Higgs boson pair production

Status and prospects

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Outline

- **The SM and the self-coupling**
- **Searching for HH at the LHC**
- **HH as a probe for new physics**
- **Future prospects**

Outline

The SM and the self-coupling

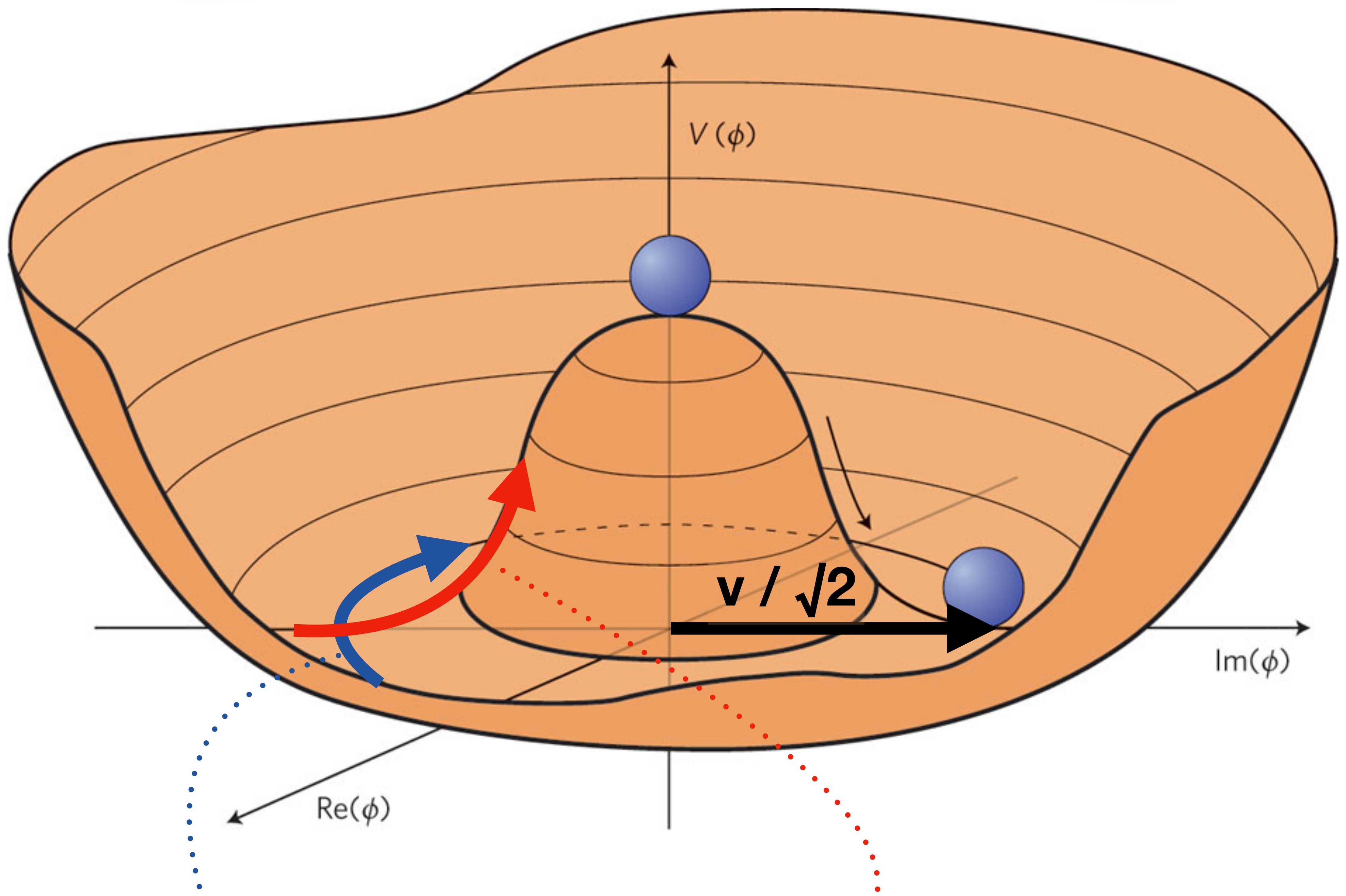
The BEH mechanism and the scalar potential

The self-coupling and its relevance

HH production at the LHC

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**

$$m_H^2 = 2\lambda v^2 = 2\mu^2$$

The SM structure:

- **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

EWSB and the self-coupling

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

EWSB

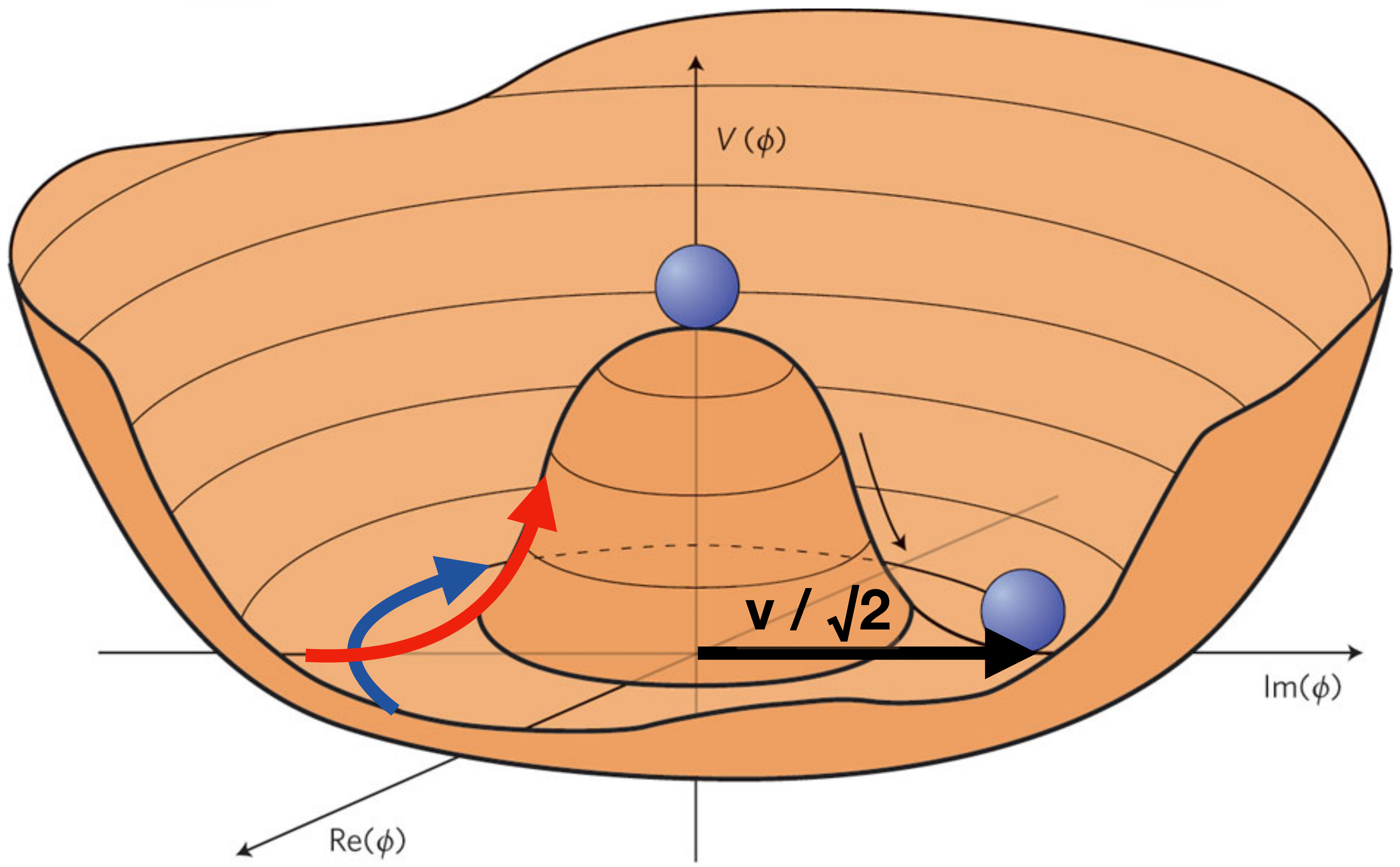
$$V(H) = \frac{1}{2}m_\mathrm{H}^2 H^2 + \lambda_\mathrm{HHH} v H^3 + \frac{1}{4}\lambda_\mathrm{HHHH} H^4 - \frac{\lambda}{4}v^4$$

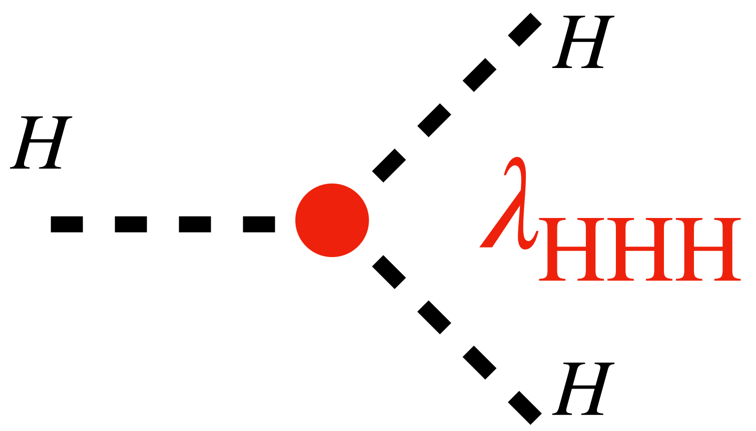
Higgs boson mass

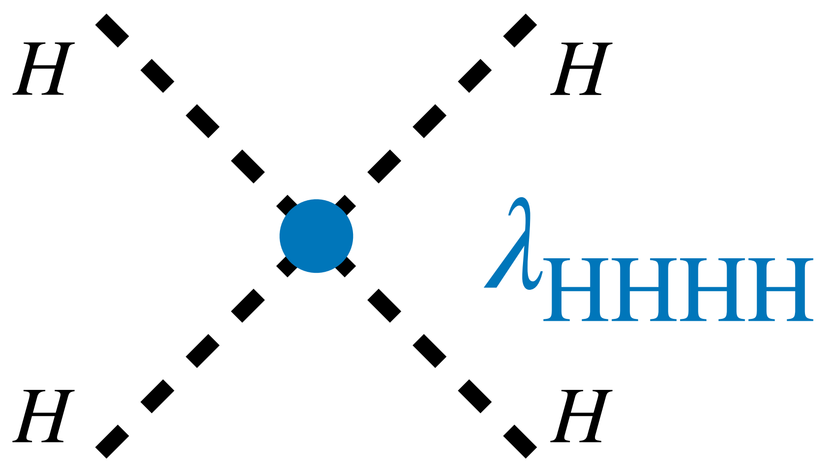
Cubic self-coupling

Quartic self-coupling

Vacuum energy density







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

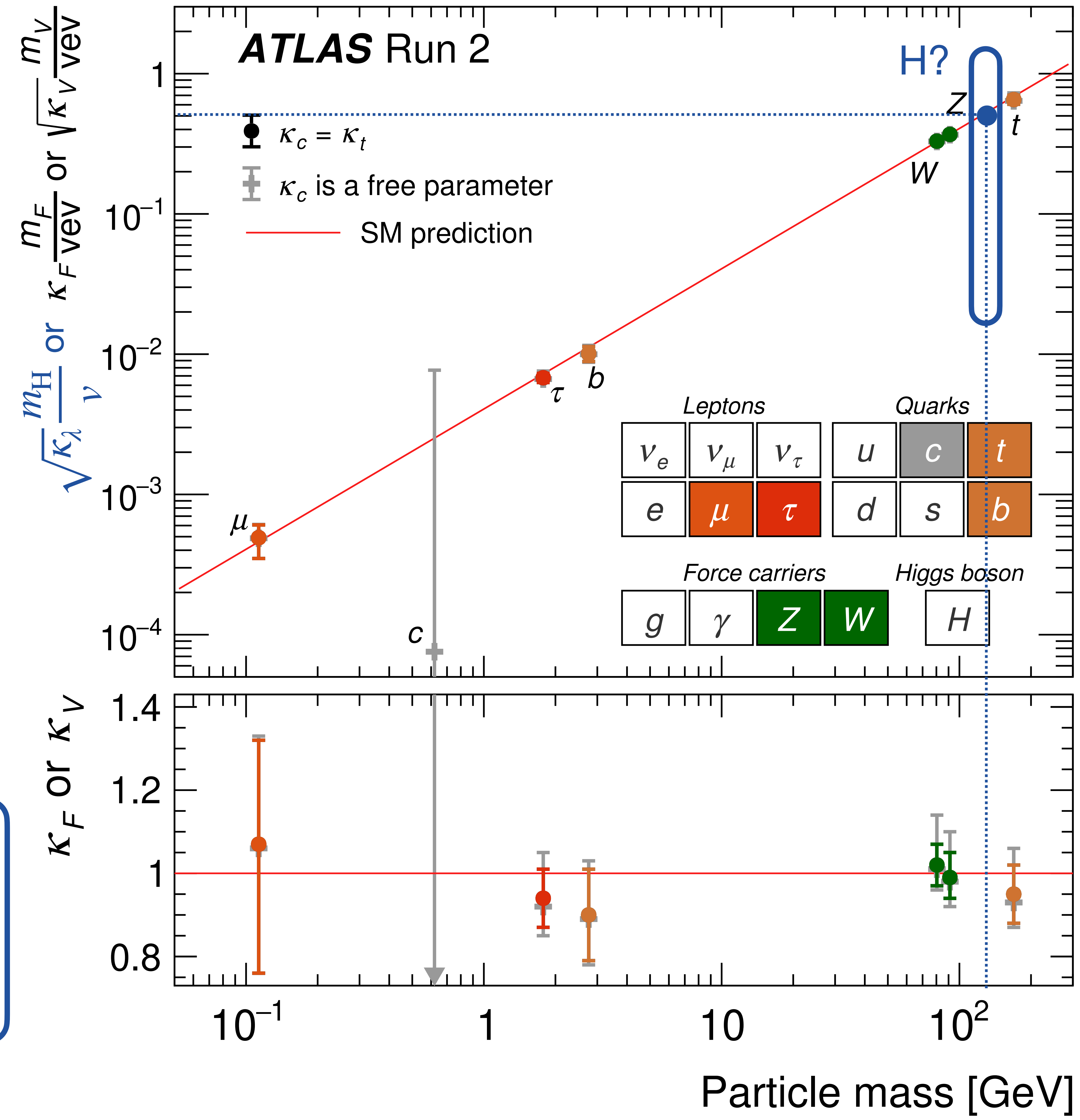
The self-coupling is directly connected to the shape of the scalar potential

The Higgs boson and the self-coupling

- The Higgs boson mass is measured at the per-mille precision level
  $m_H = 125.38 \pm 0.14\,\text{GeV}$, CMS PLB 805 (2020) 135425
  $m_H = 125.22 \pm 0.14\,\text{GeV}$, ATLAS PLB 847 (2023) 138315
- Most Higgs boson couplings are precisely known and compatible with the SM prediction
- The Higgs boson self-coupling is experimentally unknown!

Major experimental effort is ongoing to characterize the Higgs boson, with λ determination as the next key goal

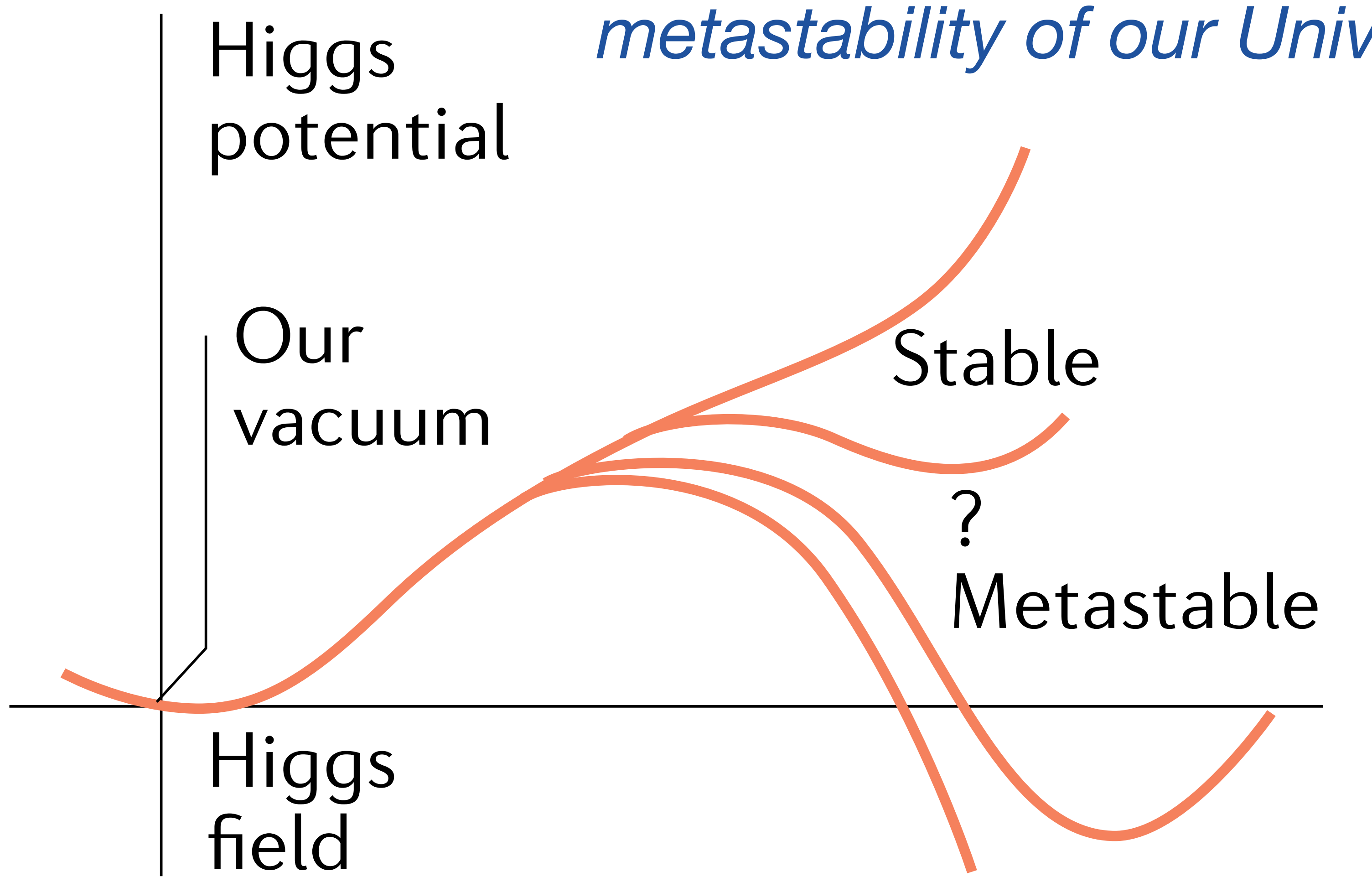
Nature 607, p. 52-59 (2022)



Why is it important?

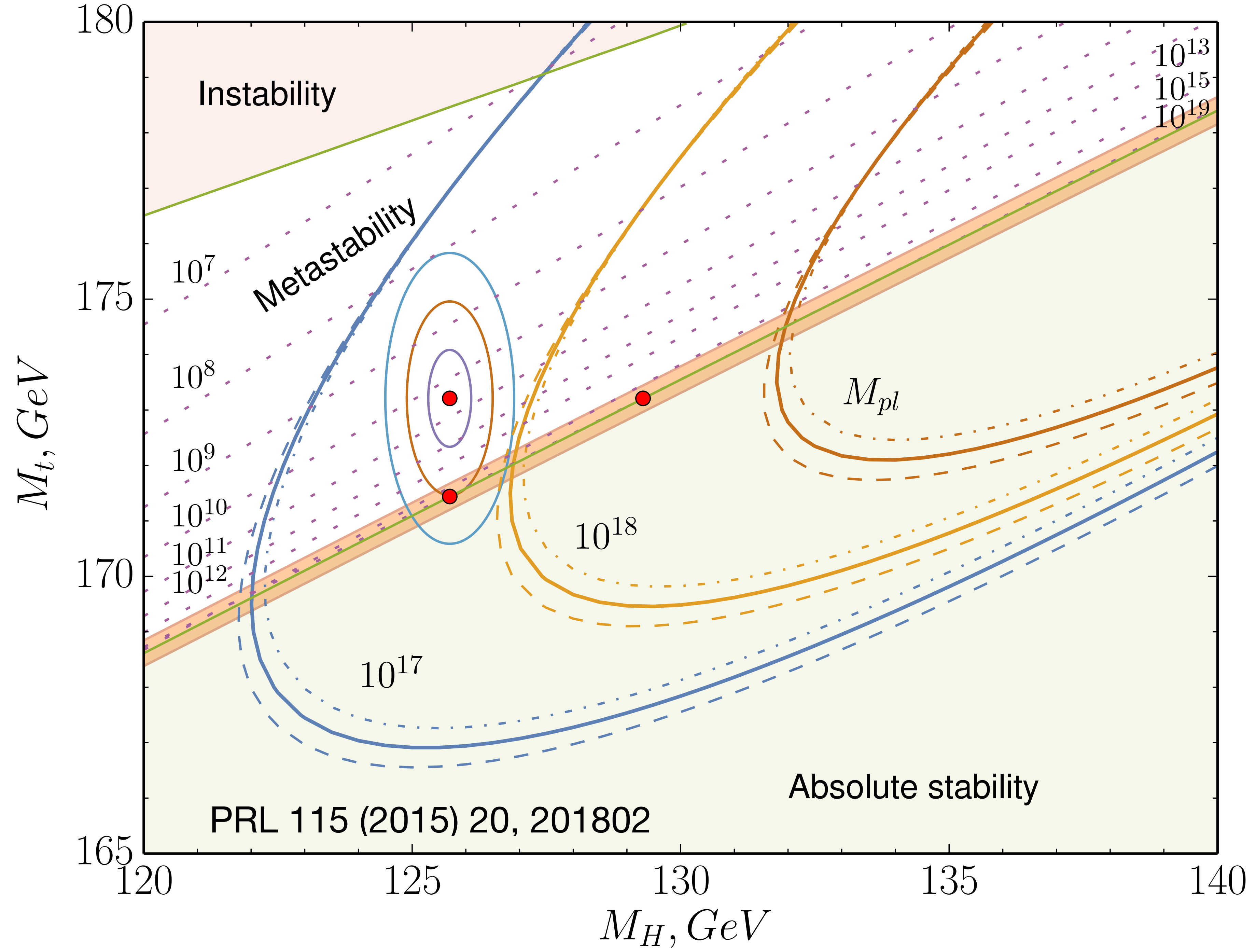
The shape of the scalar potential connects to many open questions of particle physics and cosmology

The evolution of the self-coupling with the energy scale may imply a metastability of our Universe



Nature Rev.Phys. 3 (2021) 9, 608-624

PLB 709 (2012) 222



PRL 115 (2015) 20, 201802

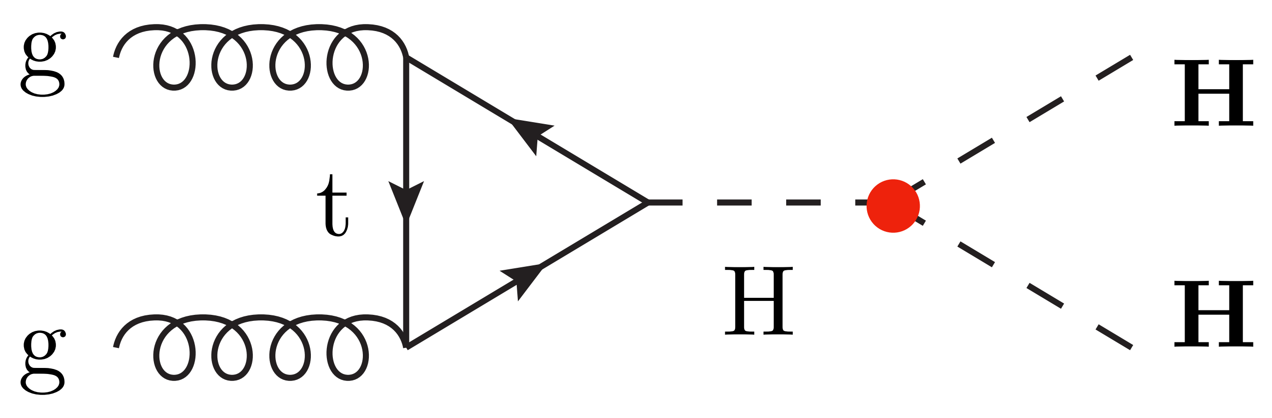
λ

- Metastability or the Universe
- EWSB phase transition and link to baryogenesis
- Cosmological constant

λ_{HHH} : how measure it?

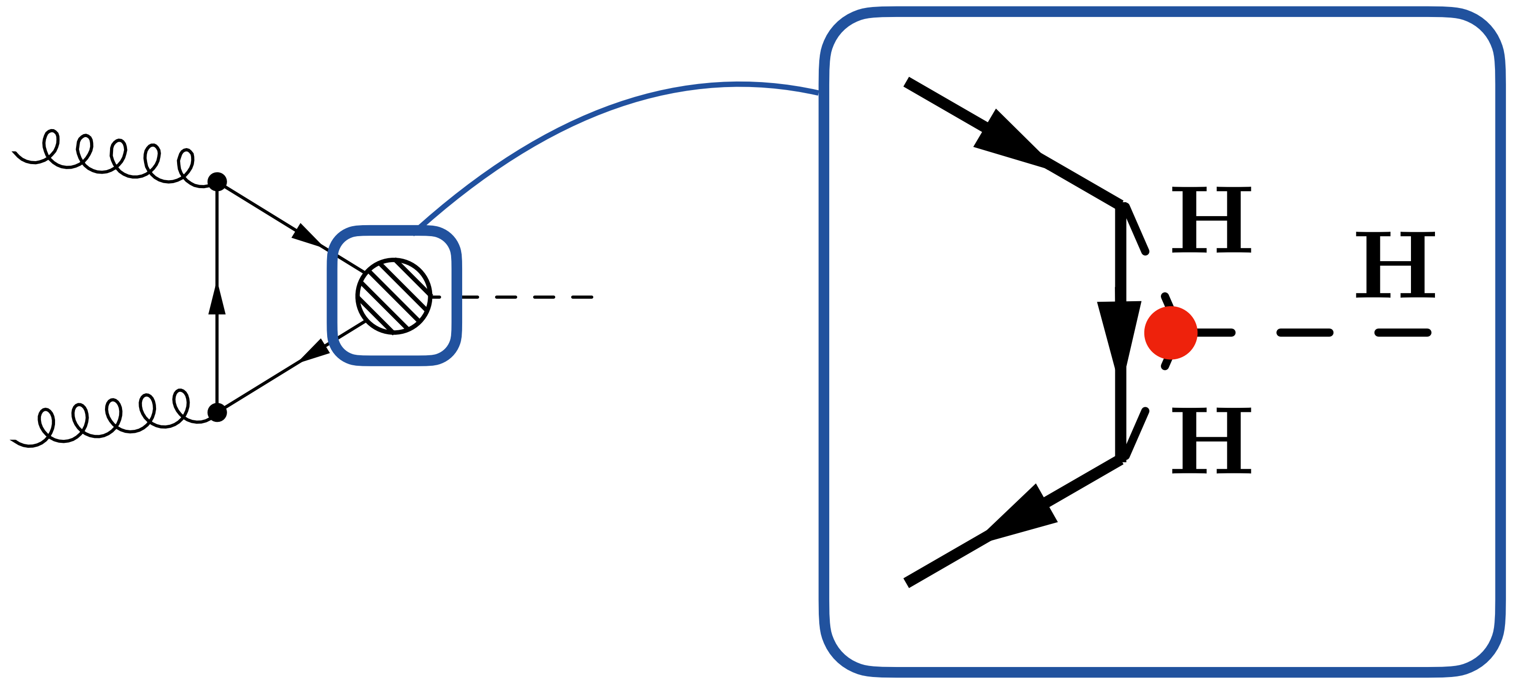
Two complementary strategies exist:

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

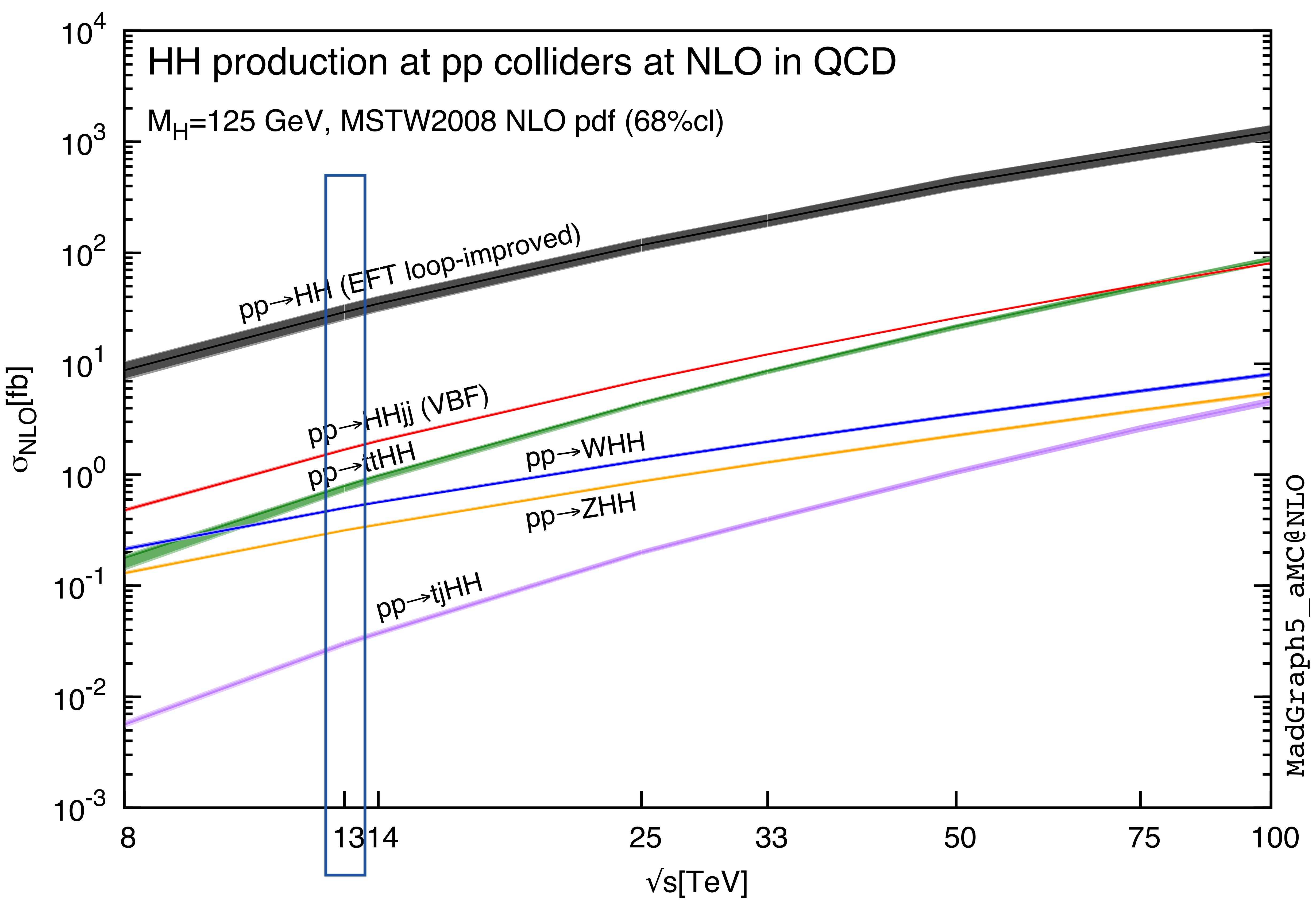
Indirect measurements in single H

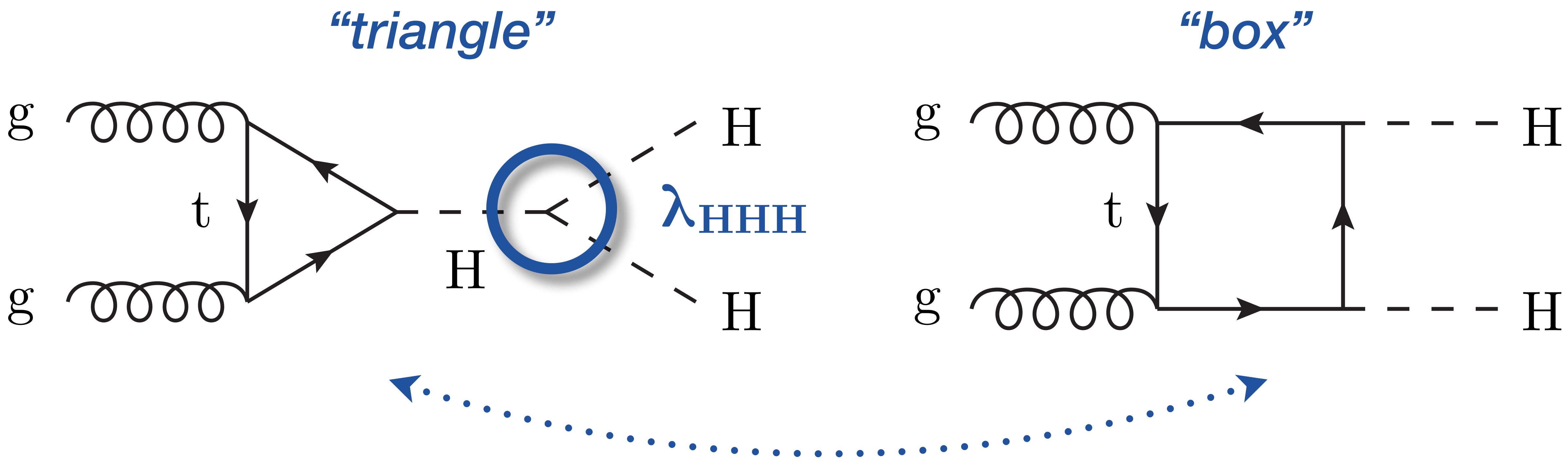


- Extract the value of λ_{HHH} from precision single H cross section measurements
  - indirect measurement: stronger theory assumptions needed to disentangle NLO λ_{HHH} effects from other couplings / new physics
  - benefit of the large single H cross section (~ 1000 $\times$ σ_{HH})

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

HH production at the LHC





Strong destructive interference

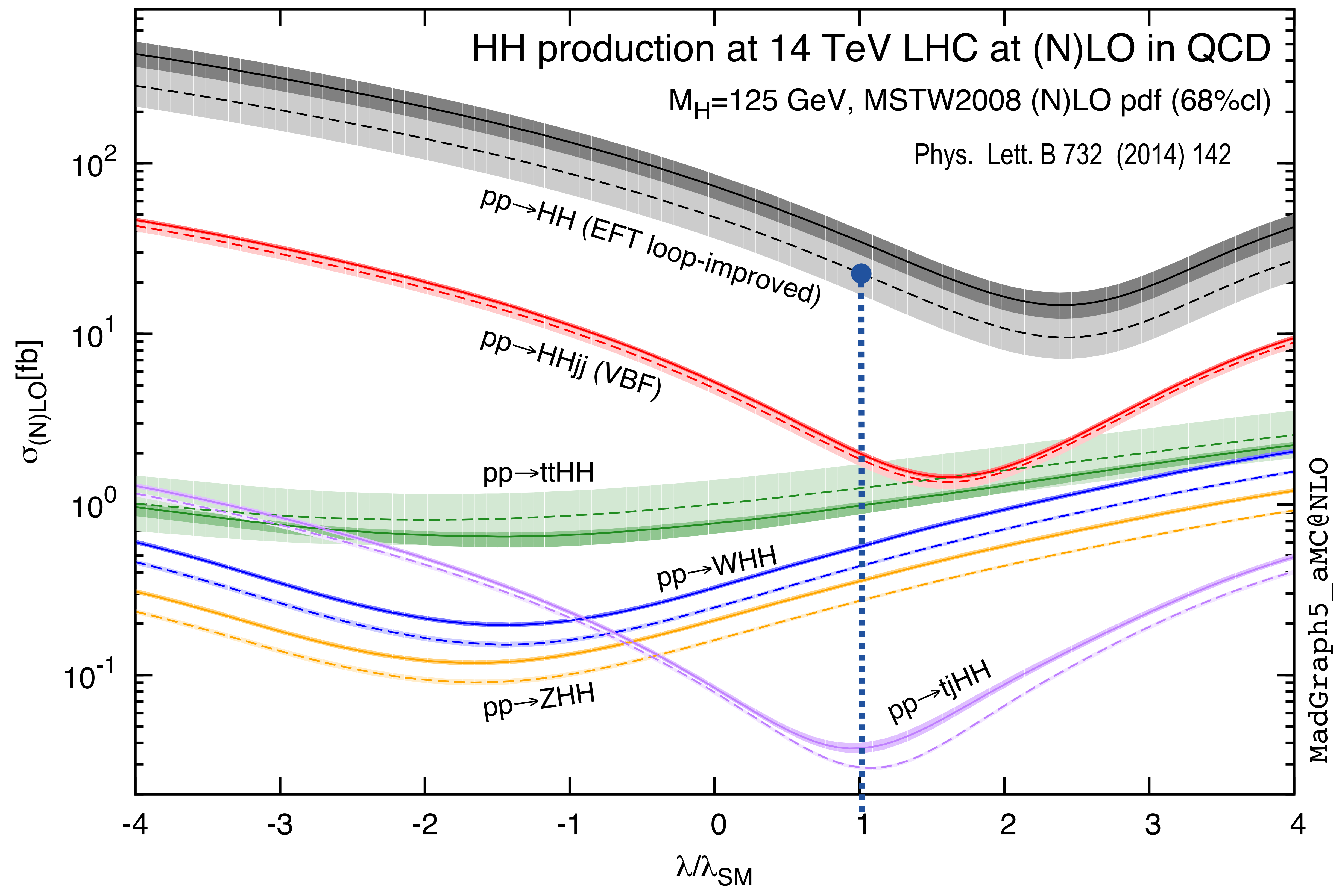
$$\sigma_{HH}^{SM} = 30.77\ (34.13)\ ^{+6.4\%}_{-23.1\%} \text{ at } 13\ (13.6) \text{ TeV}$$

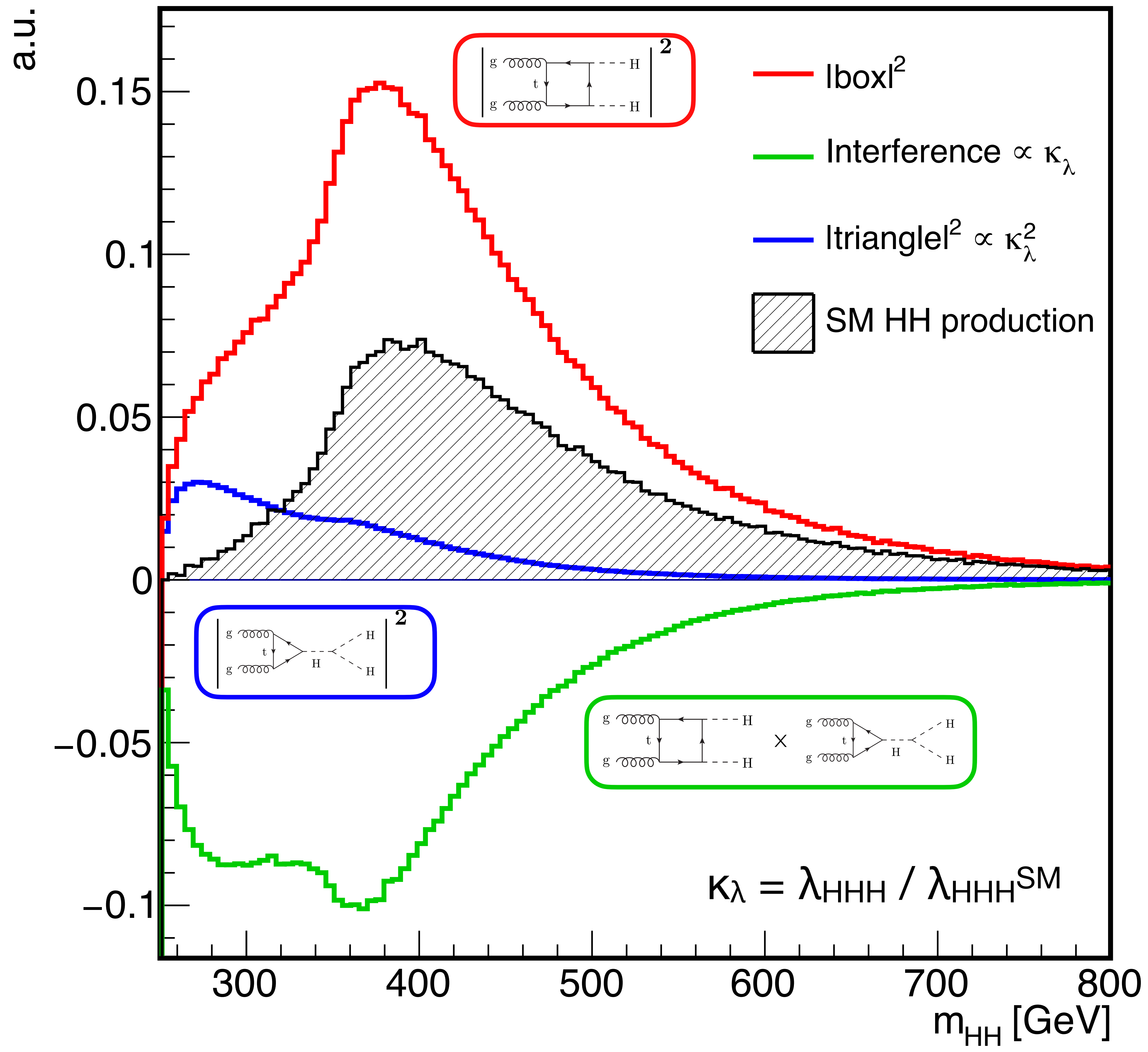
NNLO FT-approx [JHEP 05 (2018) 059]
+ m_t unc [PRD 103, 056002 (2021)]

$(\text{scale} \oplus \text{PDF} \oplus \alpha_S \oplus m_t)$

- **Gluon fusion**: dominant production mode
  - about 4300 HH events in the Run 2 datasets
- Tiny cross section : experimentally challenging!
  - ~1000 times rarer than single H production

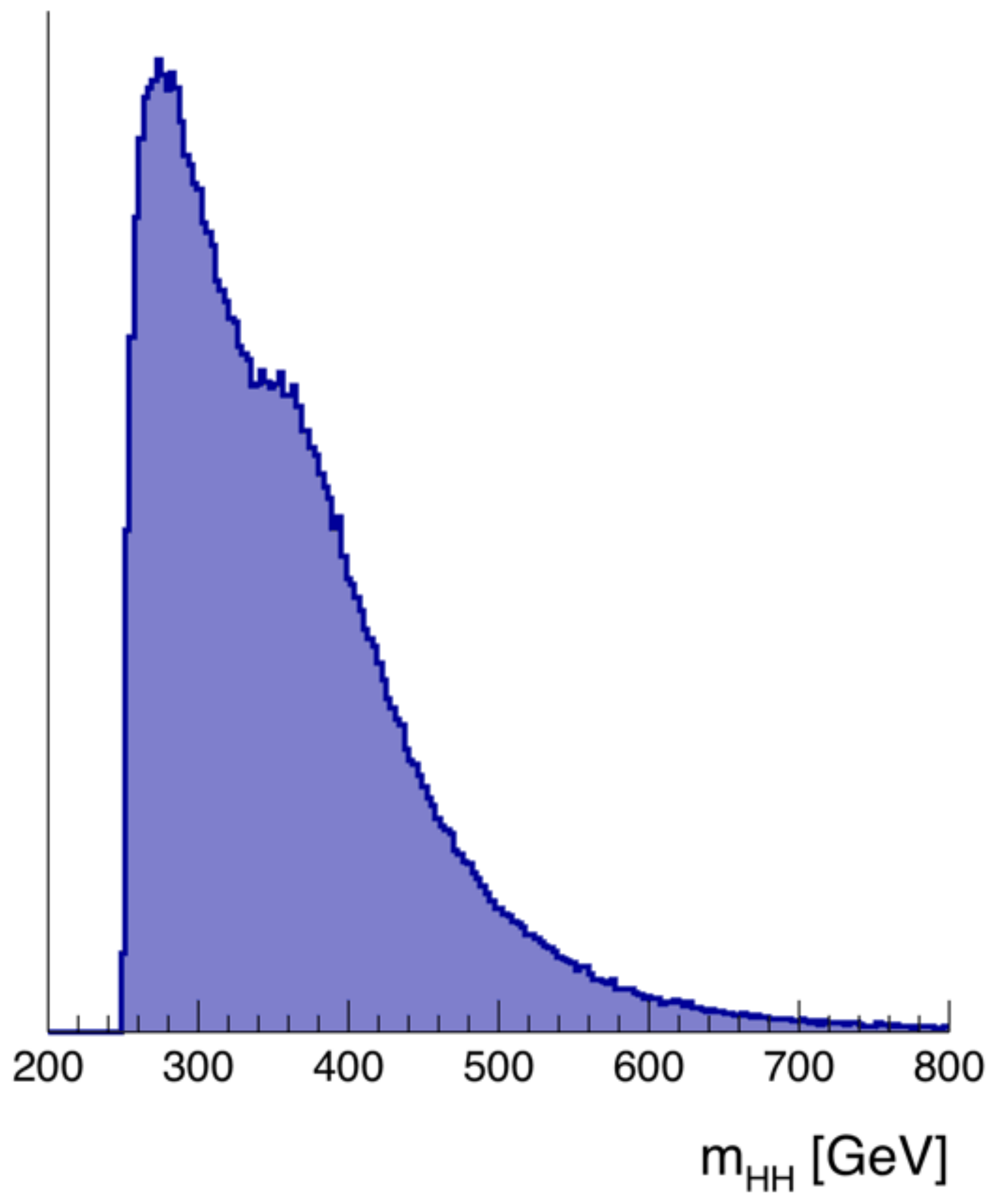
Extracting λ_{HHH} from HH measurements

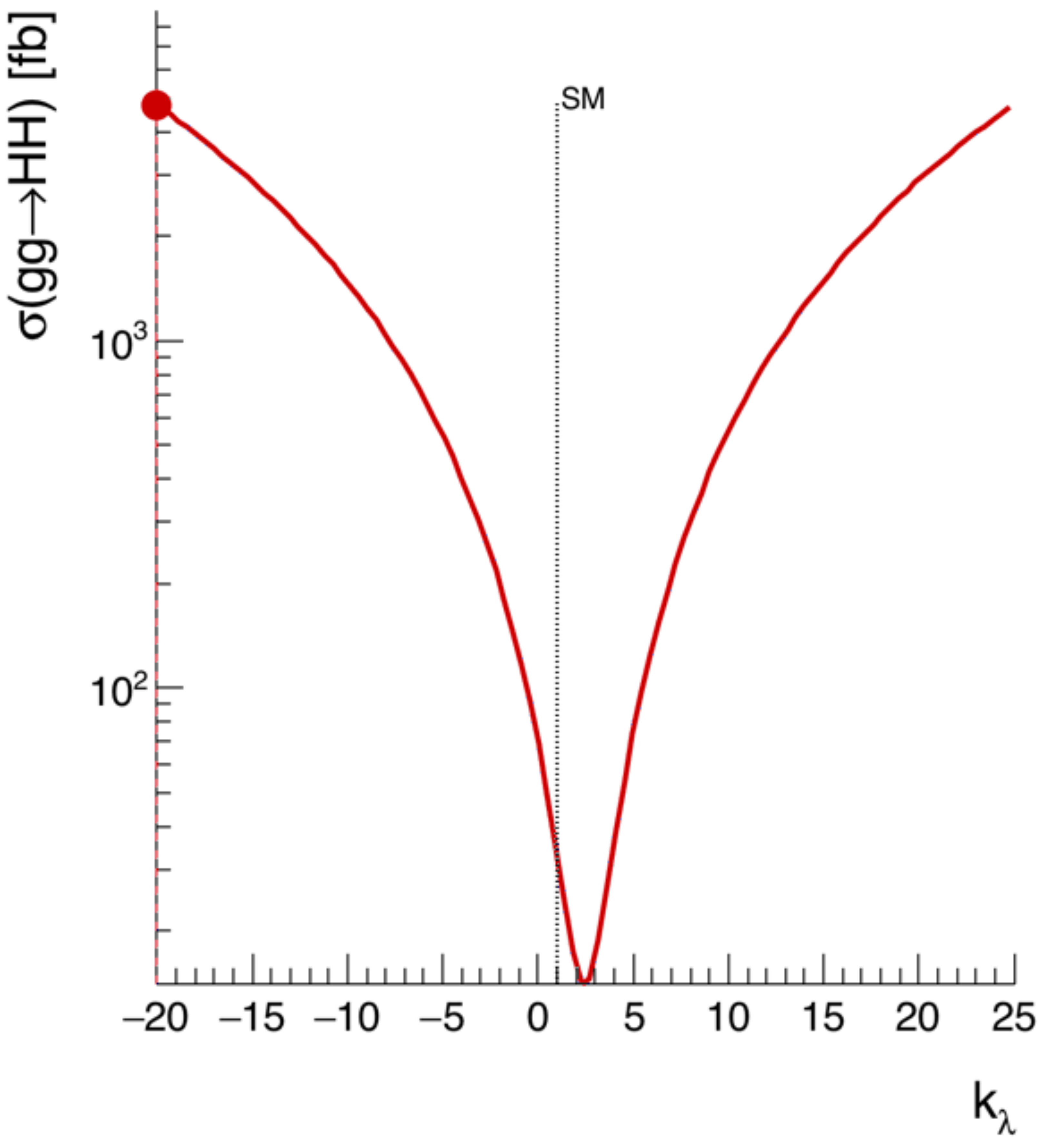




- $\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}(SM)$
- Information on κ_λ is obtained from both the total and the differential production cross section

Illustration of shape effects





Interference effects have important consequences for the sensitivity of the searches

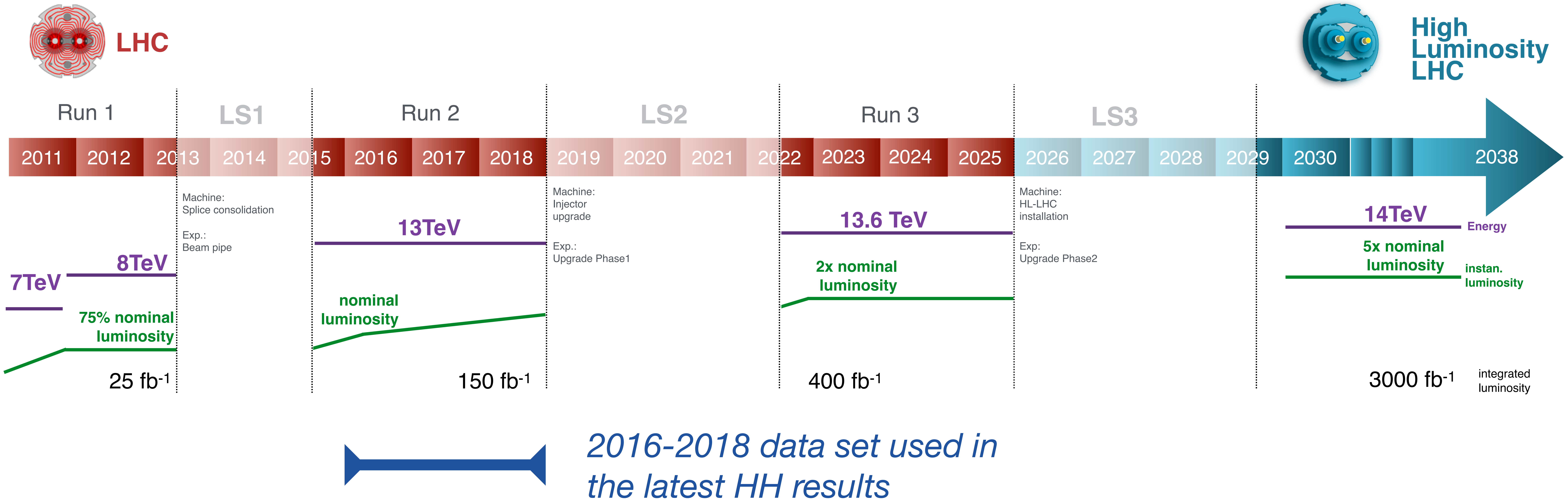
Outline

Searching for HH at the LHC

- *Overview of decay channels*
- *Main experimental analyses : bbbb, $bb\tau\tau$, $bb\gamma\gamma$*
- *LHC Run 2 combined results*
- *Looking back at the road done*
- *Combination with single H*

The Large Hadron Collider

- The CERN LHC is designed to deliver pp collisions at $\sqrt{s}$ = 14 TeV and $\mathcal{L} = 10^{34}$ cm^{-2} s^{-1}
- Broad program of H and HH measurements with the ATLAS and CMS experiments



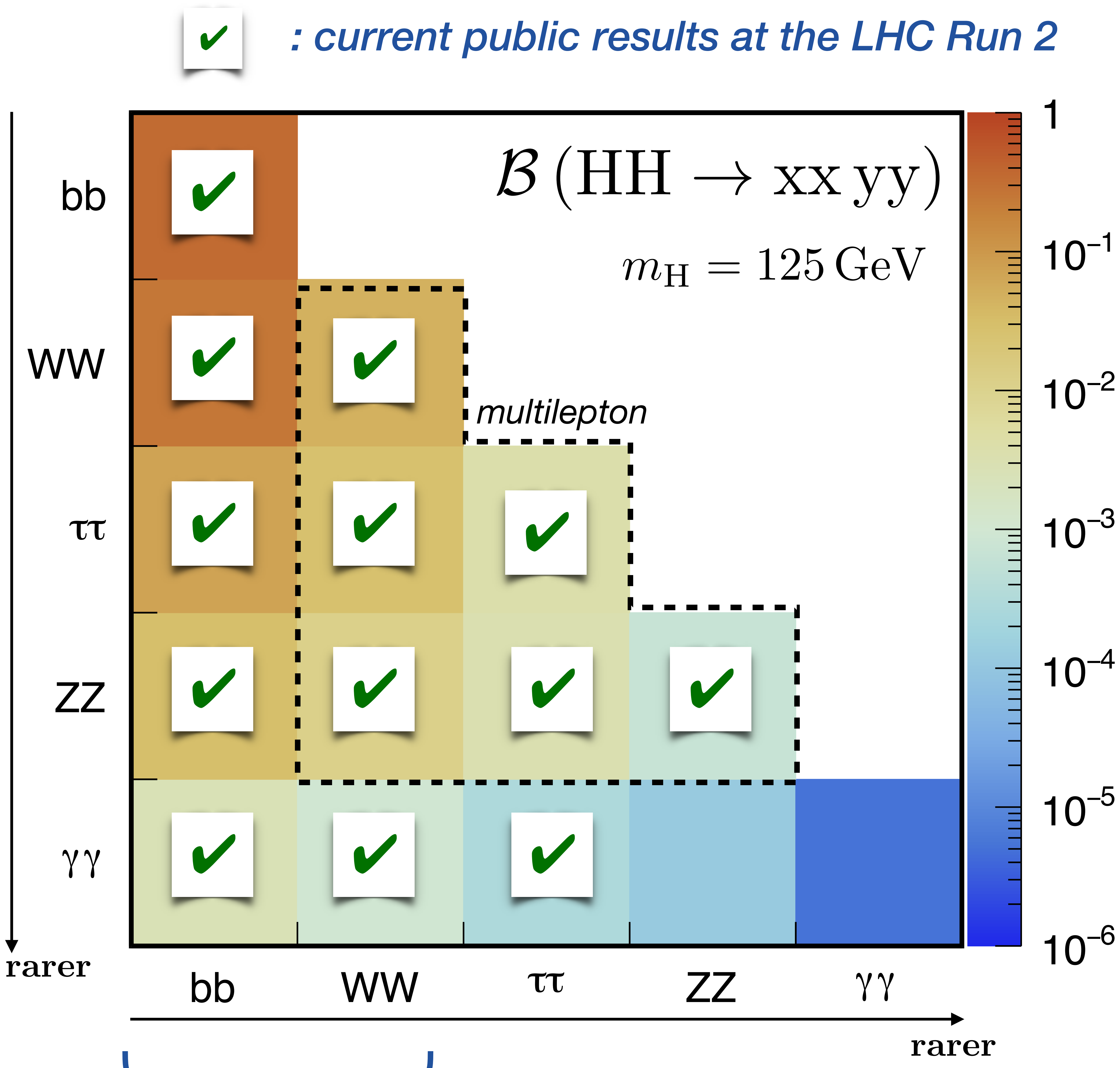
2016-2018 data set used in the latest HH results

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 experimental programme by the ATLAS and CMS Collaborations

Trade-off between $\mathcal{B}$ and purity

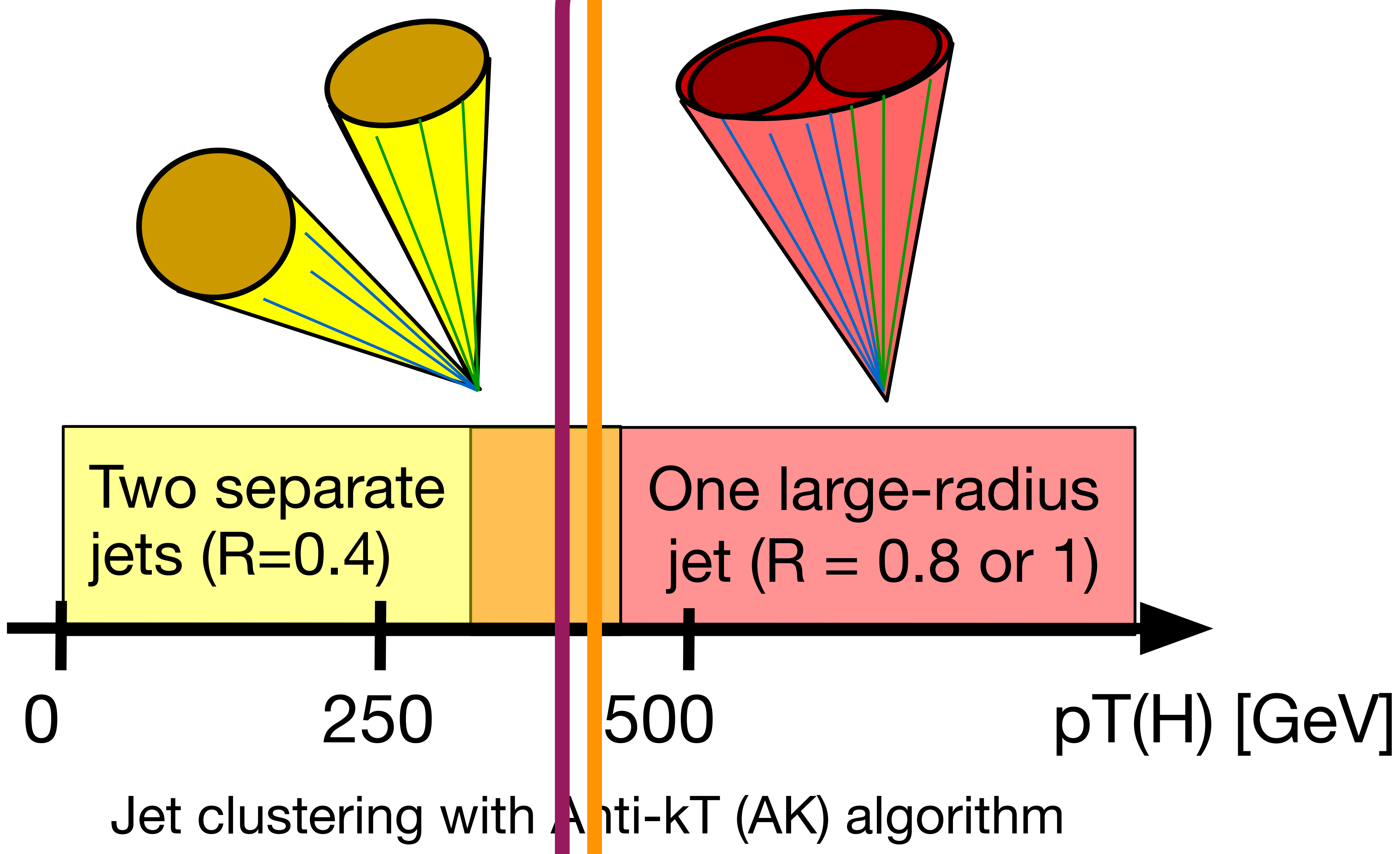


Keep $\mathcal{B}$ high enough

High $\mathcal{B}$, low S/B : HH→bbbb

Resolved searches

- Each b quark reconstructed as separate jets
- Largest fraction of signal, large QCD background
  - challenging trigger and identification

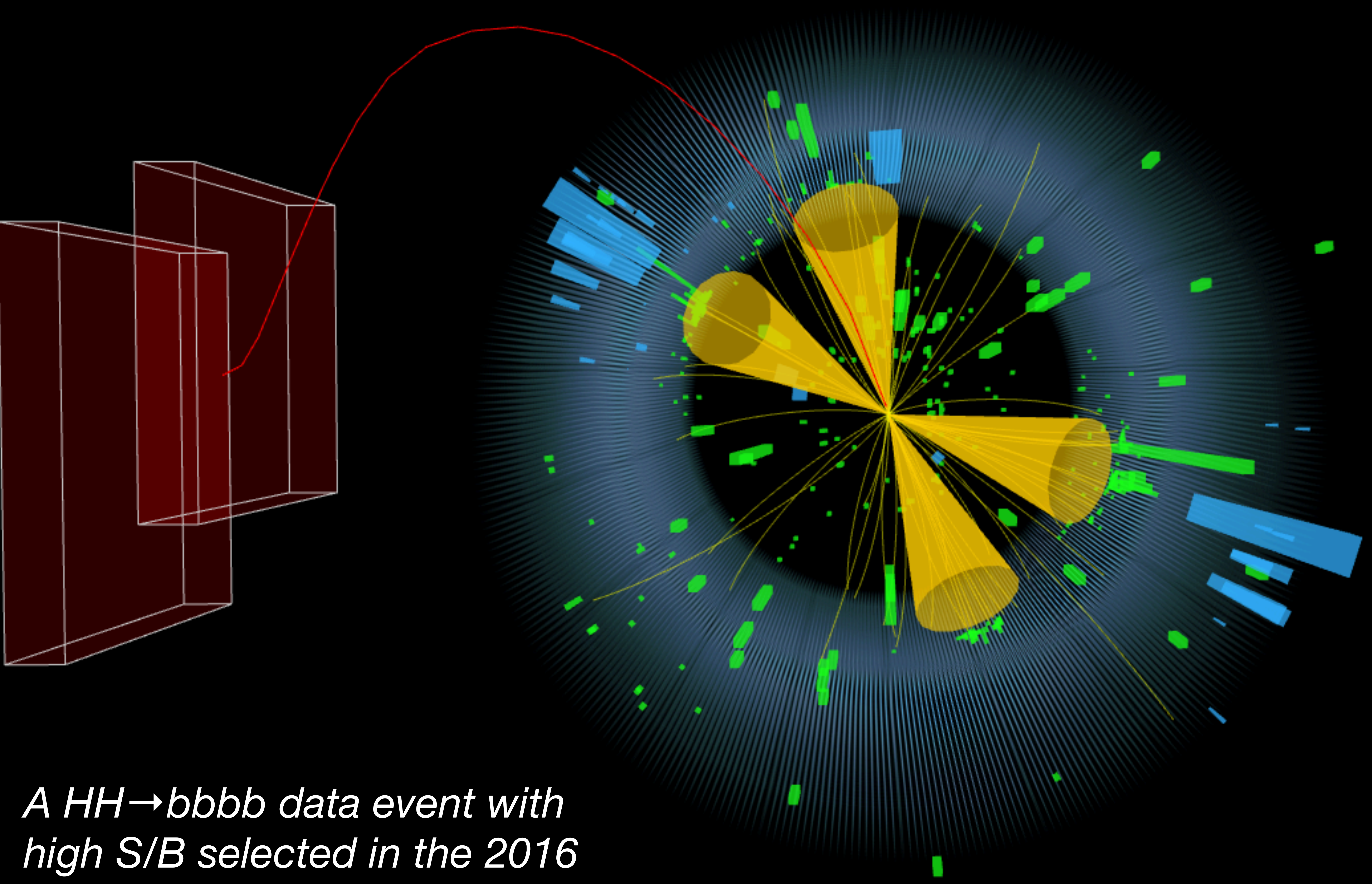


Boosted searches

- H→bb decay reconstructed as a single jet
- O(%) signal acceptance, supressed backgrounds
- Leading m_X > 1 TeV sensitivity

Partial overlap between the two types of searches, can be optimized in analyses
Optimal exploration of the full phase space

Resolved High $\mathcal{B}$, low S/B : HH→bbbb



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

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

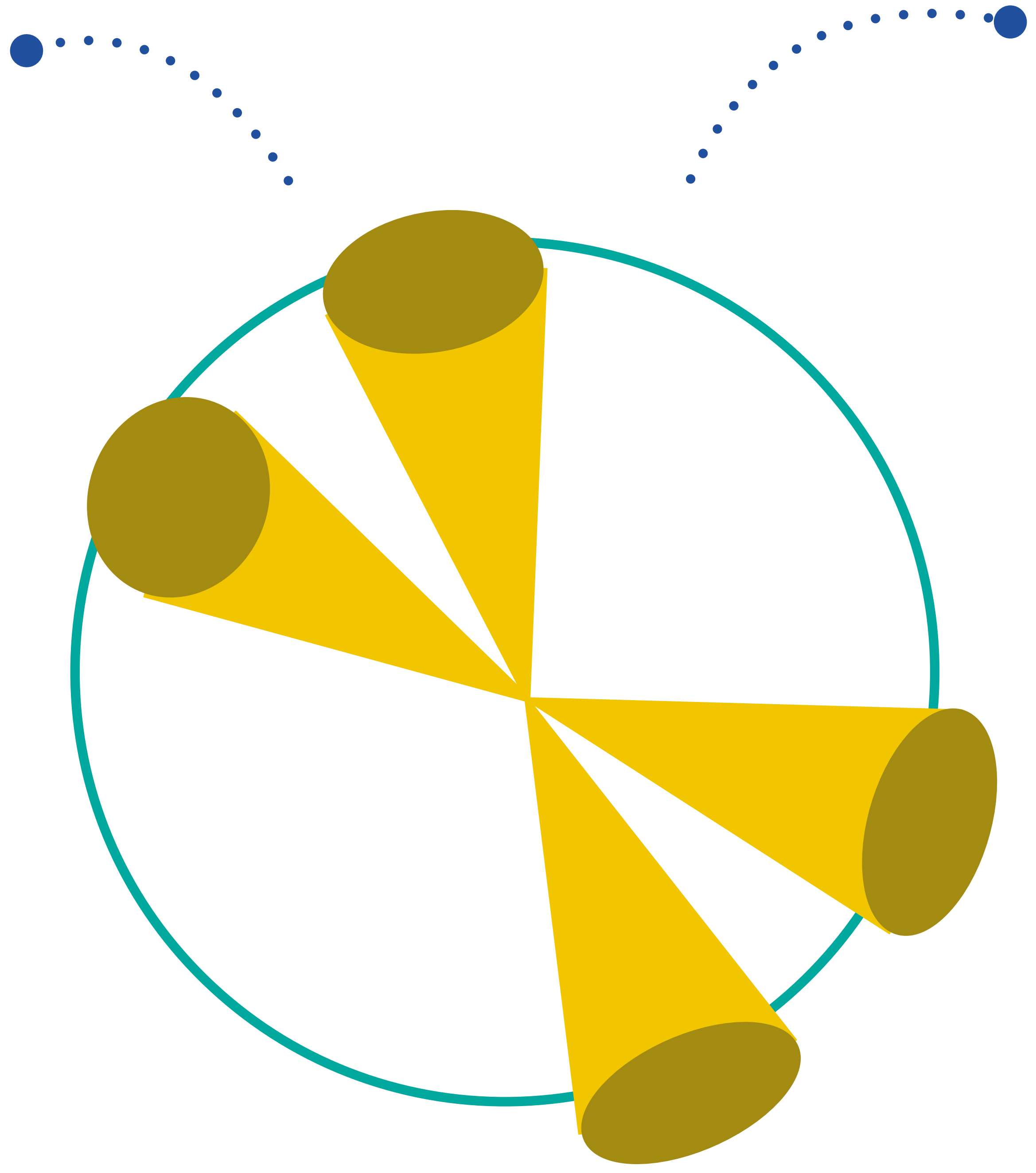
Resolved HH→bbbb : selecting the events

Event selection

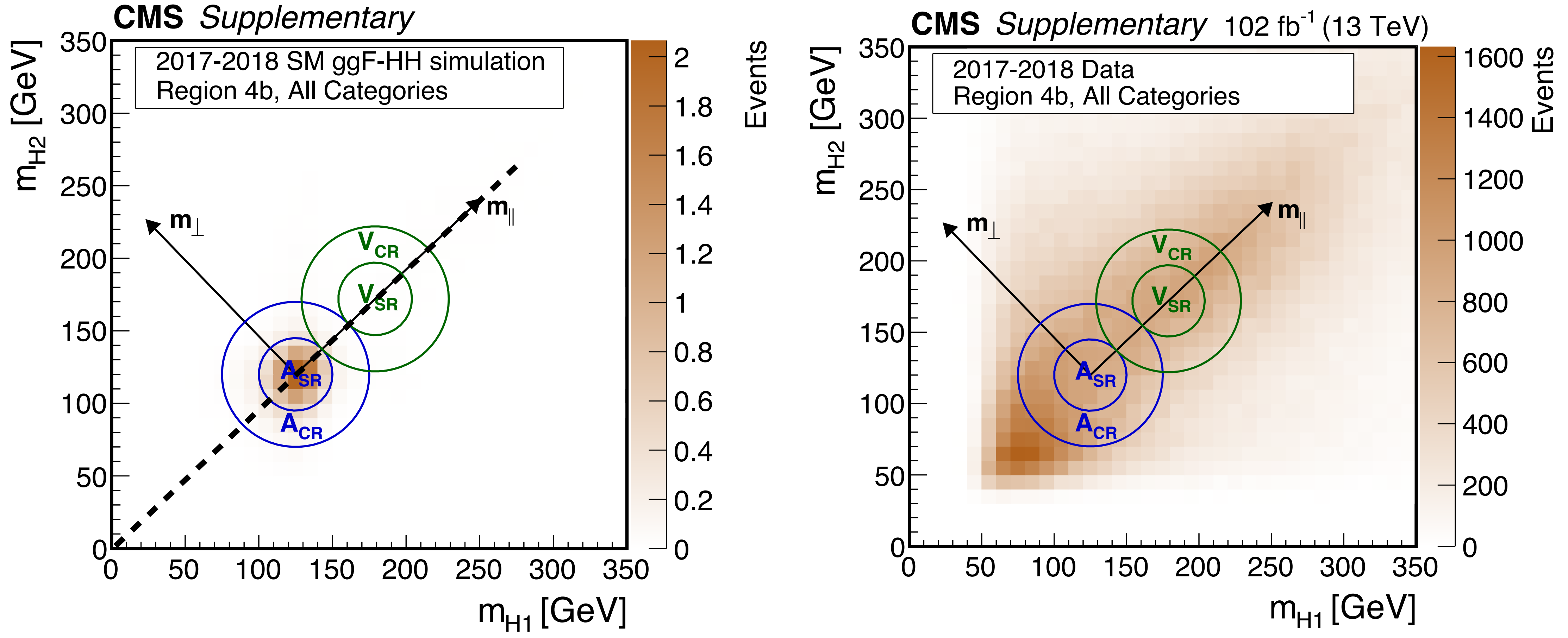
- Target fully resolved topology (4 jets)
- Events selected with online b triggers

Event categorization

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



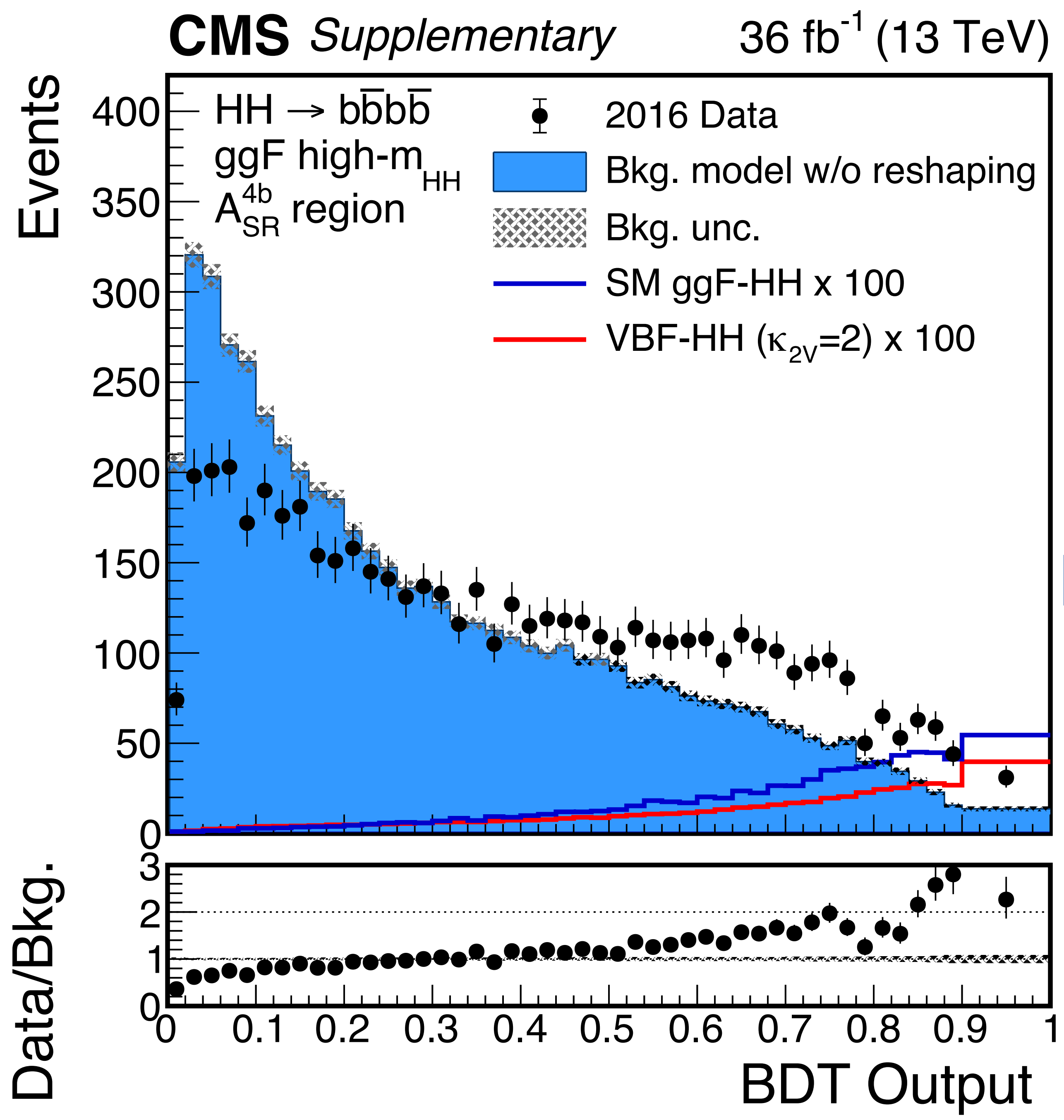
H candidates reconstruction



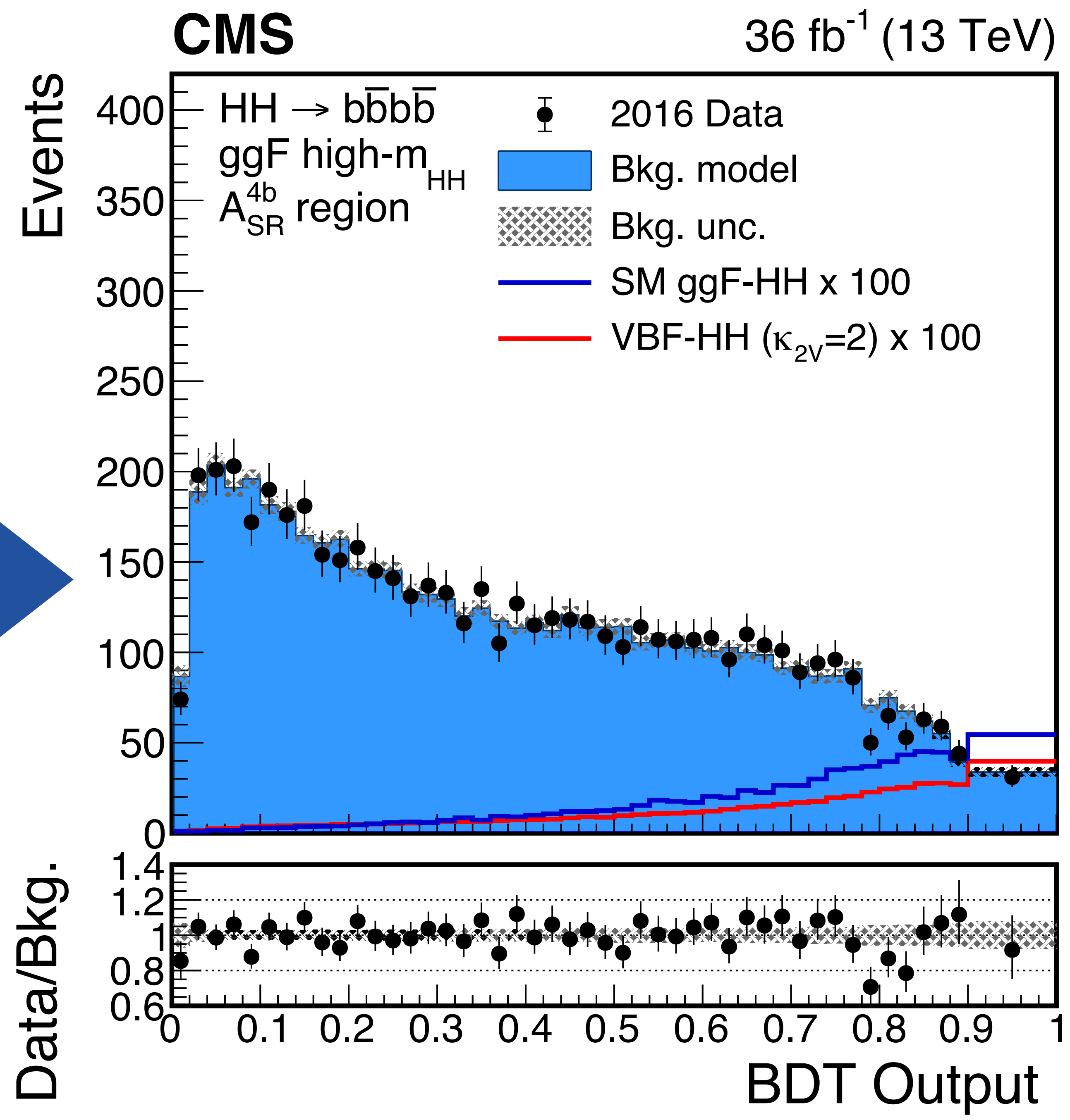
- Pair jets to reconstruct the m_H peaks with minimal bias on the bkg distribution
  - min Δ(mass) or min ΔR(j,j)
- Definition of regions for signal extraction and background estimation and validation

HH→bbbb : the multijet challenge

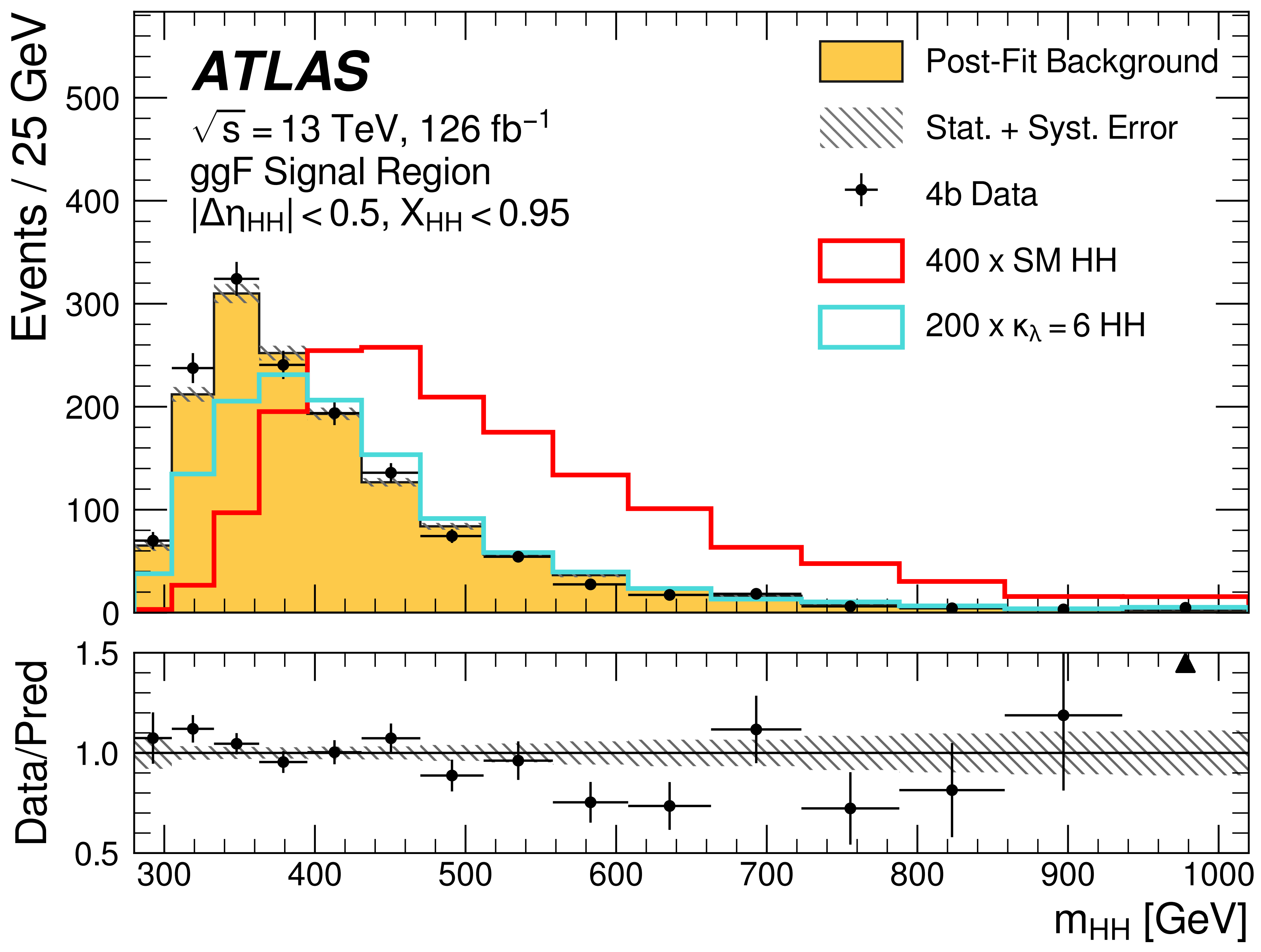
Overwhelming multijet background | **Accurate data-driven estimates from control regions**



Bkg. template from 3b uncorrected data



ML-based correction to bkg. template

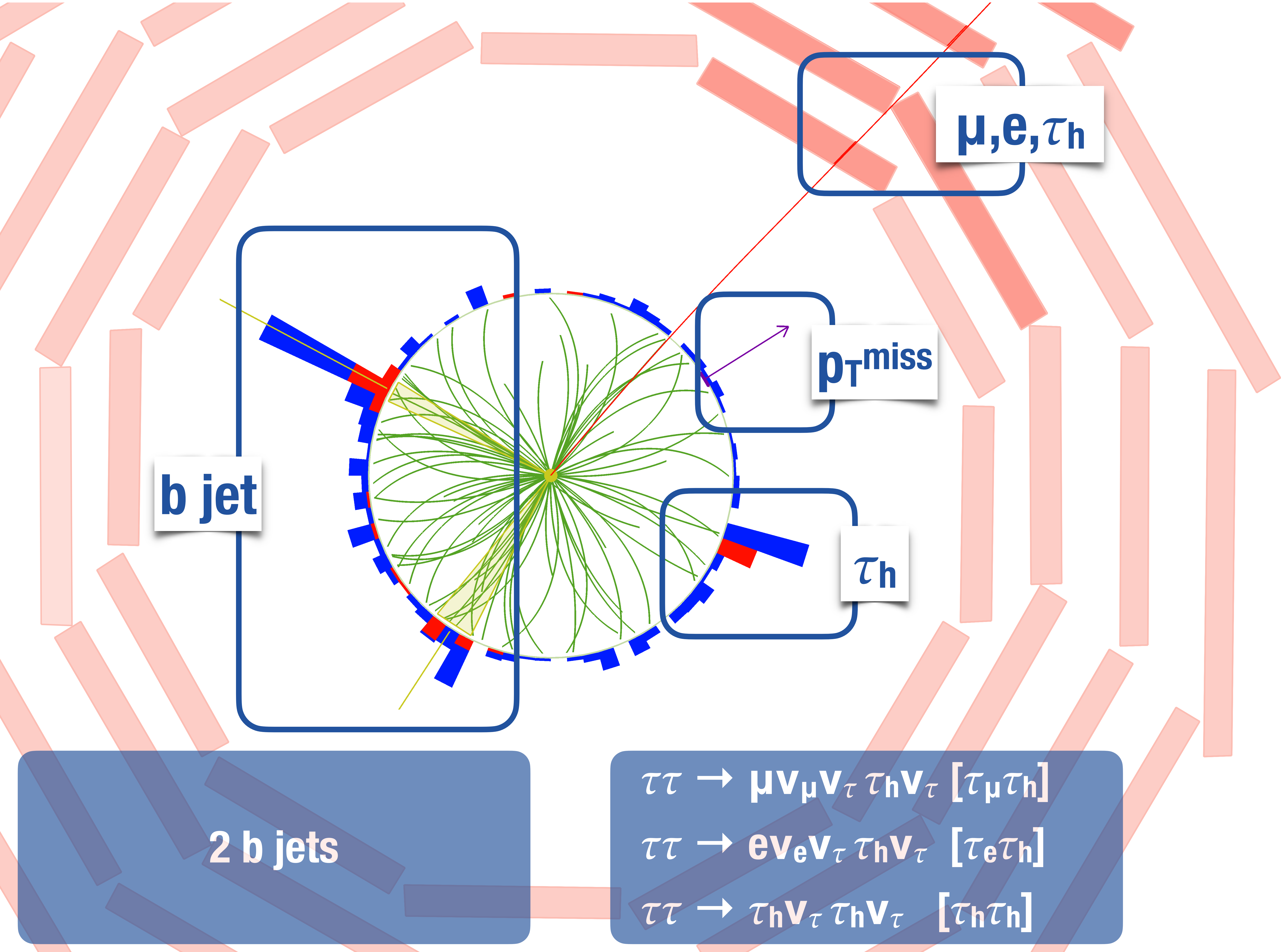


- Background from 3b region (CMS) or 2b region (ATLAS) [trigger]
  - 2b/3b→4b transfer function from ML methods trained in mass sidebands
- S/B separation with BDT discriminant (CMS) or fit to m_{HH} (ATLAS)

Observed (expected)

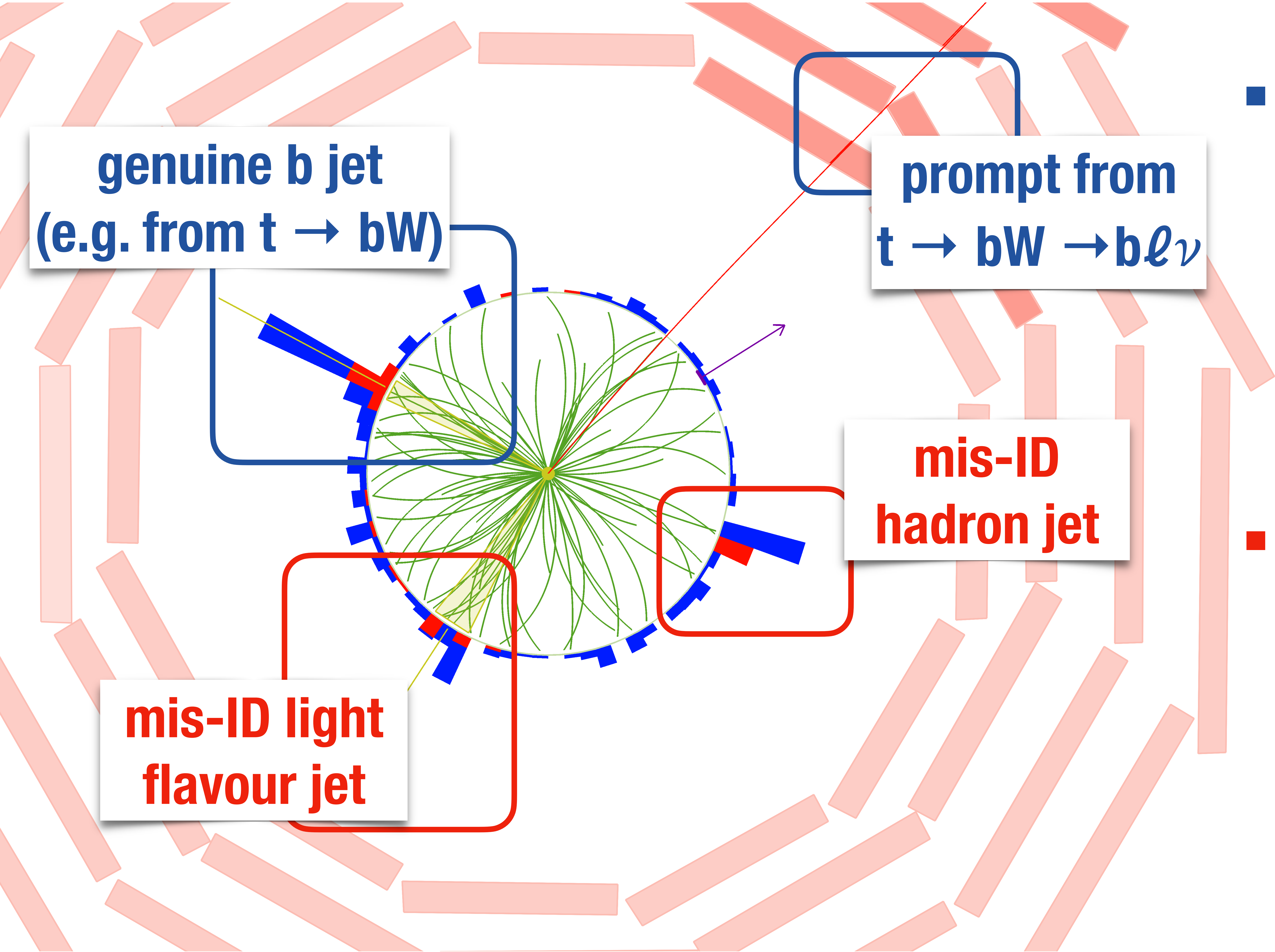
5.3 (8.1) × σ_{HH}^{SM} [ATLAS]
3.9 (7.8) × σ_{HH}^{SM} [CMS]

Medium $\mathcal{B}$, 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
- Neutrinos in the $\tau\tau$ system decays → partial energy reconstruction → likelihood method to estimate $m_{\tau\tau}$
  - used to suppress backgrounds

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



- **Irreducible** backgrounds
  - tt → bbWW → bb $\tau\tau$
  - Z/γ^* → $\tau\tau$ + 2 b jets
  - (above two: simulation + correction in CR)
  - di-boson, ZH, H+b (minor) — simulation
- **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 → bb$\tau\tau$: classification and signal extraction

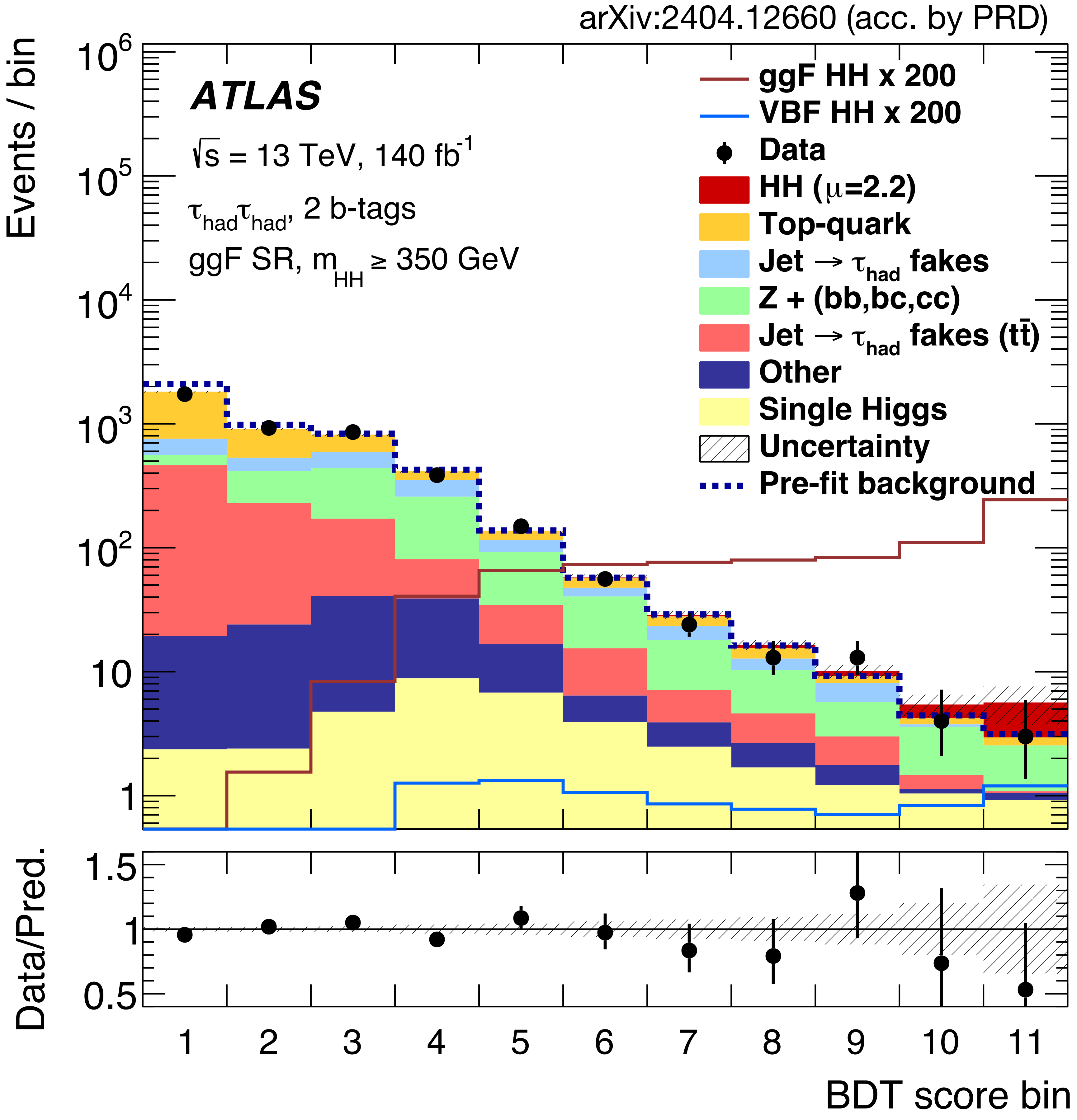
Complex topology with several final state objects

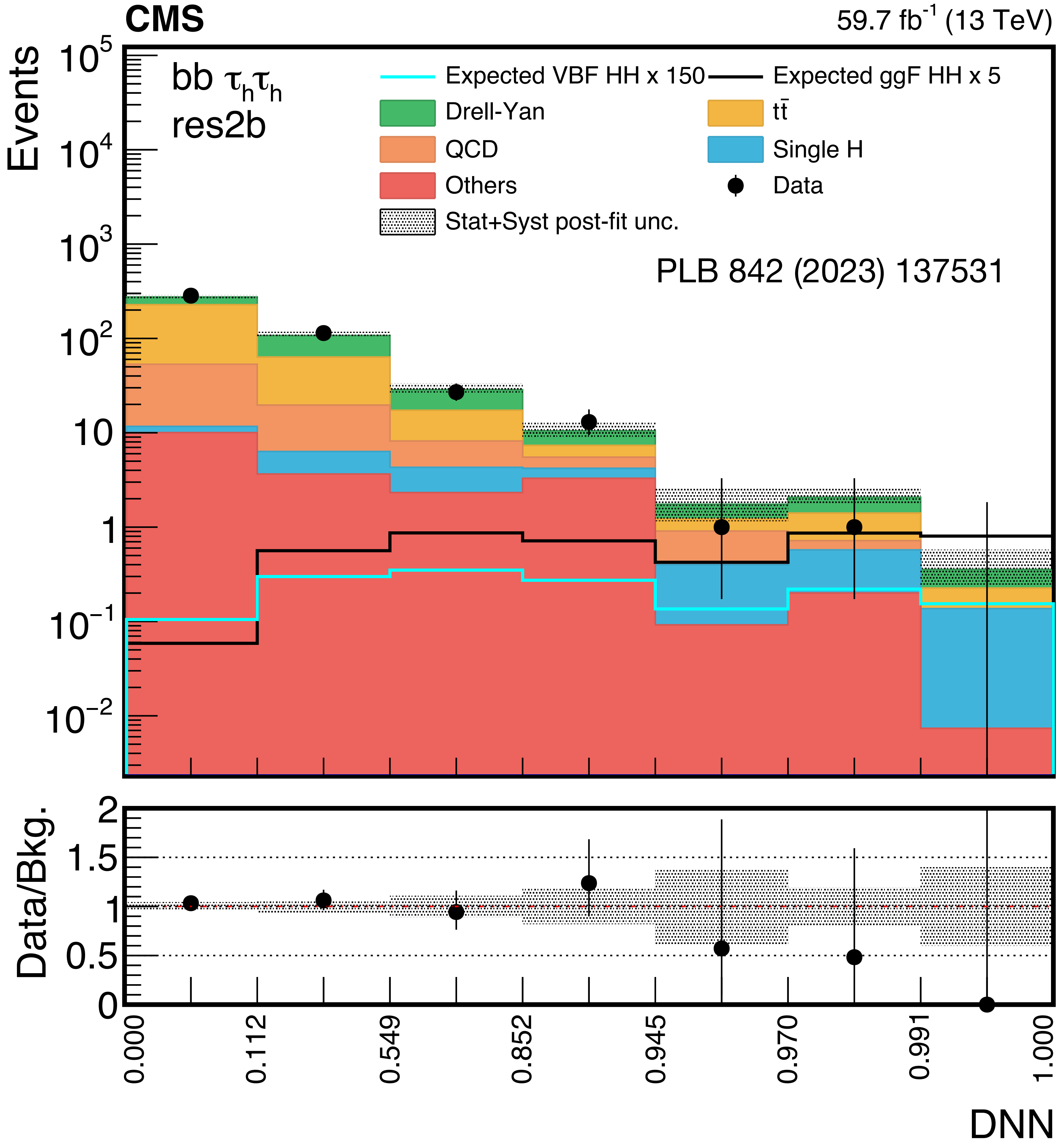
Extensive even categorization by $\tau\tau$ decay mode ($\mu\tau_h$/$e\tau_h$, $\tau_h\tau_h$), production mode, low/high m_{HH} (κ_λ sensitivity)

- Identify signal with a multivariate discriminant based on the event kinematics
- Sensitivity lead by fully hadronic categories

Observed (expected)

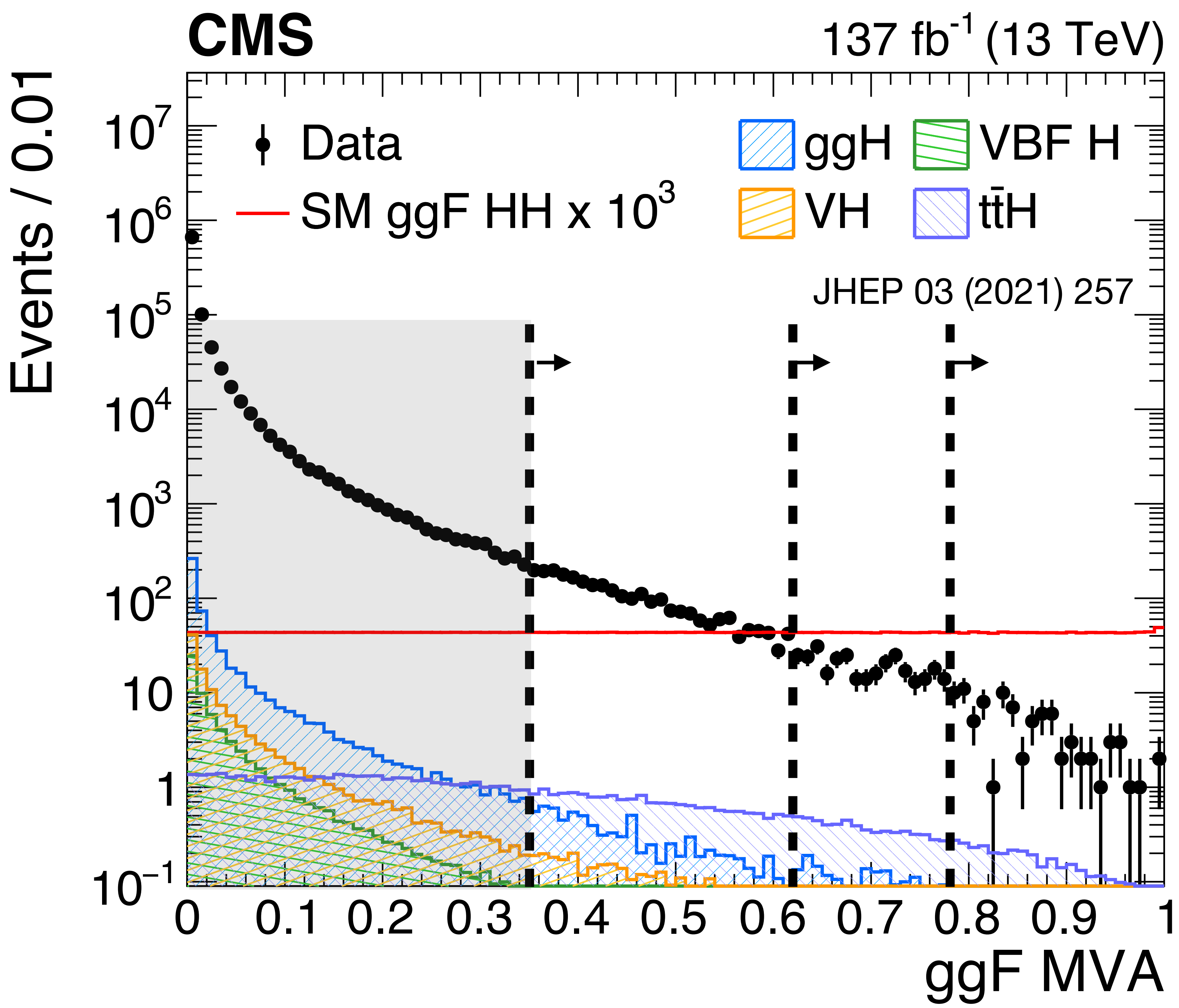
5.9 (3.3) × σ_{HH}^{SM} [ATLAS]
3.3 (5.2) × σ_{HH}^{SM} [CMS]

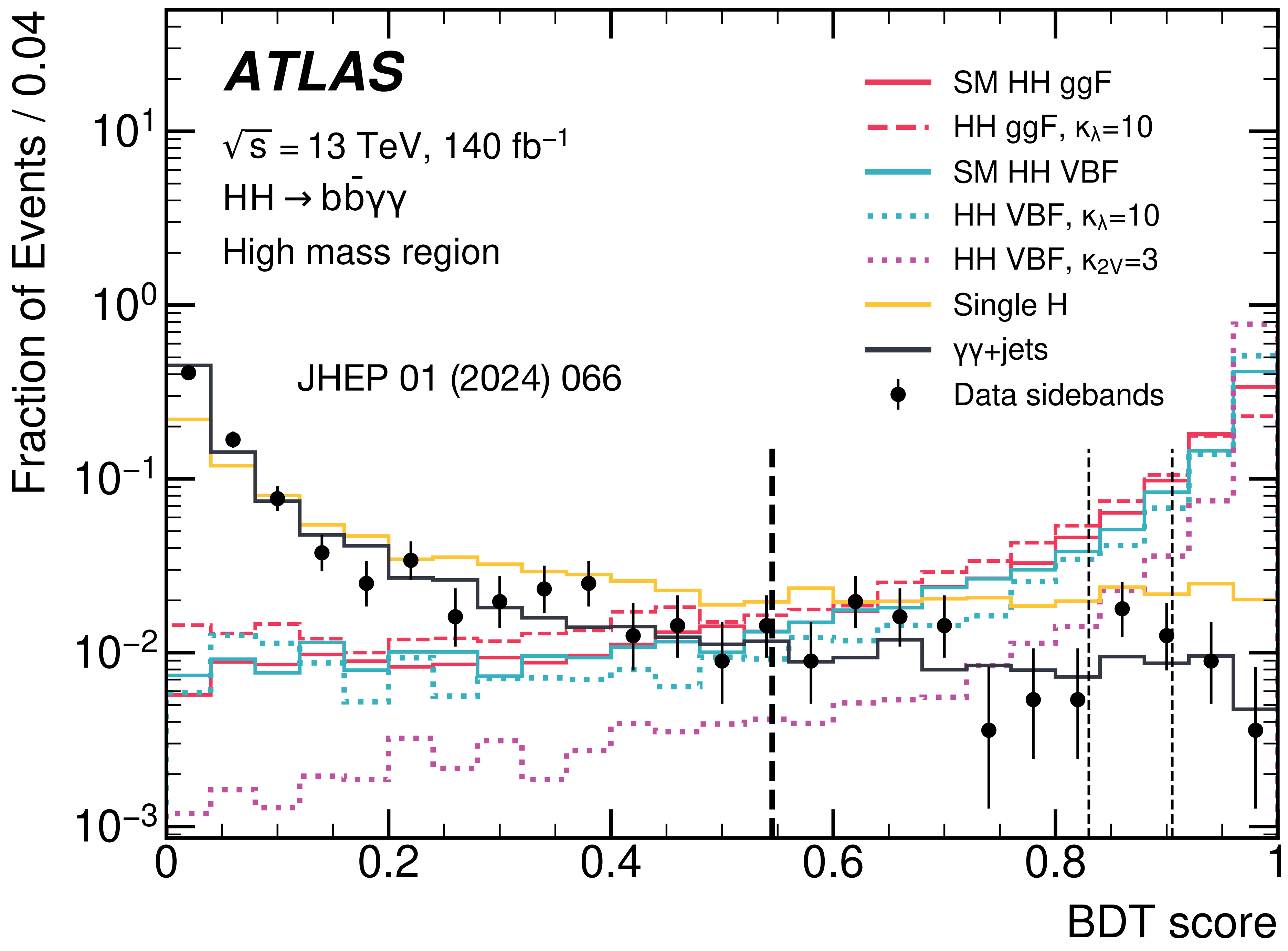




Low $\mathcal{B}$, high S/B : HH → bb$\gamma\gamma$

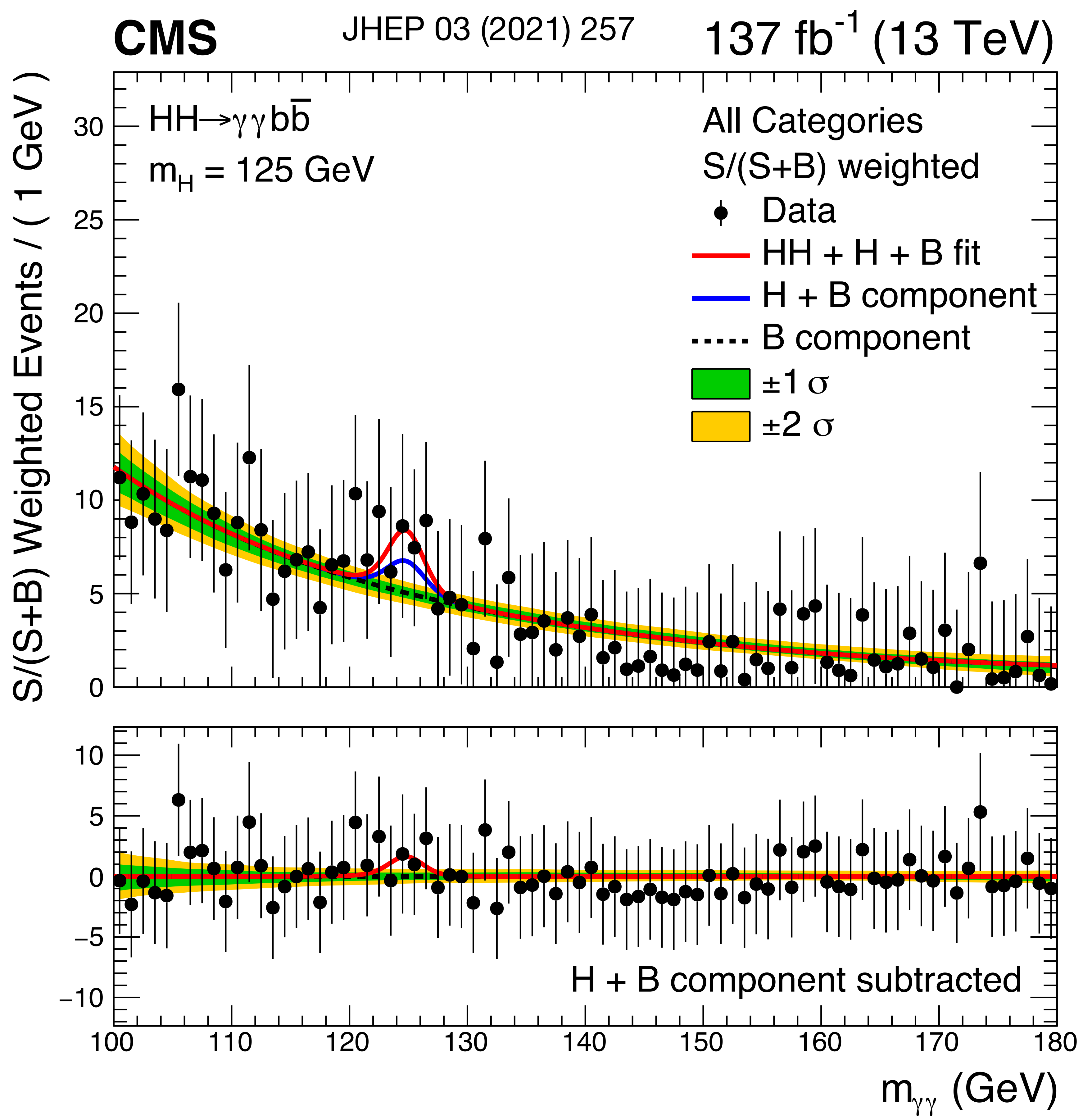
Clean but rare decay channel | **Maximisation of acceptance and purity in event selection**





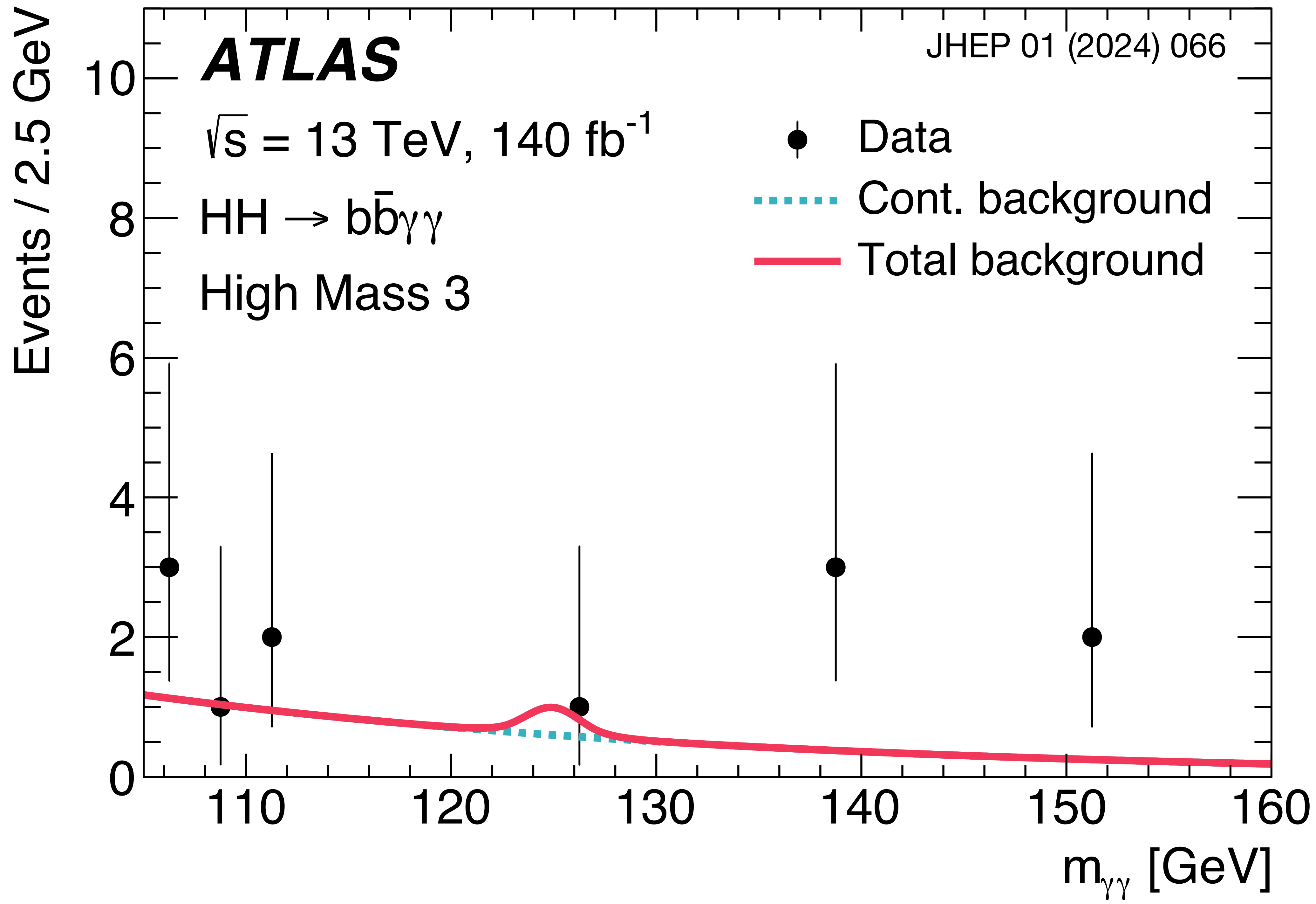
- Main backgrounds: $\gamma/\gamma\gamma$ + jets continuum, single H
- Dedicated MVAs for background suppression and event classification (MVA, low/high m_{HH})
  - optimal acceptance and max sensitivity for anomalous κ_λ

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 dominated by the limited number of events

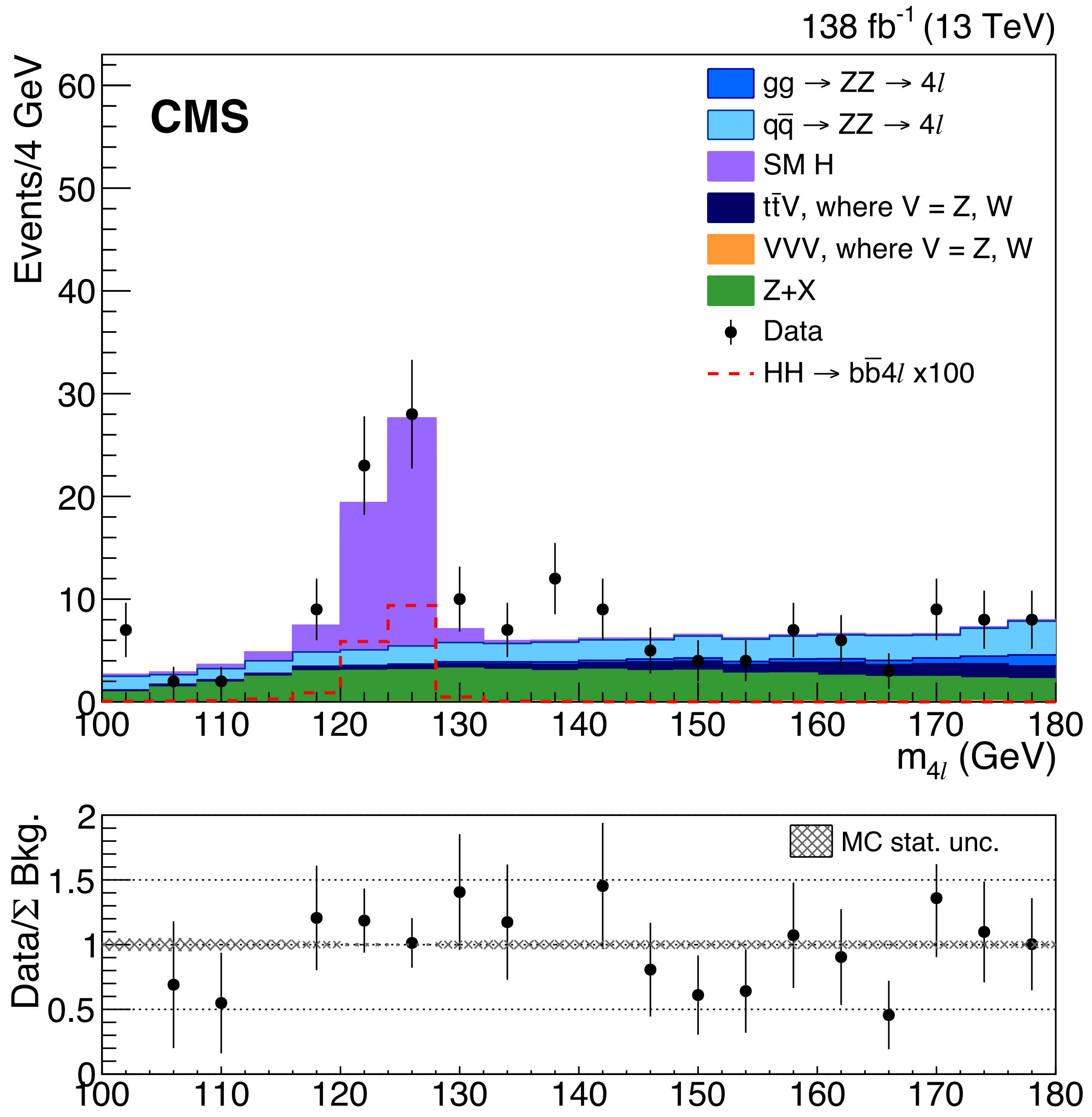
Simultaneous fit with $m_{\gamma\gamma}$ / m_{bb}

Obs. (exp.) : 8.4 (5.5) × σ_{HH}^{SM}

Fit of $m_{\gamma\gamma}$

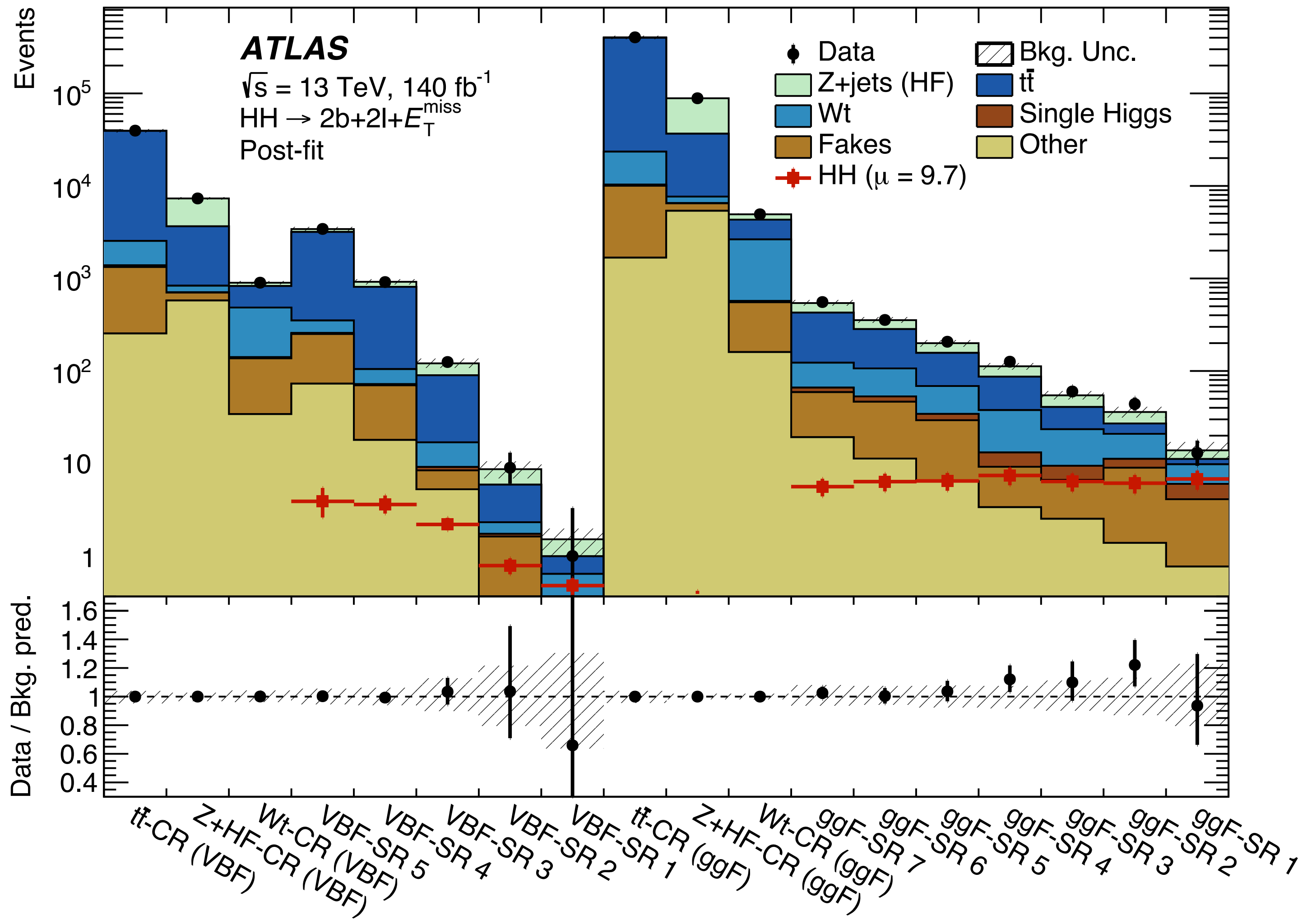
Obs. (exp.) : 4.0 (5.0) × σ_{HH}^{SM}

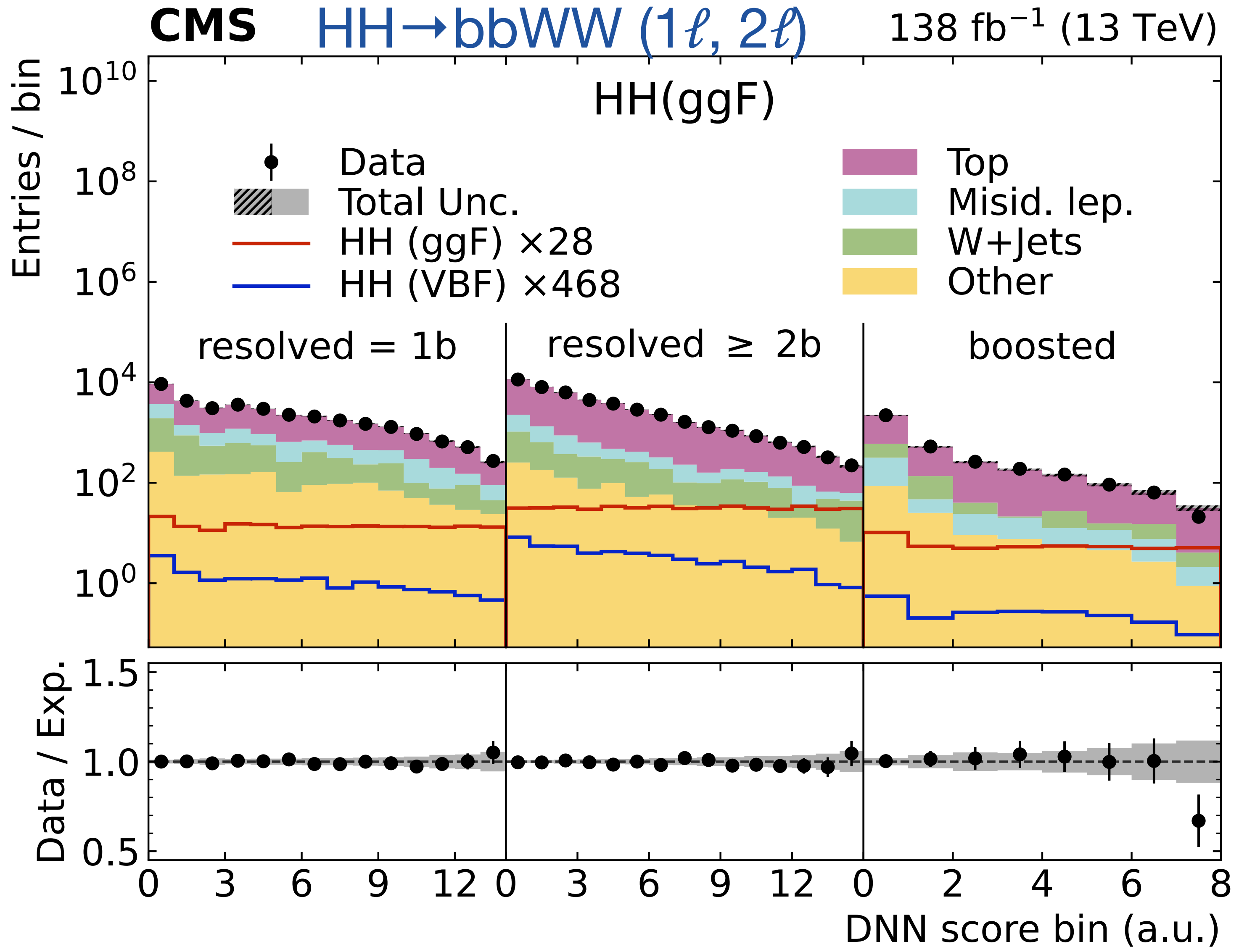
And many more channels



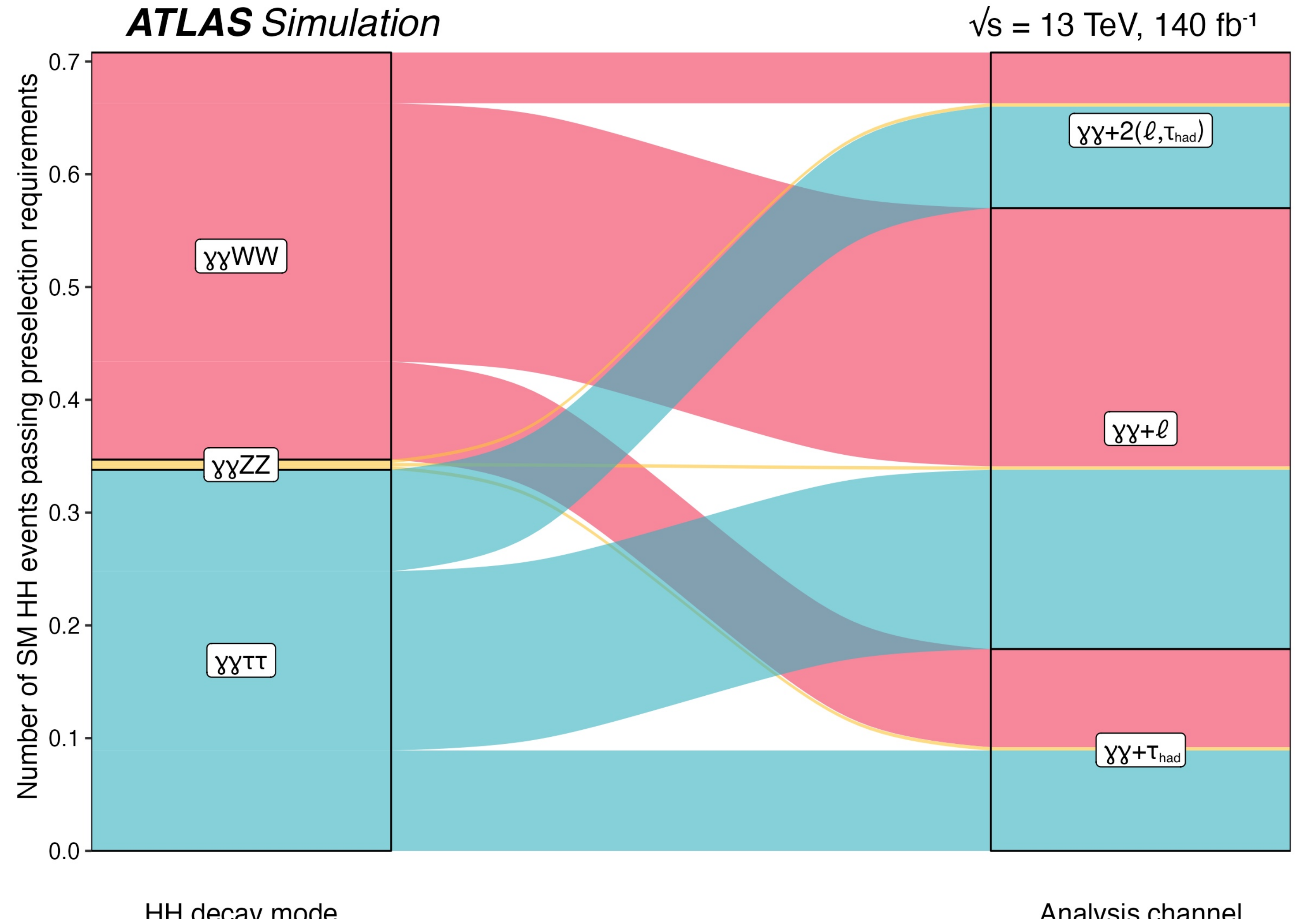
HH→bbZZ(ℓℓℓℓ)

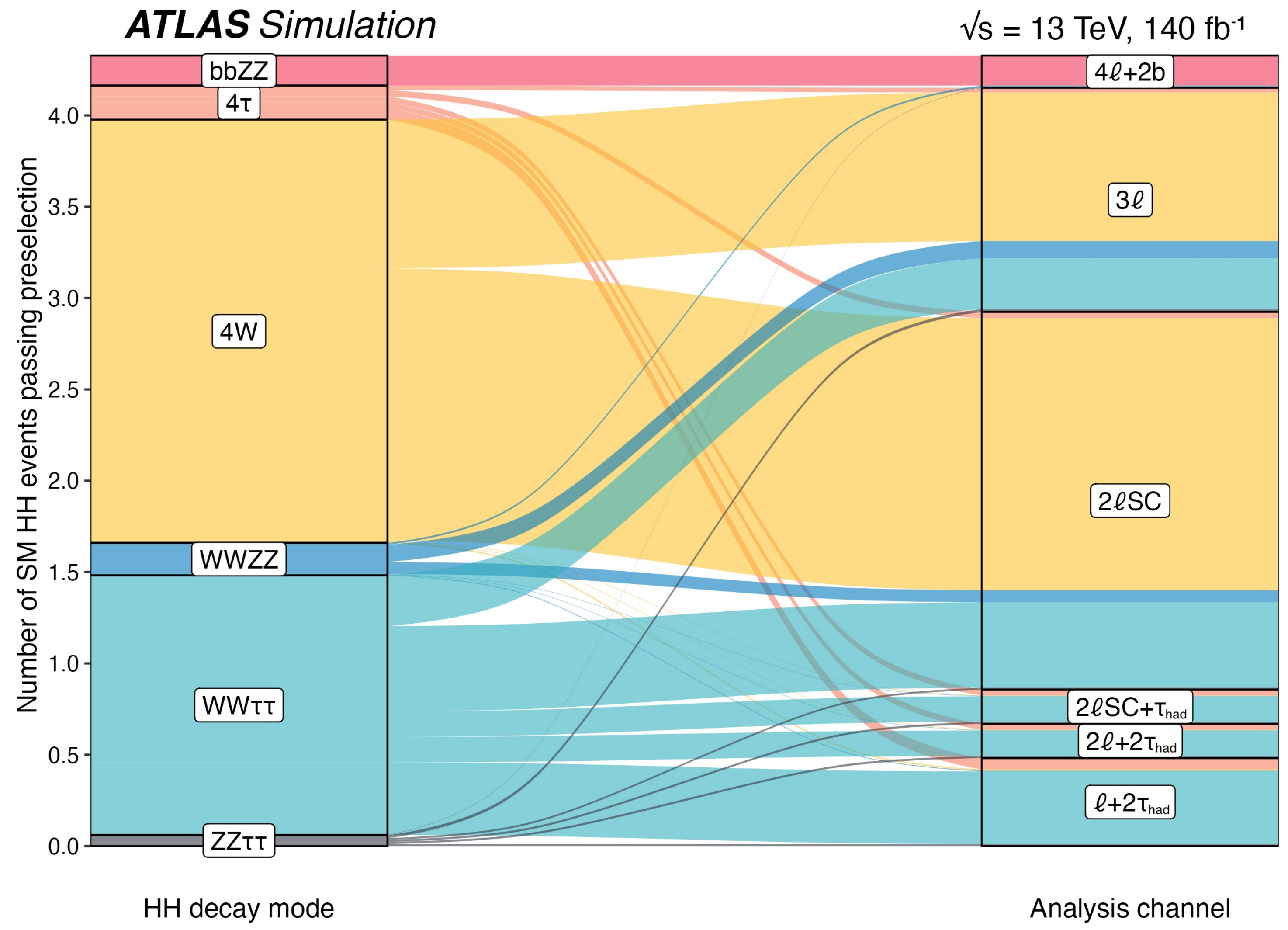
HH→bbℓℓ





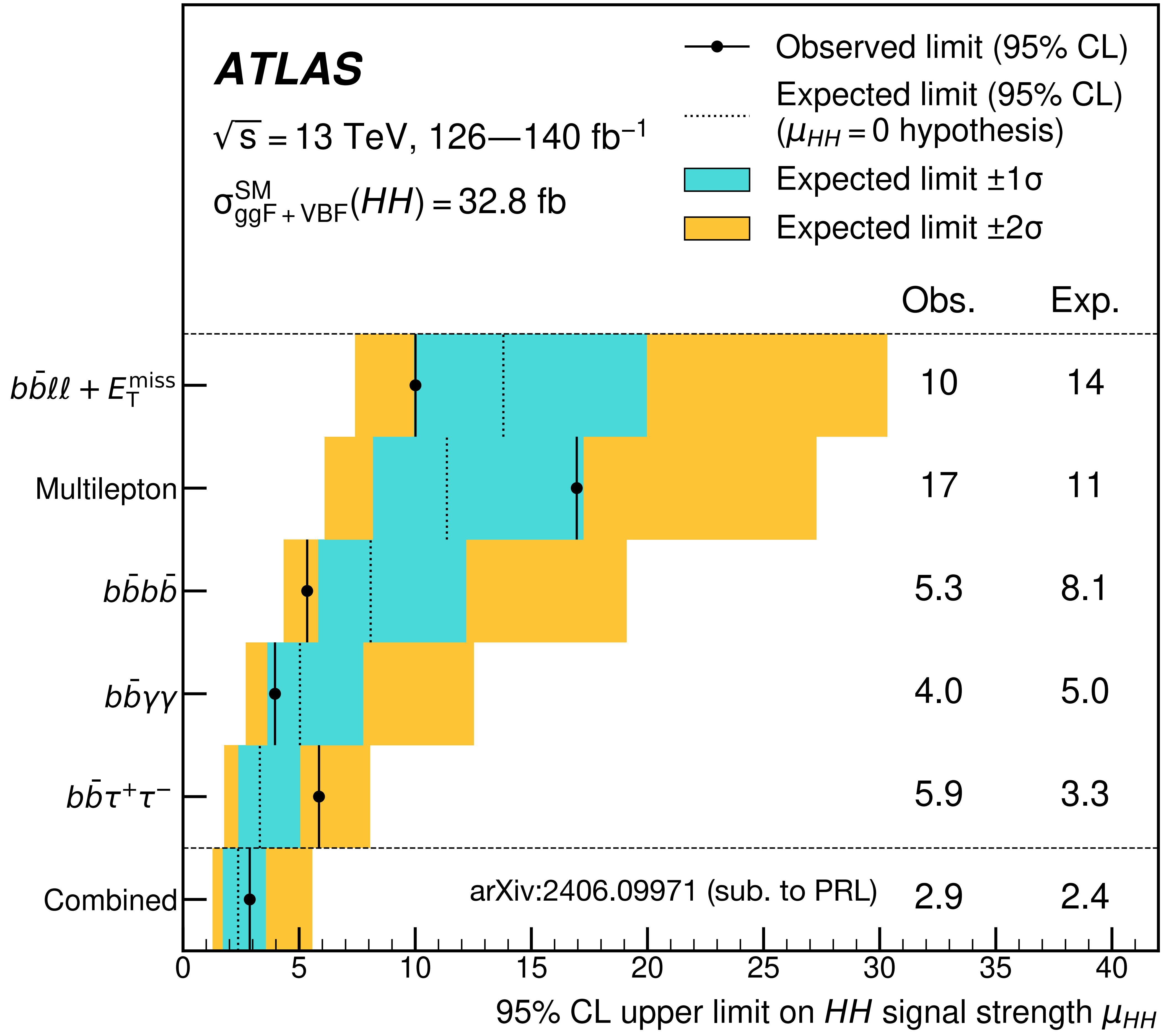
Multi-lepton and photons

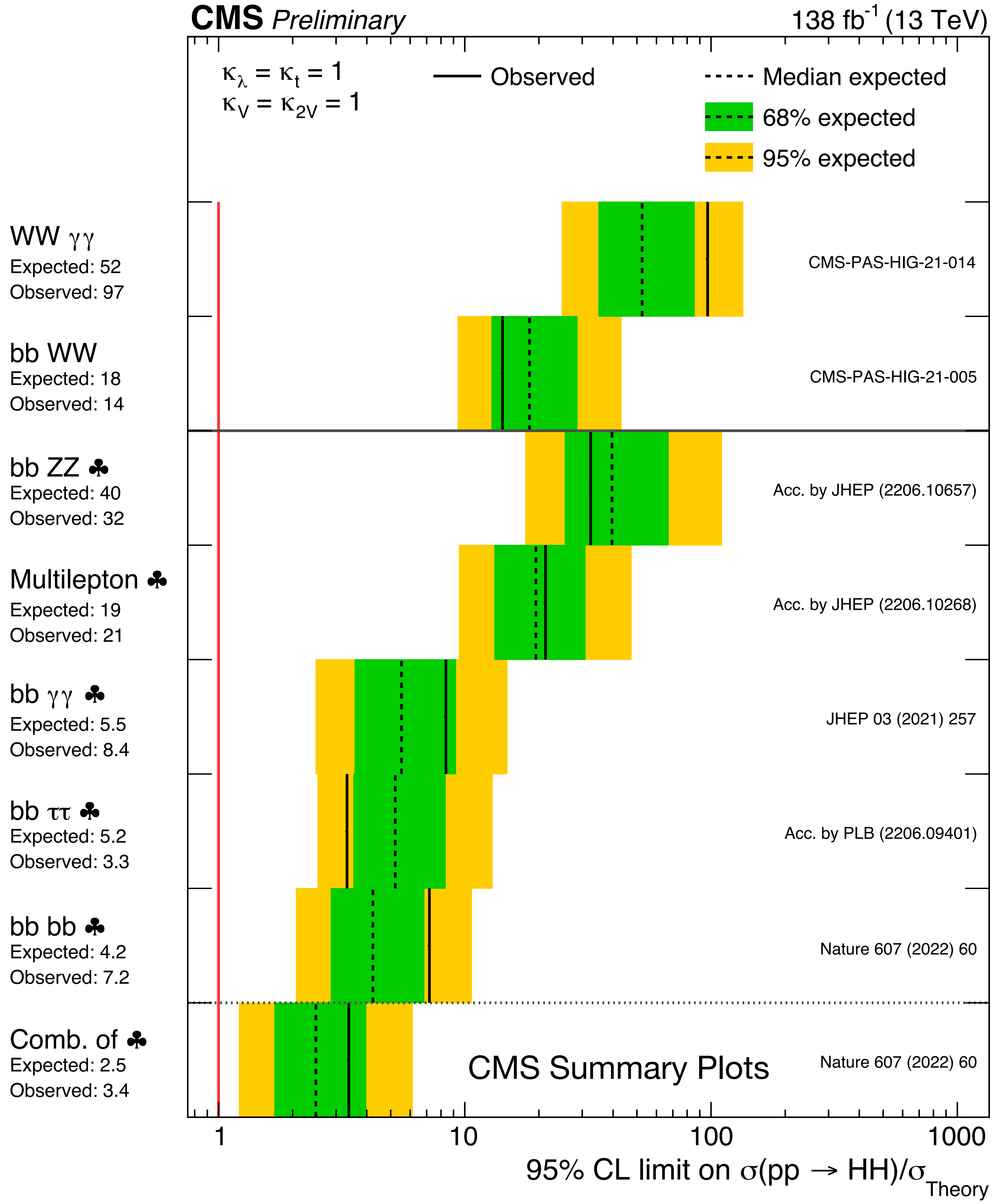




- More channels, albeit less sensitive, are studied to maximise the overall experimental sensitivity to HH

Summary of the full Run 2 results : SM HH



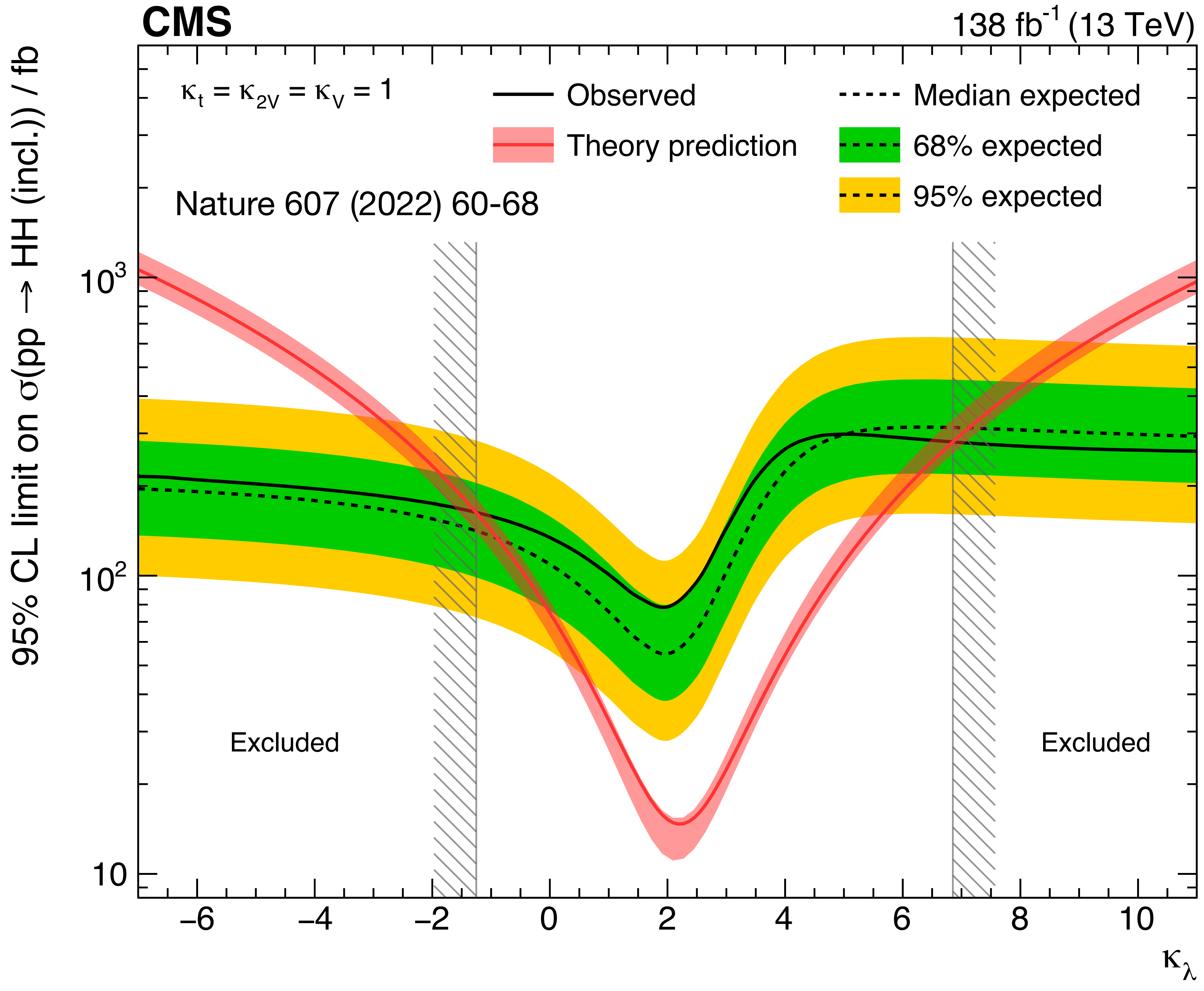


Obs (exp) : 2.9 (2.4) × SM

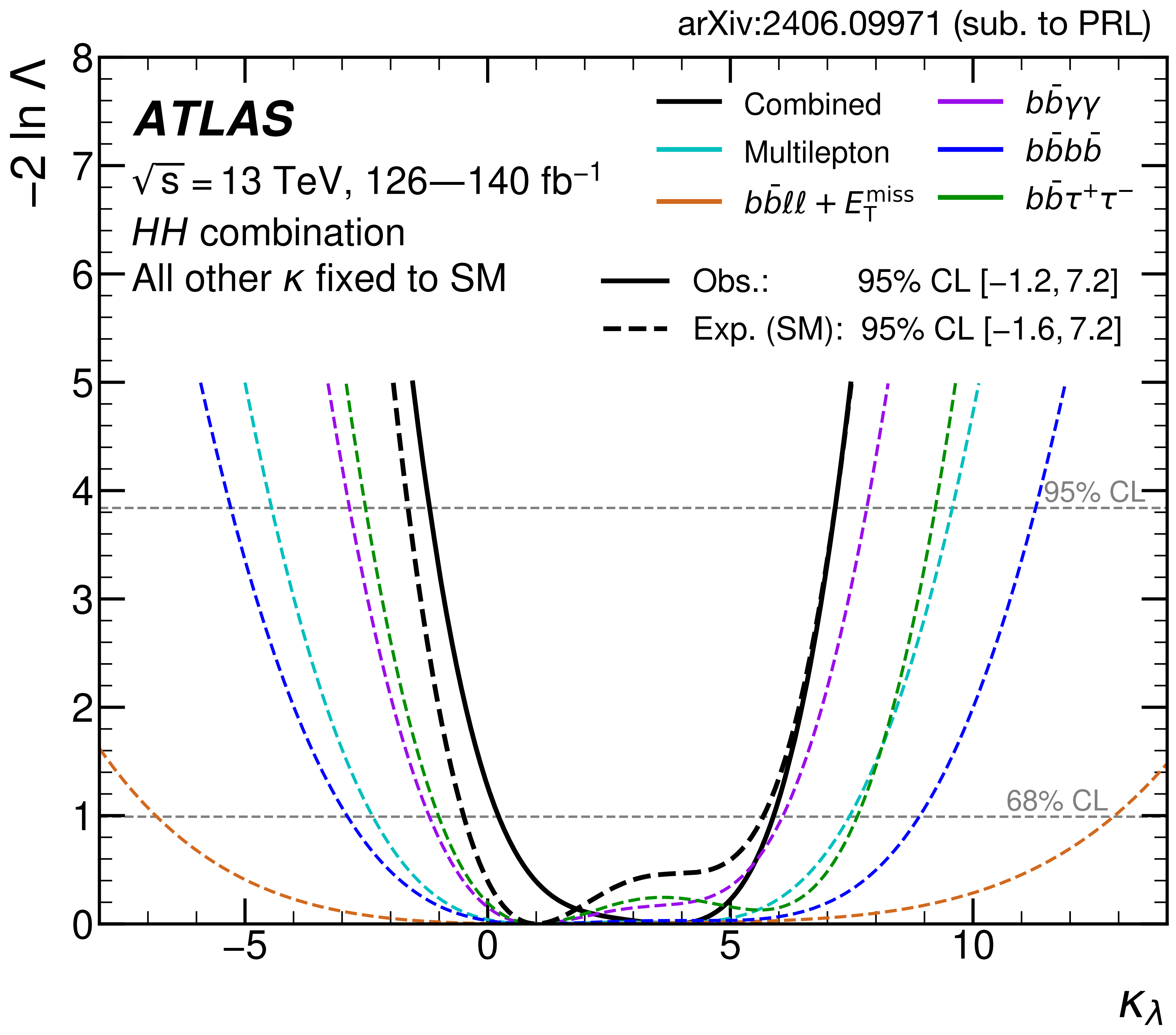
Obs (exp) : 3.4 (2.5) × SM

- Similar sensitivity from ATLAS and CMS
- Results are limited by stat. uncertainties
  - leading theo syst : σ_{HH} cross section (m_{top} scheme), H + heavy flavour bkg normalisation
  - leading exp syst: bkg modelling (bbbb)
- Ongoing effort for an ATLAS+CMS combination

Summary of the full Run 2 results : λ



Observed : $-1.2 < \kappa_\lambda < 6.5$
(95% CL upper limits on σ)

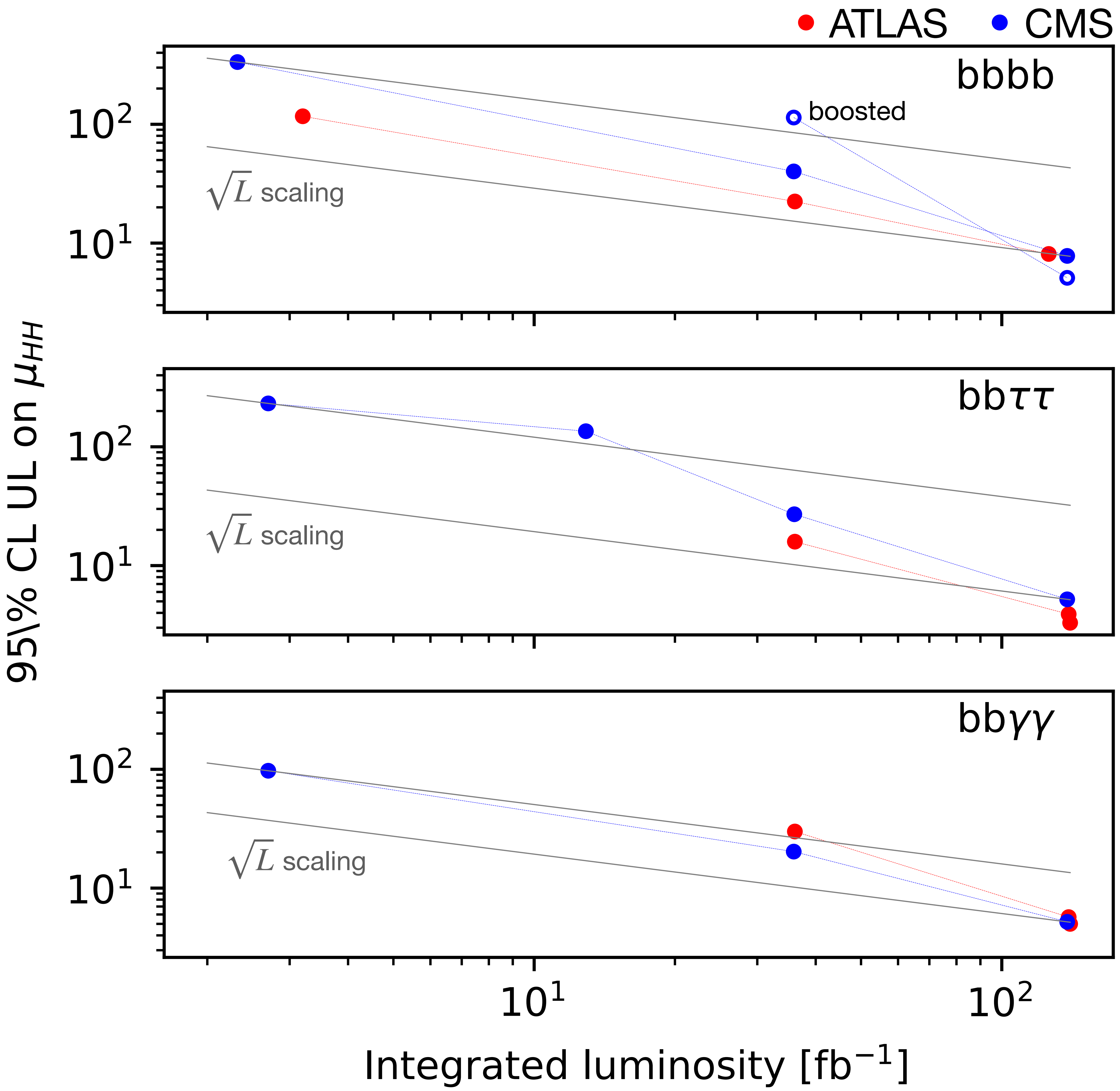


Observed : $-1.2 < \kappa_\lambda < 7.2$
Expected : $-1.6 < \kappa_\lambda < 6.5$
(95% CL from likelihood)

- Effect of interference in gg→HH clearly visible
- $1 \lesssim \lambda \lesssim 5$ hardest region to probe (min xs, soft spectrum)
- Complementarity of channels to cover full κ_λ (m_{HH}) spectrum

Sensitivity maximised with combination

An impressive evolution over the Run 2



- Three main analysis iterations over the Run 2
  - 2015 first Run 2 data set (2.3-3.2 fb^{-1})
  - 2016 data set (~ 36 fb^{-1})
  - full Run 2 data set (~ 140 fb^{-1})
- ×2-3 analysis sensitivity improvement on **top of the luminosity scaling** at each iteration
  - equivalent impact to further ×4-×9 dataset increase

Analysis improvement largely exceeded the simple luminosity scaling

Just a few years ago…

A few examples from papers from 10-20 years ago

HH→bbbb was considered hopeless

In total, inclusive dihiggs production with decay to four b quarks has a signal-over-background ratio S/B which is too bad to be a suitable search channel, al-

As concerns the various decay channels, although the $4b$ final state is the dominant one, it suffers from huge QCD background. The most promising channel at the LHC is thought to be the rare decay

The decay with the highest branching ratio is the $b\bar{b}$ channel. However, the production of a Higgs boson pair decaying into four b quarks is overwhelmed at the LHC by a huge QCD background that results in a very small signal to background ratio. Main decay

The small signal cross section combined with the huge QCD $4b$ background make it essentially impossible to determine the Higgs boson self-coupling in $pp \to 4b$. We quantify

Today, bbbb is a leading channel in the HH study

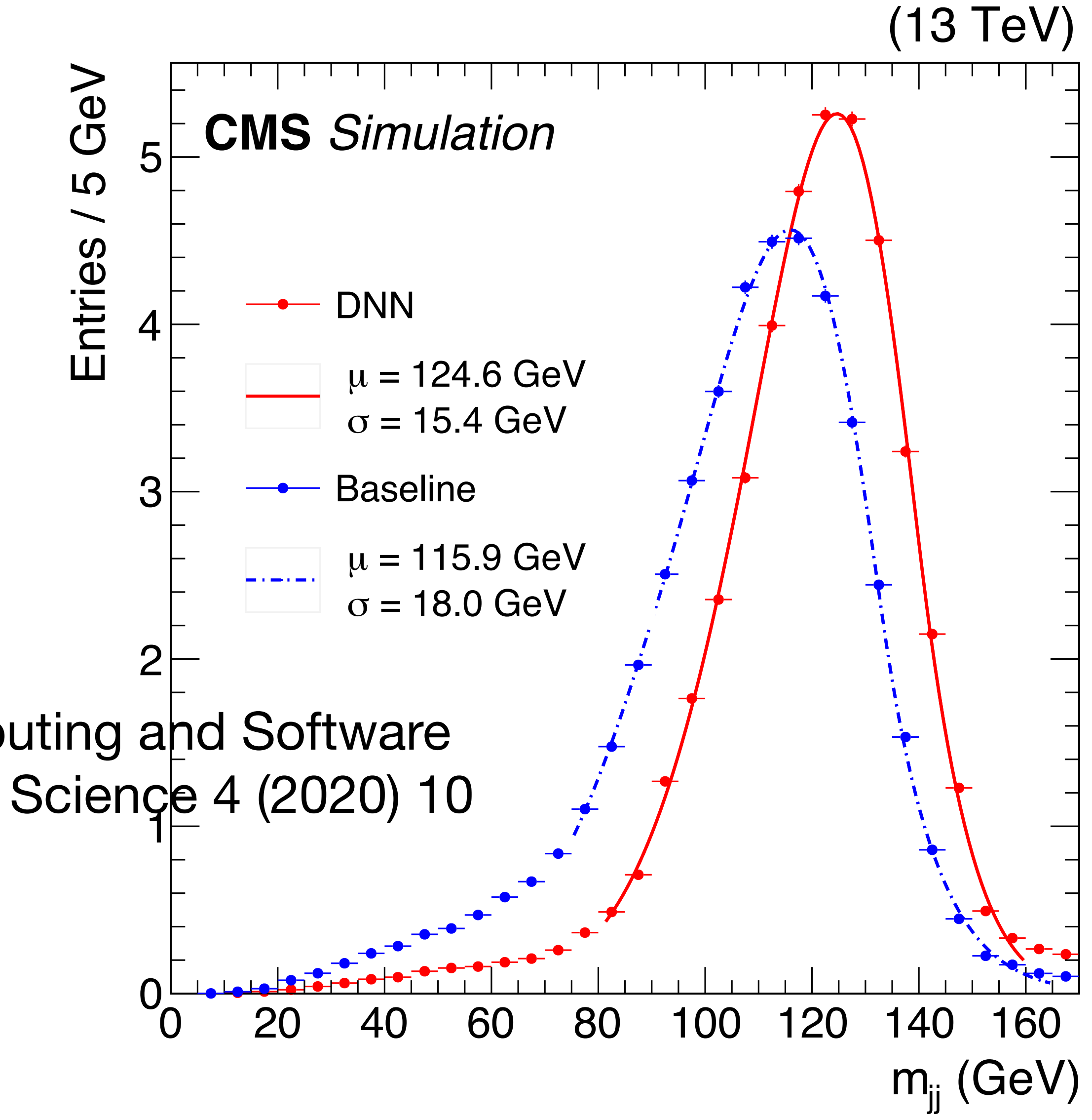
Statements that did not age well

They illustrate the impressive experimental improvements over the past few years

What enabled this improvement?

Improved analysis techniques

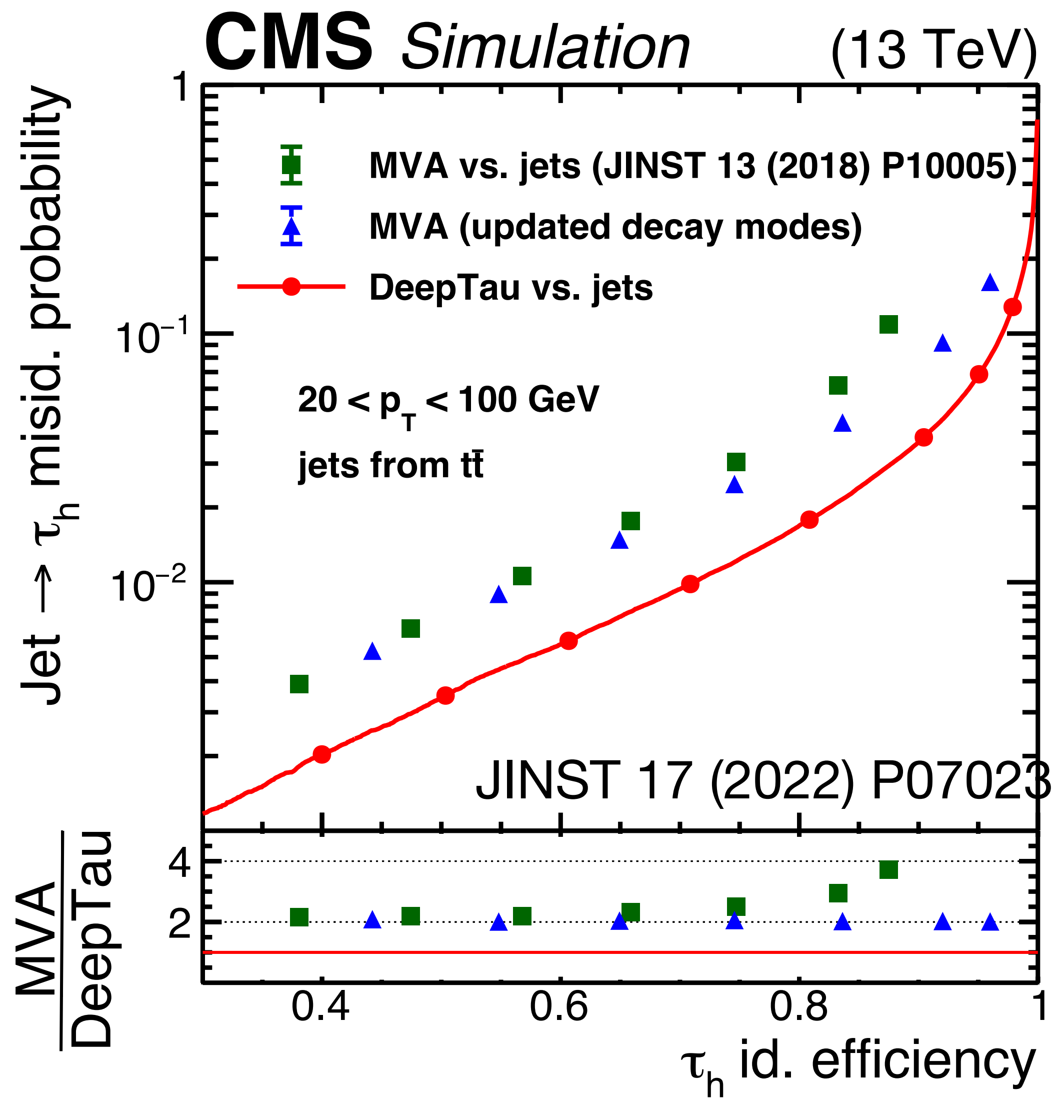
- More data → better exploration of the phase space (categories, selection)
- Better usage of selected events (e.g. bkg estimates, S/B separation)



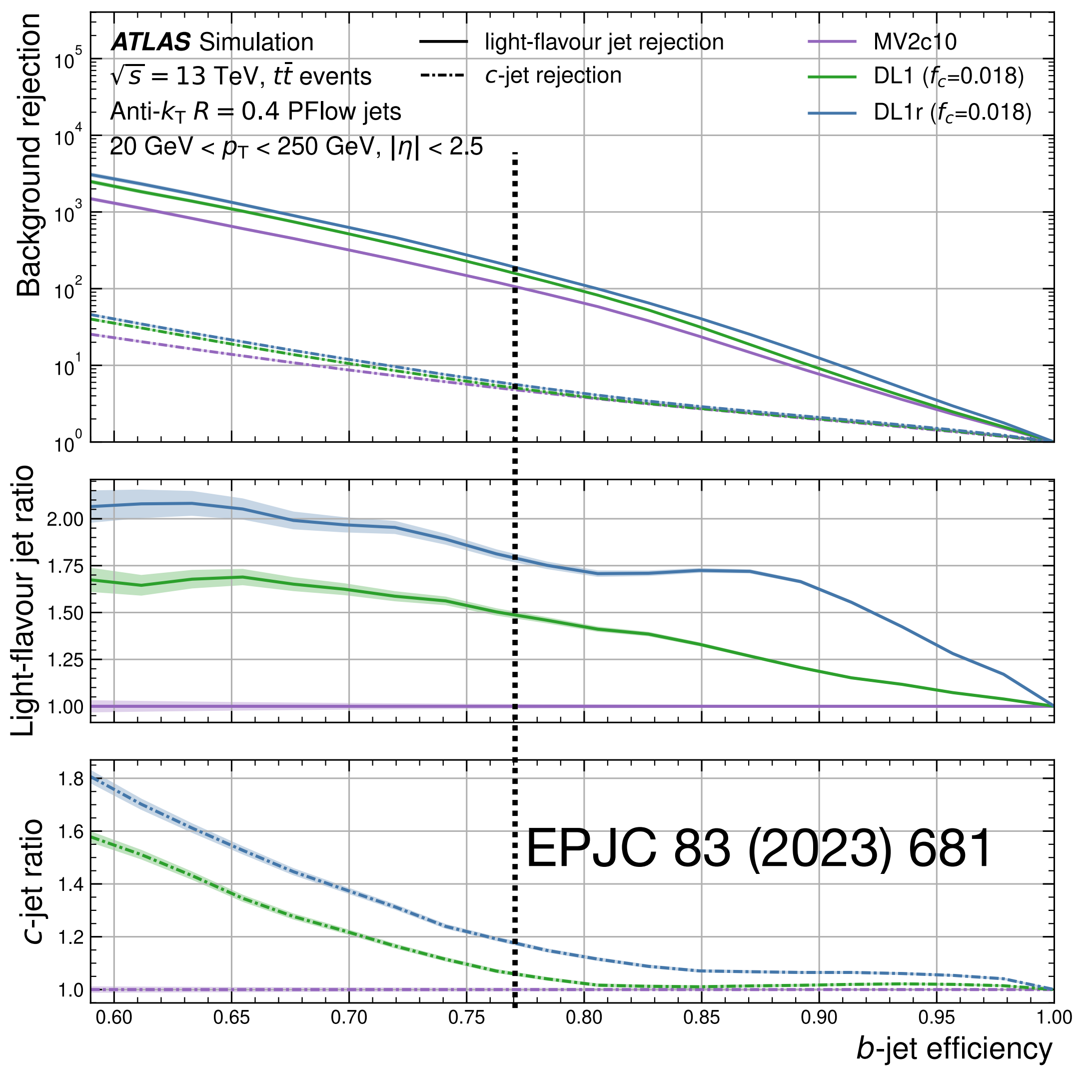
DNN-based m_{bb} regression

Improved object identification

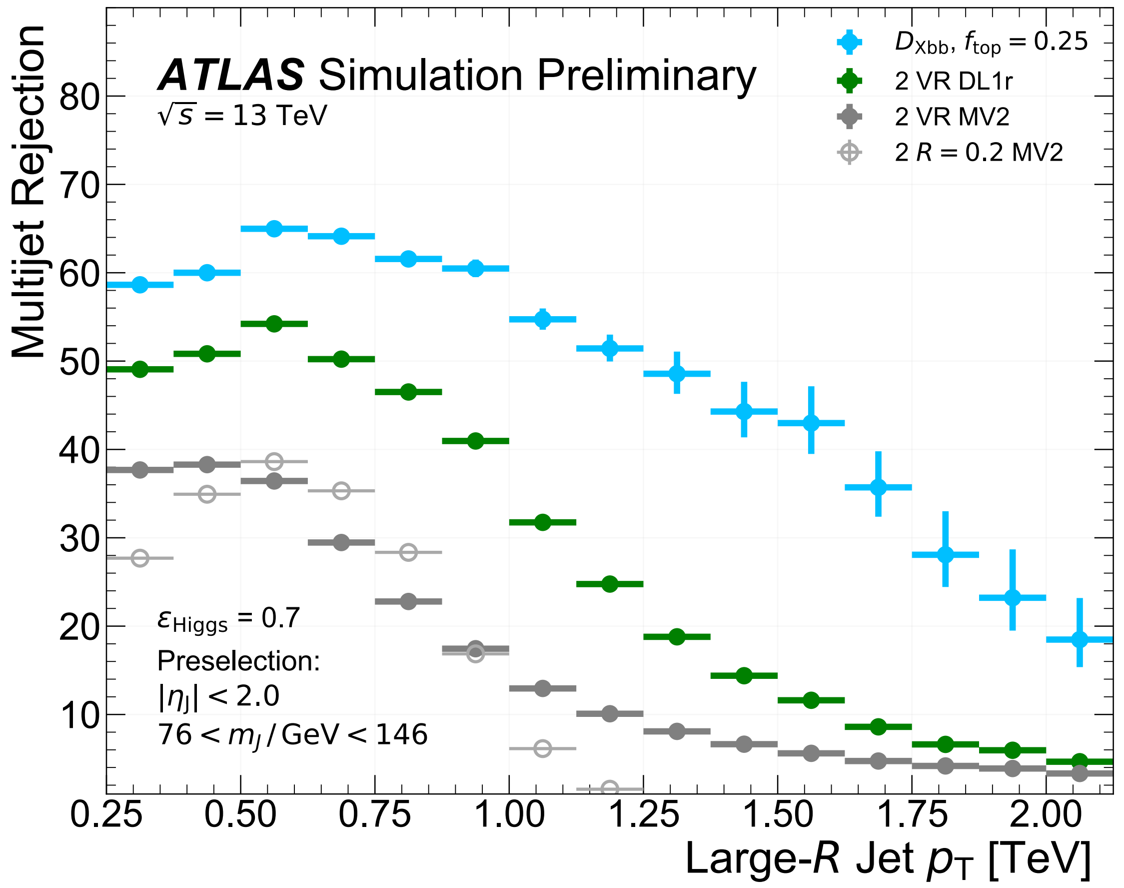
A few examples with a key role in Run 2



Deep Tau for τ_h ID : DNN Particle + high-level inputs



DNN-based for b jet tagging

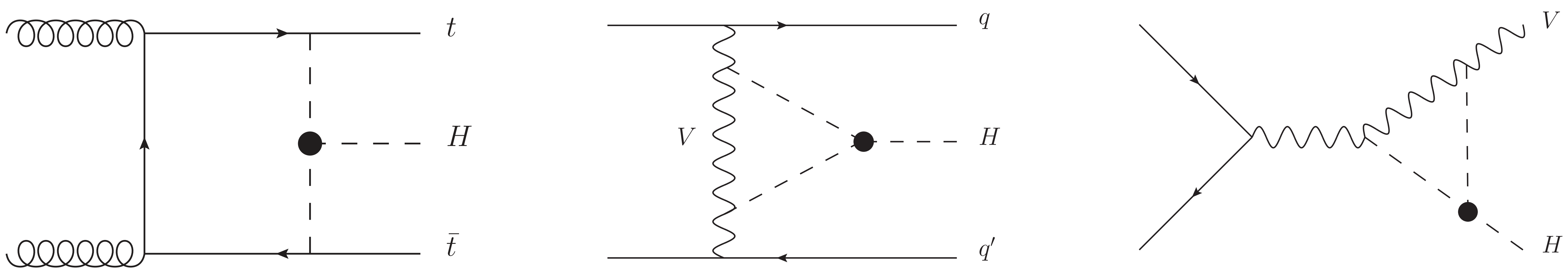


NN for X→bb tagging

- Essential element for the performance of the analysis

Modern ML methods are a key element in both areas

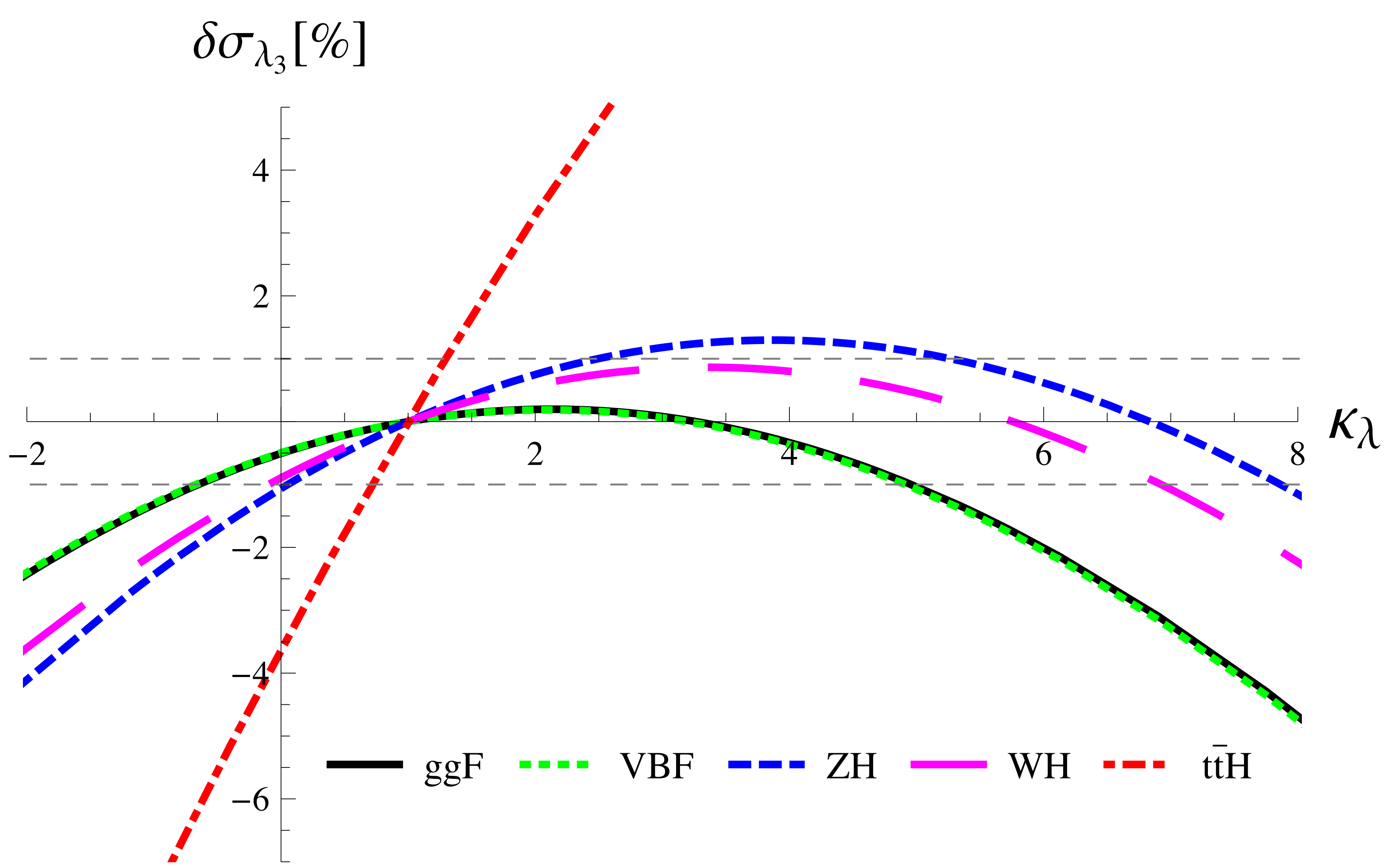
Indirect λ constraints from single H production

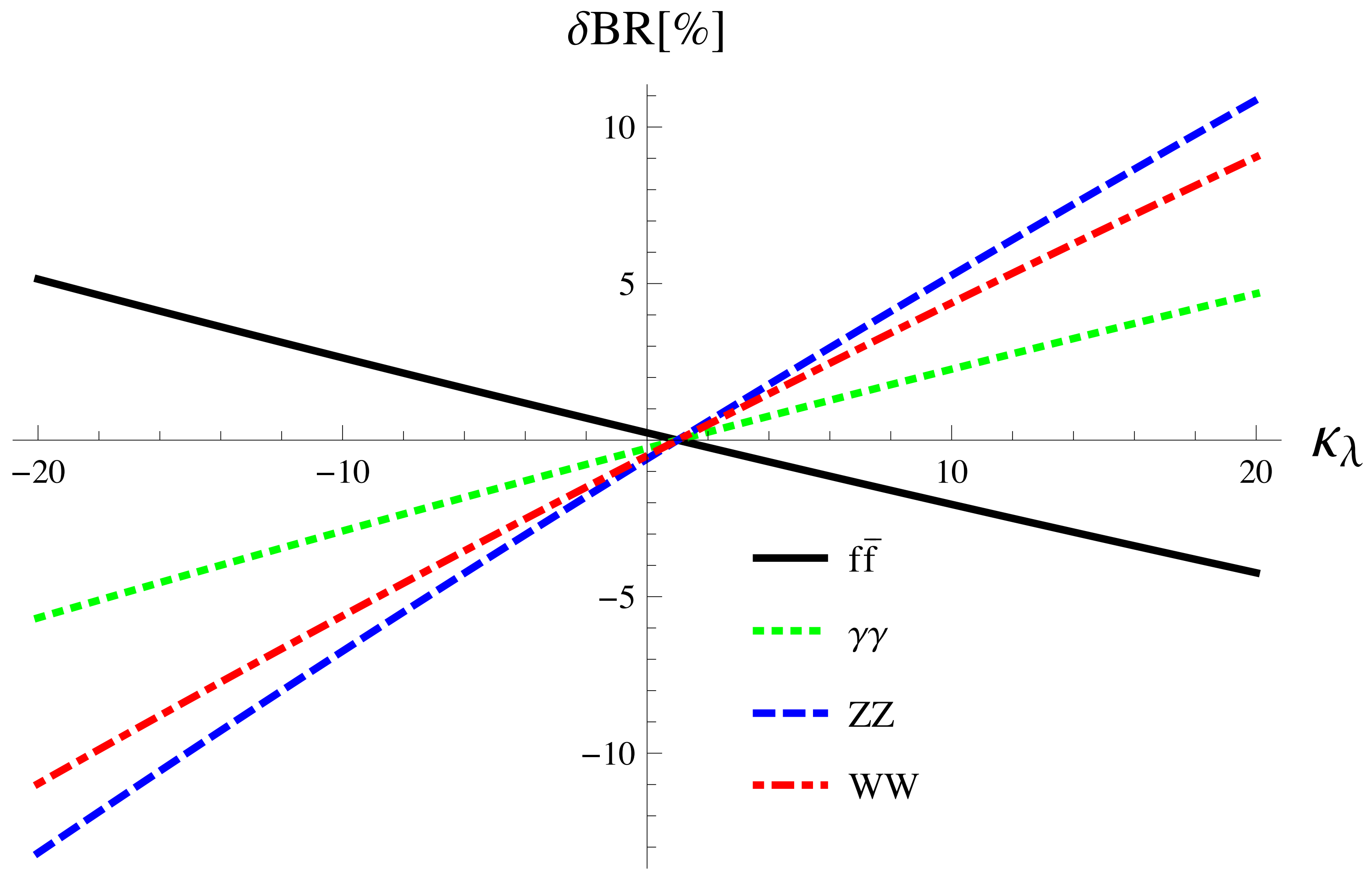


Single H production as a precision tool to look for NLO effects from λ_{HHH}

Simplified template XS single H measurements used as input

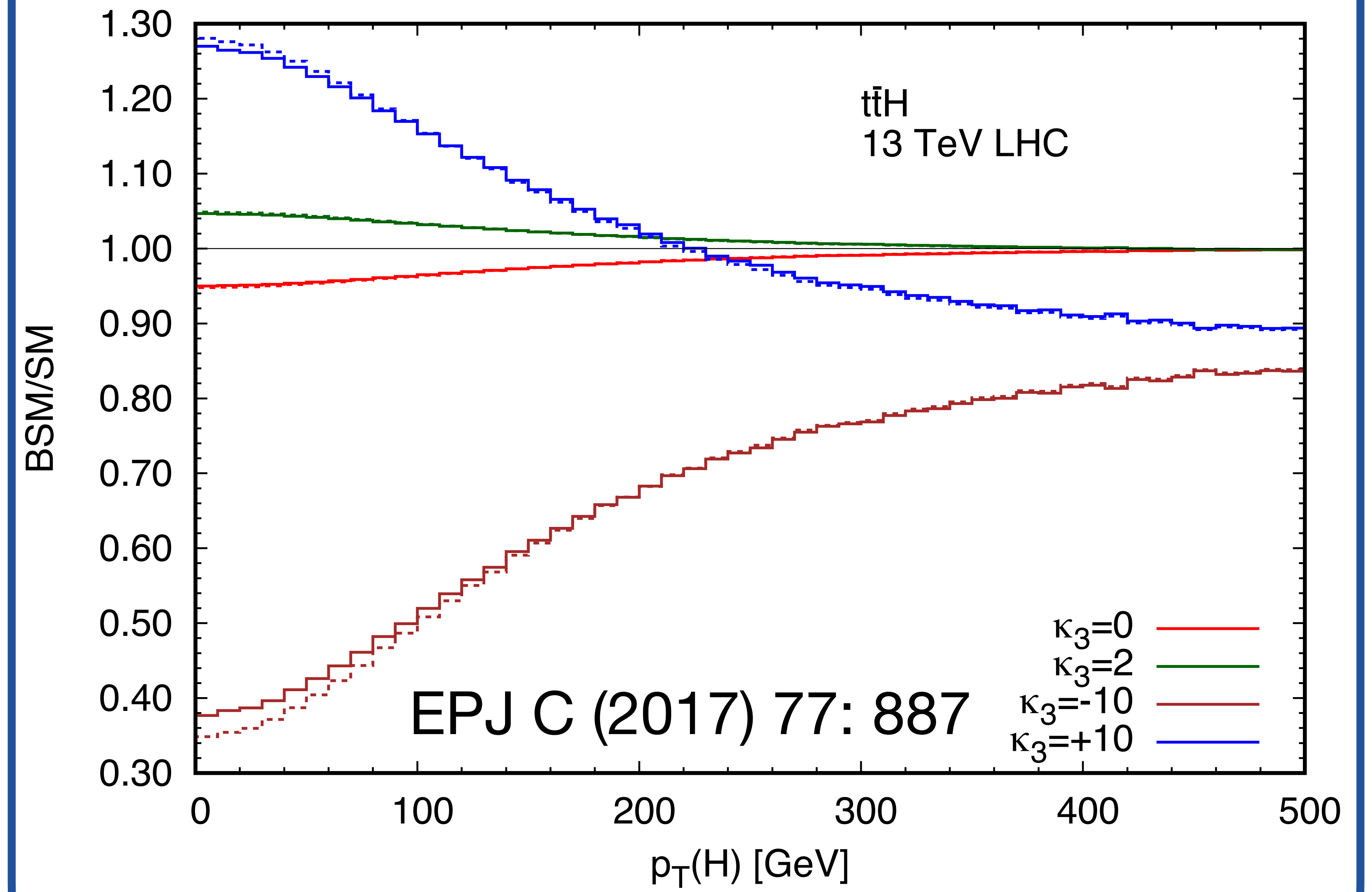
Production xs and decay BR





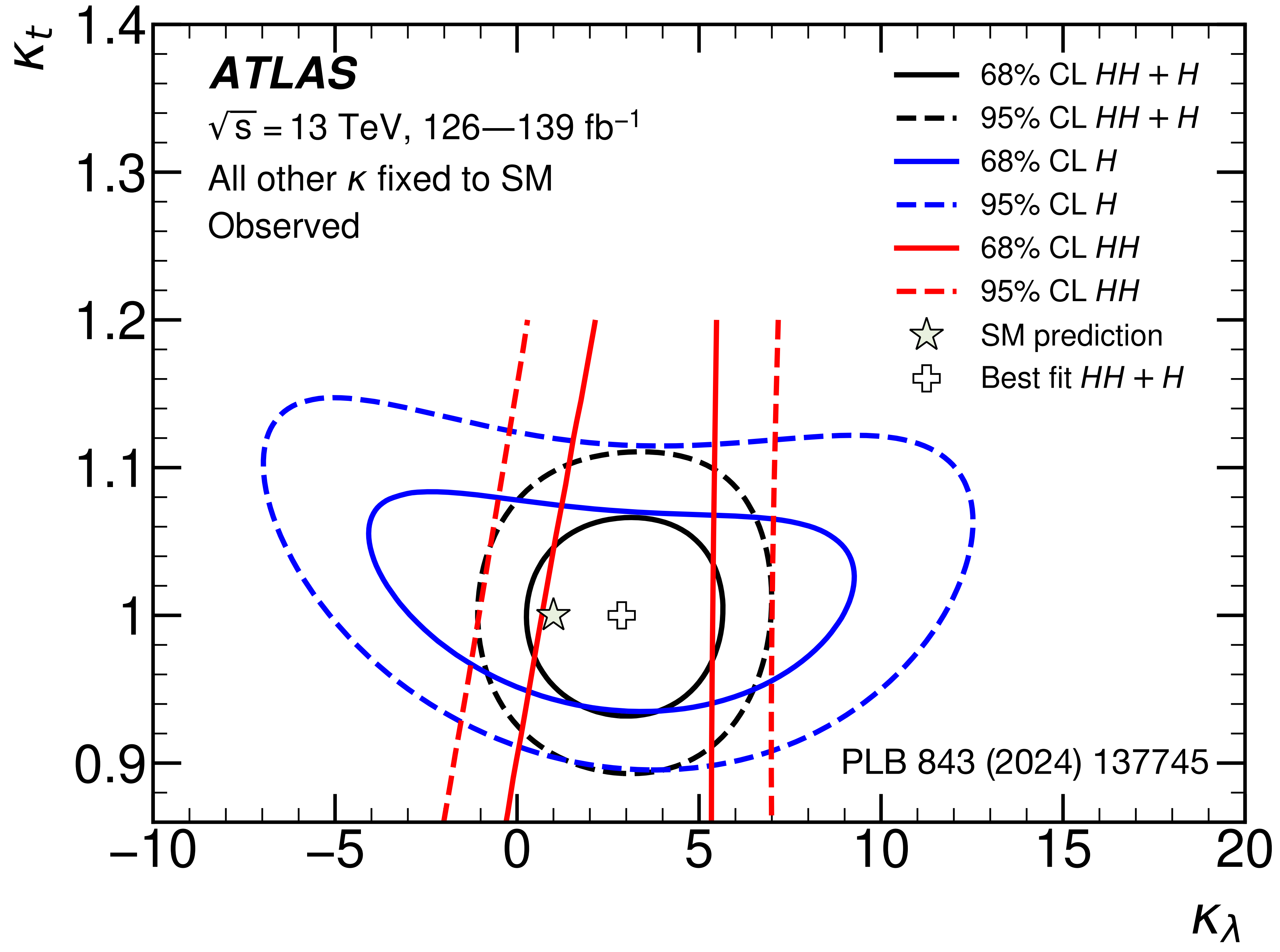
JHEP 1612, 080 (2016)

Differential distributions



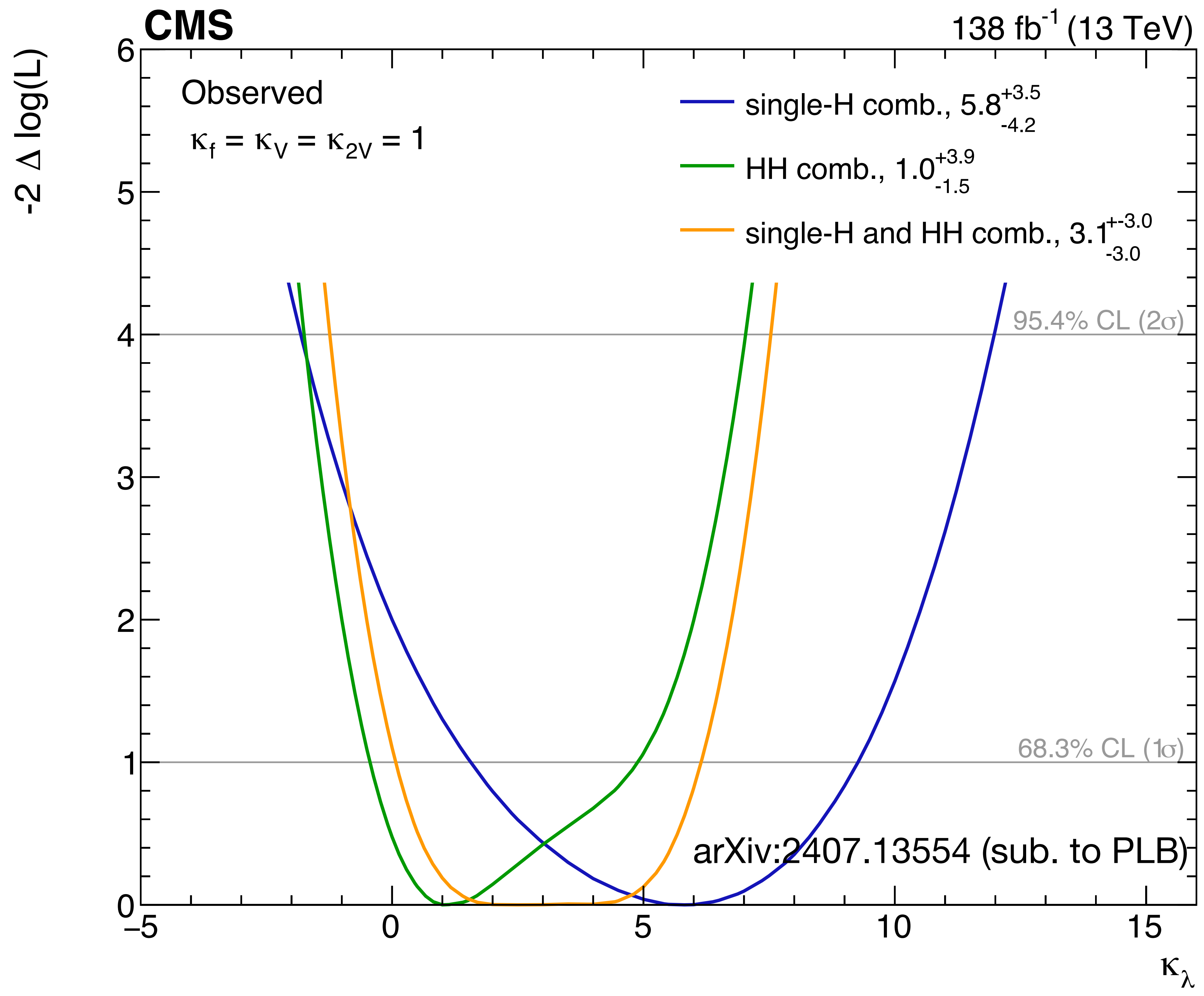
H + HH combination

In gg→HH production
$d\sigma/dx \propto \kappa_t^4\left(1+r+r^2\right)$ with $r = \kappa_\lambda/\kappa_t$



Degeneracy with κ_t in HH lifted thanks to the independent κ_t measurement

κ_λ effects in single H standalone cannot be disentangled from other couplings



Degeneracy with κ_V, κ_f in single H lifted thanks to combined κ_λ constraint

Outline

Effective field theories in HH

Vector boson fusion production of HH

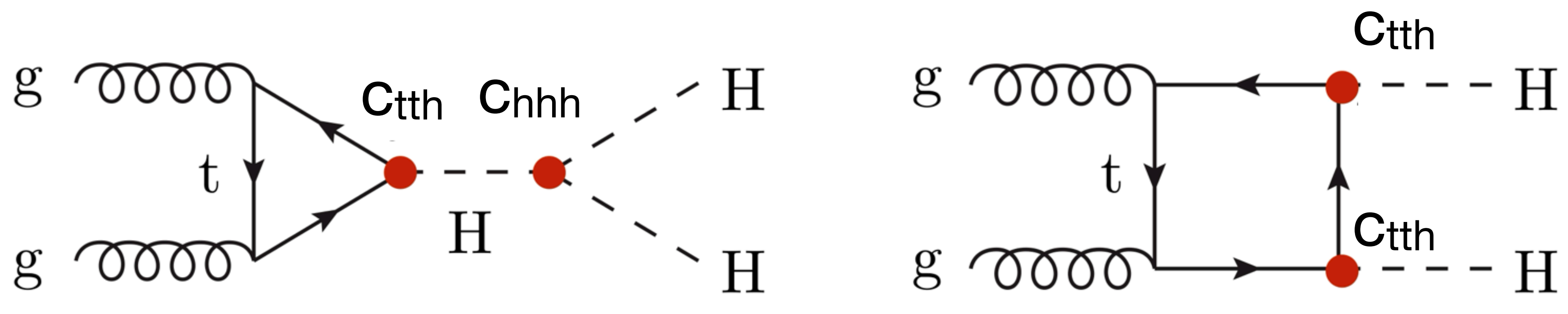
Resonant HH and YH production

HH as a probe for new physics

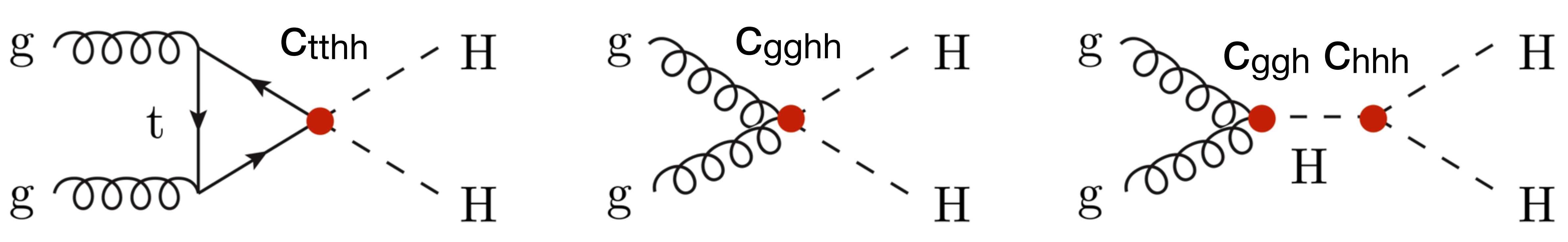
Effective Field Theories in HH

New physics might be beyond the direct energy reach of the LHC

Parametrise its low energy effects with Effective Field Theories



Modification of the strength of SM interactions



New BSM effective contact interactions

SMEFT

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

dim-6 ggF HH studied so far

Wilson Coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$
c_{HG}	$H^\dagger H G^A_{\mu\nu} G^{\mu\nu}_A$
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}G^A_{\mu\nu}$

- Preserves SM symmetries (Higgs doublet)
- Correlation between interaction strengths (ggH-ggHH, ttH-ttHH)

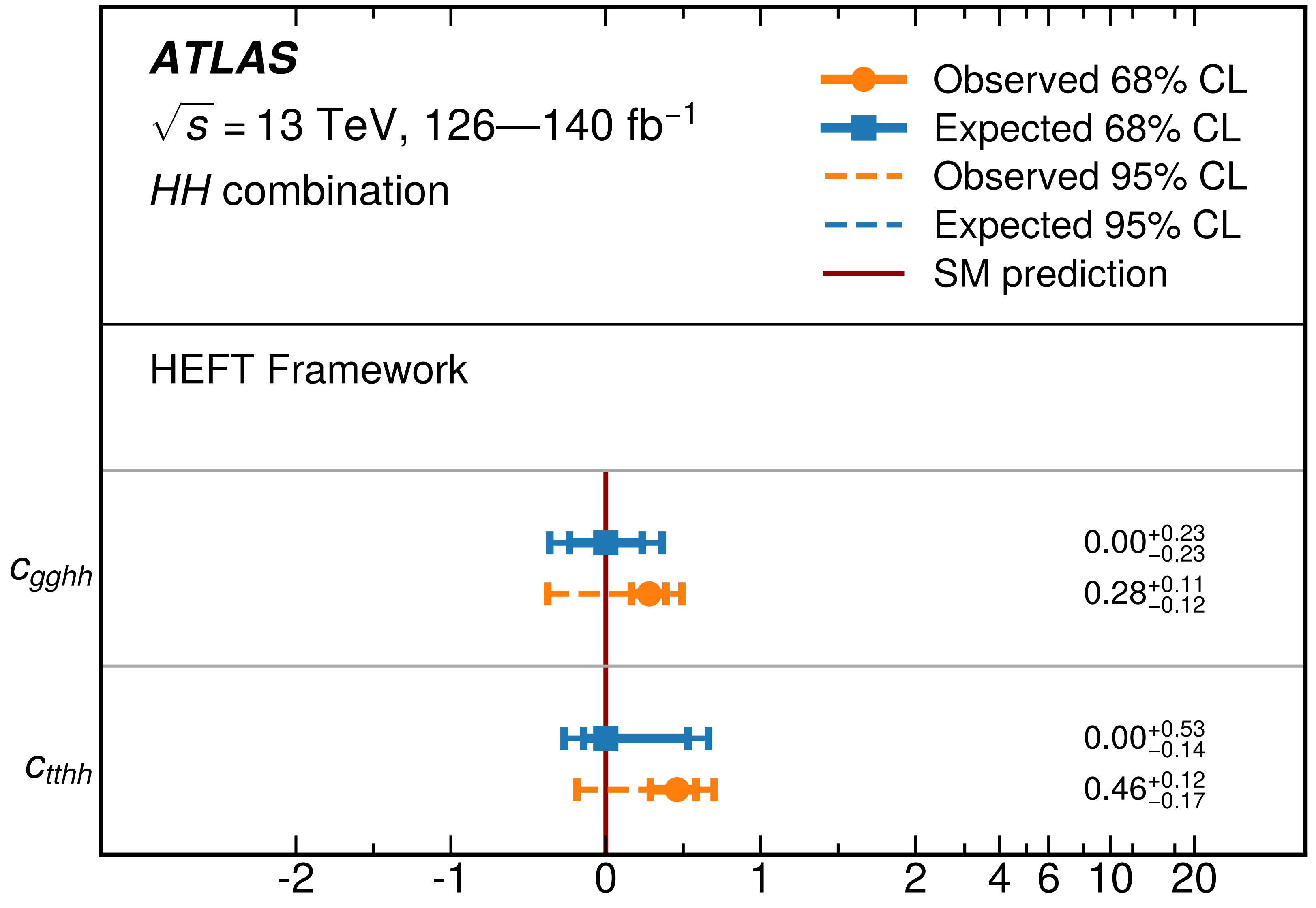
HEFT

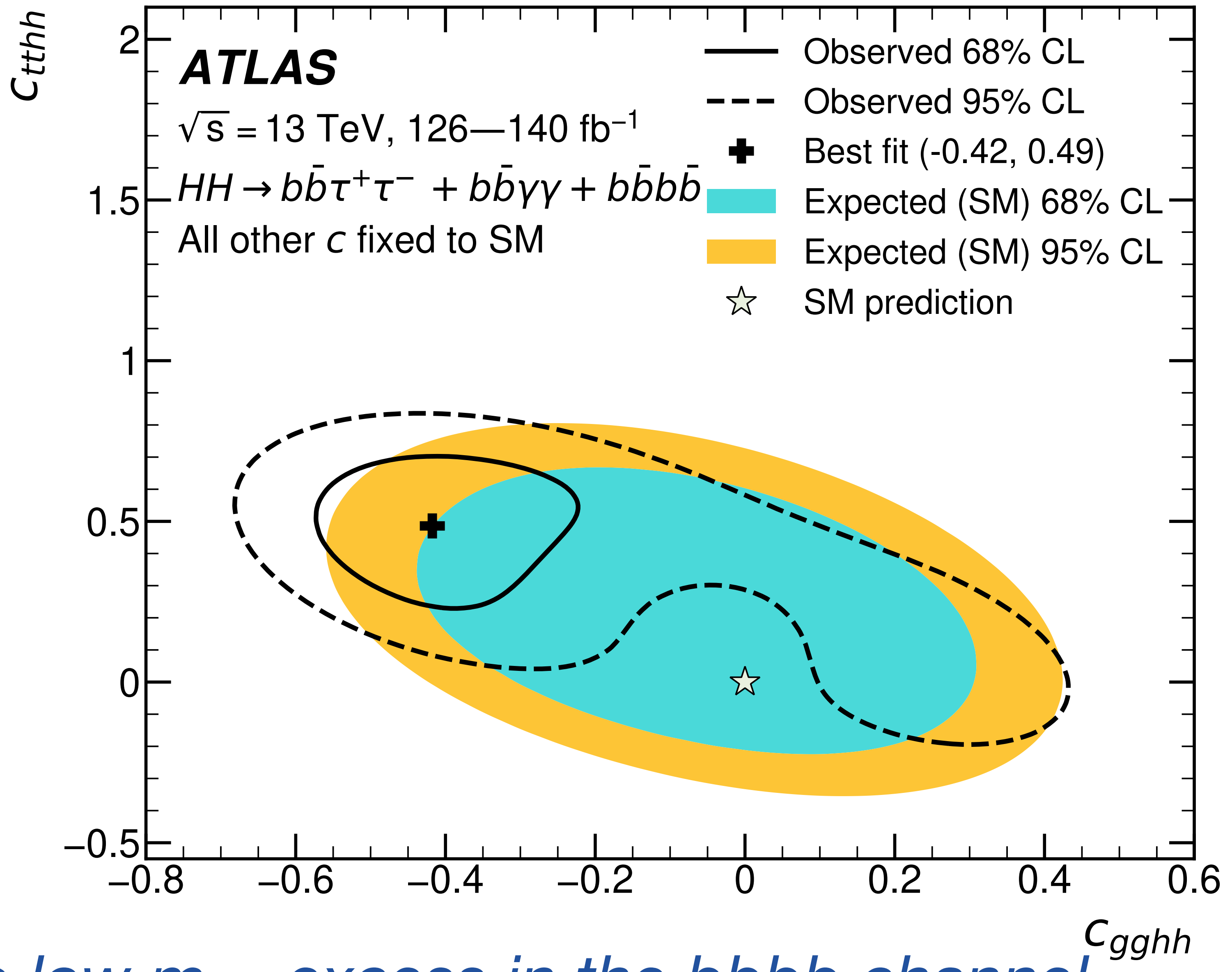
- More generic extensions of the SM
- More parameters → 5 independent interactions strengths for gg→HH

$$\mathscr{L}_{\text{HEFT}} \supset -m_t\left(C_{tth}\frac{h}{v} + C_{tthh}\frac{h^2}{v^2}\right)\bar{t}t - C_{hhh}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}\left(C_{ggh}\frac{h}{v} + C_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}$$

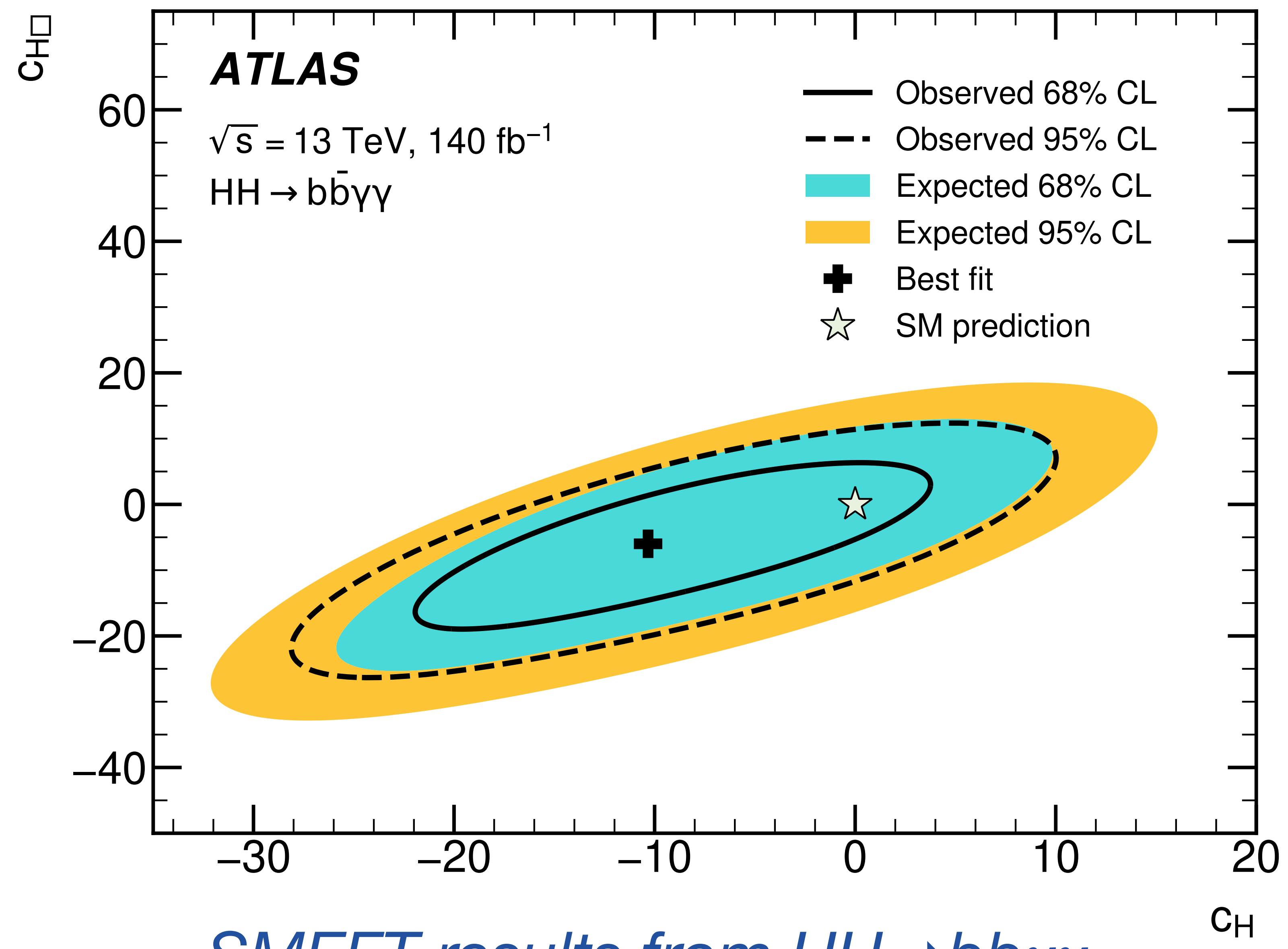
EFT results

- Large EFT effects on total and differential cross section (LHCHWG-2022-004) modelled by analyses





JHEP 01 (2024) 066



Tension with the SM in HEFT fit mostly due to low m_{HH} excess in the bbbb channel

HEFT results also from CMS in individual analyses

SMEFT results from HH→bbγγ

- Constraints on operators with HHx vertices
- Will benefit from the analysis of dedicated modes (e.g. ttHH)

- Constraints at the edge of the EFT validity (e.g. lin vs lin+quad boundaries)

Degeneracy between operators : impossible a 5D simultaneous fit

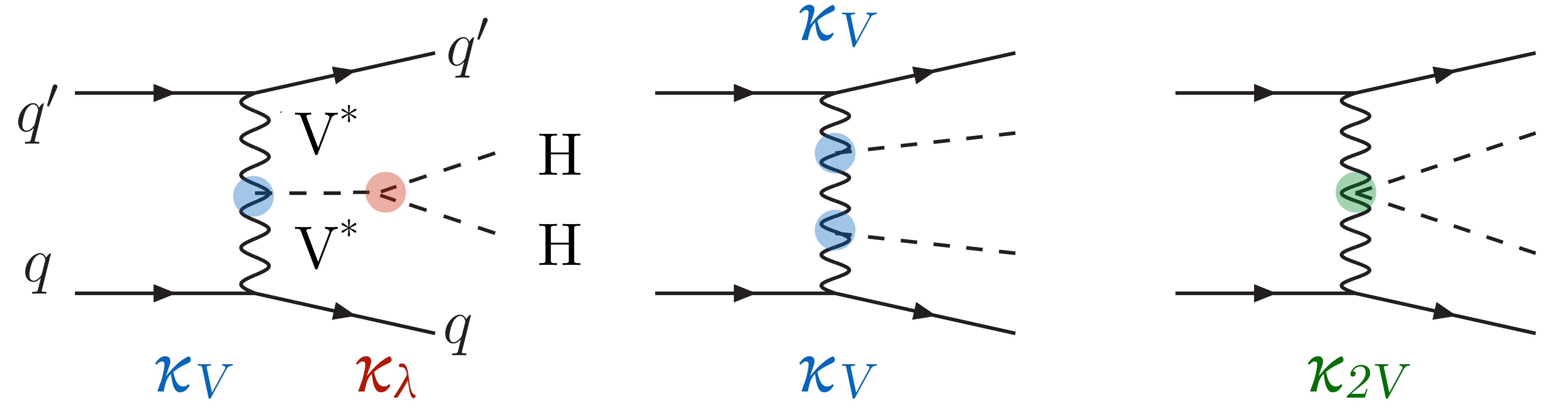
HH as input to full SMEFT fit

HH production via vector boson fusion

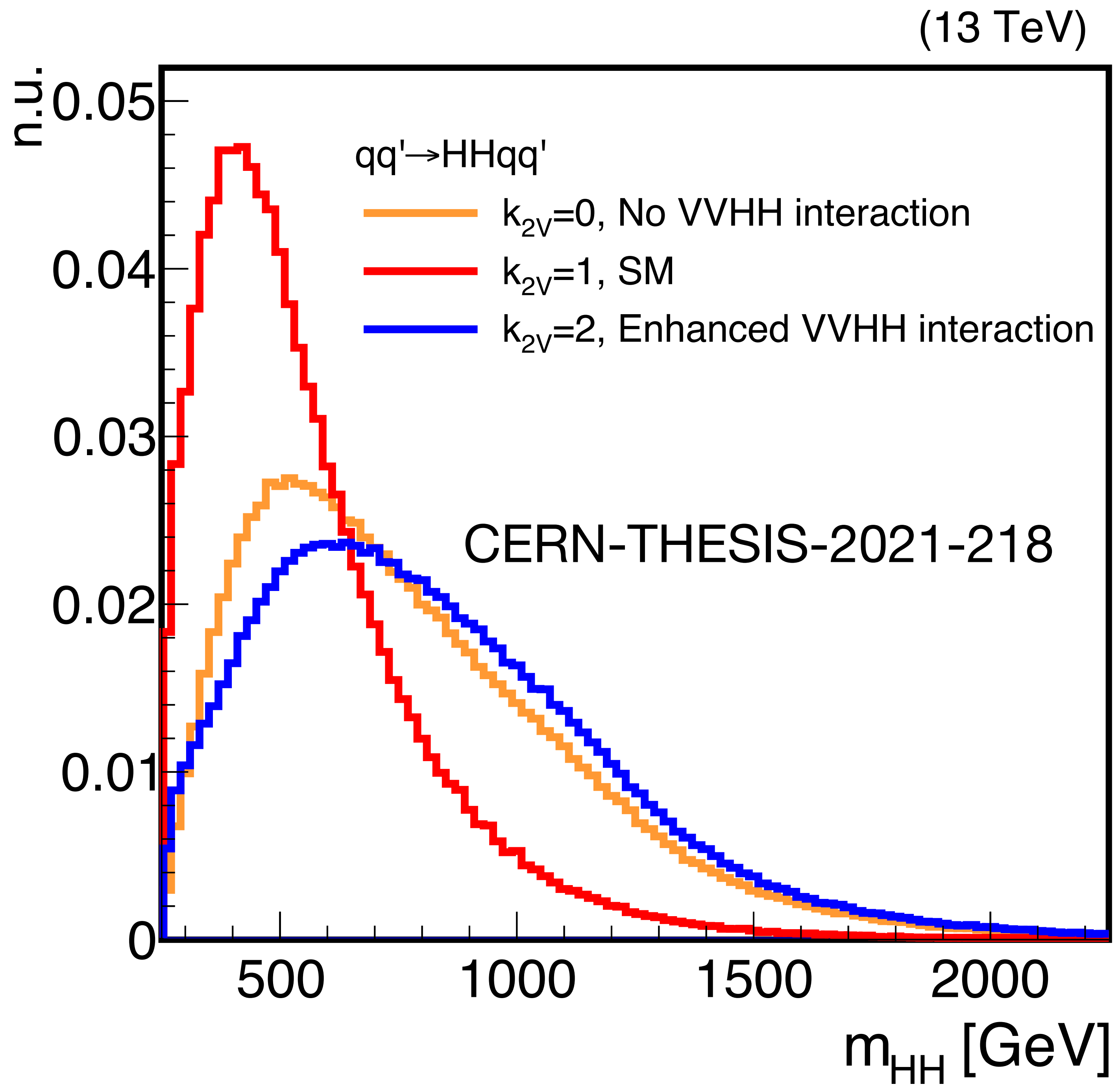
PRD 98, 114016 (2018)

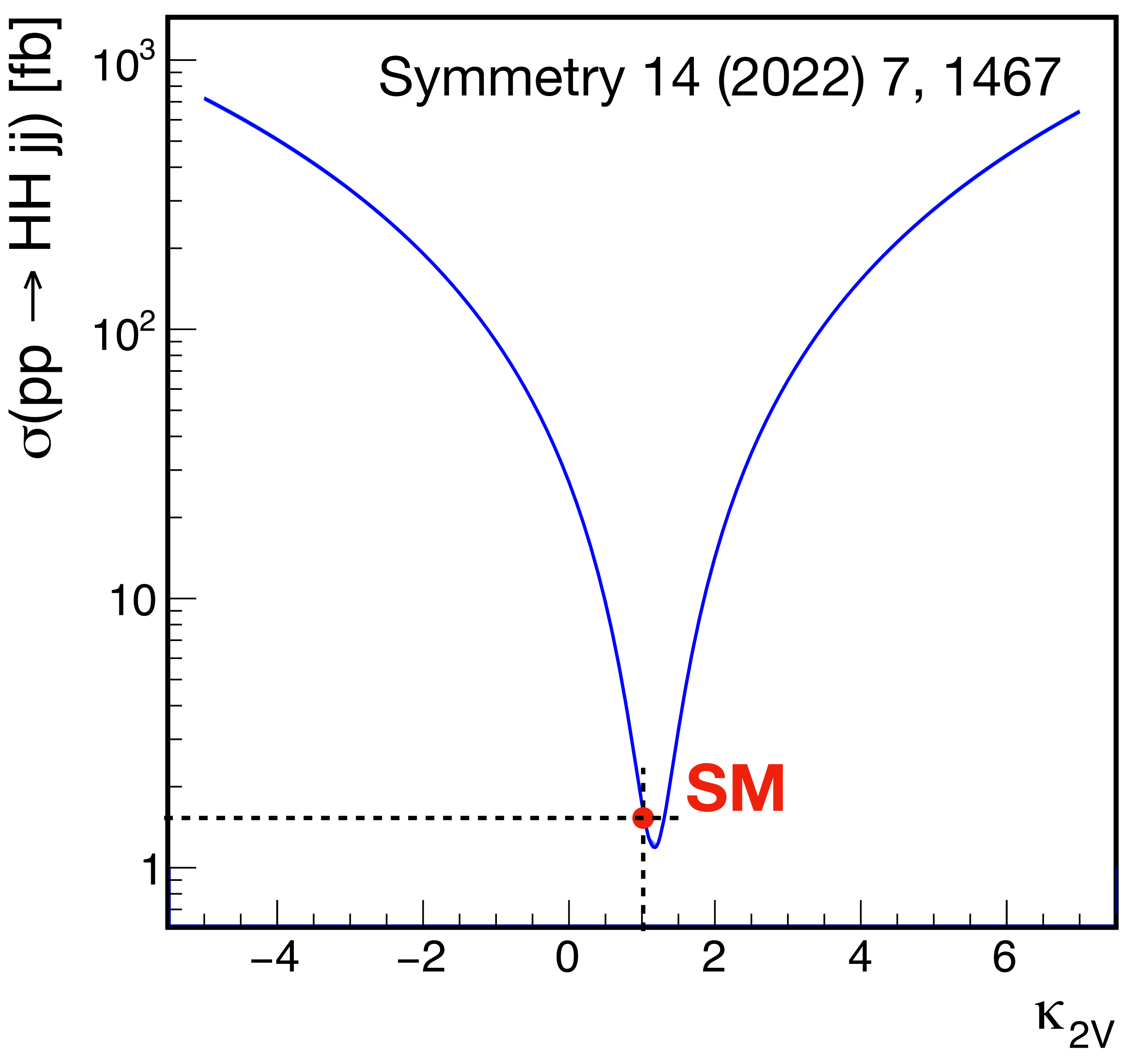
$$\sigma = \begin{matrix} 1.68 \text{ fb } [13 \text{ TeV}] \\ 1.87 \text{ fb } [13.6 \text{ TeV}] \end{matrix} \pm 2.7\%$$

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



Probe for to new physics which could alter this cancellation





- Second production mode at the LHC
- 20 times rares than ggF HH, but unique access to VVHH coupling
- Excellent experimental sensitivity to anomalous VVHH values via high p_T (H)
- In the SM, VVH, VVHH and EWSB are tightly related

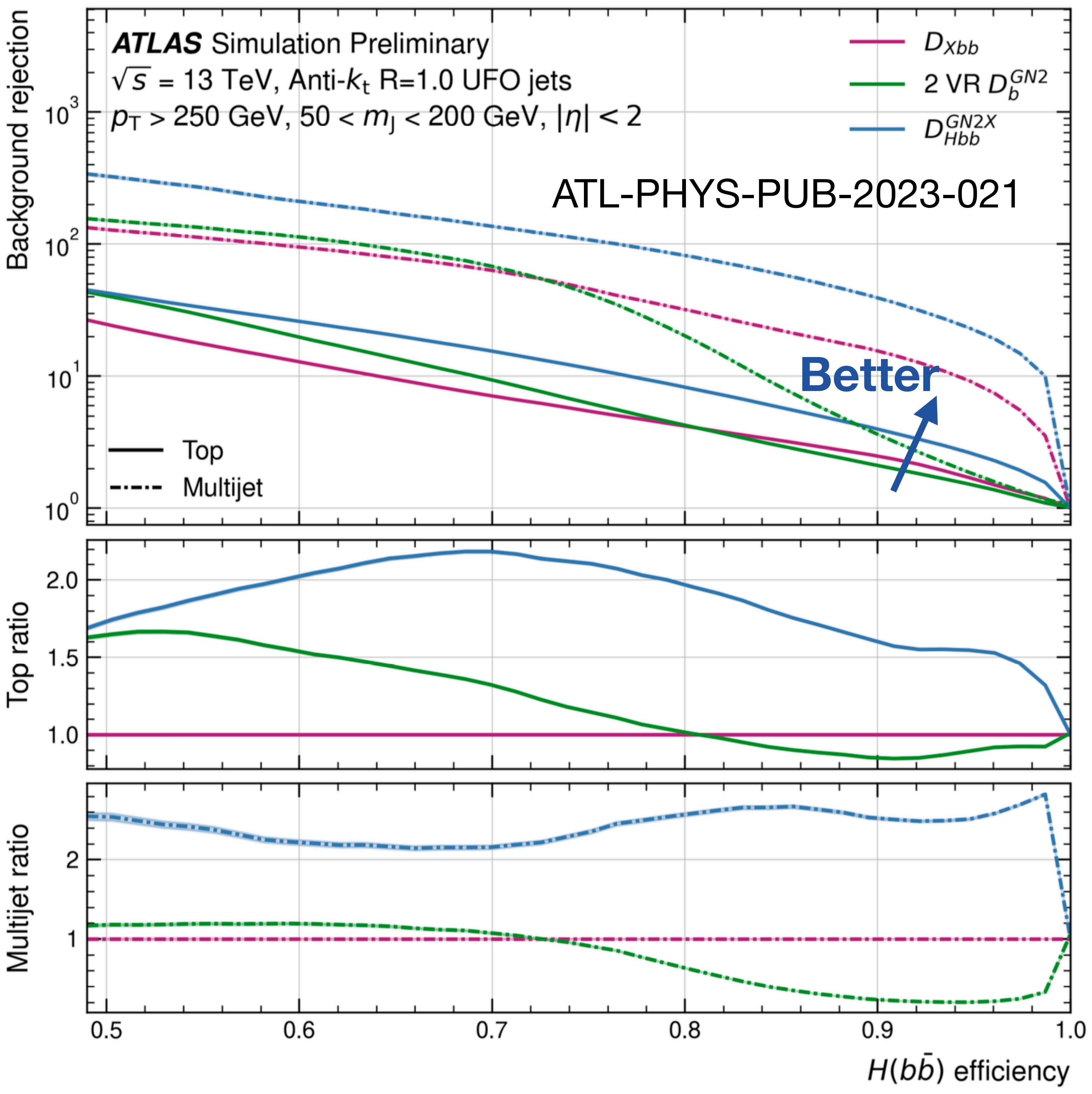
$$\left[\left(\frac{gv}{2}\right)^2 W^{\mu+}W^-_\mu + \frac{1}{2}\frac{(g^2+g'^2)v^2}{4}Z^\mu Z_\mu\right]\left(1+\frac{H}{v}\right)^2$$

Searching for VBF HH

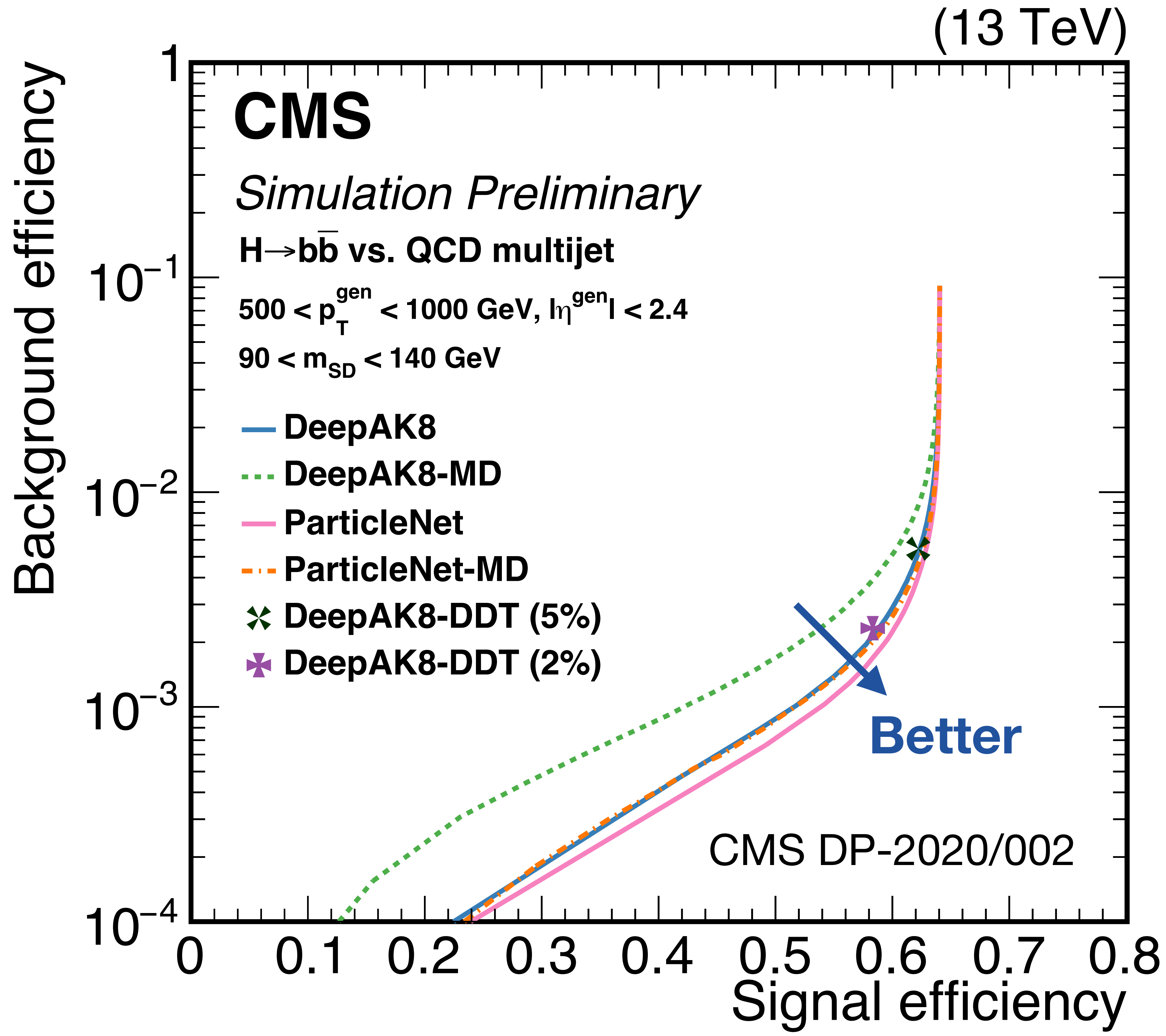
Leading κ_{2V} sensitivity from boosted bbbb (high BR, high $p_T(H)$)

High Δη jet pair : VBF signature

Boosted jet tagging



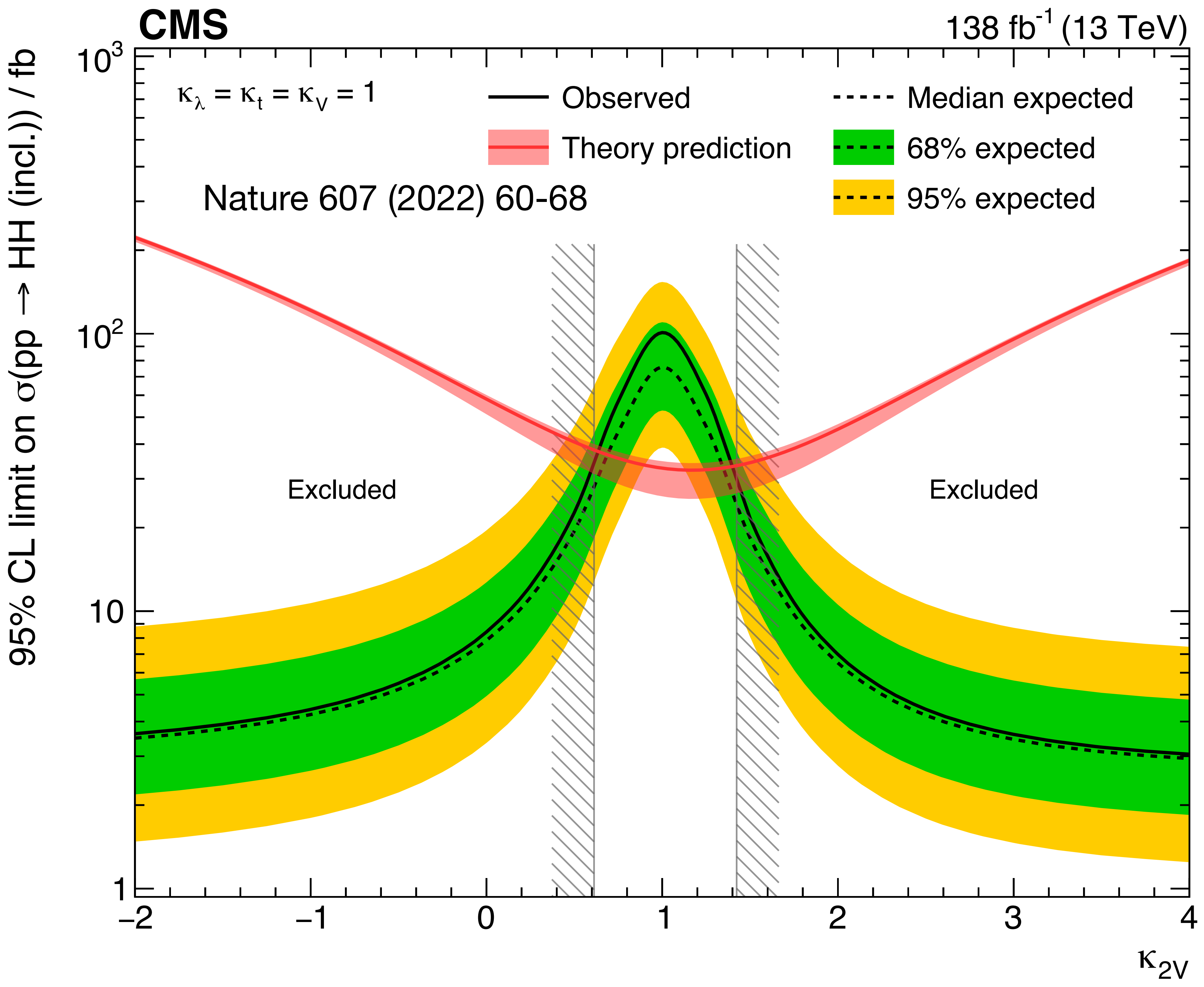
GN2X (transformer architecture)
Not yet used in Run 2 HH results



ParticleNET (graph NN)
Used in VBF boosted HH→bbbb

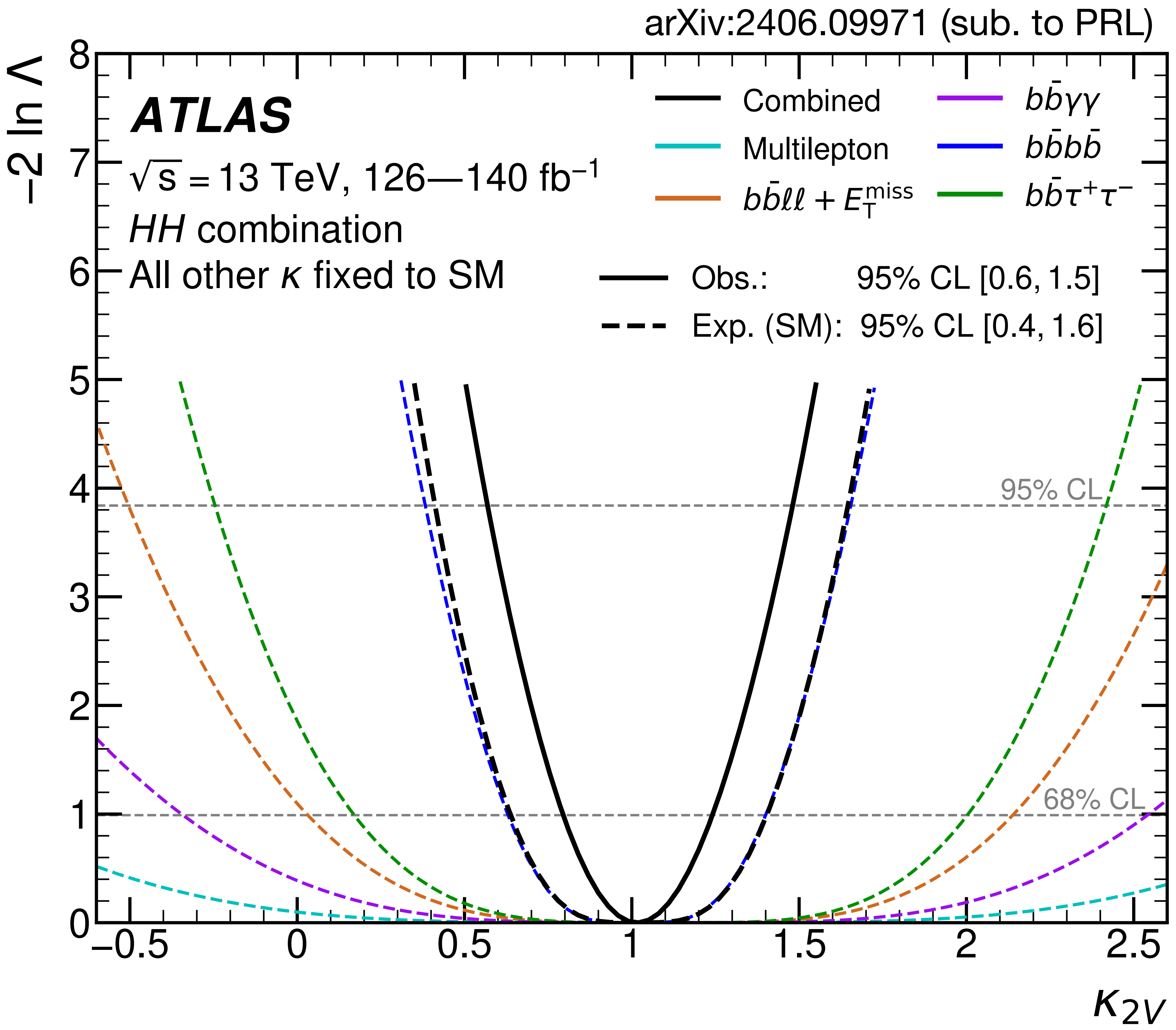
- Shift of paradigm over the last few years : from high-level inputs to individual constituents
- Clear benefits in the performance
  - can be ported to other hadronic objects (e.g. $H\to\tau\tau$ decays)
- Main ingredient in the analysis sensitivity
  - events selected with two boosted jets
  - backgrounds estimated from data control regions
  - signal extracted on m_{HH}

VBF HH results



Observed : $0.7 < \kappa_{2V} < 1.4$
(95% CL upper limits on σ)

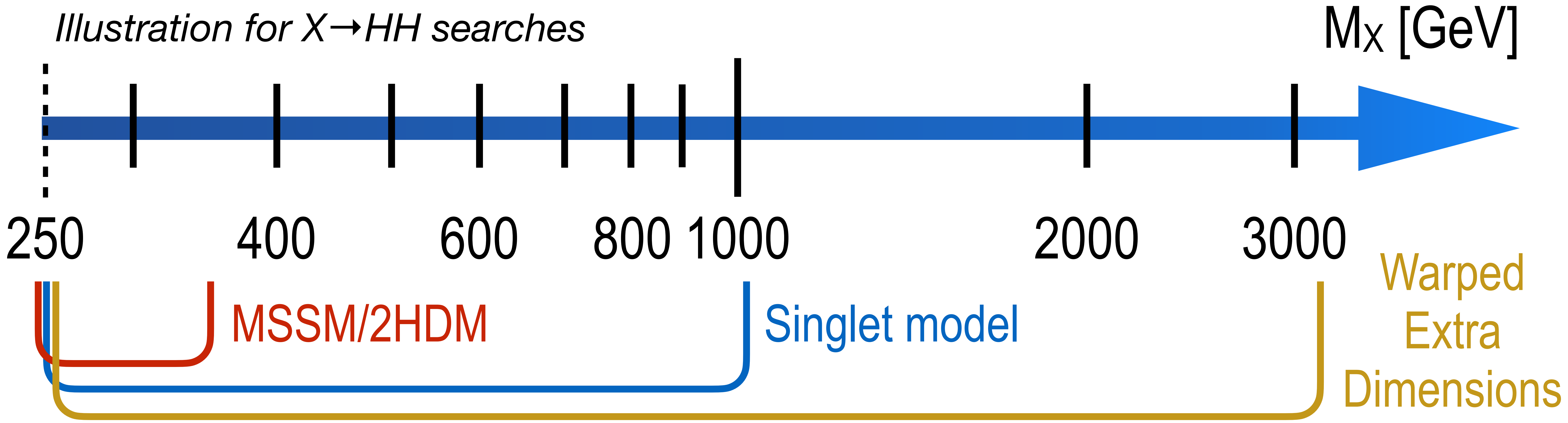
$\kappa_{2V} = 0$ excluded at 6.6σ
assuming other interactions at the SM

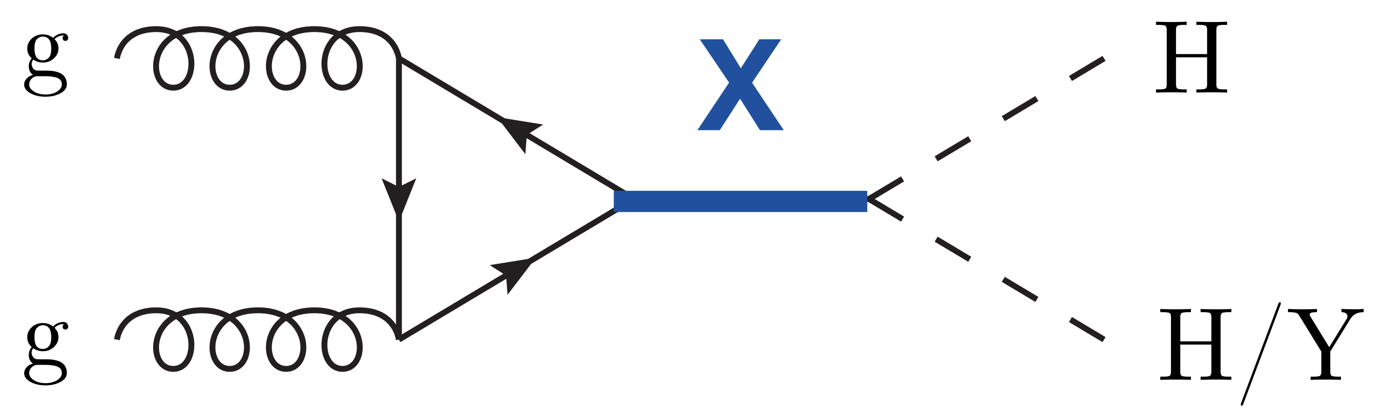


Observed : $0.6 < \kappa_{2V} < 1.5$
Expected : $0.4 < \kappa_{2V}$ 1.6
(95% CL from likelihood)

- Sensitivity driven by boosted bbbb
- Absence of κ_{2V} interaction excluded with Run 2 data set!
  - in a simple κ framework
- New physics implications on Higgs (e.g. compositeness) to be fully studied
- For EFT dim-8, competitive with VBS (JHEP 09 (2022) 038, see backup)
  - yet to be explored by experimental analyses

Resonant HH production

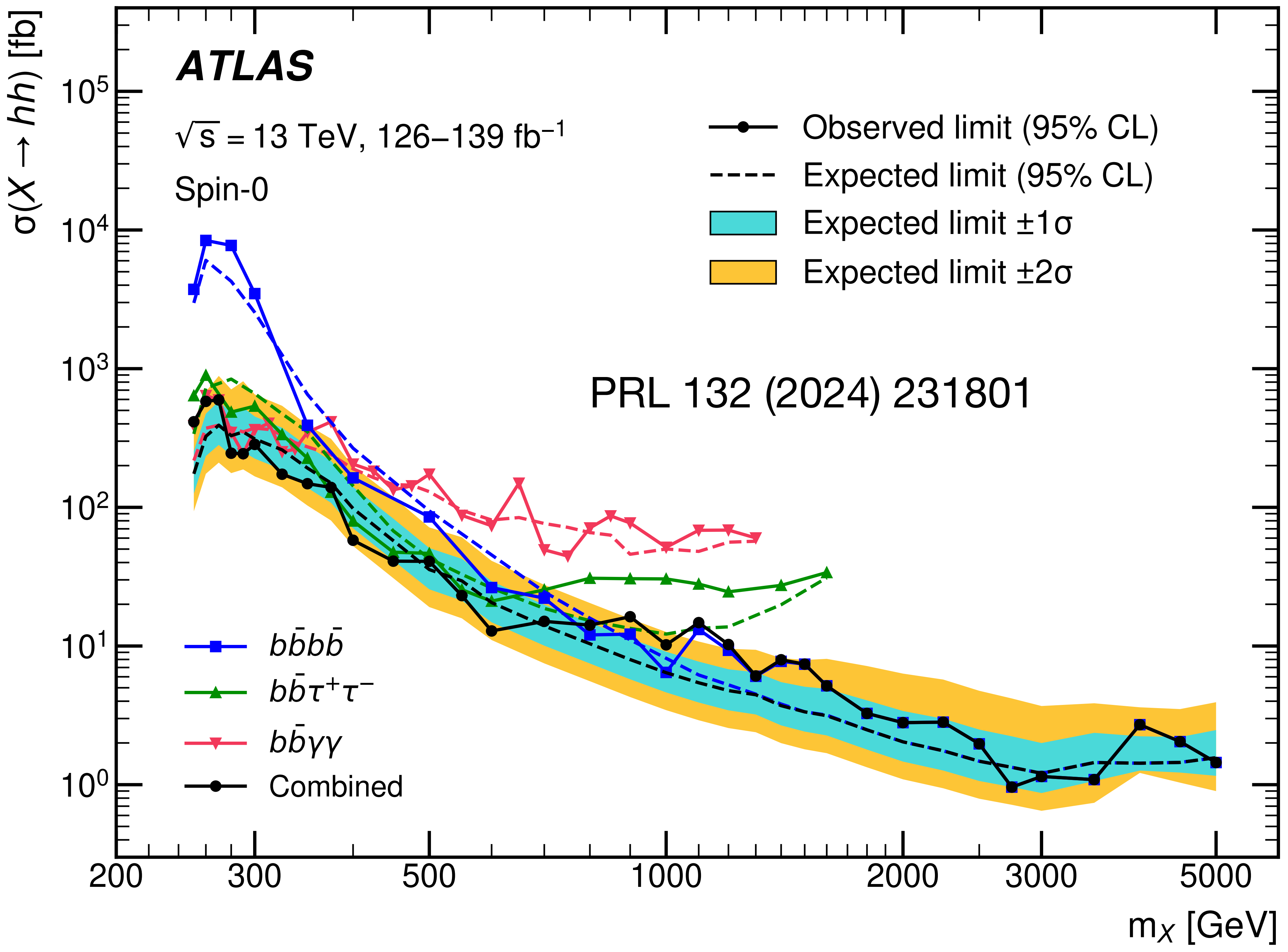


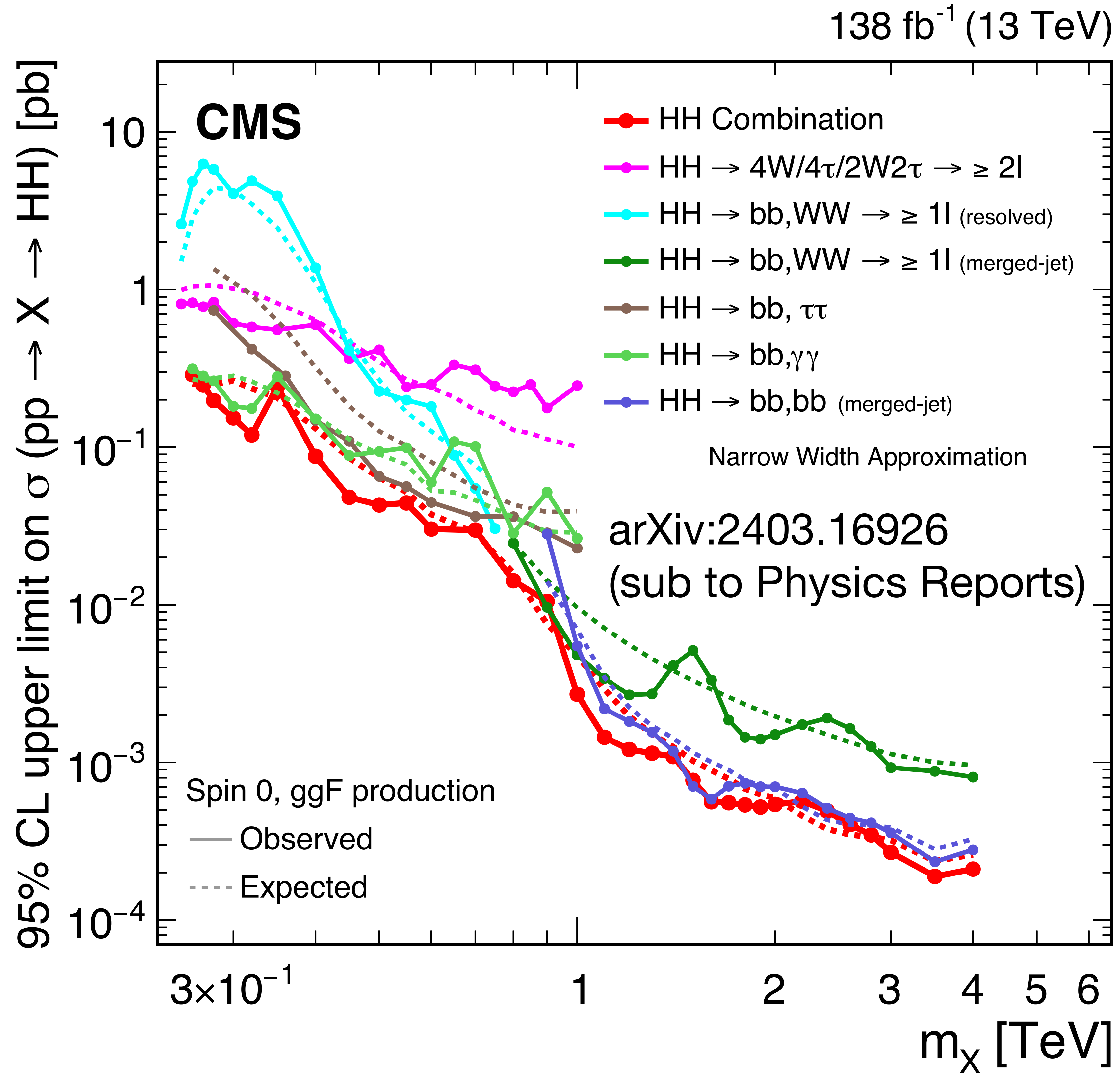


- Resonant HH/HY production predicted in a variety of models
  - from extended scalar sectors to exotic new physics
- A broad mass range must be covered to ensure maximal sensitivity to new physics
  - complementarity of the different decay channels

HH is an ideal place for direct searches for BSM physics
Sensitive with current LHC data

Run 2 results on X→HH

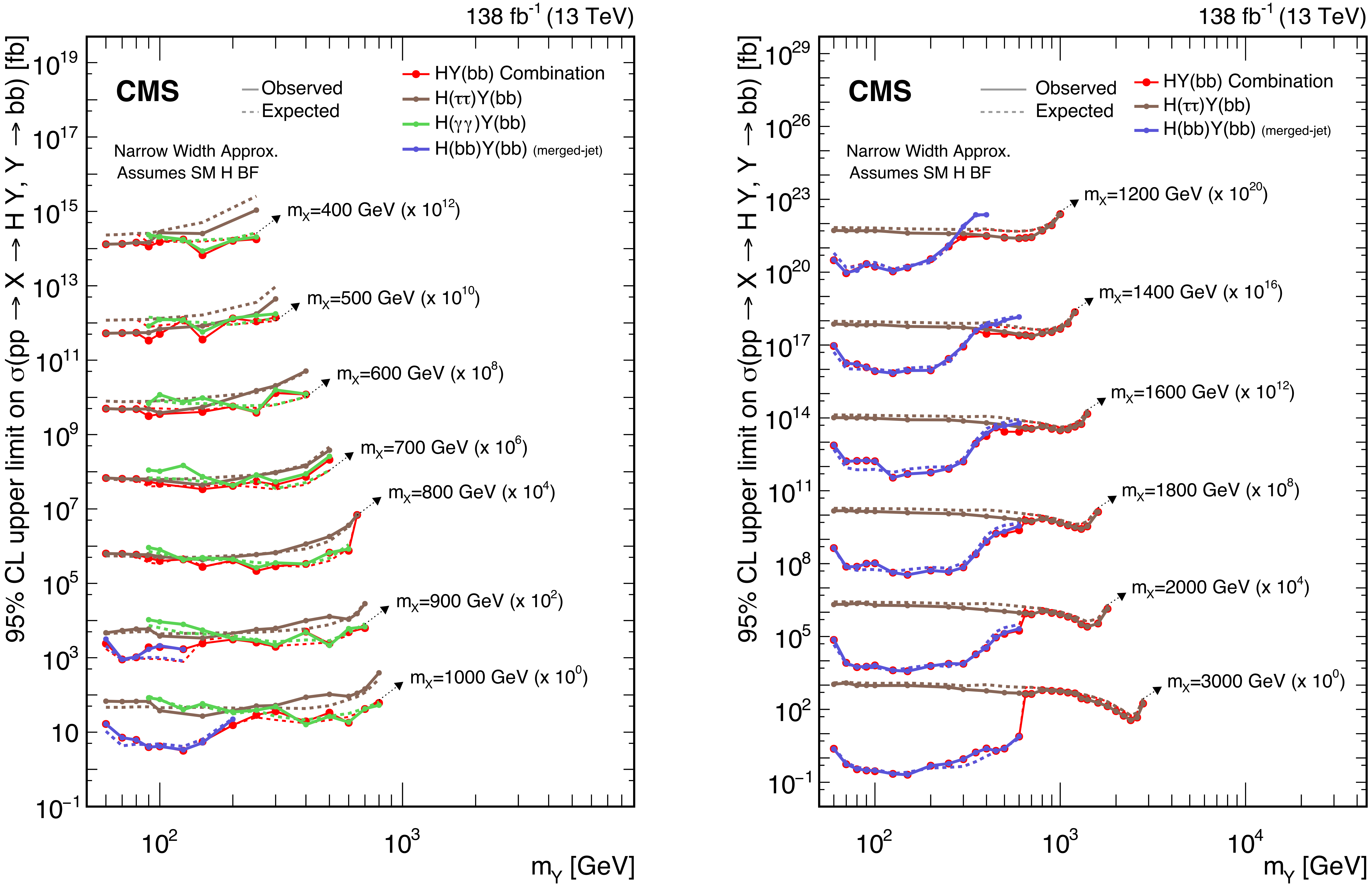




- Both spin 0 and spin 2 resonances explored under narrow width approximation
  - important effects from finite width shown in arXiv:2403.16926
- Excellent complementarity of decay channels to cover the full m$_X$ spectrum
- Interpretations in several BSM scenarios

More in backup!

X→YH production : extended scalar sectors



arXiv:2403.16926 (sub to Physics Reports)

- Searches scan over the X and Y new resonances masses
- Three decay channels are combined assuming the Y→bb decay and SM BR for the Higgs boson

A very broad phase space is explored in the search for extended scalar sectors

Outline

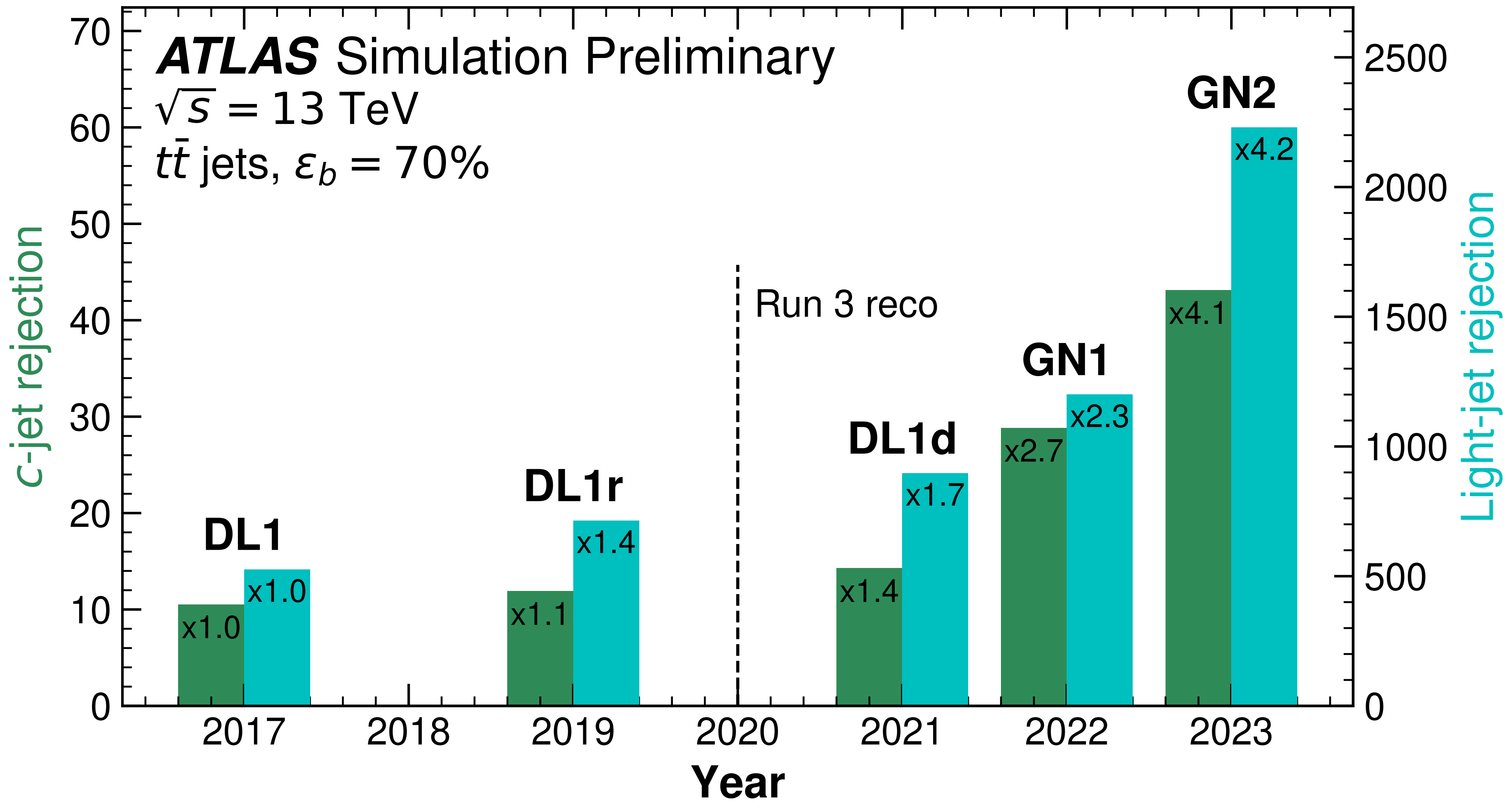
Short term : opportunities at the LHC Run 3

Medium term : HH at the HL-LHC

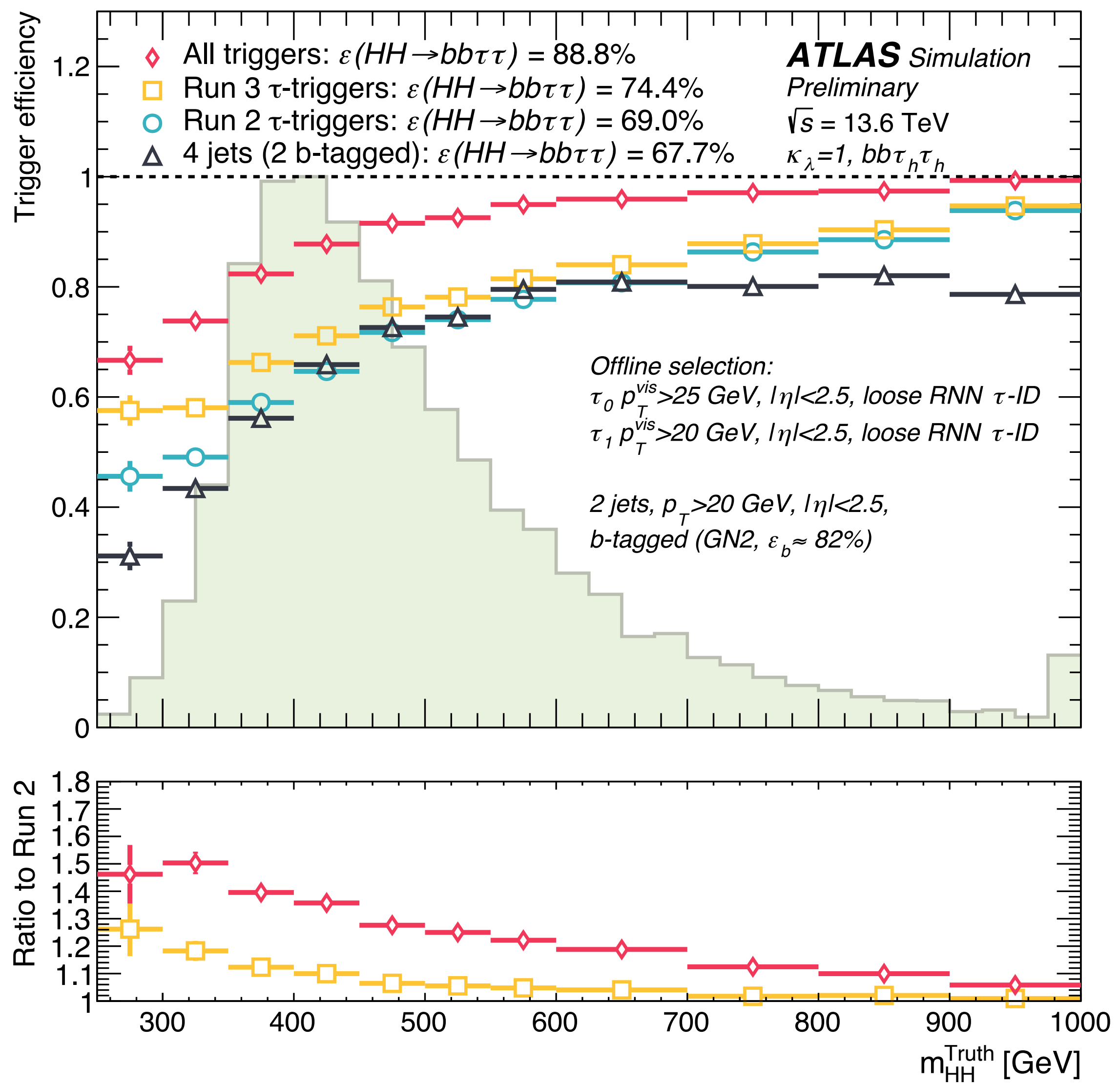
Long term : HH at future colliders

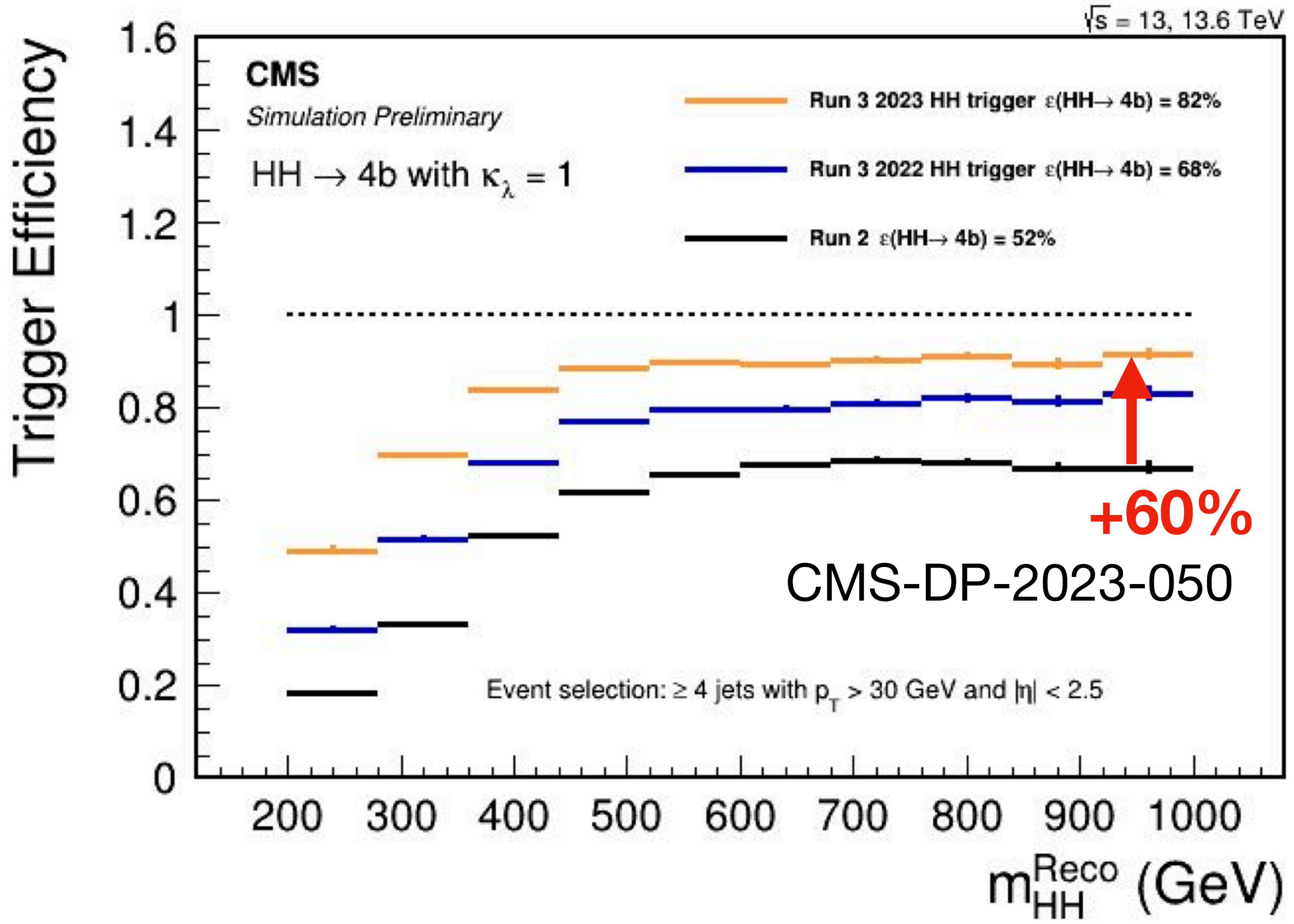
Future prospects

HH at the LHC Run 3



Improved object identification leveraging on modern machine learning methods





Improved triggers on hadronic signatures (bbbb, $bb\tau_h\tau_h$)

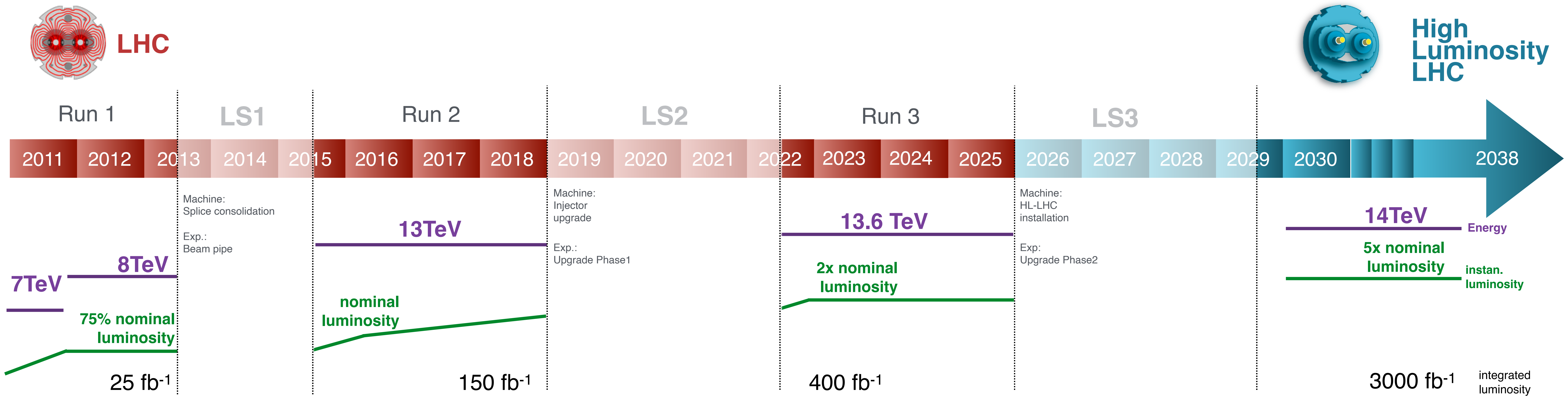
- Maximise the analysis sensitivity
- Expand the interpretations and physics reach : new HH production modes, EFT, VBF HH / VBS interplay in new physics study

@ Run 2 : ~2.4 × SM per experiment
→ 1.4 × SM / experiment (Run 2 + 3 lumi scaling)
→ 1 × SM ATLAS+CMS (Run 2 + 3 lumi scaling)
→ analysis improvements : **HH evidence @ Run 3?**

Exciting opportunities for HH physics at Run 3

The high-luminosity LHC

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



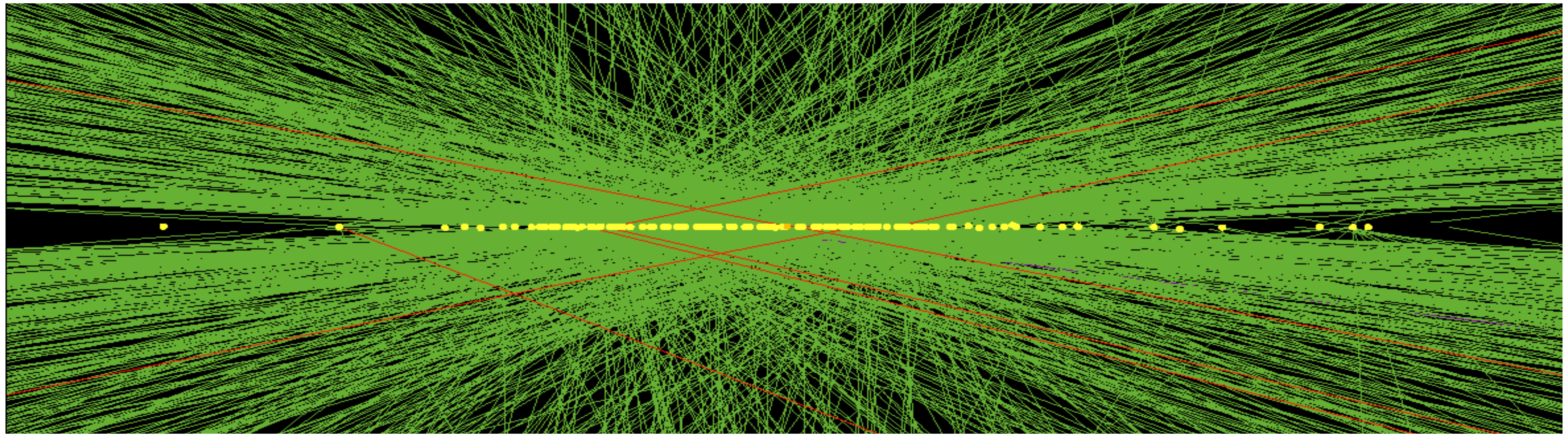
- Increase of the instantaneous luminosity by ~5 w.r.t. design values

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

Unique possibility for very high precision Higgs physics

Ultimate LHC sensitivity on HH

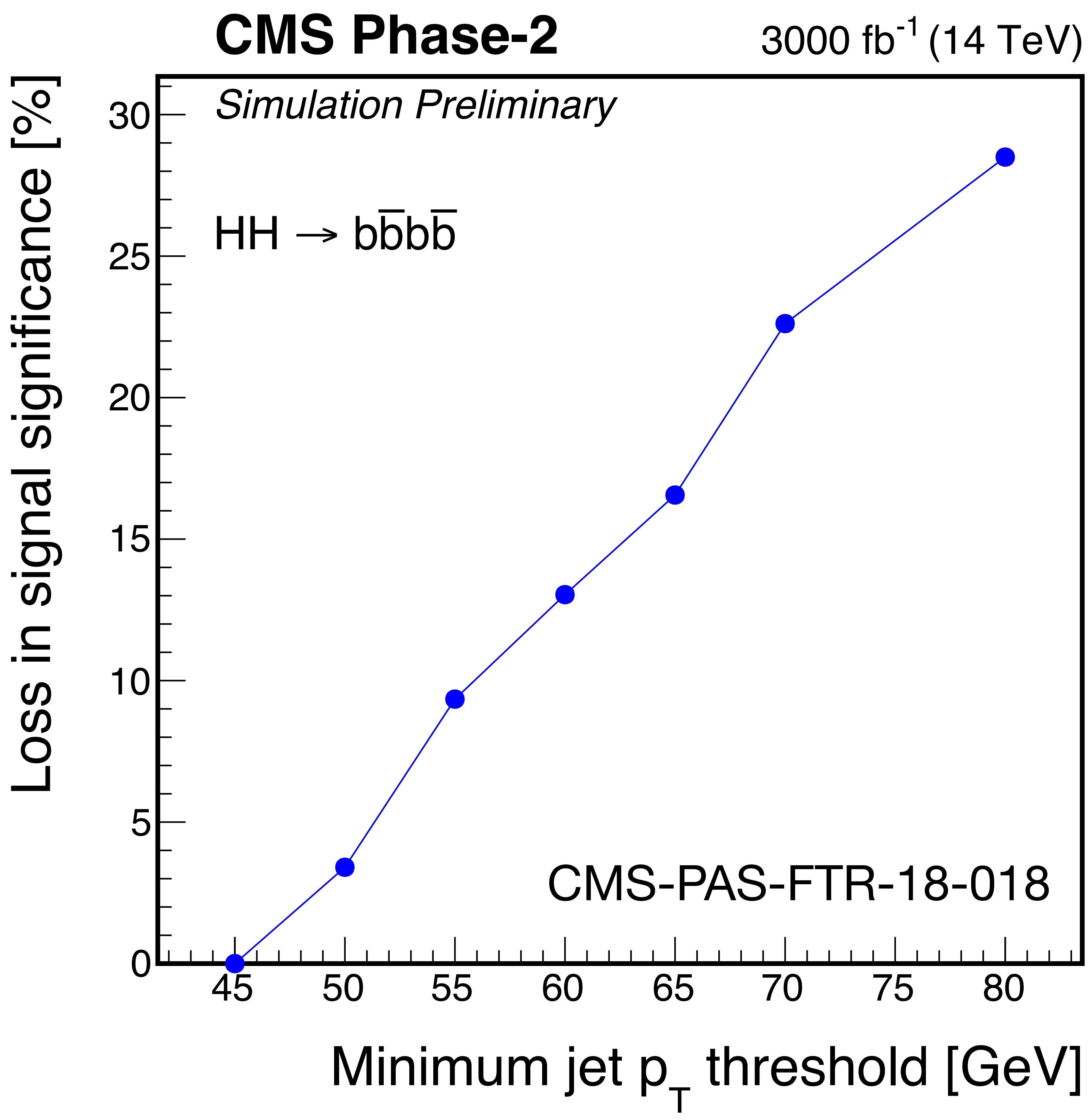
The high-luminosity challenge



- 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

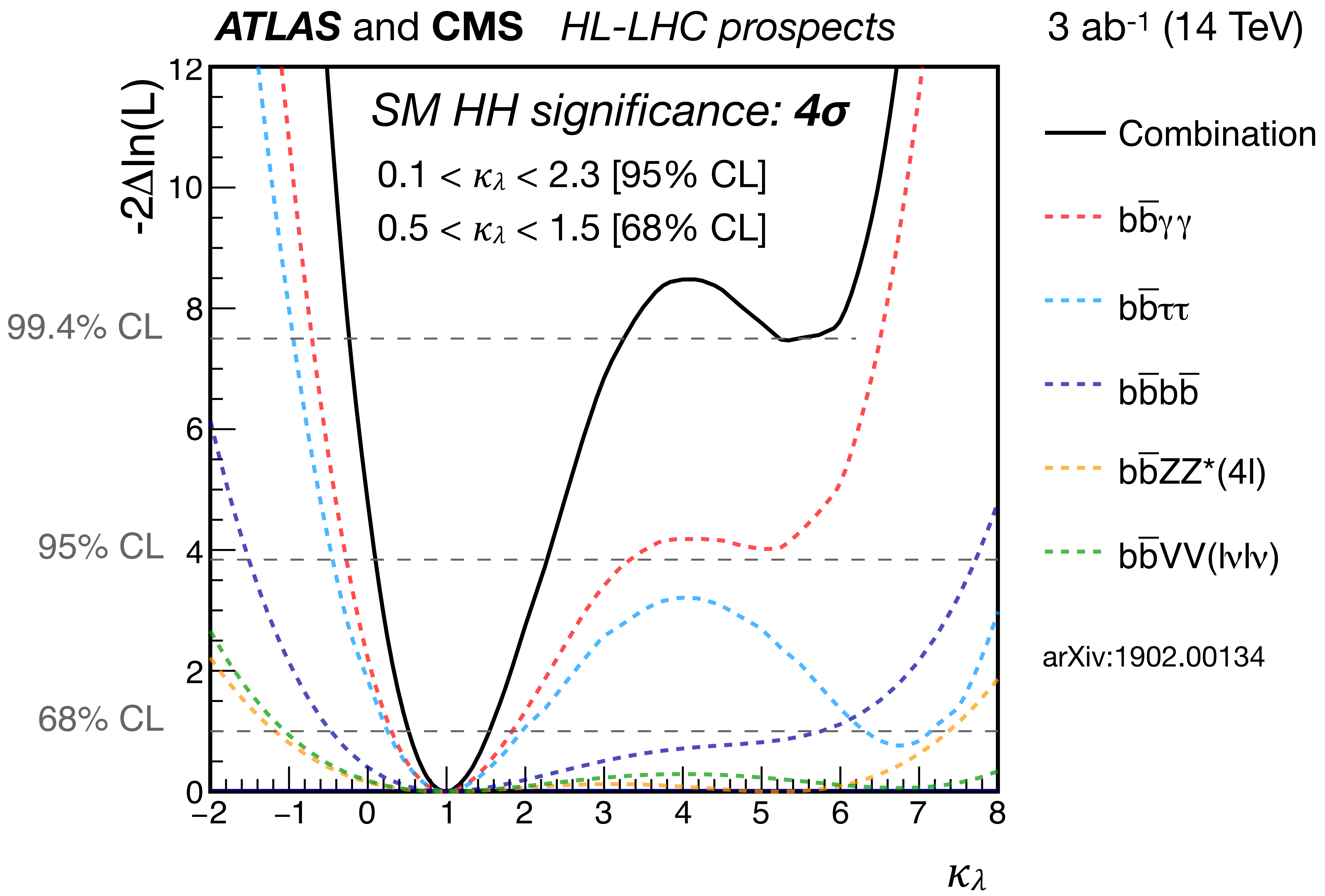
The HH physics programme crucially relies on the success of the Phase-2 upgrades



Essential to maintain low thresholds and efficient object identification

Current HH prospects at the HL-LHC…

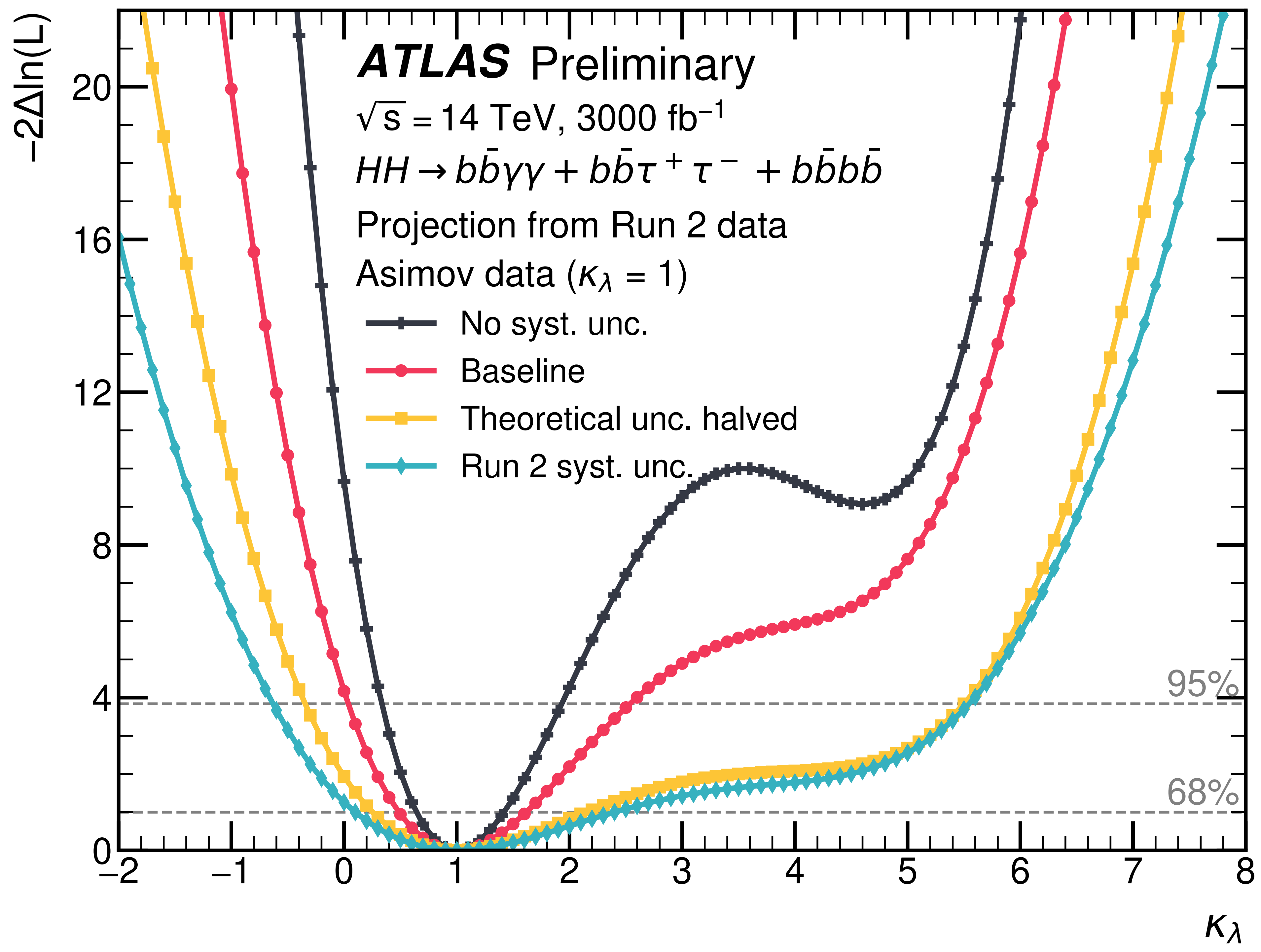
- HH sensitivity projections in the context of the last European Strategy for Particle Physics and Snowmass
- Based on 2016 analyses extrapolation or simplified parametric analyses
- Expect 50% (100%) precision on κ_λ at 68% (95%) CL, and to exclude the no self-coupling hypothesis
  - with the current analysis techniques! Further improvements should come in the next 20 years

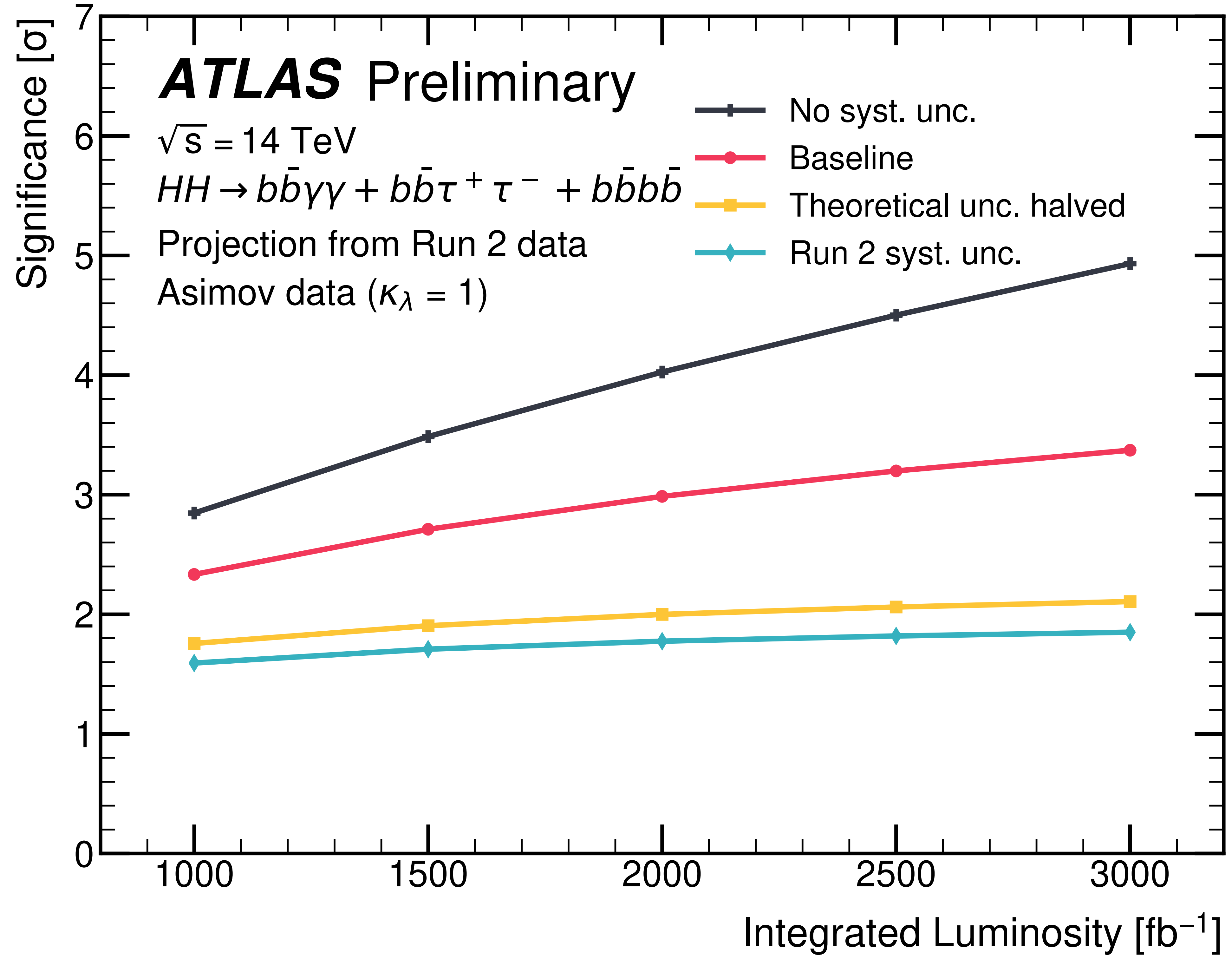


Combination of channels and experiments is crucial to achieve sensitivity at the HL-LHC

… are likely conservative

ATL-PHYS-PUB-2022-053





- Recent projections for Snowmass already showed improved sensitivity on key channels
- Ongoing effort to update the projections for the next European Strategy

HH beyond the LHC

High energy pp machines

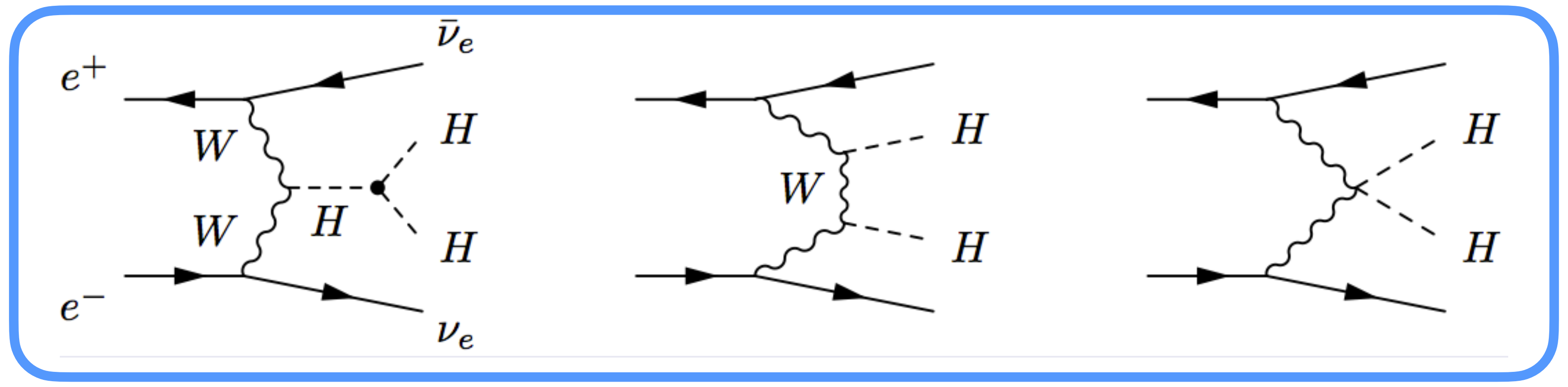
"HH factories" : ultimate precision on λ from direct determination

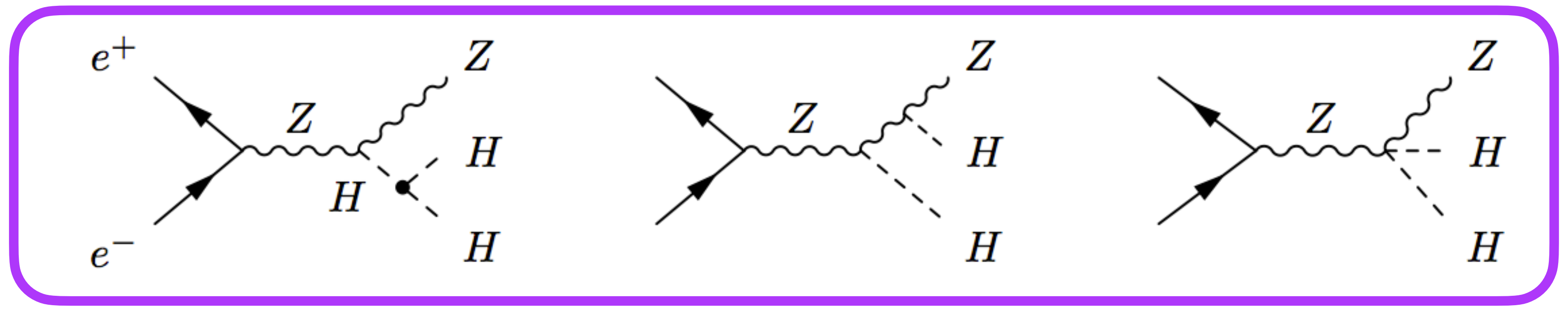
- HL-LHC → FCC-hh : ×33 σ(gg→HH), ×10 ∫ℒ ⟹ > 30M HH events for study

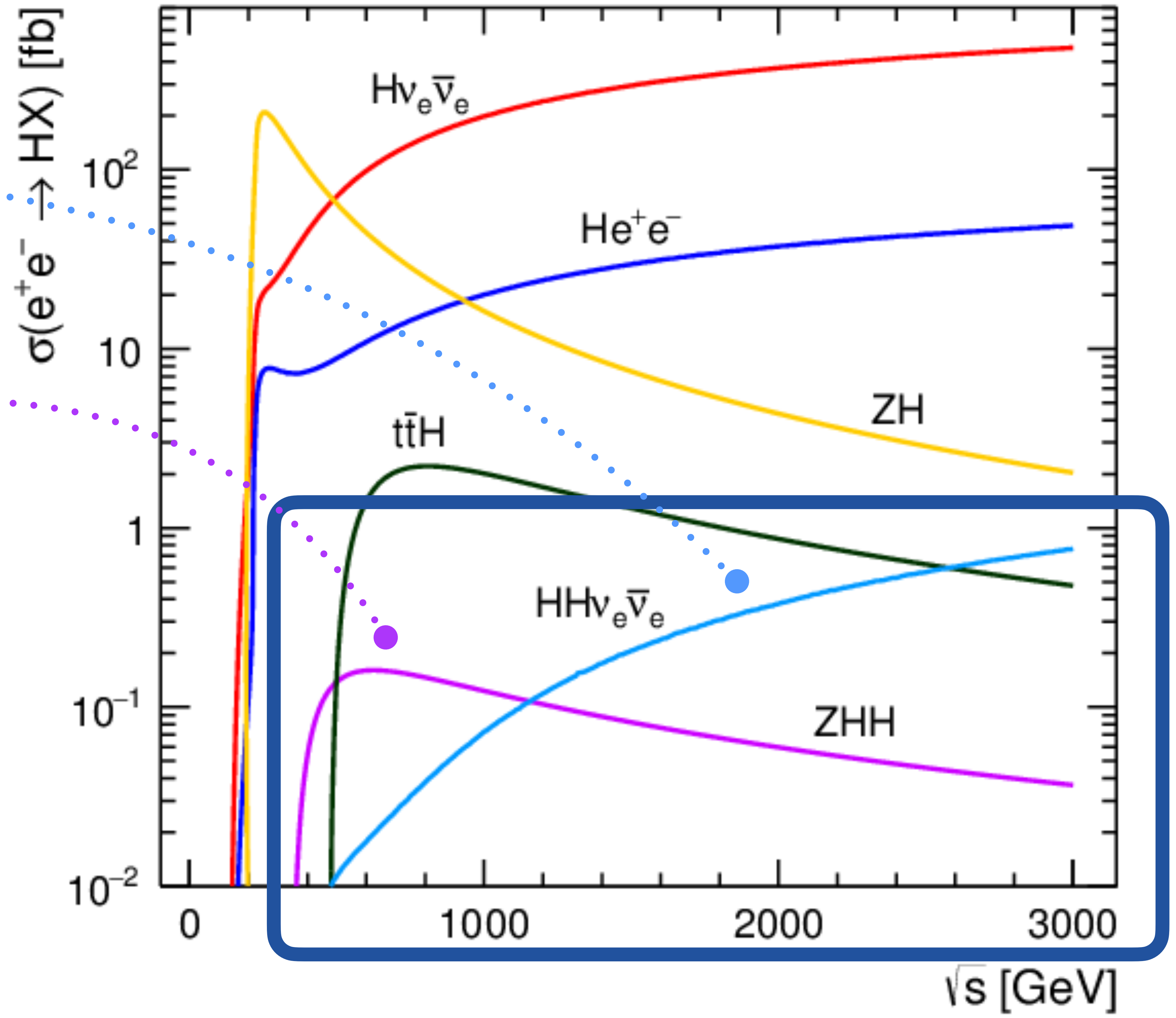
Precision e+e- machines

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

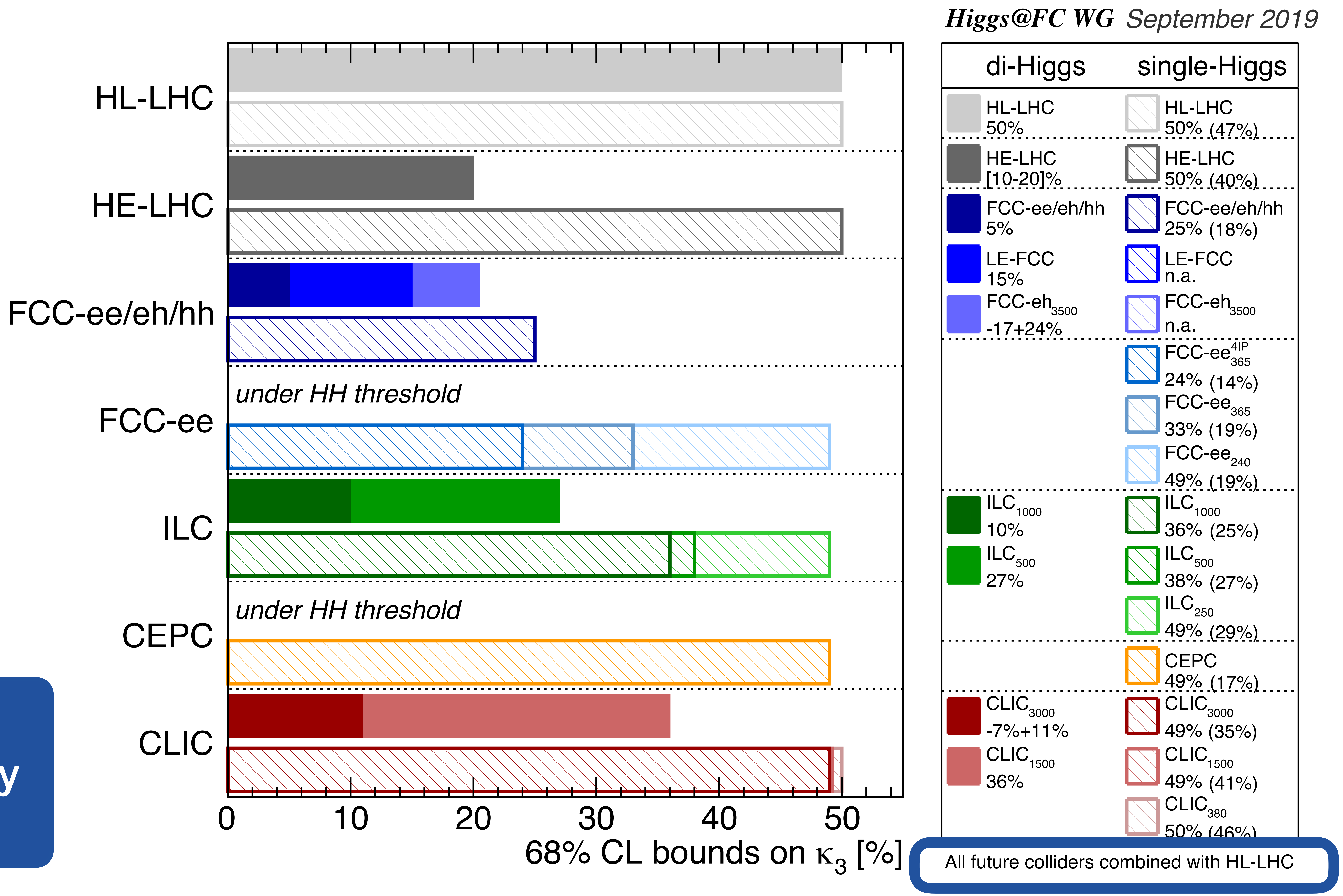
Direct HH ■

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

Indirect single-H ▨

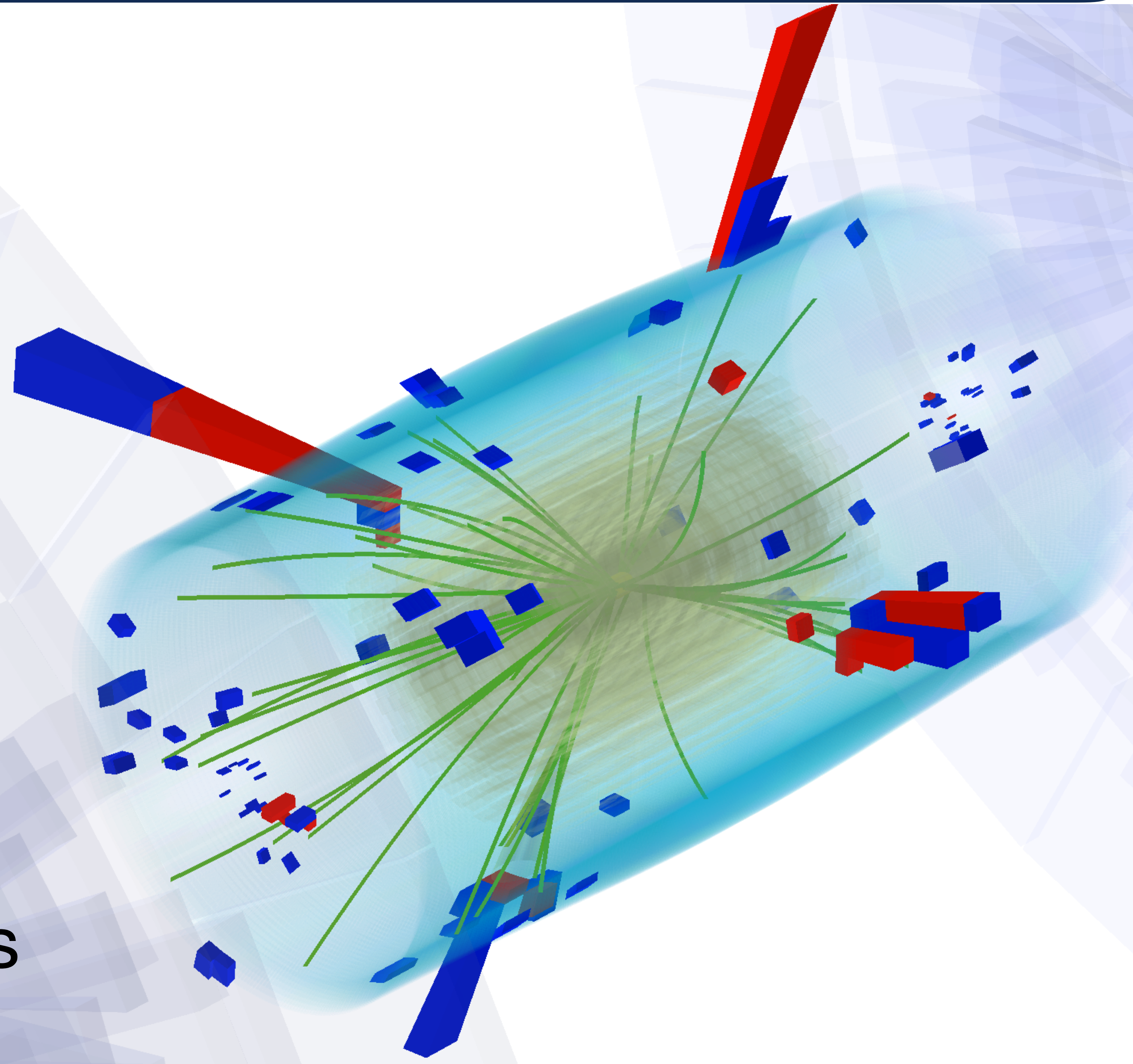
- limited by HH HL-LHC reach until higher energies and luminosities are achieved

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



Conclusions

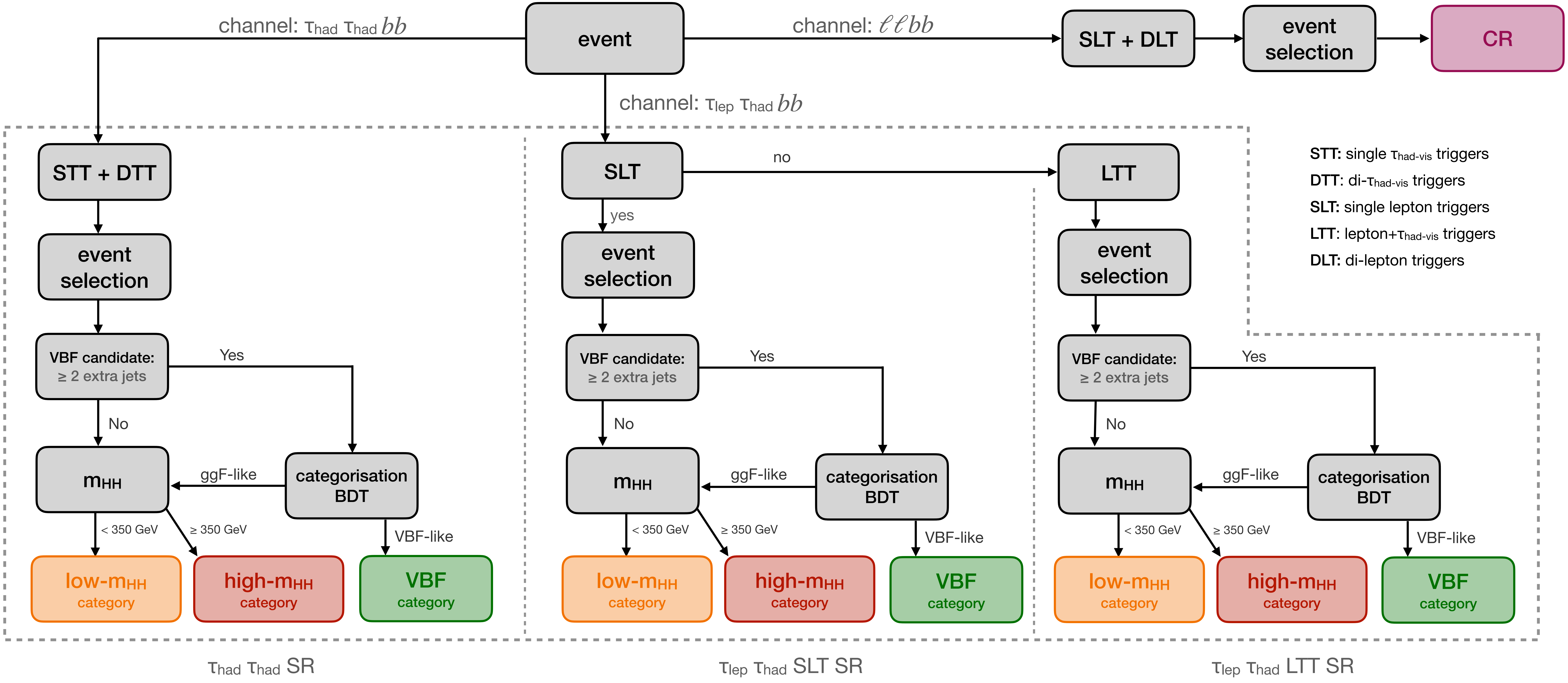
- The shape of the Higgs potential is so far largely unknown
  - connects to deep question on the origin and destiny of our Universe
- HH is the key process to directly measure λ_{HHH}
  - small cross section : experimentally challenging
  - crucial to explore and combine several decay channels
- HH is also an ideal place to look for new physics
  - new resonances decaying to HH in extended scalar sectors
  - high energy effects in EFT in ggF and VBF, interplay with VBS
- Impressive experimental effort by the ATLAS and CMS Collaborations
  - many decay channels analysed and combined with the LHC Run 2 data set
  - current sensitive to signals around 2.4 times the SM prediction
- Excellent prospects for future measurements
  - important experimental challenges to tackle with upgrades
  - might reach an evidence at Run 3, observation at reach for HL-LHC



Measuring λ_{HHH} is a key goal in the short and long term programme of current and future accelerators

Additional material

Categorising $bb\tau\tau$ events



STT: single $\tau_{had\text{-}vis}$ triggers
DTT: di-$\tau_{had\text{-}vis}$ triggers
SLT: single lepton triggers
LTT: lepton+$\tau_{had\text{-}vis}$ triggers
DLT: di-lepton triggers

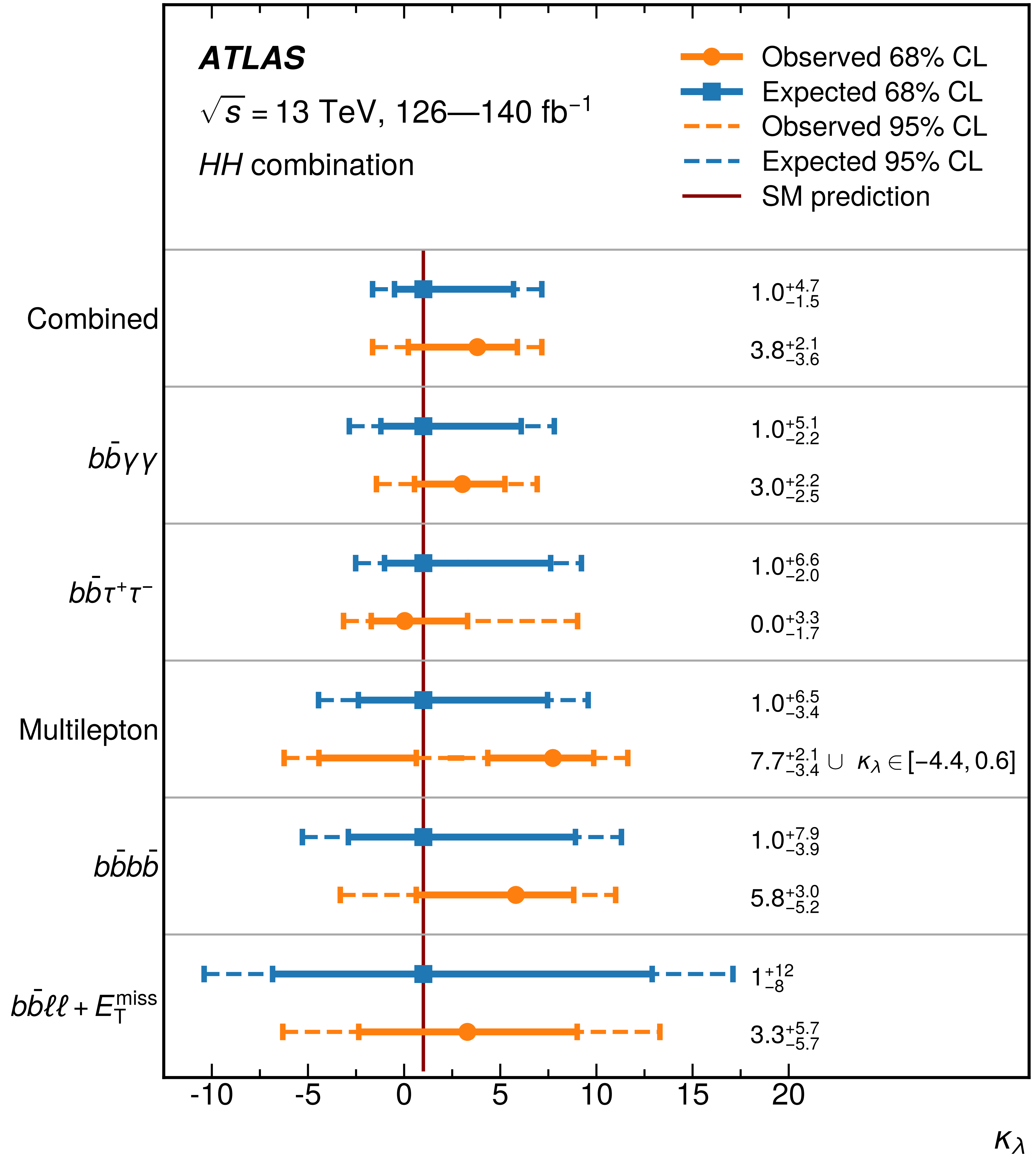
VBS and VBF HH

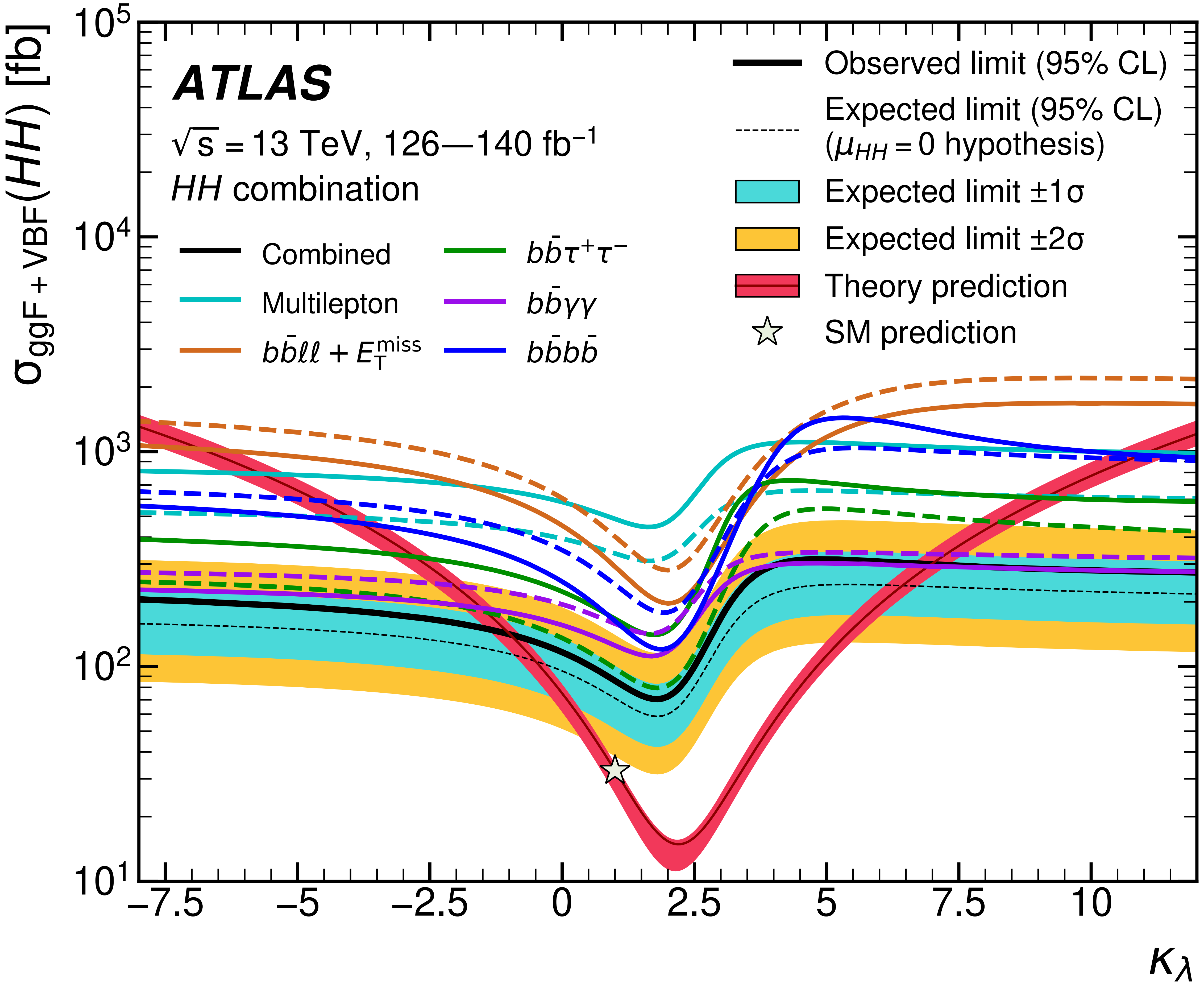
	VBS $W^{\pm}V$ semileptonic		VBF HH$\to b\bar{b}b\bar{b}$	
Coeff.	no unitarity	w/ unitarity	no unitarity	w/ unitarity
f_{M0}/Λ^4	[-0.47,0.47]	[-0.96,1.02]	[-0.43,0.43]	[-0.90,0.87]
f_{M1}/Λ^4	[-1.5,1.5]	[-2.3,2.4]	[-1.7,1.7]	[-3.5,3.5]
f_{M2}/Λ^4	[-0.69,0.68]	[-2.1,2.1]	[-0.62,0.61]	[-1.7,1.7]
f_{M3}/Λ^4	[-2.5,2.4]	[-6.8,6.3]	[-2.4,2.4]	[-6.5,6.6]
f_{M4}/Λ^4	[-1.4,1.4]	[-2.4,2.5]	[-1.8,1.8]	[-3.9,4.0]
f_{M5}/Λ^4	[-2.0,2.0]	[-3.0,3.1]	[-3.2,3.2]	[-6.9,7.0]
f_{M7}/Λ^4	[-2.4,2.4]	[-3.5,3.5]	[-3.5,3.5]	[-7.1,7.1]
f_{S0}/Λ^4	[-1.8,2.0]	[-2.6,3.3]	[-14,13]	/
f_{S1}/Λ^4	[-2.4,2.4]	[-5.8,6.1]	[-5.1,4.5]	/
f_{S2}/Λ^4	[-2.3,2.4]	[-4.8,5.2]	[-8.1,7.1]	/

- Recast of CMS HH→bbbb measurement shows that VBF HH and VBS have competing constraints on dim-8 EFT operators

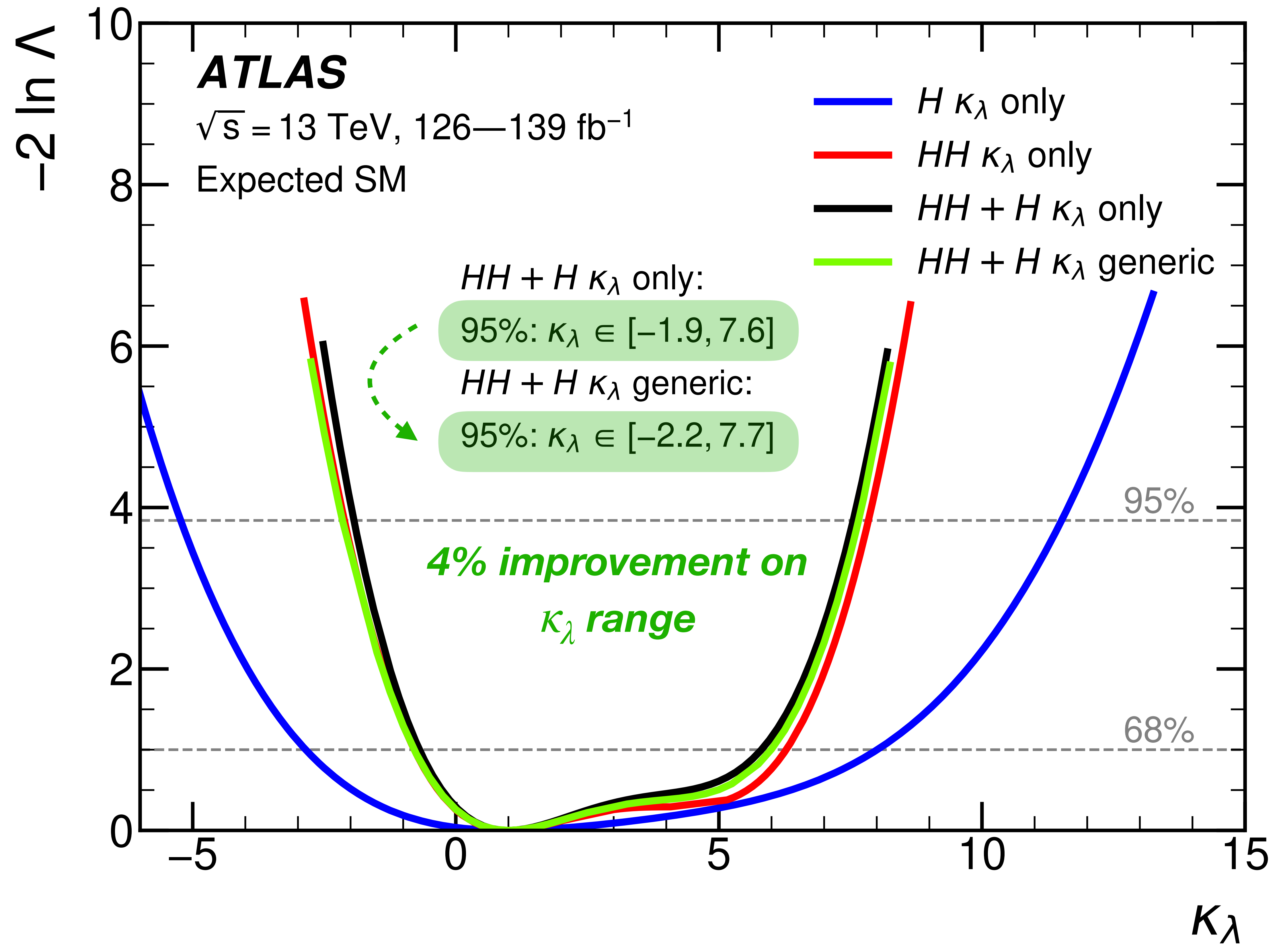
JHEP 09 (2022) 038

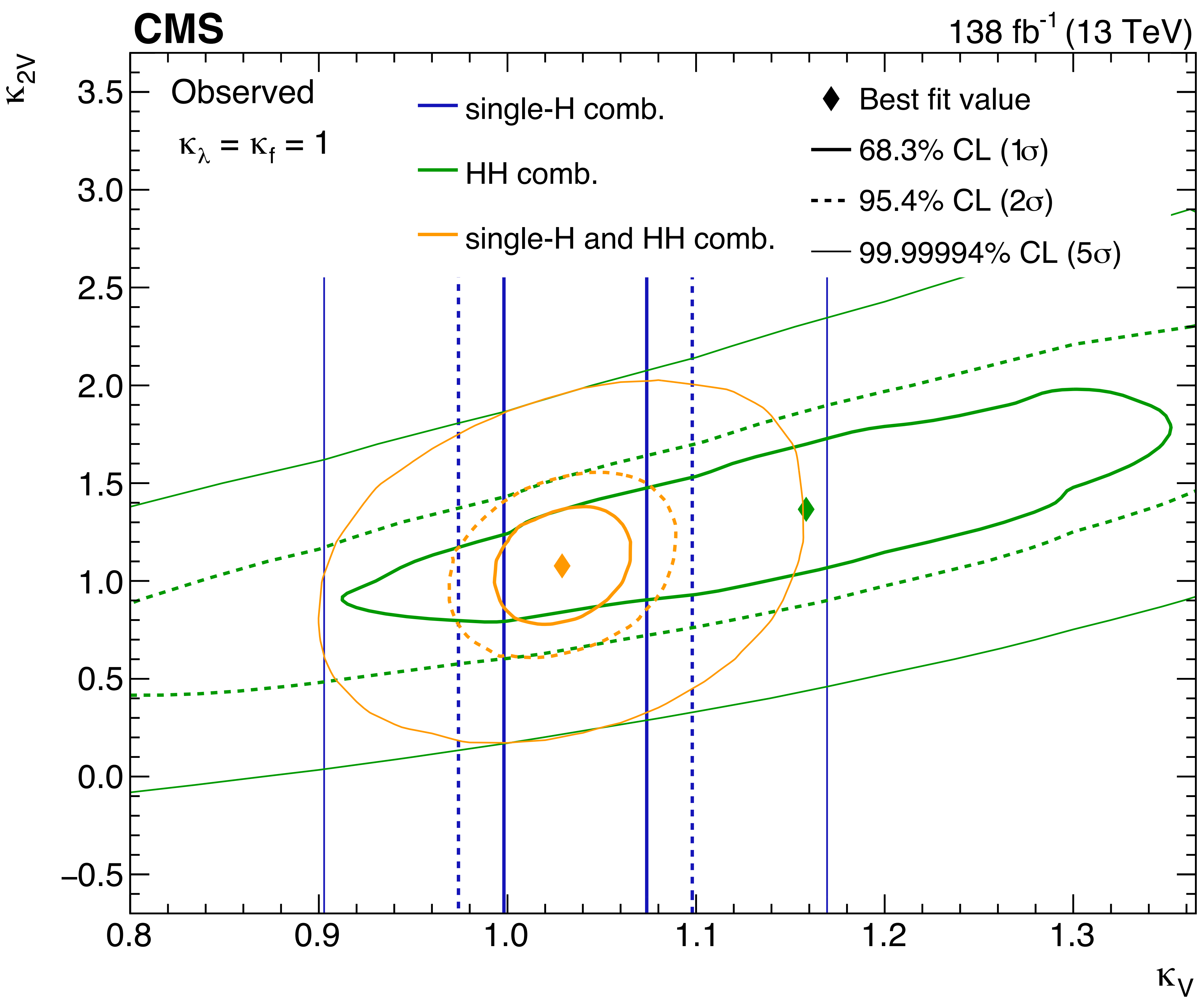
ATLAS combination - channel contributions





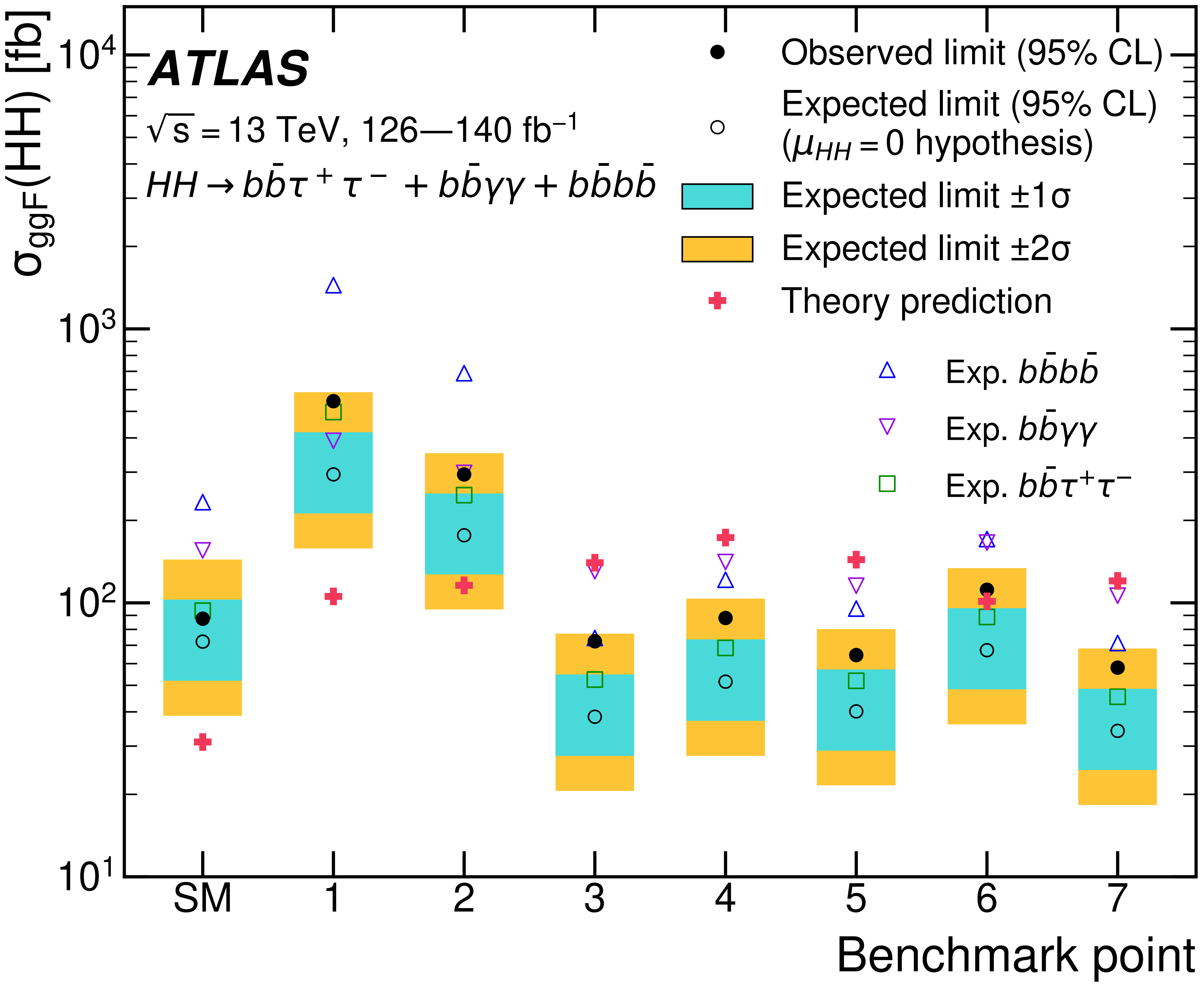
H+HH combination





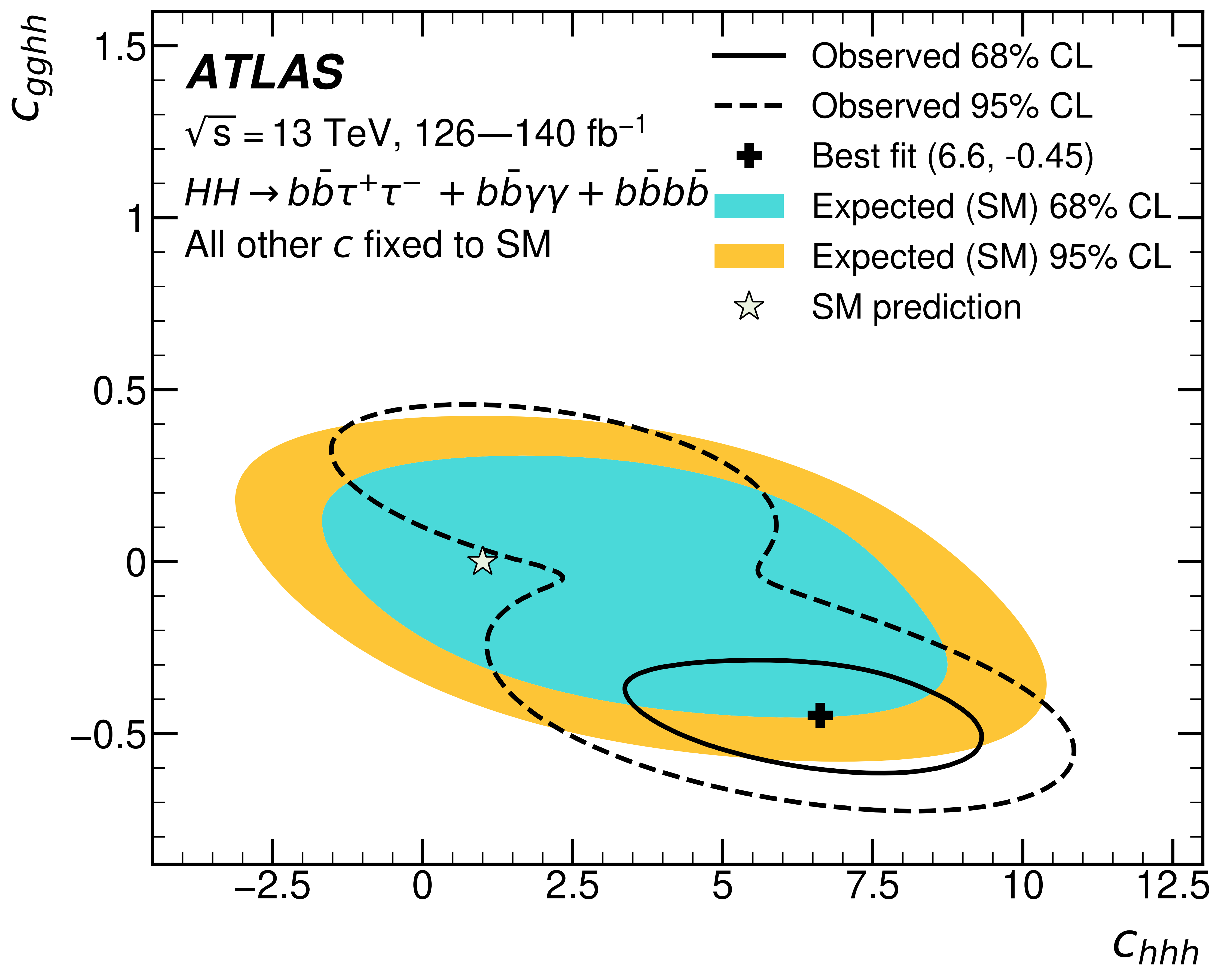
- Phys. Lett. B 843 (2024) 137745
- arXiv:2407.13554 (sub. to PLB)

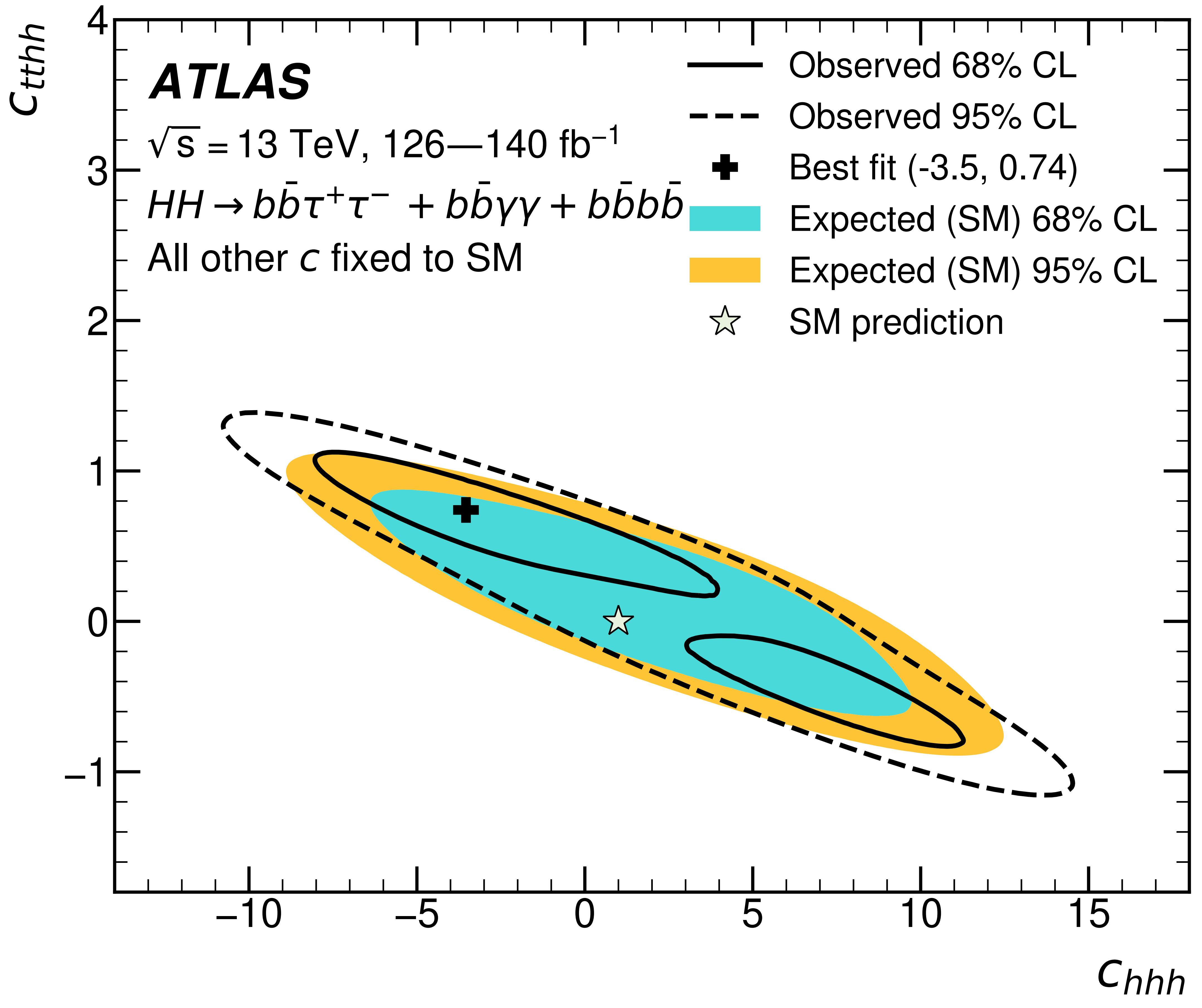
Shape benchmarks



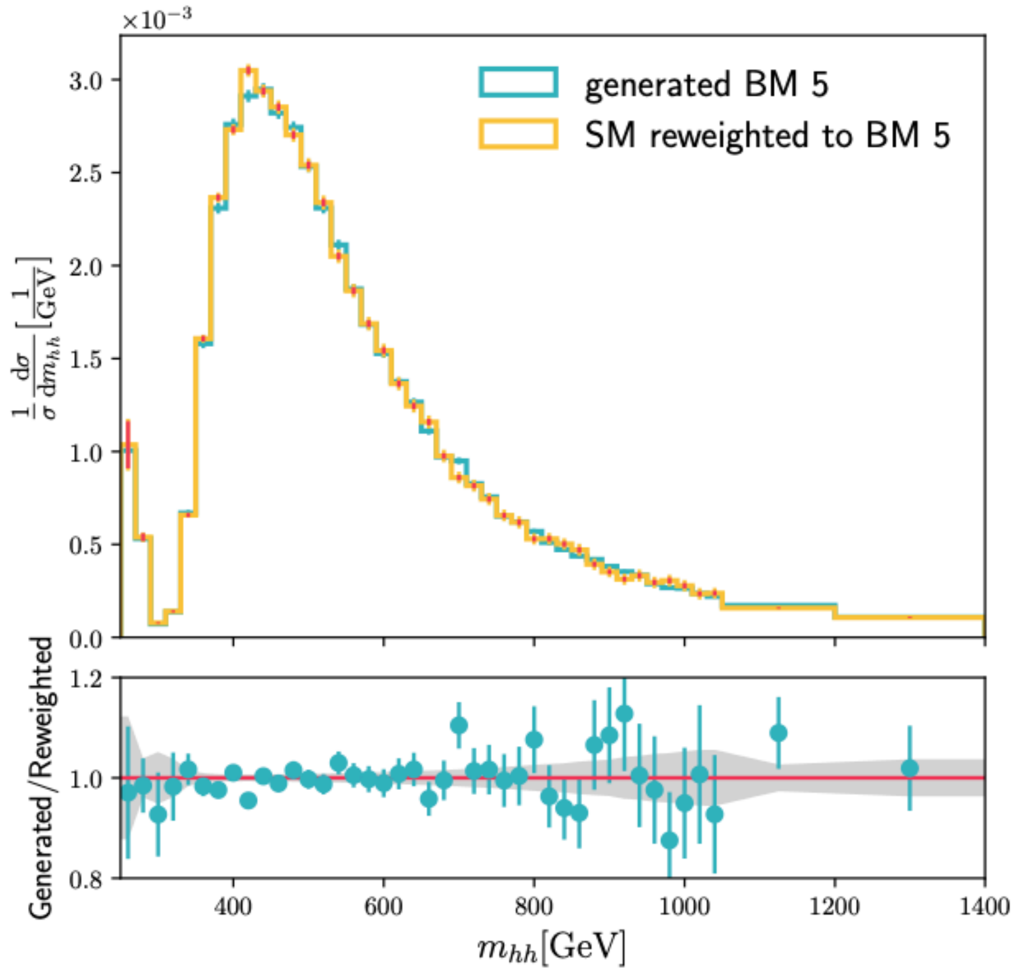
- 95% CL upper limits for the shape benchmark hypotheses
- Shape benchmarks are specific combinations of couplings characterized by a given m_{HH} distribution (event kinematics)
- Spread of sensitivity across benchmarks illustrates the change in sensitivity of the analyses to various EFT coupling hypotheses

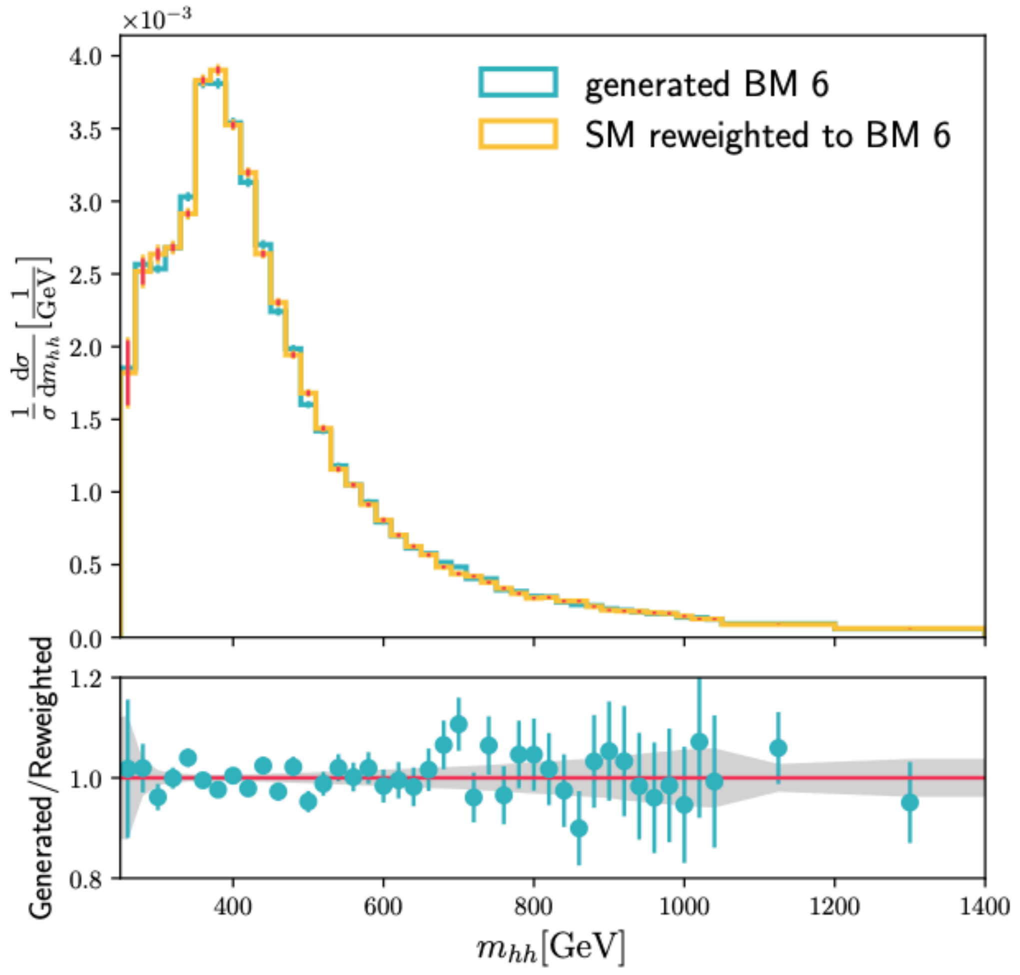
2D contraints on HEFT from ATLAS combination

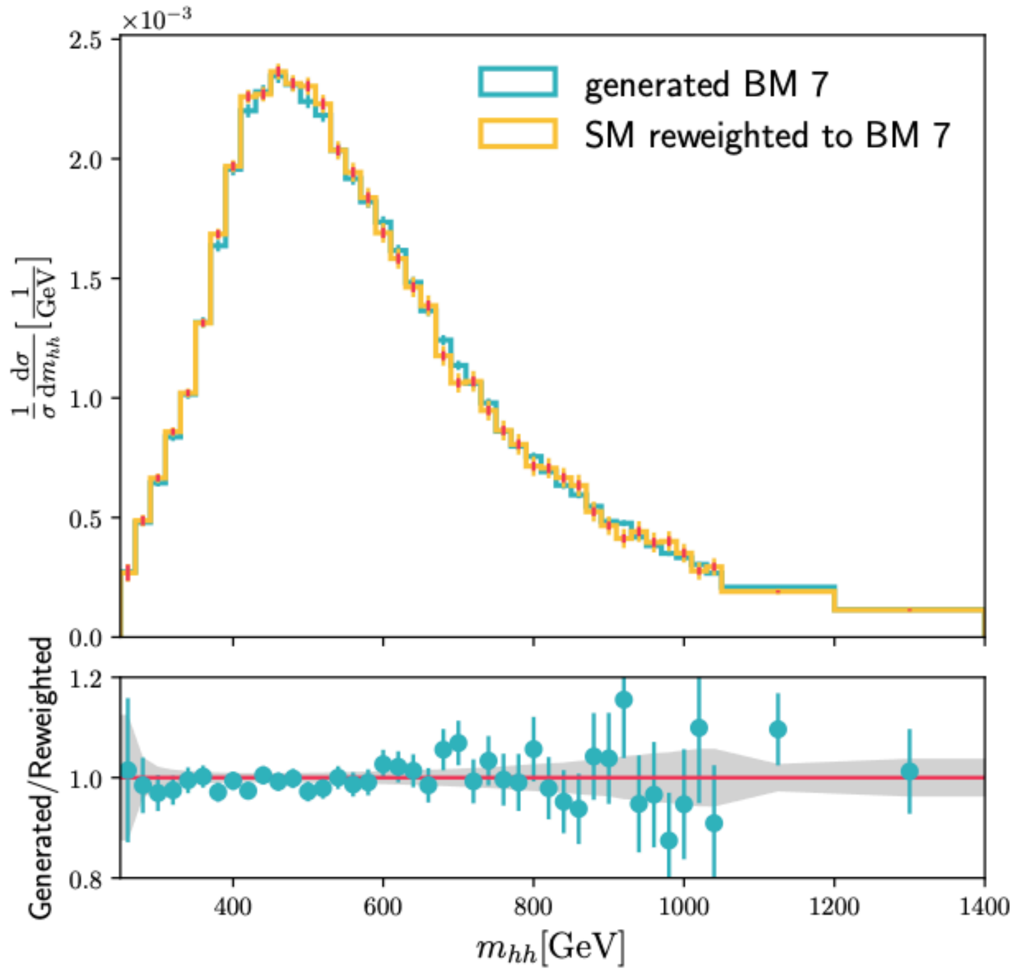




Shape benchmark definition



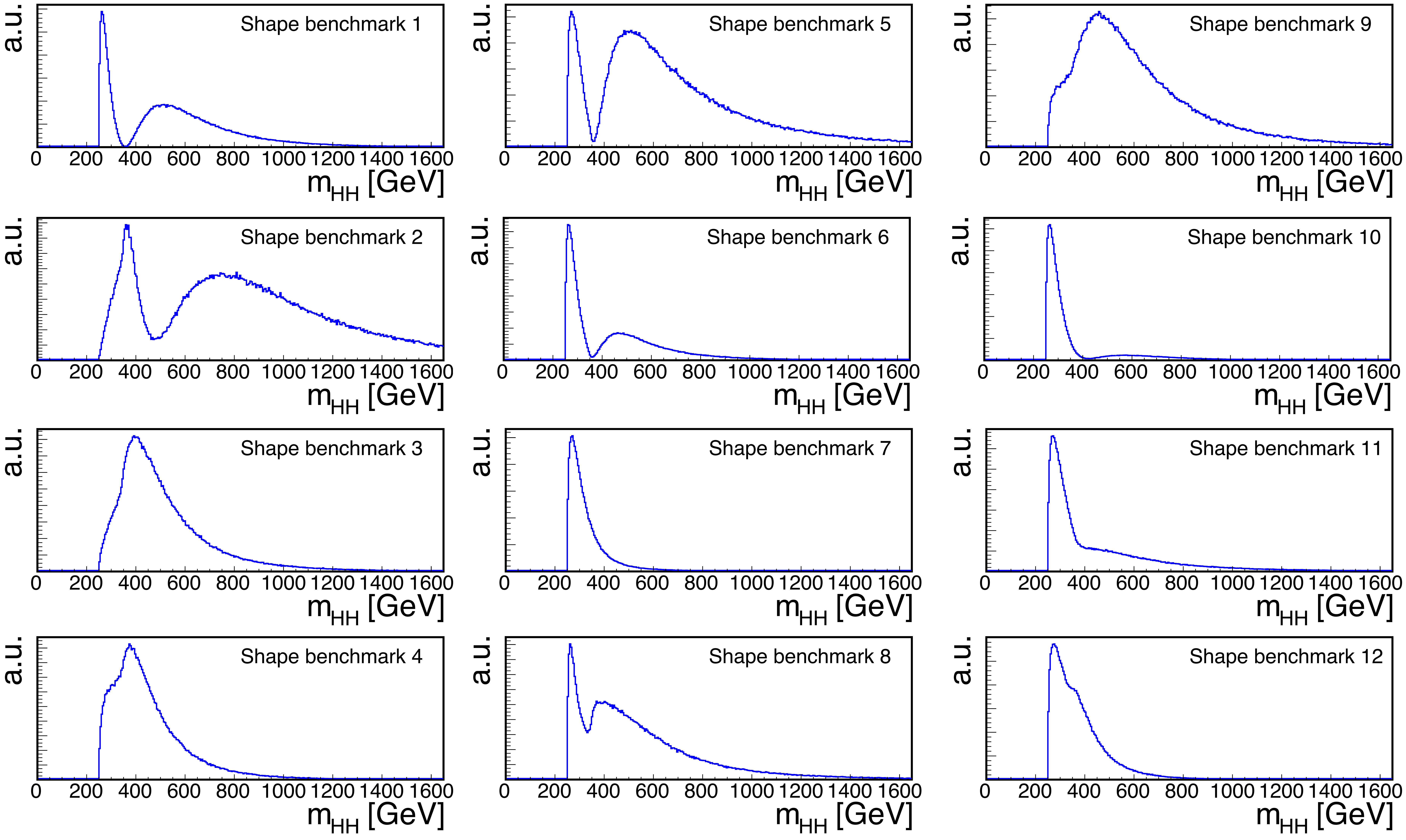




benchmark	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	$\frac{1}{6}$	$-\frac{1}{3}$	0
3	2.21	1.05	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$
4	2.79	0.90	$-\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$
5	3.95	1.17	$-\frac{1}{3}$	$\frac{1}{6}$	$-\frac{1}{2}$
6	−0.68	0.90	$-\frac{1}{6}$	$\frac{1}{2}$	0.25
7	−0.10	0.94	1	$\frac{1}{6}$	$-\frac{1}{6}$

- From LHCHWG-2022-004

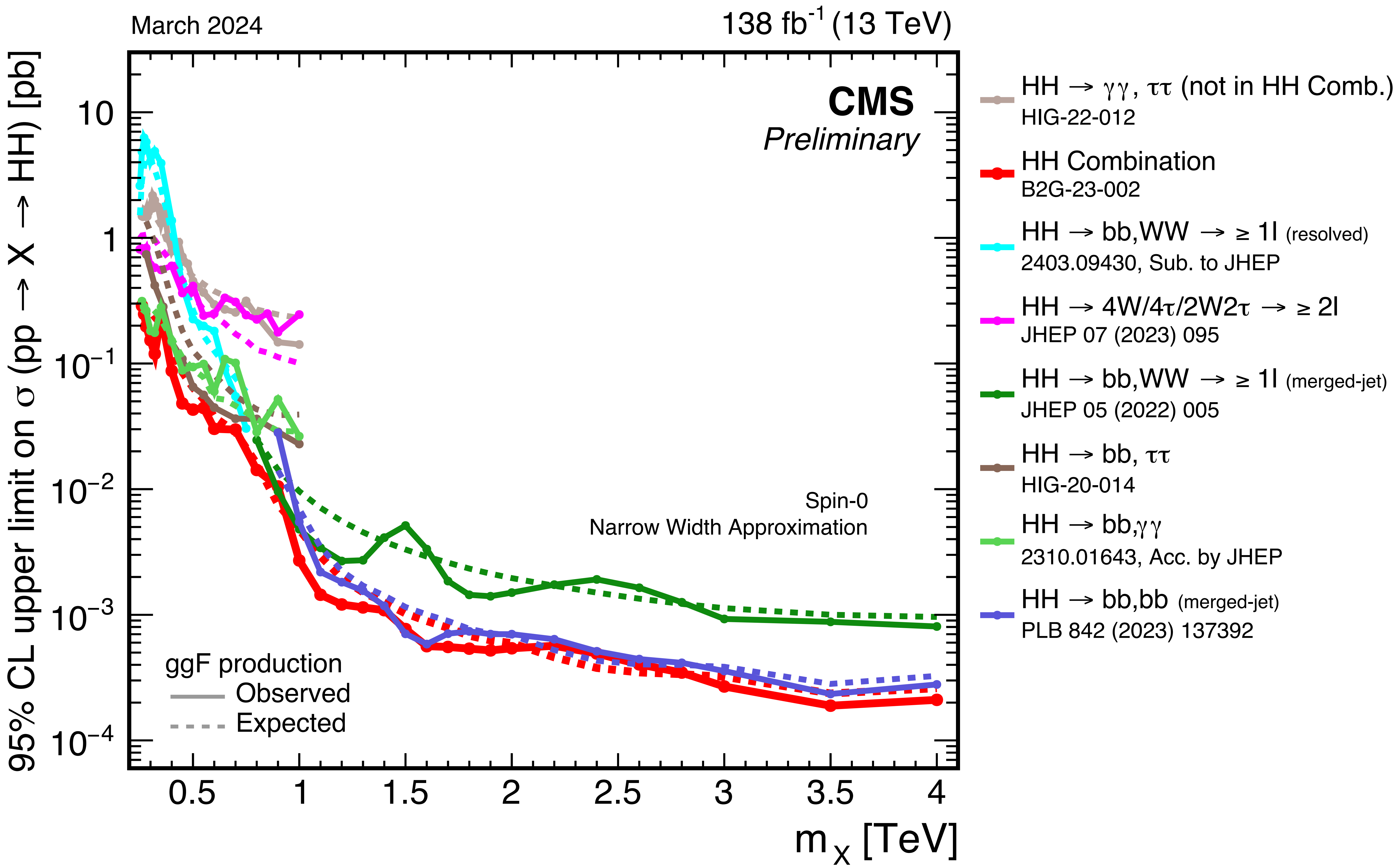
Old HH shape benchmarks

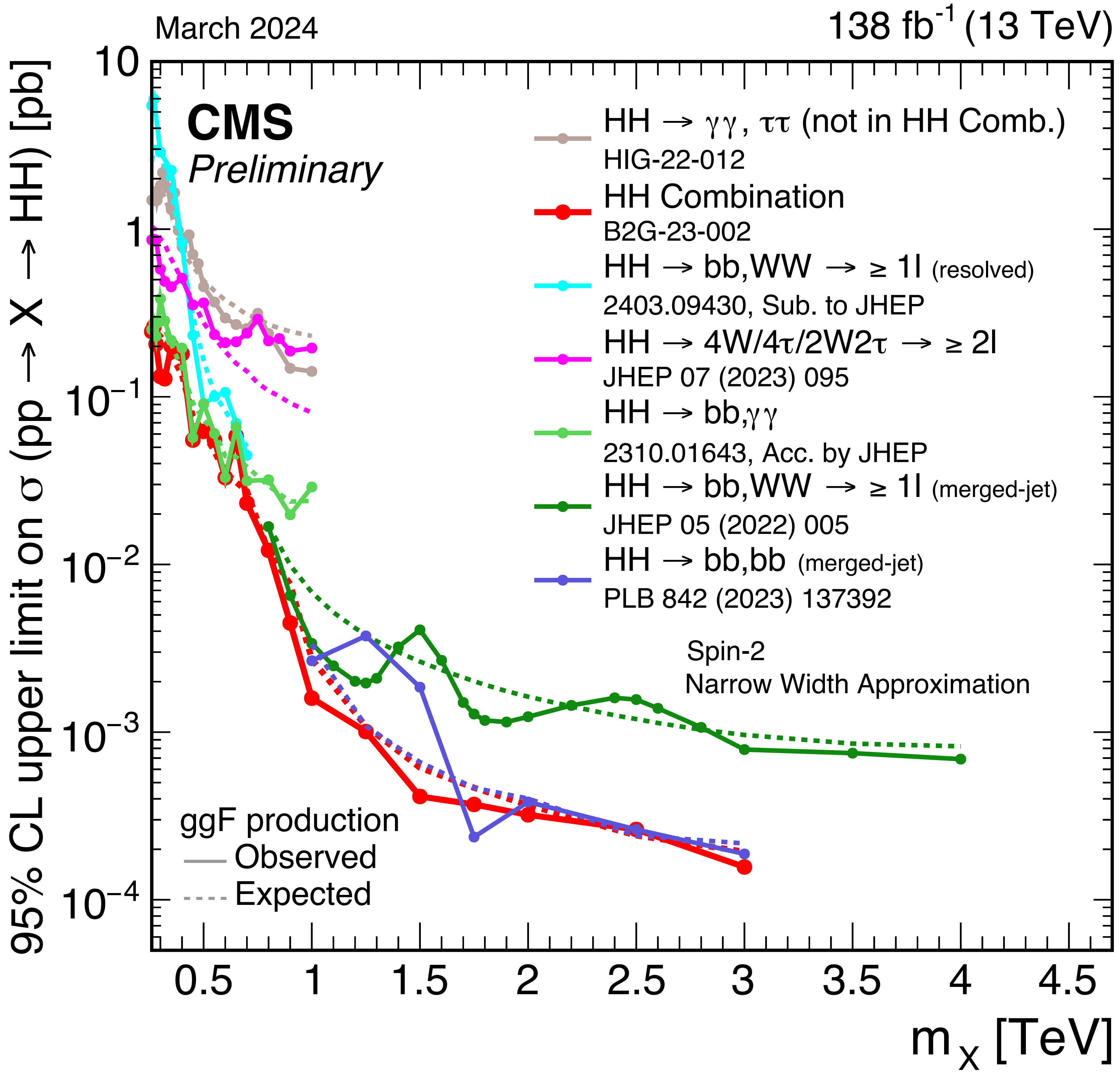


Nr.	k_λ	k_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1.0
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1.0	1.0
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1.0	-1.0
12	15.0	1.0	1.0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

- Just for illustration of shame effects
- Actual benchmarks values are updated in LHCHWG-2022-004

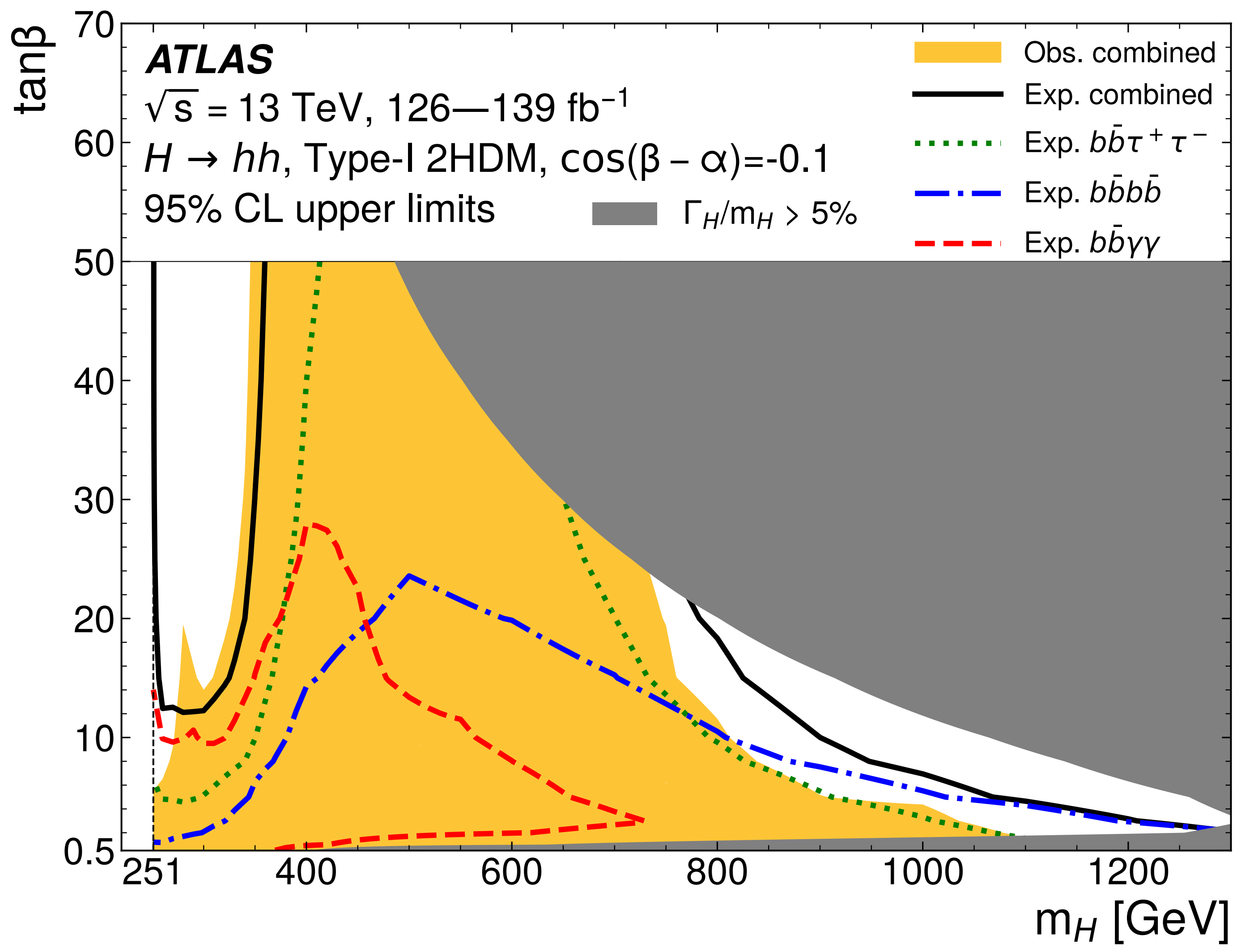
Resonant searches X→HH

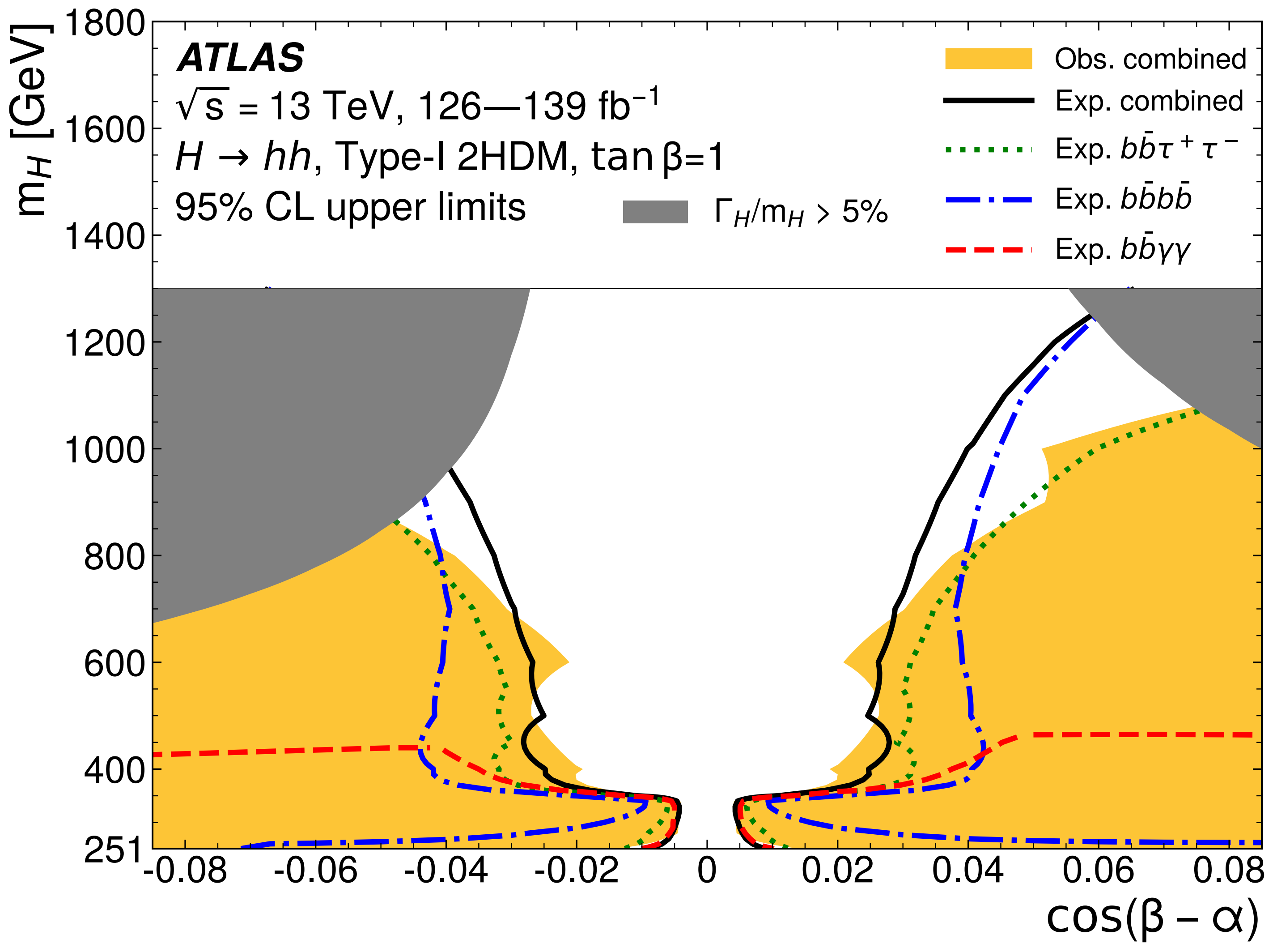


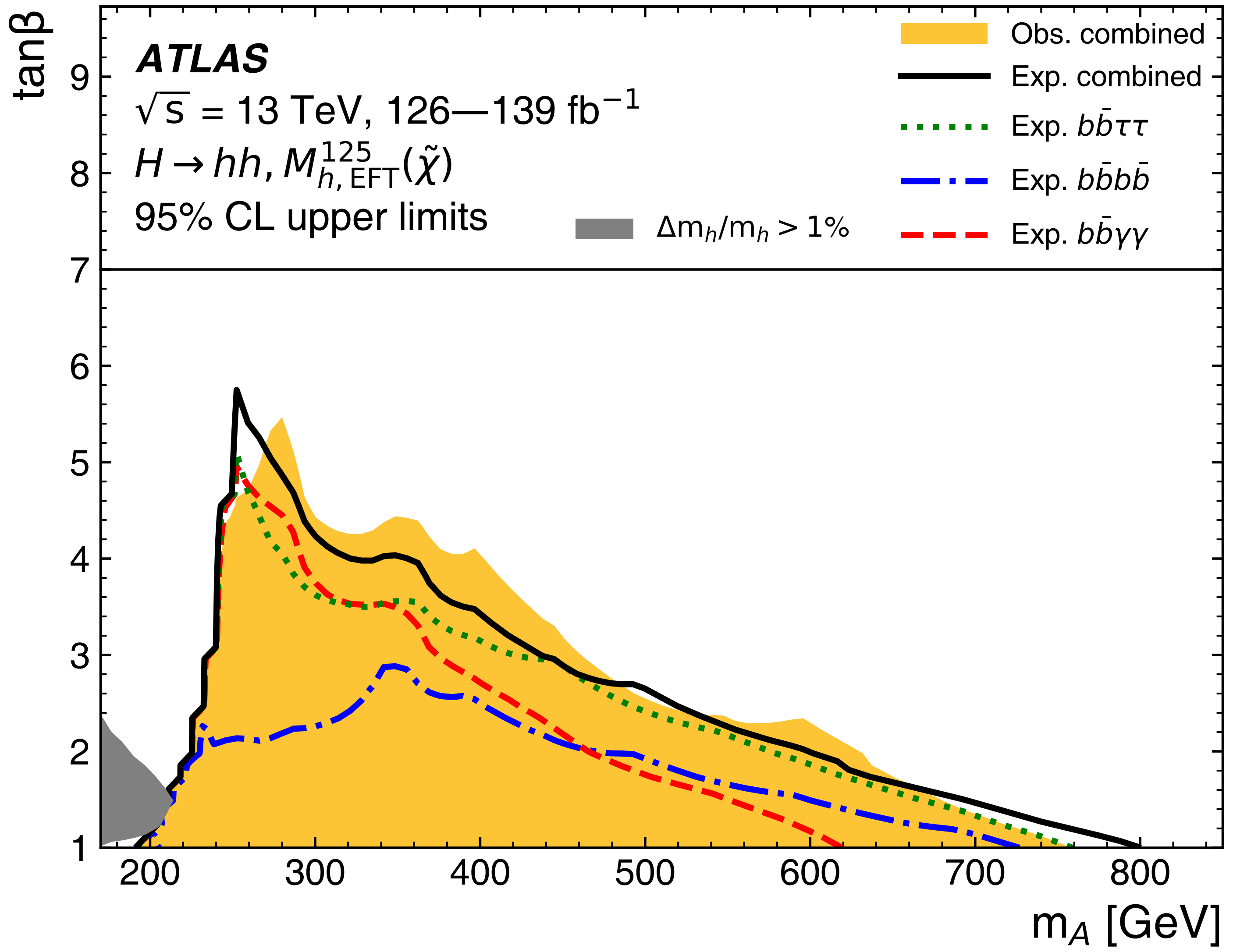


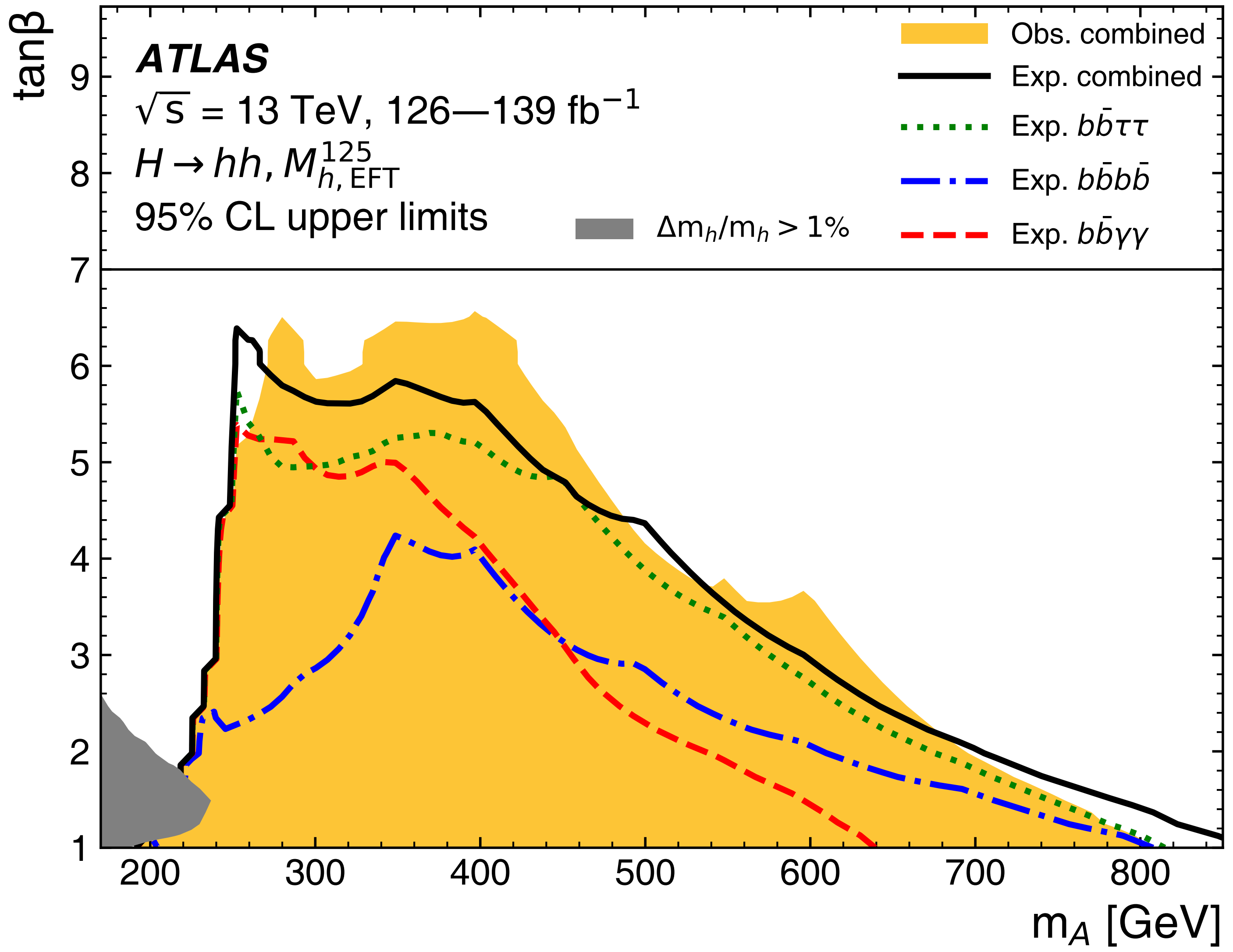
- Spin 0 and spin 2 resonances with narrow width approximation
- From CMS B2G Summary plots

Interpretations of resonant analyses



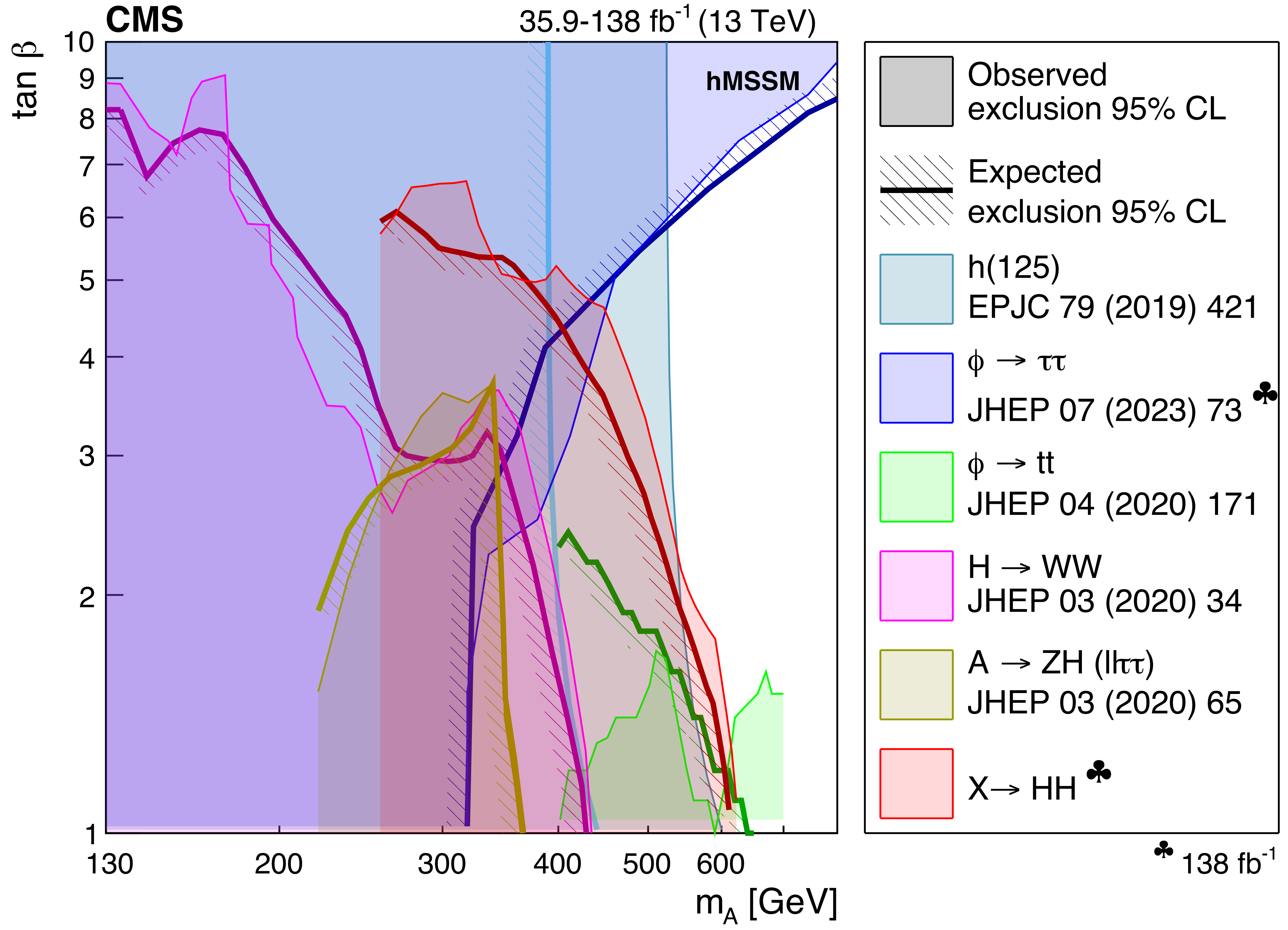


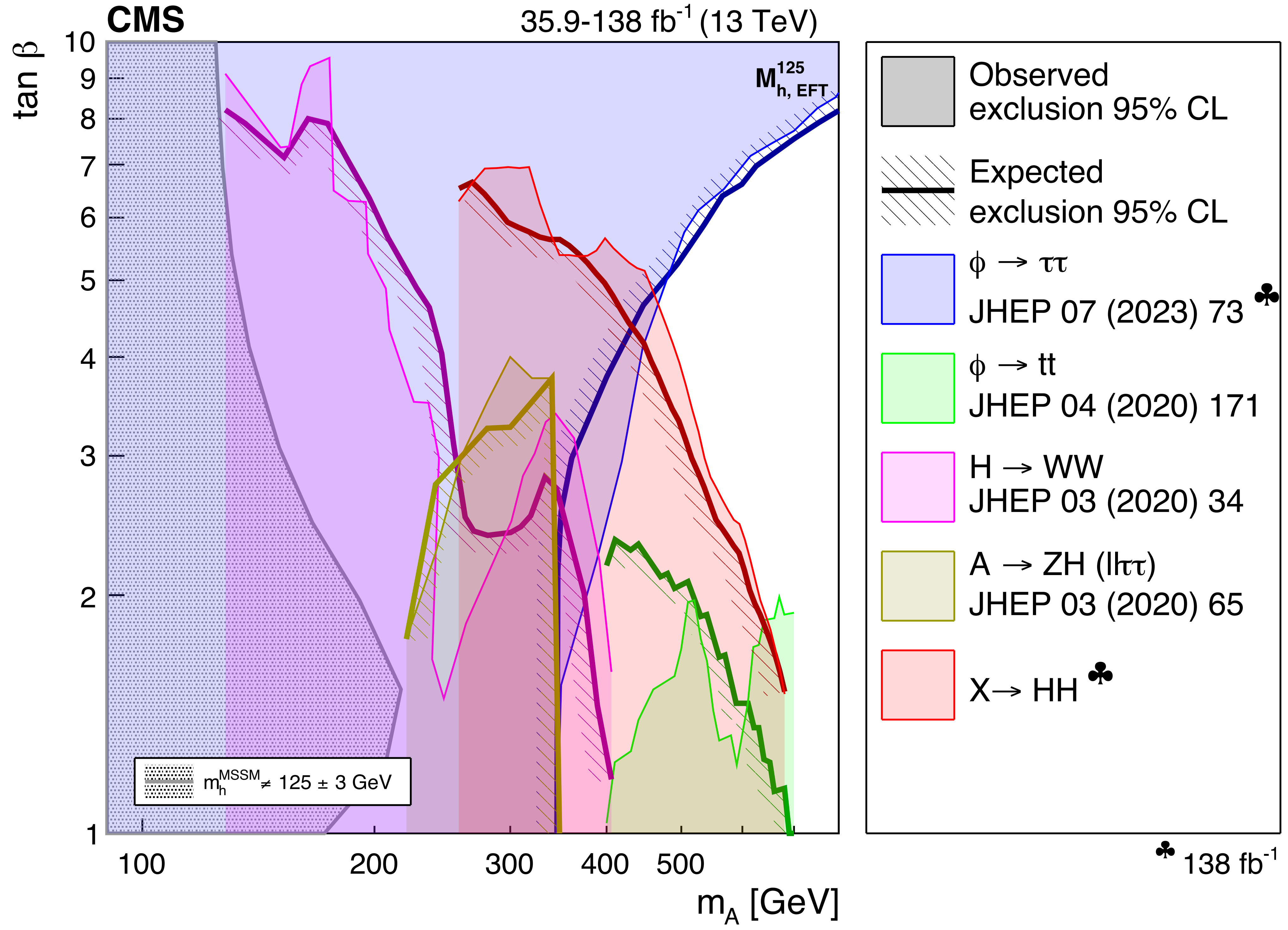




- Direct recast from ATLAS in extended scalar sector models (hMSSM, 2HDM, singlet)
- Ref : PRL 132 (2024) 231801

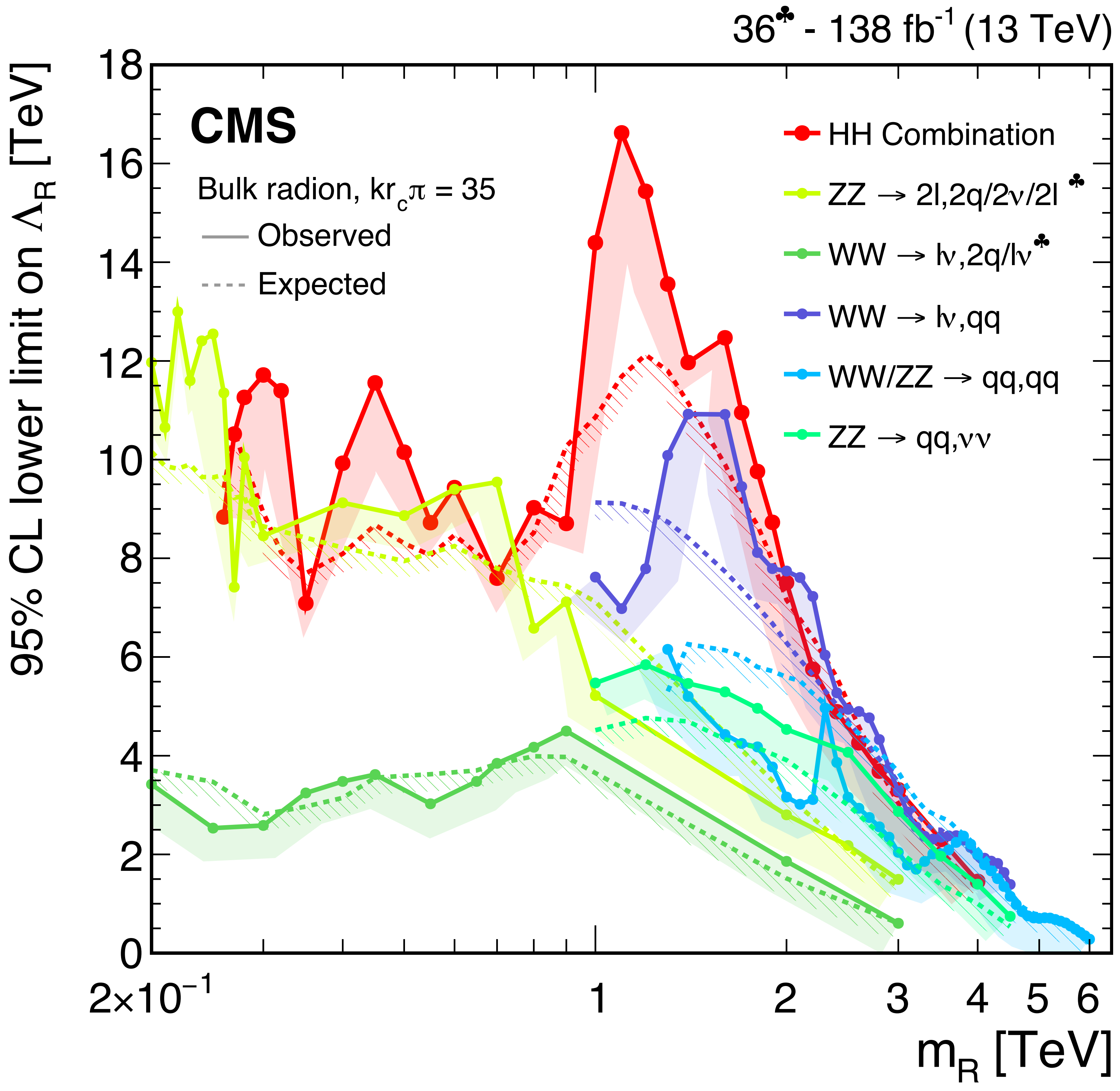
Interpretations of resonant analyses

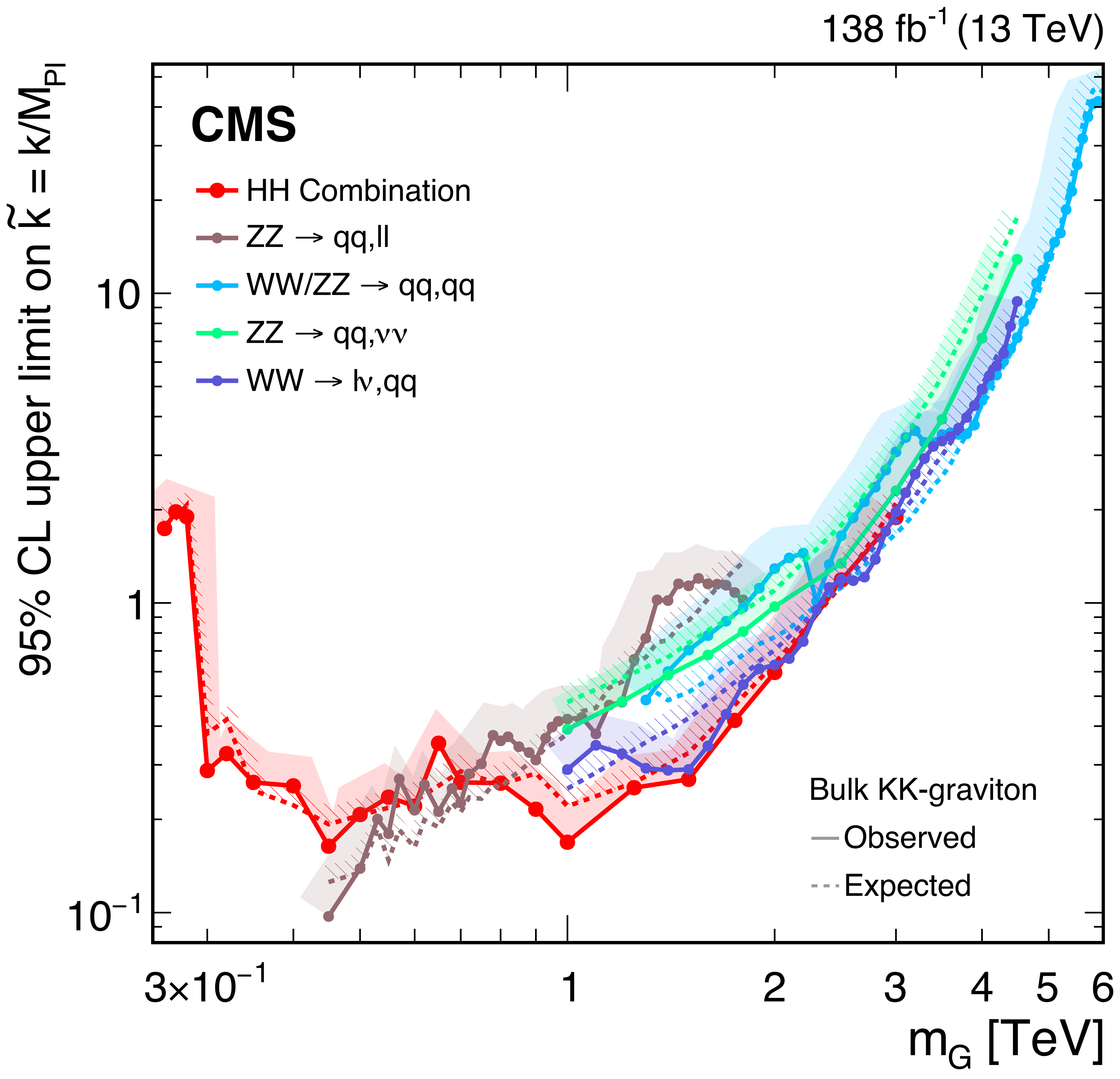




- Interpretations on extended scalar sector models
- HH sets some leading contraints on the parameters space
- Ref: arXiv:2403.16926

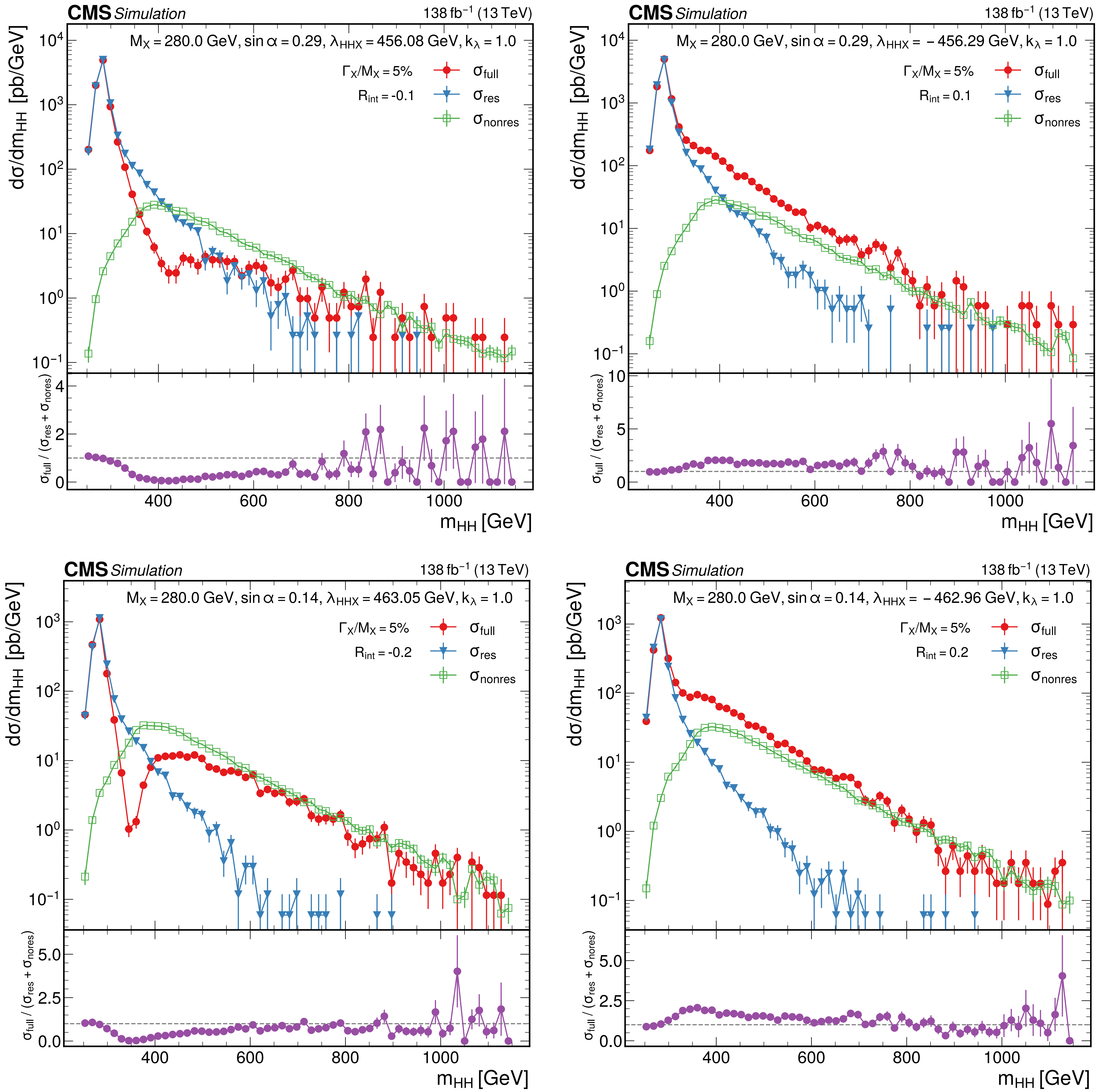
Interpretations of resonant analyses





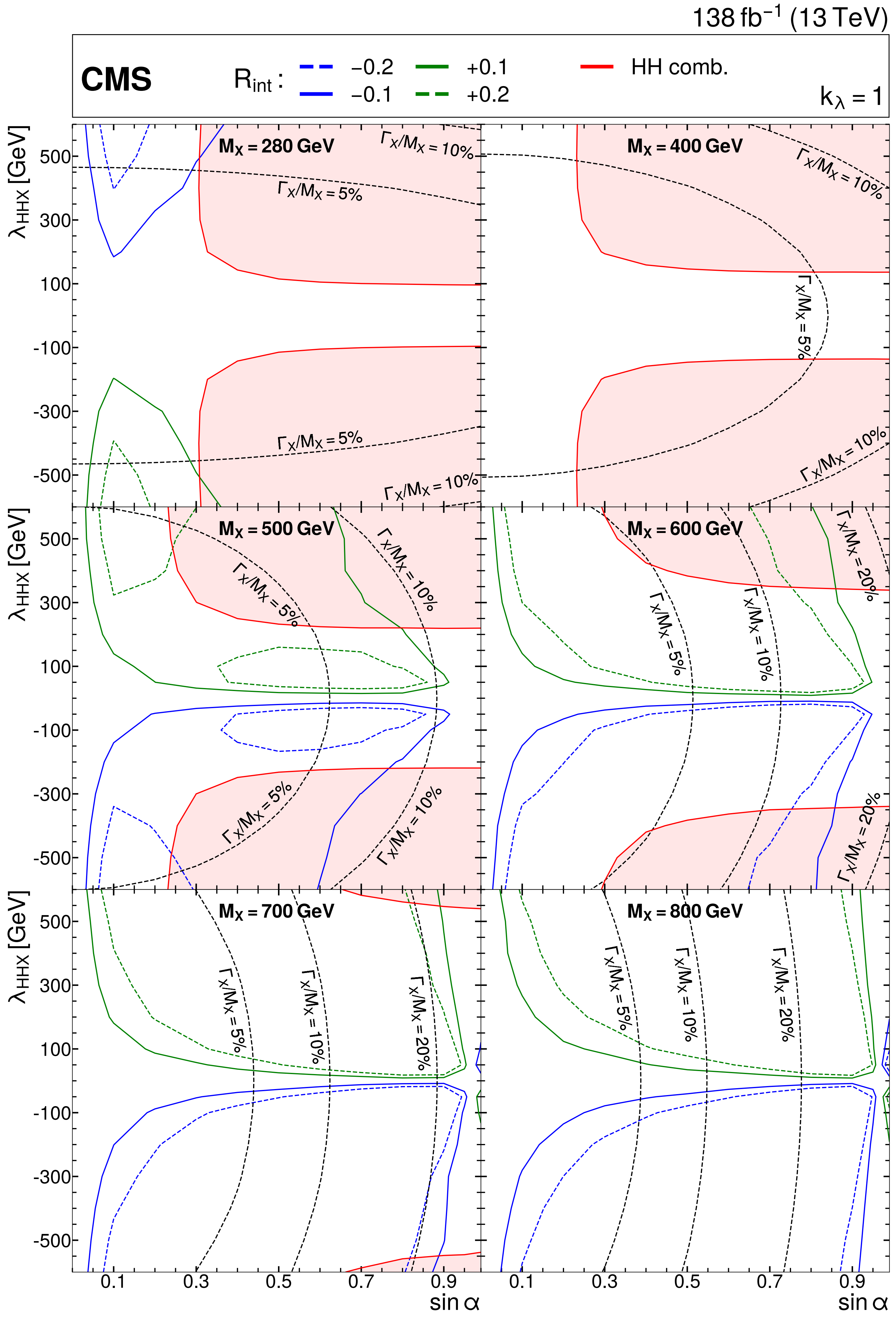
- Interpretations on warped extra dimensions
- Ref: arXiv:2403.16926

Effect of finite width



- Clear interference structures in the full prediction, including peak-dip features
- Model dependent!
- Ref: arXiv:2403.16926

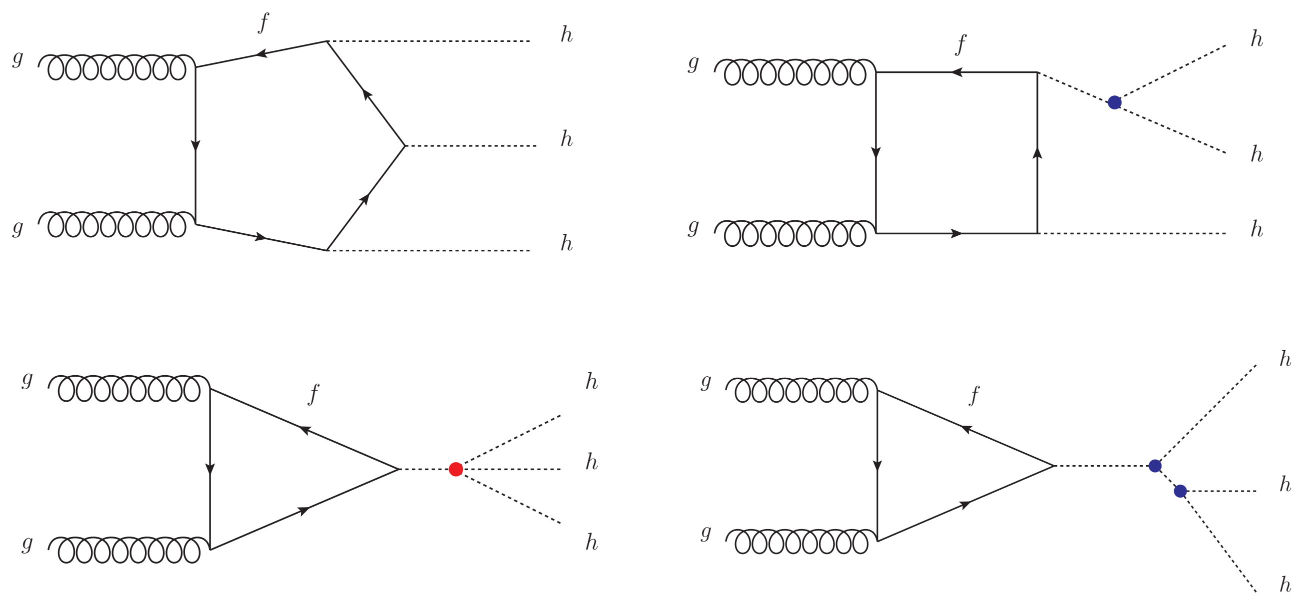
Effect of finite width



$$R_{\text{int}} = \frac{\sigma^{\text{full}} - \left(\sigma^{\text{resonant-only}} + \sigma^{\text{nonresonant}}\right)}{\sigma^{\text{resonant-only}} + \sigma^{\text{nonresonant}}}$$

- Effects from interference can be large even when the width of the resonance is below the detector resolution

How about HHH?

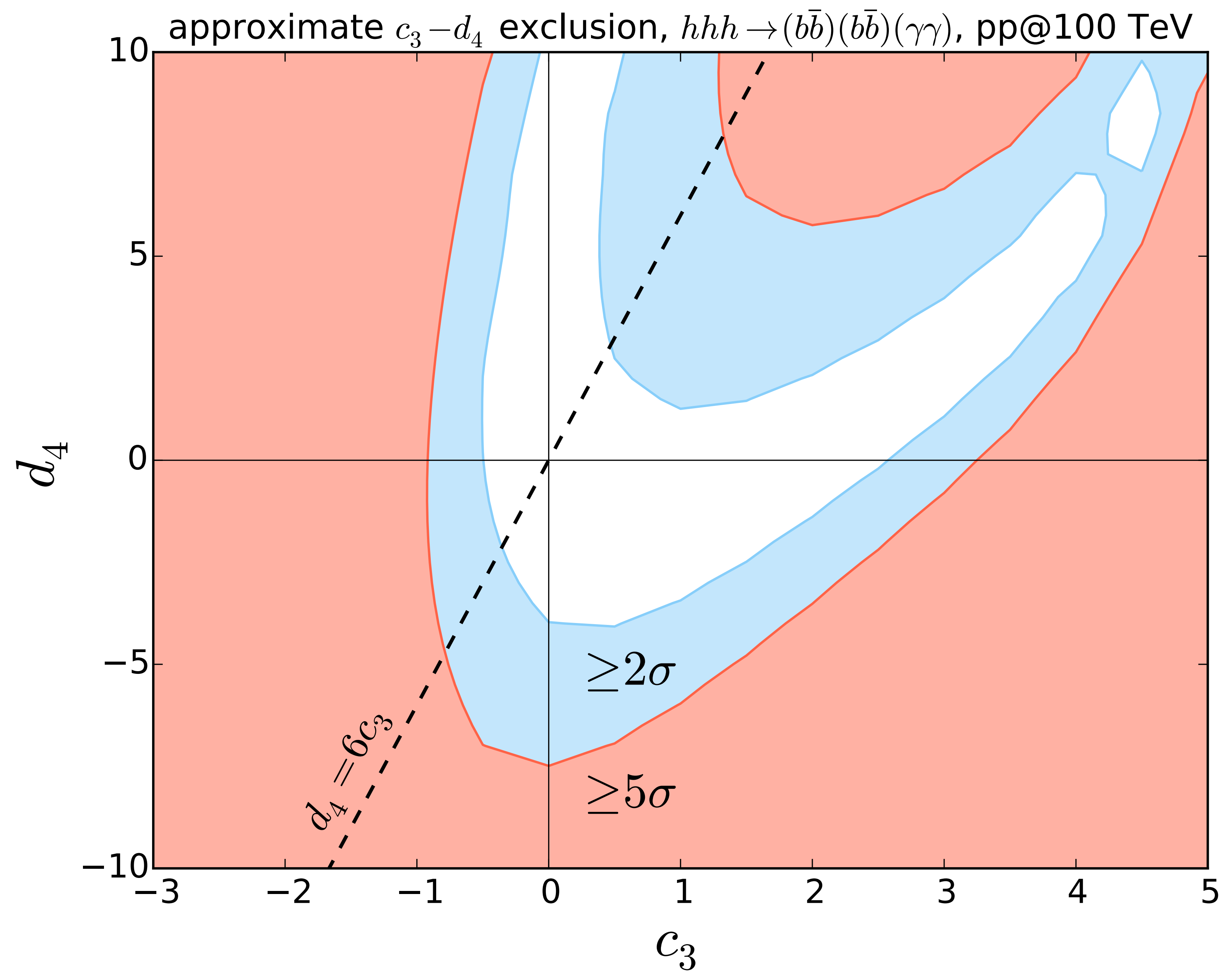


Depends also on trilinear coupling

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}	$9.91^{+19.3\%}_{-16.6\%} \pm 5.3\%$	$15.14^{+18.4\%}_{-16.0\%} \pm 4.7\%$	$63.32^{+16.1\%}_{-14.1\%} \pm 3.4\%$	$76.15^{+15.9\%}_{-14.0\%} \pm 3.2\%$	$4306^{+14.0\%}_{-12.3\%} \pm 1.8\%$

aptobarn!

- 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)