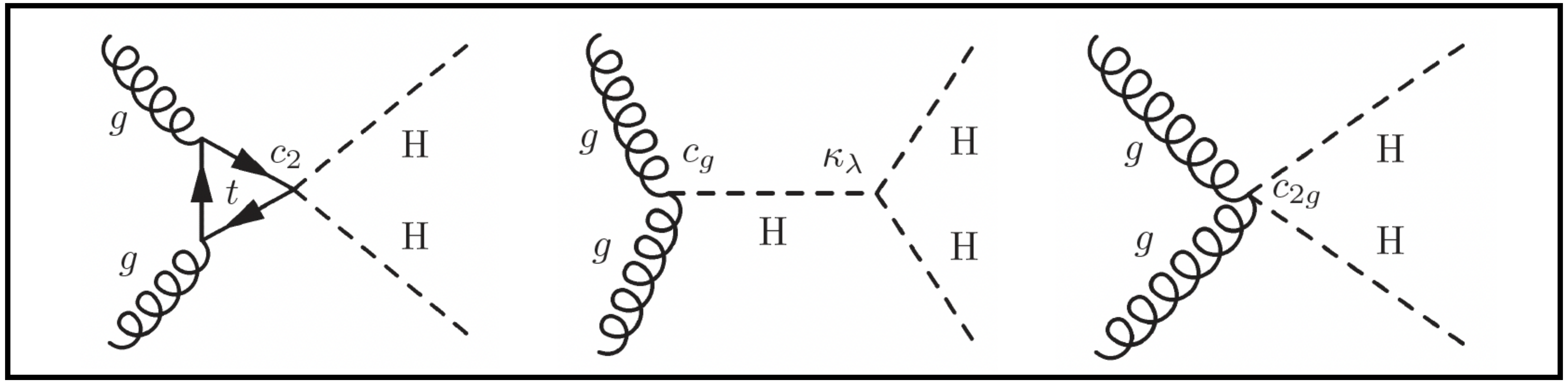
- Especially in ggF production (BSM-like couplings)



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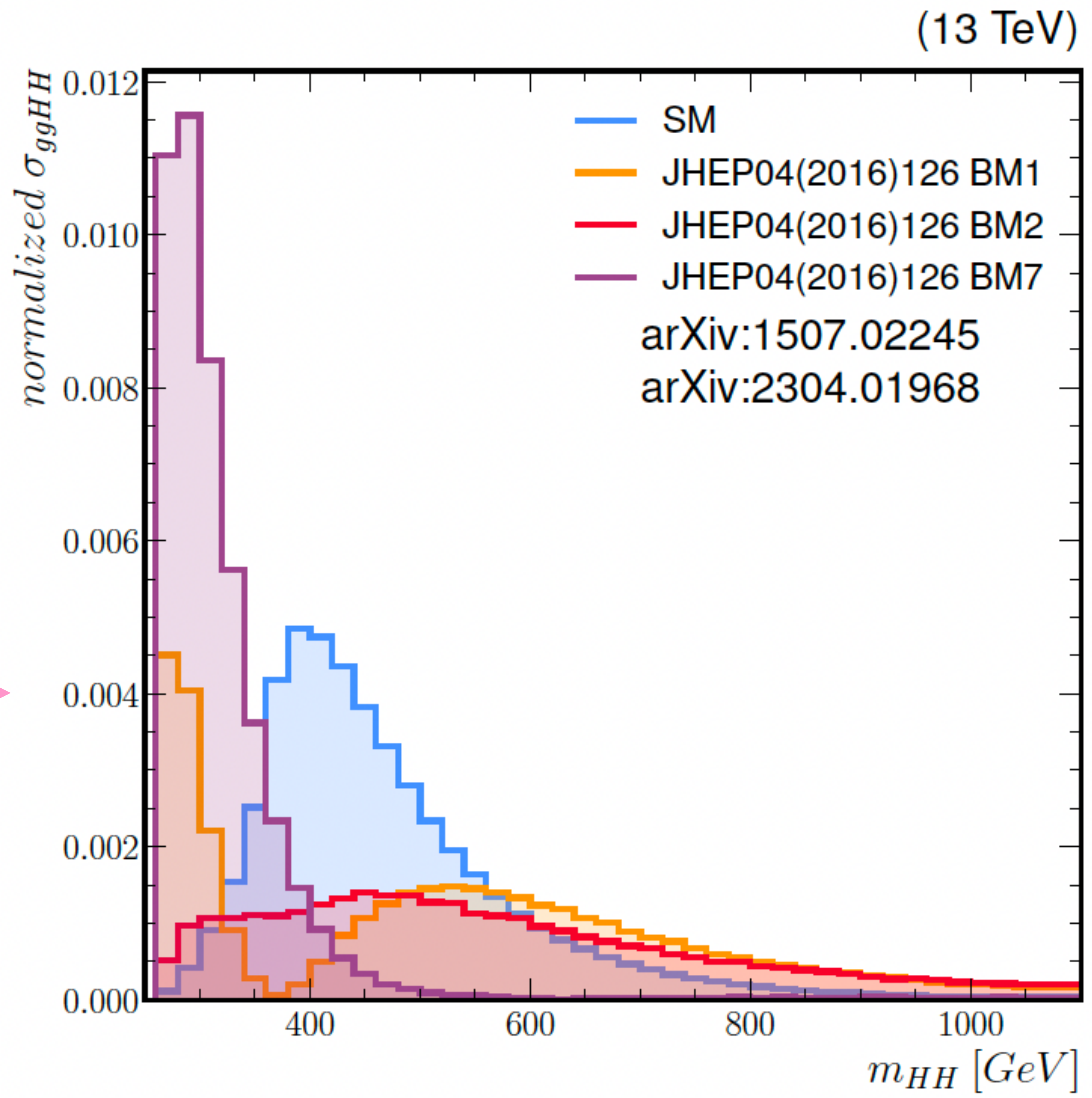

- We assumed these in the Higgs EFT (HEFT) scenario
  => linear variation of couplings

- Upper limits in representative signal topologies scanning all couplings
  ==> shape Benchmarks
- Parameter scans: We give priority to scan the ttHH coupling (c_2)
  ==> deeply connected with κ_λ and κ_t in most complete theories

Deviations of c2 from the SM prediction ==> harder signal

The CMS saga towards the H potential

H125 discovery July 2012

↓

First non-resonant HH search
PRD 94 (2016) 5, 052012

↓

κ_λ ~ [-17, 22]
19.7/fb @ 8 TeV

→ Several results in full Run2 data! / Theory updates →

Combination CMS full Run 2 HH searches
Nature 607 (2022) 7917

↑ More channels!

Combination between single Higgs measurements and HH searches
arXiv:2407.13554, *accepted by PLB*

→ More channels! / Theory updates / HEFT →

Legacy Combination CMS full Run 2 HH searches
PAS-HIG-20-011 →

↓

κ_λ between [-1.4, 6.4] at 95% CL 138/fb @ 13 TeV

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This talk

More channels! → Theory updates HEFT

Legacy Combination CMS full Run 2 HH searches
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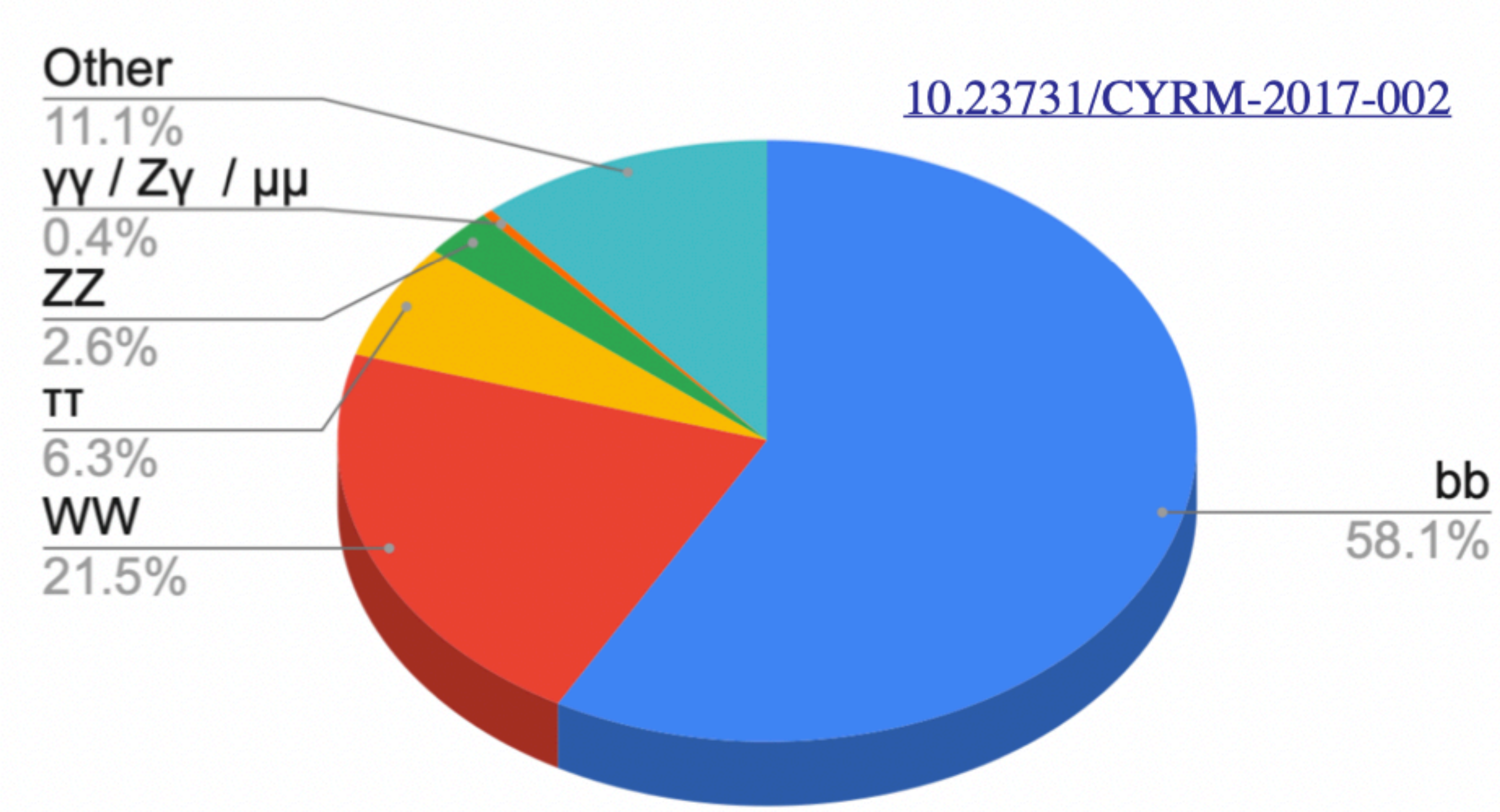
κ_λ ~ [-17, 22]
19.7/fb @ 8 TeV

κ_λ between [-1.4, 6.4] at 95% CL 138/fb @ 13 TeV

How to look for Higgs bosons?

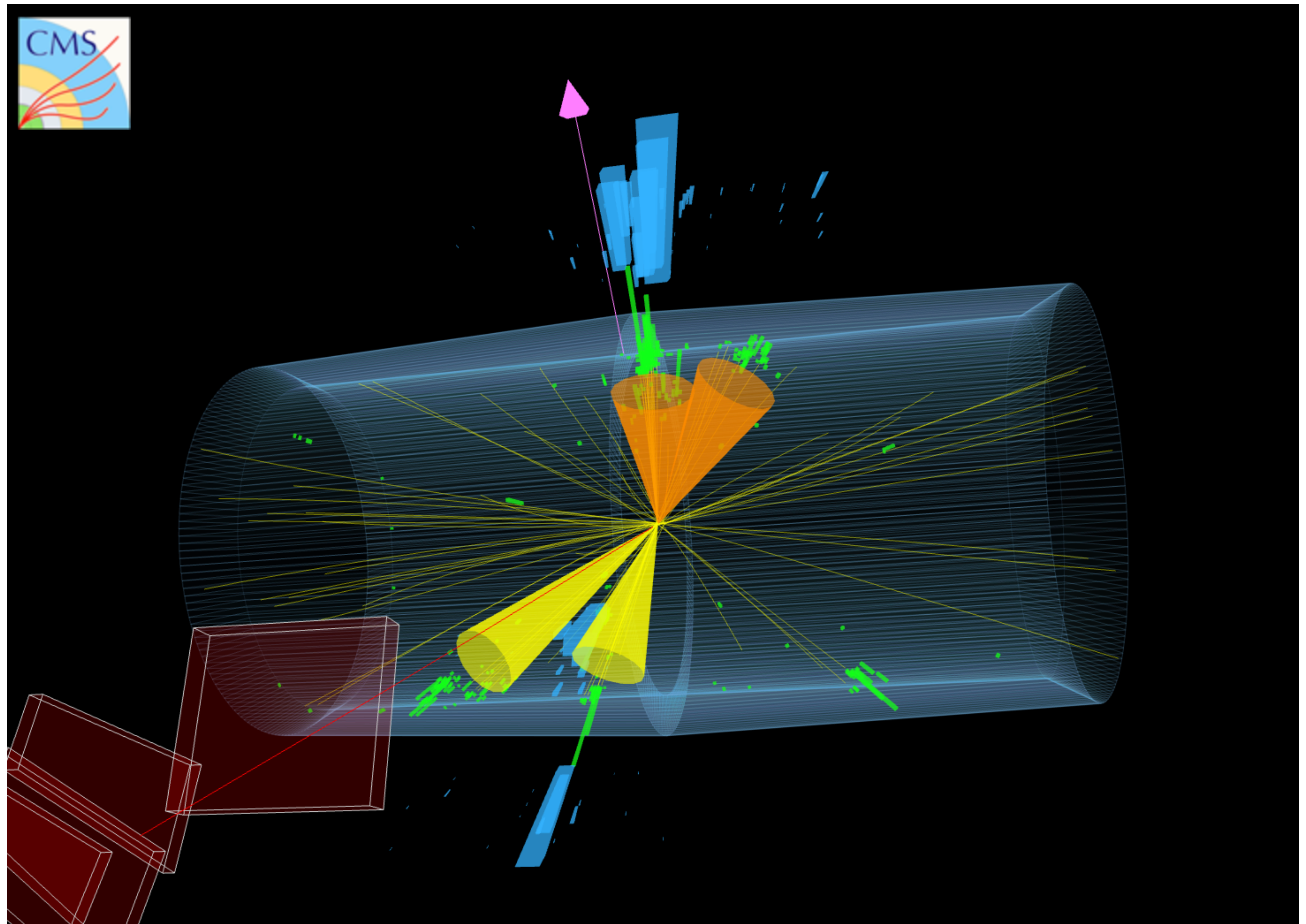
- Higgs boson decays:



- At CMS we can identify as objects:
  - Photons, electrons and muons are clean (low BKG) signatures
  - Jets (b-jets) and hadronic tau leptons hold big portion of branching ratio (BR)

- Decays to photons, hadronic taus and b-jets are fully reconstructable
- Leptonic decays of W and tau leptons also involve a neutrino and therefore loss of information
  - To recover, Multivariate Analysis (MVA) is imperative

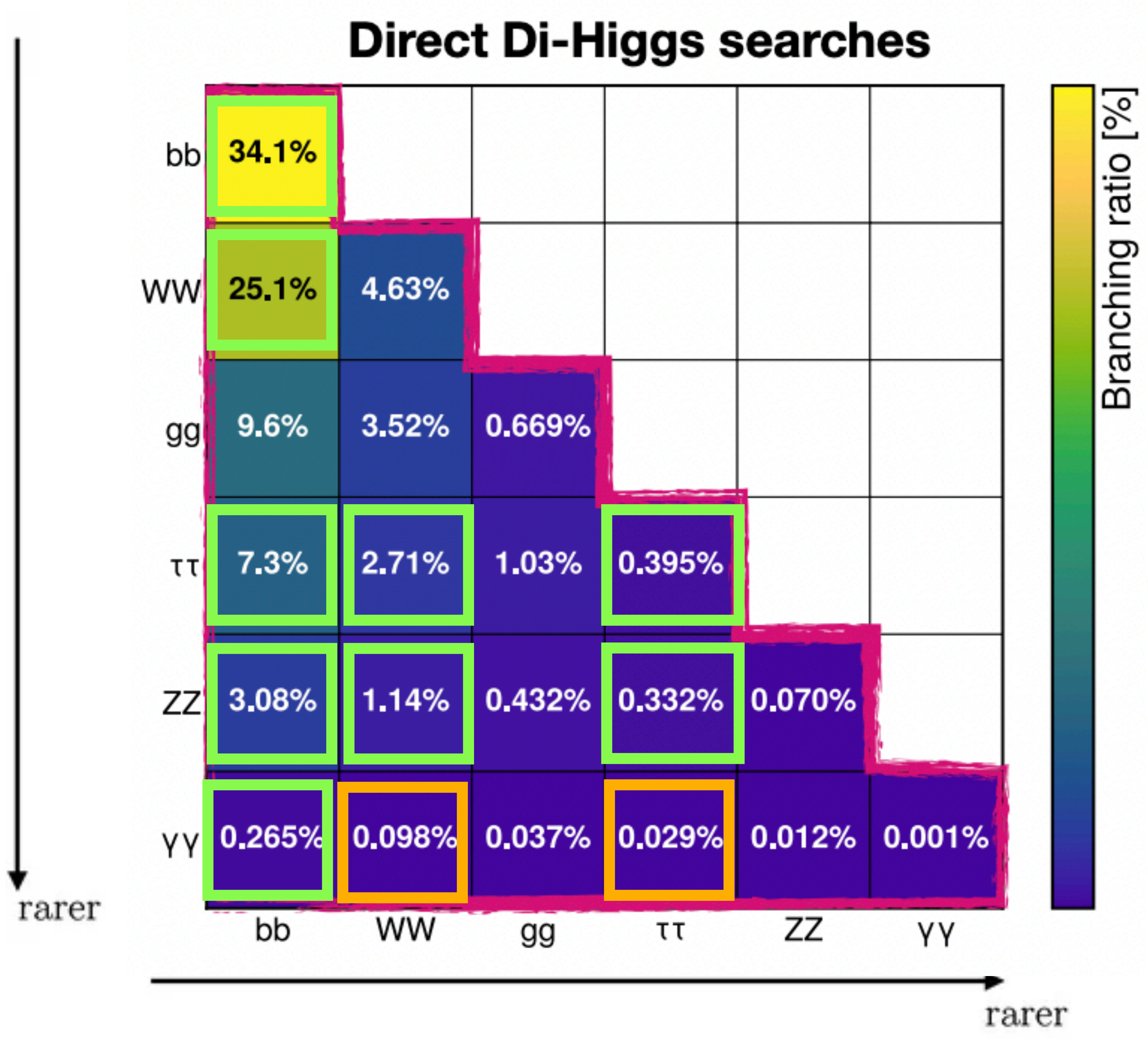
Balance between resolution, reconstructebility and branching ratio define each channel importance



Possible bbWW (leptonic) event

Input channels for CMS legacy HH combination

- We have a rich coverage of Higgs pairs final states and production modes



Final state		Reference
bbγγ	★●	JHEP 03 (2021) 257
bbττ	★●	PL B 842.137531
bbbb (resolved)	★●	PRL. 129.081802
bbbb (boosted)	★●	PRL. 131.041803
Multilepton	★●	JHEP 07 (2023) 095
bbZZ (4ℓ)	★	JHEP 06 (2023) 130
bbbb (VHH)	■	CMS-PAS-HIG-22-006
bbWW (leptonic)	★●	JHEP 07 (2024) 293
bbWW (hadronic)	★●	CMS-PAS-HIG-23-012
ττγγ	★●	CMS-PAS-HIG-22-012
WWγγ	★	CMS-PAS-HIG-21-014

Includes HEFT and shape-BM

Most added especially for this publication!

Nature
PRD 94 (2016) 5, 052012
PAS-HIG-20-011

Production modes:
★ ggF
● VBF ■ V-associated

- There is no time to cover all channels, for an overview, I will talk about main channels and the brand new additions

4b final state

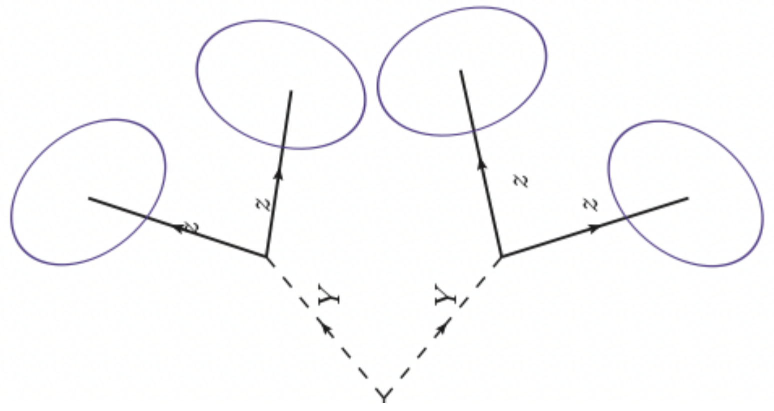
Largest Br = 34% X Large QCD bkg

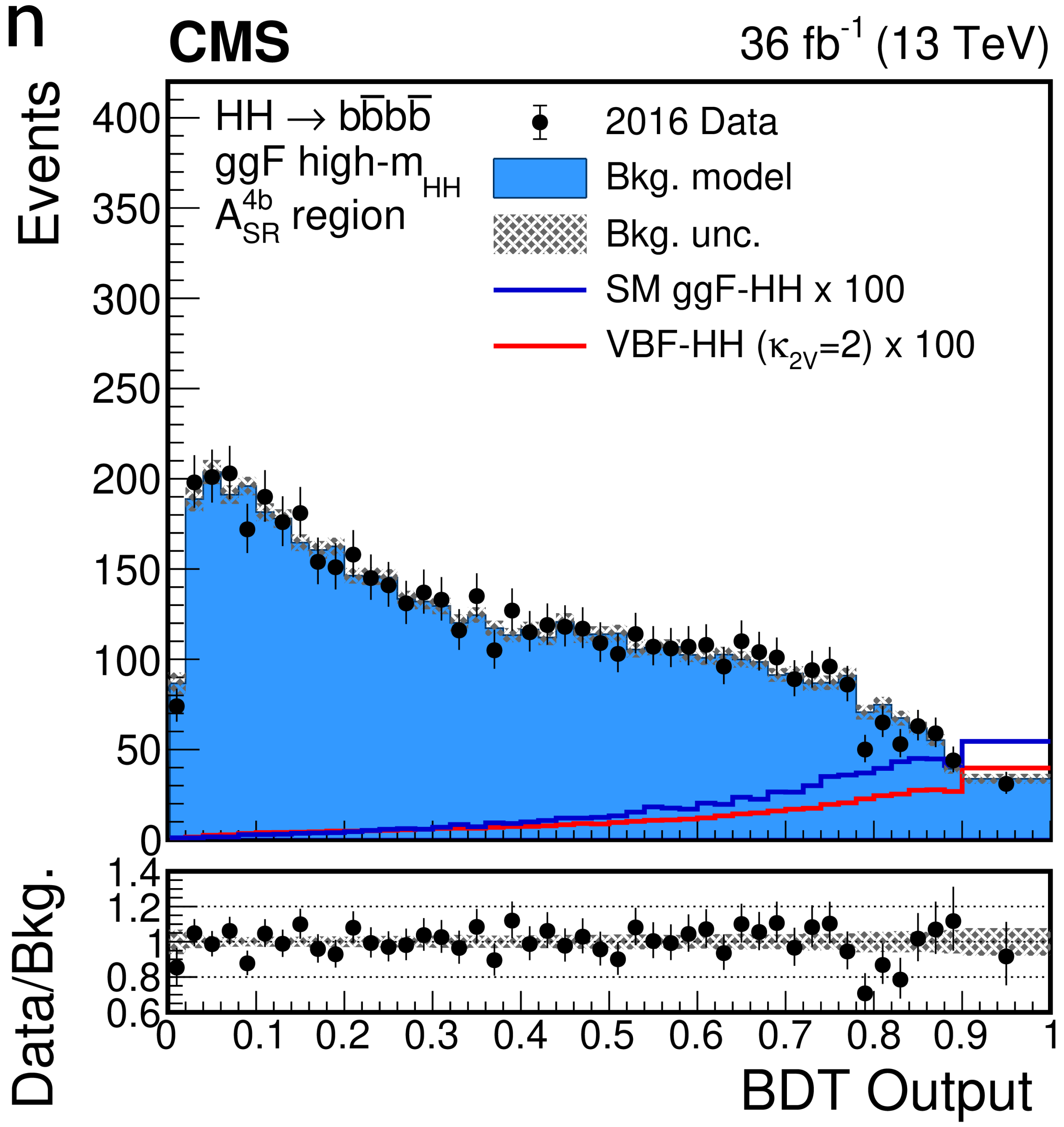
Four resolved jets

PRL 129.081802

- b-jet identification with deep NN [ref.]
- Fully data-driven background estimation
  - Jets are paired to reconstruct both H
    - Control regions defined by events out of the 2D H mass region extrapolate the BKG on the signal region

- Simultaneous fit of:
  - MVA for ggF
  - mHH for VBF





3.9 (7.8) times the SM

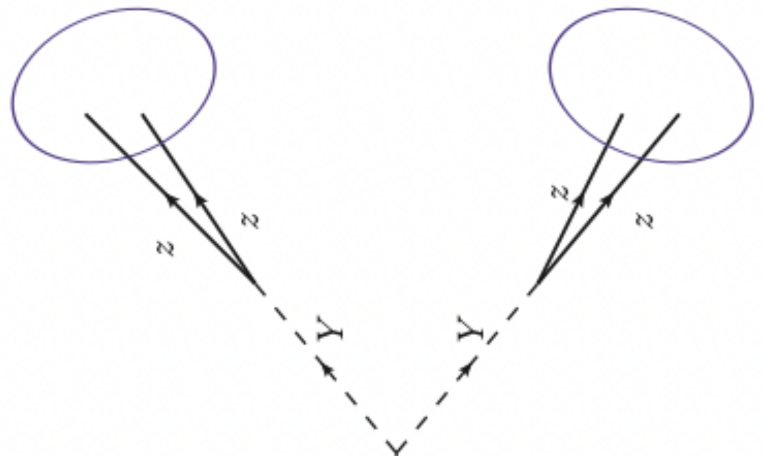
Fully boosted

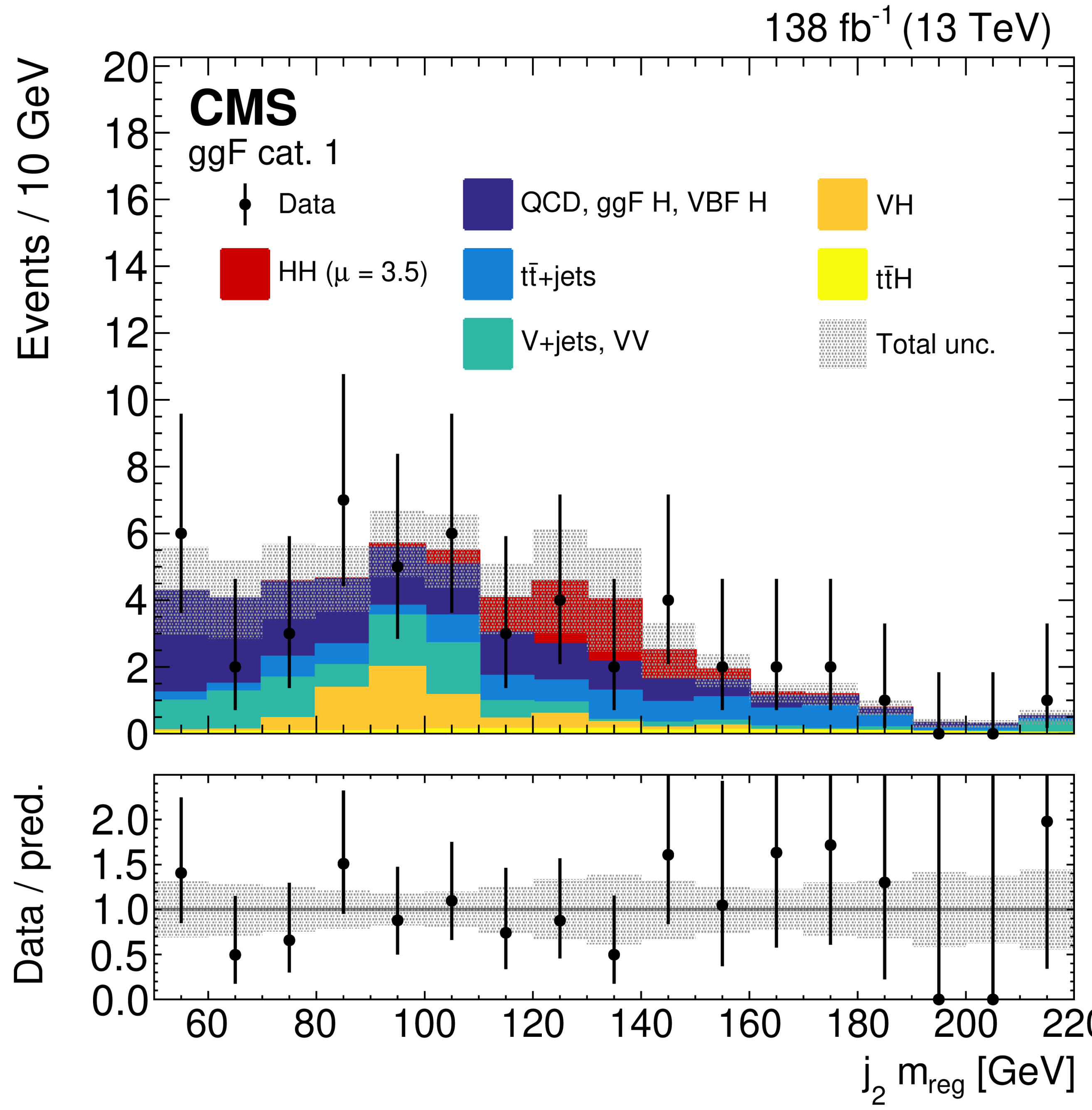
PRL 131.041803

- Select events with energetic two large-cone jets
- ID with GraphNN-based jet flavour [ref.]

==> Considerable BKG reduction

- Simultaneous fit of :
  - Sub-lead. H for ggF
  - mHH for VBF





9.9 (5.1) times the SM

Specially good constraining anomalous κ2V and c2 !

When combining both results overlap is removed with priority to keep events in the boosted region

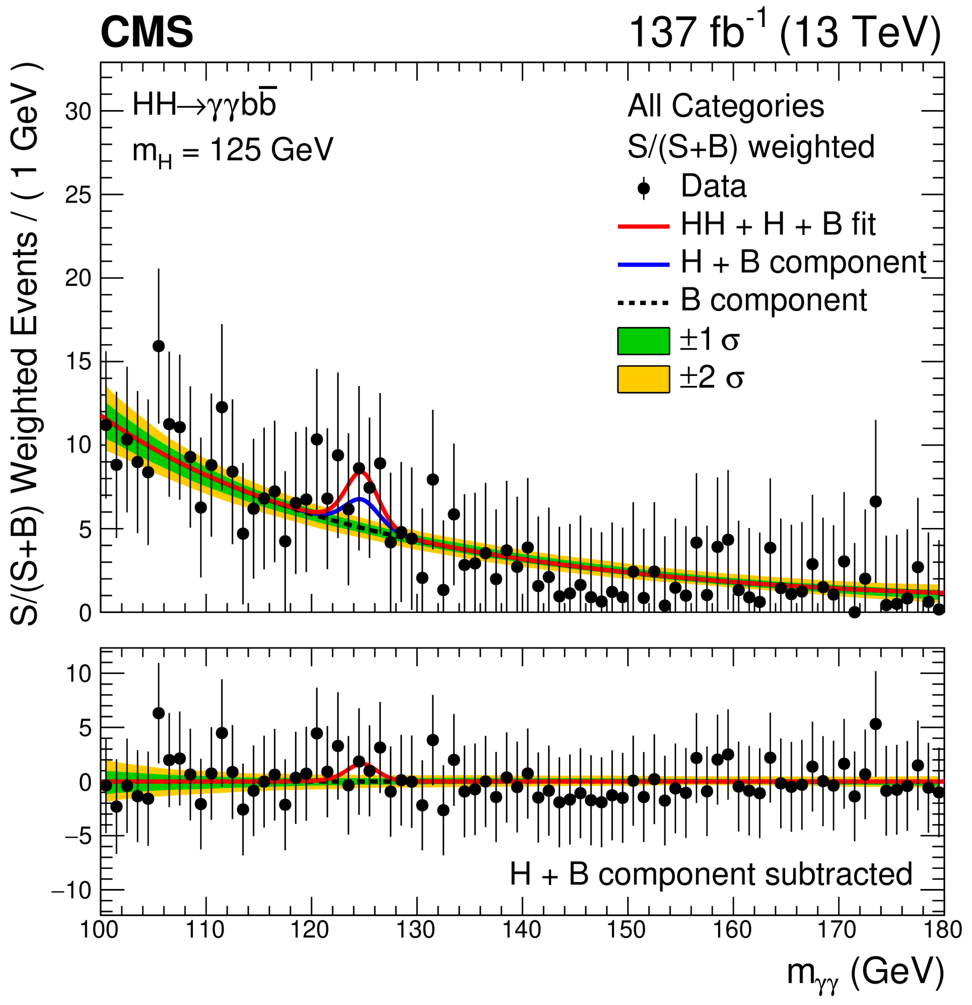
- The V-associated production is probed in CMS-PAS-HIG-22-006

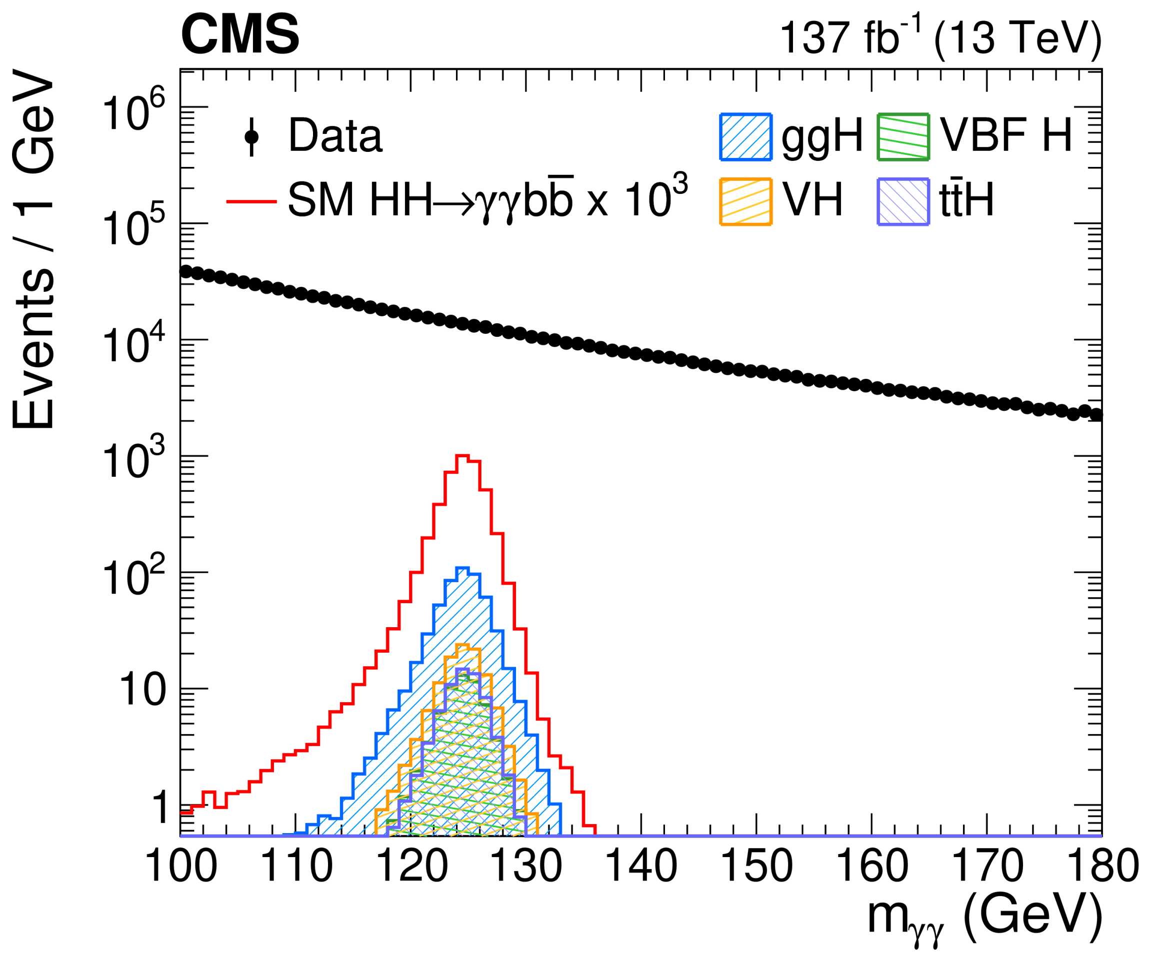
bbγγ and bbττ

smaller BR X Better BKG control

BR ~ 0.3% — bbγγ — JHEP 03 (2021) 257

- MVA separates main BKGs
- 2D fit on mγγ and mbb in bins of mHH
  - Data-driven bkg estimate: H->γγ bump on a smooth falling bkg





- Peaking bkg from ttH(γγ)
  - Separate area to constraint it on the fit

Excellent Hγγ resolution + fully reconstructable = possibiliity of separate mHH areas

8.4 (5.6) times the SM

BR ~ 7.3% — bbττ — PRB 842.137531

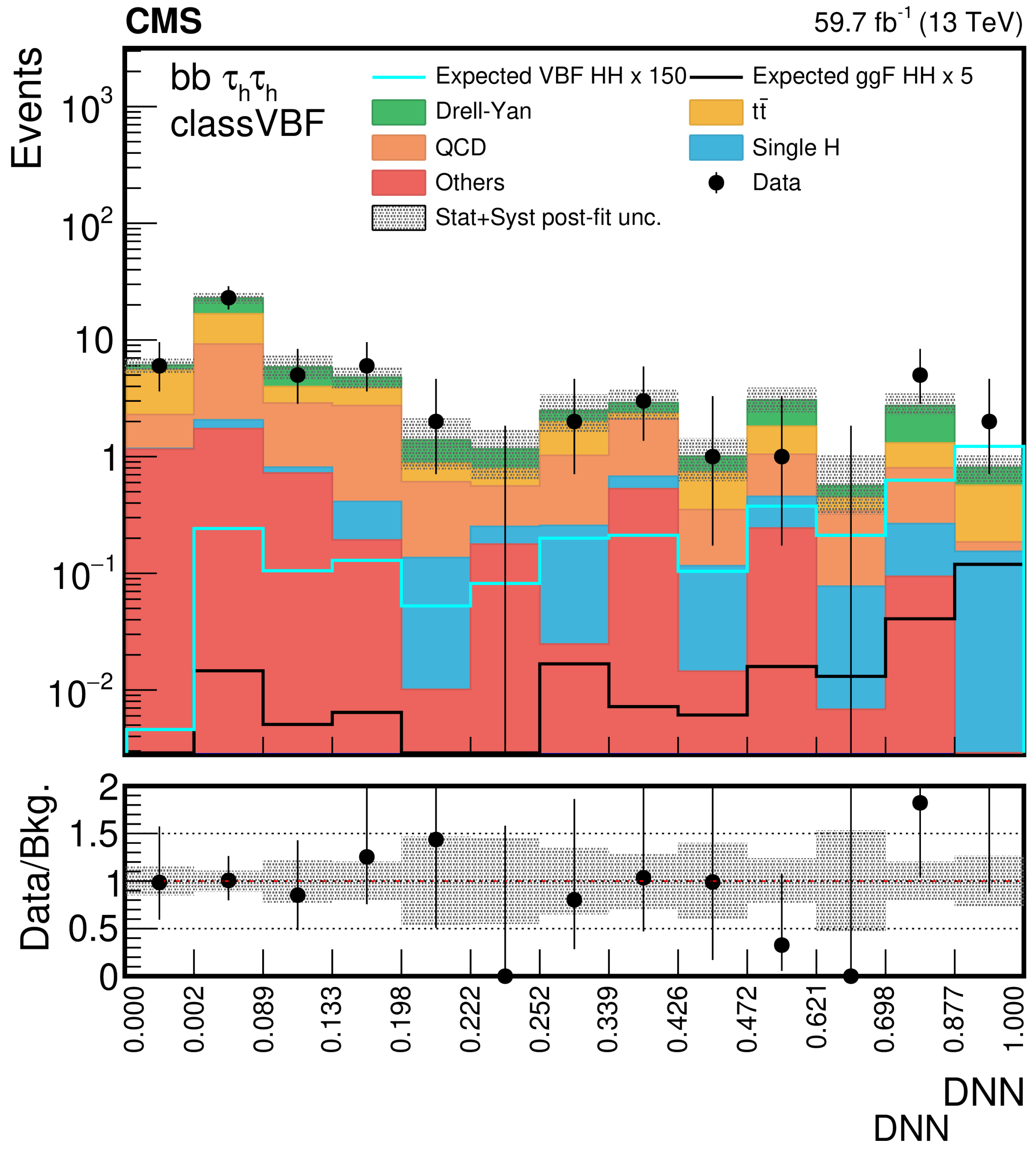
- b-jet identification with deep NN [ref.]
- τ-lepton ID with deep NN developed to this ana. [ref.]

==> Considerable BKG reduction

- Multiclassification MVA separates main BKGs,
  - fit on this MVA to extract signal

Considers events with merged-jet Hbb

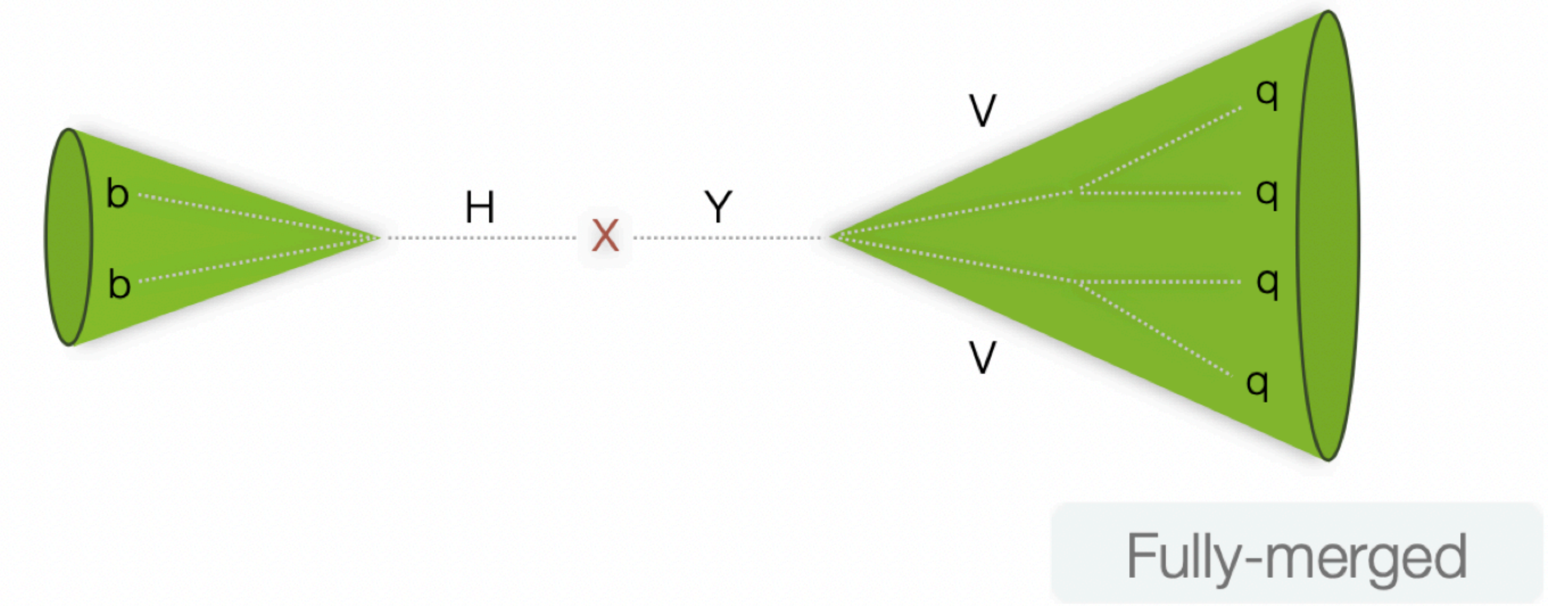
3rd best channel to constrain anomalous qqHH and second best constraining the ttHH coupling !



3.4 (5.3) times the SM

Newcomers: bb VV hadronic

CMS-PAS-HIG-23-012



Large Br = 28% X Large QCD bkg

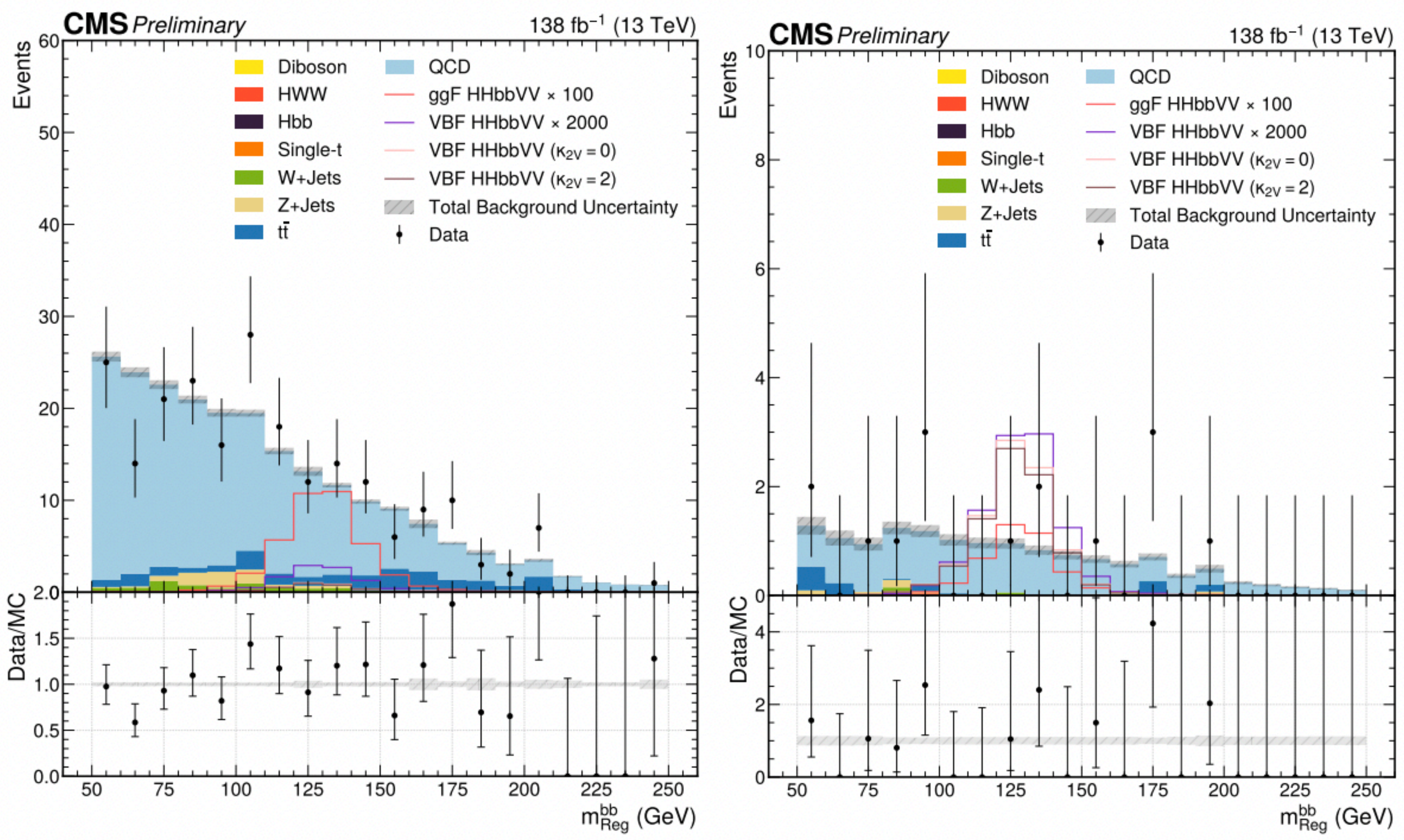
- b-jet identification with deep NN [ref.]
- V → 4 jets ID with deep NN developed to this ana. [ref.]

==> Considerable BKG reduction

- MVA separates ggF and VBF production from BKGs
  - V → 4 jets tagger used on selection
  - Fit on reconstructed m_{bb}

69 (142) times the SM

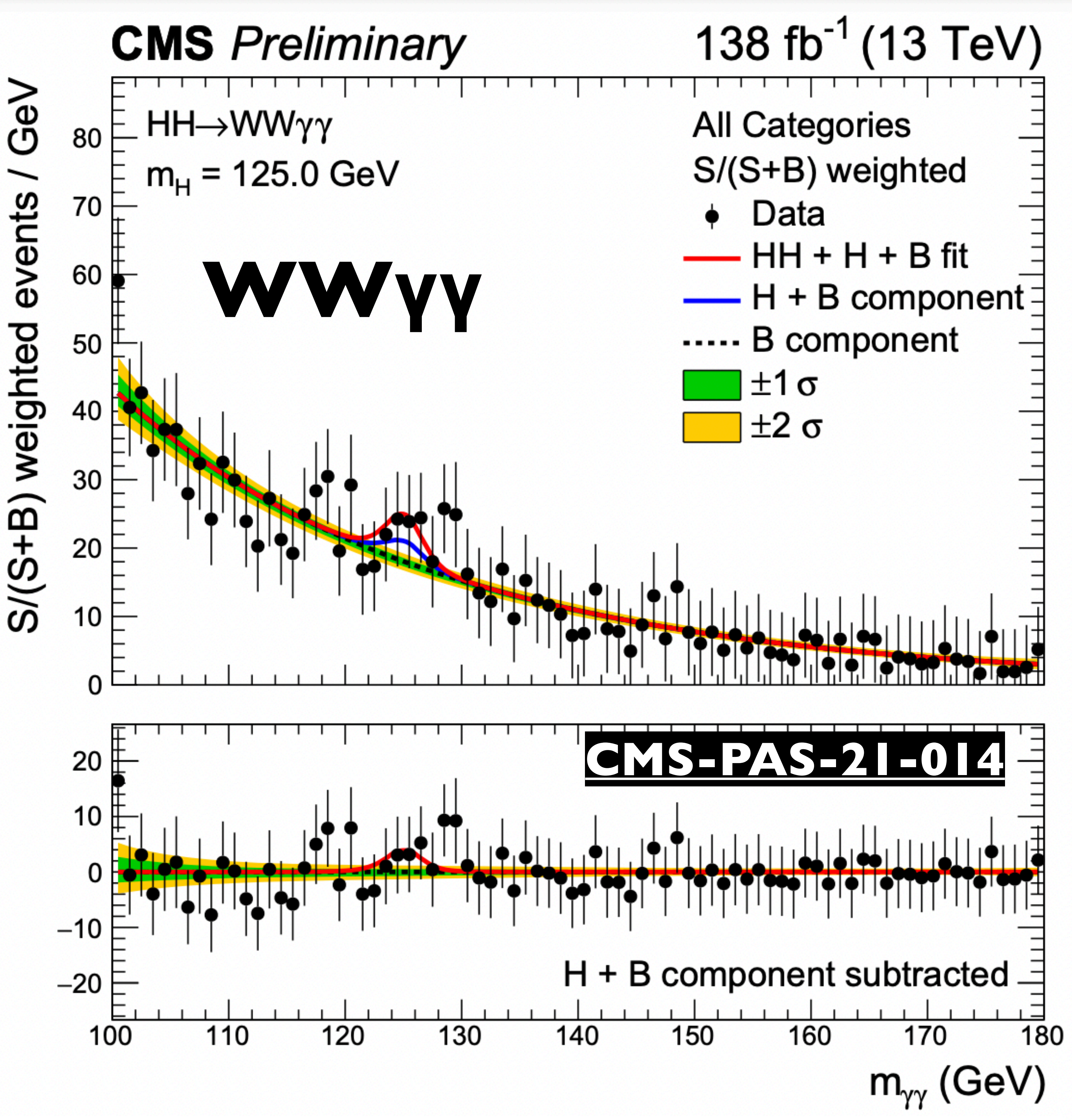
2nd best channel to constrain anomalous VBF production !



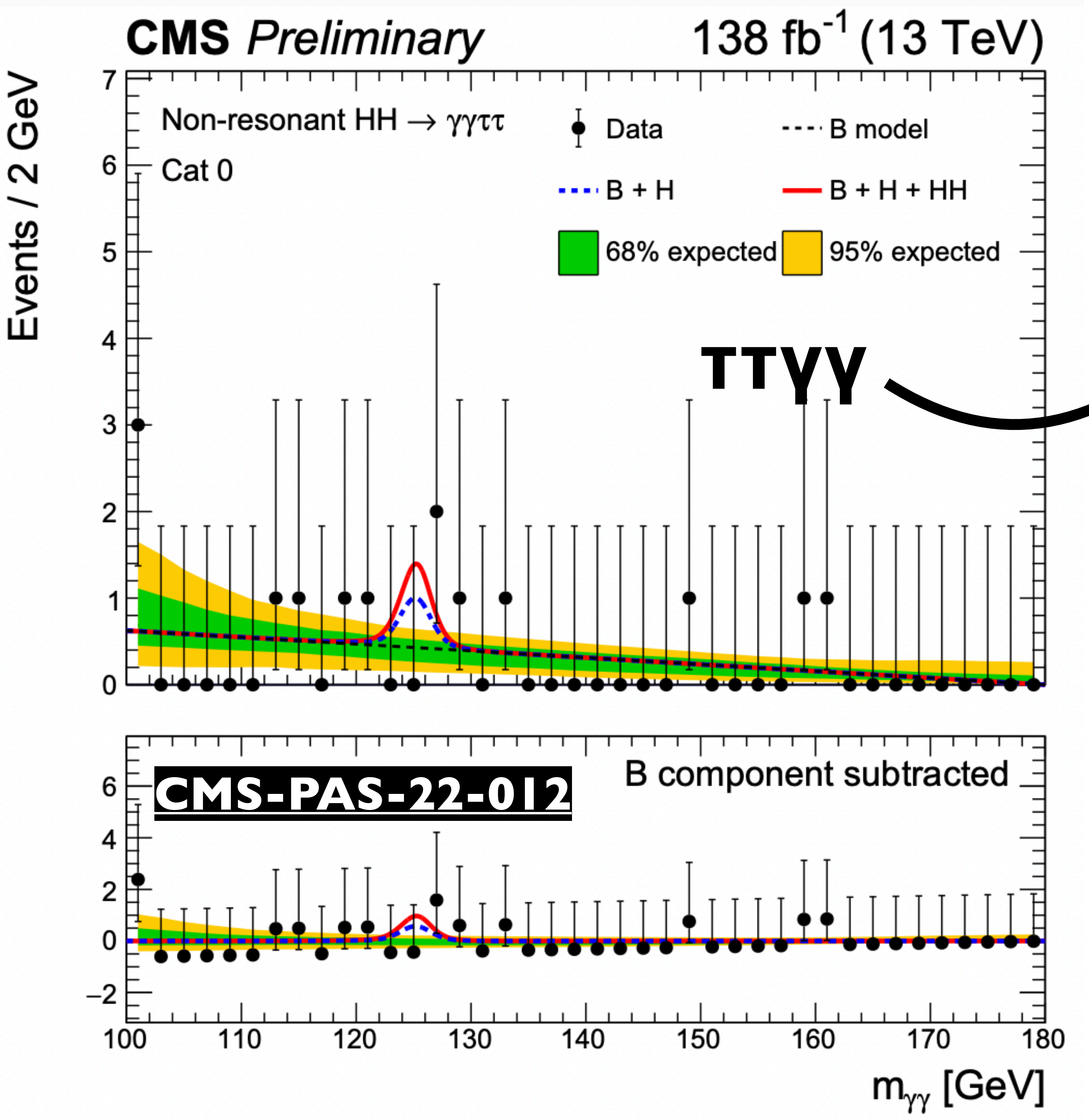
Newcomers: WWγγ and ττγγ

Explore excellent Hγγ resolution, closing all HH decays possibilities

- MVA separates main BKGs
- Fit on mγγ
  - Data-driven bkg estimate: H->γγ bump on a smooth falling bkg



95 (54) times the SM



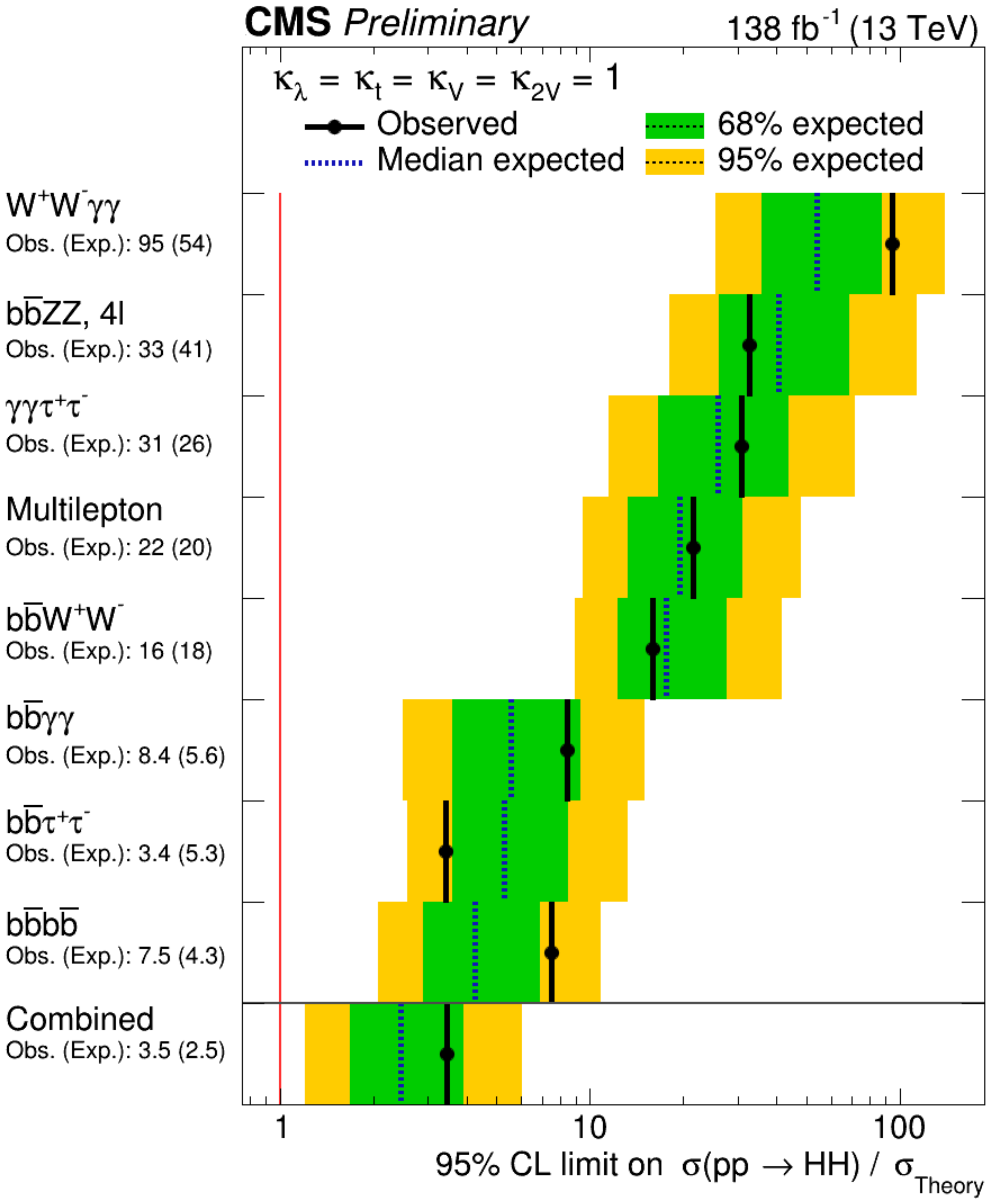
31(26) times the SM

Despite the tiny BR (0.03%) it is the 6th best channel constrainning SM HH

The HH combination in the SM-like scenario

- The most complete CMS combination to date!
  - Latest theory developments!

Upper limit on the SM signal topology
3.5 (2.5) times SM



The HH combination in the SM-like scenario

PAS-HIG-20-011

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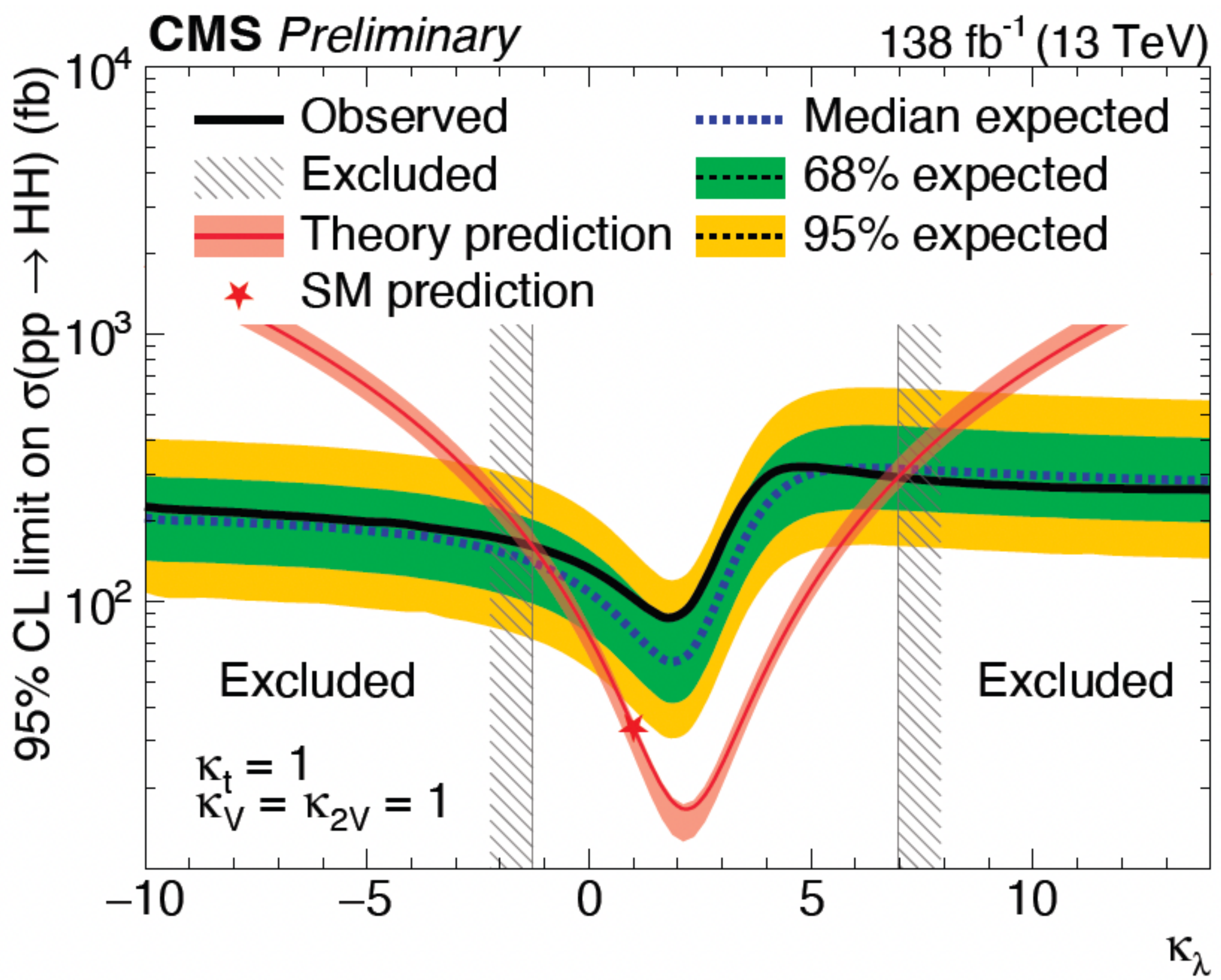
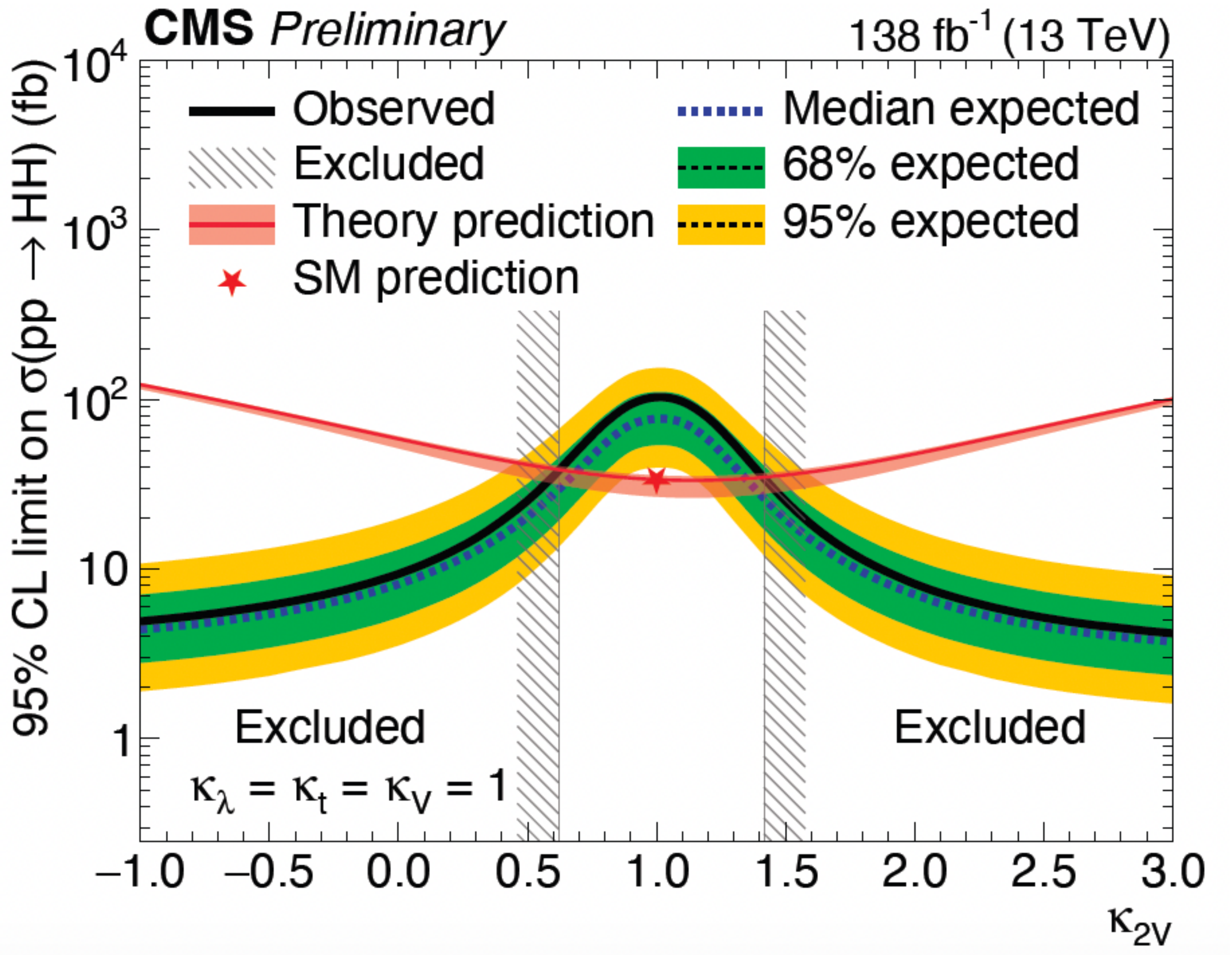


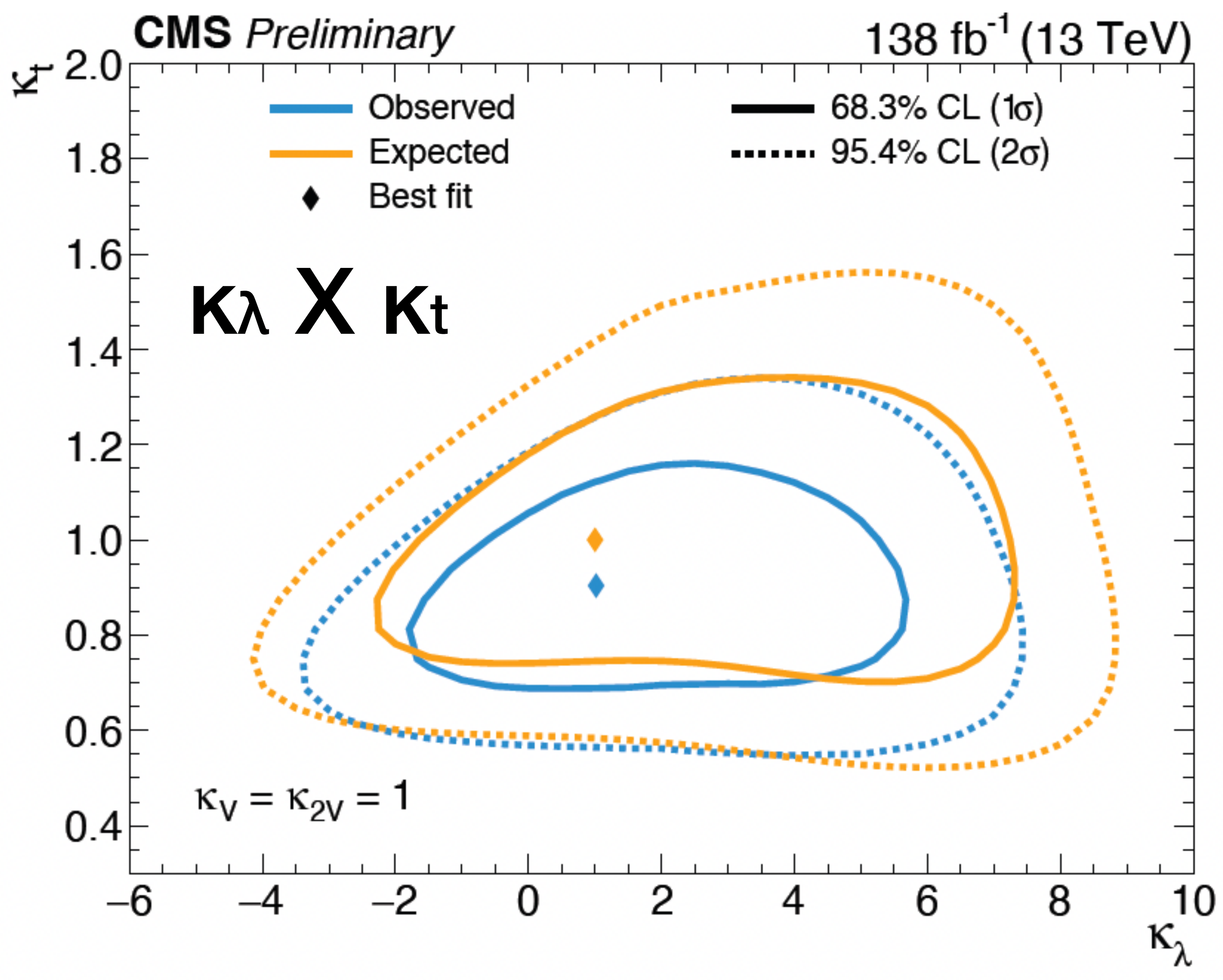


Upper limits considering coupling scans
κ_λ between [-1.4, 6.4] at 95% CL
κ_{2V} between [0.6, 1.4] at 95% CL

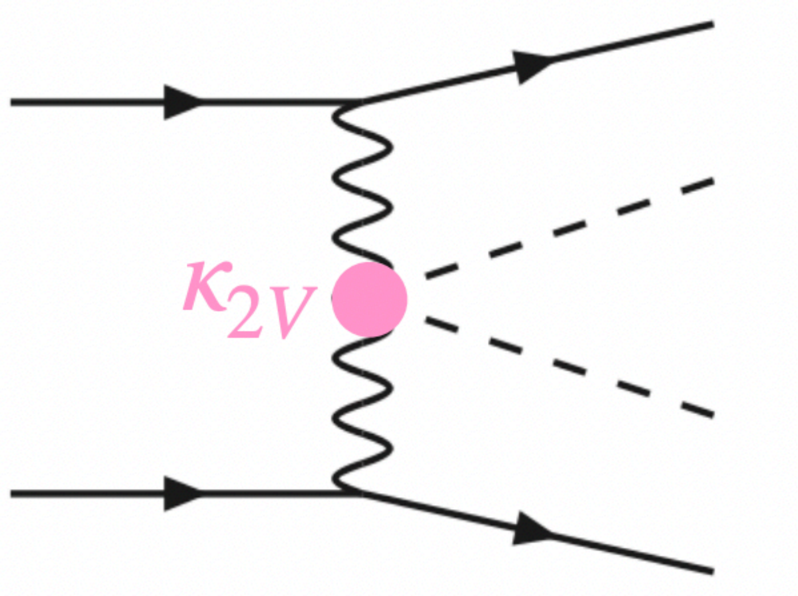
Results in SM-like scenario - coupling constraints

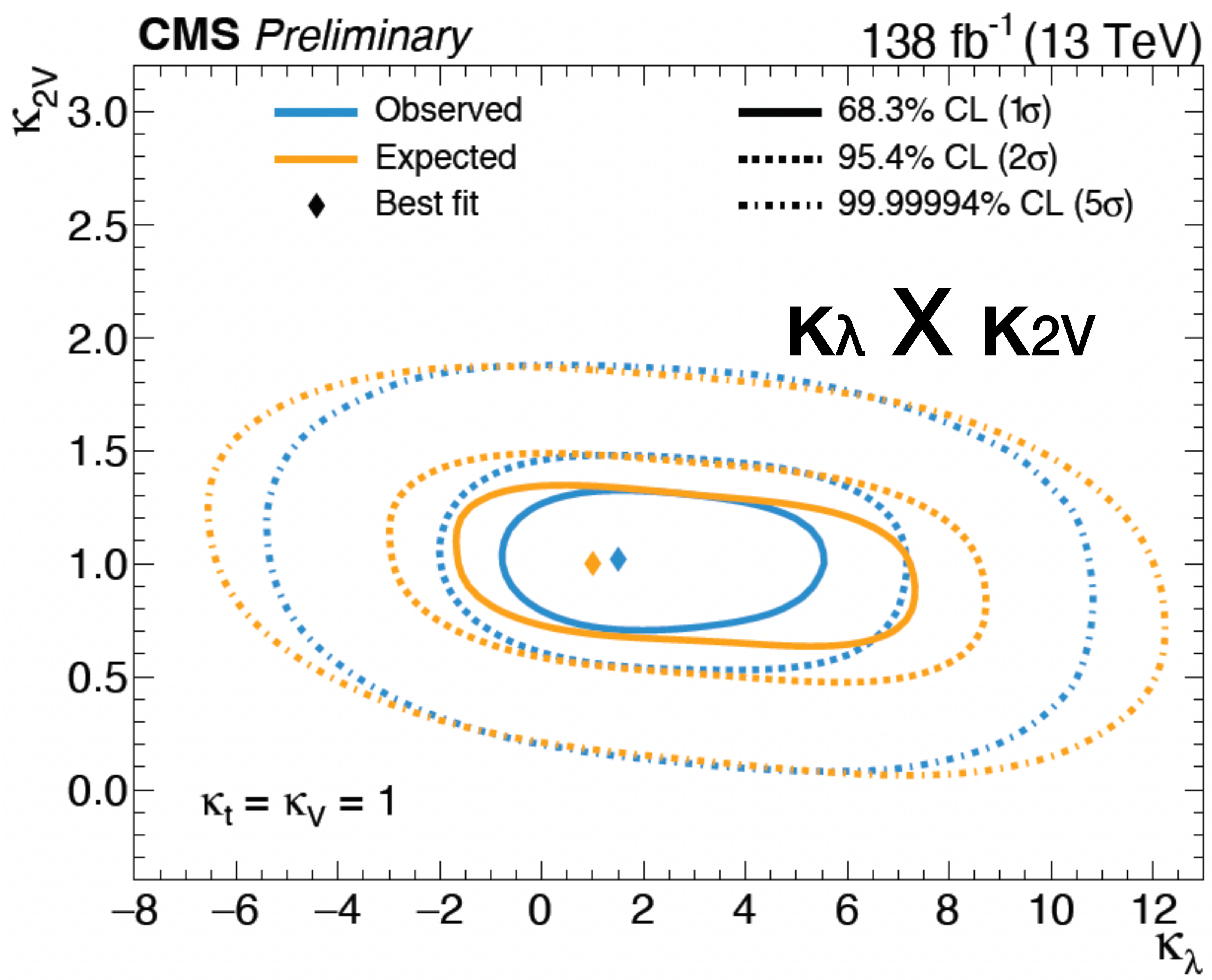
PAS-HIG-20-011

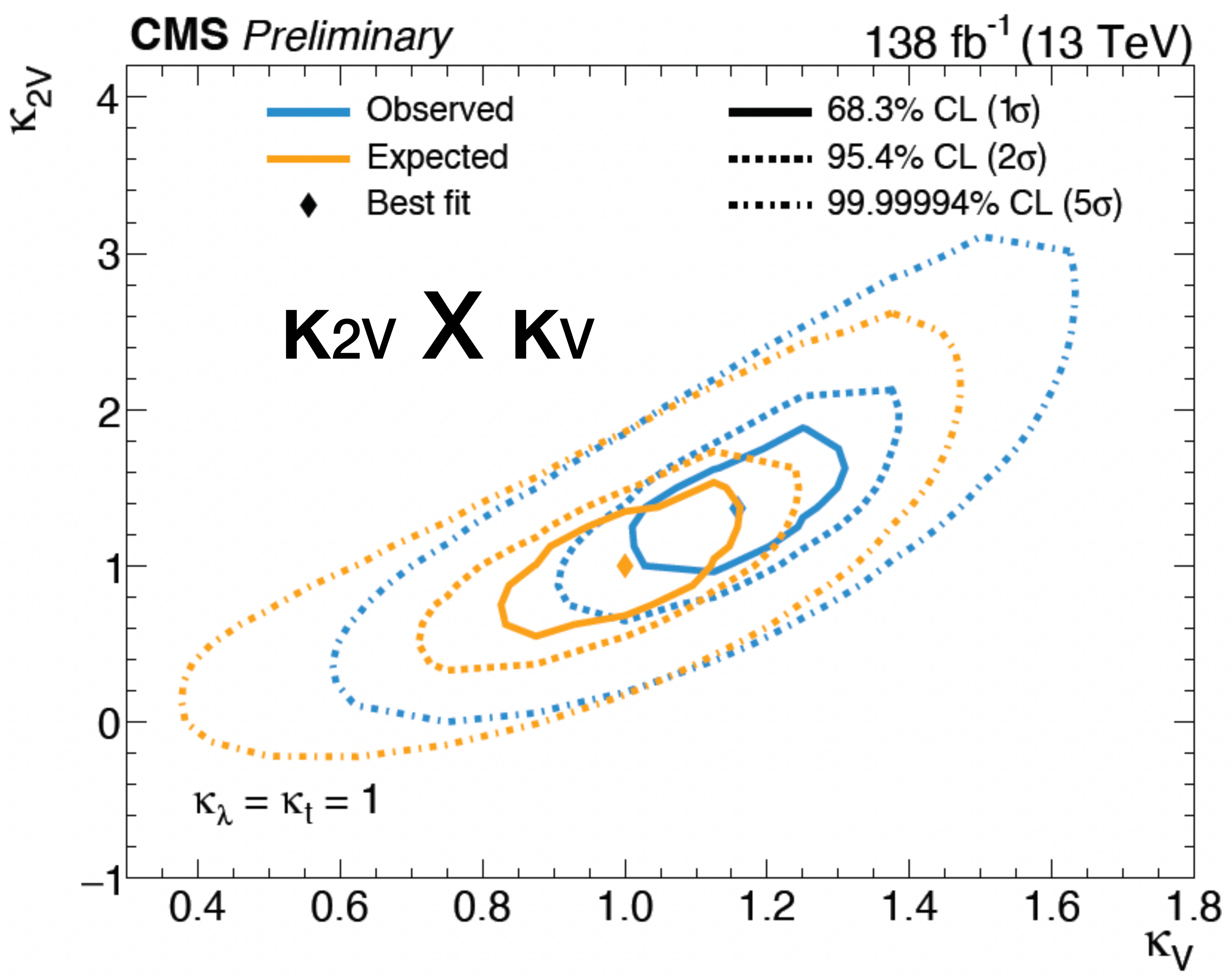
Slight correlation between κλ and κt



When considering the κ2V coupling the constraints are dominated by the VBF channel





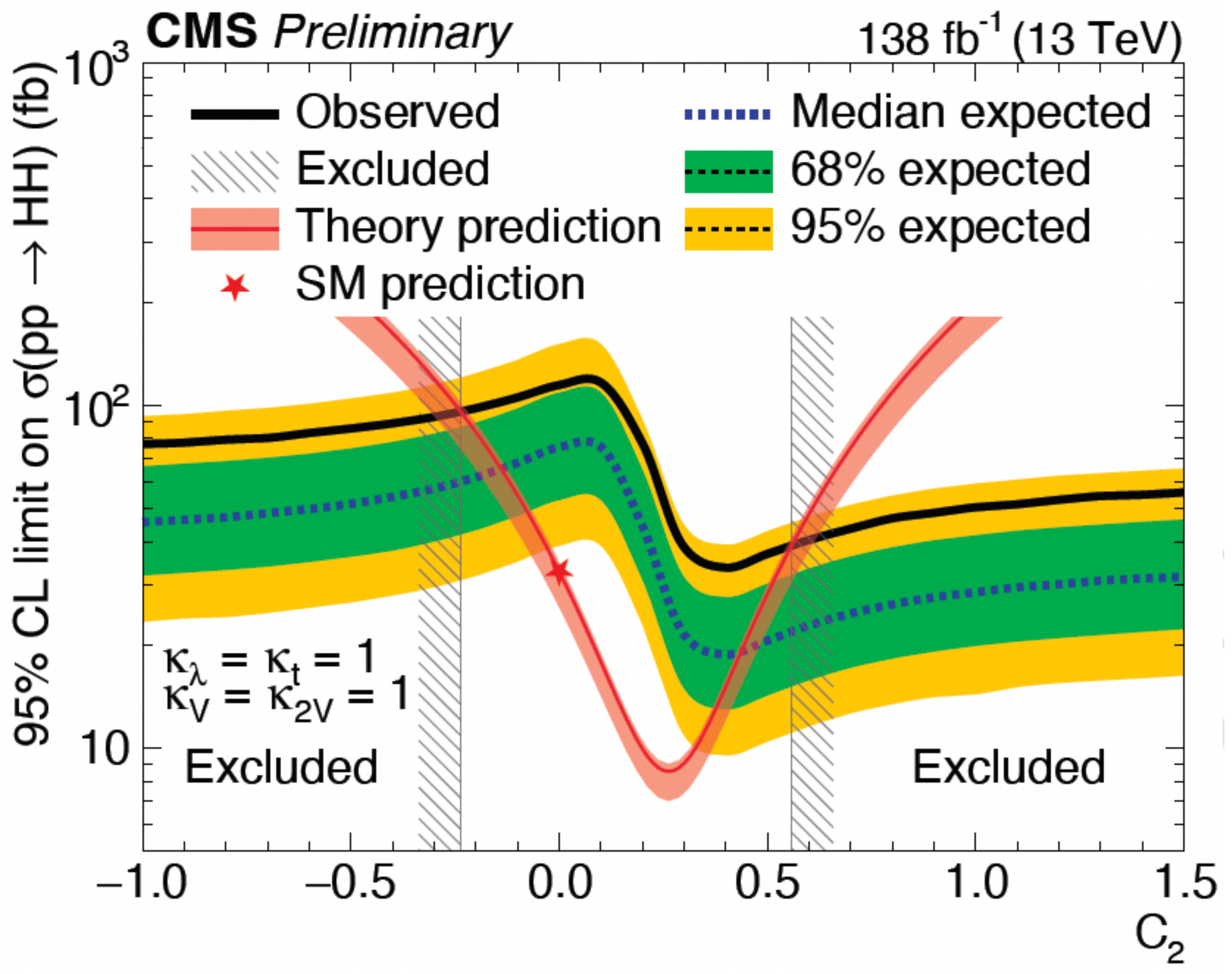


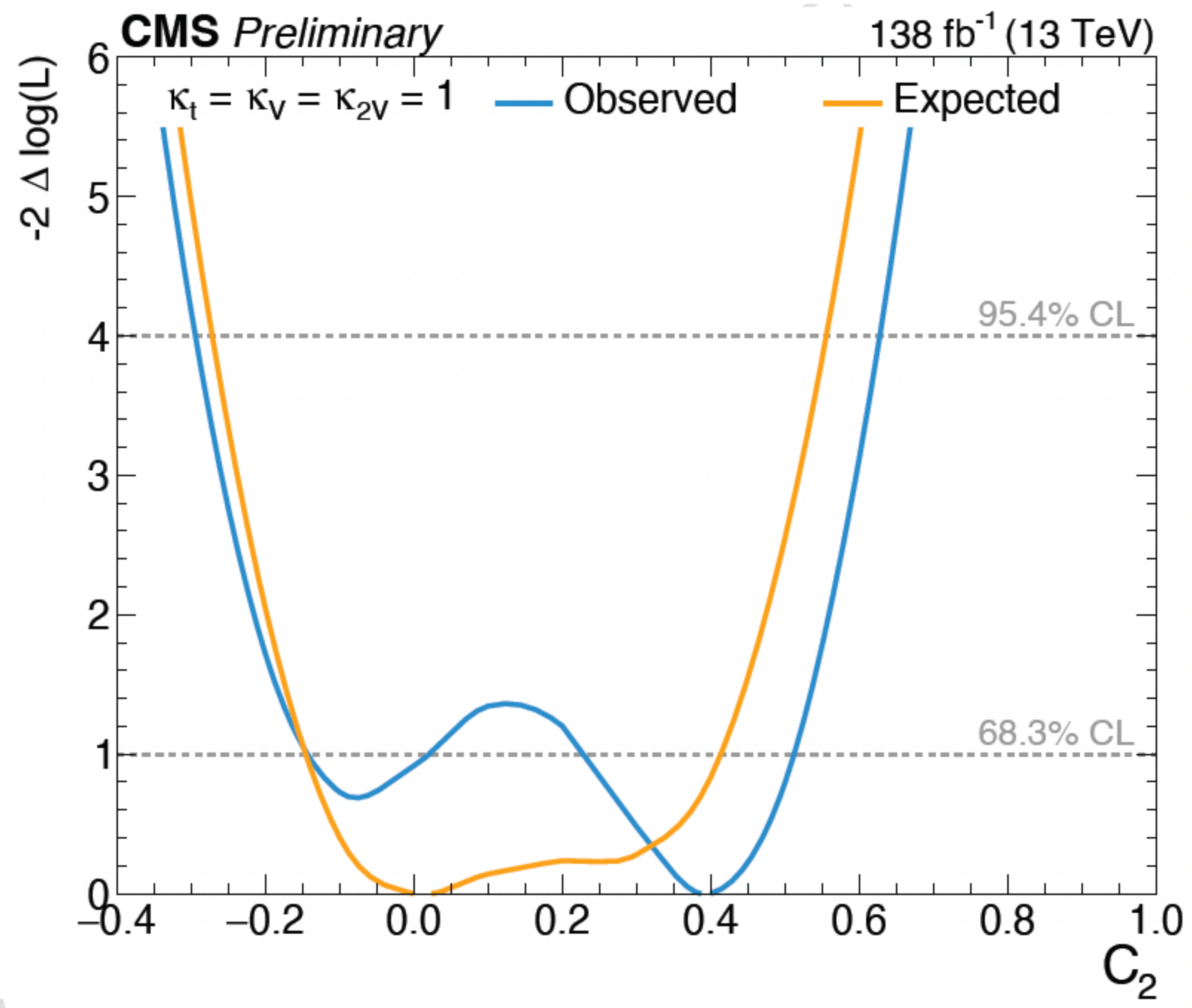
κ2V = 0 is excluded at more than 5 sigmas to any value of κλ or κV

Results in BSM-like scenario - c2 scan

PAS-HIG-20-011

- Constraint in c_2 between [-0.23 0.63] @ 95% CL



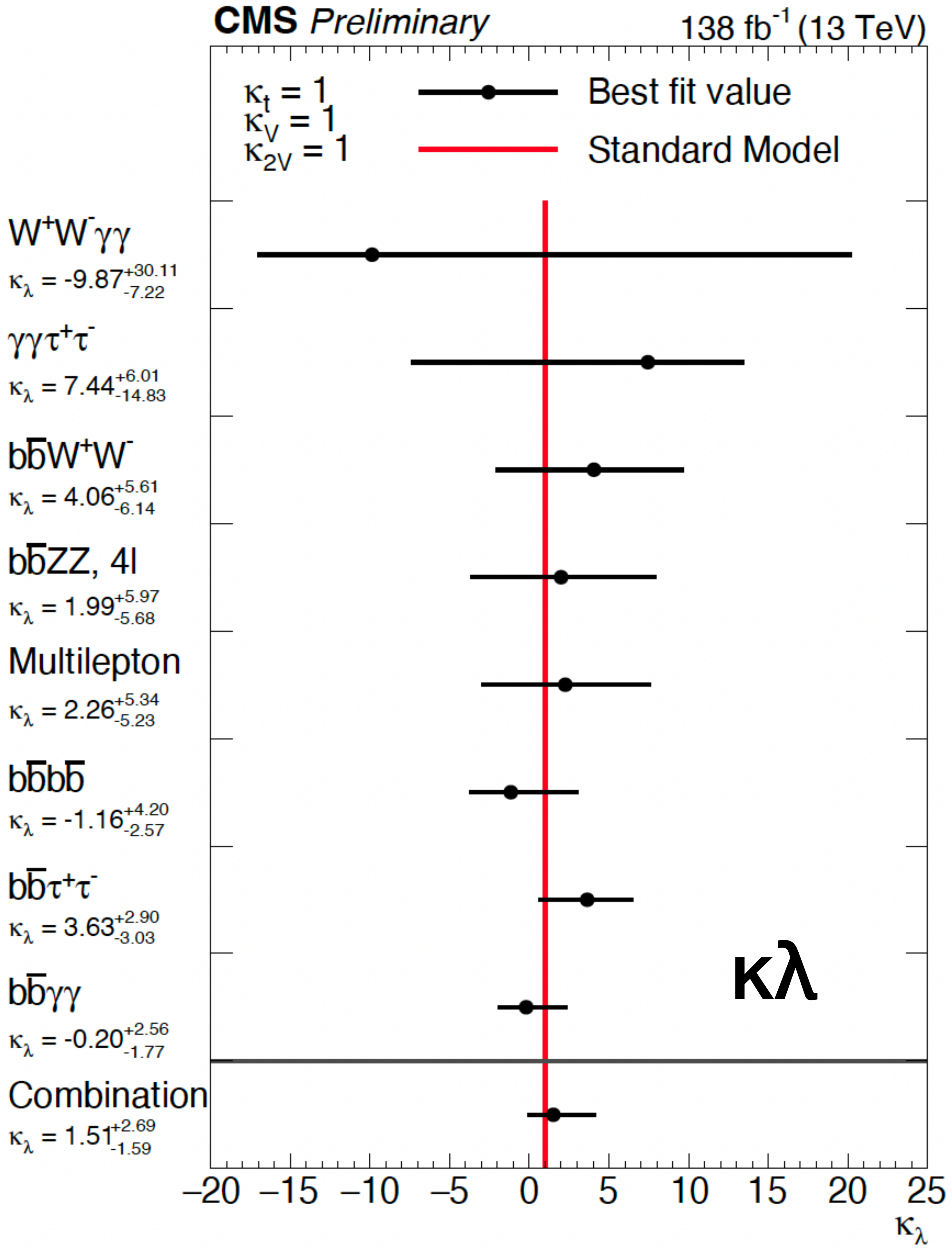


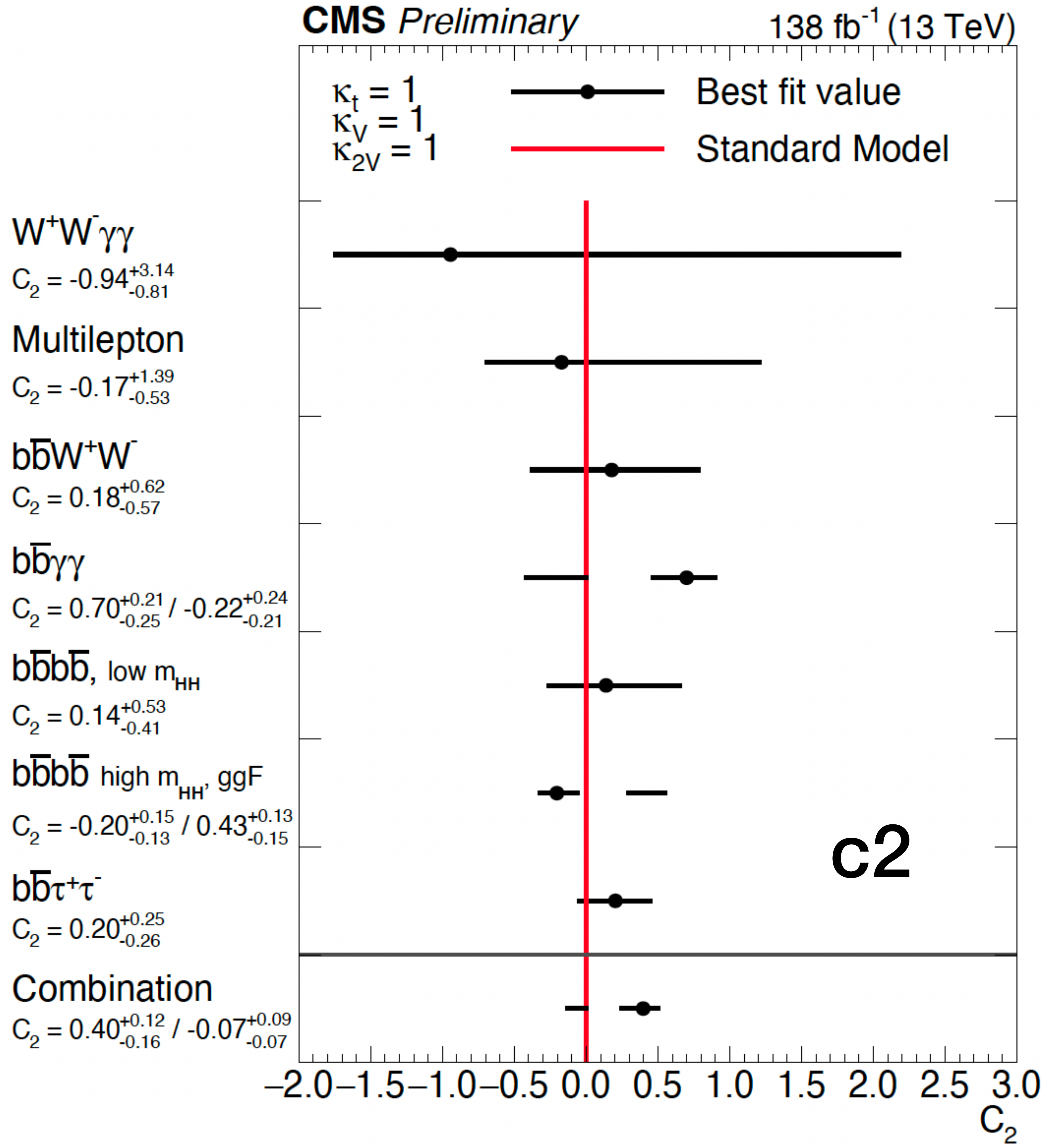
- When looking at the best fit, slight preference for $c_2 \sim 0.4$,
  - Statistically compatible with the SM ($c_2 = 0$)

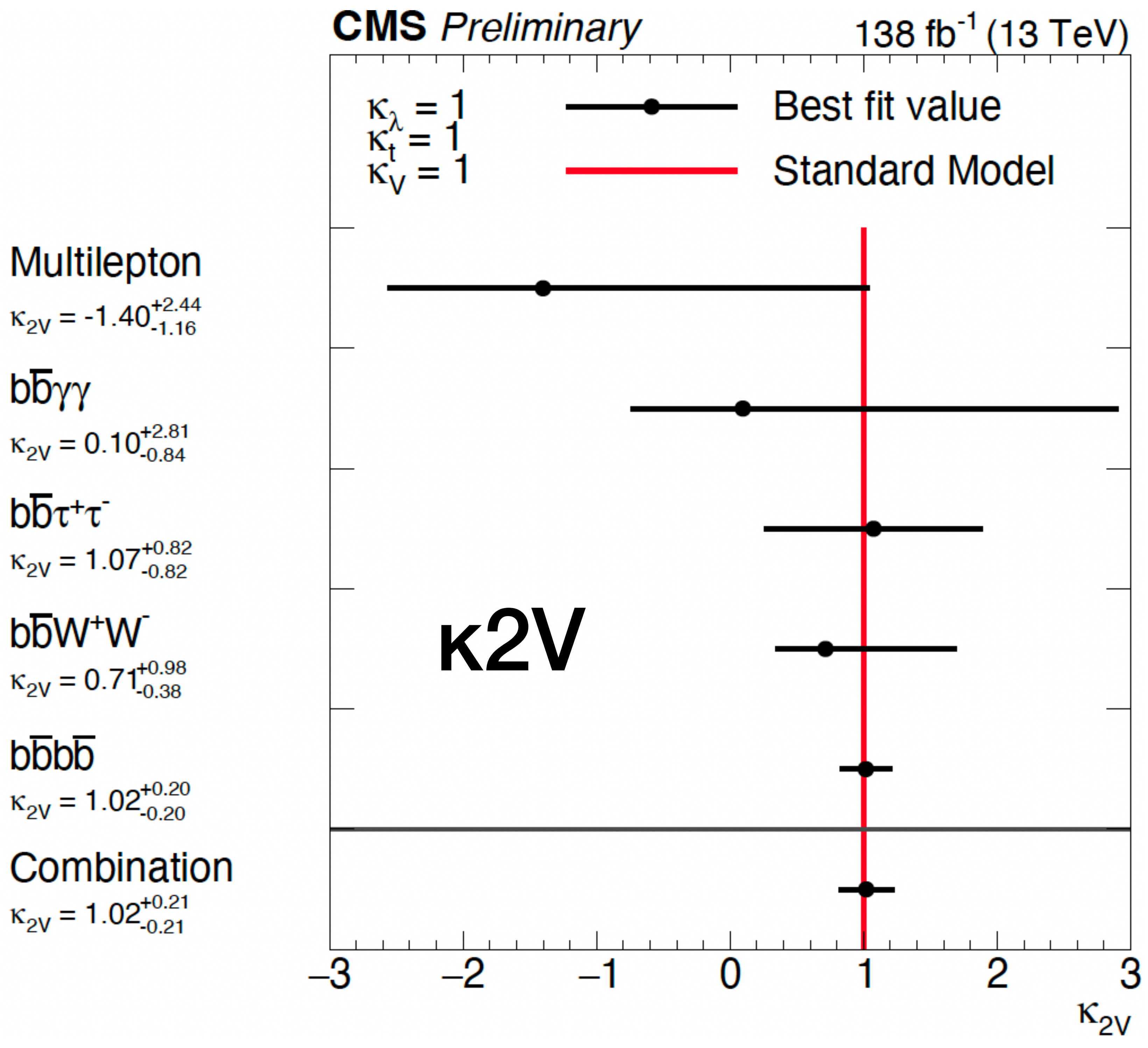
On channels complementarity

PAS-HIG-20-011

In the constraints of κλ and c2 we clearly see that the combined measurement gains from channels complementarity

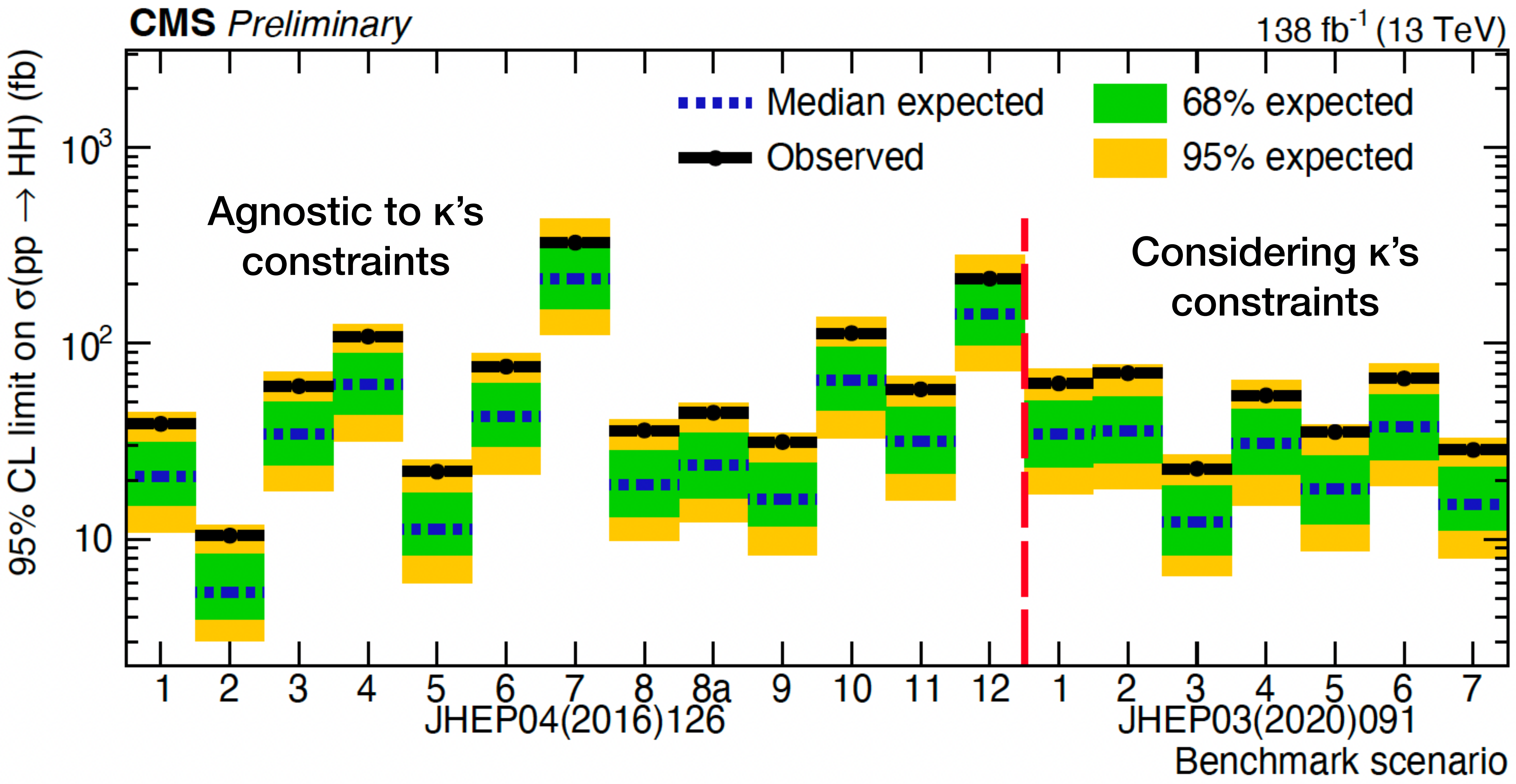






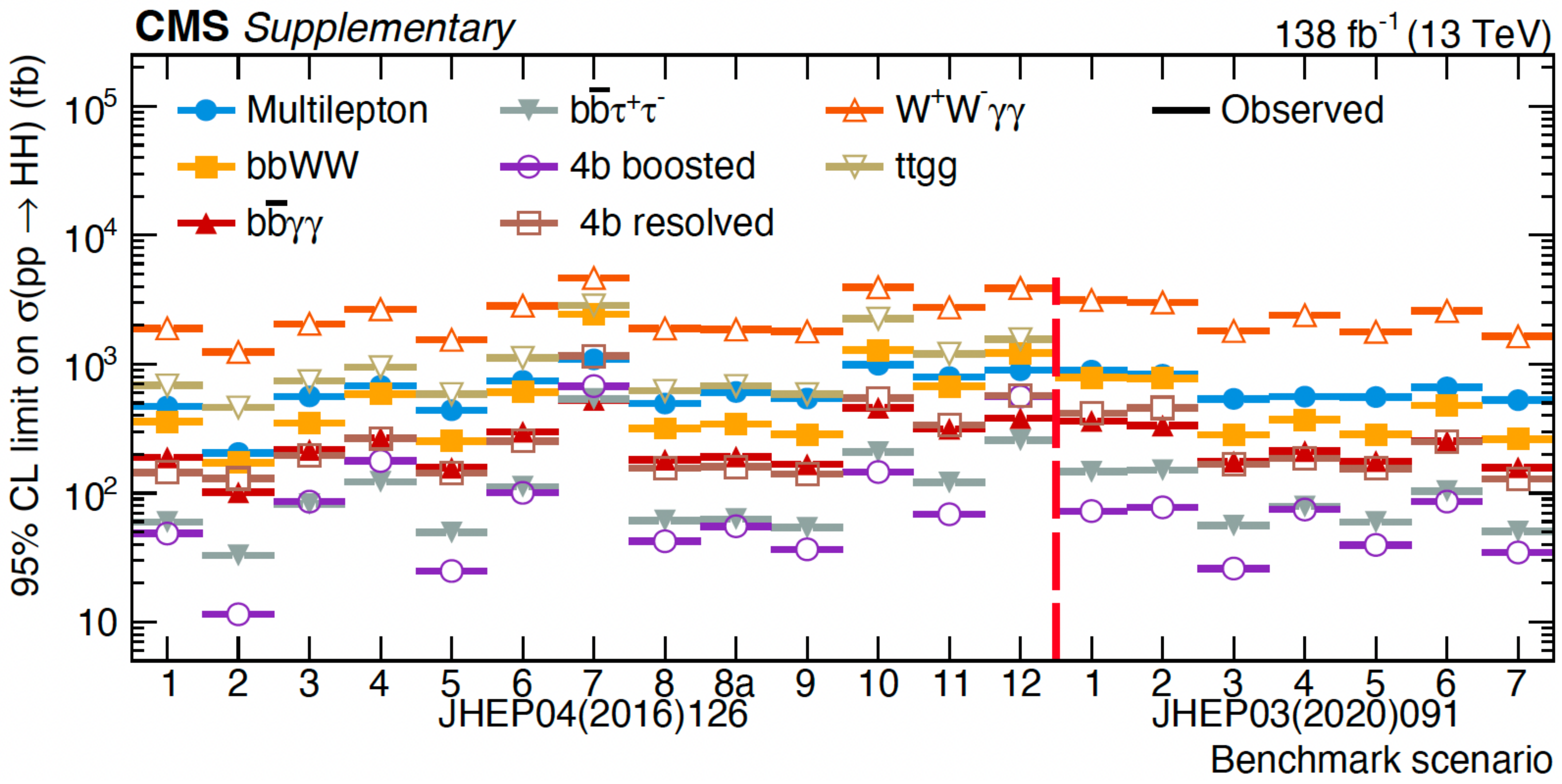
Results in BSM-like scenario - shape benchmarks

PAS-HIG-20-011



- Despite limits variating more than one order of magnitude due signal topology variations, no excess is found

- In different parameter space we observe a different composition of channels
  - BM7 (JHEP4) the softer mHH
    - bb γγ and bbττ best limits
  - BM2 (JHEP4) the harder mHH
    - Limits dominated by 4b boosted

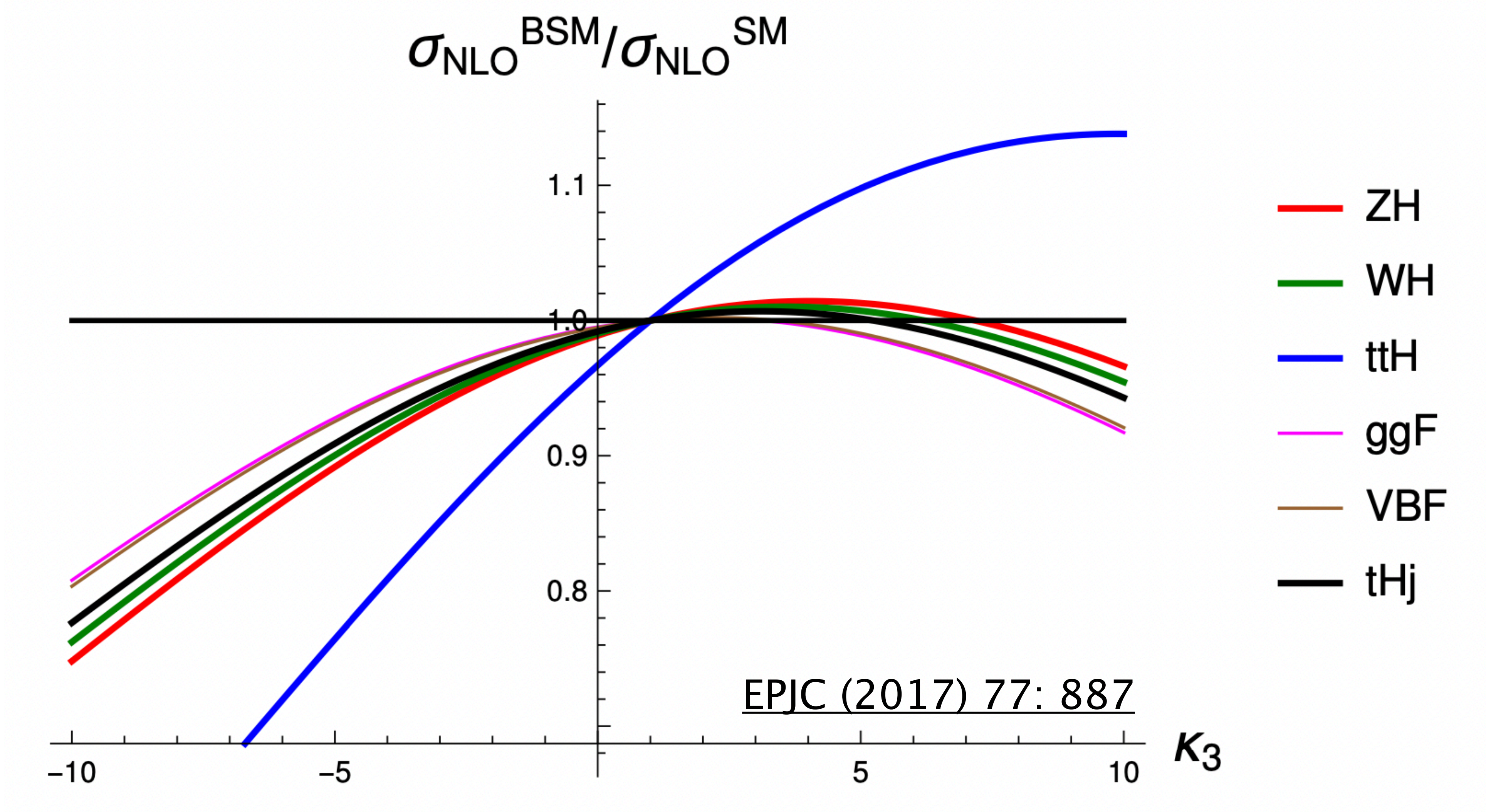


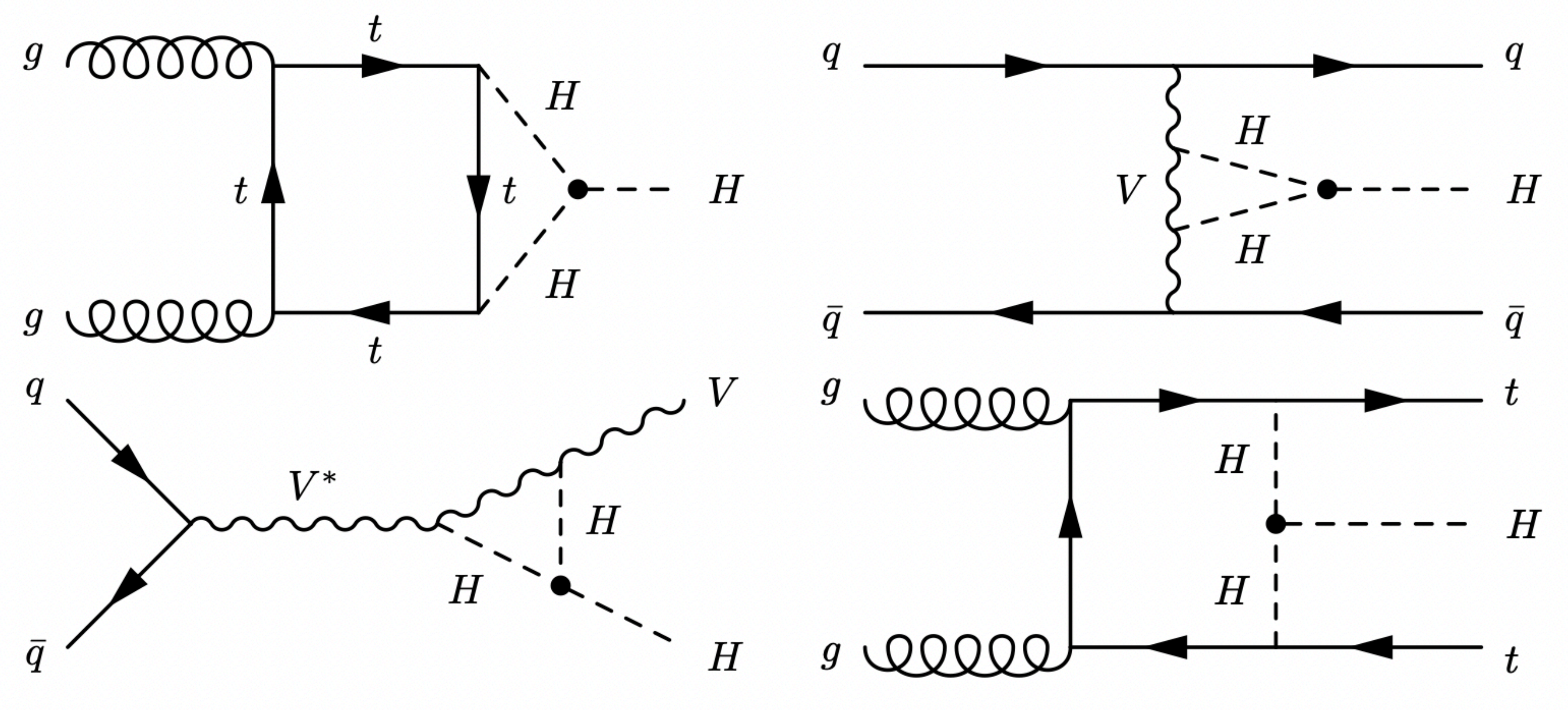
Adding indirect constraints

arXiv:2407.13554, *accepted by PLB*

Measurements of κλ and κ2V are entangled with κt and κV (better measured in single H production)

- That is not the whole story
  - At one loop the single H production (with much higher cross section) and decay is sensitive to variations in kλ **





- Changes signal topology and production rates
  - Signal topology modifications can be modelled when the search is made considering an specific glanularity on fit (Simplified Template Cross Sections - STXS)

Ultimate precision on the H potential <u>in the SM scenario</u> in a given dataset can only be achieved considering a global fit including all H and HH production modes

** These effects are considered in the HH combination

H + HH combination

arXiv:2407.13554, *accepted by PLB*

- This result was made prior to the HH legacy combination
  - The main channels for H pair production are considered
  - Several production and decay modes for single H production are considered
    - A few including glanurality sufficient to consider a differential dependency in kλ

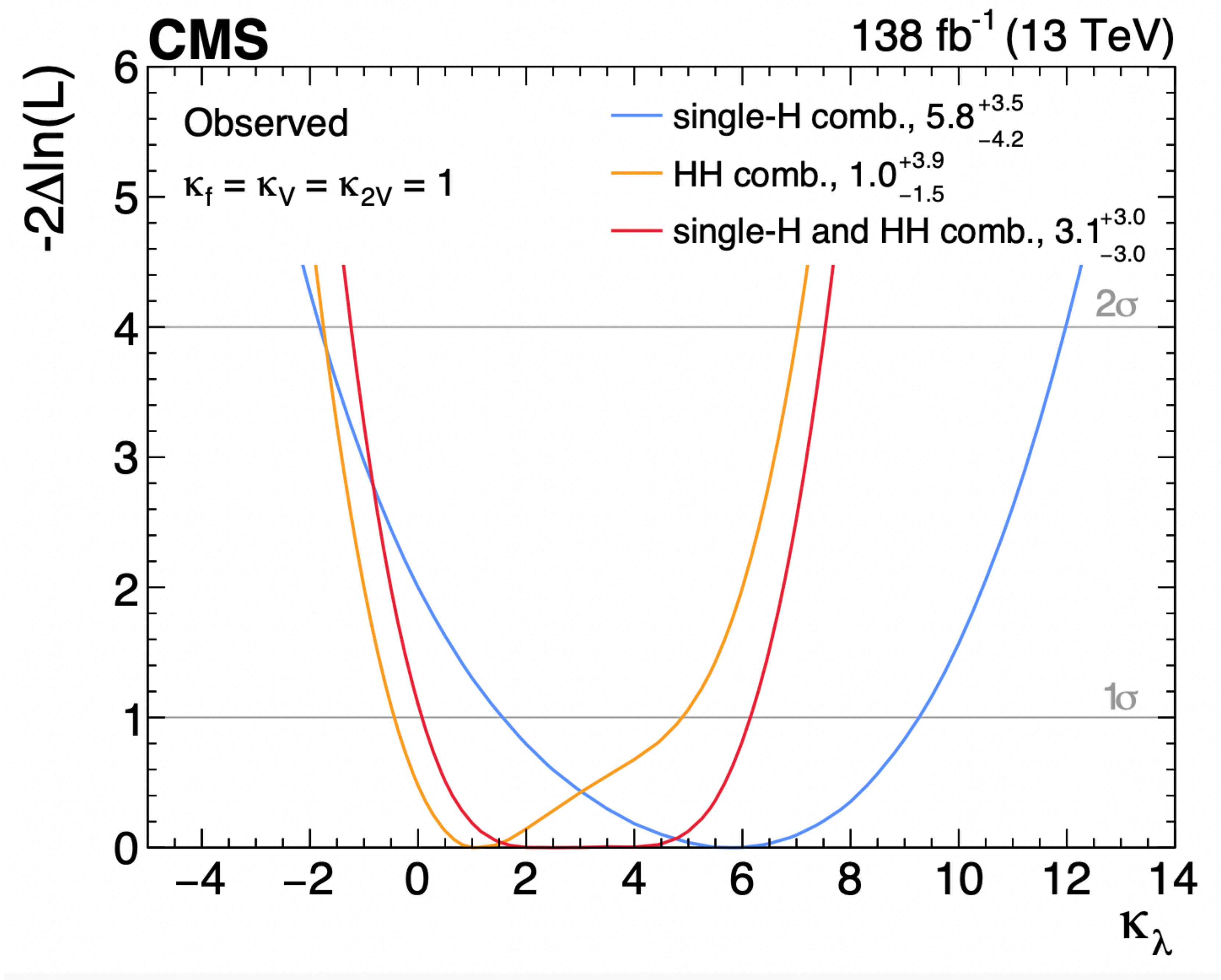
Analysis	Integrated luminosity (fb^{-1})	Targeted H production modes	Maximum granularity
$H \to 4l$	138	ggF, VBF, VH, $t\bar{t}H$	STXS 1.2
$H \to \gamma\gamma$	138	ggF, VBF, VH, $t\bar{t}H$, tH	STXS 1.2
$H \to WW$	138	ggF, VBF, VH	STXS 1.2
$H \to$ leptons ($t\bar{t}H$)	138	$t\bar{t}H$	Inclusive
$H \to b\bar{b}$ (ggF)	138	ggF	Inclusive
$H \to b\bar{b}$ (VH)	77	VH	Inclusive
$H \to b\bar{b}$ ($t\bar{t}H$)	36	$t\bar{t}H$	Inclusive
$H \to \tau\tau$	138	ggF, VBF, VH	STXS 1.2
$H \to \mu\mu$	138	ggF, VBF	Inclusive

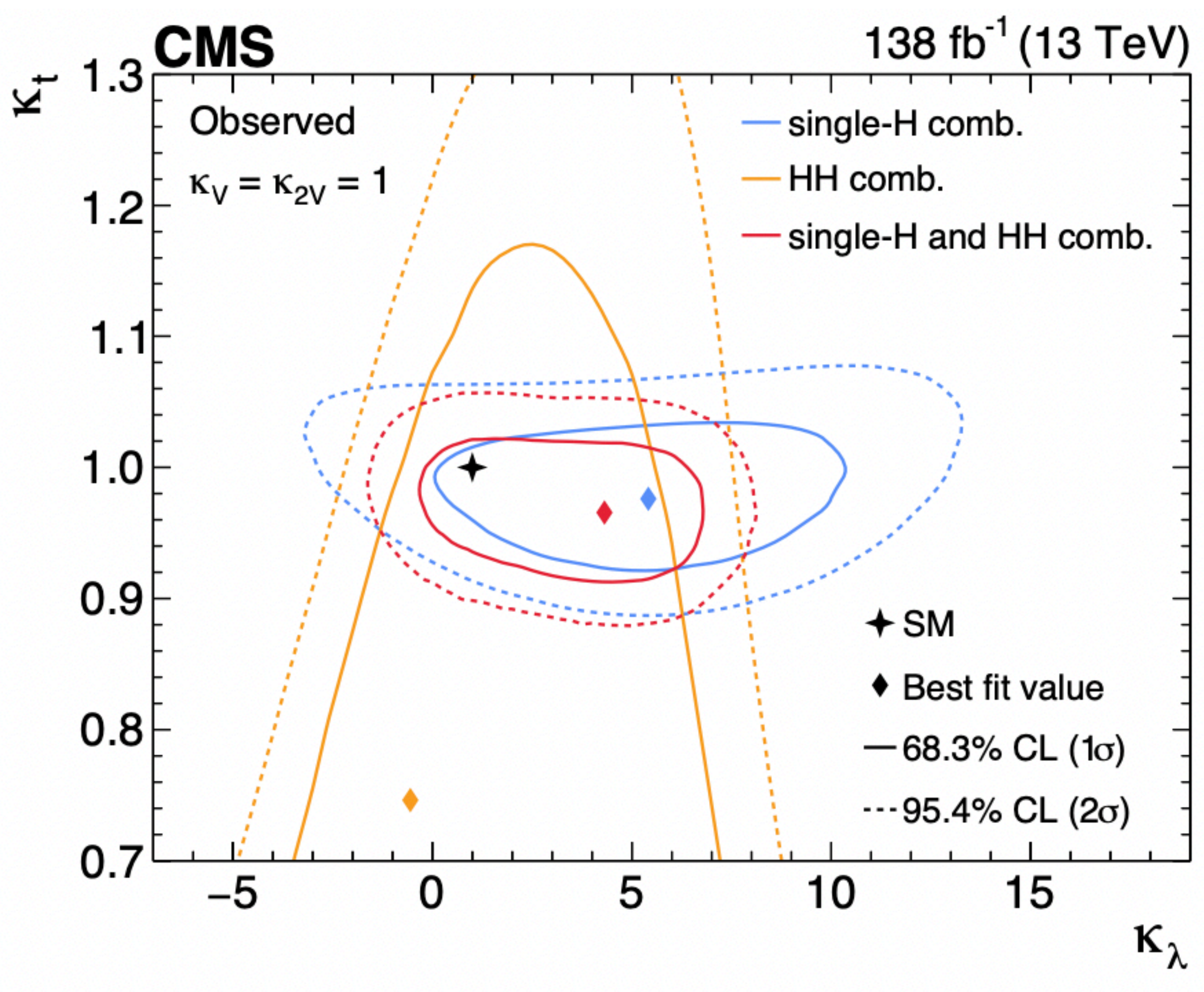
H + HH combination

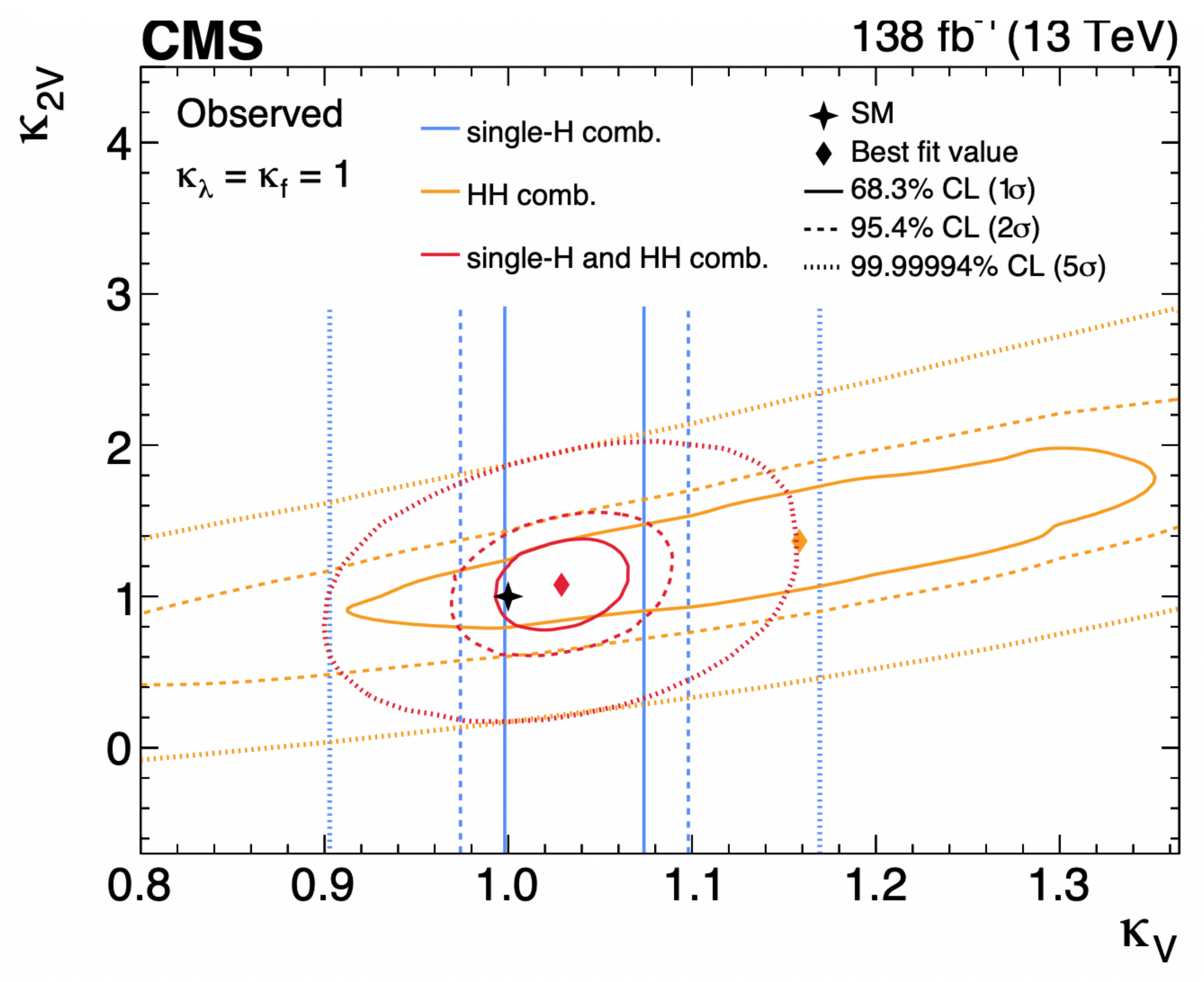
arXiv:2407.13554, *accepted by PLB*

- In a combined measurement we are able to
  - Achieve a better precision on κ_λ
    - Also under minimal assumptions on the other H couplings

Hypothesis	Best fit $\pm 1\sigma$ Expected	Best fit $\pm 1\sigma$ Observed
Other couplings fixed to SM	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$
Floating ($\kappa_V, \kappa_{2V}, \kappa_f$)	$1.0^{+4.7}_{-1.8}$	$4.5^{+1.8}_{-4.7}$
Floating ($\kappa_V, \kappa_t, \kappa_b, \kappa_\tau$)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.1}$
Floating ($\kappa_V, \kappa_{2V}, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.2}$

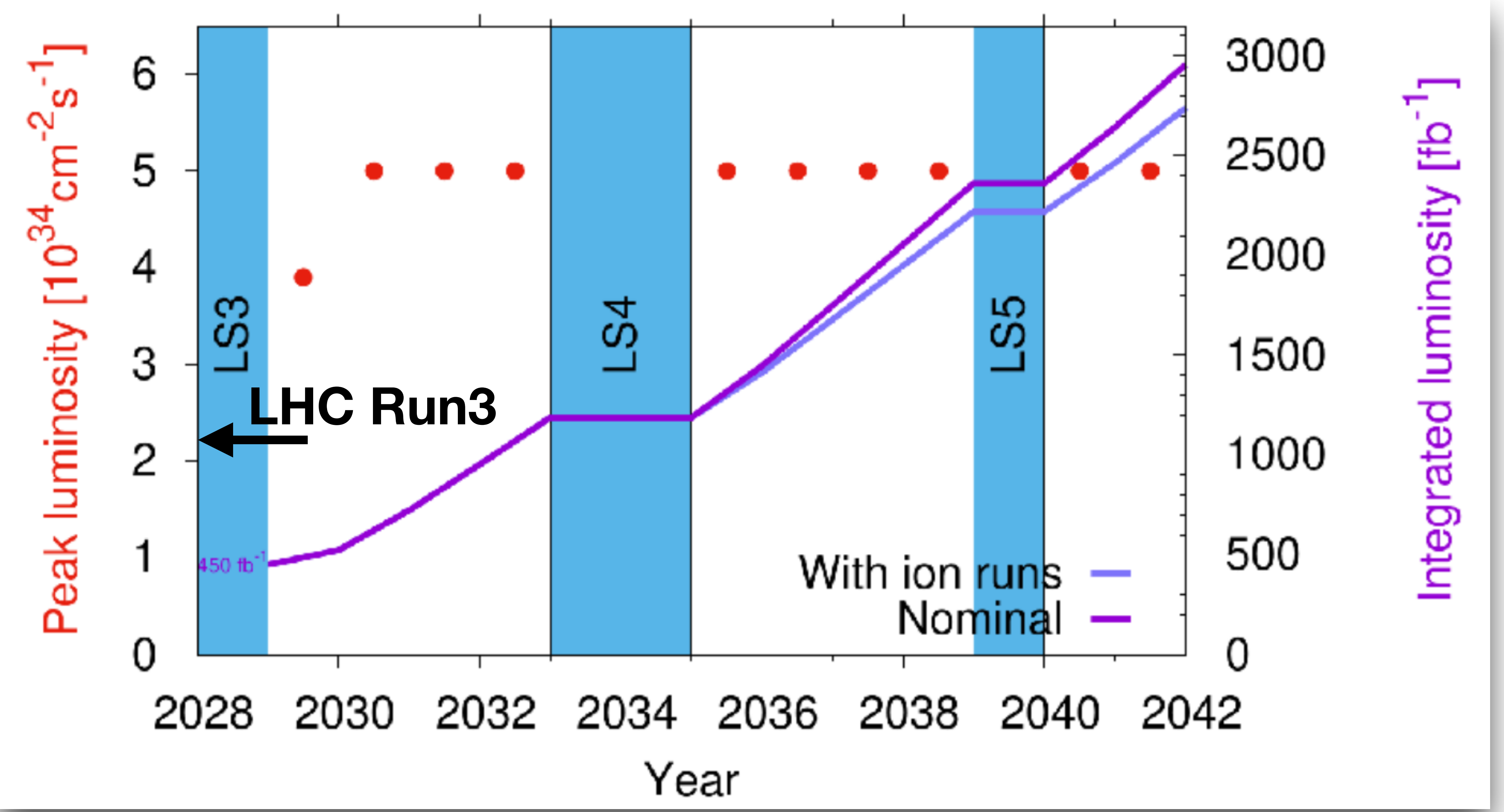






When shall we extect to measure kλ with H pairs?

- In the near future the LHC upgrade to HL-LHC
- Much higher peak luminosity than the LHC => data equivalent to 3000 fb^{-1} in 10 years of operation



- **Upgraded CMS detector** to cope with higher pileup and radiation damage
  - the tracker will be way more granular
  - HGCAL will have a very good reconstruction of the jet energy
  - Introduction of Mip Timing Detector (CMS-TDR-020)
    - Dedicated detector for precision timing of charged minimum ionizing particles (MIPs)

- The MTD is instrumental in maintaining CMS resolution and reconstruction efficiency thanks to improvements brought to events observables:
  - Rejection of tracks from pile up interactions by adding requirements on track time
  - Pile-up jet suppression with the employment of Pile Up per Particle Identification (PUPPI) algorithm
  - Removal of spurious secondary vertices in heavy-flavour tagging with time information

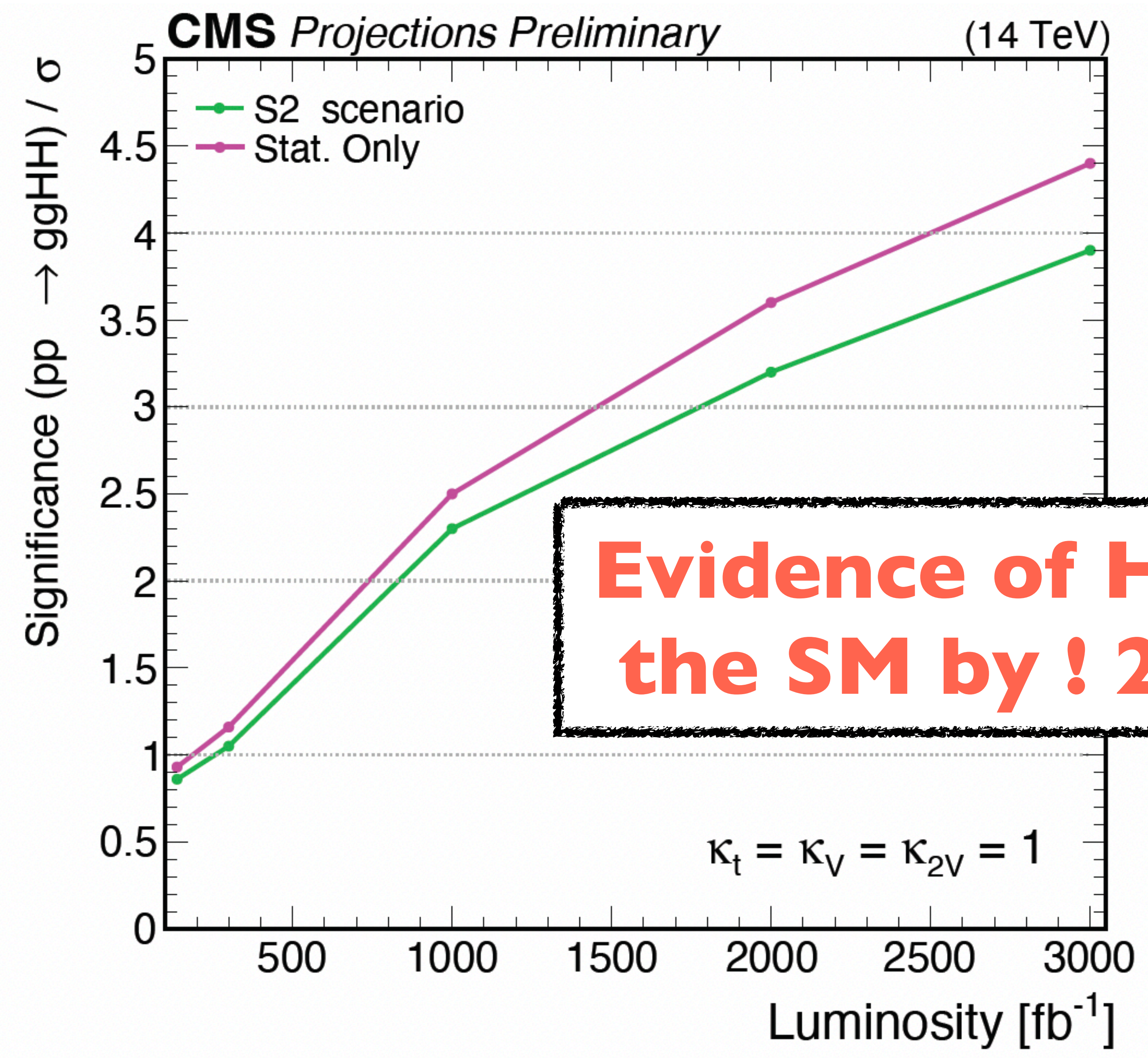
Improvements on physics objects will bring gain in several searches: Including searches for H pairs

H pairs @ HL-LHC

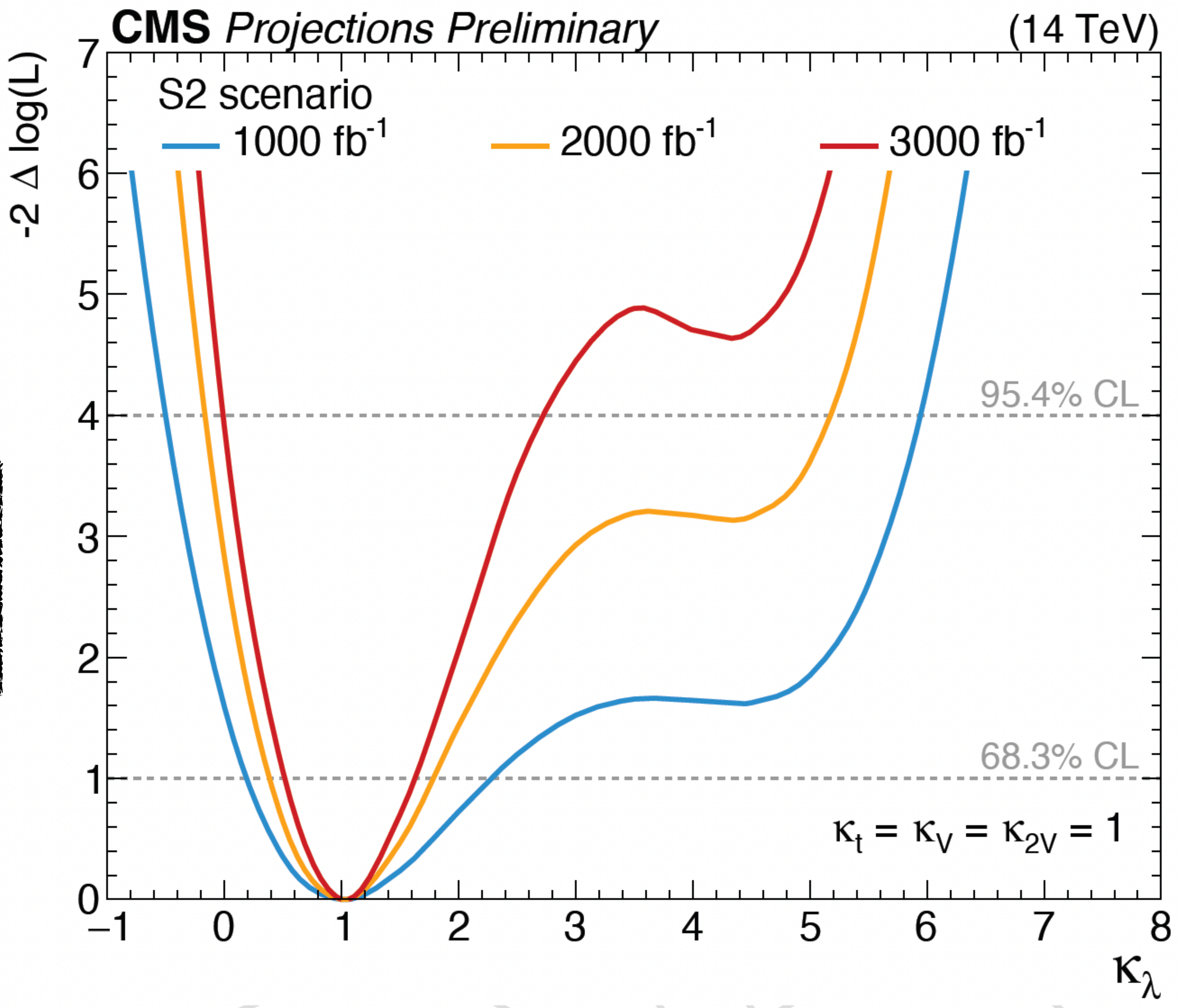
PAS-HIG-20-011

- Projections: Yields scaled by a factor $k_L = L/L_{Run2}$ (L = integrated luminosity)
- Efficiency of physics object reco, id, misid and resolution are assumed to be same as Run 2 (LHC YR4)
  - We are neglecting the effect of the increase on Pileup in the projections thanks to MTD

Channels: 4b, bbγγ, bbττ, bbWW, multilepton



Evidence of HH as in the SM by ! 2000/fb



Best fit on kλ between [0.5, 1.6] @ 68% CL by the end of the HL-LHC run

- That is a lower bound for the constraints: we expect significant improvements in this picture!
  - Already at Run 3 we are improving object identification algoritmns, trigger strategies and analyses techniques beyond the scope of mere scale with luminosity

Conclusions

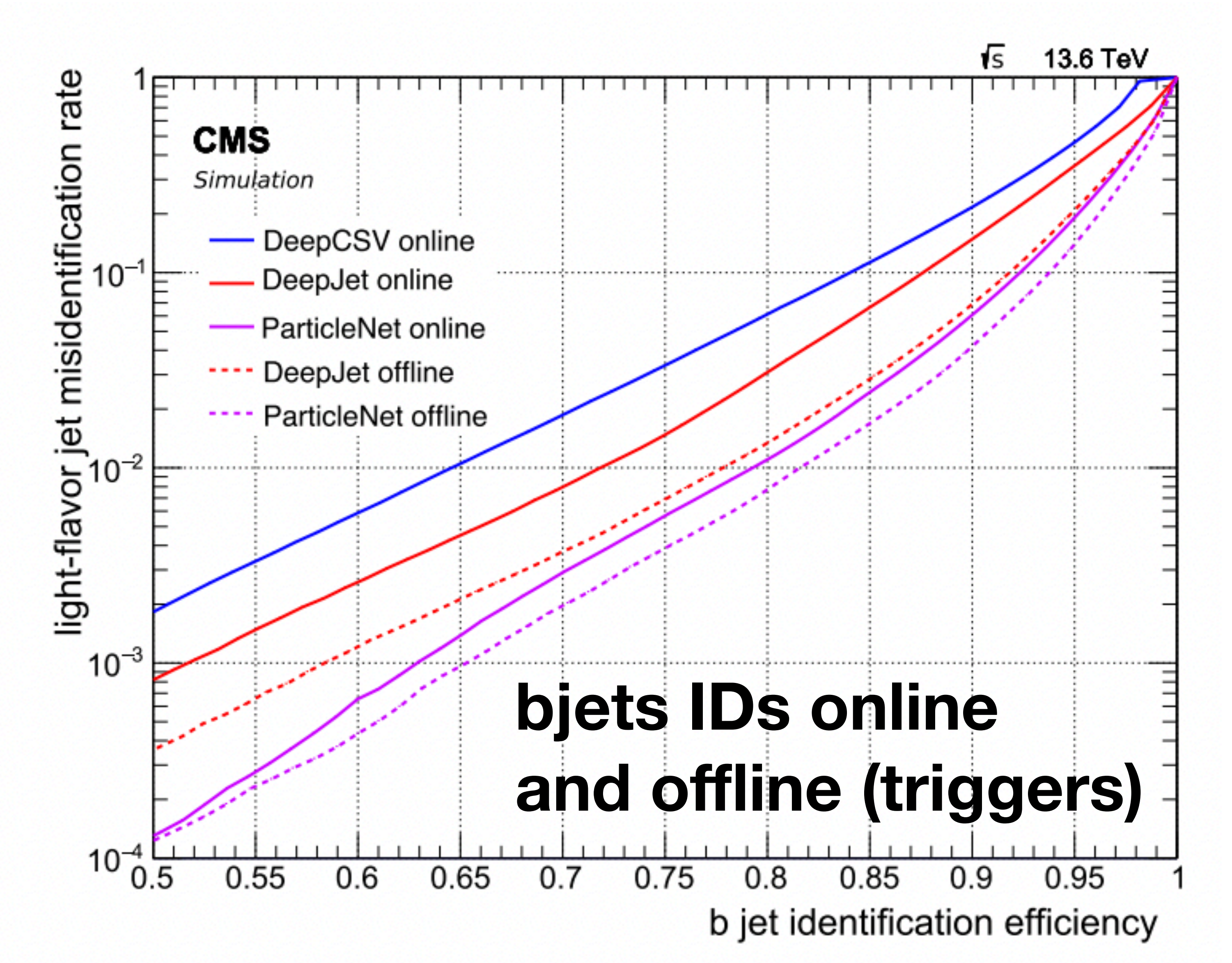
- The measurement of the H potential is one of the key physics topics in High Energy Physics
- That is achieved directly by the searches for H pairs at LHC
  - Allows to access another rare quartic gauge coupling → HHVV interactions
- CMS performed several searches for H pairs
  - Brand new results form the legacy combination from using full Run 2 data!
- The correlation of constraints on the Higgs couplings from HH and single H production is an important element towards precision measurements on the Higgs couplings
  - Achieve better precision on the H potential in the SM scenario under minimal assuptions
- We project the legacy HH combination to anticipate our sensitivity at the HL-LHC as a lower bound for future reach
  - Future is bright: in a pessimistic scenario we shall have the evidence for the process by 2040!

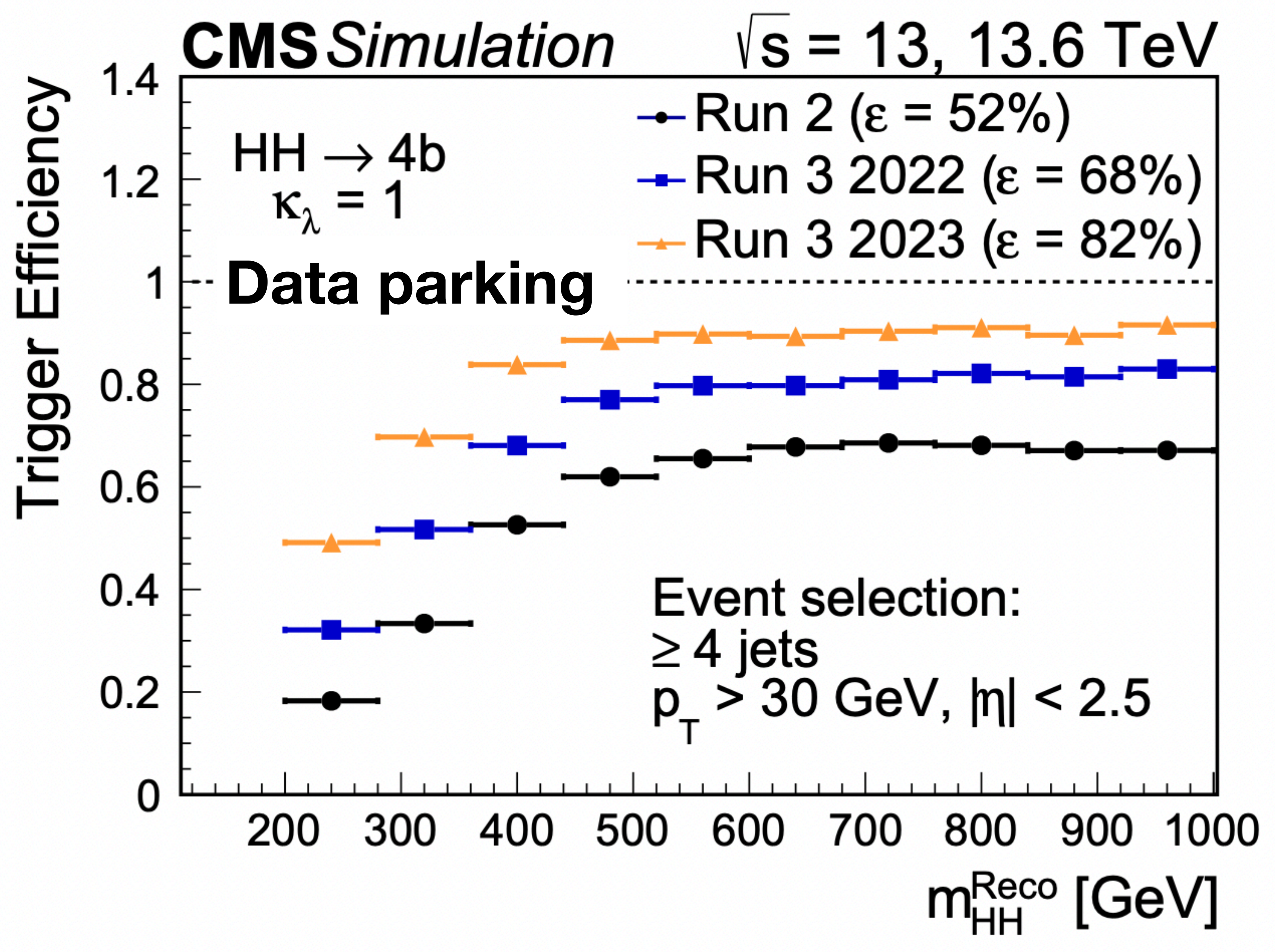
Thank you for attention!

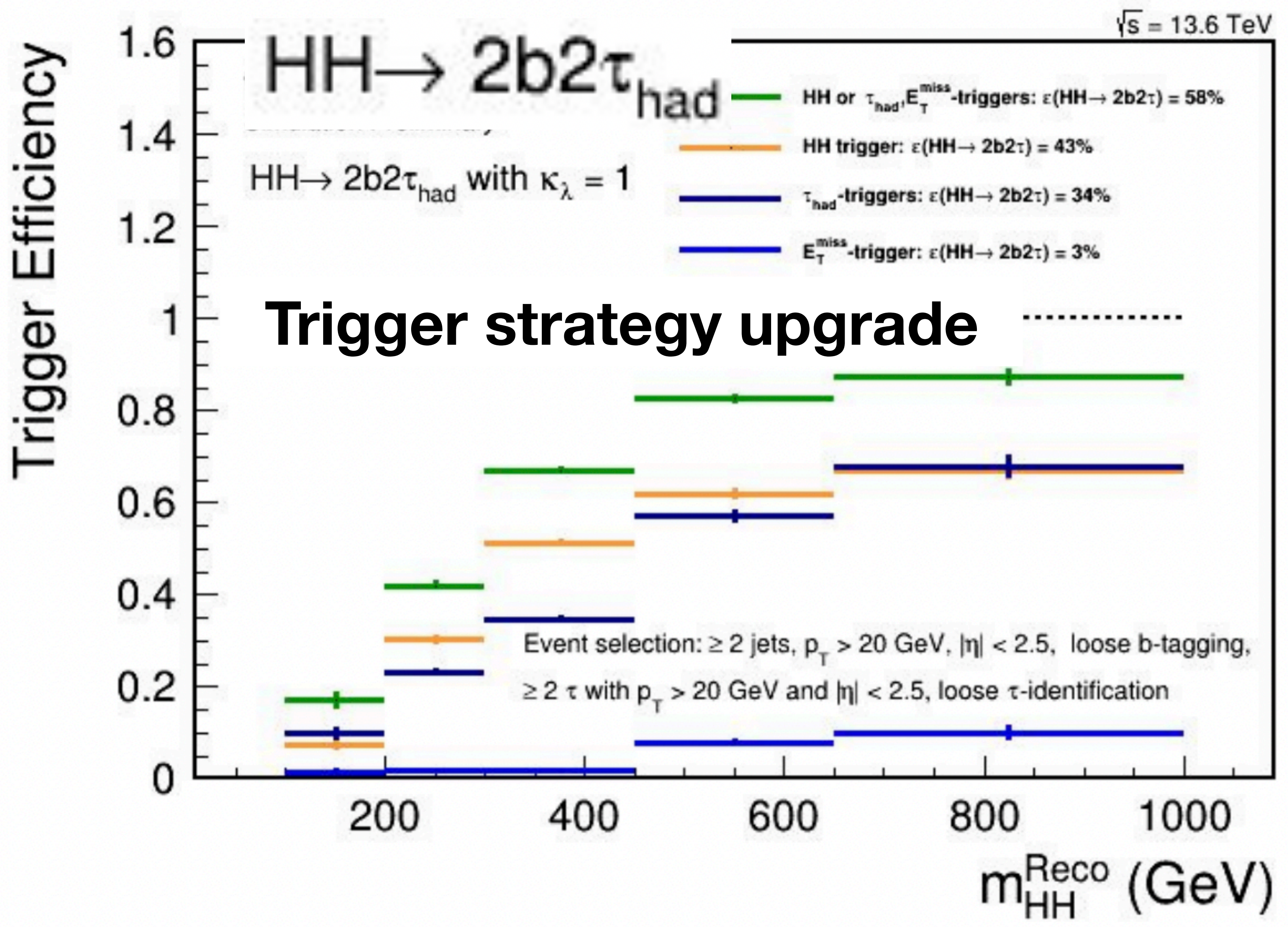
Expected Improvements in LHC Run3

Confirmed % improvement in object and event reconstruction

- **b-jets Triggers: 31-58% gain in efficiency in resolved 4b [here]**
- **b-tag efficiency: 5% better tagging + 10% on the mbb resolution improvement [here]**
- **τ-lepton Triggers 57% gain in efficiency in hadronic tau channels of bbττ [here]**
- **T-lepton ID 5%-10% better tagging [here]**
- **Parking triggers 10% gain in efficiency on 4b triggers, on top of trigger above-mentioned gain [here]**



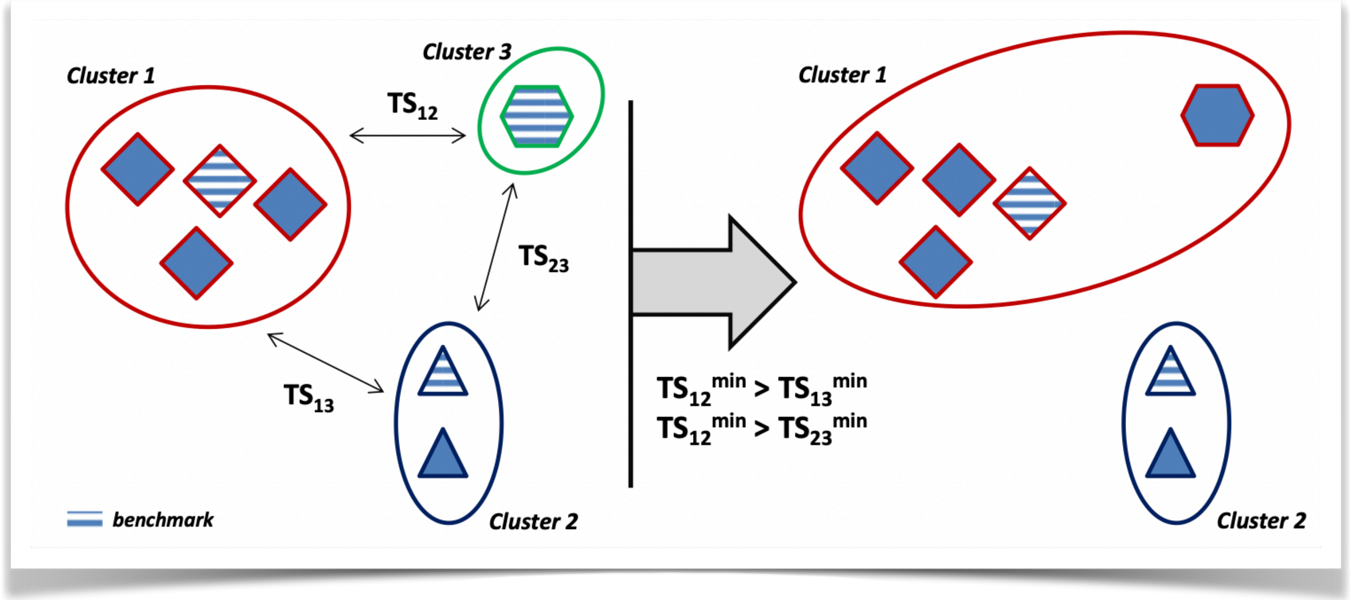




The improvement at analysis level is yet to be checked
Those allow amelioration in analysis strategies, the gain can go beyond the shown expectations

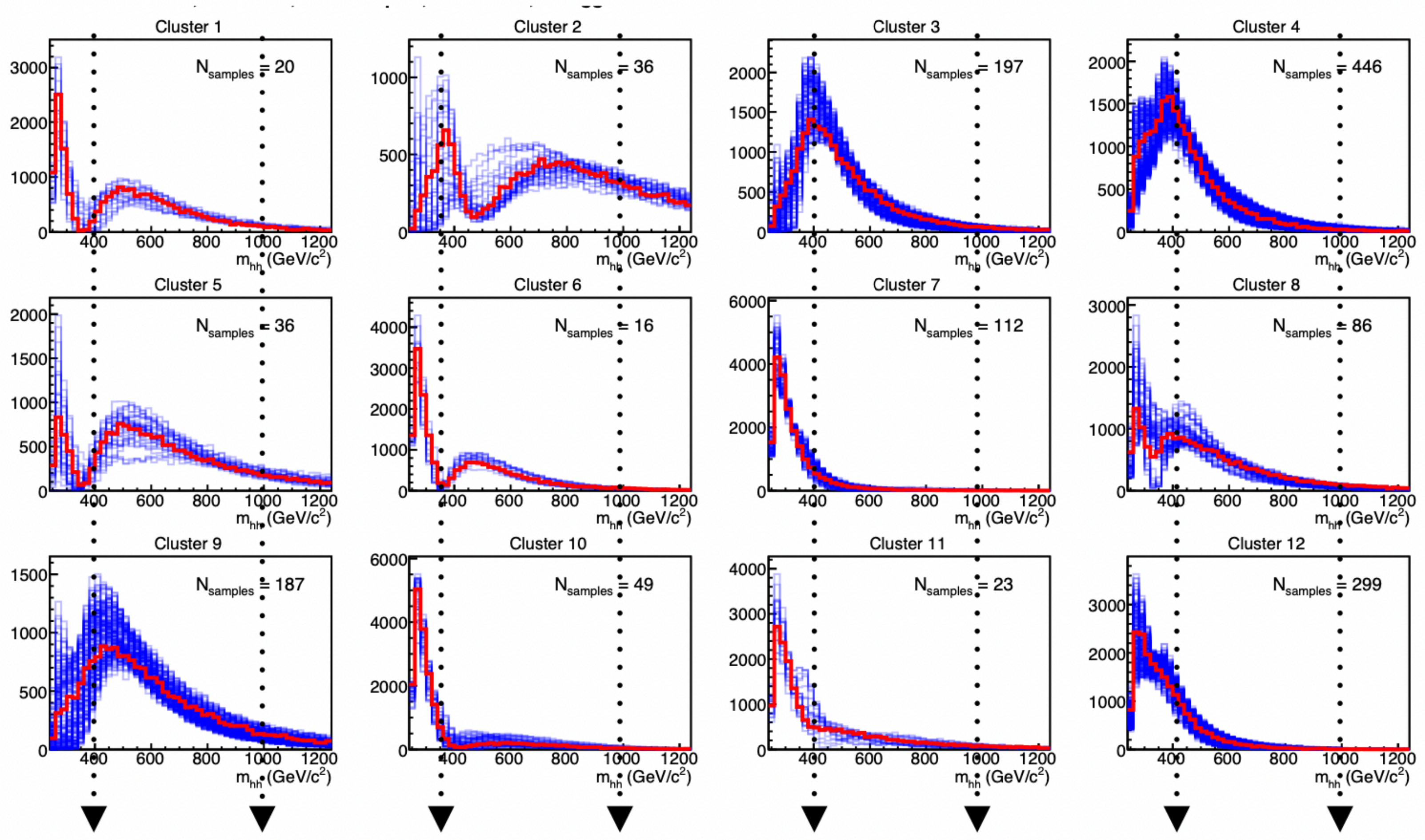
Shape benchmarks idea and table of couplings

Stat. test of similarity between mHH shapes



Broad couplings scan

—>distributions into clusters



Mhh = 400, 1000, 400, 1000, 400, 1000, 400, 1000, GeV

Red: the benchmark
Blue: the other samples in the cluster

The benchmarks are part of the LHCXSWG YR4

- Recomputed @NLO precision in simulation [2019], improved ML strategy and including present constraints in H couplings [here]
  - Recomputed one more time, updating constraints in H couplings and added as LHC WG4 recomendation [2022]

Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
JHEP04 BM1	7.5	1.0	−1.0	0.0	0.0
JHEP04 BM2	1.0	1.0	0.5	−0.8	0.6
JHEP04 BM3	1.0	1.0	−1.5	0.0	−0.8
JHEP04 BM4	−3.5	1.5	−3.0	0.0	0.0
JHEP04 BM5	1.0	1.0	0.0	0.8	−1.0
JHEP04 BM6	2.4	1.0	0.0	0.2	−0.2
JHEP04 BM7	5.0	1.0	0.0	0.2	−0.2
JHEP04 BM8	15.0	1.0	0.0	−1.0	1.0
JHEP04 BM8a	1.0	1.0	0.5	4/15	0.0
JHEP04 BM9	1.0	1.0	1.0	−0.6	0.6
JHEP04 BM10	10.0	1.5	−1.0	0.0	0.0
JHEP04 BM11	2.4	1.0	0.0	1.0	−1.0
JHEP04 BM12	15.0	1.0	1.0	0.0	0.0
JHEP03 BM1	3.94	0.94	−1/3	0.75	−1
JHEP03 BM2	6.84	0.61	1/3	0	1
JHEP03 BM3	2.21	1.05	−1/3	0.75	−1.5
JHEP03 BM4	2.79	0.61	1/3	−0.75	−0.5
JHEP03 BM5	3.95	1.17	−1/3	0.25	1.5
JHEP03 BM6	5.68	0.83	1/3	−0.75	−1
JHEP03 BM7	−0.10	0.94	1	0.25	0.5
SM	1.0	1.0	0.0	0.0	0.0

We keep using the first version (couplings agnostic) as New Physics proxy, and the most updated set