Exploring the Higgs boson self-coupling at the LHC

UF | UNIVERSITY of FLORIDA

Distinguished researcher
in 2019 and 2020

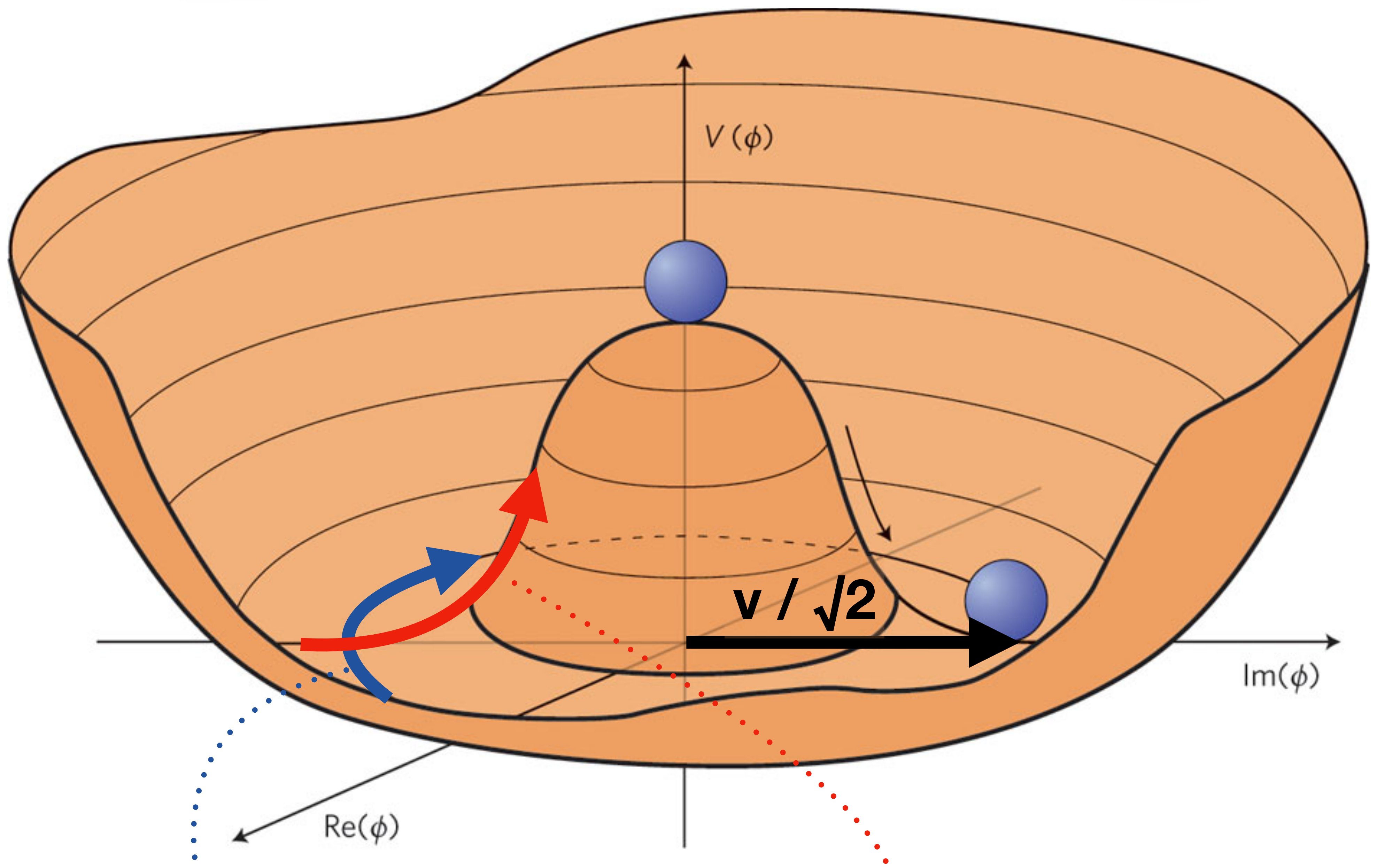
Fermilab

Luca Cadamuro
University of Florida

Séminaires de Physique des Hautes Energies
Institut Pluridisciplinaire Hubert Curien (IPHC)
February 18th, 2021

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**

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

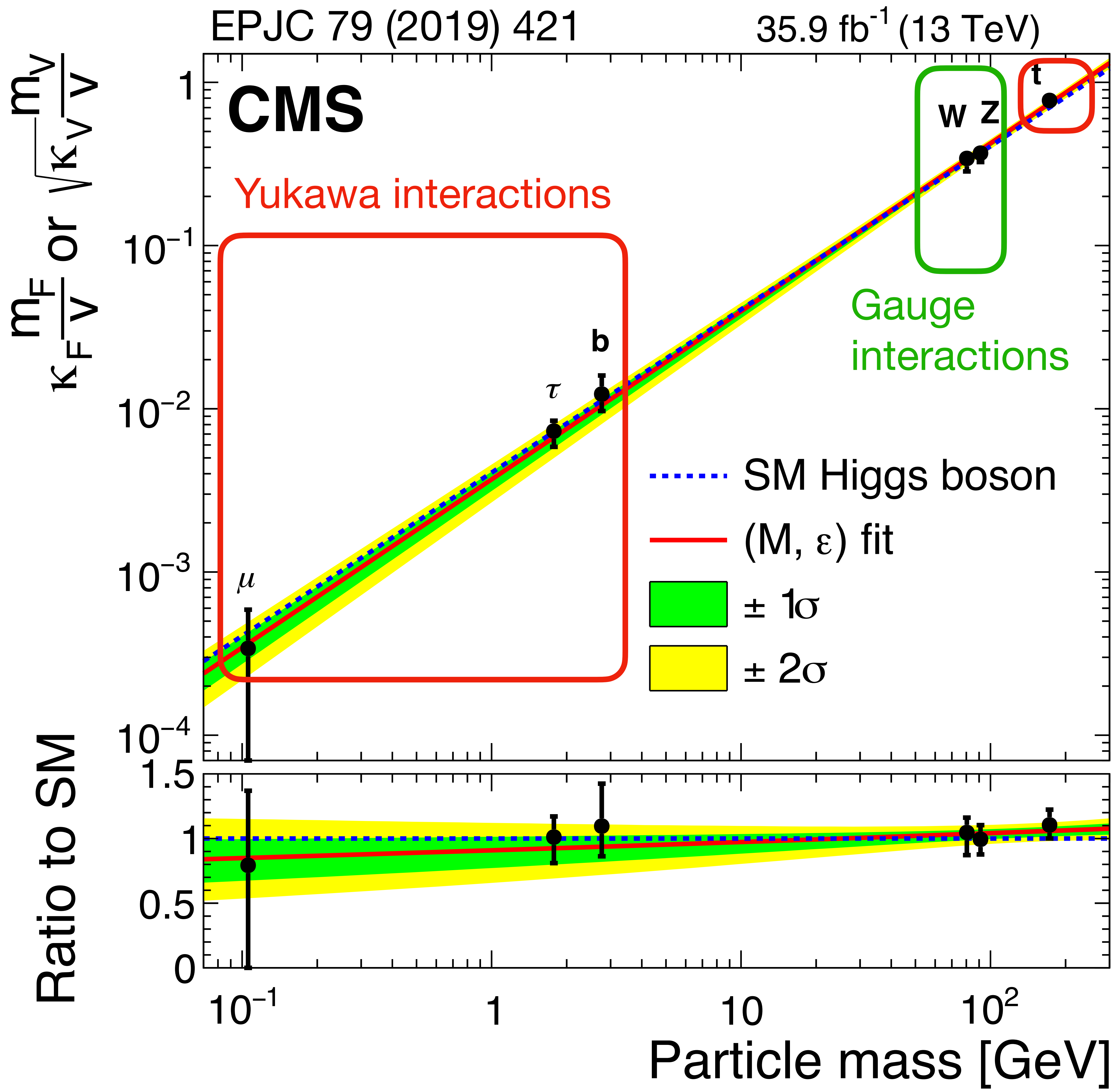
Two main sectors of the SM:

- **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

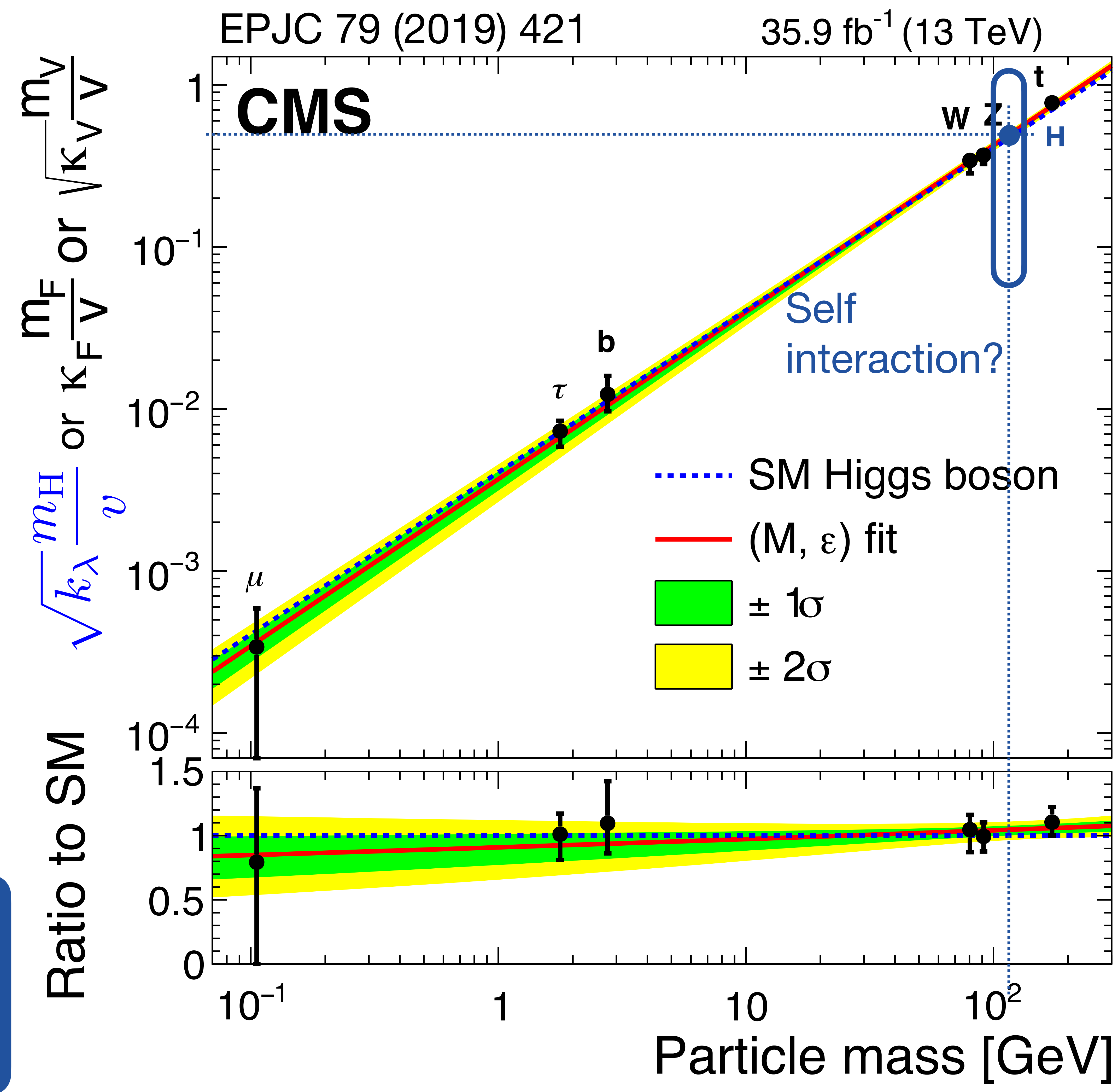
- Observed by ATLAS and CMS in 2012
- Mass precisely determined:
  $m_H = 125.09 \pm 0.24$ GeV
- Precise study of its interactions with fermions and vector bosons…
- … but self-interactions not measured experimentally!

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

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

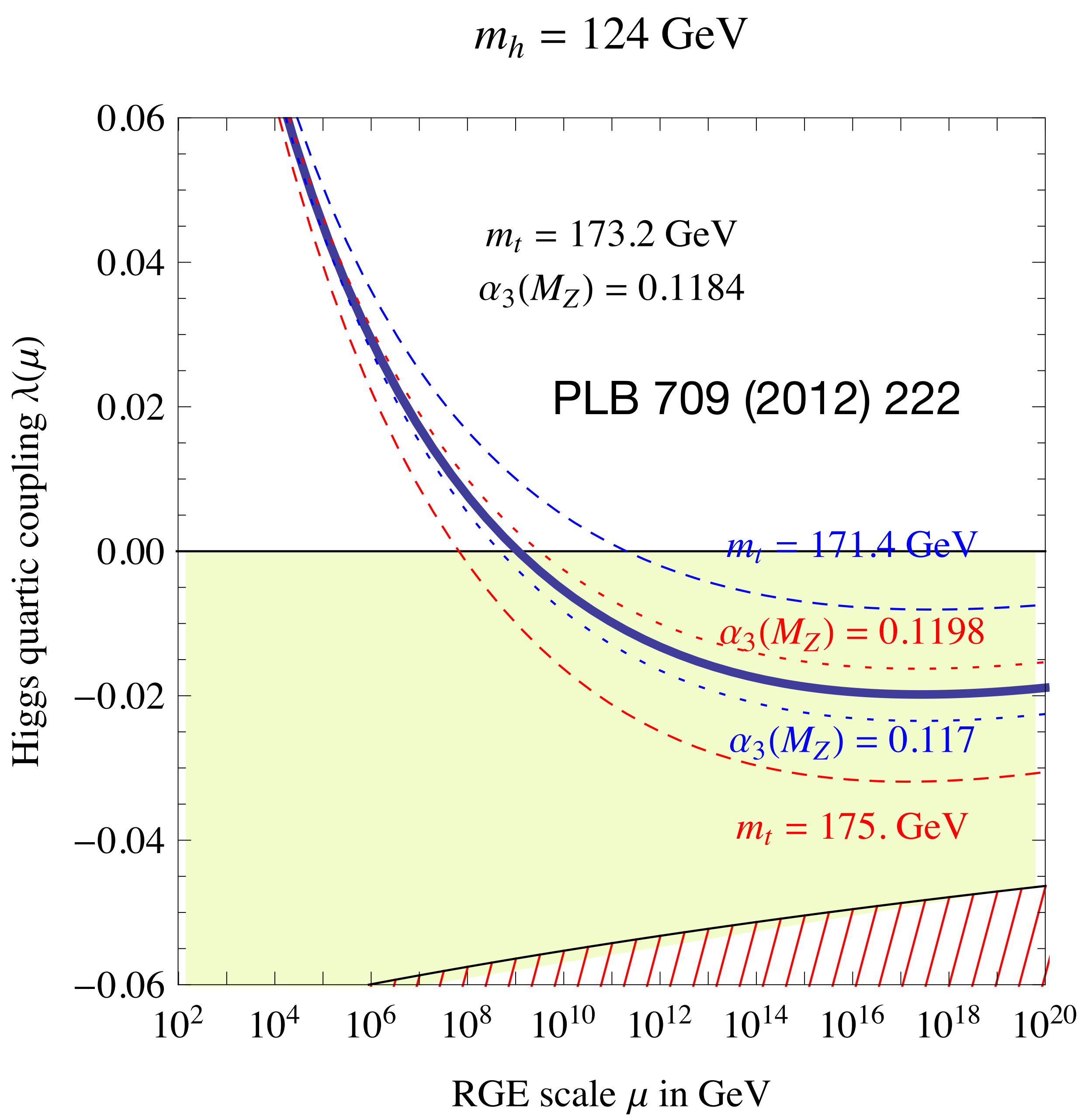
$\lambda_{\rm HHH}$: direct access to the shape of the scalar potential

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



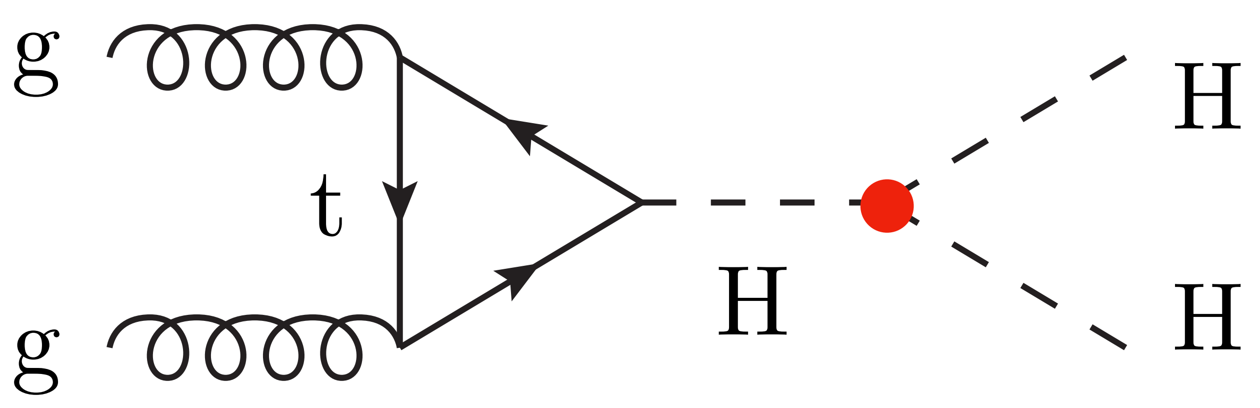
PLB 709 (2012) 222

- 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?

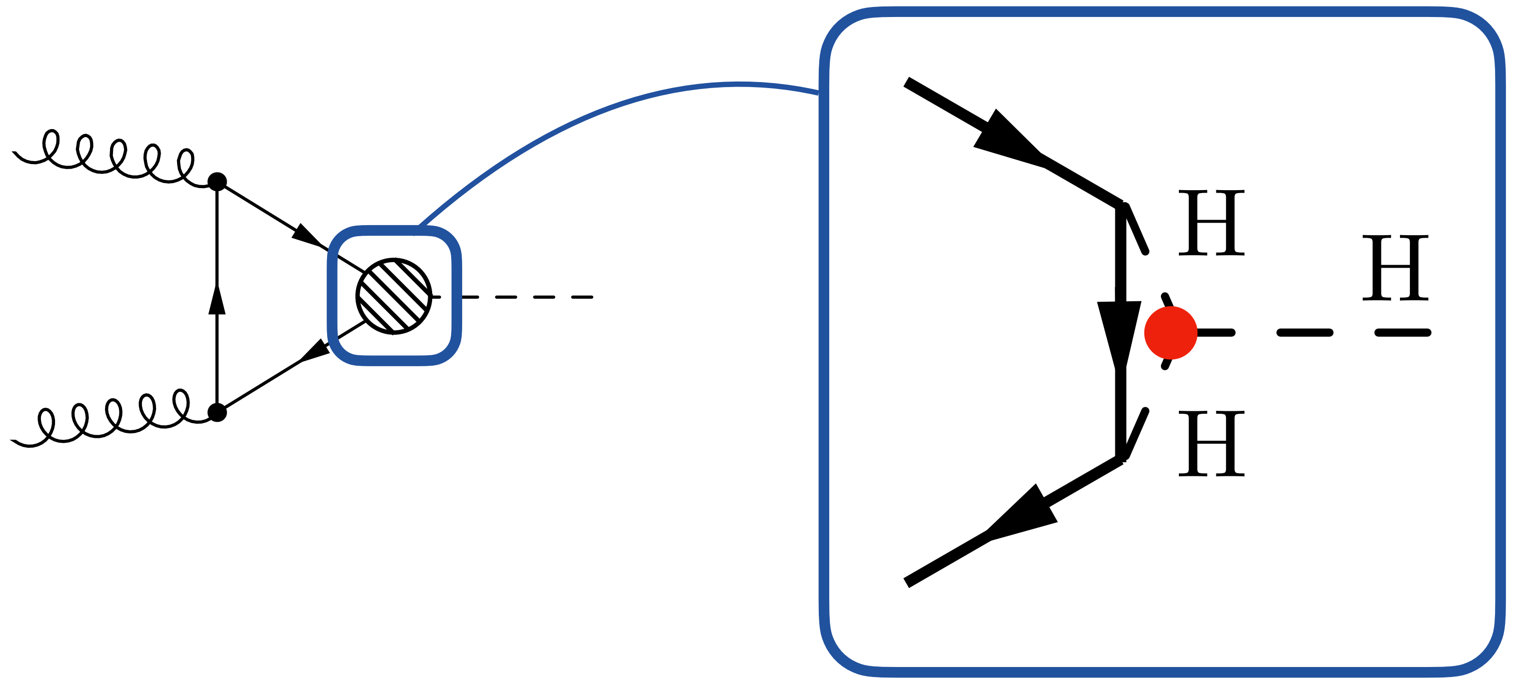
Two complementary strategies exist:

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 × 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 $\mathscr{L} = 10^{34}\ \mathrm{cm^{-2}\ s^{-1}}$
- 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

LHC

High Luminosity LHC

Run-I | LS1 | Run-II | LS2 | Run-III | LS3

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2035

Machine:
Splice consolidation

Exp.:
Beam pipe

Machine:
Injector
upgrade

Exp.:
Upgrade Phase1

Machine:
HL-LHC
installation

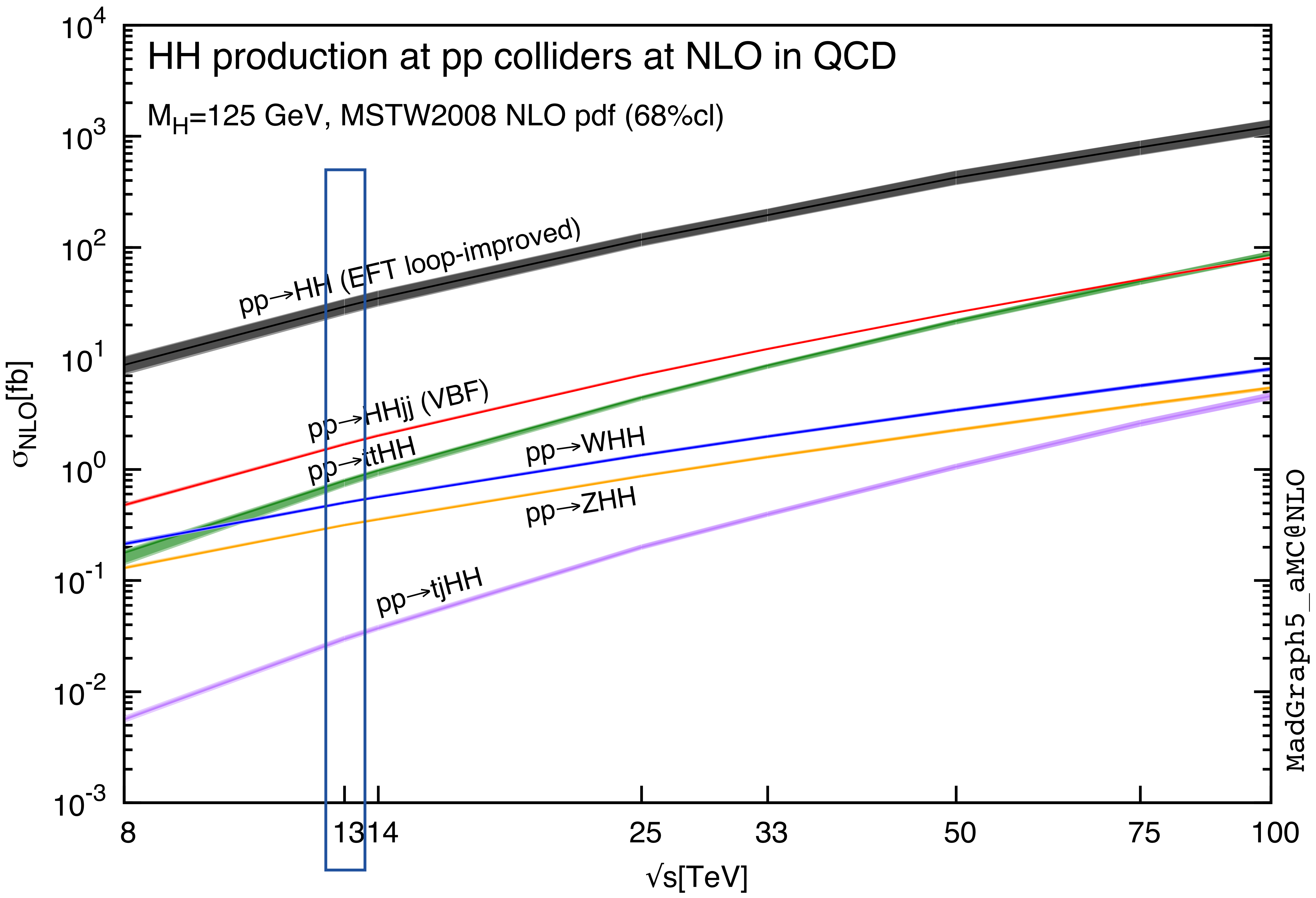
Exp:
Upgrade Phase2

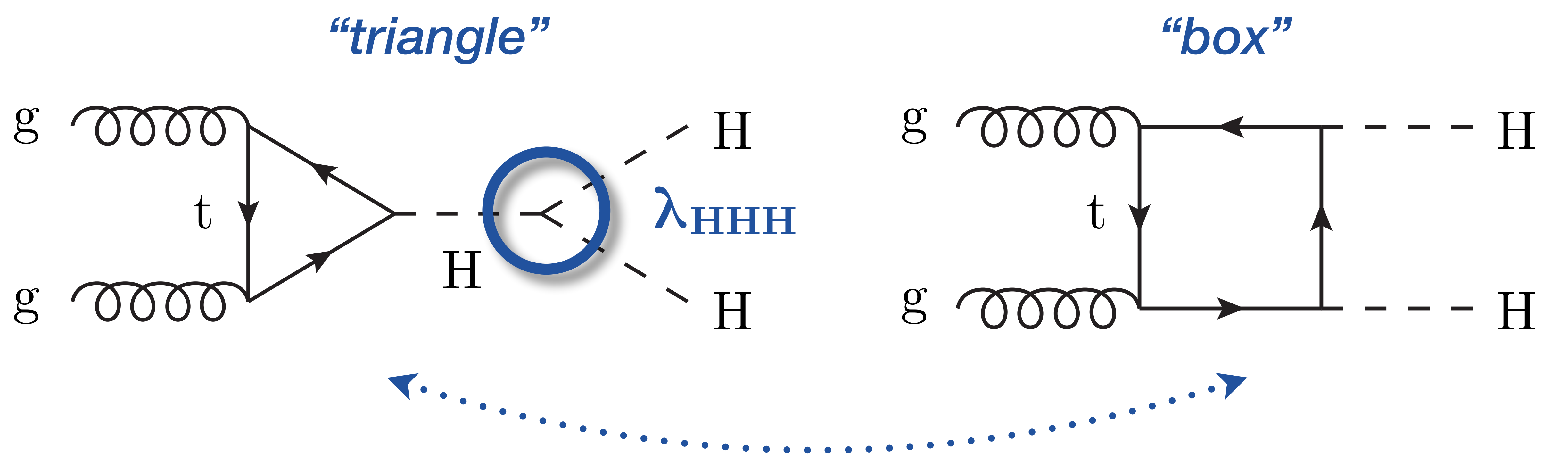
7TeV | 8TeV | 13TeV | 14TeV | 14TeV | Energy

75% nominal luminosity | nominal luminosity | 2x nominal luminosity | 5x nominal luminosity | instan. luminosity

25 fb^{-1} | 150 fb^{-1} | > 300 fb^{-1} | 3000 fb^{-1} | integrated luminosity

HH production at the LHC





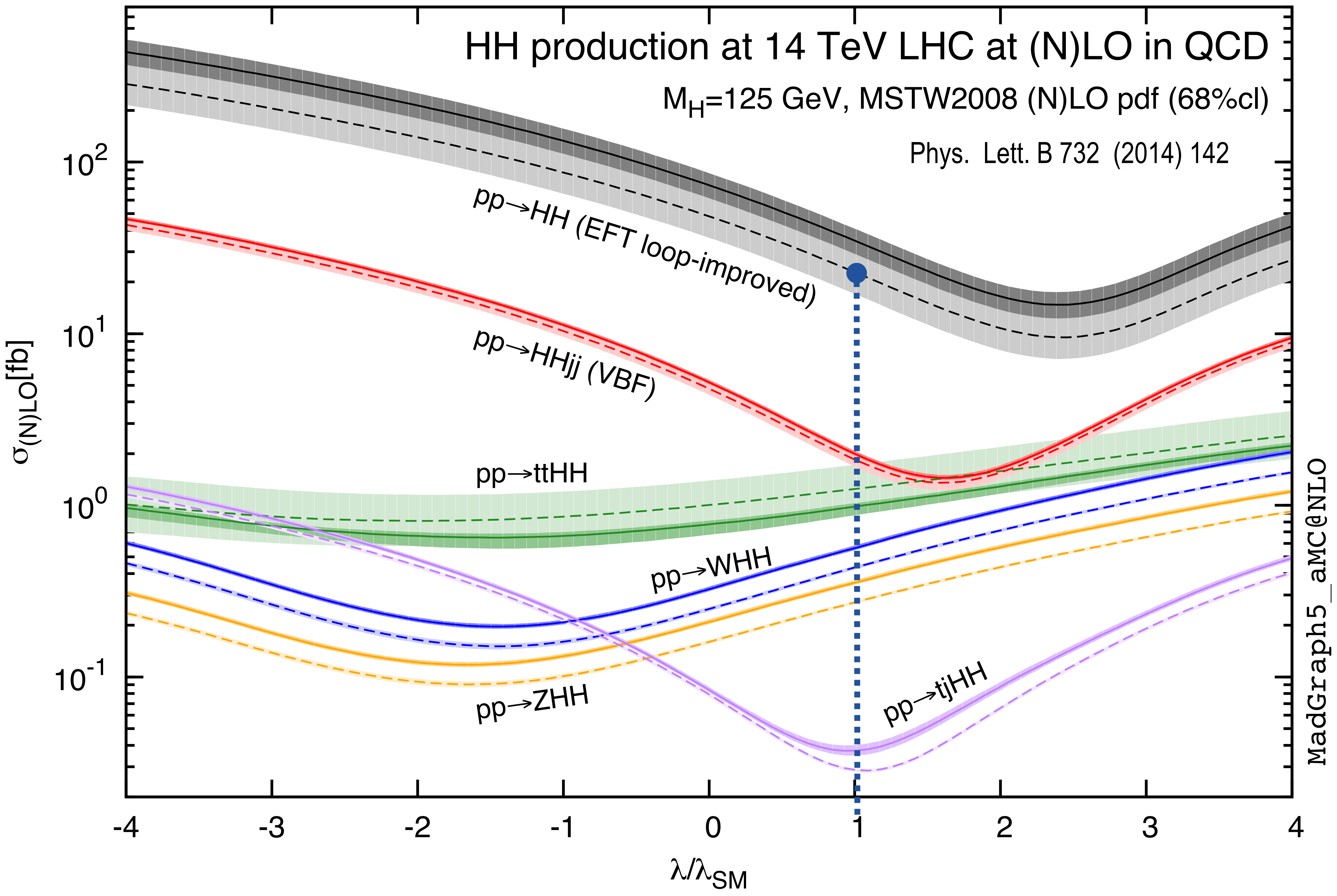
Strong destructive interference

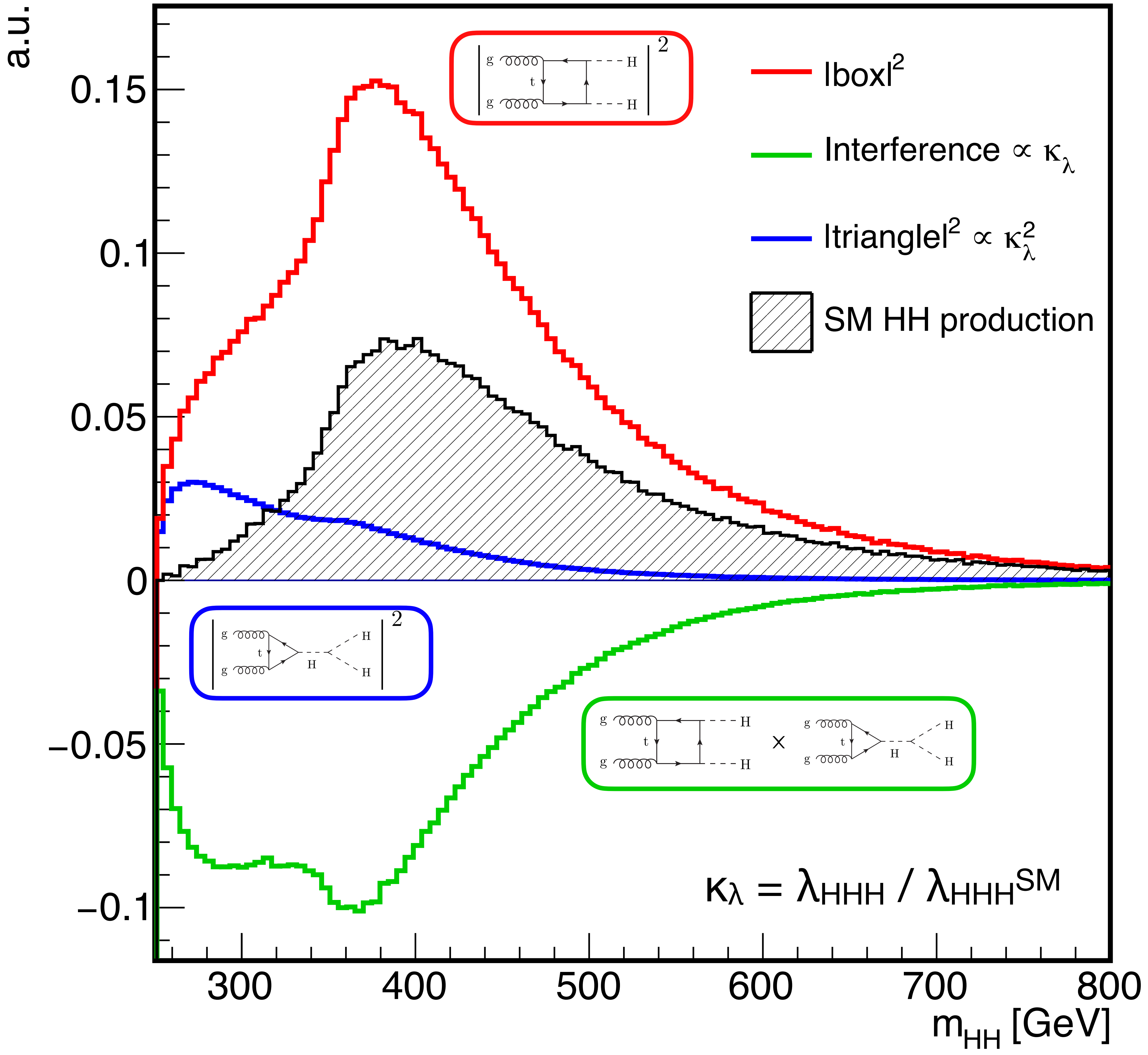
$$\boxed{\sigma^{\mathrm{SM}}_{\mathrm{HH}} = 31.05^{+4.5\%}_{-6.4\%}\ \mathrm{fb}\ (\mathrm{scale} \oplus \mathrm{PDF} \oplus \alpha_{\mathrm{S}} \oplus m_{\mathrm{t}})}$$

NNLO FT-approx (JHEP 1805 (2018) 059)

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

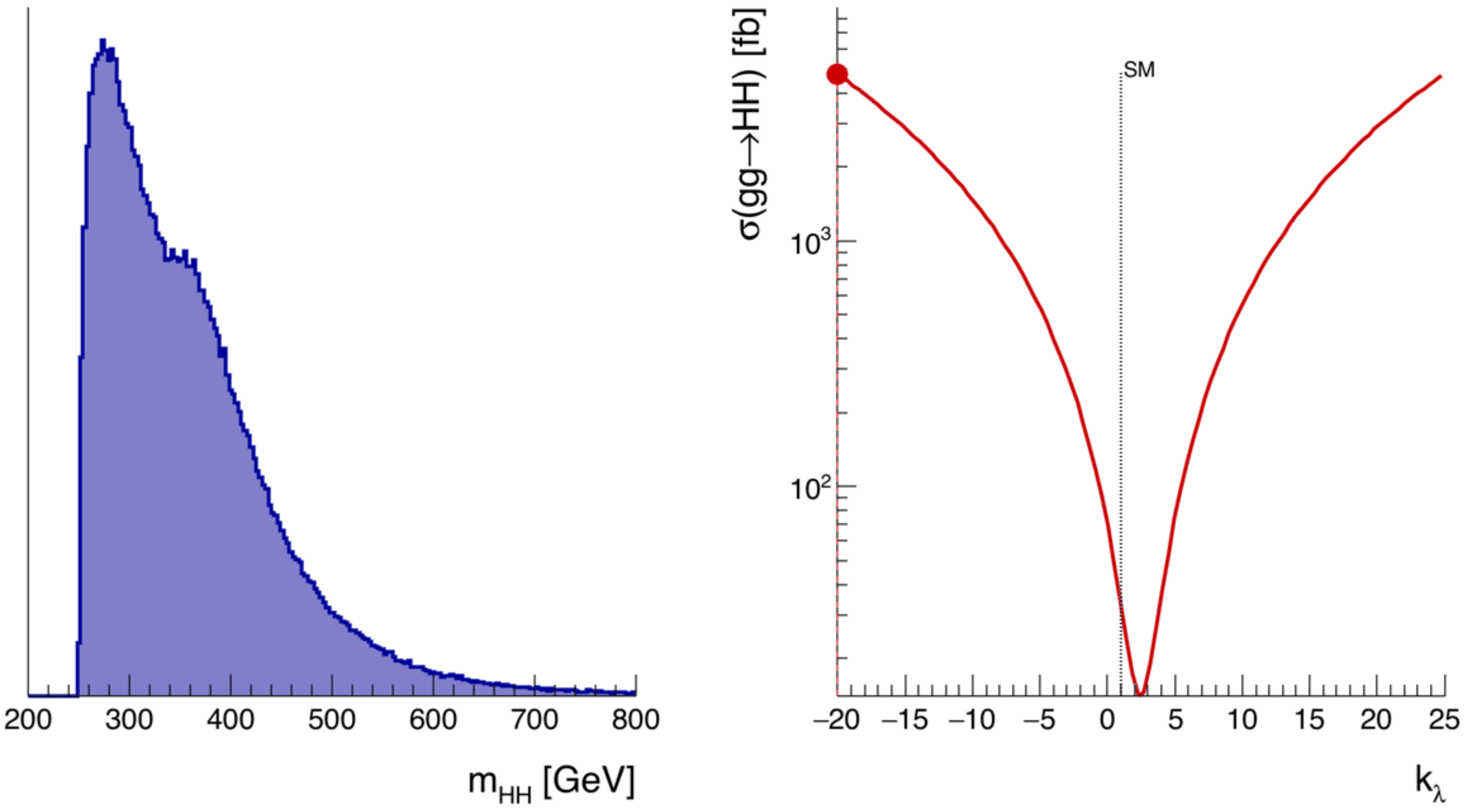
Extracting λ_{HHH} from HH measurements





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

Illustration of shape effects

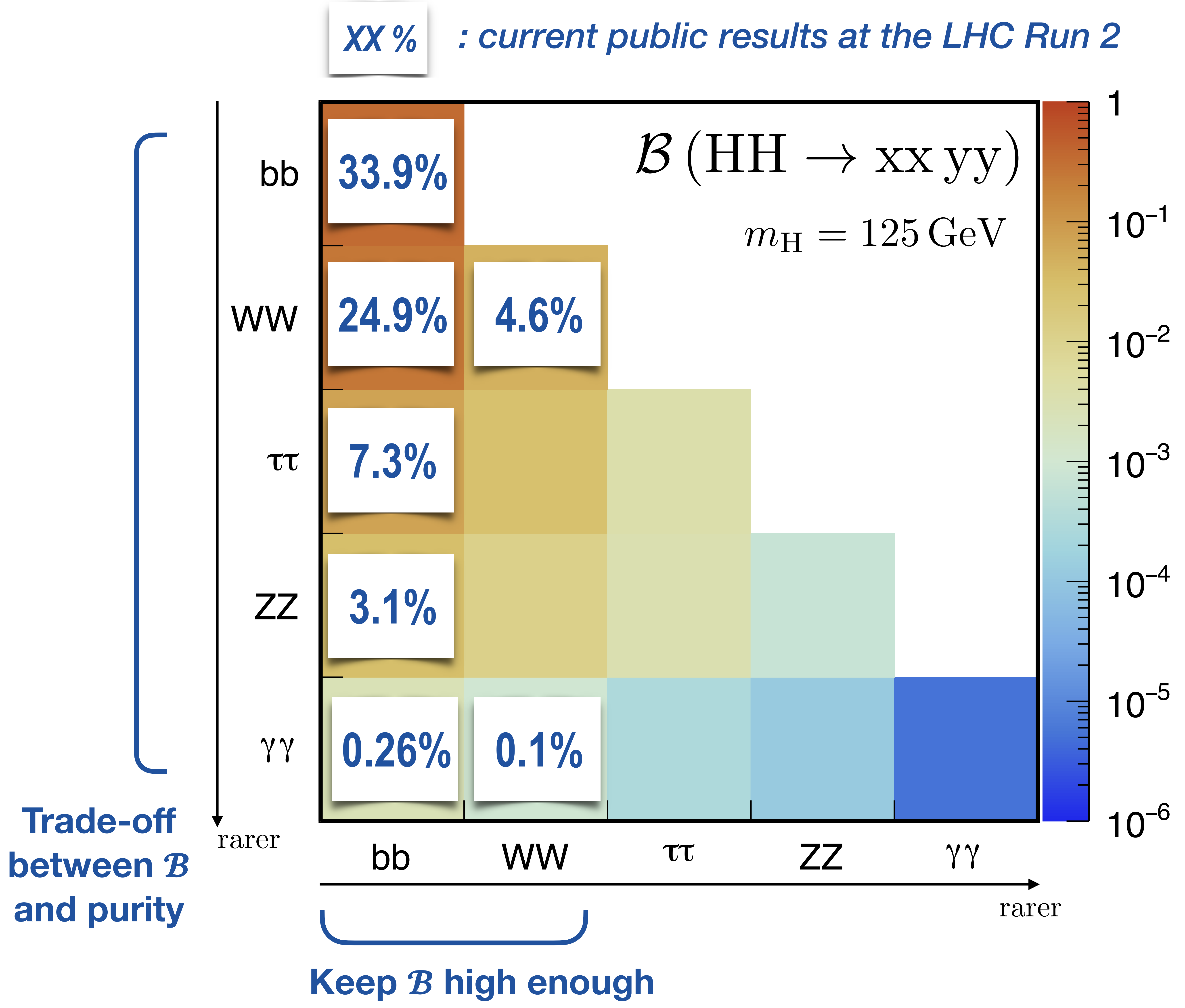


Interference effects have important consequences for the sensitivity of the searches

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**

*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.*



XX % *: current public results at the LHC Run 2*

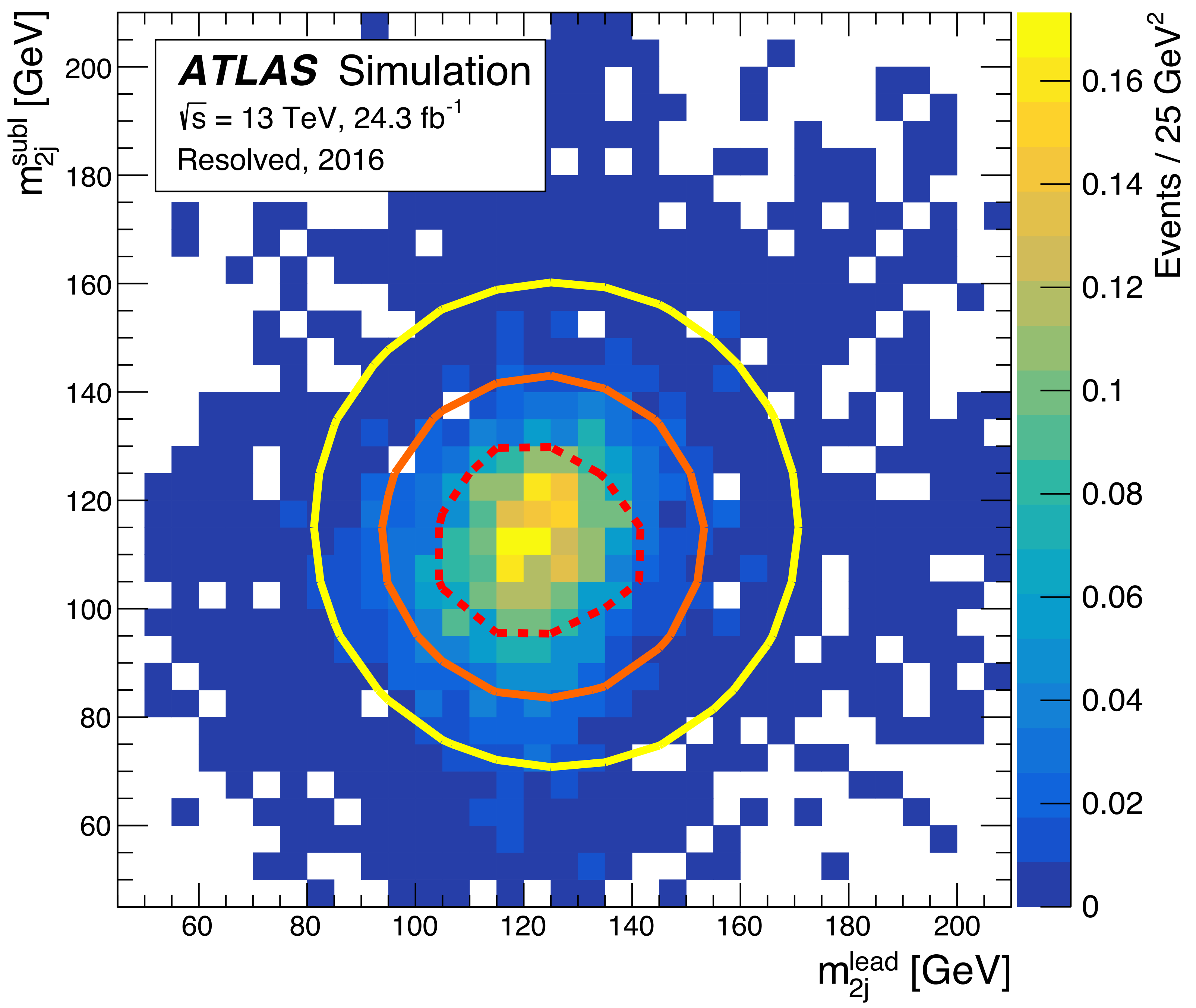
Trade-off between $\mathcal{B}$ and purity

Keep $\mathcal{B}$ high enough

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

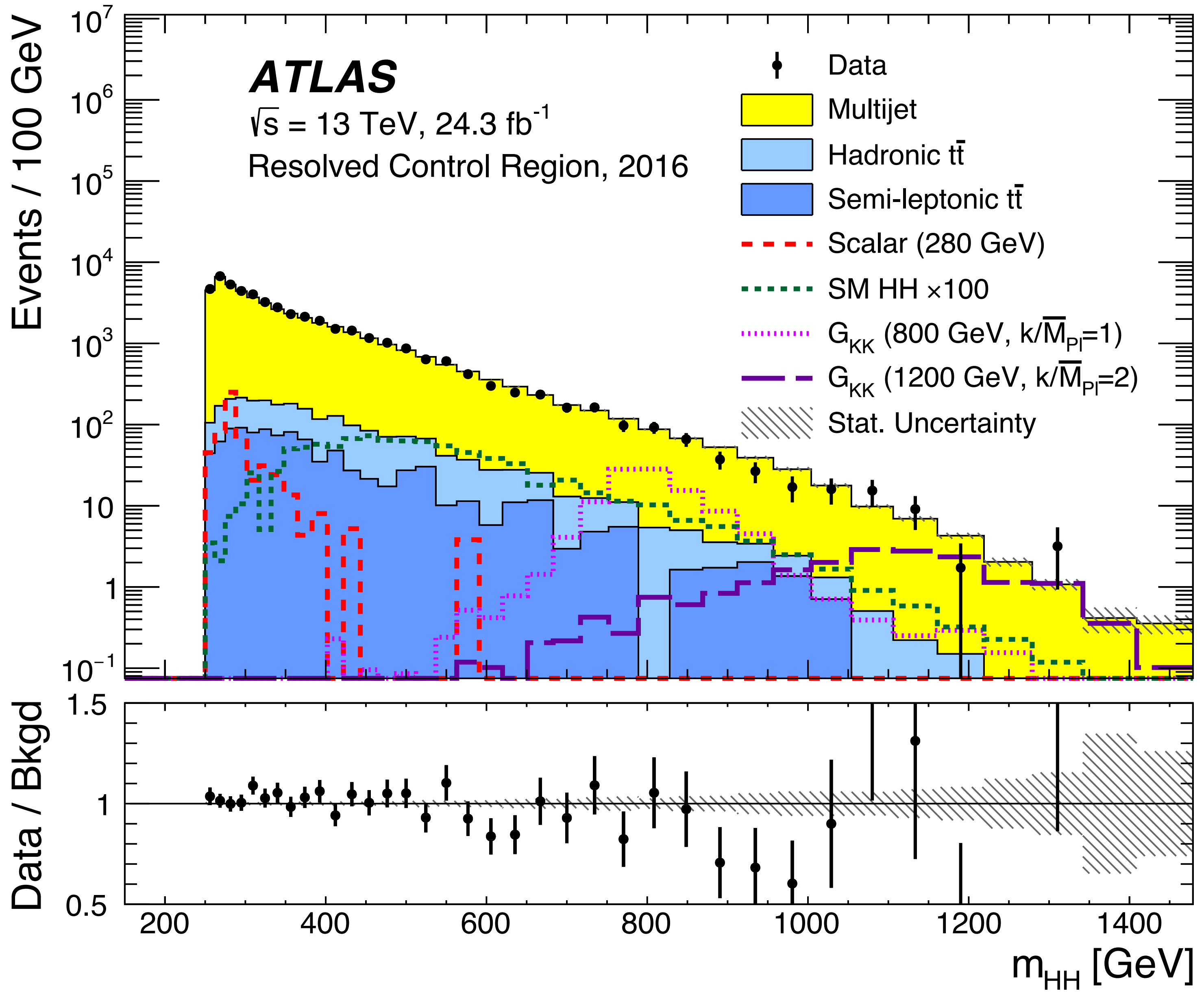
Event selection

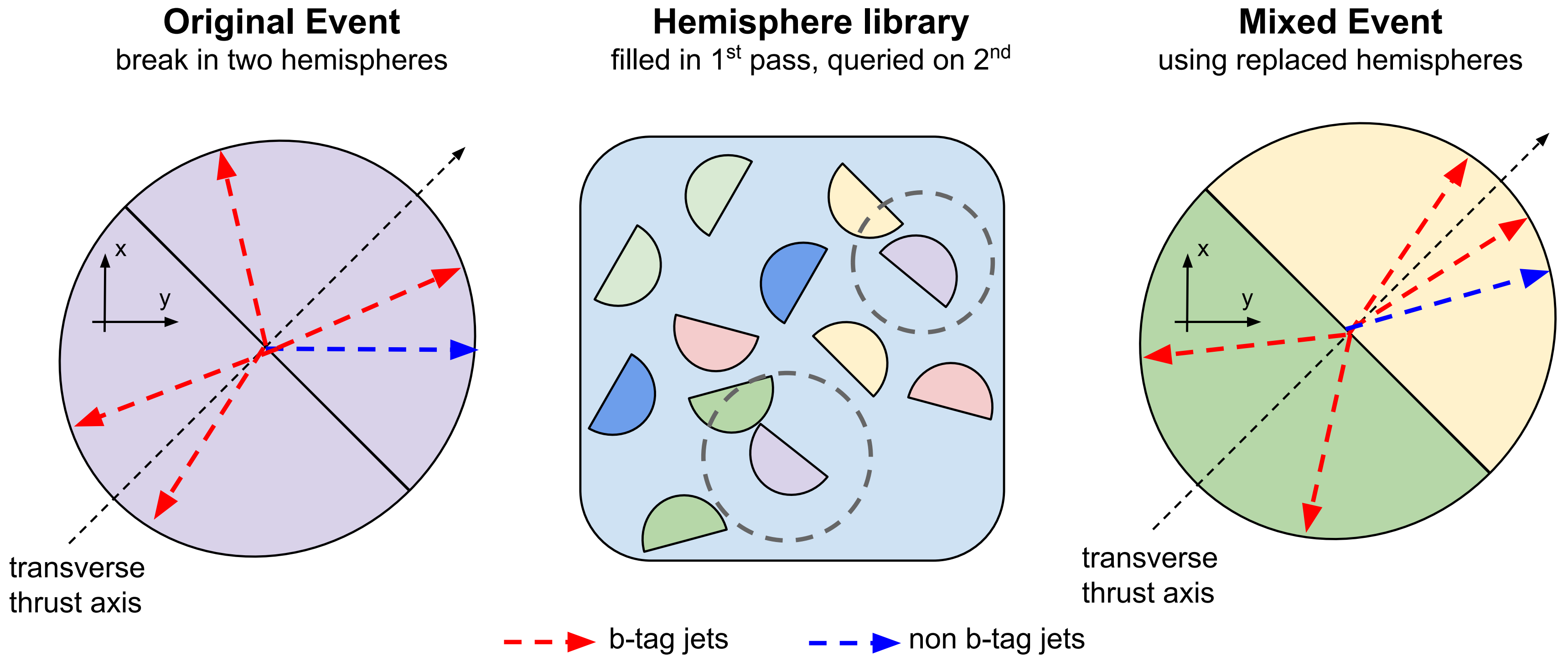
- Four b jets: crucially relies on tagging performance since trigger
- Use H→bb signature to reject the backgrounds



Multijet background estimation with data-driven methods

- ATLAS: from a anti-b tag region. Use a sideband for the estimation and a control region for the validation

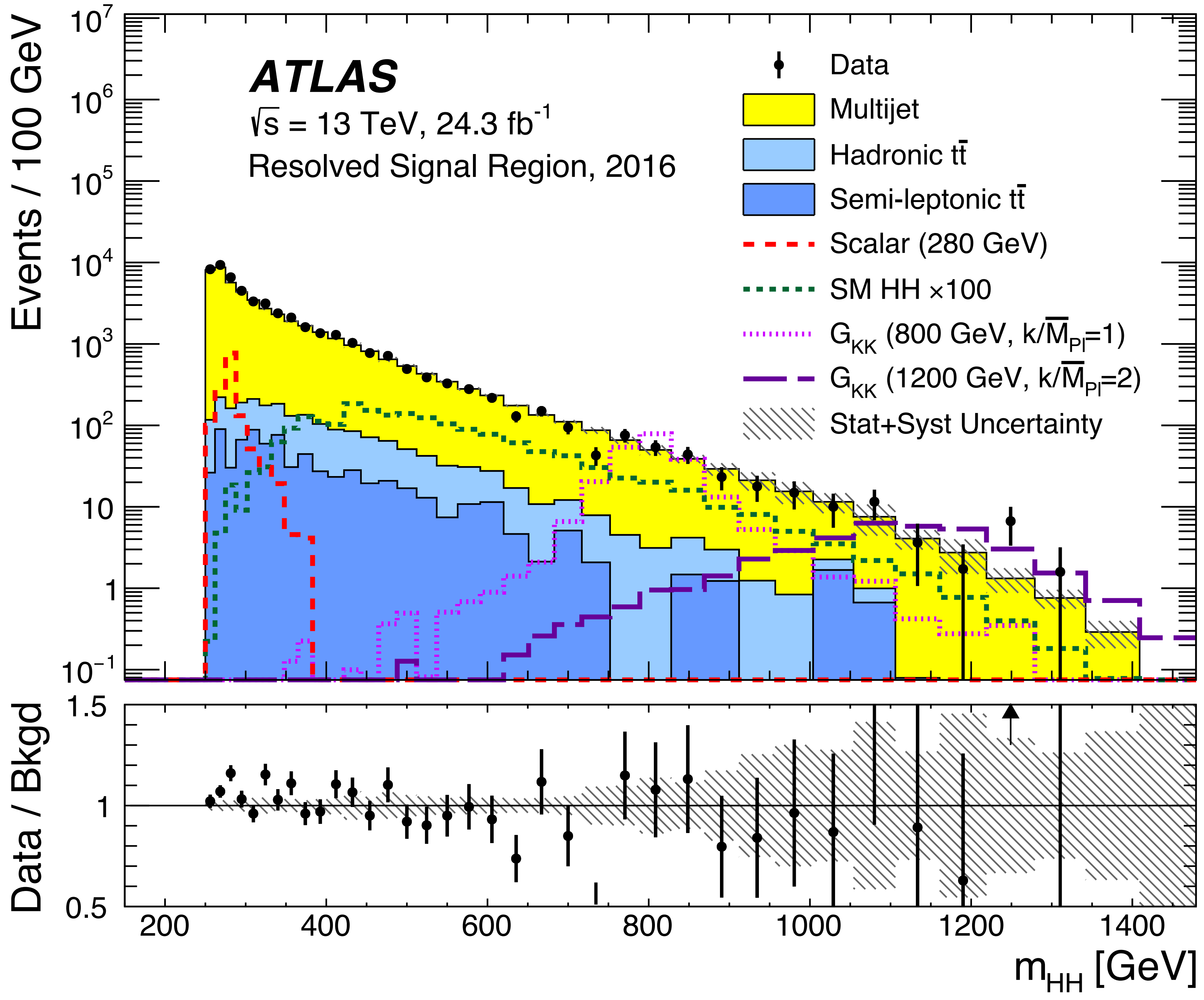




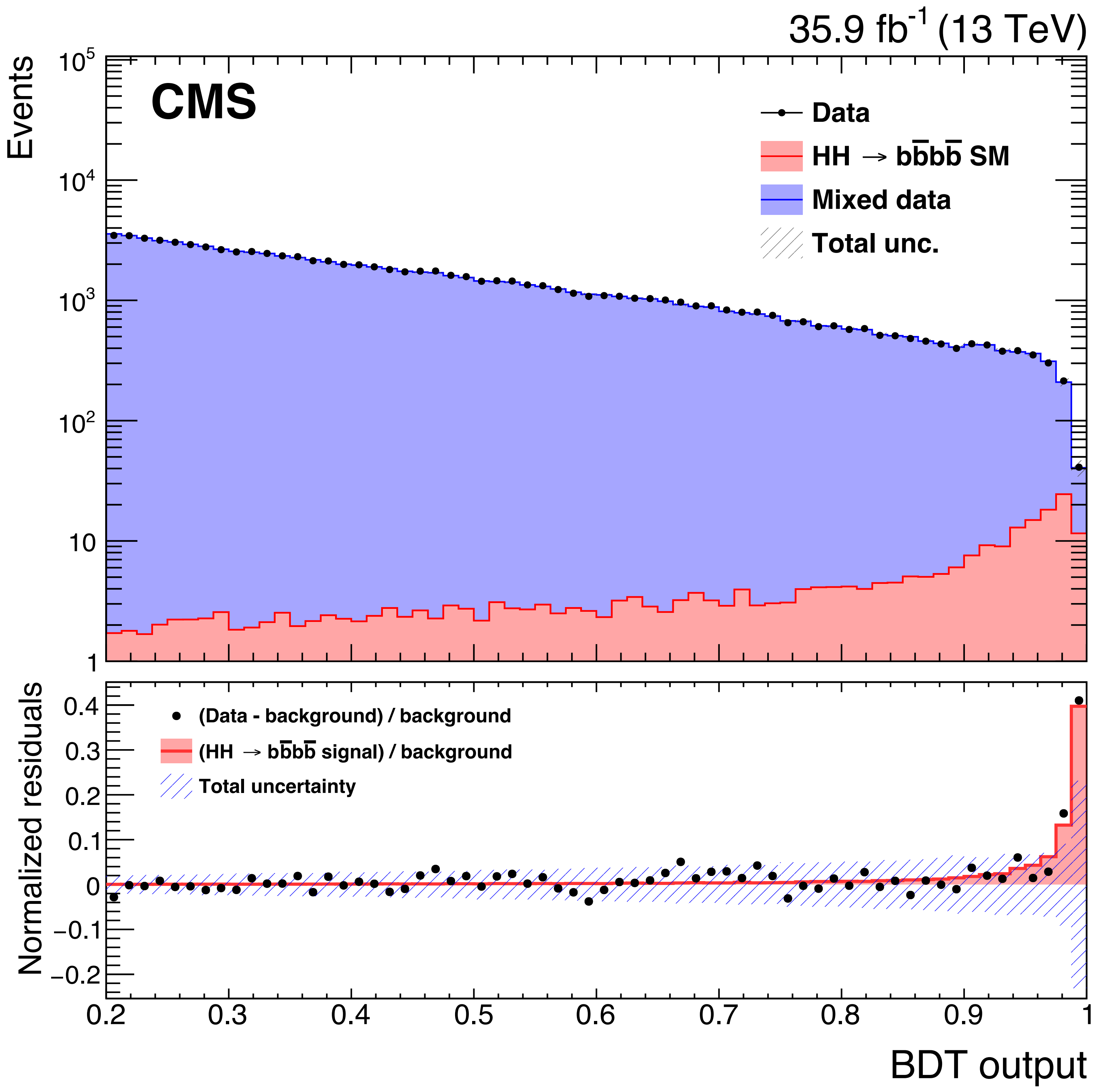
- CMS: "hemisphere mixing" to build background events from recorded data

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

Separation from the multijet background is essential



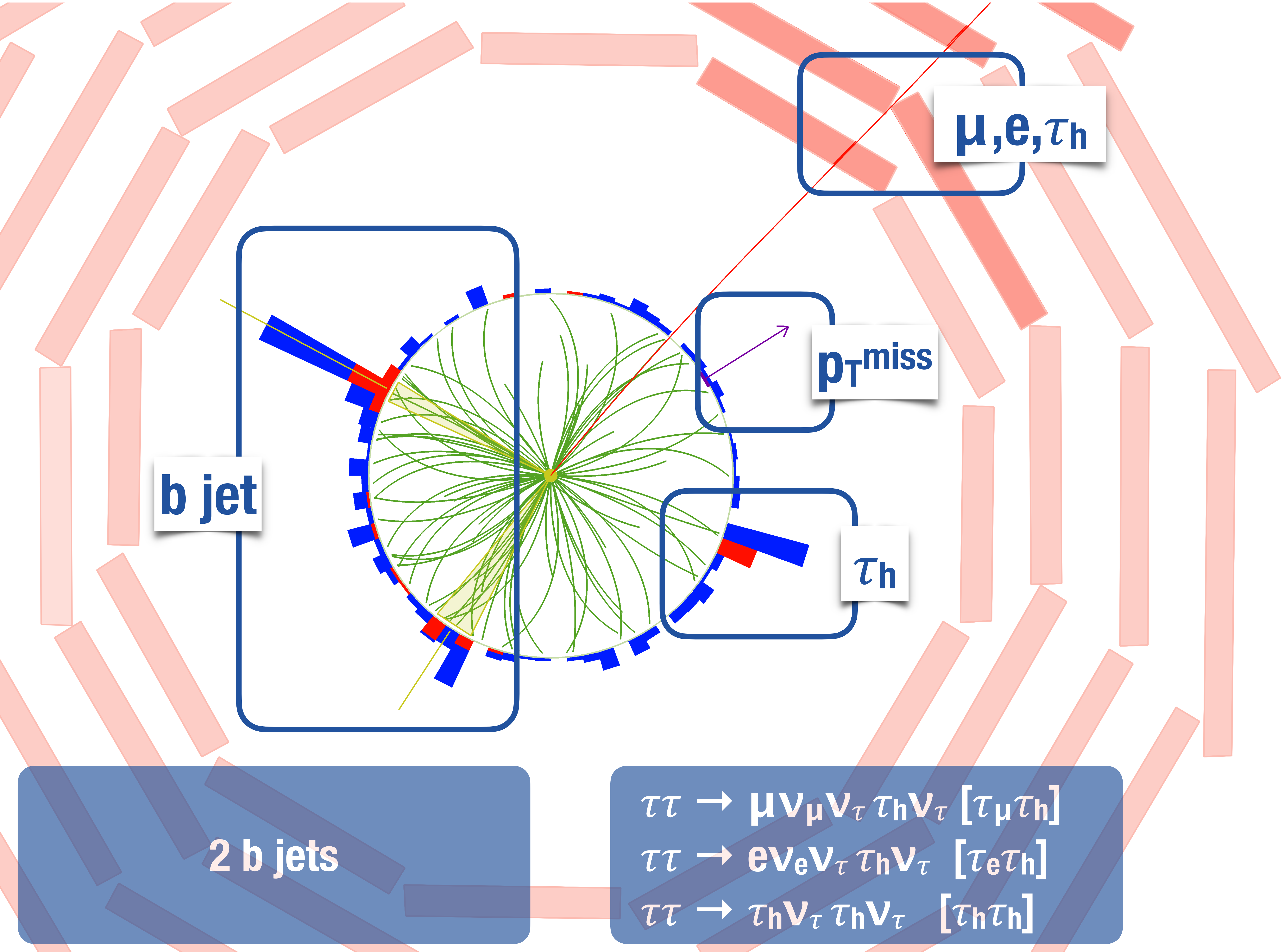
Obs. (Exp.) : 12.9 (21) × σ_{HH}^{SM}



Obs. (Exp.) : 74.6 (36.9) × σ_{HH}^{SM}

- Kinematic properties used to suppress the huge multijet background
- Discrimination based on jet angles, p_T, b tagging scores, invariant masses
  - ATLAS: selections on kinematic variables + fit on m_{HH}
  - CMS: variables combined into a BDT used for signal extraction

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

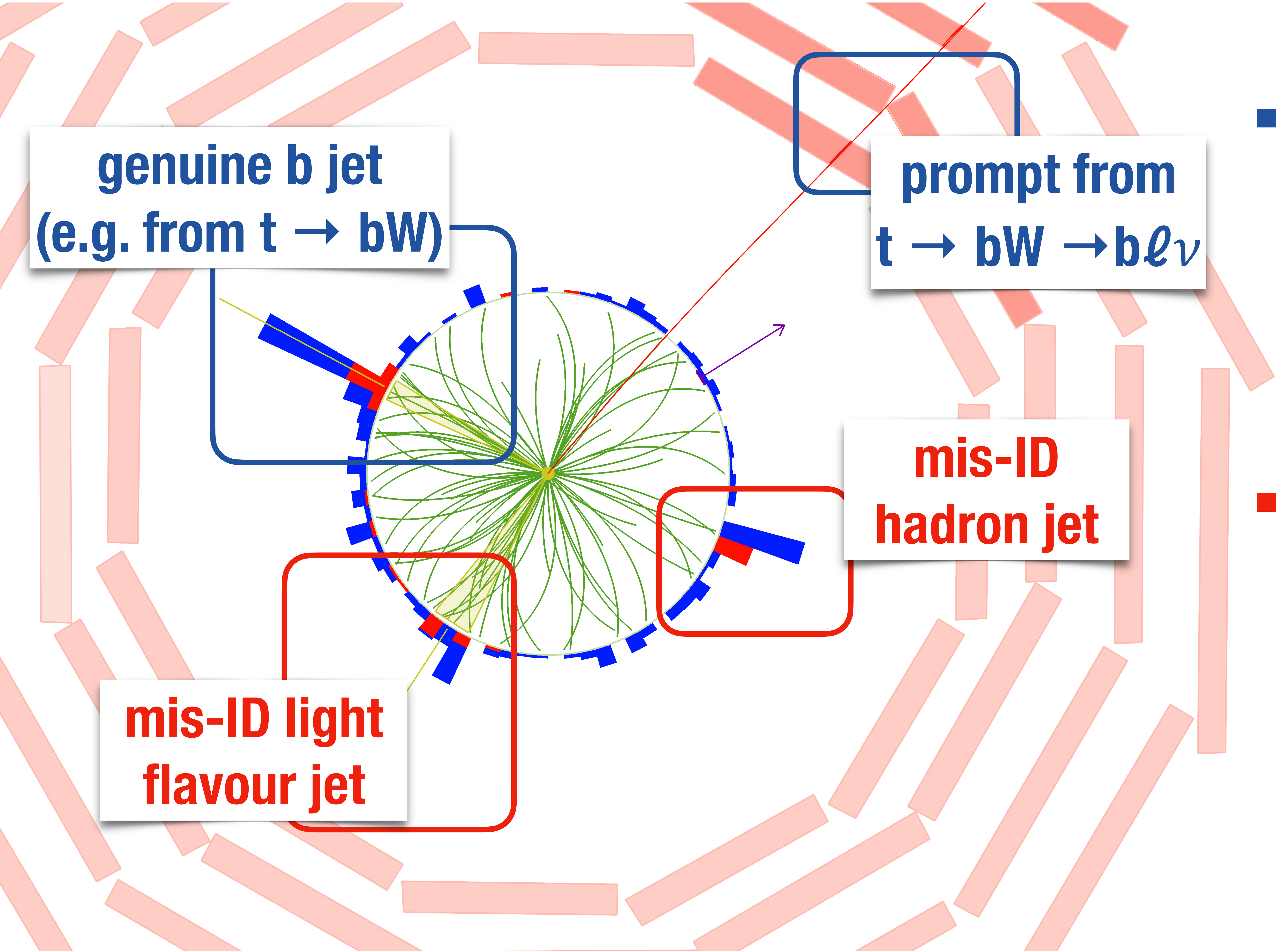


2 b jets

$\tau\tau \rightarrow \mu\nu_\mu\nu_\tau\,\tau_h\nu_\tau$ [$\tau_\mu\tau_h$]
$\tau\tau \rightarrow e\nu_e\nu_\tau\,\tau_h\nu_\tau$ [$\tau_e\tau_h$]
$\tau\tau \rightarrow \tau_h\nu_\tau\,\tau_h\nu_\tau$ [$\tau_h\tau_h$]

- 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 $\tau\tau$
  - □ di-boson, ZH (minor)
  - □ Z/γ^* → $\tau\tau$ + 2 b jets

simulation

simulation + correction in Z→$\mu\mu$

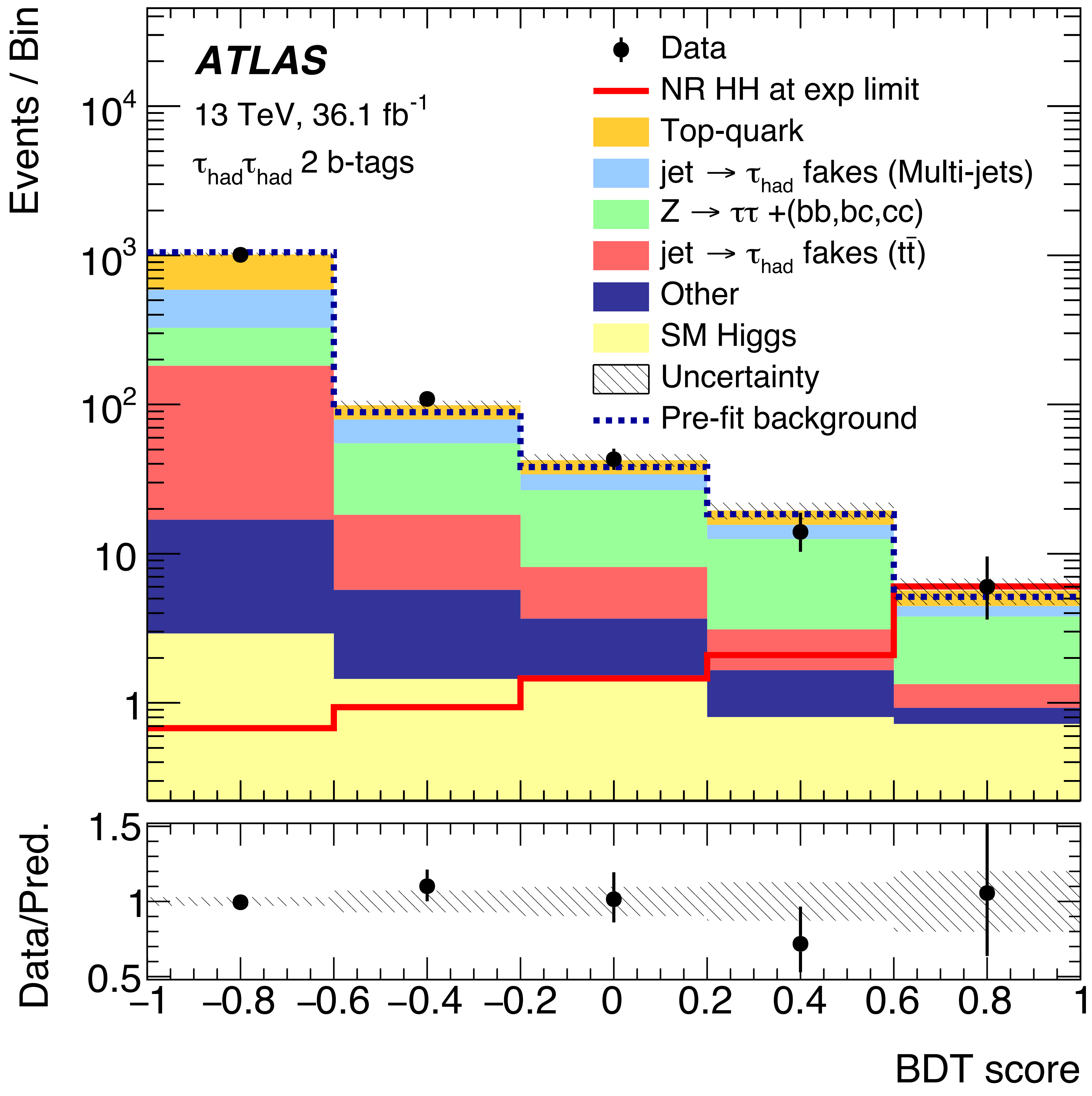
- **Instrumental (reducible)** backgrounds
  - □ tt, Z/γ^*, multijet with misidentified jets as τ_h or b jet
  - □ single top, W+jets (minor)

simulation + data-driven estimate

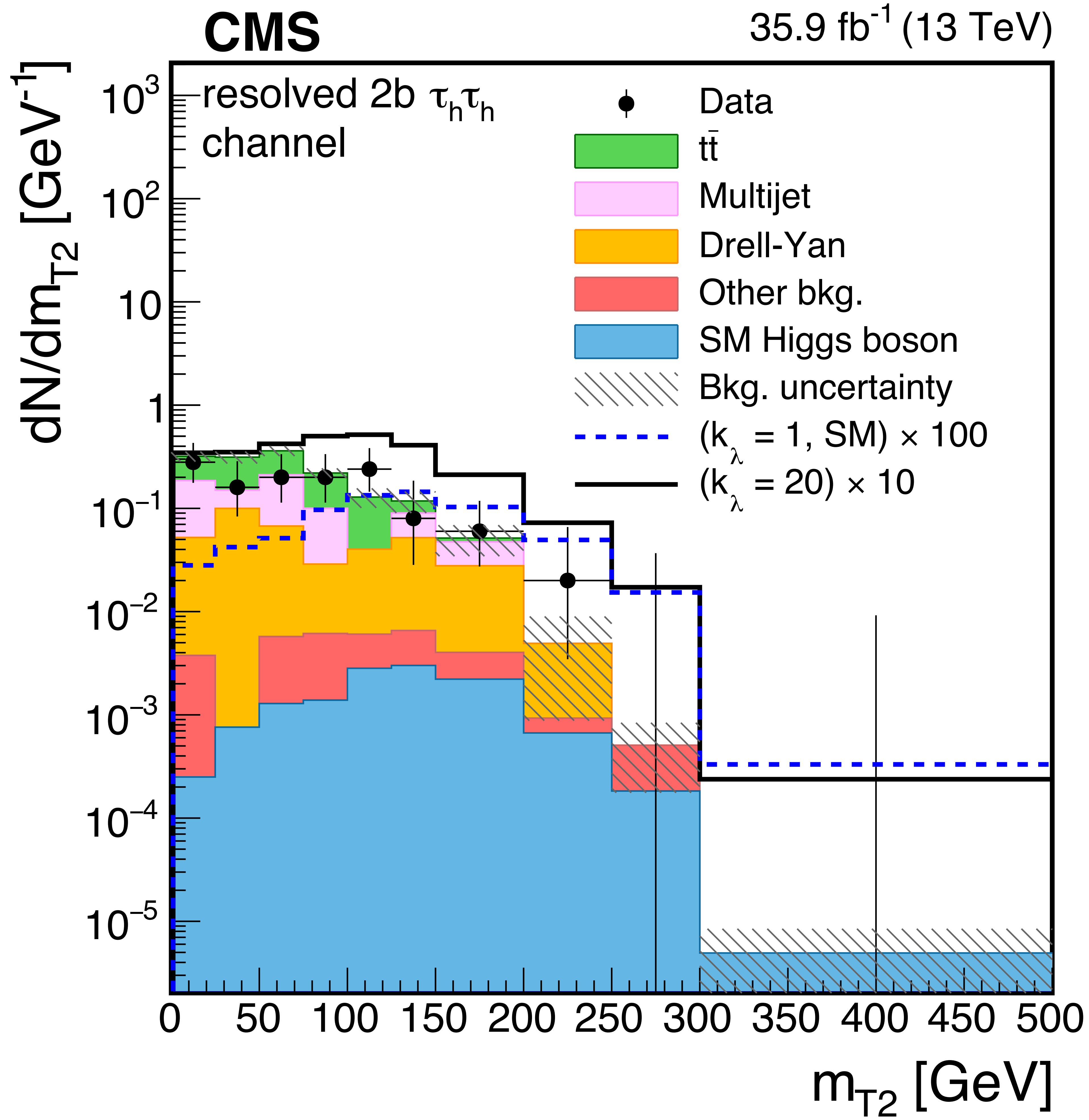
simulation

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

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



Fit the output of a BDT
Obs. (Exp.) : 12.5 (15) × σ_{HH}^{SM}



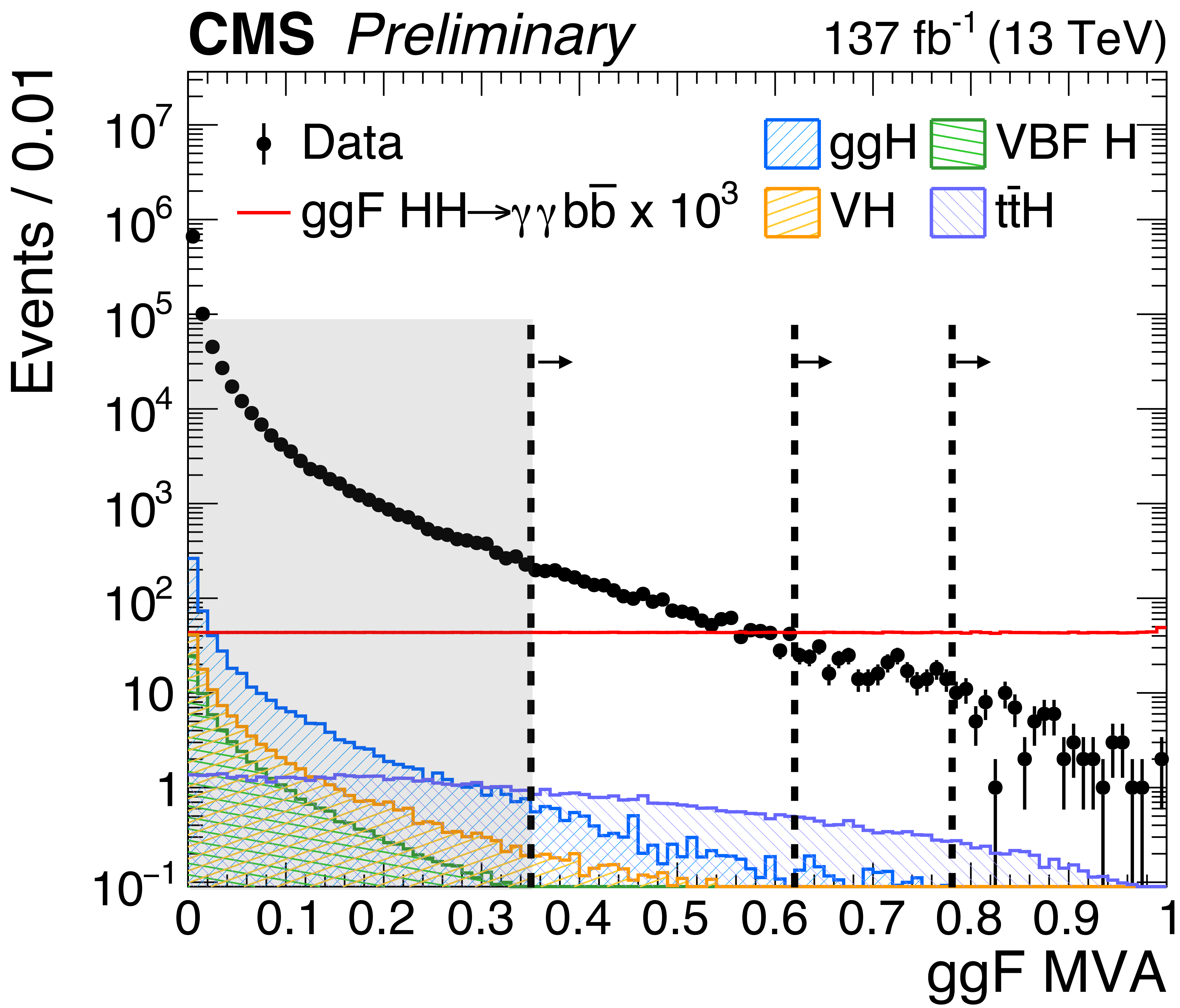
Use the m_{T2} variable
Obs. (Exp.) : 31.4 (25.1) × σ_{HH}^{SM}

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

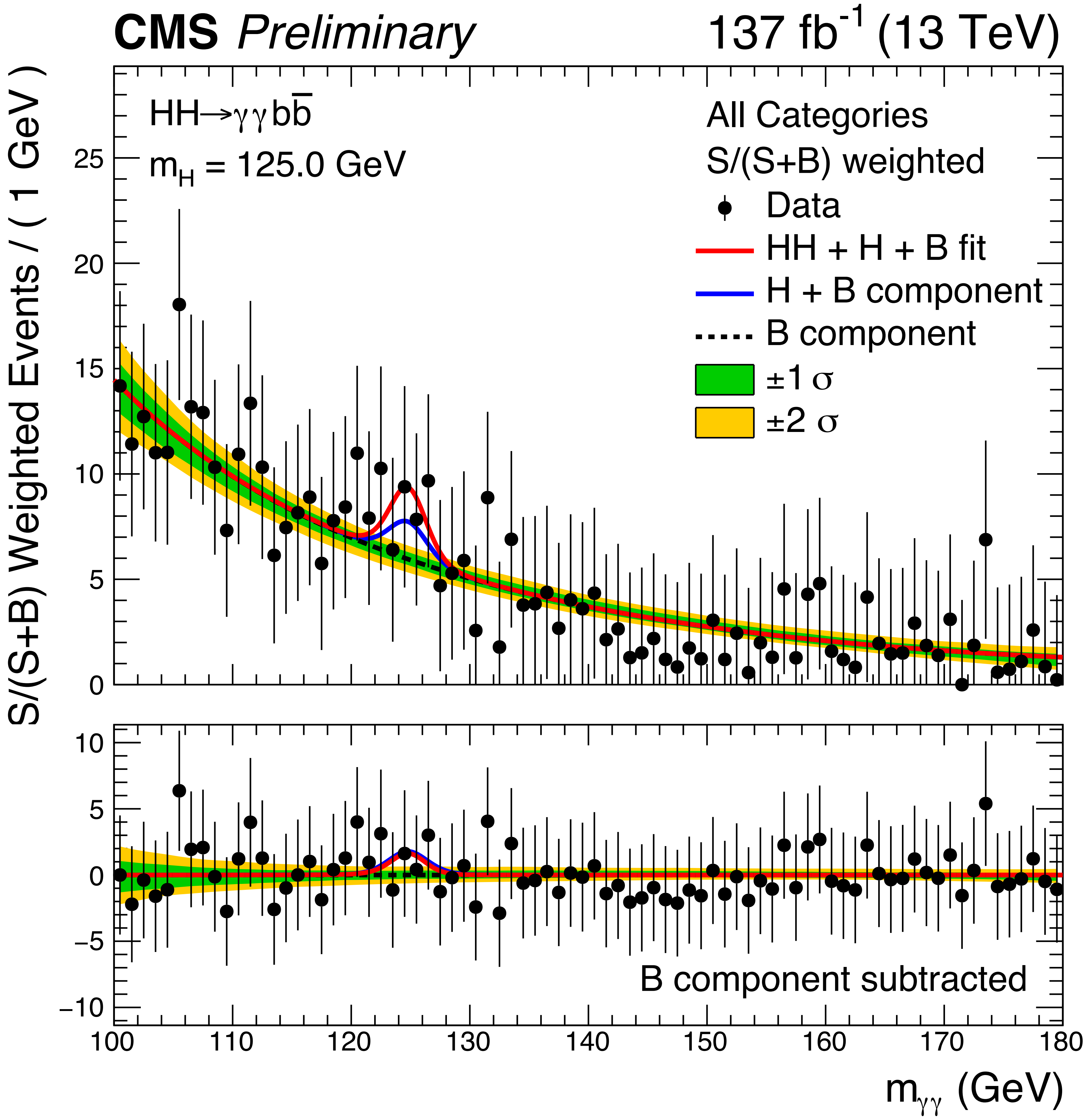
Very rare but clean channel

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
  - ☐ ggF: 3 MVA categories × 4 m_{HH} categories
  - ☐ VBF: 2 categories for low and high m_{HH}
  - ☐ ATLAS: simpler categorisation by number of b jets

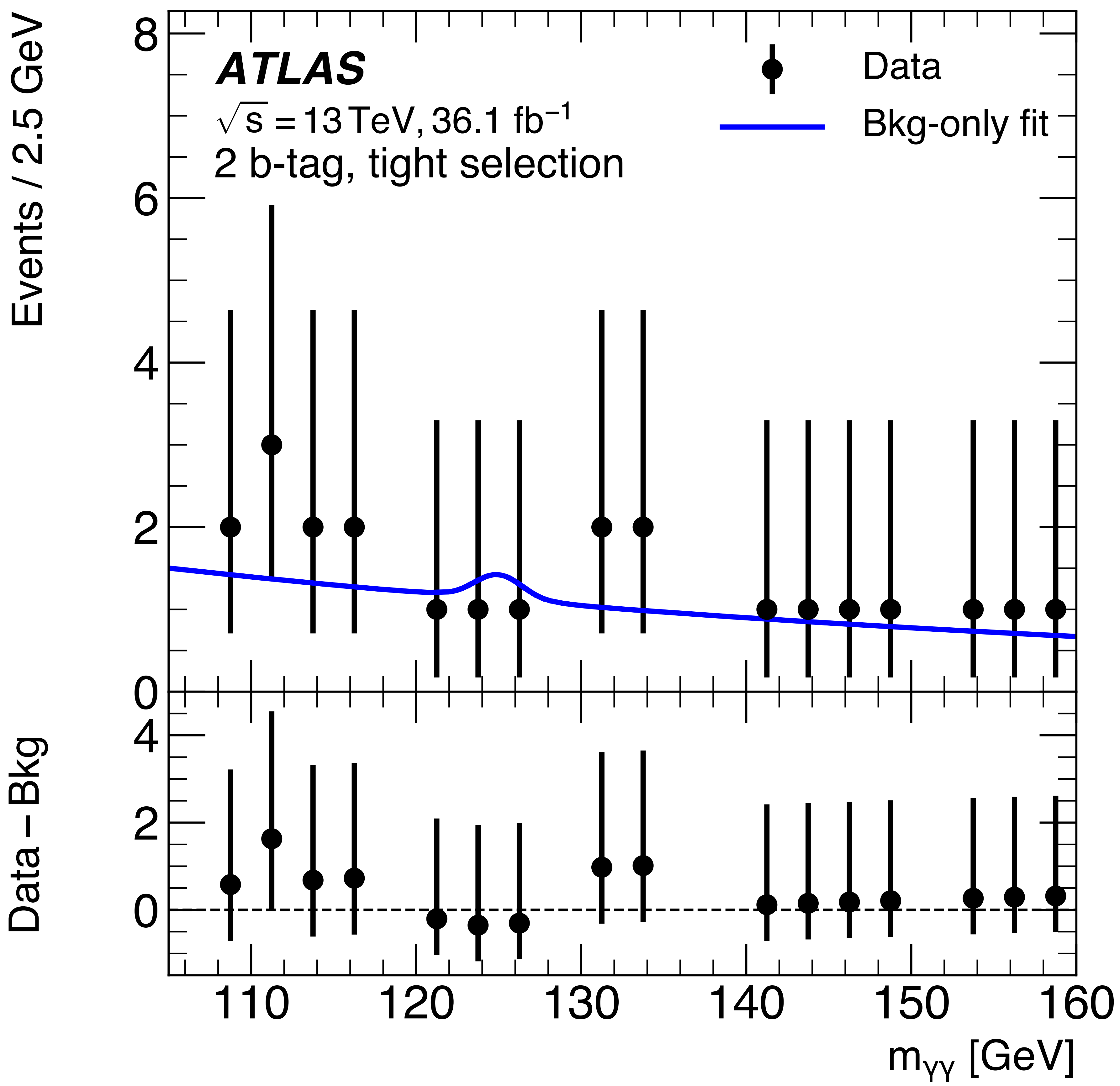


Low $\mathscr{B}$, high S/B : HH → bb$\gamma\gamma$



Simultaneous fit with m_{bb}

Obs. (Exp.) : 7.7 (5.2) × σ_{HH}^{SM}

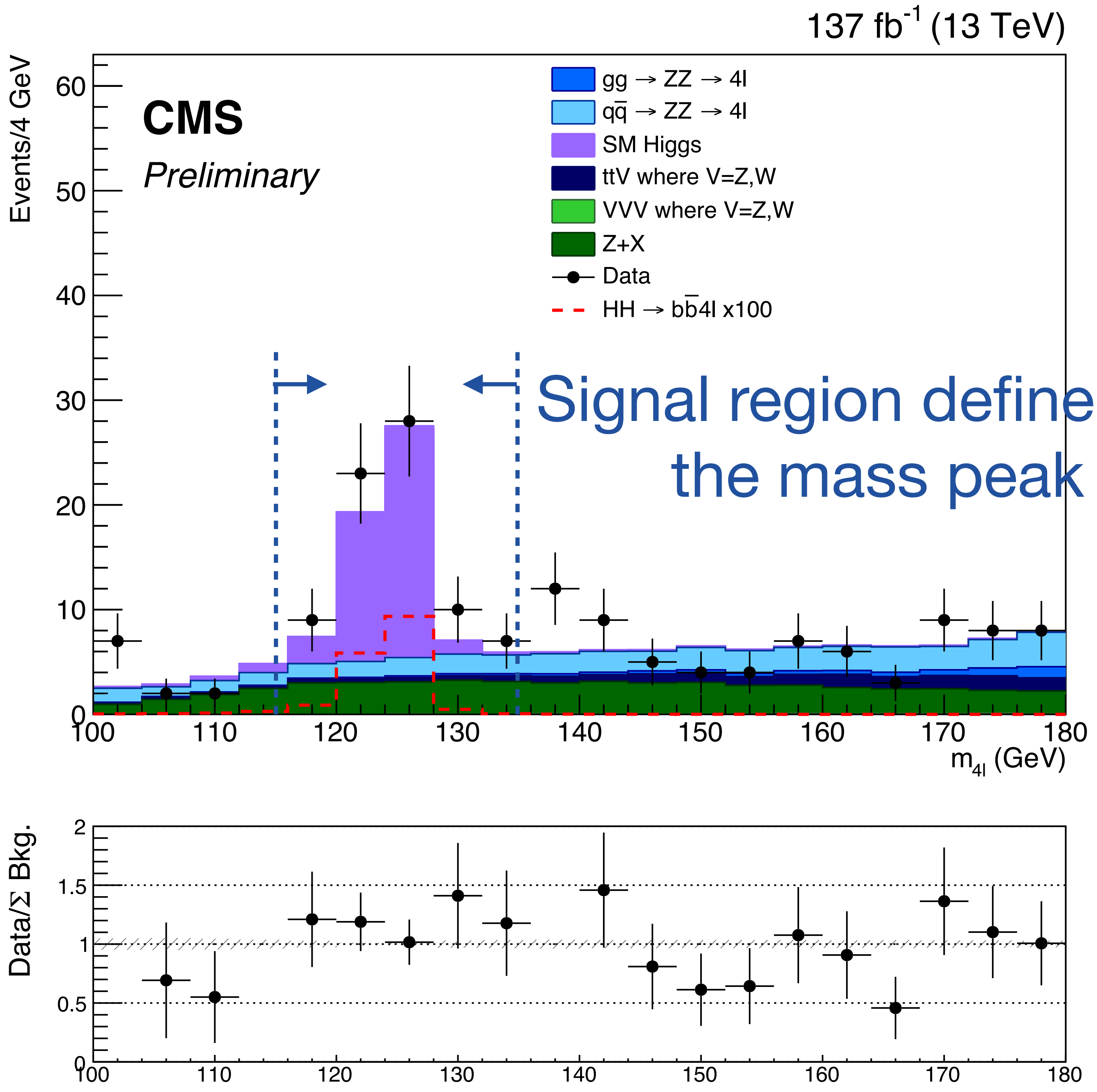


Obs. (Exp.) : 20.3 (26) × σ_{HH}^{SM}

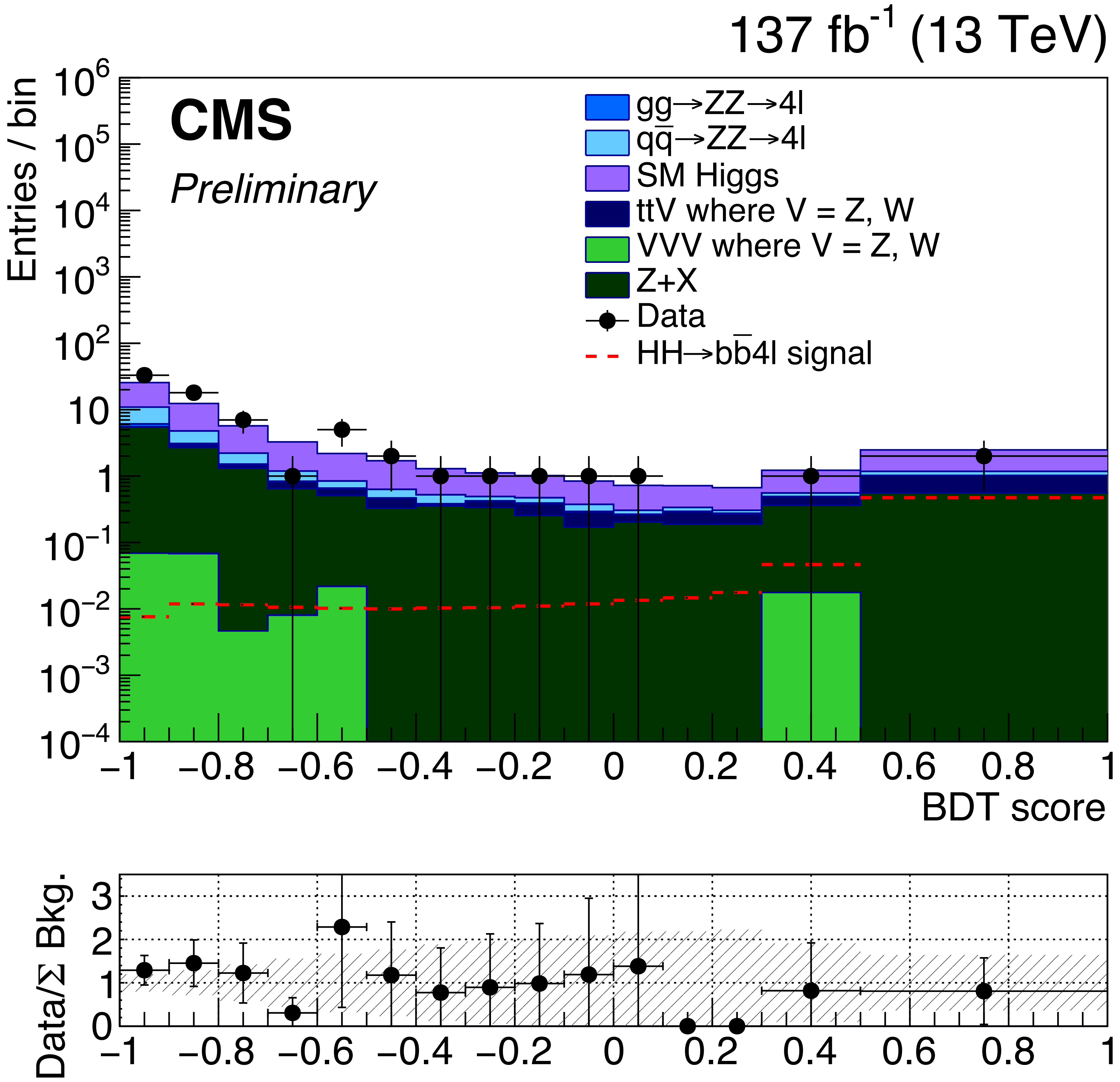
- Powerful signature from the H→$\gamma\gamma$ decay used to search for a signal
- Sensitivity clearly dominated by the limited event statistics

Using the full Run 2 dataset : bbZZ (4ℓ)

- First study of this final state at the LHC
- Very rare BR (0.0145%) but very small backgrounds + clean signature from the 4ℓ peak
- Signal extracted with a BDT
  - uses p_T, angles, inv. masses, b tag scores



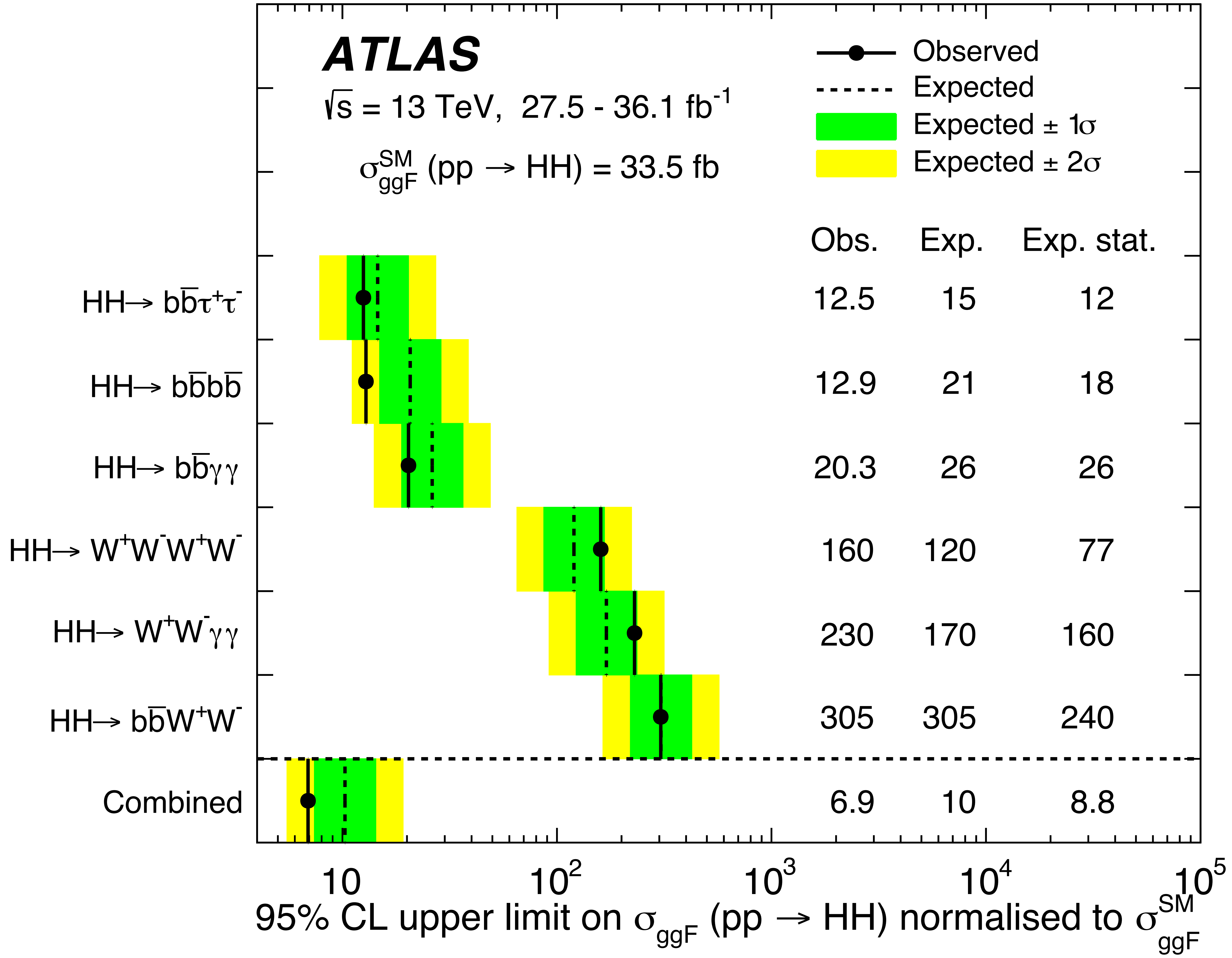
Signal region defined by the mass peak



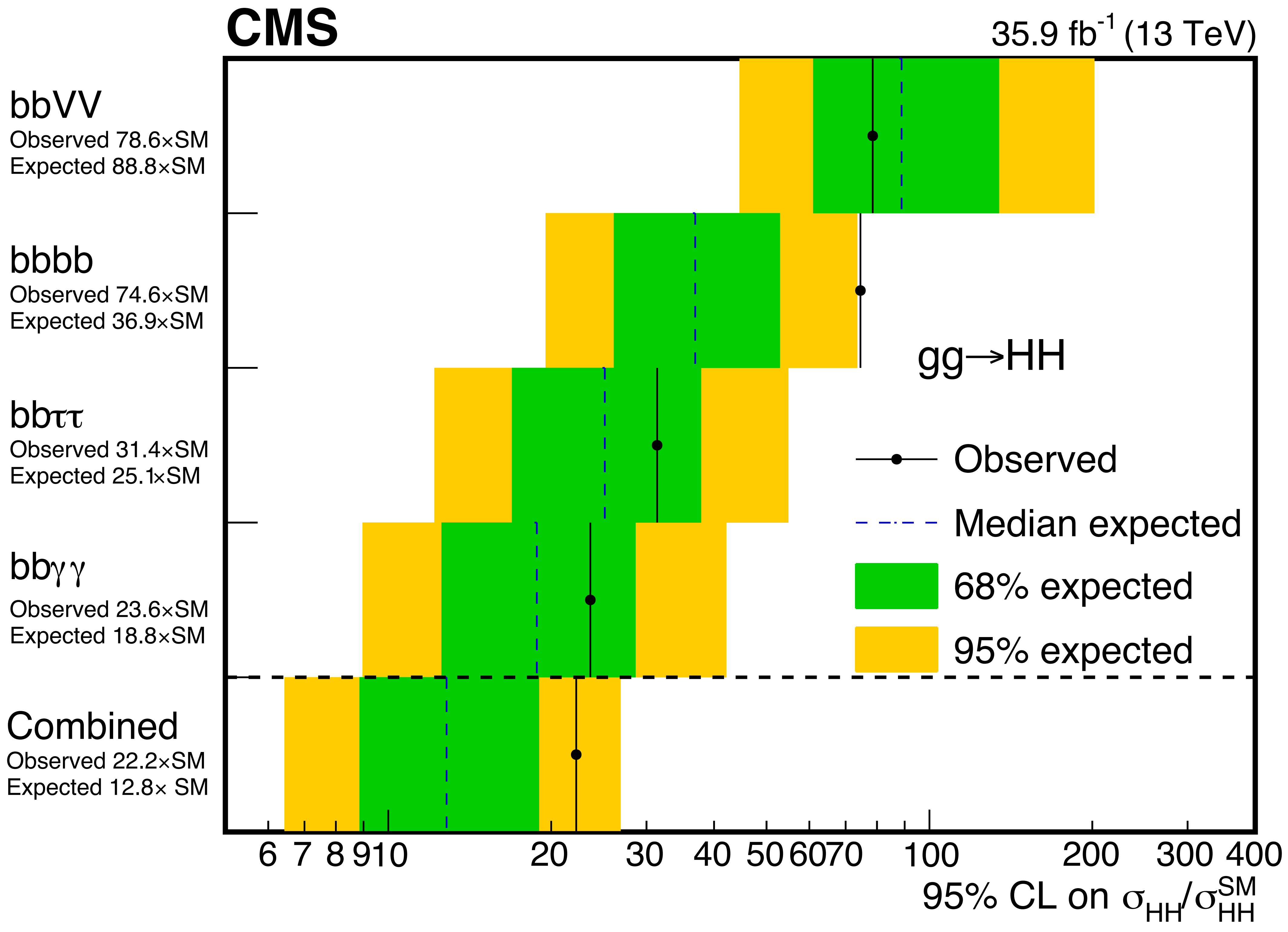
95% CL upper limit
30 (37) × SM

The full Run 2 dataset enables the exploration of very rare channels

Combination of the results



	Obs.	Exp.	Exp. stat.
HH→ $b\bar{b}\tau^+\tau^-$	12.5	15	12
HH→ $b\bar{b}b\bar{b}$	12.9	21	18
HH→ $b\bar{b}\gamma\gamma$	20.3	26	26
HH→ $W^+W^-W^+W^-$	160	120	77
HH→ $W^+W^-\gamma\gamma$	230	170	160
HH→ $b\bar{b}W^+W^-$	305	305	240
Combined	6.9	10	8.8

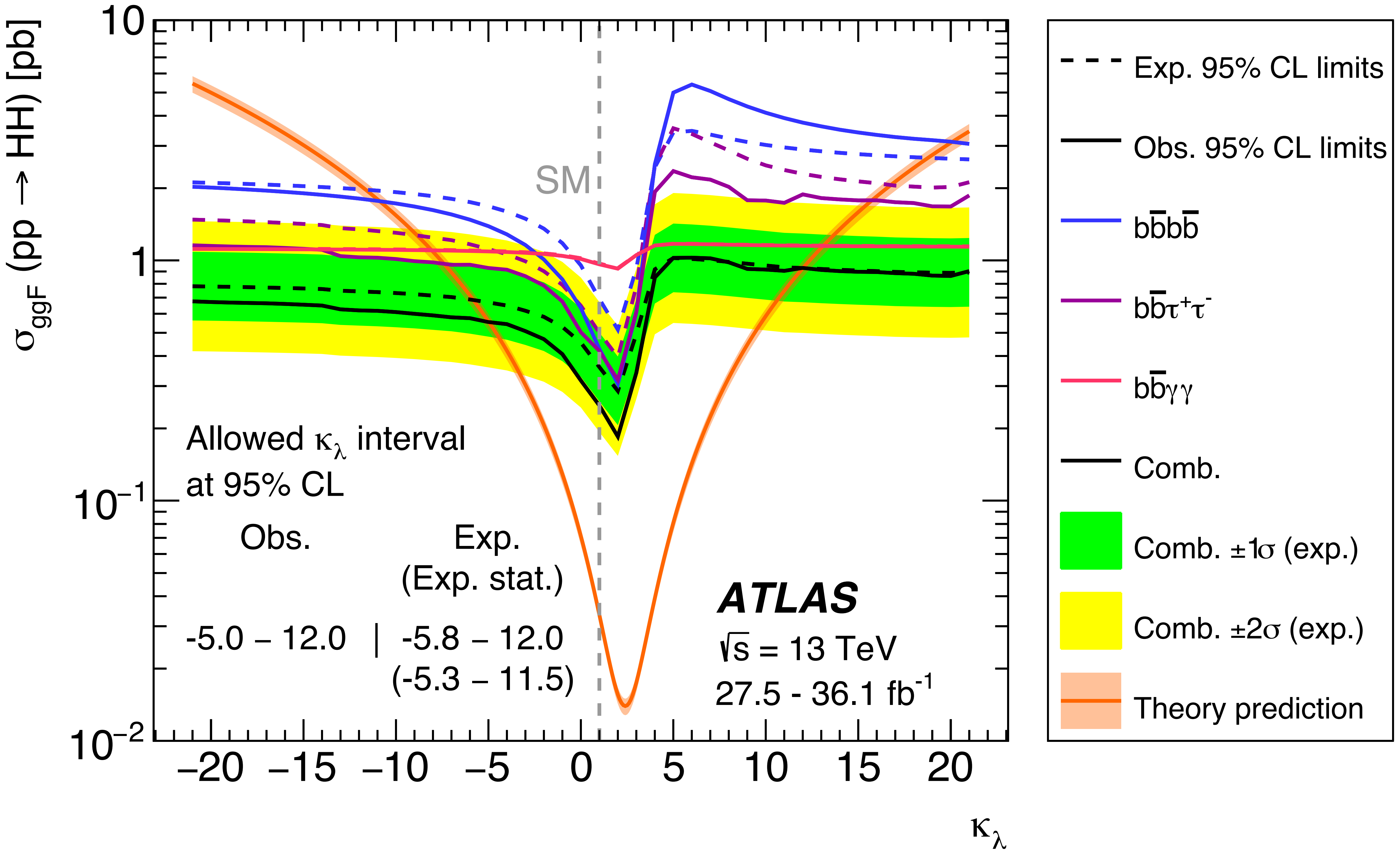


- The combined results benefits from the similar sensitivity in several channels

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

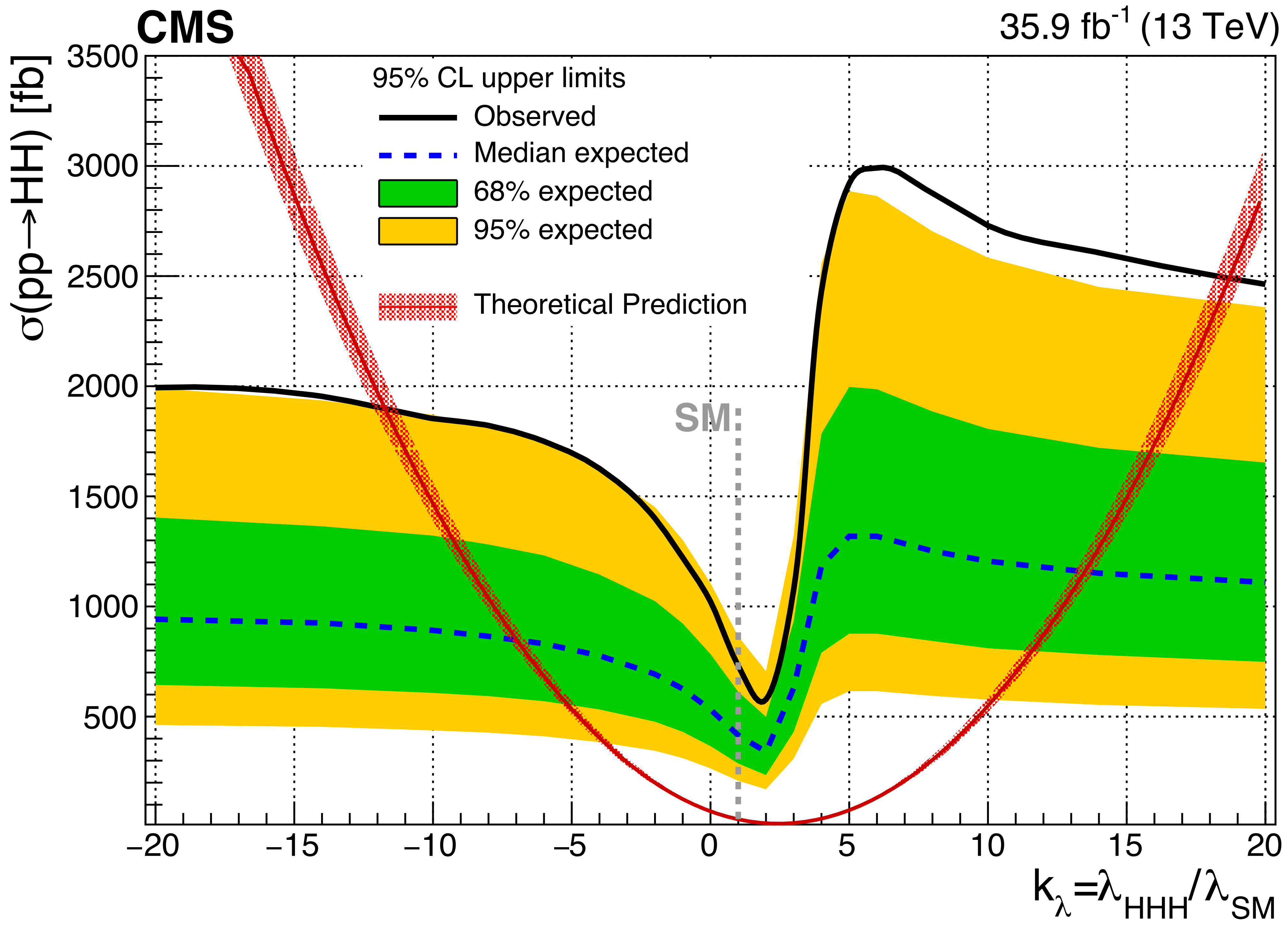
Full Run 2 dataset (×4 more data) current under analysis
×2 more sensitive (from stat.) + analysis improvements

Combination of the results



Observed: ***-5.0 < κλ < 12***

Expected: -5.8 < κλ < 12

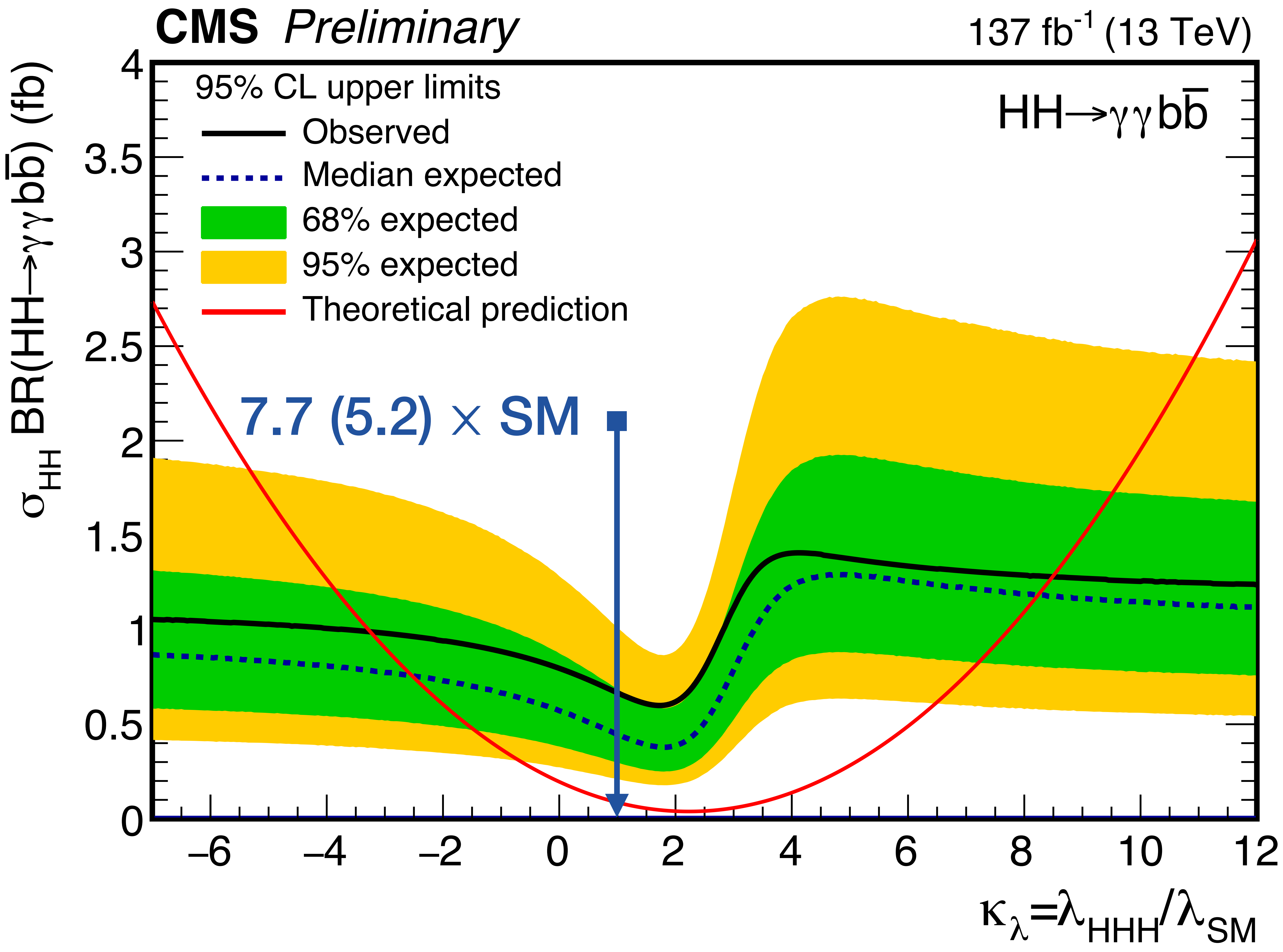


Observed: ***-11.8 < κλ < 18.8***

Expected: -7.1 < κλ < 13.6

- Impact of the changes in the m_{HH} spectrum clearly visible in the shape of the upper limits

Benefiting of the Run 2 dataset



7.7 (5.2) × SM

Observed: ***-3.3 < κλ < 8.5***

Expected: *-2.5 < κλ < 8.2*

- The bb$\gamma\gamma$ alone achieves a larger sensitivity to than the 2016 combinations of 4-6 channels
  - simple lumi scaling of the CMS 2016 bb$\gamma\gamma$ result:

$$18.8 \times \sqrt{36/137} = 9.6 \times \text{SM}$$

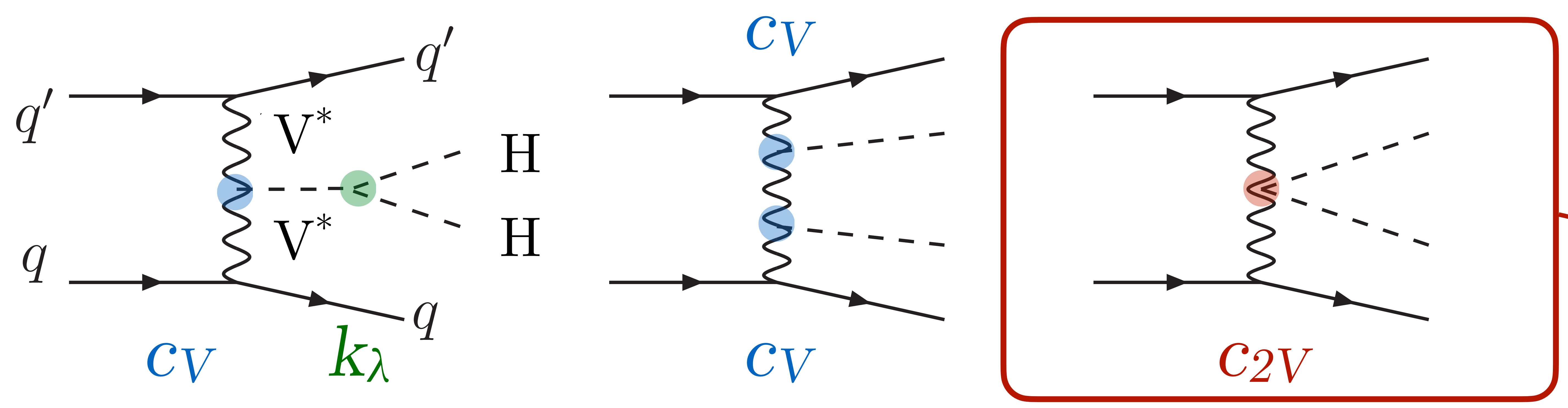
$\Longrightarrow$ almost ×2 improvement

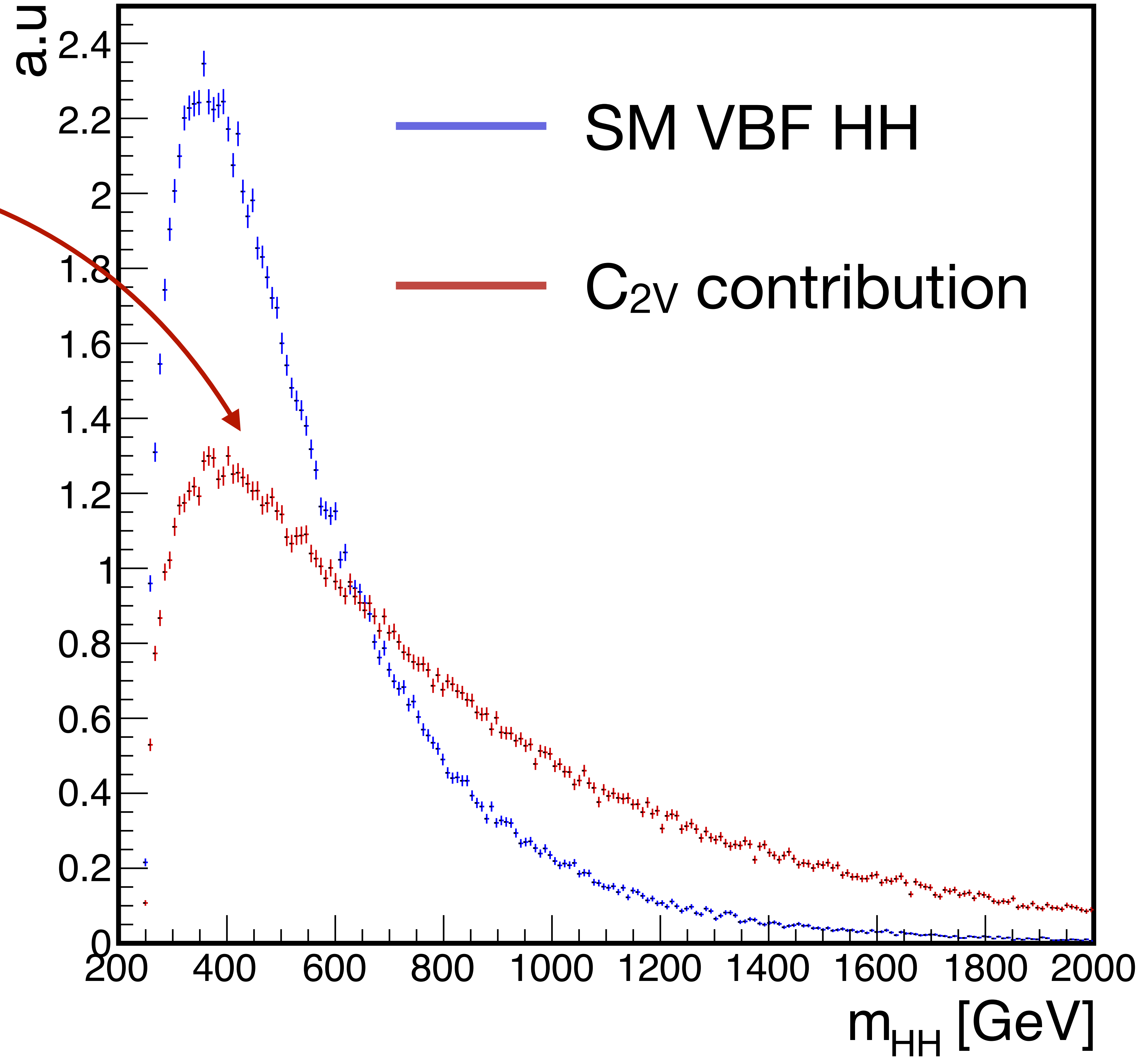
Larger datasets enable smarter analyses

Improvement in the sensitivity beyond the simple luminosity increase

Excellent prospects for the full Run 2 legacy results and beyond

Beyond gluon fusion





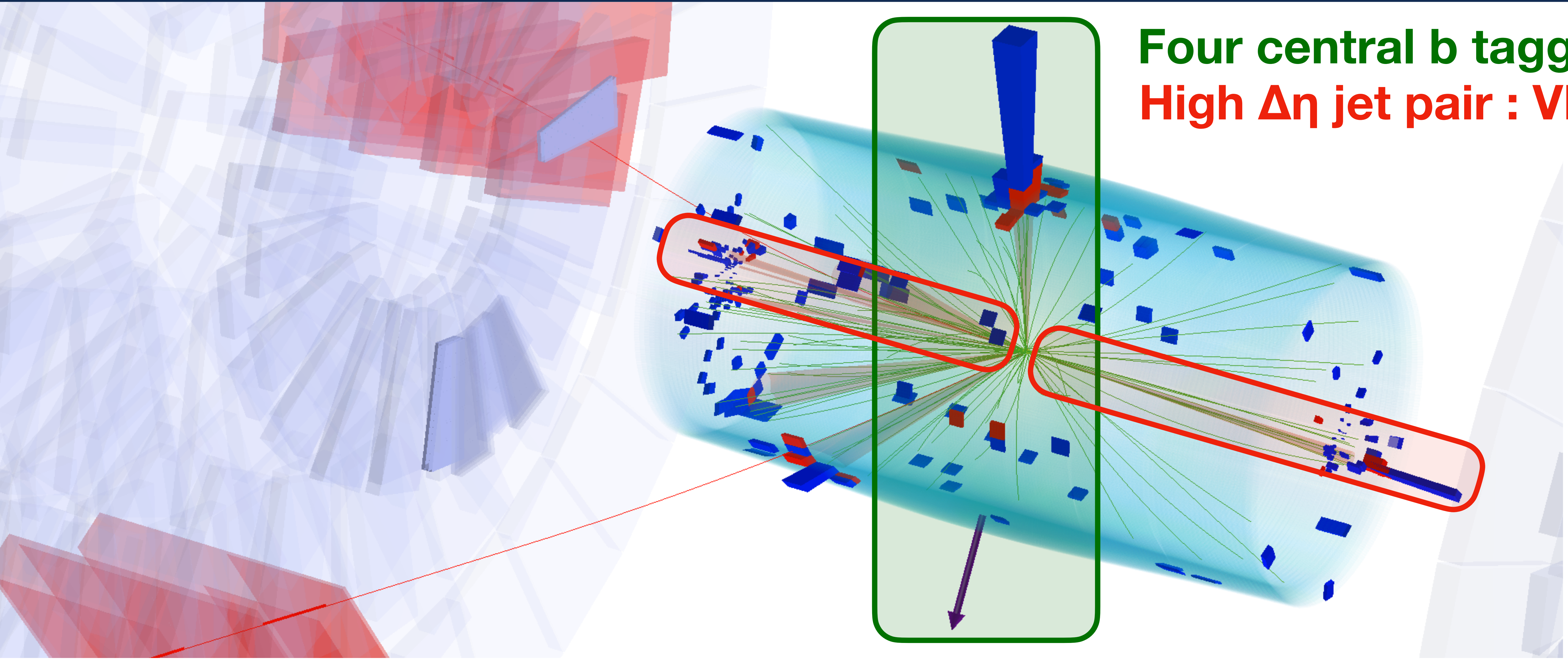
$\sigma = 1.73 \pm 2.1\%$ fb

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

- 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*")
- The two VBF jets give extra handles to identify the signal

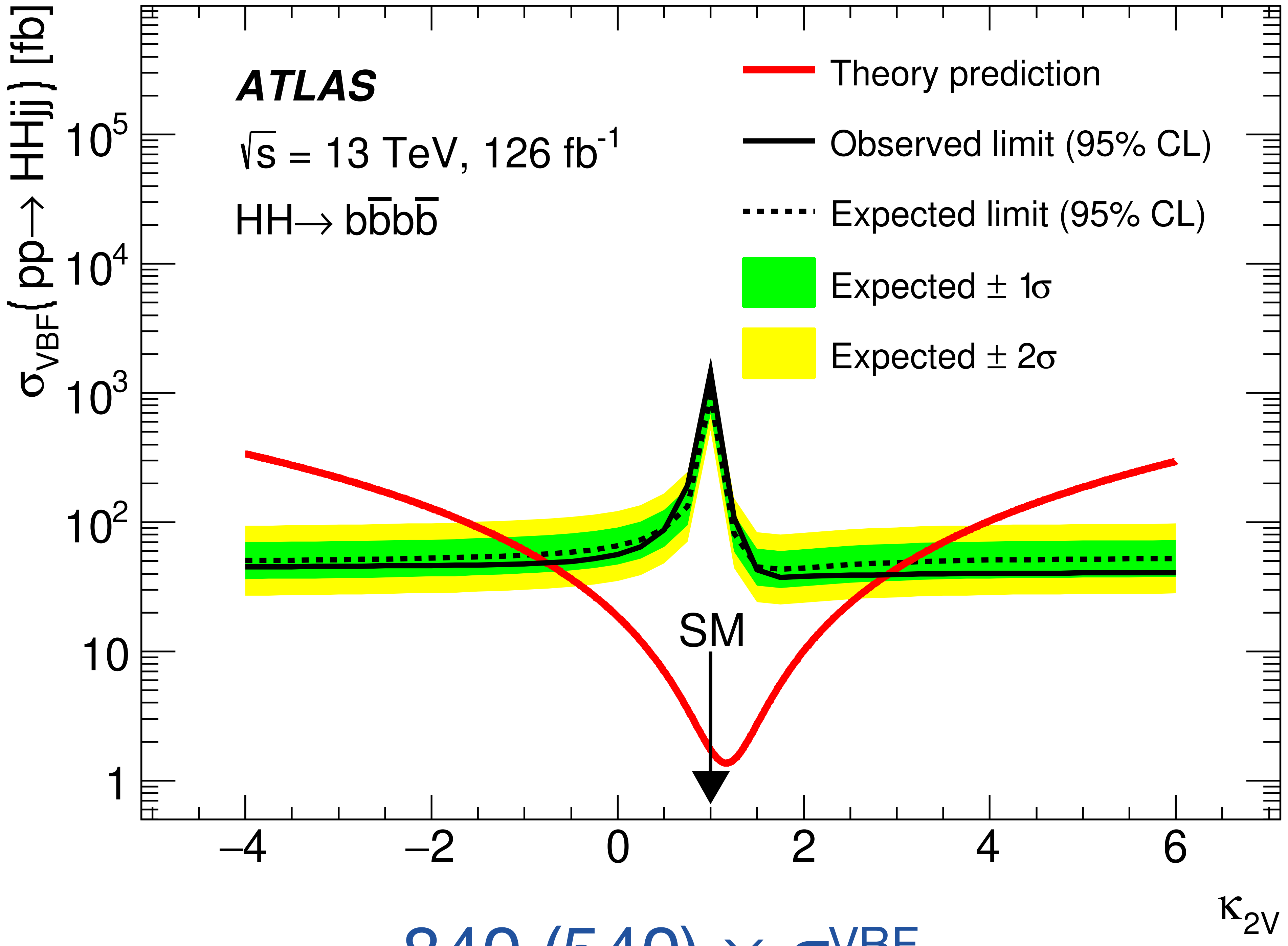
The study of other HH production modes give new insights on the properties of the scalar sector

Search for VBF HH



Four central b tagged jets : m_H signature to reject bkg.

High Δη jet pair : VBF signature



- Benefit of high purity or high BR final states
- Extend HH analyses with dedicated VBF categories
  - **bbbb** analysis (ATLAS) : extra jet pair with properties (m_{jj}, Δη) compatible with VBF production →
  - **bb$\gamma\gamma$** analysis (CMS): dedicated categories and selections →

840 (540) × $\sigma^{VBF}{}_{SM}$

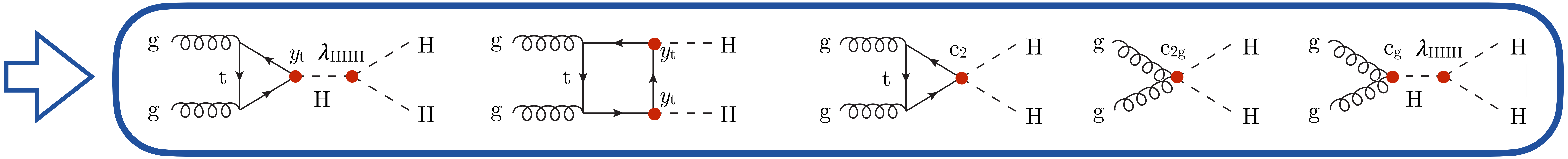
$-0.8 < C_{2V} < 2.9$ ($-0.9 < C_{2V} < 3.1$)

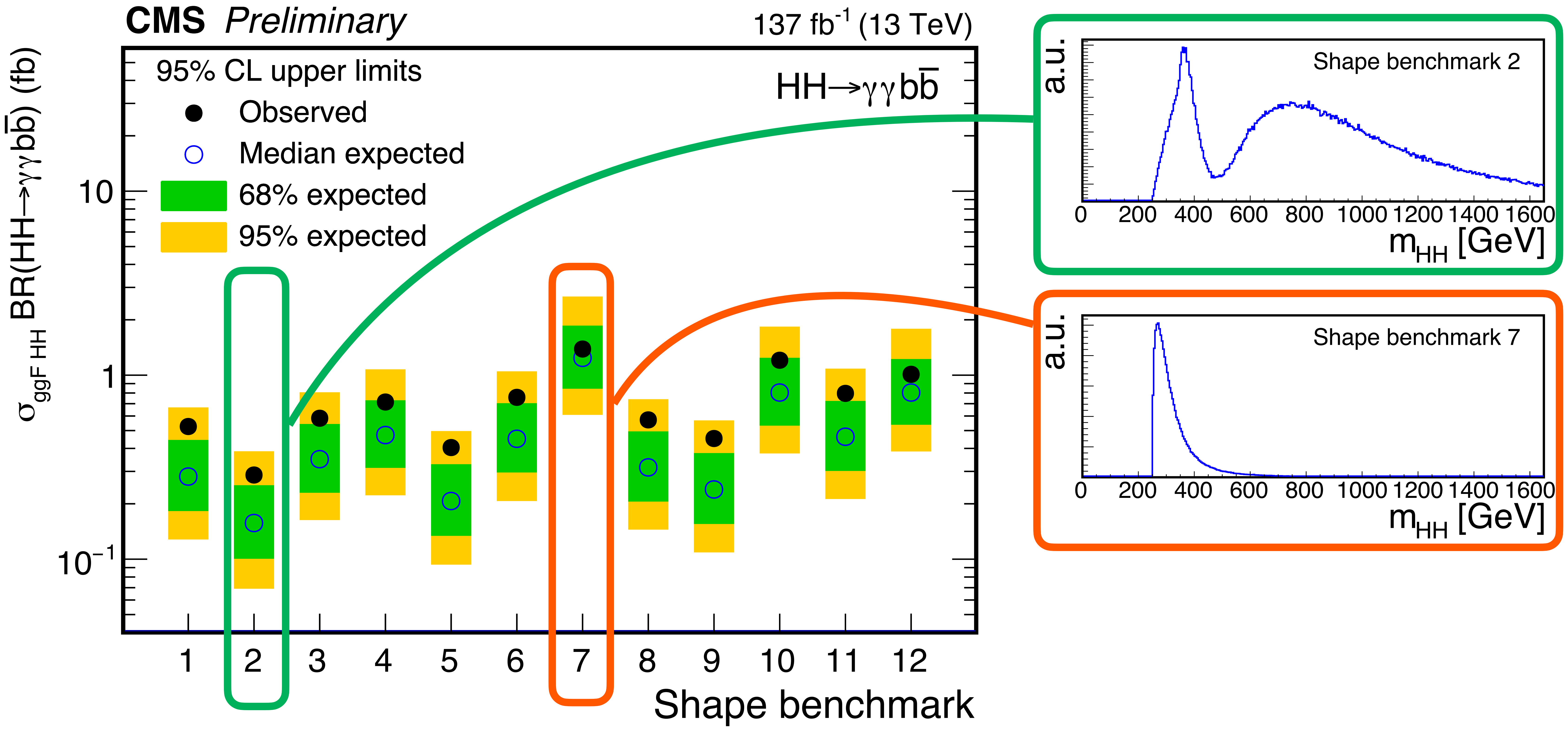
225 (208) × $\sigma^{VBF}{}_{SM}$

$-1.3 < C2V < 3.5$ ($-0.9 < C2V < 3.1$)

A broader BSM picture

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

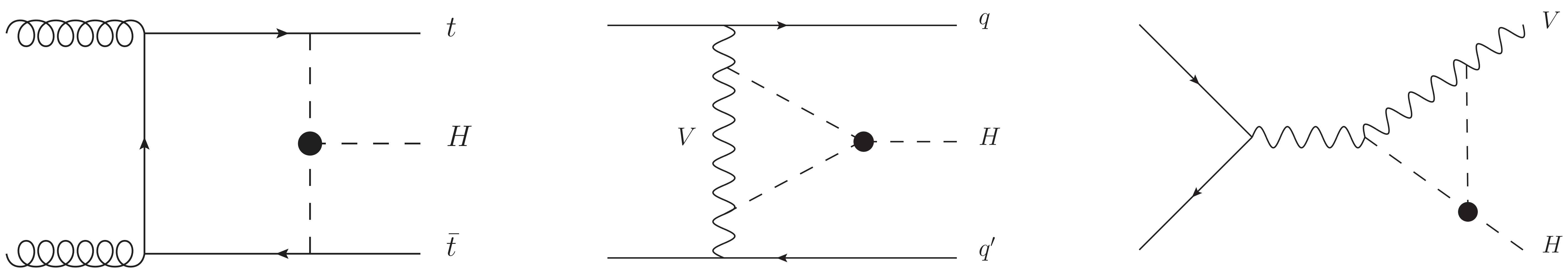




- 5D parameter space, contact interactions, large kinematic modifications
  - probed with representative signal shape benchmarks
- EFT effects become more important as the experimental sensitivity approaches the SM

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

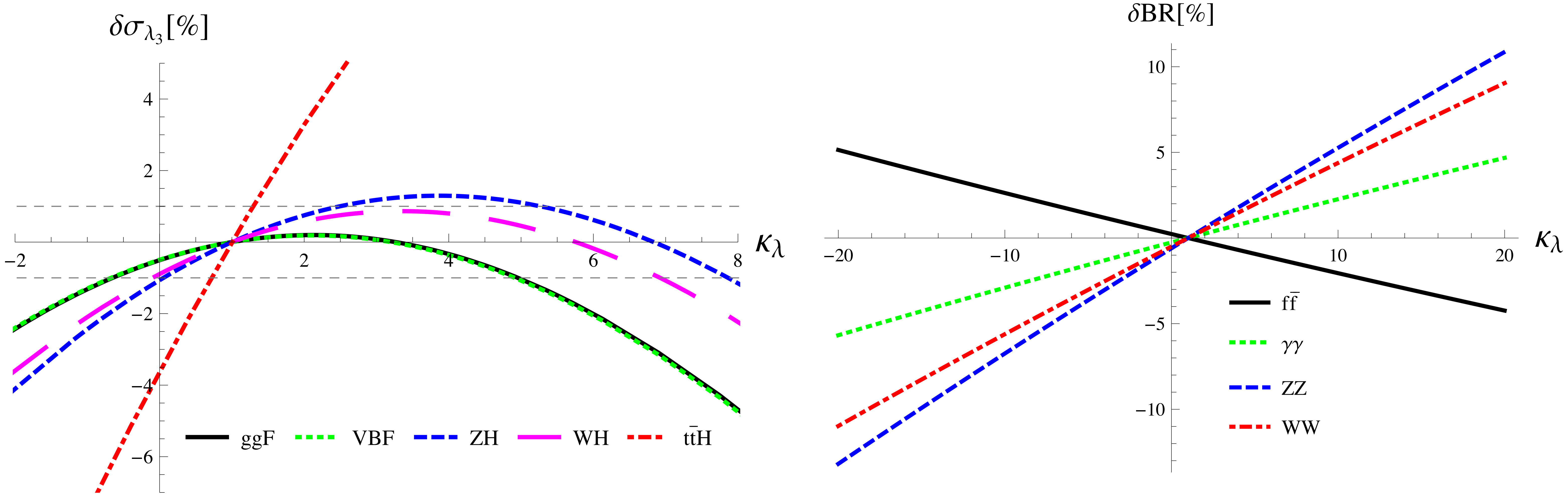
Extracting λ_{HHH} from single Higgs



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

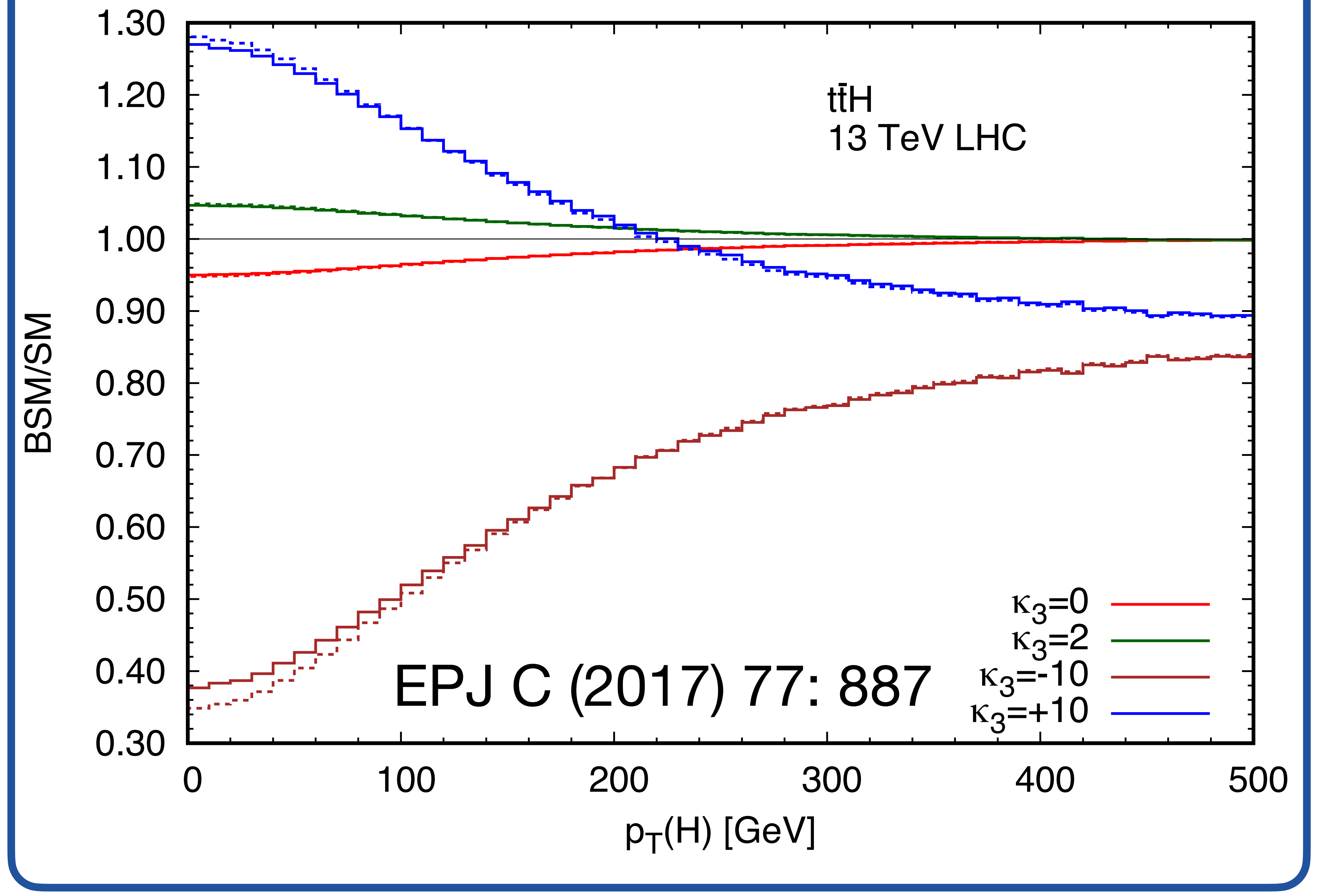
Simplified template XS single H measurements used as input

Production xs and decay BR



JHEP 1612, 080 (2016)

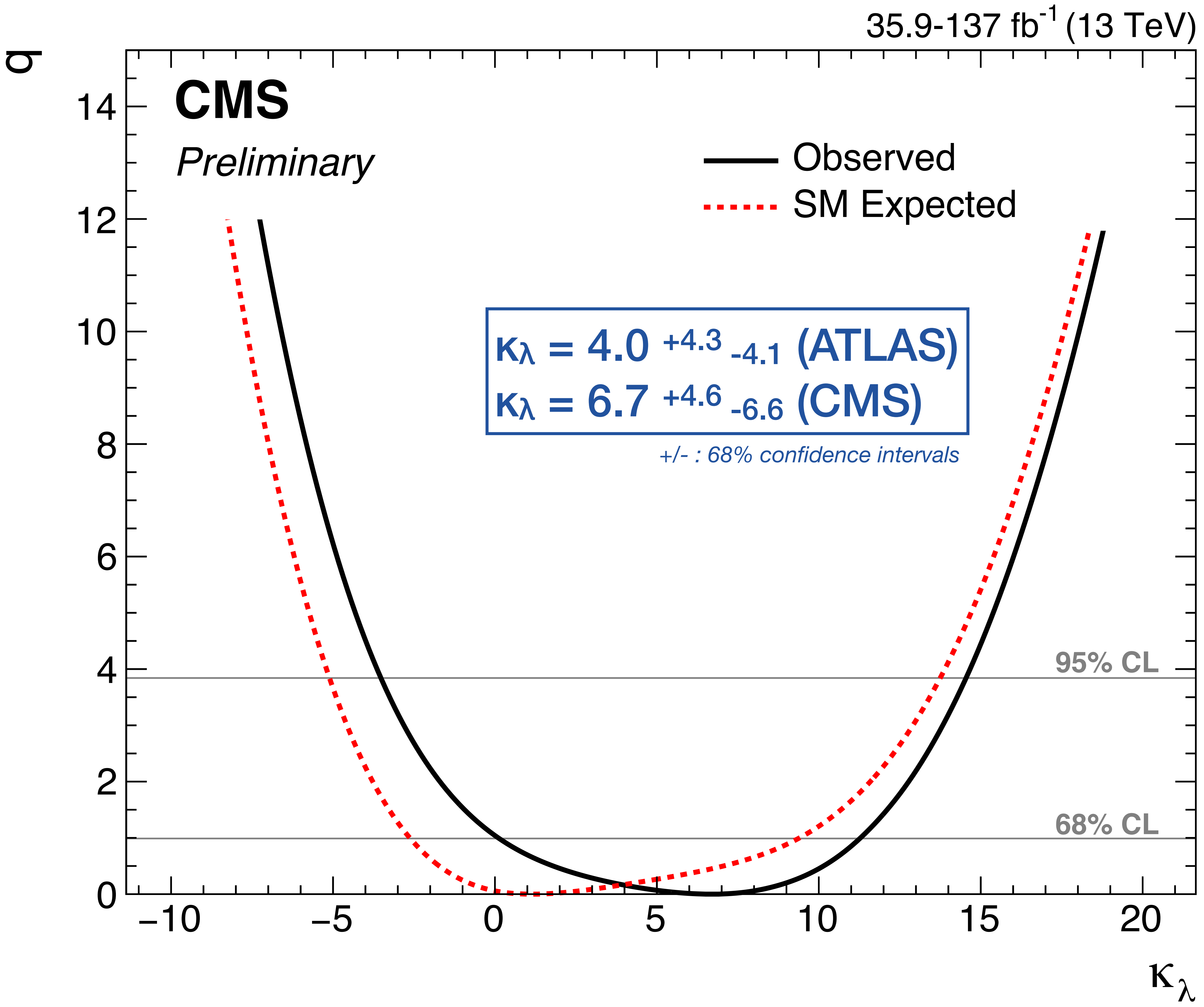
Differential distributions



EPJ C (2017) 77: 887

Extracting λ_{HHH}

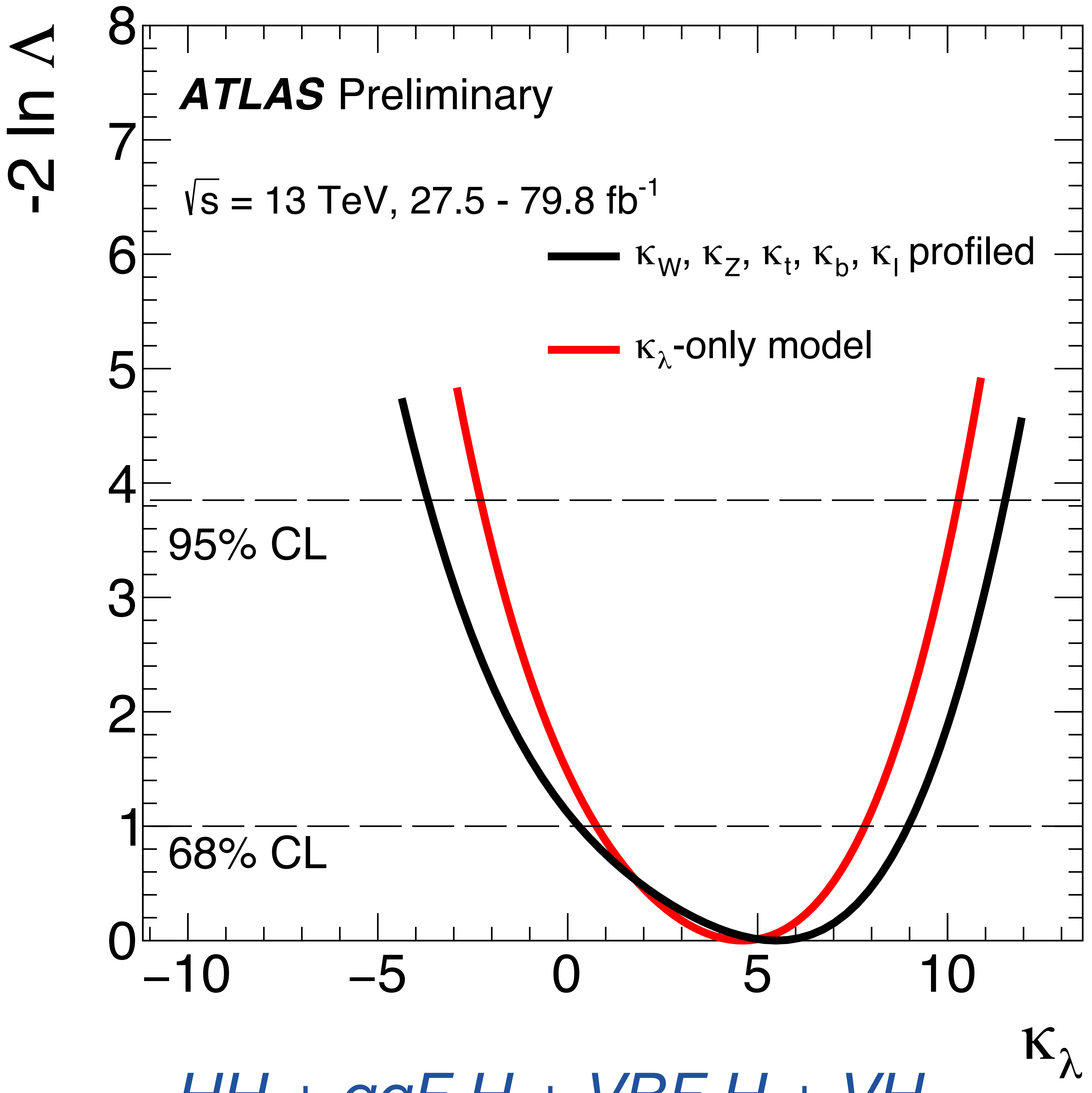
- Reinterpretation of the simplified template cross section combined measurements
- Assume that all the other couplings are fixed to the SM prediction
- Variations of λ_{HHH} and of other couplings cannot be distinguished
  - ☐ reduced sensitivity by 50% if κ_V also fitted
  - ☐ no sensitivity if further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



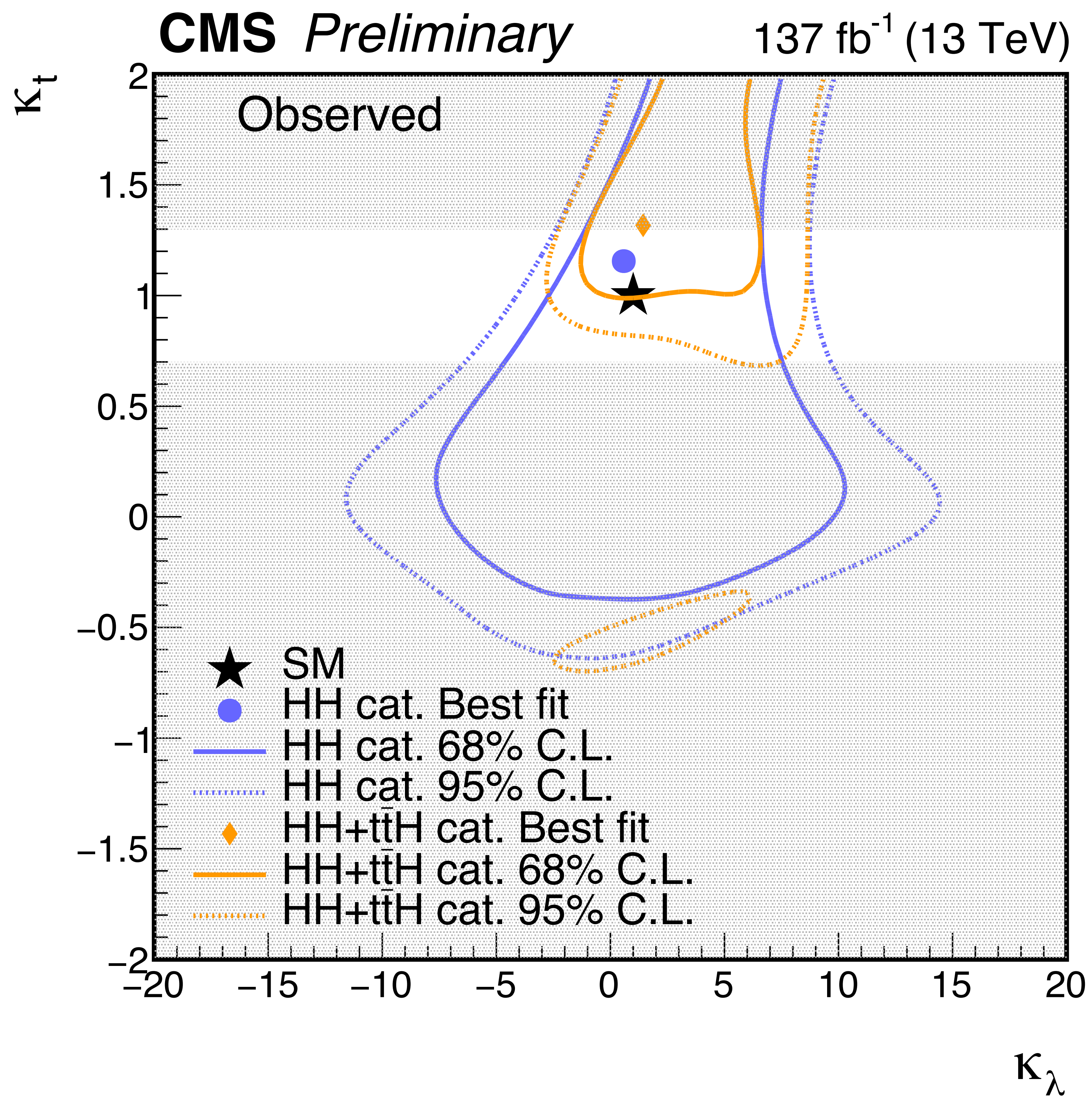
Complements direct determination from HH

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($\gamma\gamma$))



HH(bb$\gamma\gamma$) + ttH($\gamma\gamma$)

- 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!

Towards the Run 3

Expanding the direct HH measurements

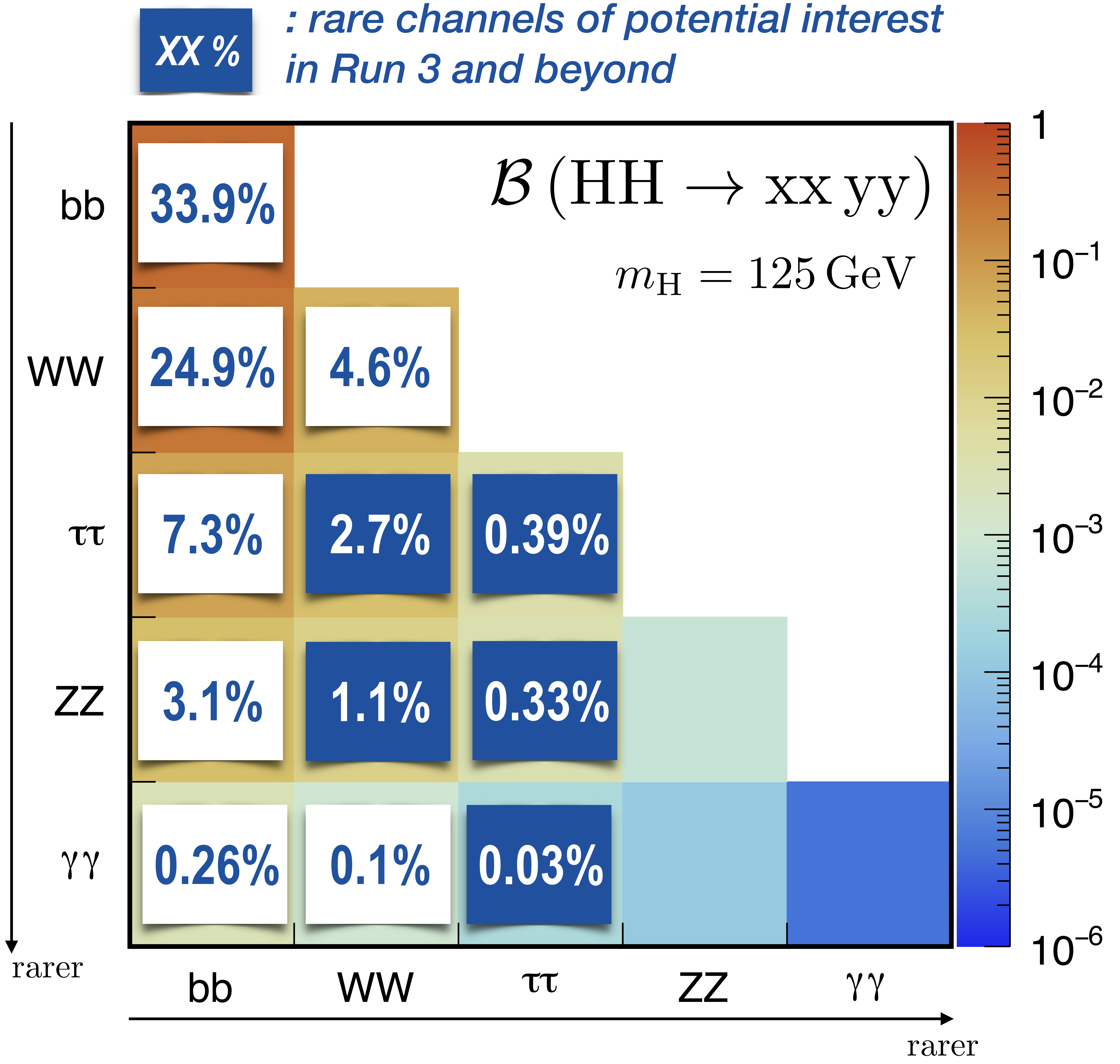
- Expect in total ~300 fb^{-1} collected, 13 → 14 TeV
  $\Longrightarrow$ ~ 10k HH events produced!
- Channels will sub-percent BR but very clean will start to be sensitive to SM-like values
- Possibility to capitalise on the Run 2 experience to improve the analyses and develop dedicated HH triggers

More precision in indirect H measurements

- Benefit of the ×2 increase in the statistics

Opportunities for direct BSM searches

- Resonant HH(-like) signatures to probe extended scalar sectors

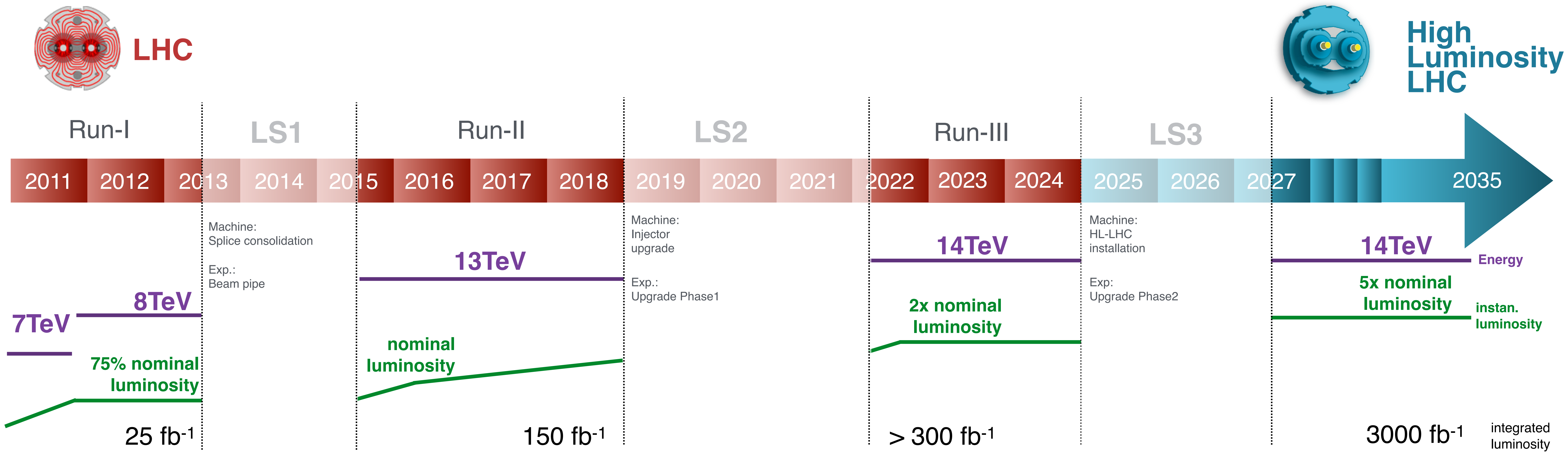


XX % : *rare channels of potential interest in Run 3 and beyond*

	bb	WW	ττ	ZZ	γγ
bb	33.9%				
WW	24.9%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%		
γγ	0.26%	0.1%	0.03%		

The high-luminosity LHC

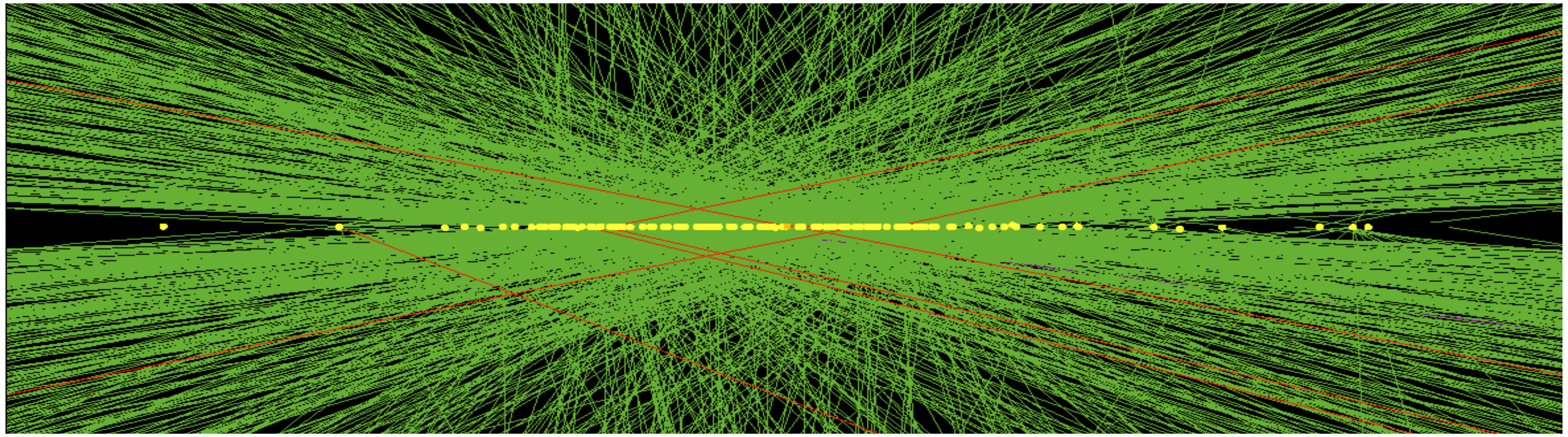
- Upgrade of the LHC planned to start after the LS3
  - upgrade of the quadrupoles to focus more the beams
  - “crab cavities” to reduce the bunch crossing angle
- Increase of the instantaneous luminosity by ~5 w.r.t. design values
  - levelling of the luminosity for a large part of the fill
- **3 ab^{-1} during a decade of operations**



Unique possibility for very high precision Higgs physics

Expect to reach the ultimate sensitivity on HH

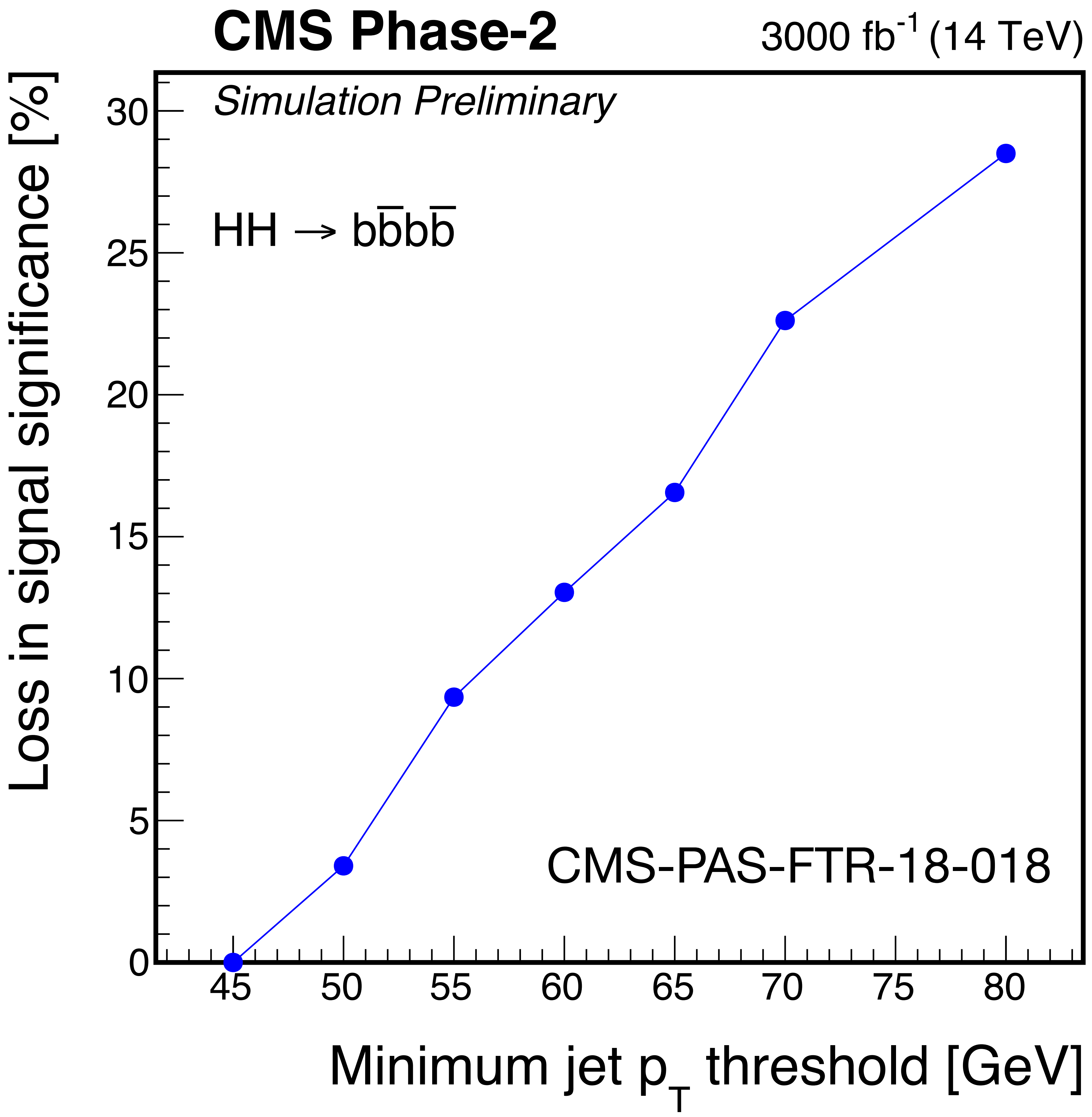
Why is it challenging?



- Up to 200 simultaneous pp interactions per bunch crossing!
  - radiation hardness and reconstruction are key challenges
  - triggering is particularly difficult in the harsh HL-LHC enviroment
- 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

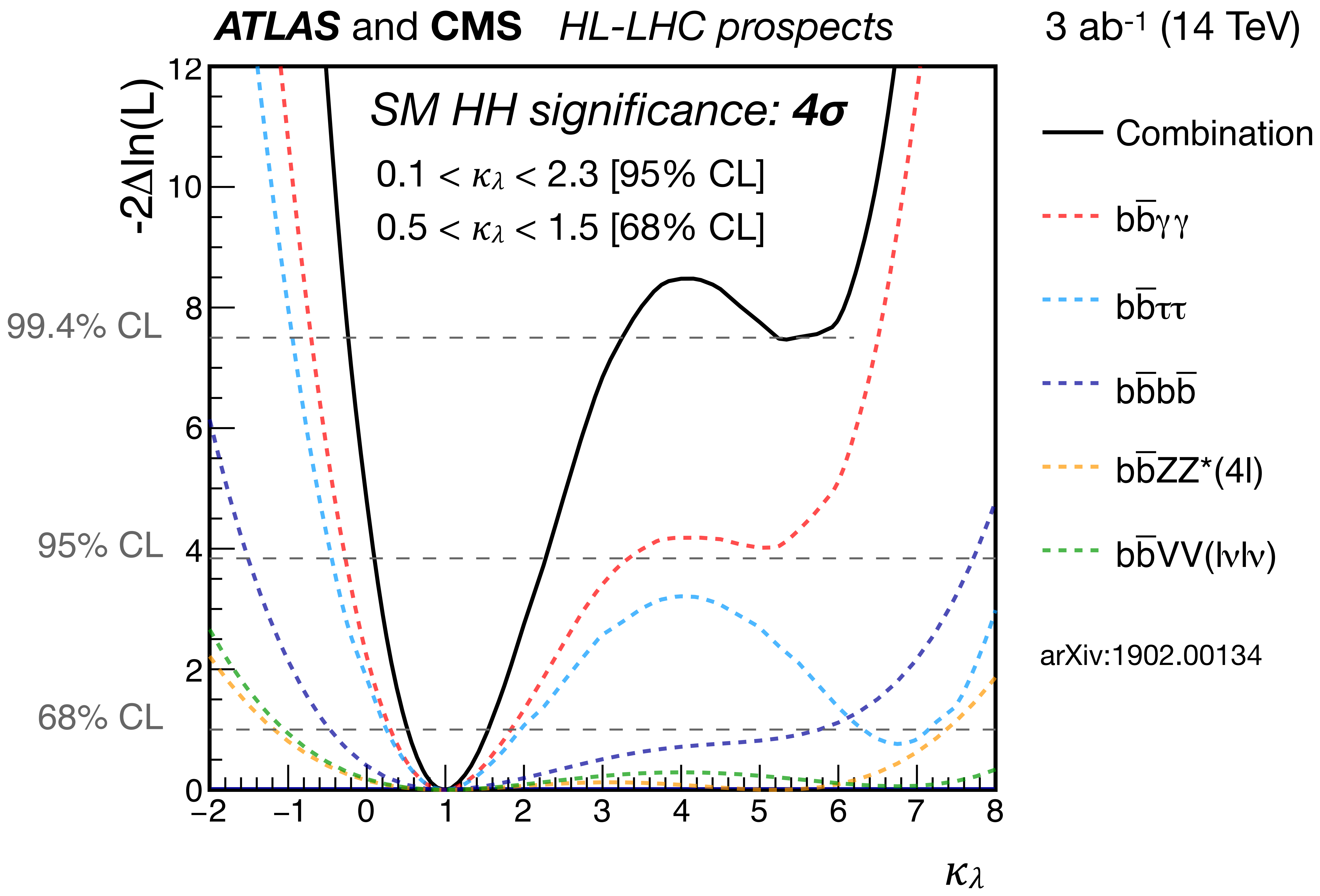
Unique opportunity to expand the physics capabilities of the experiments, key for the success of the physics programme



Essential to maintain low thresholds!

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
    - with the current analysis techniques! Further improvements should come in the next 20 years
- Can determine whether Higgs boson self-coupling exists ($\kappa_\lambda \neq 0$)
- Looser constraints from single H measurements

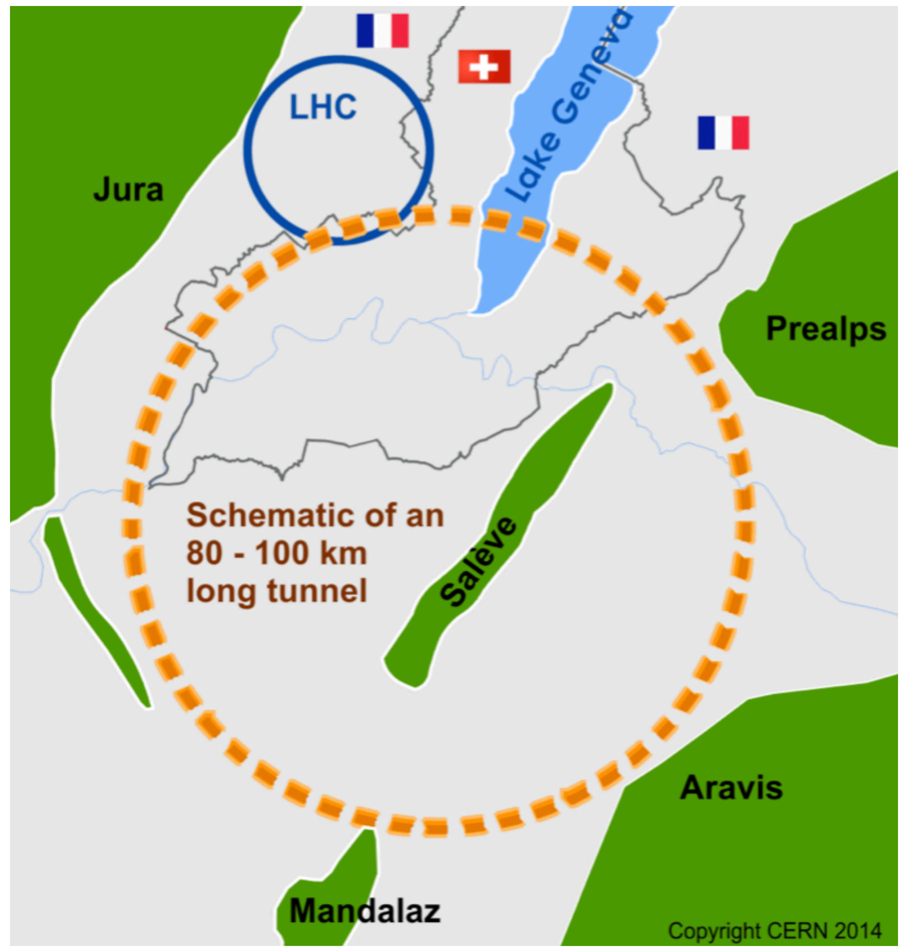


arXiv:1902.00134

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

Future colliders : a general overview

pp colliders

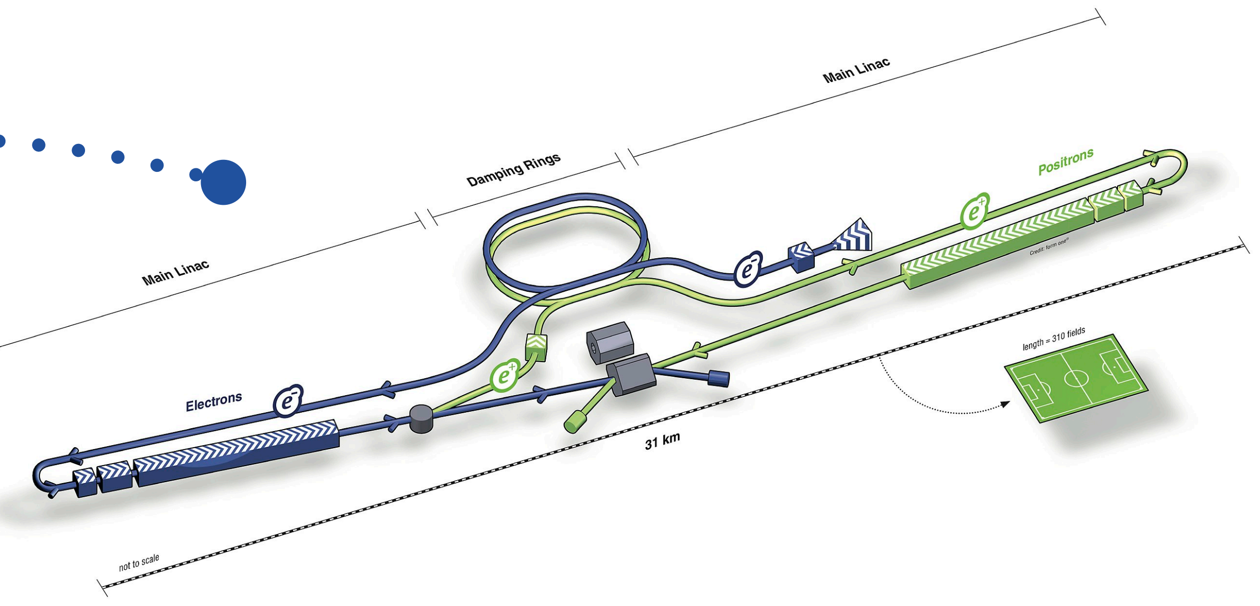


- FCC-hh
  - 100-km tunnel at CERN
  - 16 T magnets for 100 TeV
  - low-E (LE-FCC) option with 6 T magnets → 37 TeV
- HE-LHC
  - 16 T magnets in the LHC tunnel for 27 TeV

Towards high energies

σ(HH) ×33 xs, ×10 lumi w.r.t HL-LHC

e^+e^- colliders

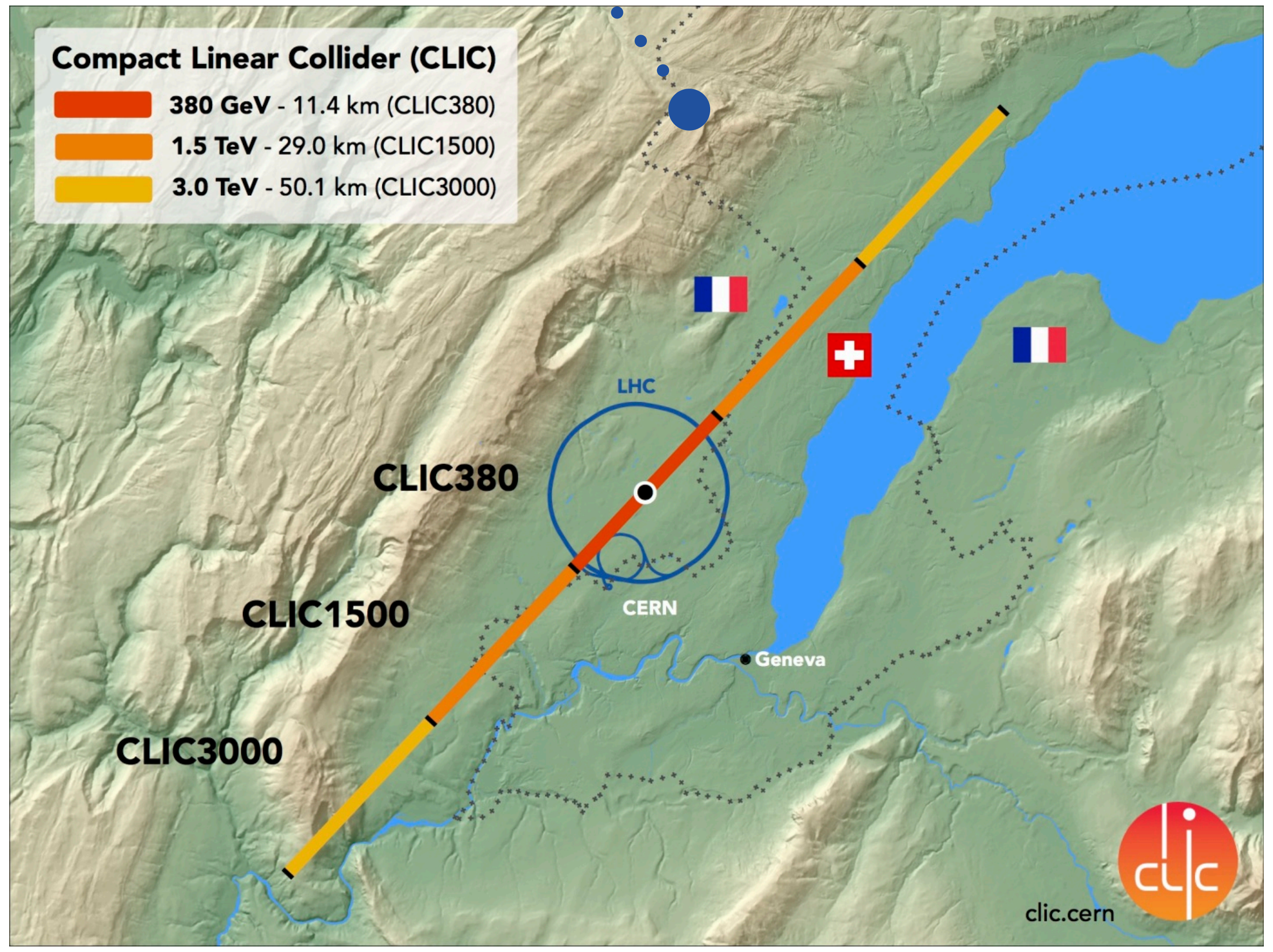


Linear colliders

- ILC : super-conductive RF cavities
  - staged, $\sqrt{s}$ = 250 GeV - 1 TeV, L ~ 1-3 ab^{-1}
- CLIC : two-beam acceleration scheme
  - staged, $\sqrt{s}$ = 380 GeV - 3 TeV, L ~ 1-5 ab^{-1}

Circular colliders

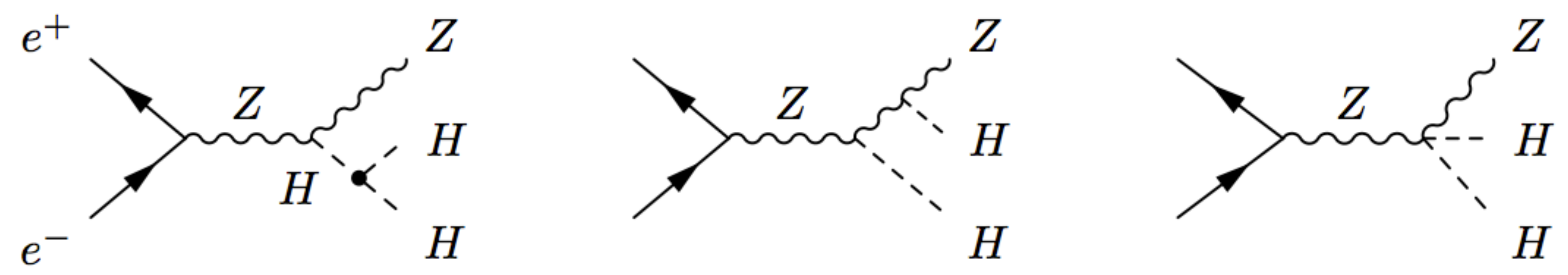
- FCC-ee : same tunnel as FCC-hh
  - $\sqrt{s}$ = 180 - 380 GeV, L = 150 - 1.5 ab^{-1}
- CepC : same tunnel as SppC (upgrade to a pp collider)
  - $\sqrt{s}$ = 90 - 240 GeV, L = 16 - 6 ab^{-1}



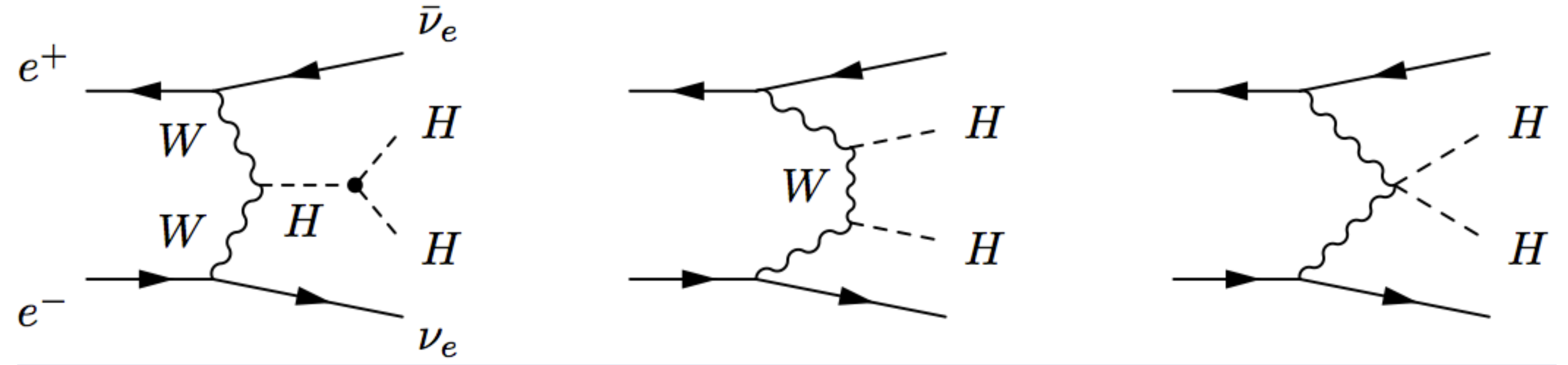
Towards precision Higgs physics

HH at e^+e^- colliders

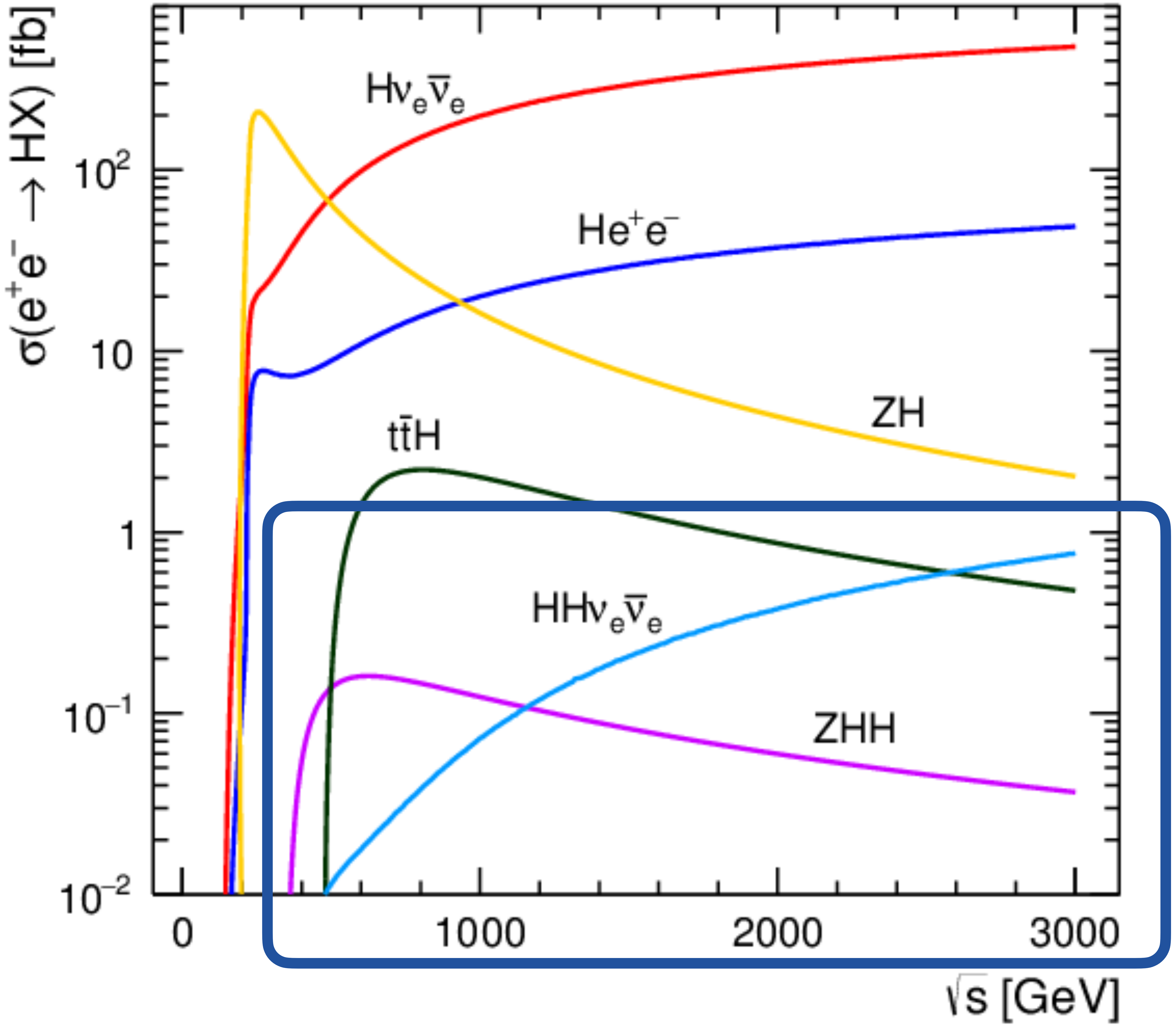
Z-strahlung



VBF



- $\sqrt{s} \gtrsim 400$ GeV needed for HH production
  - only achievable in $\mathrm{ILC}_{500/1000}$ and $\mathrm{CLIC}_{1500/3000}$
- Small cross sections for ZHH → O(500) events expected for the full run
- VBF production interesting for $\sqrt{s} > 1$ TeV



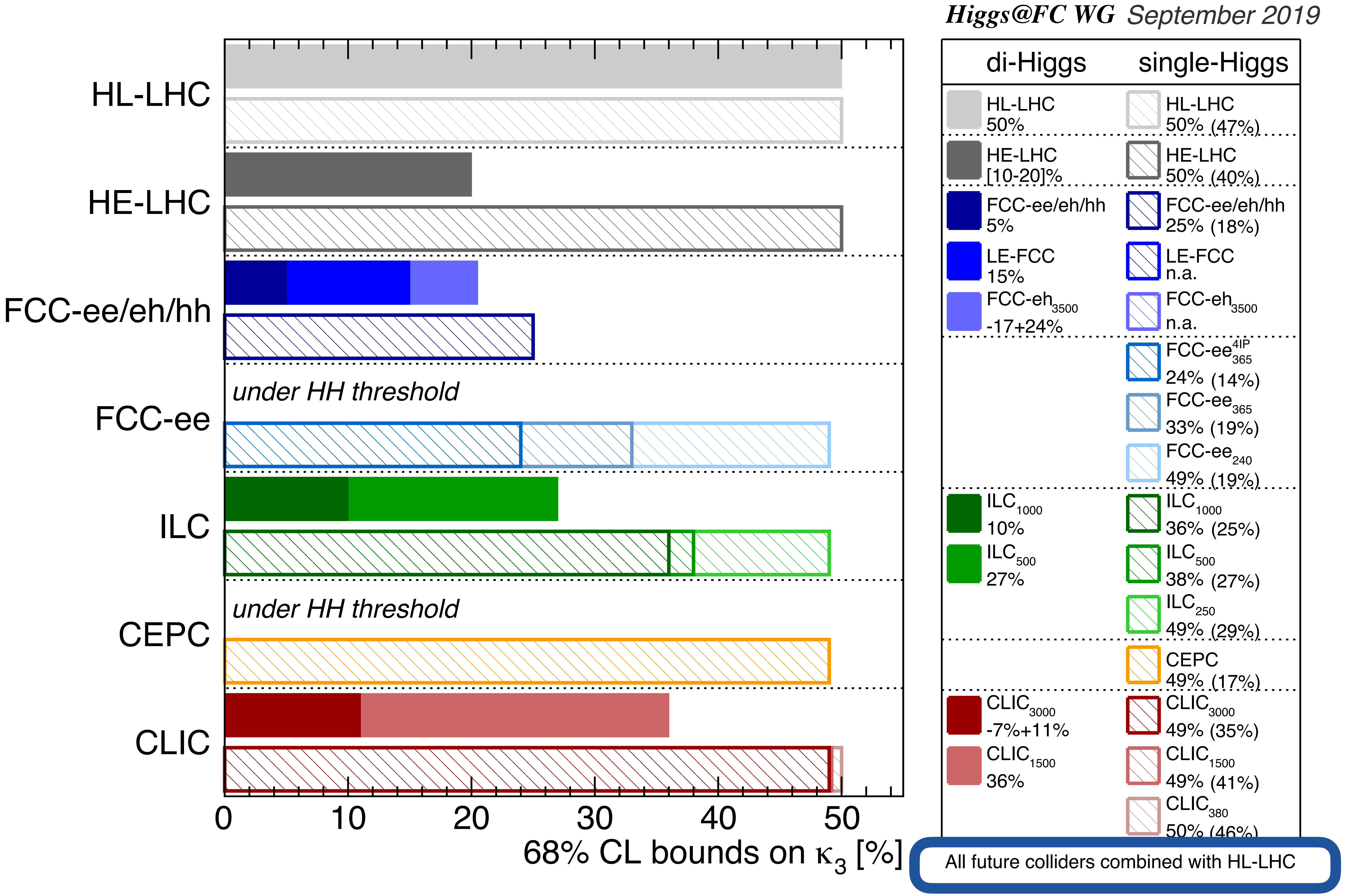
Comparison of the sensitivities

Direct HH ■

- leading the future sensitivity on λ_{HHH}
- need high energies at e^+e^- colliders
- ultimate precision of 5% achieved at FCC-hh

Indirect single-H ▨

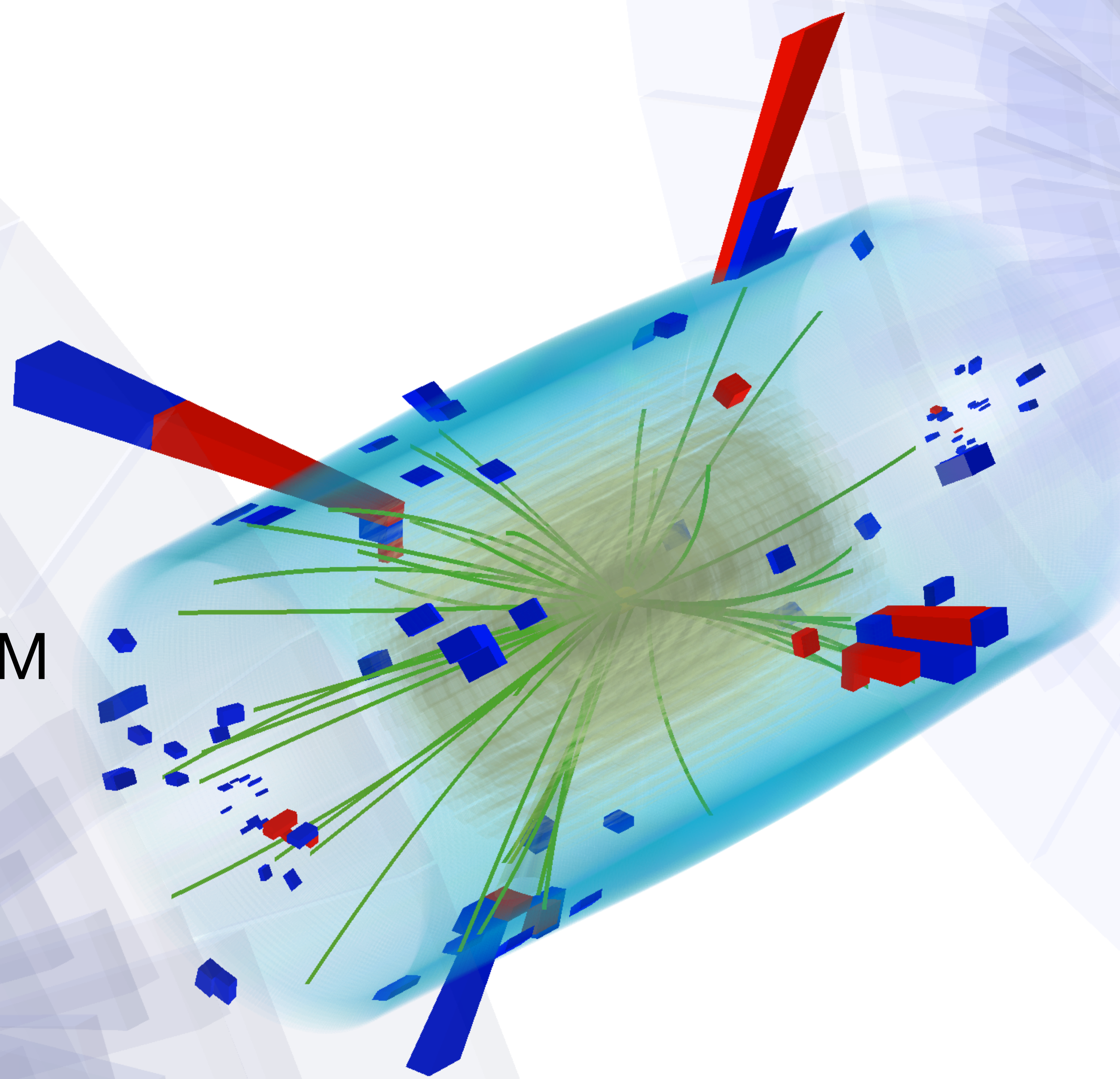
- limited by HH HL-LHC reach until higher energies and luminosities are achieved



All future colliders combined with HL-LHC

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
- One of the key physics topics for future accelerators



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

Additional material

Evaluating the prospects

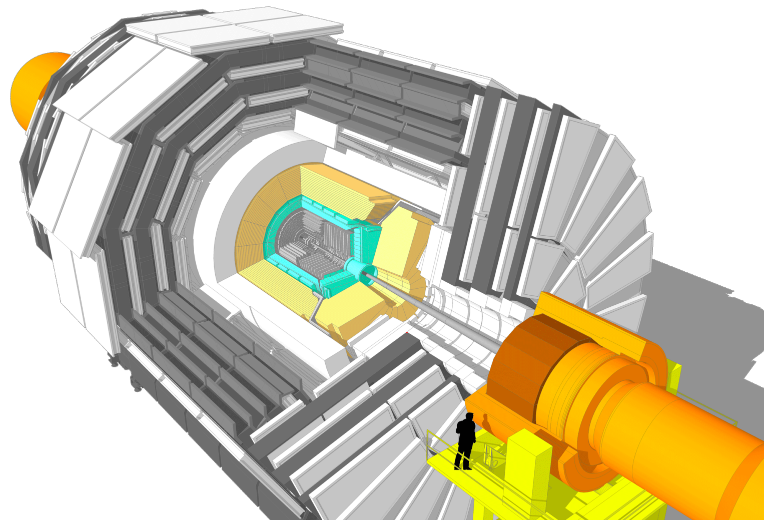
Extrapolations:
Same upgraded detector performance @ PU 200 as Run 2
Phase-2 MC-based analyses:
Fast or full sim with Phase 2 performance from TDRs

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



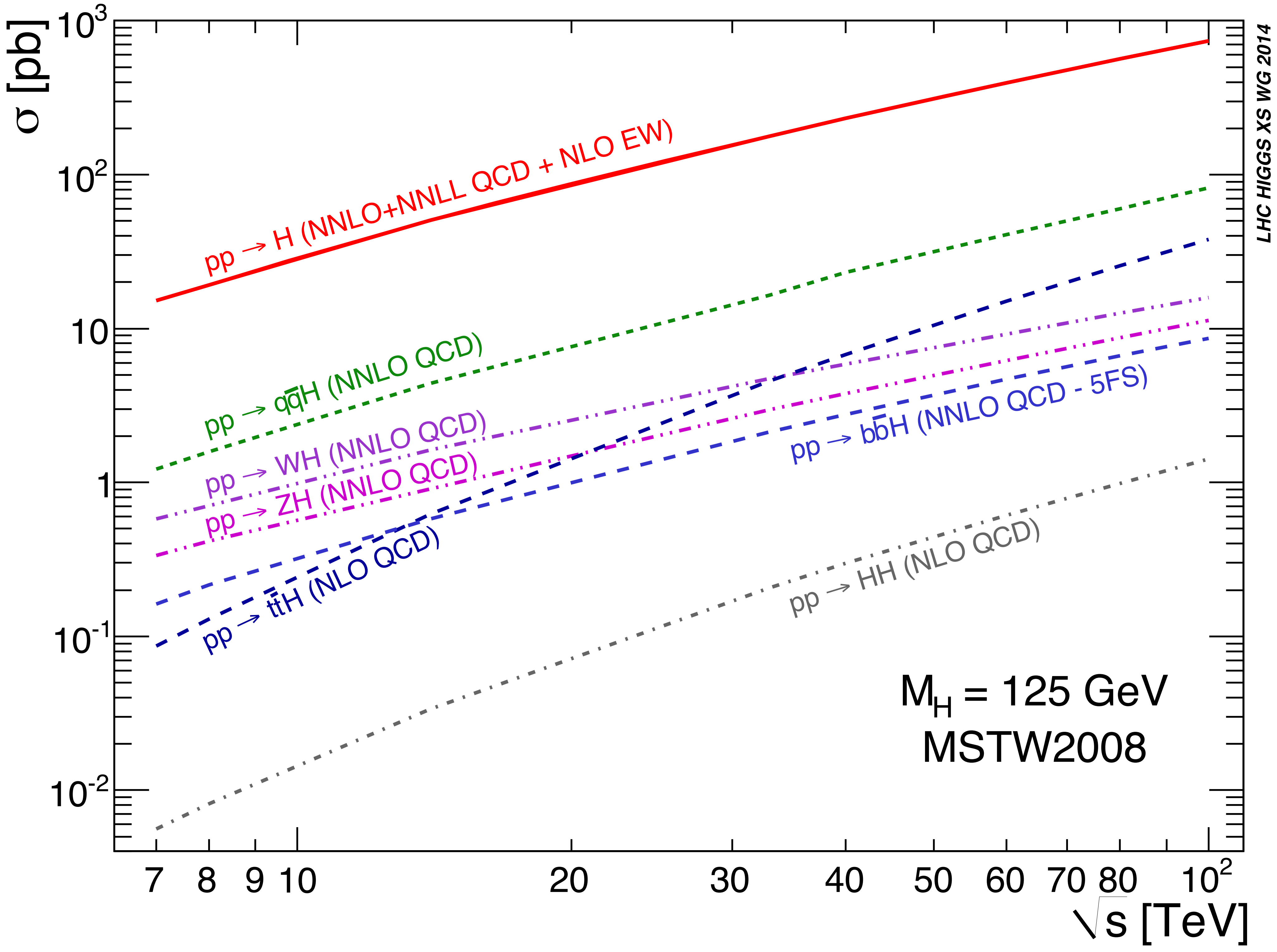
Theory developments

Analysis improvements

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

Assumptions based on Run 2 experience

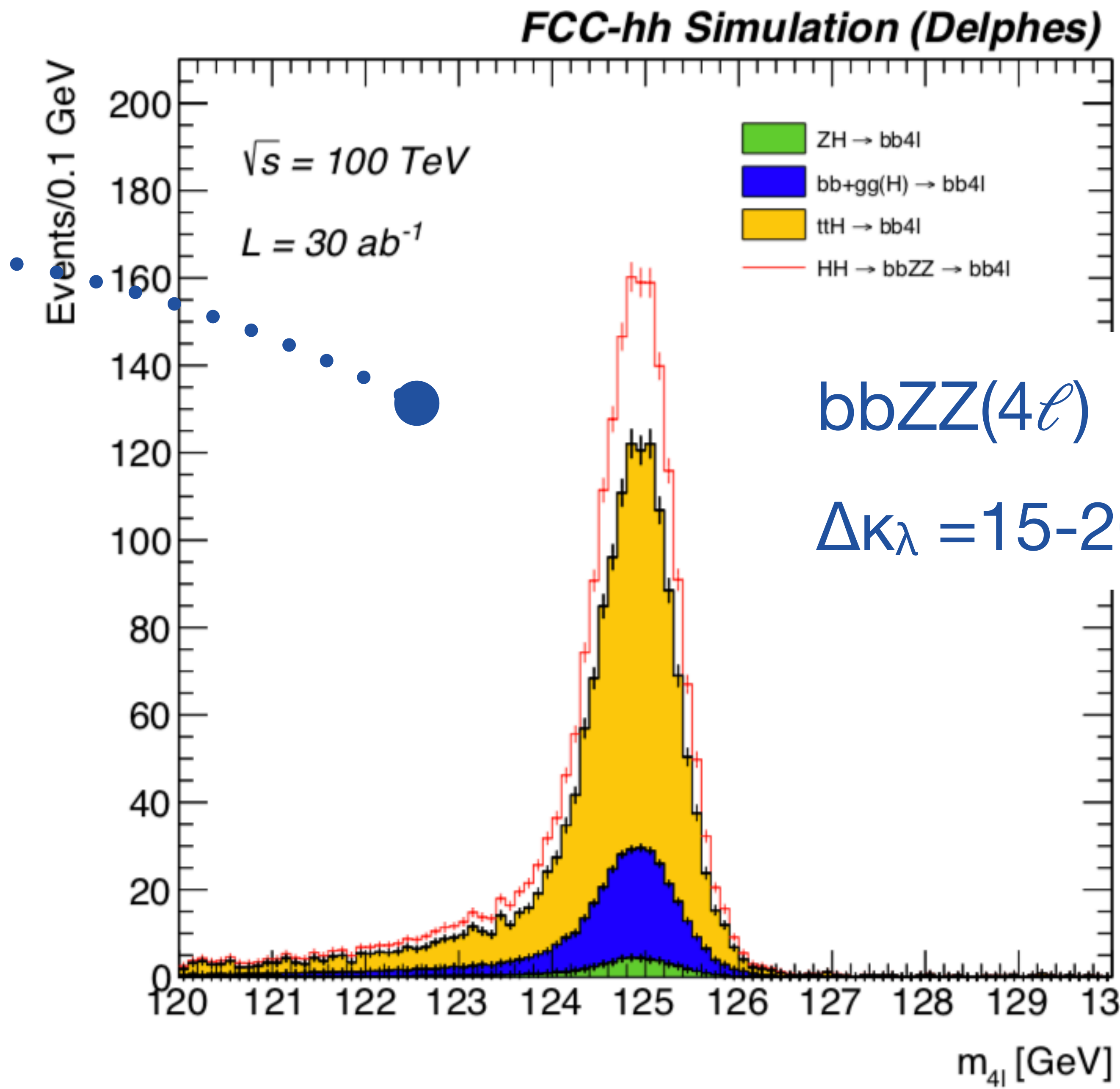
HH at future pp colliders



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



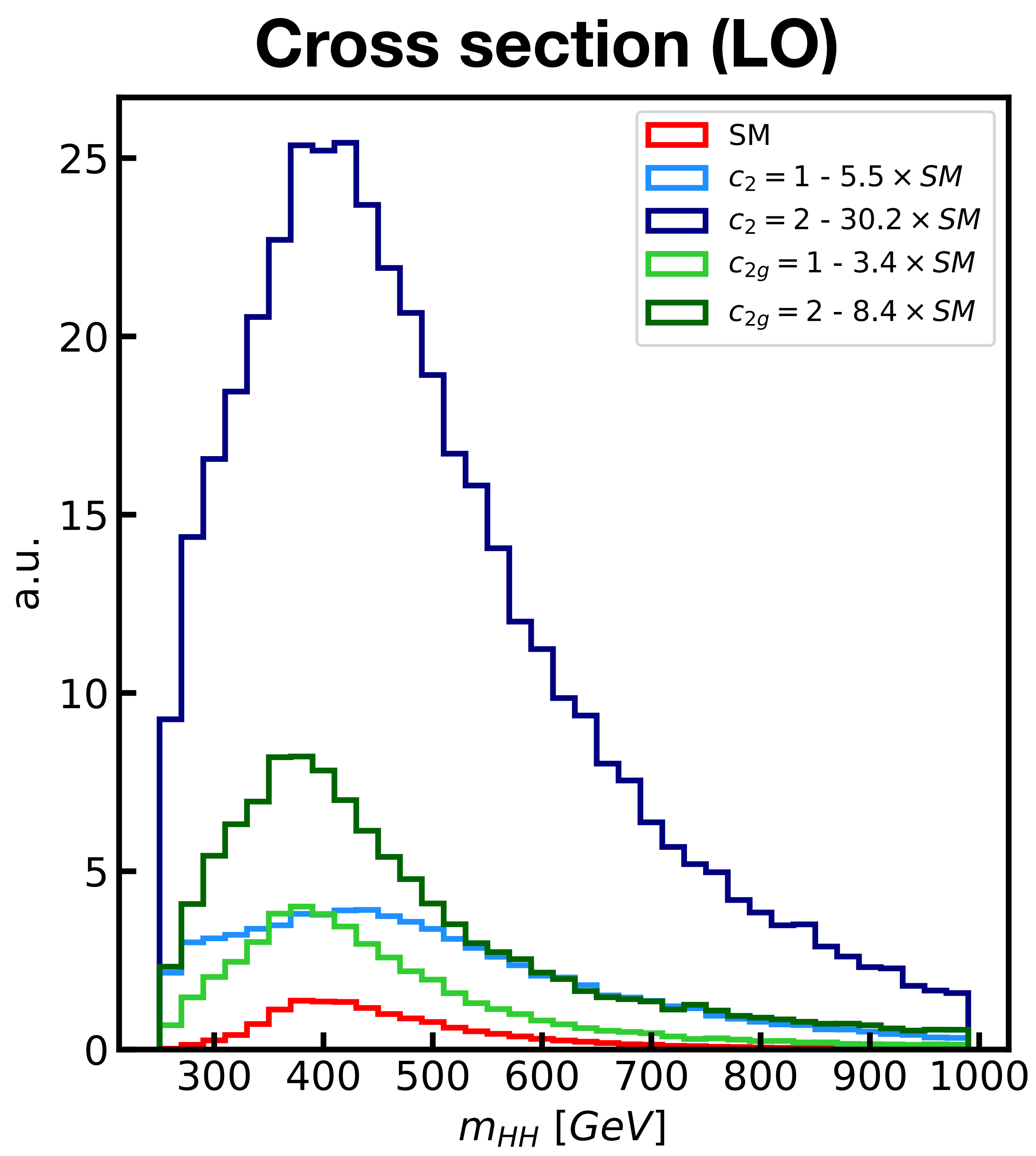
bbZZ(4ℓ)

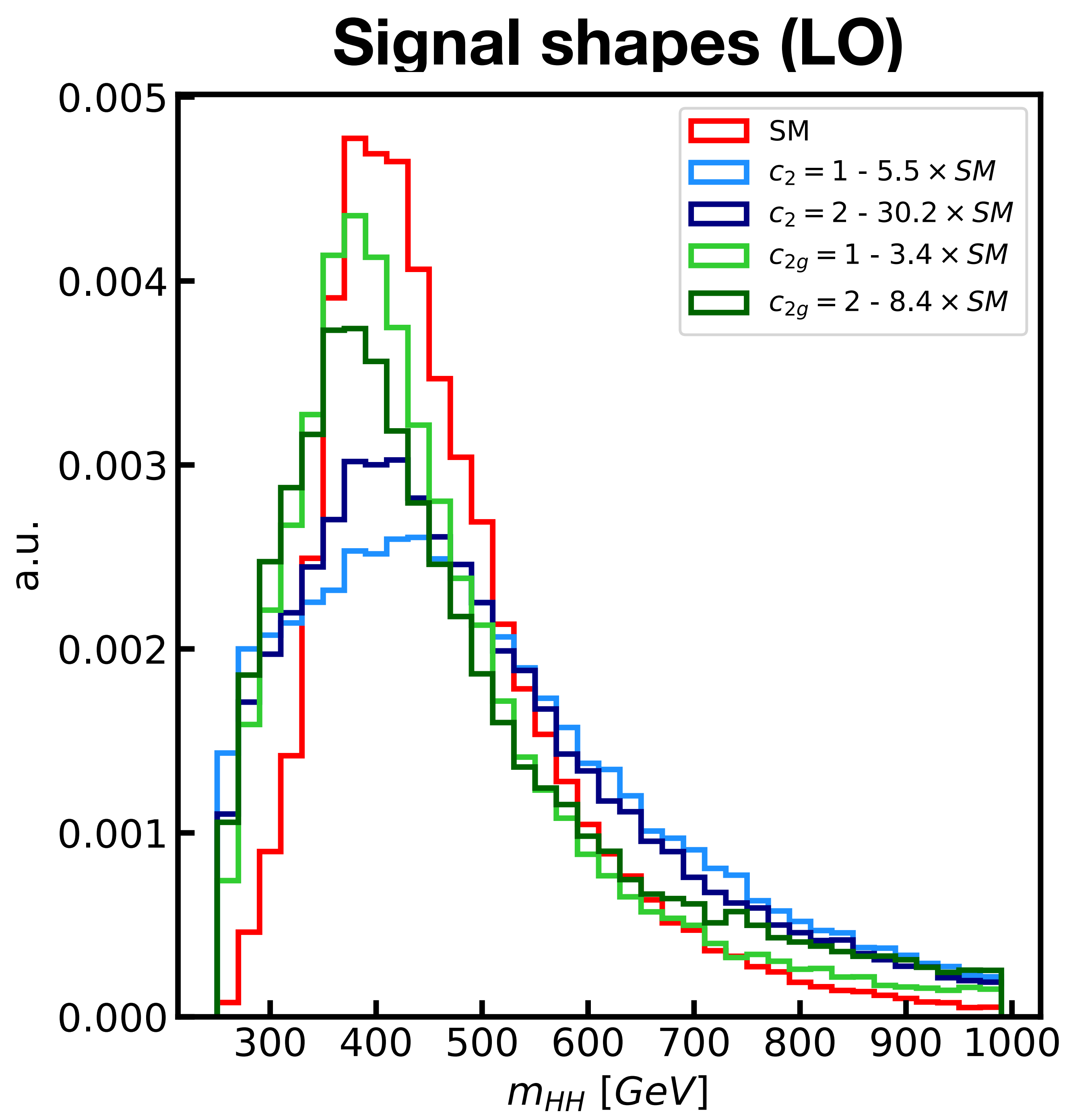
$\Delta\kappa_\lambda$ =15-20%

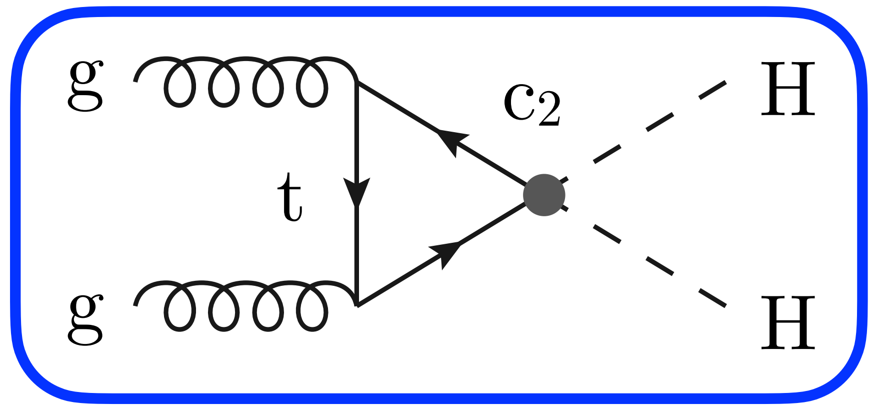
- For bbbb, use HH + jets
  - boosted jets easier to separate from the background
  - the centre-of-mass boost allows to maintain access to events close to the m_{HH} threshold

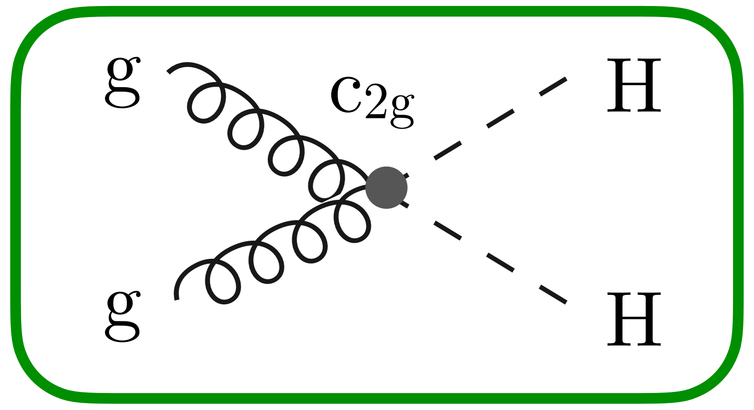
Benefit of the high energy and luminosity
Clean channels and new topologies used to fight the PU

EFT effects in HH


Cross section (LO)


Signal shapes (LO)





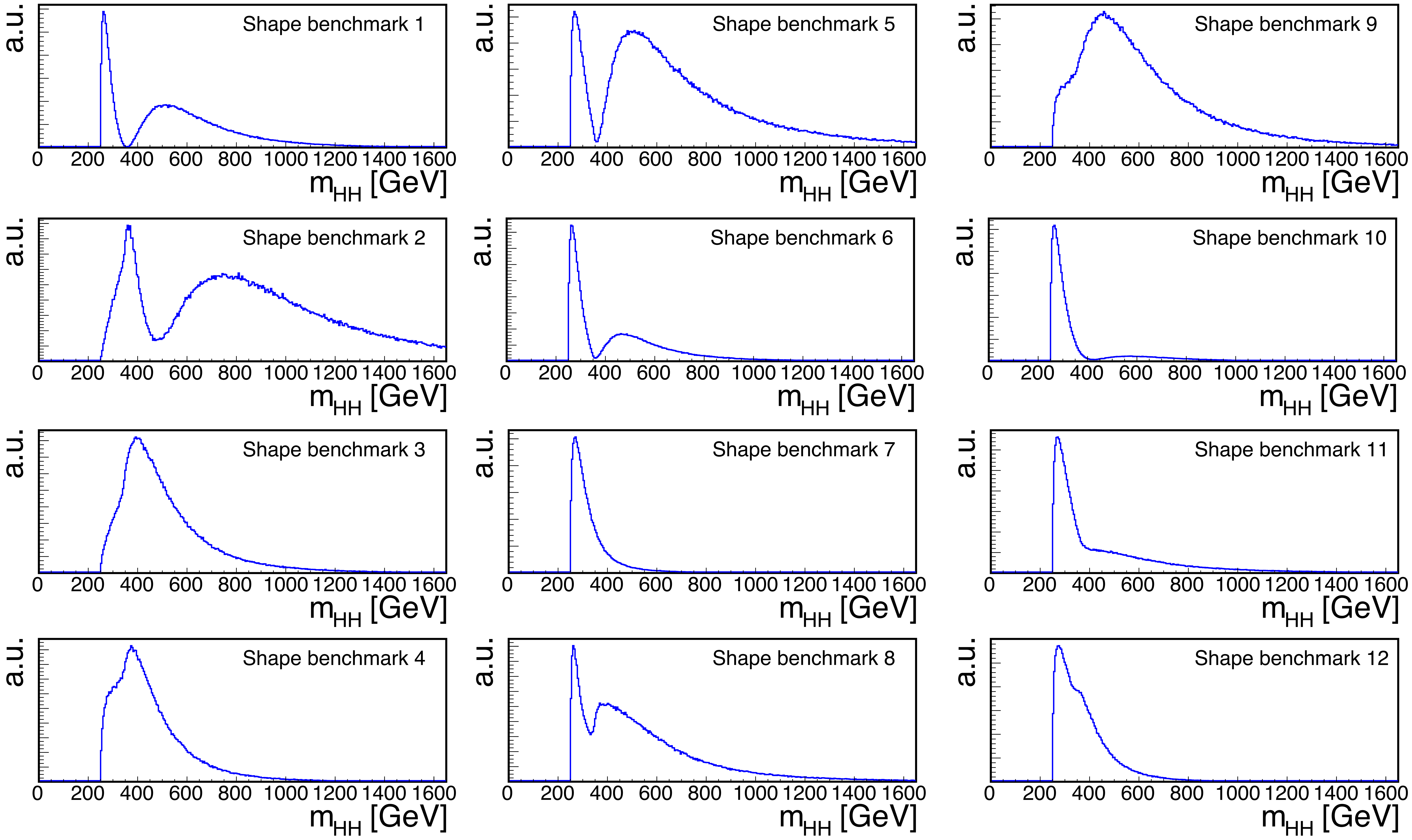
- 5 interactions involved in ggF
  - ☐ 3 specific to HH : λ, c_{2g}, c_2
  - ☐ 2 constrained also in single H: c_g, y_t
- 3 interactions involved in VBF
  - ☐ 2 specific to HH: λ, c_{2V}
  - ☐ 1 constrained also in single H: c_V
- Correlations between these parameters depend on the way EFT is realised

Results typically assume λ-only variations

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

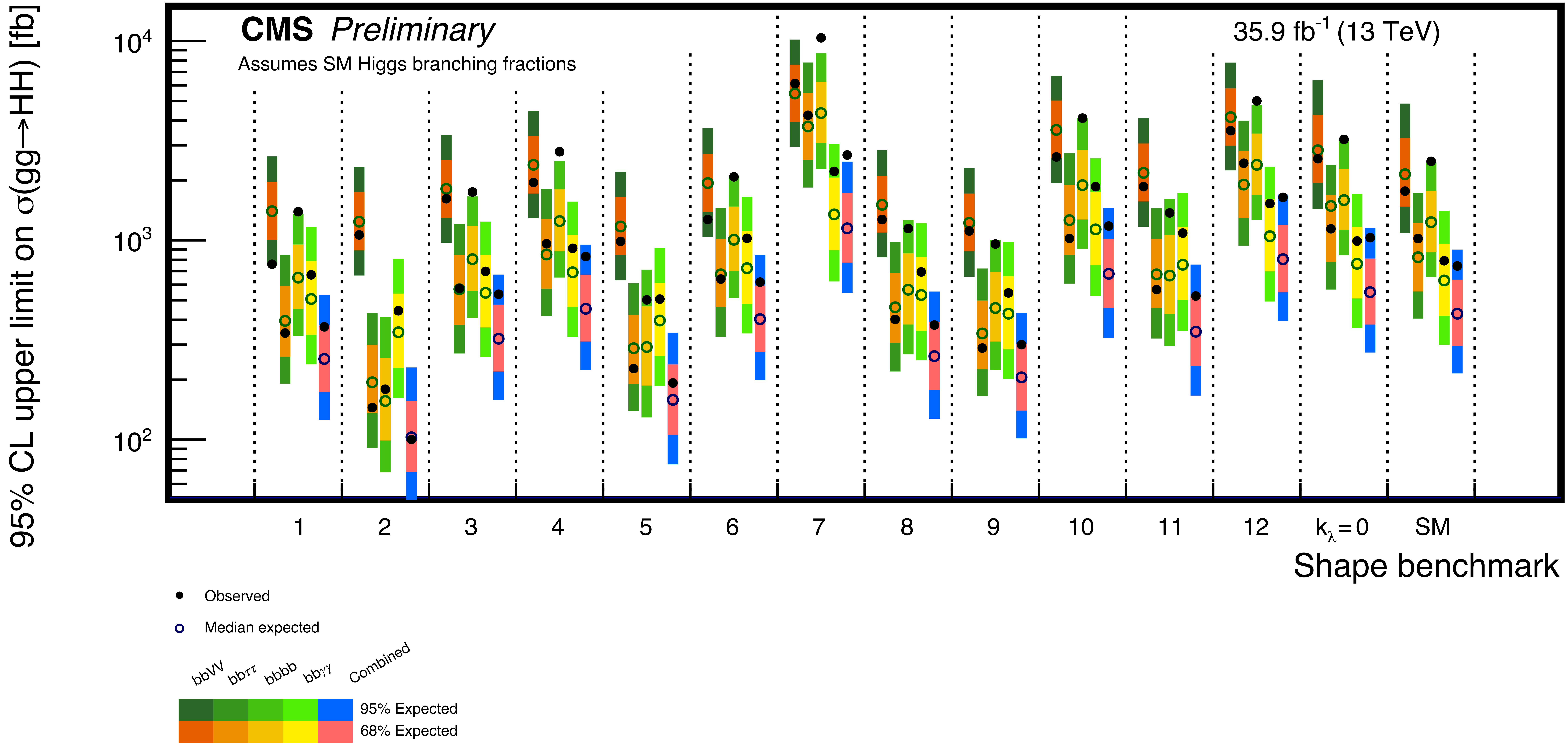
Cross sections of O(1) c_2/c_{2g} are within experimental reach

HH shape benchmarks



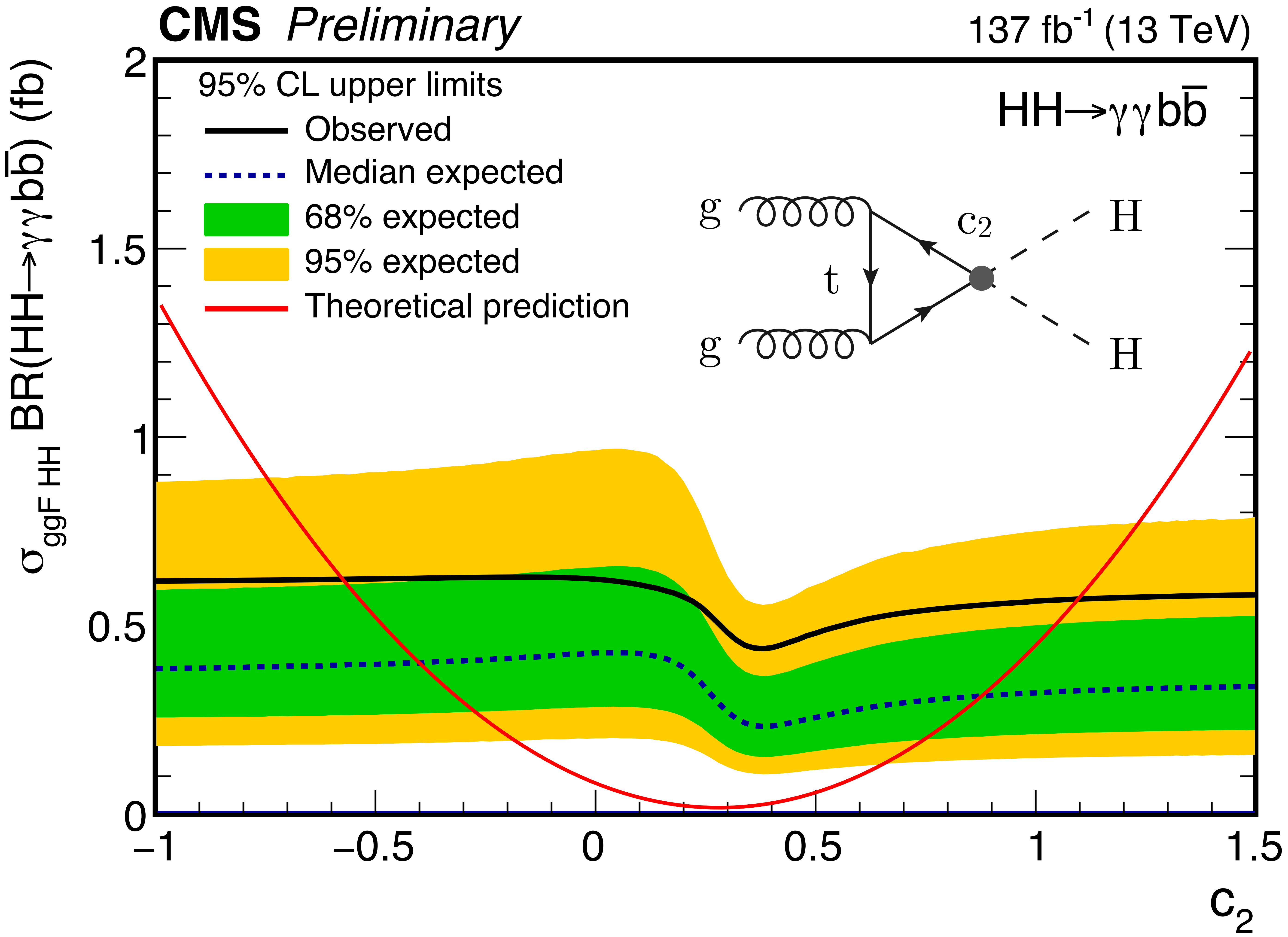
Nr.	k_λ	k_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1.0
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1.0	1.0
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1.0	-1.0
12	15.0	1.0	1.0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

Shape benchmark results - 2016 combination



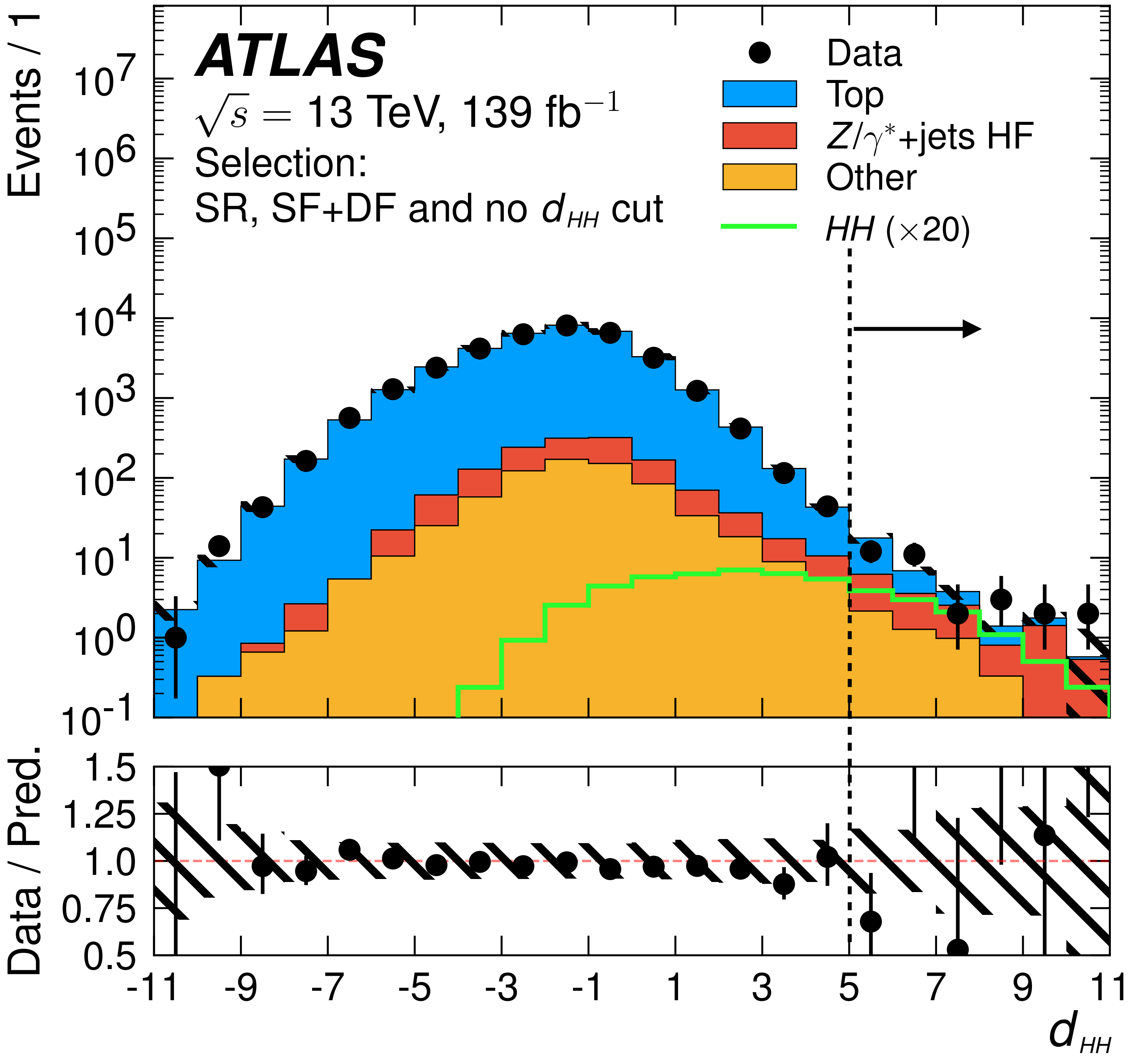
Single coupling scans

- 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

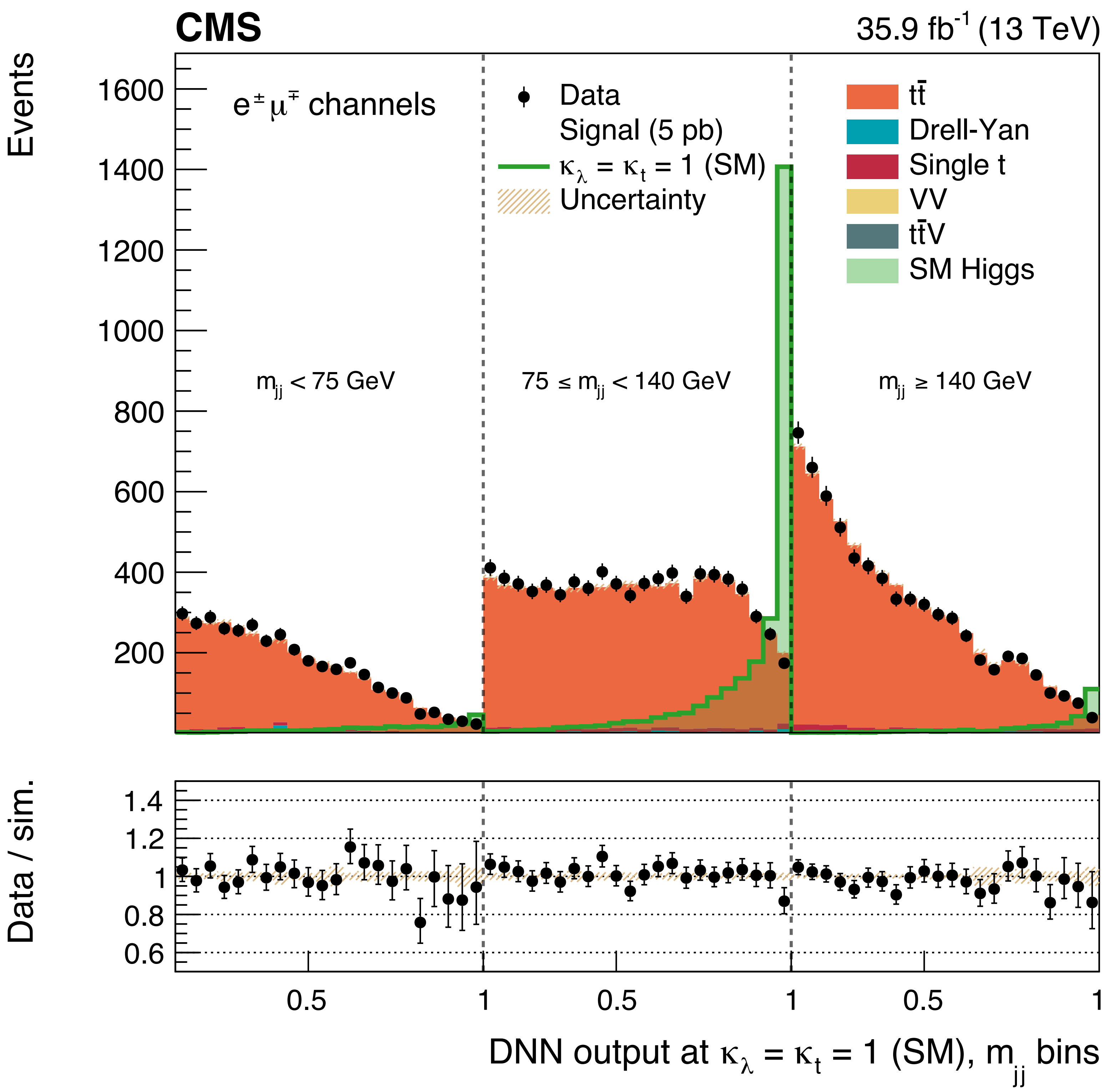


HH → bbWW

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



Obs. (Exp.) : 40 (29) × σ_{HH}^{SM}

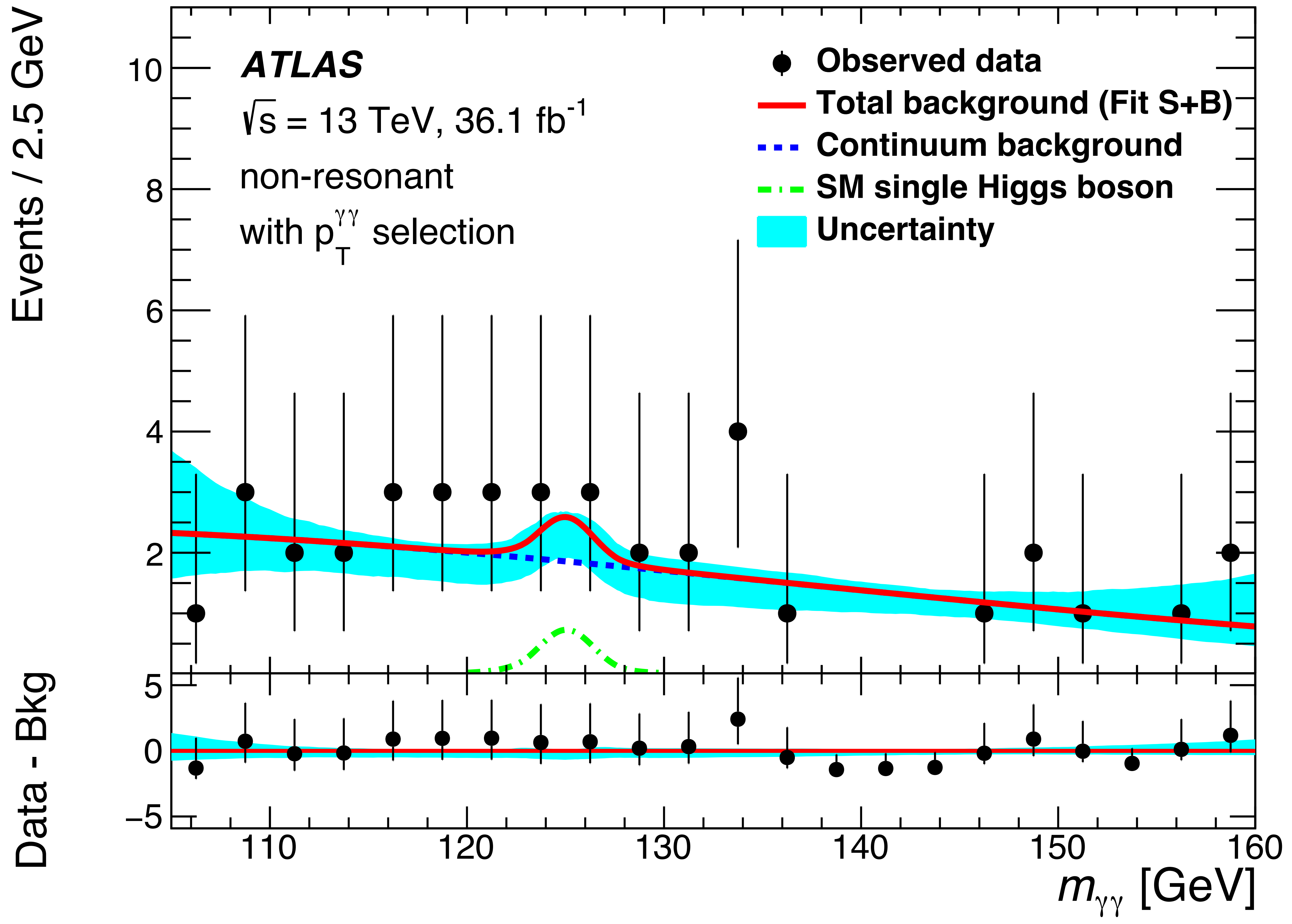


Obs. (Exp.) : 78.6 (88.8) × σ_{HH}^{SM}

- 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

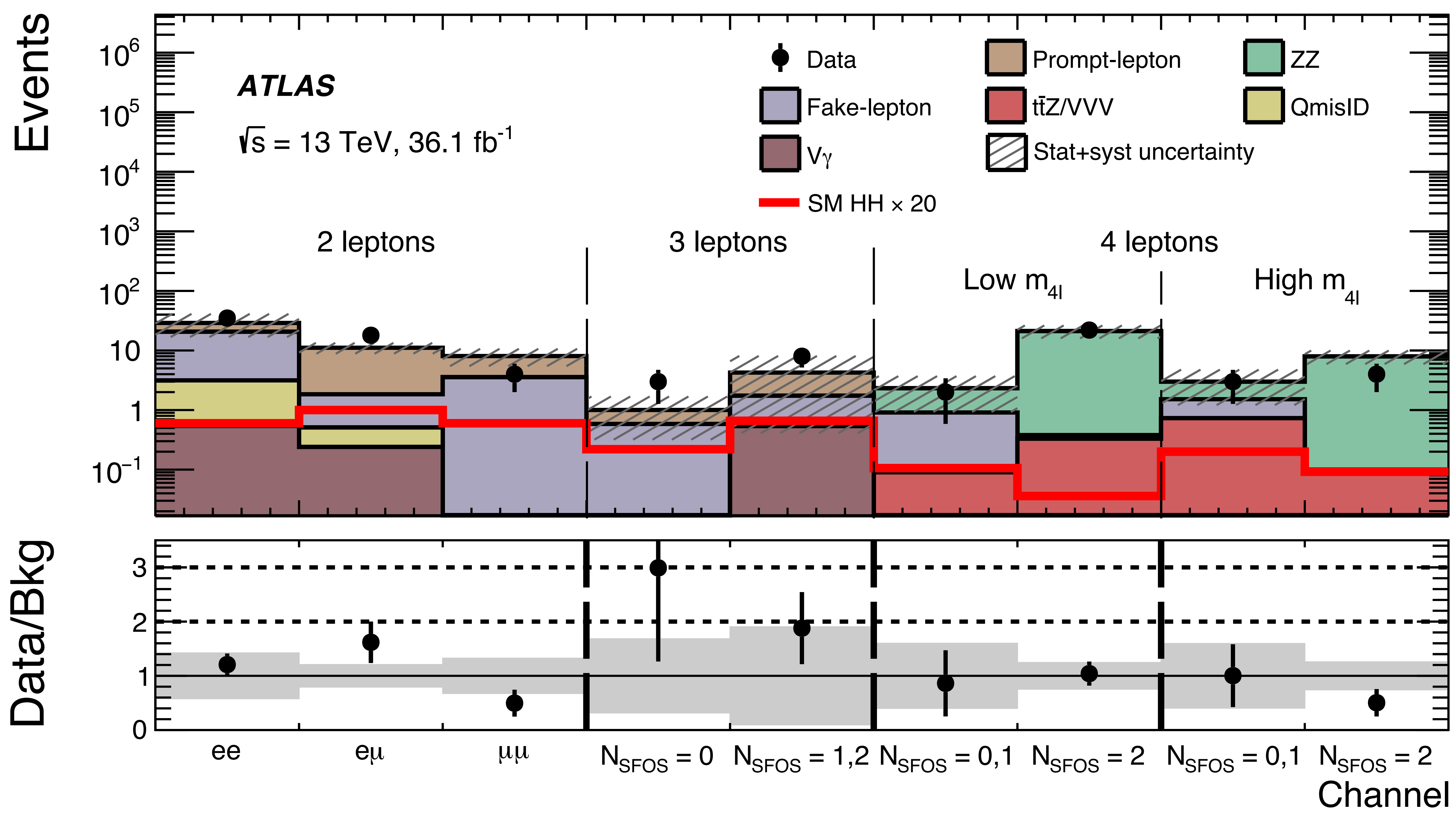
Rare HH channels

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



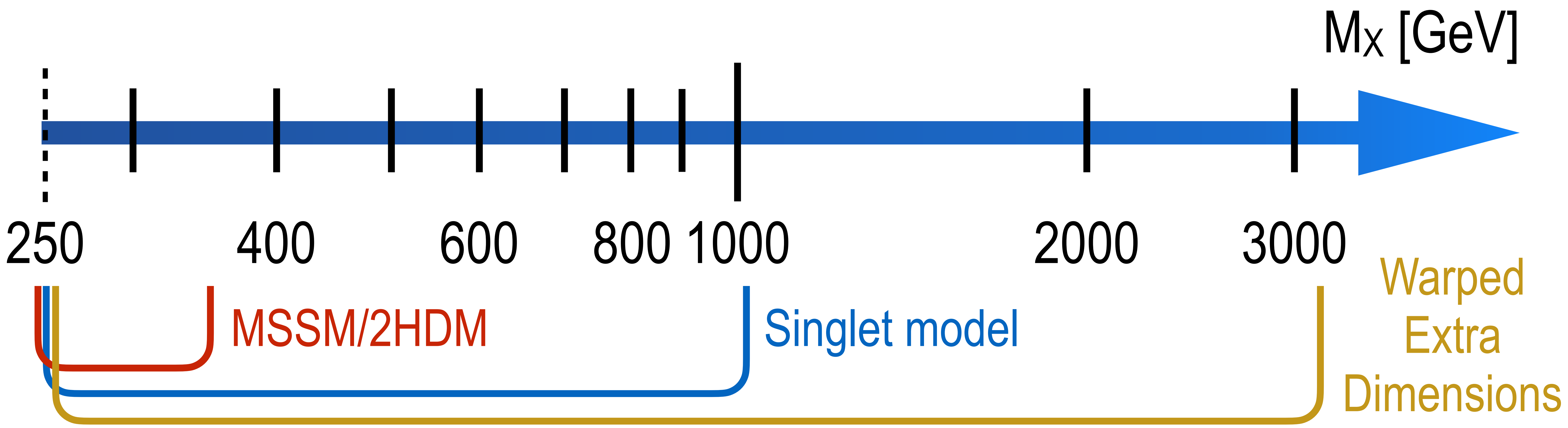
- Targets WW→$\ell\nu$qq decays
- Look for a signal using the $m_{\gamma\gamma}$ spectrum

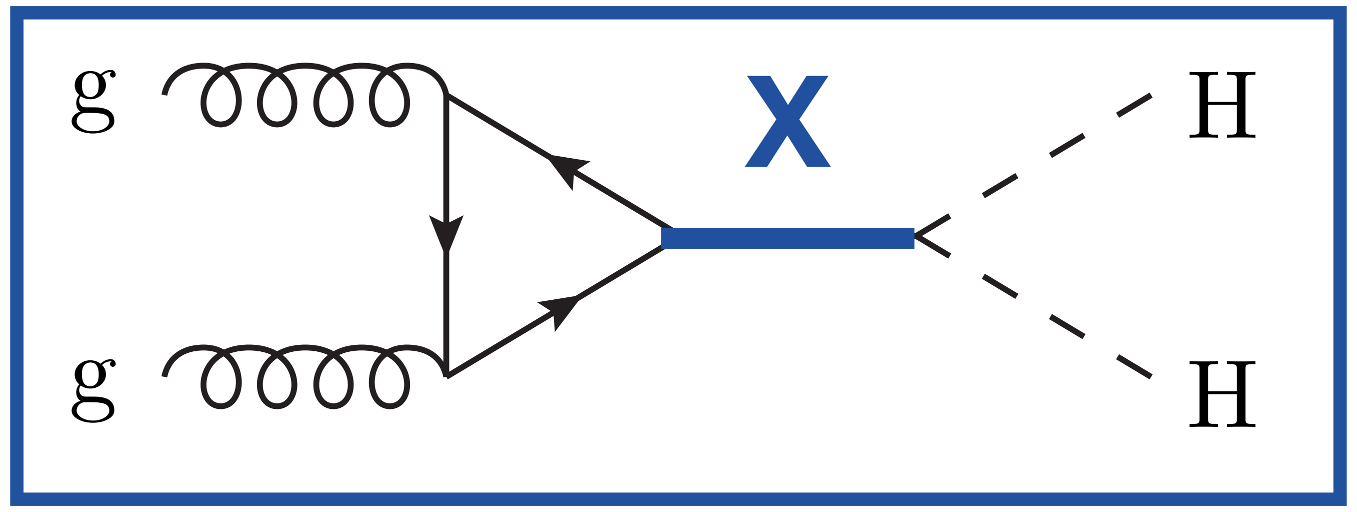
WWWW Obs (Exp) : 160 (120) × σ_{HH}^{SM}



- 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





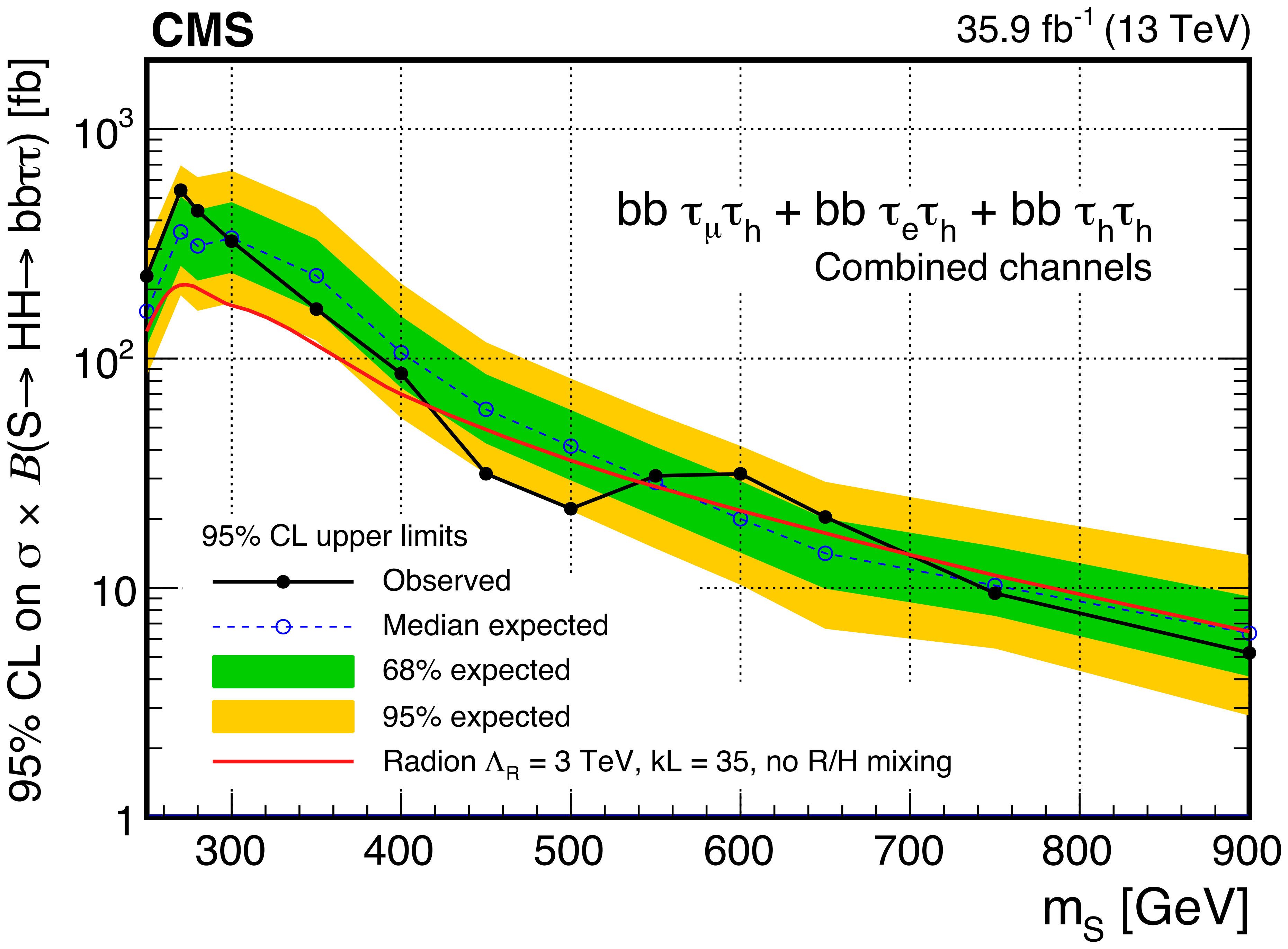
- Resonant HH production predicted in a variety of models
  - from extended scalar sectors to exotic new physics
- A broad mass range must be covered to ensure maximal sensitivity to new physics
  - complementarity of the different decay channels

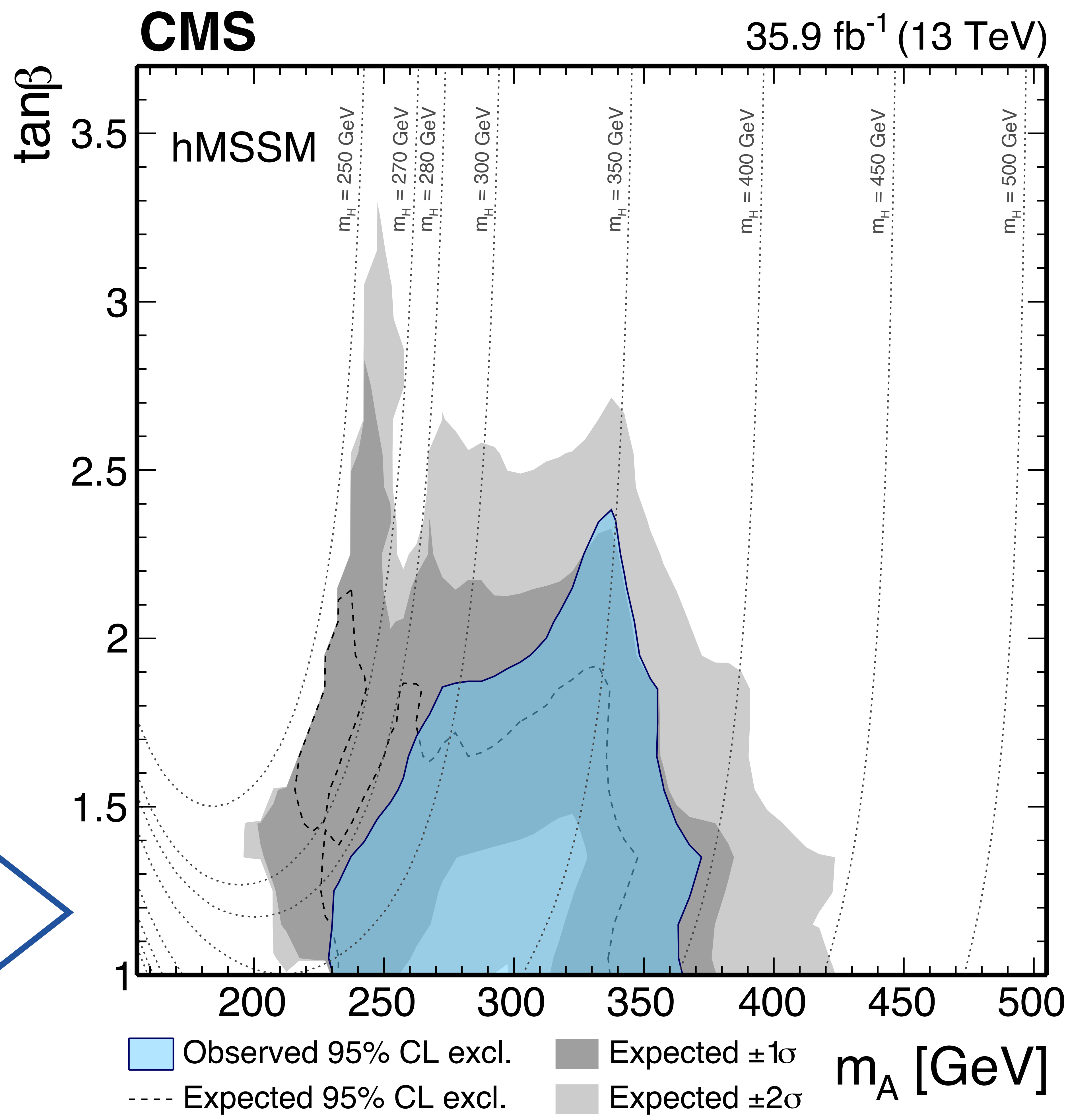
HH is an ideal place to look for BSM physics
Sensitive with current LHC data

An example: extended scalar sector with X→HH→bb$\tau\tau$

- Search strategy similar to the one used for nonresonant production
  - final discriminant: kinematic fit of the bb$\tau\tau$ system reconstruct m_X

- Resonant signal searched for masses up to 900 GeV
  - at higher values the $\tau\tau$ decay products overlap → dedicated analysis for the high mass regime

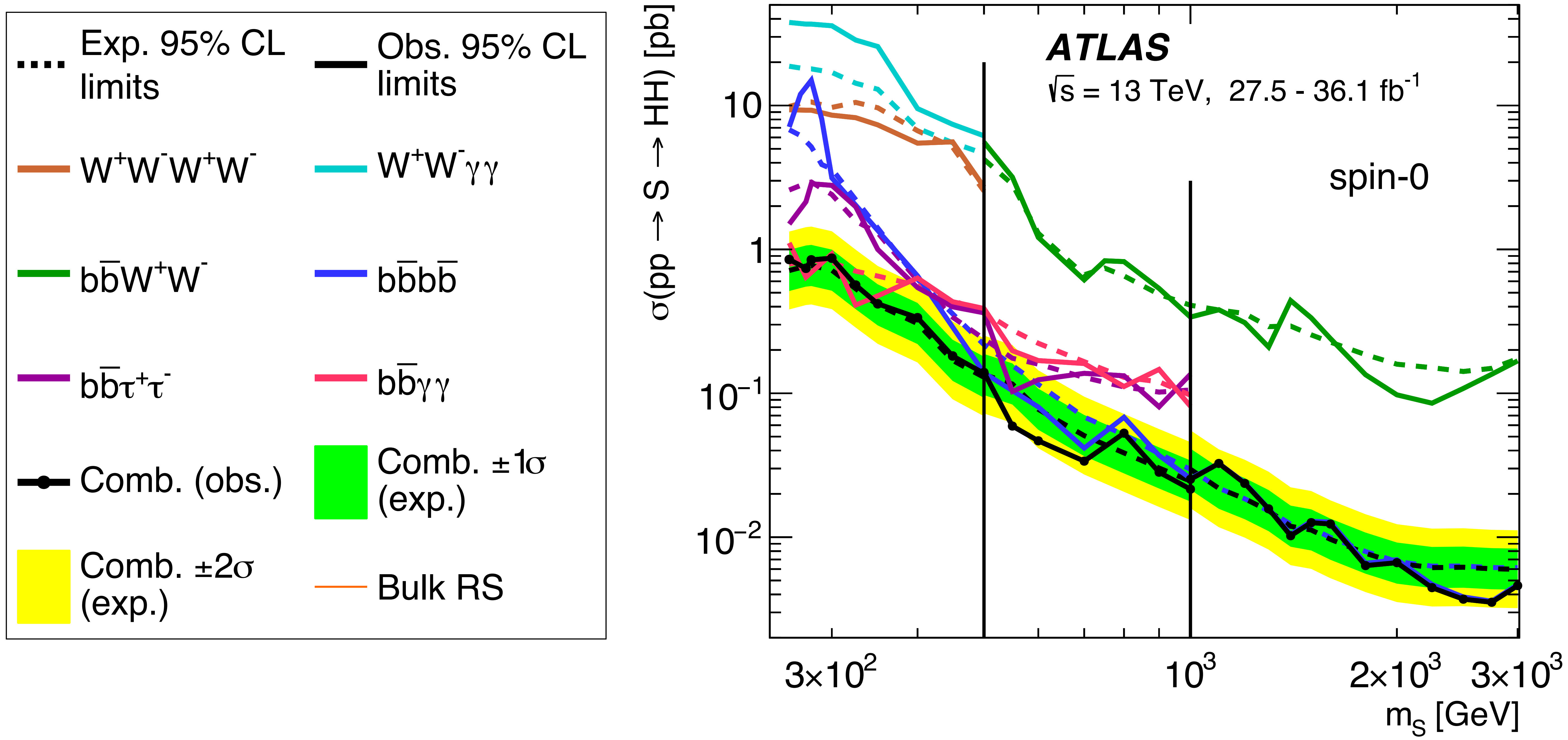


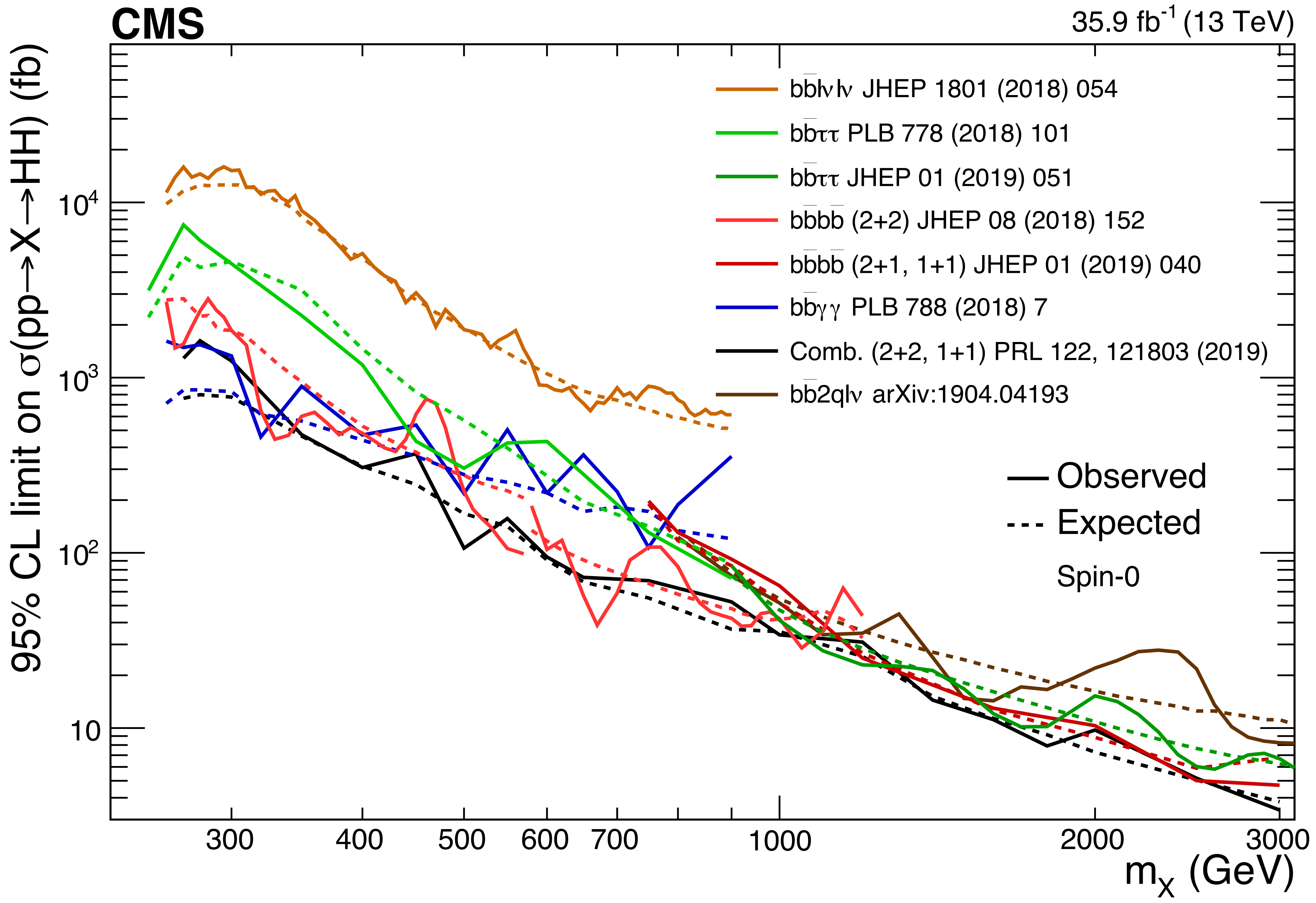


Resonant HH analyses probe extended scalar sectors

PLB 800 (2020) 135103
PRL 122, 121803 (2019)

Resonant searches: status

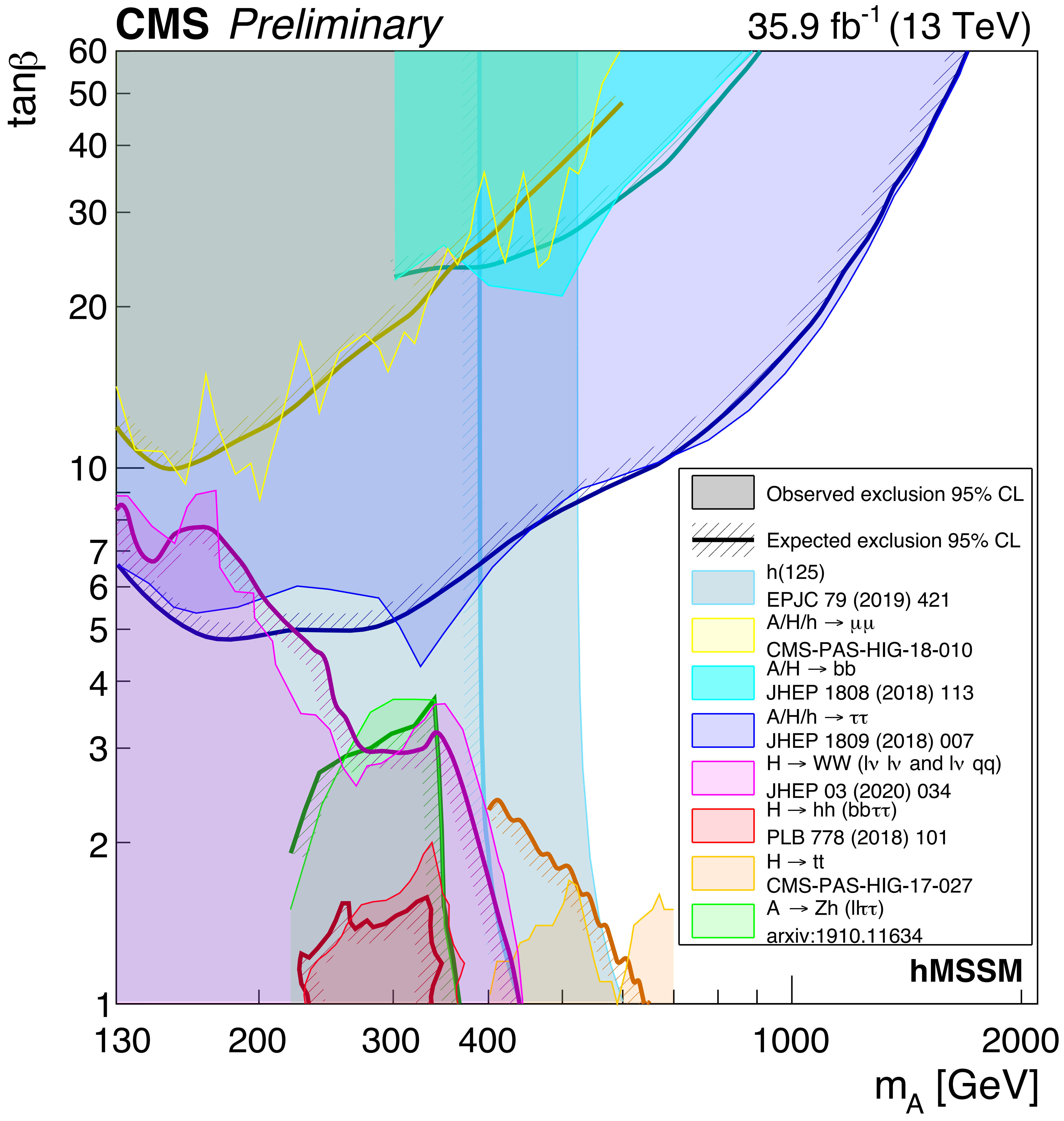




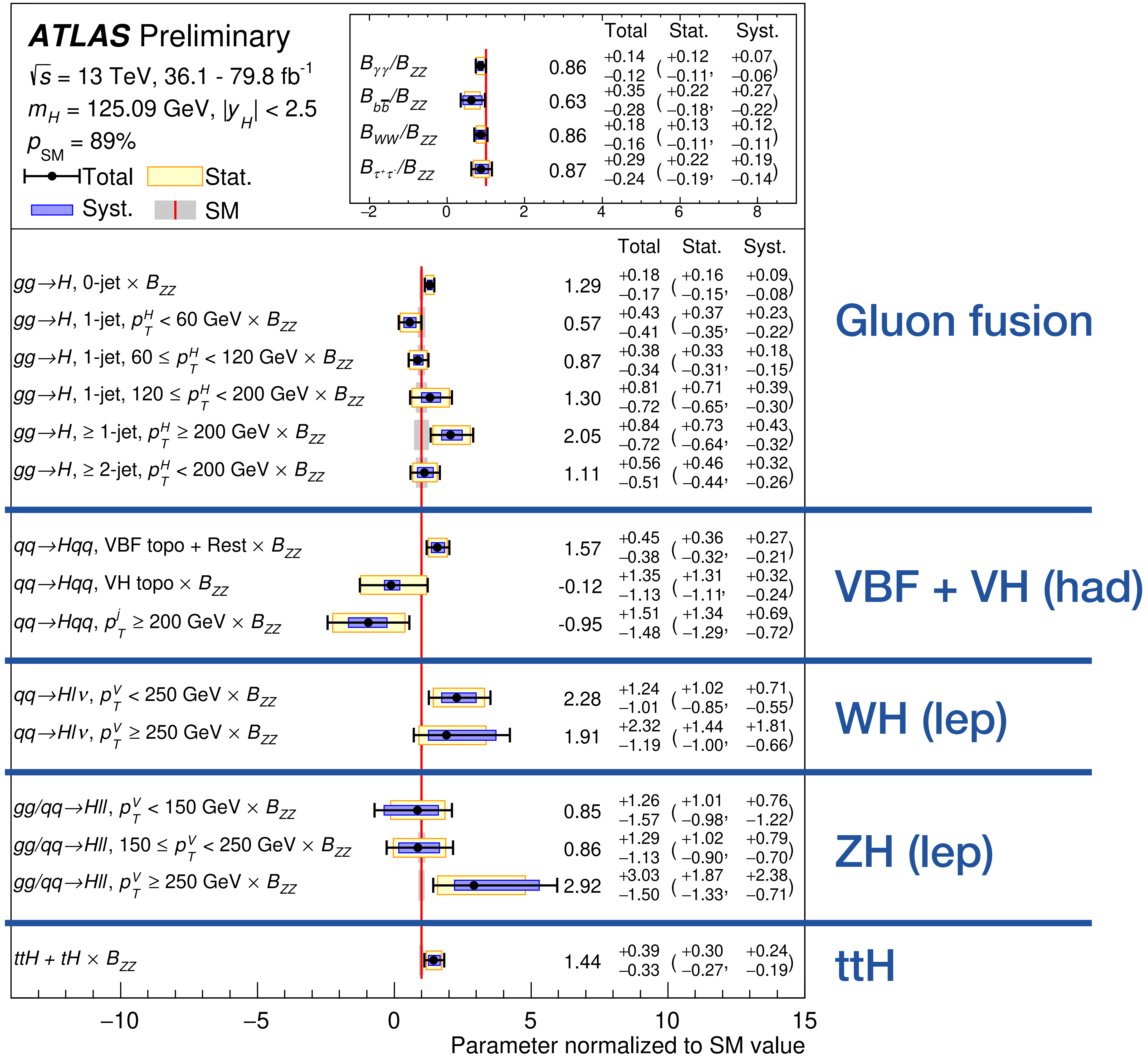
- New resonances explored in a broad mass range up to 3 TeV
  - both spin 0 and spin 2 hypotheses
- Complementarity between the final states in the low/medium/high mass regimes
  - same trend in the two experiments with some analysis-related differences
- HH-like signatures (X→YH, X→YY) are not yet systematically explored at the LHC
  - they will give a new access to the exploration of extended scalar sectors

HH in the quest for extended scalar sectors

- In minimal extended scalar sector models such as the MSSM, HH is sensitive in the low tanβ region
- Non-minimal models are yet largely unexplored at the LHC
  - HH and HH-like signatures (scalar-to-scalar decays) are characteristic signatures of these models

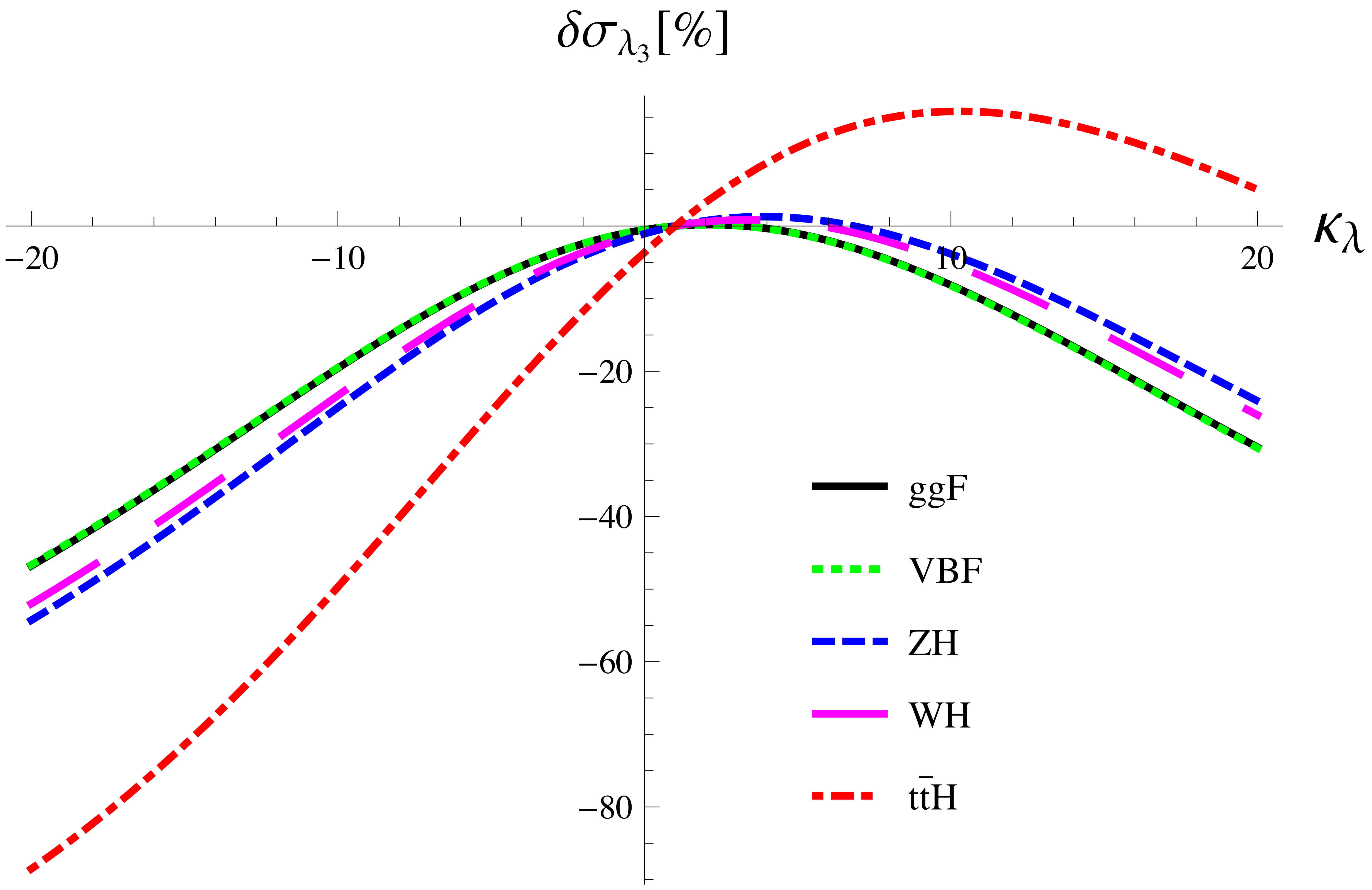


Single H : input

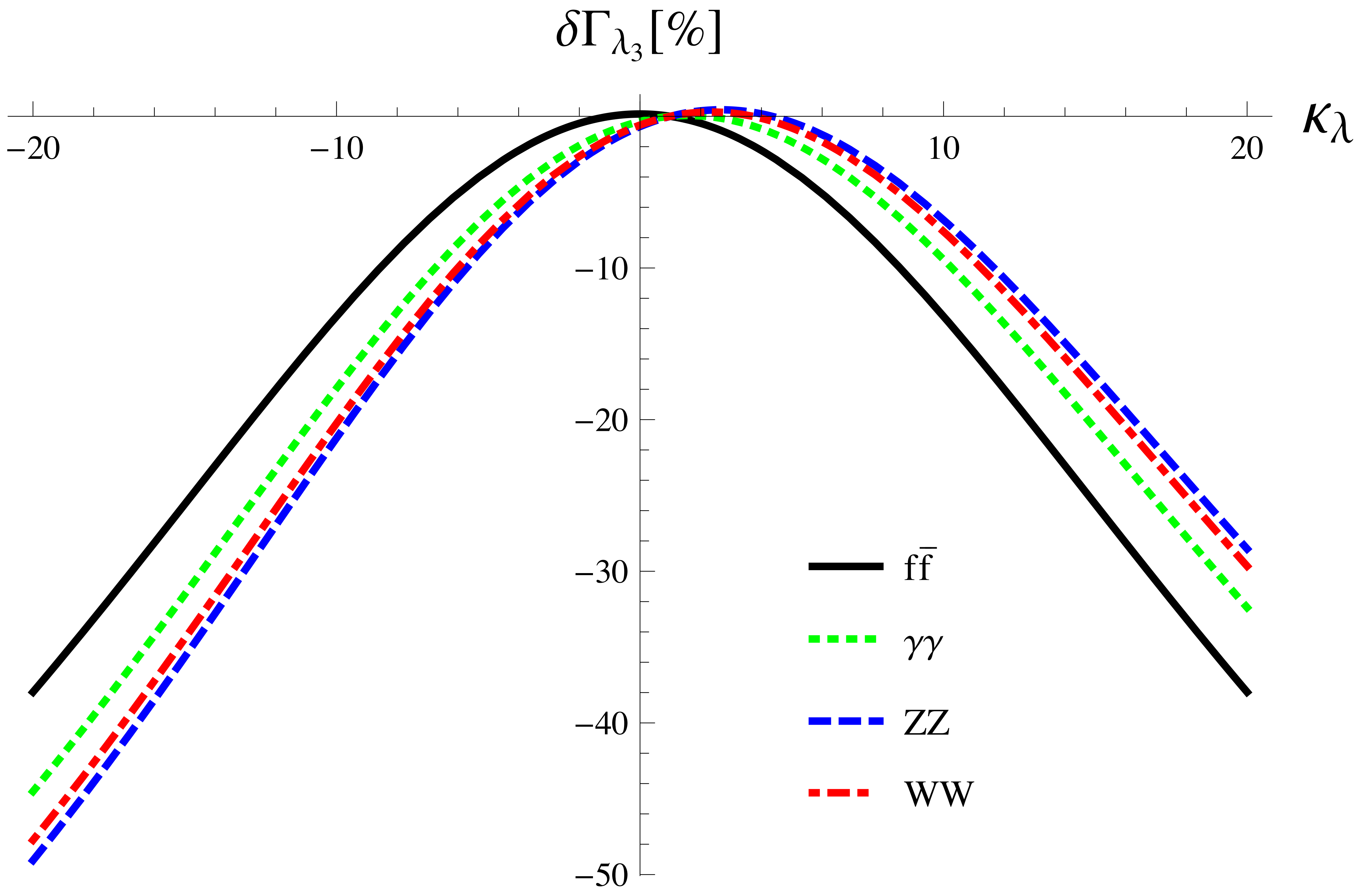


- Combination of single H measurements in various production modes and decay channels
- Fiducial Higgs boson production modes and kinematics phase space regions: "*simplified template cross section"*
- The impact of λ_{HHH} corrections is evaluated for each process and bin
  - parametrise single H yields 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}

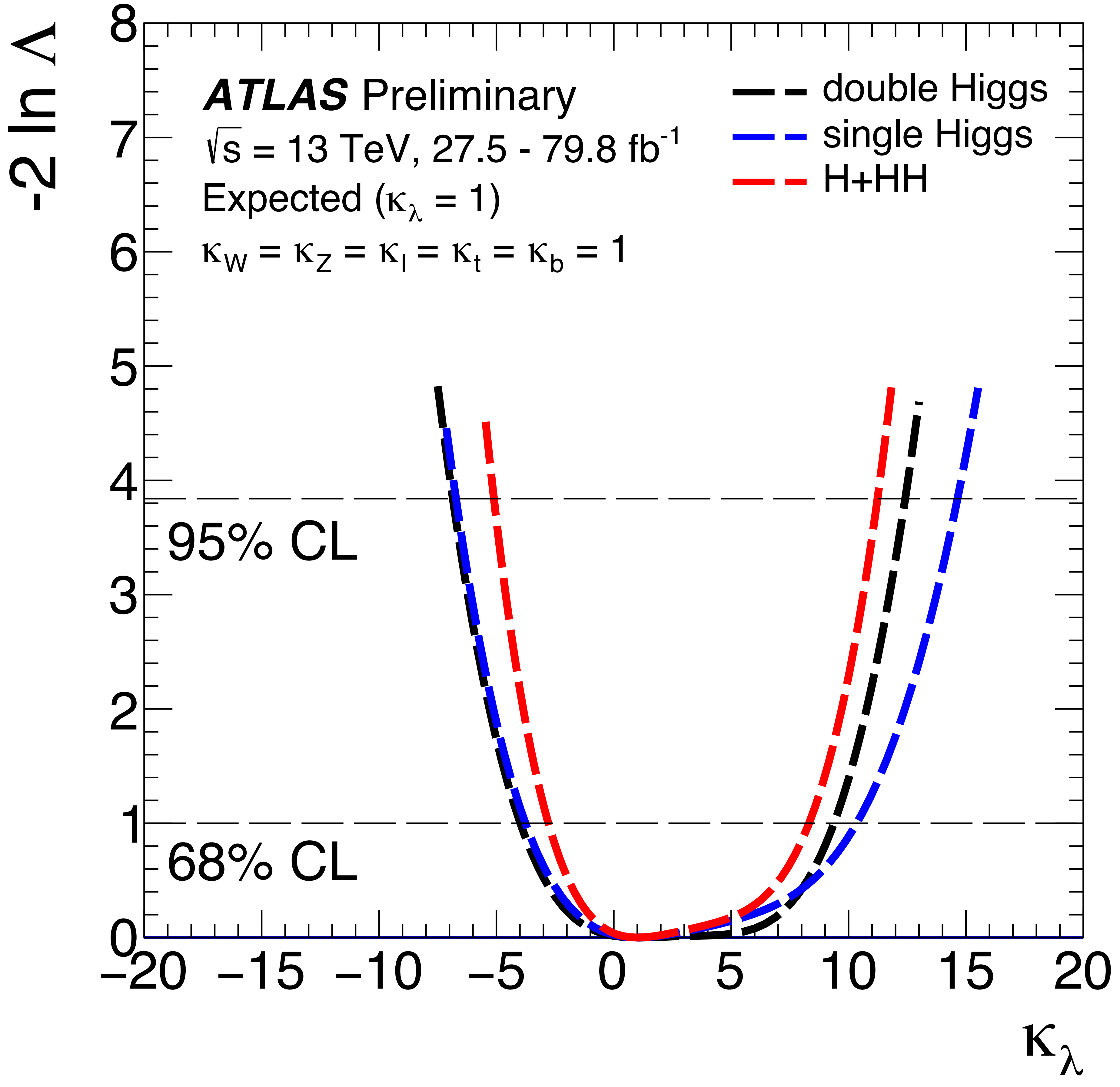


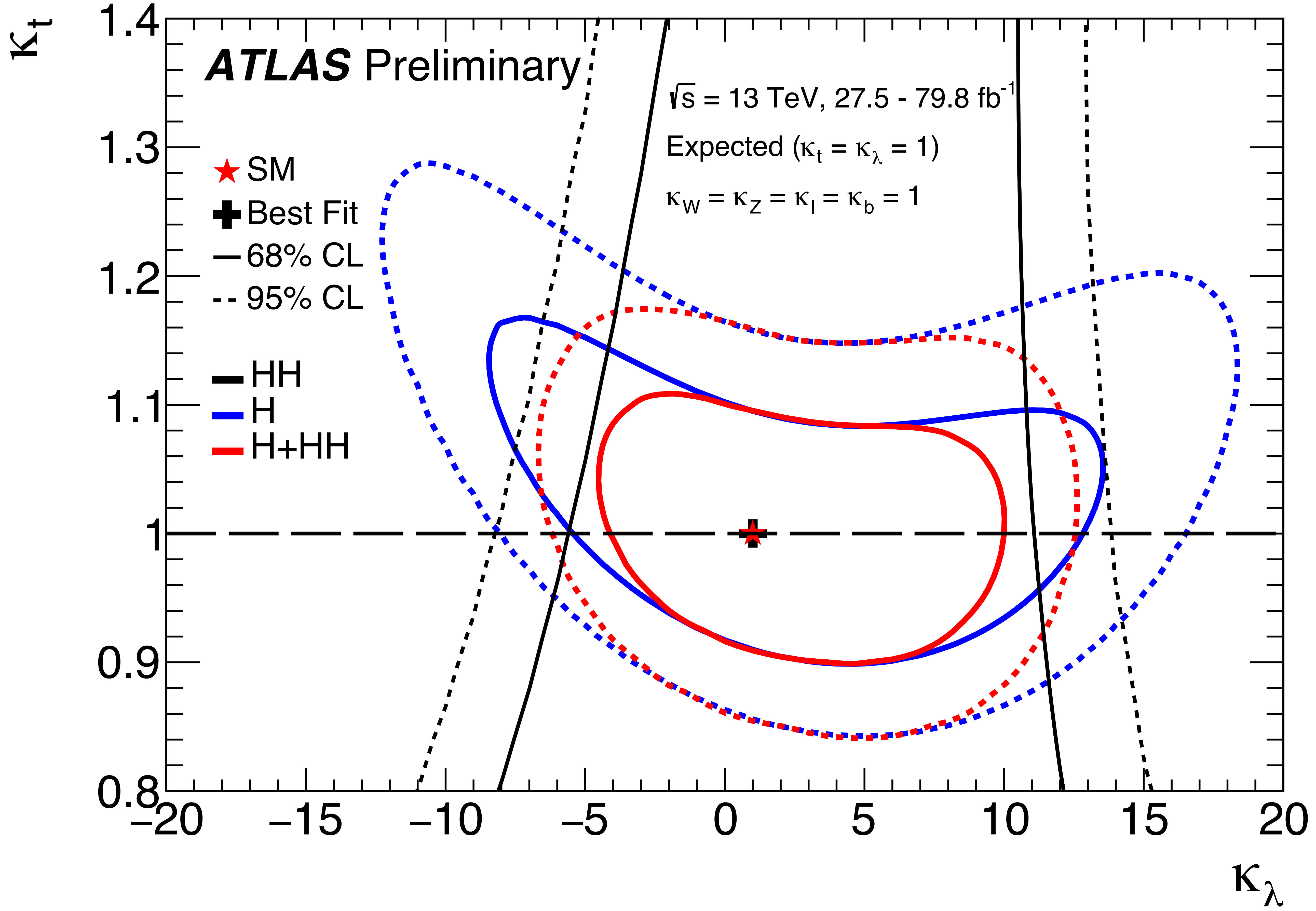
Cross section



Branching fraction

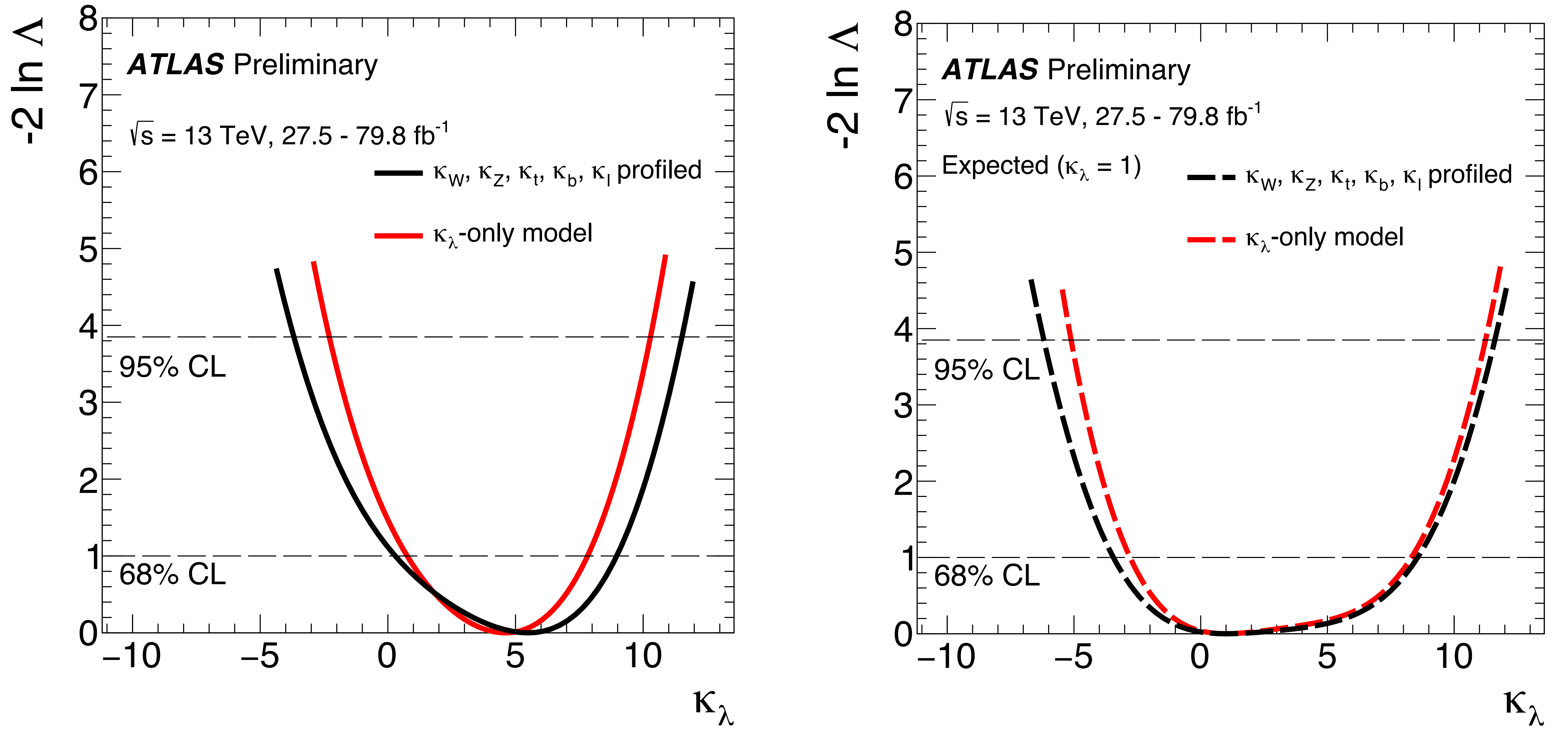
H + HH : expected results





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

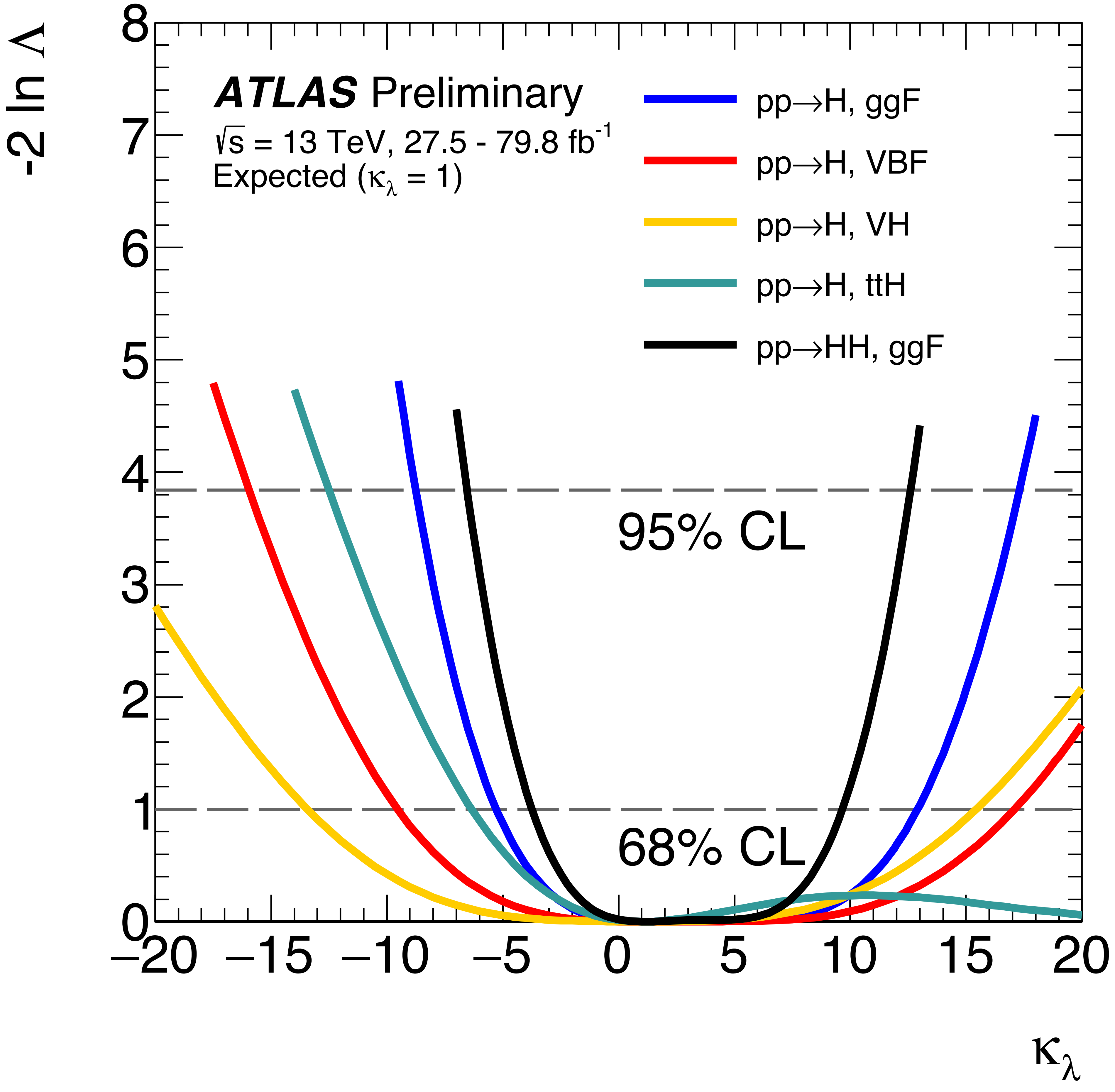
H + HH : fixed vs floating κ

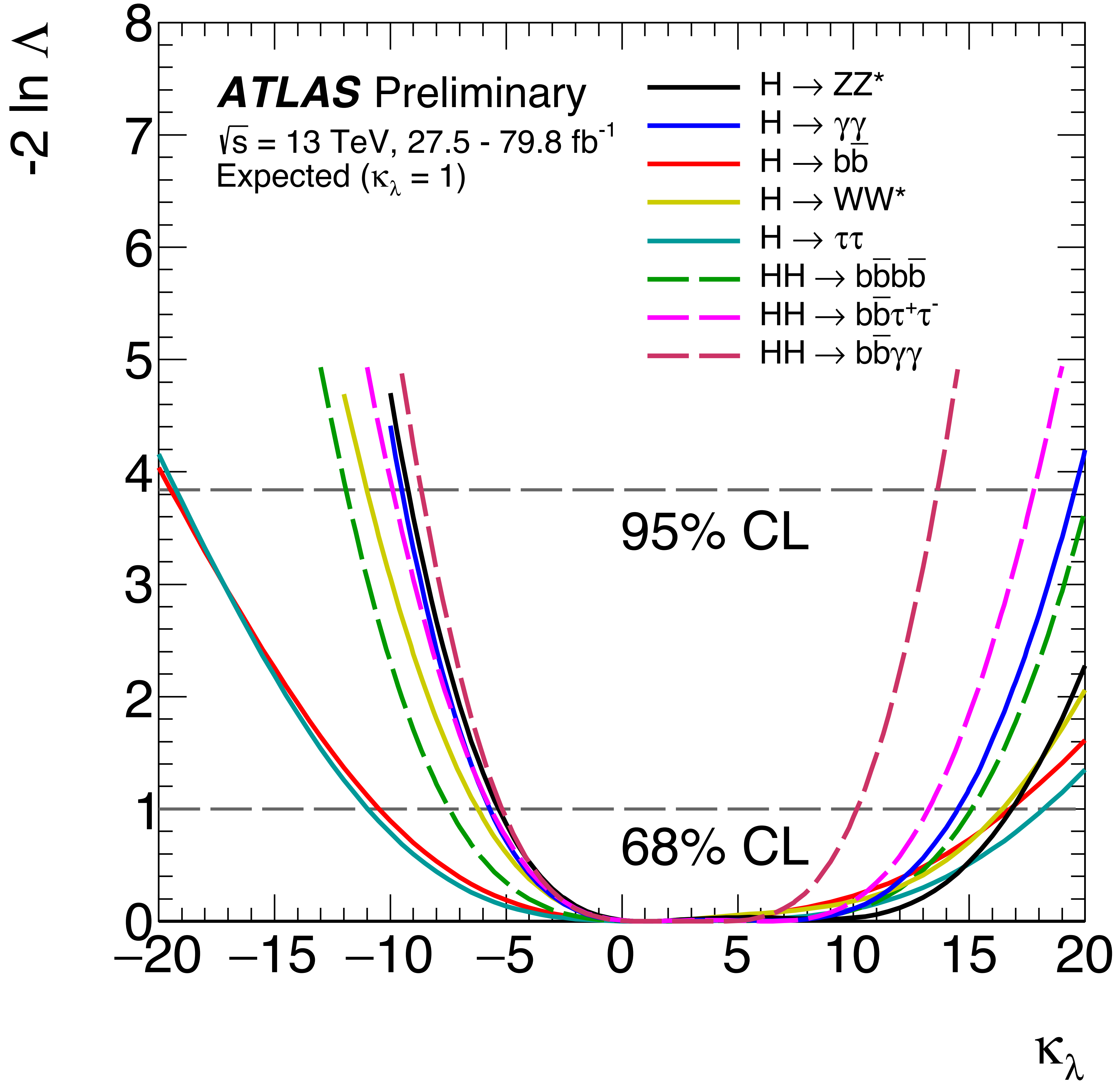


Model	$\kappa_W{}^{+1\sigma}_{-1\sigma}$	$\kappa_Z{}^{+1\sigma}_{-1\sigma}$	$\kappa_t{}^{+1\sigma}_{-1\sigma}$	$\kappa_b{}^{+1\sigma}_{-1\sigma}$	$\kappa_\ell{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
Generic	$1.03^{+0.08}_{-0.08}$	$1.10^{+0.09}_{-0.09}$	$1.00^{+0.12}_{-0.11}$	$1.03^{+0.20}_{-0.18}$	$1.06^{+0.16}_{-0.16}$	$5.5^{+3.5}_{-5.2}$	$[-3.7, 11.5]$	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 κλ 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

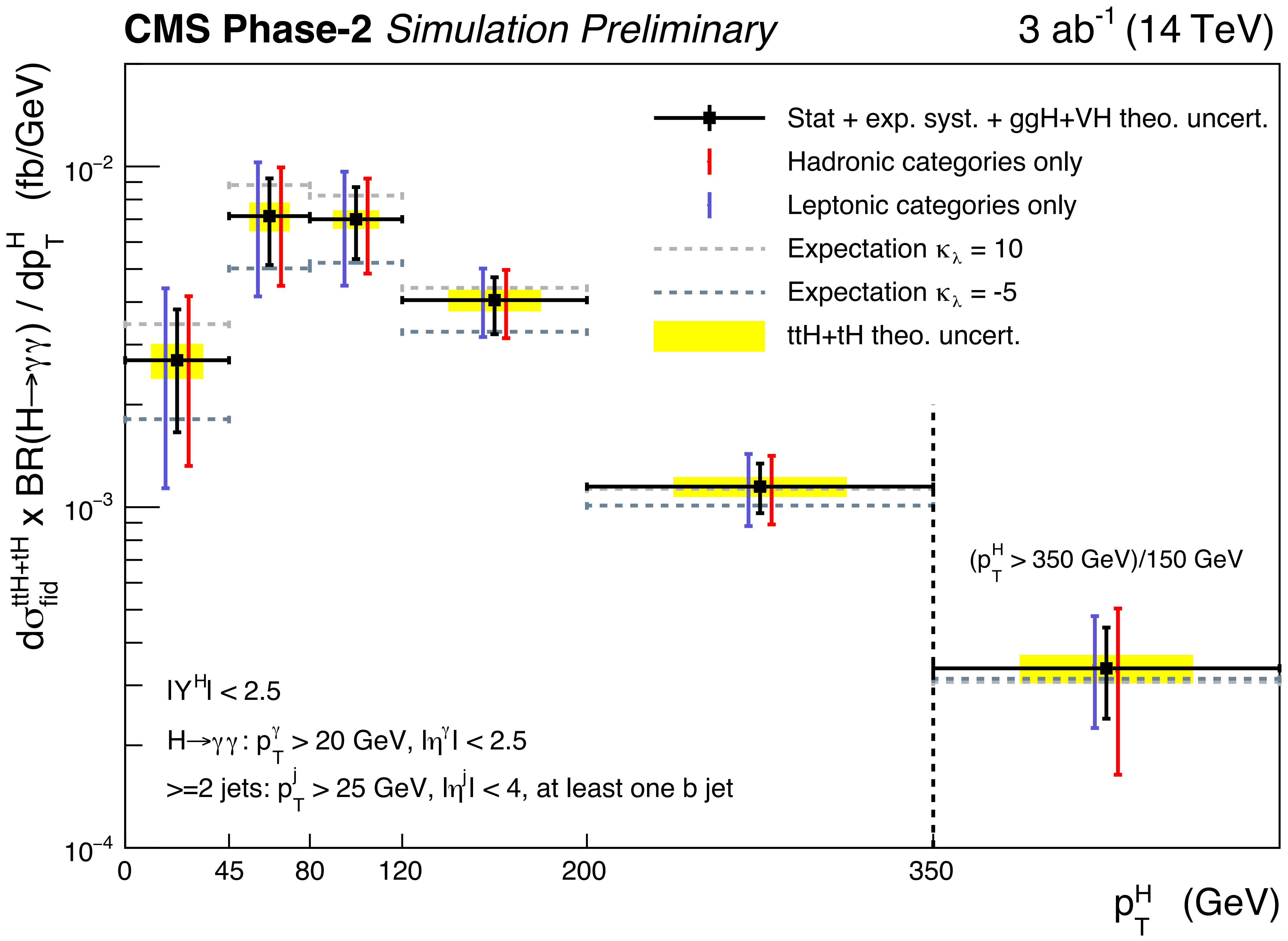
H + HH : input comparison

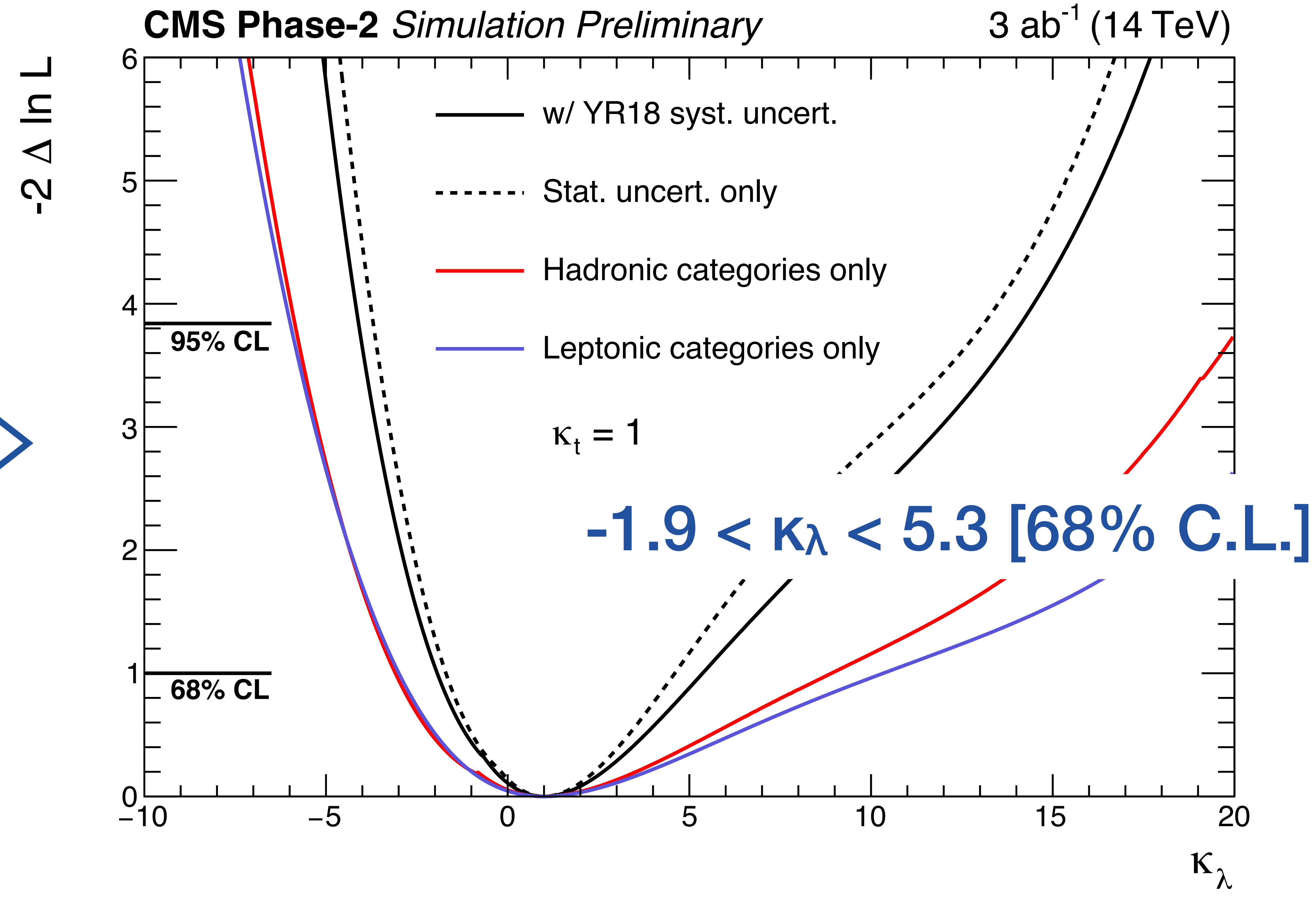




- HH drives the sensitivity
- ggF is the most sensitive single H production mode
  - sensitivity from total cross-section
- ttH not sensitive for $\kappa_\lambda > 0$ because of the degeneracy (second minimum) in the cross-section

Using the differential information in single H



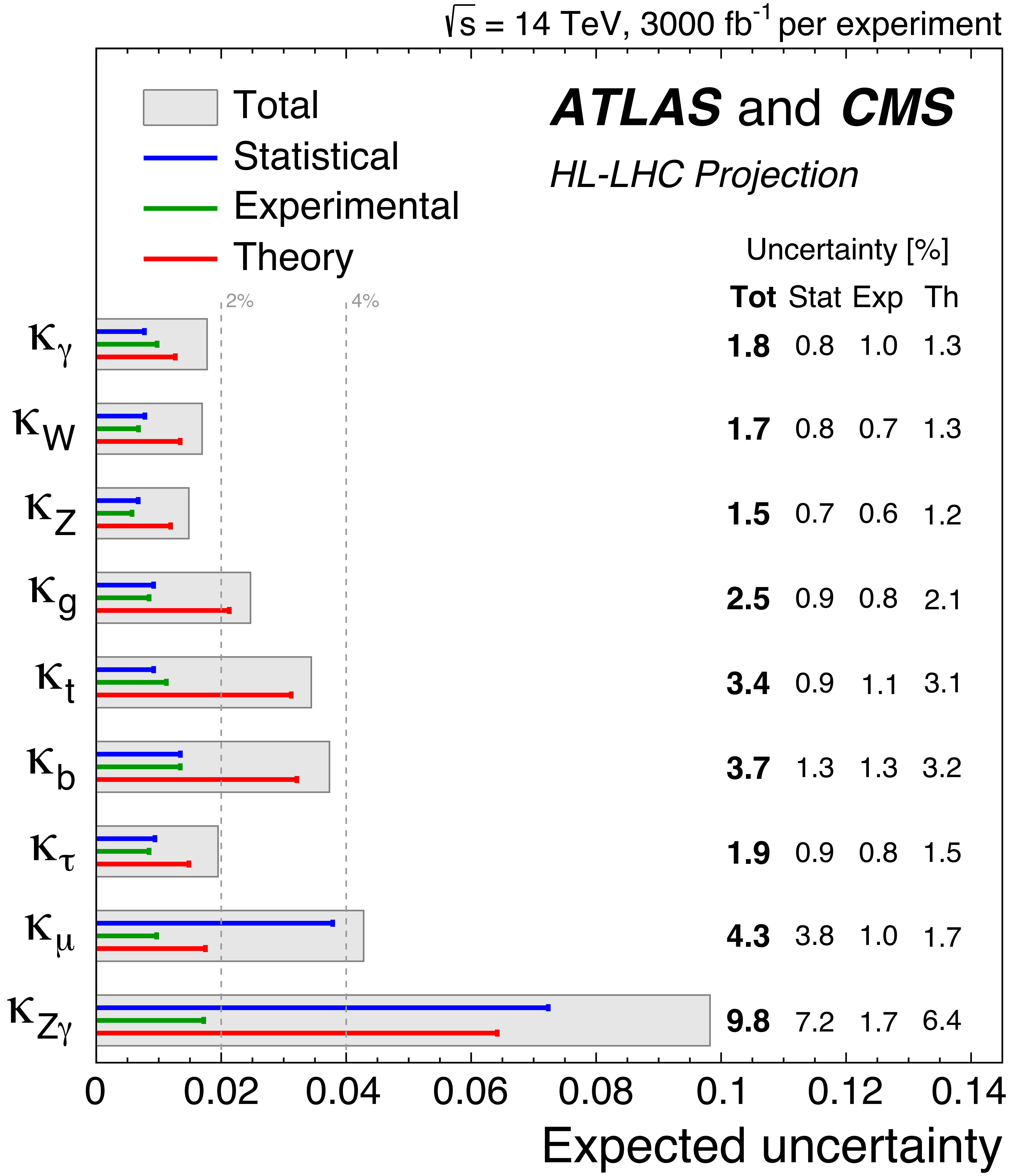


$-1.9 < \kappa_\lambda < 5.3$ [68% C.L.]

- 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

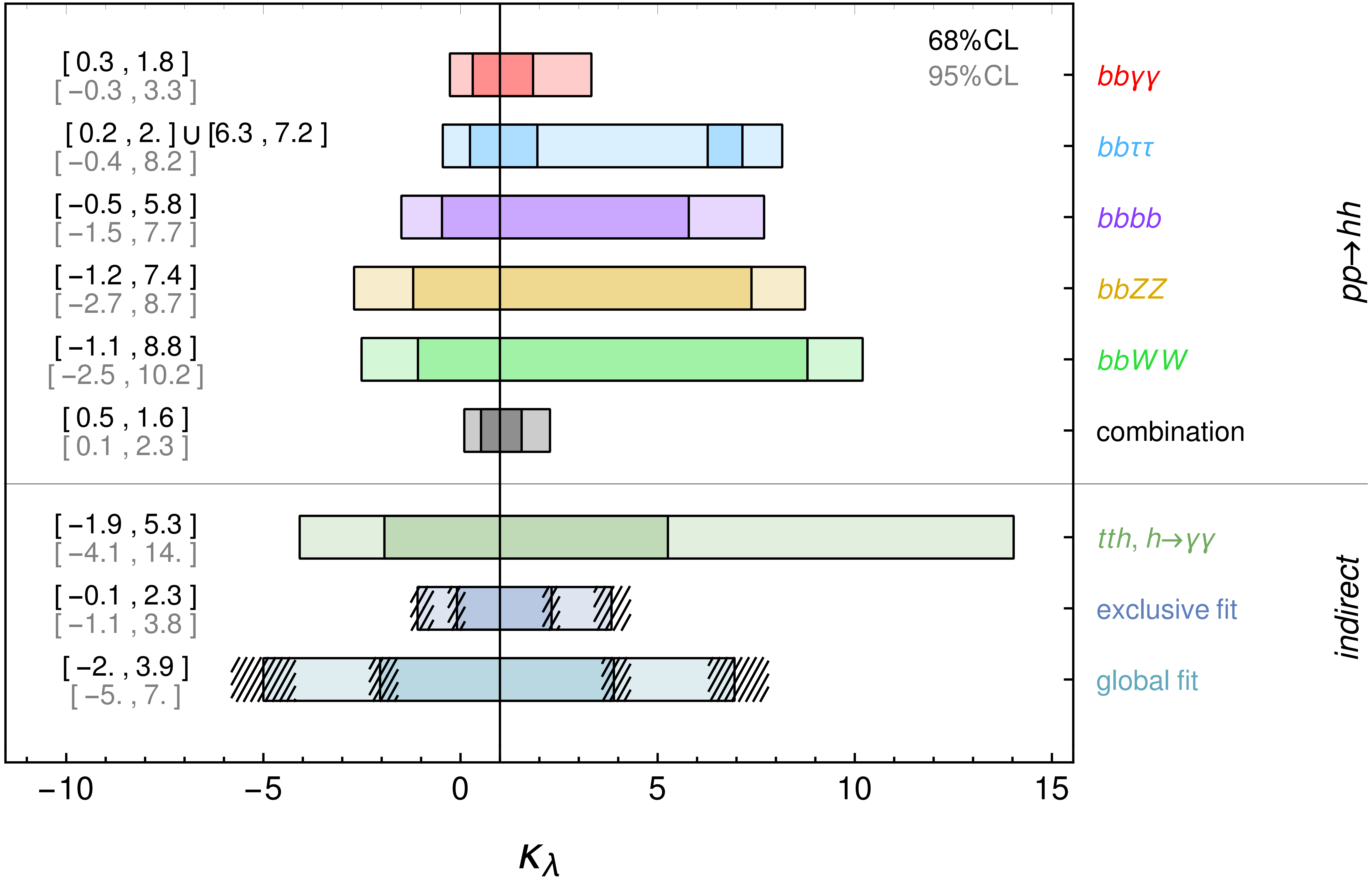
Single H future prospects at the HL-LHC

- 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

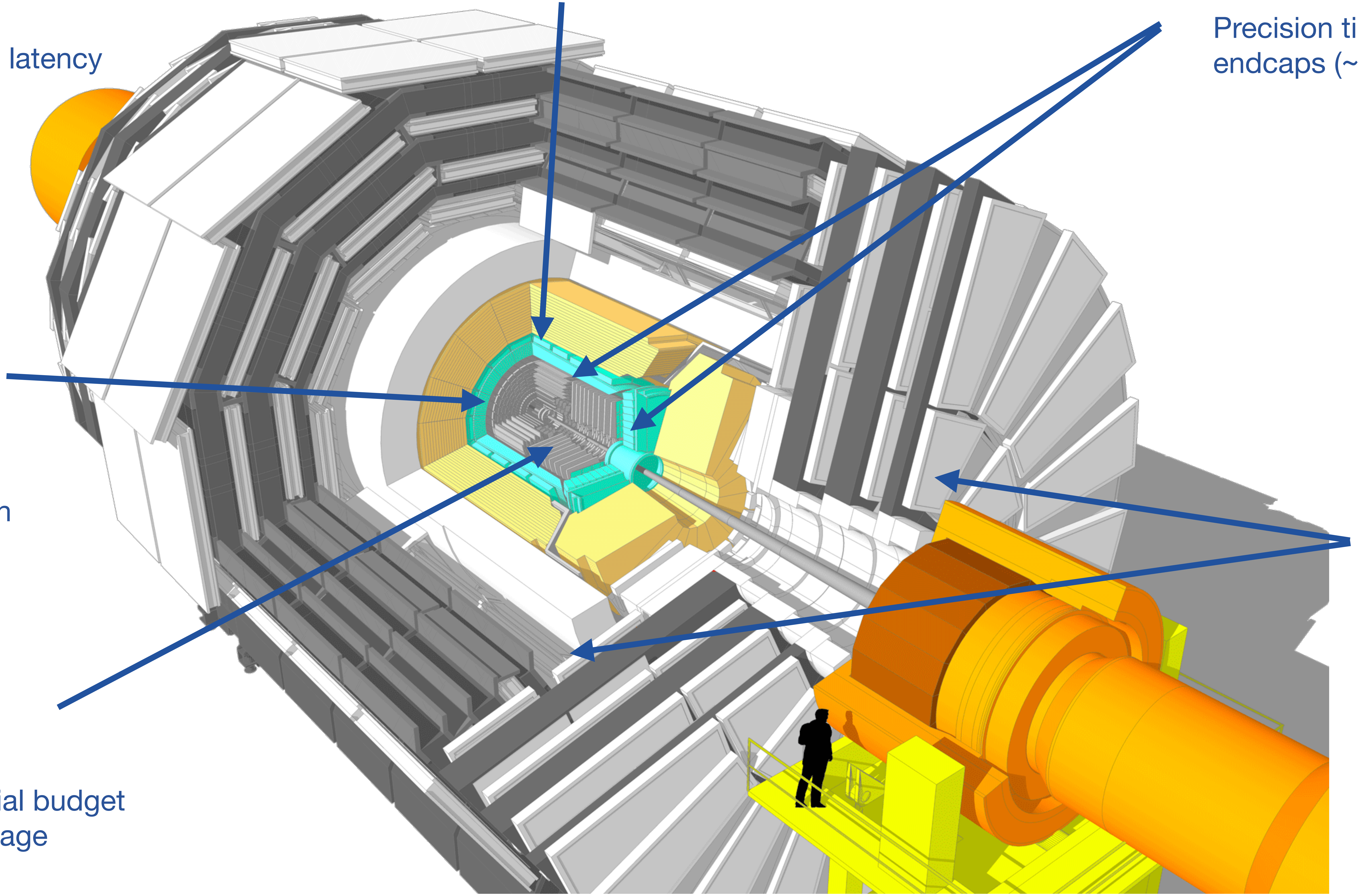


The HL-LHC view of λ_{HHH}

- 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



CMS detector Phase-2 upgrades



Barrel ECAL
Front-end electronics upgrade

Trigger/DAQ
750 kHz @ L1, 12.5 μs latency
7.5 kHZ @ HLT

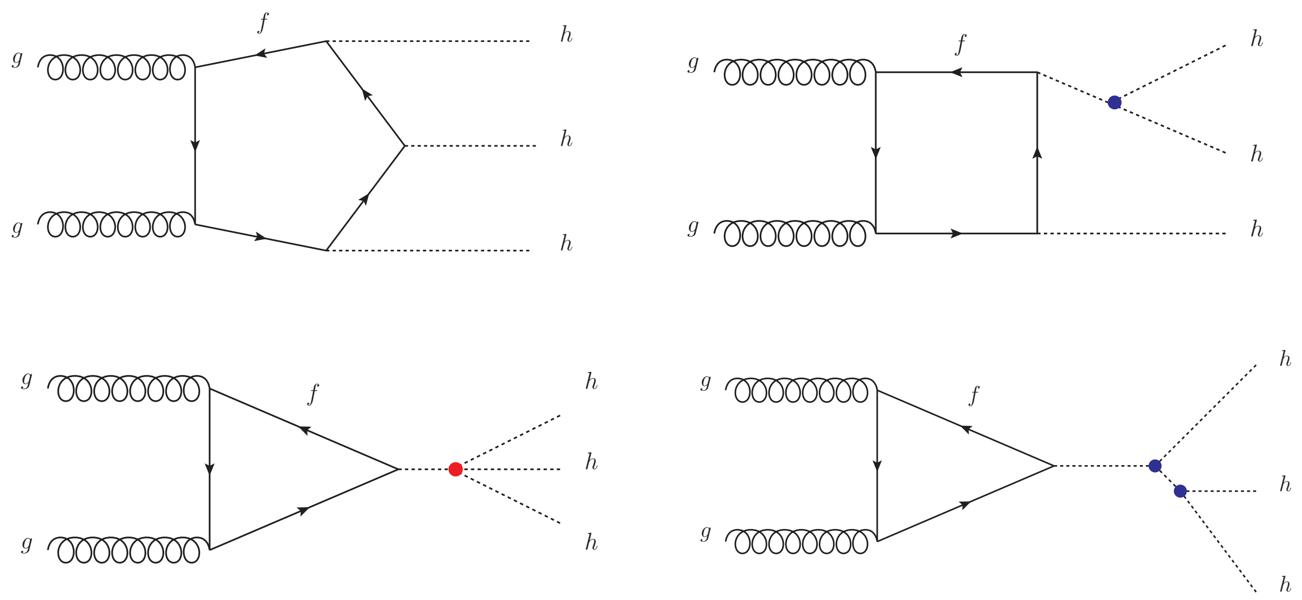
MIP timing detector
Precision timing in the barrel and endcaps (~30 ps resolution)

HGCal: forward calorimeter
High granularity
3D + timing information

Muon detectors
Barrel DT and endcaps CSC electronics upgrade
New forward detectors

Tracker
High granularity
Reduced material budget
Extended coverage

How about HHH?

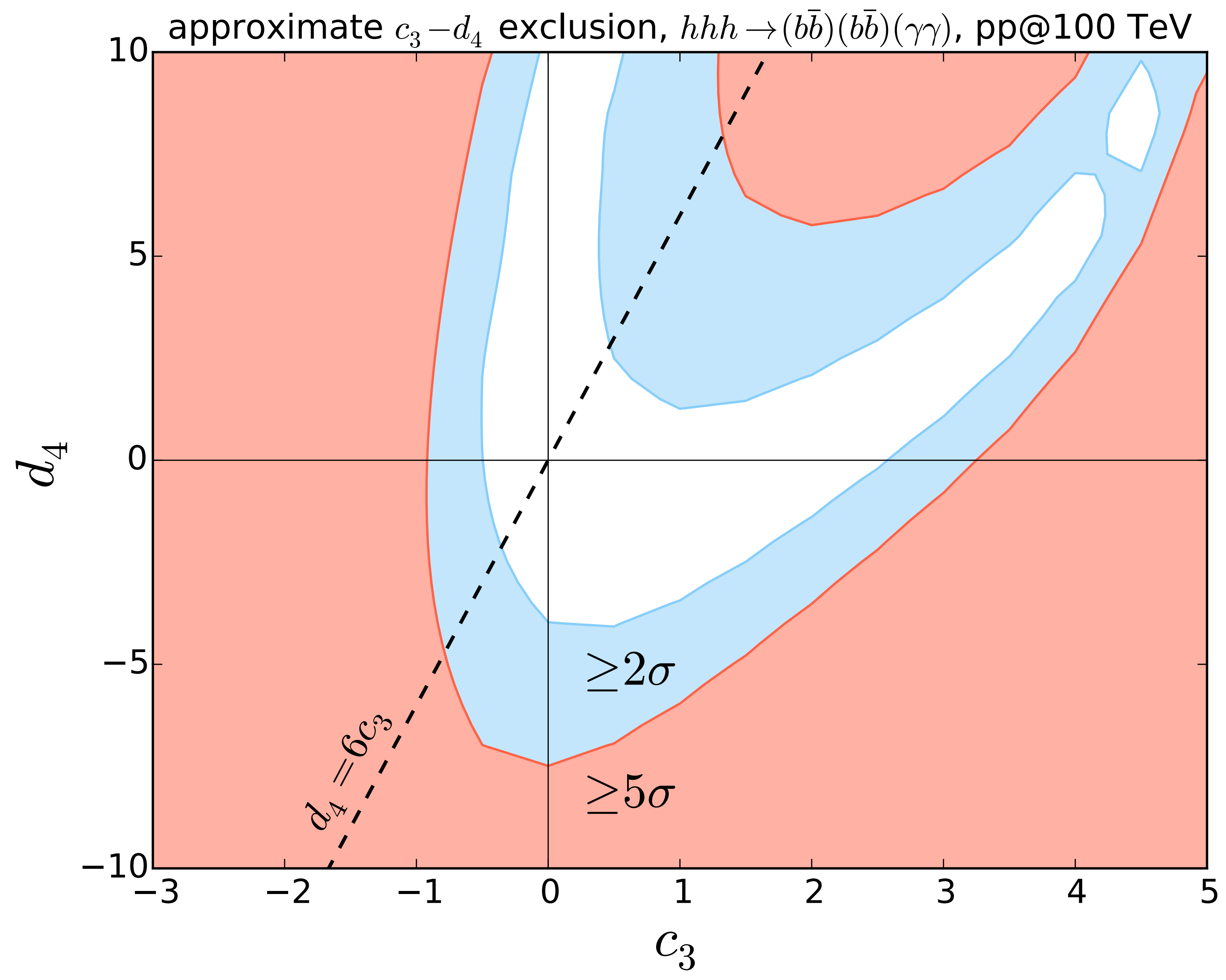


Depends also on trilinear coupling

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
  - □ √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 |η| ≈ 3.5
- Sensitivity: at FCC, O(100%) precision on σ$_{HHH}$, λ$_{HHHH}$ ∈ [-4, +16]



(a)