Exploring the Higgs boson self-coupling at the LHC

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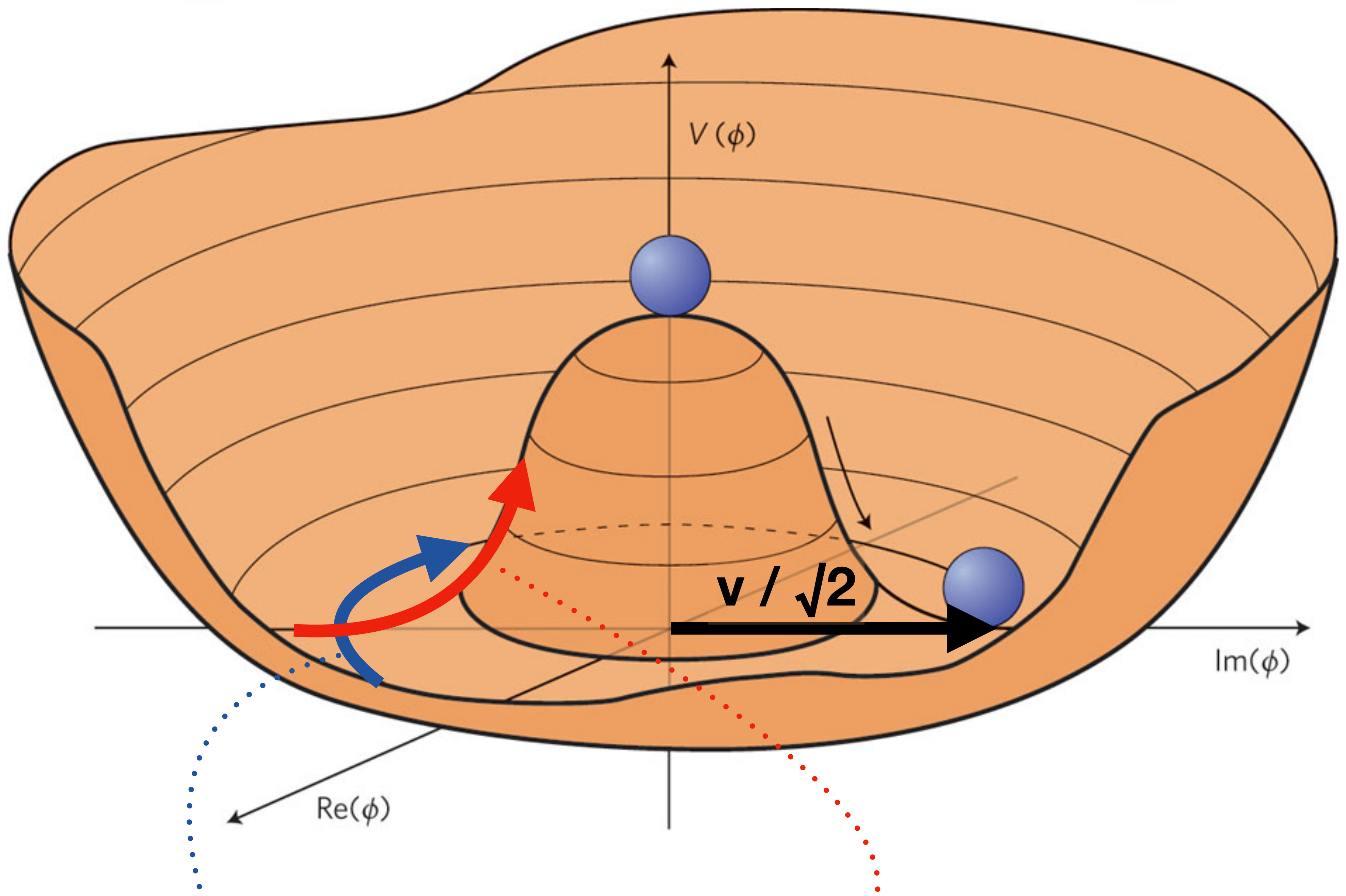
The scalar sector of the standard model

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



Additional d.o.f.
⟹ **W and Z polarisation**

Quantum of the field
⟹ **Higgs boson**

$$m_{\mathrm{H}}^2 = 2\lambda v^2 = 2\mu^2$$

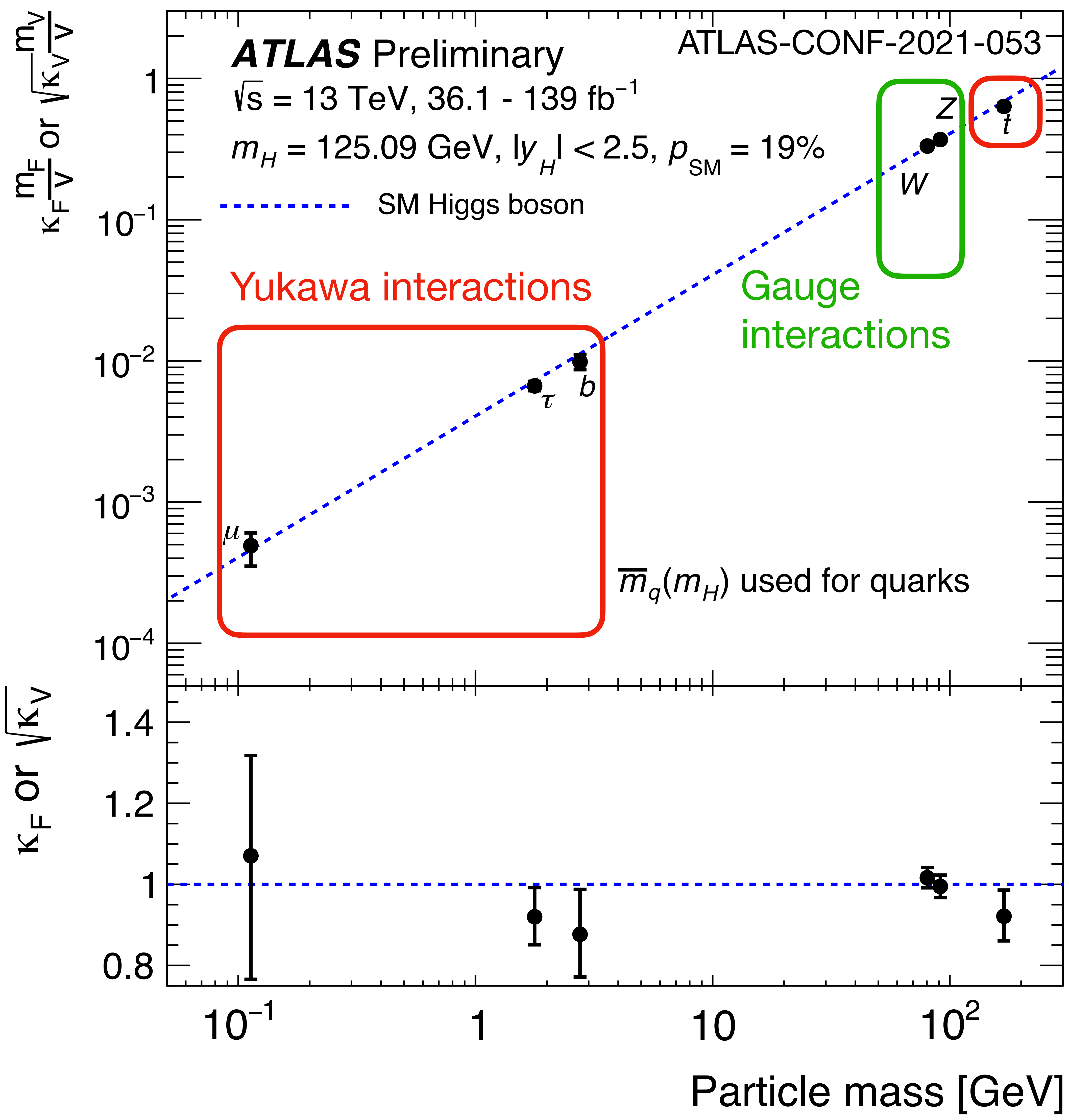
Two main sectors of the SM:

- **Gauge sector:** electroweak and strong interactions explained with local gauge symmetries
- **Scalar sector:** complex scalar doublet of fields and potential with VEV ≠ 0
  - spontaneous electroweak symmetry breaking (Brout-Englert-Higgs mechanism)
- The scalar sector is a necessary element of the SM
  - $W^\pm$ and Z bosons masses
  - fermions masses via Yukawa interactions
  - regularises the theory at the TeV scale

The scalar sector properties are determined by the shape of the scalar potential

The Higgs boson…

- Observed by ATLAS and CMS in 2012
- Mass precisely determined:
  $m_H = 125.09 \pm 0.24$ GeV
- Precise study of its interactions with fermions and vector bosons…



… and its self-coupling

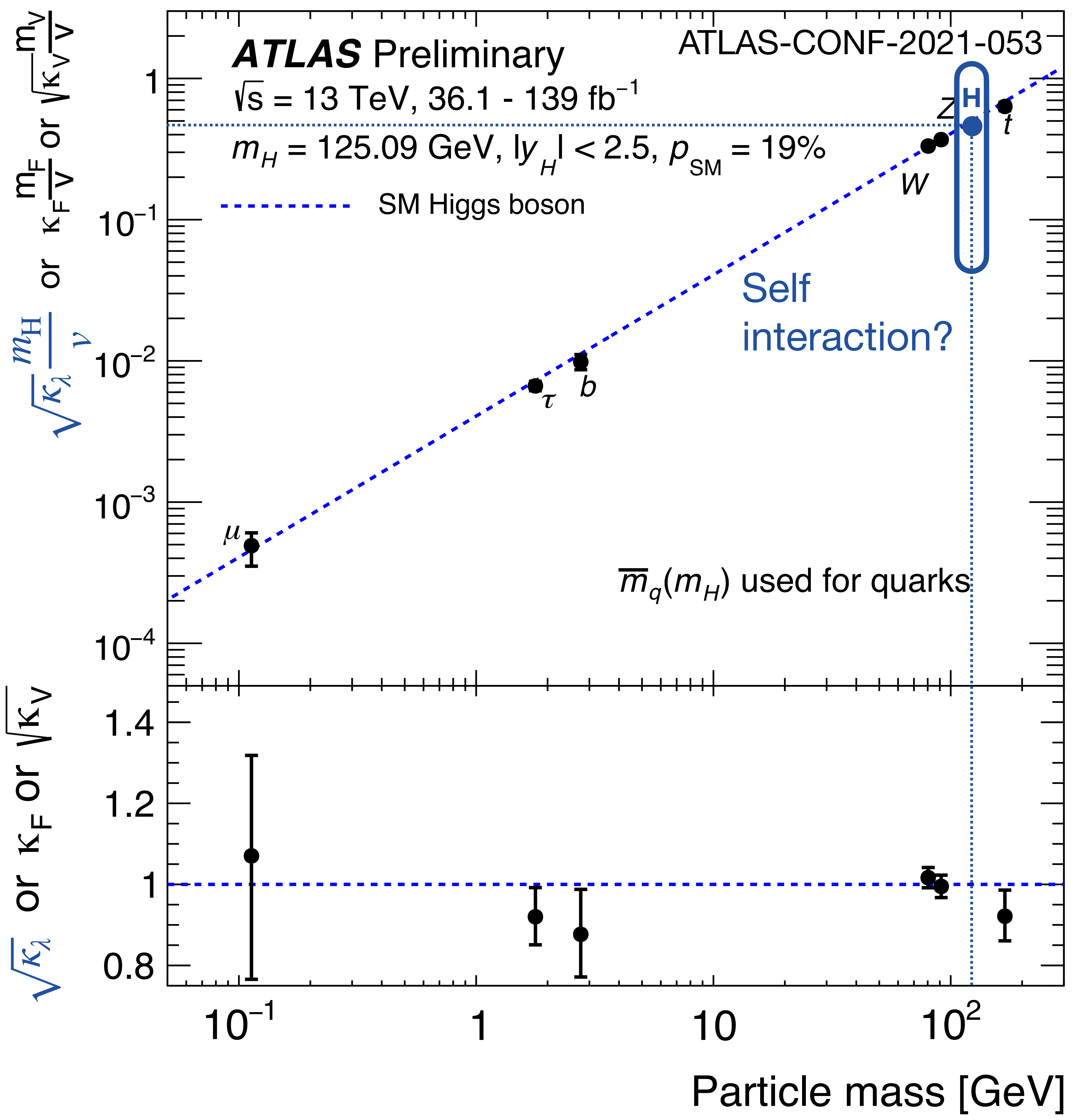
- Observed by ATLAS and CMS in 2012
- Mass precisely determined:
  $m_H = 125.09 \pm 0.24$ GeV
- Precise study of its interactions with fermions and vector bosons…
- … but self-interactions not measured experimentally!

$$V(H) = \frac{1}{2} m_{\mathrm{H}}^2 H^2 + \lambda_{\mathrm{HHH}} v H^3 + \frac{1}{4} \lambda_{\mathrm{HHHH}} H^4 - \frac{\lambda}{4} v^4$$

$$\lambda_{\mathrm{HHH}} = \lambda_{\mathrm{HHHH}} = \lambda = \frac{m_{\mathrm{H}}^2}{2v^2} \approx 0.13$$

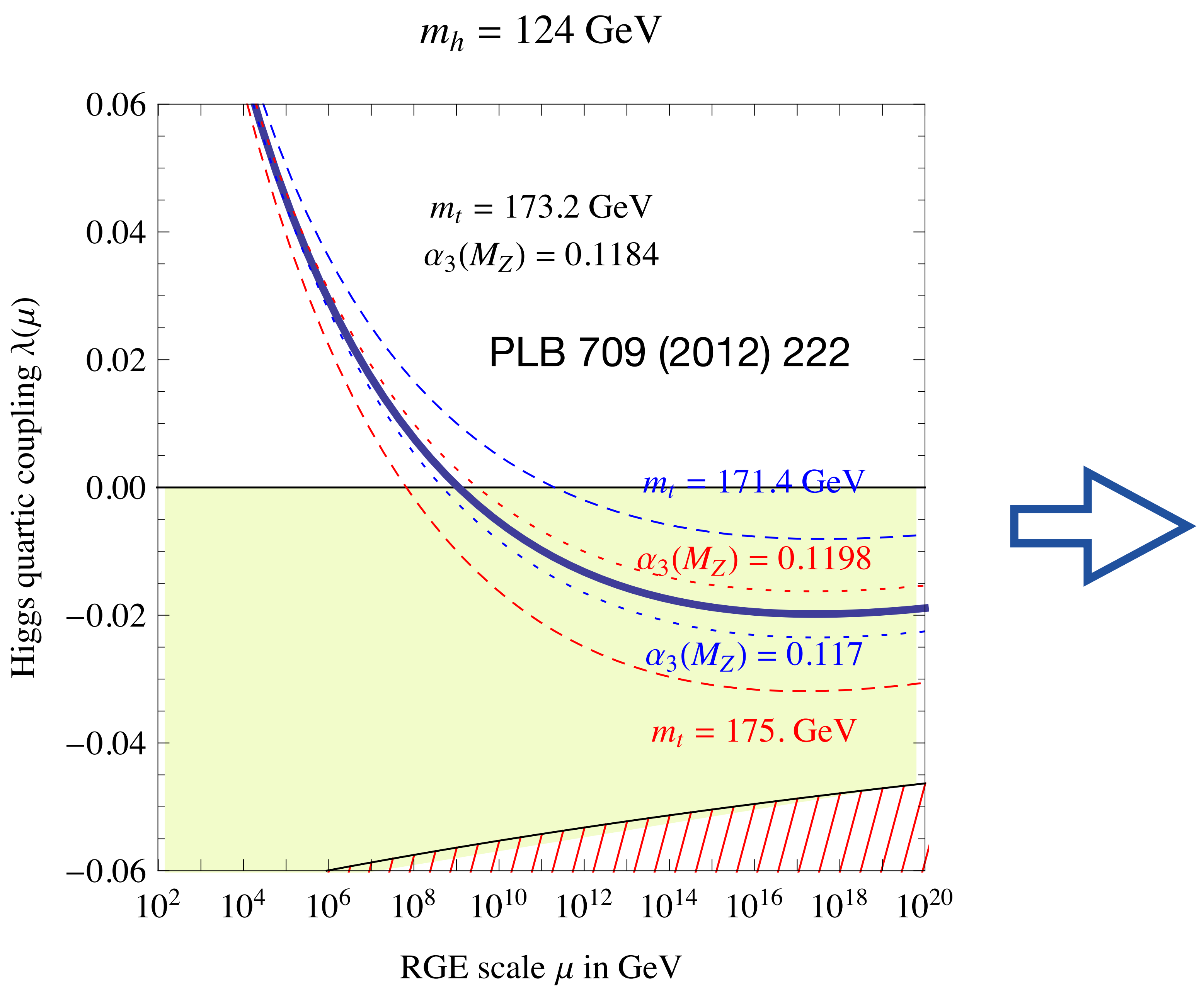
λ_{HHH} : direct access to the shape of the scalar potential

Direct test of the EW symmetry breaking



Why is it important?

The shape of the scalar potential is linked to many open questions of particle physics and cosmology



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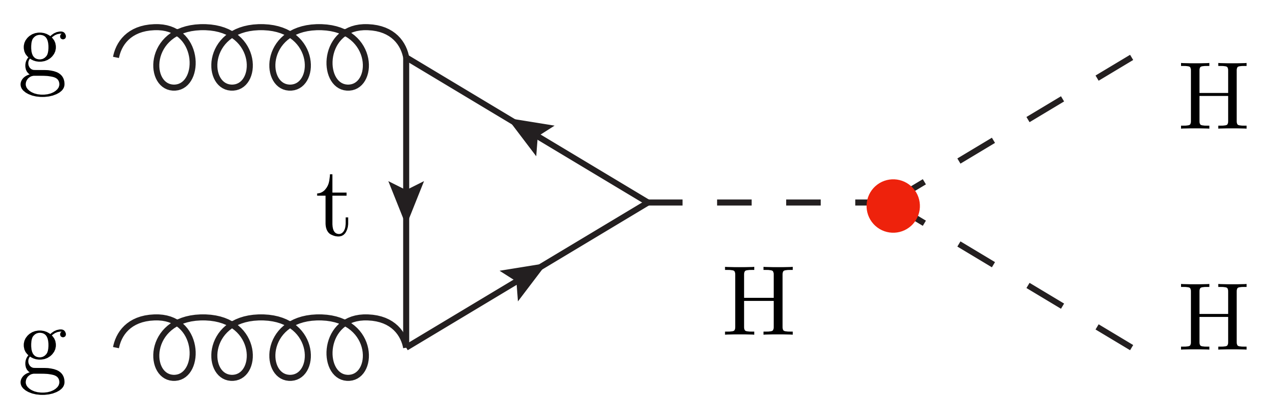
- The modification of the shape of the scalar potential at high scales makes the EW vacuum metastable
- The stability of the potential at high has an impact of the possible role of the Higgs boson as the inflaton in the primordial Universe

λ_{HHH} : how measure it?

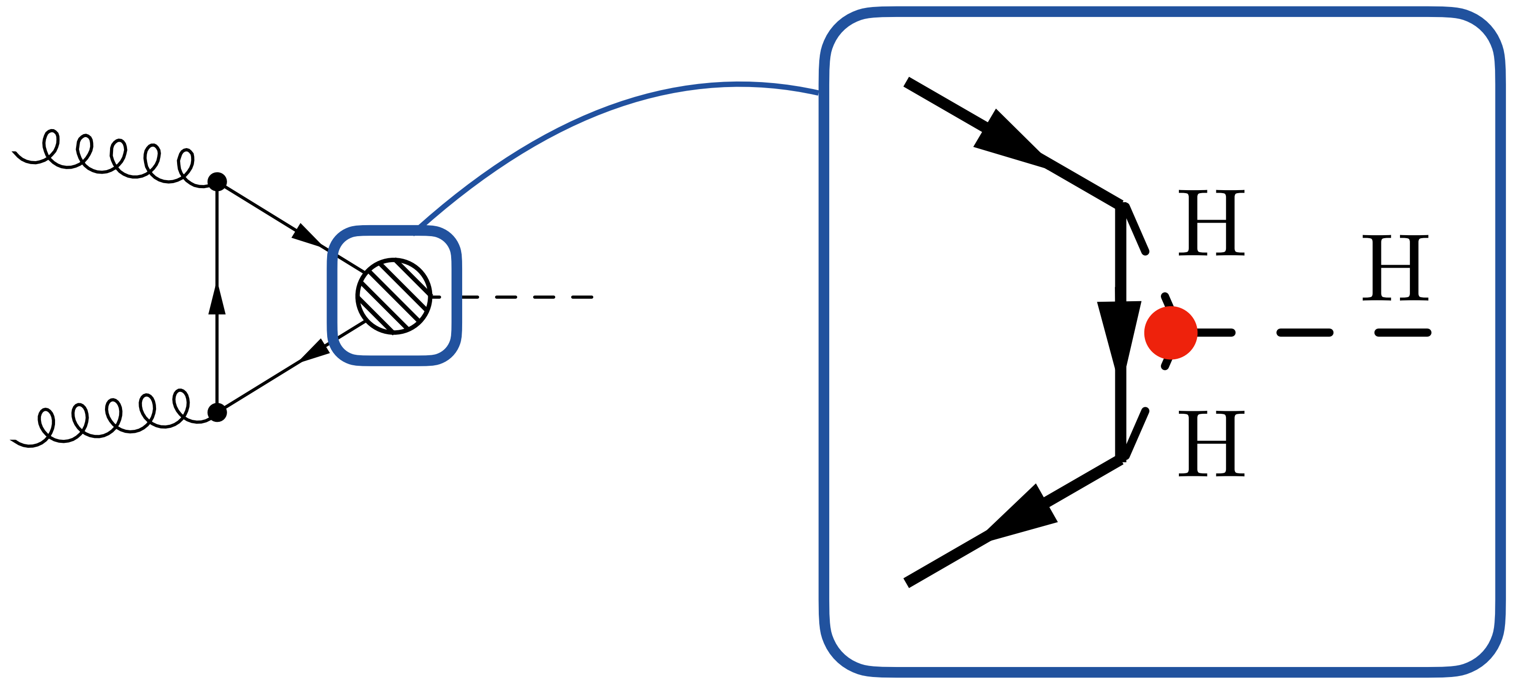
Two complementary strategies exist:

Direct measurements in HH



- Use the production of two Higgs bosons to probe λ_{HHH}
  - direct measurement: theoretically clean
  - very rare process $\Longrightarrow$ experimentally challenging

Indirect measurements in single H

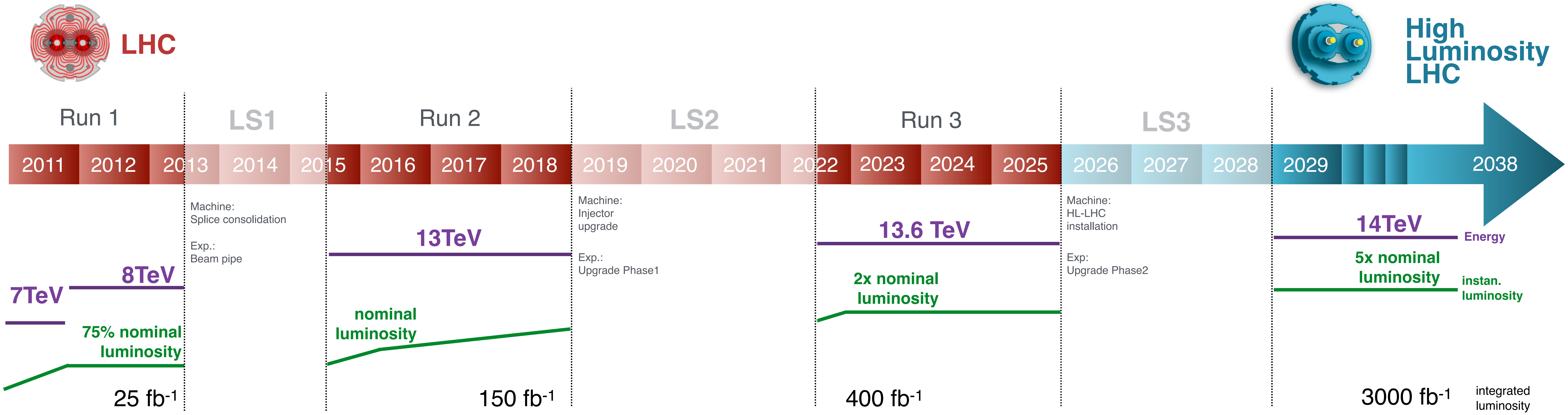


- Extract the value of λ_{HHH} from precision single H cross section measurements
  - indirect measurement: stronger theory assumptions needed to disentangle NLO λ_{HHH} effects from other couplings / new physics
  - benefit of the large single H cross section (~ 1000 $\times$ σ_{HH})

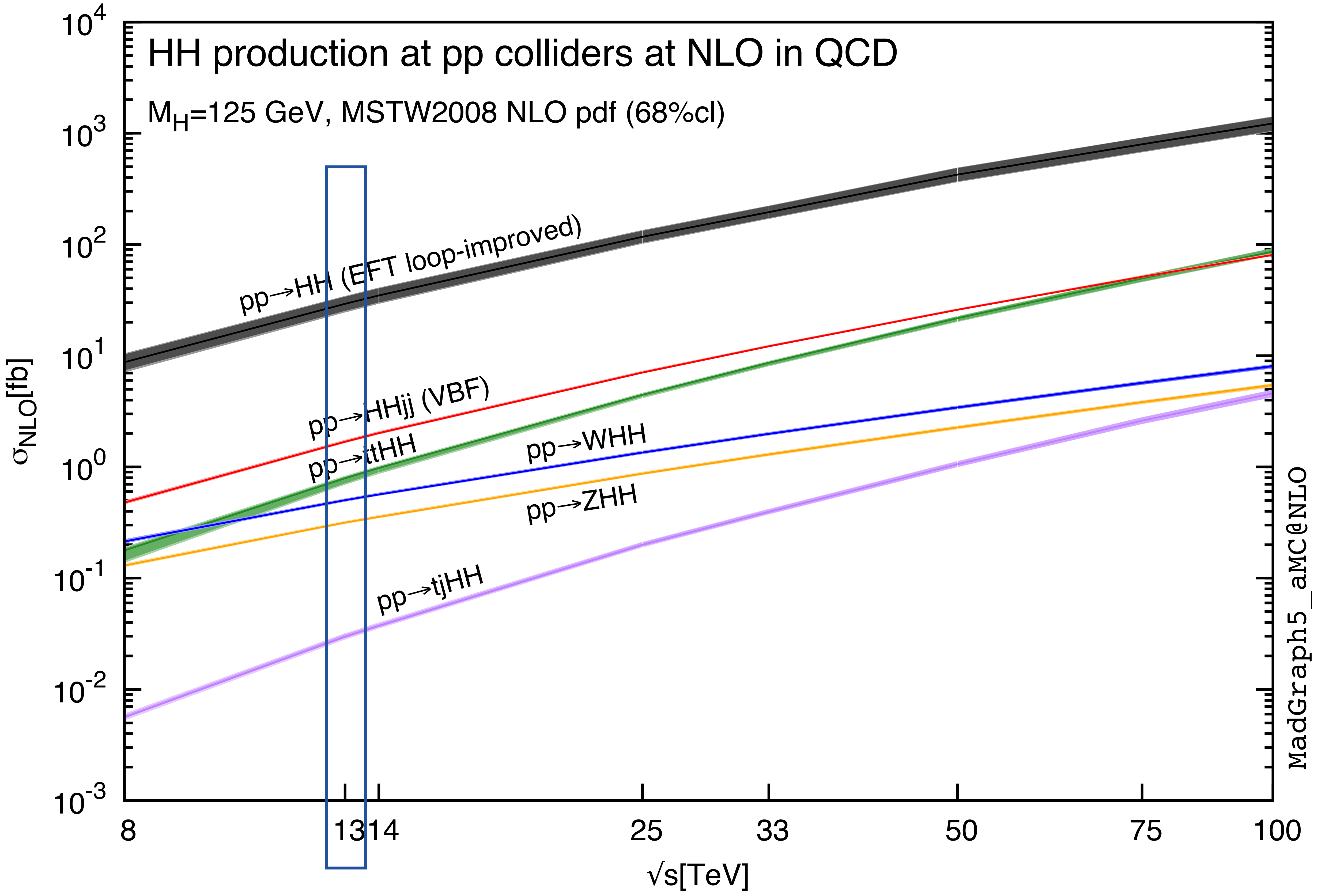
The combination of both strategies maximises our sensitivity to λ_{HHH}

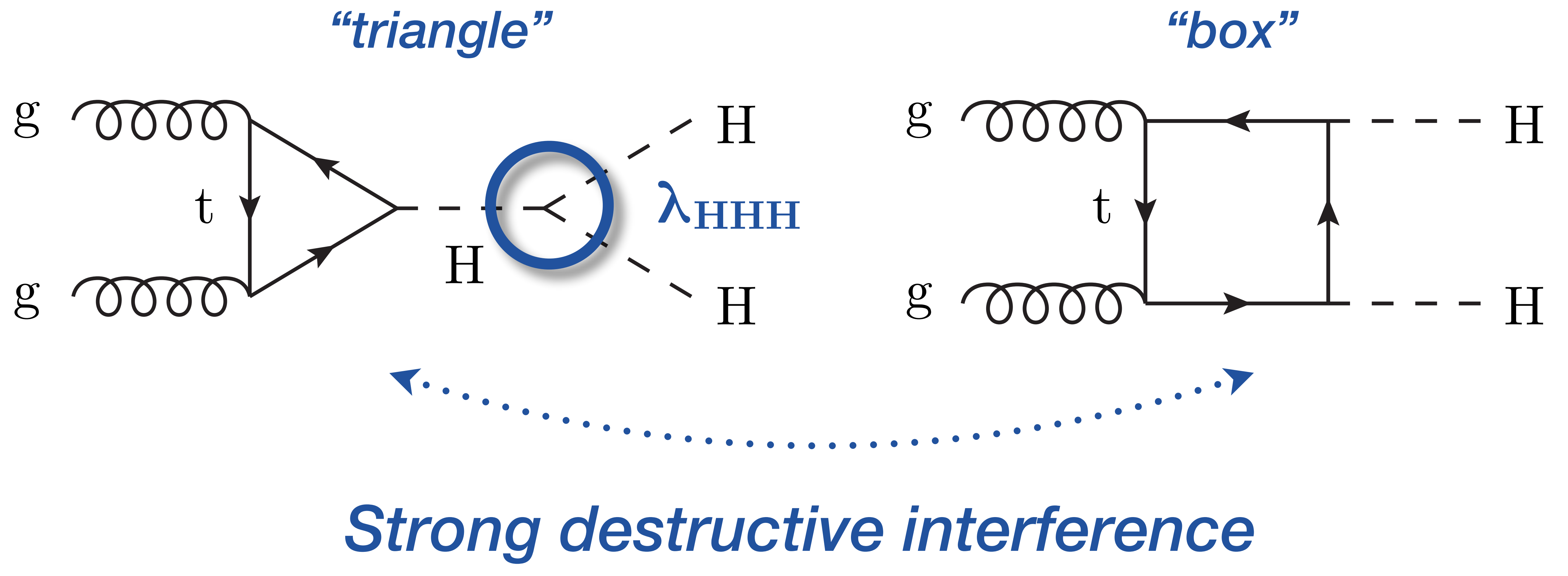
The Large Hadron Collider

- The CERN LHC is designed to deliver pp collisions at $\sqrt{s}$ = 14 TeV and $\mathscr{L} = 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$
- Design instantaneous luminosity exceeded throughout the Run 2 operations at $\sqrt{s}$ = 13 TeV!
- Broad program of H and HH measurements with the ATLAS and CMS experiments



HH production at the LHC



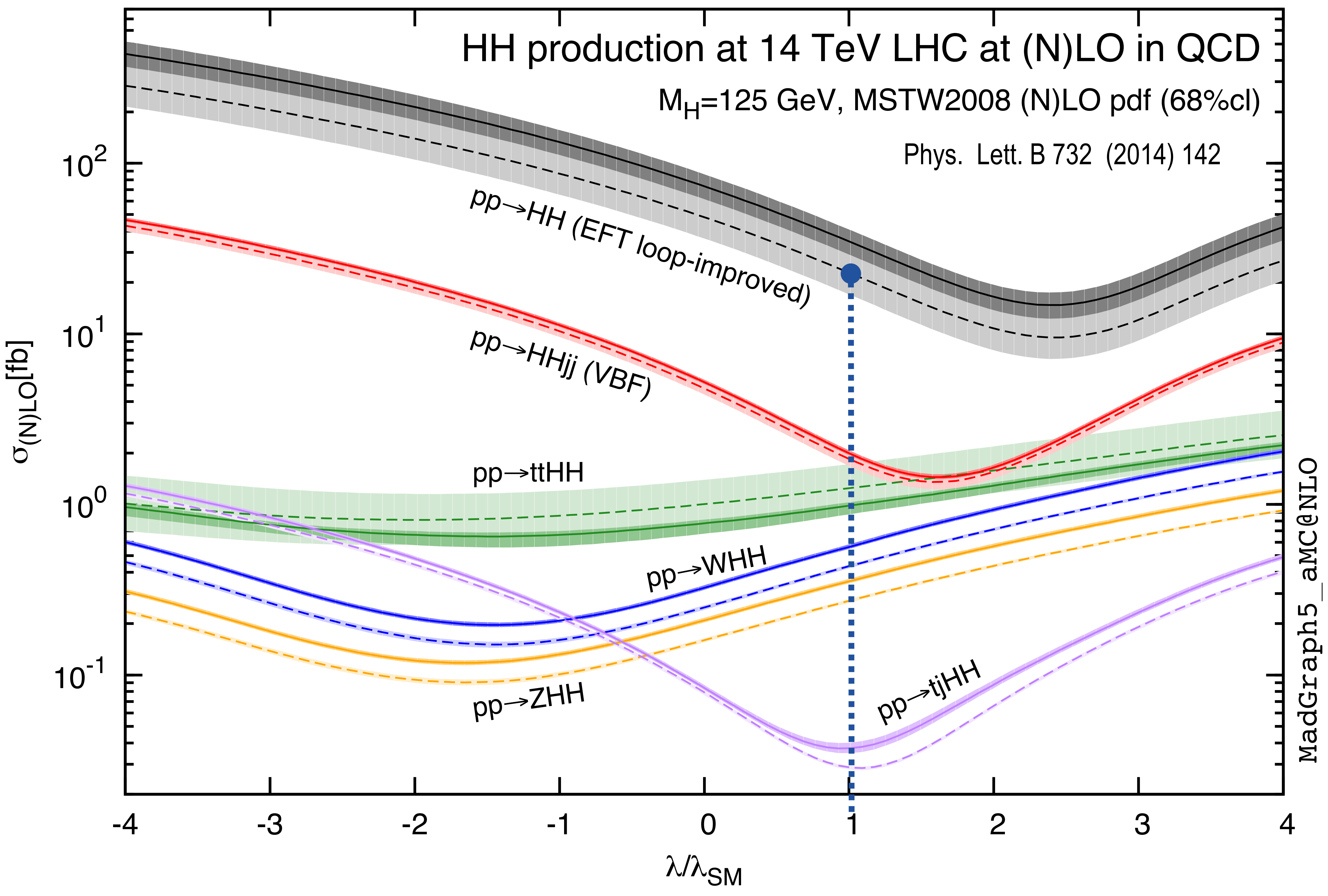


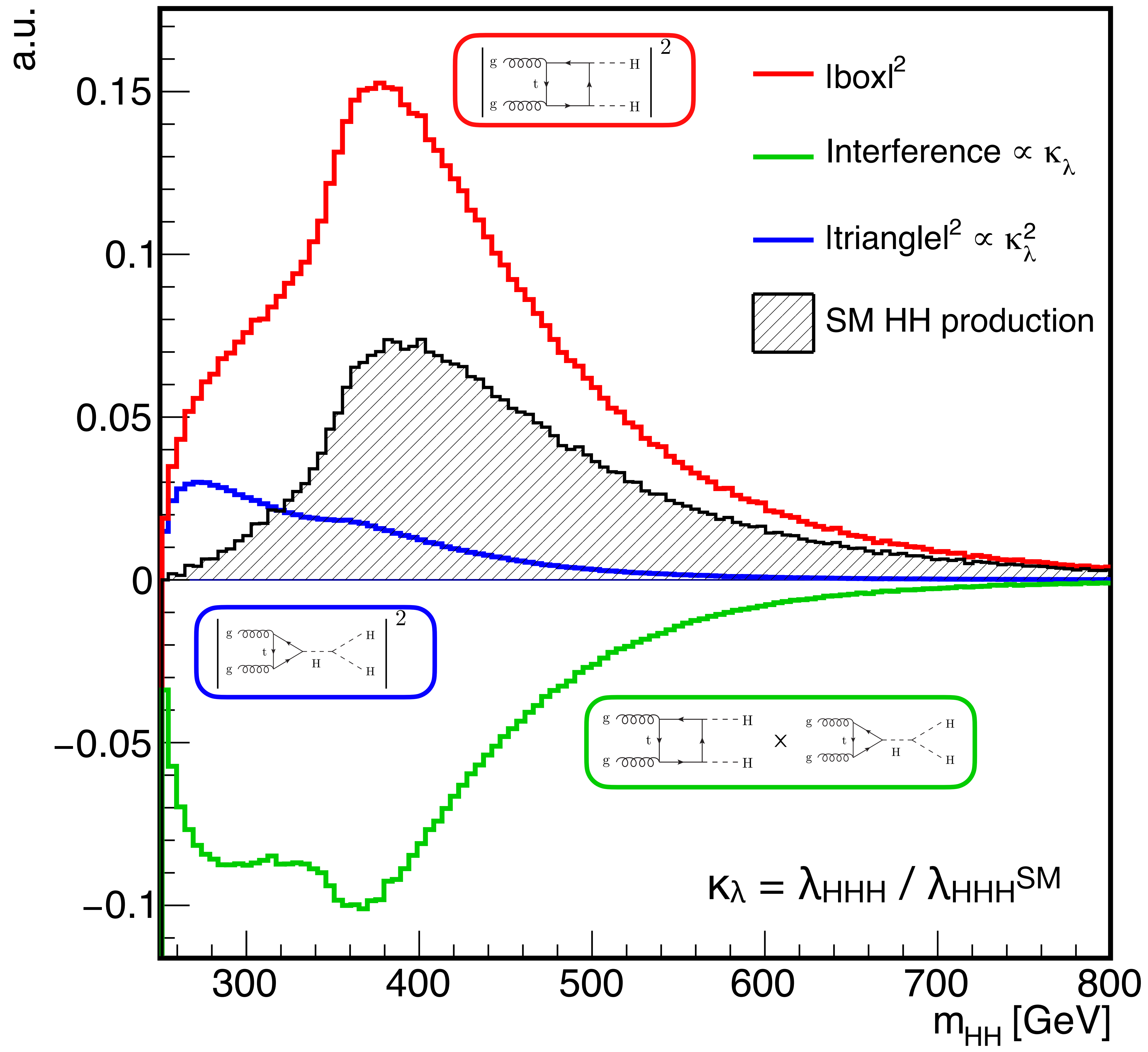
$$\sigma_{HH}^{SM} = 31.05^{+6.7\%}_{-23.2\%}\ \text{fb}\ (\text{scale} \oplus \text{PDF} \oplus \alpha_S \oplus m_t)$$

NNLO FT-approx [JHEP 05 (2018) 059] + m_t unc [PRD 103, 056002 (2021)]

- **Gluon fusion**: dominant production mode
  - about 4300 HH events in the Run 2 datasets
- Tiny cross section : experimentally very challenging!

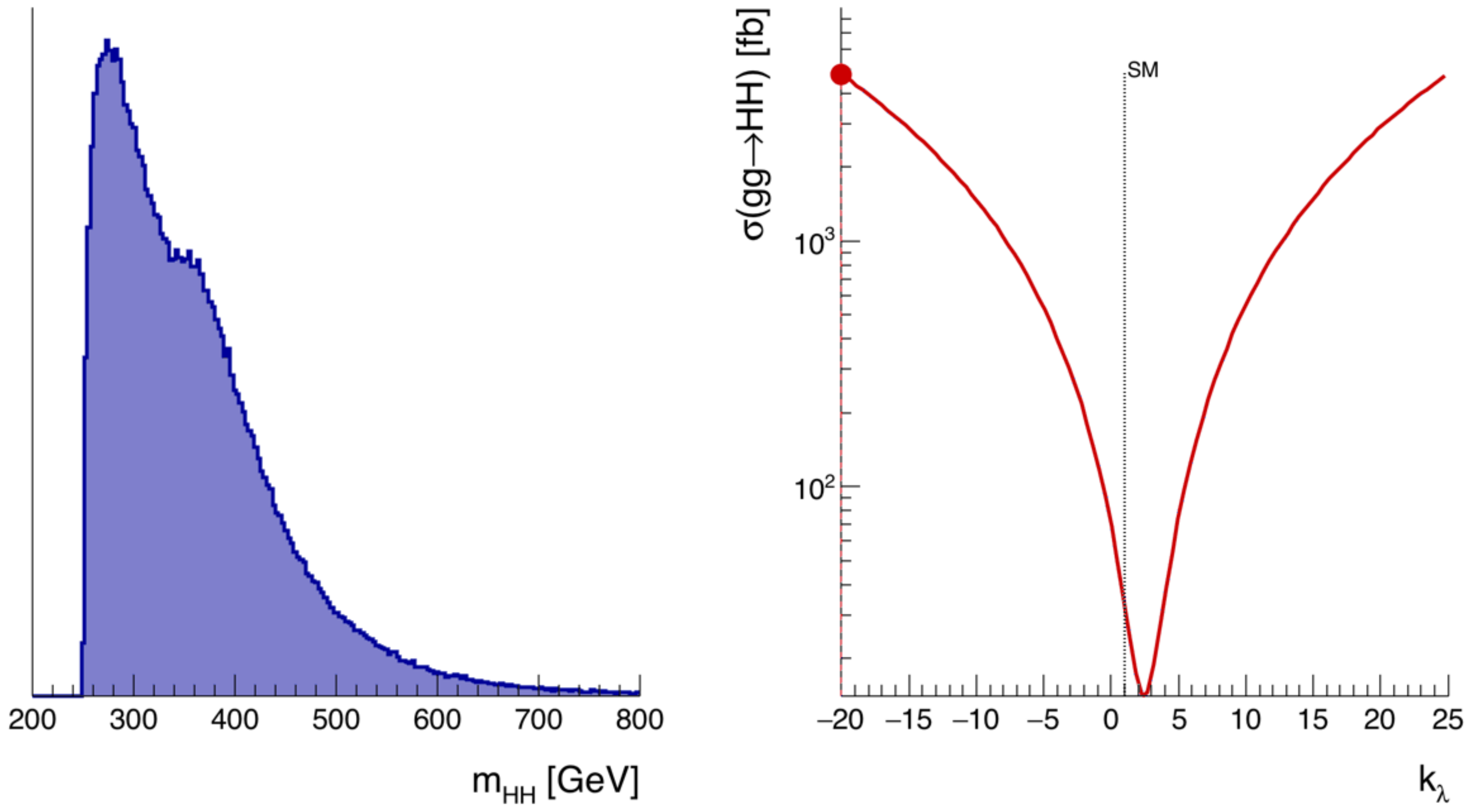
Extracting λ_{HHH} from HH measurements





- Information on λ_{HHH} is obtained from both the total and the differential production cross section

Illustration of shape effects



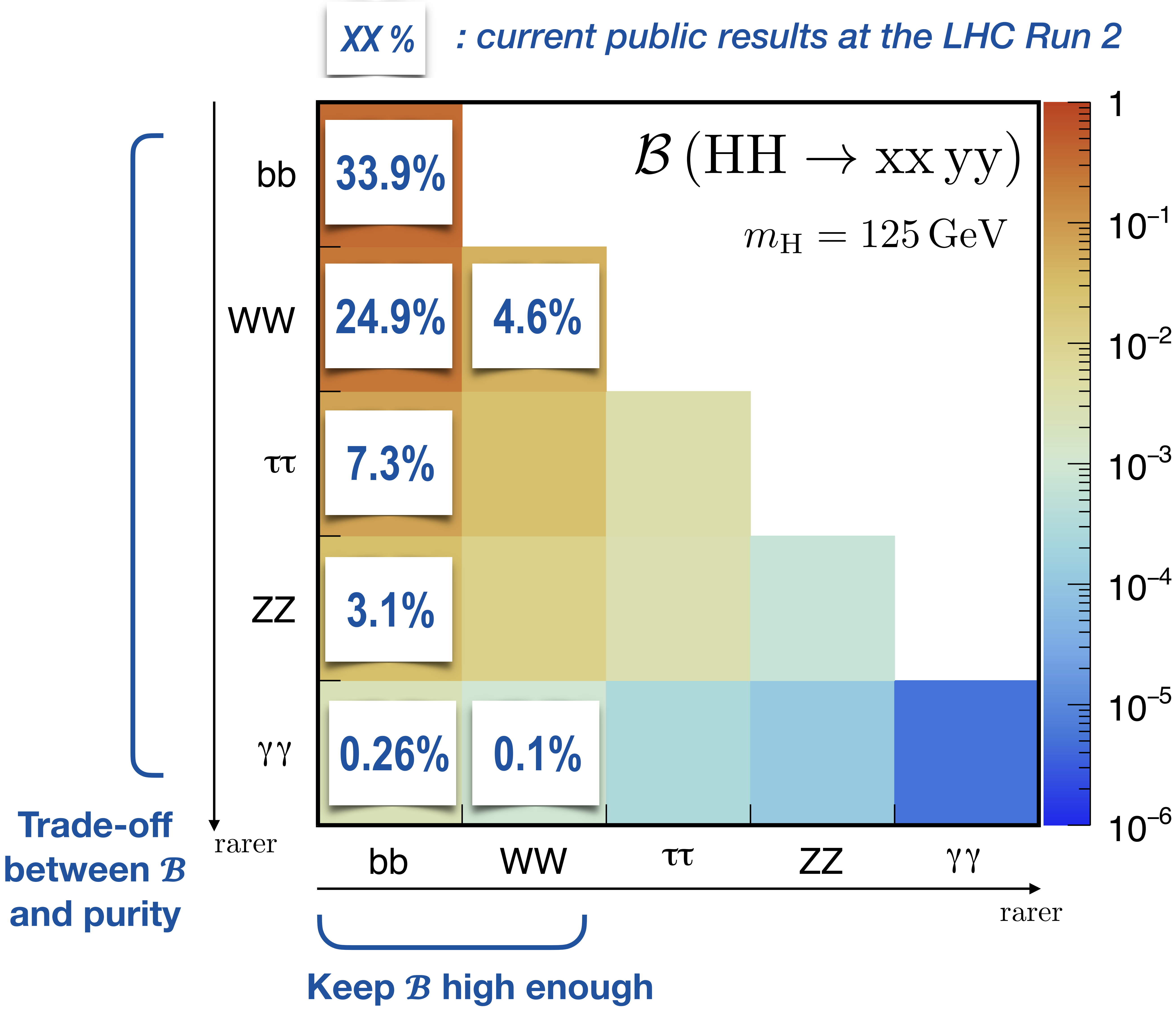
Interference effects have important consequences for the sensitivity of the searches

HH : which decay channels?

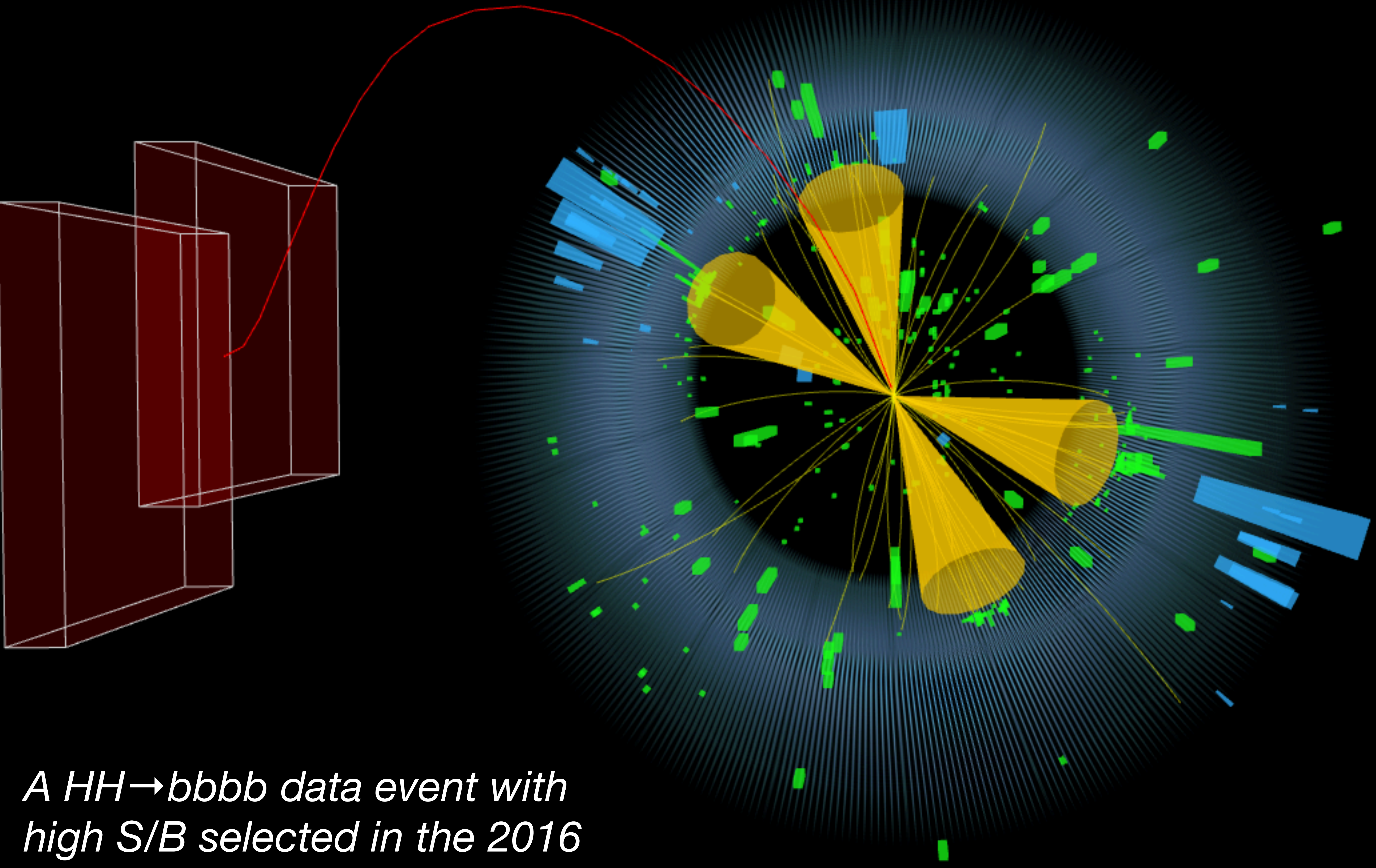
- Phenomenologically rich set of final states
- Branching fraction and S/B largely vary across channels
- Common analysis techniques (e.g. H→bb reconstruction) and channel-specific challenges
- **Broad study ongoing by the ATLAS and CMS Collaborations**
  - many results with the full Run 2 dataset

*A **rich program of physics** can be investigated with HH, including BSM searches (extended scalar sectors, extra dimensions, …) with **resonant production** (X→HH) in a large m_X range up to few TeV.*

A broad topic worth another seminar, not covered today



High $\mathscr{B}$, low S/B : HH→bbbb



A HH→bbbb data event with high S/B selected in the 2016 dataset

- Most abоundant final state : ~1400 events expected in the Run 2 dataset
- Four b-jet signature : large multijet background

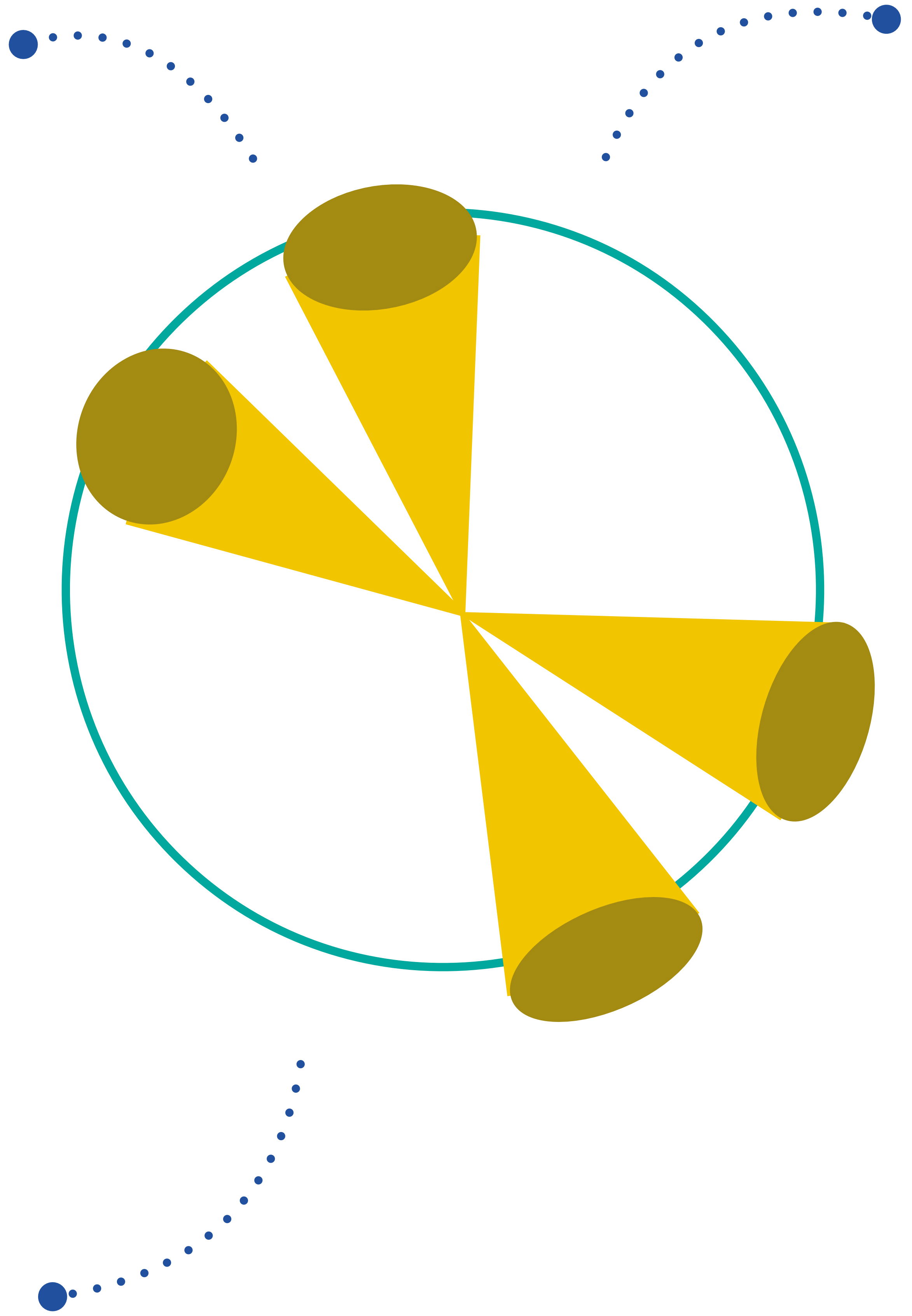
HH → bbbb : selecting the events

Event selection

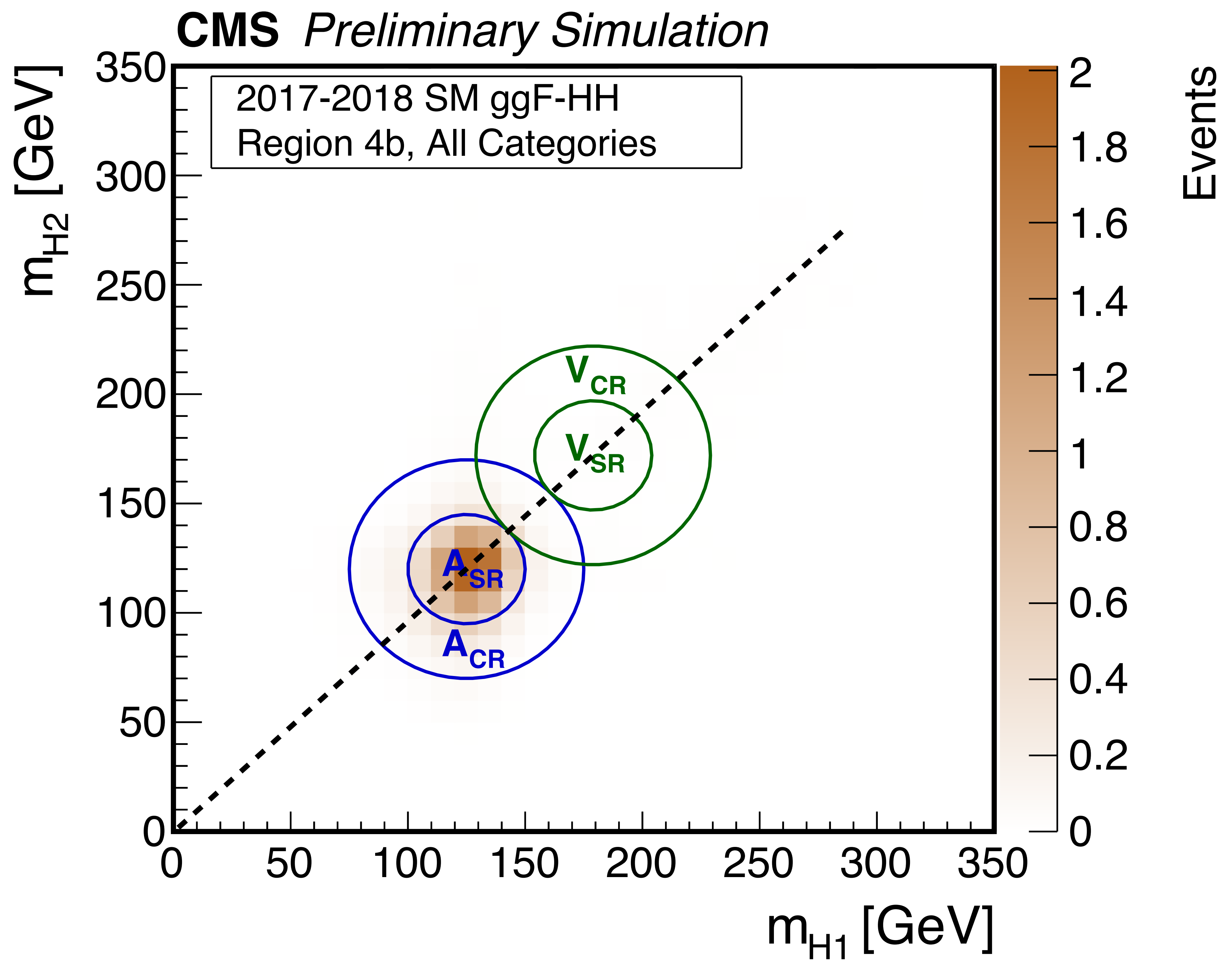
- Target fully resolved topology (4 jets)
- Events selected with ≥ 3 b jets (HLT + offline)
  - largely rely on b tag performance (ML based)

Event categorization

- HH production mode
- kinematics (low/high m_{HH}, SM- and BSM-like) : max sensitivity to anomalous couplings



H candidates reconstruction

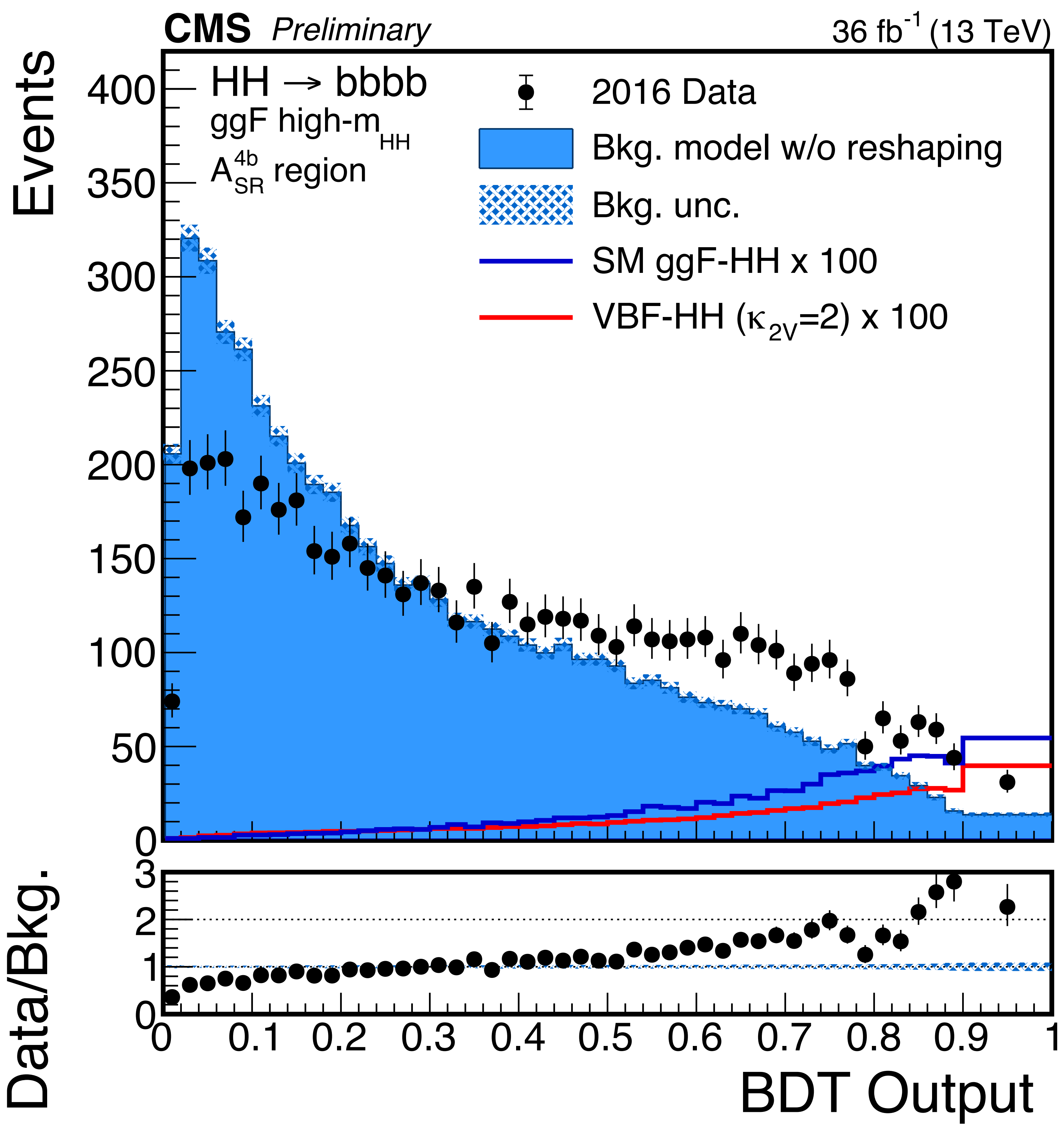


- Pair jets using the “equal mass hypothesis”
  - minimal bias of the bkg in the signal region
  - natural definition of signal, control, and validation regions

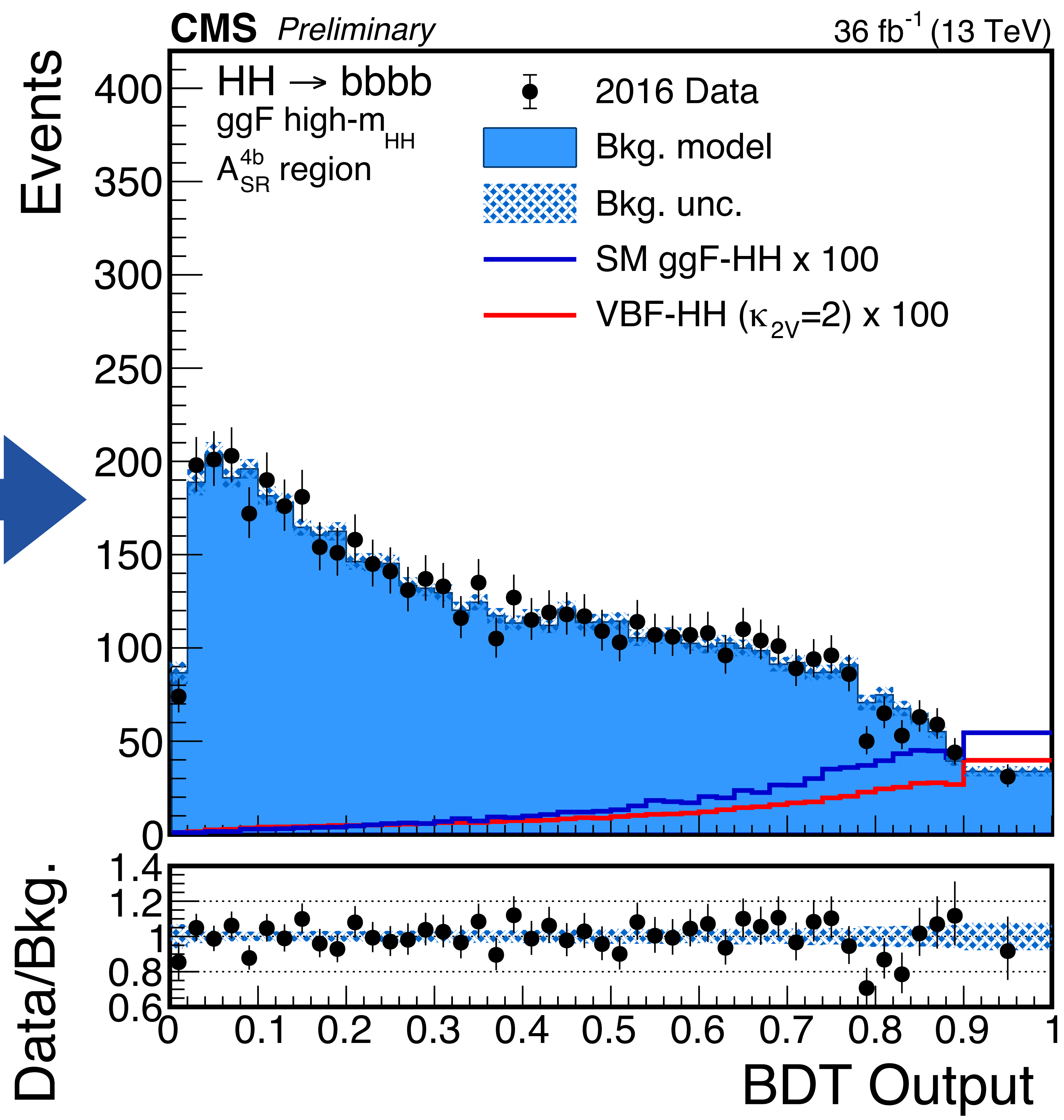
HH→bbbb : the multijet challenge

Overwhelming multijet background

Powerful discriminants and data driven estimate
Leverage on ML techniques to boost the analysis performance



Bkg. template from 3b uncorrected data

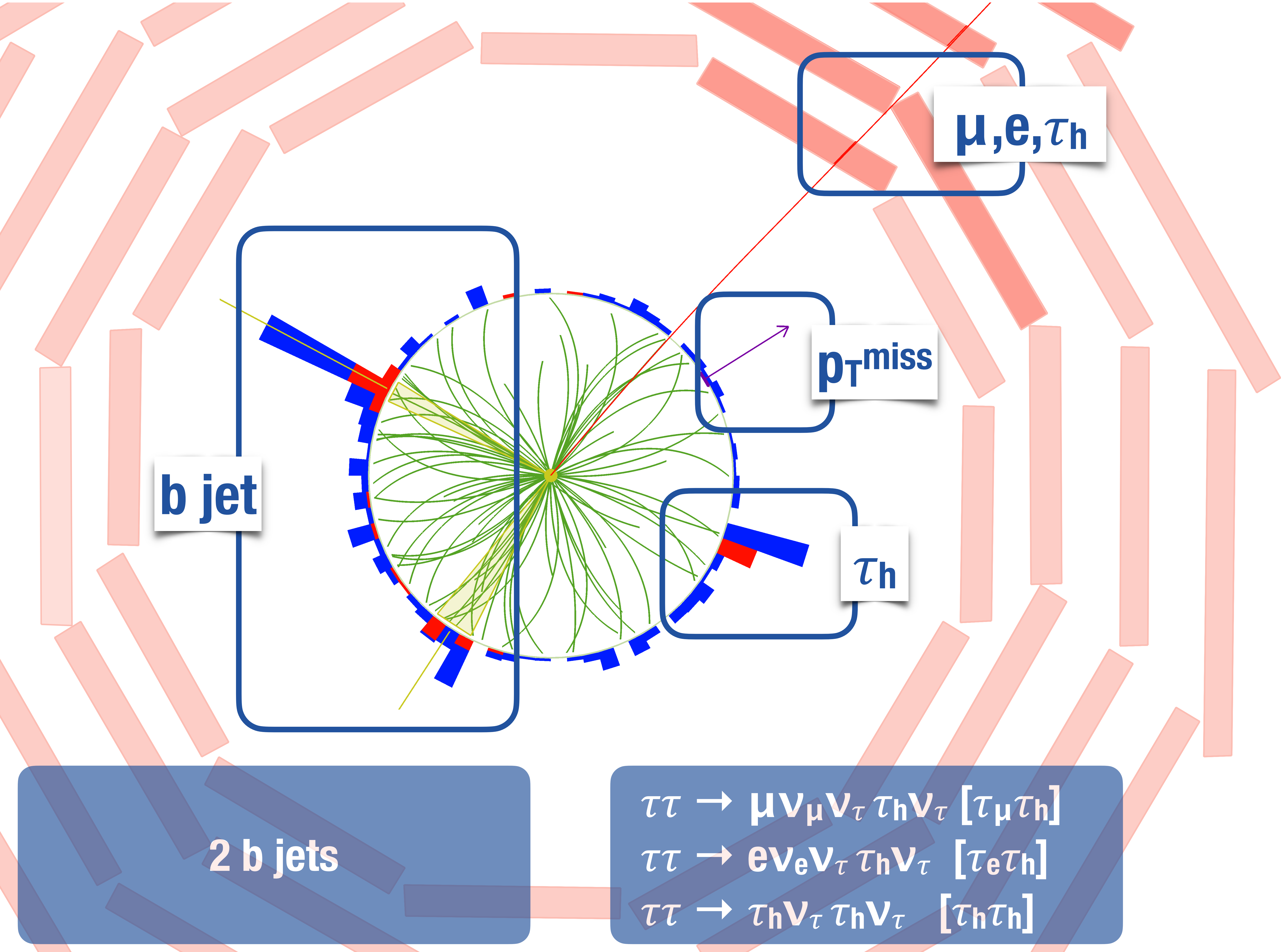


ML-based correction to bkg. template

- Background from 3b region
  - 3b→4b transfer function trained with BDT reweighting method in m_H control region
  - applied to data in the SR(3b) to model SR(4b)
  - accurate method verification in signal-free validation region
- Separate background from signal with a powerful multivariate discriminant

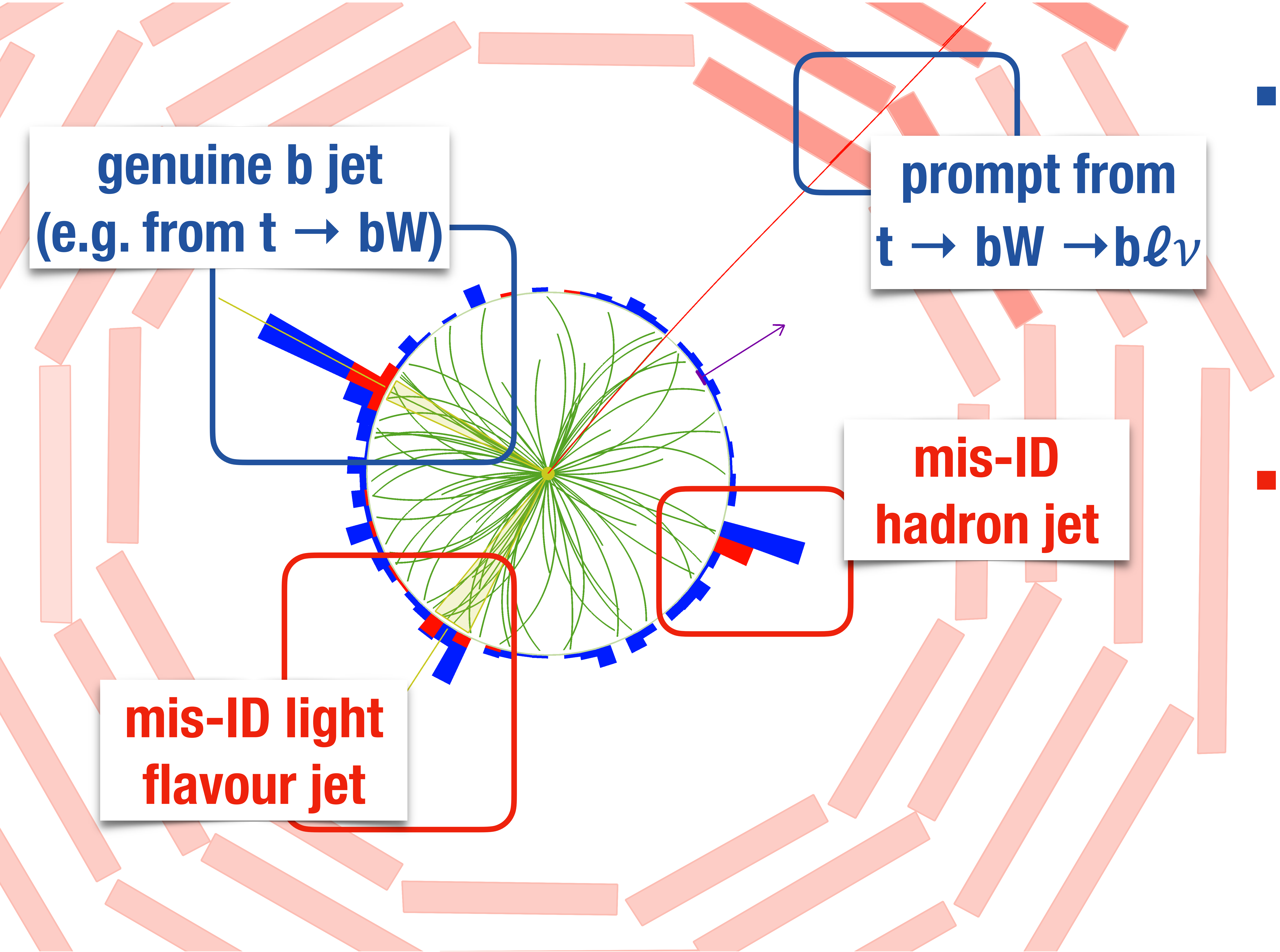
Obs. (exp.) : 3.9 (7.8) × σ_{HH}^{SM}
Best single-channel constraint to date on SM HH

Medium $\mathscr{B}$, medium S/B : HH → bb$\tau\tau$



- Three $\tau\tau$ final states
  - $\tau_\mu\tau_h$, $\tau_e\tau_h$, $\tau_h\tau_h$: 88% of $\tau\tau$ decays
- Challenge of triggering for the fully hadronic final state
- Mass of the $\tau\tau$ system reconstructed with a likelihood method
  - used to suppress the backgrounds

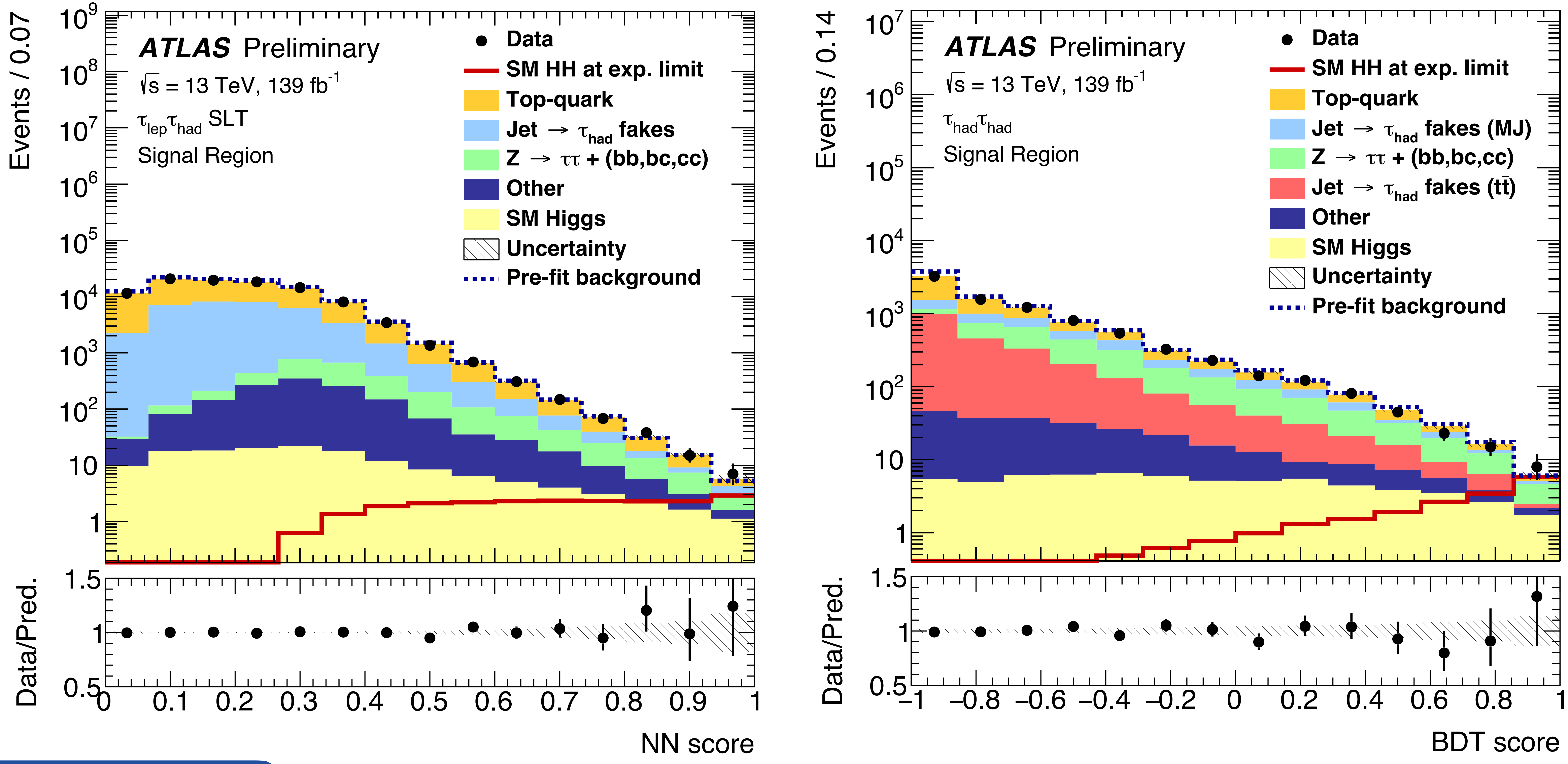
Medium $\mathscr{B}$, medium S/B : HH → bb$\tau\tau$



- **Irreducible** backgrounds
  - tt → bbWW → bb $\tau\tau$ — simulation
  - di-boson, ZH (minor) — simulation
  - Z/γ^* → $\tau\tau$ + 2 b jets — simulation + correction in Z→$\mu\mu$
- **Instrumental (reducible)** backgrounds
  - tt, Z/γ^*, multijet with misidentified jets as τ_h or b jet — simulation + data-driven estimate
  - single top, W+jets (minor) — simulation

HH → bbττ : signal extraction

- Sophisticated variables based on the kinematics are used to look for a signal
- Sensitivity lead by fully hadronic categories



Obs. (exp.) : 4.7 (3.9) × σ_{HH}^{SM}

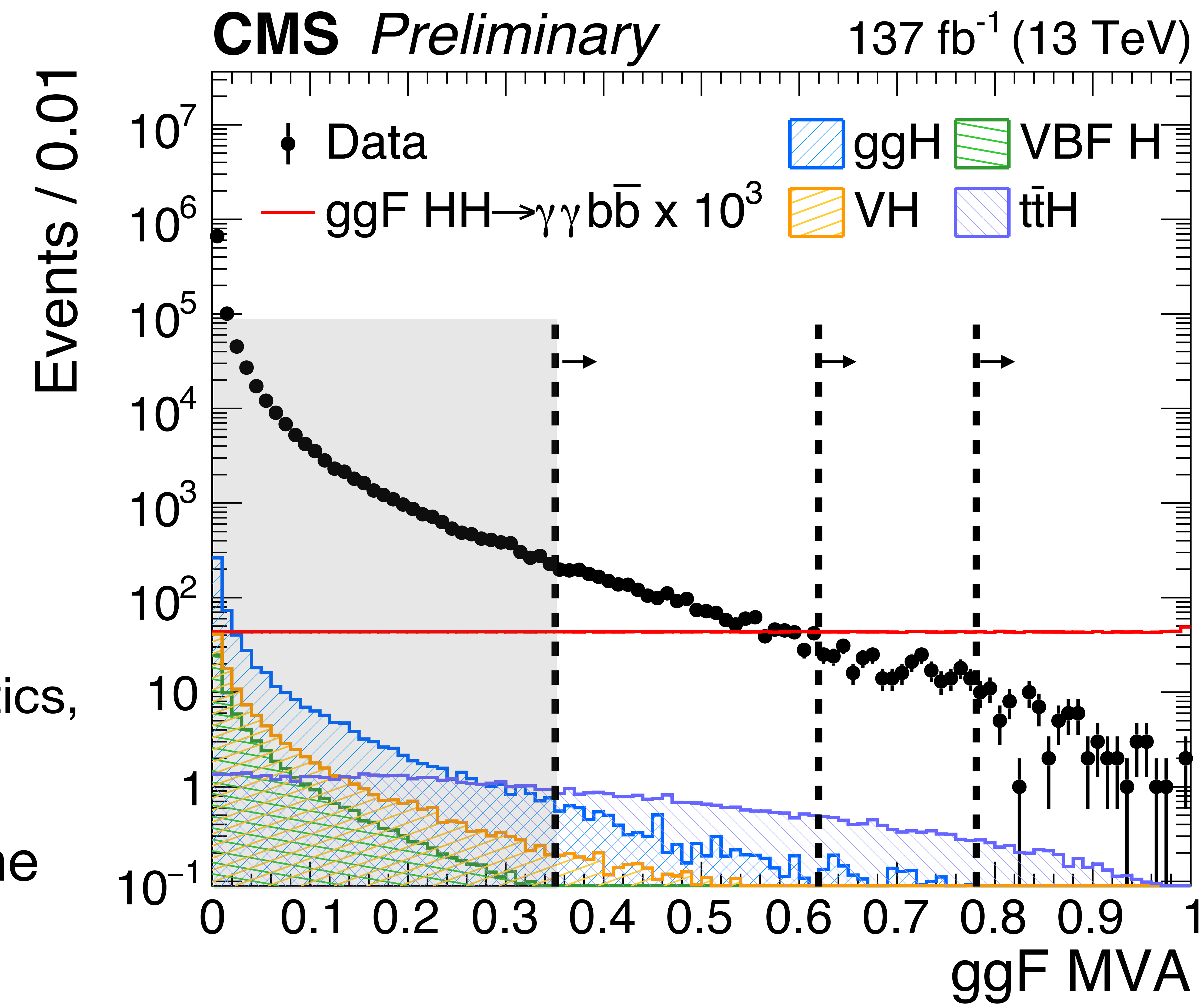
ℓ+τh events *τh+τh events*

Low $\mathcal{B}$, high S/B : HH → bb$\gamma\gamma$

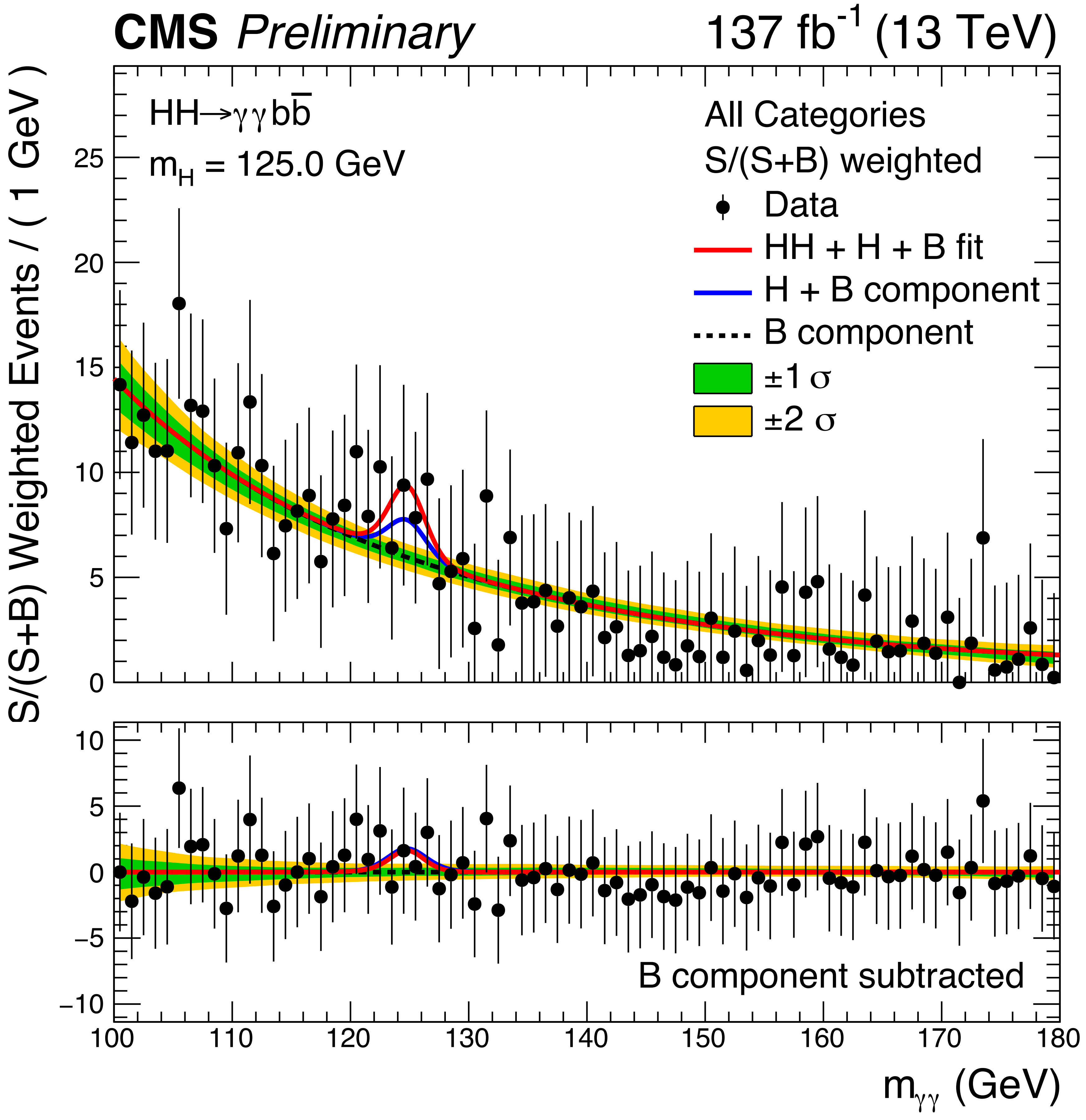
Very rare but clean channel

Maximisation of acceptance and purity is essential

- Main backgrounds: $\gamma/\gamma\gamma$ + jets continuum, single H
- Dedicated MVAs for background suppression
  - Deep NN against ttH
  - BDT against nonresonant $\gamma(\gamma)$ + jet (uses object kinematics, ID, resolution)
- Event classification based on the MVA purity and the HH invariant mass
  - optimal acceptance and max sensitivity for anomalous κ_λ

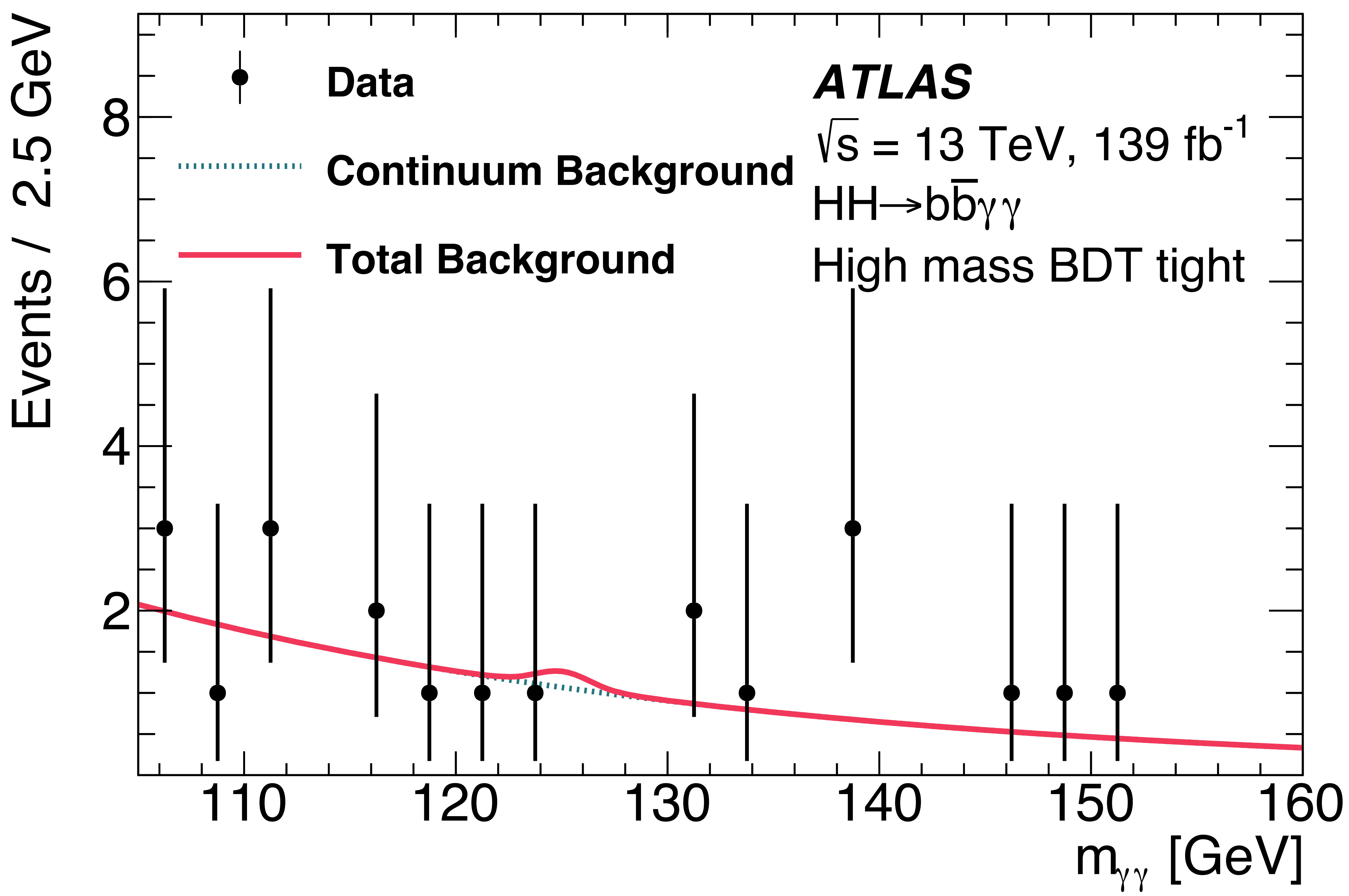


HH → bb$\gamma\gamma$: signal extraction



◀ All categories S/(S+B) weighted

▼ Most sensitive category



- Powerful signature from the H→$\gamma\gamma$ decay used to search for a signal
- Sensitivity clearly dominated by the limited number of events

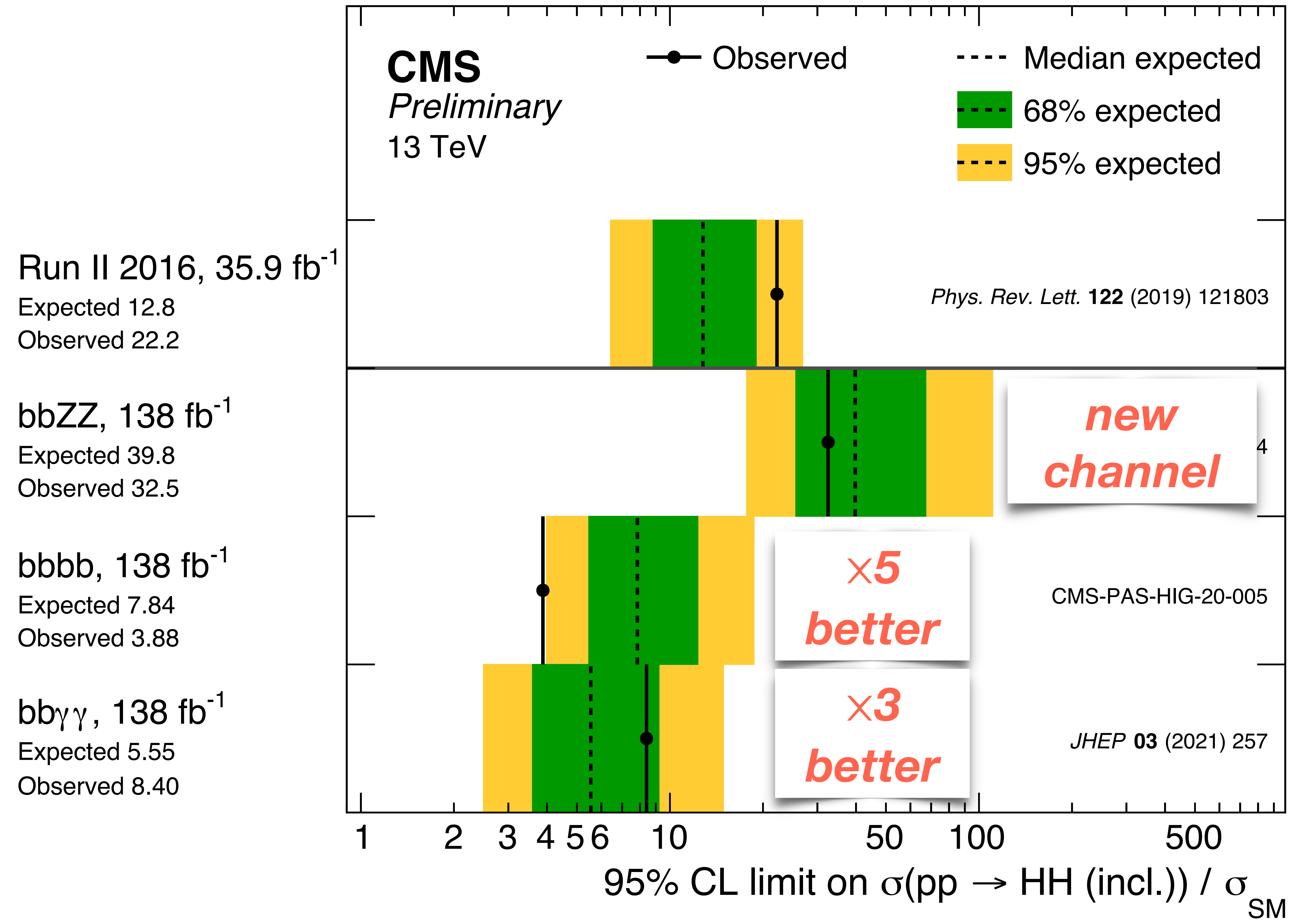
Simultaneous fit with m_{bb}

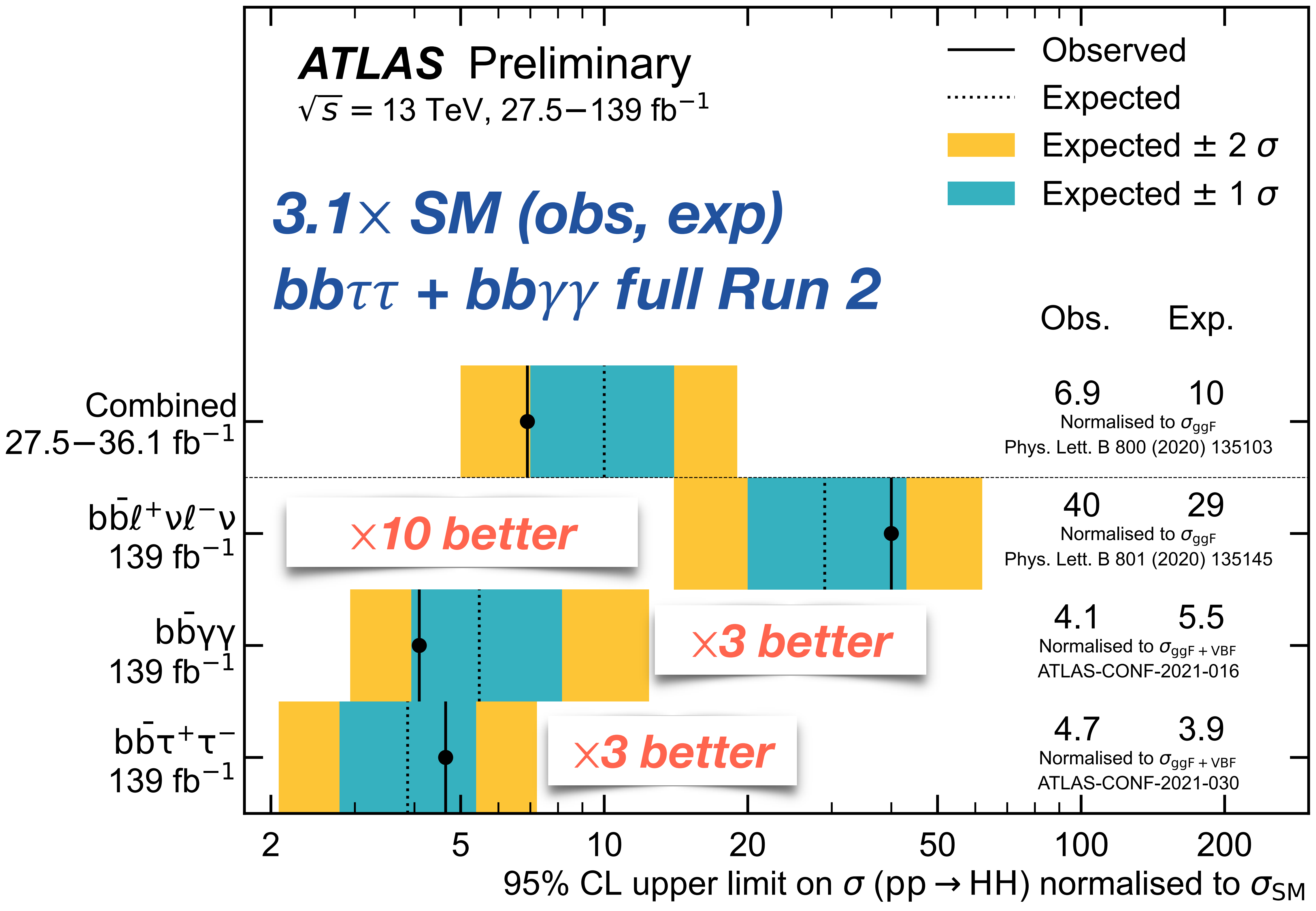
Obs. (Exp.) : 7.7 (5.2) × σ_{HH}^{SM}

Fit of $m_{\gamma\gamma}$

Obs. (Exp.) : 4.2 (5.7) × σ_{HH}^{SM}

Summary of the full Run 2 results





Improvement w.r.t. the result in the same channel based on the 2016 dataset

Expected from luminosity scaling: sqrt(36/140) = ×2 better

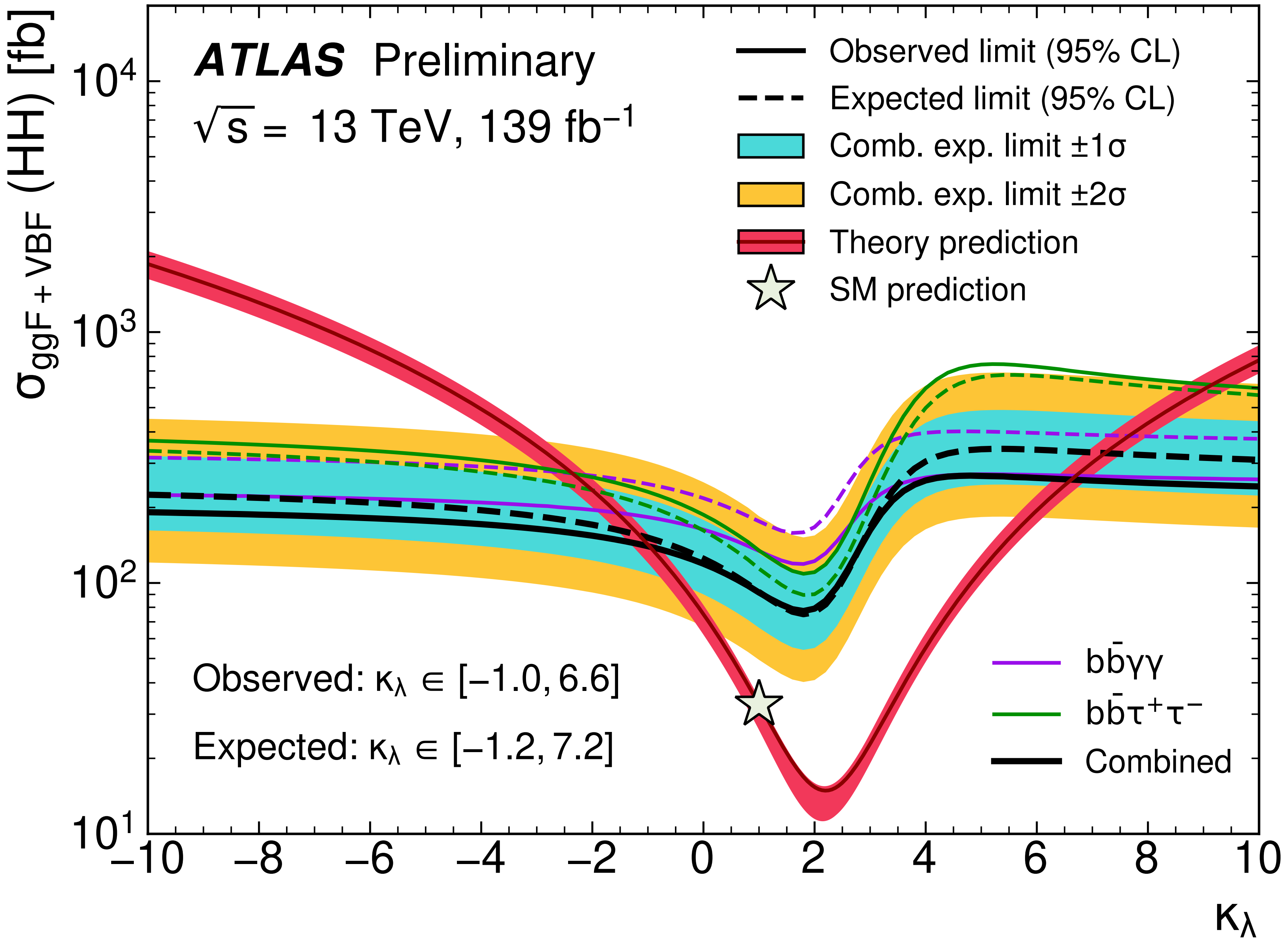
- Impressive improvements compared to the previous round of results
  - much faster than luminosity!
    Larger datsets enable smarter analyses

Excellent prospects for the Run 2 combination

Work ongoing to finalize all Run 2 analyses and update the combined results

Constraints on the self-coupling

HH → bbγγ + HH → bbττ

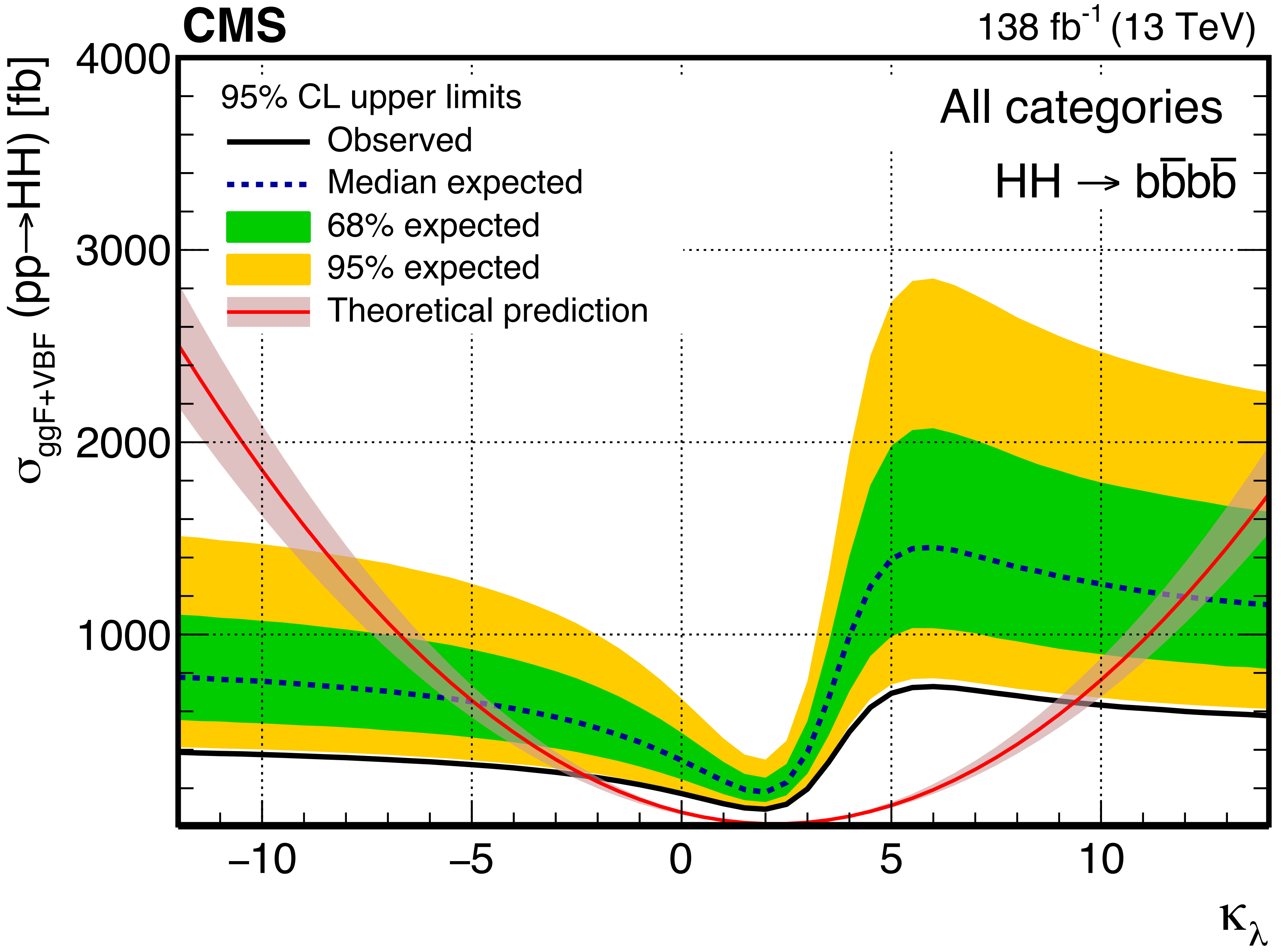


Observed: ***$-1.0 < \kappa_\lambda < 6.6$***

Expected: *$-1.2 < \kappa_\lambda < 7.2$*

In bbγγ, similar constraint by CMS

HH → bbbb



Observed: ***$-2.3 < \kappa_\lambda < 9.4$***

Expected: *$-5.0 < \kappa_\lambda < 12.0$*

- Clear effect in the limit shape from m_{HH} variations vs κ_λ
- Interference effects limit the capability to constrain $\kappa_\lambda > 0$ values

Towards the Run 3

Expect a total dataset of ~400 fb^{-1} (×2.5 current) after 3 years of Run 3

Explore more HH channels

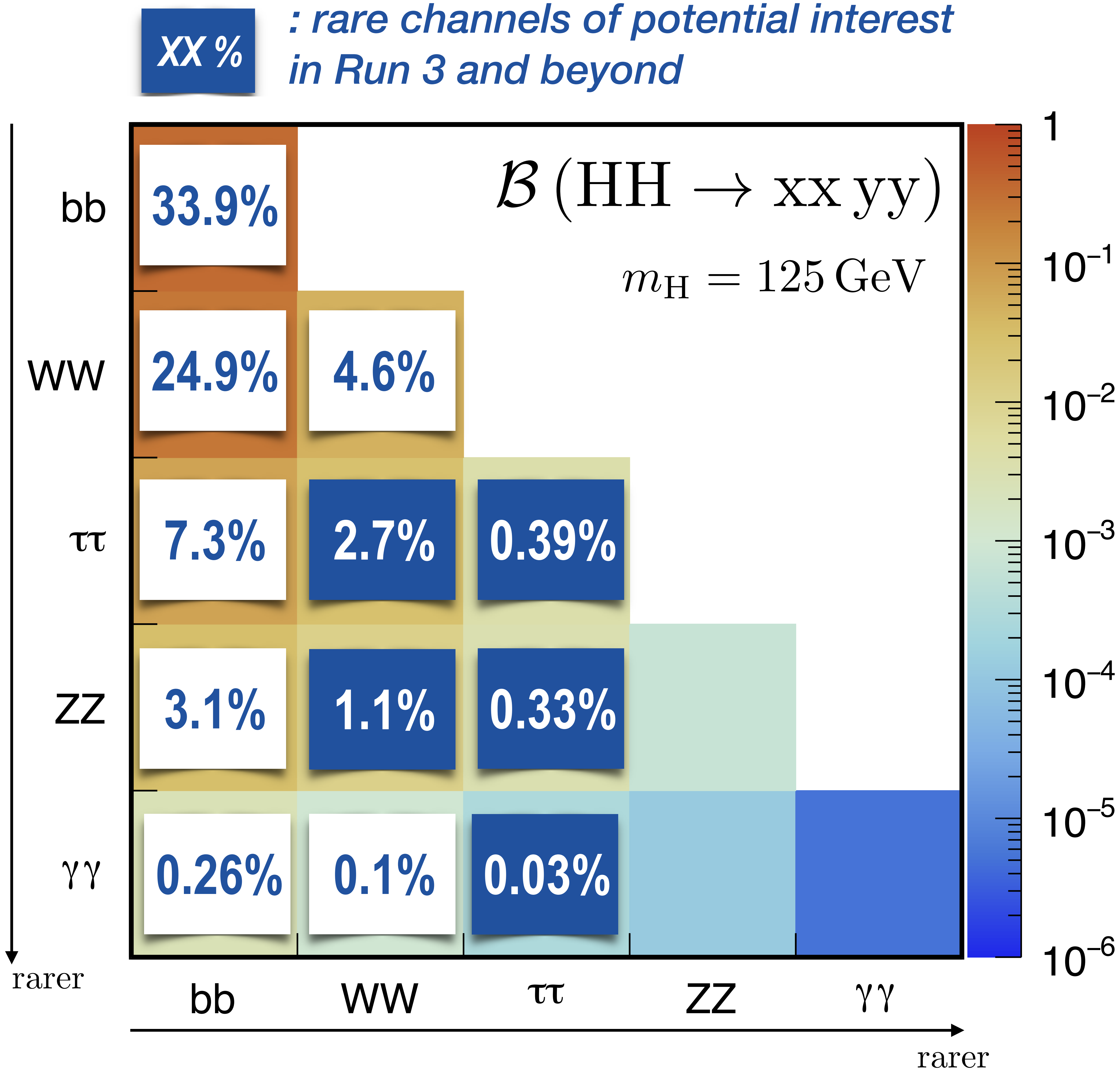
- rare but clean channels can be explored

Improve the HH analyses

- Capitalise on the Run 2 experience: new dedicated triggers, more advanced techniques

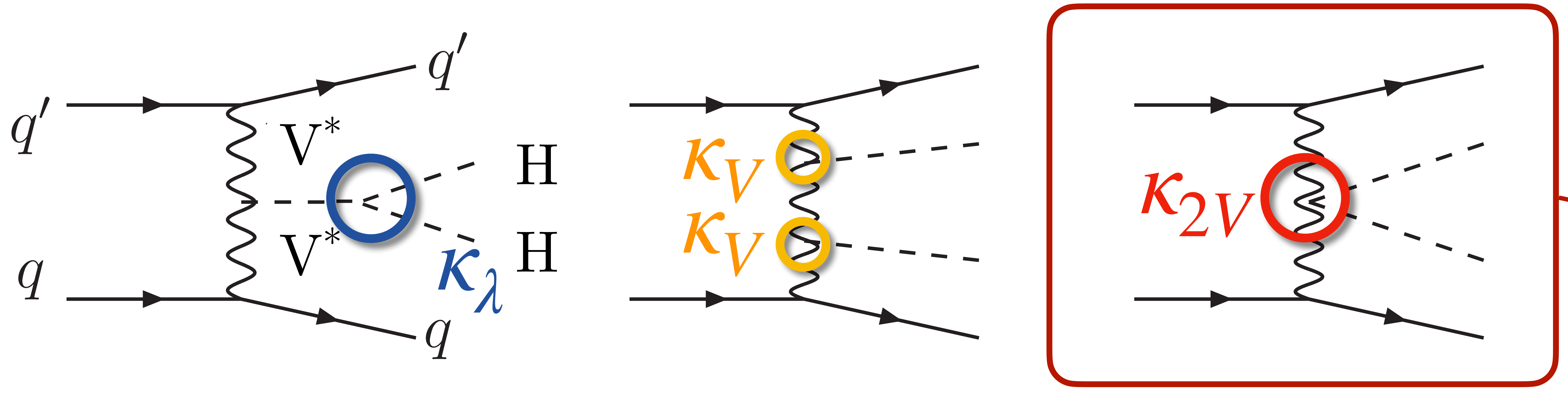
A very rough estimation:

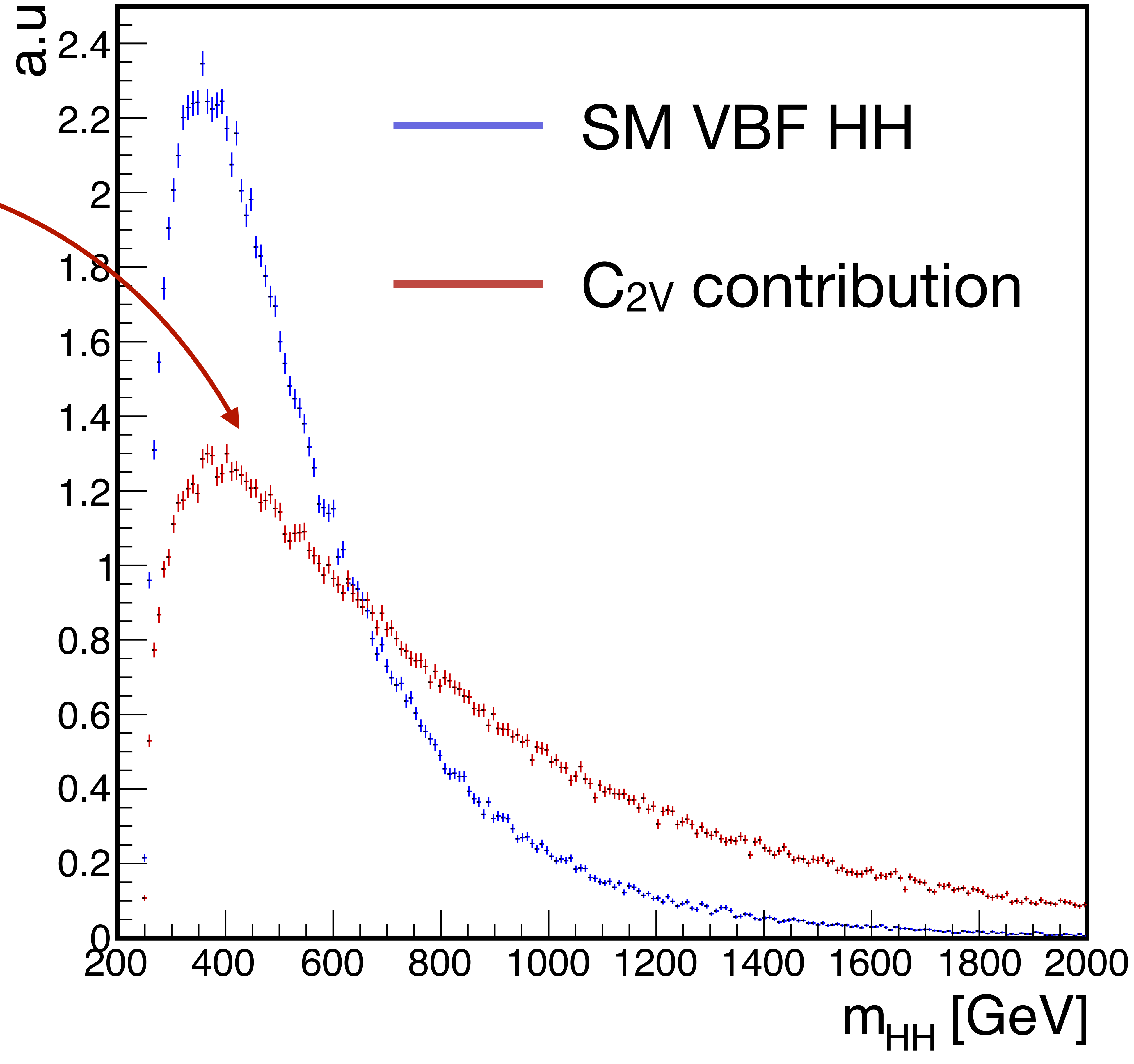
- Run 2 results: 2.5 - 3 × SM / experiment
- ⇒ ~2 × SM LHC Run 2 limit (1/sqrt(2) scaling)
- ⇒ ~1 × SM LHC Run 3 limit (1/sqrt(2.5) lumi scaling)



- With further improvements on the analyses: possibility of first LHC evidence for HH at Run 3?

Beyond gluon fusion





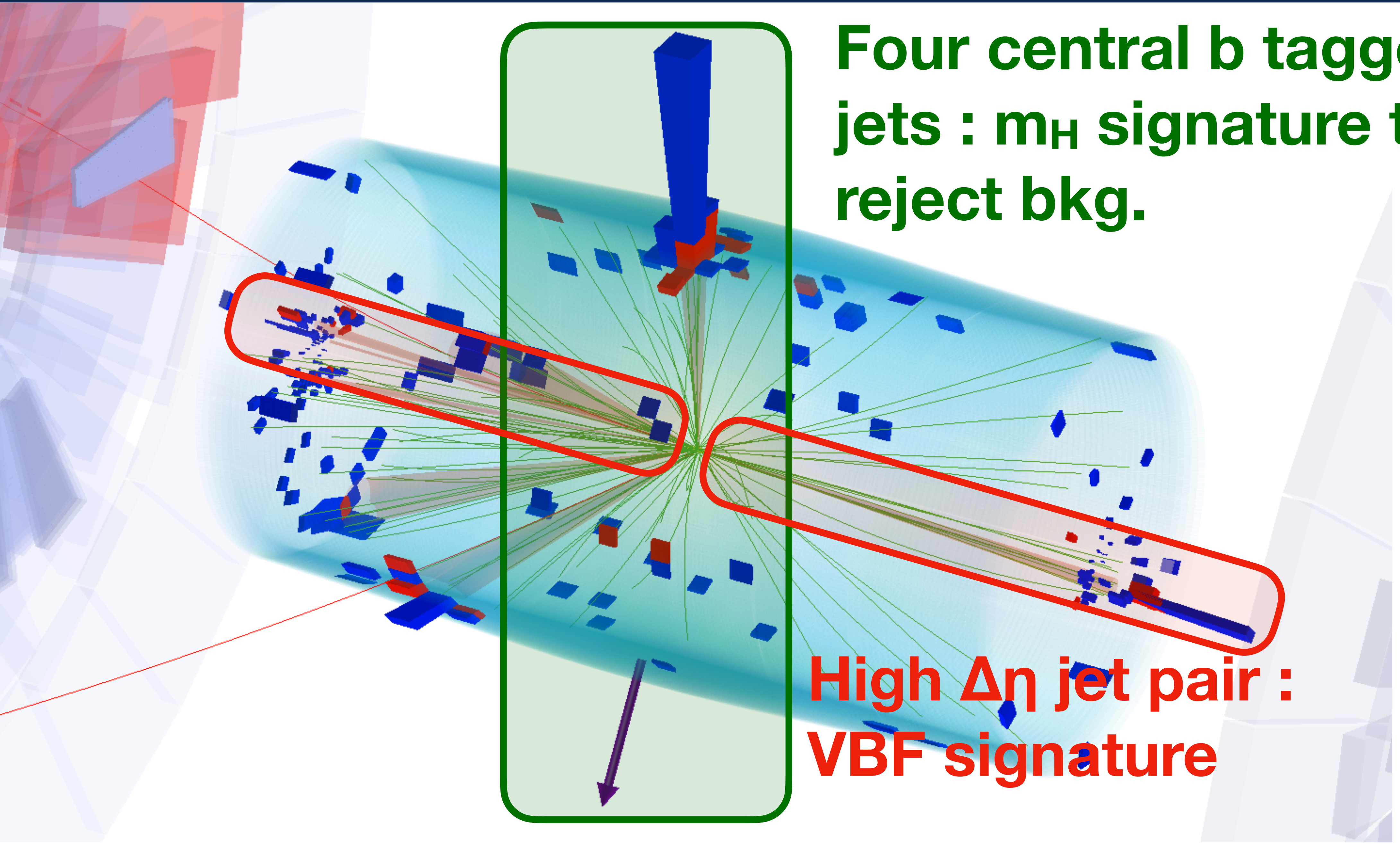
$\sigma = 1.73 \pm 2.1\%$ fb

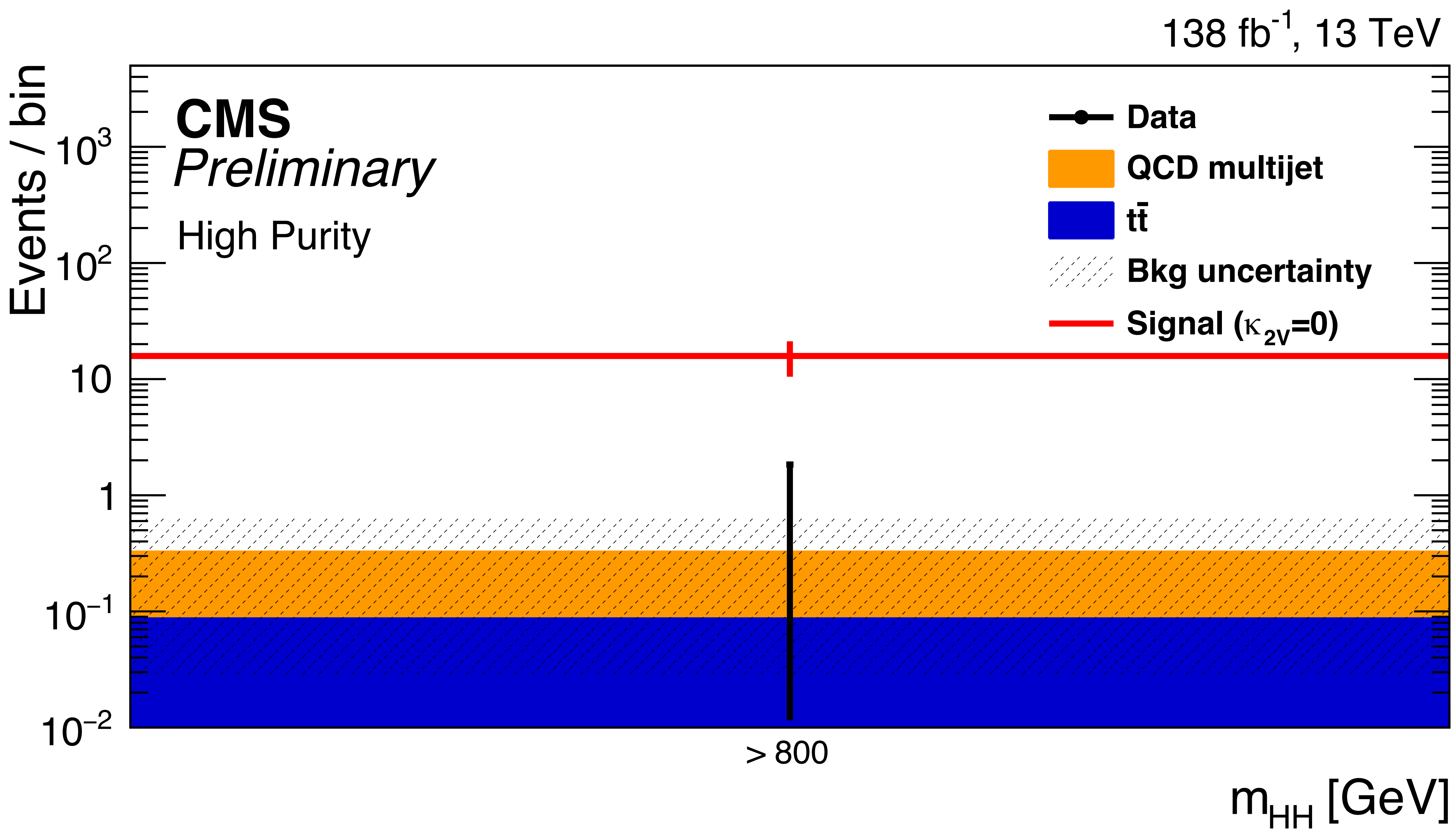
$$\mathcal{A}(V_L V_L \to \mathrm{HH}) \simeq \frac{\hat{s}}{v^2}\left(C_{2V} - C_V^2\right)$$

- Second production mode at the LHC
- Unique access to the VVHH interaction
  - should differ from SM prediction if the Higgs boson emerges from some new dynamics at the TeV scale (“*composite Higgs*")
- Highly sensitive to anomalous κ_{2V} !
  - O(1) κ_{2V} variation → O(10) xs increase , high m_{HH} events

The study of other HH production modes give new insights on the properties of the scalar sector

Searching for VBF HH → bbbb

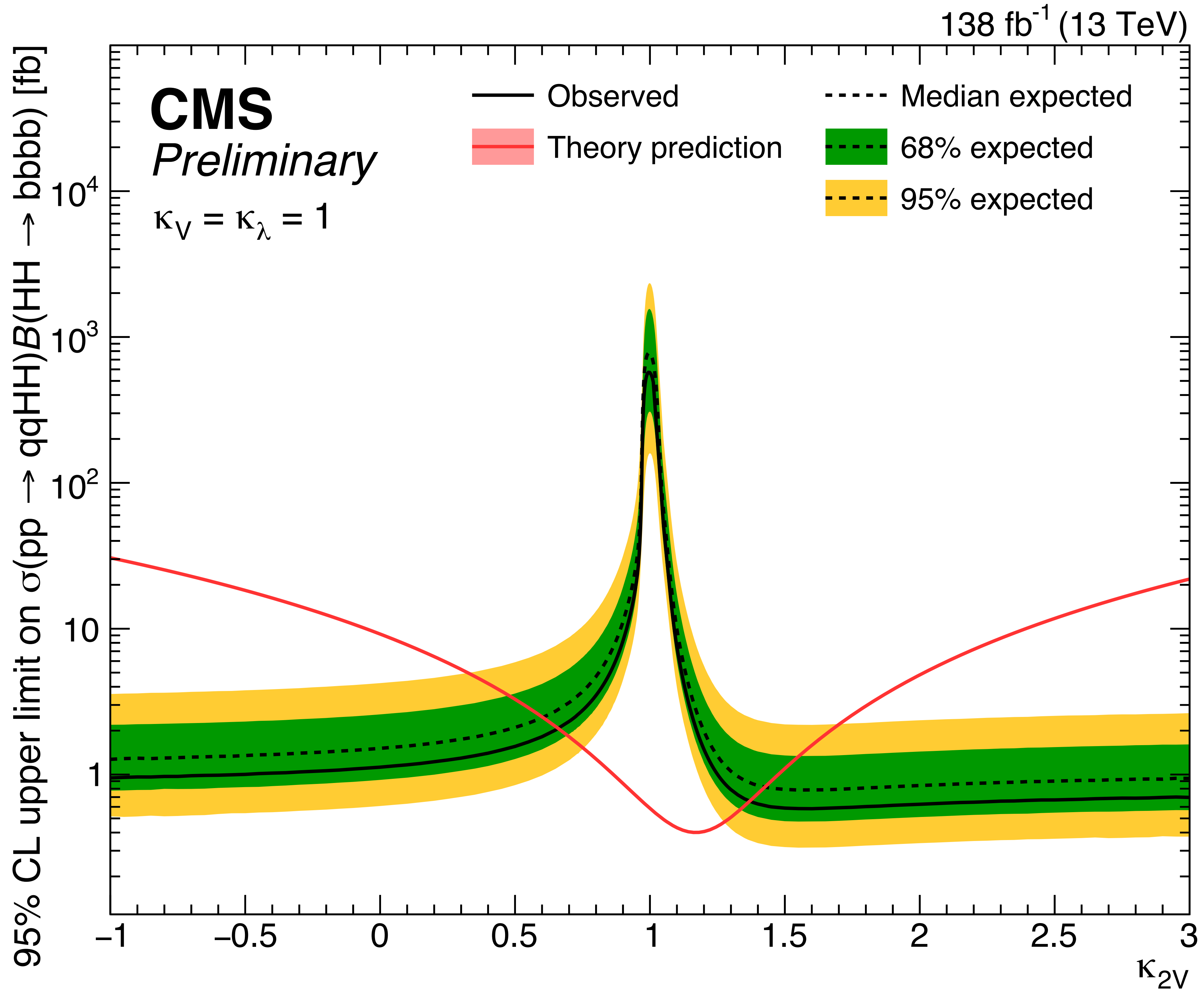


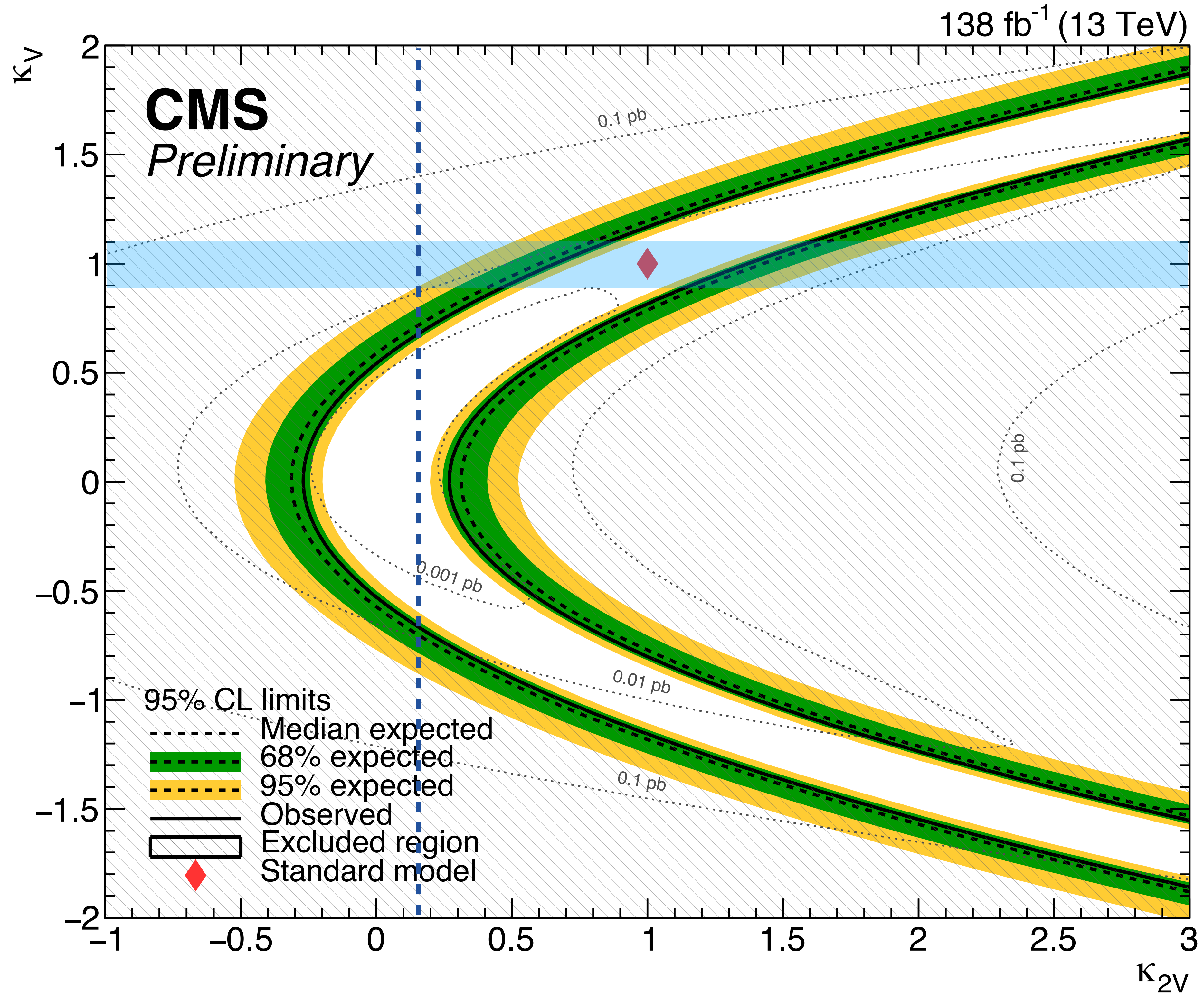


- One resolved analysis with dedicated VBF category
- One boosted analysis targeting $p_T(H) > 400/500$ GeV
  - dedicated ParticleNet discriminant D_{bb} to identify the bb candidates
  - 3 purity categories based on D_{bb}
  - m_{bb} reconstructed with DNN regression and used to define SR

Excellent separation at high m_{HH} leading to good S/B ratio

VBF HH at high m_{HH} : results





Single H measurements constrain κ_V at the 5-10%
→ the non observation of VBF HH signal implies that the VVHH interaction exists!

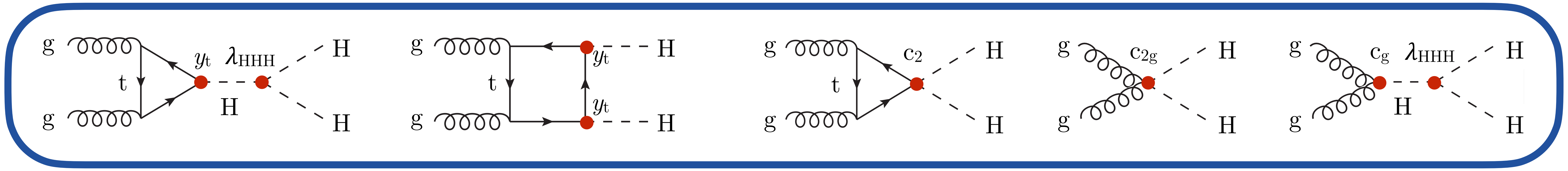
Observed: ***$0.6 < \kappa_{2V} < 1.4$***

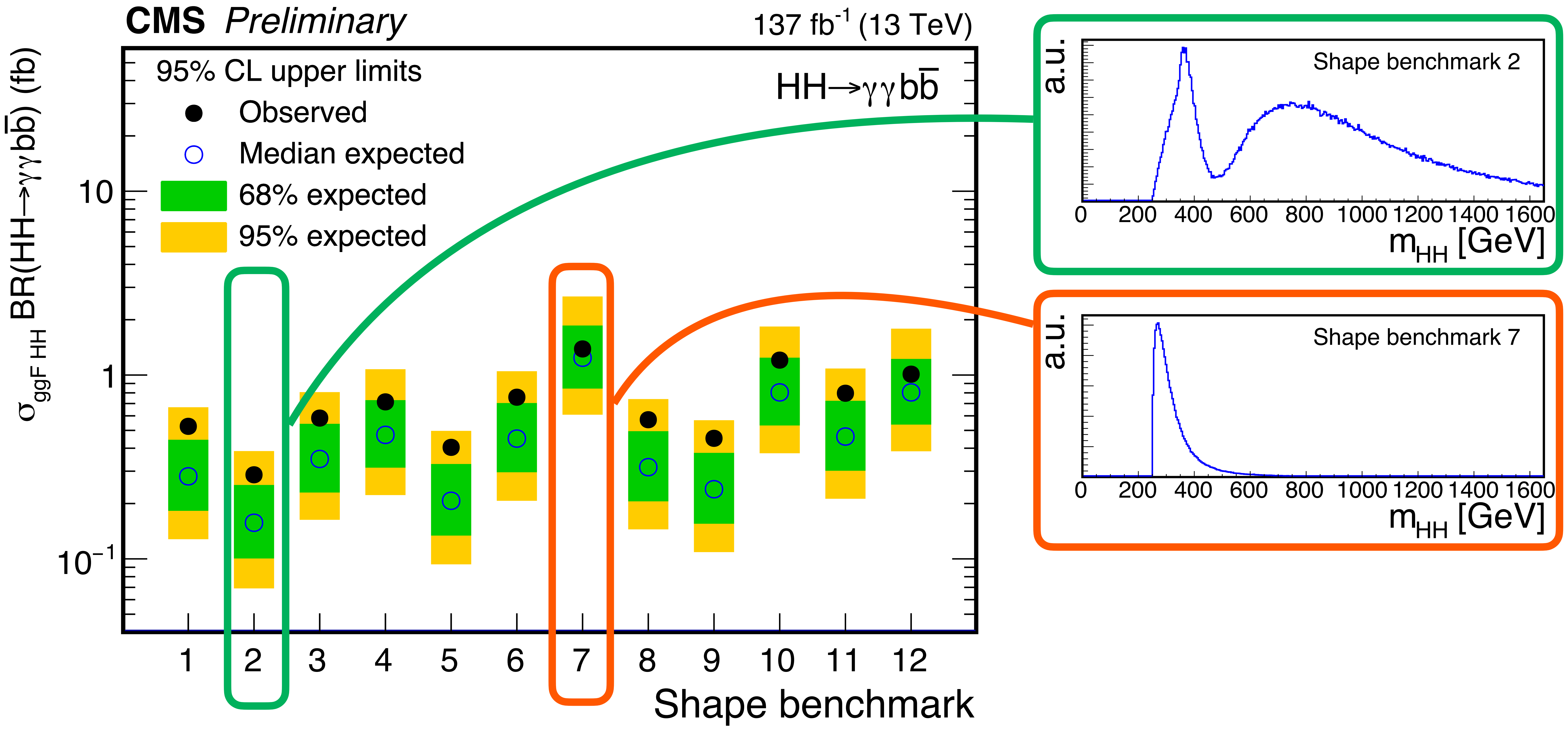
Best sensitivity to SM production from resolved CMS analysis : ***226*** *(412) × SM*

Interplay between κ_{2V} and κ_V related to the amplitude dependence

A broader BSM picture

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^6 + \cdots$$

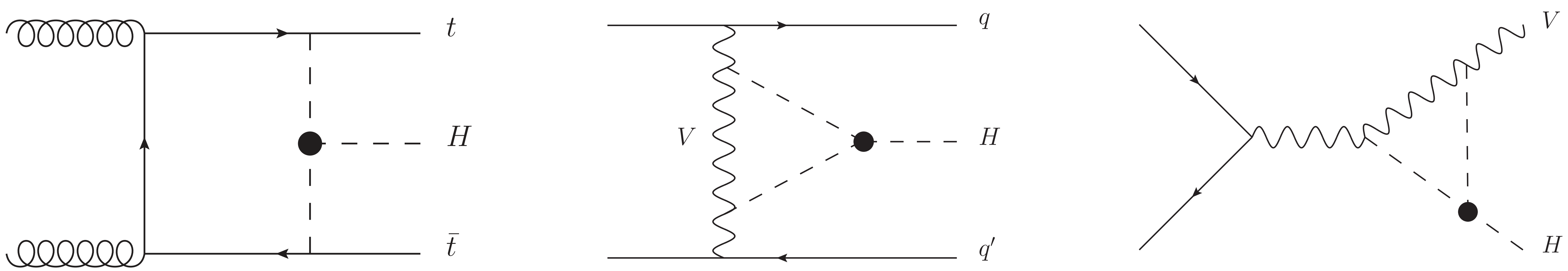




- 5D parameter space, contact interactions, large kinematic modifications
  - probed with representative signal shape benchmarks
- EFT effects become more important as the experimental sensitivity approaches the SM

HH as a probe of high energy BSM effects | **Full EFT fit as a next step**

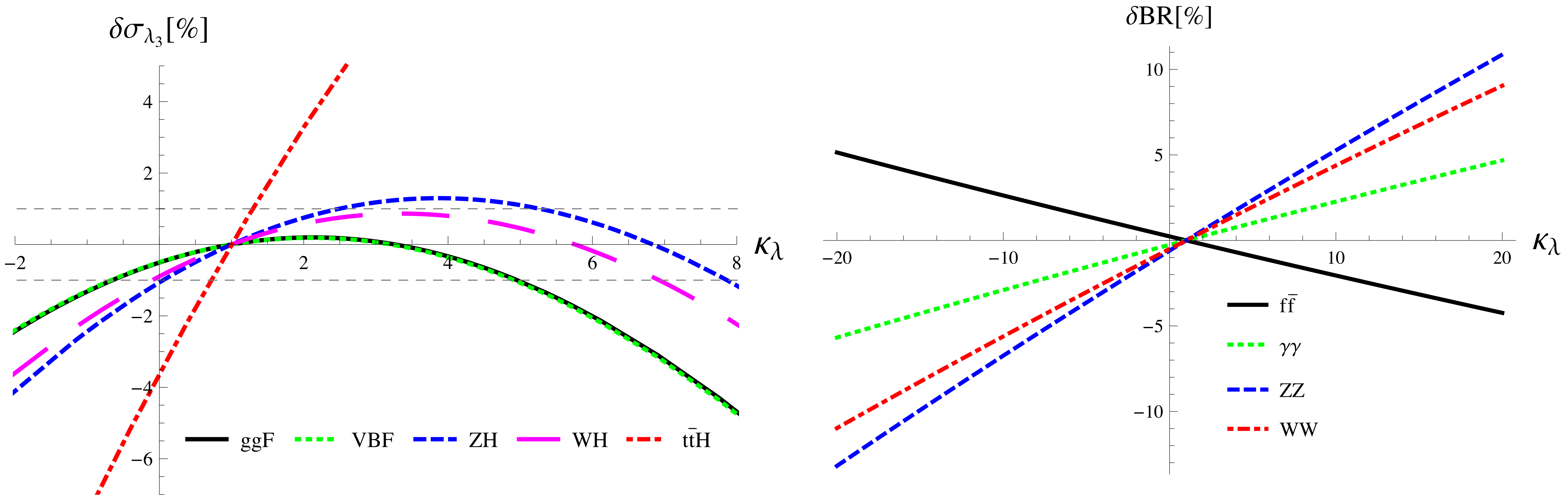
Extracting λ_{HHH} from single Higgs



Single H production as a precision tool to look for NLO effects from λ_{HHH}

Simplified template XS single H measurements used as input

Production xs and decay BR



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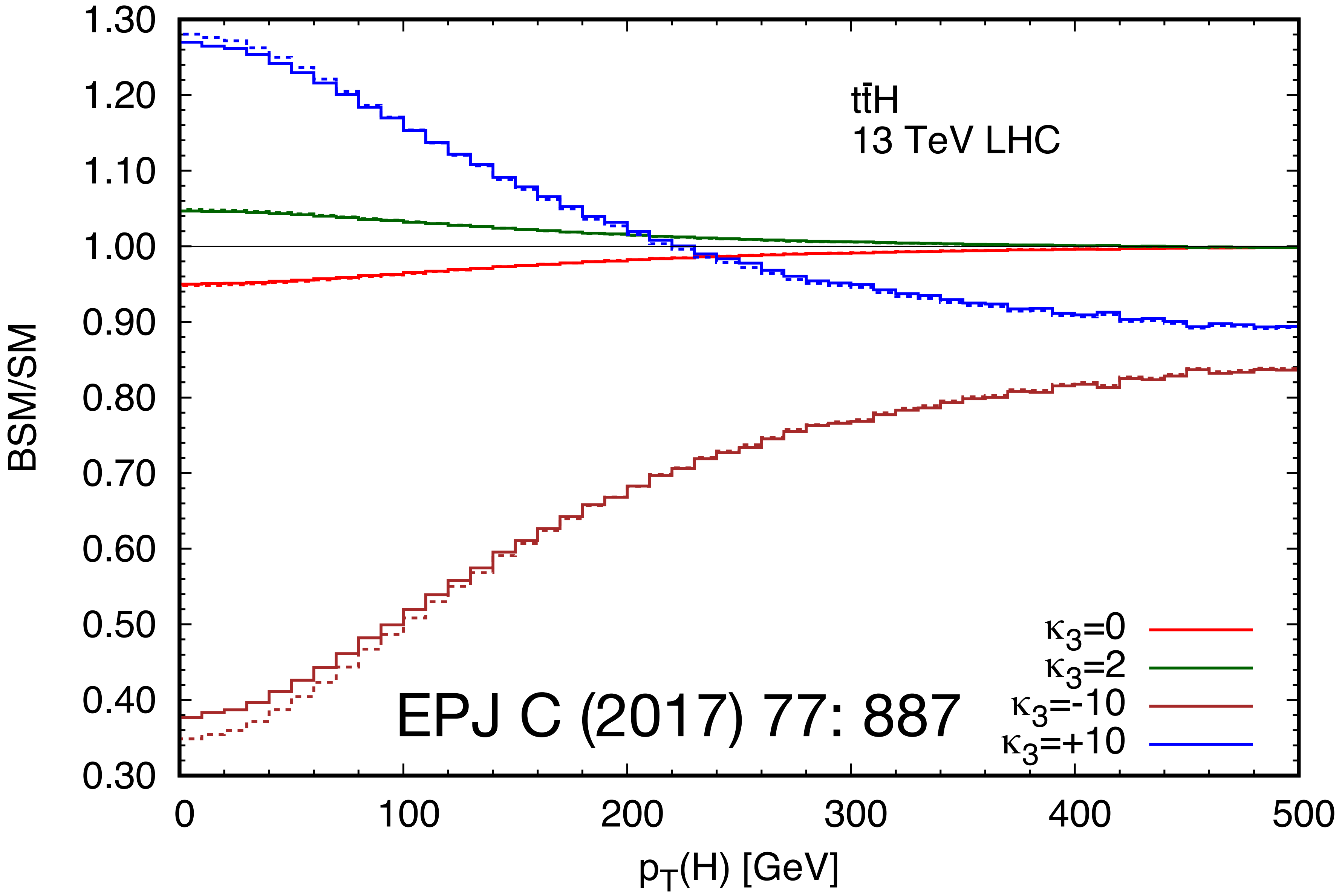
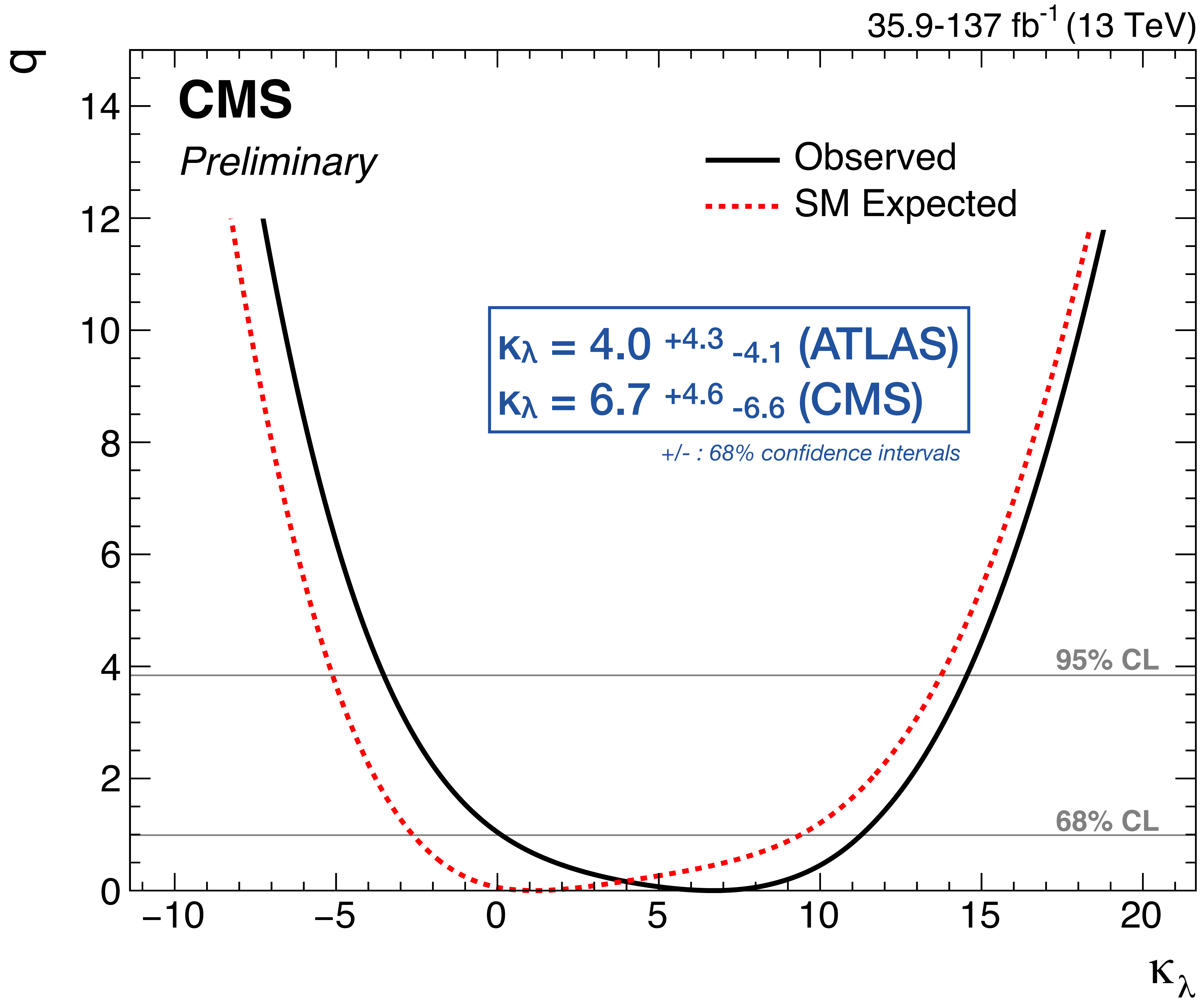
Differential distributions



Extracting λ_{HHH}

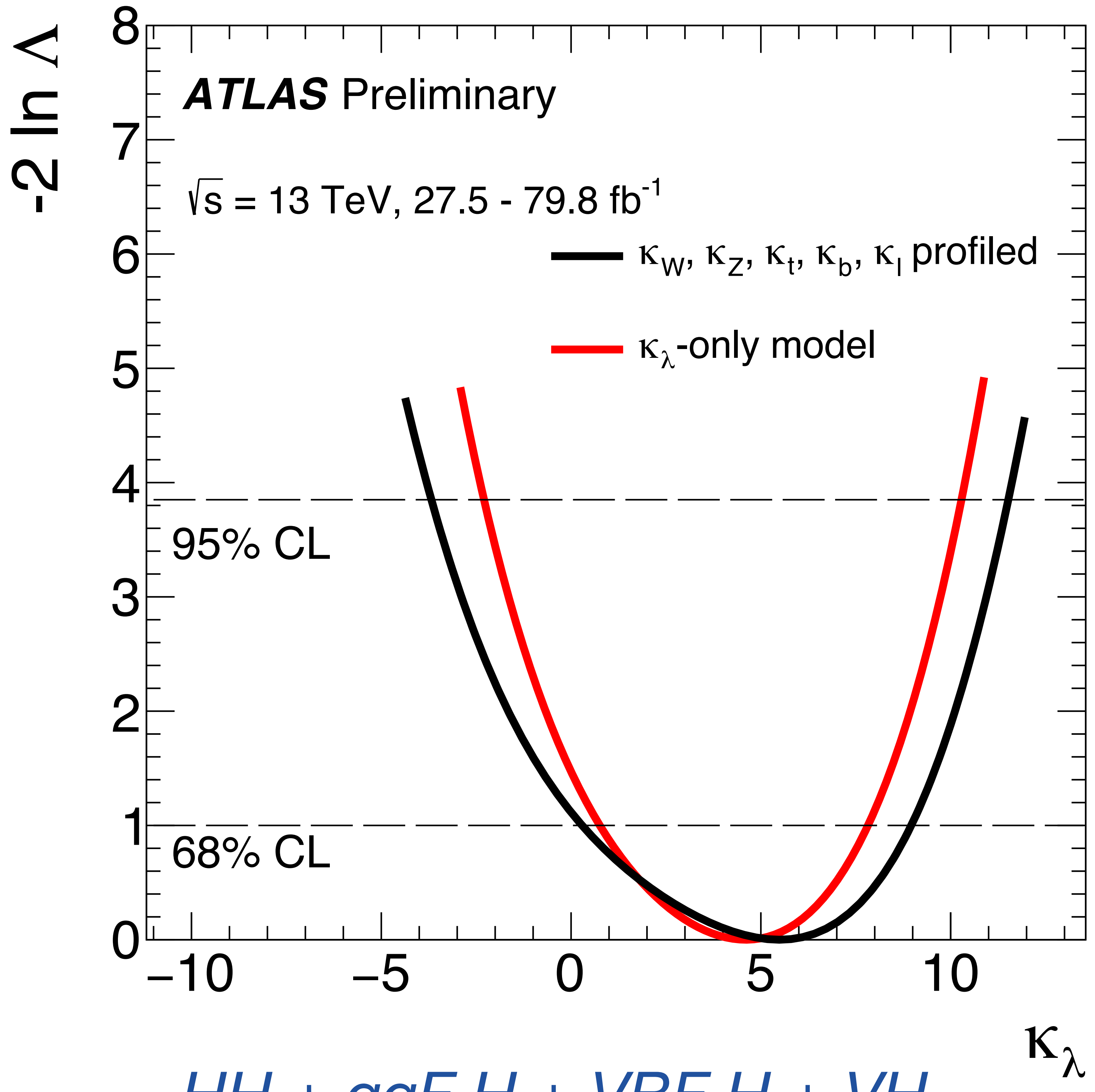
- Reinterpretation of the simplified template cross section combined measurements
- Assume that all the other couplings are fixed to the SM prediction
- Variations of λ_{HHH} and of other couplings cannot be distinguished
  - reduced sensitivity by 50% if κ_V also fitted
  - no sensitivity if further degrees of freedom are introduced



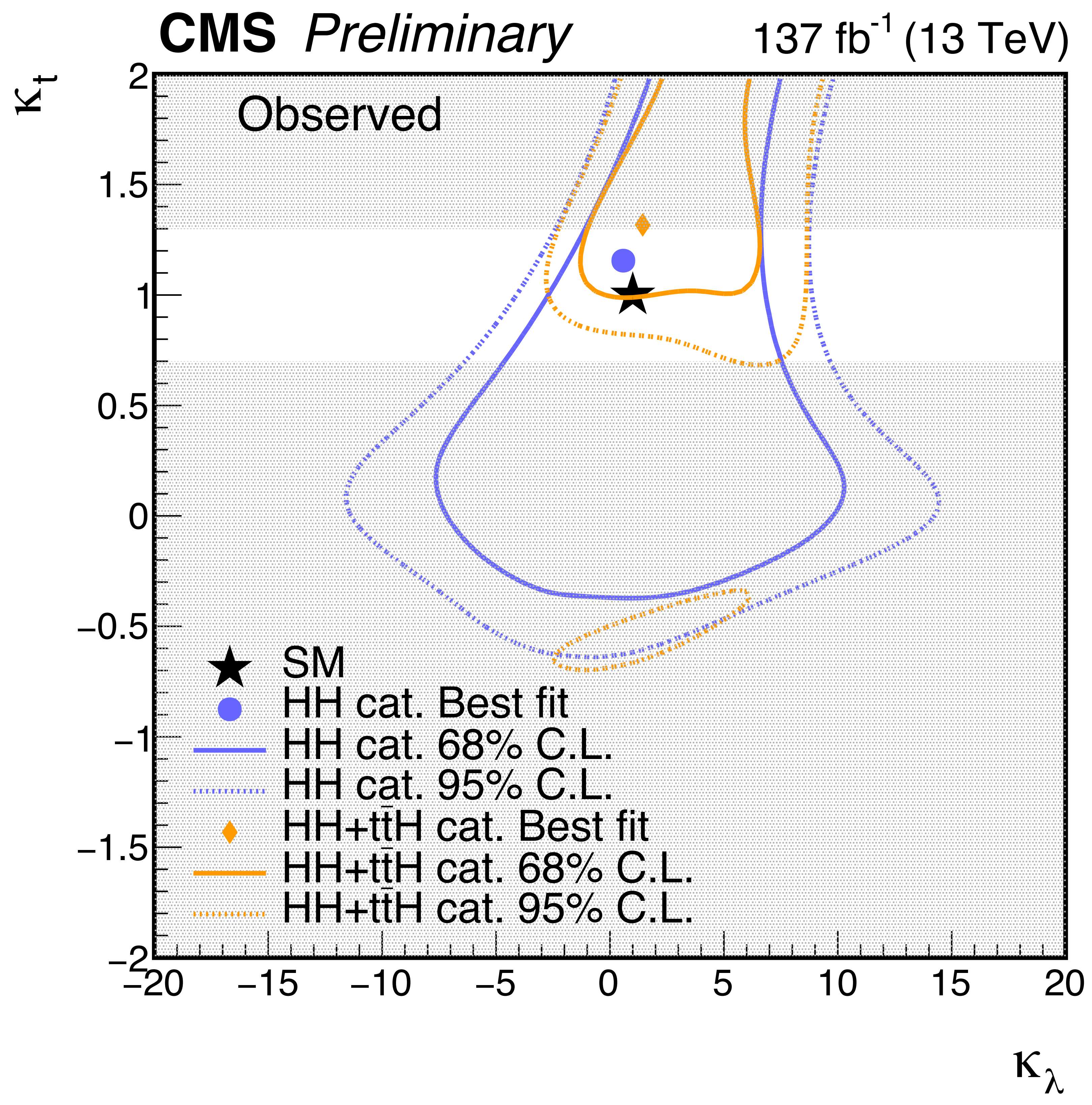
Complements direct determination from HH

Measurement sensitive only under strict assumptions on other Higgs boson couplings

A global view of the self coupling



HH + ggF H + VBF H + VH + ttH (excl ttH(γγ))



HH(bbγγ) + ttH(γγ)

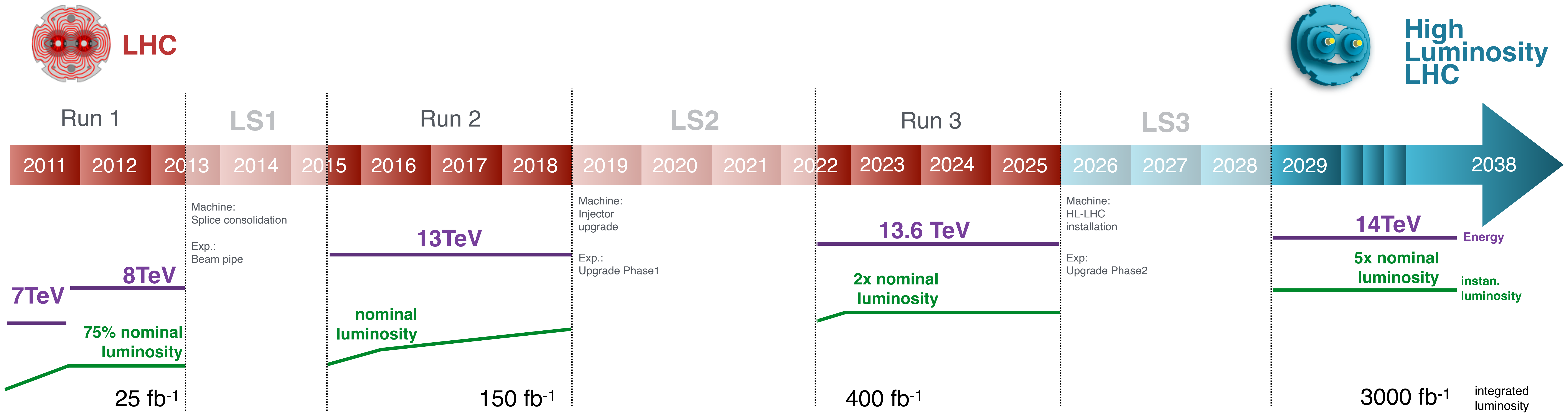
- H+HH: probe simultaneously λ_{HHH} and other couplings variations
- Remove degeneracies with κ_t
- ~20% improvement in sensitivity to λ_{HHH} when adding single H

Probe more generic models with all couplings variations

LO (HH) with NLO (H) effects combined within a κ-framework
Not fully coherent theoretically ⟹ full EFT fit as a next step!

The high-luminosity LHC

- Upgrade of the LHC planned to start after the LS3
  - expect first beams in 2029



- Increase of the instantaneous luminosity by ~5 w.r.t. design values

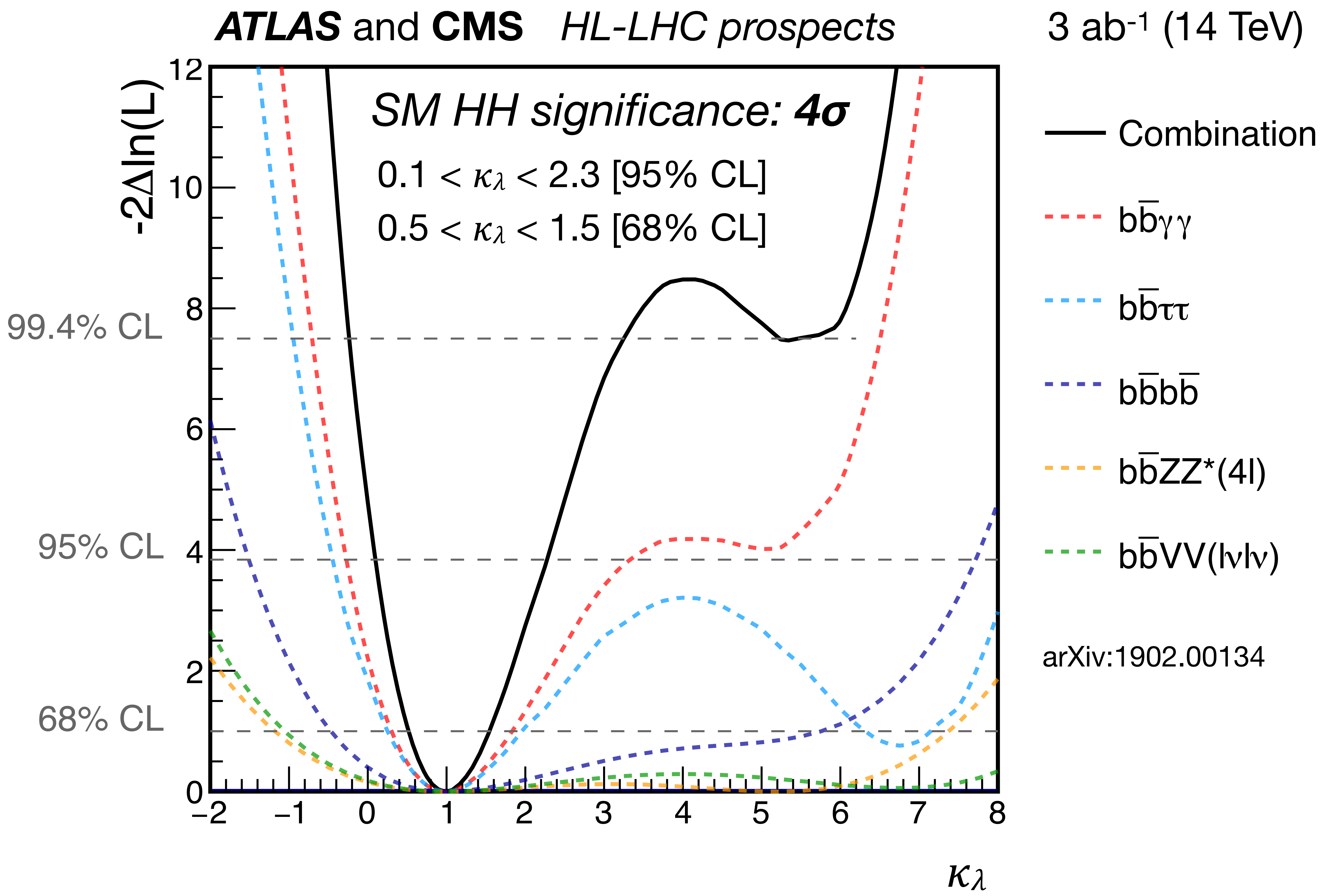
- **3 ab^{-1} during a decade of operations**

Unique possibility for very high precision Higgs physics

Ultimate LHC sensitivity on HH

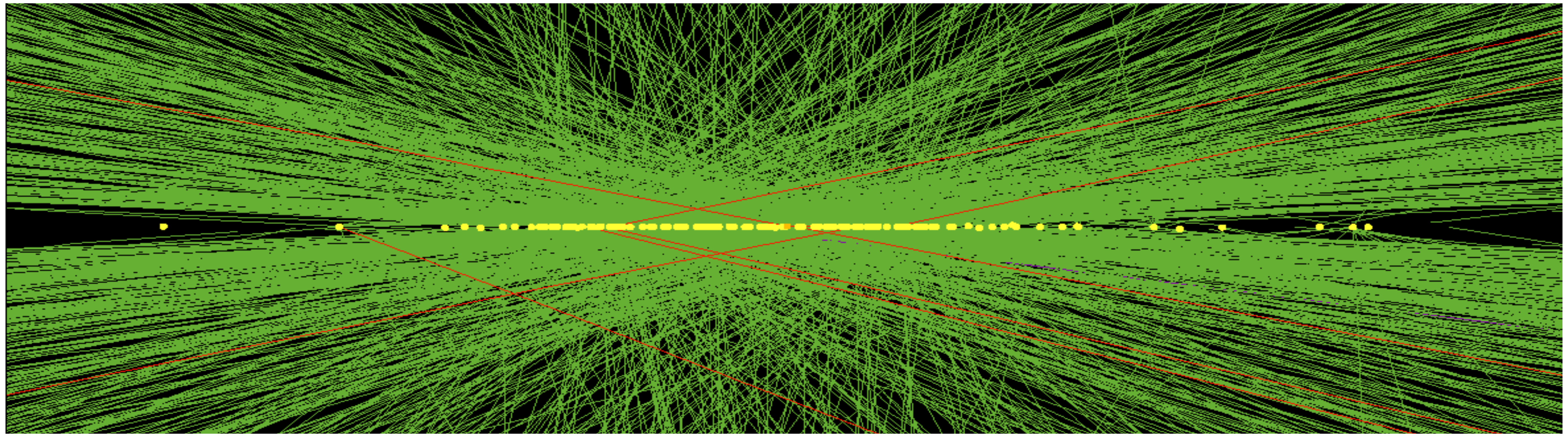
HH prospects at the HL-LHC

- HH sensitivity projected with Run 2 extrapolation and dedicated Phase-2 analyses
  - small impact of systematic uncertainties observed in most channels
- Expect 50% (100%) precision on κ_λ at 68% (95%) CL, and to exclude the no self-coupling hypothesis
  - with the current analysis techniques! Further improvements should come in the next 20 years
- New projections are in preparation (Snowmass)



Combination of channels and experiments is crucial to achieve sensitivity at the HL-LHC

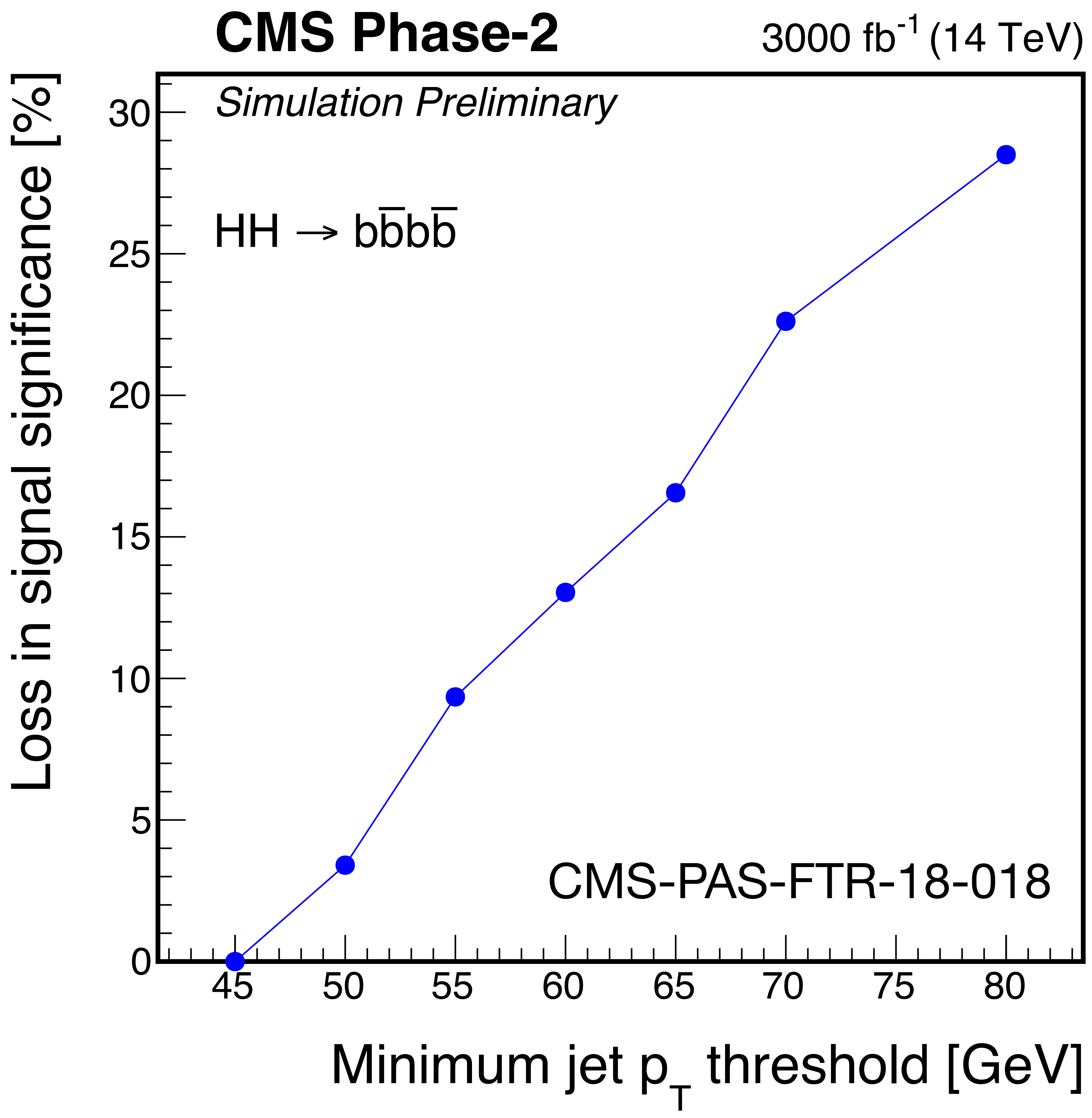
Why is it challenging?



- Up to 200 simultaneous pp interactions per bunch crossing!
  - radiation hardness and reconstruction are key challenges
  - challenging triggering and PU suppression
- HH analyses sensitivity to λ_{HHH} crucially relies on low m_{HH}
  - soft objects → difficult region at high pileup

An ambitious program of detector upgrades is planned to maintain and improve the performance at the HL-LHC

The HH physics programme crucially relies on the success of the Phase-2 upgrades



Essential to maintain low thresholds!

HH at future colliders : a quick glimpse

High energy pp machines

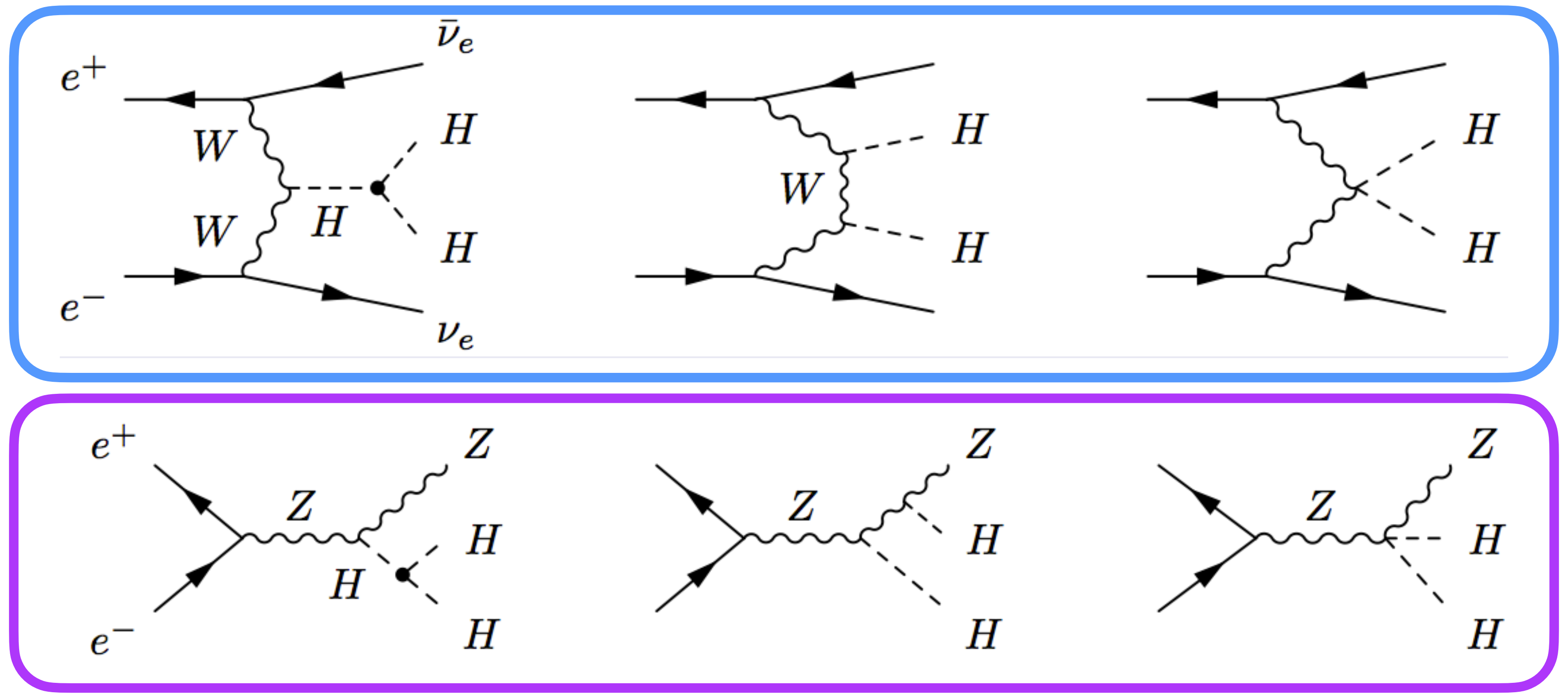
"HH factories" : ultimate precision on λ from direct determination

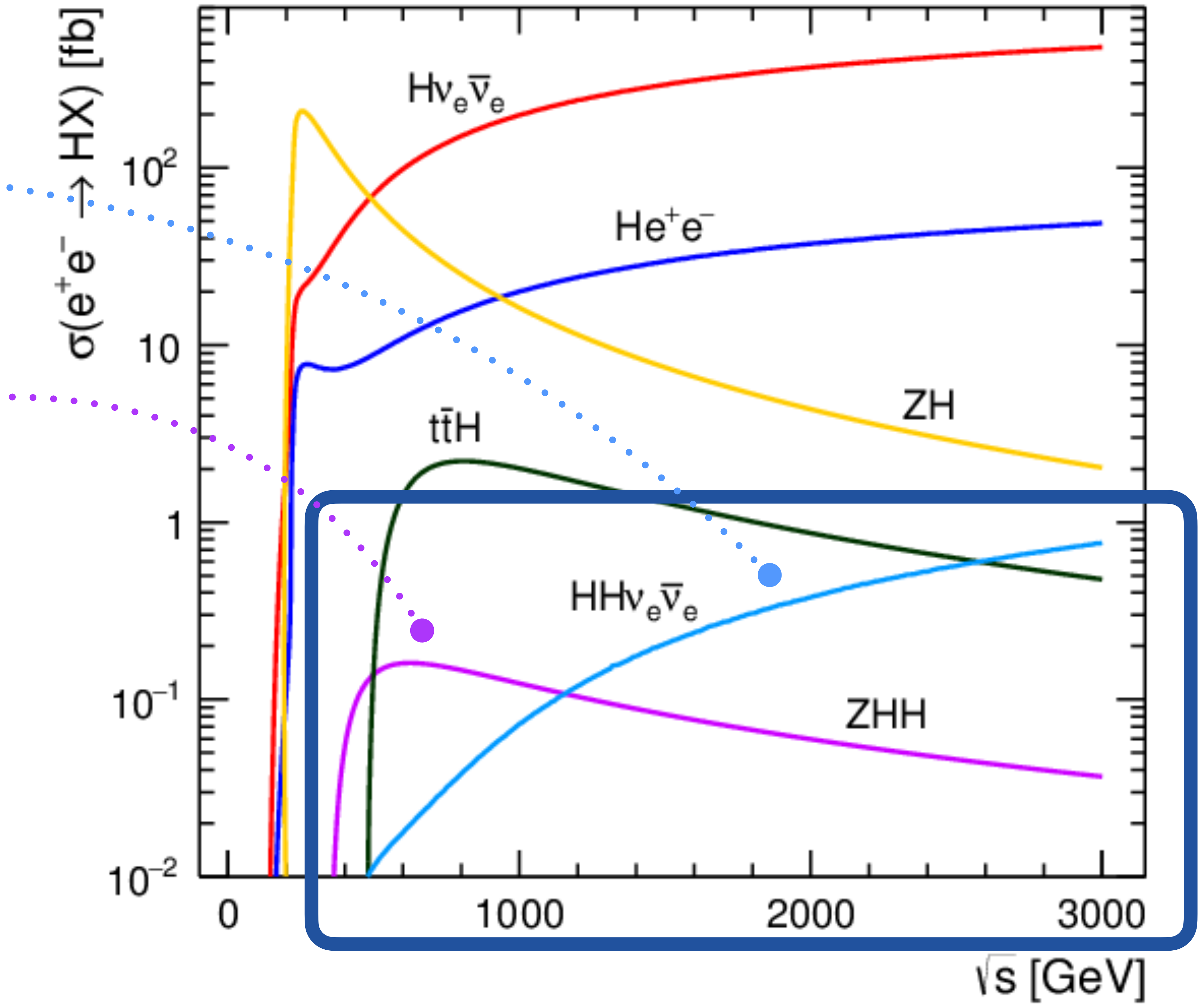
- HL-LHC → FCC-hh : ×33 σ(gg→HH), ×10 $\int\mathscr{L} \Longrightarrow$ > 30M HH events for study

Precision e+e- machines

Direct HH study only at high sqrt(s), indirect λ determination from H

- √s ≳ 400 GeV needed for HH production
  - only achievable in $ILC_{500/1000}$ and $CLIC_{1500/3000}$





- Small cross sections for ZHH → O(500) events expected for the full run
- VBF production interesting for √s > 1 TeV

Prospects for future sensitivities

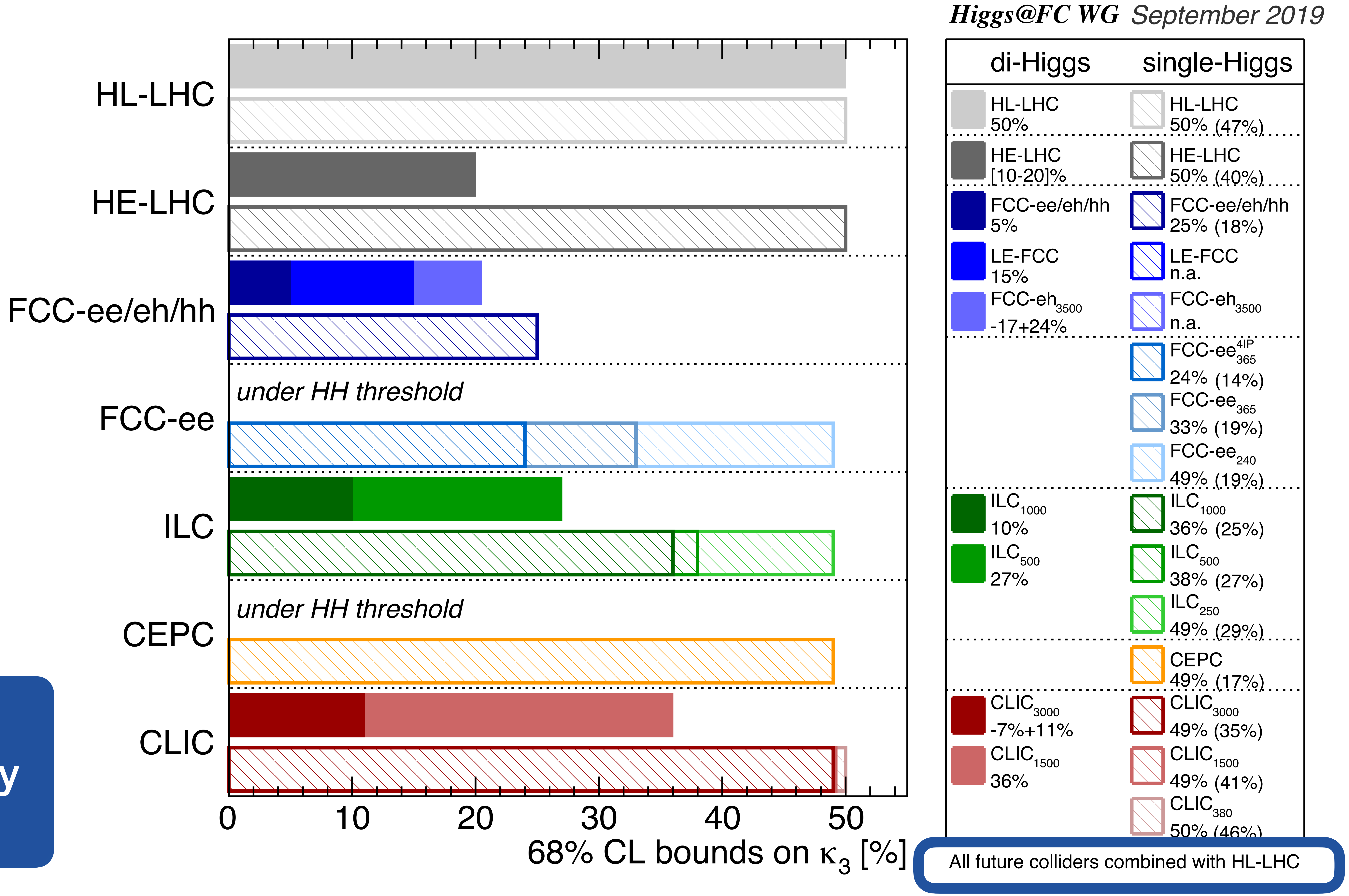
Direct HH

- leading the λ_{HHH} sensitivity
- require high sqrt(s) in e^+e^-
- ultimate precision of 5% achieved at FCC-hh

Indirect single-H

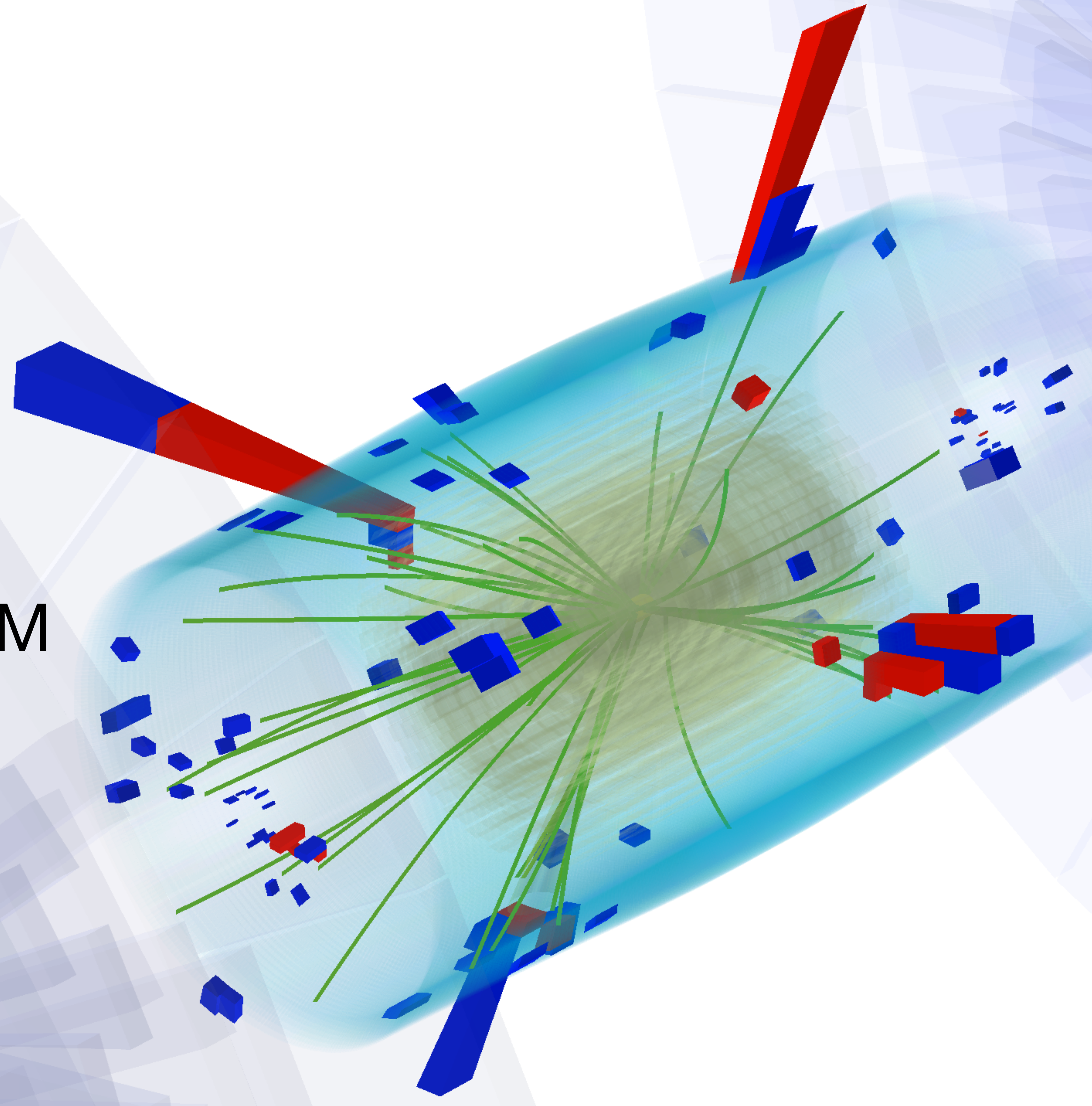
- limited by HH HL-LHC reach until higher energies and luminosities are achieved

λ_{HHH} results at HL-LHC will represent an important legacy for the long term future



Conclusions

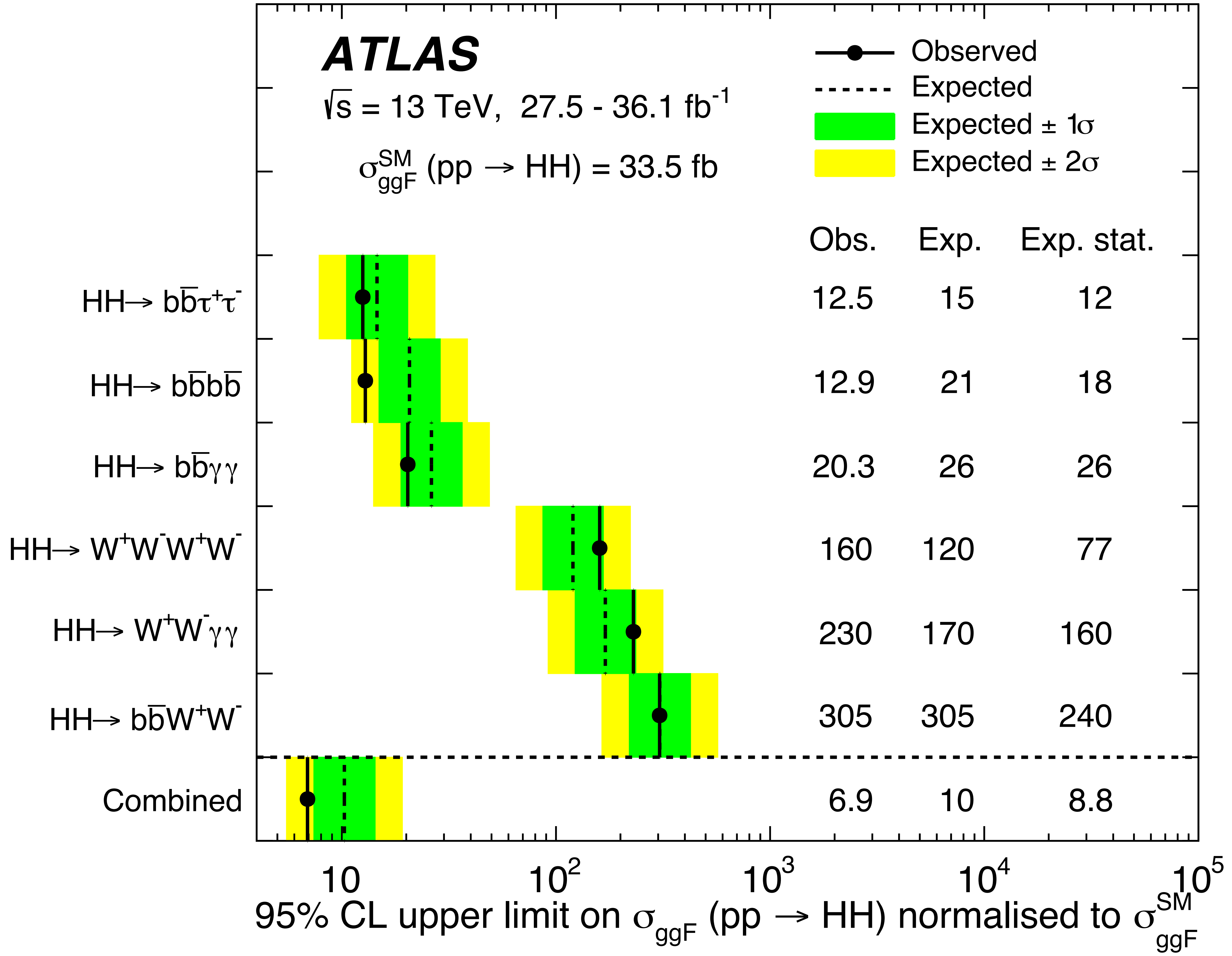
- The shape of the Higgs potential is so far largely unknown
  - its measurement will deepen our understanding of the scalar sector
- HH measurements give direct access to λ_{HHH}
  - small cross section : experimentally challenging
  - crucial to explore and combine several decay channels
  - broad spectrum of analyses by ATLAS and CMS
- Sensitivity from single H measurements via NLO effects
  - need to disentangle λ_{HHH} from other effects of physics beyond the SM
  - benefit of a H + HH combination for maximal sensitivity
- Full Run 2 dataset under publication, and Run 3 close to start!
- Very good prospects for measurements at the HL-LHC
  - with important experimental challenges to tackle
- λ_{HHH} is a key topic in the short and long term programme of current and future accelerators

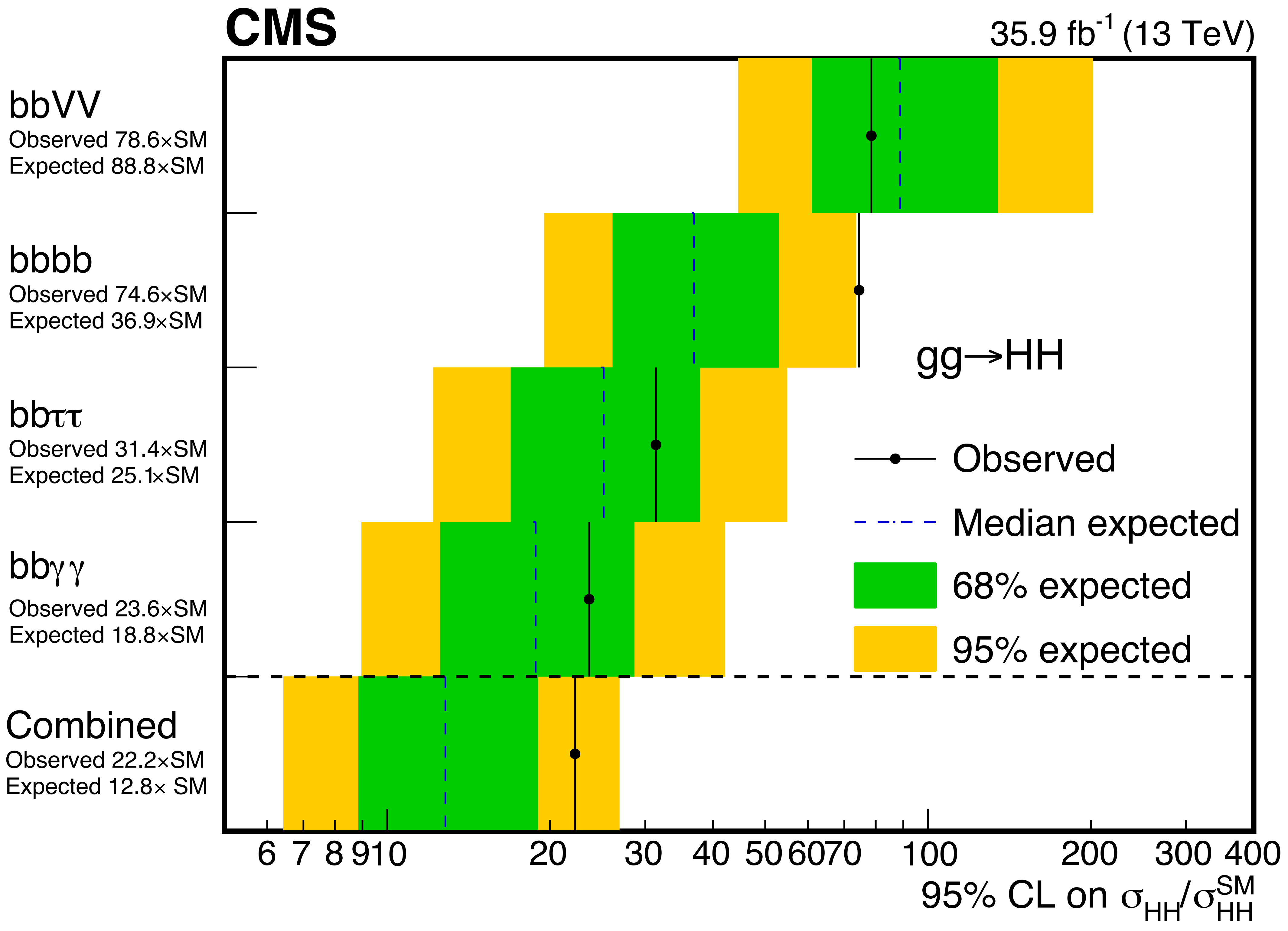


A HH→bb$\tau\tau$ event candidate in the CMS 2016 dataset

Additional material

Combination of the 2016 results



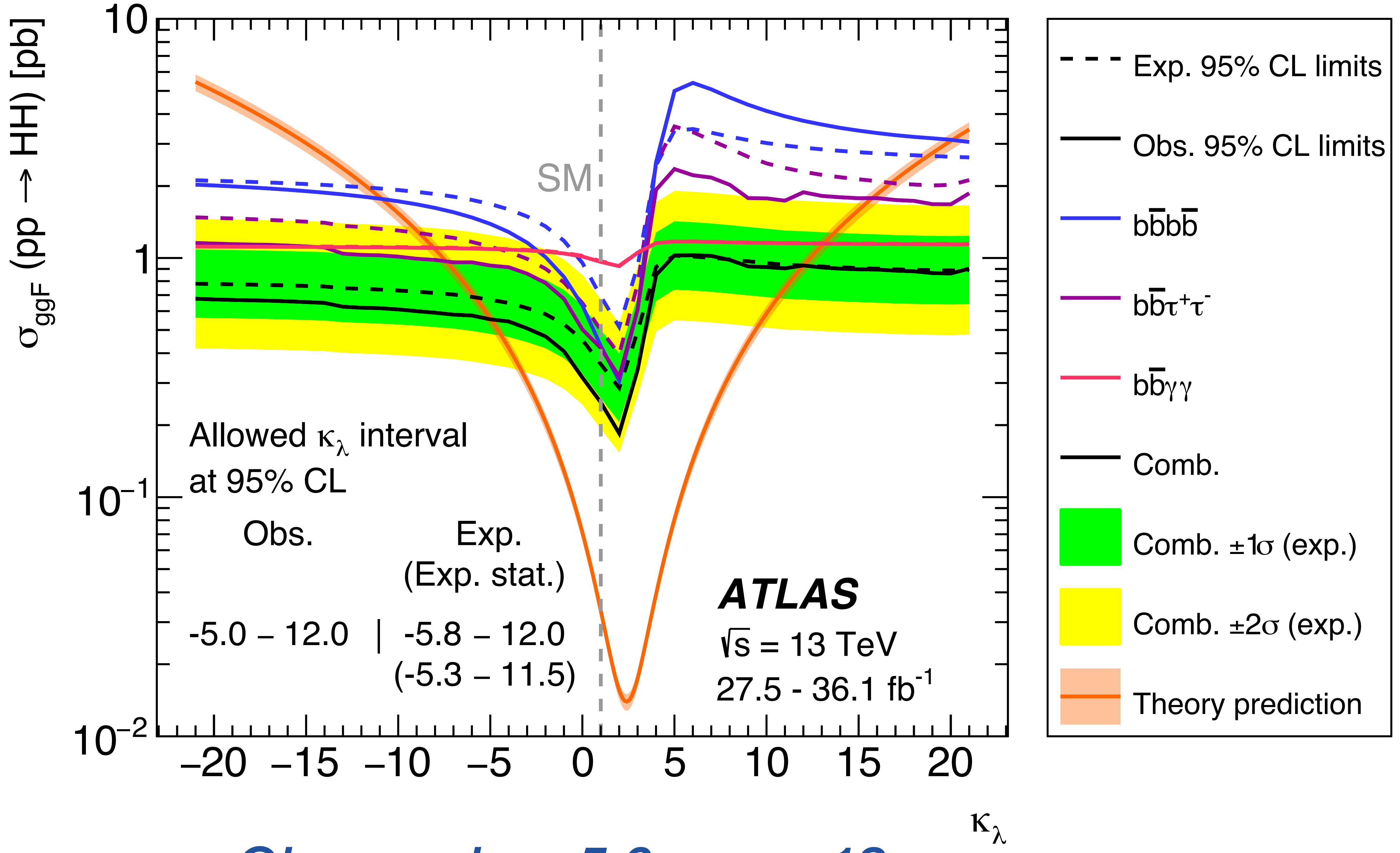


- The combined results benefits from the similar sensitivity in several channels

Approaching a sensitivity of 10 × σ^{SM} with the 2016 dataset only

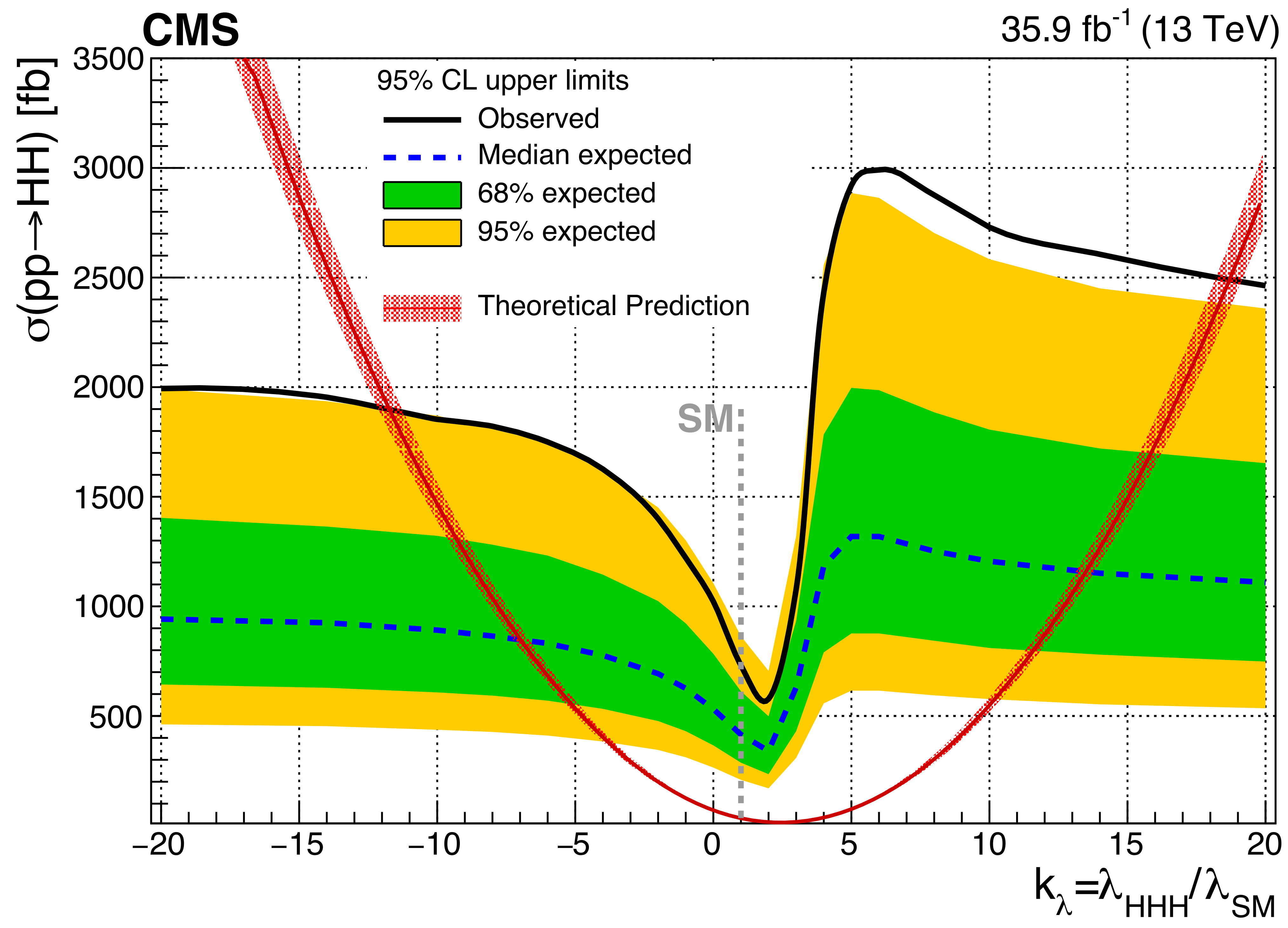
Full Run 2 dataset (×4 more data) current under analysis
×2 more sensitive (from stat.) + analysis improvements

Self-coupling limits with the 2016 dataset



Observed: ***-5.0 < κλ < 12***

Expected: *-5.8 < κλ < 12*



Observed: ***-11.8 < κλ < 18.8***

Expected: *-7.1 < κλ < 13.6*

Evaluating the prospects

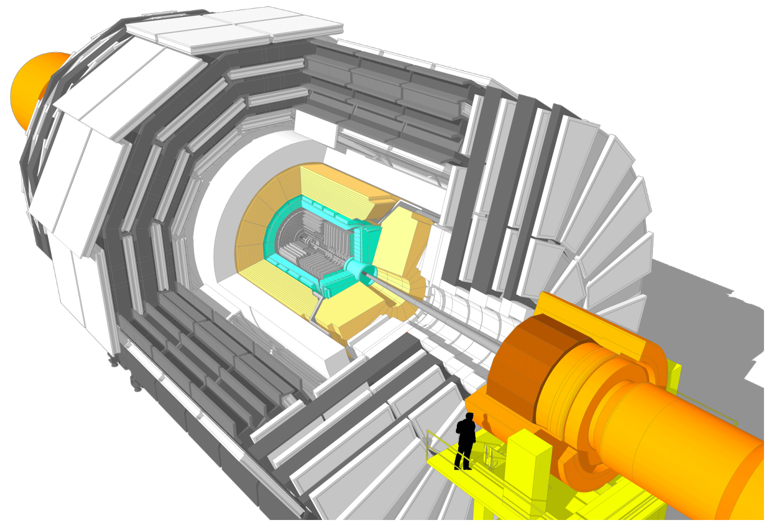
Extrapolations:
Same upgraded detector performance @ PU 200 as Run 2
Phase-2 MC-based analyses:
Fast or full sim with Phase 2 performance from TDRs

Assume uncertainties halved w.r.t. current values

Syst. uncertainties: scaled with luminosity until "floor" levels

Analysis methods: using today's ideas + future detector potentialities

Detector upgrades



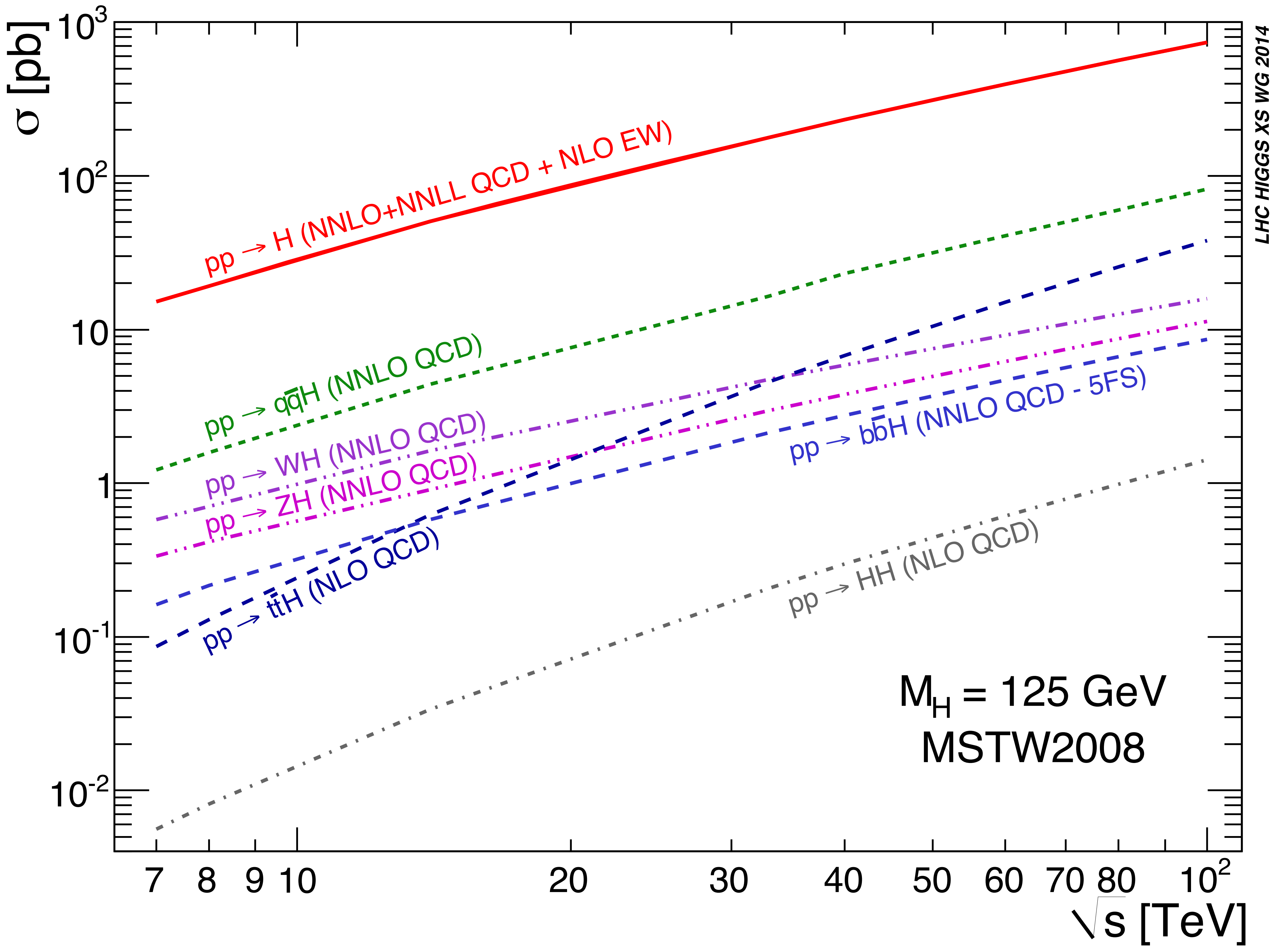
Theory developments

Analysis improvements

Performance scenarios studied to bracket the future performance at the HL-LHC

Assumptions based on Run 2 experience

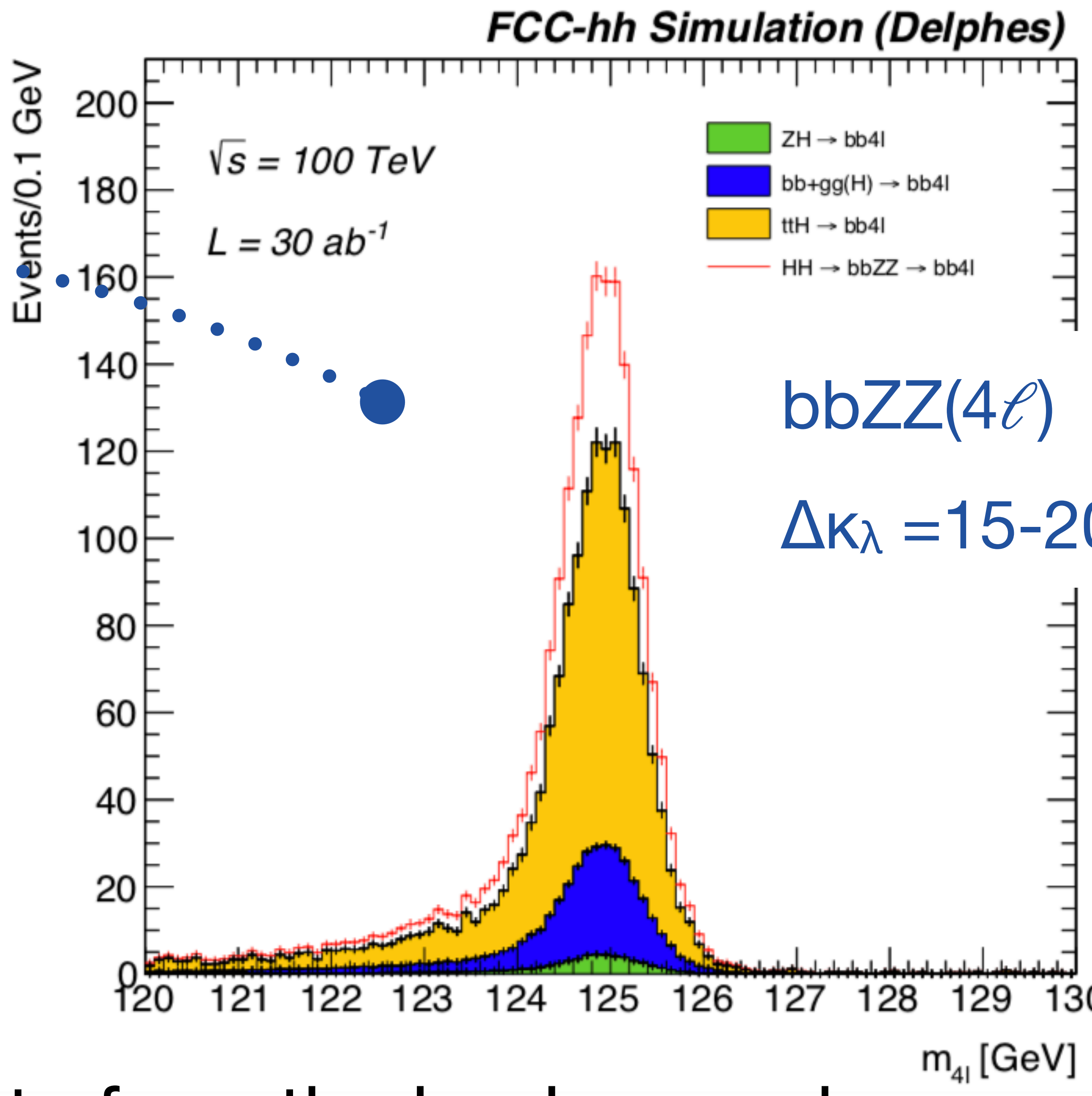
HH at future pp colliders



σ_{HH} (100 TeV) = 1224 fb

×33 xs, ×10 lumi w.r.t HL-LHC

- Very rare channels and clean achieve good sensitivity
- $bb\gamma\gamma$, $bb\tau\tau$ leading the sensitivity because of the good purity
- For bbbb, use HH + jets
  - boosted jets easier to separate from the background
  - the centre-of-mass boost allows to maintain access to events close to the m_{HH} threshold

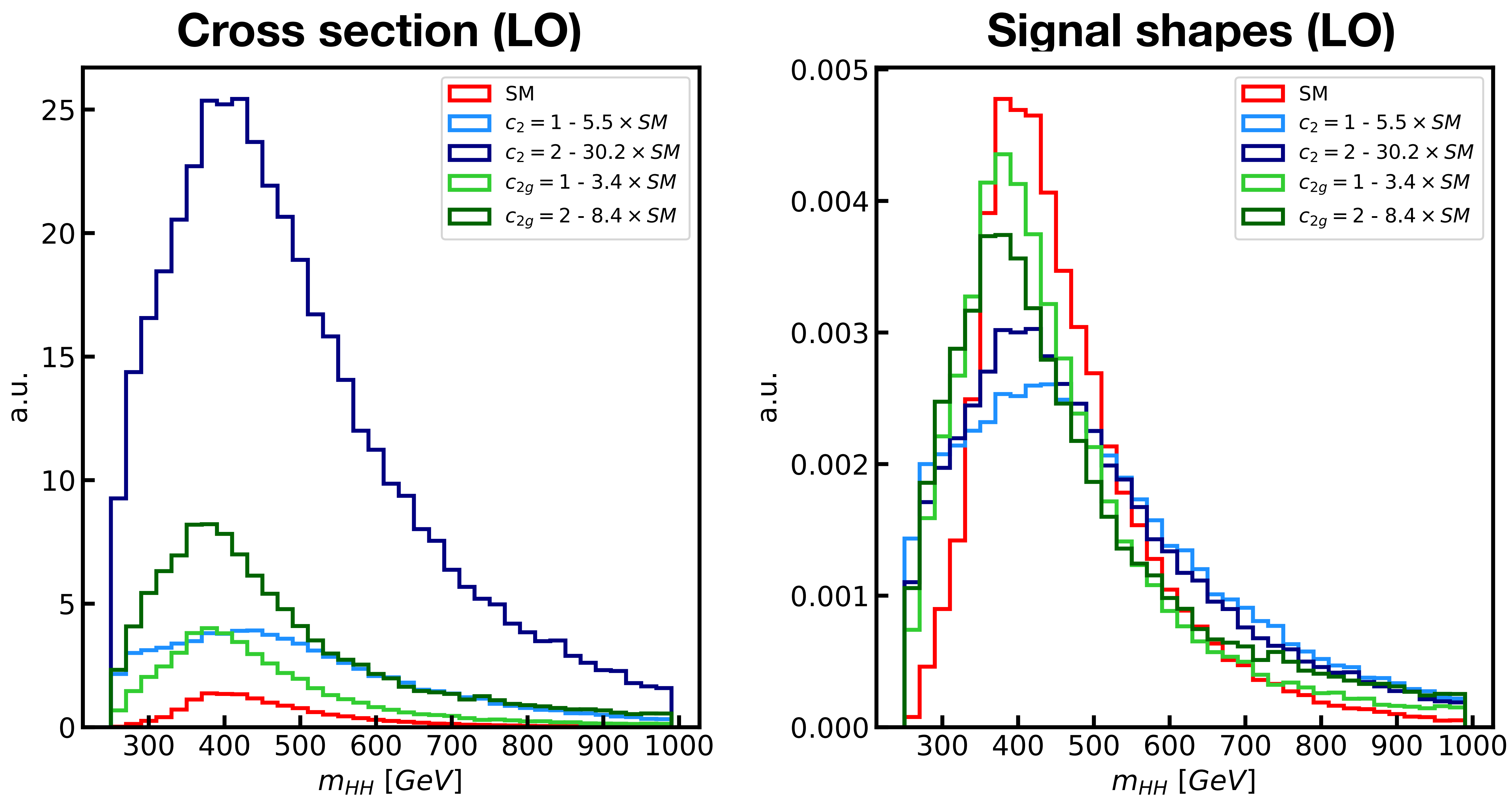


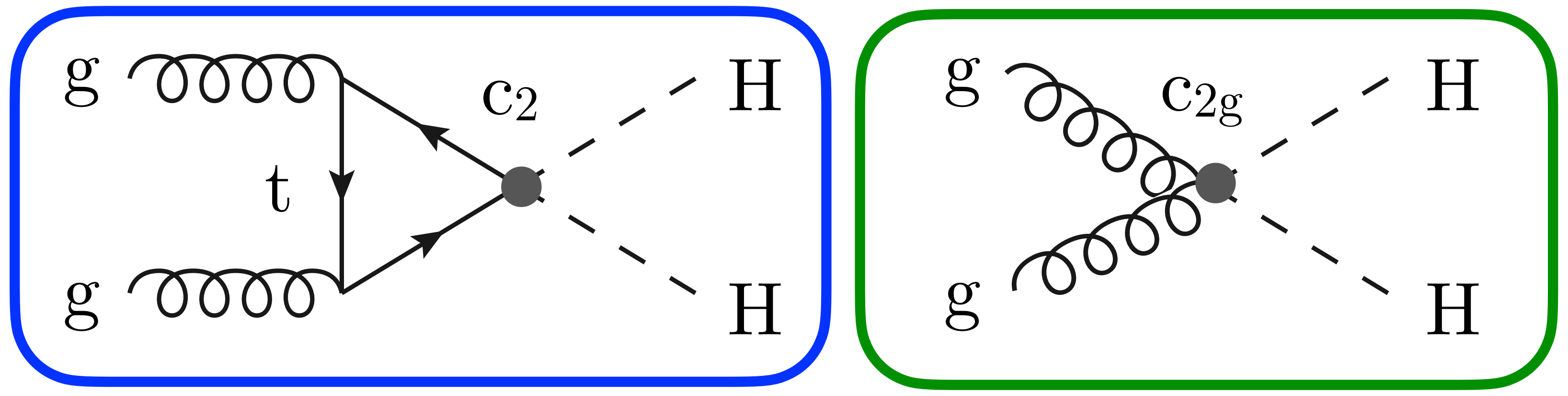
bbZZ(4ℓ)

$\Delta\kappa_\lambda$ =15-20%

Benefit of the high energy and luminosity
Clean channels and new topologies used to fight the PU

EFT effects in HH





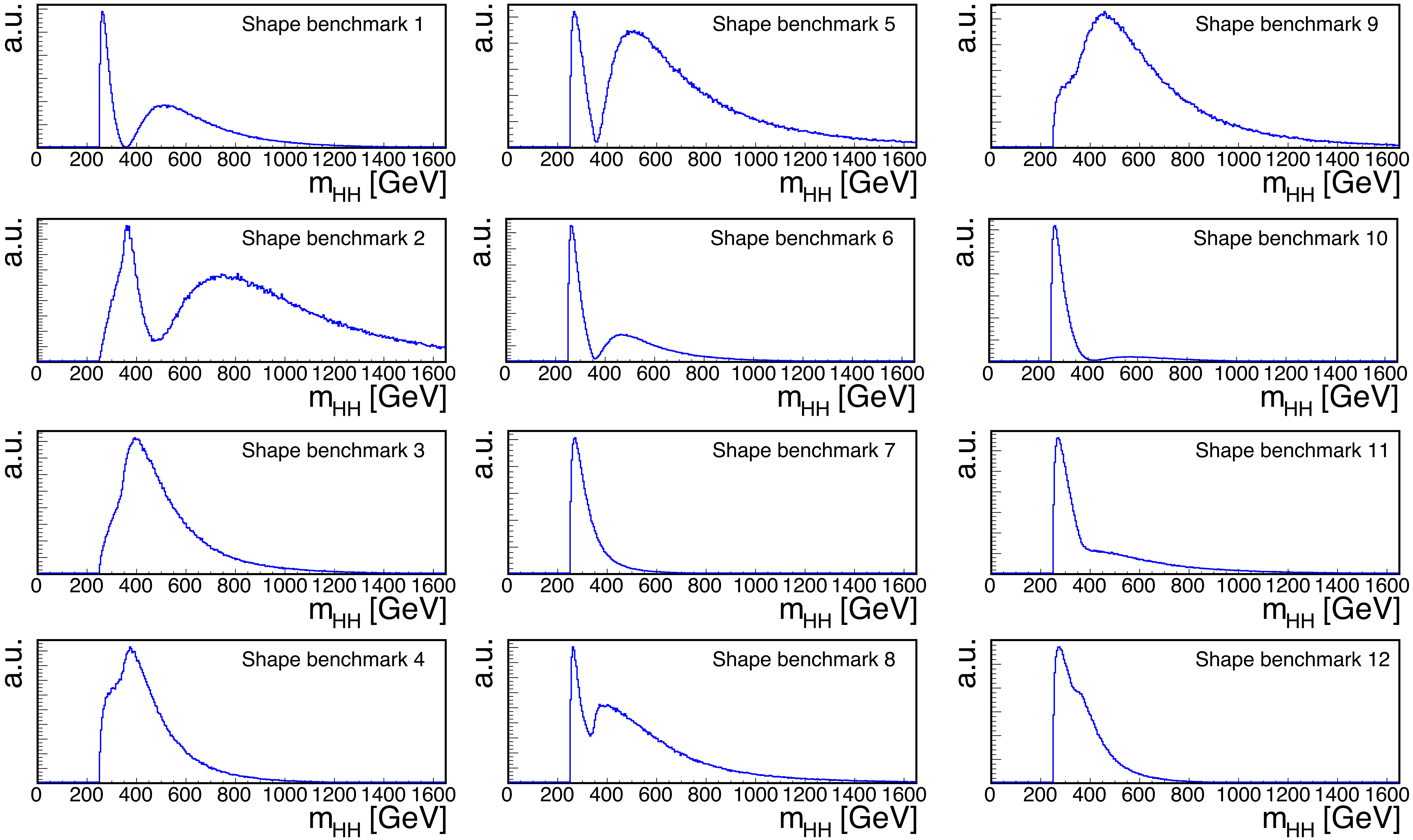
- 5 interactions involved in ggF
  - 3 specific to HH : λ, c_{2g}, c_2
  - 2 constrained also in single H: c_g, y_t
- 3 interactions involved in VBF
  - 2 specific to HH: λ, c_{2V}
  - 1 constrained also in single H: c_V
- Correlations between these parameters depend on the way EFT is realised

Results typically assume λ-only variations

A more generic result needs to account for the effect of other contributions

Cross sections of O(1) c_2/c_{2g} are within experimental reach

HH shape benchmarks

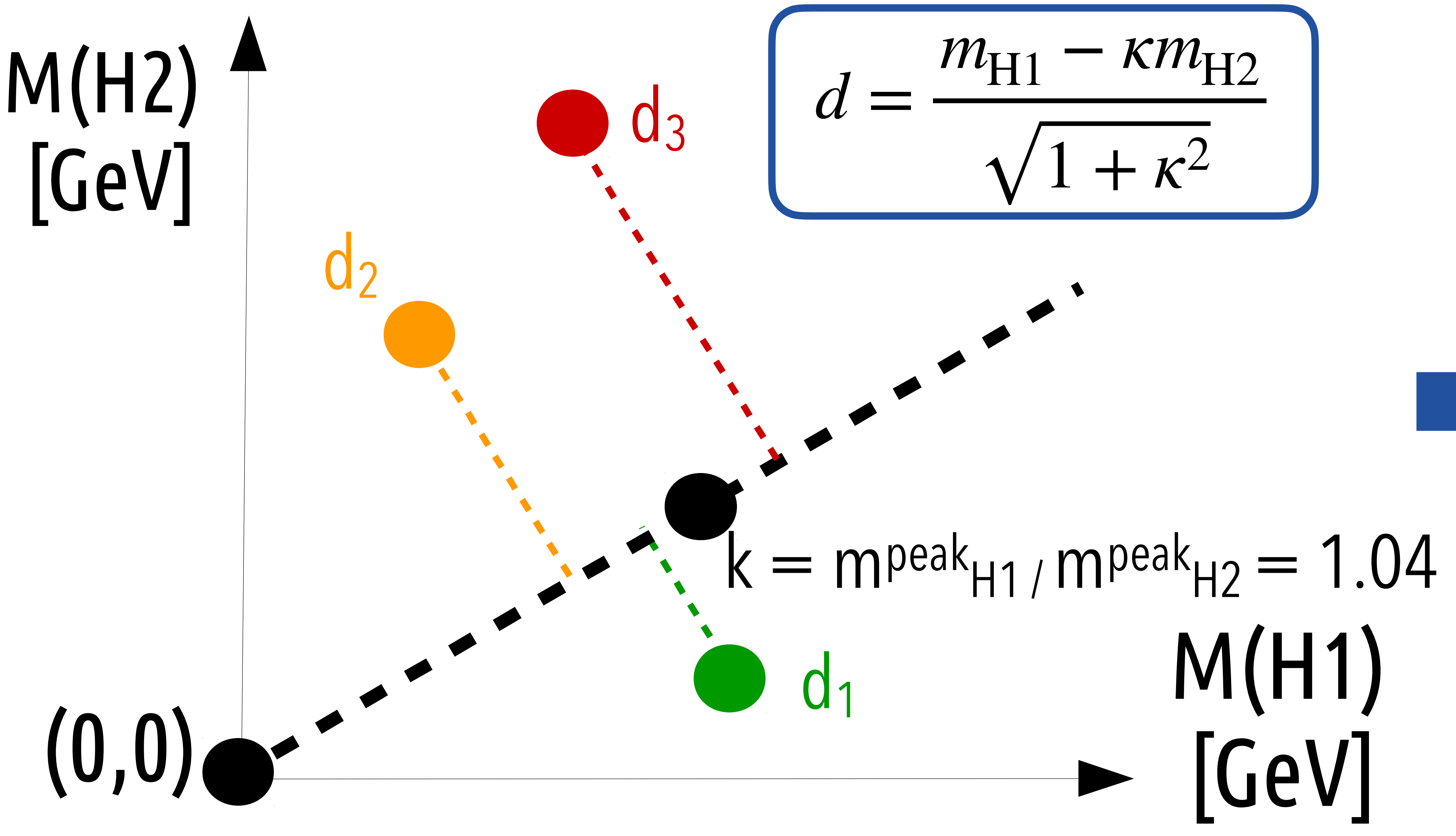


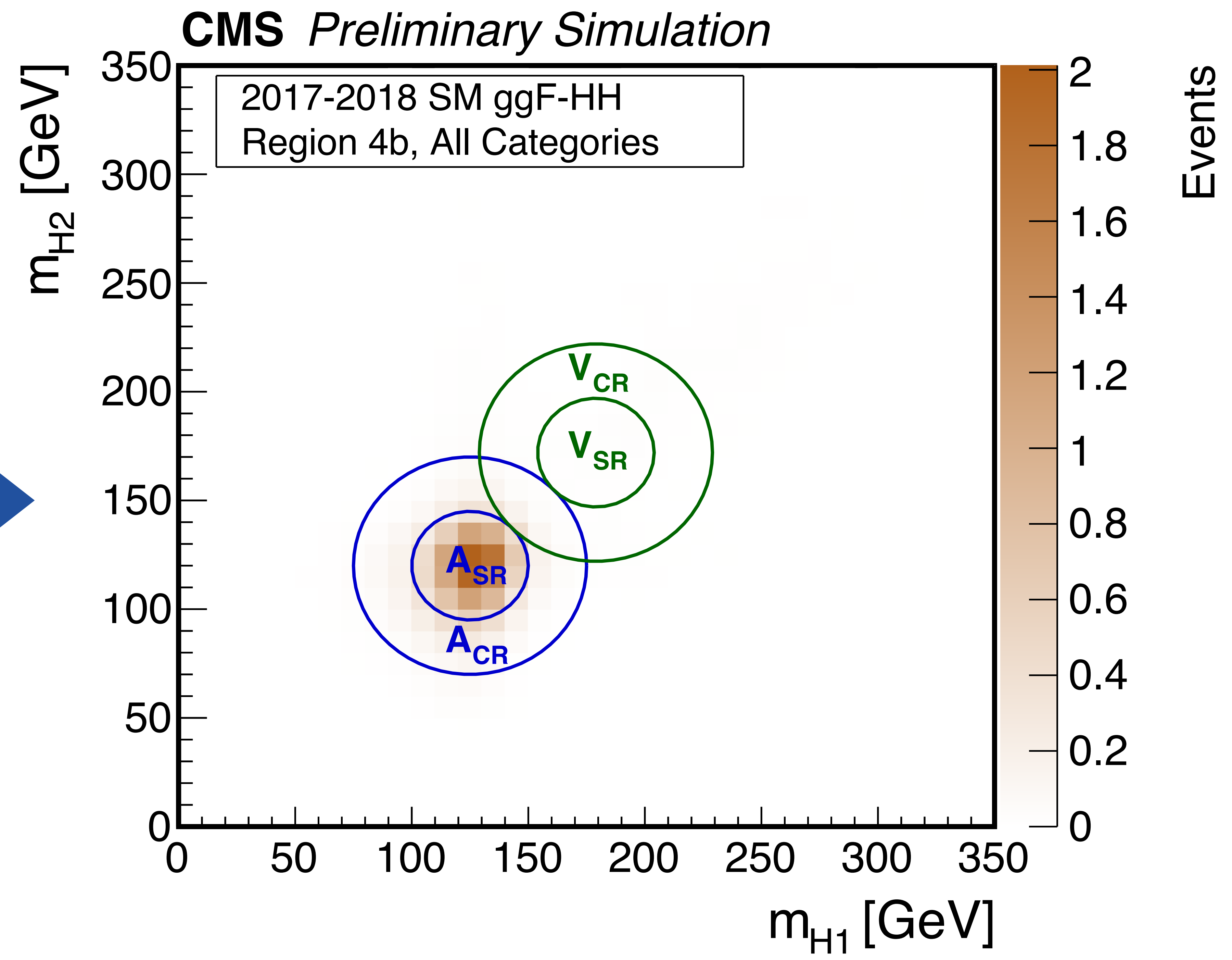
Nr.	k_λ	k_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1.0
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1.0	1.0
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1.0	-1.0
12	15.0	1.0	1.0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

HH → bbbb : Higgs candidate reconstruction

- 4jet+3b trigger, offline preselection of the four jets with the highest b-tag score (≥3 b tagged)
- Three possible pairings of the four b jets exist ⟹ exploit the "equal-mass" hypothesis
  - if $\Delta d = d_2 - d_1 > 30$ GeV, select d_1 pair
  - otherwise, select between pairs d_1 and d_2 the one giving the highest $p_T(H)$ in the 4b rest frame
- Achieve correct pairing in 82-98% of events

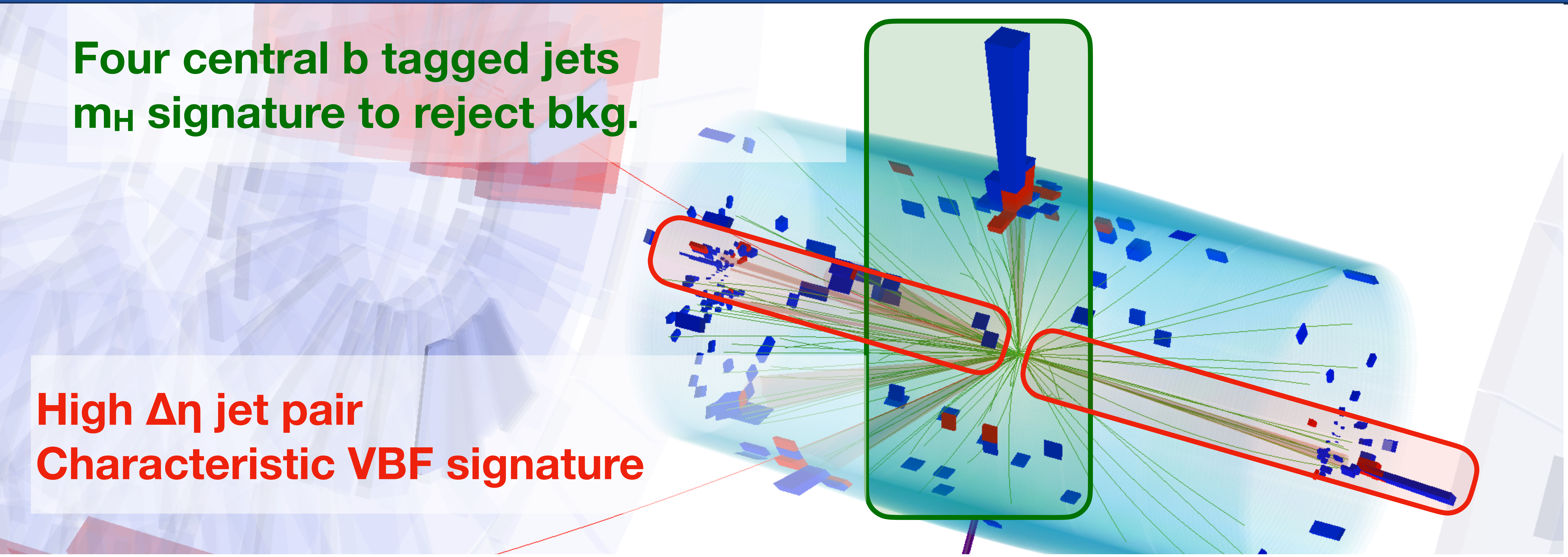
$$d = \frac{m_{H1} - \kappa m_{H2}}{\sqrt{1+\kappa^2}}$$





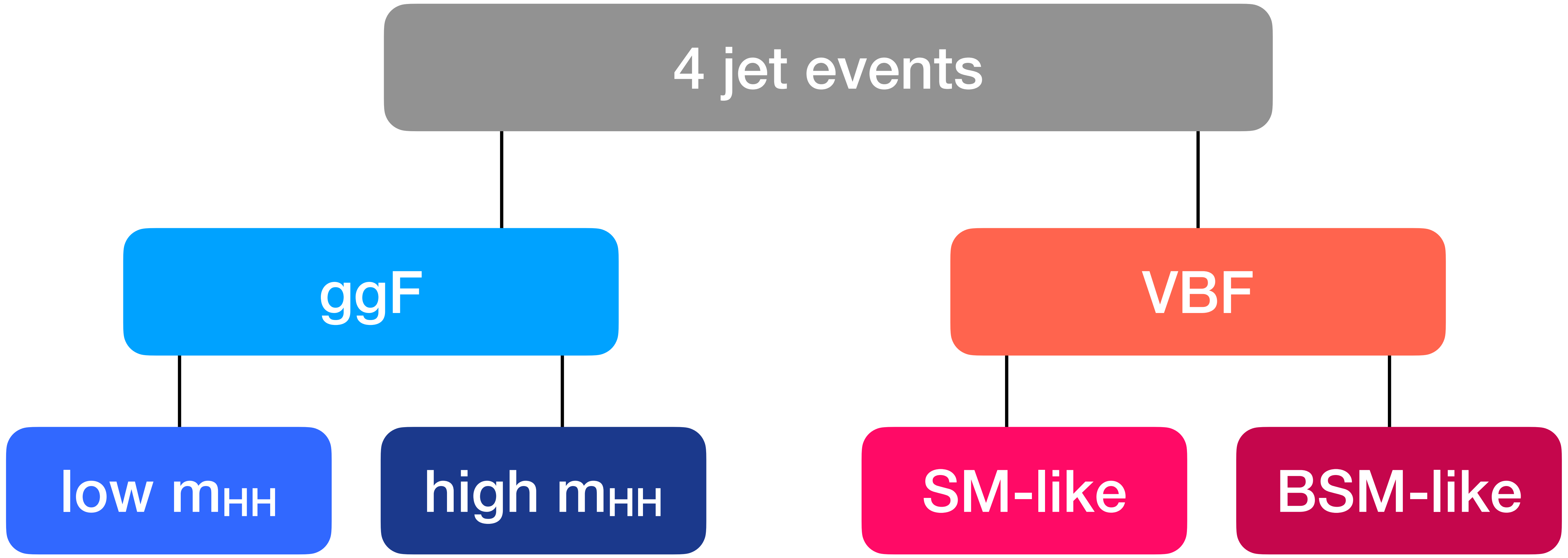
Optimal performance without biasing the bkg events

HH → bbbb : event categories



- VBF events contain two additional jets with $\eta_1 \times \eta_2 < 0$
- A BDT is trained to separate misclassified ggF + 2 jets events
  - use kinematic properties of jet and H candidates
  - 97% of ggF events correctly classified

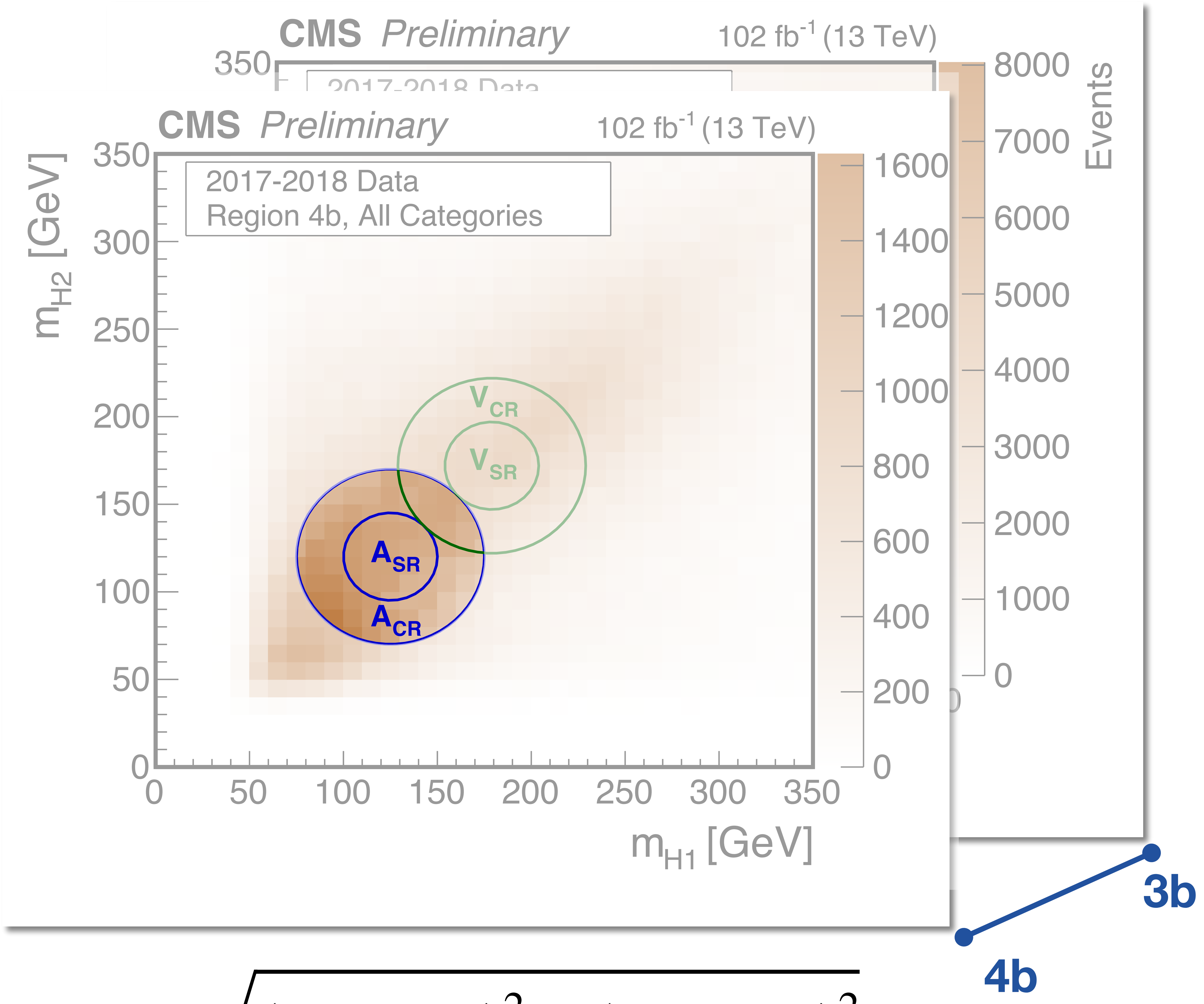
- ggF events split in low- and high-m_{HH} (450 GeV) to capture κ_λ dependence
- VBF events split in SM-like and BSM-like based on BDT score to enhance anomalous κ_{2V} contribution



HH → bbbb : backgorund normalization

- Signal region (SR): $\chi < 25\,\mathrm{GeV}$
- Control region (CR): $25 < \chi < 50\,\mathrm{GeV}$
- Data are divided into a 3b and a 4b sample
  - 5-10× more data in 3b w.r.t. 4b
- Background yield = $N_{CR}^{4b}/N_{CR}^{3b} \times N_{SR}^{3b}$

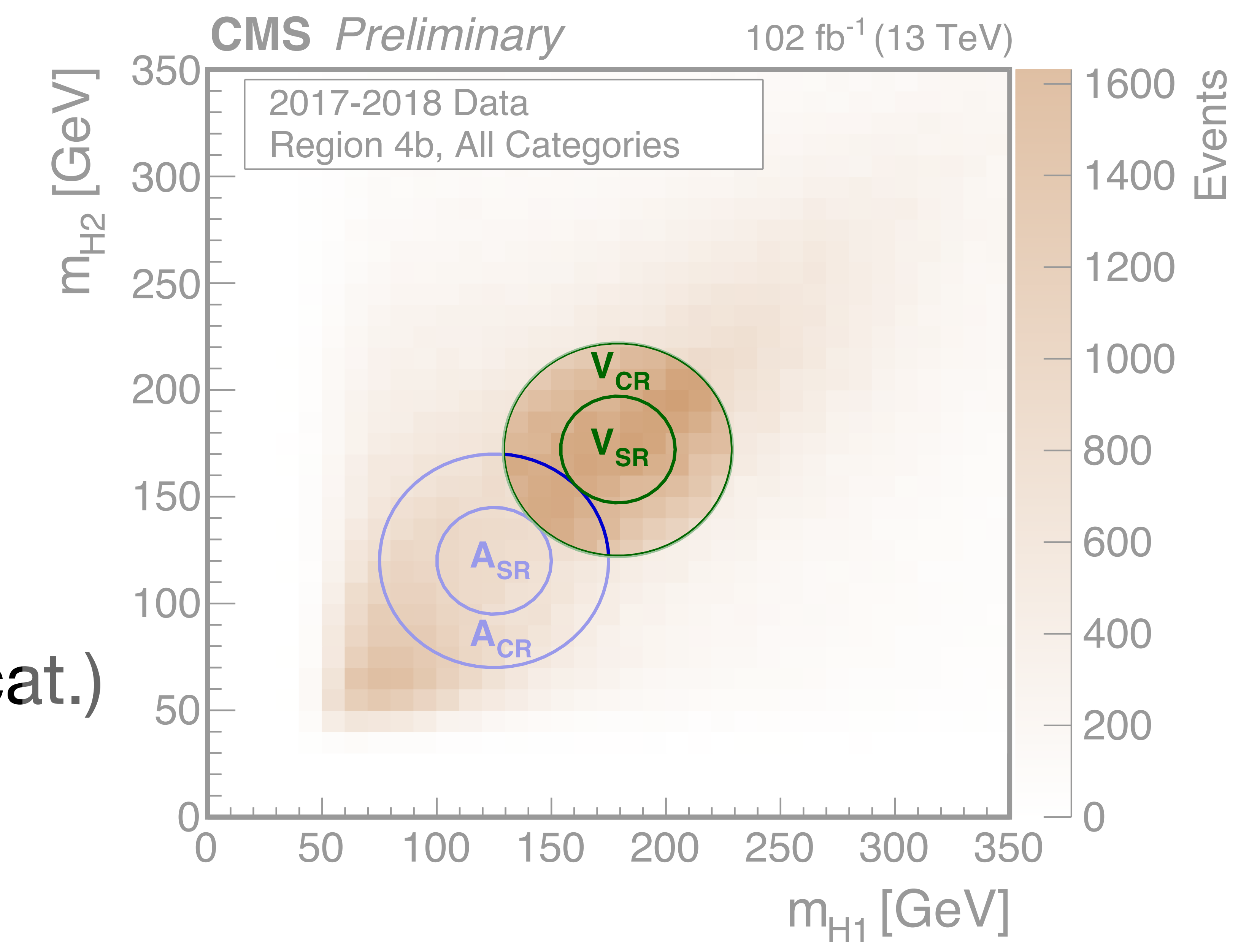
Background yield determined from data

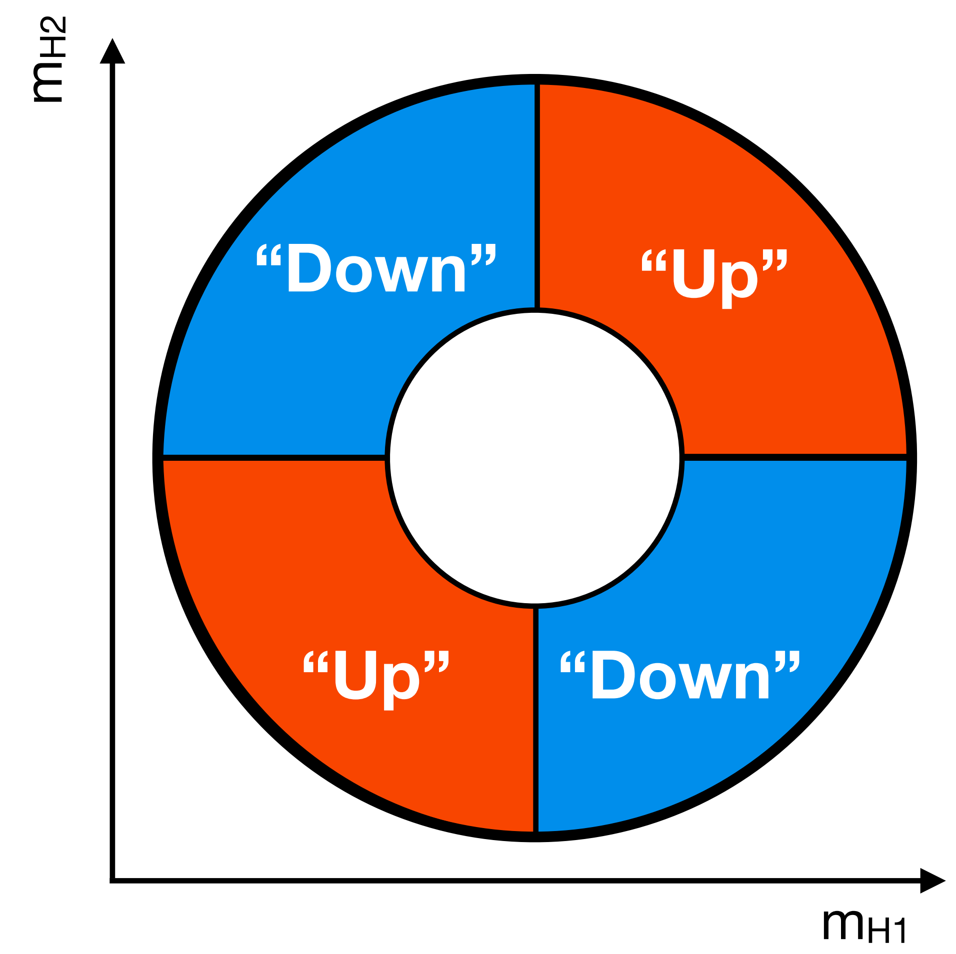


$$\chi = \sqrt{(m_{H1} - c_1)^2 + (m_{H2} - c_2)^2}$$

HH → bbbb : validation and uncertainties

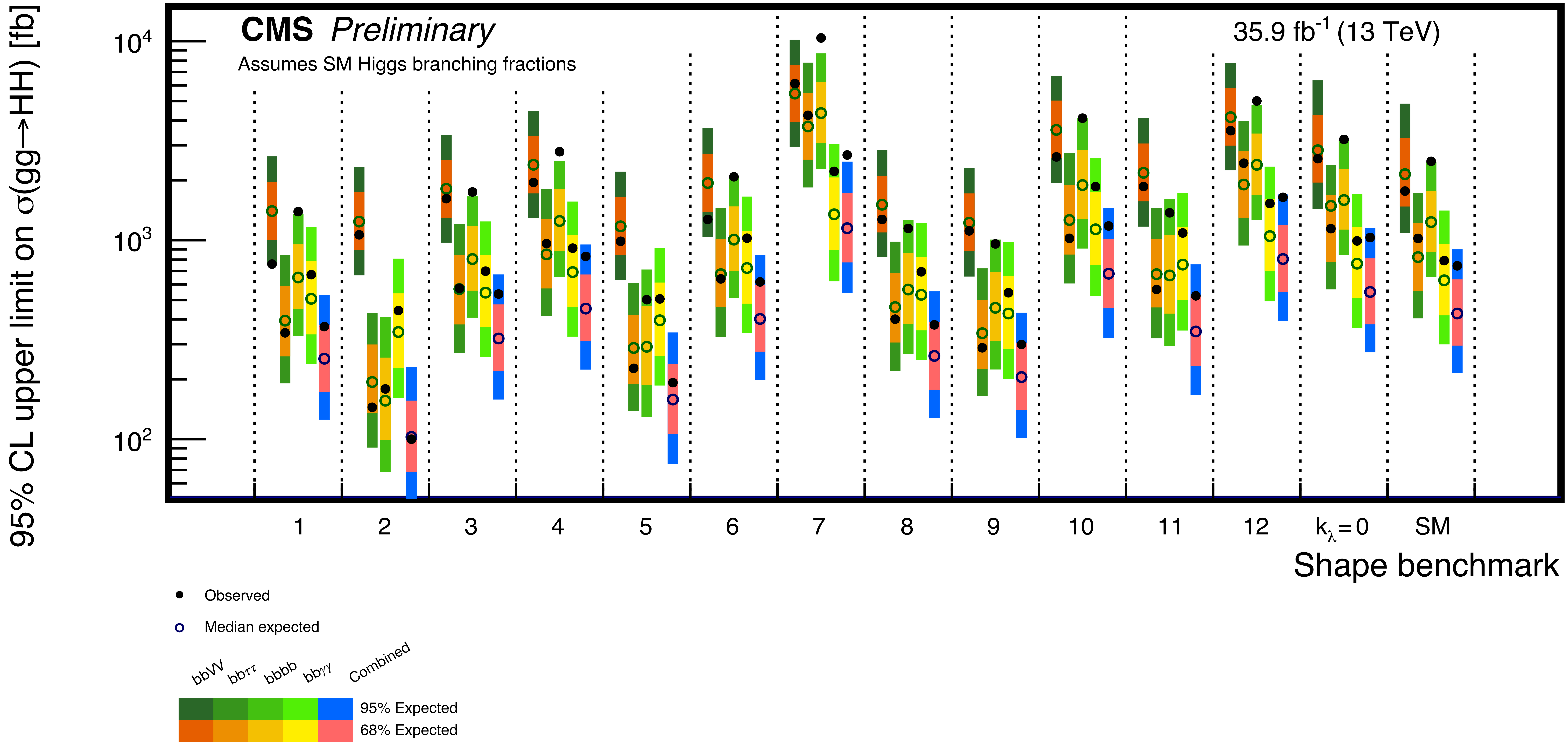
- Signal-free validation region (VR) used
  - apply same methods as in the SR
  - VR shifted along the (m_{H1}, m_{H2}) diagonal → no bias from H reconstruction
- Good statistical agreement for all variables observed in VR
  - add uncertainties for total yields non-closures (1.5-4.7%)
  - uncertainties for the validation vs analysis region statistics (3-30% for VBF cat.)
- Additional SR uncertainties considered on the background templates
  - bin-bin-bin template variations (poisson counts in 3b data)
  - CR statistical uncertainties
  - alternative bkg. templates from trainings in sub-portions of the CR





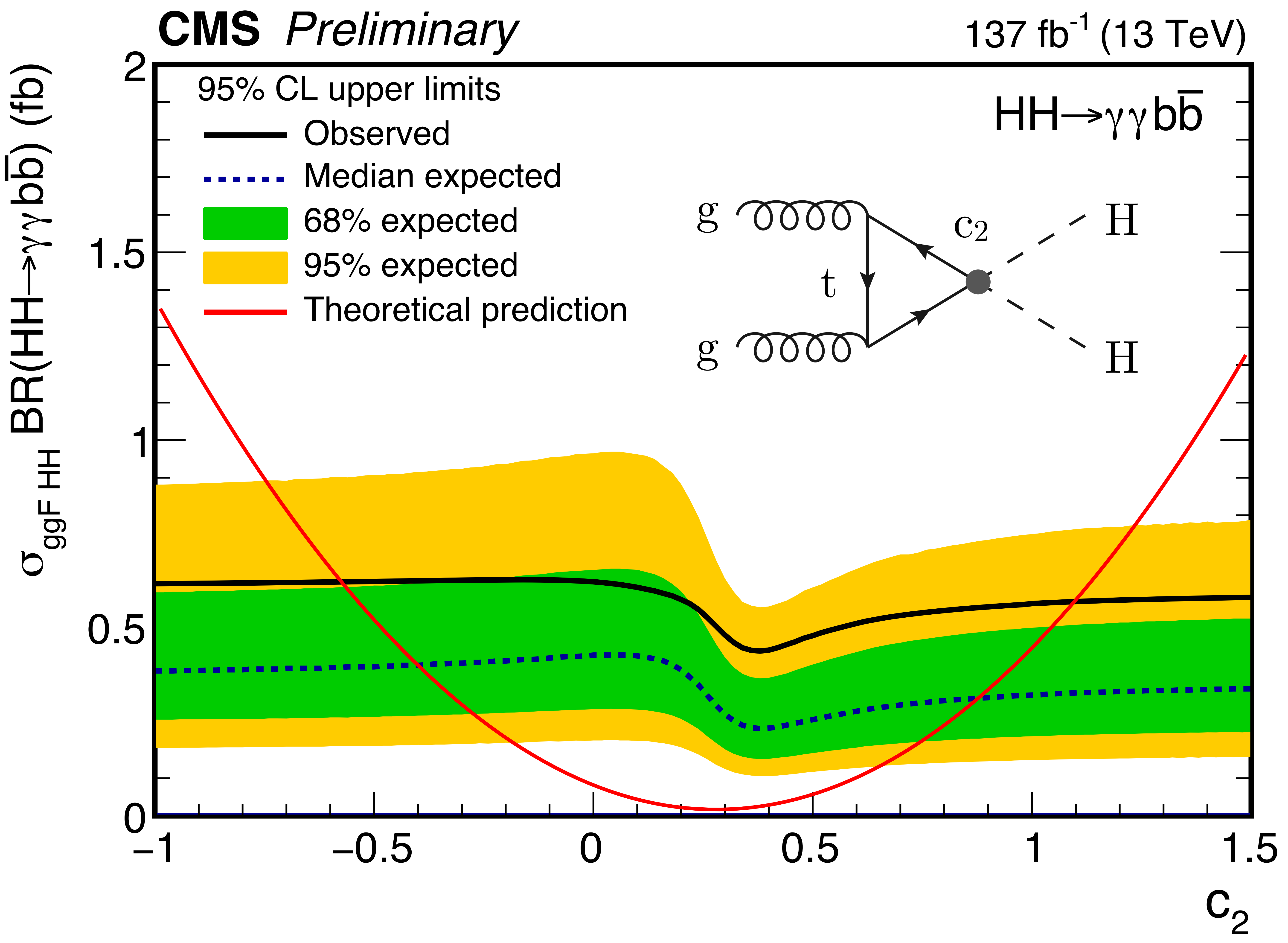
Good performance of bkg estimation method validated with data

Shape benchmark results - 2016 combination



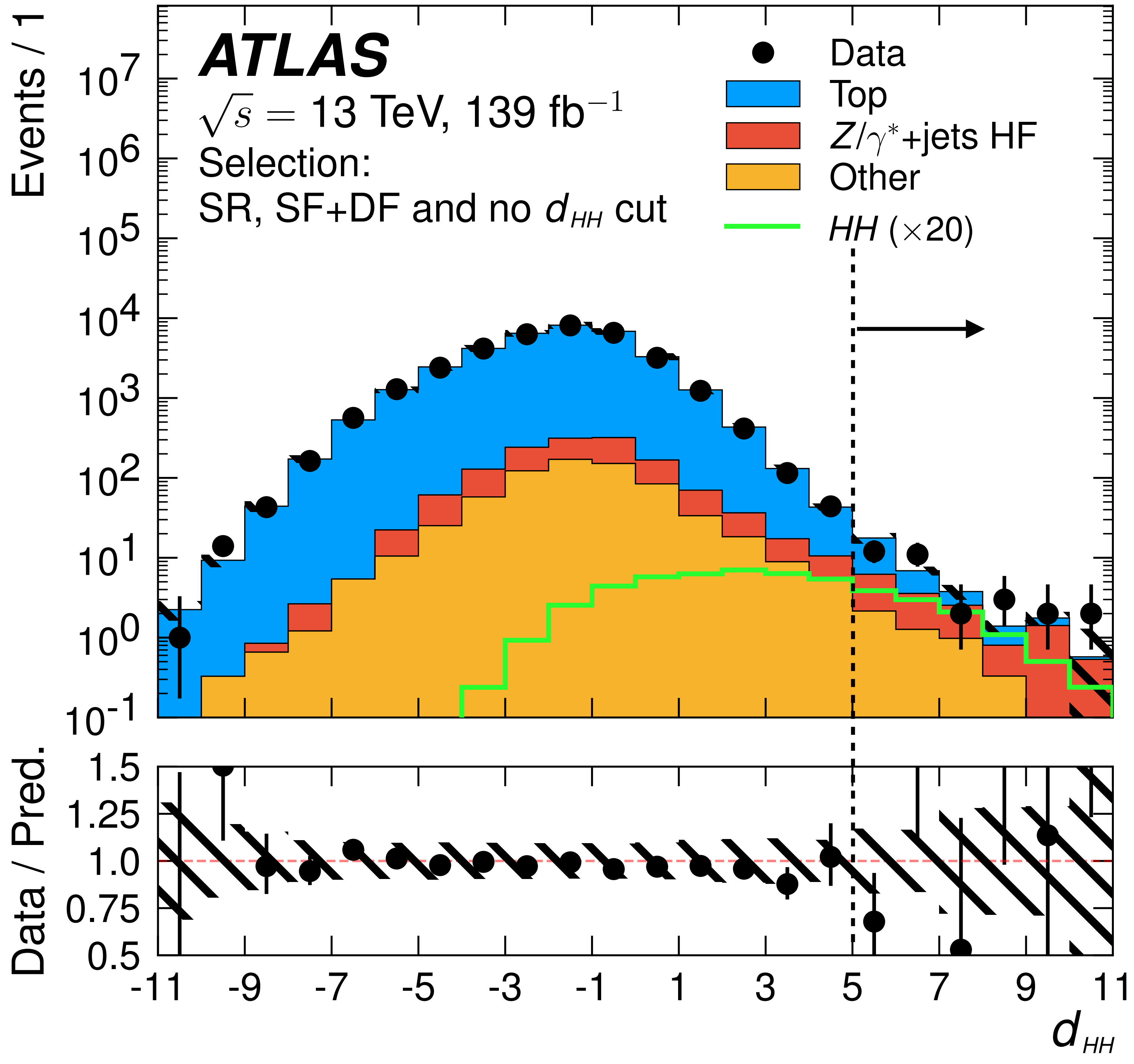
Single coupling scans

- Upper limit plot as function of c_2 from the bb$\gamma\gamma$ analysis
- Assumes that only c_2 is varied and other couplings are fixed to the SM value
- Under this assumption, observe $-0.6 < c_2 < 1.1$ (exp. $-0.4 < c_2 < 0.9$)
  - correlation with other couplings are expected to reduce the sensitivity

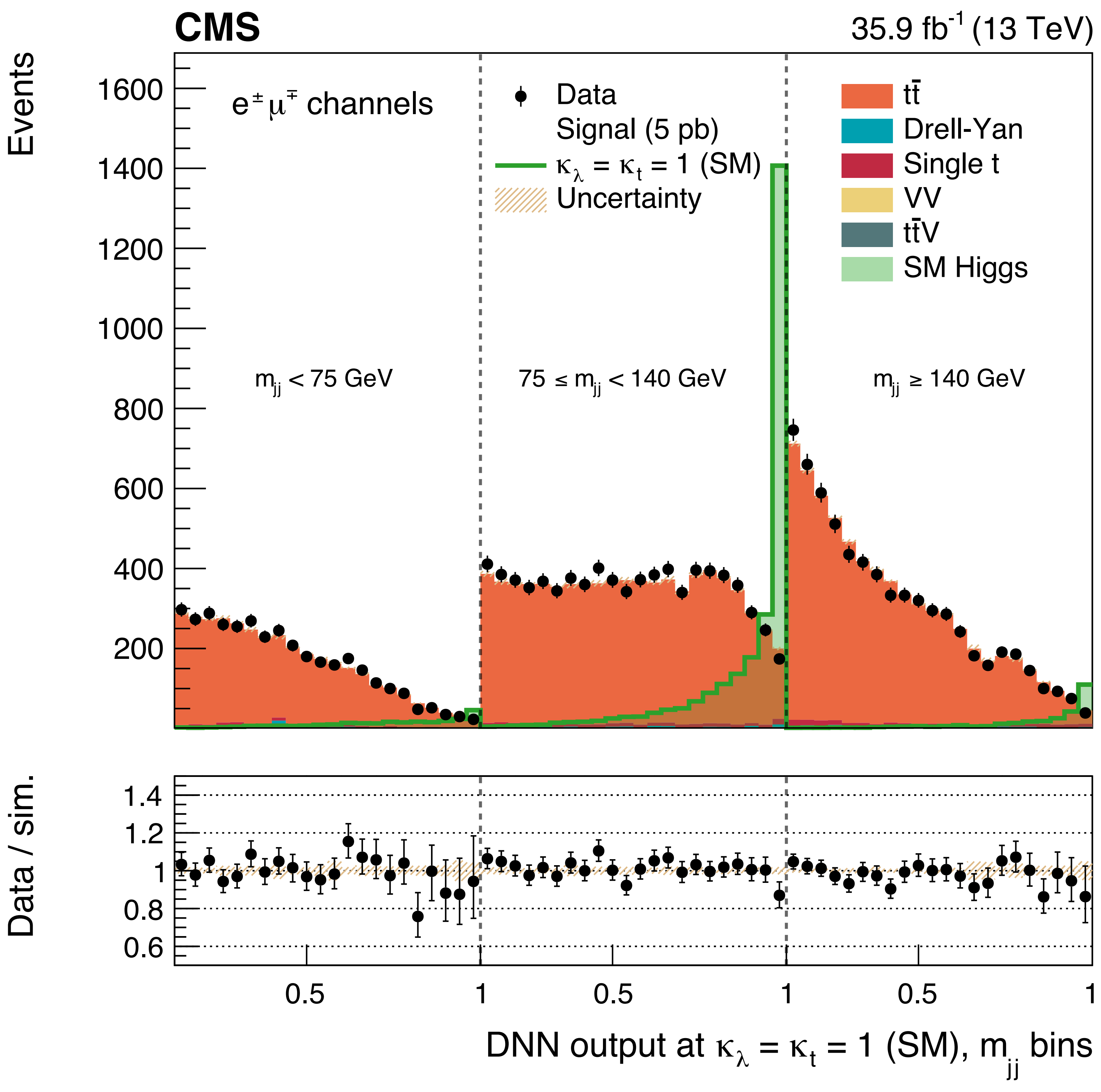


HH → bbWW

Irreducible tt background | **Advanced ML methods for signal identification**



Obs. (Exp.) : 40 (29) × σ_{HH}^{SM}

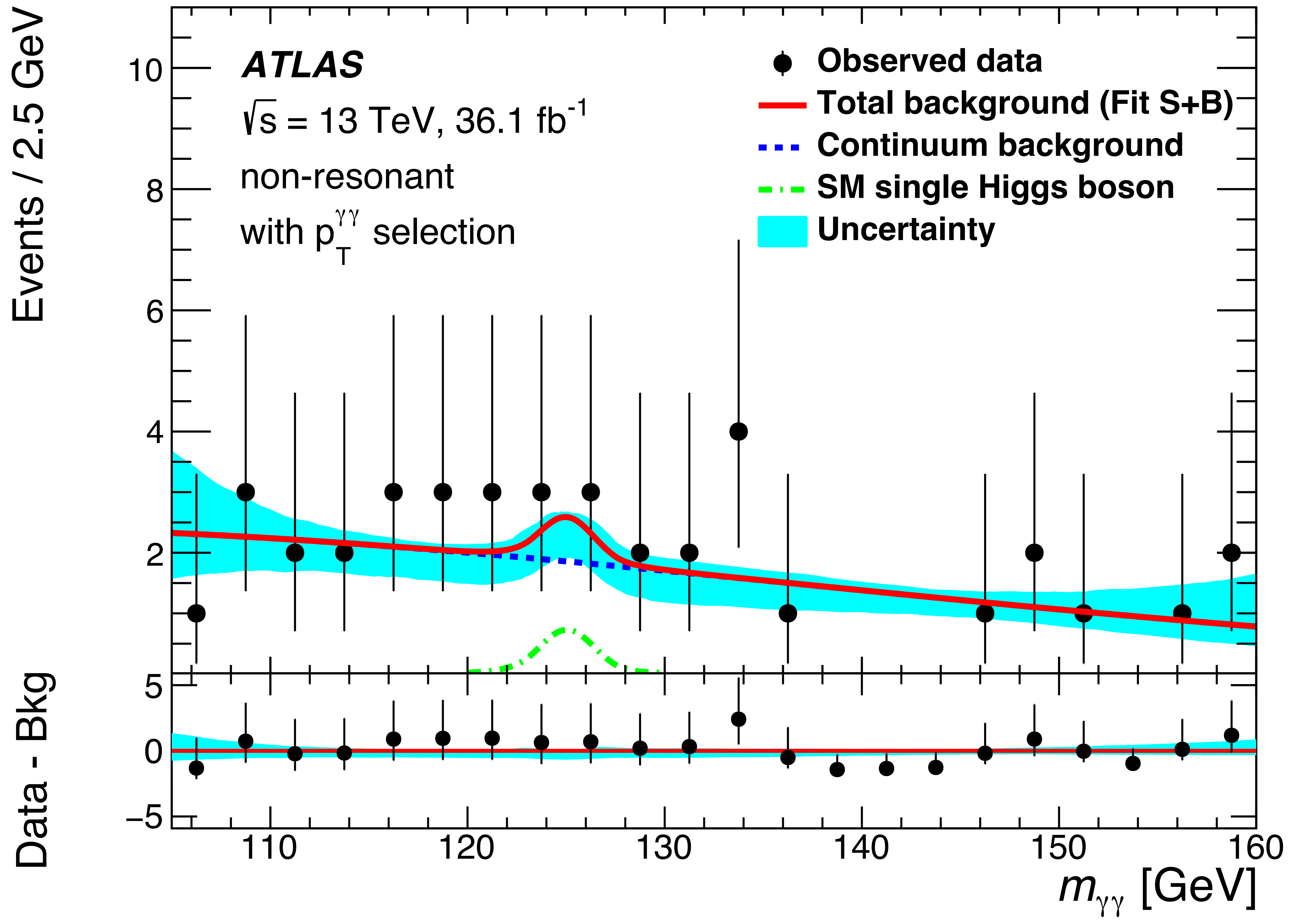


Obs. (Exp.) : 78.6 (88.8) × σ_{HH}^{SM}

- Target WW→$\ell\nu\ell\nu$ decays
- tt irreducible background suppressed with DNN method
  - use kinematic information of the objects in the event: mass. p_T, angles
  - CMS uses a parametrised DNN for maximal sensitivity over κ_λ
- The ML discriminant used to look for a signal
  - ATLAS: counting exp. at high score
  - CMS: fit to the DNN distribution

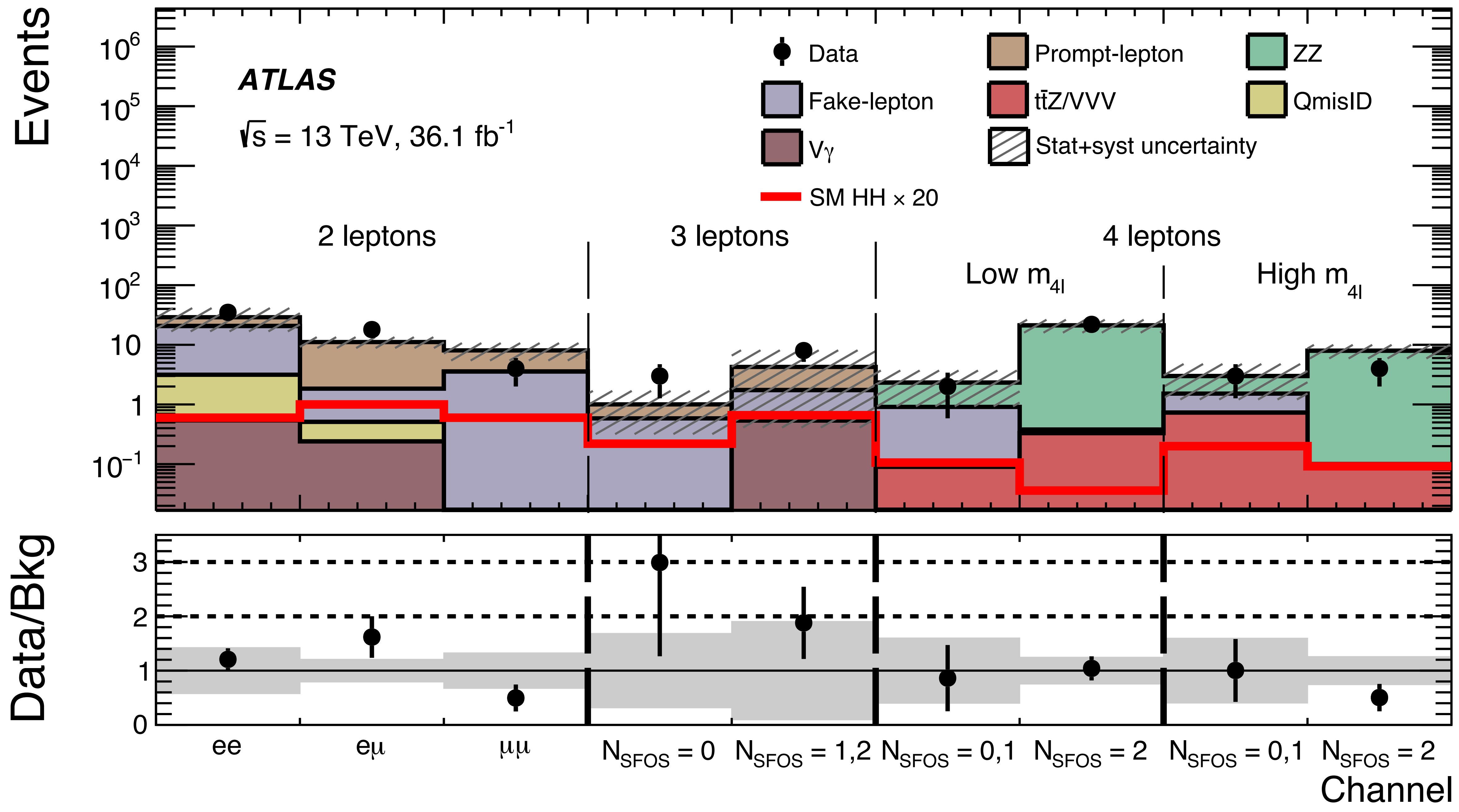
Rare HH channels

WW$\gamma\gamma$ — Obs (Exp) : 230 (160) × σ_{HH}^{SM}



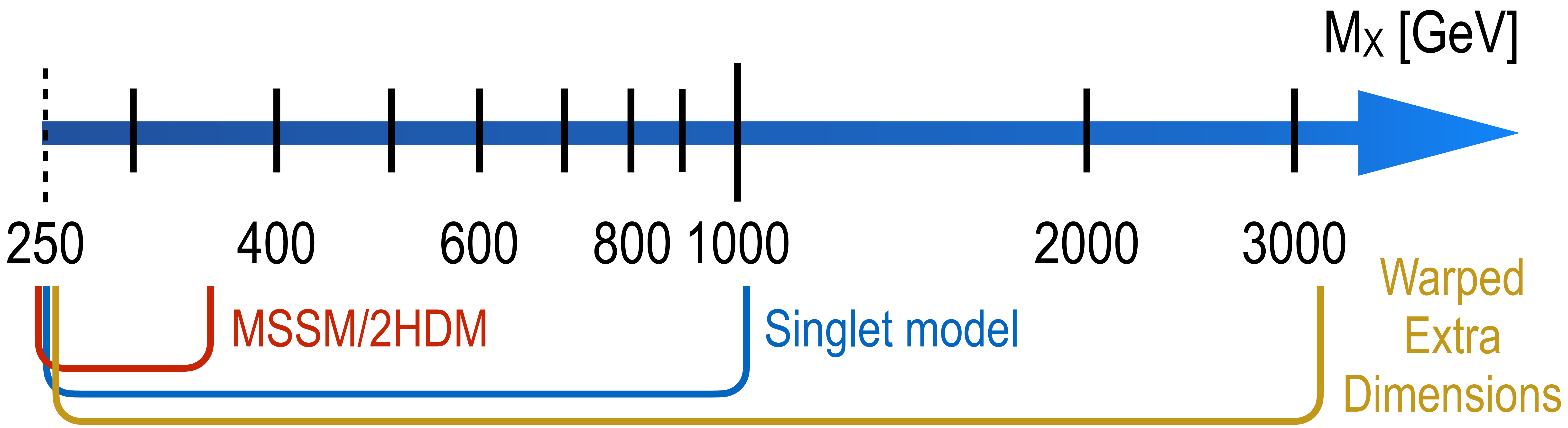
- Targets $WW \rightarrow \ell \nu qq$ decays
- Look for a signal using the $m_{\gamma\gamma}$ spectrum

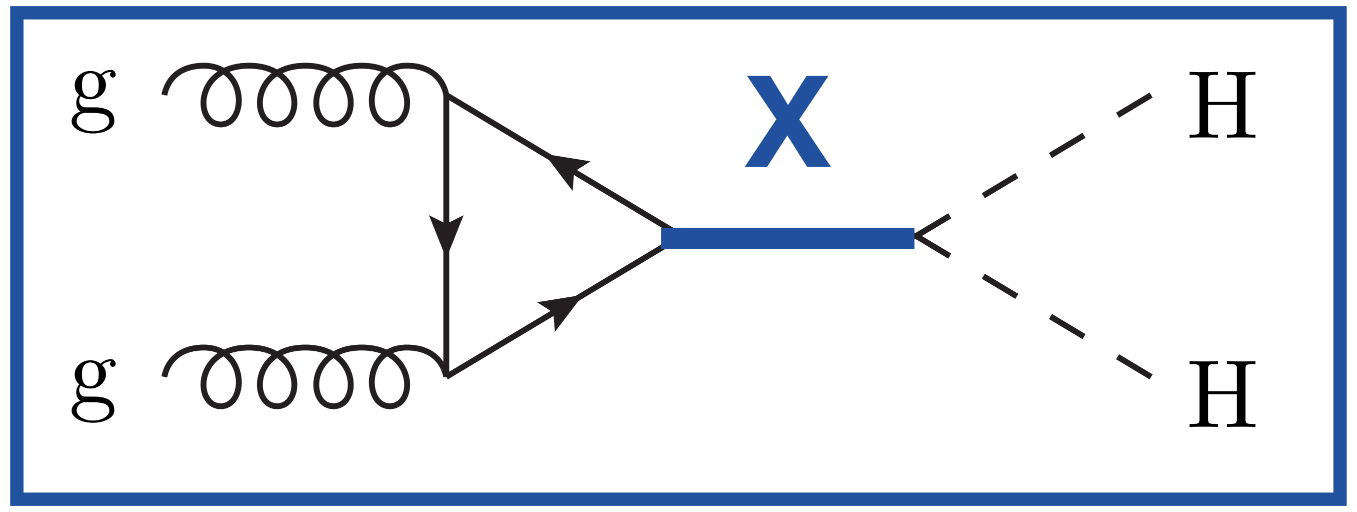
WWWW — Obs (Exp) : 160 (120) × σ_{HH}^{SM}



- 2ℓ, 3ℓ, 4ℓ final states, veto on b jets
- Prompt and fake lepton backgrounds from control regions
- Counting experiment in each region

Resonant HH production

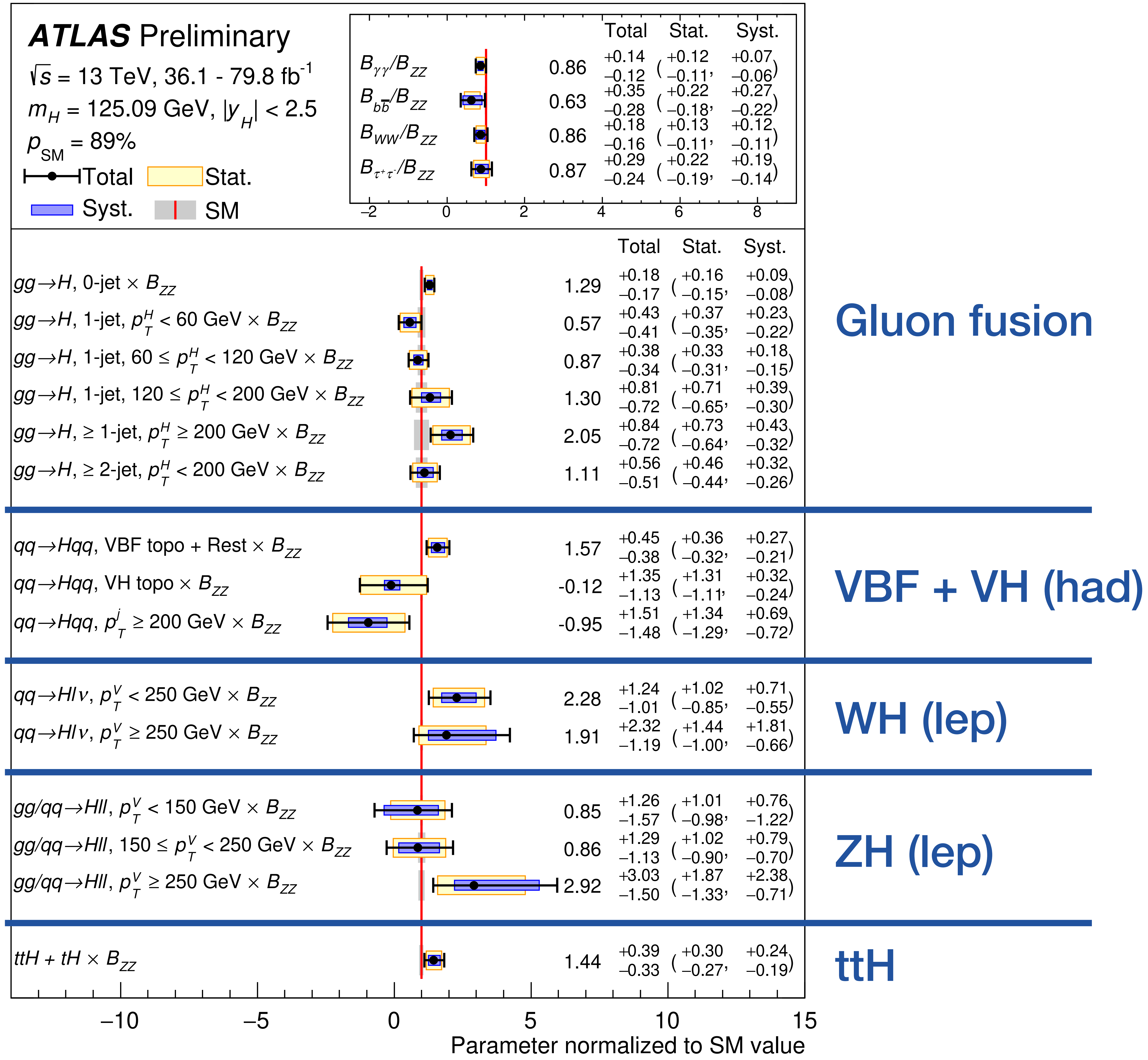




- Resonant HH production predicted in a variety of models
  - from extended scalar sectors to exotic new physics
- A broad mass range must be covered to ensure maximal sensitivity to new physics
  - complementarity of the different decay channels

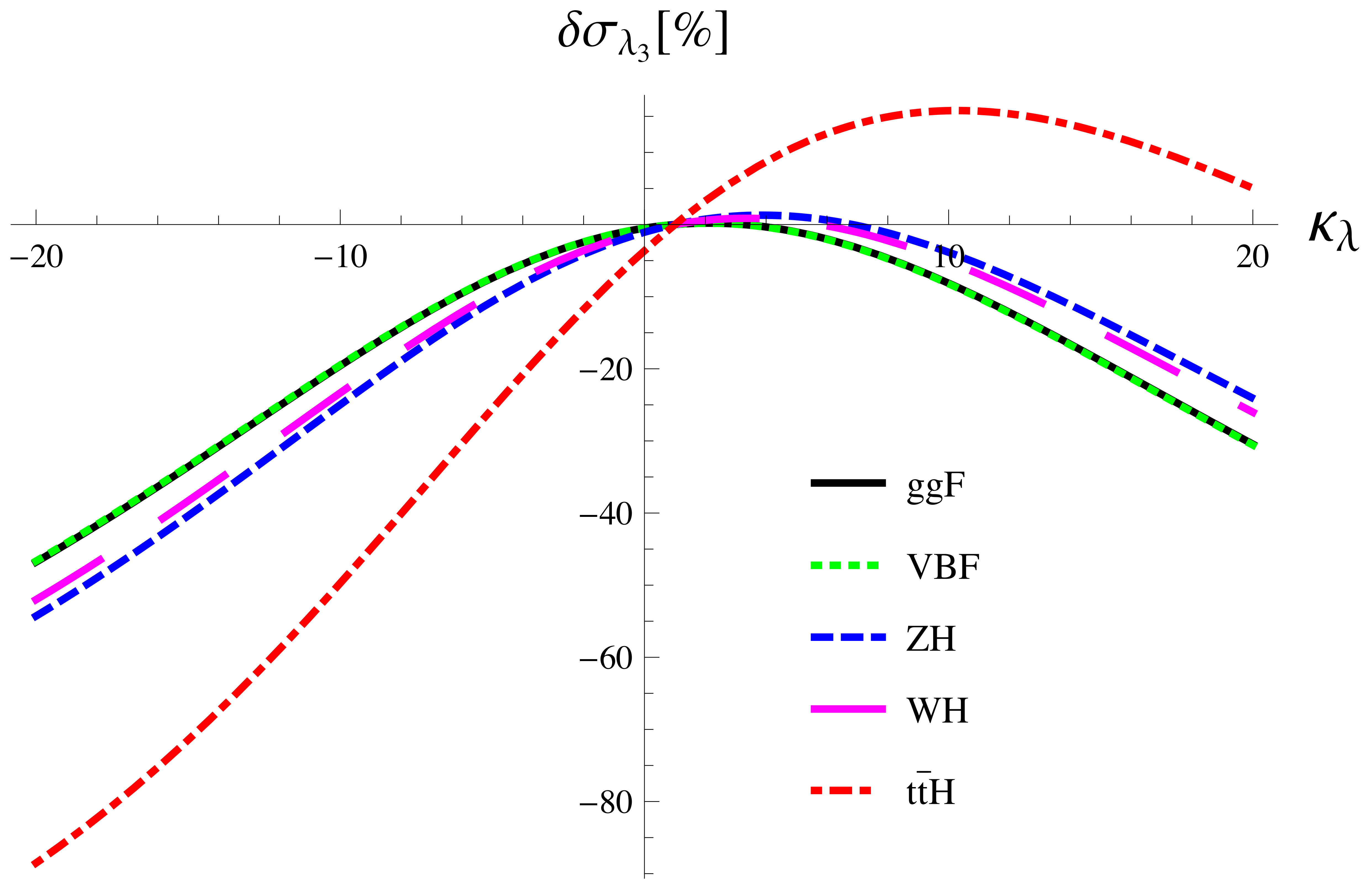
HH is an ideal place to look for BSM physics
Sensitive with current LHC data

Single H : input

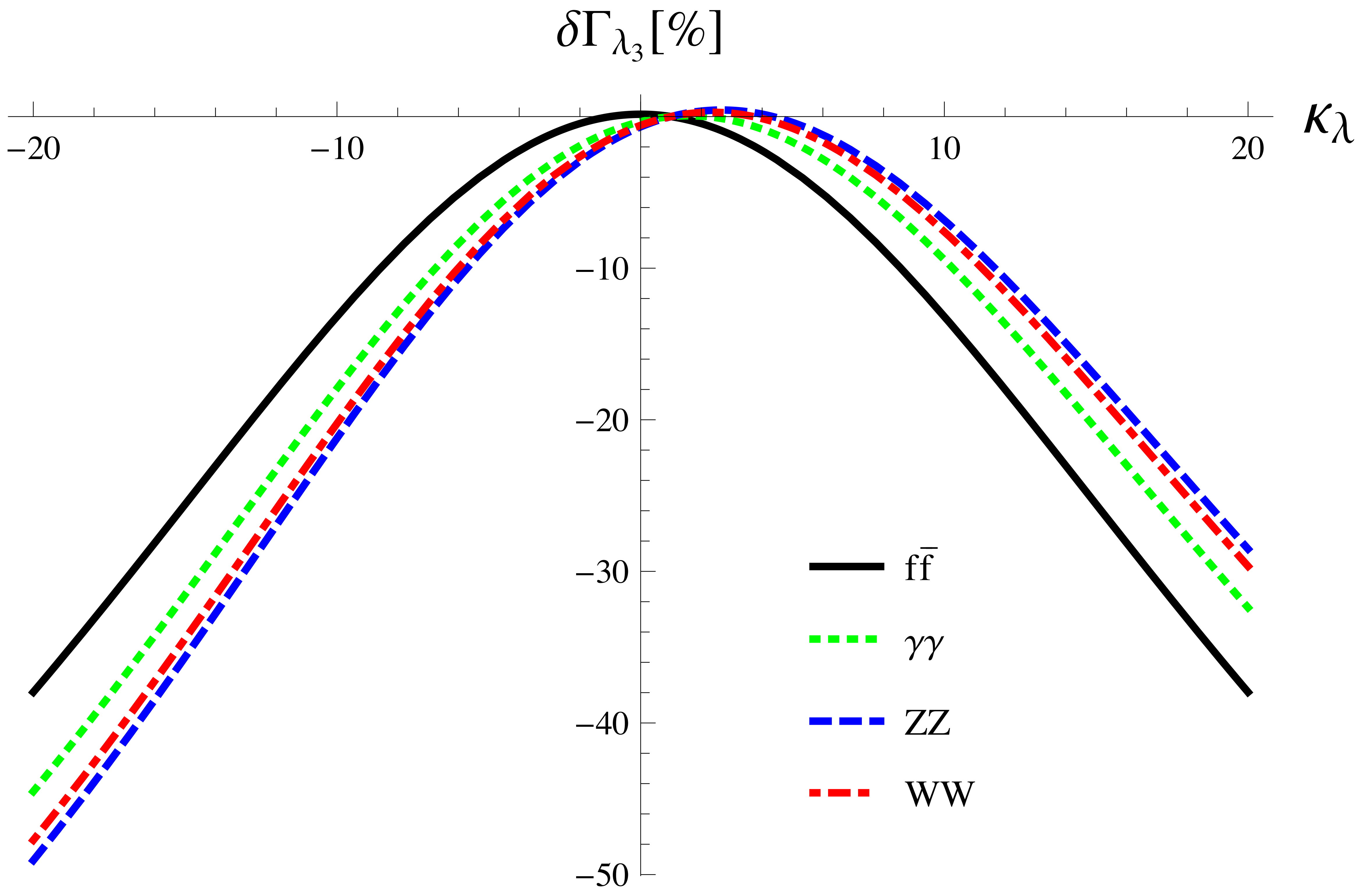


- Combination of single H measurements in various production modes and decay channels
- Fiducial Higgs boson production modes and kinematics phase space regions: "*simplified template cross section"*
- The impact of λ_{HHH} corrections is evaluated for each process and bin
  - parametrise single H yields vs κ_λ, assume no relevant inter-bin changes w.r.t. SM
  - no differential effects available for ggF (expected small), single ttH bin $\Longrightarrow$ limited access to differential information

Single Higgs effects from λ_{HHH}

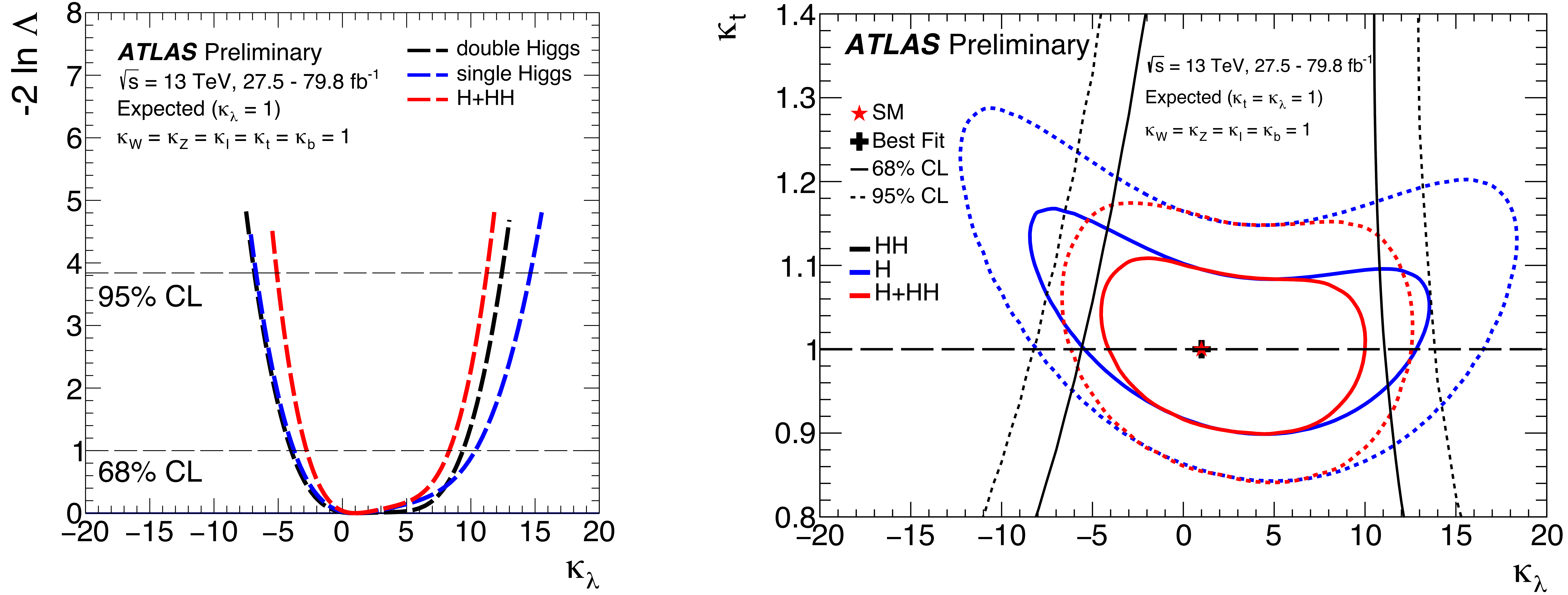


Cross section



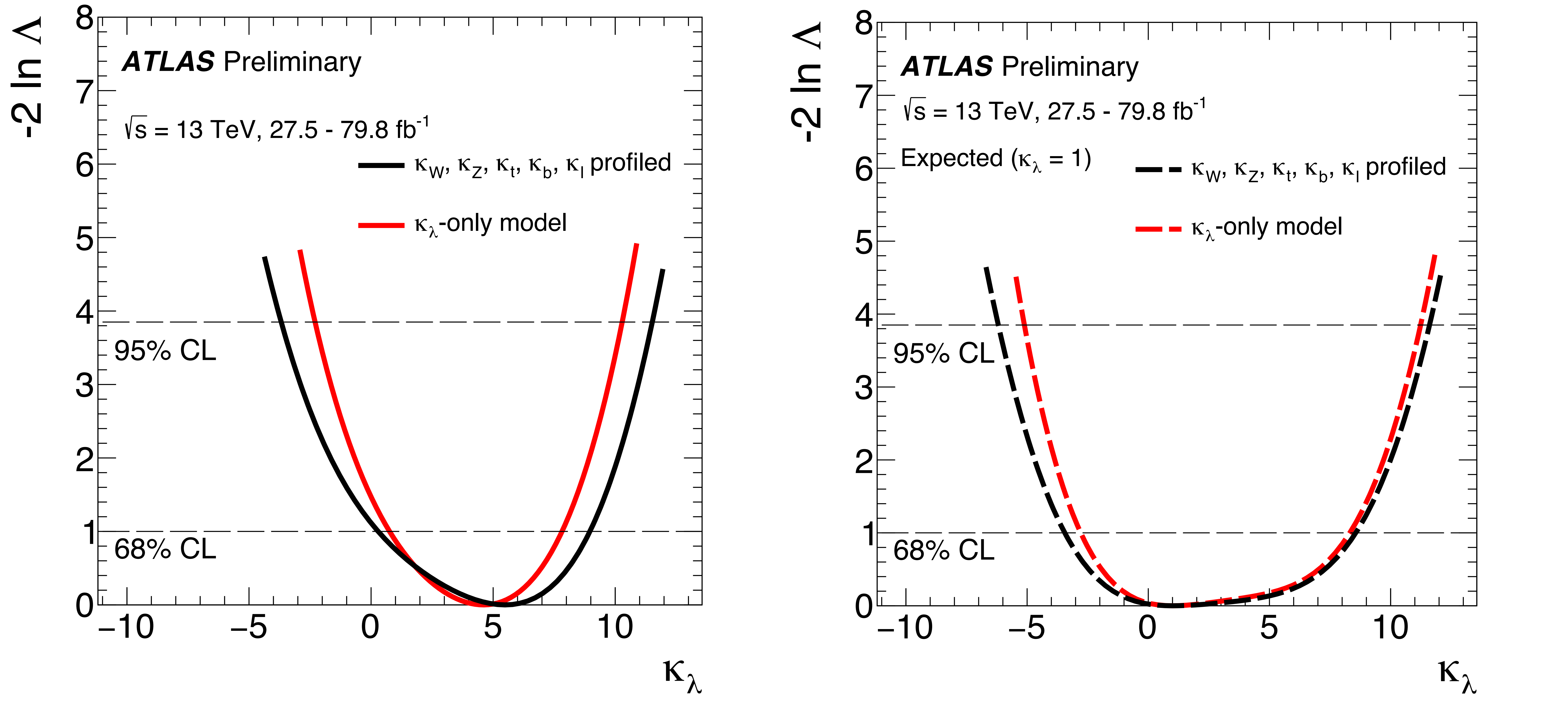
Branching fraction

H + HH : expected results



$k_\lambda = 1.0^{+7.3}_{-3.8}$

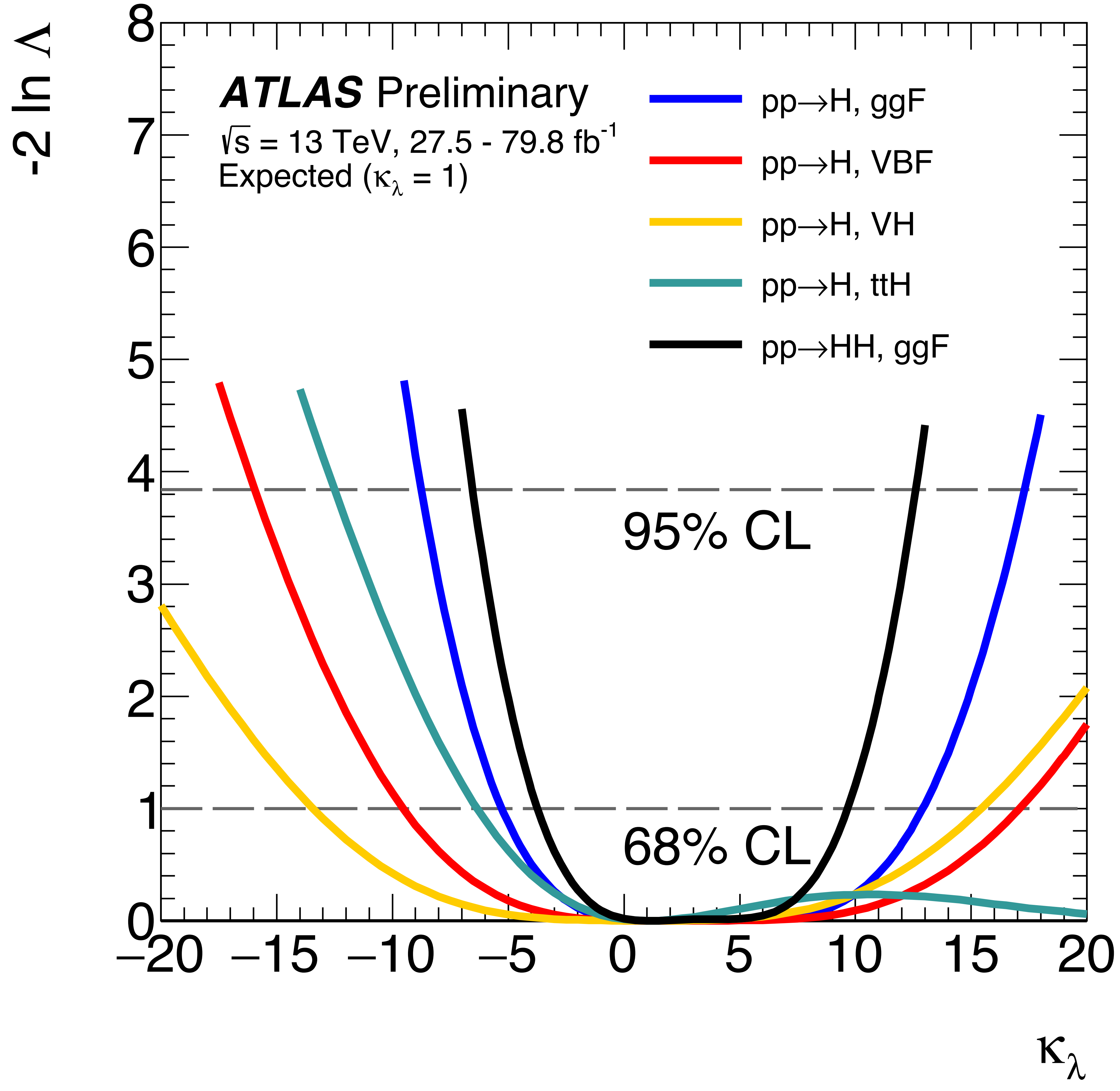
H + HH : fixed vs floating κ

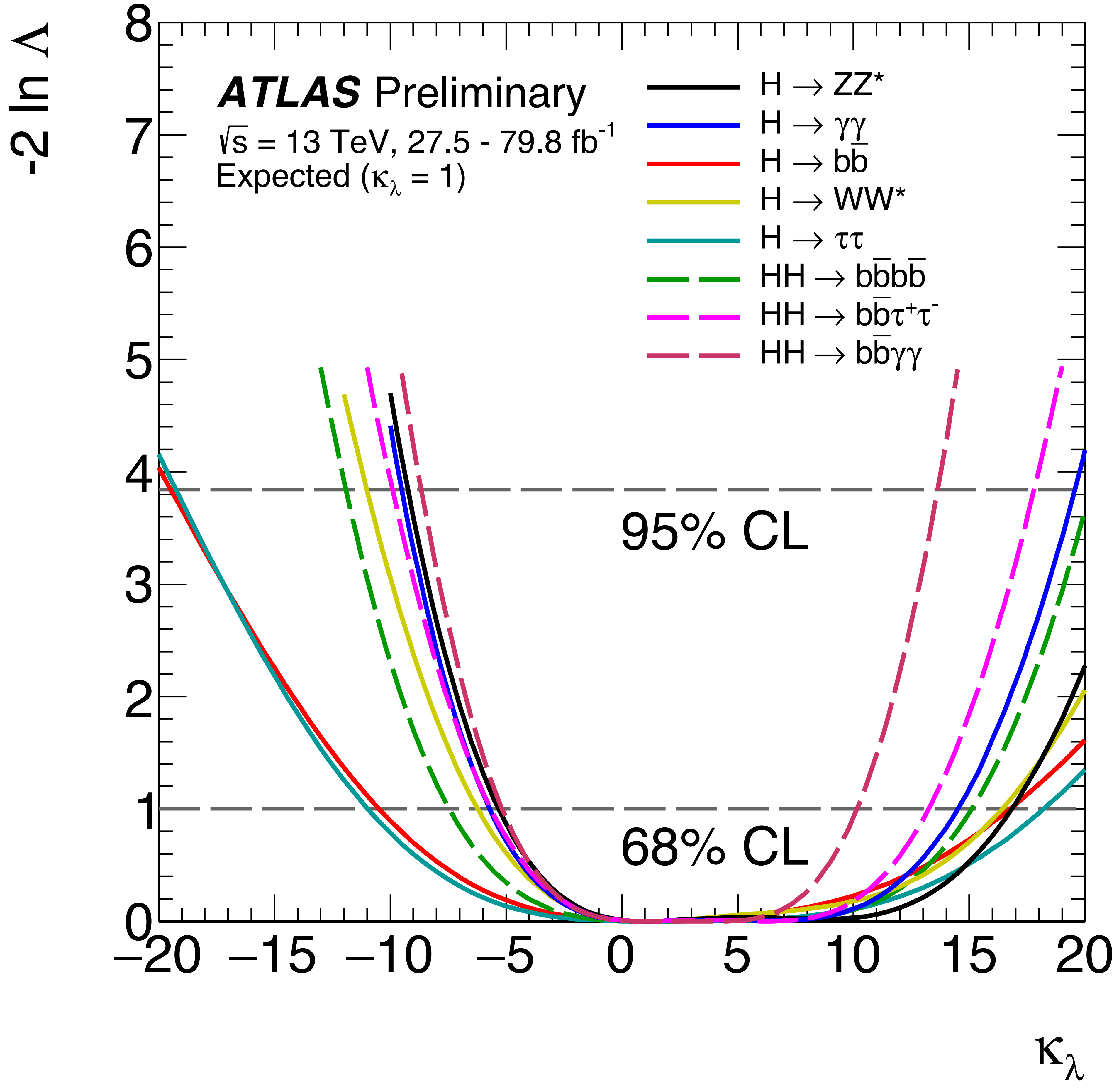


Model	$\kappa_W{}^{+1\sigma}_{-1\sigma}$	$\kappa_Z{}^{+1\sigma}_{-1\sigma}$	$\kappa_t{}^{+1\sigma}_{-1\sigma}$	$\kappa_b{}^{+1\sigma}_{-1\sigma}$	$\kappa_\ell{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
Generic	$1.03^{+0.08}_{-0.08}$	$1.10^{+0.09}_{-0.09}$	$1.00^{+0.12}_{-0.11}$	$1.03^{+0.20}_{-0.18}$	$1.06^{+0.16}_{-0.16}$	$5.5^{+3.5}_{-5.2}$	$[-3.7, 11.5]$	obs.
	$1.00^{+0.08}_{-0.08}$	$1.00^{+0.08}_{-0.08}$	$1.00^{+0.12}_{-0.12}$	$1.00^{+0.21}_{-0.19}$	$1.00^{+0.16}_{-0.15}$	$1.0^{+7.6}_{-4.5}$	$[-6.2, 11.6]$	exp.

- The combination of H and HH allows to retain sensitivity to κ_λ even when introducing additional degrees of freedom: HH needed to solve the degeneracy with other couplings
- The best-fit values for all the couplings are compatible with the SM prediction

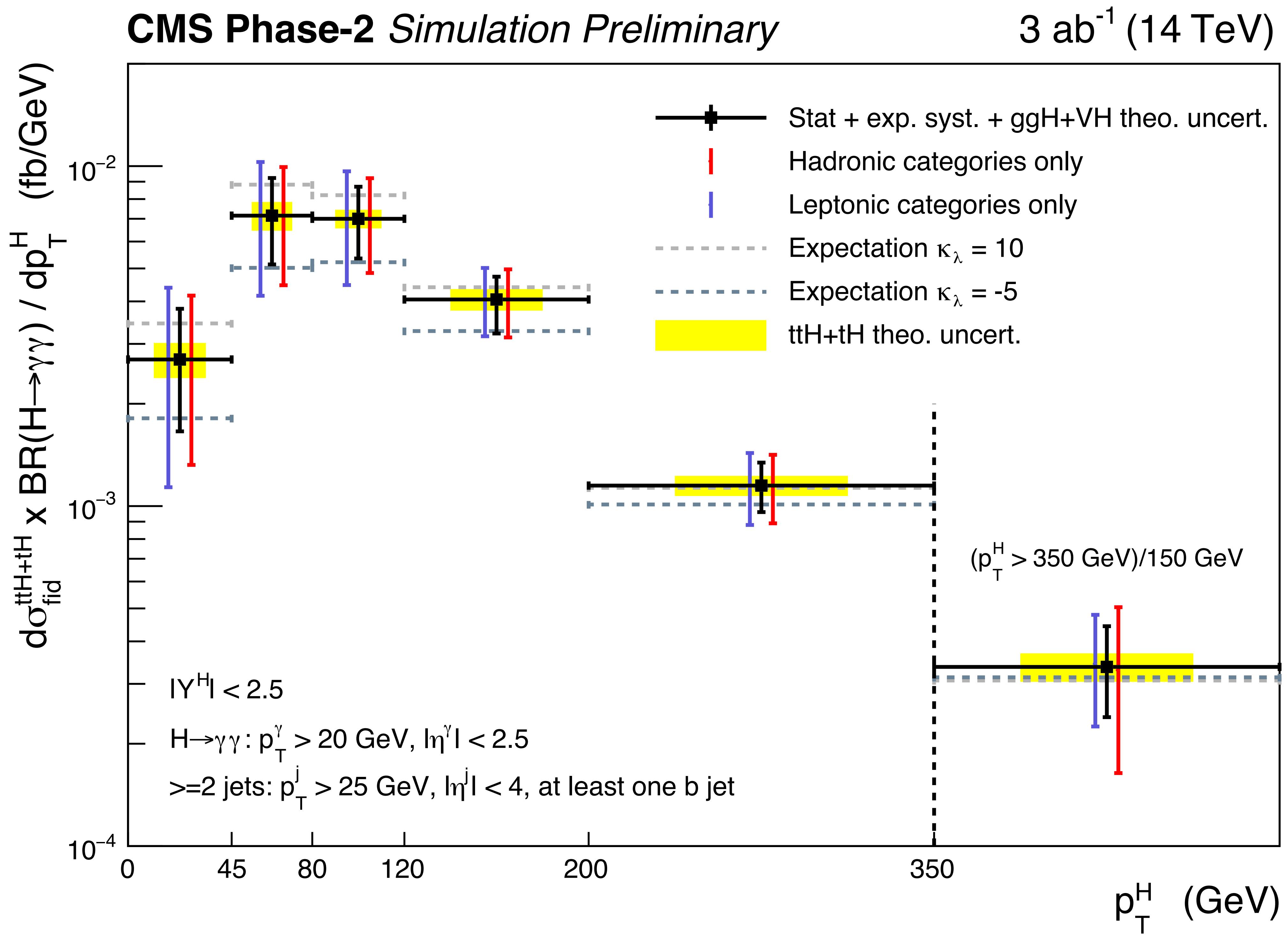
H + HH : input comparison

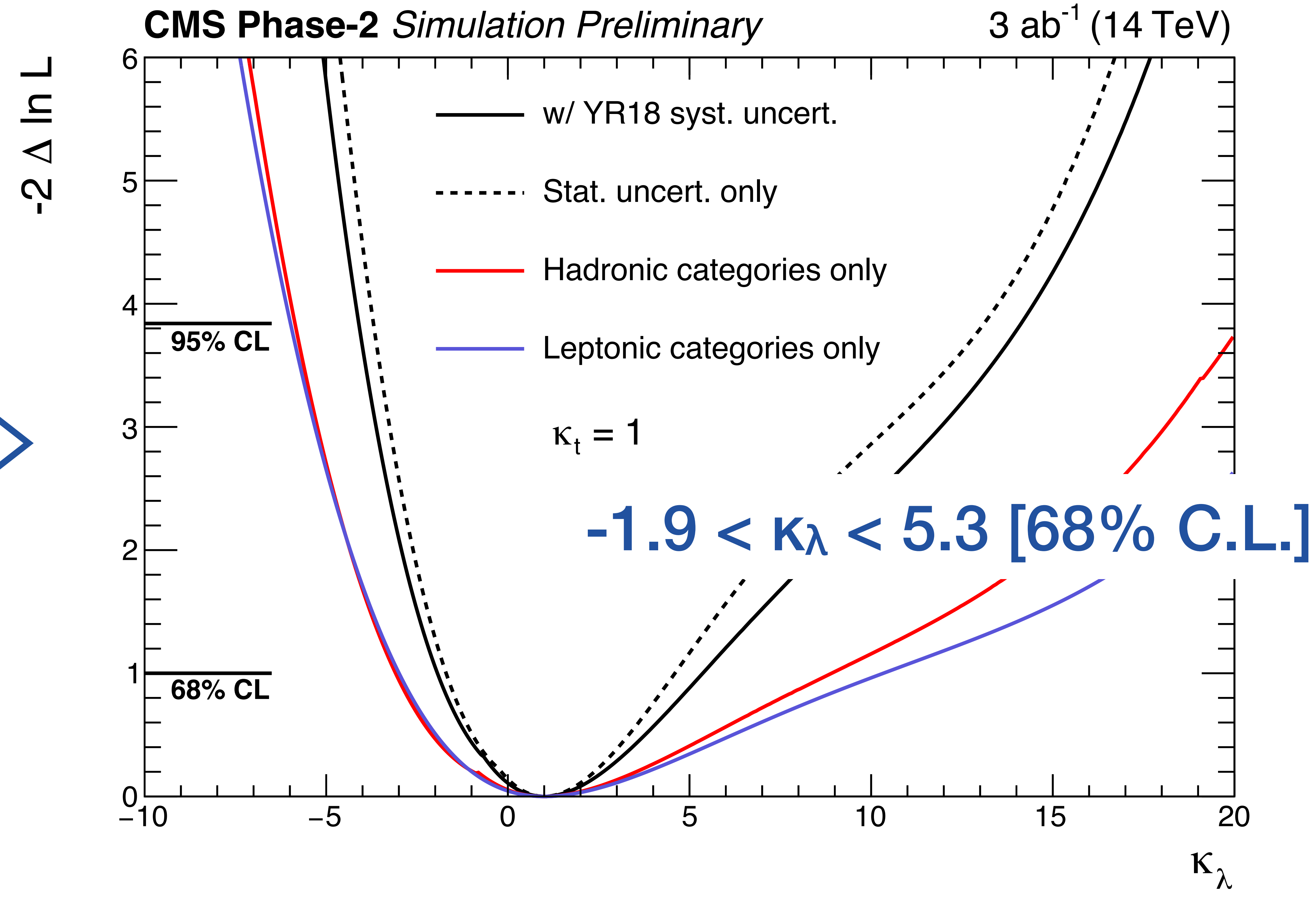




- HH drives the sensitivity
- ggF is the most sensitive single H production mode
  - sensitivity from total cross-section
- ttH not sensitive for $\kappa_\lambda > 0$ because of the degeneracy (second minimum) in the cross-section

Using the differential information in single H

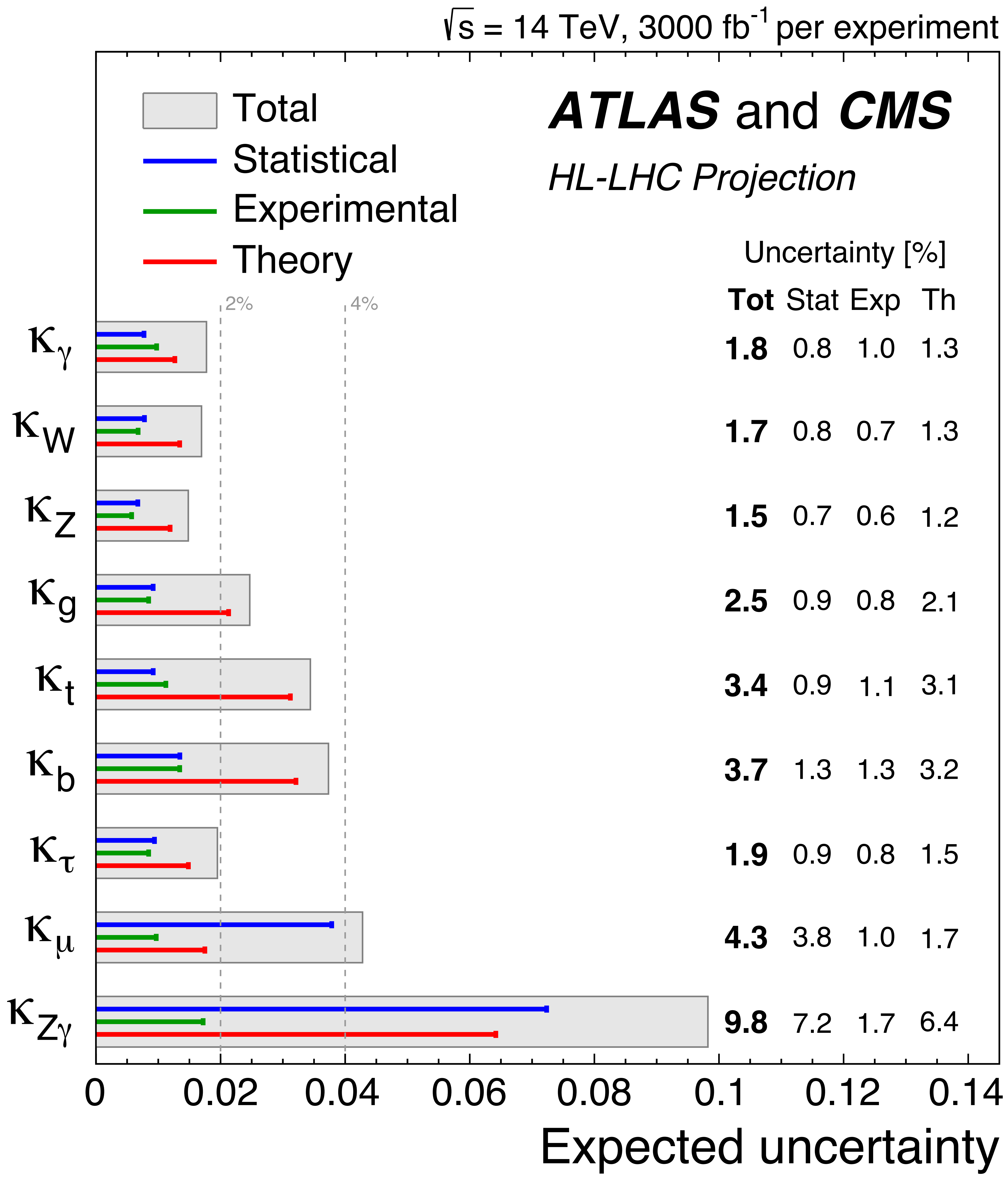




- ttH: from the observation to fully differential information at the HL-LHC
- The differential spectrum encodes information on κ_λ
  → retains sensitivity also if μ_{ttH} is left floating
- Goal: extract the best sensitivity from a H + HH combination

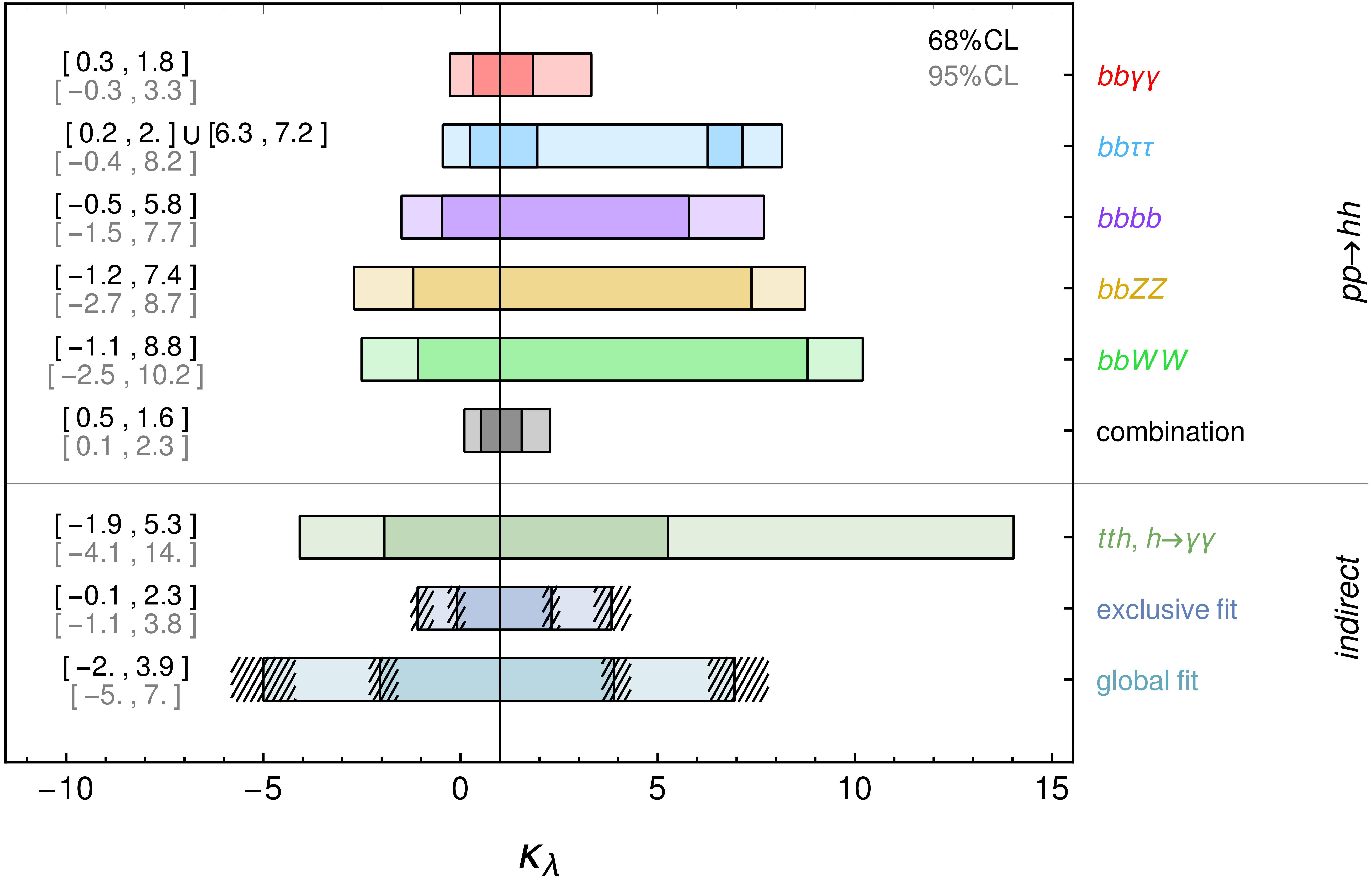
Single H future prospects at the HL-LHC

- Extrapolation of the current measurements to 3 ab^{-1}
  - under assumptions on the evolution of the systematic uncertainties and detector performance
- Most couplings known at a precision of 2-4% !
  - with theory uncertainties as the dominant ones
  - stat. uncertainties remaining relevant for very rare processes

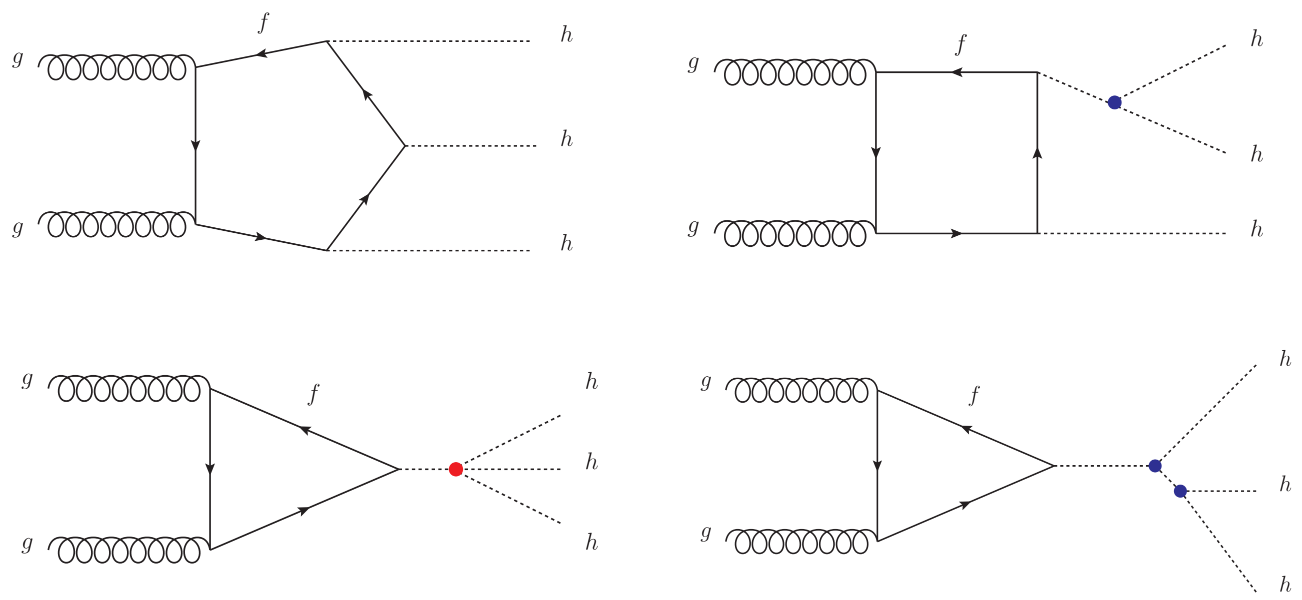


The HL-LHC view of λ_{HHH}

- HH driving the sensitivity on κ_λ at the HL-LHC
- Large differences from single Higgs measurements assuming κ_λ-only variations or globally fitting all coupling modifications



How about HHH?



Depends also on trilinear coupling

μ_0	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 13$ TeV	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 100$ TeV
$M_{hhh}/2$	$12.03^{+17.8\%}_{-16.3\%} \pm 5.2\%$	$17.99^{+16.5\%}_{-15.4\%} \pm 4.8\%$	$73.43^{+14.7\%}_{-13.7\%} \pm 3.3\%$	$86.84^{+14.0\%}_{-13.2\%} \pm 3.2\%$	$4732^{+11.9\%}_{-11.6\%} \pm 1.8\%$
M_{hhh}	$9.91^{+19.3\%}_{-16.6\%} \pm 5.3\%$	$15.14^{+18.4\%}_{-16.0\%} \pm 4.7\%$	$63.32^{+16.1\%}_{-14.1\%} \pm 3.4\%$	$76.15^{+15.9\%}_{-14.0\%} \pm 3.2\%$	$4306^{+14.0\%}_{-12.3\%} \pm 1.8\%$

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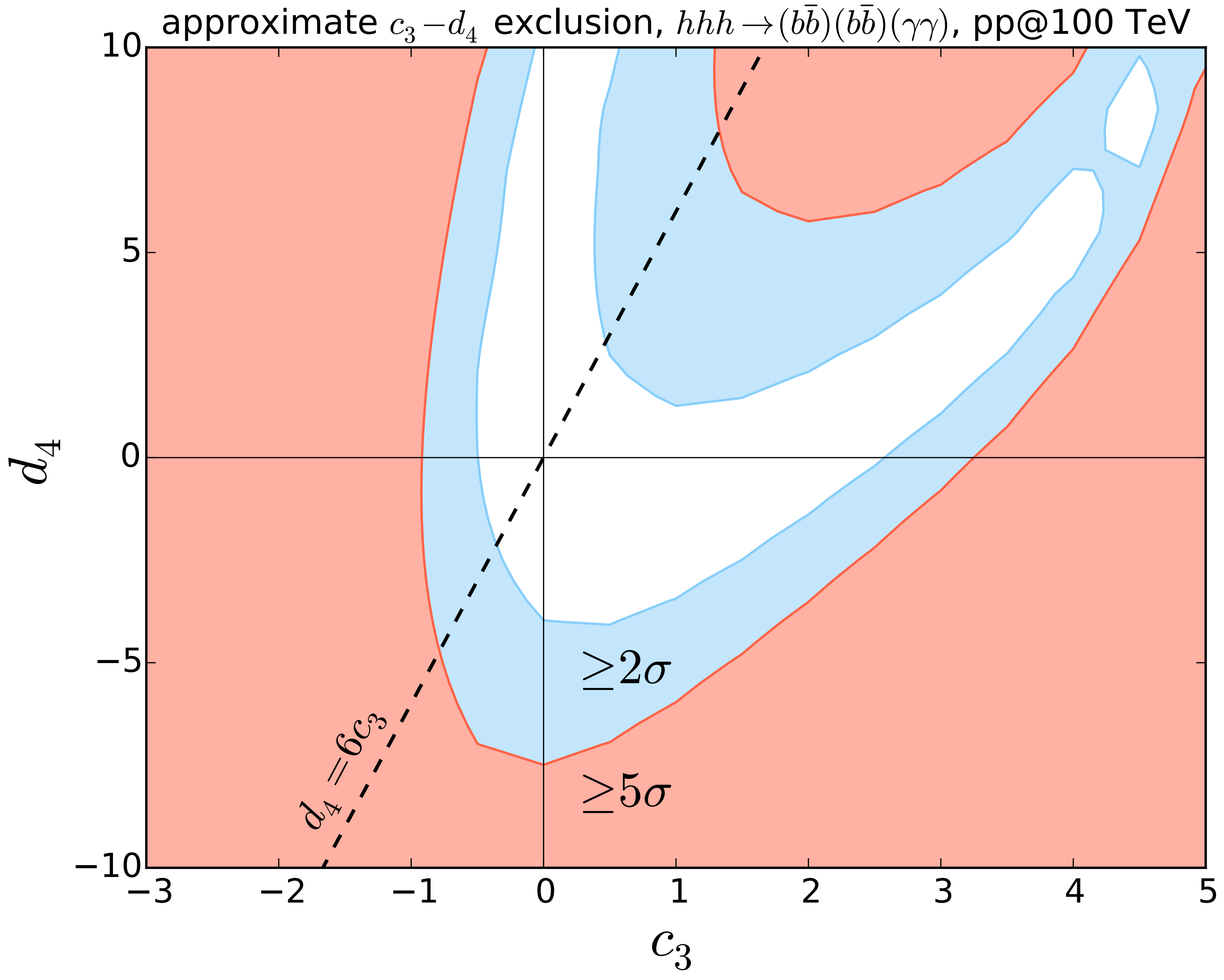
- Both high energy and high luminosity needed
  - $\sqrt{s}$ = 100 TeV, 30 ab^{-1} (FCC)
- Many possible final states!
  - Most interesting ones: bb bb bb (19.2%), bb bb $\tau\tau$ (6.3%), bb bb $WW_{2\ell}$ (0.98%), bb $\tau\tau$ $\tau\tau$ (0.69%), bb bb $\gamma\gamma$ (0.23%), bb $\tau\tau$ $WW_{2\ell}$ (0.21%)
- Performance crucially depends on detector performance! (many final state objects)
  - need also forward coverage up to $|\eta| \approx 3.5$
- Sensitivity: at FCC, O(100%) precision on σ_{HHH}, $\lambda_{HHHH} \in [-4, +16]$



(a)