Exploring the Higgs boson self-coupling at the LHC

UF UNIVERSITY of FLORIDA

LPC Distinguished researcher
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Fermilab

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Imperial College HEP seminar
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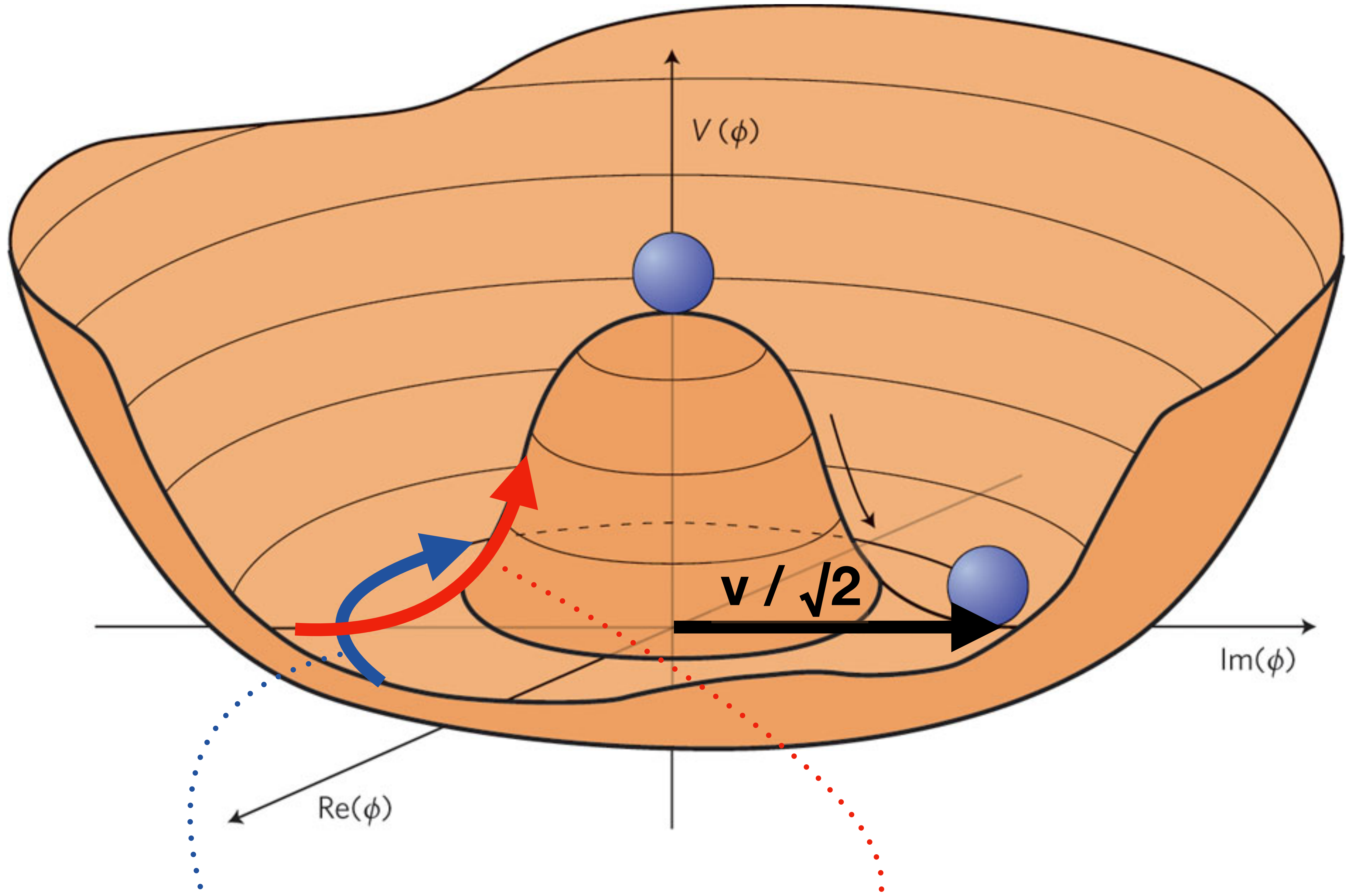
The scalar sector of the standard model

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



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

Quantum of the field
⟹ **Higgs boson**

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

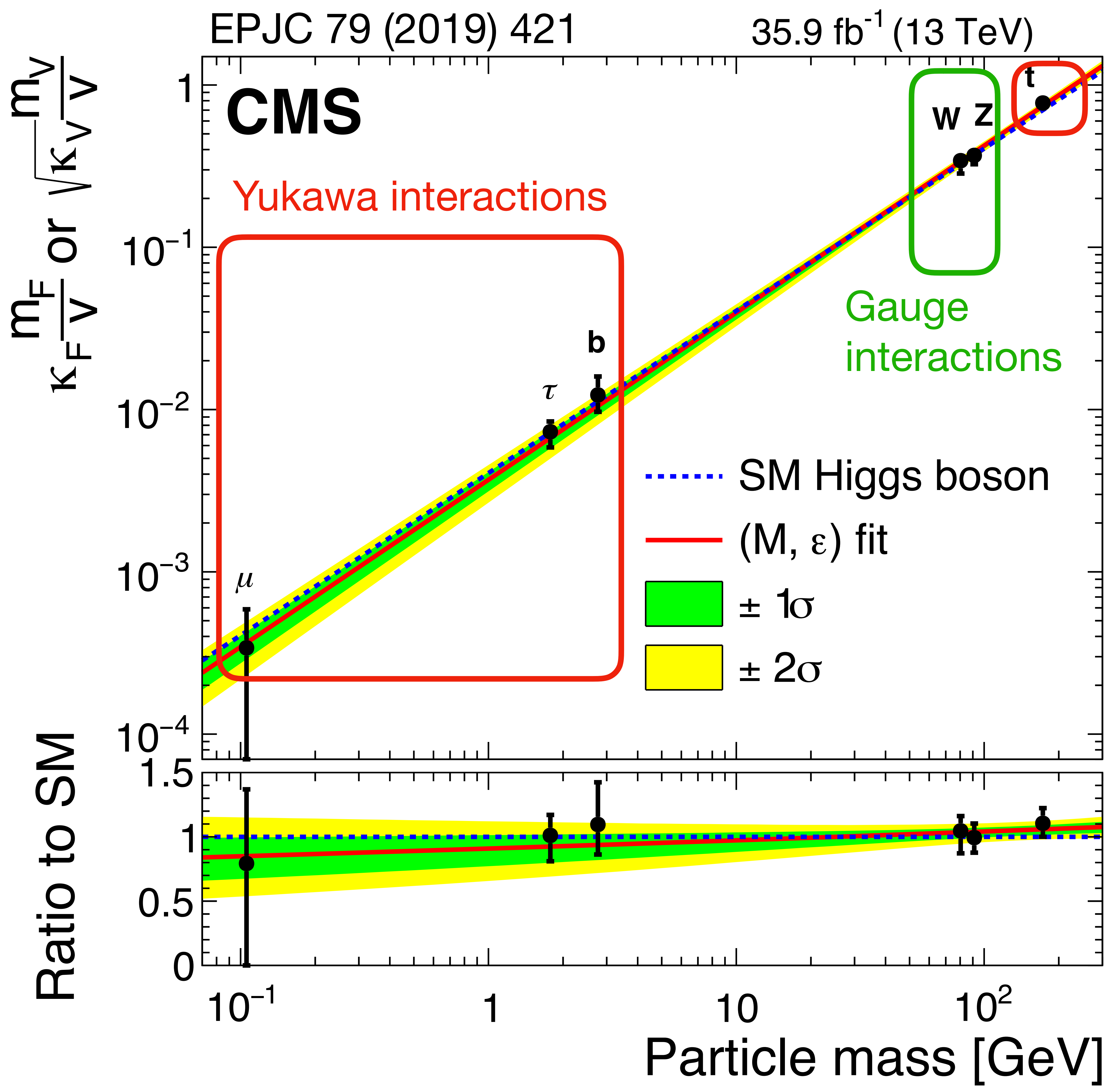
Two main sectors of the SM:

- **Gauge sector:** electroweak and strong interactions explained with local gauge symmetries
- **Scalar sector:** complex scalar doublet of fields and potential with VEV ≠ 0
  - spontaneous electroweak symmetry breaking (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 ± 0.24 GeV
- Precise study of its interactions with fermions and vector bosons…



… and its self-coupling

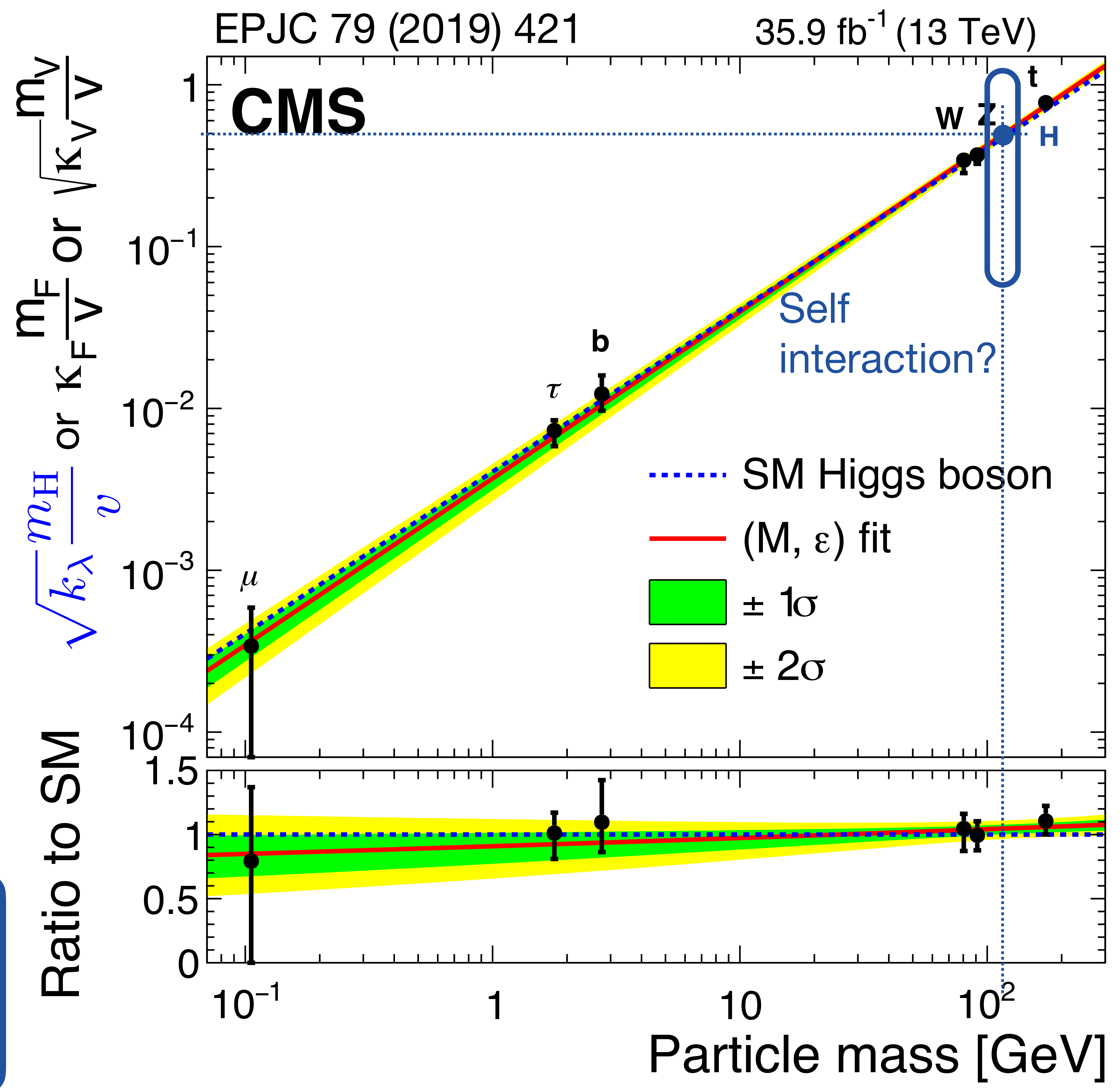
- Observed by ATLAS and CMS in 2012
- Mass precisely determined:
  m_H = 125.09 ± 0.24 GeV
- Precise study of its interactions with fermions and vector bosons…
- … but self-interactions not measured experimentally!

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

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

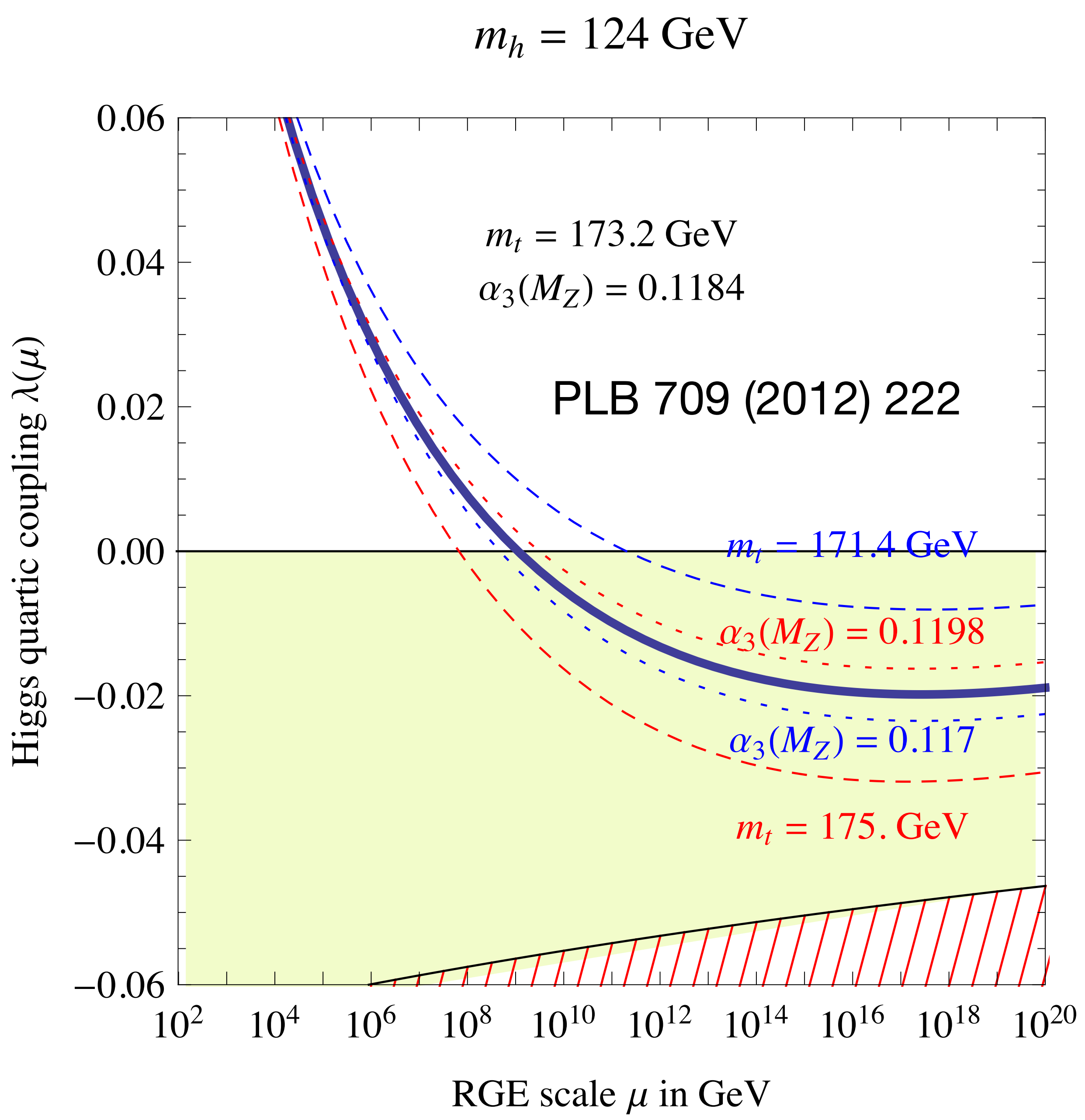
λ_{HHH} : direct access to the shape of the scalar potential

Direct test of the EW symmetry breaking



Why is it important?

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



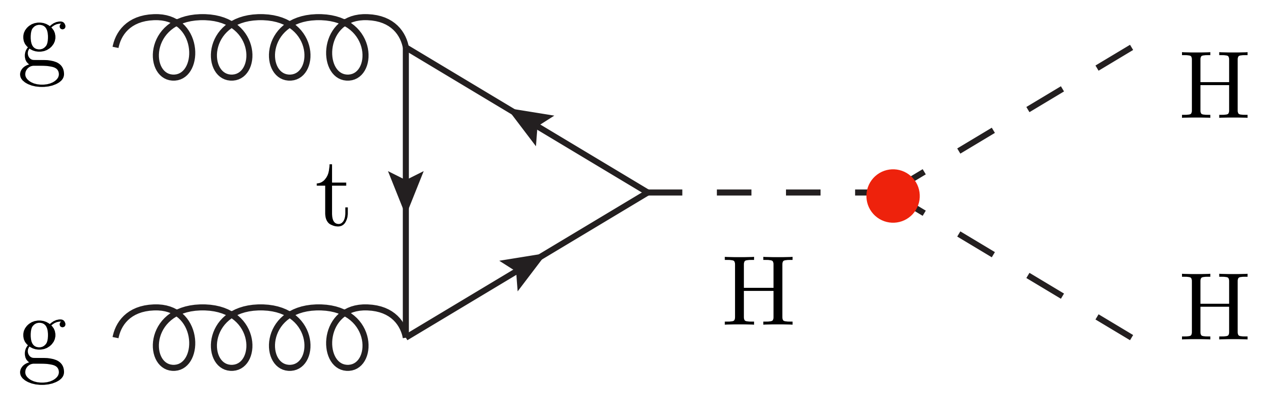
PLB 709 (2012) 222

- 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?

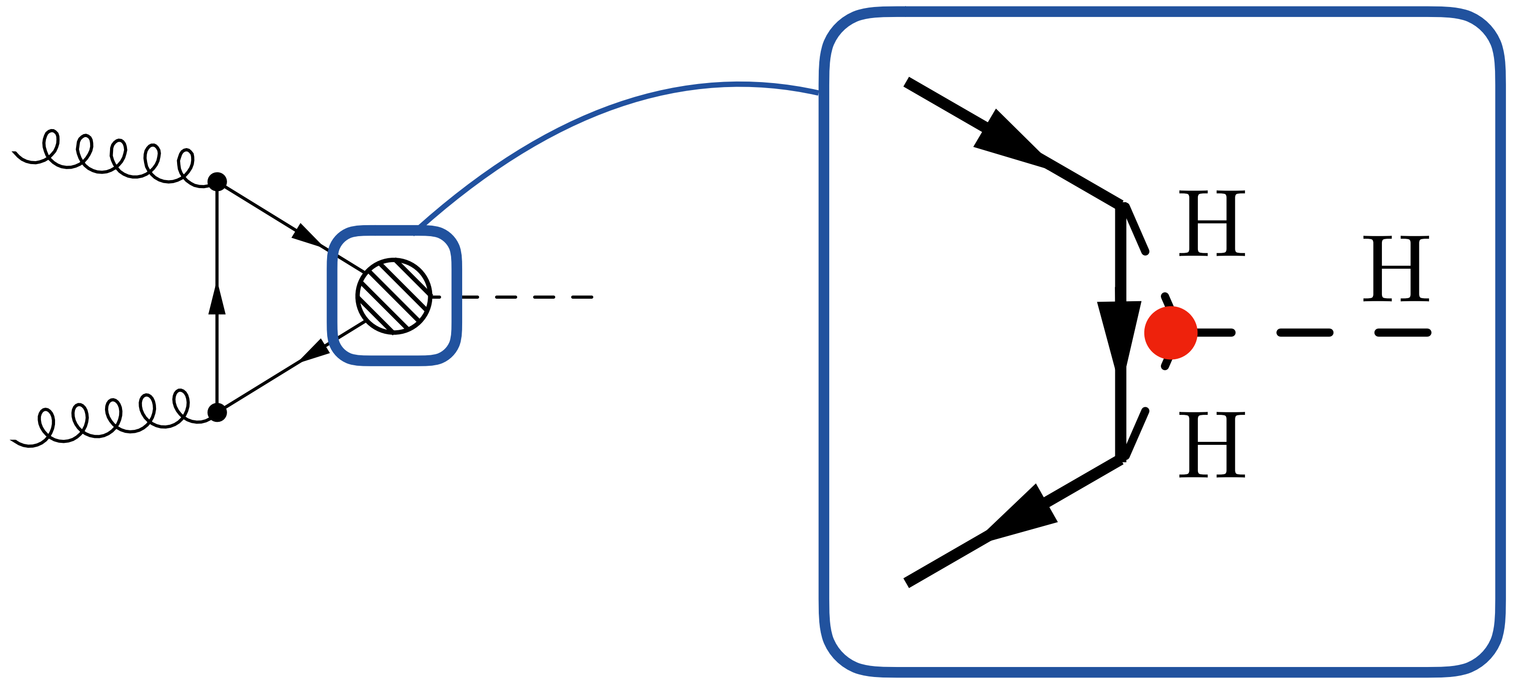
Two complementary strategies exist:

Direct measurements in HH



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

Indirect measurements in single H

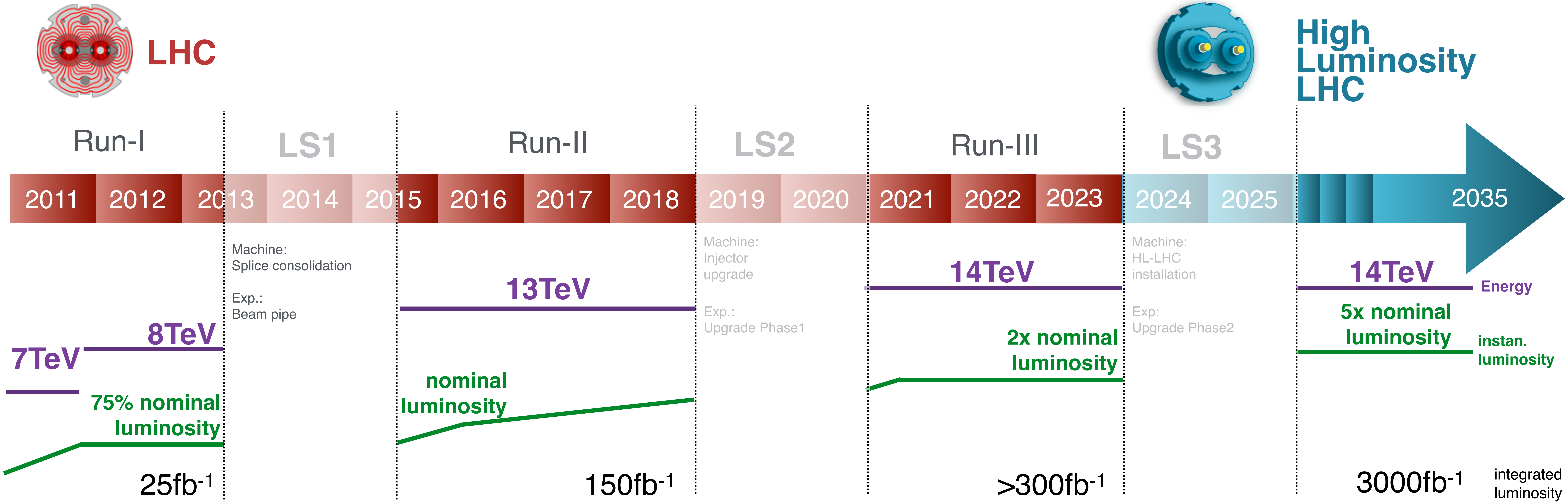


- Extract the value of λ_{HHH} from precision single H cross section measurements
  - indirect measurement: stronger theory assumptions needed to disentangle NLO λ_{HHH} effects from other couplings / new physics
  - benefit of the large single H cross section (~ 1000 × σ_{HH})

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 $\mathcal{L} = 10^{34}$ cm^{-2} s^{-1}
- Design instantaneous luminosity exceeded throughout the Run 2 operations at $\sqrt{s}$ = 13 TeV!



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 2035

7TeV **8TeV**

75% nominal luminosity

25fb^{-1}

Machine:
Splice consolidation

Exp.:
Beam pipe

13TeV

nominal luminosity

150fb^{-1}

Machine:
Injector
upgrade

Exp.:
Upgrade Phase1

14TeV

2x nominal luminosity

$>300\text{fb}^{-1}$

Machine:
HL-LHC
installation

Exp:
Upgrade Phase2

14TeV

5x nominal luminosity

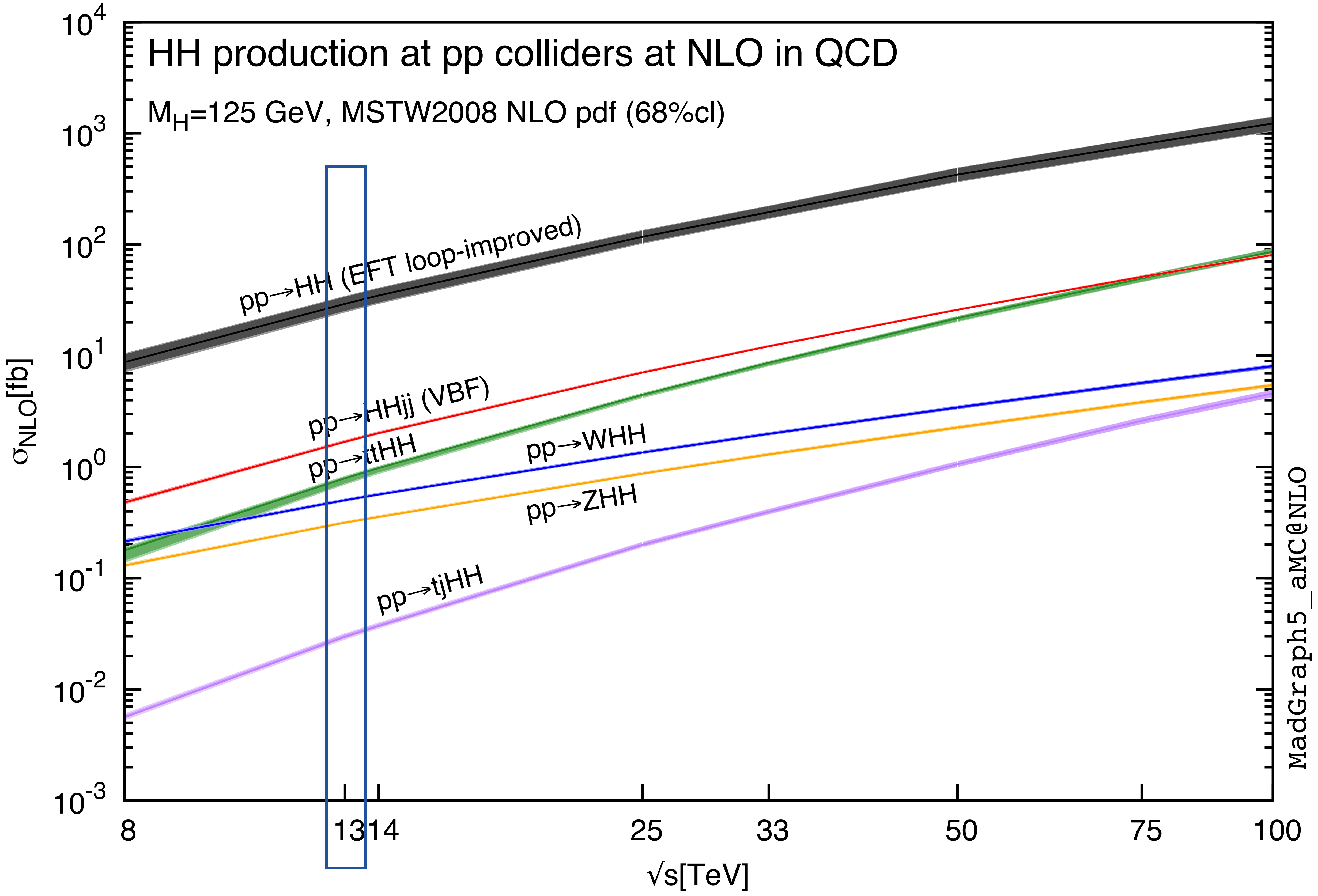
3000fb^{-1}

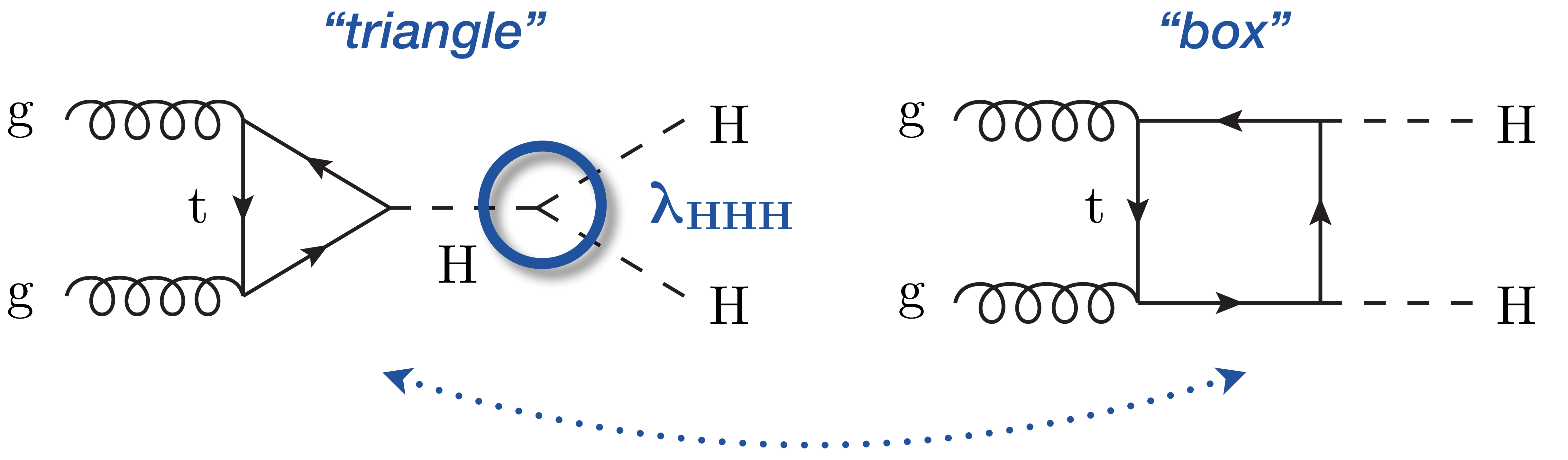
Energy

instan. luminosity

integrated
luminosity

HH production at the LHC





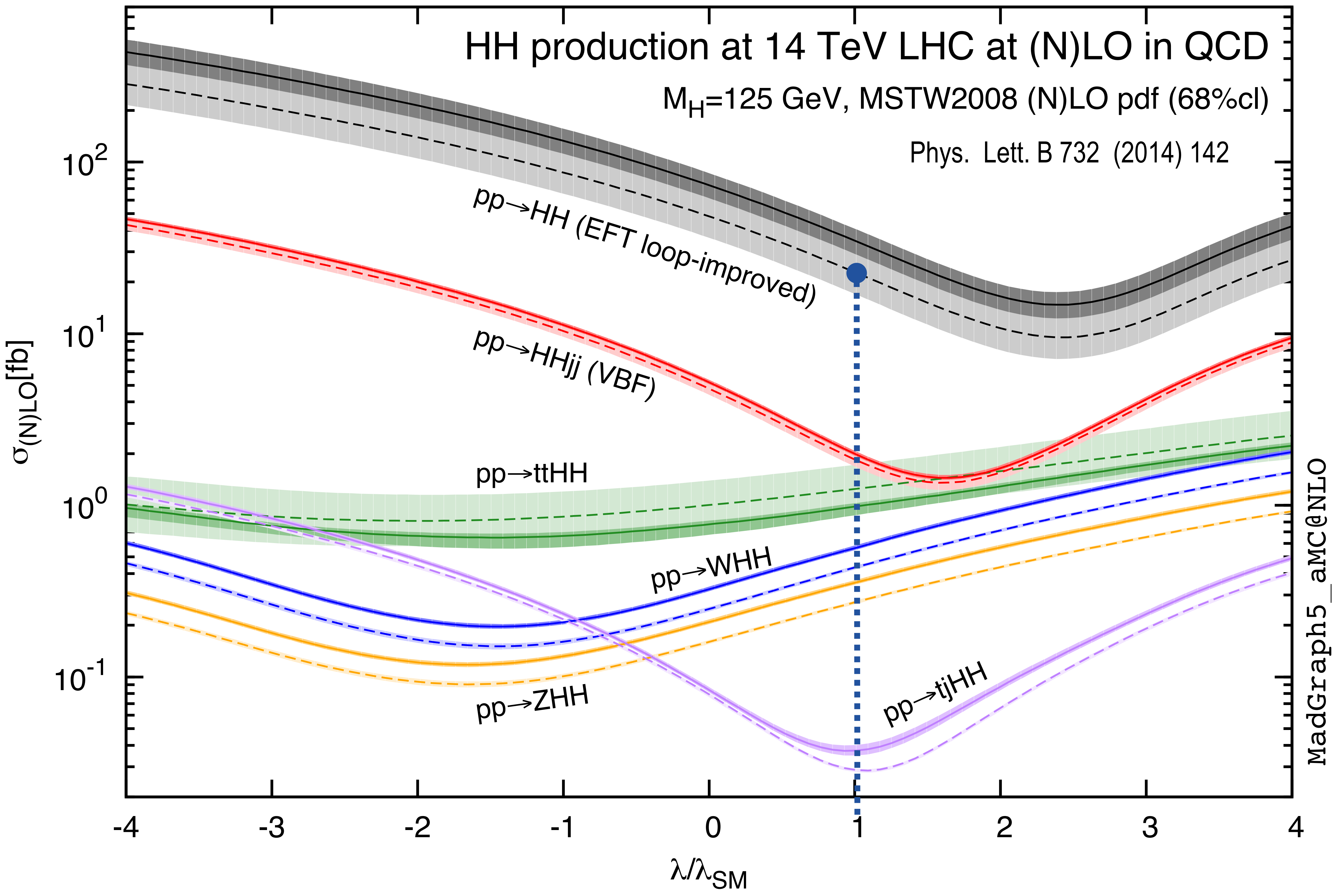
Strong destructive interference

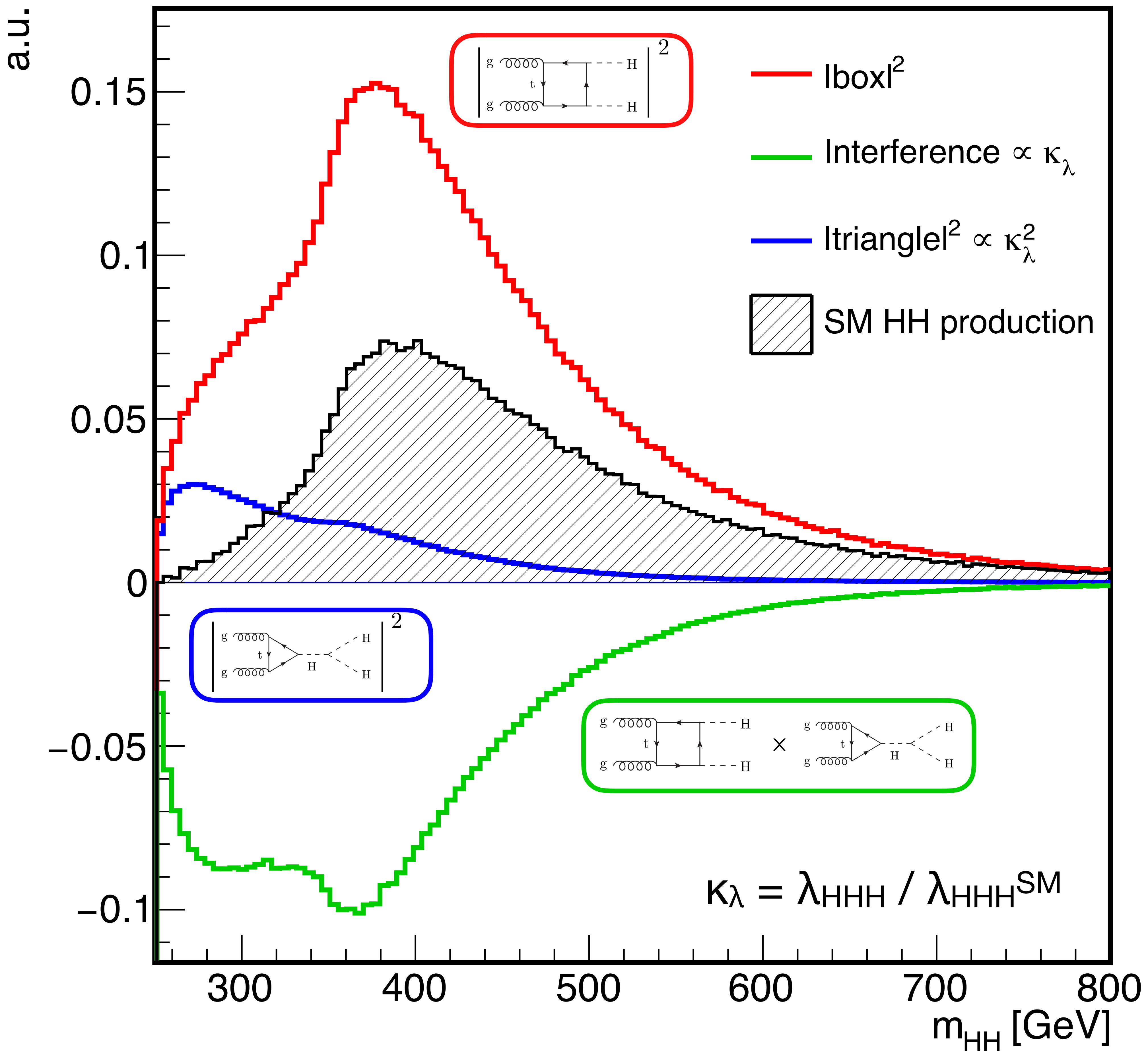
$$\boxed{\sigma^{SM}_{HH} = 31.05^{+4.5\%}_{-6.4\%}\ \text{fb}\ (\text{scale} \oplus \text{PDF} \oplus \alpha_S \oplus m_t)}$$

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!

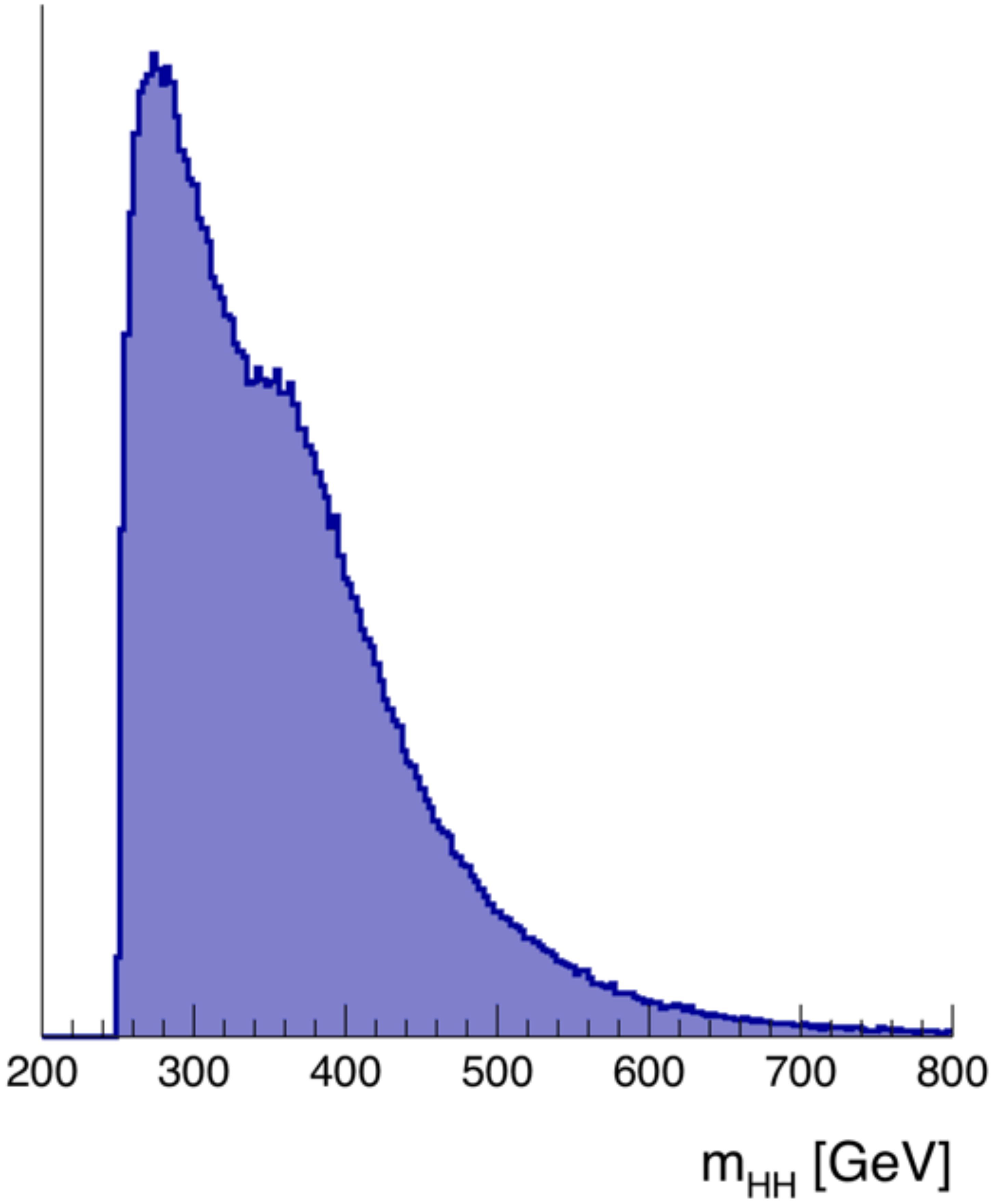
Extracting λ_{HHH} from HH measurements

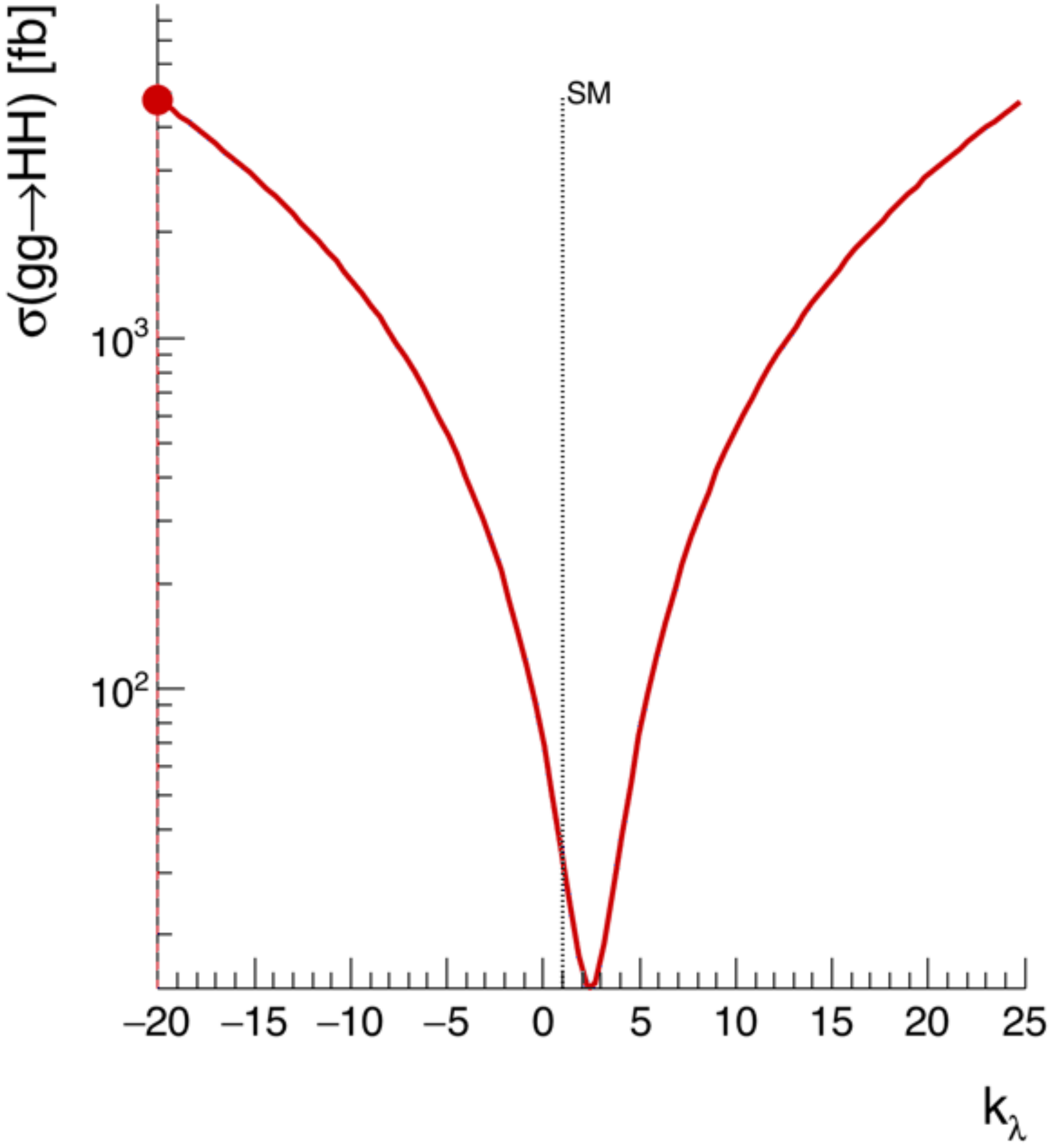




- Information on λ_{HHH} is obtained from both the total and the differential production cross section

Illustration of shape effects





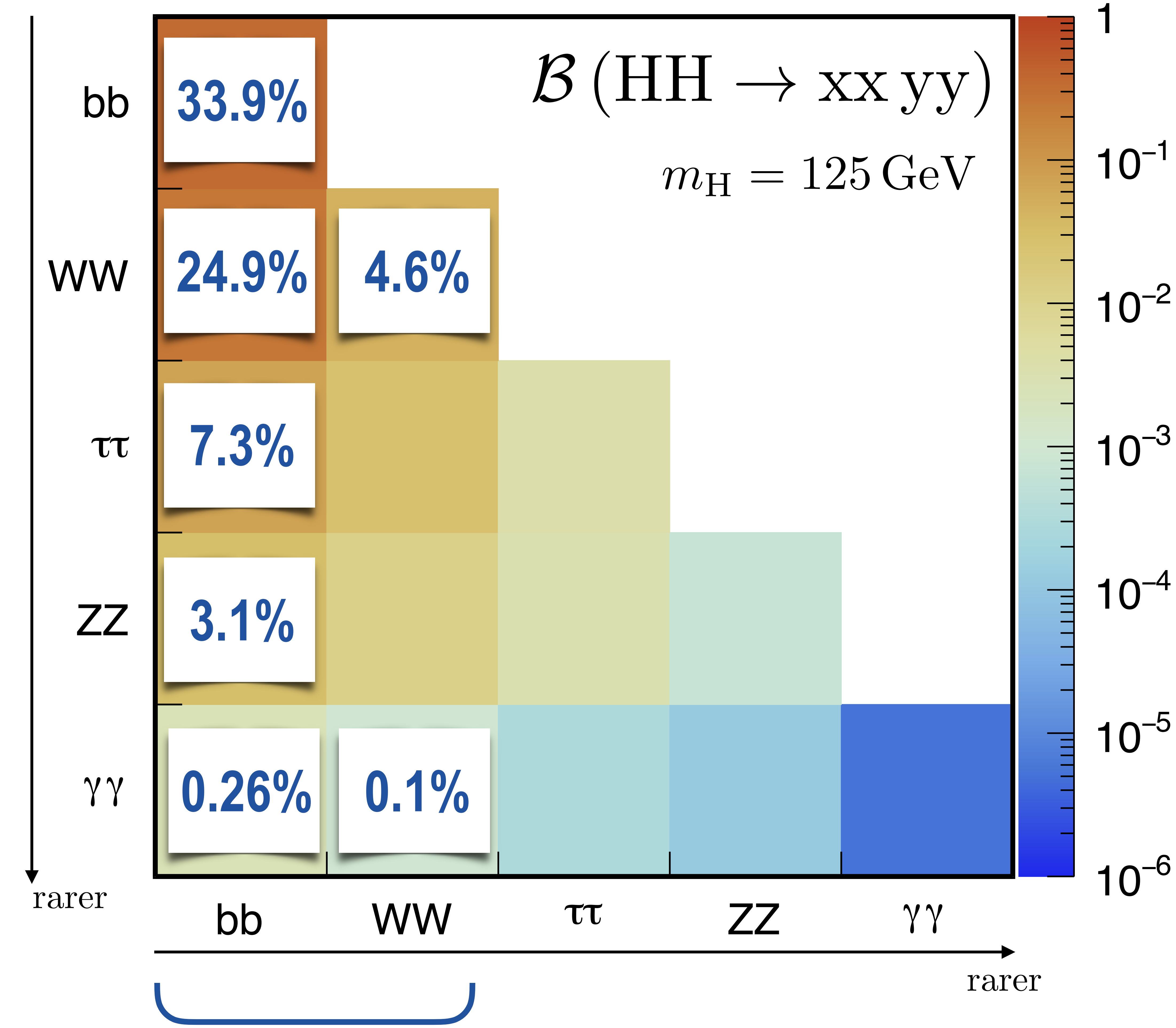
Interference effects have important consequences for the sensitivity of the searches

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

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



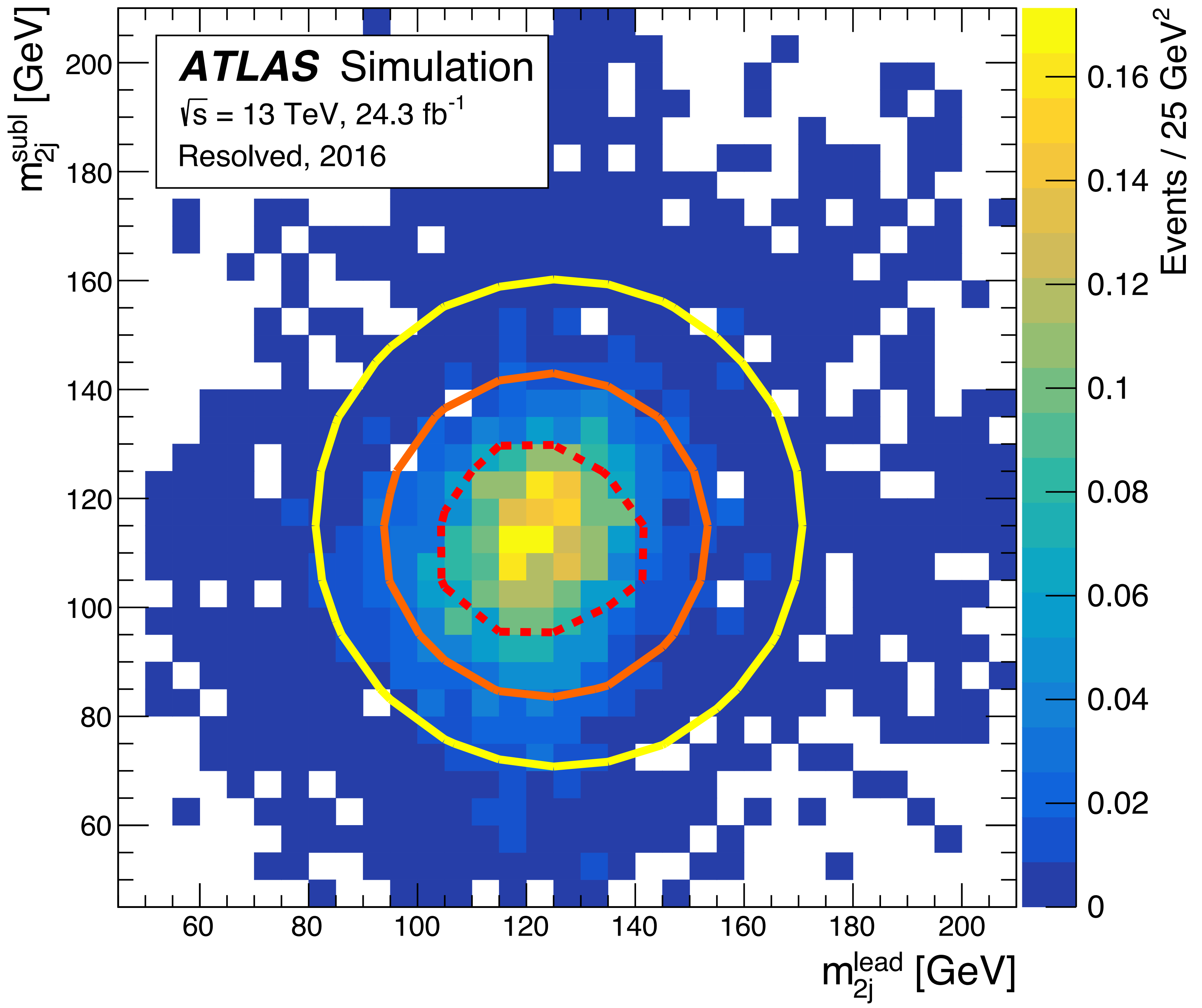
Trade-off between $\mathcal{B}$ and purity

Keep $\mathcal{B}$ high enough

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

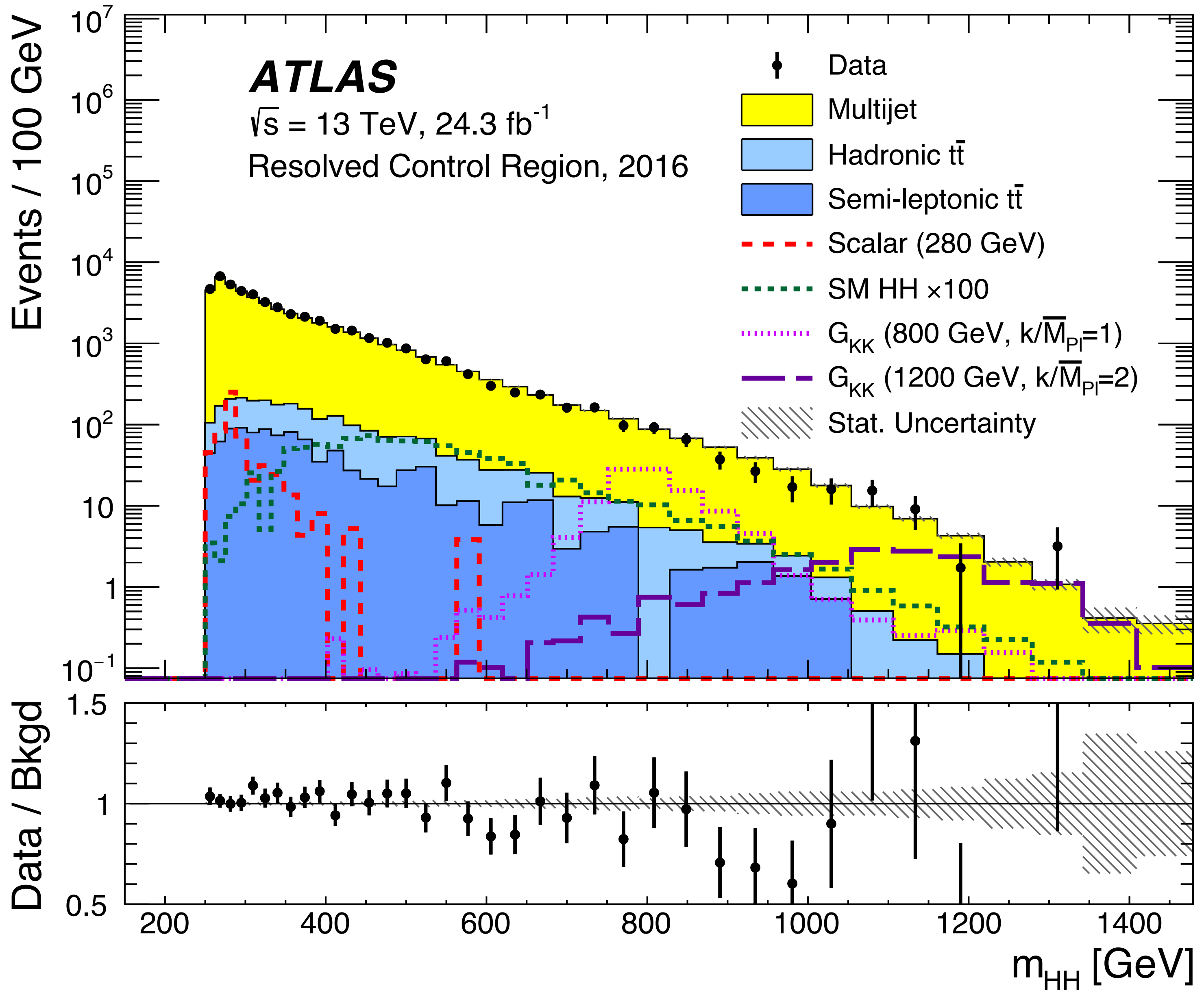
Event selection

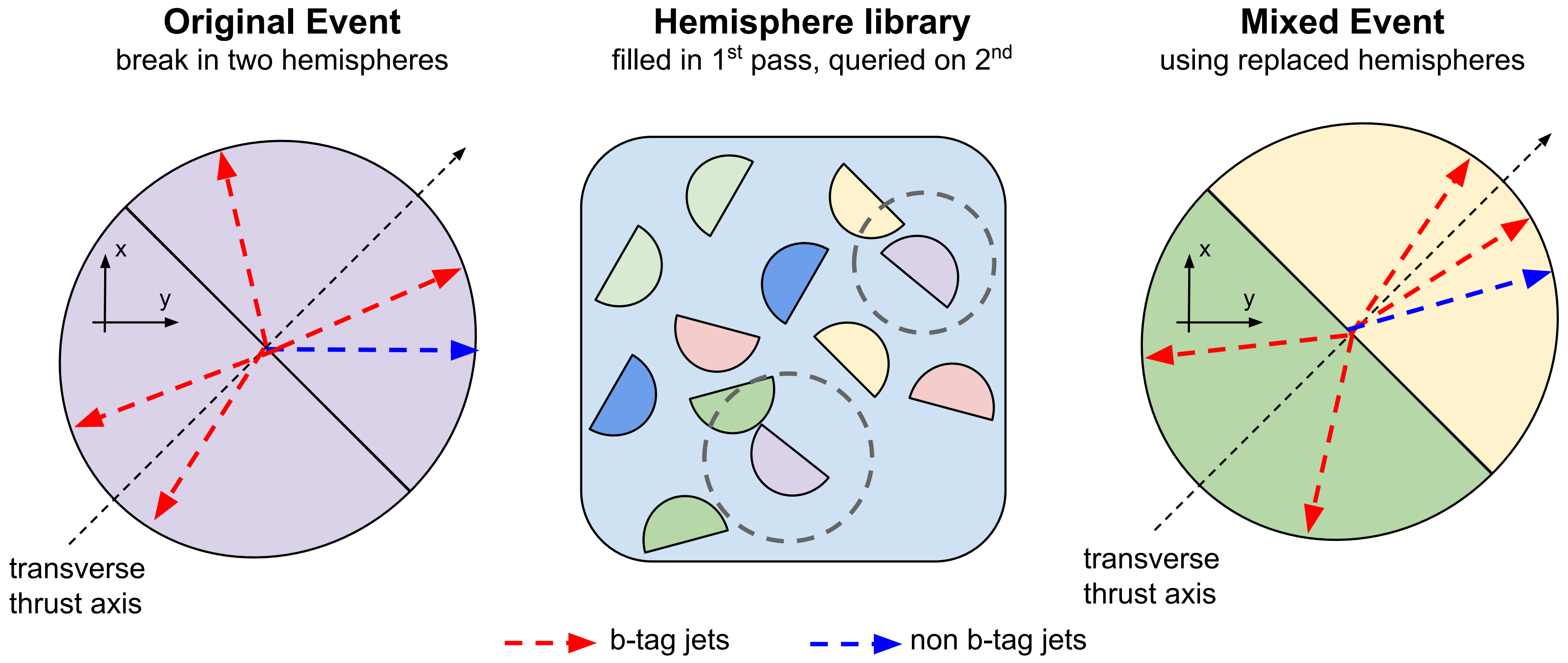
- Four b jets: crucially relies on tagging performance since trigger
- Use H→bb signature to reject the backgrounds



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

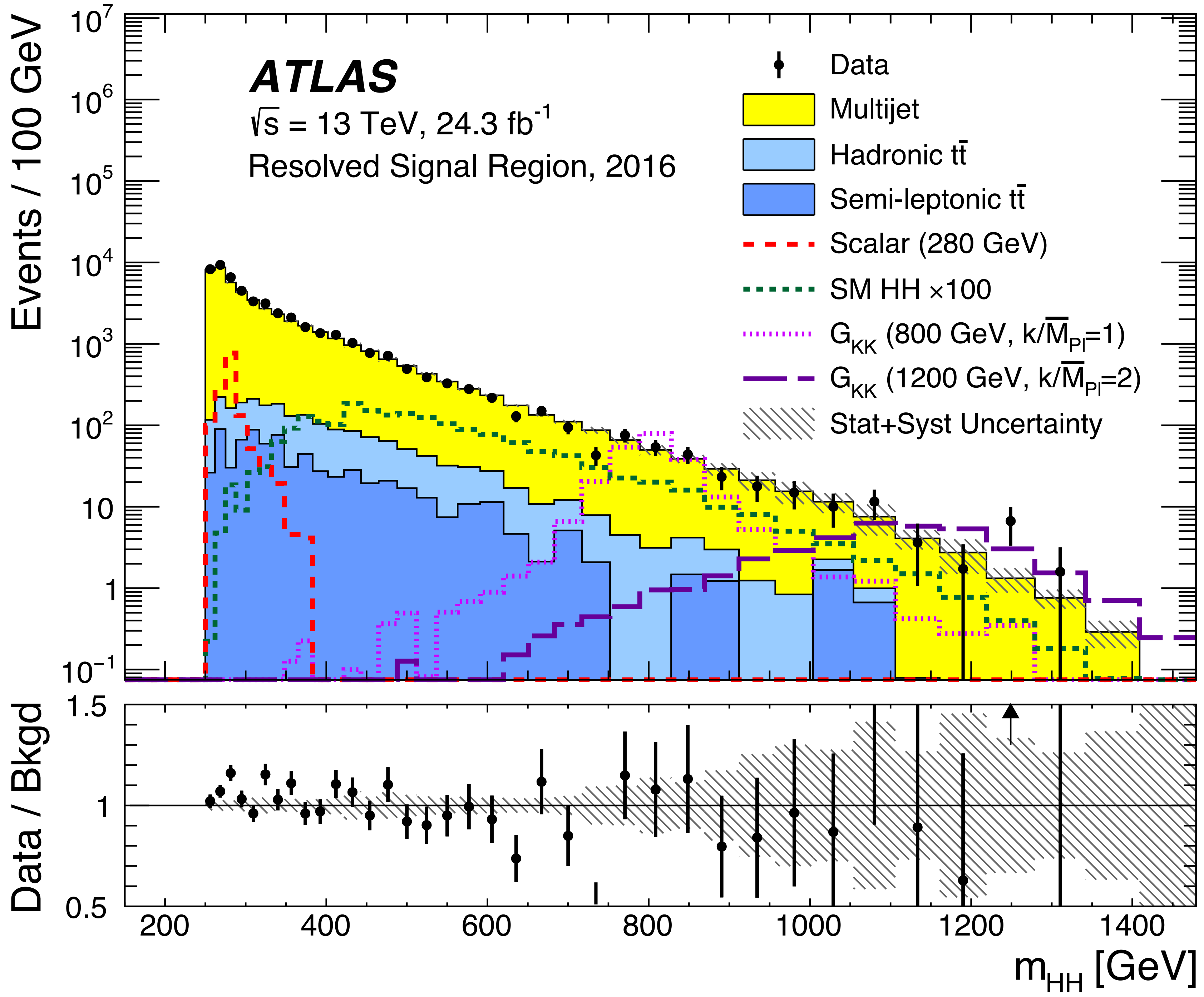




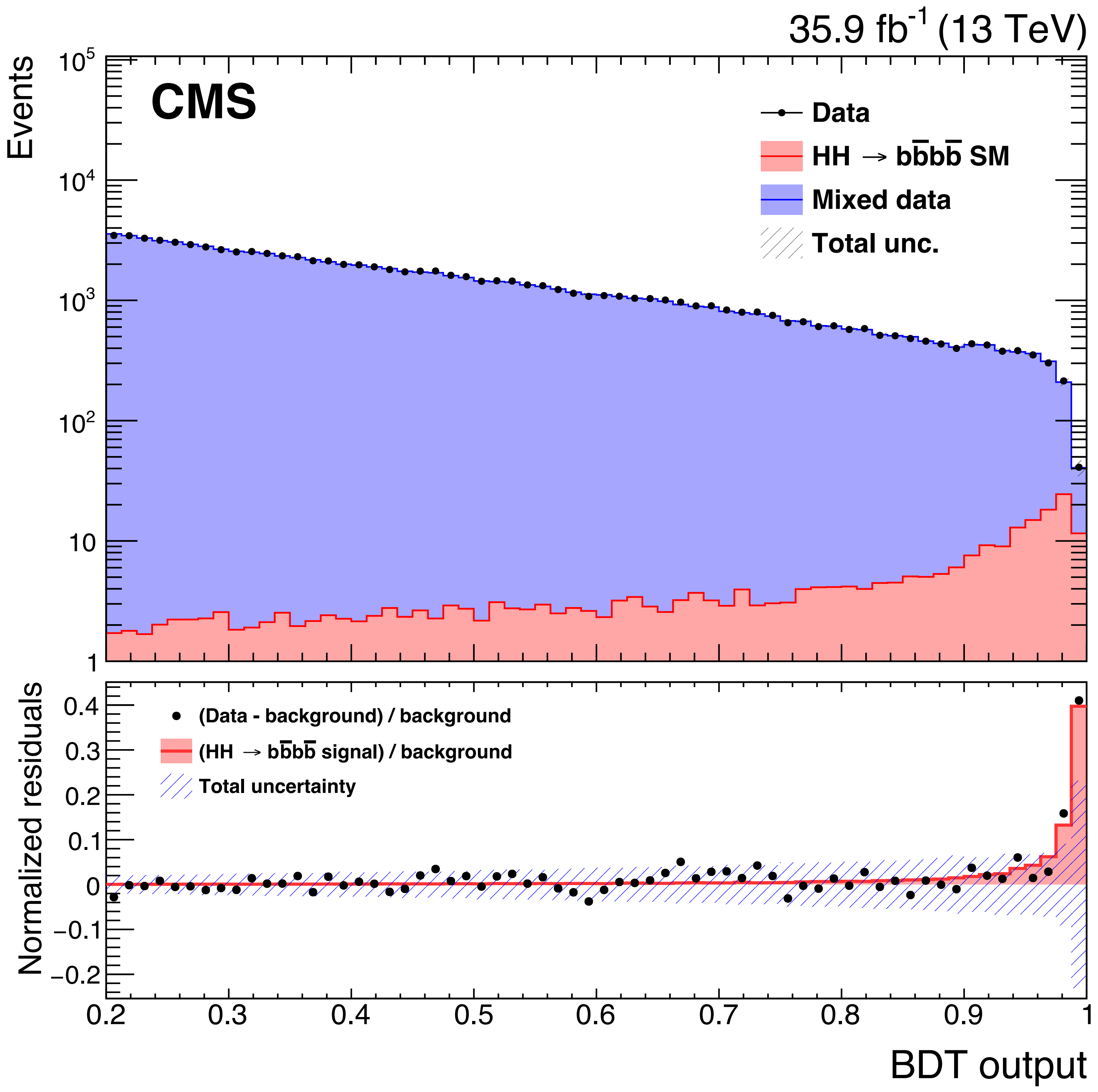
- CMS: “hemisphere mixing” to build background events from recorded data

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

Separation from the multijet background is essential



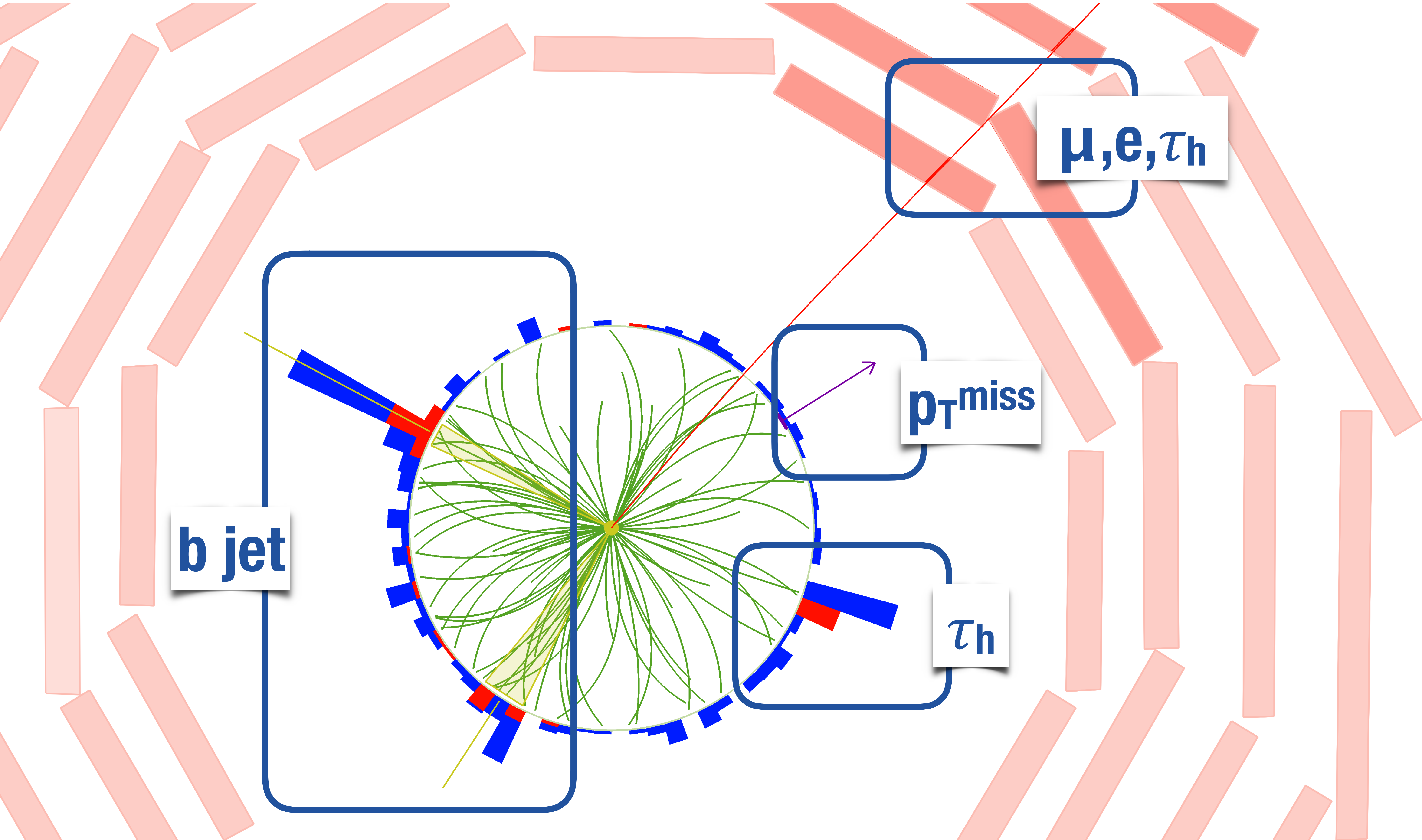
Obs. (Exp.) : 12.9 (21) × σ_{HH}^{SM}



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

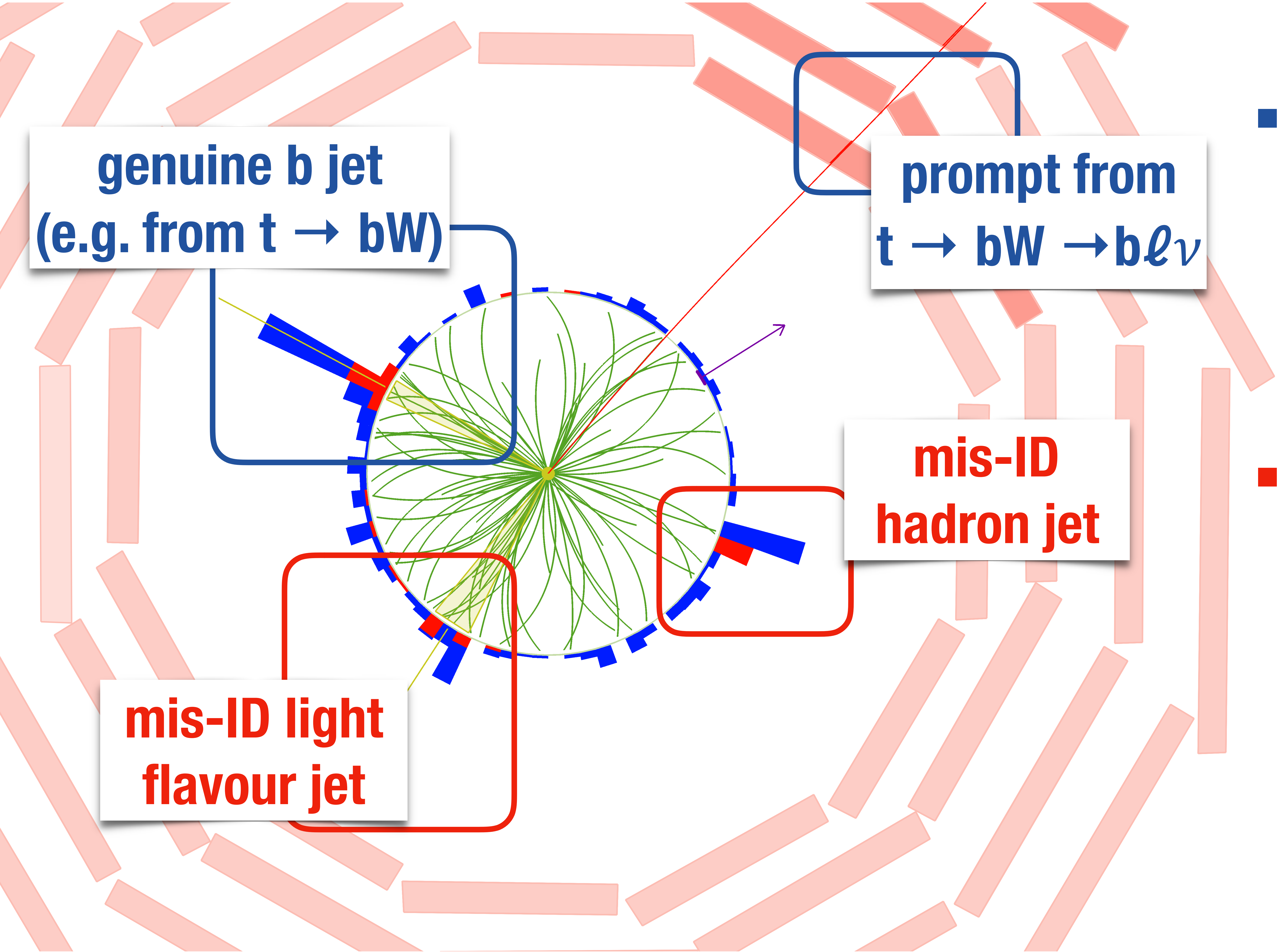


2 b jets

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

- 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 $\mathcal{B}$, 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 $Z \rightarrow \mu\mu$

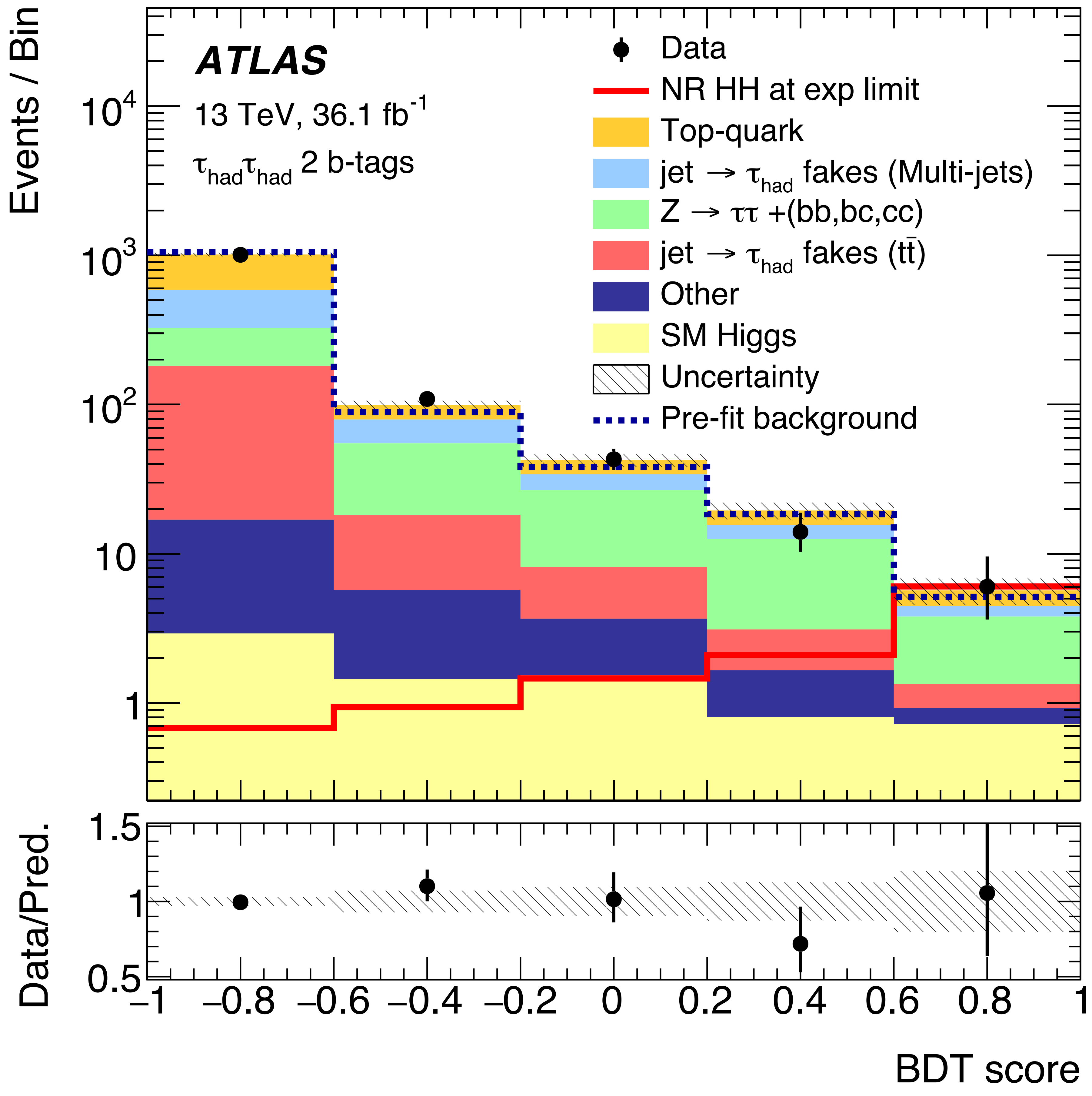
- **Instrumental (reducible)** backgrounds
  - ☐ tt, Z/γ^{*}, multijet with misidentified jets as τ_h or b jet
  - ☐ single top, W+jets (minor)

simulation + data-driven estimate

simulation

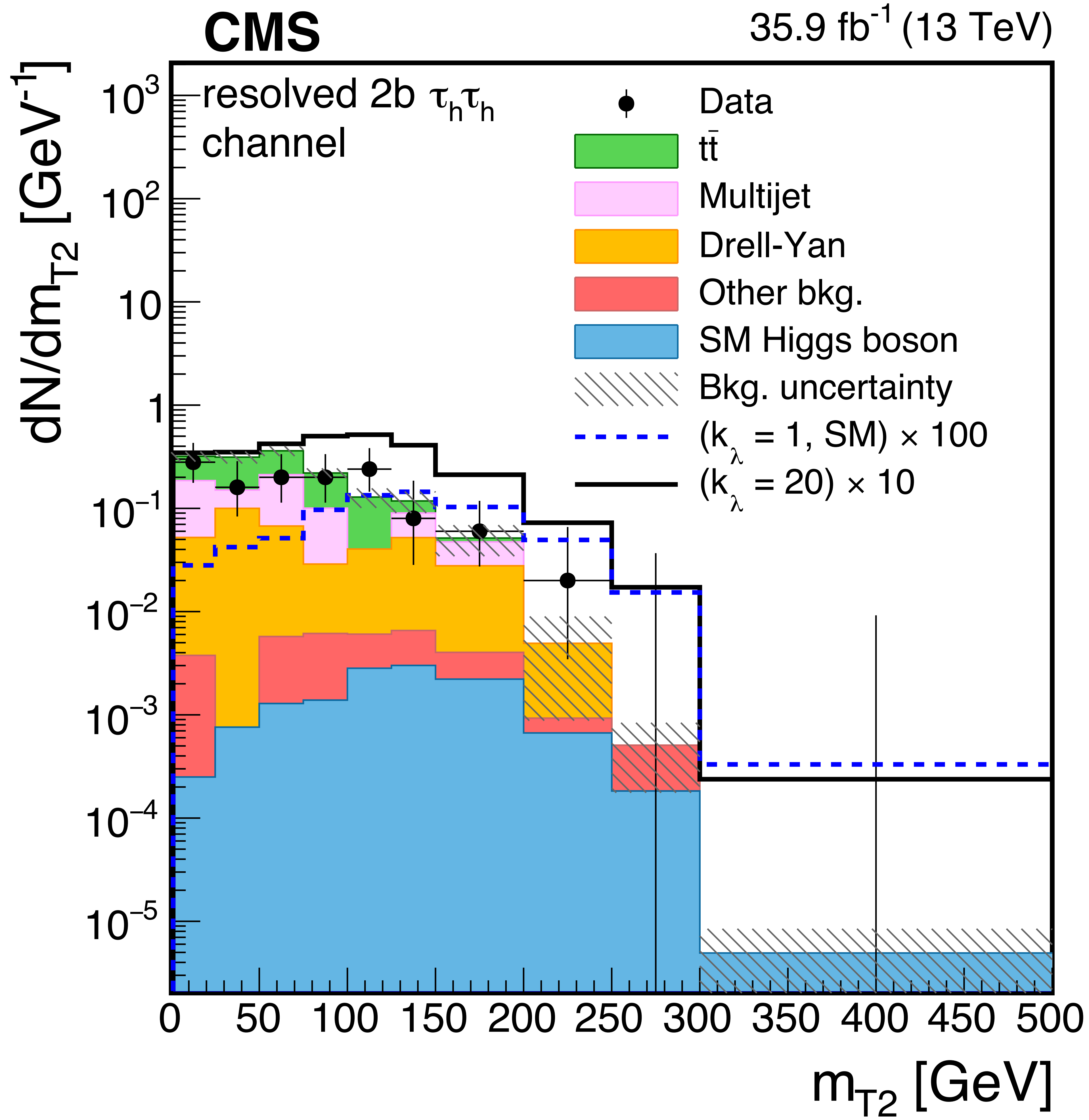
Medium $\mathcal{B}$, medium S/B : HH → bb$\tau\tau$

- 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

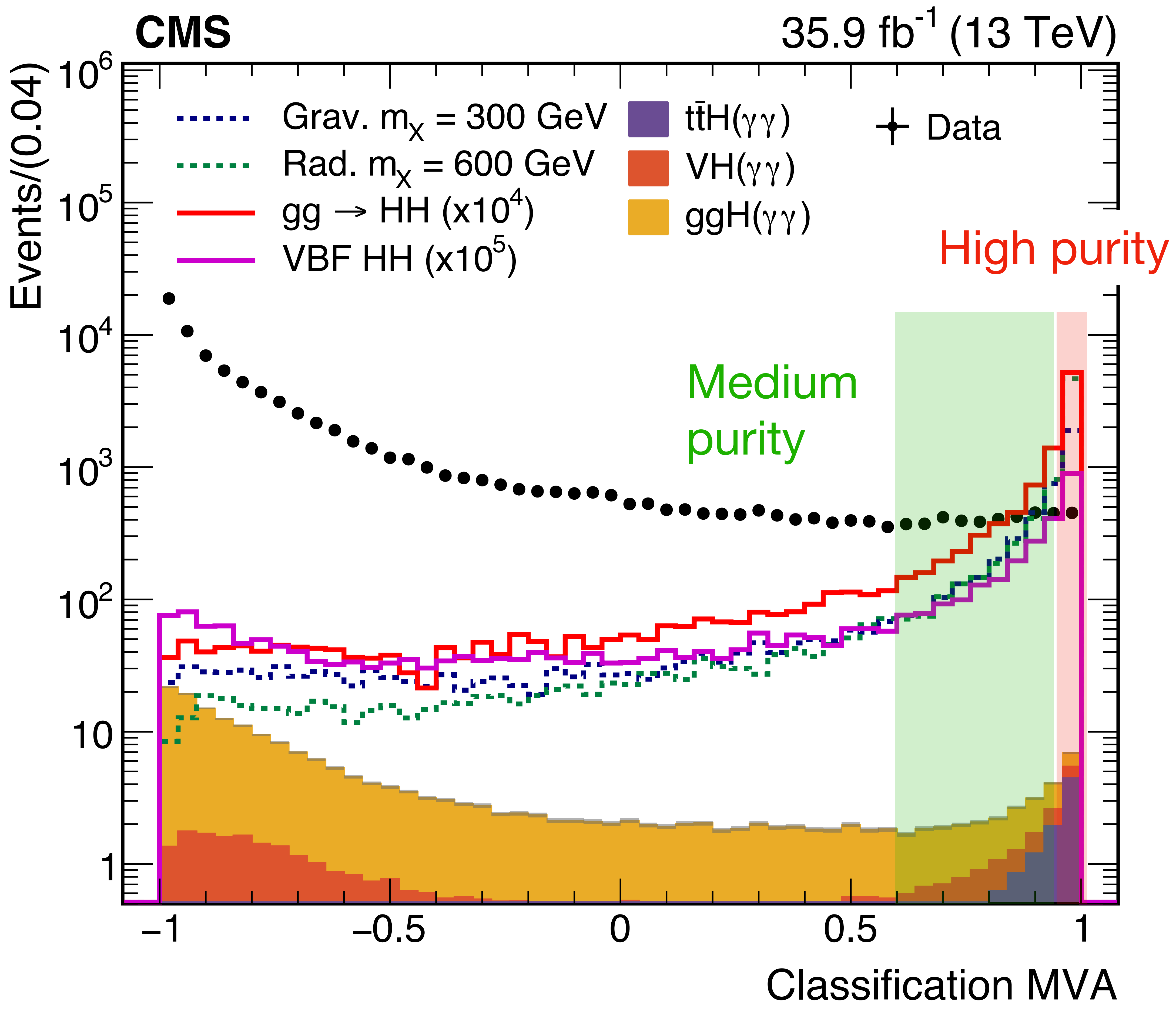
Obs. (Exp.) : 31.4 (25.1) × σ_{HH}^{SM}

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

Very rare but clean channel

Maximisation of acceptance and purity is essential

- Main backgrounds: $\gamma/\gamma\gamma$ + jets continuum, single H
- Several event categories defined to maximise the purity
  - ☐ low and high mass of the m_{HH} system
  - ☐ medium and high purity using a MVA discriminant
  - ☐ simpler categorisation in the ATLAS analysis using the number of b jets

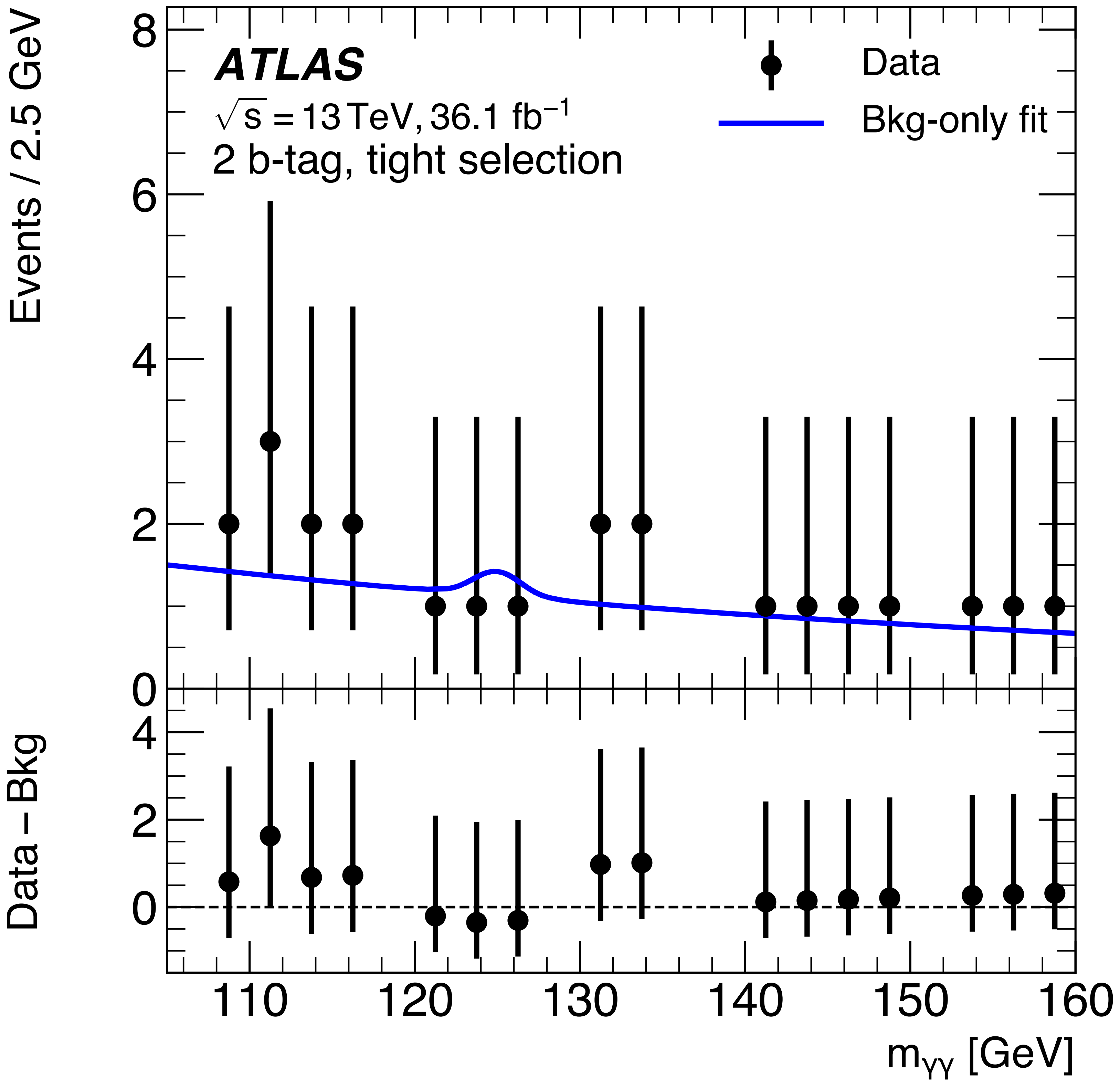


Inputs: b tag score of the jets, helicity angles, and variables related to the HH transverse balance

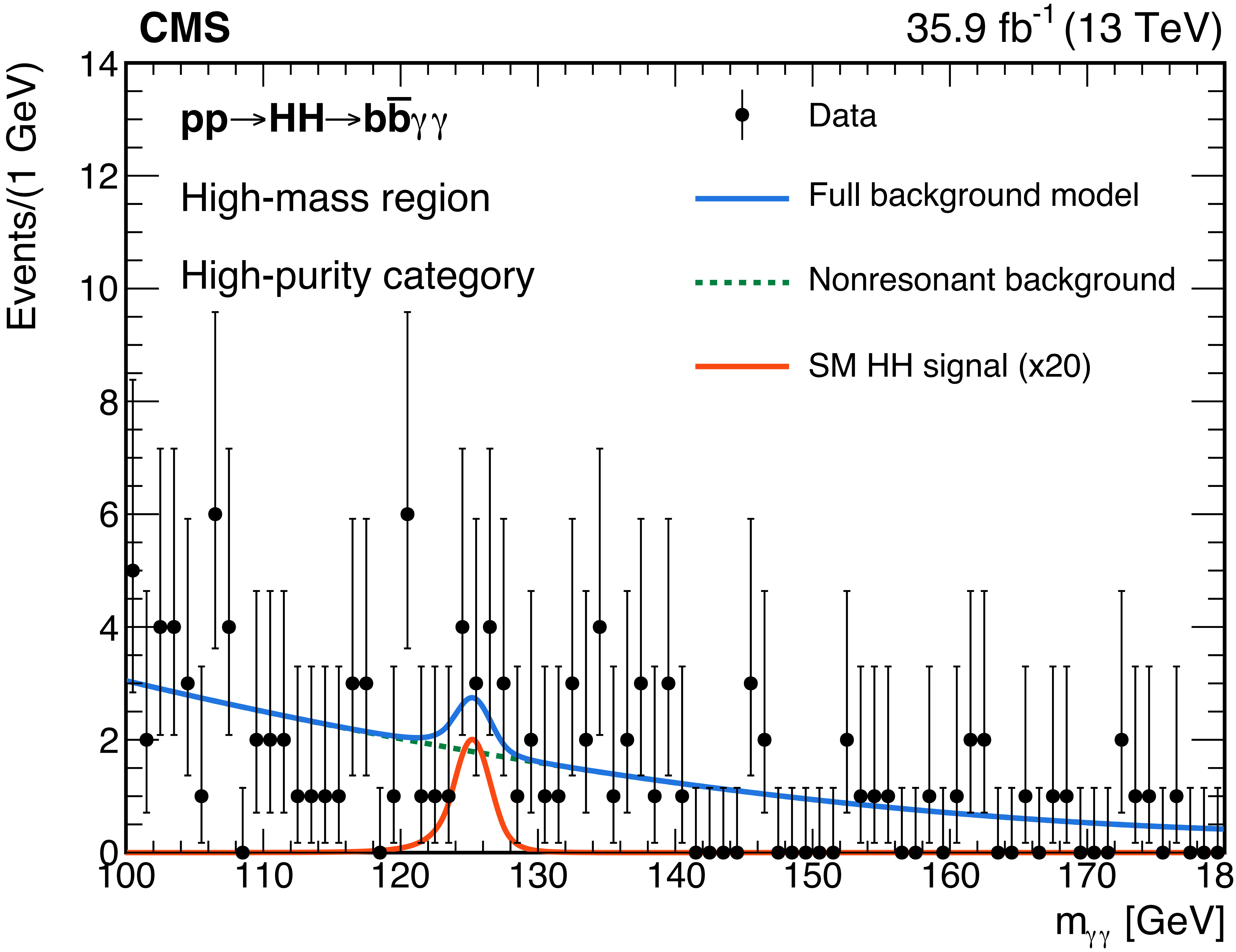
Low $\mathcal{B}$, high S/B : HH → bb$\gamma\gamma$

- Look for a signal using the $m_{\gamma\gamma}$ distribution
  - simultaneously fit with m_{bb} in the CMS analysis
- Large variations of the H kinematics when κ_λ changes
  - ATLAS: loose and tight selections for SM HH search and κ_λ scan
  - CMS: behaviour captured by the m_{HH} categories

Benefit of the excellent $m_{\gamma\gamma}$ resolution as signature

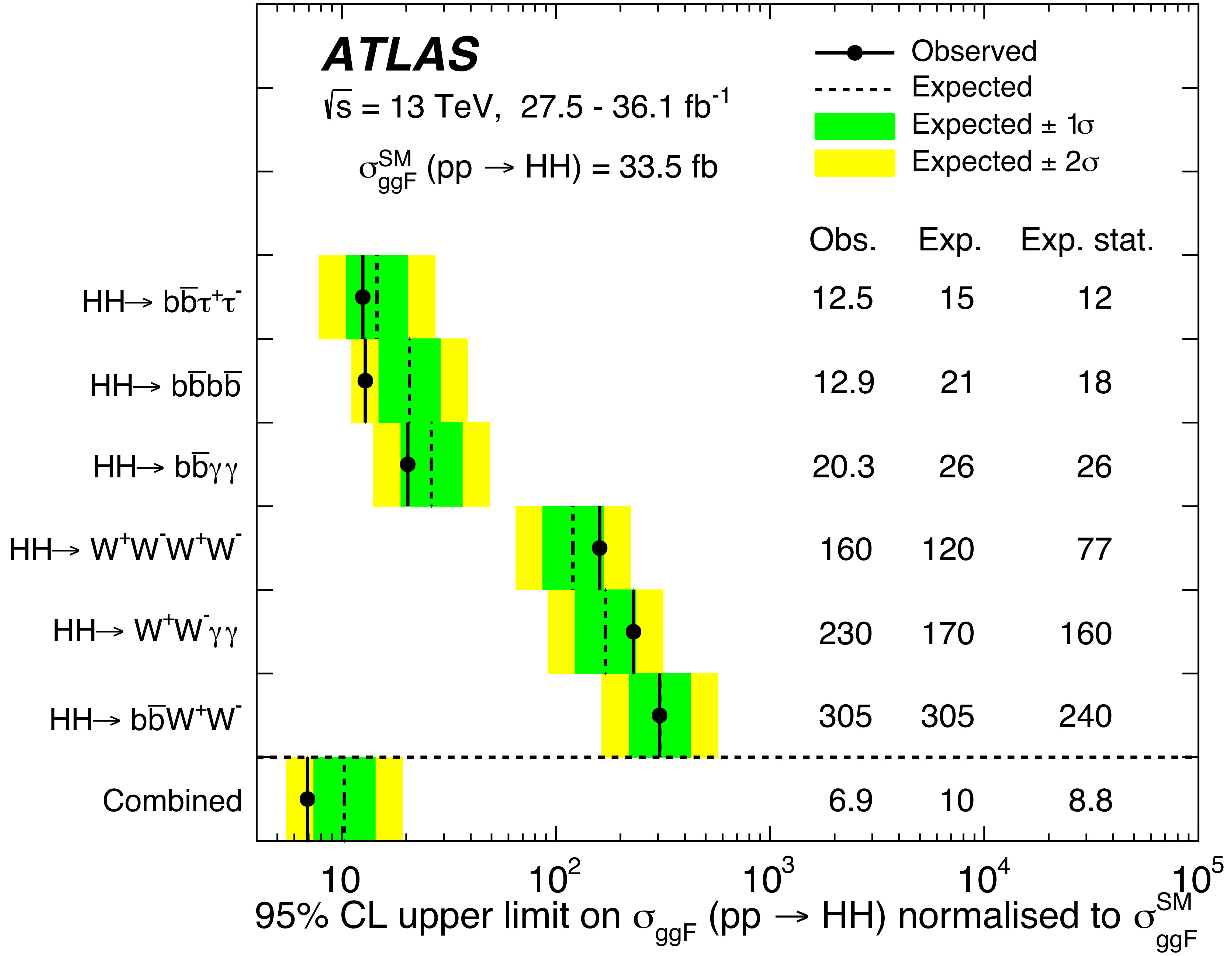


Obs. (Exp.) : 20.3 (26) × σ_{HH}^{SM}

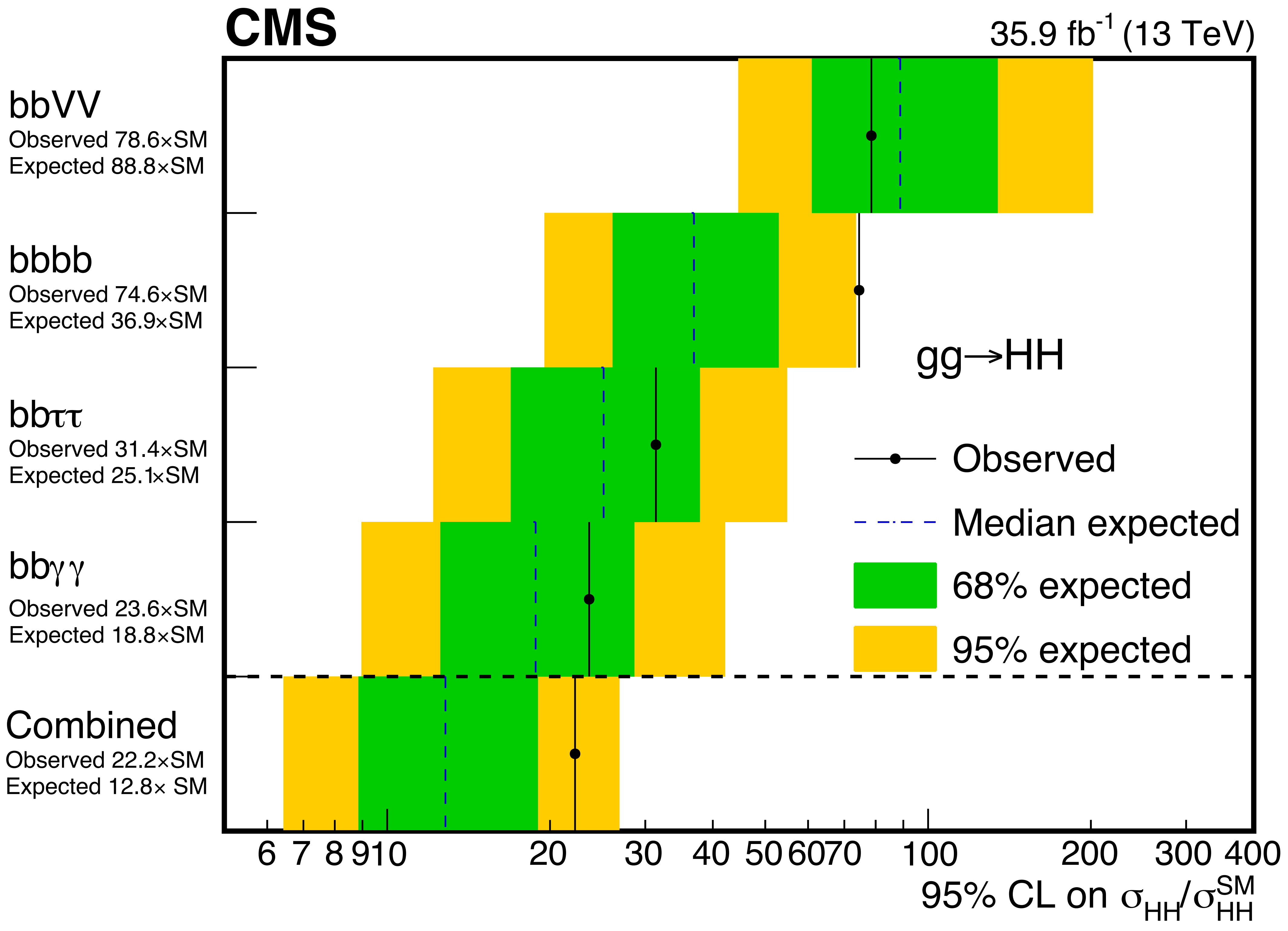


Obs. (Exp.) : 23.6 (18.8) × σ_{HH}^{SM}

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

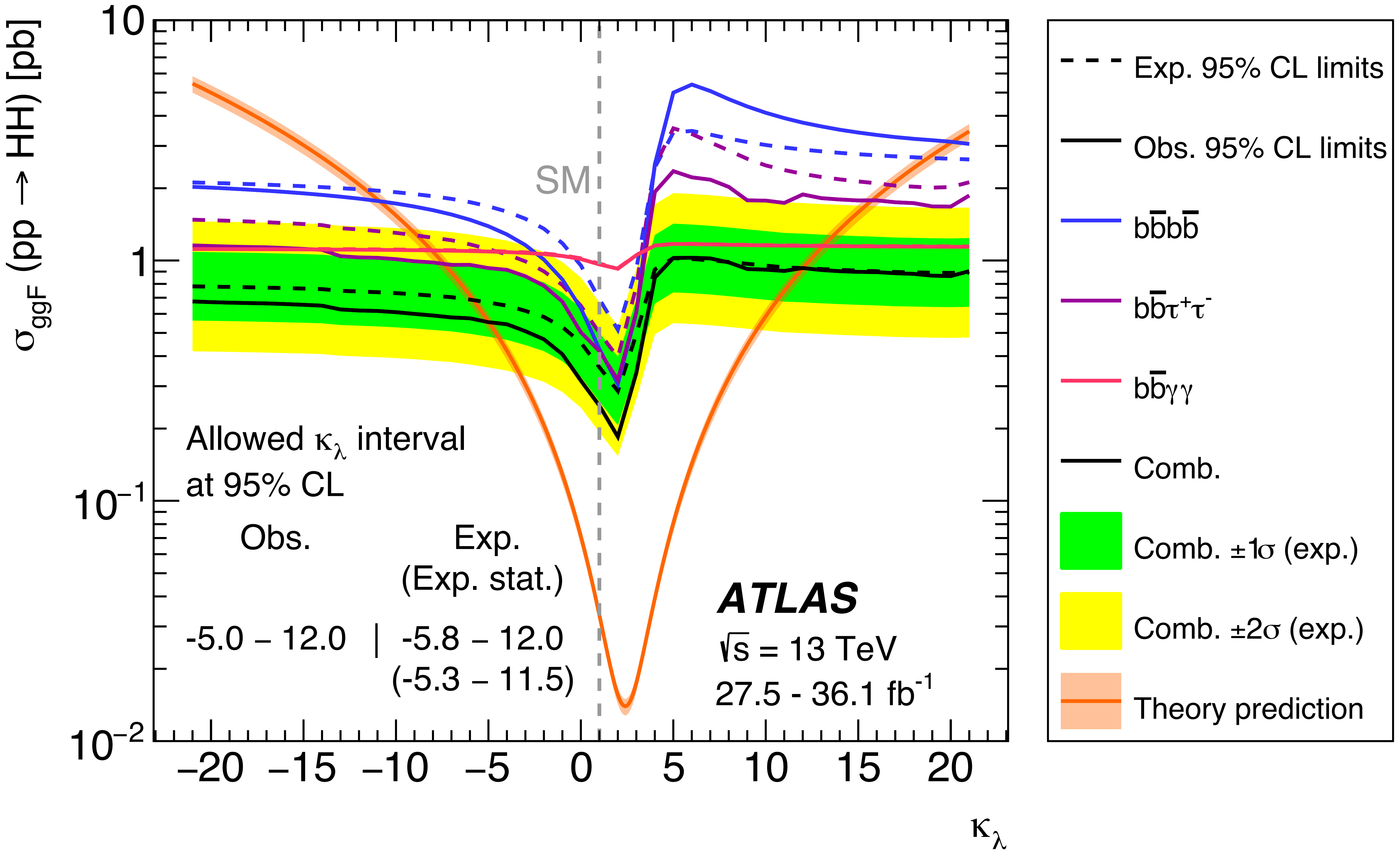


- The combined results benefits from the similar sensitivity in several channels

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

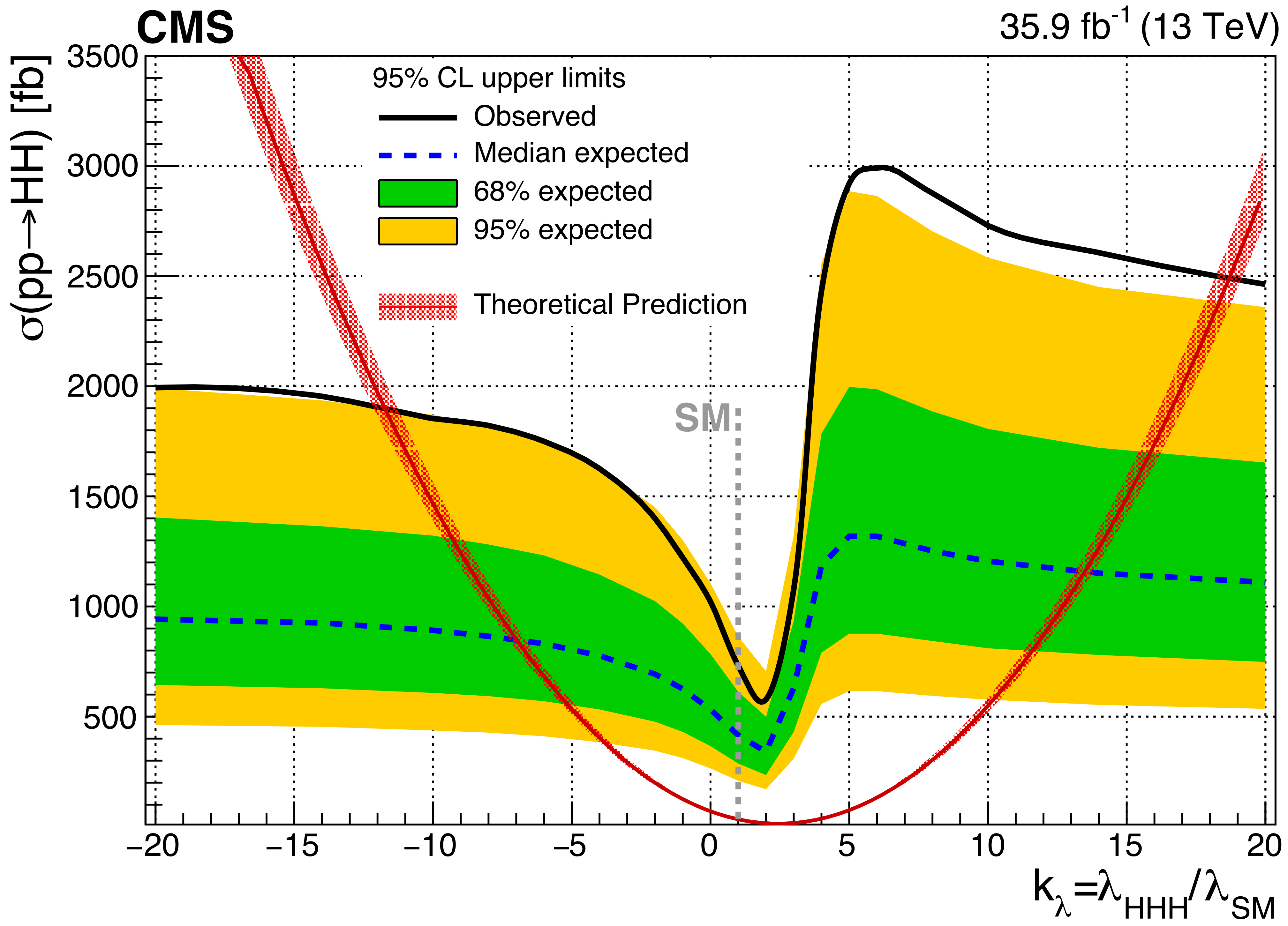
Full Run 2 dataset (×4 more data) current under analysis ×2 more sensitive (from stat.) + analysis improvements

Combination of the results



Observed: $-5.0 < \kappa_\lambda < 12$

Expected: $-5.8 < \kappa_\lambda < 12$

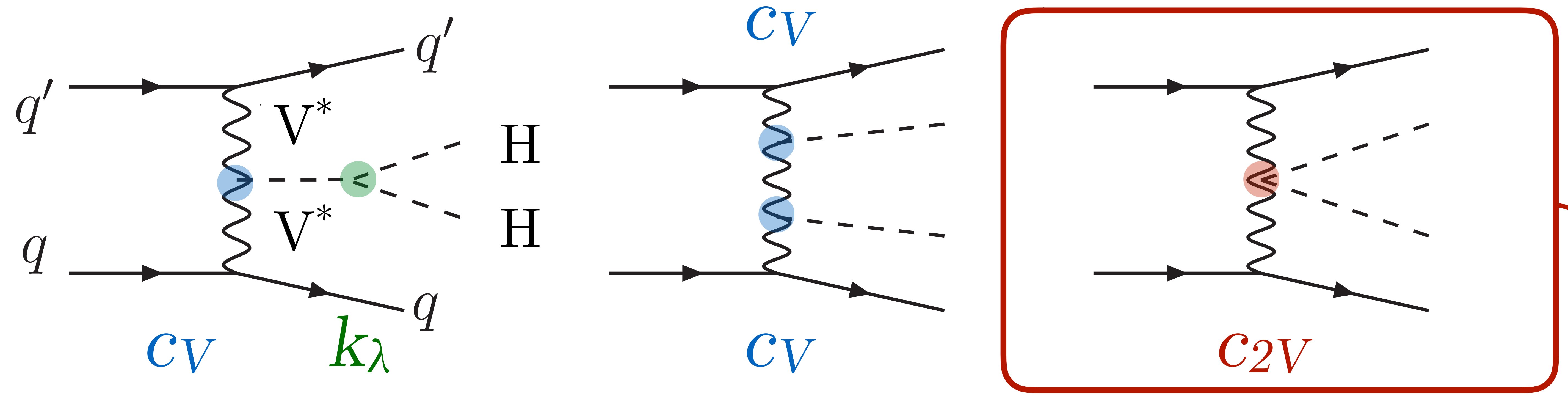


Observed: $-11.8 < \kappa_\lambda < 18.8$

Expected: $-7.1 < \kappa_\lambda < 13.6$

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

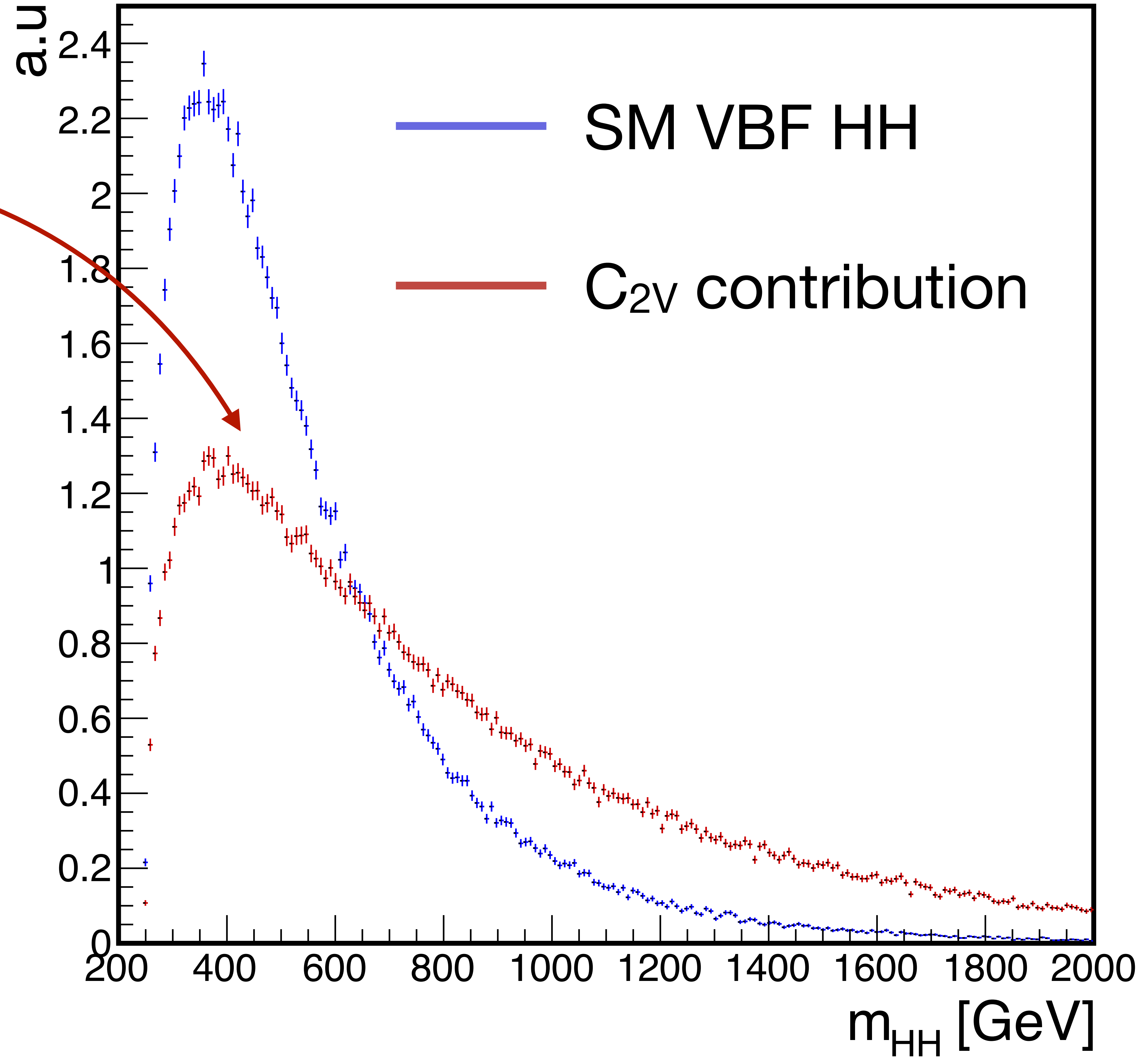
Beyond gluon fusion



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

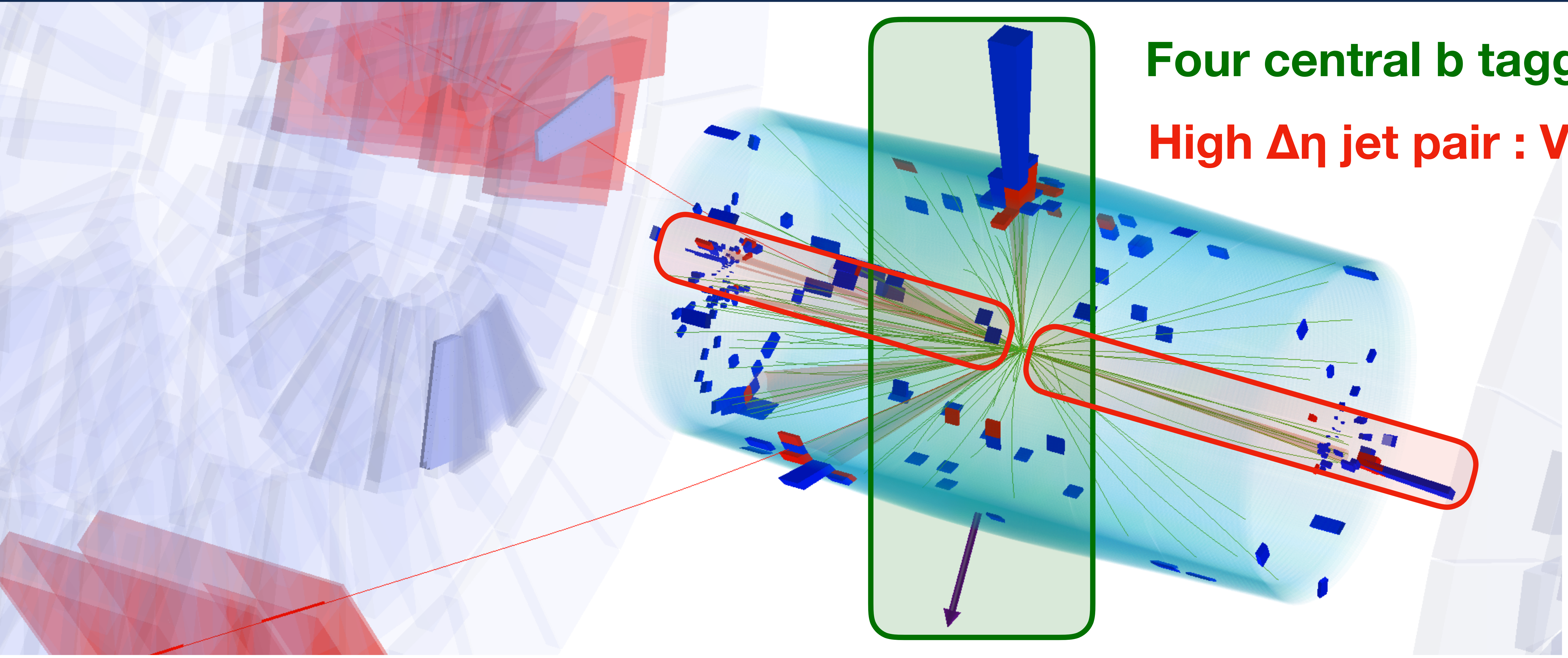
$$\mathcal{A}\,(V_L V_L \to \text{HH}) \simeq \frac{\hat{s}}{v^2}\,(C_{2V} - C_V^2)$$

- 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



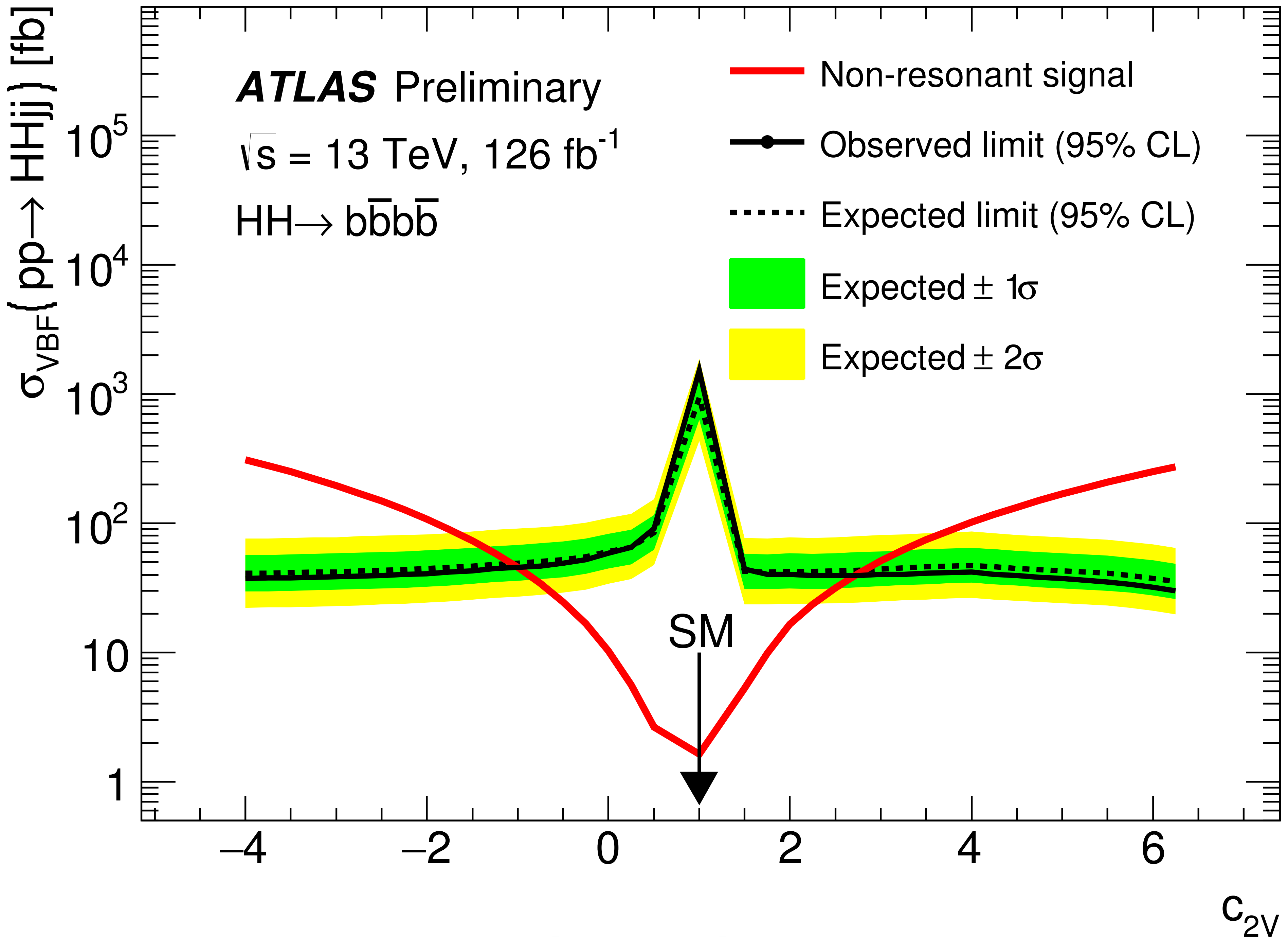
The study of other HH production modes give new insights on the properties of the scalar sector

Search for VBF HH



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

High Δη jet pair : VBF signature



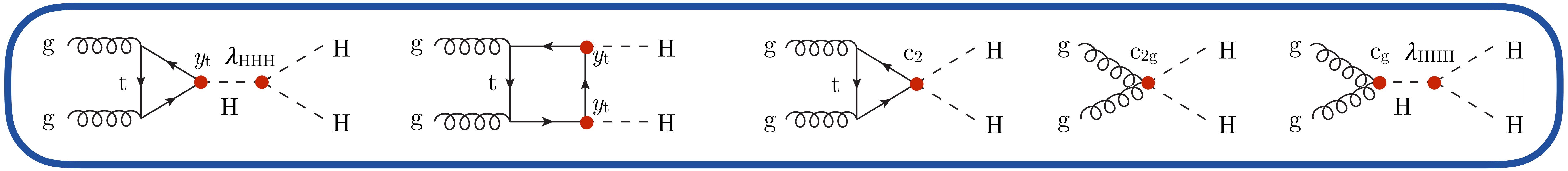
$1600\ (1000) \times \sigma^{VBF}{}_{SM}$

$-1.0 < C_{2V} < 2.7\ (-1.1 < C_{2V} < 2.8)$
allowed @ 95% CL

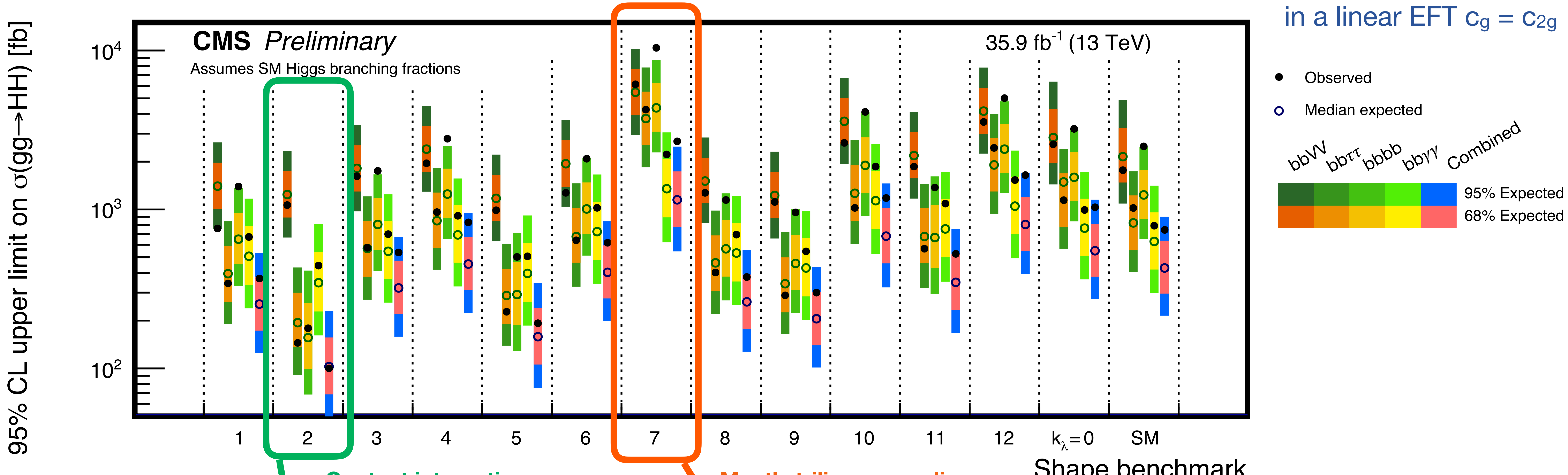
- Small cross section → high BR final state: search in the bbbb decay channel with the full Run 2 dataset
  - bbbb analysis extended with a jet pair with properties (m_{jj}, Δη) compatible with VBF production
  - look for a signal in the m_{bbbb} distribution

A broader BSM picture

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



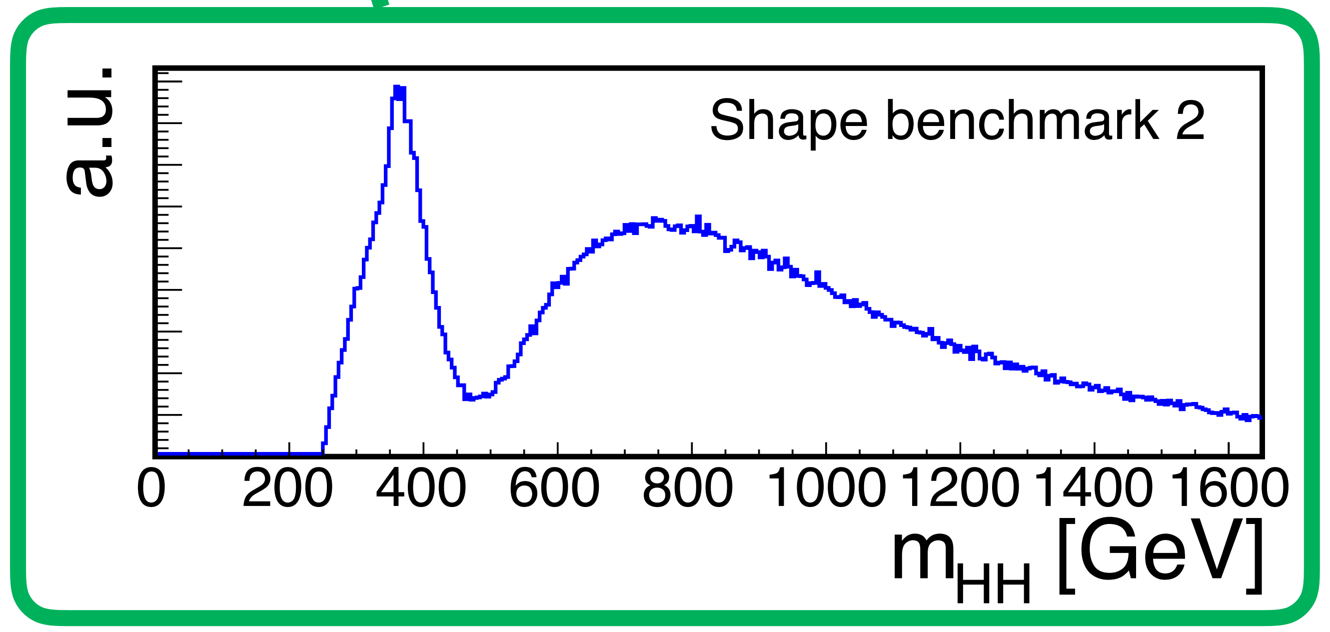
- 5D parameter space, contact interactions, large kinematic modifications
  - ☐ probed with representative signal shape benchmarks
- HH as a probe of high energy BSM effects
  - ☐ full EFT operator fit should be the focus of the next results

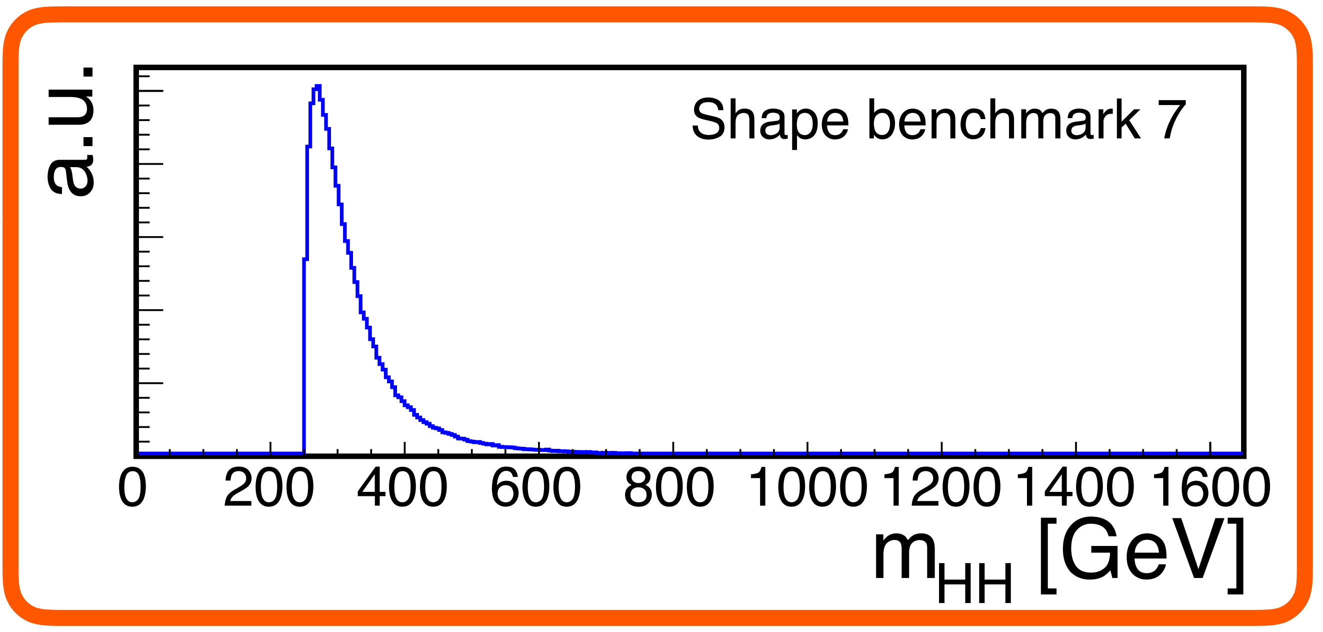


in a linear EFT $c_g = c_{2g}$

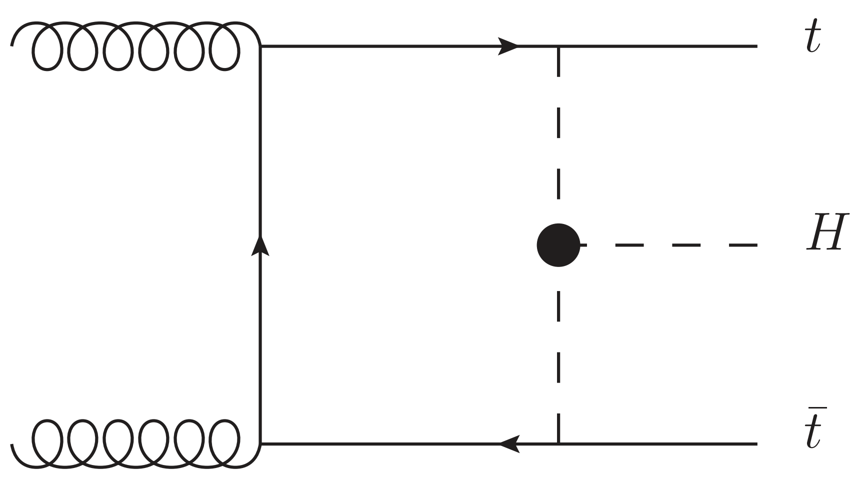
Contact interactions

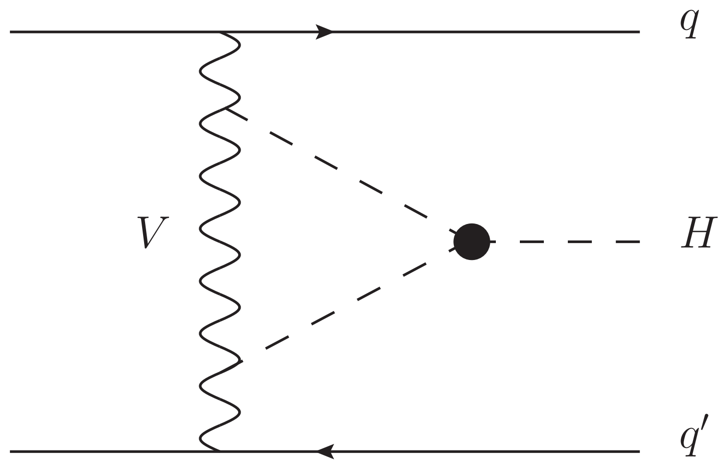
Mostly trilinear coupling

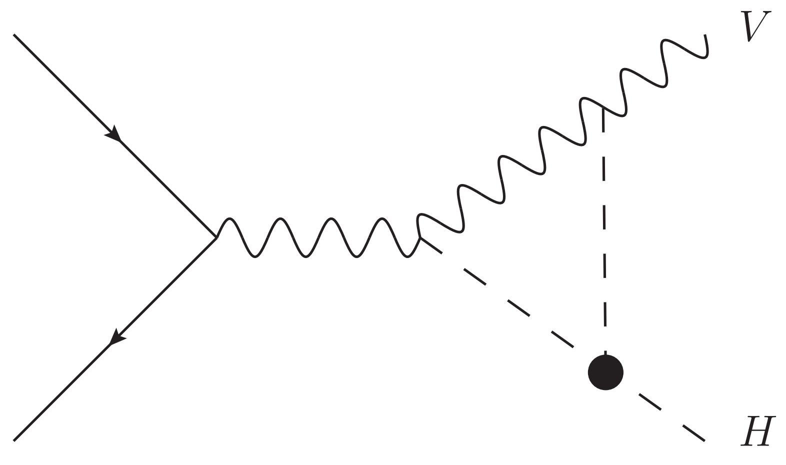




Extracting λ_{HHH} from single Higgs

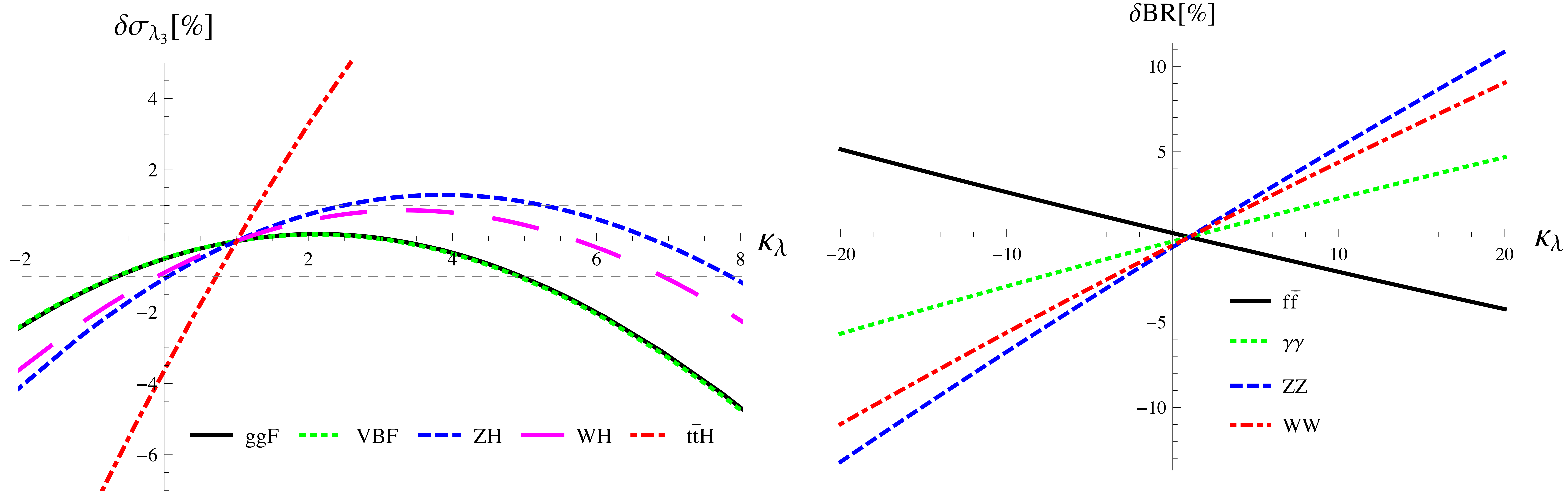






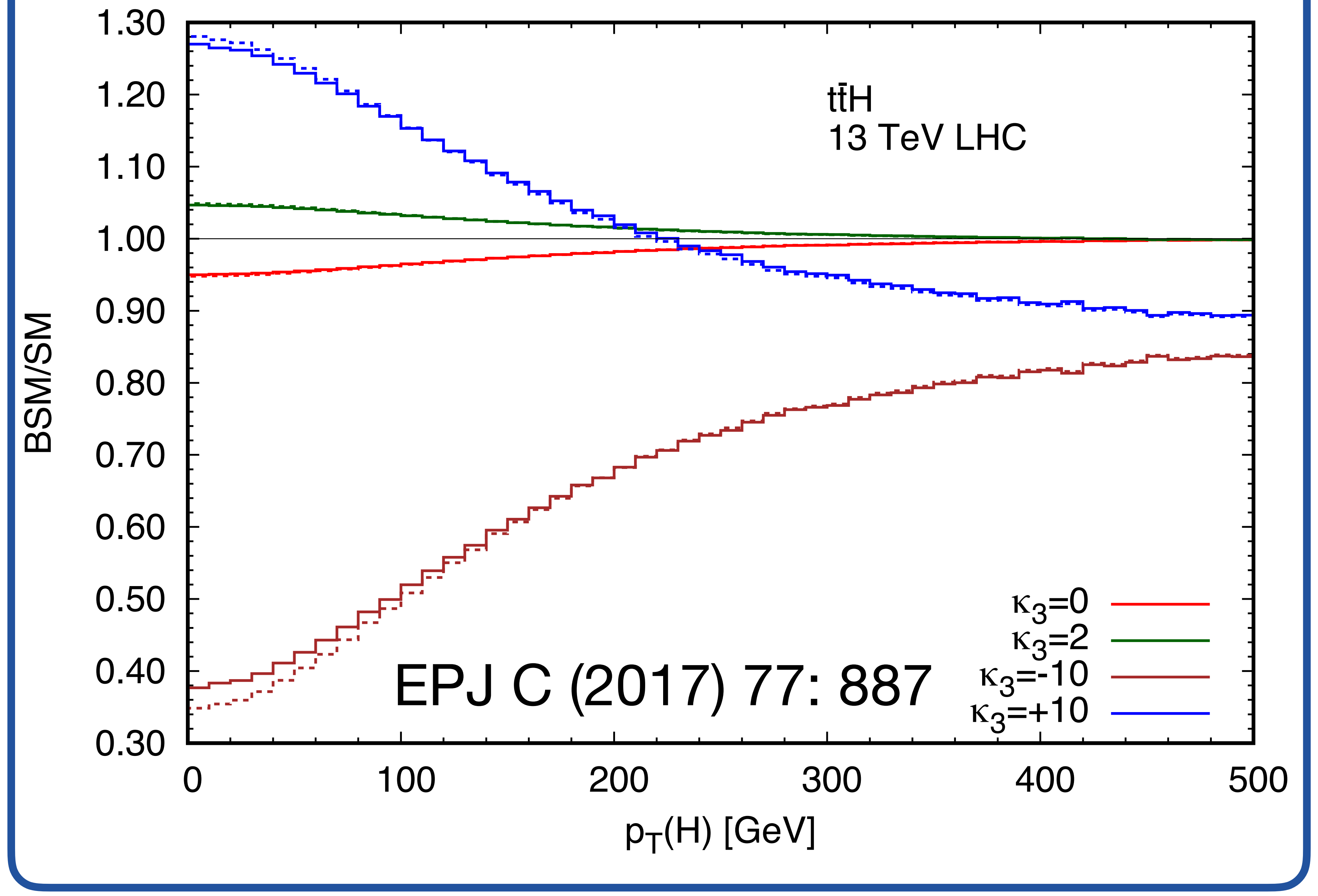
Single H production as a precision tool to look for NLO effects from λ_{HHH}

Production xs and decay BR



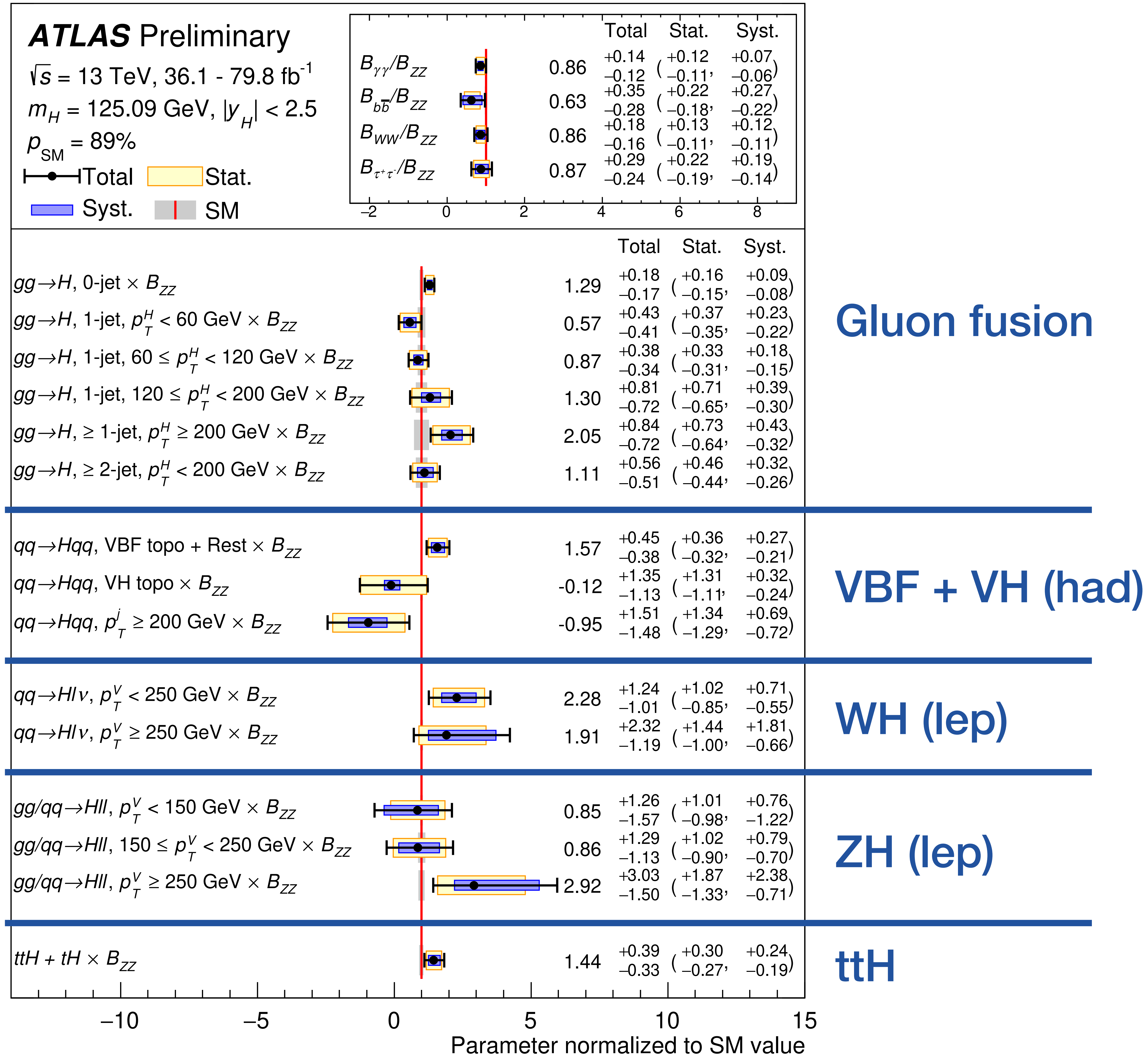
JHEP 1612, 080 (2016)

Differential distributions



EPJ C (2017) 77: 887

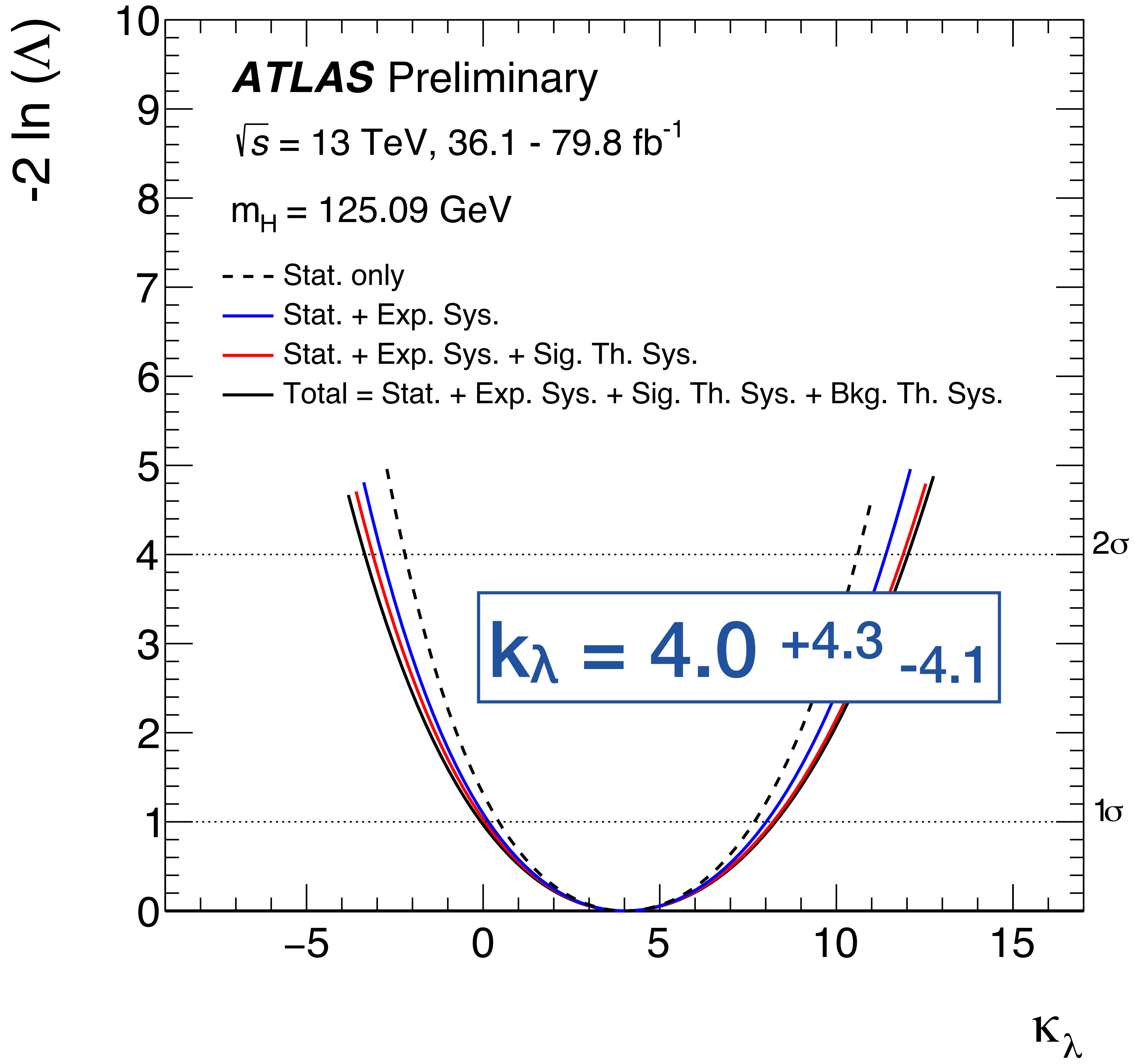
Single H : input



- 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
    ⟹ limited access to differential information

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

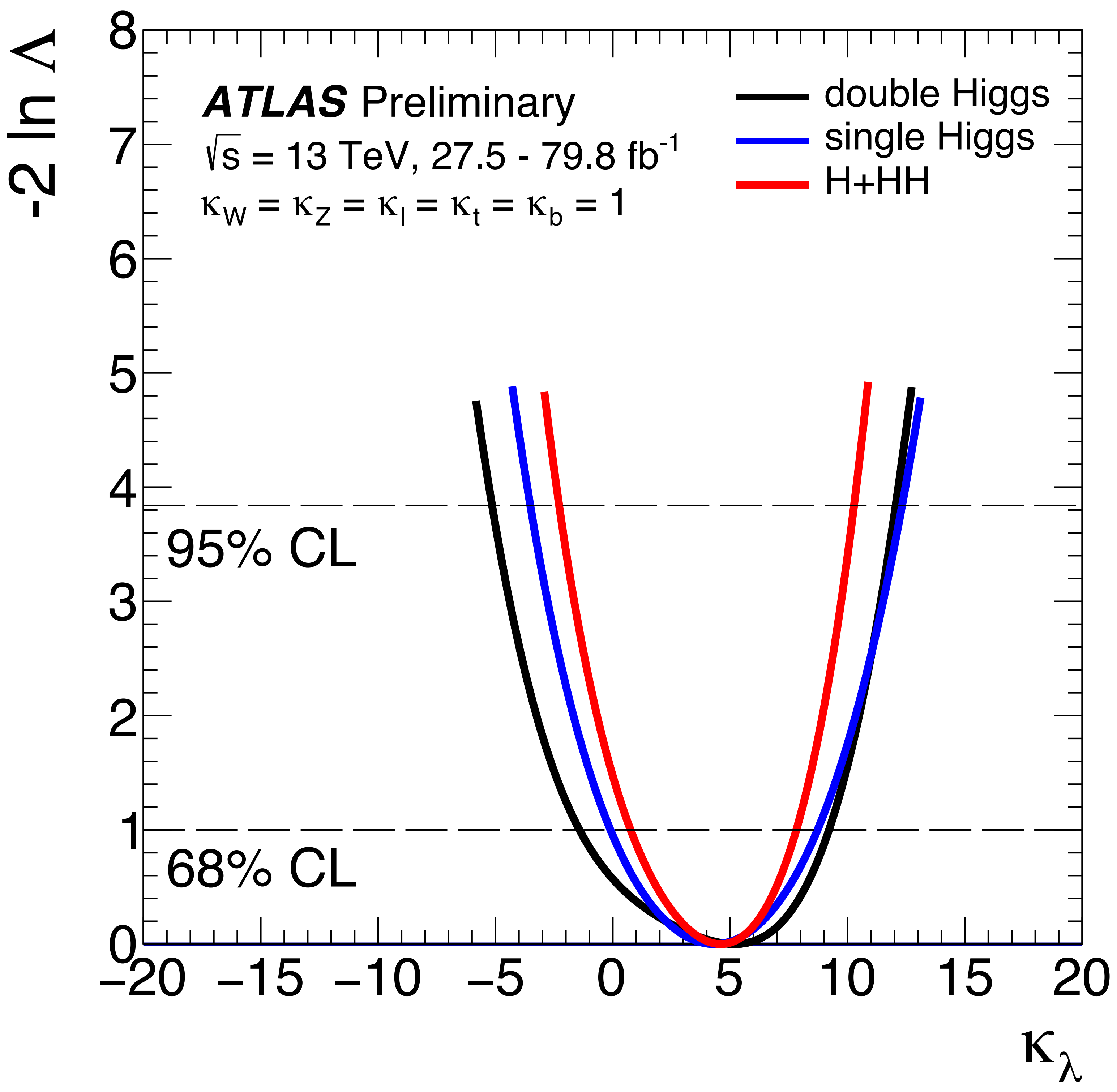


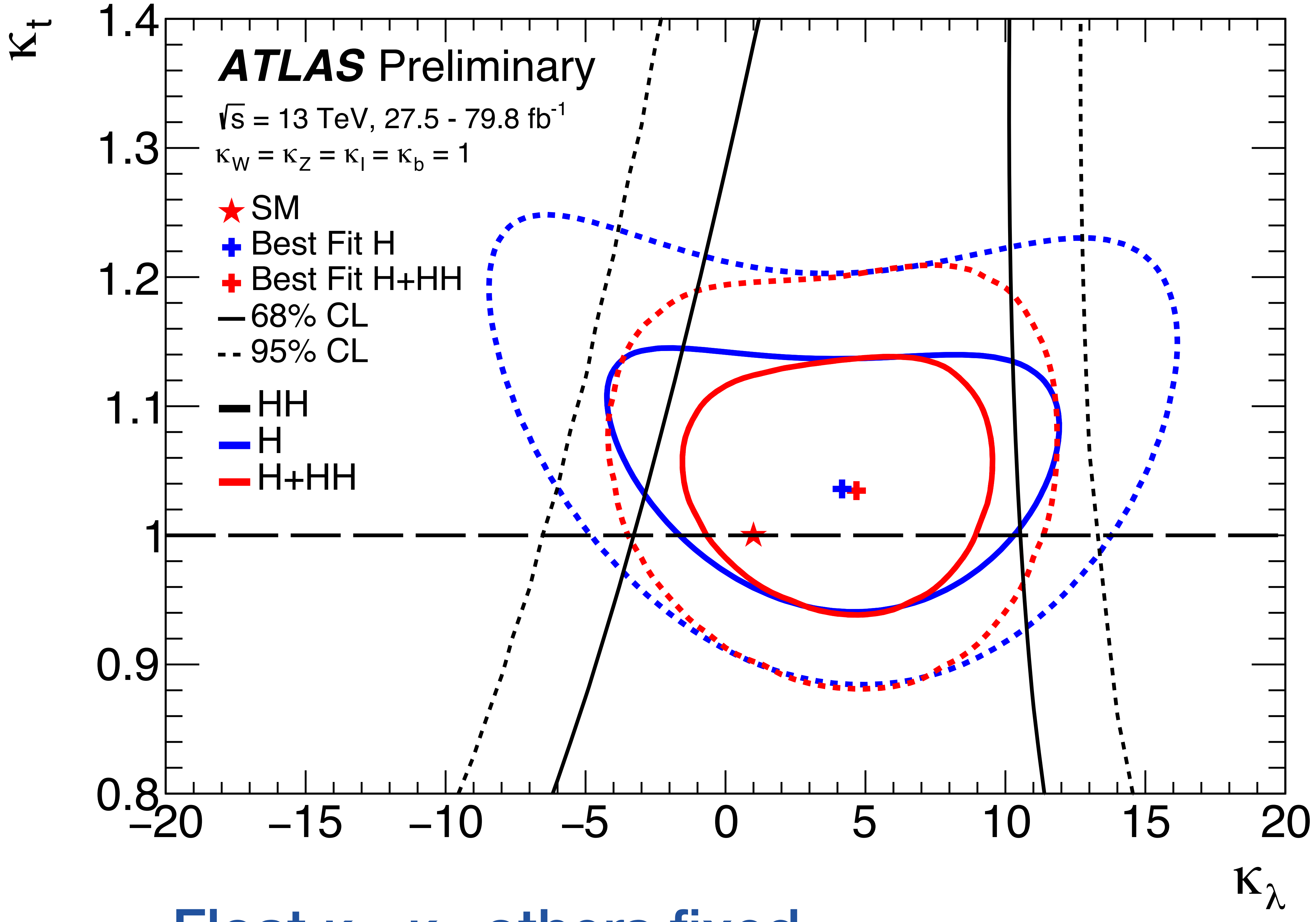
$k_\lambda = 4.0^{+4.3}_{-4.1}$

Complements direct determination from HH

Measurement sensitive only under strict assumptions on other Higgs boson couplings

A global view of the self coupling





- The combination of H and HH allows to probe simultaneously λ_{HHH} and other couplings variations
- ~20% improvement in sensitivity to λ_{HHH} when adding single H

All other κ fixed
$\kappa_\lambda = 4.6^{+3.2}_{-3.8}$

Float κ_λ, κ_t, others fixed

5-15% precision reduction on κ_λ when floating all κ → reduced theory assumptions!

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!

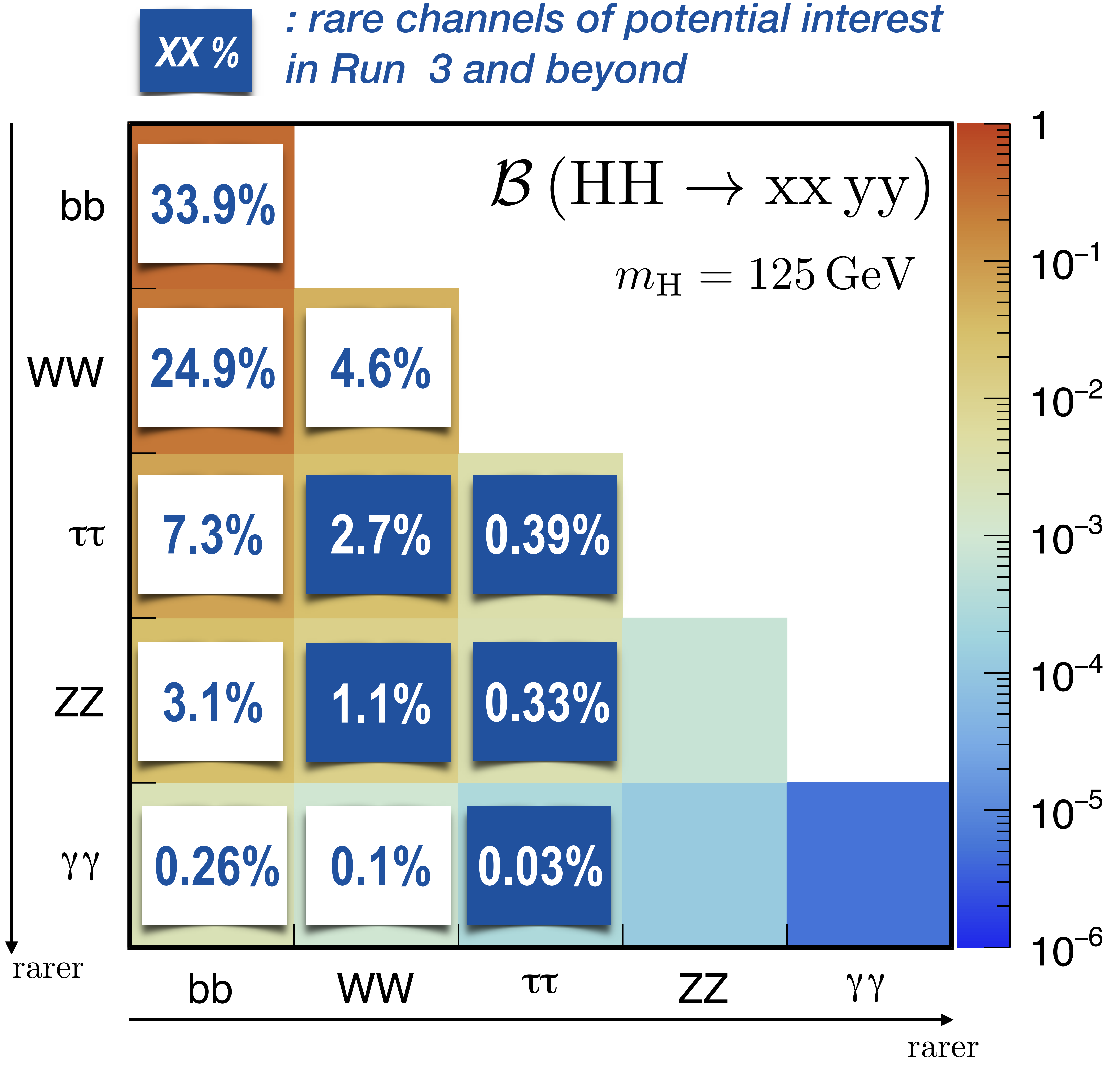
Towards the Run 3

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

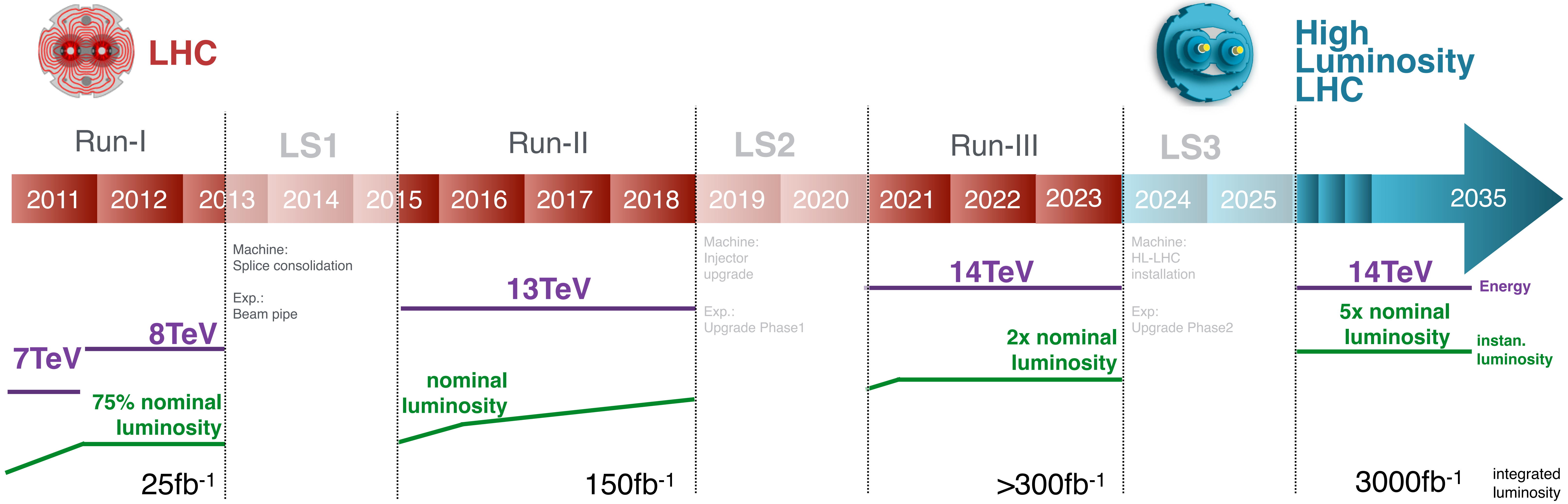


XX % : rare channels of potential interest in Run 3 and beyond

	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%		

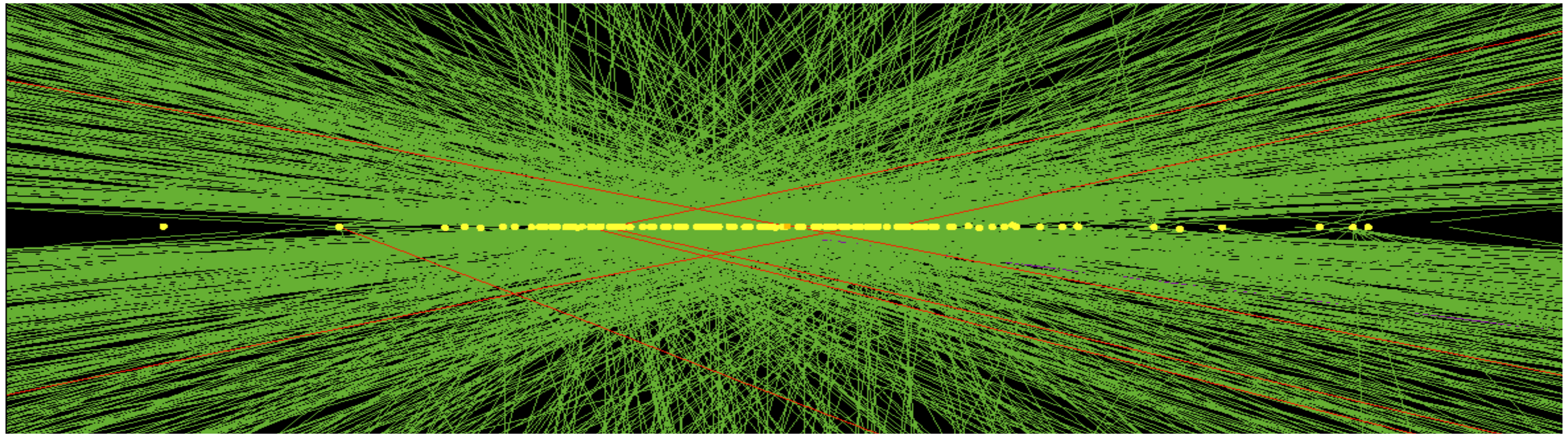
The high-luminosity LHC

- Upgrade of the LHC planned to start after the 2024-2025 shutdown
  - ☐ 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
- **Expect to collect 3 ab^{-1} during a decade of operations**



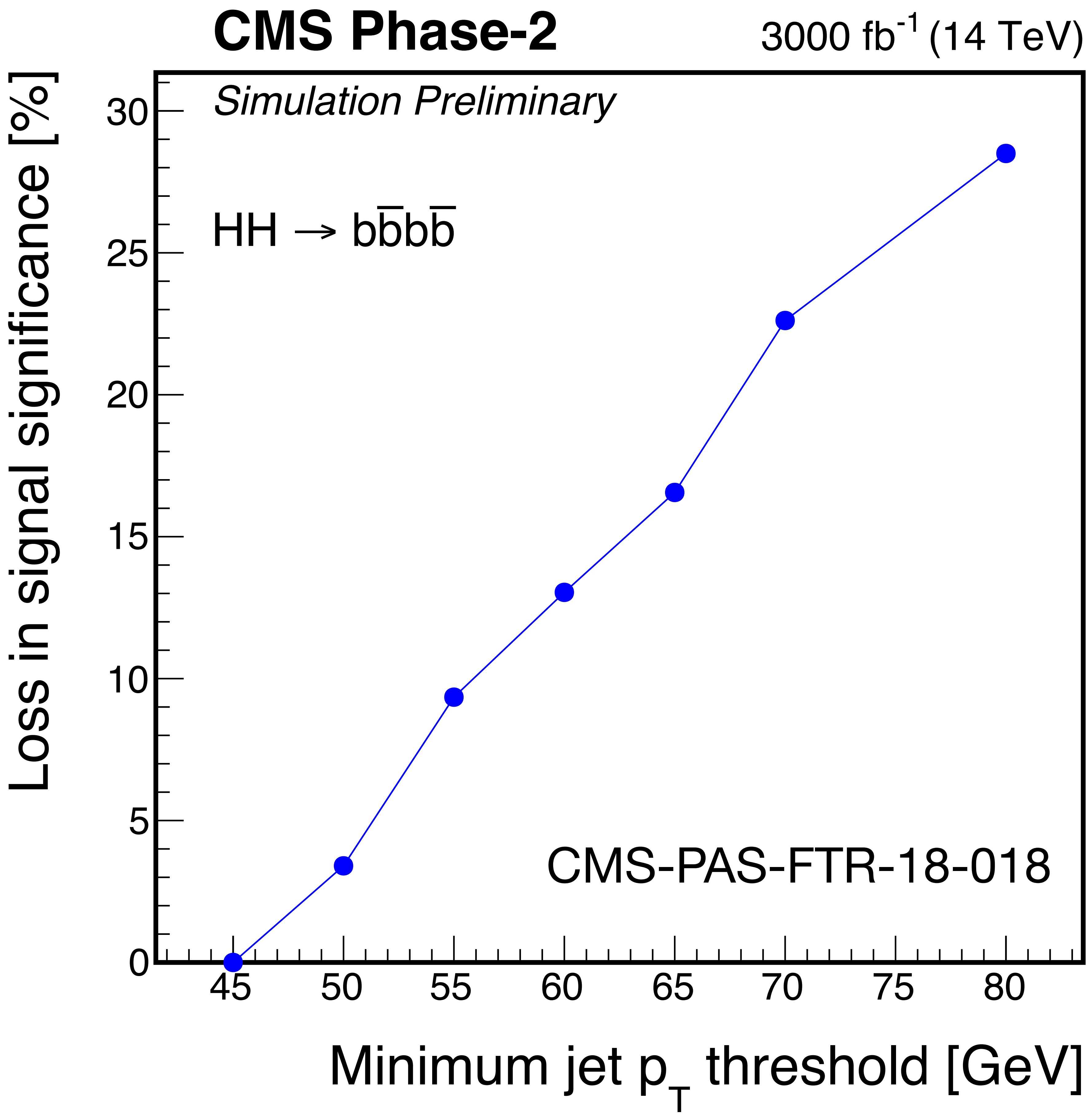
Unique possibility for very high precision on Higgs physics
Expect to reach the ultimate sensitivity on HH

Why is it challenging?



- Up to 200 simultaneous pp interactions per single 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

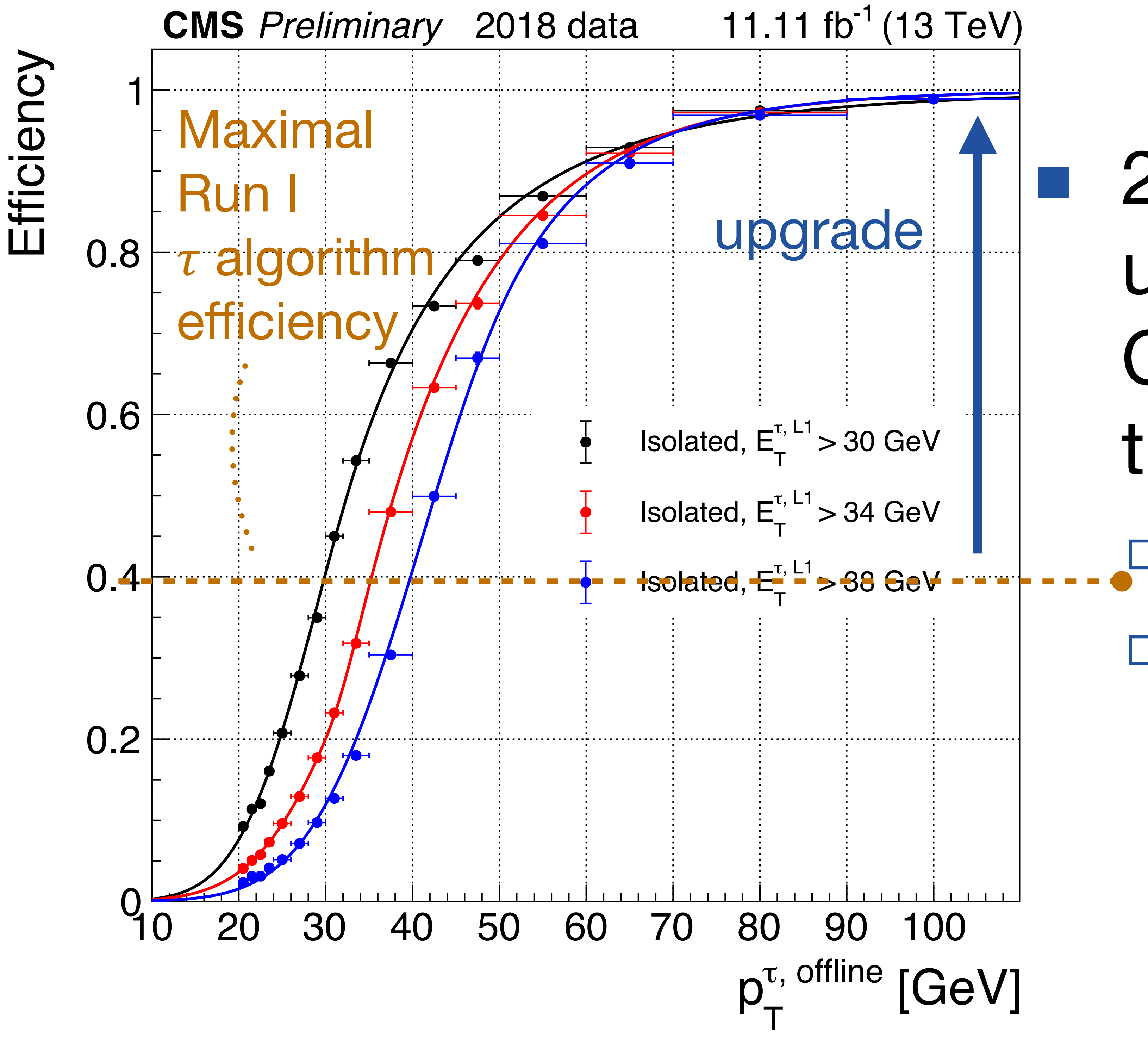
An ambitious program of detector upgrades is planned to maintain and improve the performance at the HL-LHC



Essential to maintain low thresholds!

A perspective view

From the experience of the Run 2…

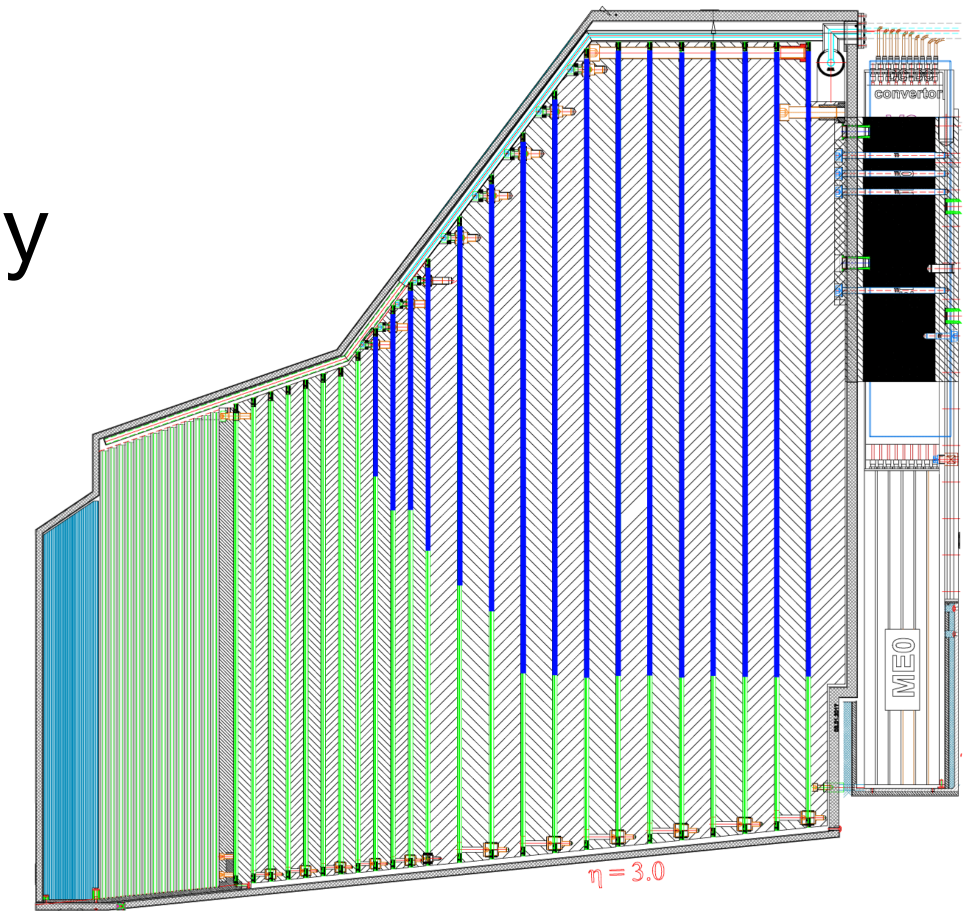


- 2016: ambitious upgrade of the CMS L1 (hw) trigger system
  - ☐ same detector
  - ☐ more granular inputs and more powerful FPGAs

Performance improved despite the higher instantaneous luminosity

… to the challenges of HL-LHC

- New L1 trigger system
  - ☐ ×7.5 bandwidth, ×3 latency
  - ☐ inputs from the tracker!
- New highly-granular endcap calorimeter
  - ☐ 5D calorimetry: position + energy + time
- Precision timing for PU suppression



CMS HGCal : more than 6M channels

Unique opportunities to expand the physics capabilities of the experiments

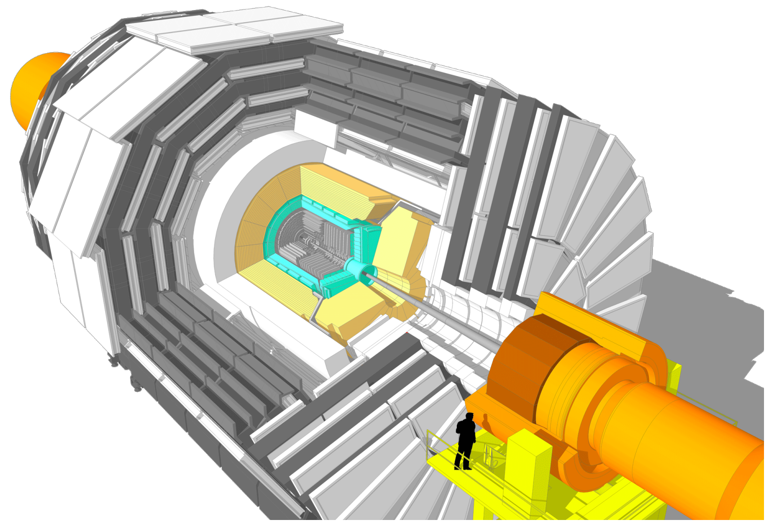
Evaluating the prospects

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

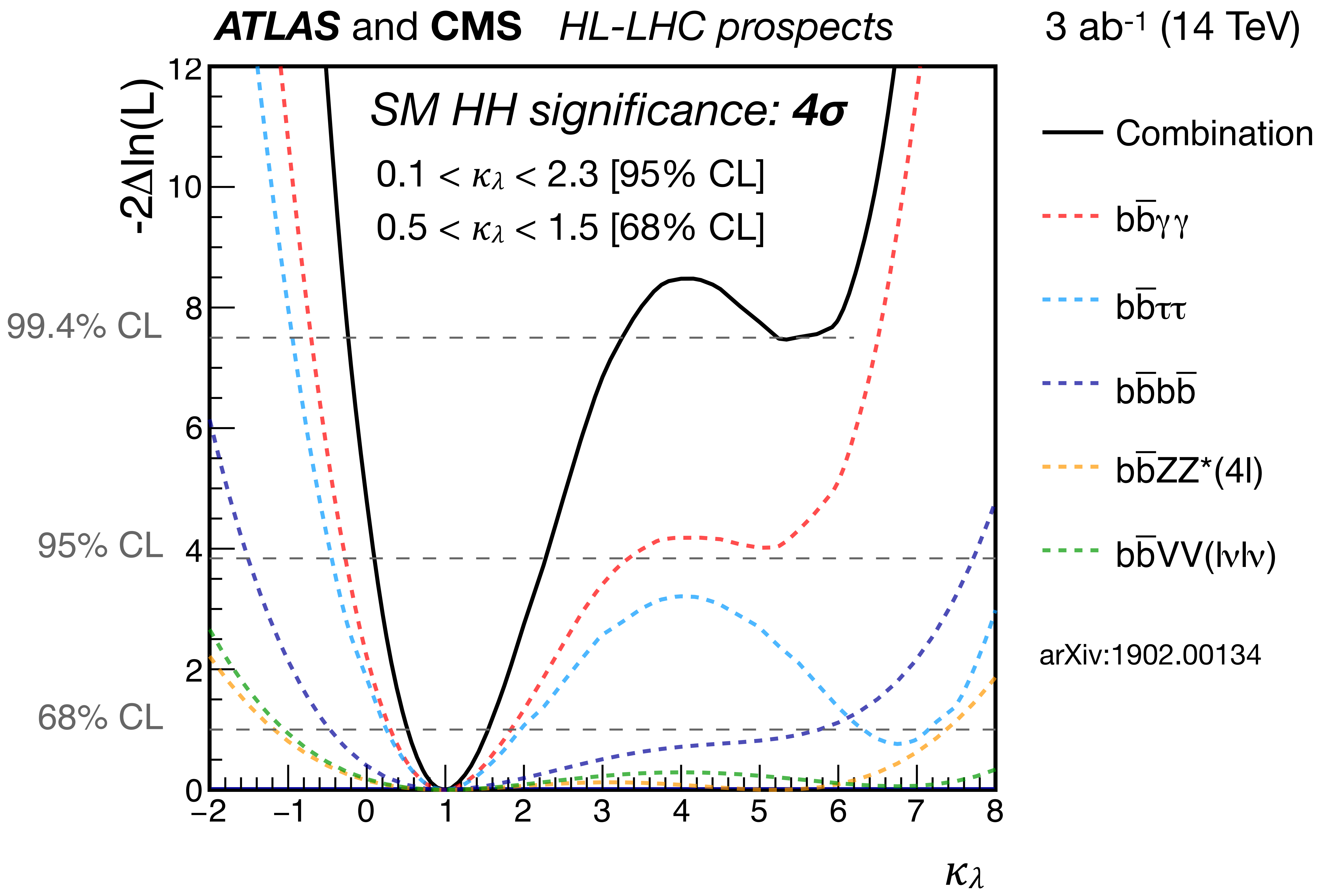
Analysis improvements

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

Assumptions based on Run 2 experience

HH 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 κλ 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 (κλ ≠ 0)

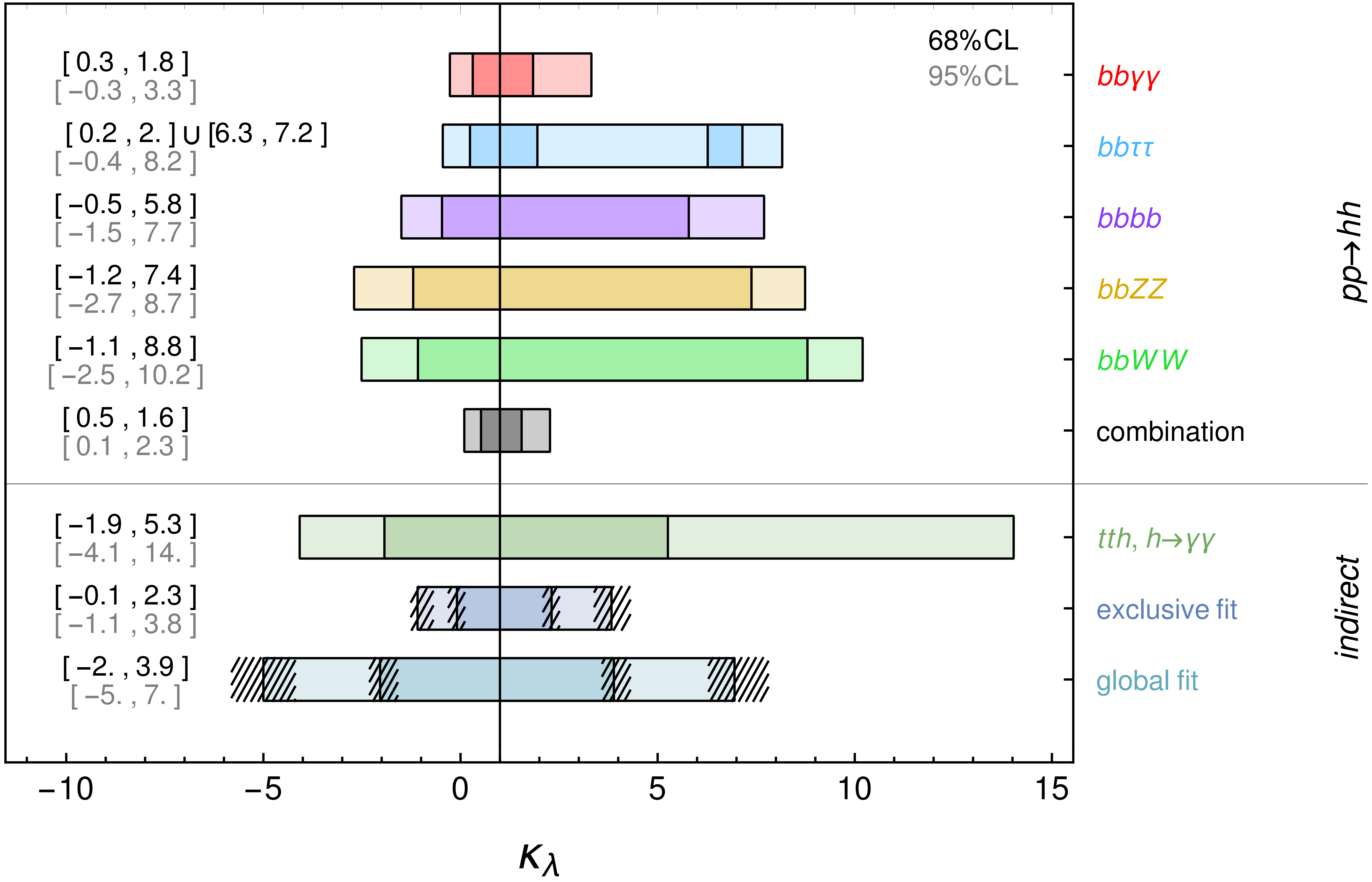


arXiv:1902.00134

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

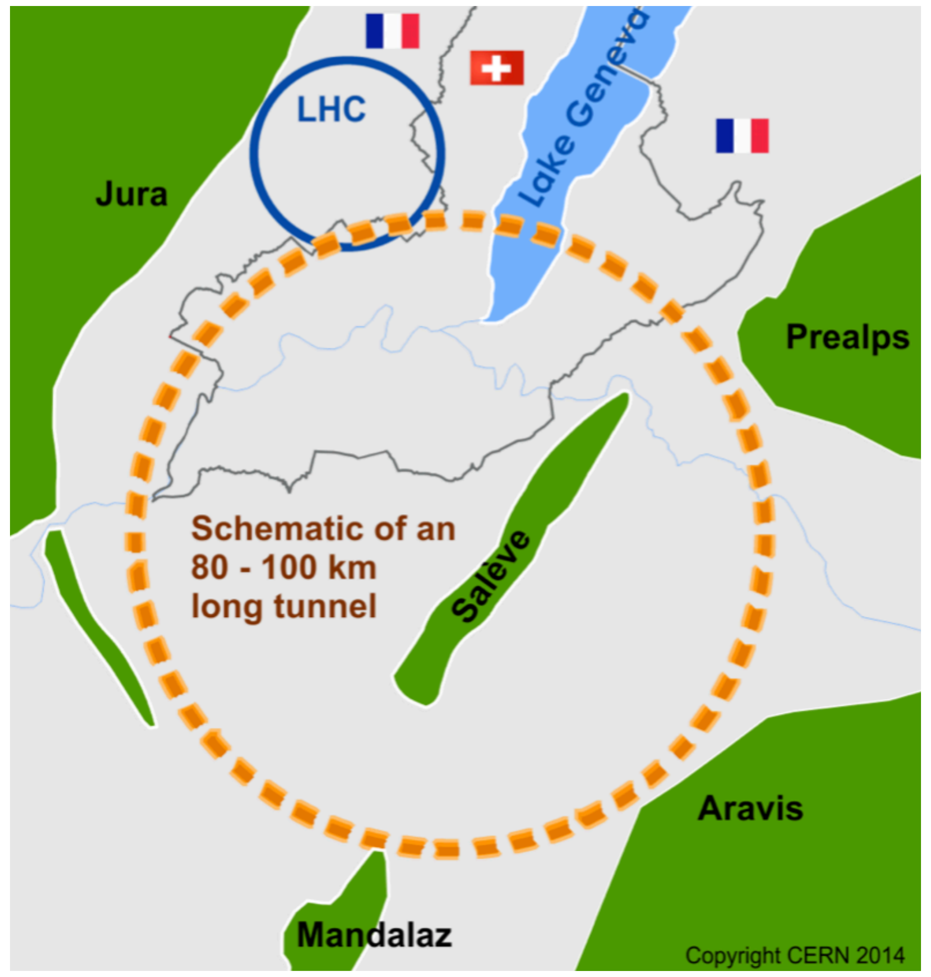
The HL-LHC view of λ_{HHH}

- 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



Future colliders : a general overview

pp colliders

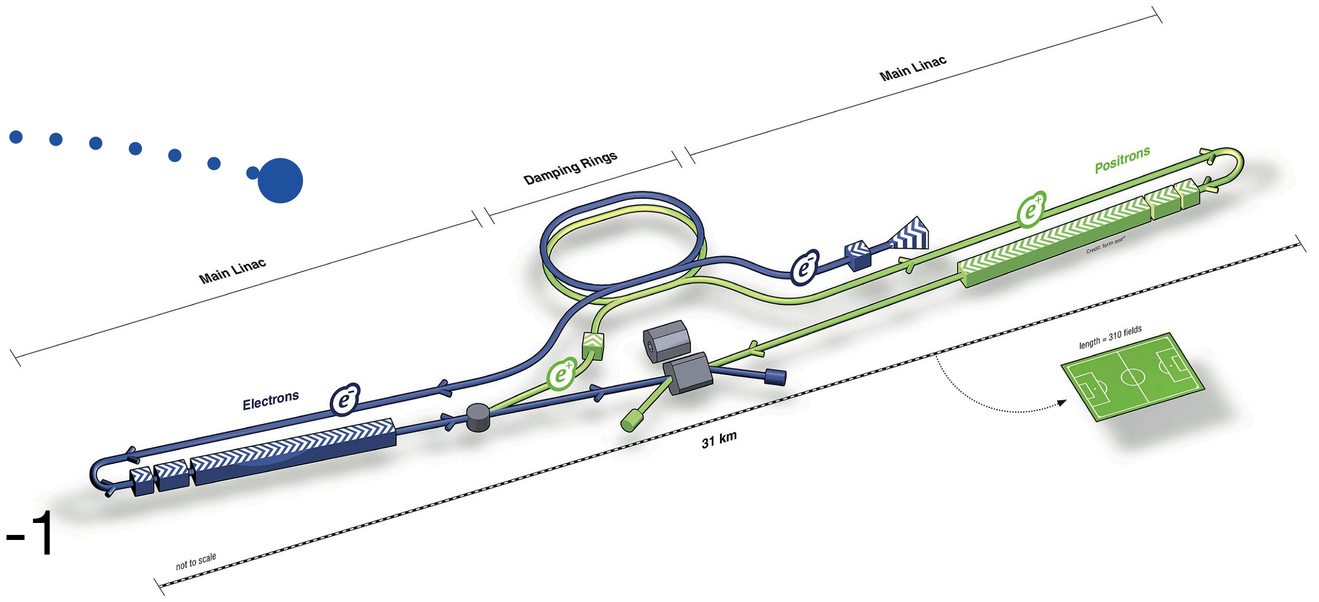


- FCC-hh
  - 100-km tunnel at CERN
  - 16 T magnets for 100 TeV
  - low-E (LE-FCC) option with 6 T magnets → 37 TeV
- HE-LHC
  - 16 T magnets in the LHC tunnel for 27 TeV

Towards high energies

e$^+$e$^-$ colliders

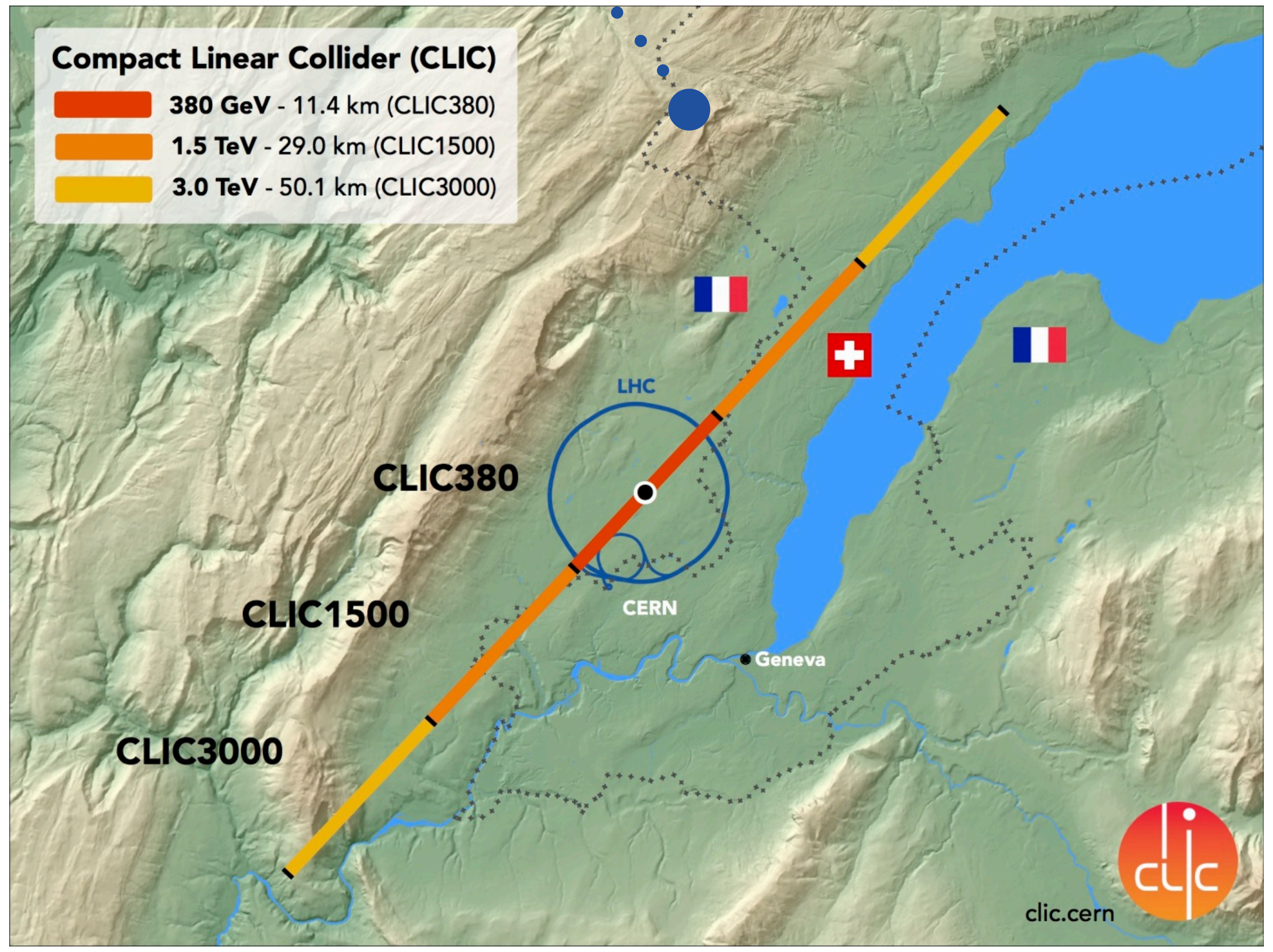
Linear colliders



- 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}

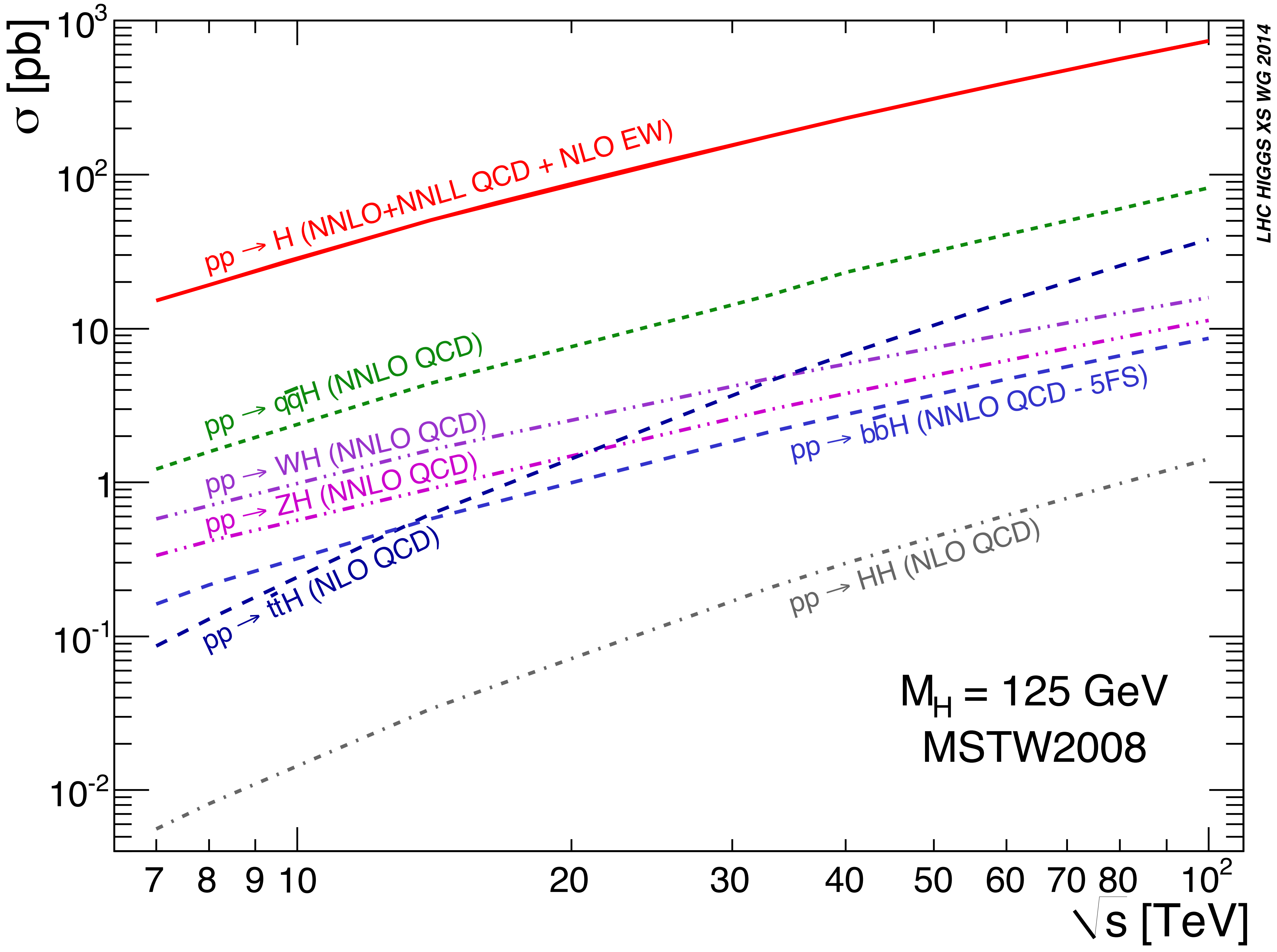
Circular colliders

- 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

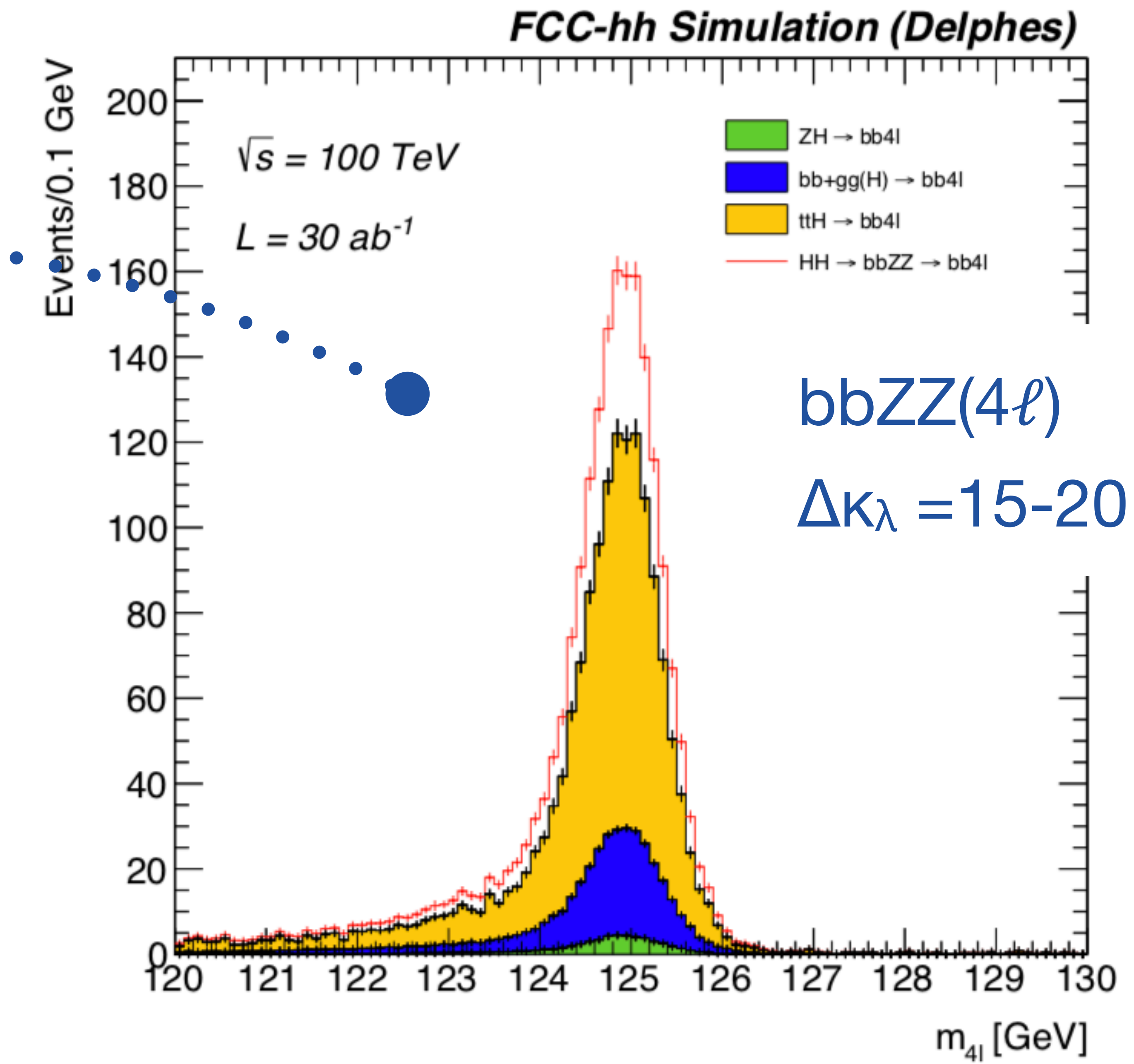
HH at future pp colliders



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)

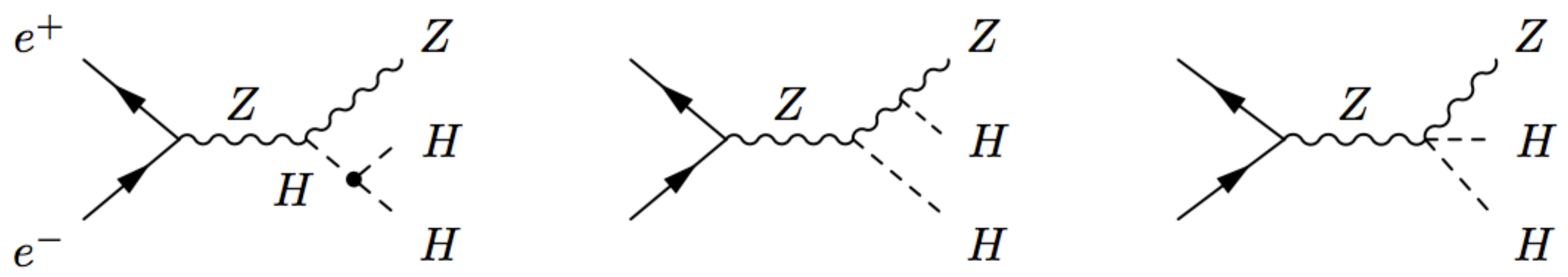
$\Delta\kappa_\lambda$ =15-20%

- 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

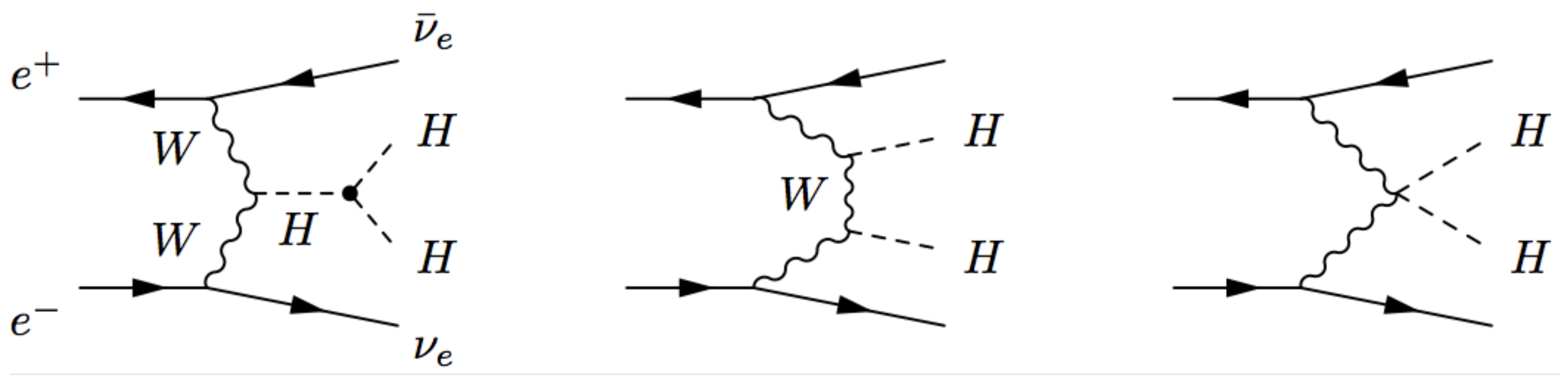
Benefit of the high energy and luminosity
Clean channels and new topologies used to fight the PU

HH at e^+e^- colliders

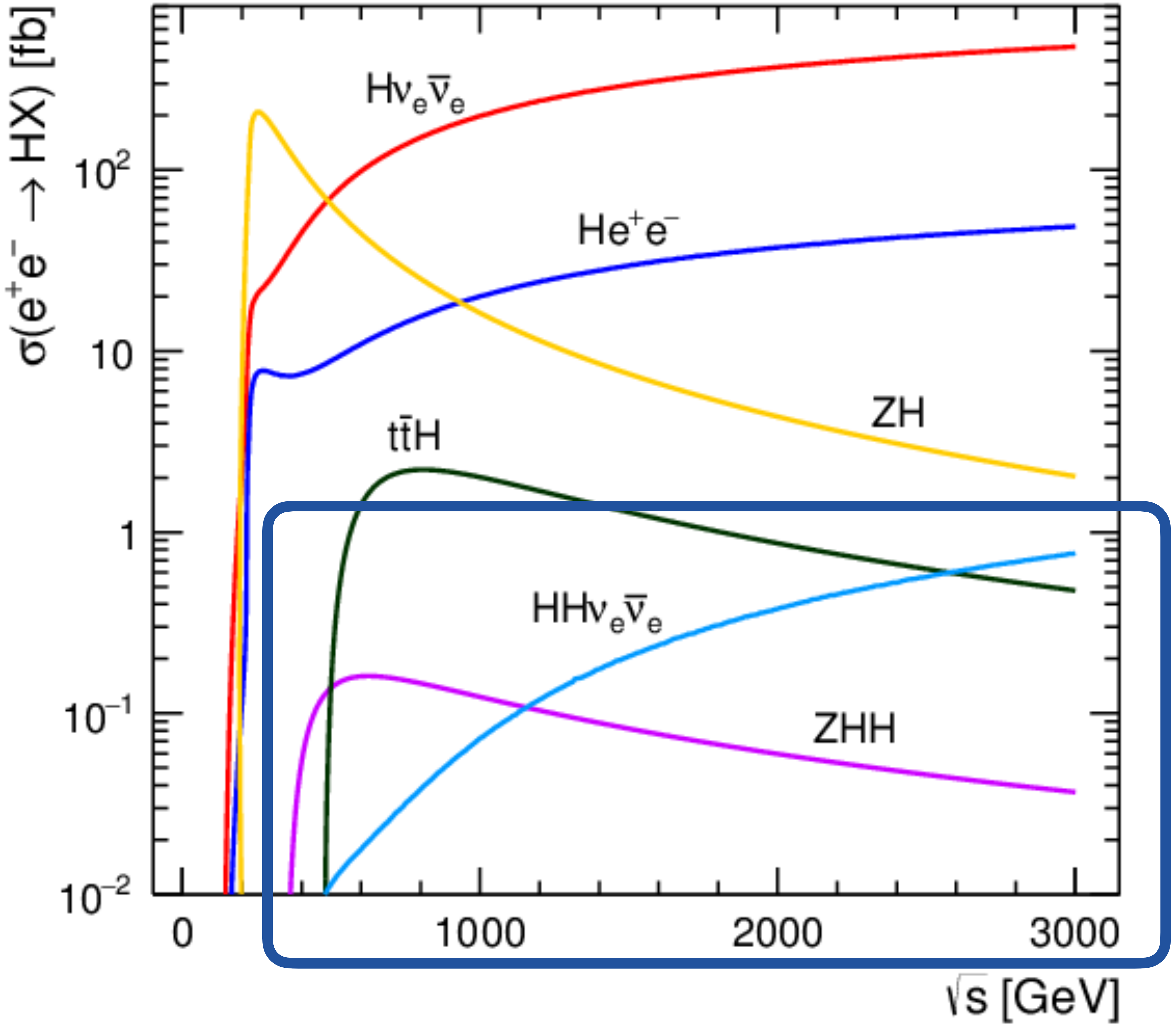
Z-strahlung



VBF



- $\sqrt{s} \gtrsim 400$ 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 $\sqrt{s} > 1$ TeV



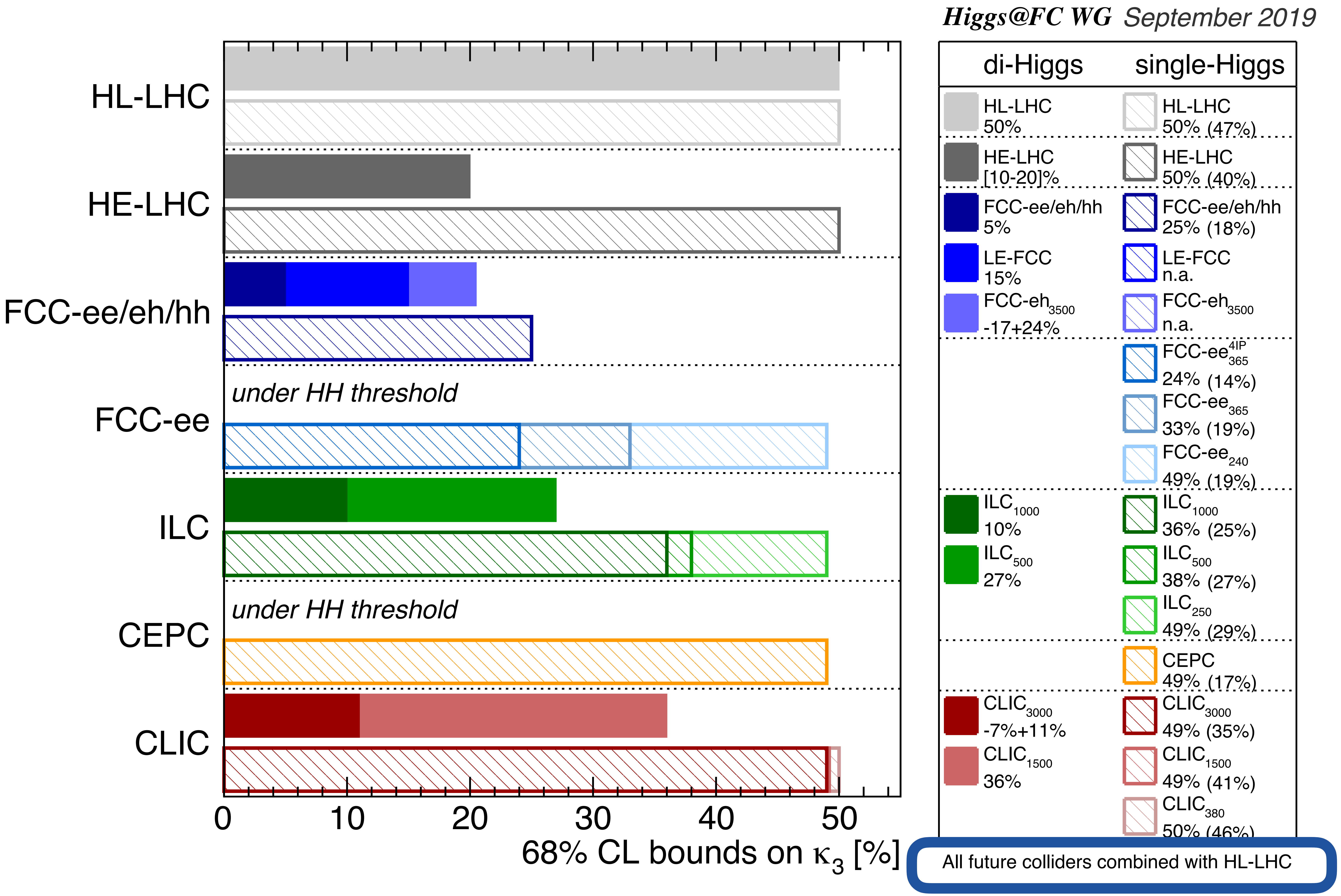
Comparison of the sensitivities

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 ▨

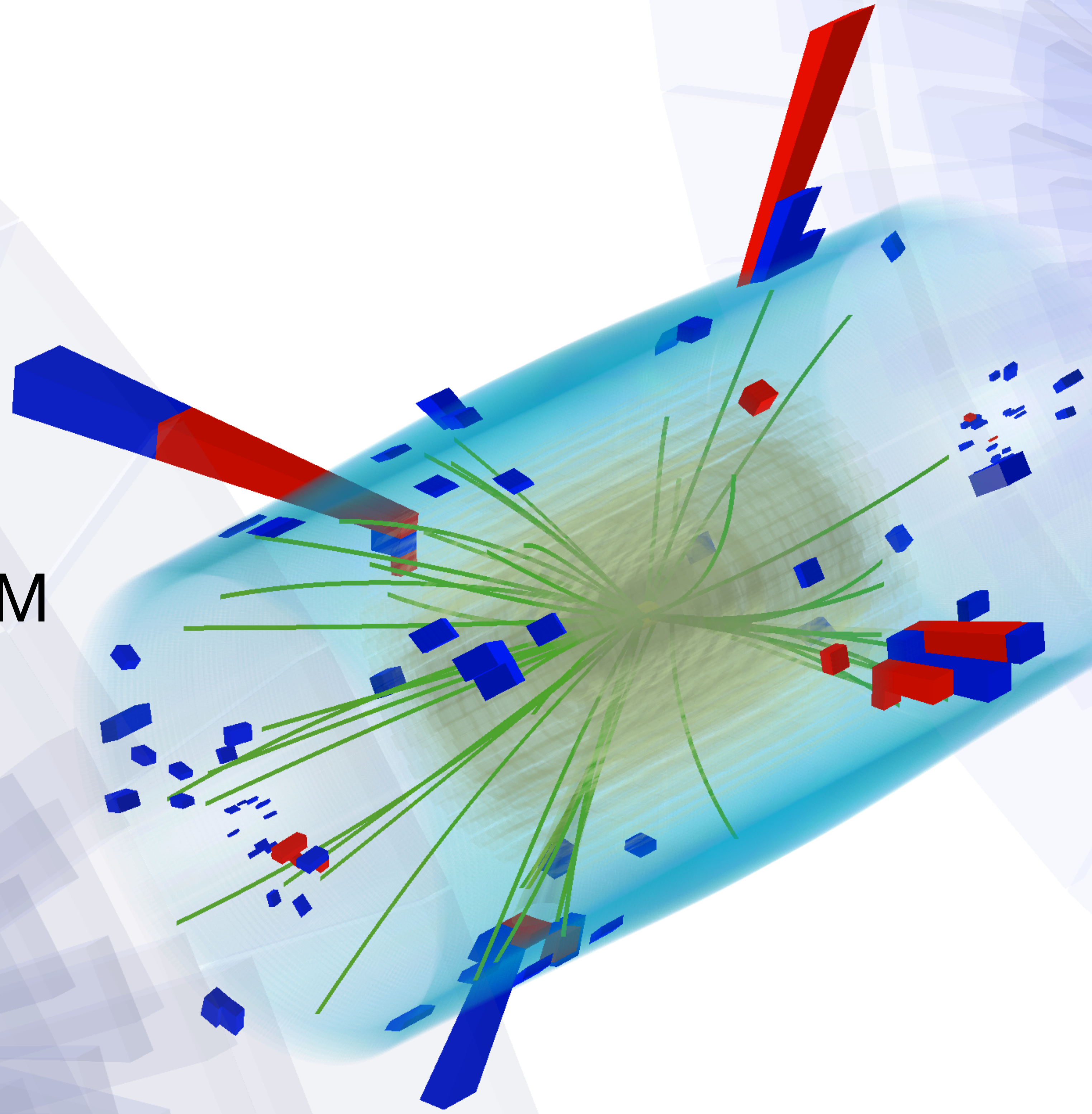
- limited by HH HL-LHC reach until higher energies and luminosities are achieved



All future colliders combined with HL-LHC

Conclusions

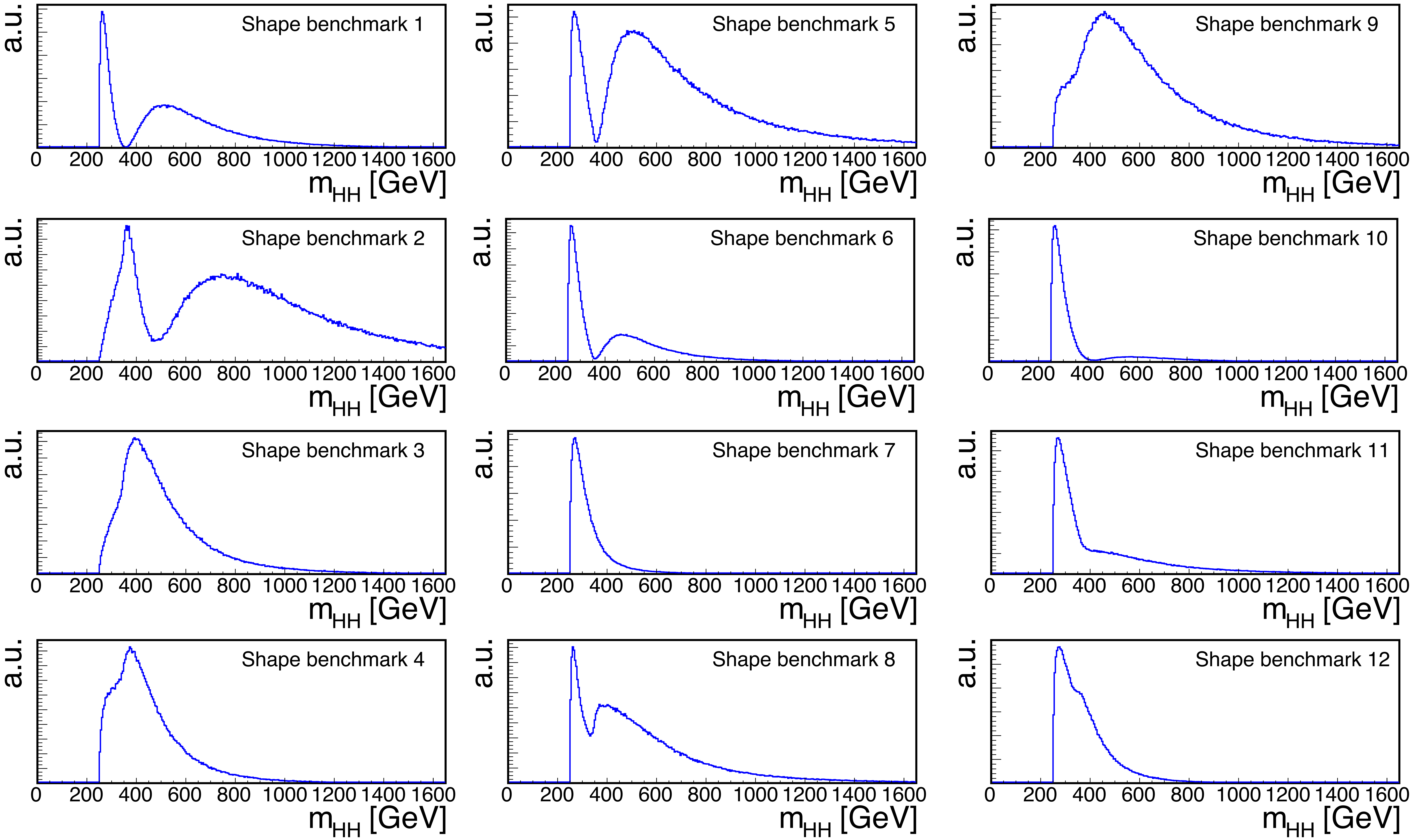
- The shape of the Higgs potential is so far largely unknown
  - ☐ its measurement will deepen our understanding of the scalar sector
- HH measurements give direct access to λ_{HHH}
  - ☐ small cross section : experimentally challenging
  - ☐ crucial to explore and combine several decay channels
  - ☐ 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
  - ☐ a full EFT view as the way to move forward
- Full Run 2 dataset under analysis, 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

HH shape benchmarks

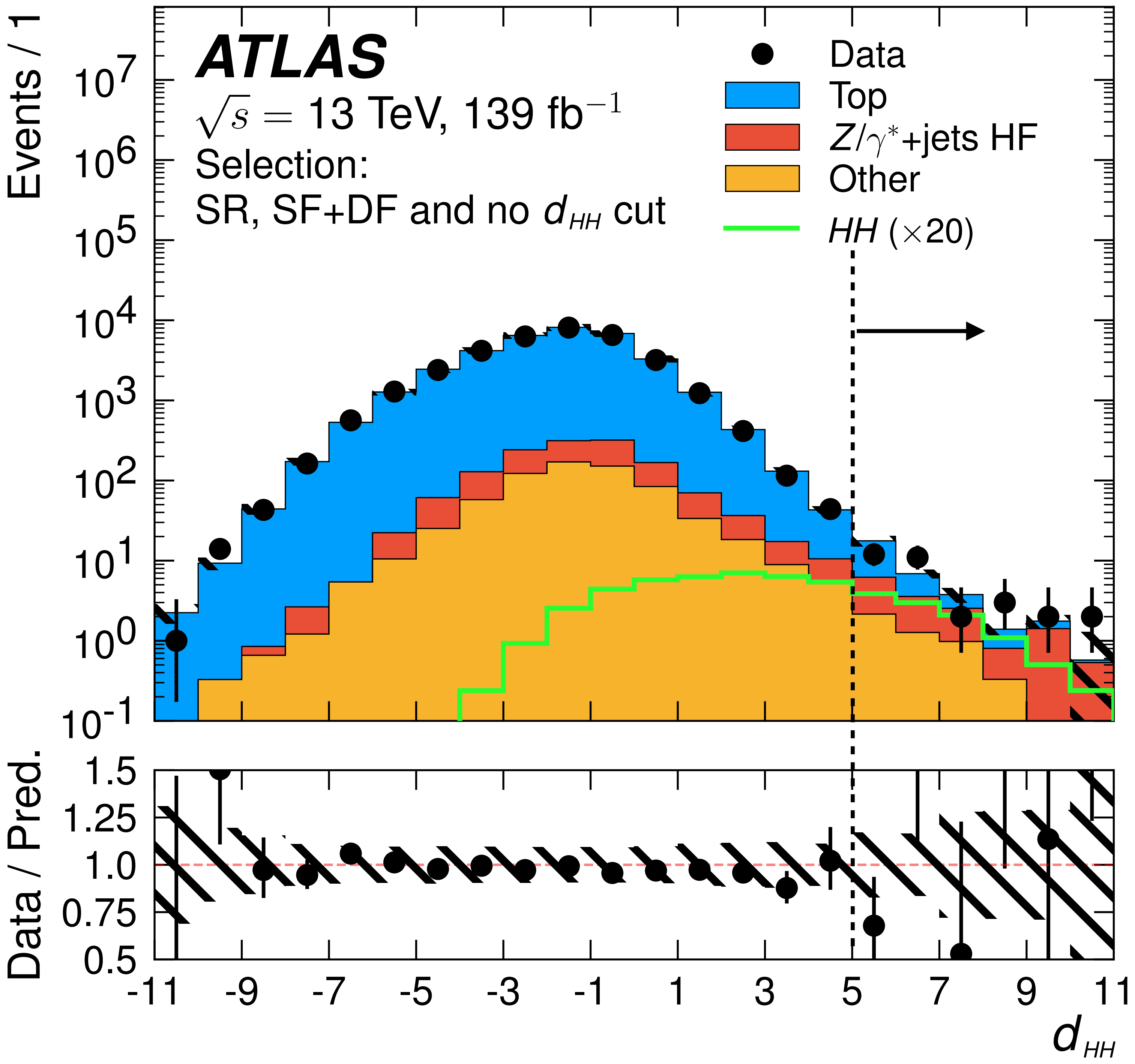


Nr.	k_λ	k_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1.0
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1.0	1.0
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1.0	-1.0
12	15.0	1.0	1.0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

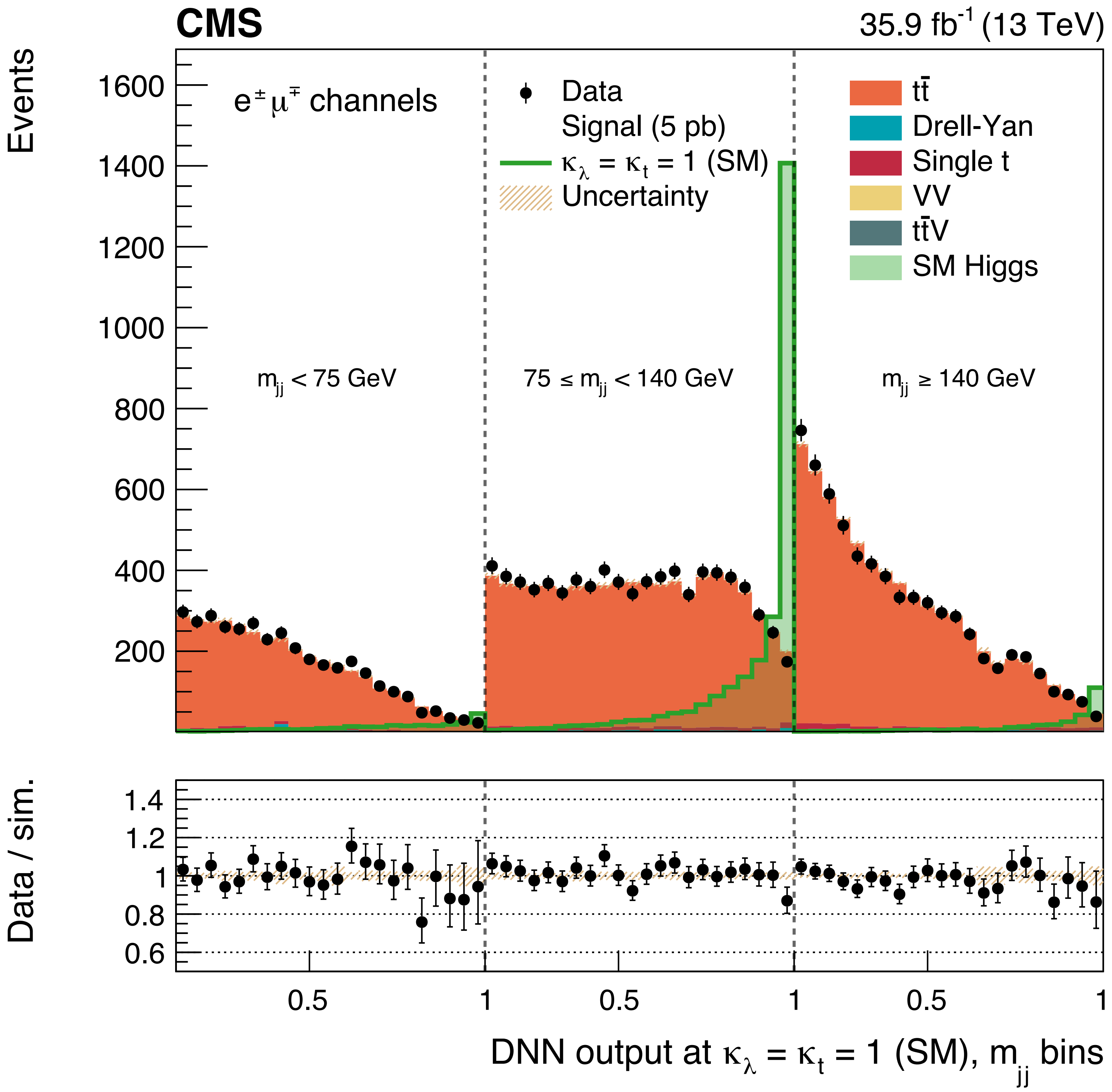
HH → bbWW

Irreducible tt background

Advanced ML methods for signal identification



Obs. (Exp.) : 40 (29) × σ_{HH}^{SM}

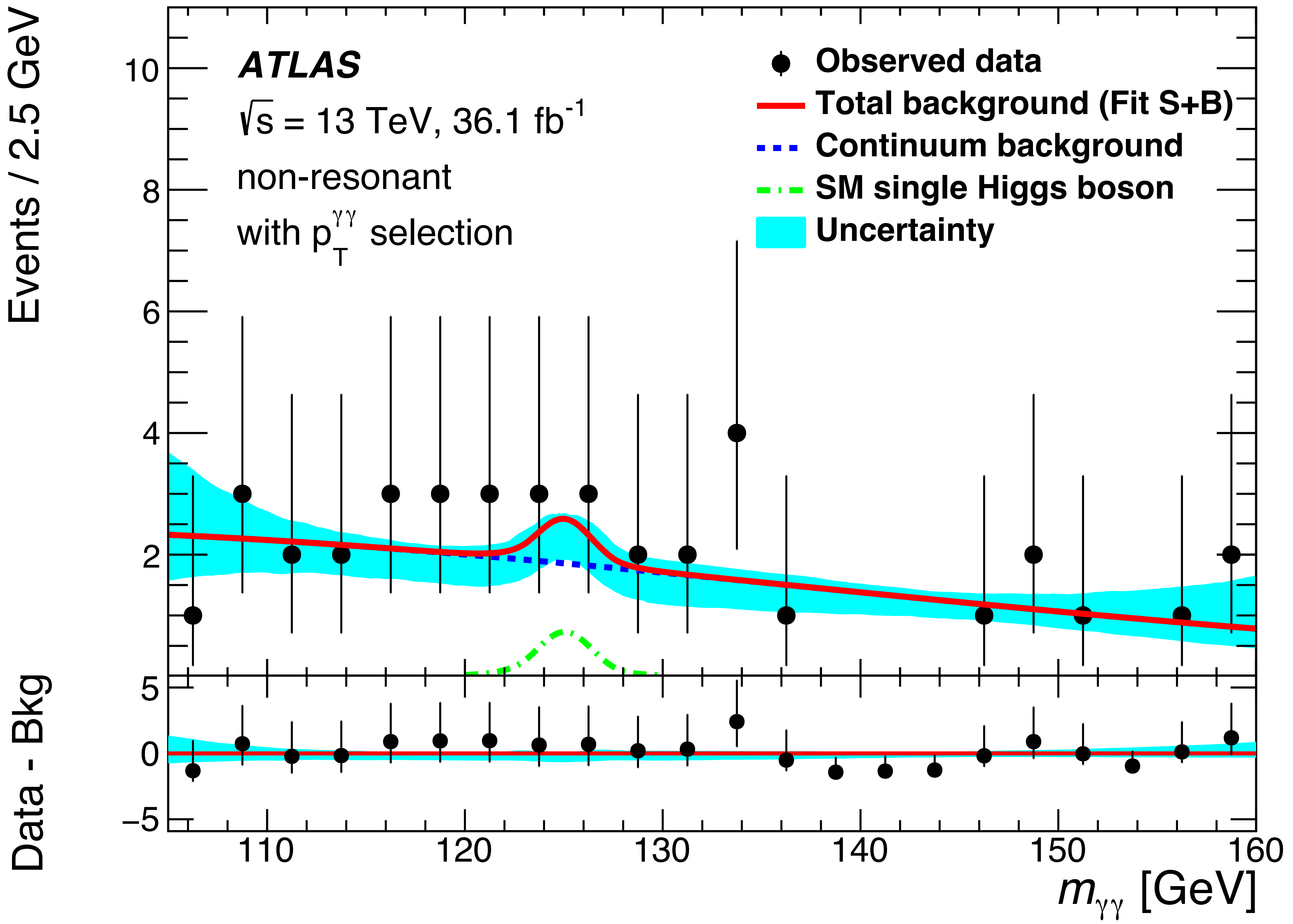


Obs. (Exp.) : 78.6 (88.8) × σ_{HH}^{SM}

- Target $WW \rightarrow \ell\nu\ell\nu$ 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

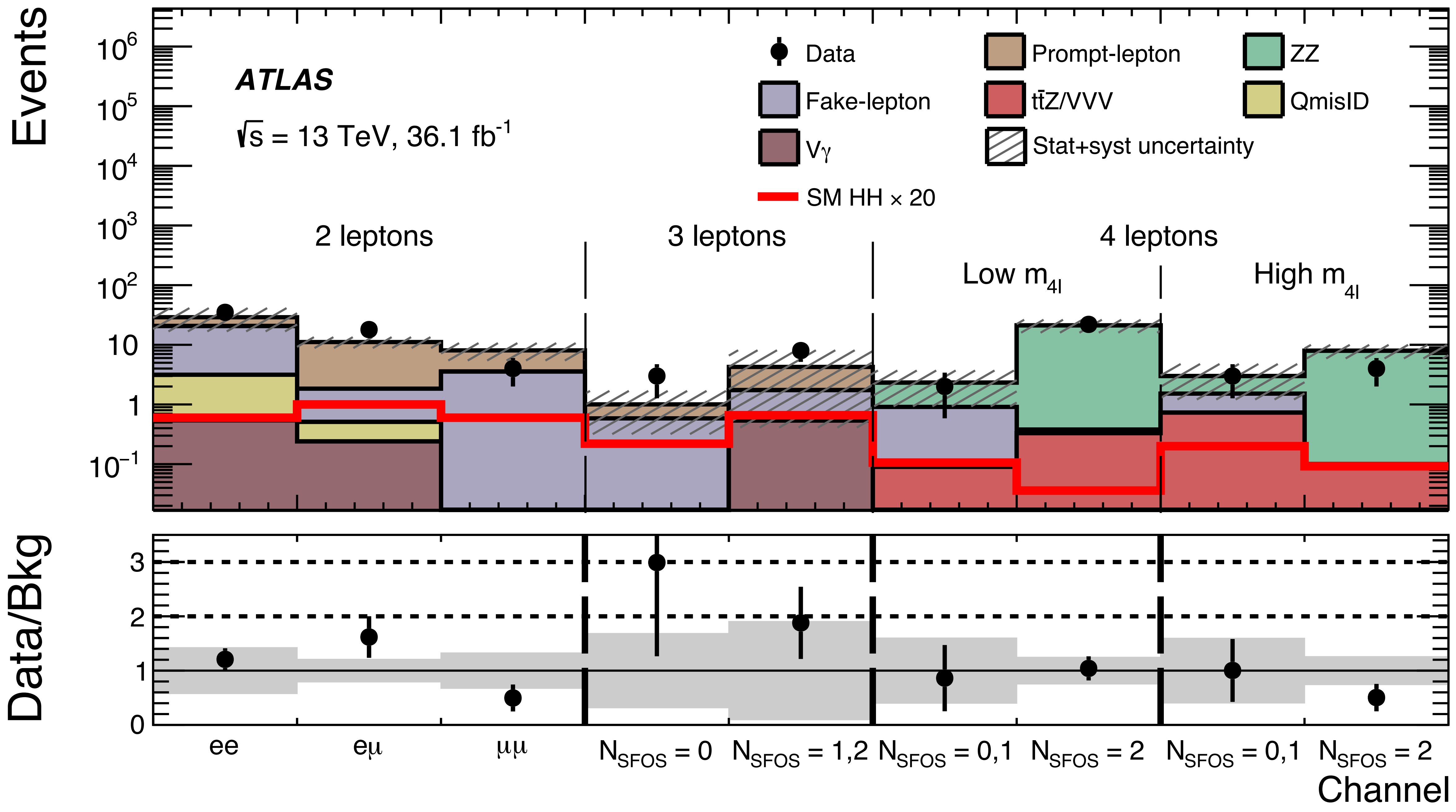
Rare HH channels

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



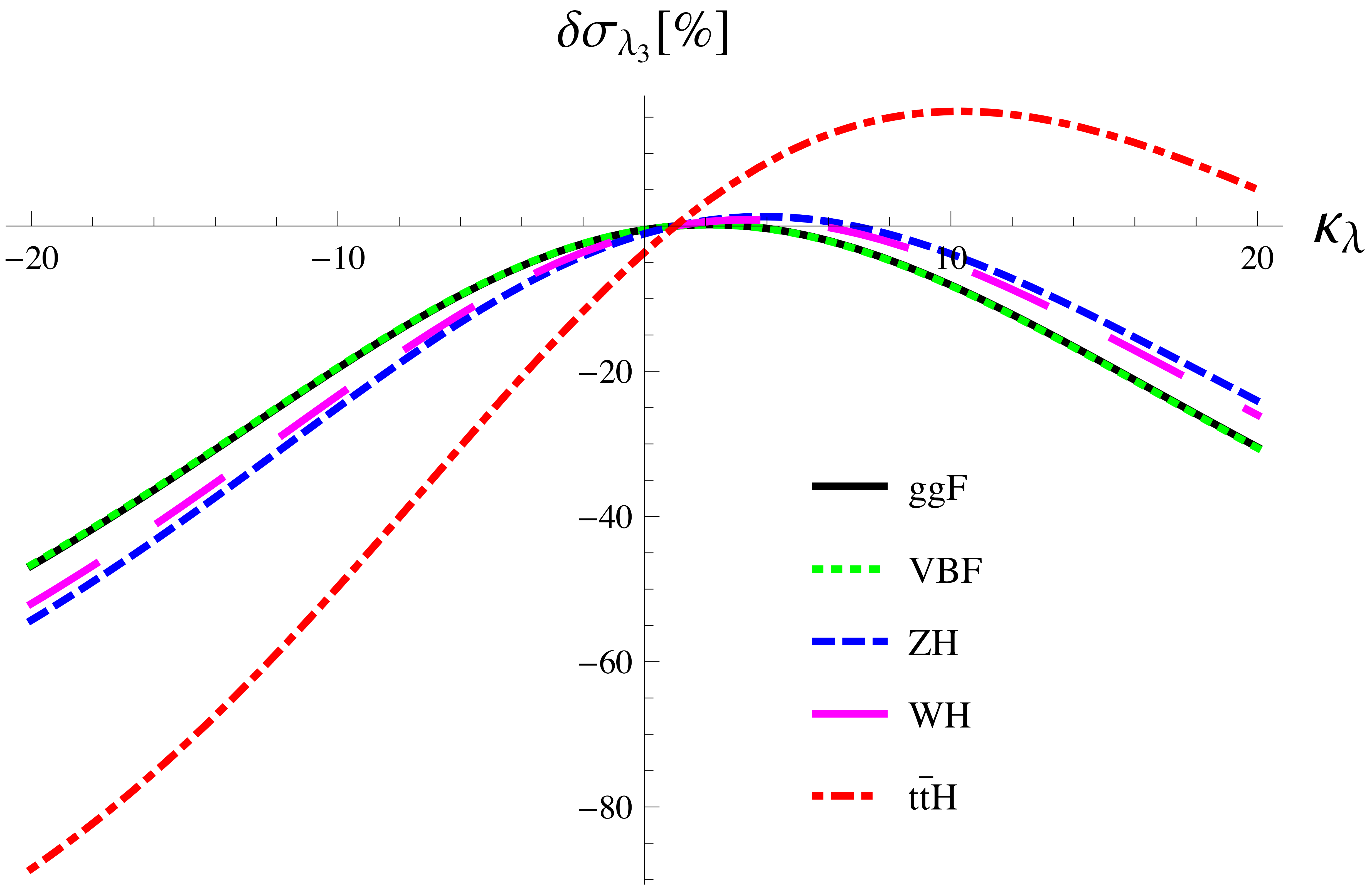
- Targets WW→$\ell\nu$qq decays
- Look for a signal using the $m_{\gamma\gamma}$ spectrum

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

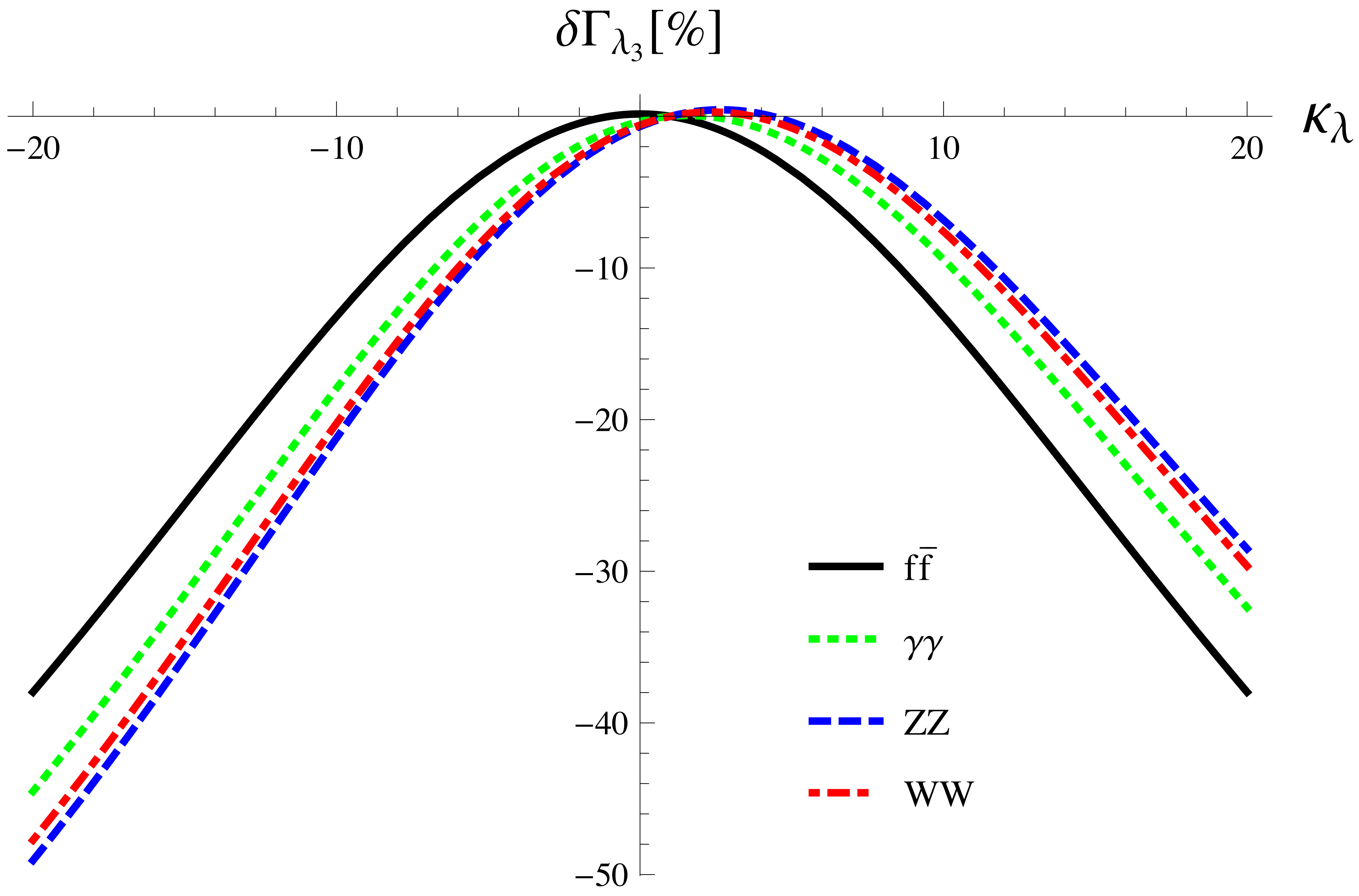


- 2ℓ, 3ℓ, 4ℓ final states, veto on b jets
- Prompt and fake lepton backgrounds from control regions
- Counting experiment in each region

Single Higgs effects from λ_{HHH}

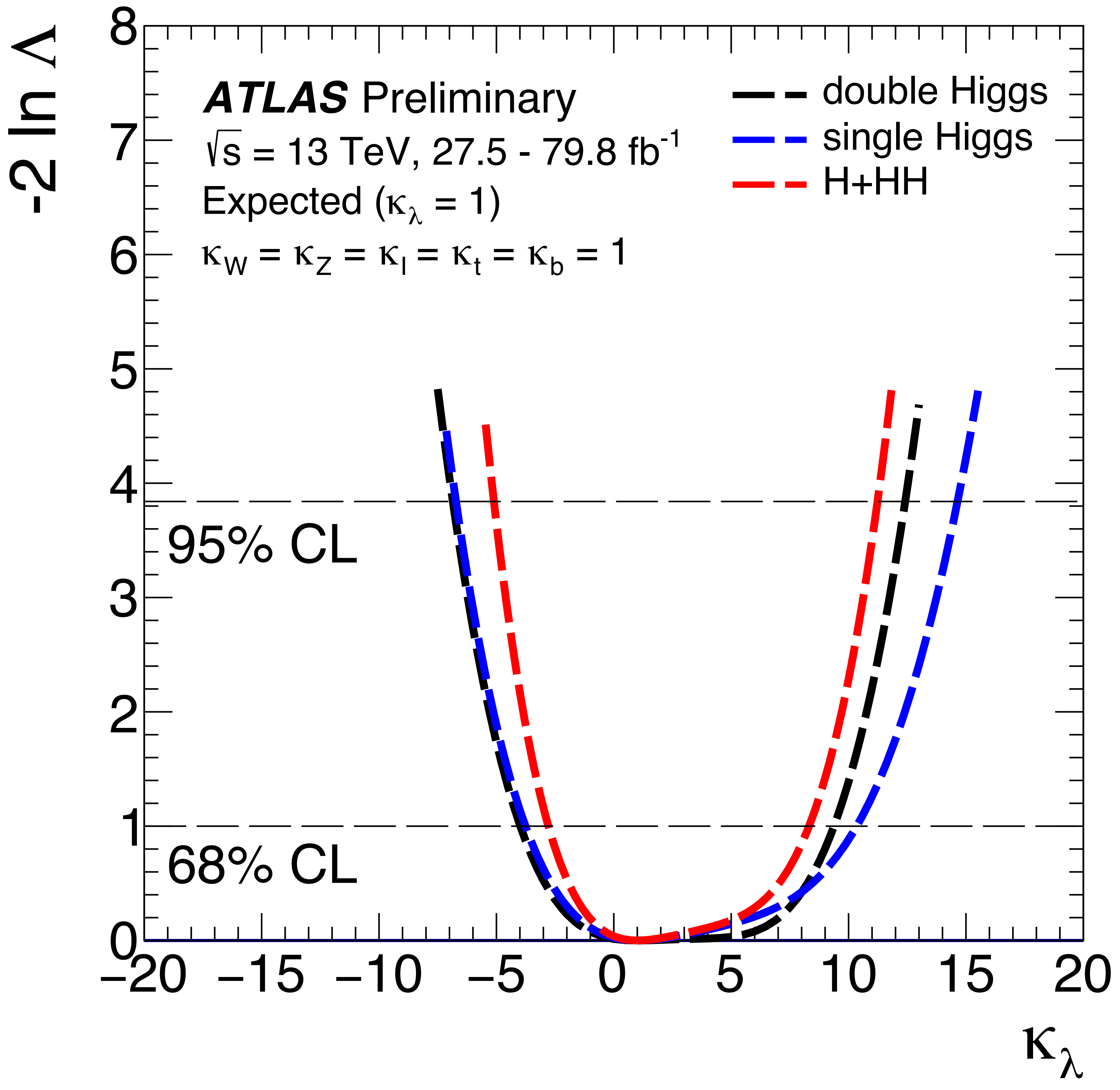


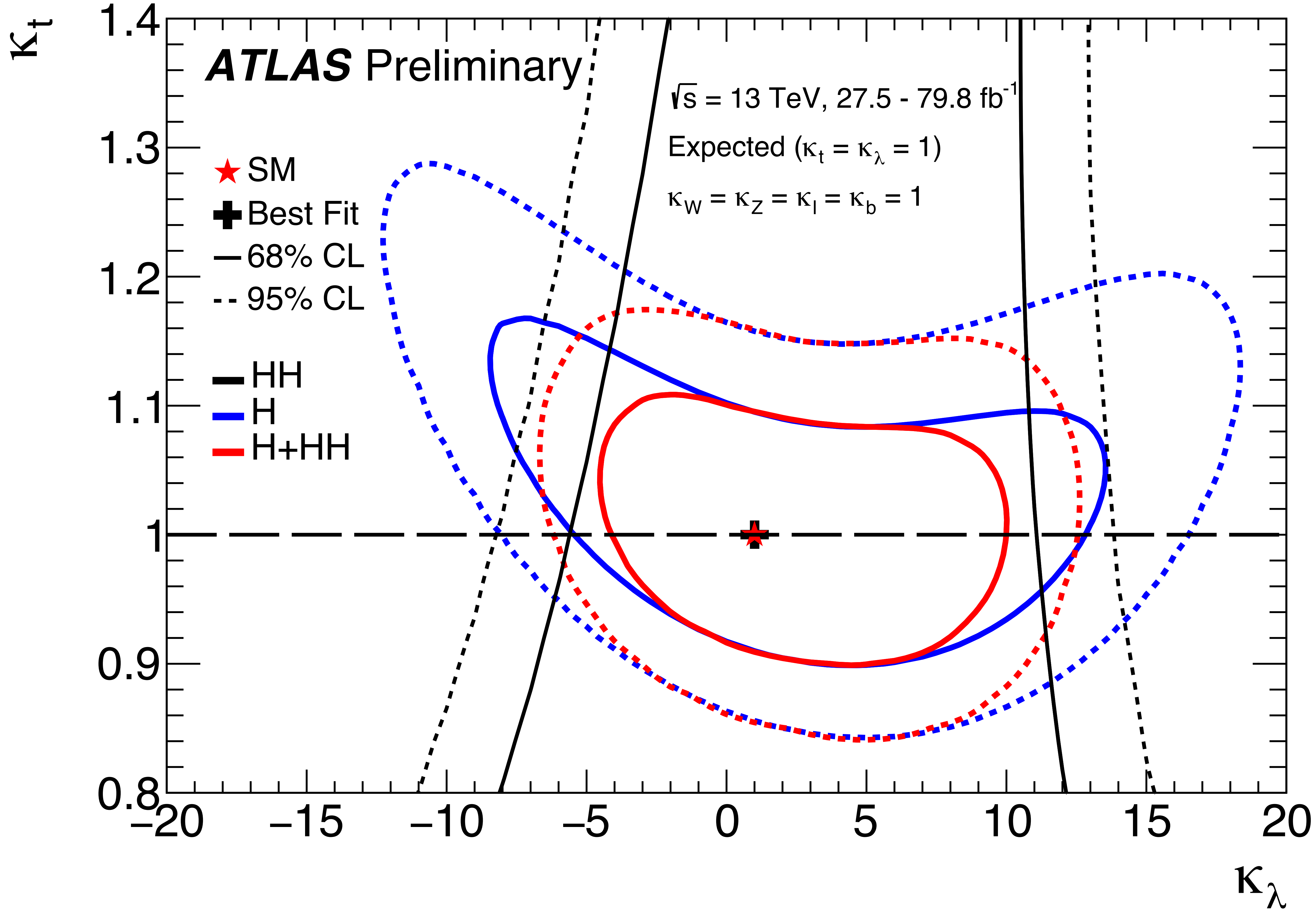
Cross section



Branching fraction

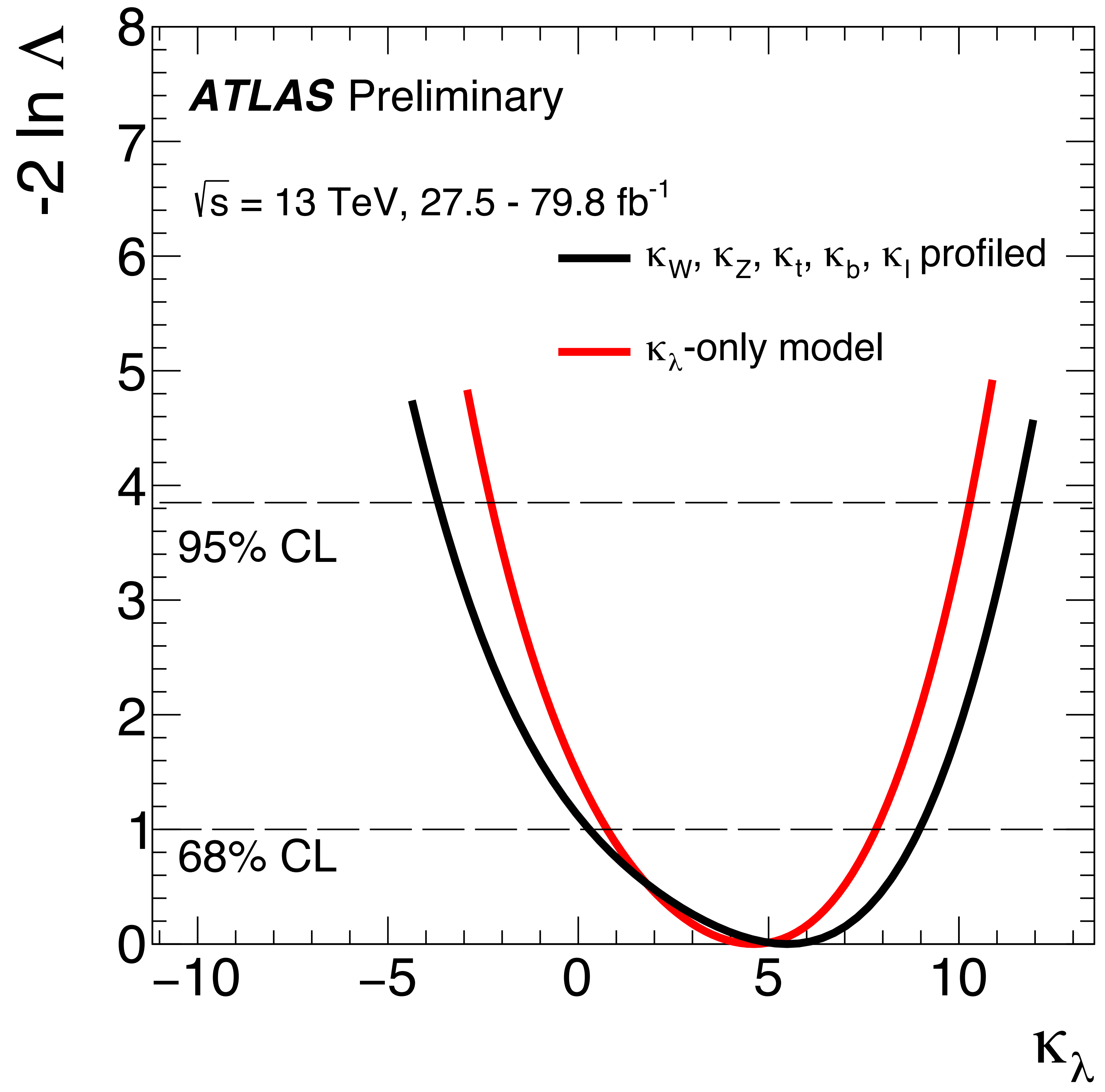
H + HH : expected results

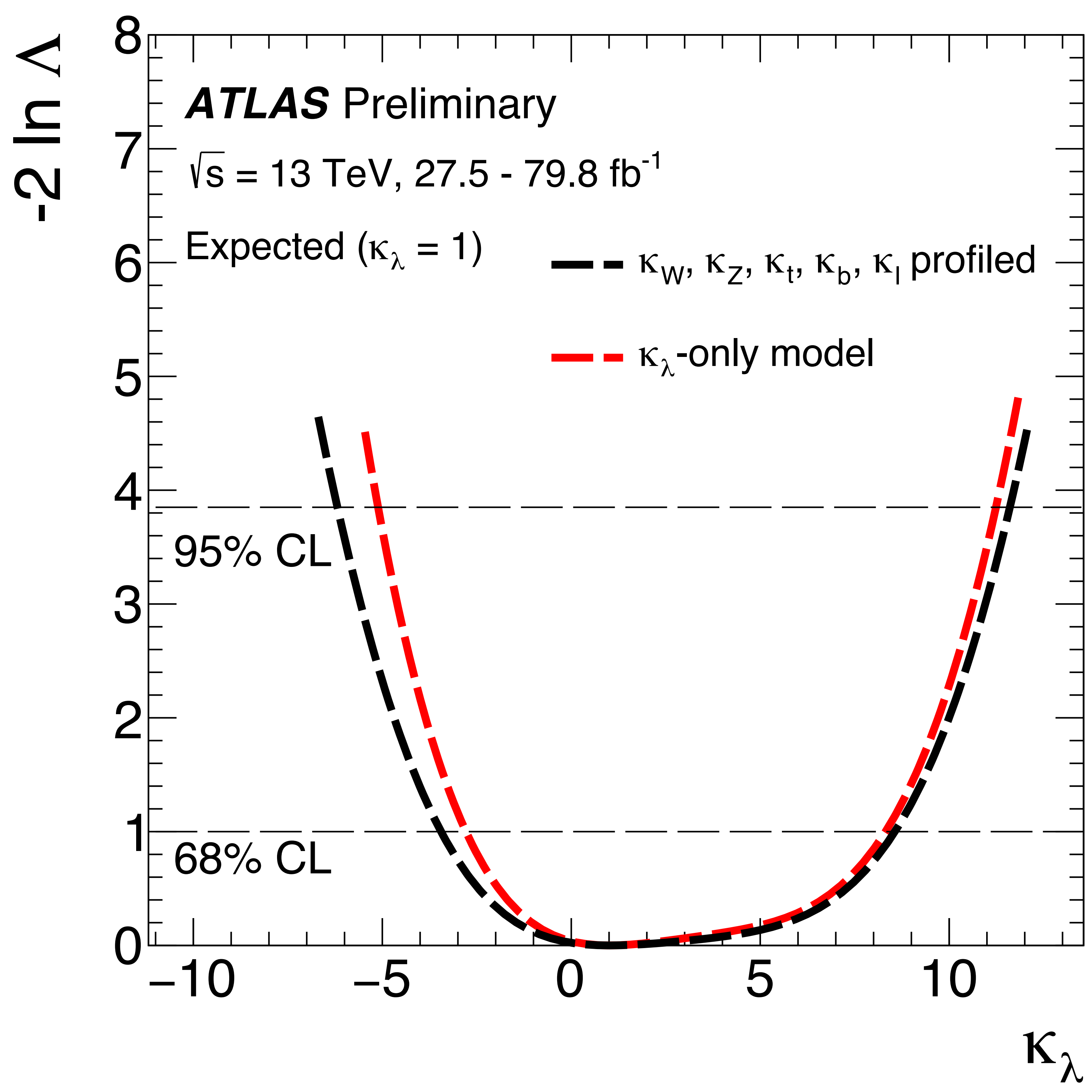




$k_\lambda = 1.0^{+7.3}_{-3.8}$

H + HH : fixed vs floating κ

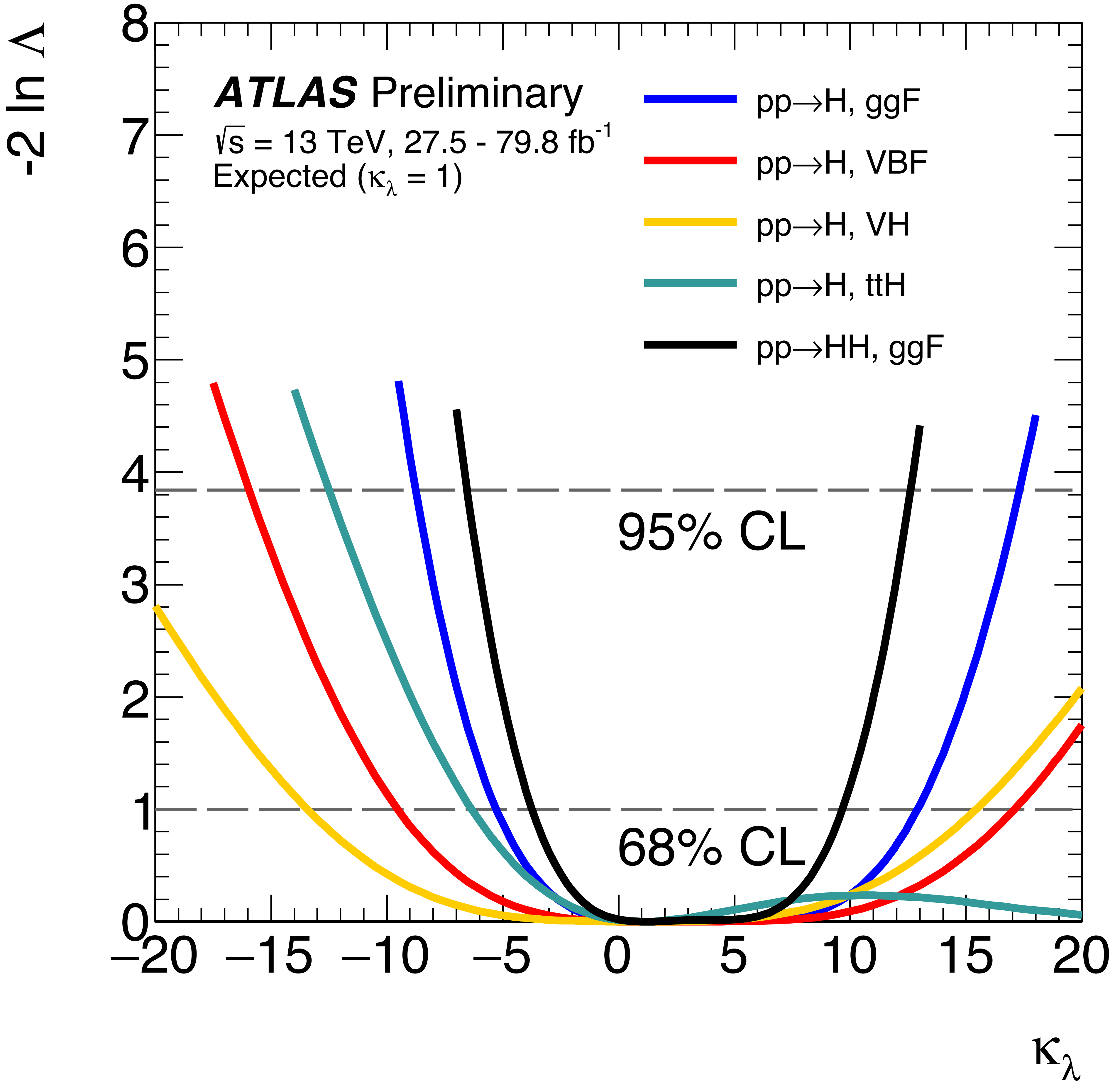


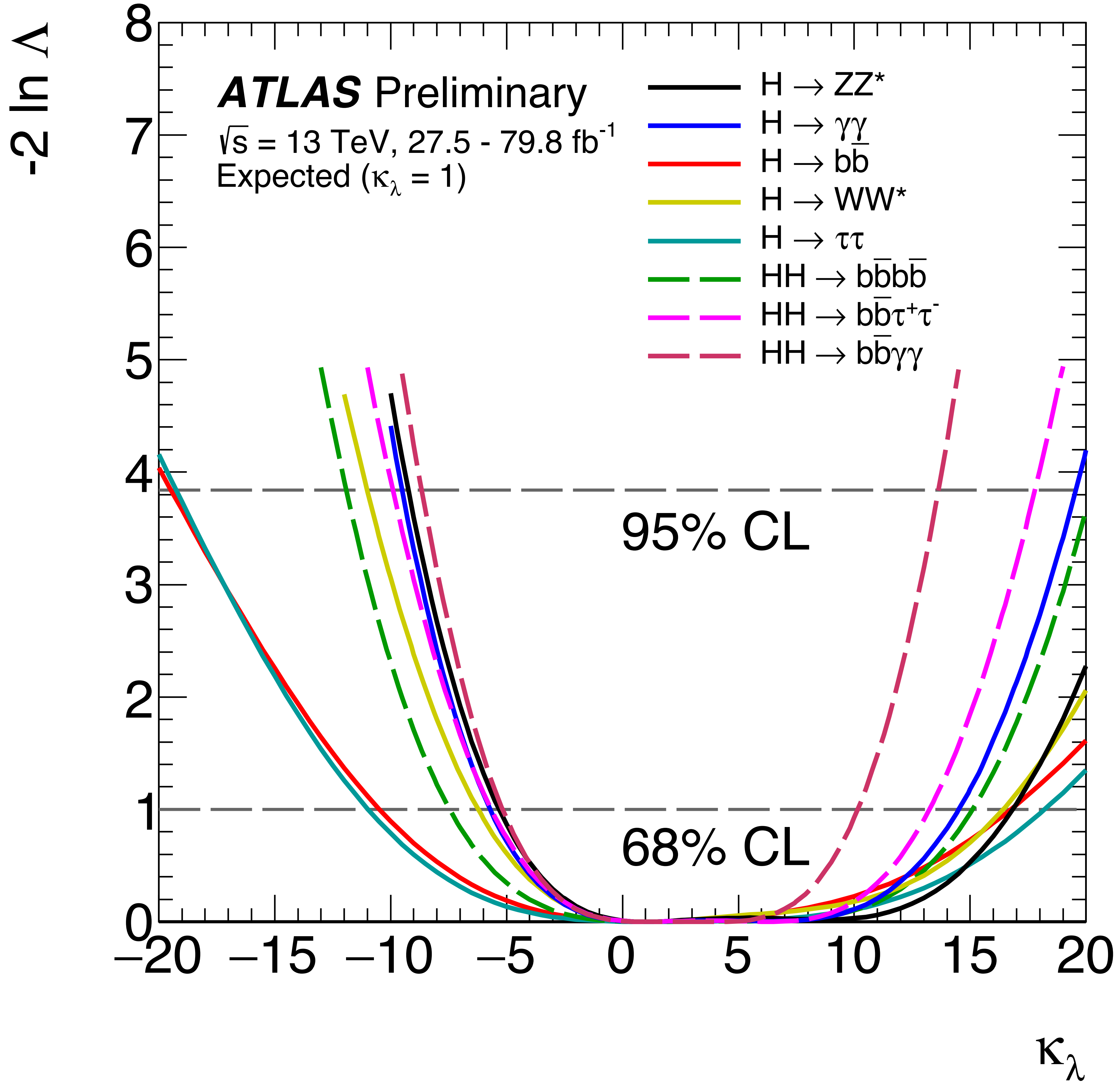


Model	$\kappa_W{}^{+1\sigma}_{-1\sigma}$	$\kappa_Z{}^{+1\sigma}_{-1\sigma}$	$\kappa_t{}^{+1\sigma}_{-1\sigma}$	$\kappa_b{}^{+1\sigma}_{-1\sigma}$	$\kappa_\ell{}^{+1\sigma}_{-1\sigma}$	$\kappa_\lambda{}^{+1\sigma}_{-1\sigma}$	κ_λ [95% CL]	
Generic	$1.03^{+0.08}_{-0.08}$	$1.10^{+0.09}_{-0.09}$	$1.00^{+0.12}_{-0.11}$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

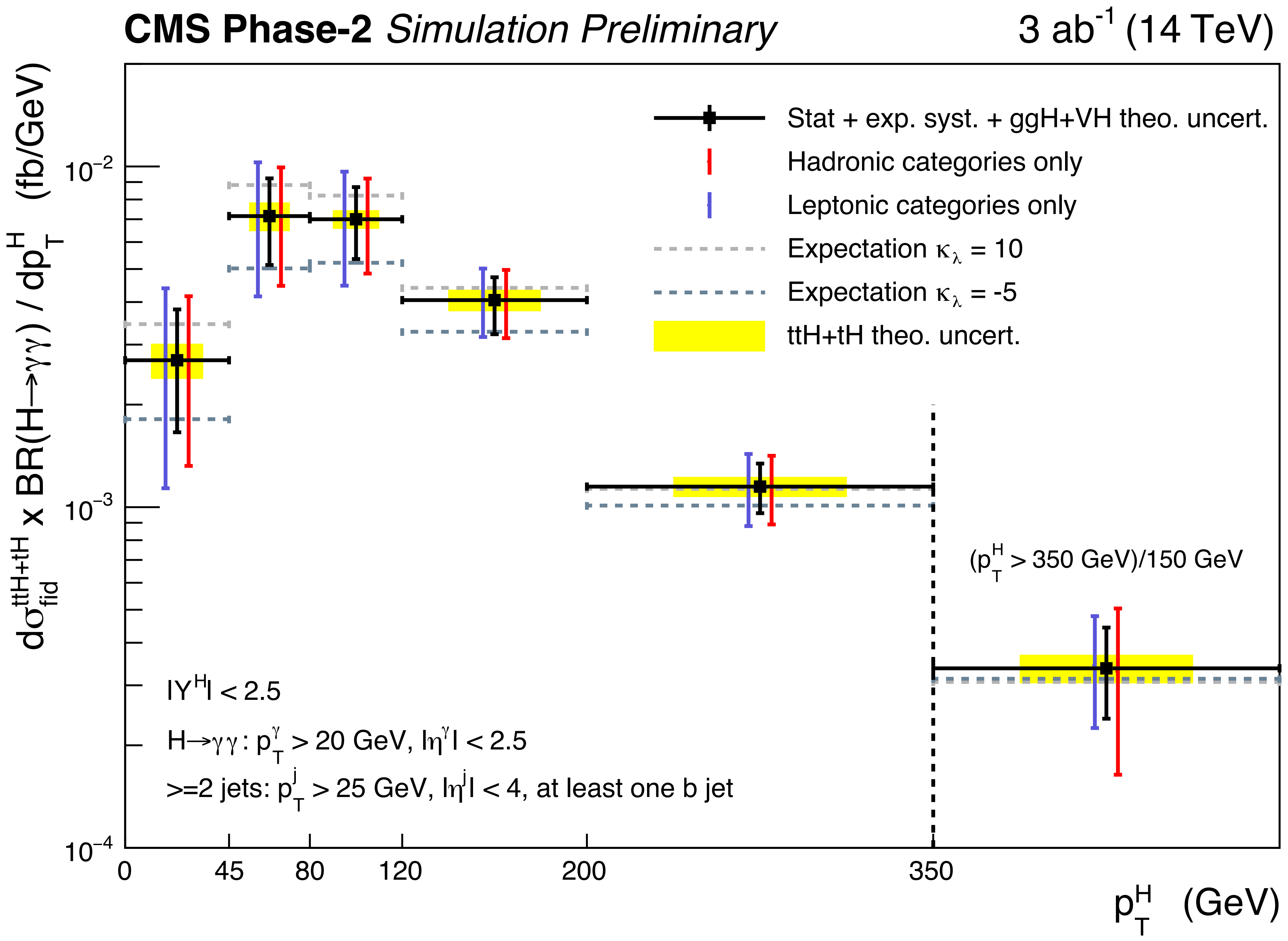
H + HH : input comparison

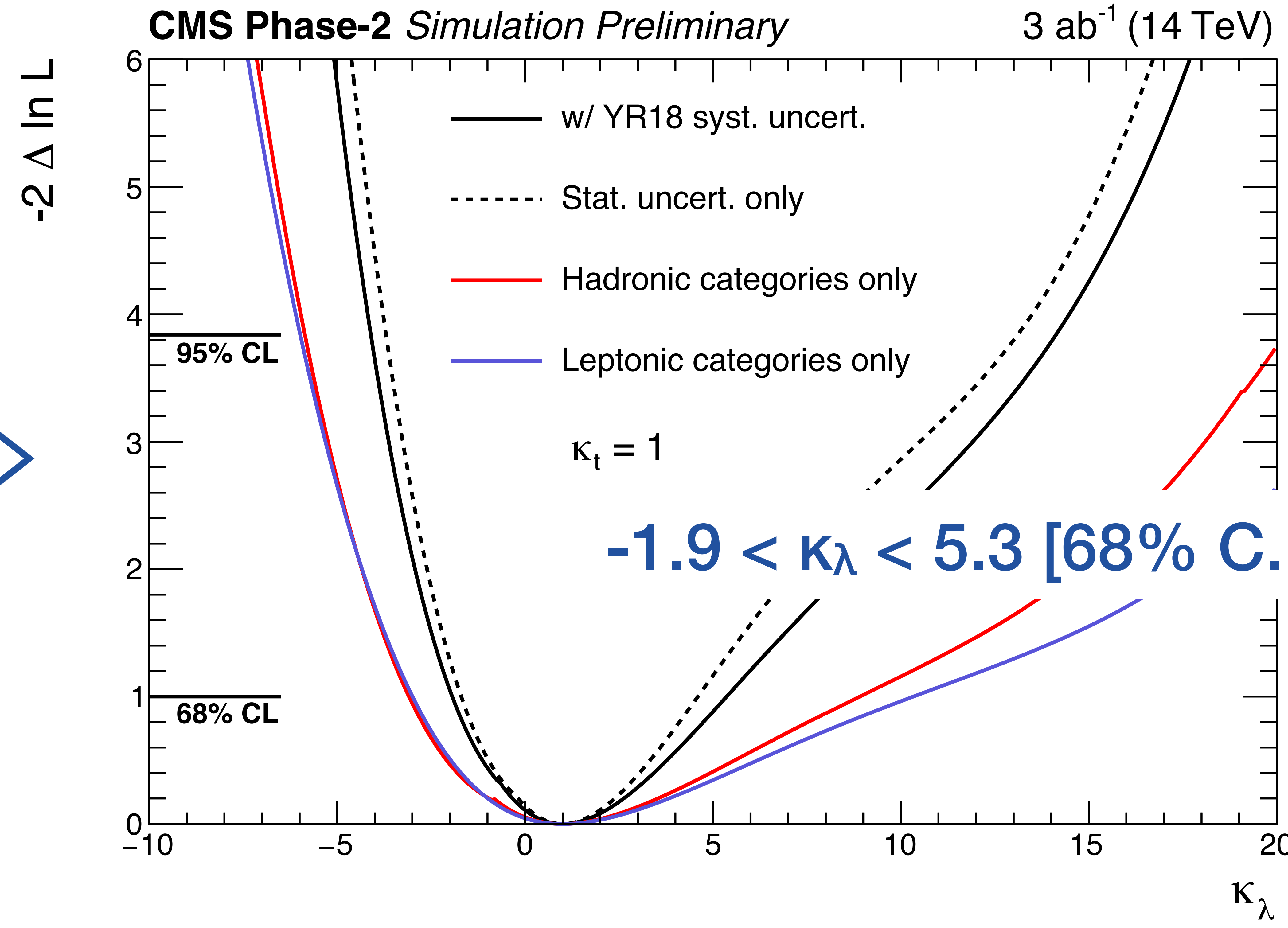




- HH drives the sensitivity
- ggF is the most sensitive single H production mode
  - sensitivity from total cross-section
- ttH not sensitive for $\kappa_\lambda > 0$ because of the degeneracy (second minimum) in the cross-section

Using the differential information in single H



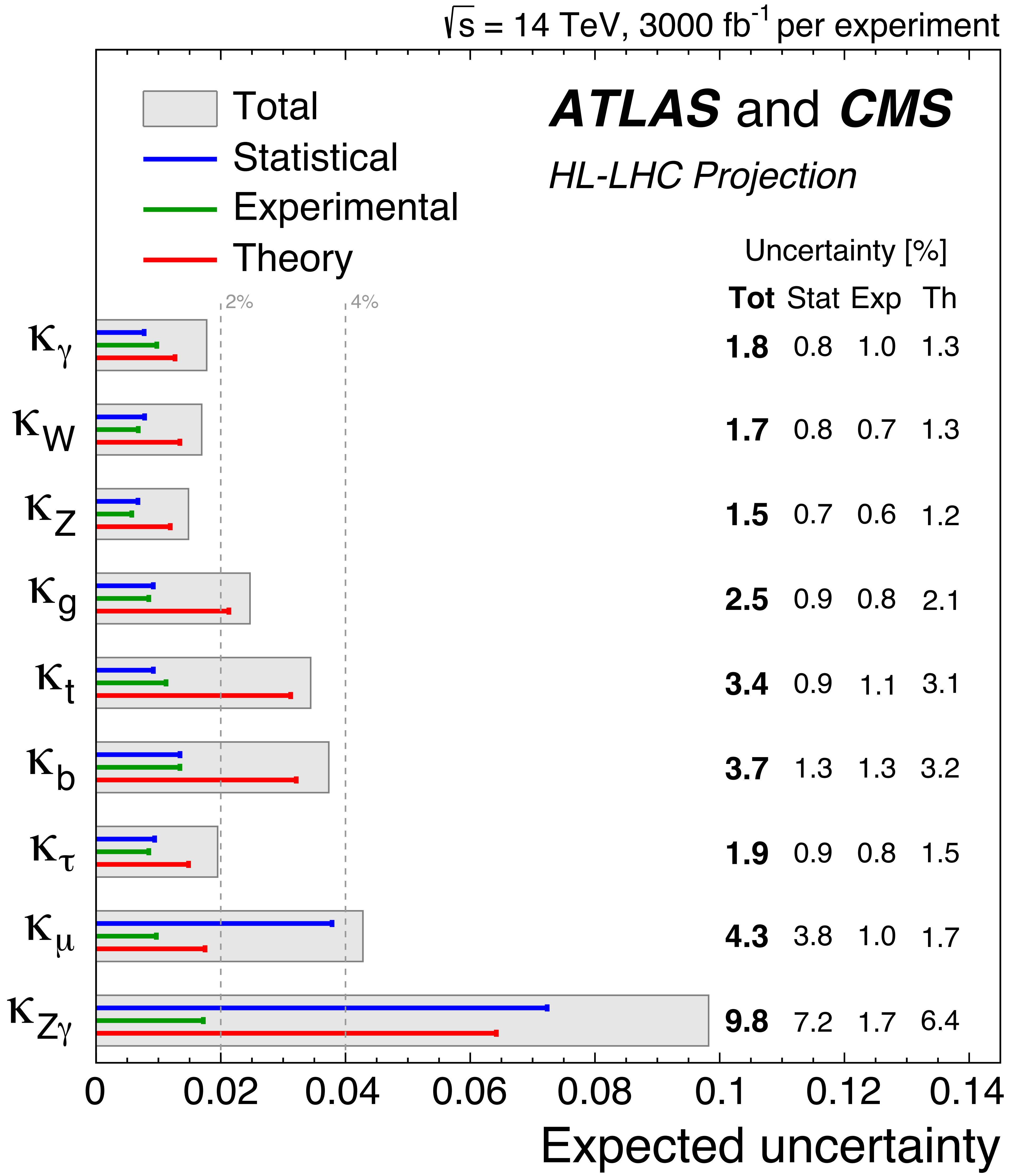


$-1.9 < \kappa_\lambda < 5.3$ [68% C.L.]

- 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

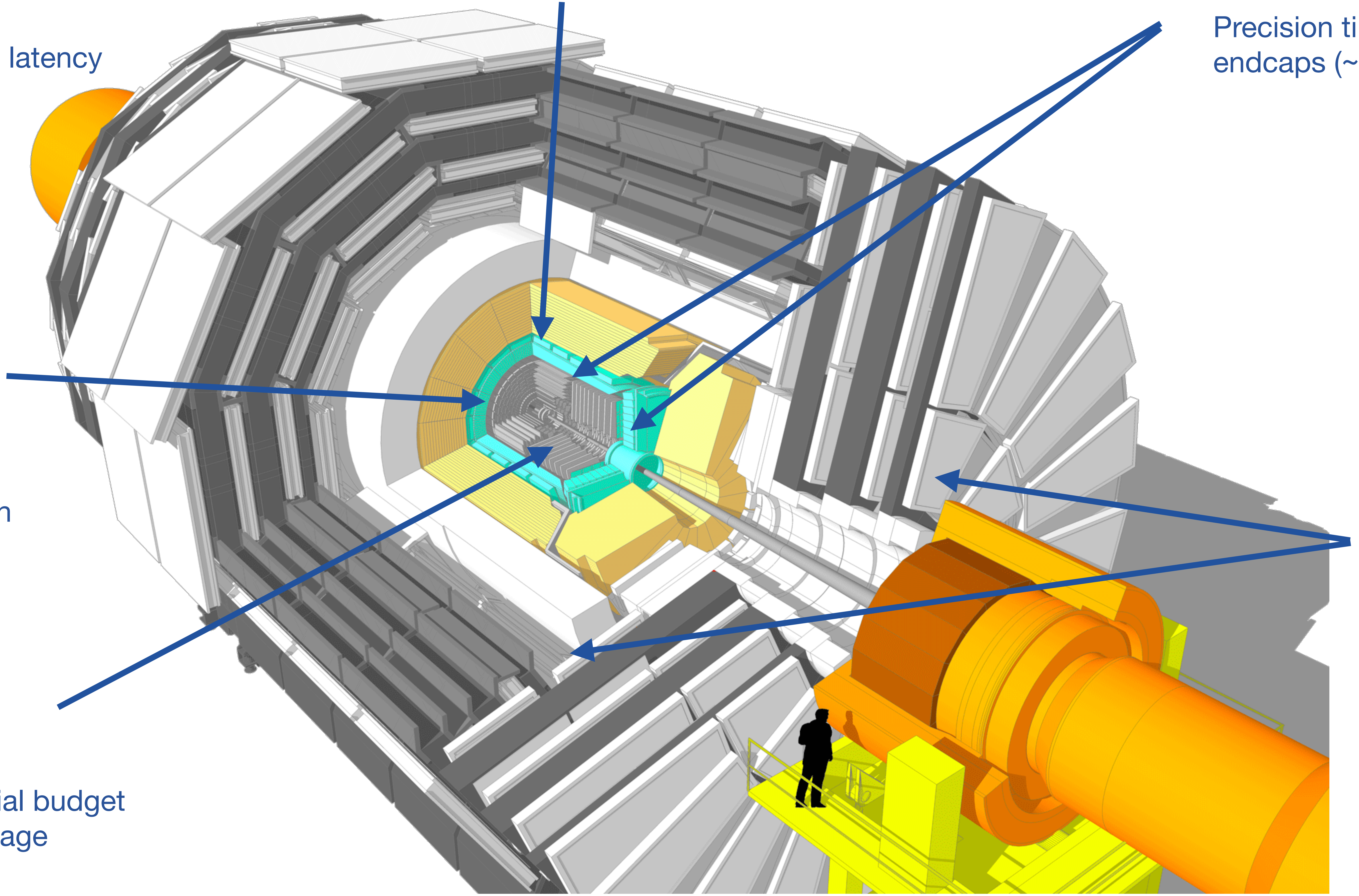
- Extrapolation of the current measurements to 3 ab^{-1}
  - under assumptions on the evolution of the systematic uncertainties and detector performance
- Most couplings known at a precision of 2-4% !
  - with theory uncertainties as the dominant ones
  - stat. uncertainties remaining relevant for very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



Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

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

Future colliders operations

<table>
<tr><th></th><th>T_0</th><th></th><th></th><th></th><th>+5</th><th></th><th></th><th></th><th></th><th>+10</th><th></th><th></th><th></th><th></th><th>+15</th><th></th><th></th><th></th><th></th><th>+20</th><th></th><th></th><th>...</th><th>+26</th></tr>
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250 GeV</td><td></td><td colspan="4">1.0/ab
500 GeV</td><td>0.2/ab
$2m_{top}$</td><td colspan="5">3/ab
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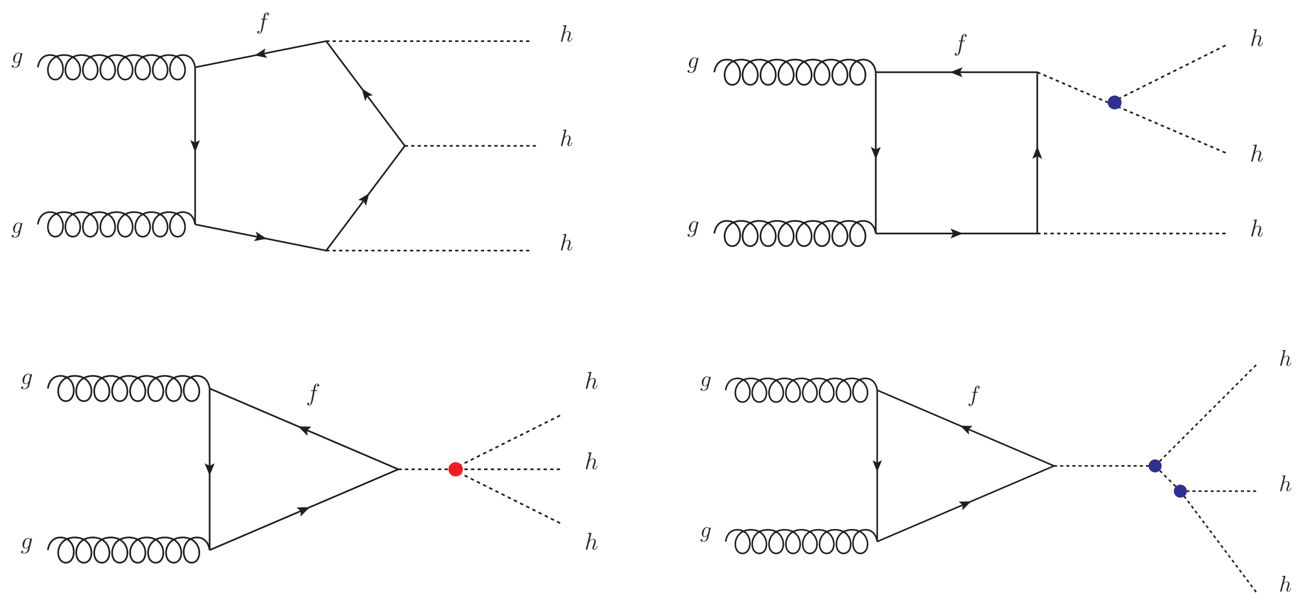
240 GeV</td><td colspan="2">16/ab
M_Z</td><td>2.6
/ab
$2M_W$</td><td colspan="9"></td><td colspan="5">SppC =></td></tr>
<tr><td>CLIC</td><td colspan="8">1.0/ab
380 GeV</td><td colspan="2"></td><td colspan="7">2.5/ab
1.5 TeV</td><td colspan="2"></td><td colspan="5">5.0/ab => until +28
3.0 TeV</td></tr>
<tr><td>FCC</td><td colspan="4">150/ab
ee, M_Z</td><td colspan="2">10/ab
ee, $2M_W$</td><td colspan="3">5/ab
ee, 240 GeV</td><td></td><td colspan="5">1.7/ab
ee, $2m_{top}$</td><td colspan="7"></td><td colspan="2">hh,eh
=></td></tr>
<tr><td>LHeC</td><td colspan="5">0.06/ab</td><td></td><td colspan="4">0.2/ab</td><td></td><td colspan="4">0.72/ab</td><td colspan="9"></td></tr>
<tr><td>HE-
LHC</td><td colspan="20">10/ab per experiment in 20y</td><td colspan="4"></td></tr>
<tr><td>FCC
eh/hh</td><td colspan="23">20/ab per experiment in 25y</td><td></td></tr>
</table>

How about HHH?

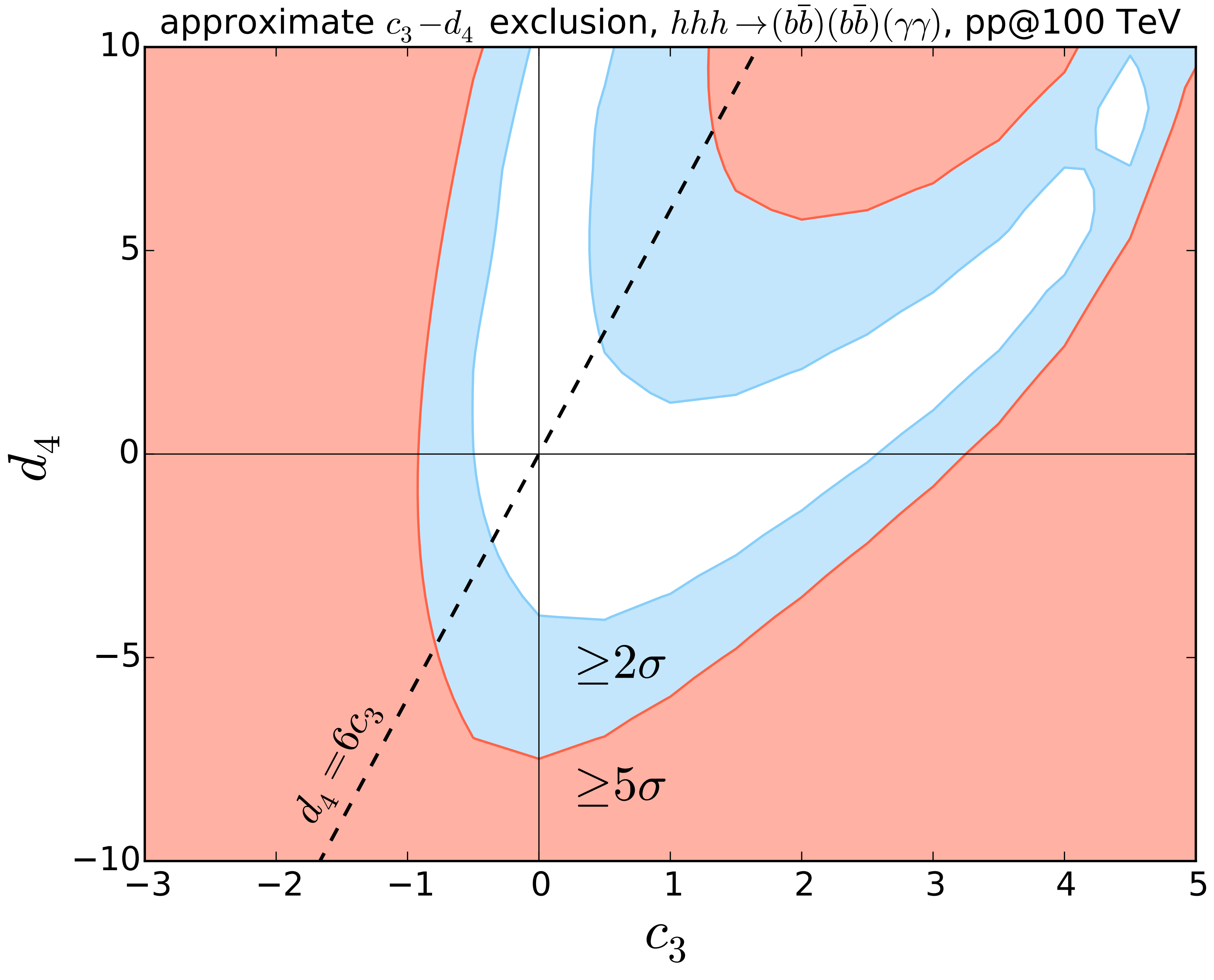


Depends also on trilinear coupling

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 |η| ≈ 3.5
- Sensitivity: at FCC, O(100%) precision on σ_{HHH}, $\lambda_{HHHH} \in [-4, +16]$



(a)