Double Higgs boson searches

overview

Roberto Salerno

The primary target of the Higgs boson physics

“Standard” direction

Determination of the Higgs boson properties and their connection with ElectroWeak Symmetry Breaking

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More profound questions could be asked

- ✓ Is the Higgs boson elementary or composite?
- ✓ Does the Higgs boson interact with itself?
- ✓ Does the Higgs boson mediate a Yukawa force (insight into flavour puzzle)
- ✓ Can the invisible Higgs boson width be associated with DM?
- ✓ Can we directly probe new physics in the Higgs sector?

Additionally there are questions on causality, naturalness, greatly discussed in the N. Craig's talk at Higgs Hunting 2021

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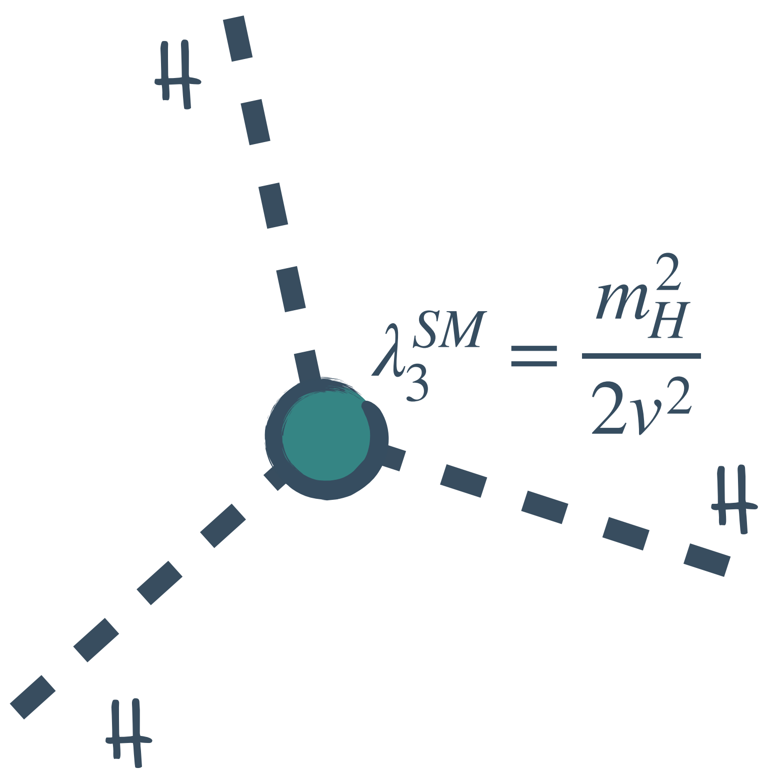
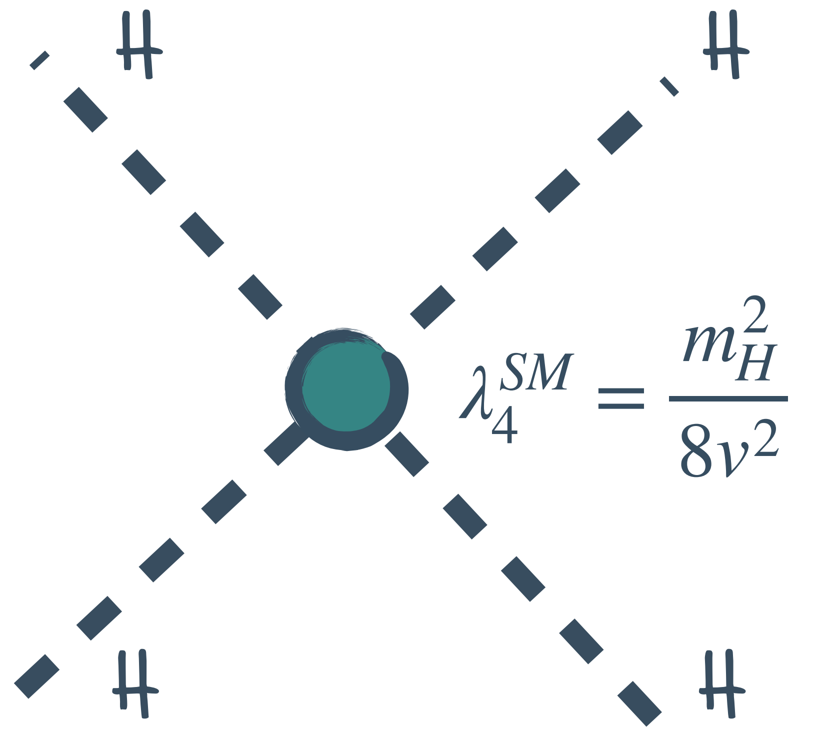
Does the Higgs boson interact with itself?

A self-interacting Higgs (as SM predicts) would be unlike anything yet seen in nature. All other interactions change particle identity.

The Higgs boson **cubic** (λ_3^{SM}) and **quartic** (λ_4^{SM}) couplings are the keys to check the EWSB. The Higgs boson potential is :

$$\mathscr{L} \subset -\frac{m_h^2}{2}h^2 - \lambda_3^{SM} v h^3 - \lambda_4^{SM} h^4$$





Direct test of cubic coupling only **with HH** production

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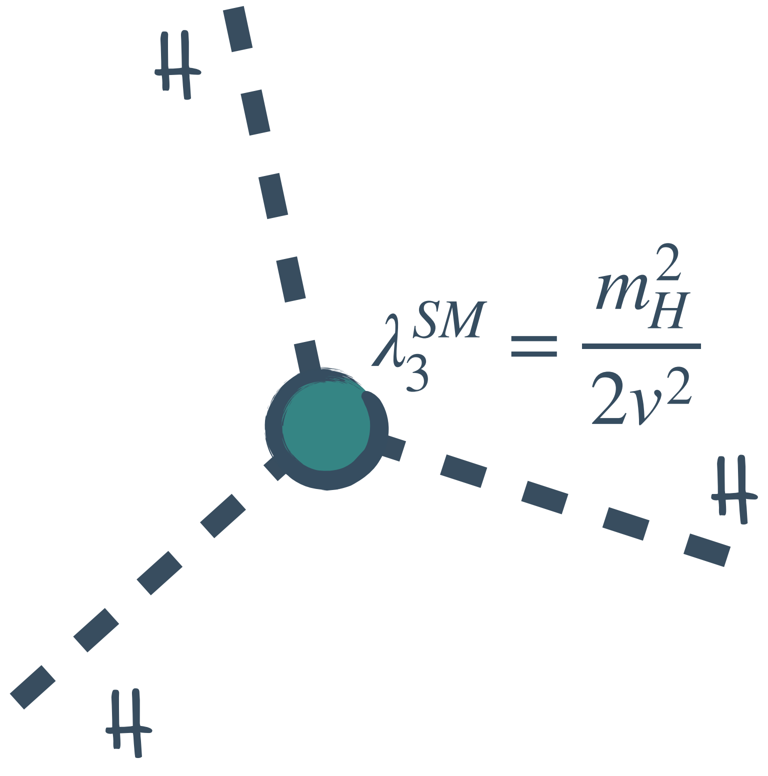
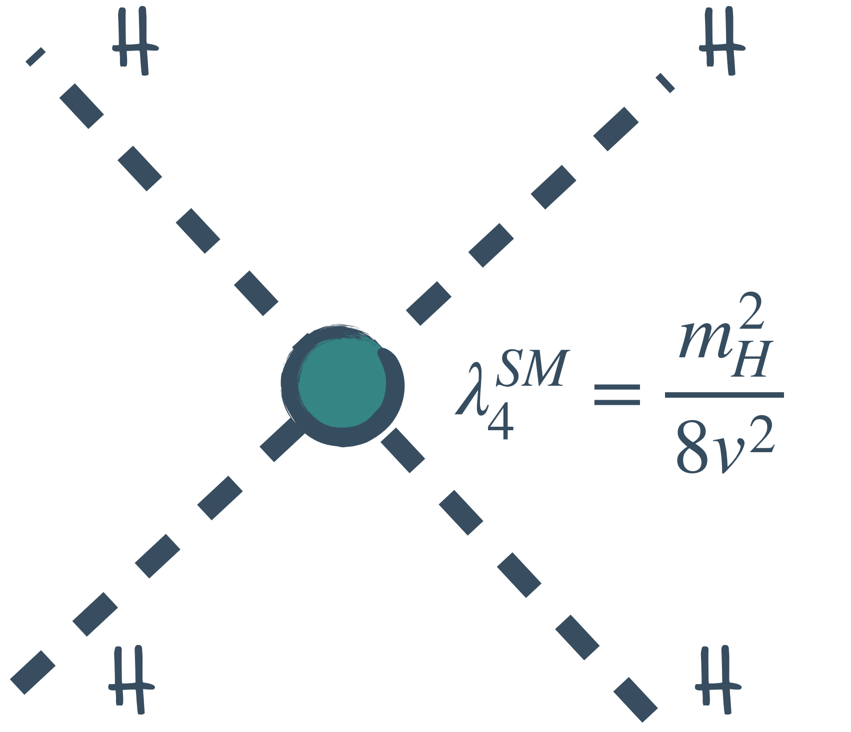
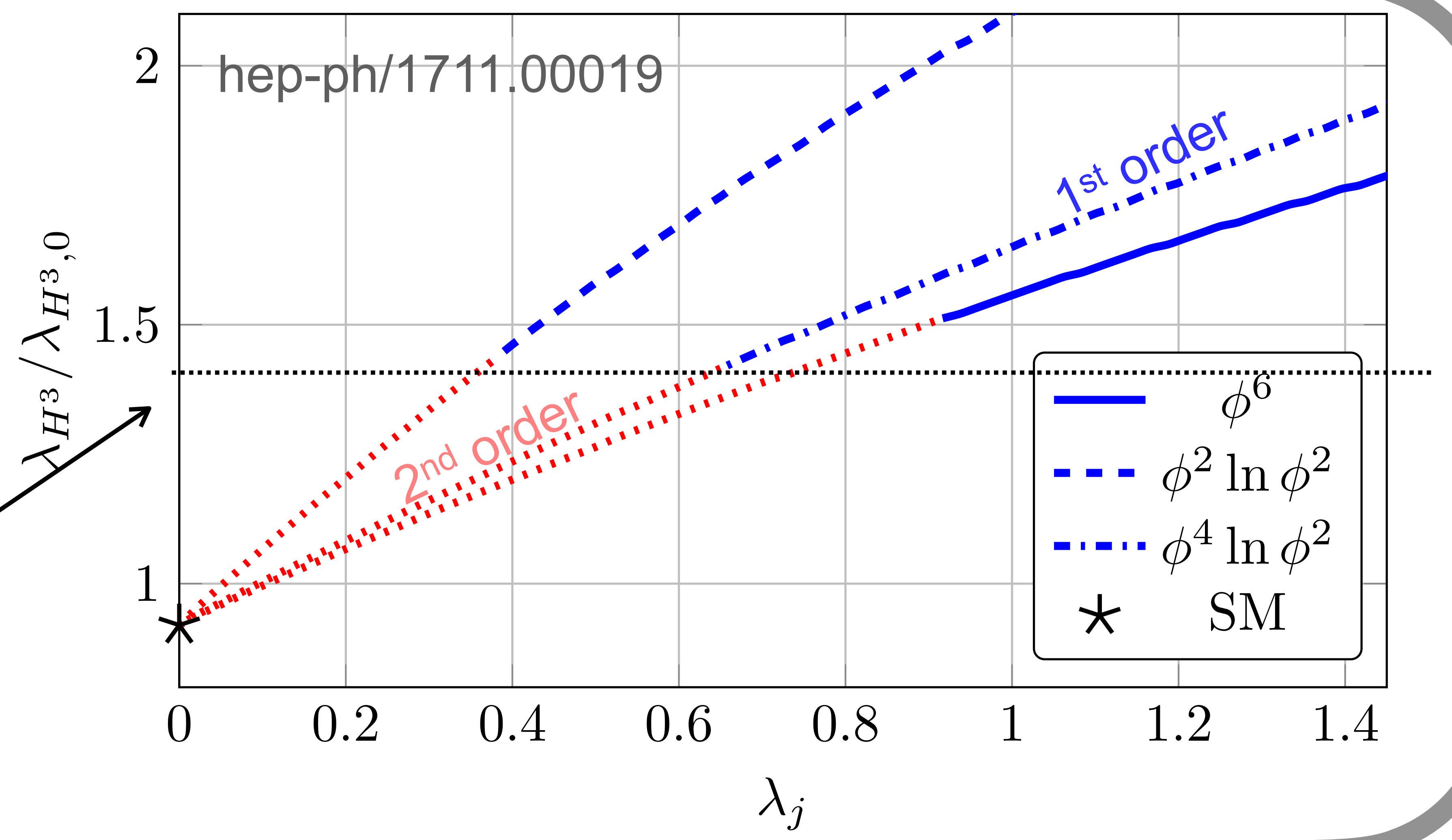




Direct test of cubic coupling only **with HH** production

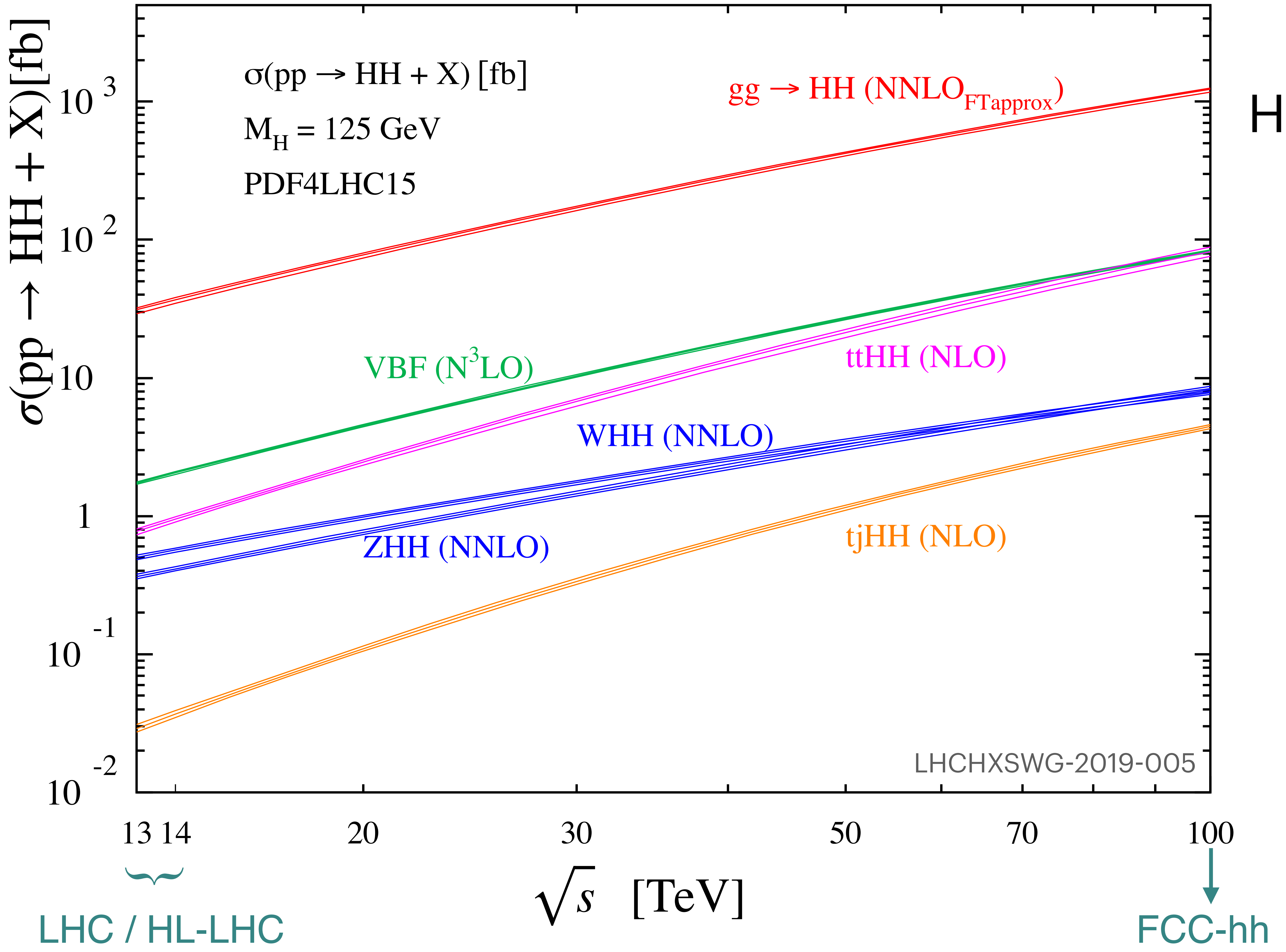
The thermal history of the Universe

Deviations from SM Higgs boson self-coupling cause a modified potential that allows **first-order electroweak phase transition** and hence an explanation of the observed matter vs anti-matter asymmetry!



We need to probe size of modification down to 1.4, the expected uncertainty of the measurement should be $\mathcal{O}(10\%)$

HH production cross sections within SM



HH production channels similar to H production,

but there is a very important difference

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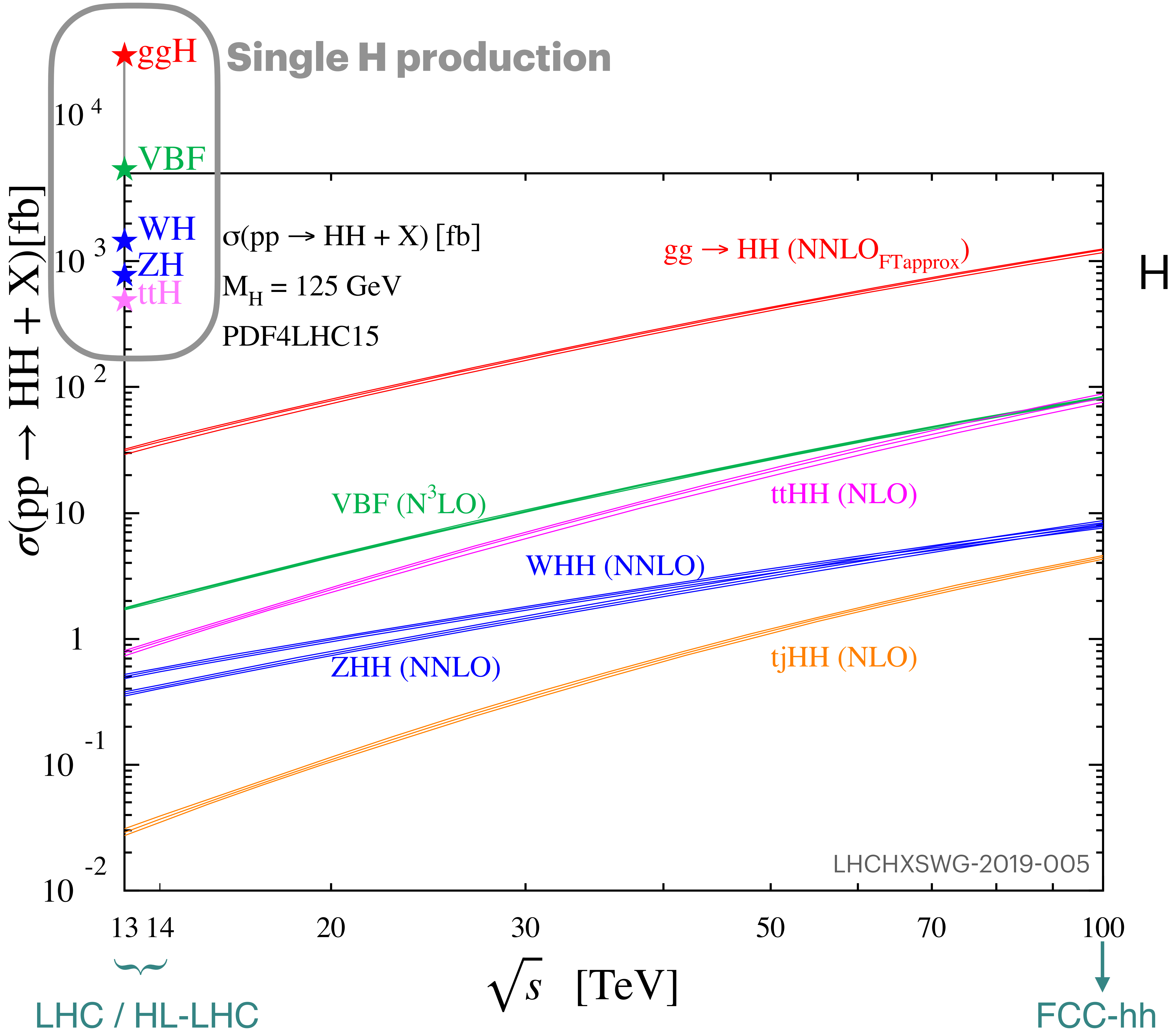
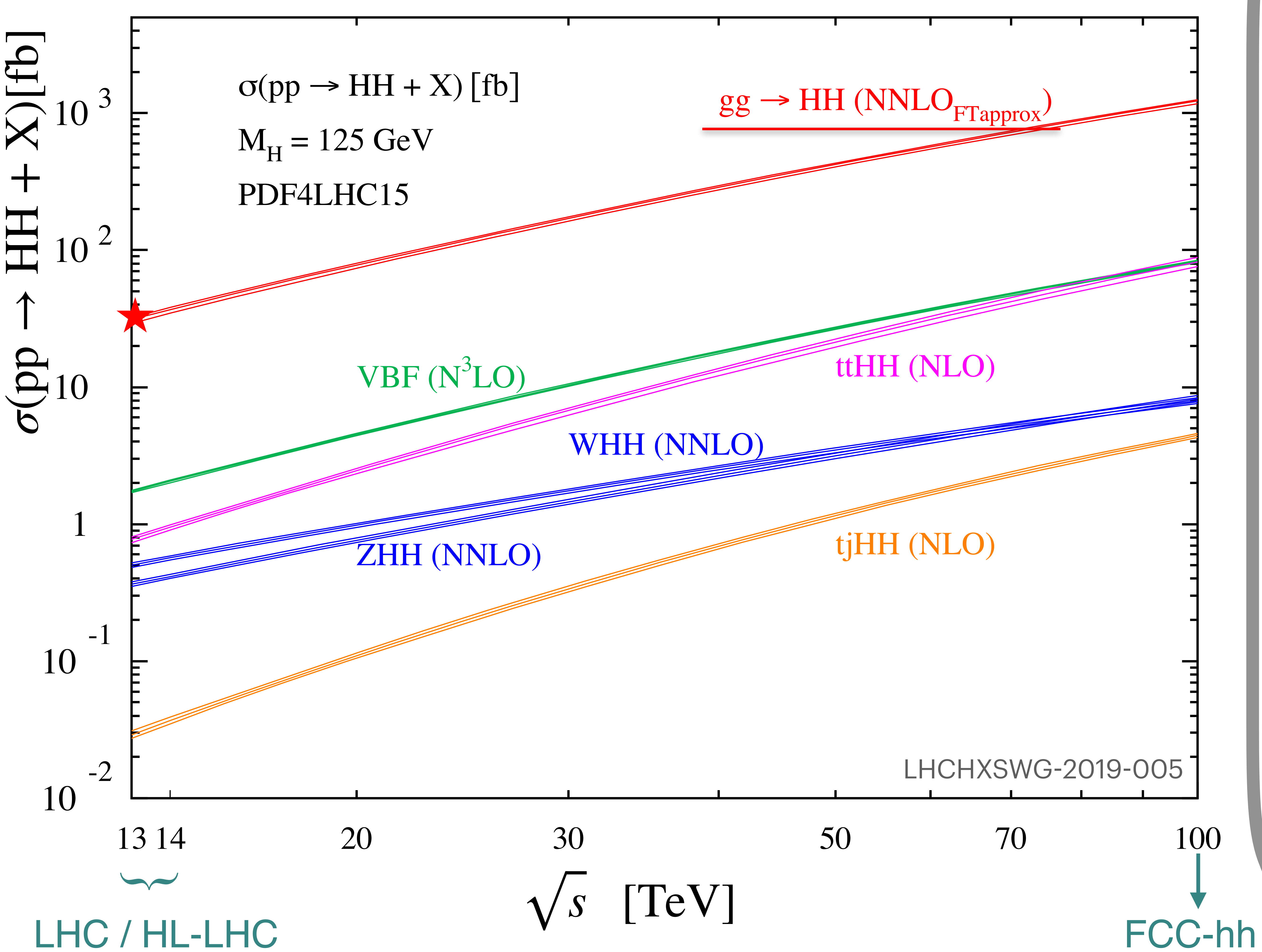


HH production channels similar to H production,
but there is a very important difference

$$\sigma(pp \to HH) \sim \frac{\sigma(pp \to H)}{1000}$$

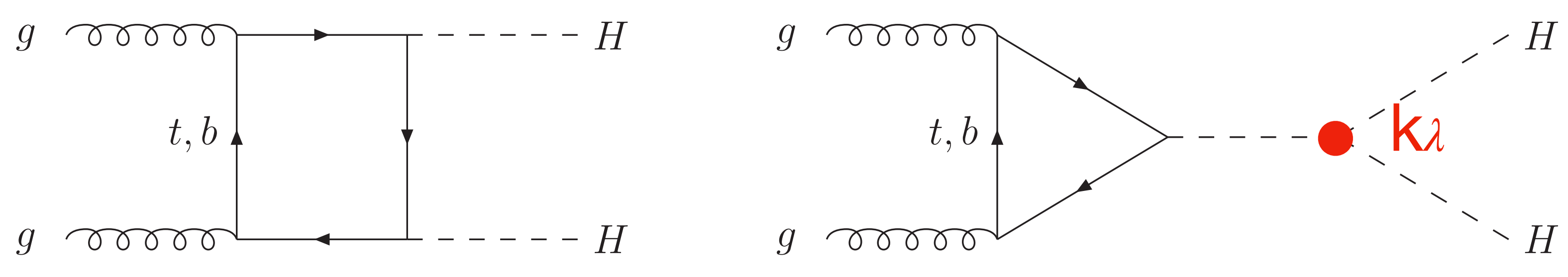
Higgs boson pairs are predicted
to be 1000× rarer than single Higgs

HH production cross sections within SM



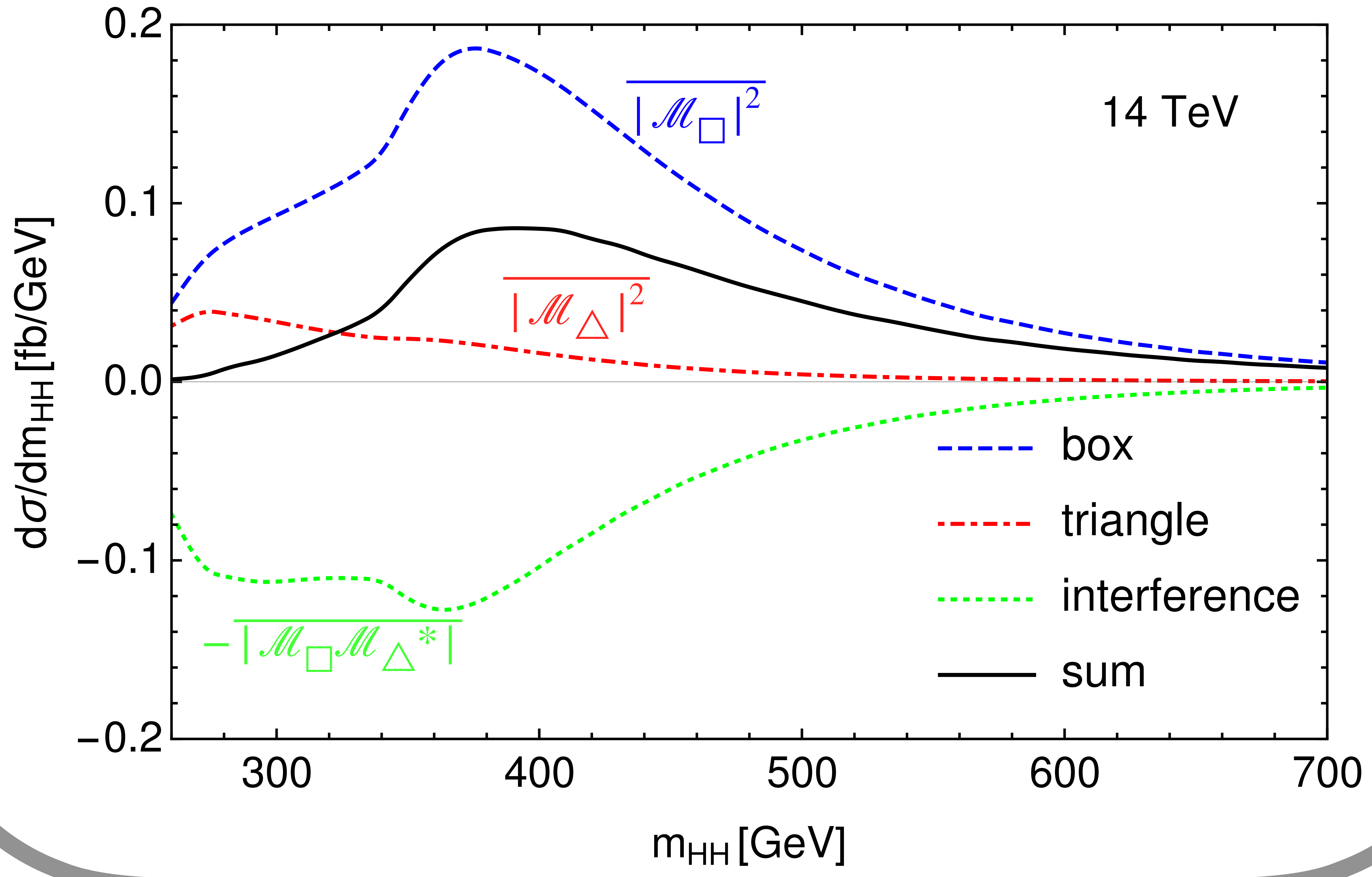
gg → HH

★ $\sigma^{SM}_{ggF} \simeq 31$ fb [13 TeV]

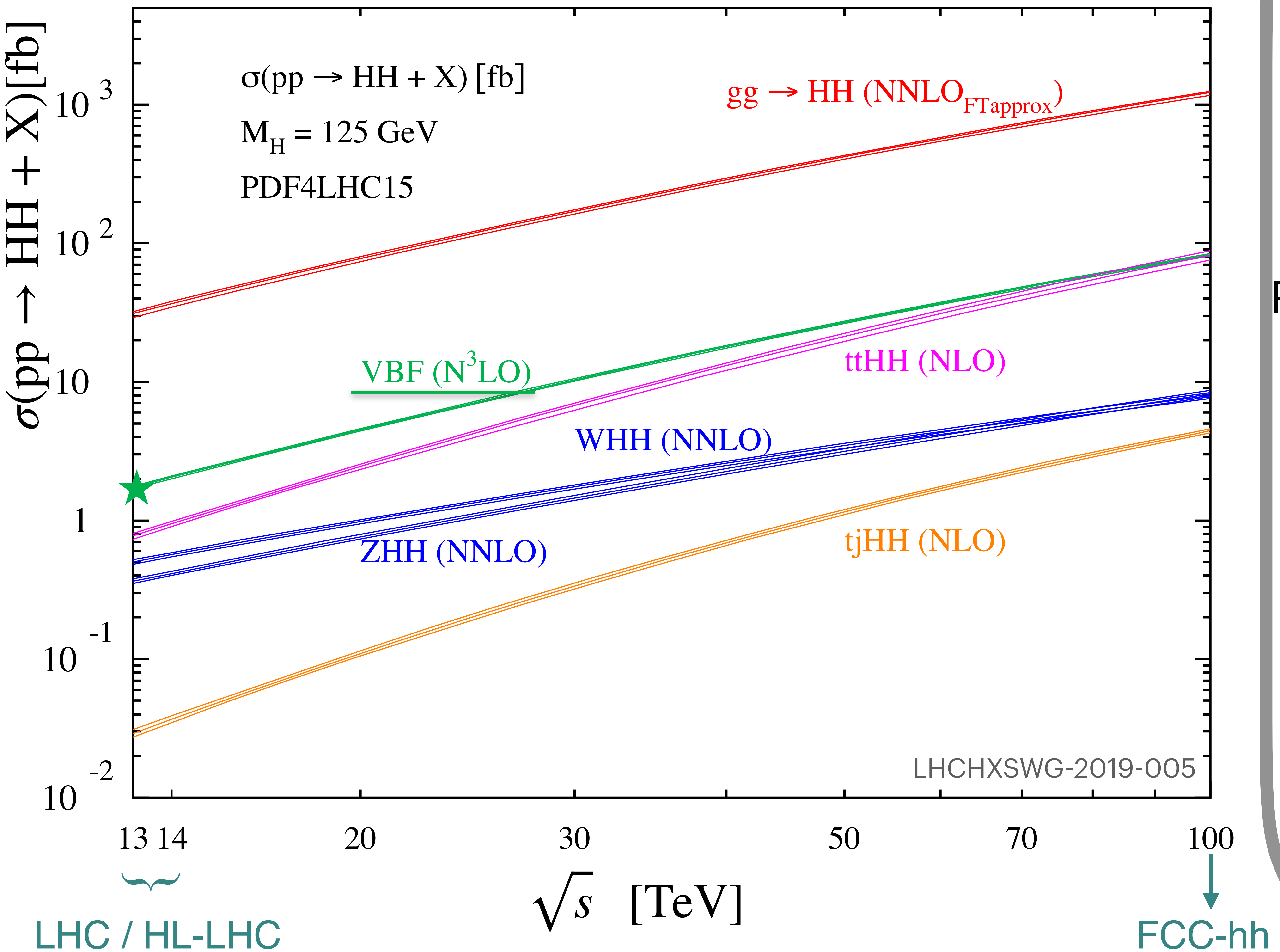


Production dominated by loop-induced gluon-fusion

Destructively interfering box and triangle diagrams

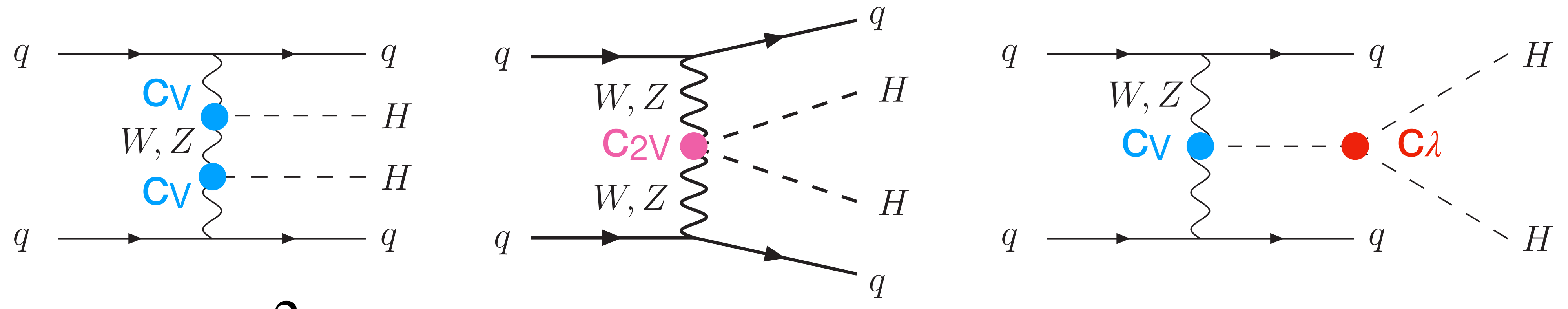


HH production cross sections within SM



VBF

★ $\sigma^{SM}_{VBF} \simeq 1.7$ fb [13 TeV]



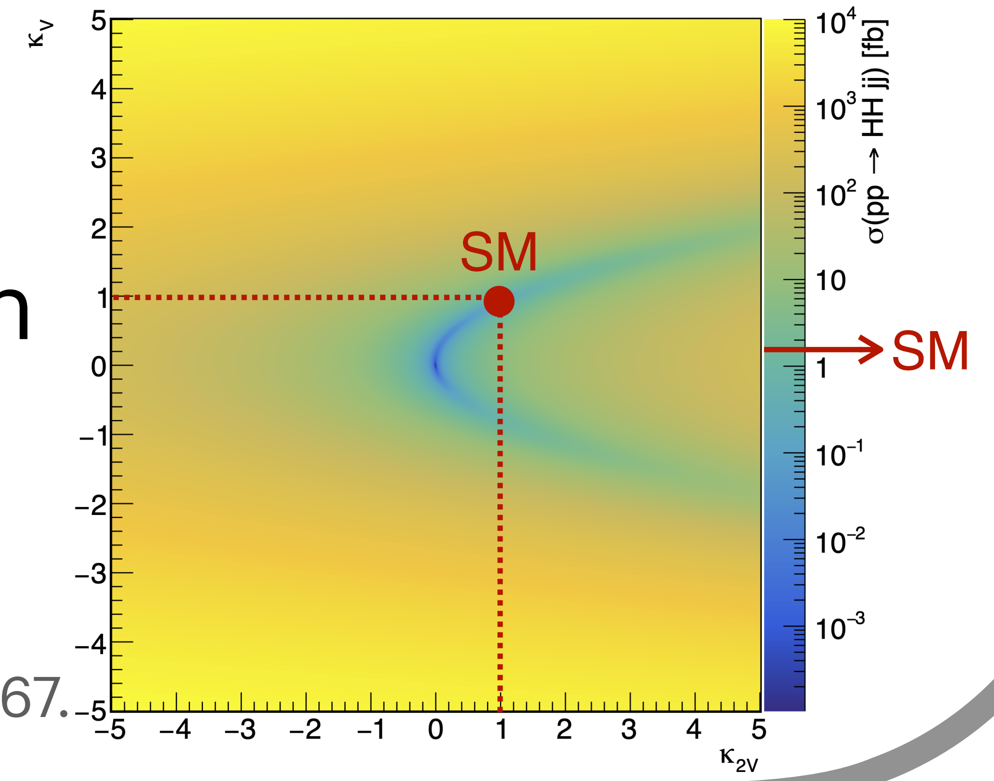
$\mathscr{A} \sim c_V^2$ $\mathscr{A} \sim c_{2V}$ $\mathscr{A} \sim c_V c_\lambda$

Production dominated by t-channel W and Z exchange

In SM a cancellation dictated by perturbative unitarity occurs for longitudinally polarized vector bosons

$$\mathscr{A}(V_L V_L \to \mathrm{HH}) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)$$

Effects of the cancellation

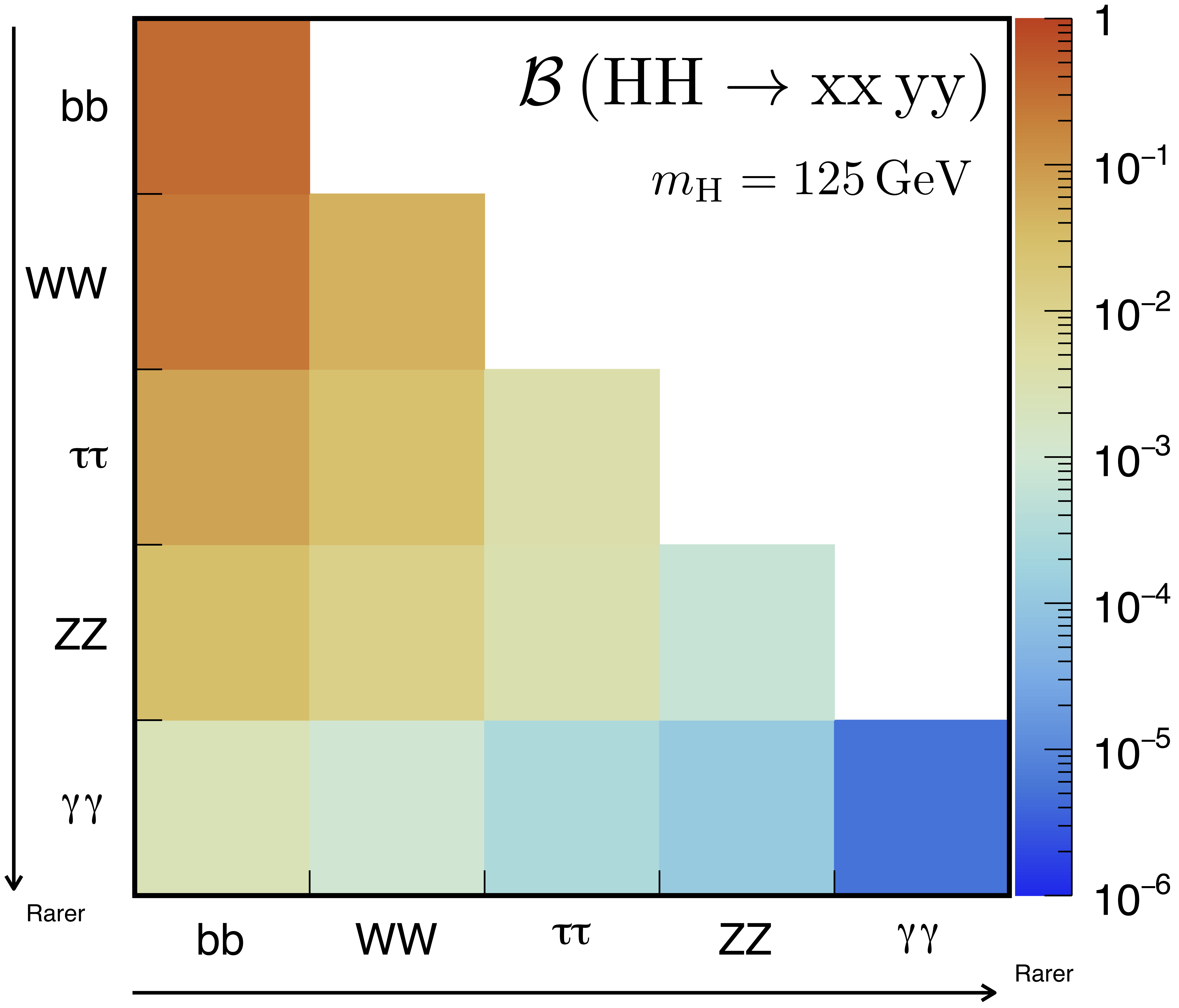


Symmetry 2022,14,1467.

HH final states within SM

A **very** rich set of final states

ATLAS/CMS results with LHC Run 2 covers



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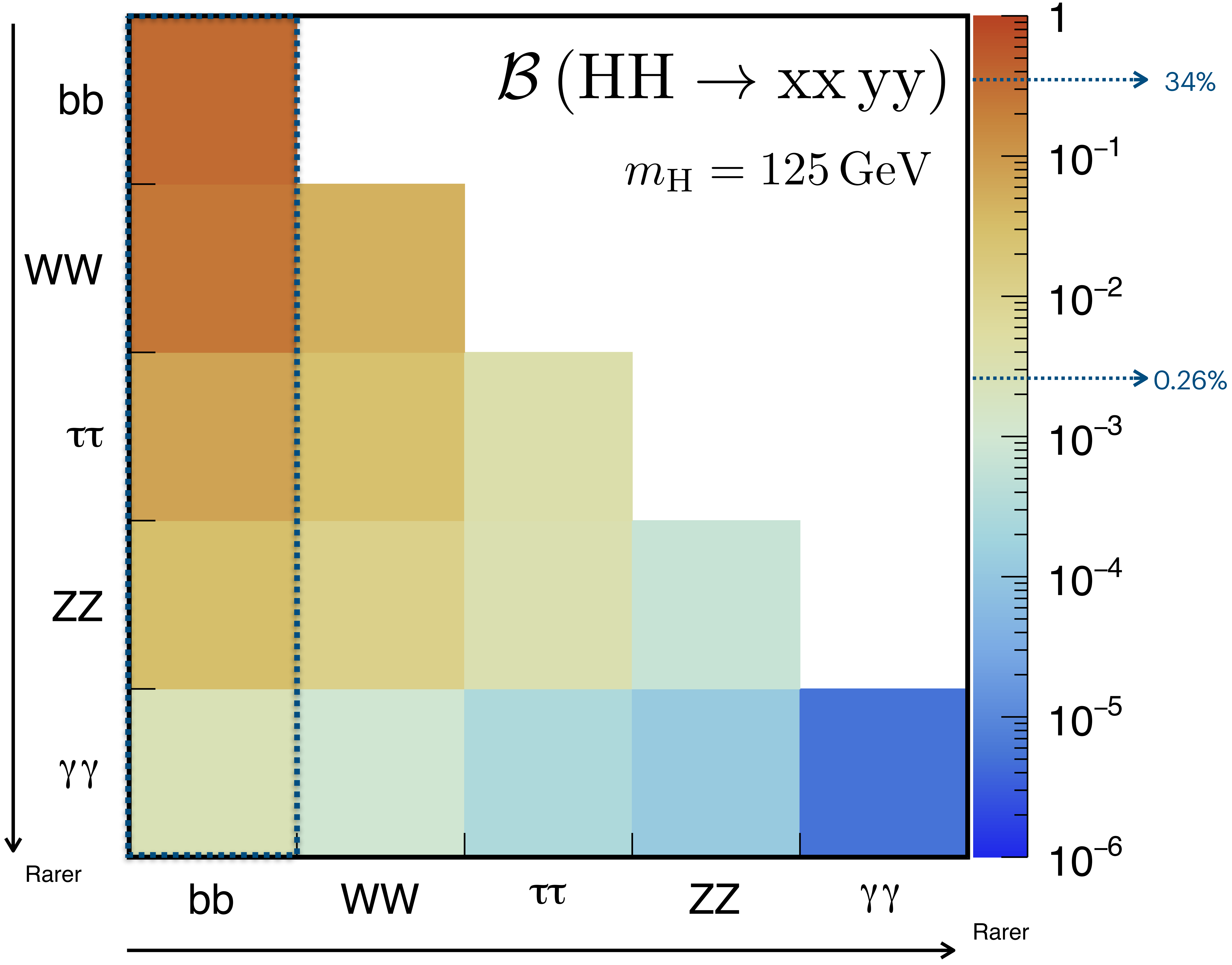
≥ 1 H decaying to b quarks channels



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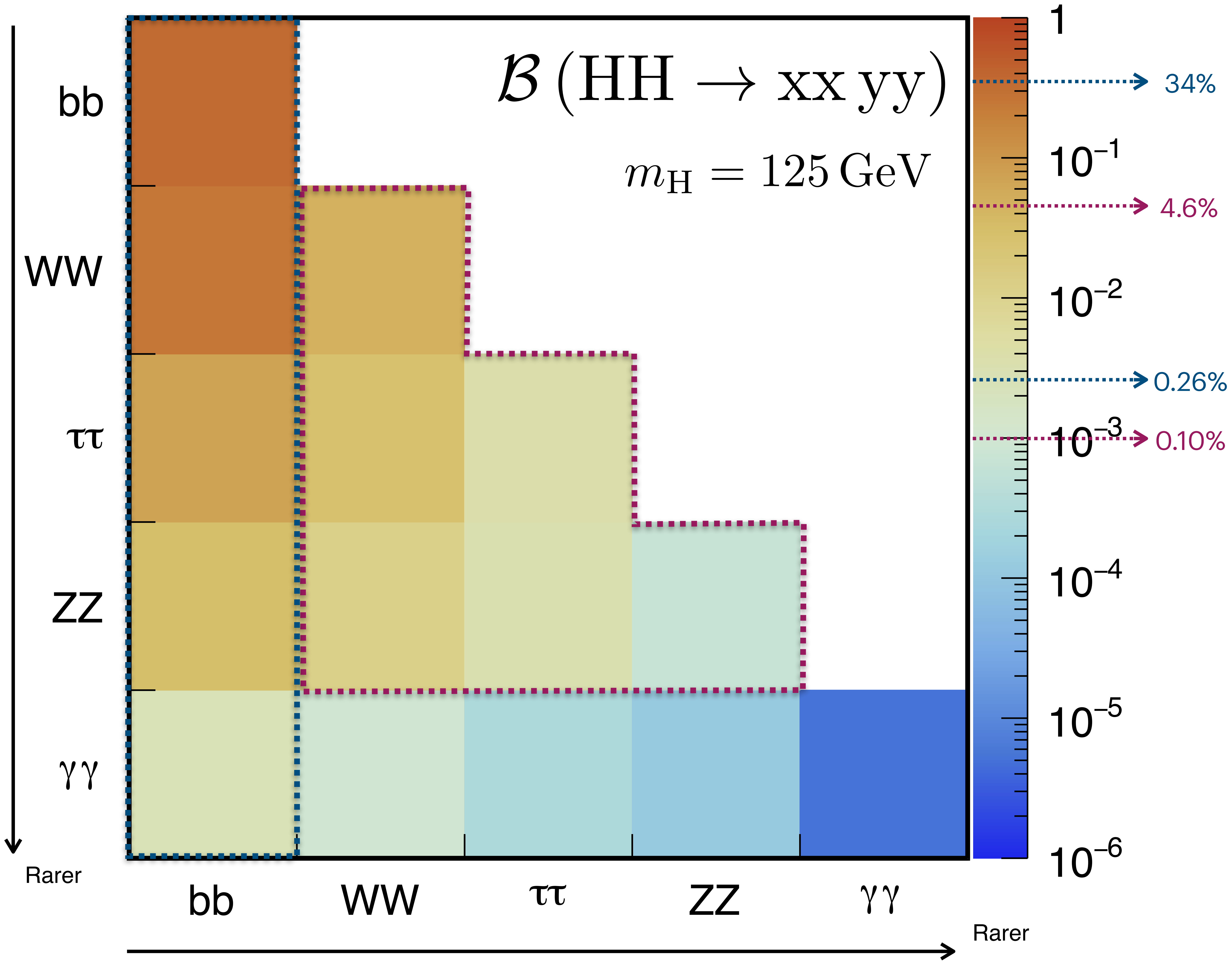

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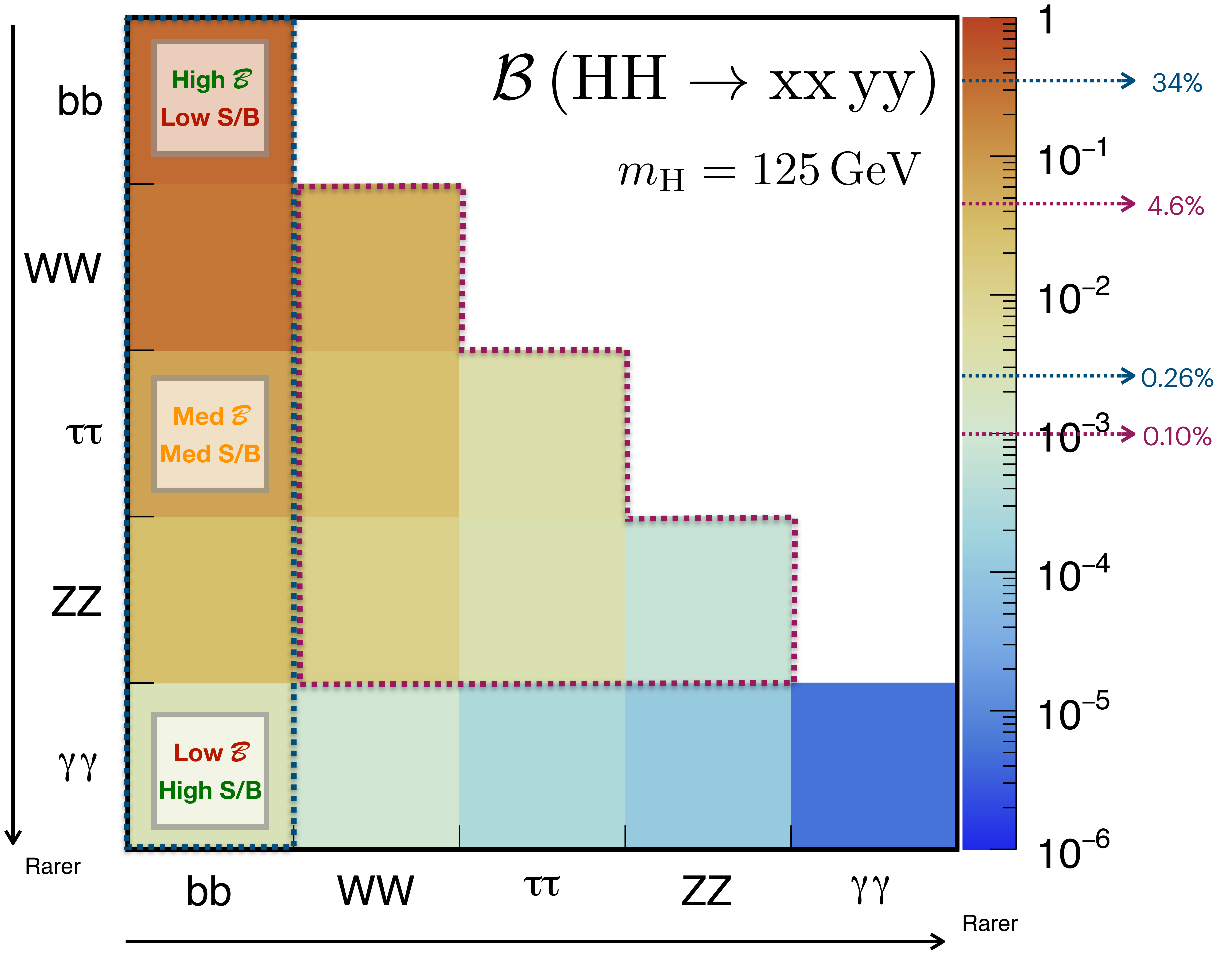
ATLAS/CMS results with LHC Run 2 covers

≥ 1 H decaying to b quarks channels

multilepton channels

Not a single **"golden"** channel
but (at least) three **"silver"** bullets



HH ideal place to probe for New Physics

Low-energy effects of New Physics **can** modify the interactions of the Higgs bosons

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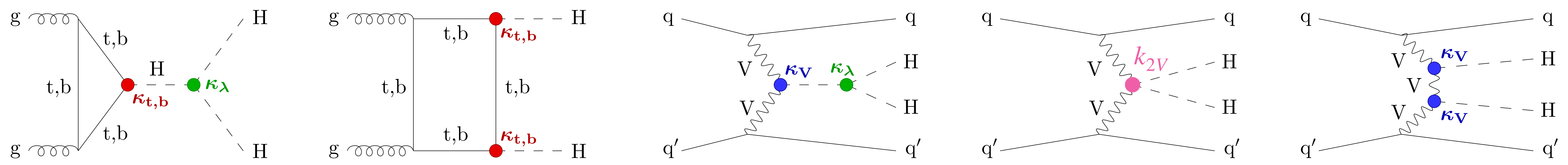
κ framework

modify HHH, ttH/bbH, VVH, VVHH vertices



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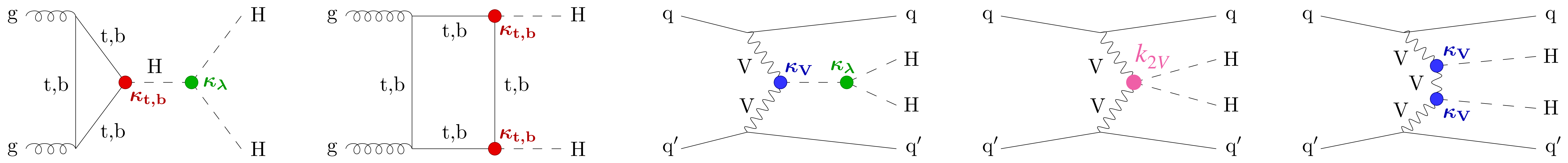
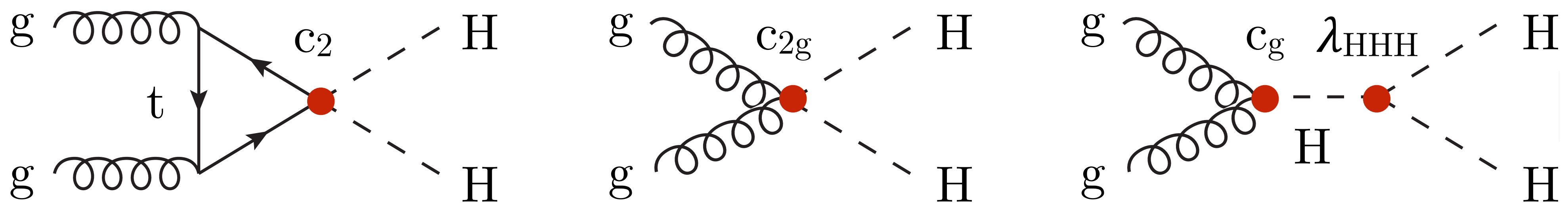


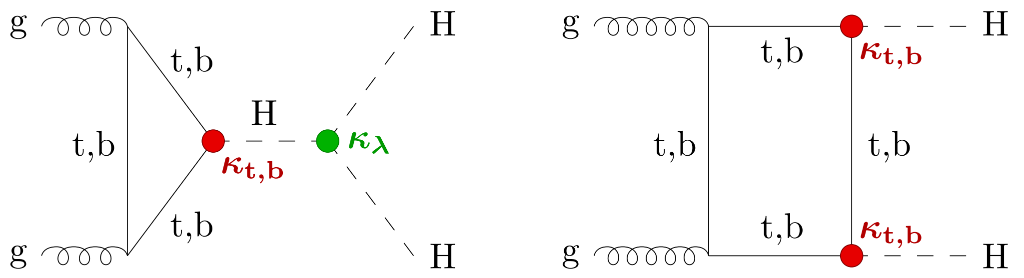
EFT

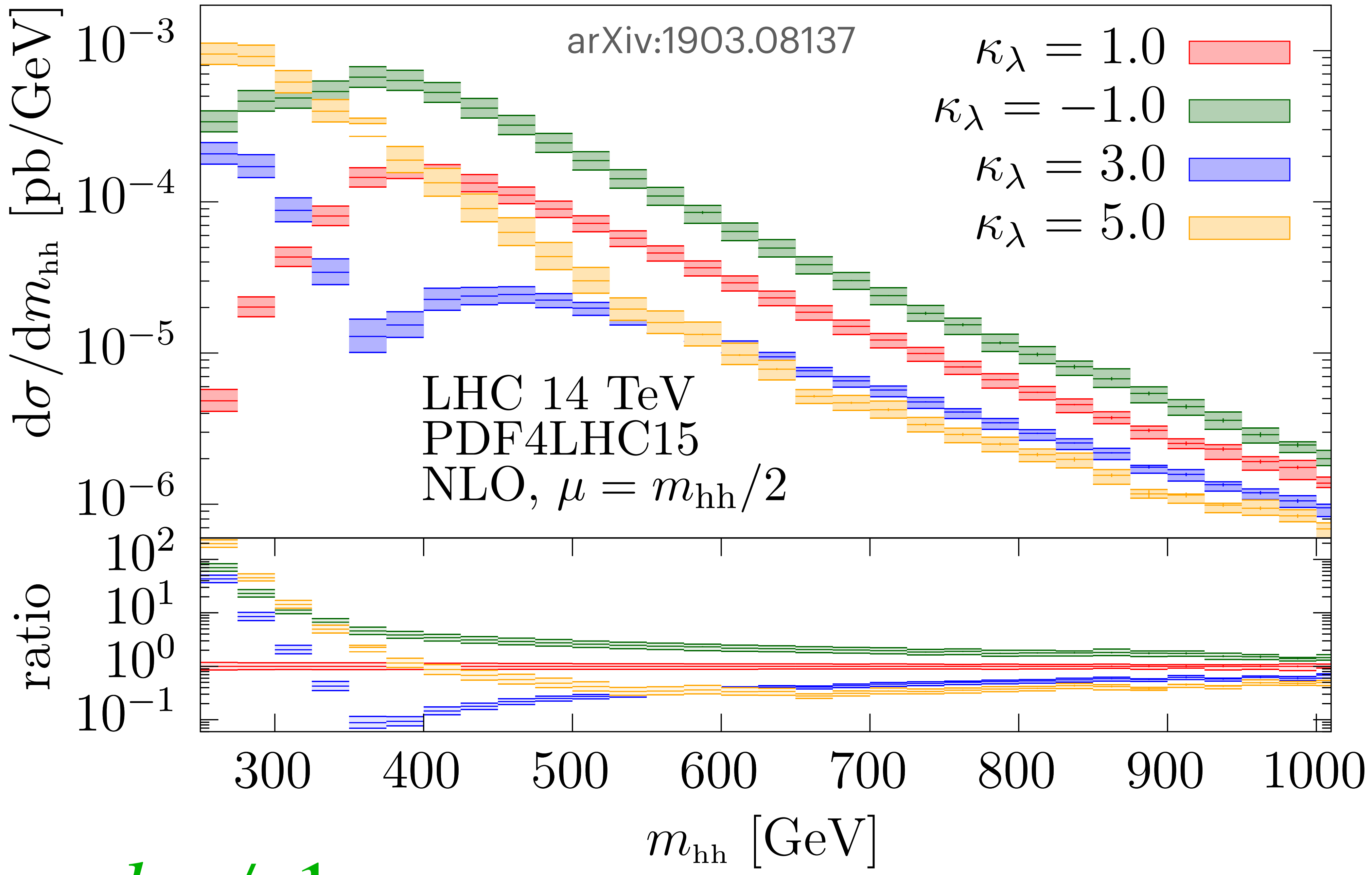
expand the SM Lagrangian with higher-order operators that represent the low-energy effects induced by a complete theory at a higher energy scale Λ

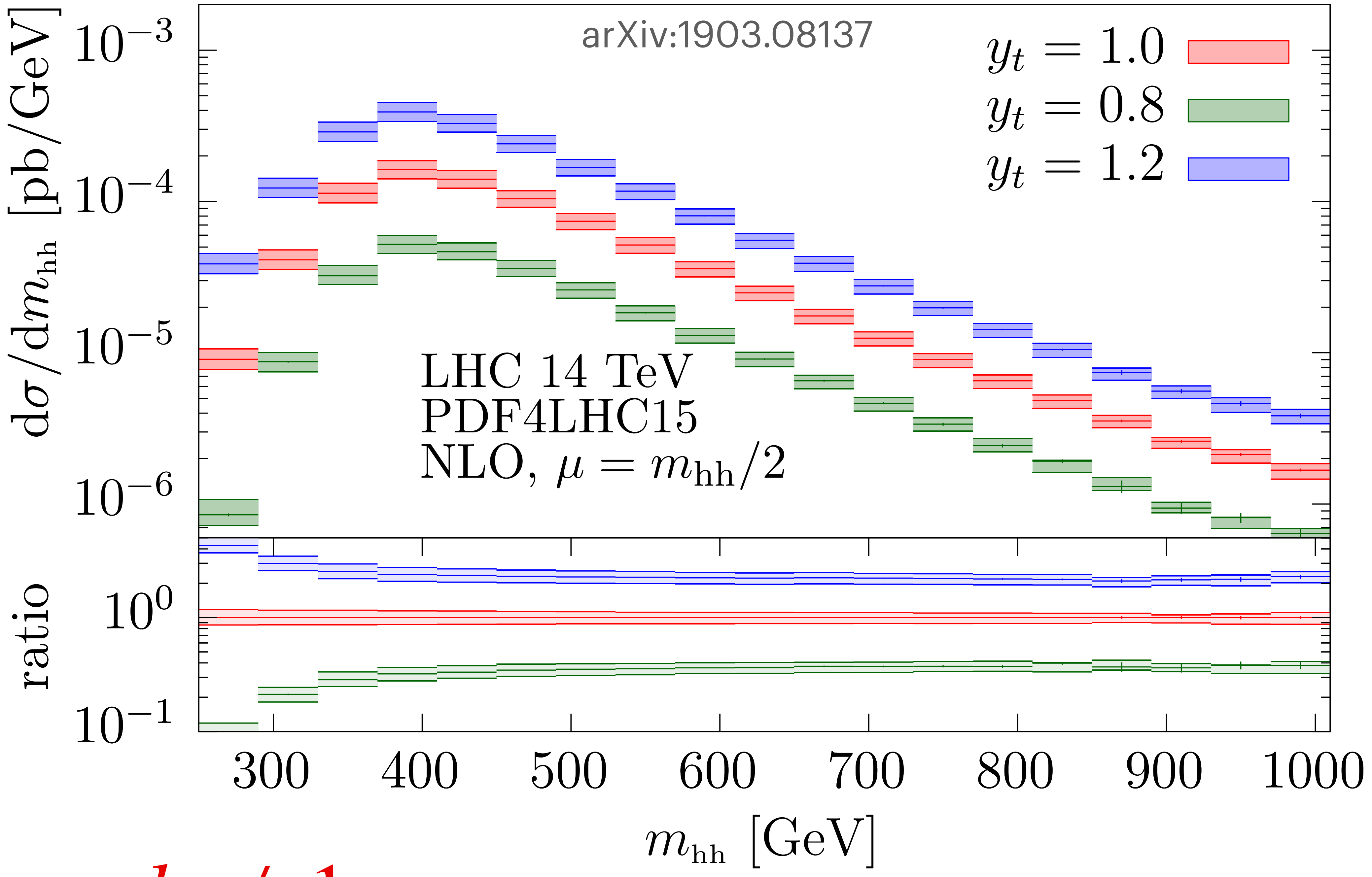


m_{HH} distribution

m_{HH} is **significantly** modified once any vertices is not SM







$k_\lambda \neq 1$

Modifications of the shape and integral.

The kinematics of the H bosons are modified.

$k_t \neq 1$

Modifications mainly of the integral but at threshold.

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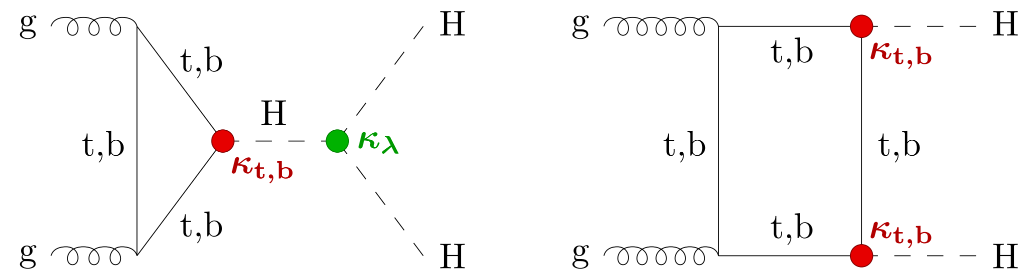

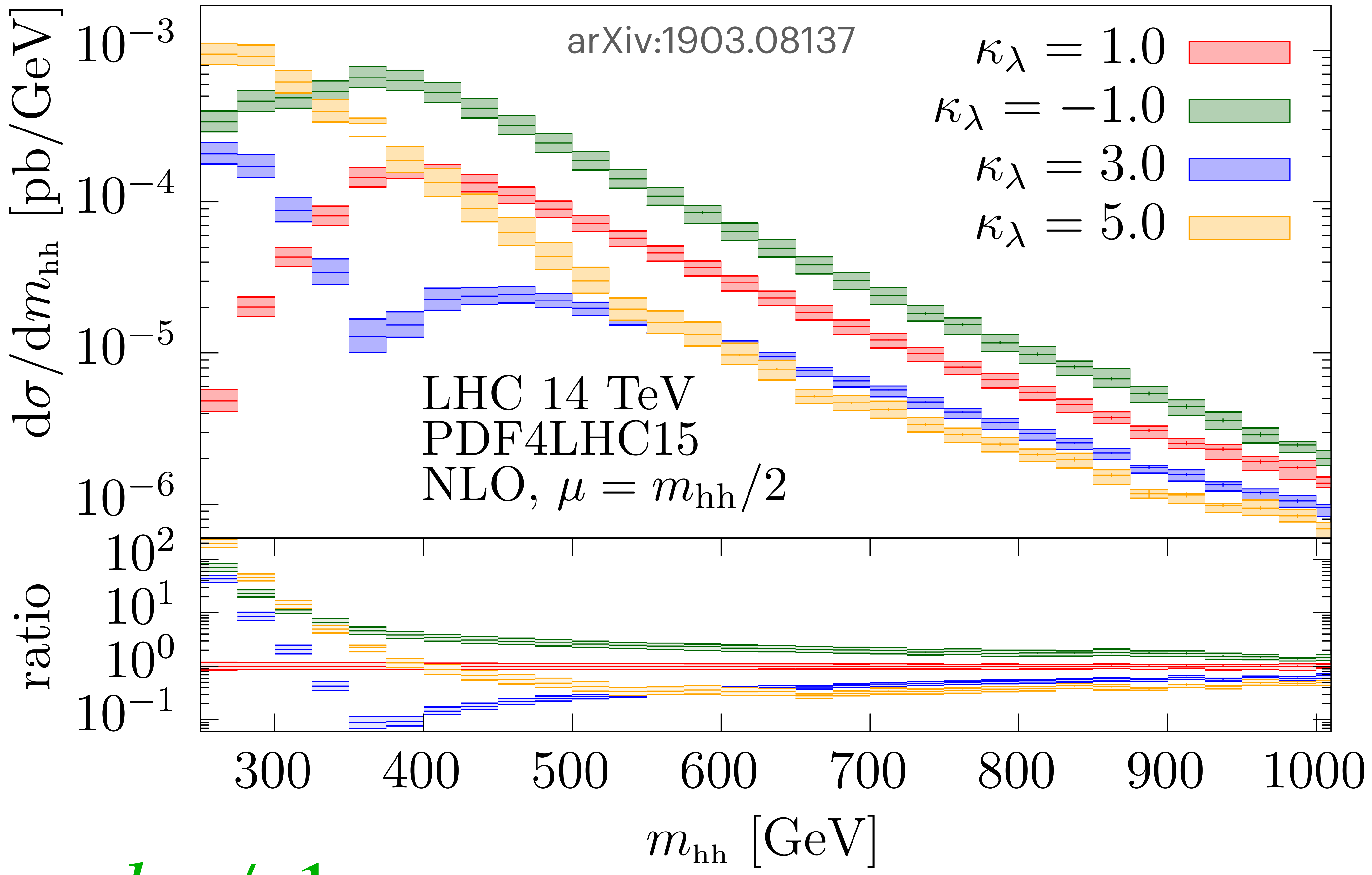

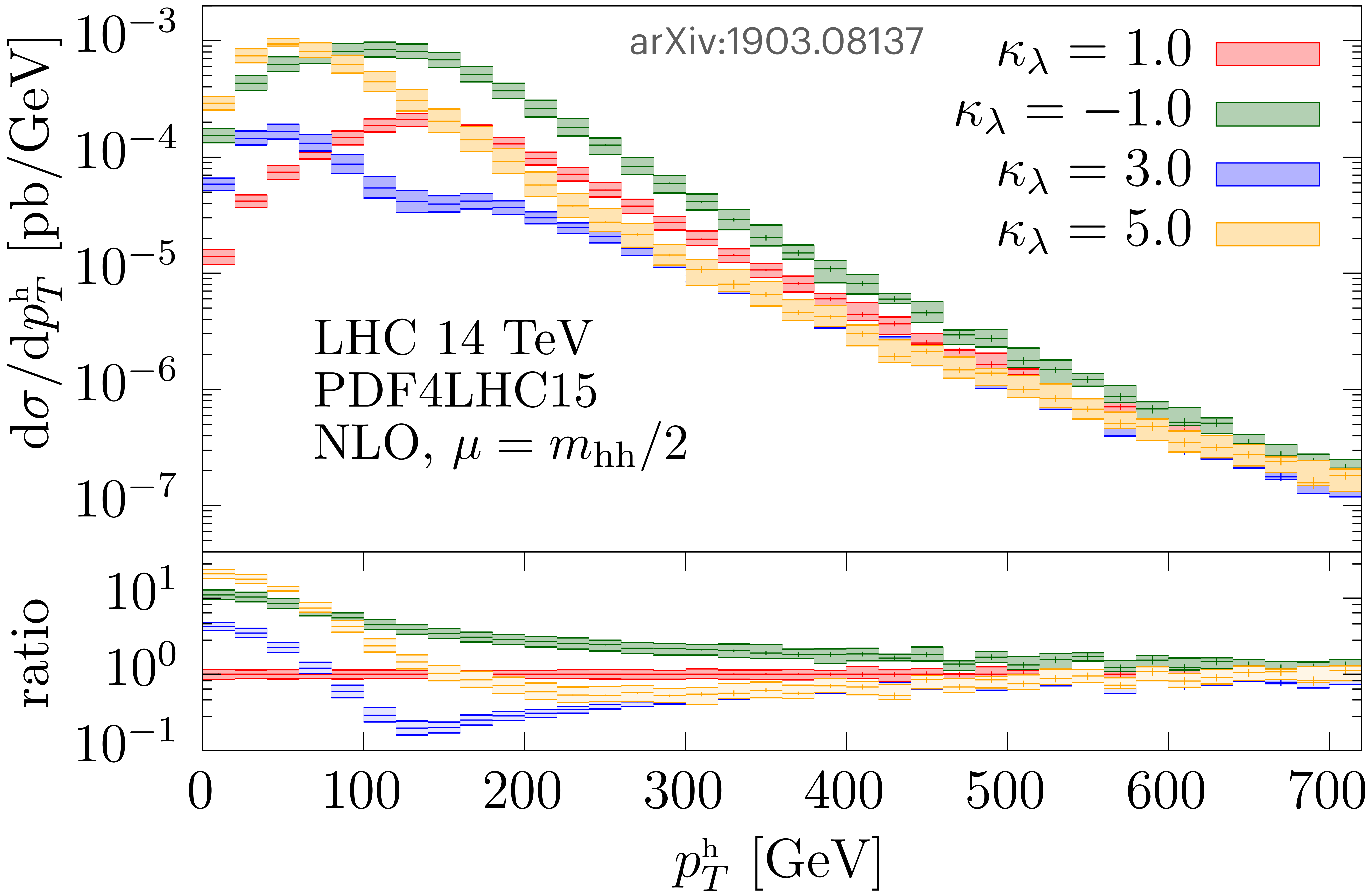

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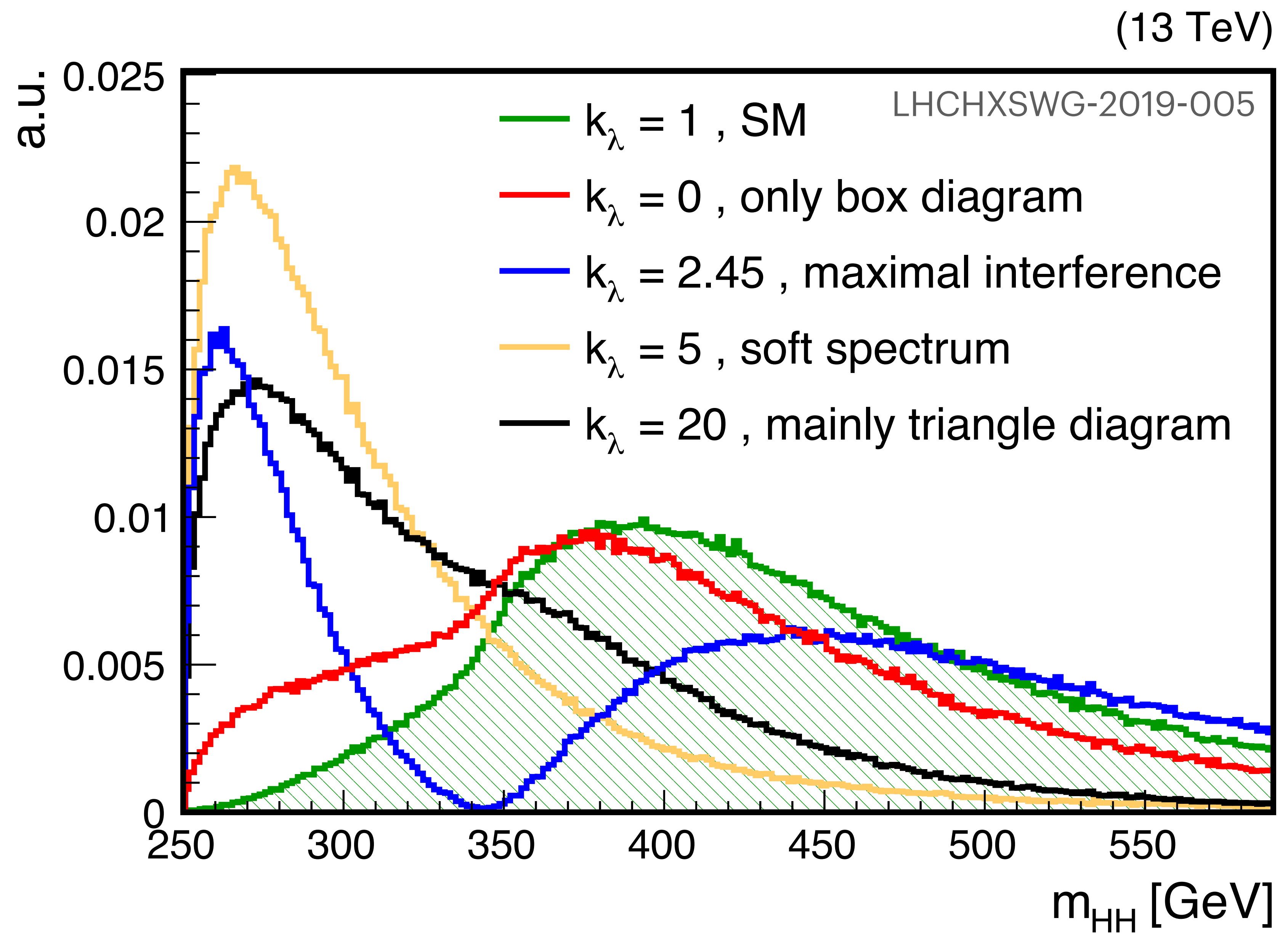
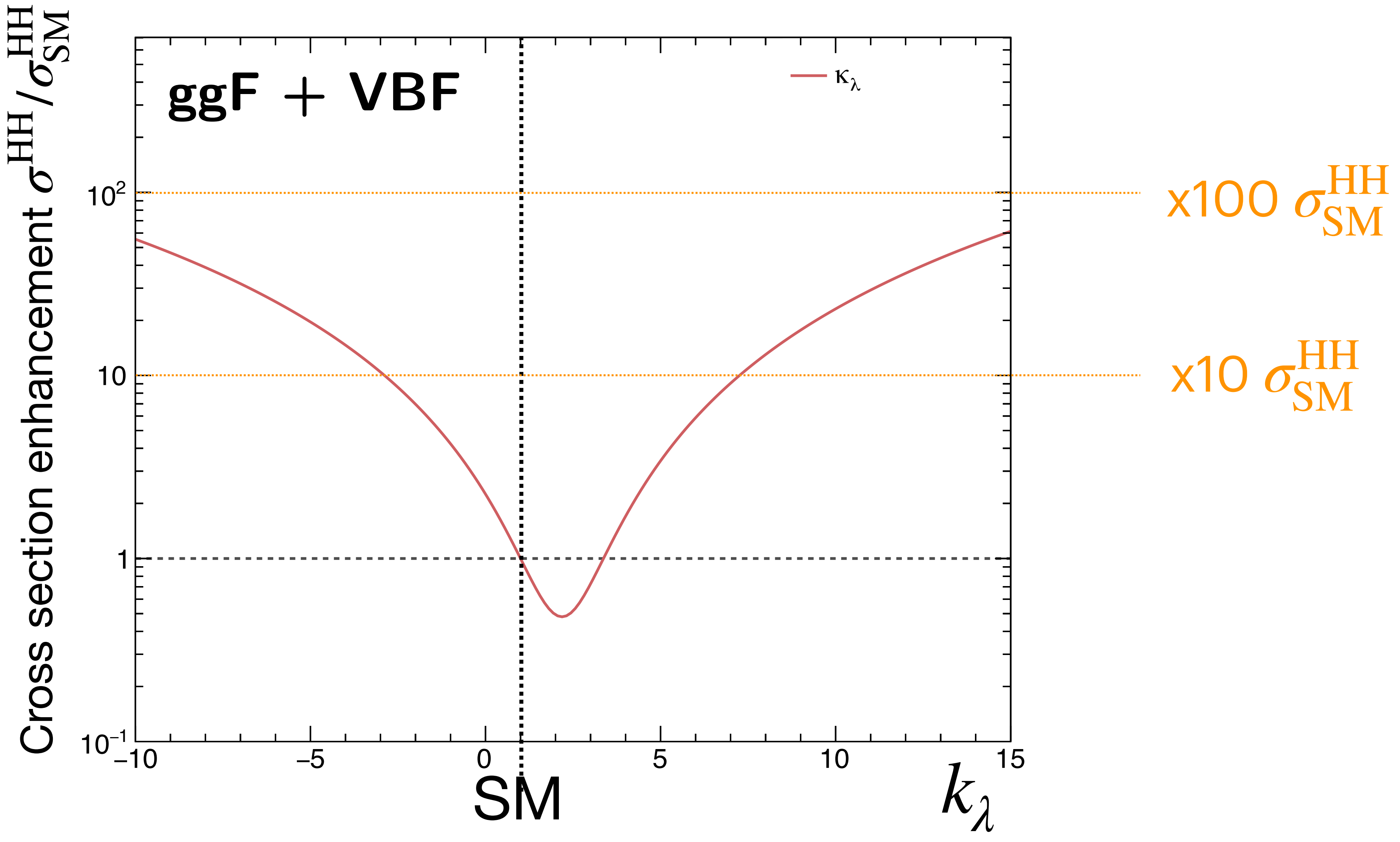
Kinematics and effect on analyses

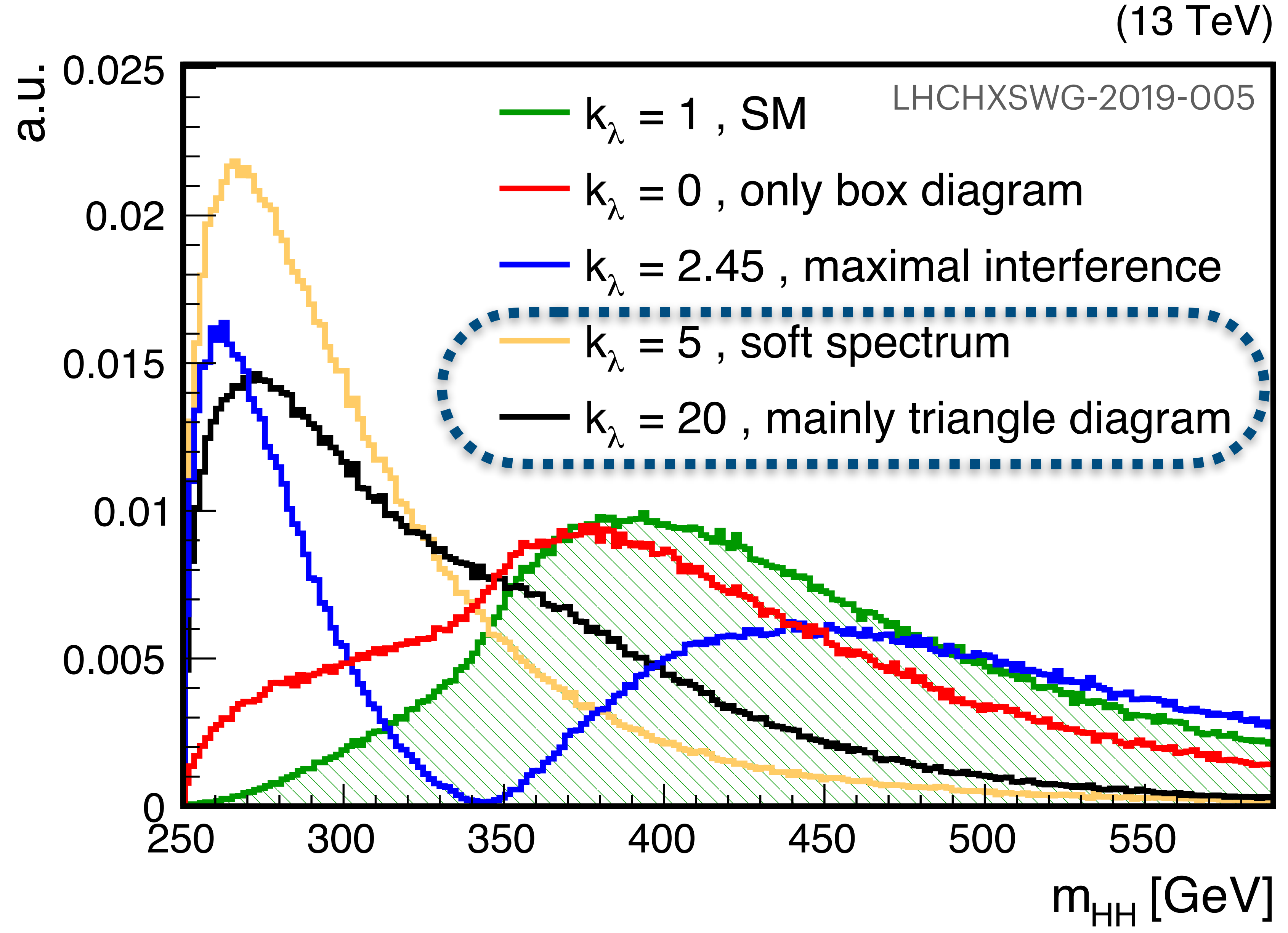


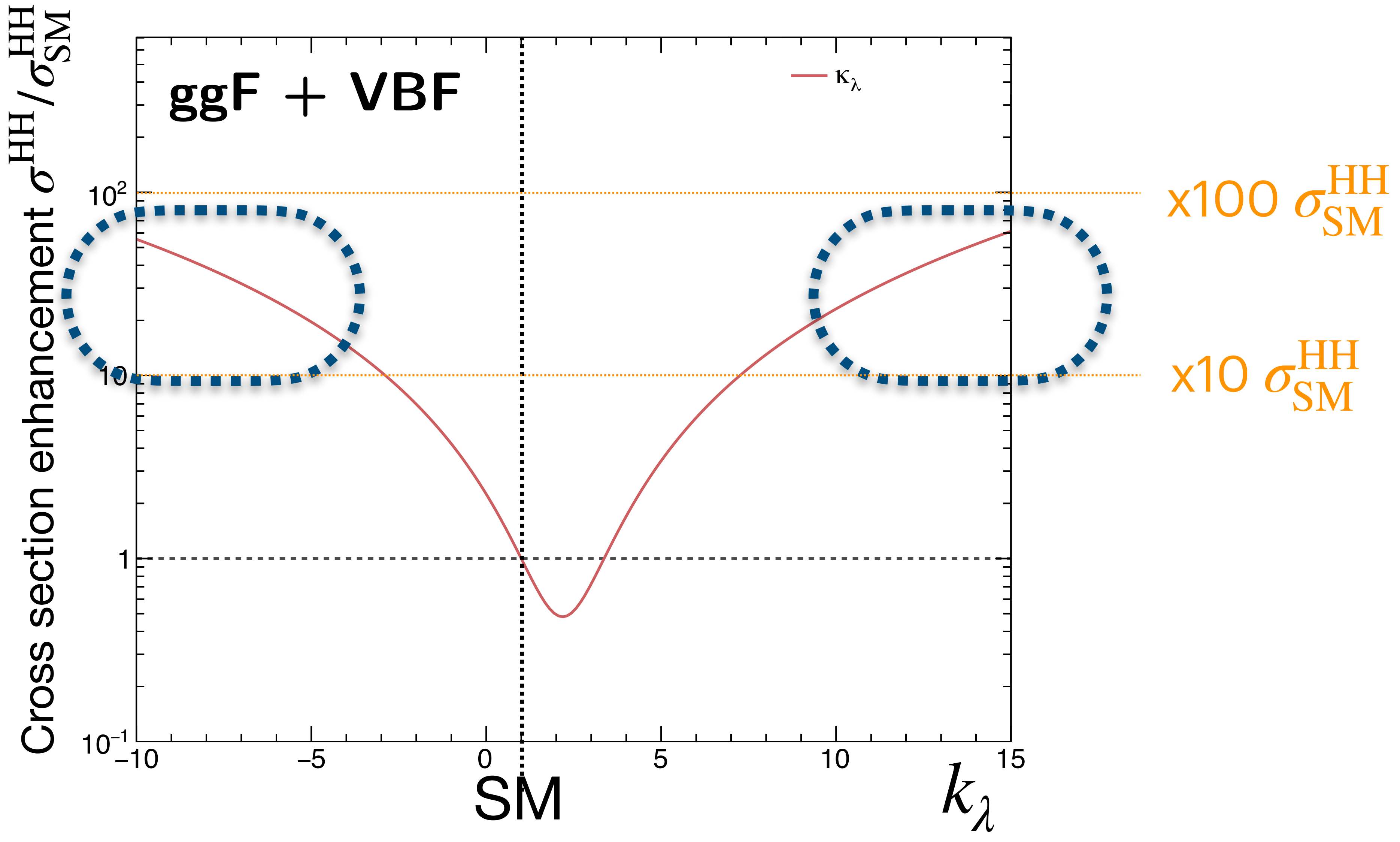


Kinematics and effect on analyses

Large $|k_\lambda|$

- ✘ Sensitivity due to enhanced cross sections
- ✔ Soft spectrum reduces the selection efficiency





Kinematics and effect on analyses

Large $|k_\lambda|$

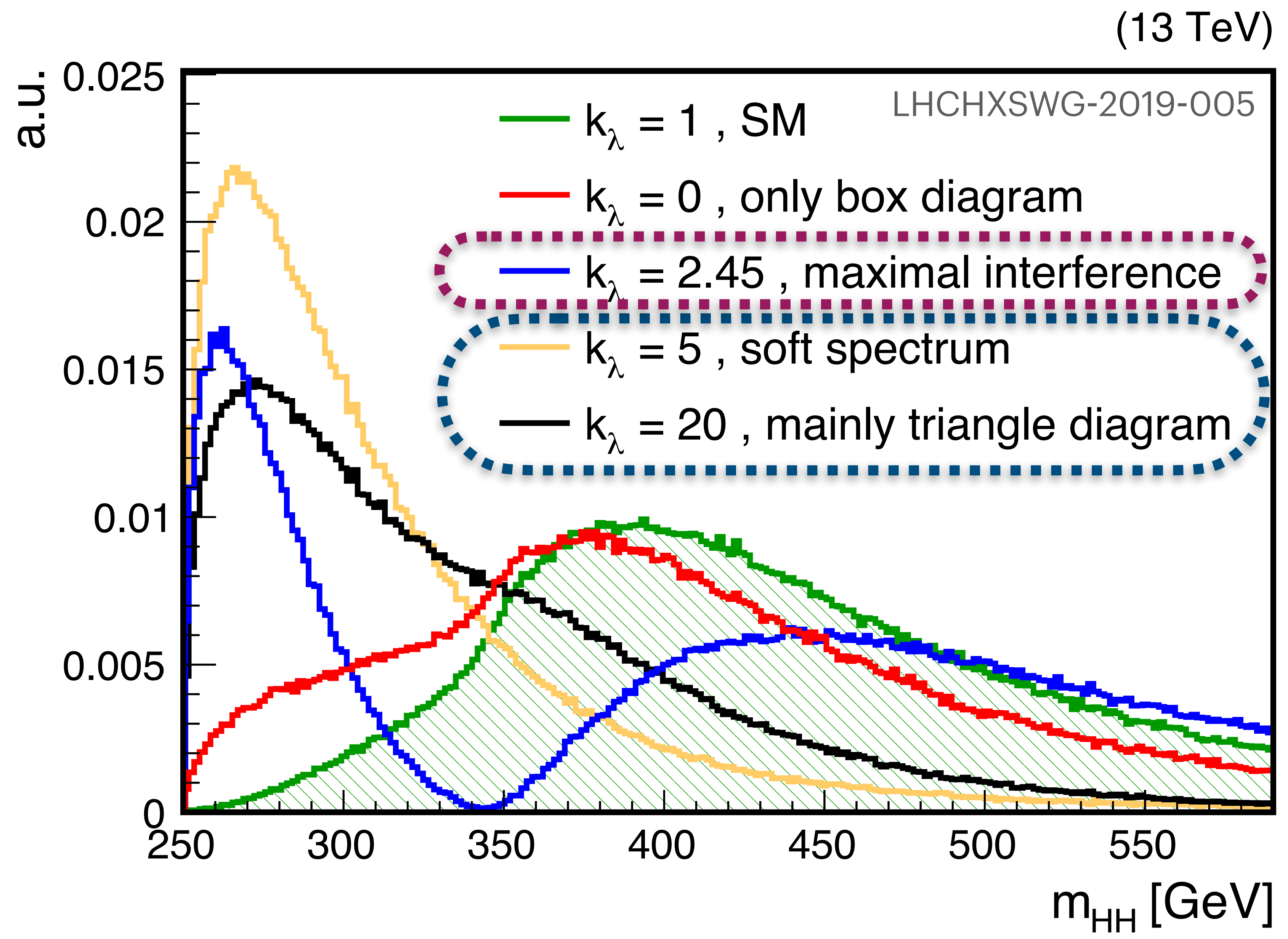
✘ Sensitivity due to enhanced cross sections

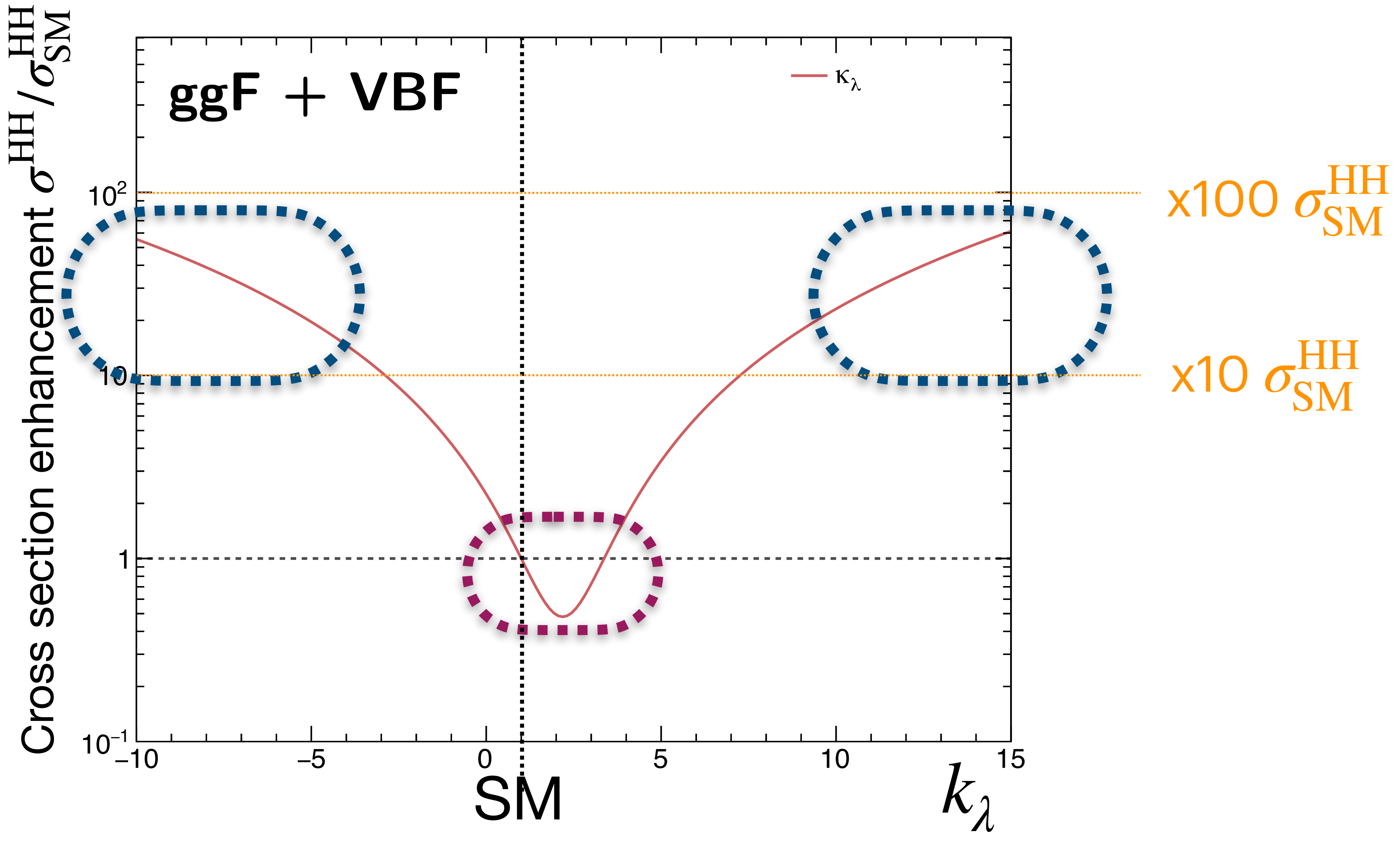
✔ Soft spectrum reduces the selection efficiency

Medium $|k_\lambda|$ (close to max interference)

✘ Hard spectrum leads to **boosted topology**

✔ Enhancement low or even negative

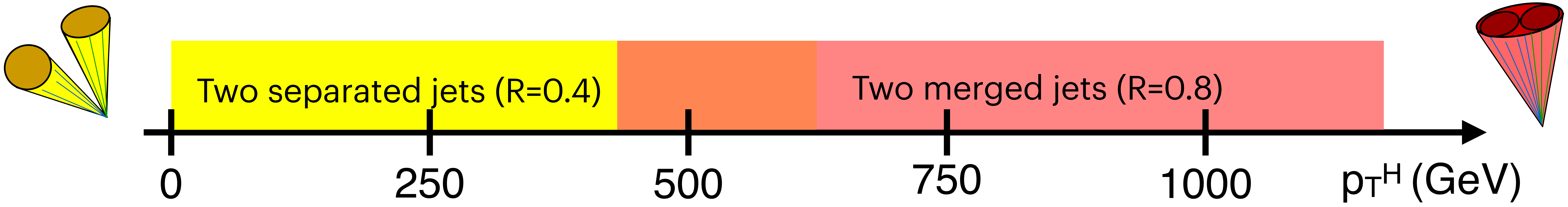




Boosted topology

The separation of the two b quarks in the H decay depends on the H Lorentz boost

$$\Delta R_{b,\bar{b}} \approx \frac{2}{\gamma} = \frac{2m_H}{E} > \frac{2m_H}{p_T}$$



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Multivariate classifiers are used to identify the jets (and their substructure).

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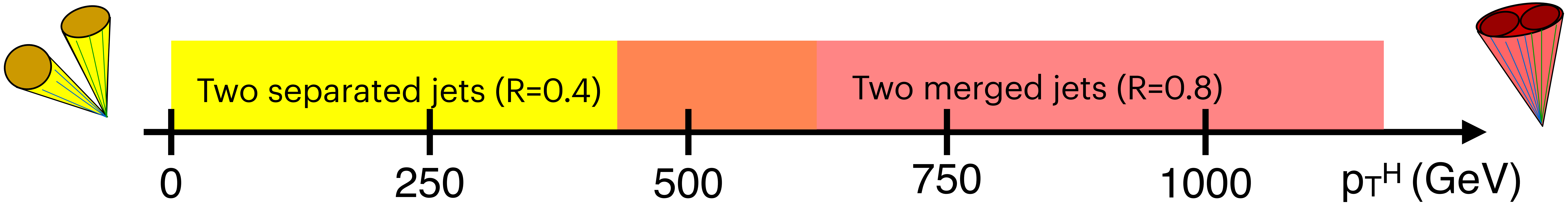

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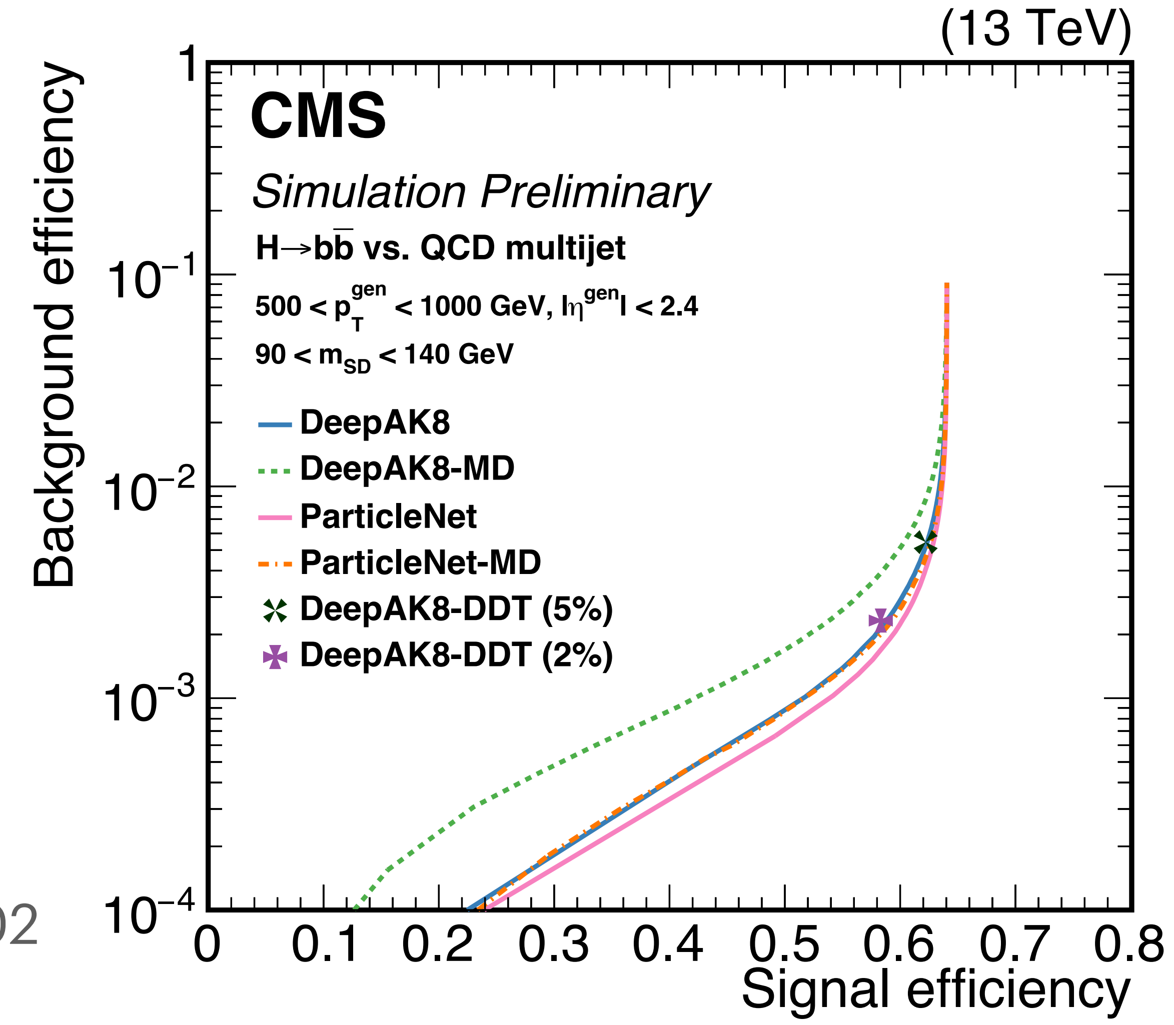
CMS uses ParticleNet a novel jet substructure algorithm based on graph neural network architecture to identify the jets that contain the Higgs boson decay products

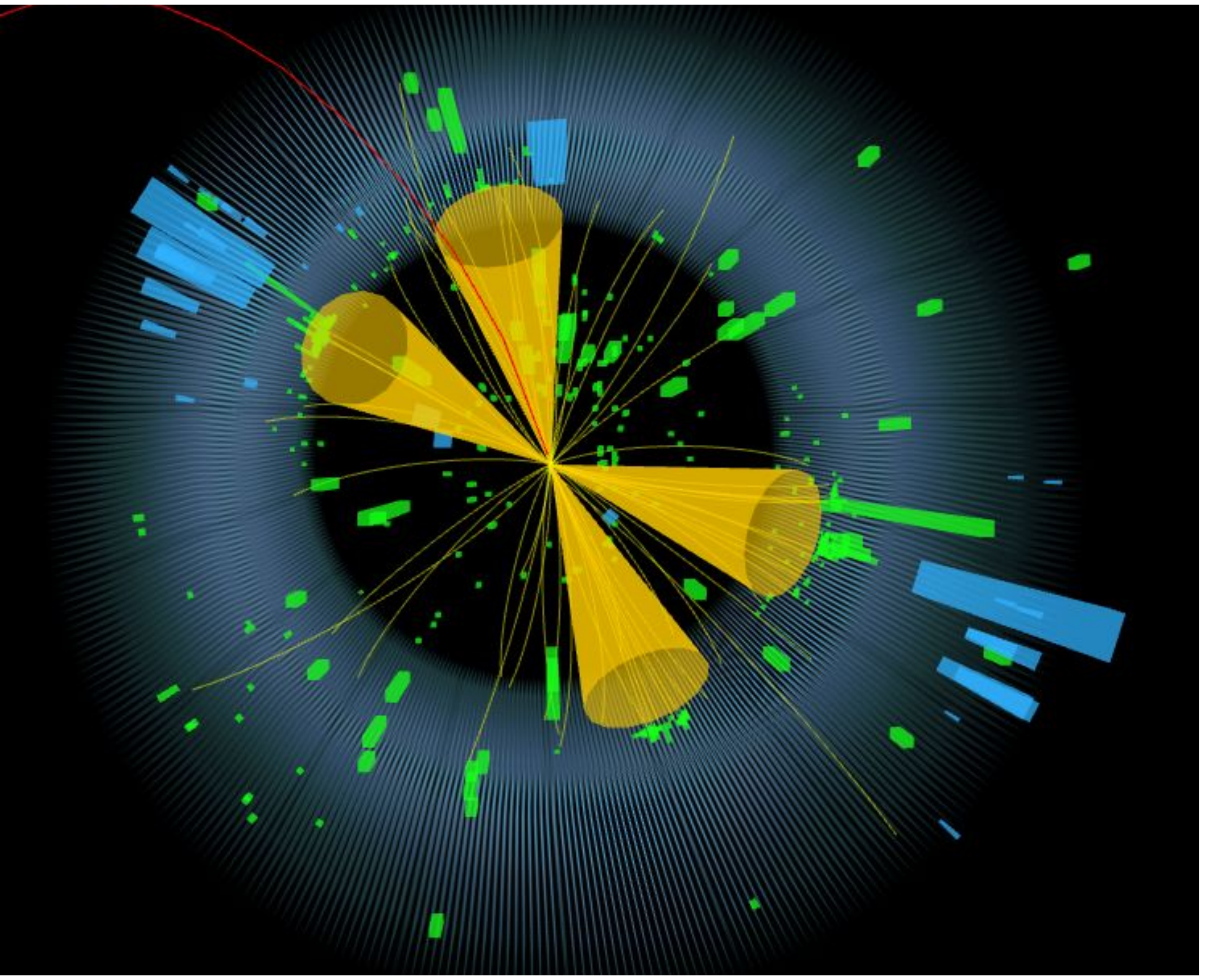
CMS DP-2020/002



HH → bbbb

High $\mathcal{B}$ **Low S/B**

Highest branching ratio… but large multi-jet background!
Mostly probes large m_{HH} ⇒ sensitivity to HH events with large p_T^H



Strategy

- Start from triggered events with ≥2 (ATLAS) or ≥3 (CMS) b-jets
- Signal Region (SR) two b-jet pairs compatible with a Higgs boson
- Data-driven background model based on SR event re-weighting
  - Main challenge is to build a precise model of the multi-jet background without a reliable simulation

ATLAS: ATLAS-CONF-2022-035 CMS: arXiv:2202.09617 / arXiv:2205.06667

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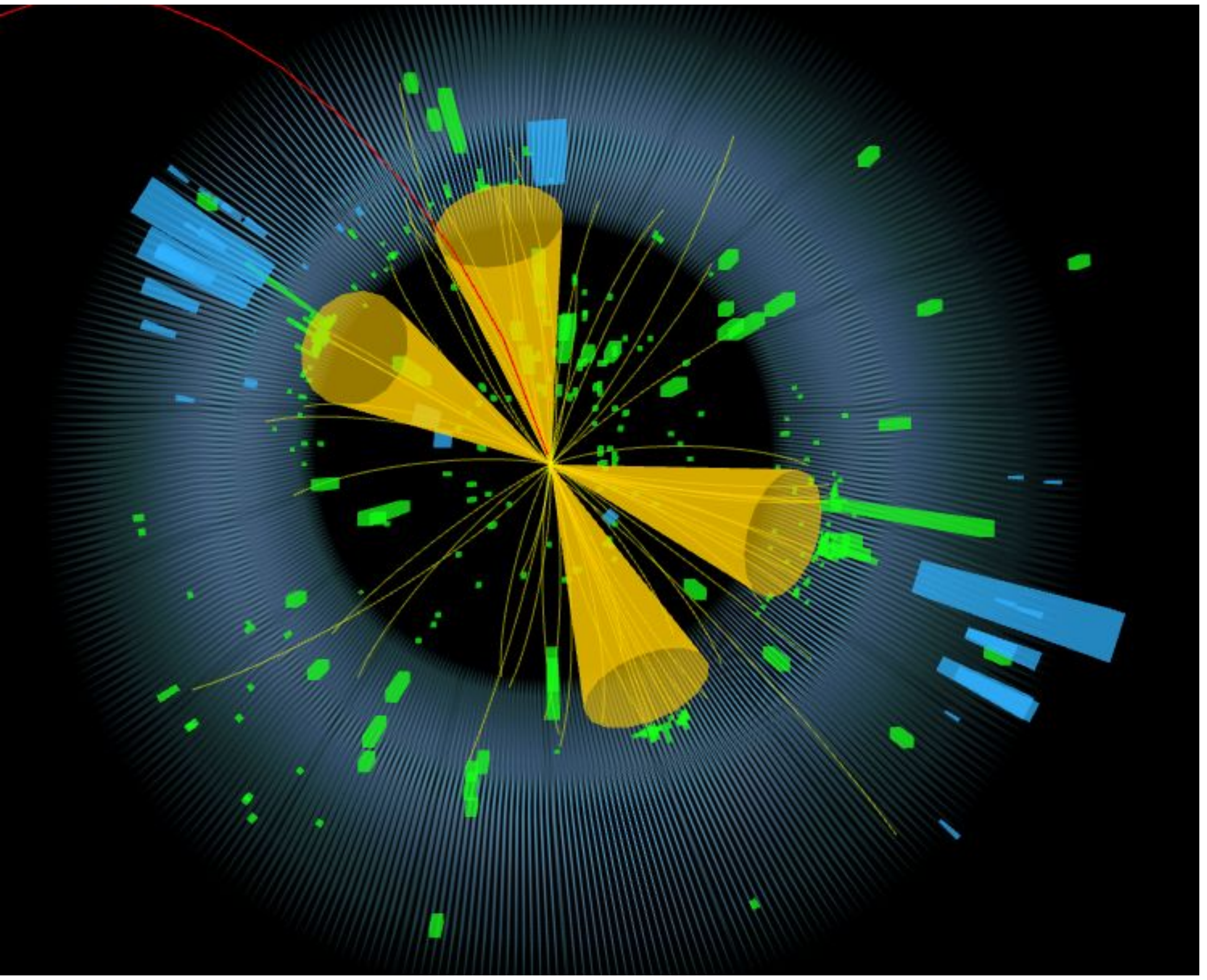

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Two topologies exploited

Resolved

Largest fraction of signal, large QCD

Boosted

O(%) signal acceptance, low QCD

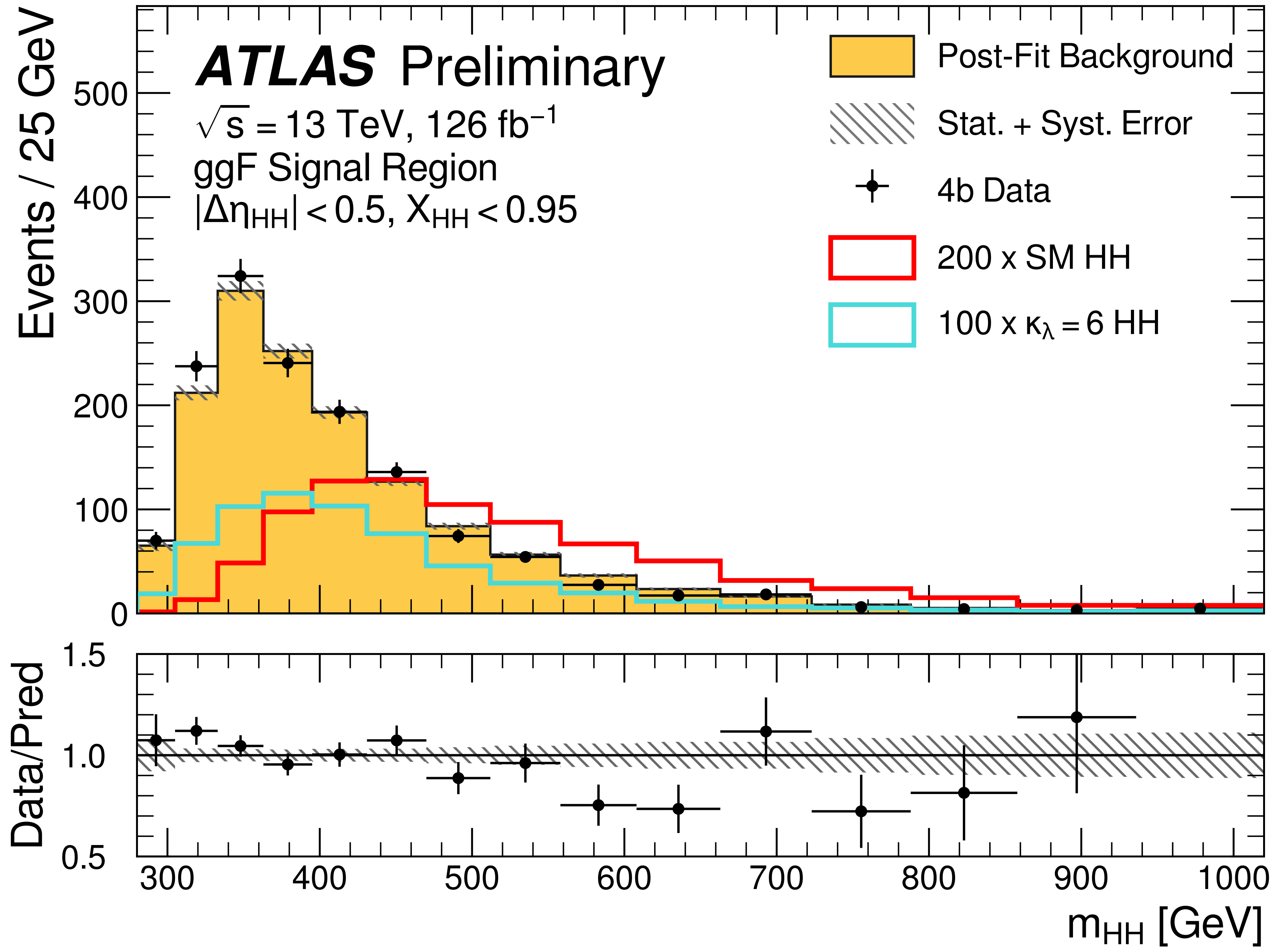
Leading m_{HH} > 1 TeV sensitivity

ATLAS: ATLAS-CONF-2022-035 CMS: arXiv:2202.09617 / arXiv:2205.06667

HH → bbbb : resolved and boosted searches

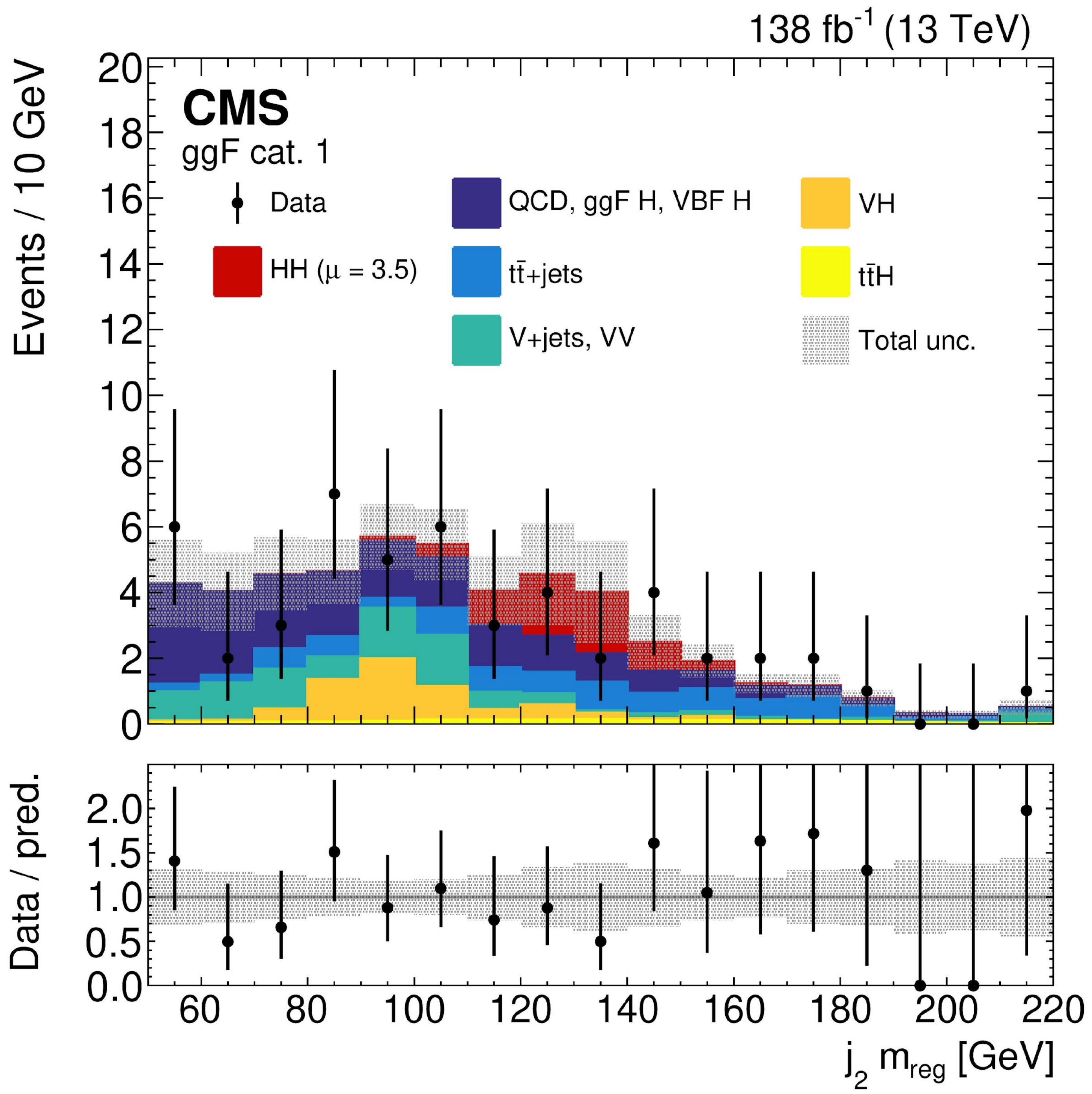
Resolved

ggF- and VBF-like event categories based on forward jets and kinematic properties of HH.
Fit : m_{HH} (ATLAS) / MVA classifier or m_{HH} (CMS).



Boosted

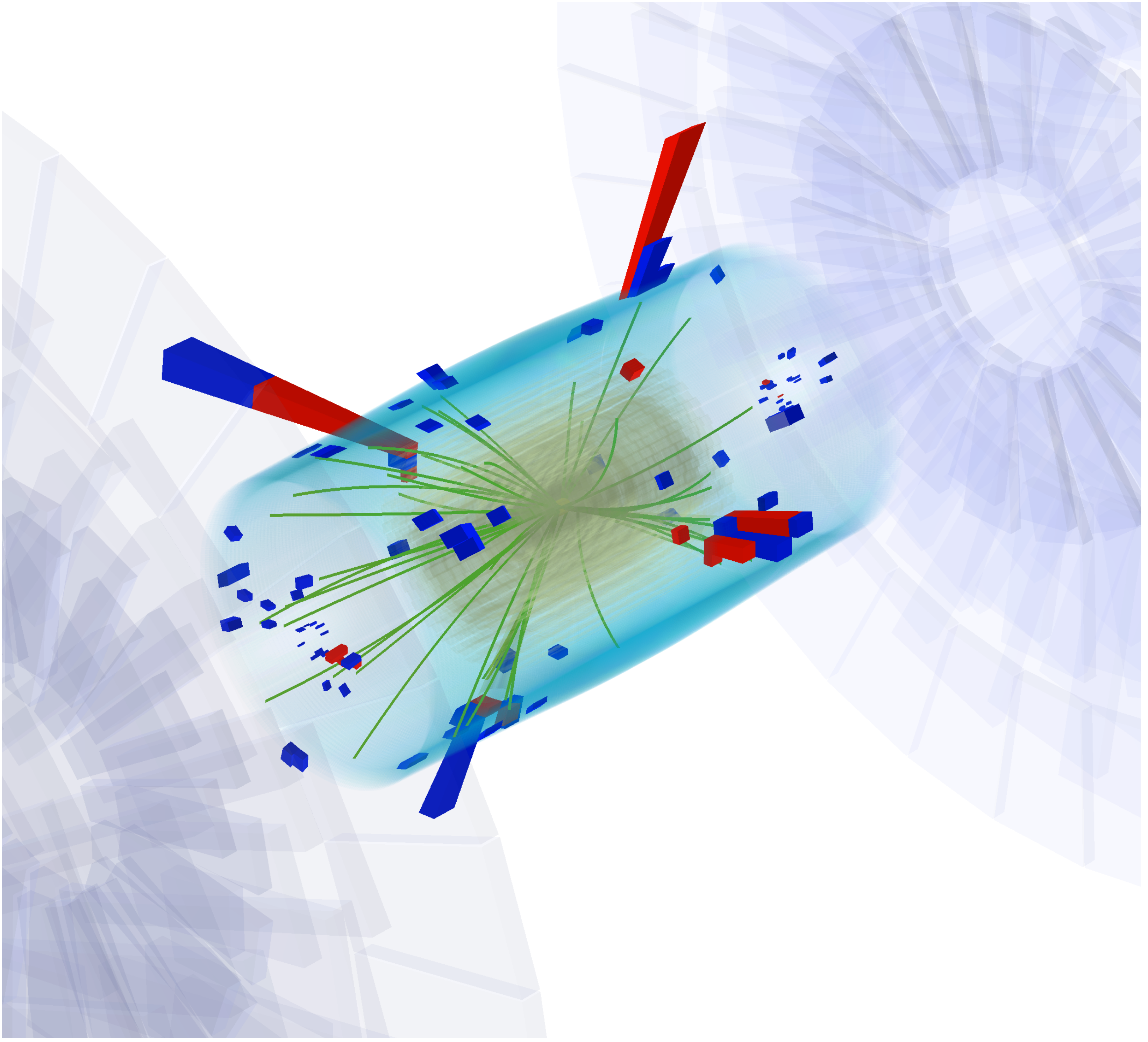
ggF- and VBF-like event categories based on forward jets and kinematic properties of HH.
Machine-learning tagger for H→bb decay ID.
Back. : data driven QCD, simulation $t\bar{t}$



HH → bb$\tau\tau$

Medium $\mathcal{B}$ Medium S/B

Intermediate branching ratio... but clean final state with moderate backgrounds!



Strategy

Channels : $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$

Categorization of events by production mode (CMS) and purity

Machine learning : b-jet and τ ID, H→bb candidate tagging

Signal extraction: MVA classifiers (using kinematic informations)

ATLAS: arXiv:2209.10910 CMS: arXiv:2206.09401

HH → bbττ

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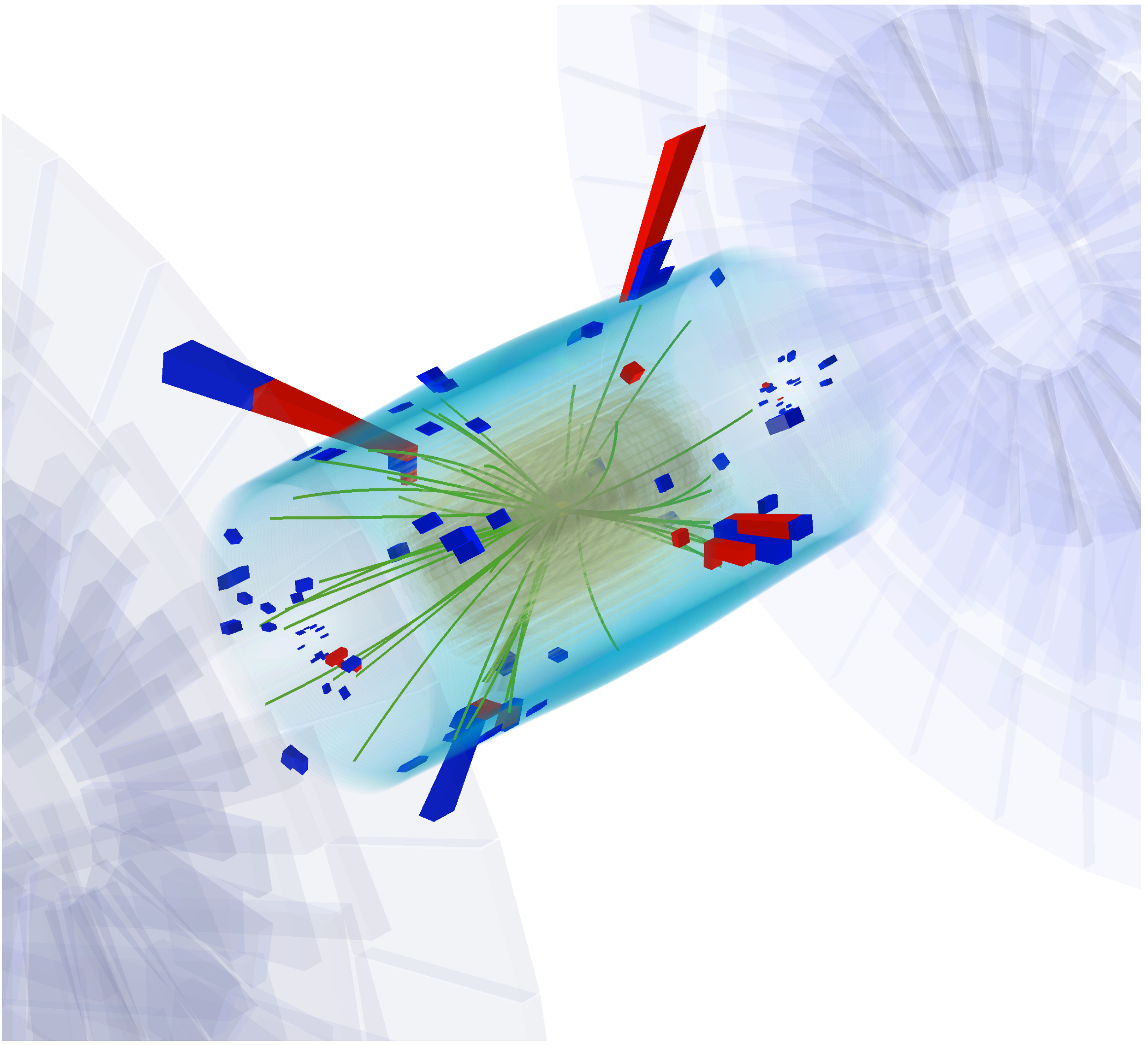

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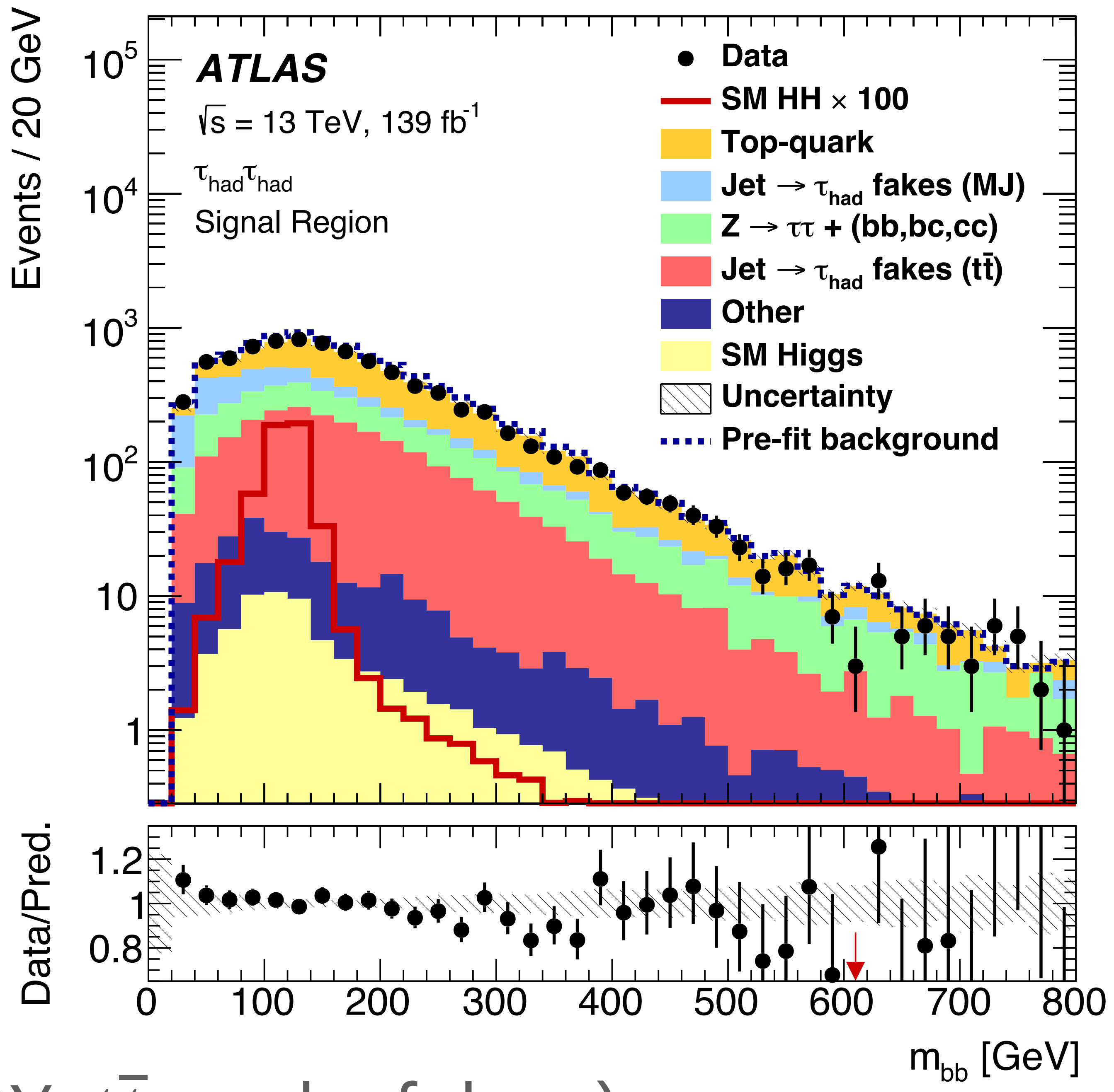
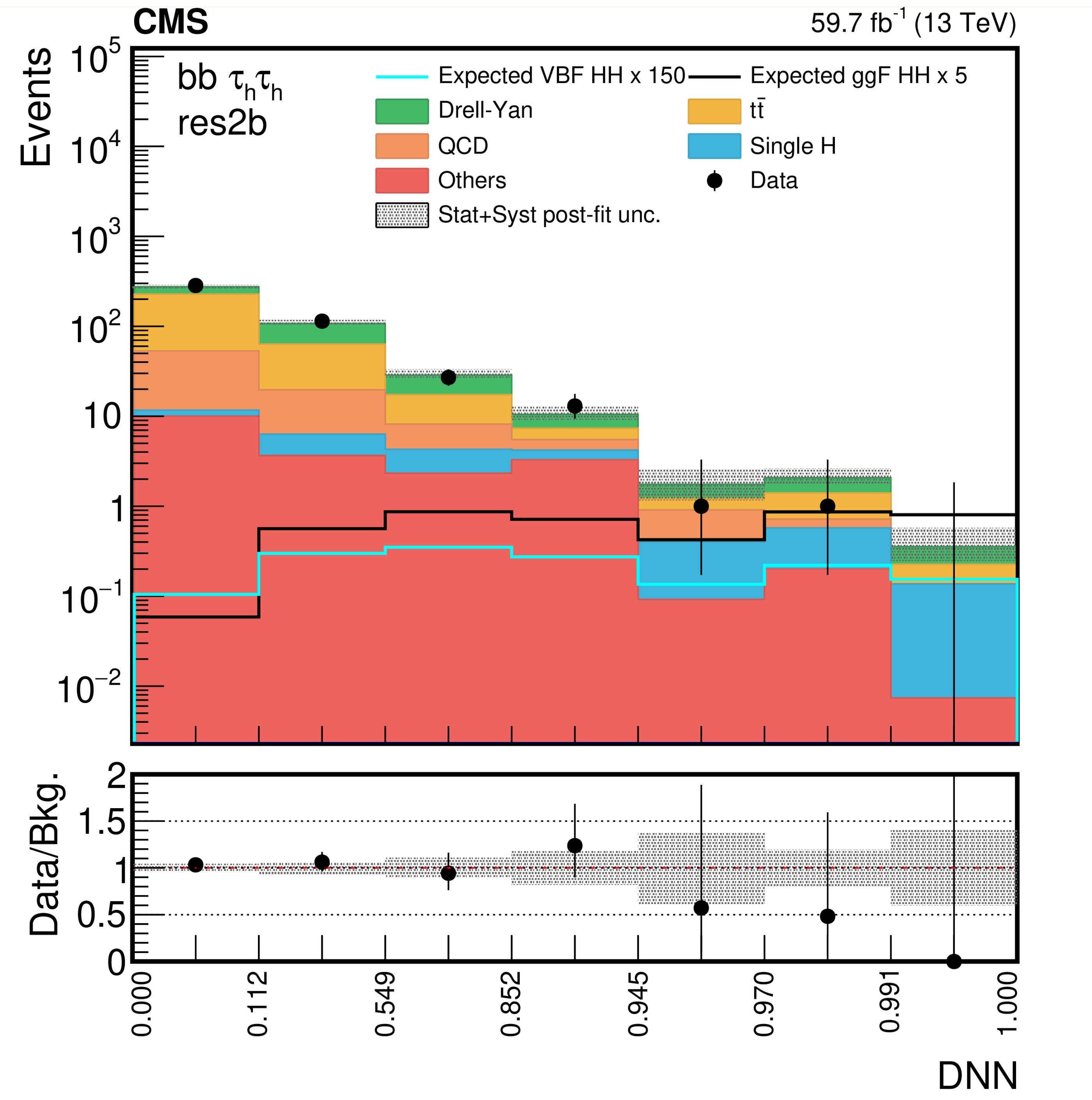




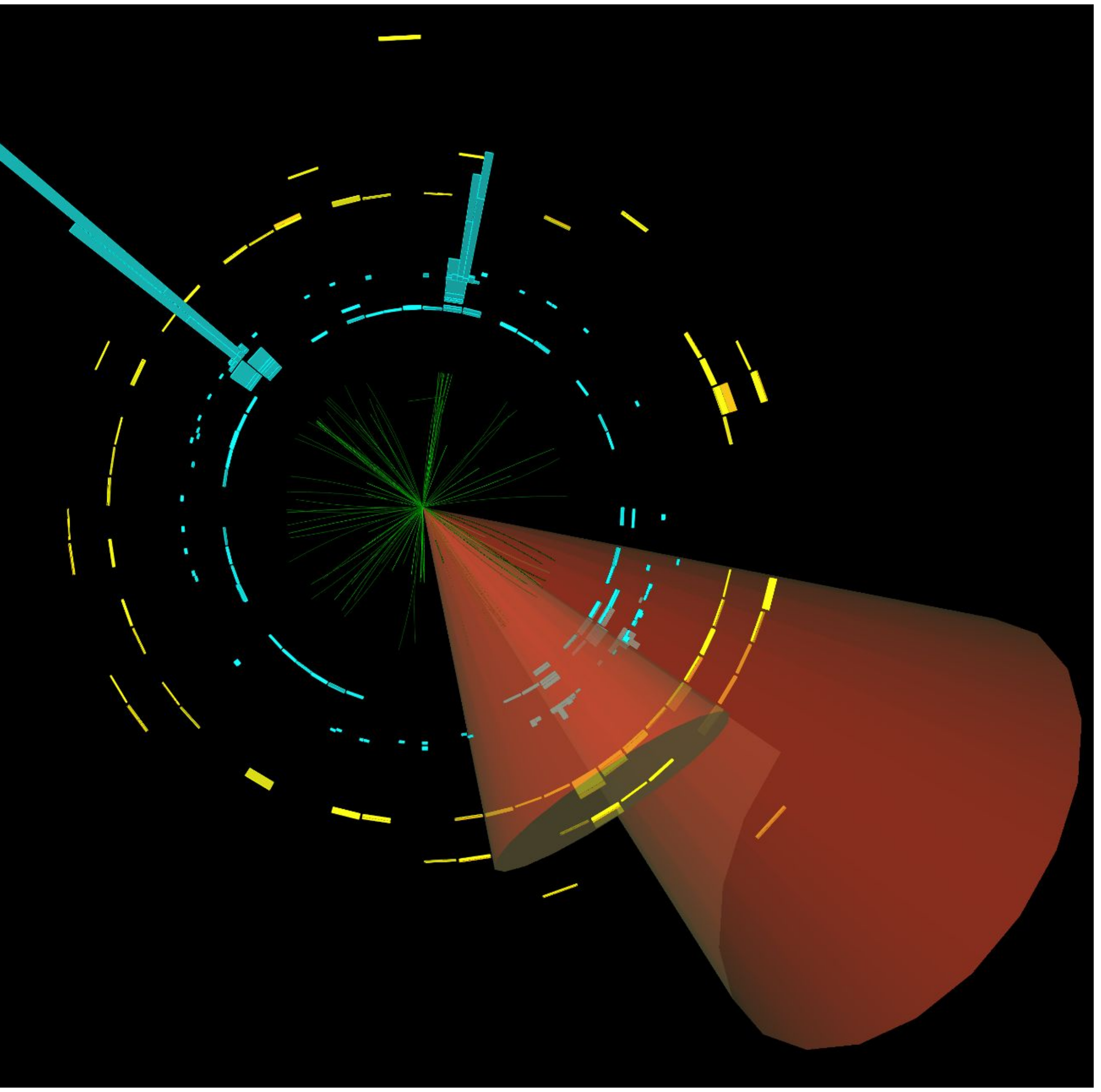
Background modelling is a key challenge (DY, $t\bar{t}$, and τ fakes)

HH → bb$\gamma\gamma$

Low $\mathcal{B}$ High S/B

Tiny branching ratio… but very clean signature: excellent $m_{\gamma\gamma}$ resolution and small backgrounds

Enhanced sensitivity at low m_{HH}, hence to the Higgs boson self-interaction.



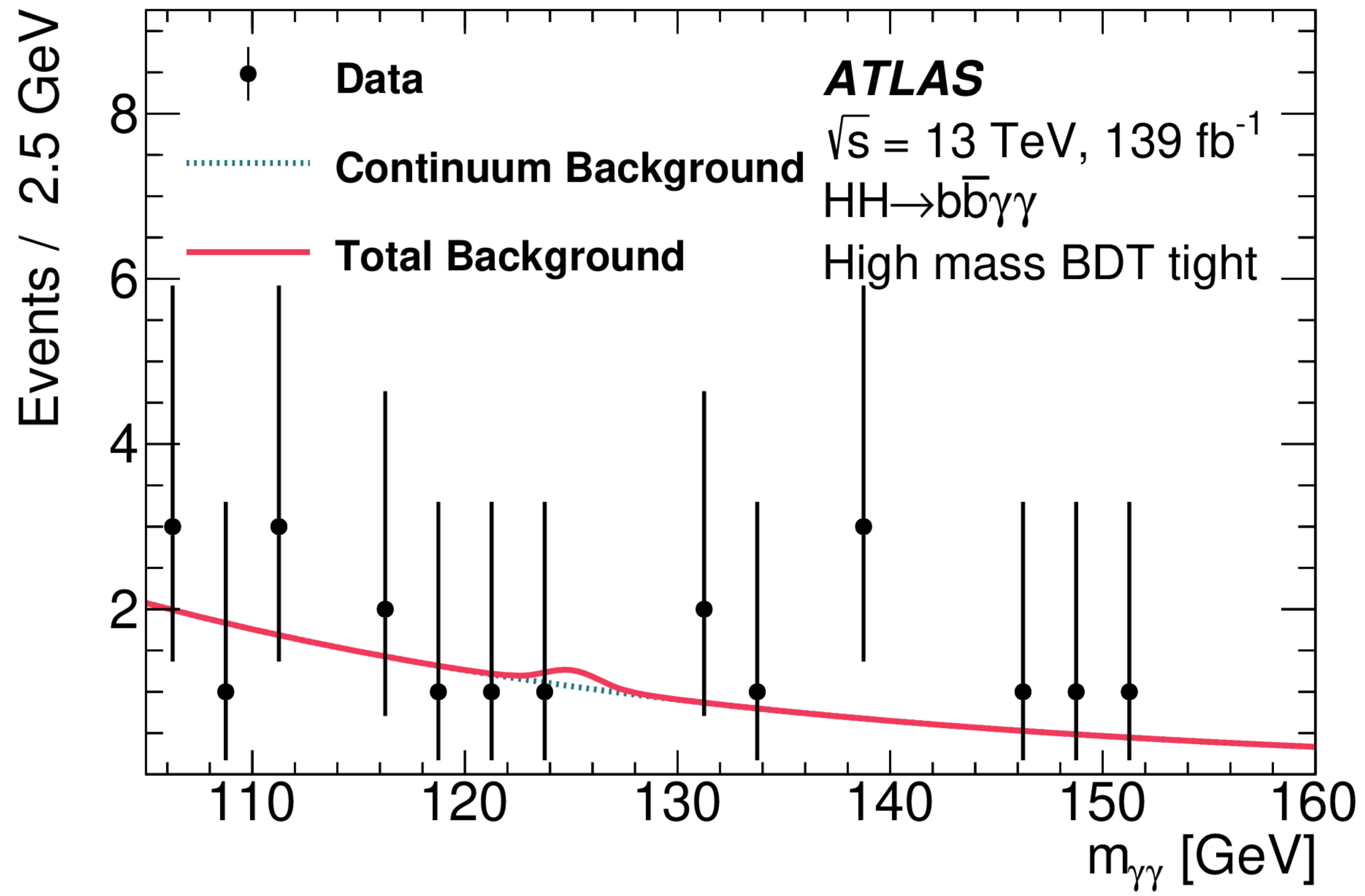
Strategy

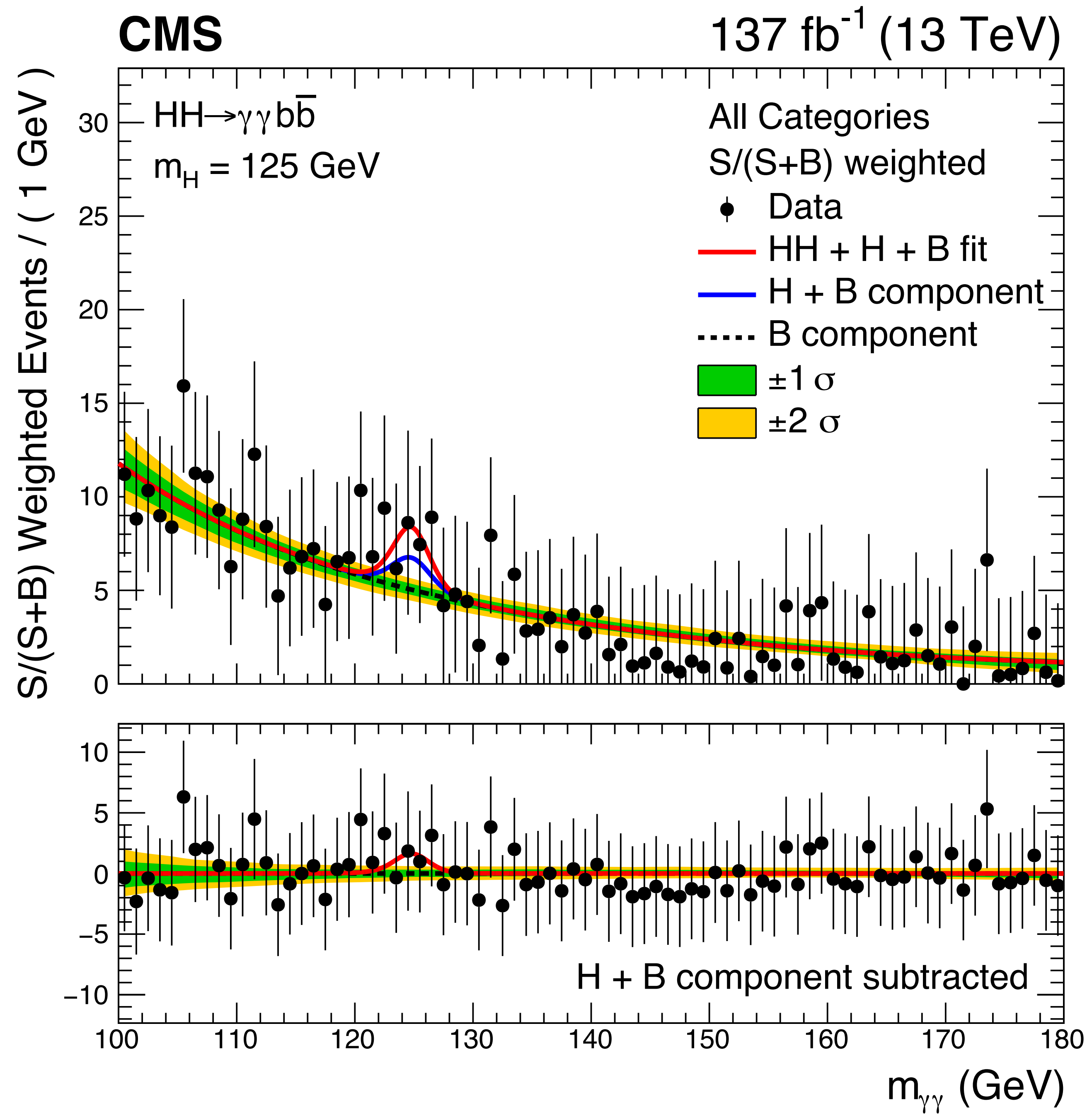
- Di-photon trigger and event selection + 2 b-jets.
- Event categories based on m_{HH}, various purity regions based on MVA outputs, ggF- and VBF-like topologies (in CMS).
- HH and single-H shapes from simulation.
- Continuum background shape from data.

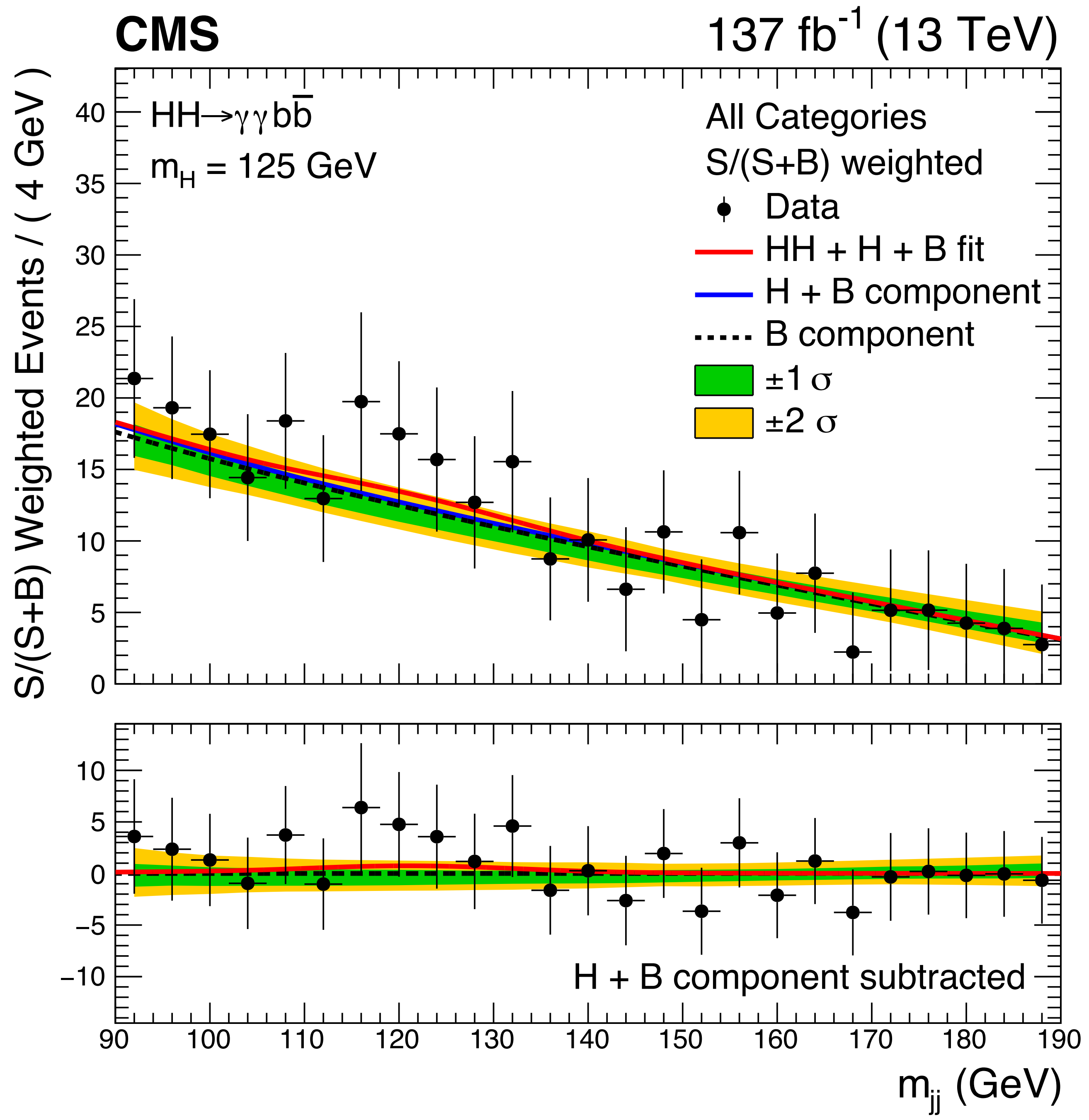
ATLAS: Phys. Rev. D 106 (2022) 05200 CMS: JHEP03 (2021) 257

HH → bbγγ - signal extraction

$m_{\gamma\gamma}$ spectrum is used to extract the final results





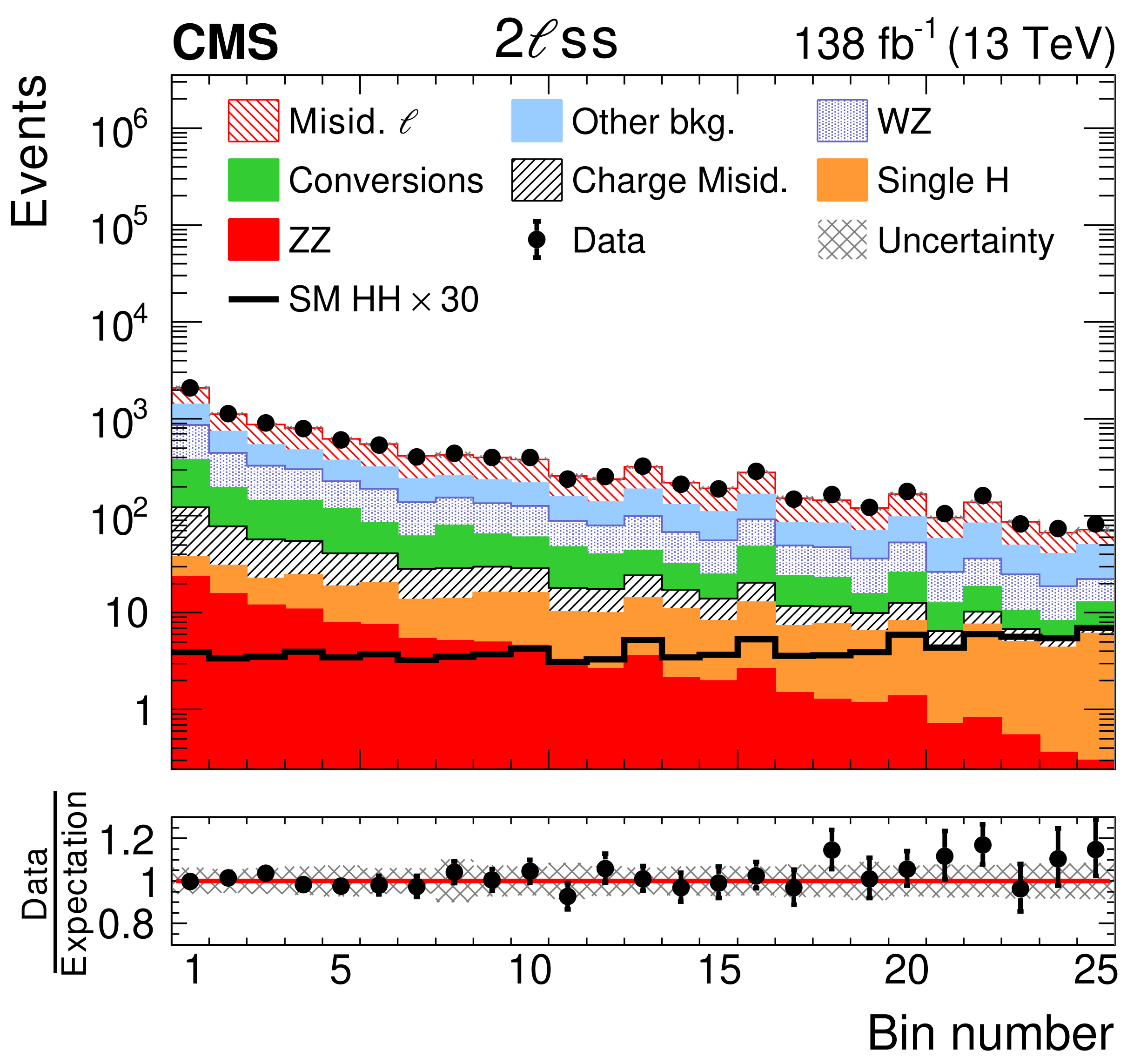


ATLAS fits the $m_{\gamma\gamma}$ spectrum in each category

CMS performs a simultaneous fit in $m_{\gamma\gamma} \times m_{jj}$ in each category

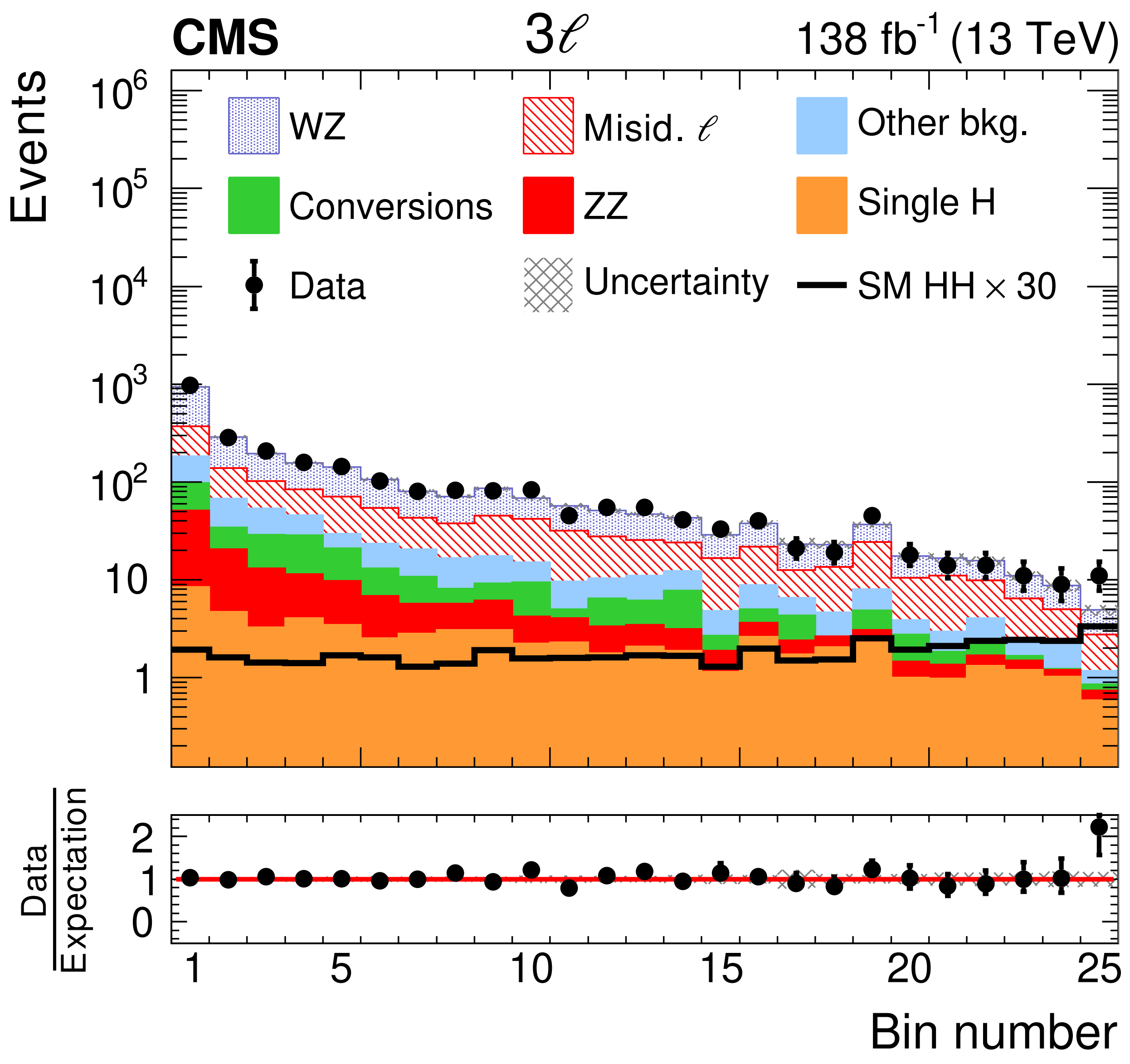
ATLAS: Phys. Rev. D 106 (2022) 05200 CMS: JHEP03 (2021) 257

..and more channels are explored!



arXiv:2206.10268

Submitted to the JHEP



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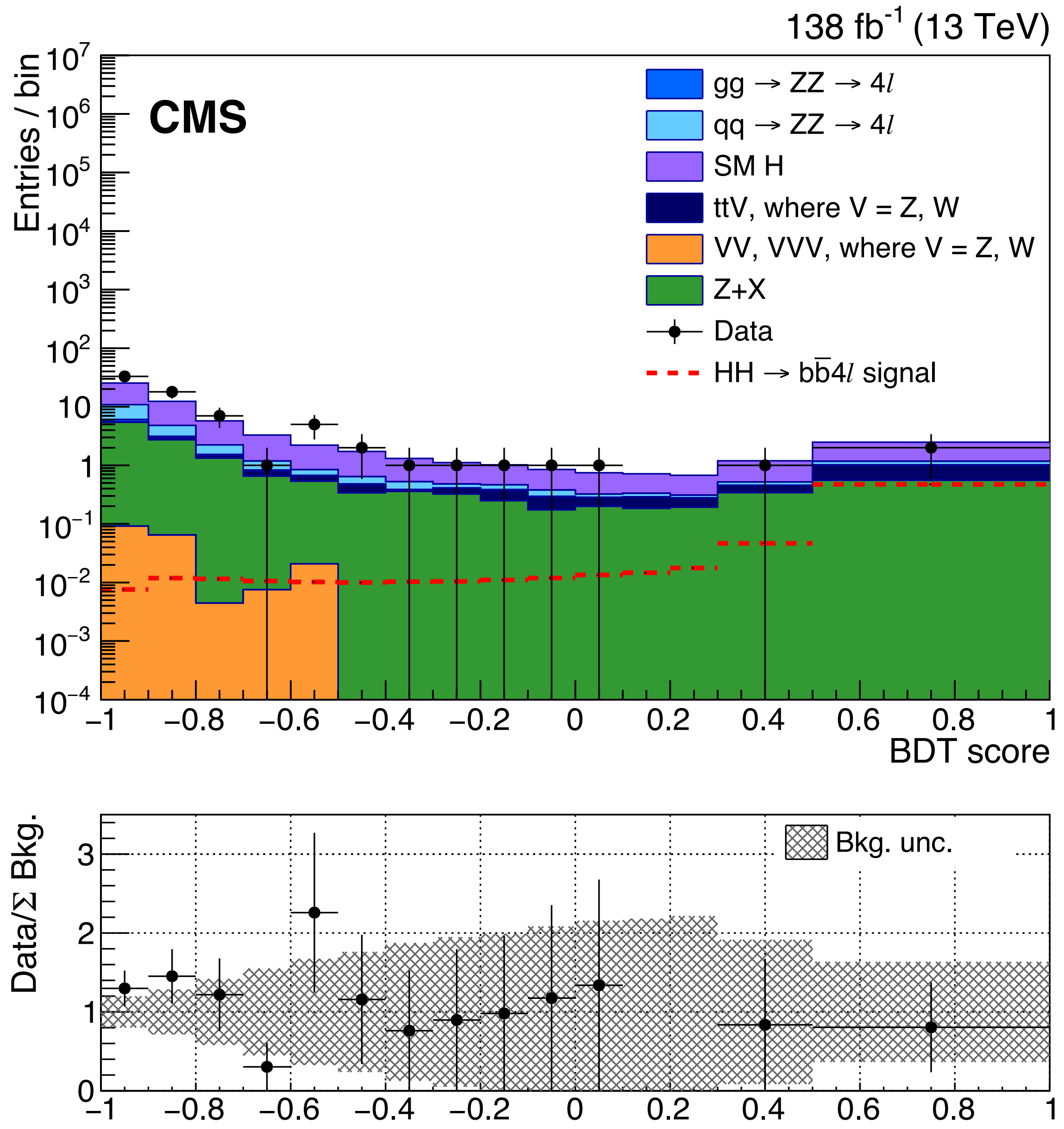
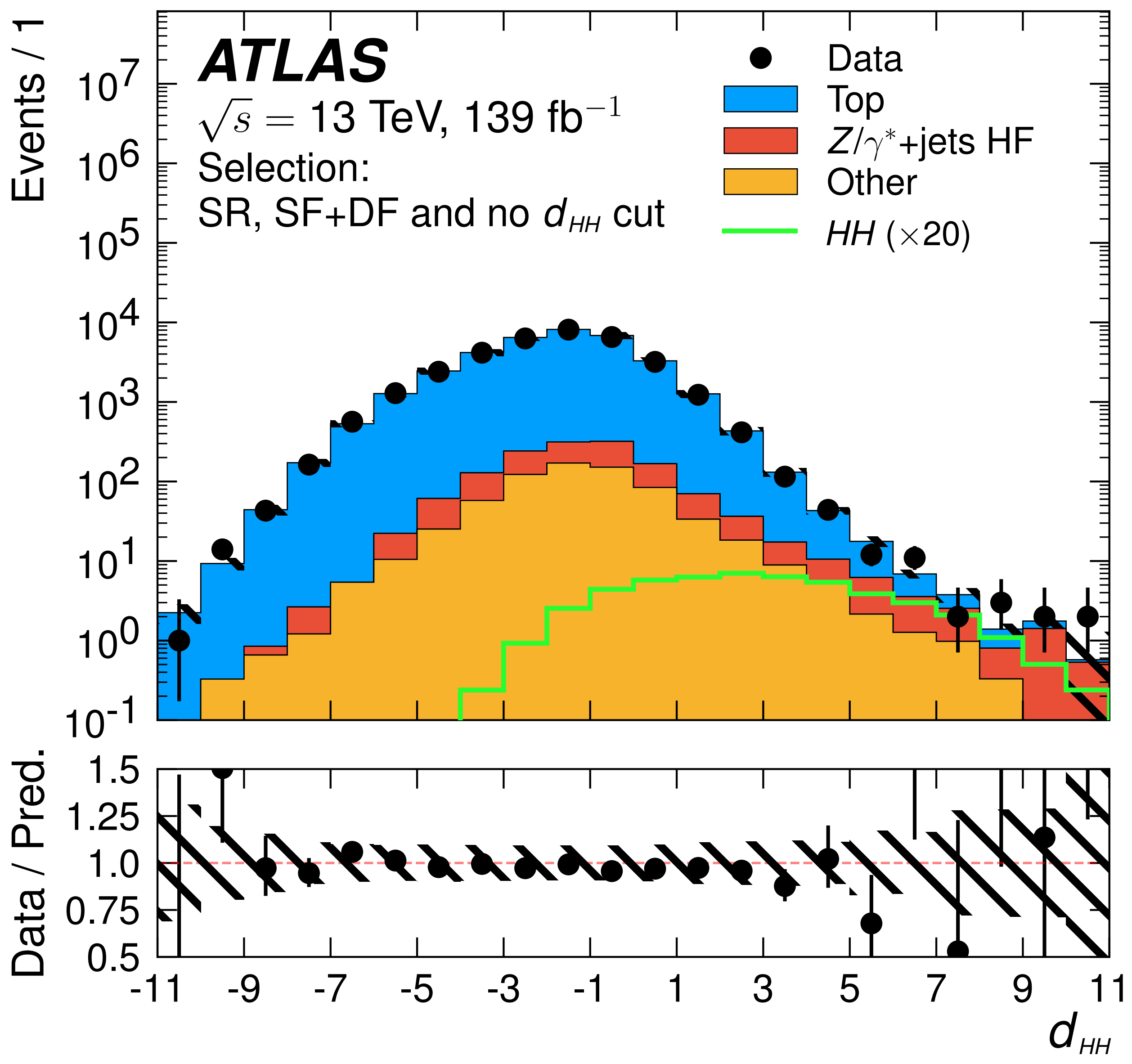
HH →WWWW/WWττ/ττττ



arXiv:2206.10657

Submitted to the JHEP

HH →4lbb



Phys. Lett. B 801 (2020) 135145

HH →WW2l

Putting all together

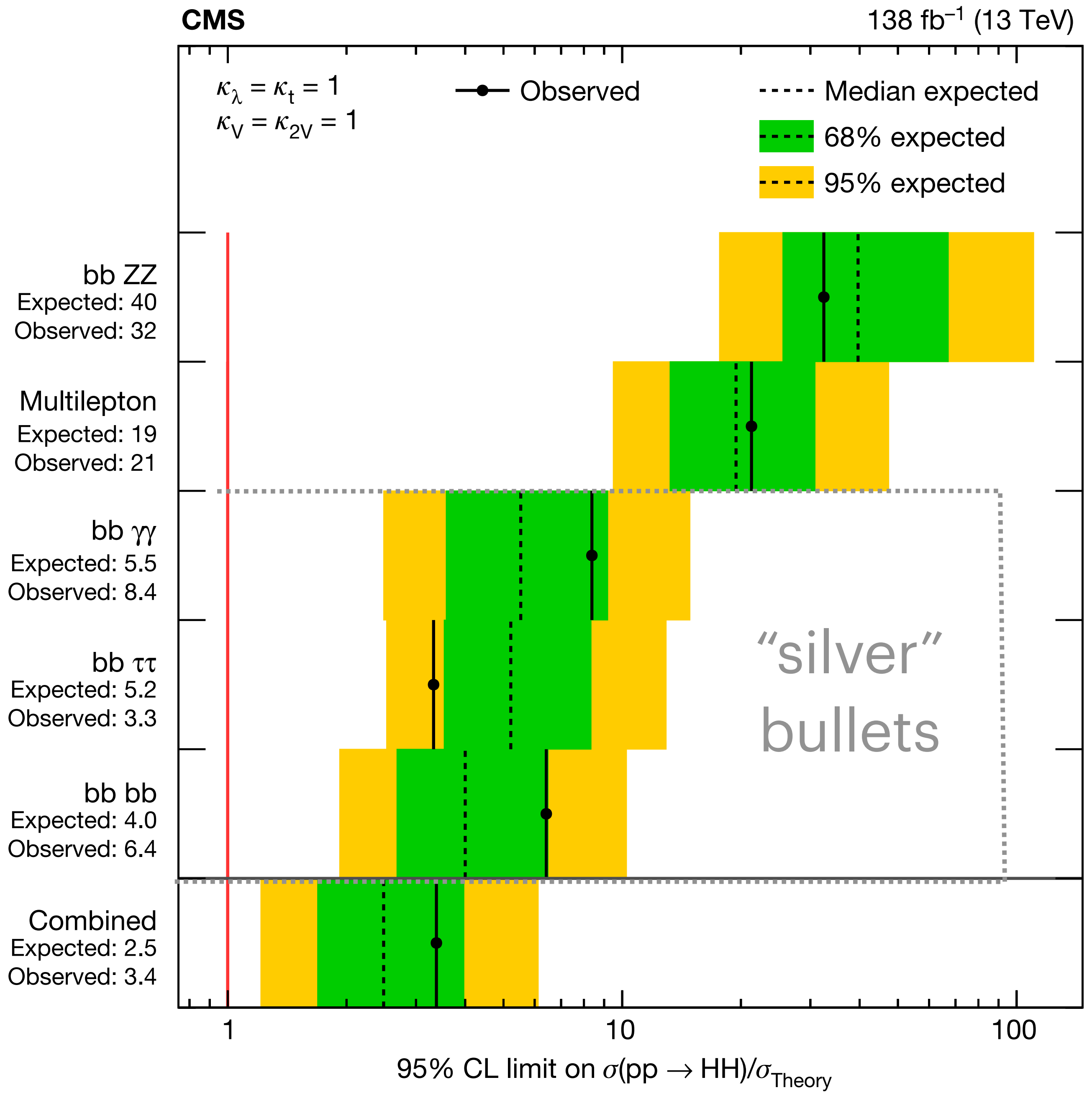
Not a single “golden” channel but various contributions to the overall sensitivity $\Rightarrow$ Combinations are key

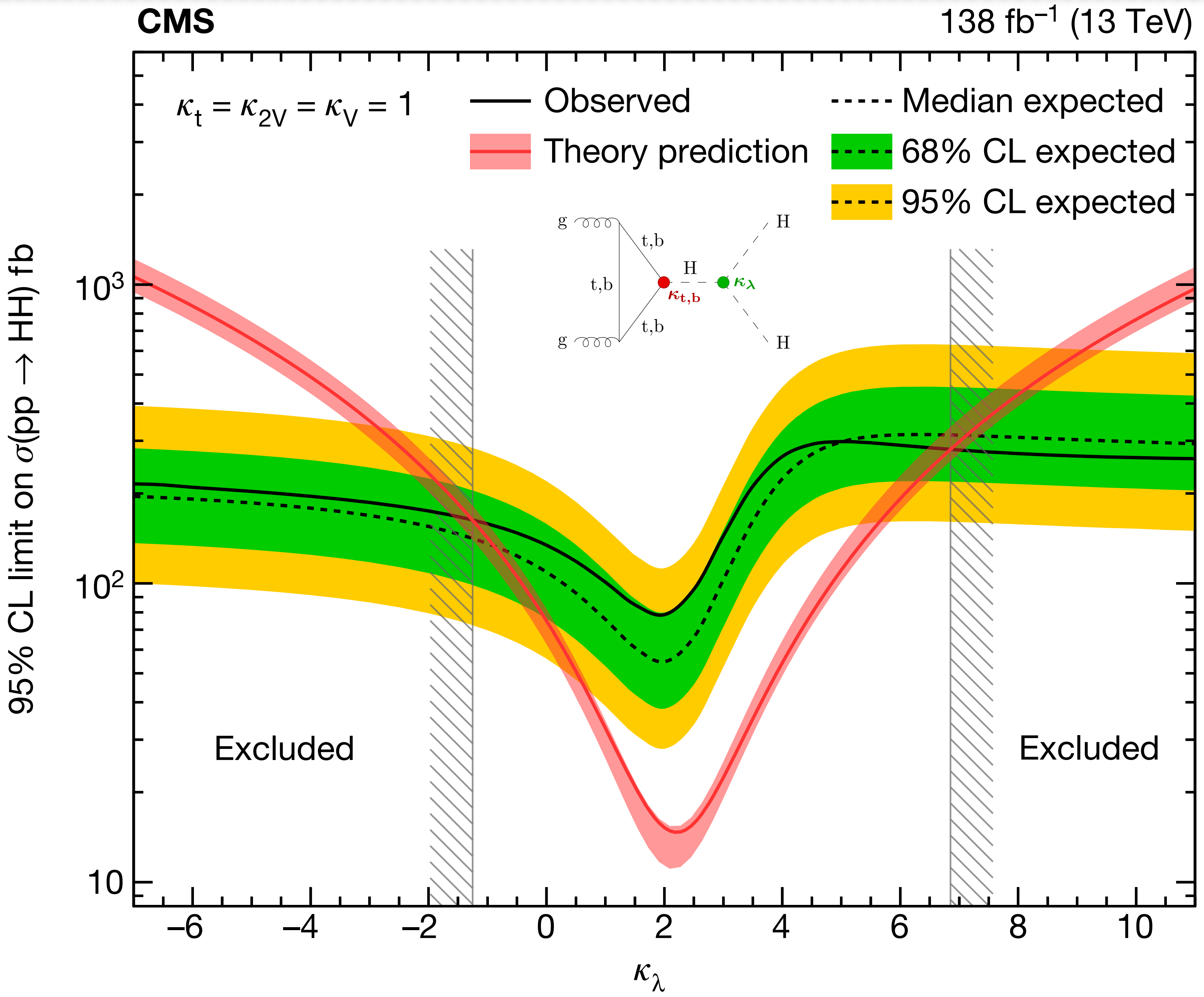
Putting all together : HH production

Not a single "golden" channel but various contributions to the overall sensitivity ⇒ Combinations are key

CMS

Combination





ATLAS

95% CL limit on $\sigma_{HH}/\sigma^{SM}_{HH}$ 2.4(2.9) obs.(exp.)

95% CL limit on $k_\lambda \in [-0.6; +6.6]$

ATLAS: ATLAS-CONF-2022-050 CMS: Nature 607, 60-68 (2022)

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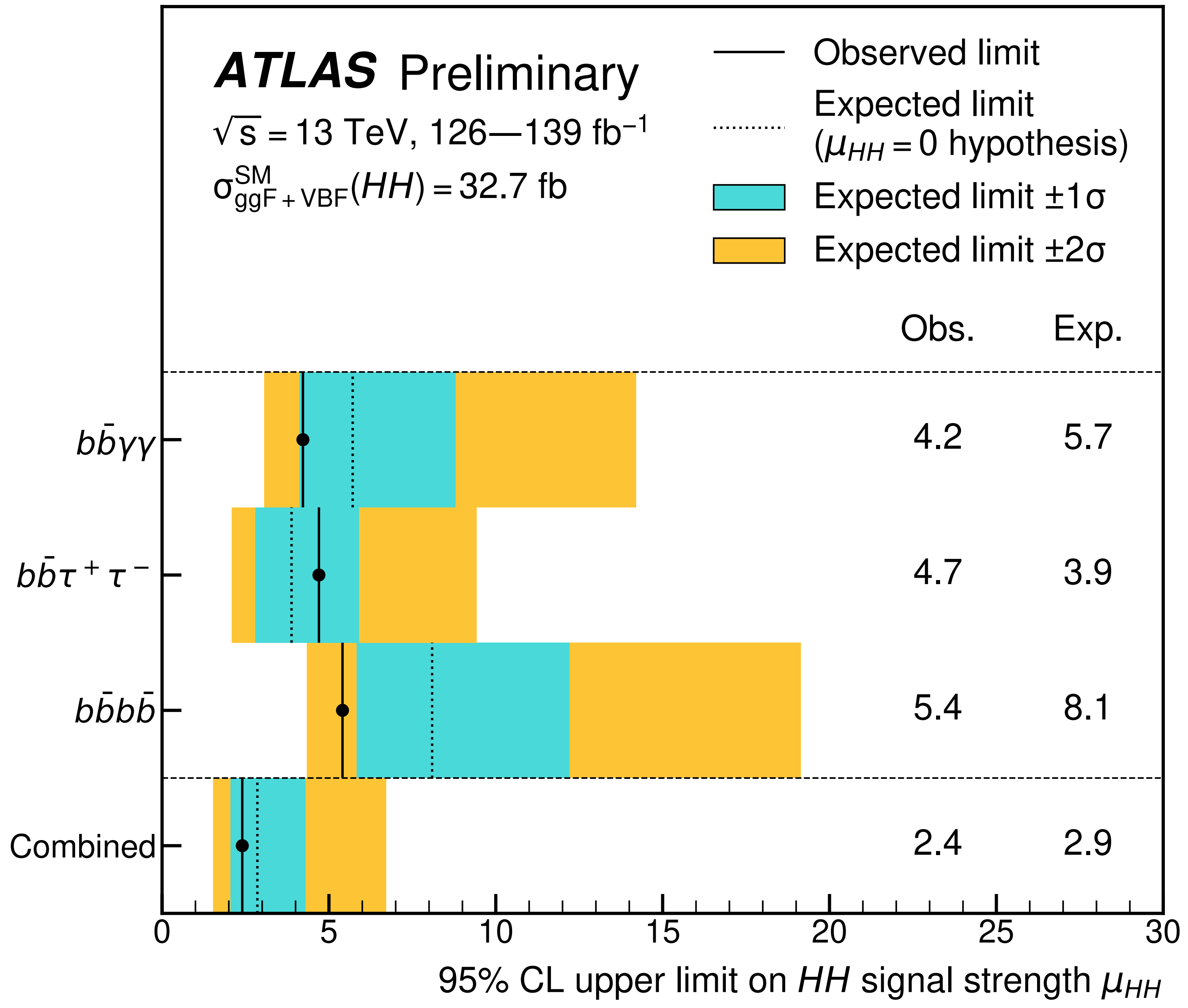
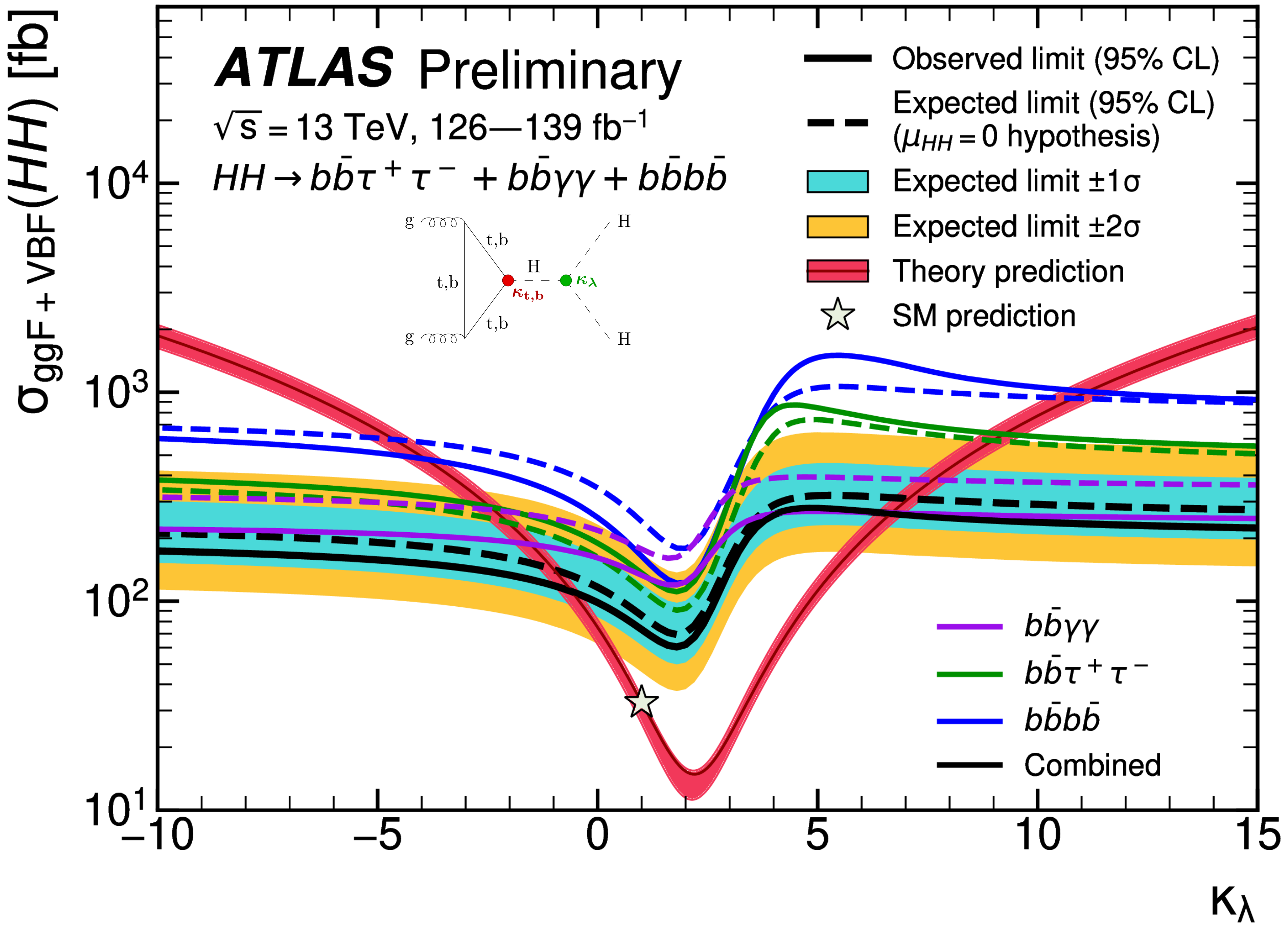




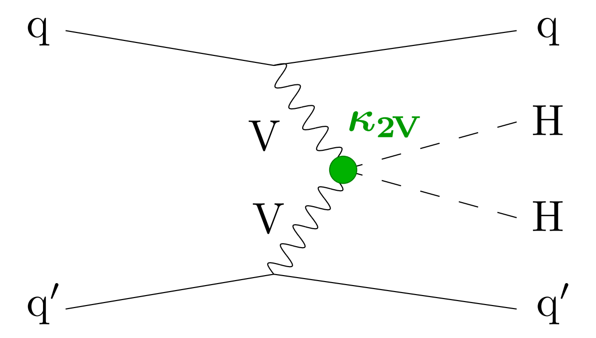
CMS

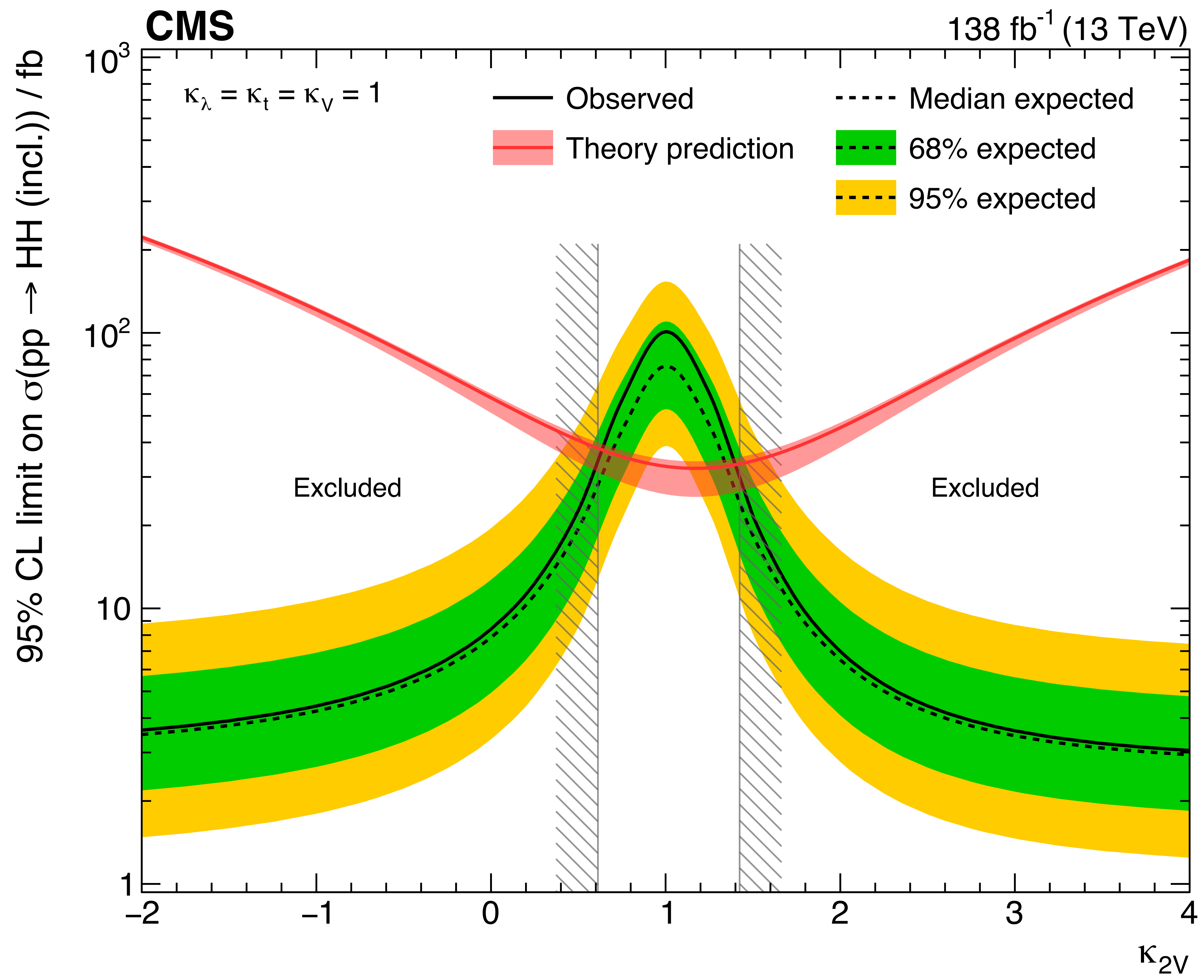
95% CL limit on $\sigma_{HH}/\sigma^{SM}_{HH}$ 3.4(2.5) obs.(exp.)

95% CL limit on $k_\lambda \in [-1.24; +6.49]$

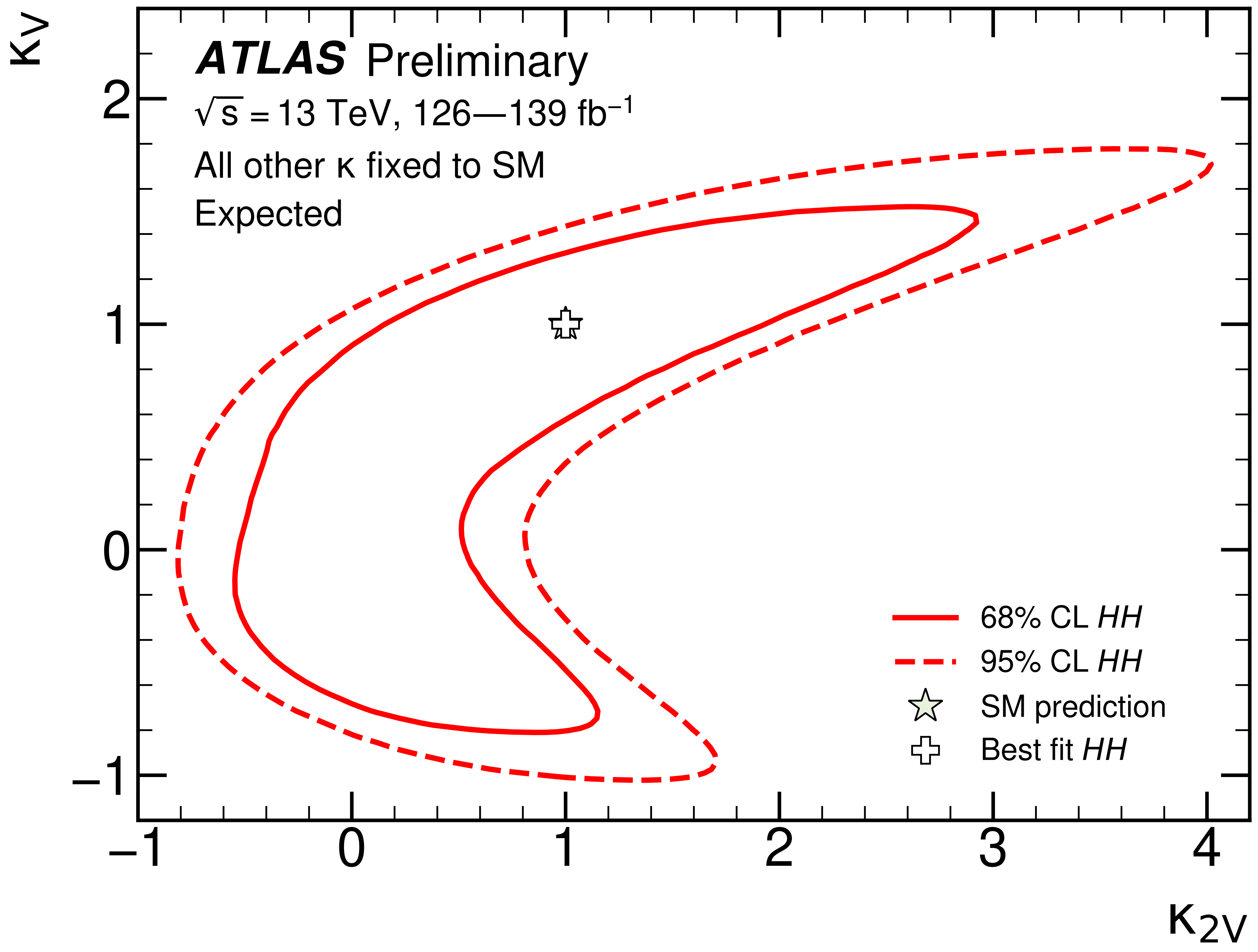
ATLAS: ATLAS-CONF-2022-050 CMS: Nature 607, 60-68 (2022)

Putting all together : VVHH interaction





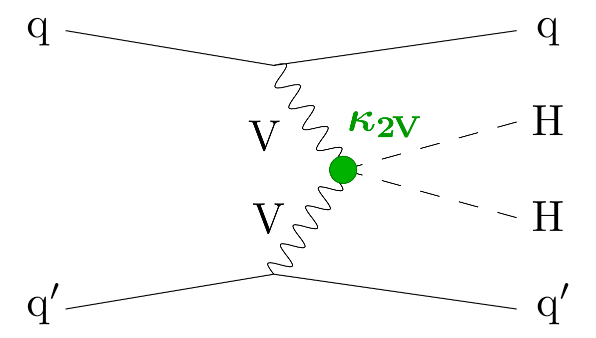
$k_{2V} = 0$ is excluded, with a significance of 6.6 s.d. assuming all other couplings to be SM

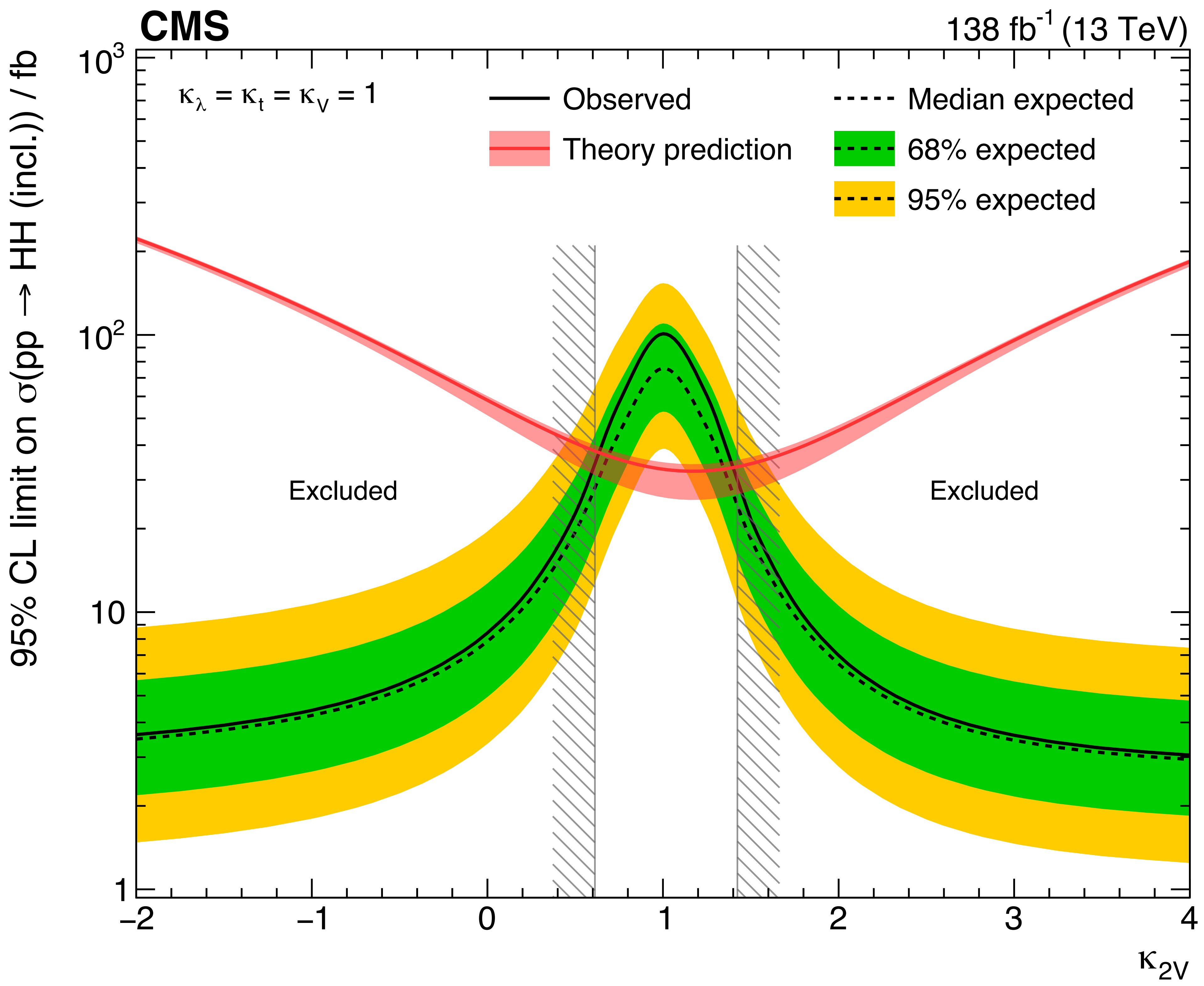


Constrained in the k_V and k_{2V} plane

ATLAS: ATLAS-CONF-2022-050 CMS: Nature 607, 60-68 (2022)

Putting all together : VVHH interaction





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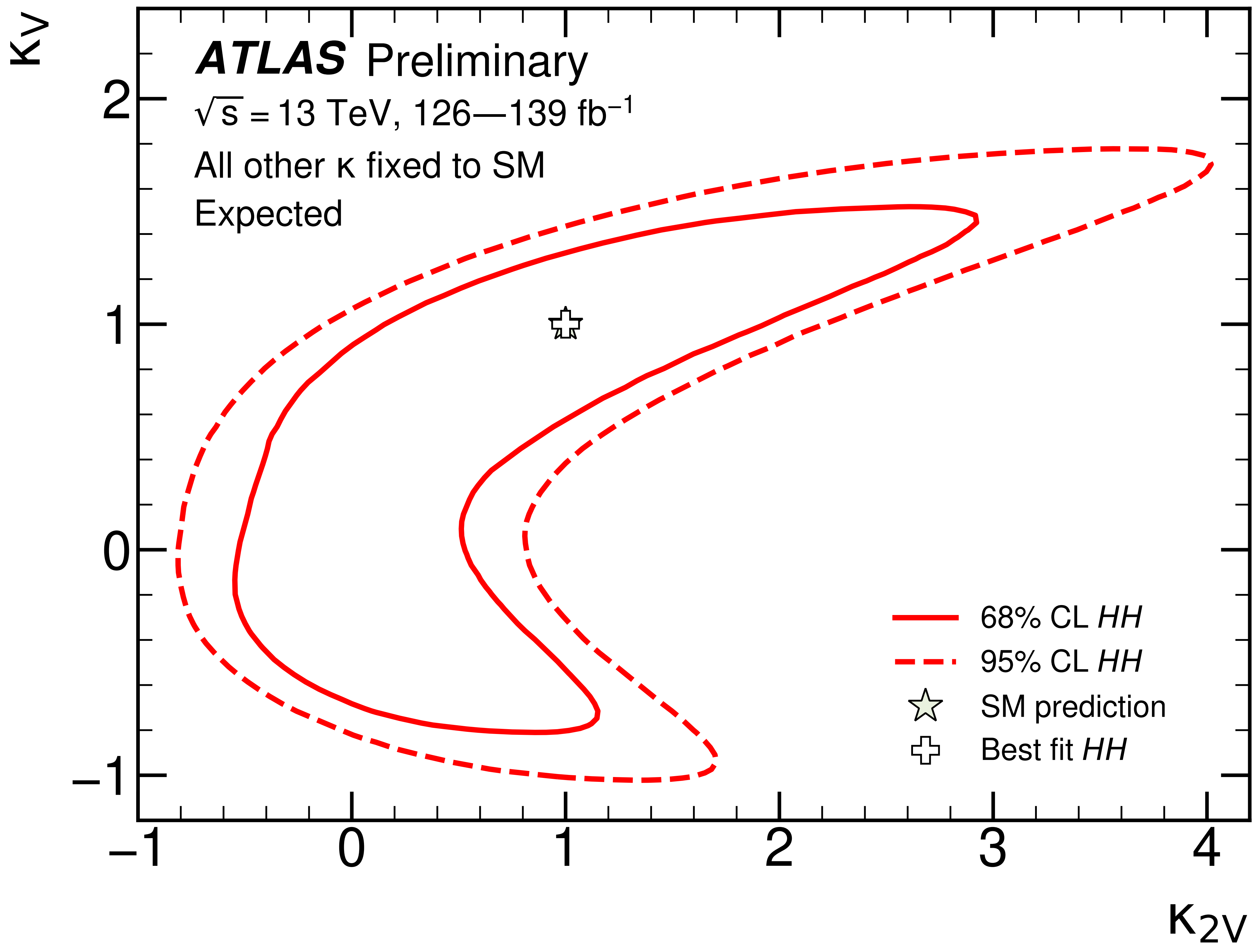


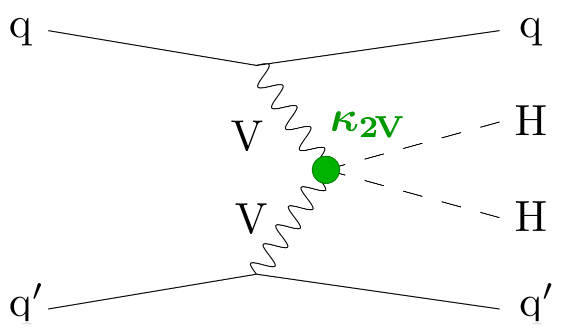
Constrained in the k_V and k_{2V} plane

Establishing the existence of the quartic coupling **VVHH**

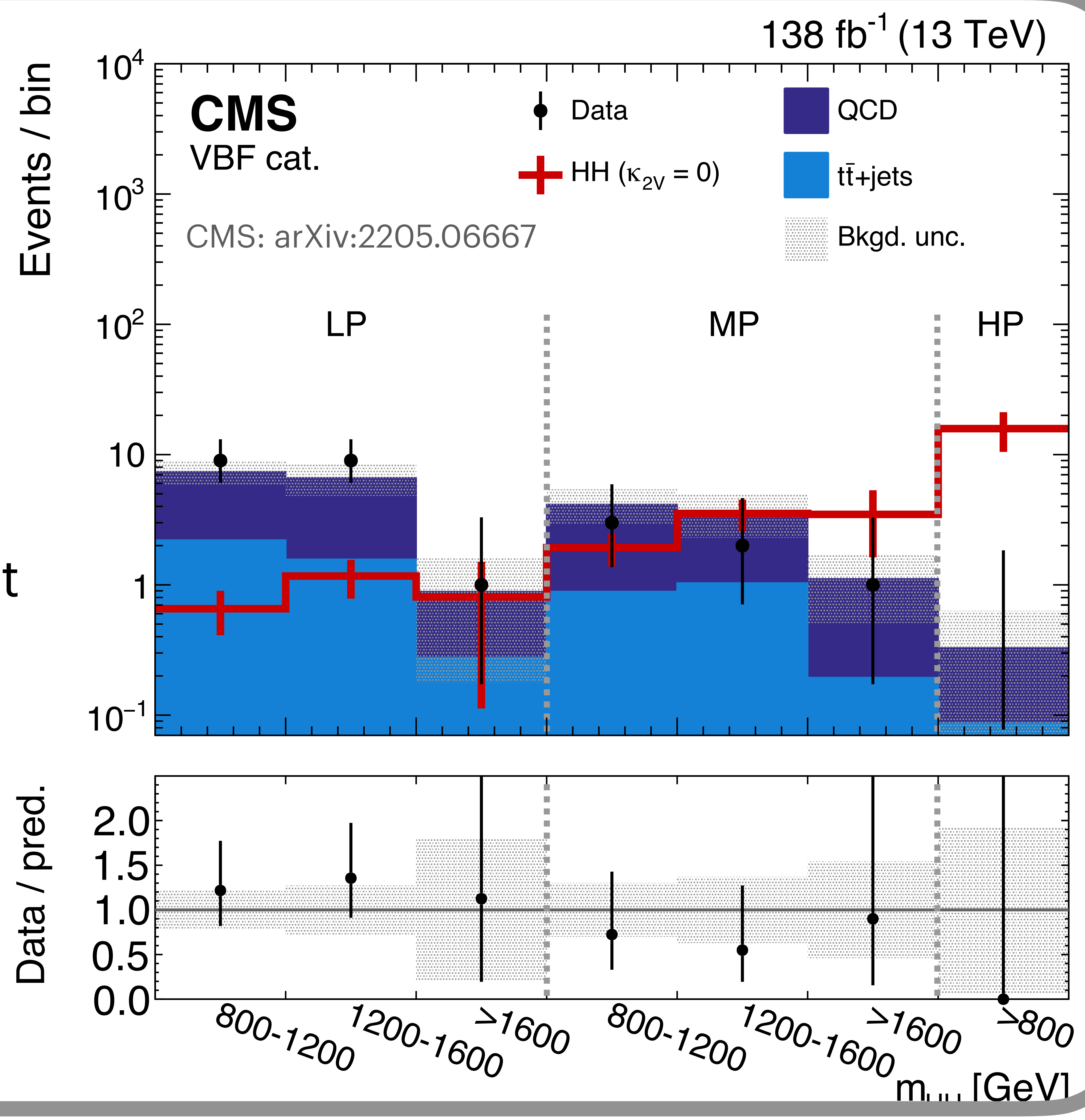
Key role of (HH→bbbb) boosted searches and ML for H→bb decay ID

ATLAS: ATLAS-CONF-2022-050 CMS: Nature 607, 60-68 (2022)

Putting all together : VVHH interaction



The distributions of the invariant mass of the HH system after a background-only fit to the data, for the VBF categories of the HH→bbbb channel



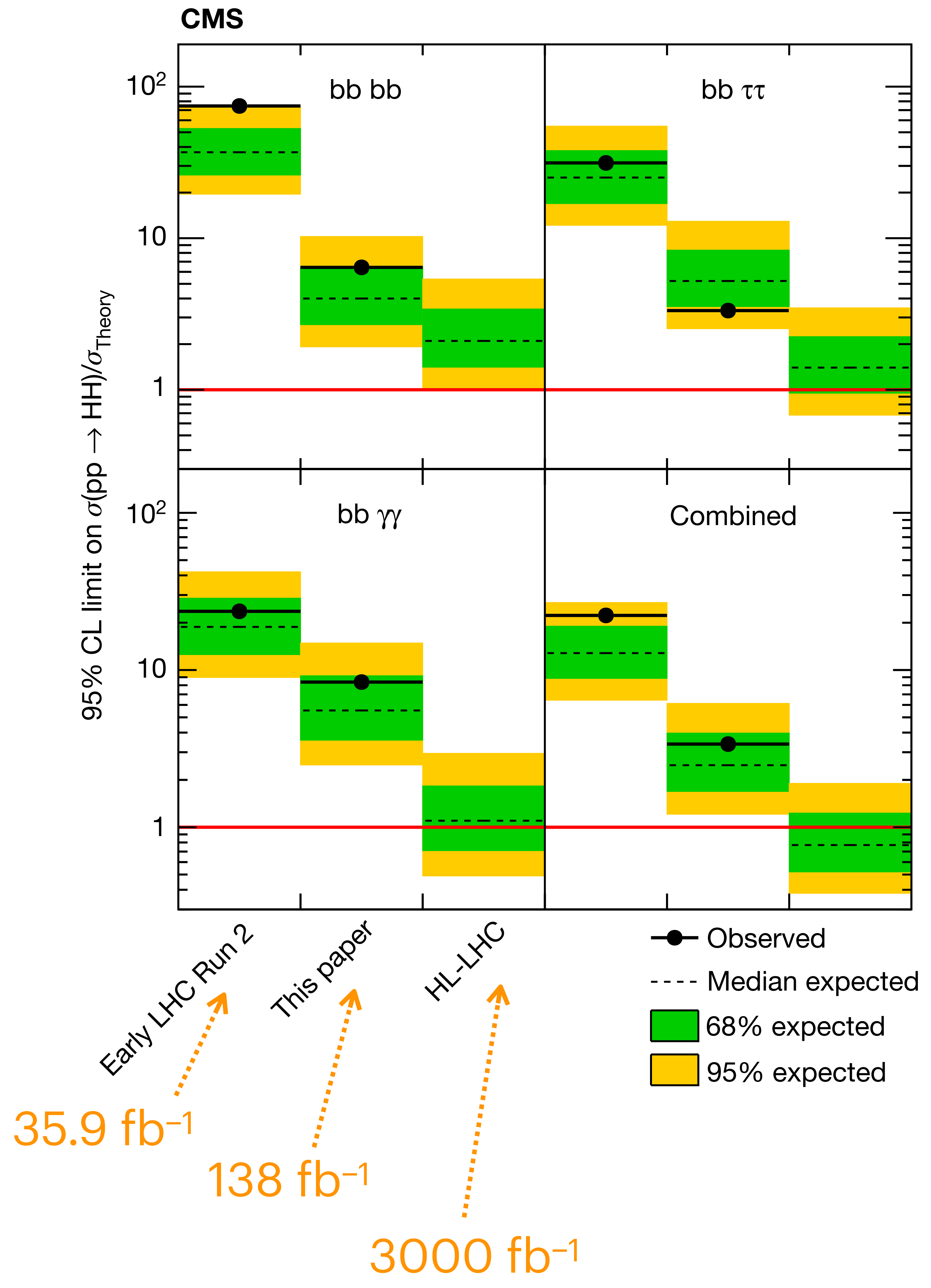
$k_{2V} = 0$ is excluded, with a significance of 6.6 s.d. assuming all other couplings to be SM

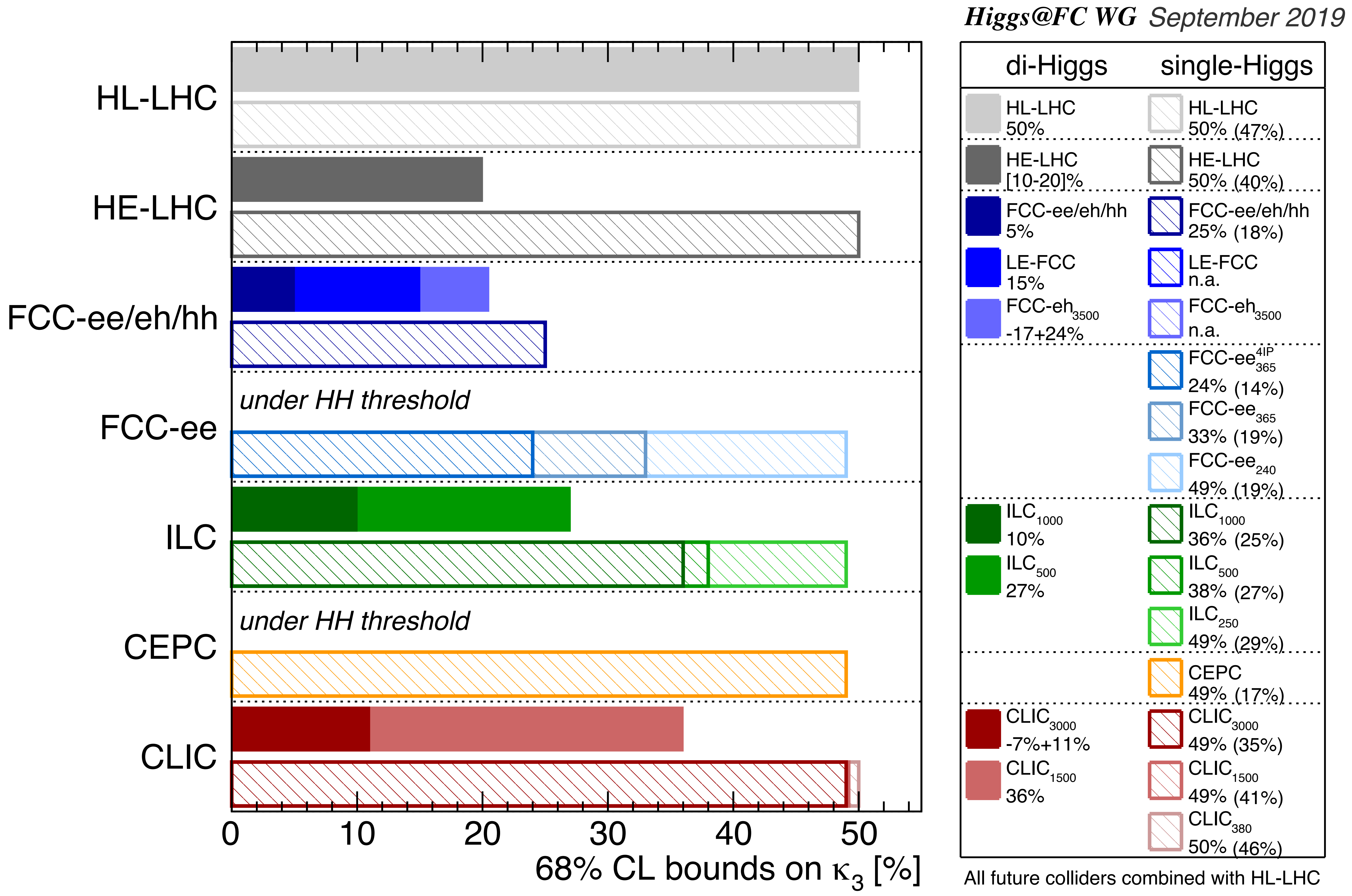
Establishing the existence of the quartic coupling **VVHH**

Key role of (HH→bbbb) boosted searches and ML for H→bb decay ID

The future : HL-LHC and beyond

Exp. and obs. limits on HH production in different datasets





Key legacy of HL-LHC:

unmatched precision over the next ≥30 years

CMS: Nature 607, 60-68 (2022)

Conclusions

We face a period of unprecedented possibilities in particle physics.
With the Higgs boson discovery **new conceptual questions are defined.**
A fundamental scalar? A self-interacting particle? A Yukawa force-carrier? ...

The answers will be all profoundly interesting, whether or not they are in agreement with SM predictions.

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A self-interacting particle?

There is an on-going broad programme of HH searches and impressive results have been already published using LHC Run2 data:

- **SM : each experiment achieve 2-3** $\times\ \sigma_{SM}$
- **self-coupling :** k_λ **constrained to approx [-1, 6]**
- **VVHH interaction : absence of VVHH excluded at >6**σ

We are poised to make substantial progress to measure the Higgs boson self-interaction throughout the lifetime of LHC and HL-LHC.