Higgs boson self-coupling overview

Summary of searches by ATLAS and CMS

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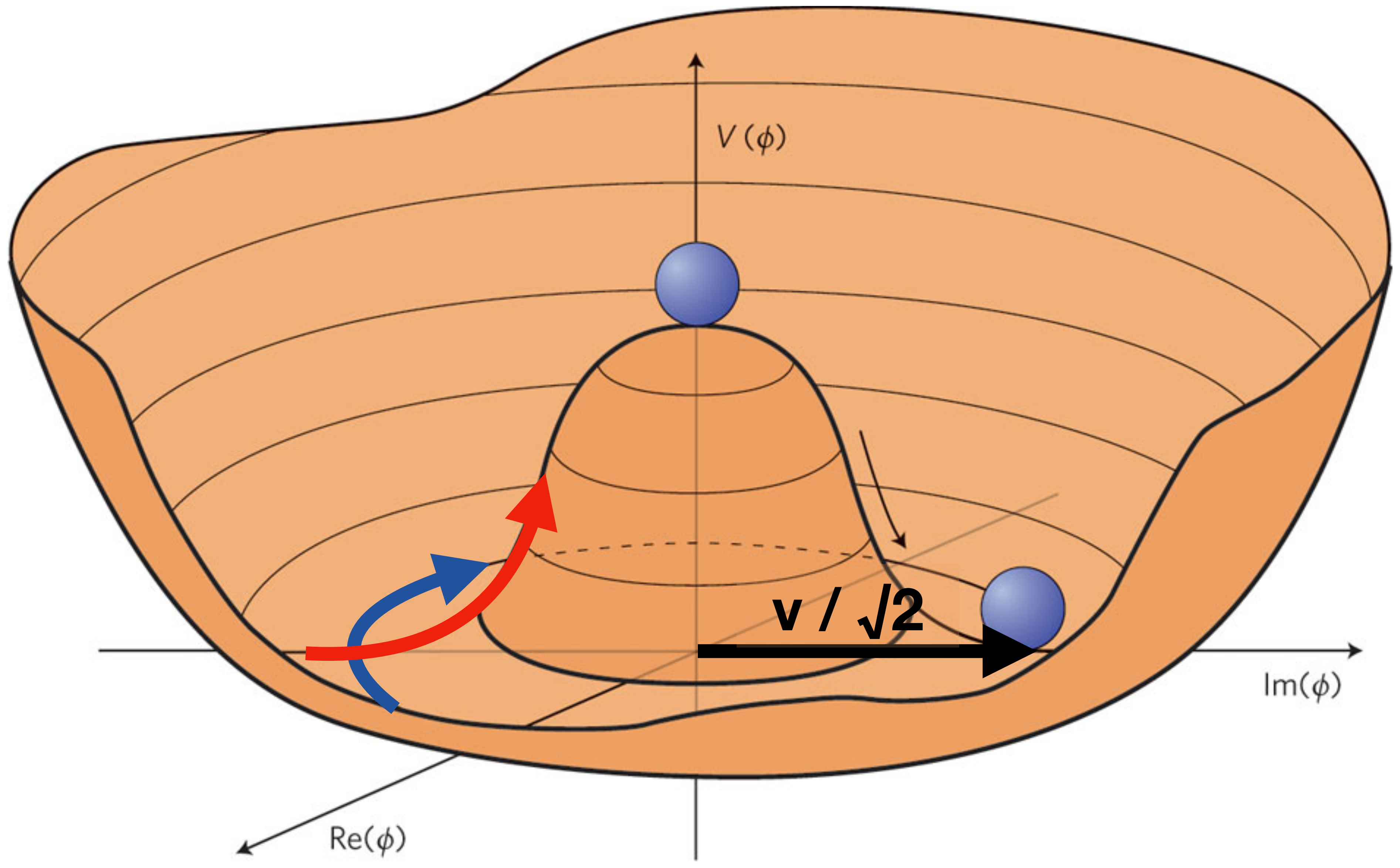
The scalar sector and the self-coupling

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



- The scalar sector : the cornerstone of the SM
- Brout-Englert-Higgs mechanism: a scalar potential with a v.e.v. ≠ 0 originates a spontaneous breaking of the electroweak symmetry
- Properties of the scalar sector ⟺ potential shape, controlled by λ ⟺ strength of the self-coupling

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

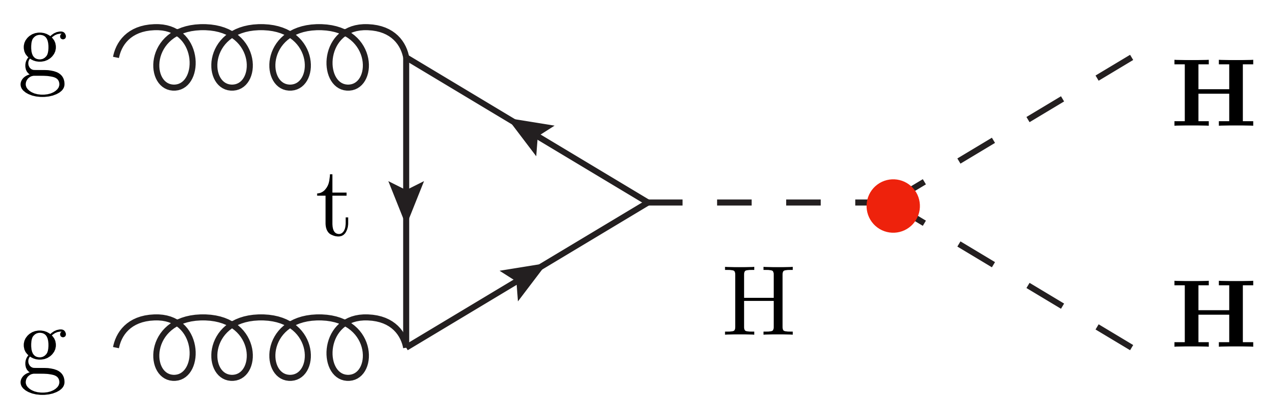
$$\lambda_{\mathrm{HHH}} = \lambda_{\mathrm{HHHH}} = \lambda = \frac{m_{\mathrm{H}}^2}{2v^2} \approx 0.13$$

The Higgs boson self-coupling is intimately connected to the EWSB in the SM

How to measure λ_{HHH}?

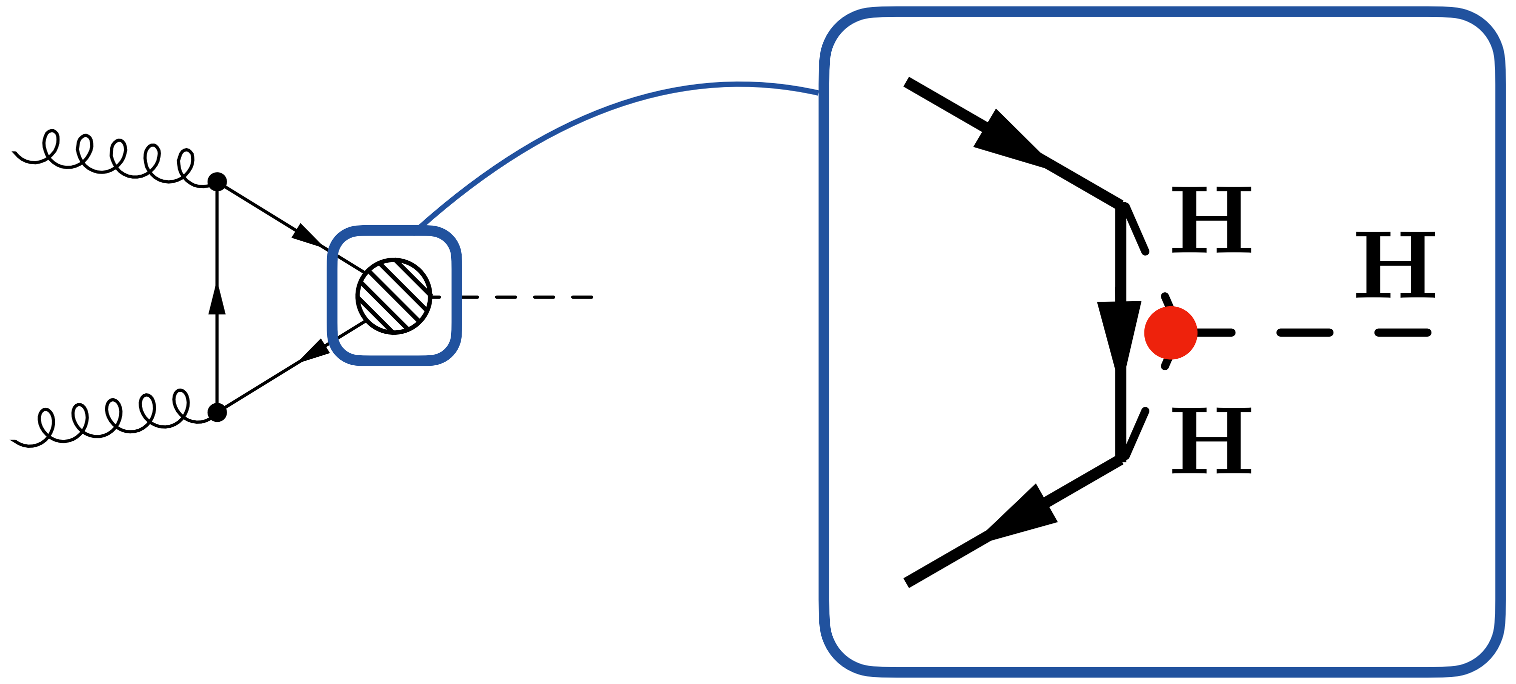
Two complementary strategies exist:

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 ($\sim 1000 \times \sigma_{HH}$)

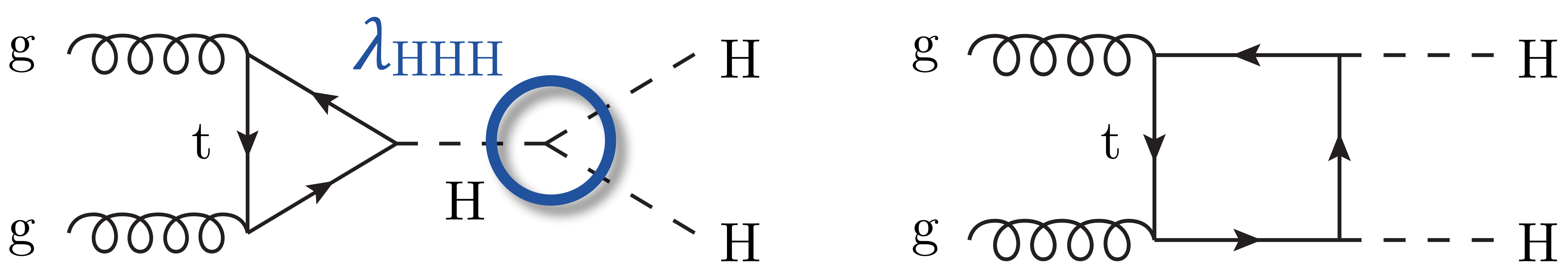
The combination of both strategies maximises our sensitivity to λ_{HHH}

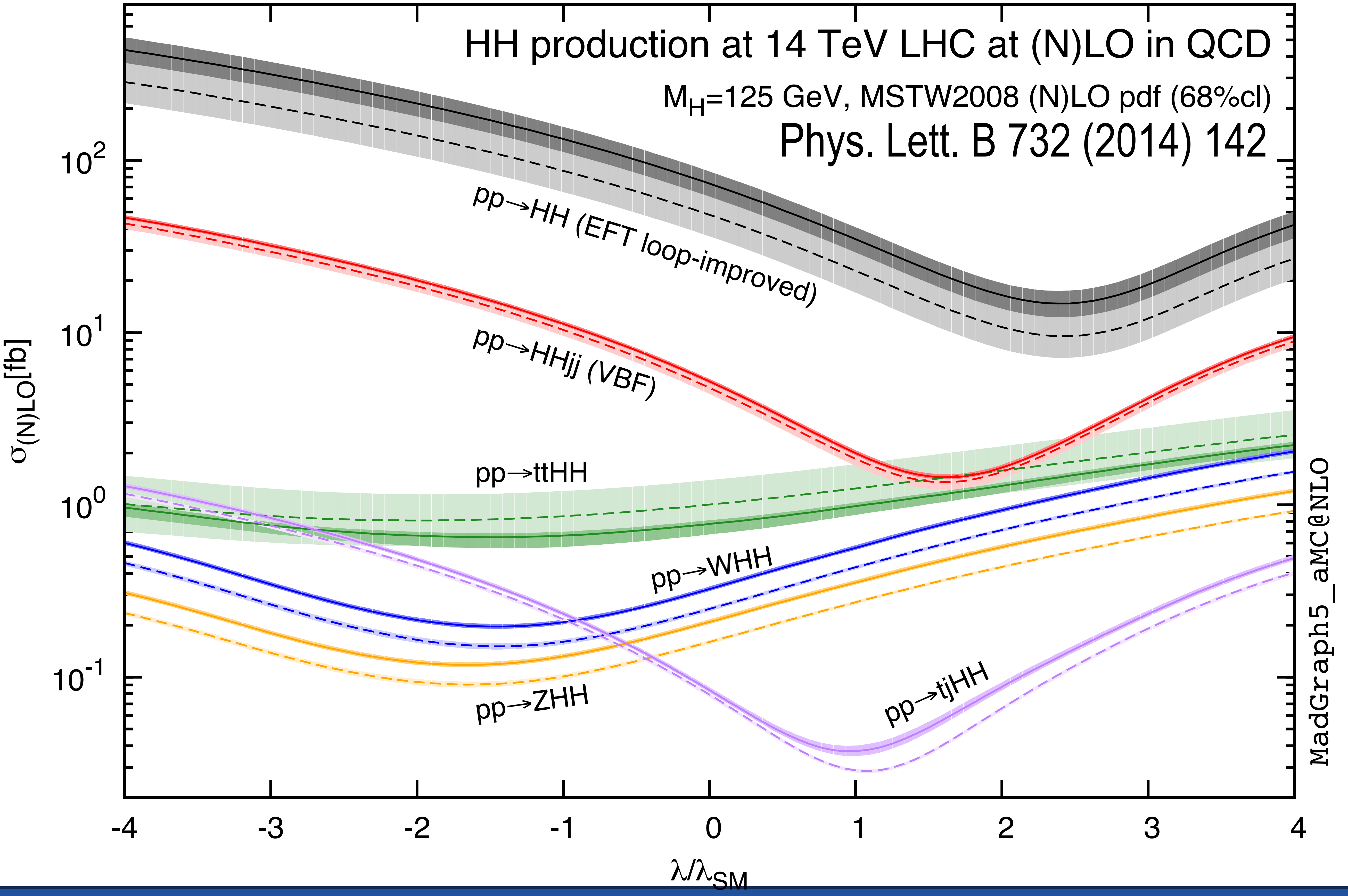
Direct measurements : HH production

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

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

(scale ⊕ PDF ⊕ α_S ⊕ m_t)





HH production ⟹ direct determination of Higgs trilinear coupling λ_{HHH}

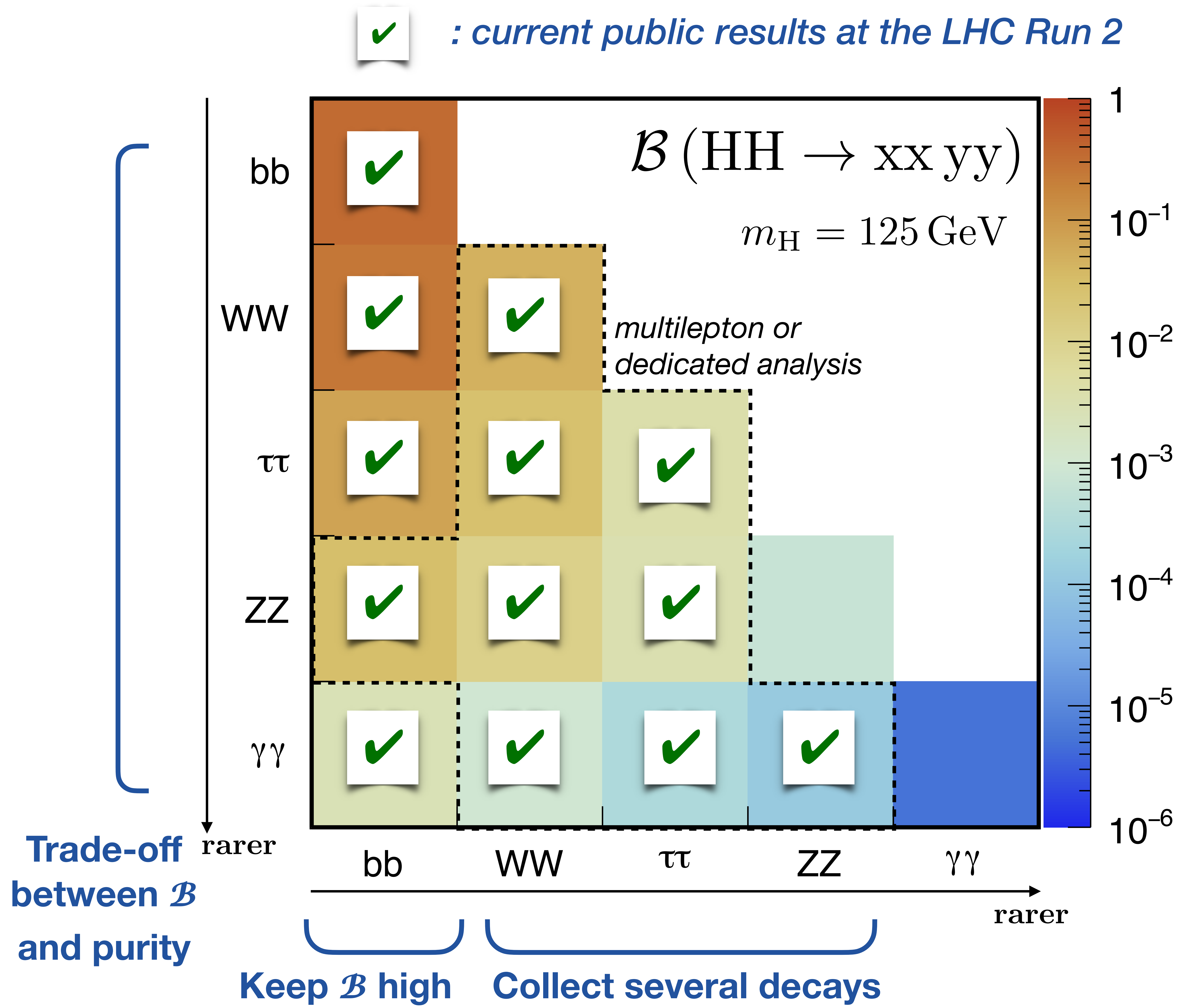
- **Gluon fusion**: dominant production mode
  - driving the determination of λ_{HHH}
- Large destructive interference ⟹ tiny cross section
- Self-coupling information both total and differential cross section (strong m_{HH} dependence on λ_{HHH})

HH final states

- Phenomenologically rich set of final states
- Branching fraction and S/B largely vary, resulting in several sensitive channels
- Sensitivity to HH maximised from combination of several decay channels

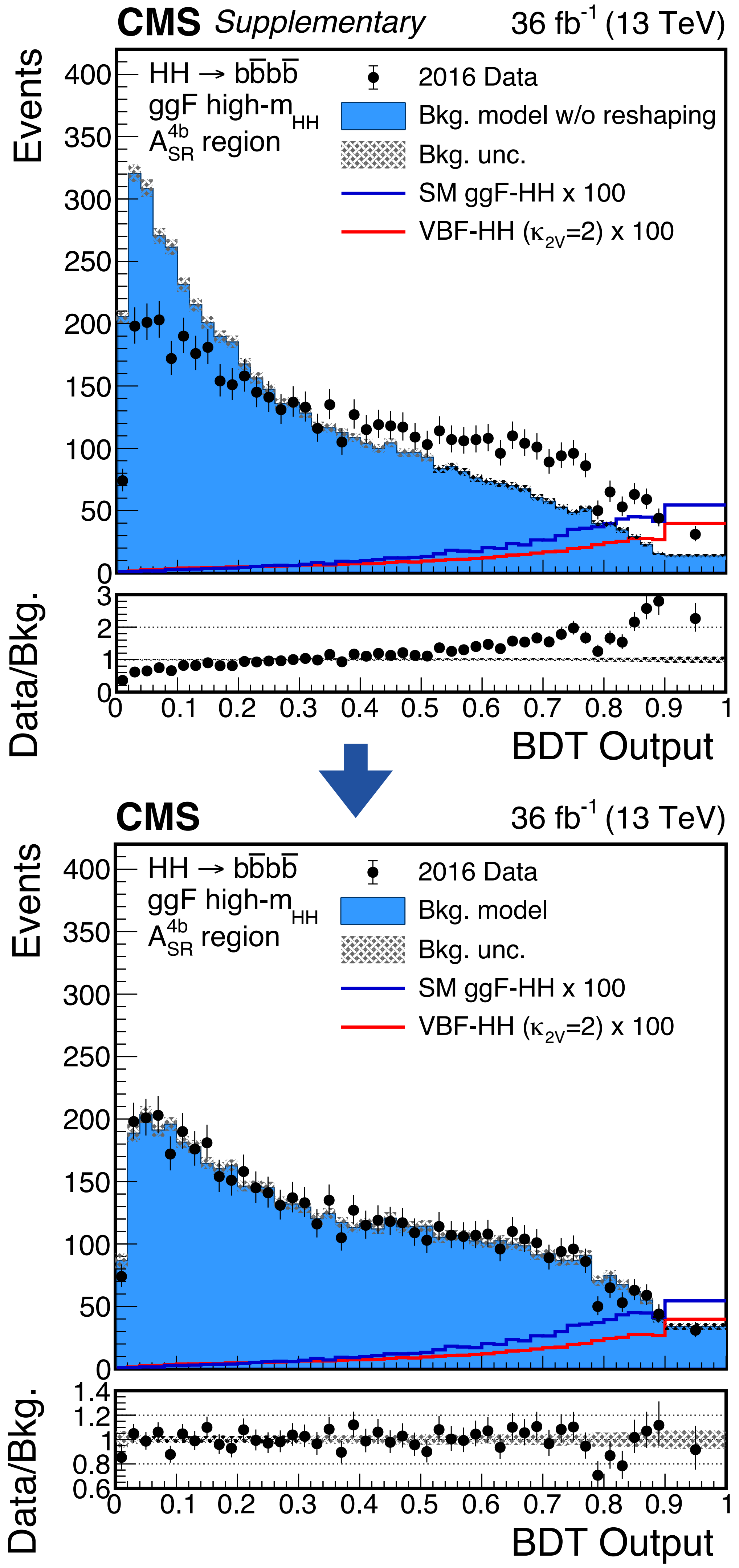
Broad experimental programme by the ATLAS and CMS Collaborations

NOTE: a broad program of searches for new resonances and similar signatures in HH also exists and is not covered in this talk



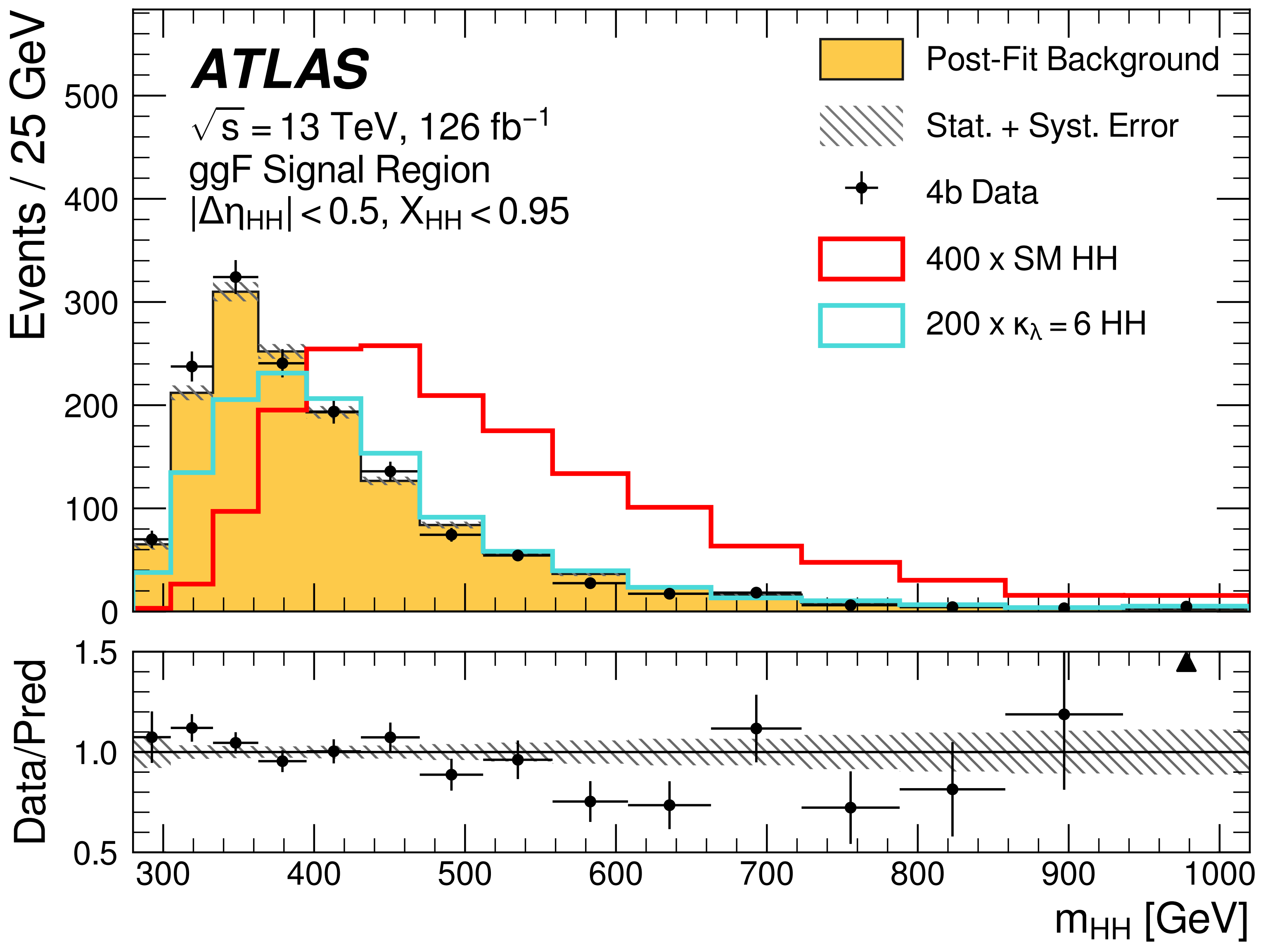
High $\mathcal{B}$, low S/B : HH→bbbb

PRD 108 (2023) 052003
PLB 858 (2024) 139007
PRL 129 (2022) 081802
PRL 131 (2023) 041803



Resolved

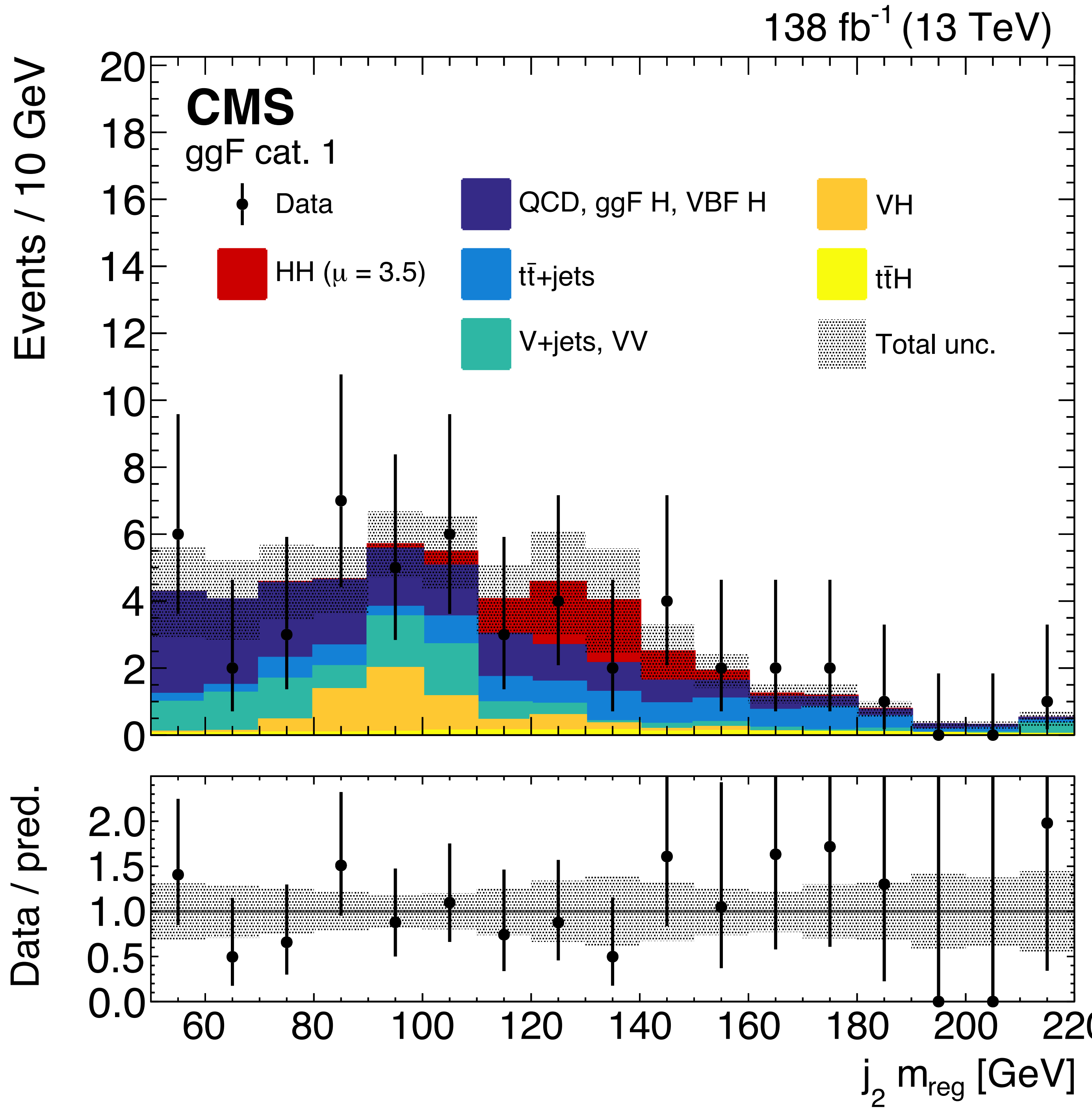
- 4 b jet signal region and b jet triggers
- High multijet bkg requires accurate data-driven modelling from 3b/2b regions



Obs. (exp.) : *5.3 (8.1) × σ_{SM} (ATLAS)*
3.9 (7.8) × σ_{SM} (CMS)

Boosted

- High p_T phase space leading to excellent S/B using powerful ML-based bb ID

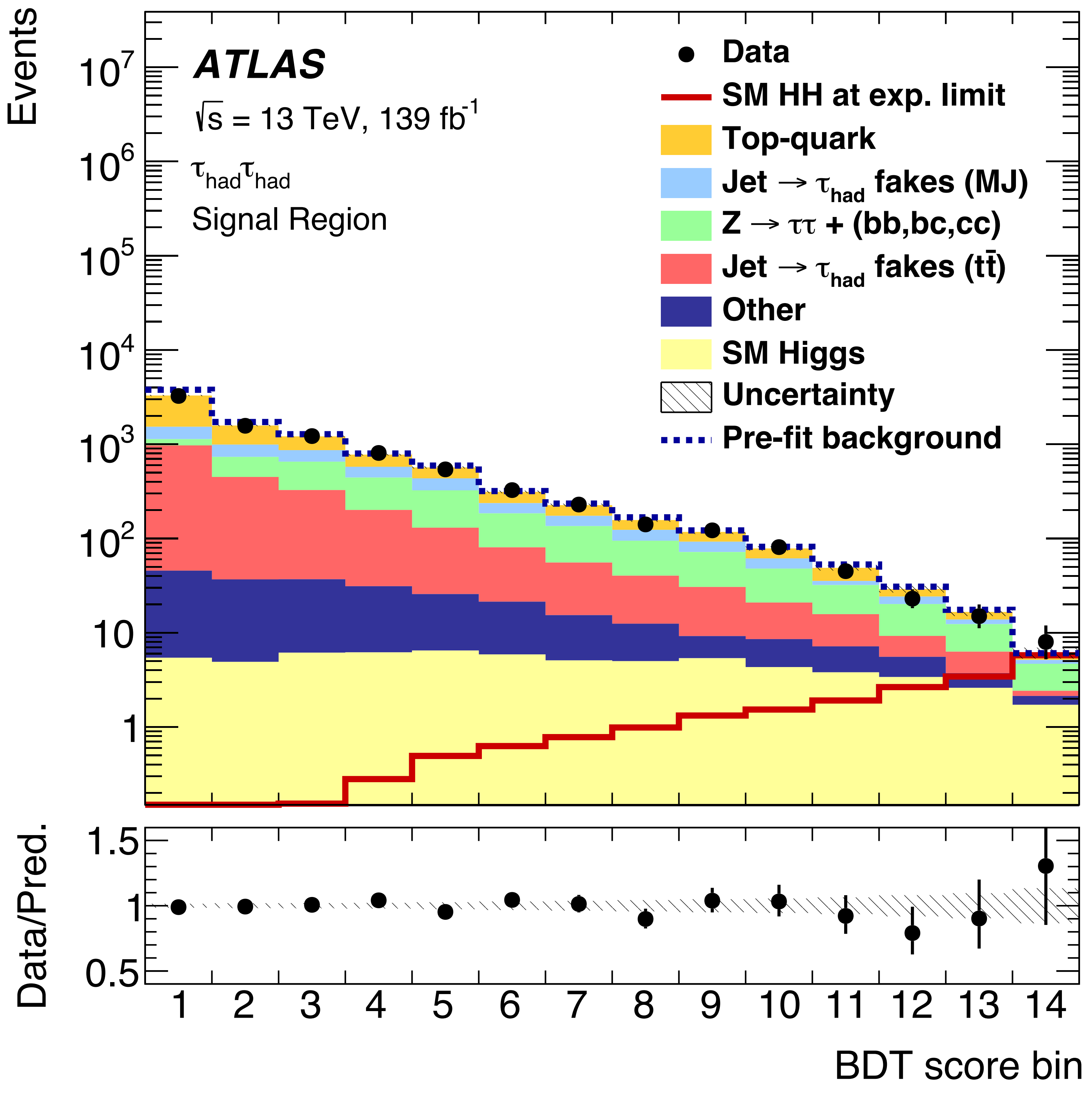


Obs. (exp.) : 9.9 (5.1) × σ_{SM} (CMS)

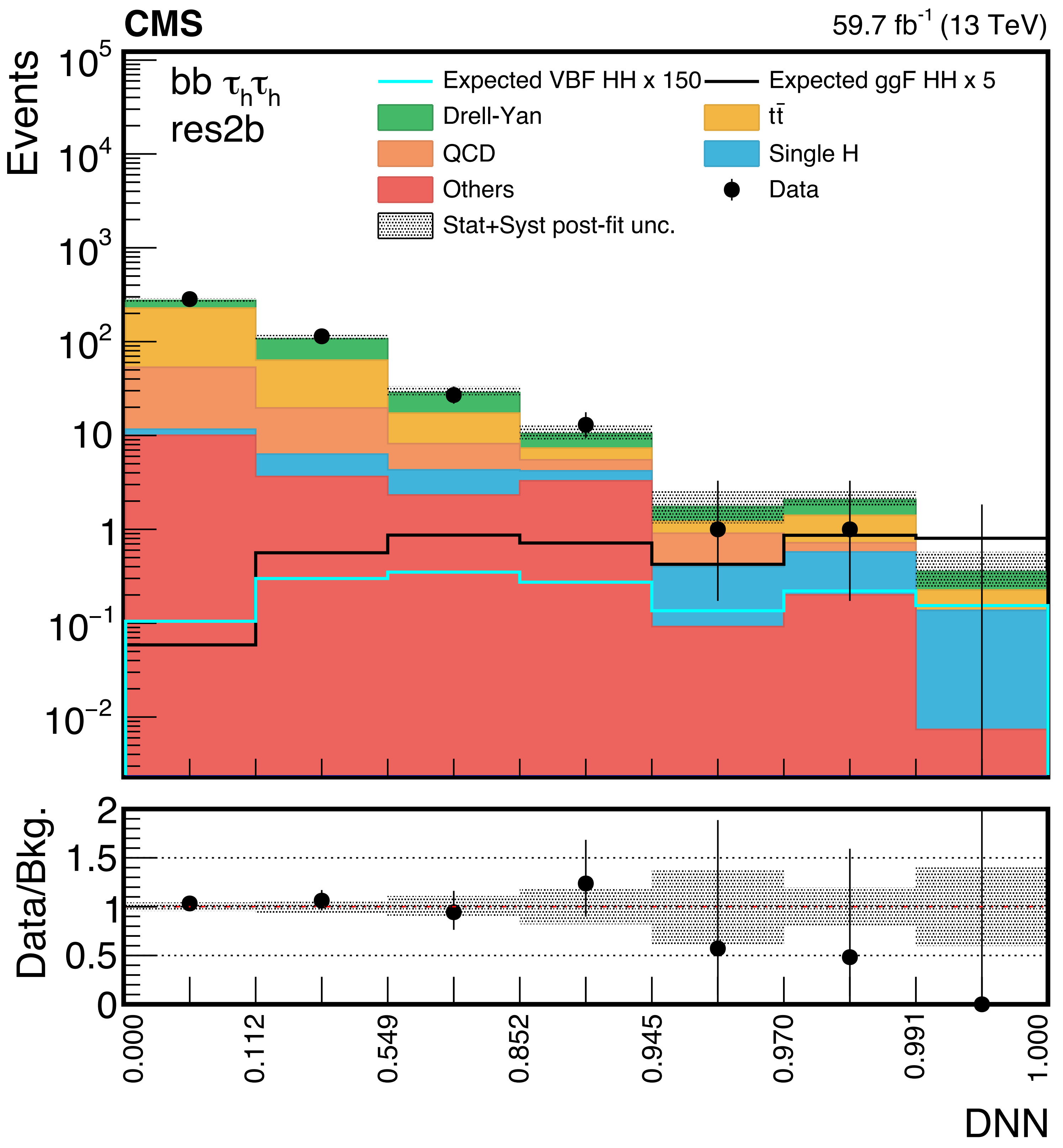
Medium S, medium B : HH→bb$\tau\tau$

JHEP 07 (2023) 040
PLB 842 (2023) 137531

- 3 $\tau\tau$ final states considered ($\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_h\tau_h$) : 88% of total decays
  - event categorised by $\tau\tau$ decay mode ($\tau_h\tau_h$, $\tau_\ell\tau_h$), production mode, and m_{HH}
- Irreducible backgrounds
  - tt : MC simulation
  - Z($\tau\tau$) + bb : simulation + data-driven correction from Z→μμ
- Reducible backgrounds (mis-ID τ_h) from QCD multijet
  - data-driven from inverted τ ID region
- Signal extracted with a BDT/NN discriminant



Observed (expected)
4.7 (3.9) × σ_{SM}

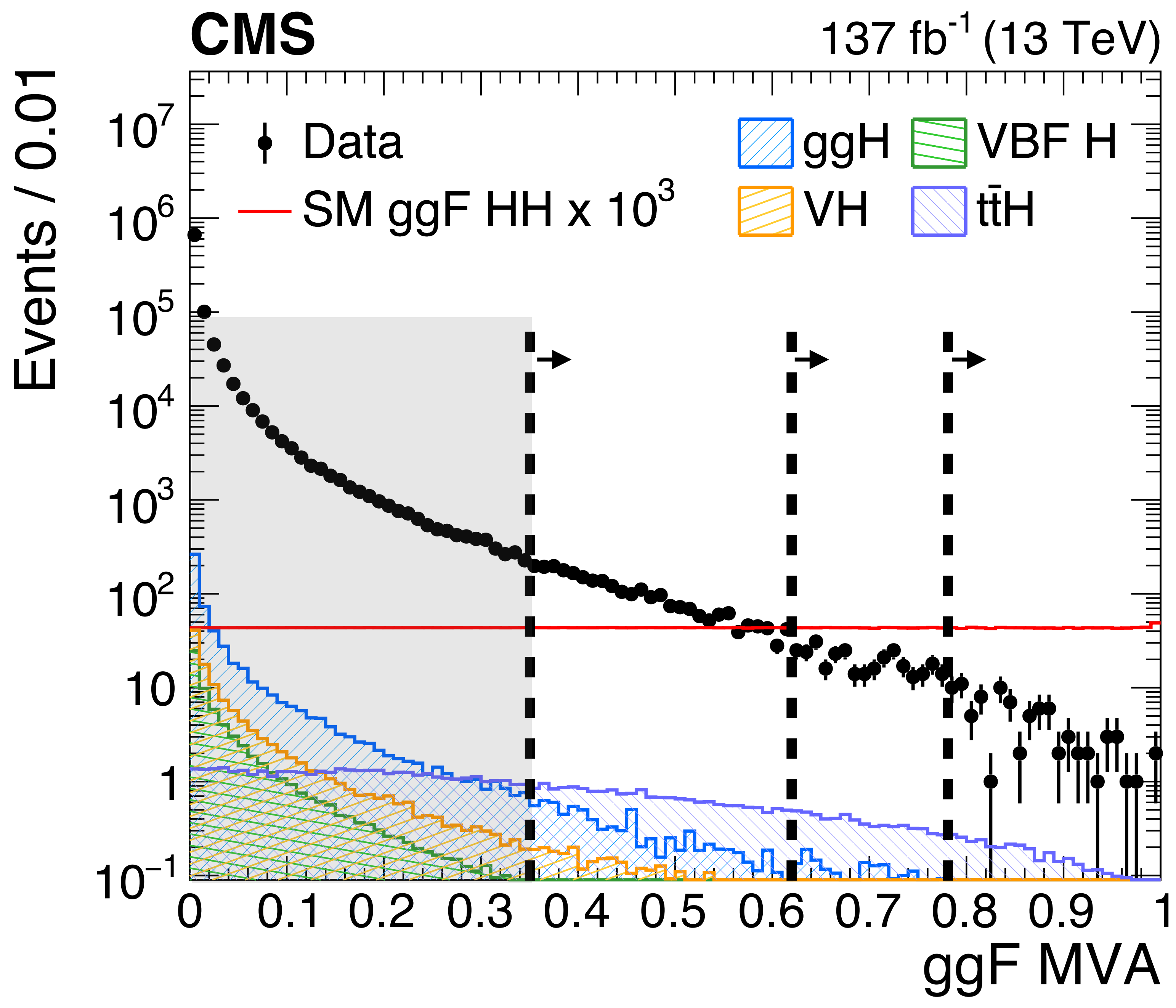


Observed (expected)
3.3 (5.2) × σ_{SM}

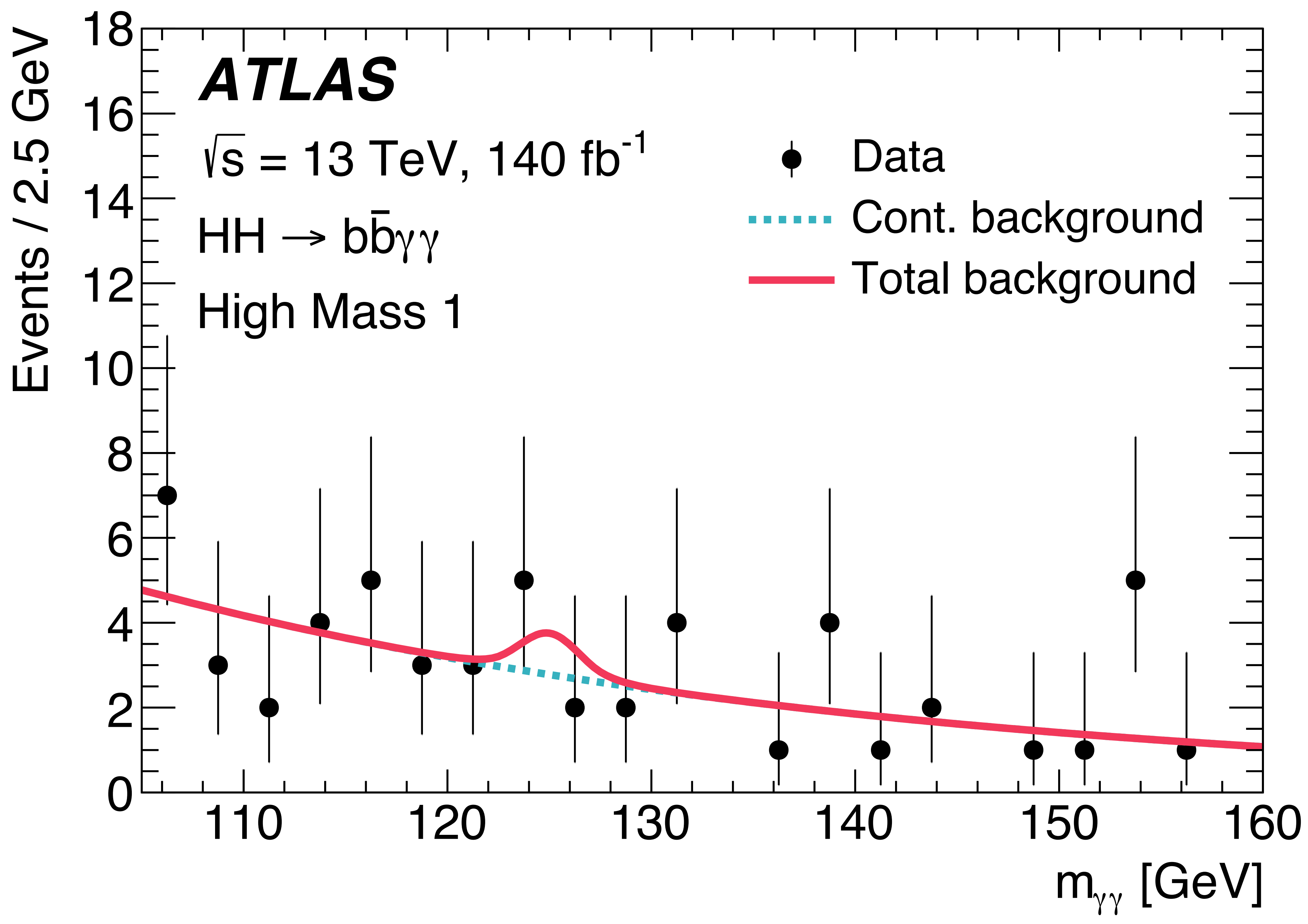
Low S, low B : HH→bb$\gamma\gamma$

Rare but pure channel | Analyses optimised to maximise acceptance and S/B

- Main backgrounds: $\gamma/\gamma\gamma$ + jets continuum, single H
  - dedicated MVA for rejection
- Purity × m_{HH} categories
- Signal extracted from a fit to the $m_{\gamma\gamma}$ distribution (+m_{bb} for CMS)
- Clearly statistically limited!



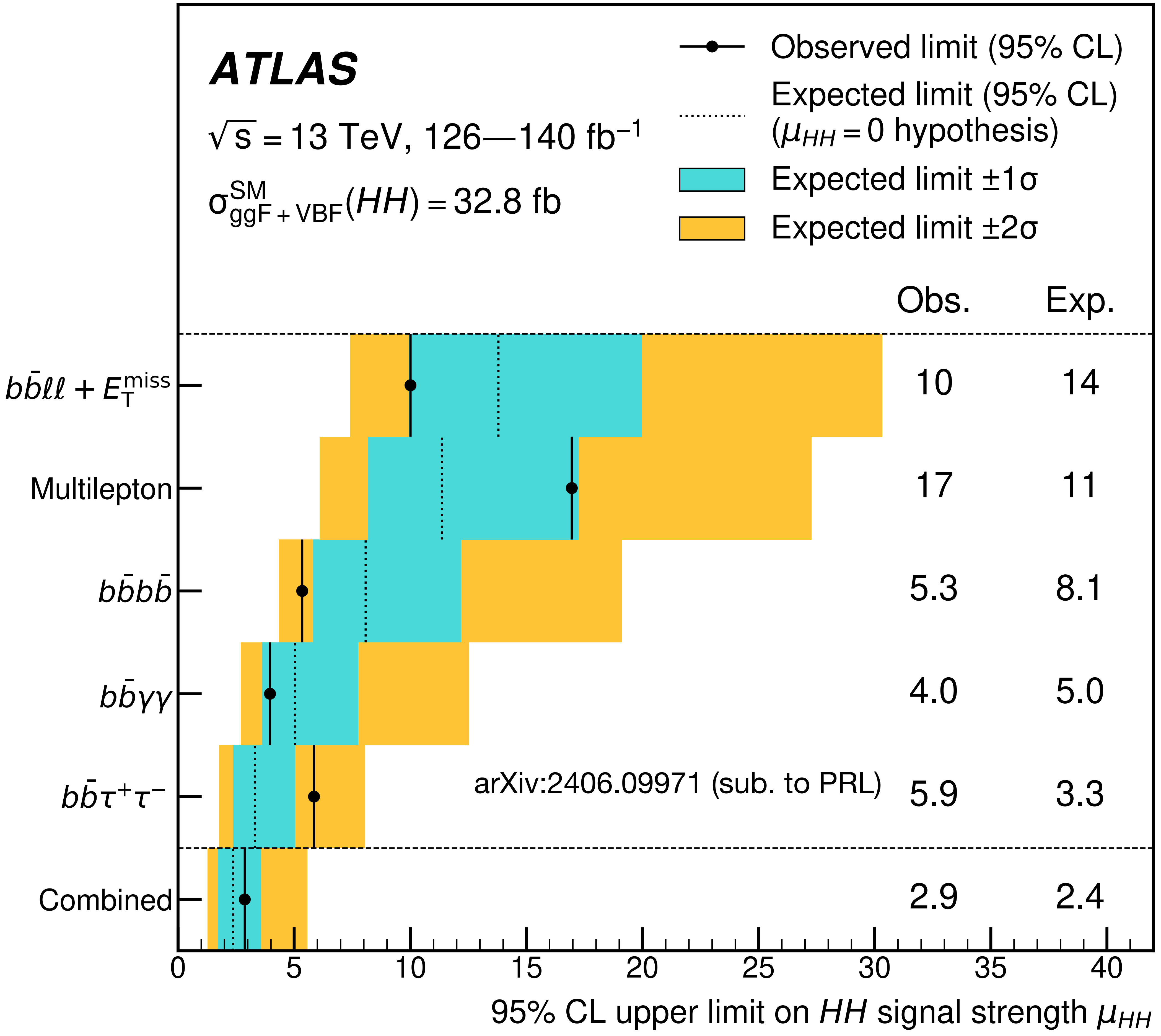
Observed (expected)
8.4 (5.5) × σ_{SM}



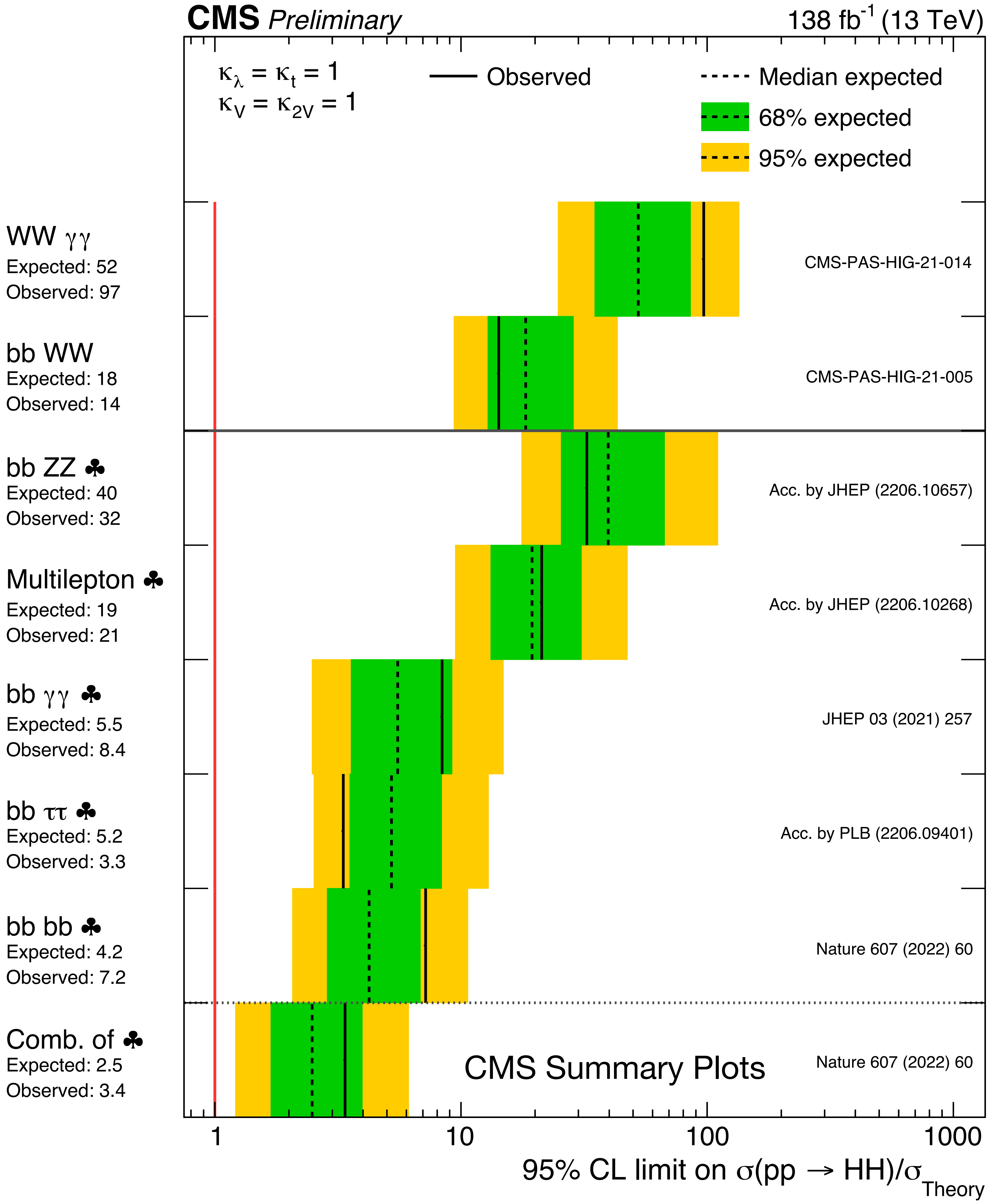
Observed (expected)
4.0 (5.0) × σ_{SM}

Combination : SM HH sensitivity

PRL 133 (2024) 101801
Nature 607 (2022) 60
CMS summary plots



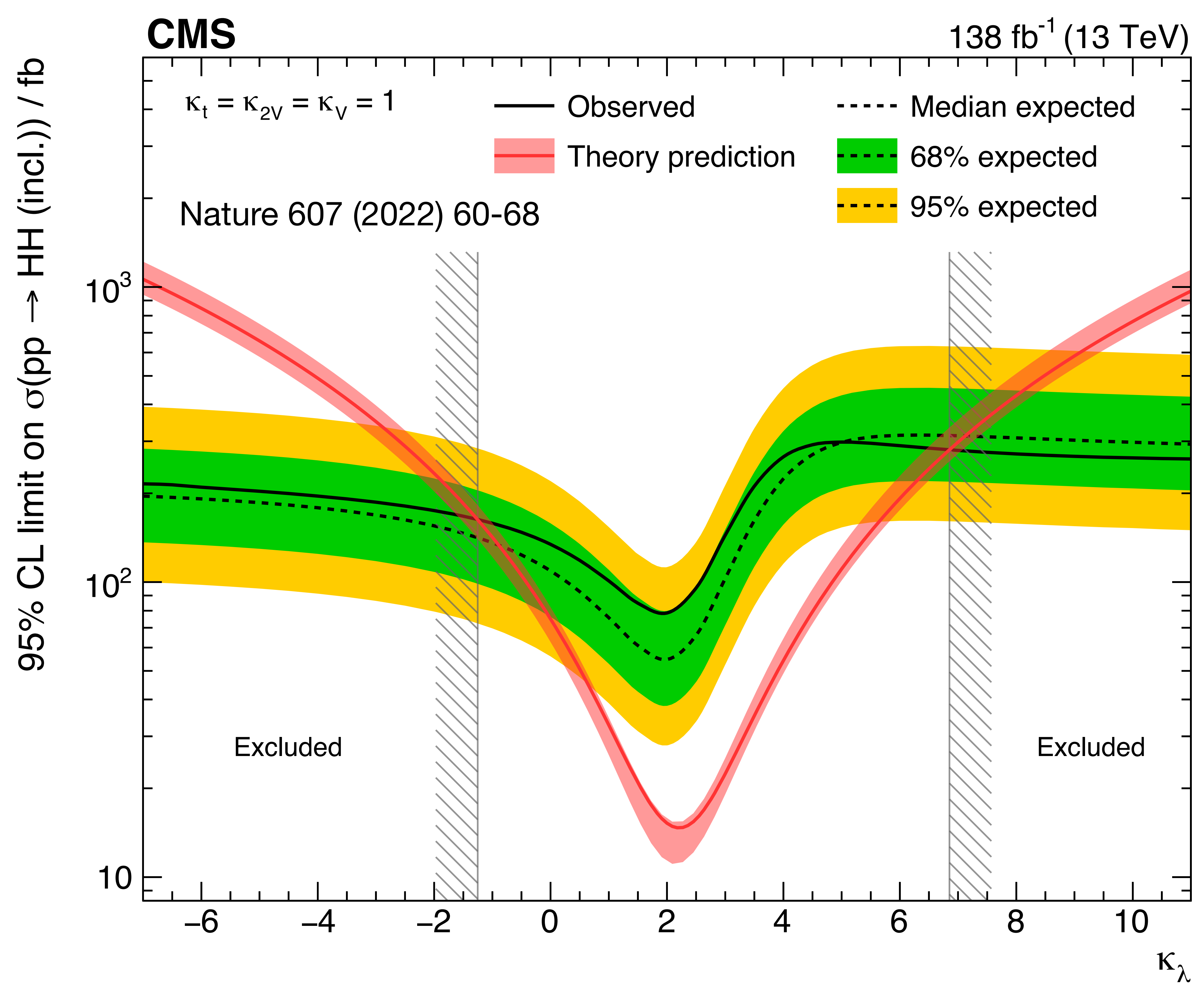
Obs (exp) : 2.9 (2.4) × SM



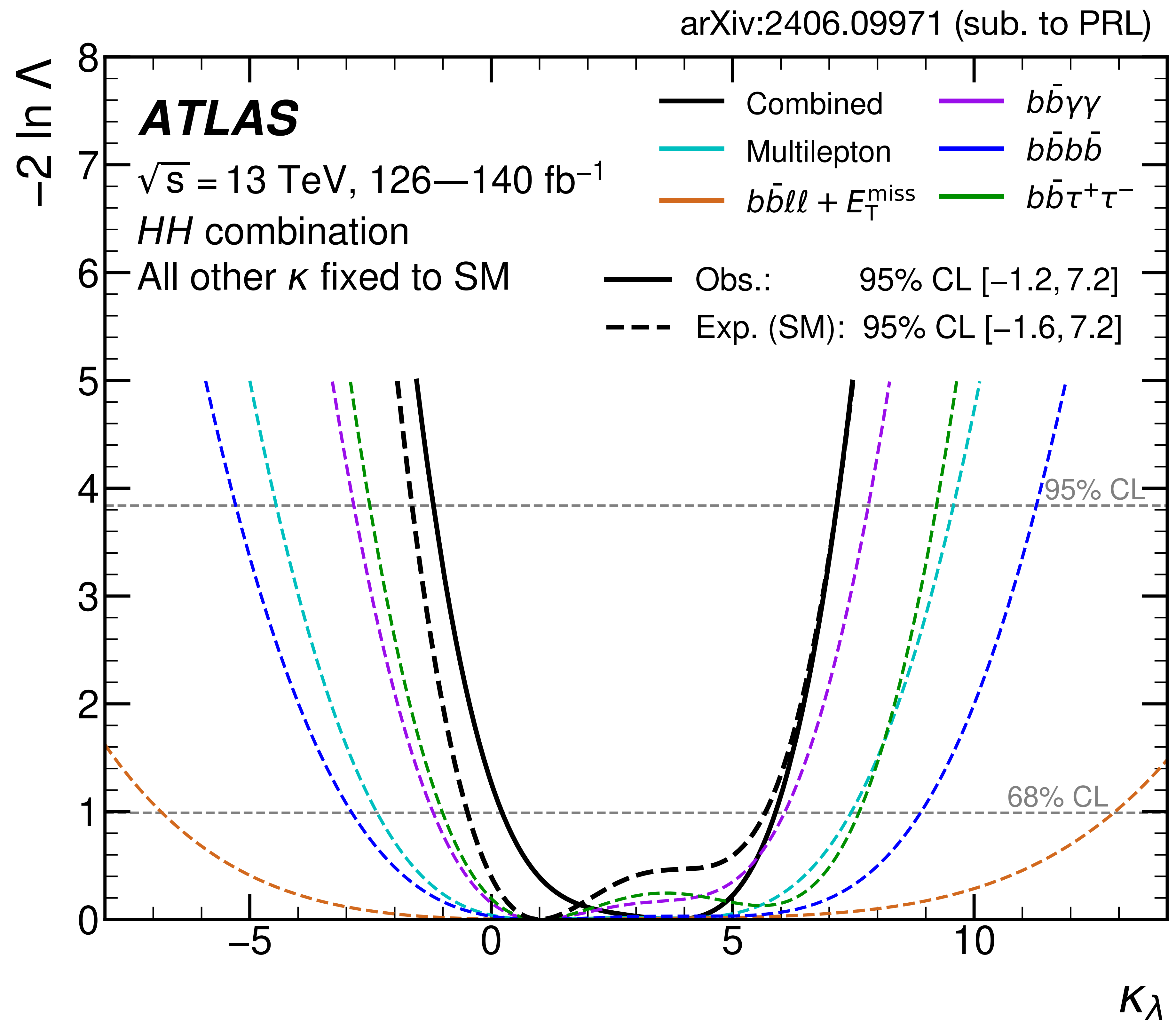
Obs (exp) : 3.4 (2.5) × SM

- Similar sensitivity from ATLAS and CMS
  - but different hierarchy across channels
- Results are limited by stat. uncertainties
  - theo (σ_{HH}) and bkg modelling as dominant uncertainties
- *Ongoing effort for an ATLAS+CMS combination*

Combination : self-coupling



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



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

Effect of interference in gg→HH clearly visible

$1 \lesssim \lambda \lesssim 5$ hardest region to probe (min xs, soft spectrum)

Complementarity of channels to cover full κ_λ (m_{HH}) spectrum

Sensitivity maximised with combination

Beyond λ : the VVHH interaction

PRL 133 (2024) 101801
Nature 607 (2022) 60

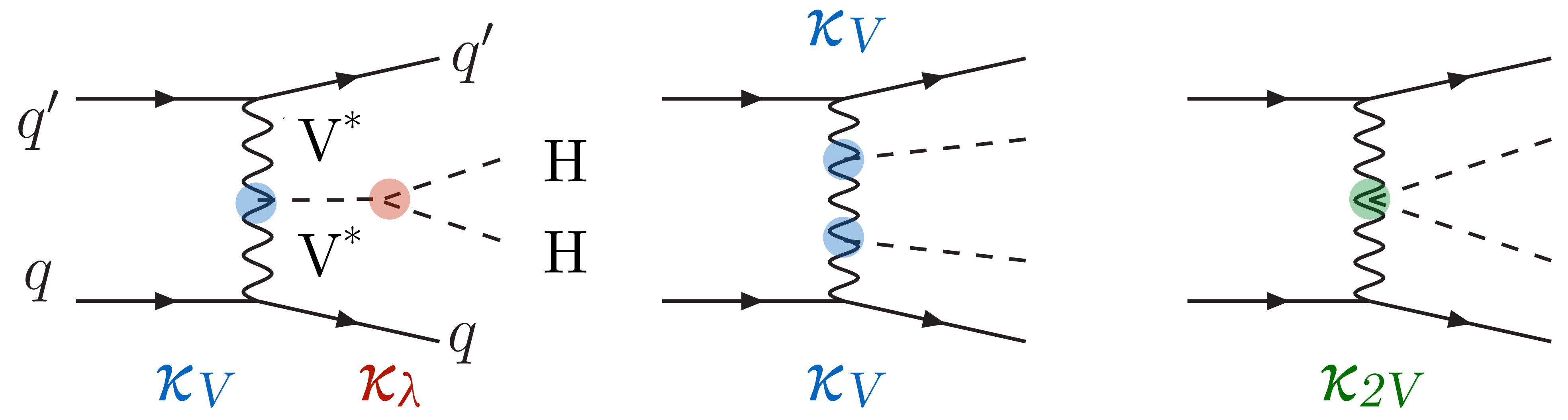
PRD 98, 114016 (2018)

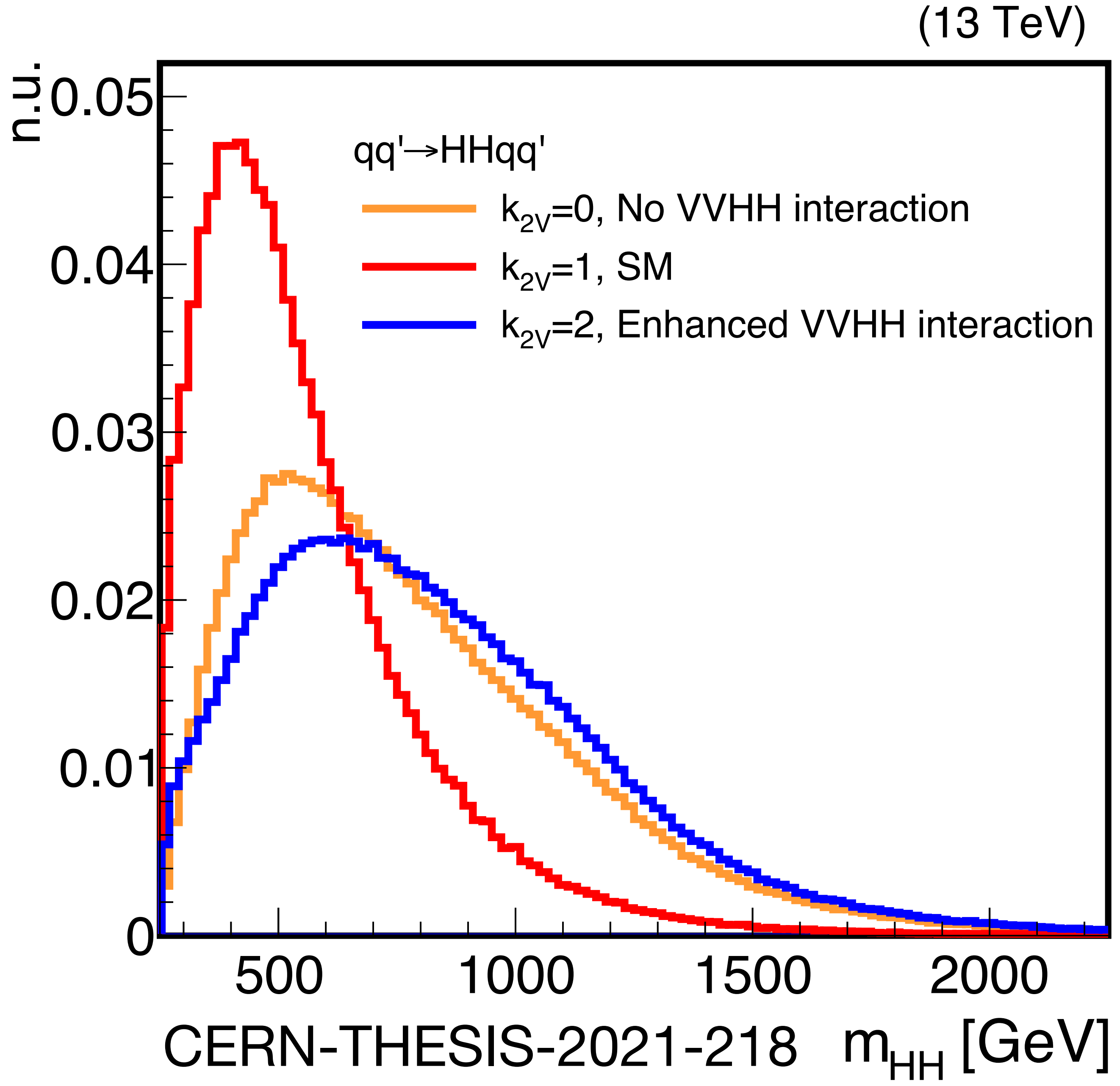
$$\sigma = \begin{matrix} 1.68 \text{ fb } [13 \text{ TeV}] \\ 1.87 \text{ fb } [13.6 \text{ TeV}] \end{matrix} \pm 2.7\%$$

EPJC 77 (2017) 7, 481

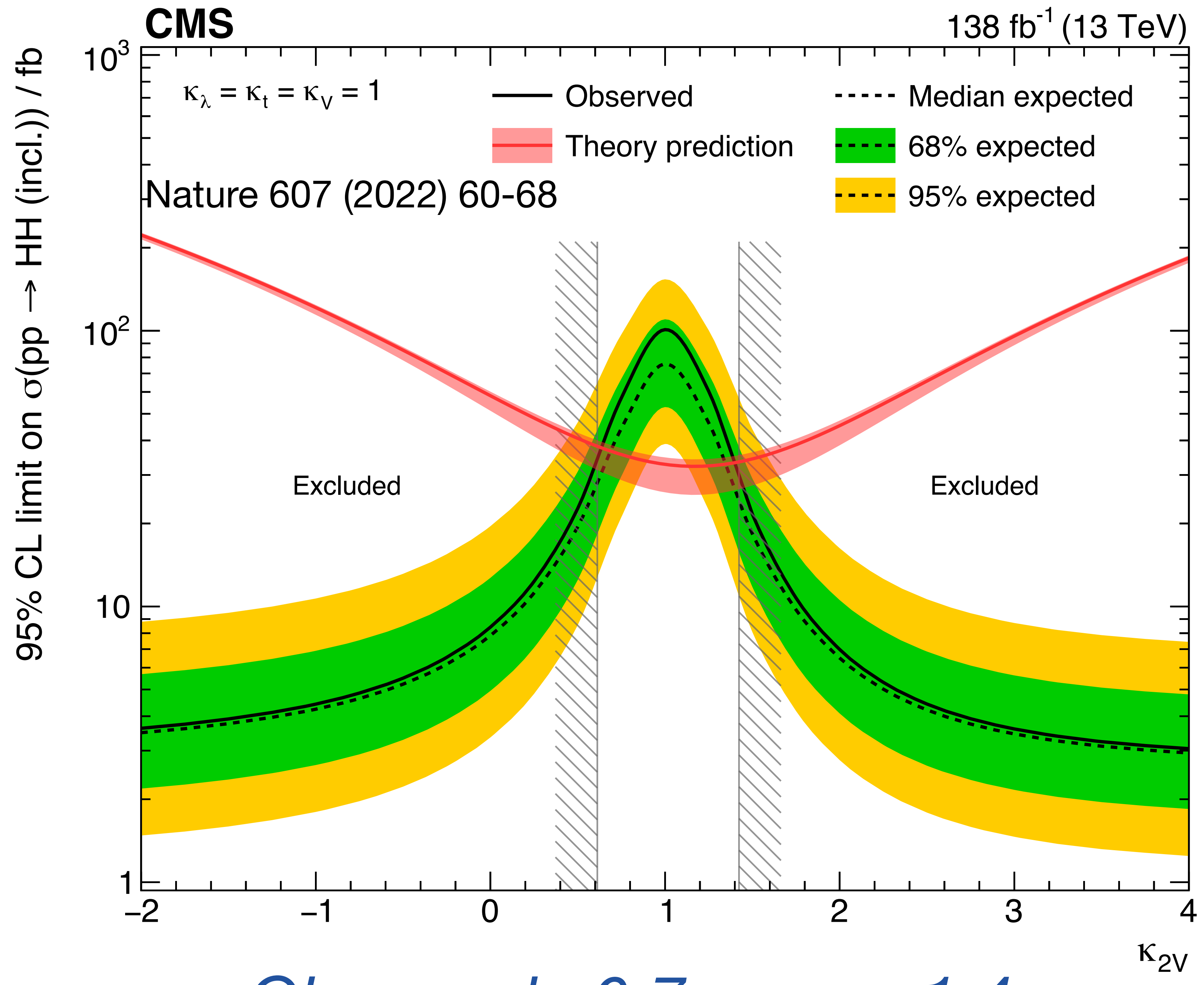
$$\mathscr{A}\left(V_L V_L \to HH\right) \simeq \frac{\hat{s}}{v^2}\left(\kappa_{2V} - \kappa_V^2\right)$$

VBF HH 20 times rarer than ggF HH, but unique access to VVHH coupling





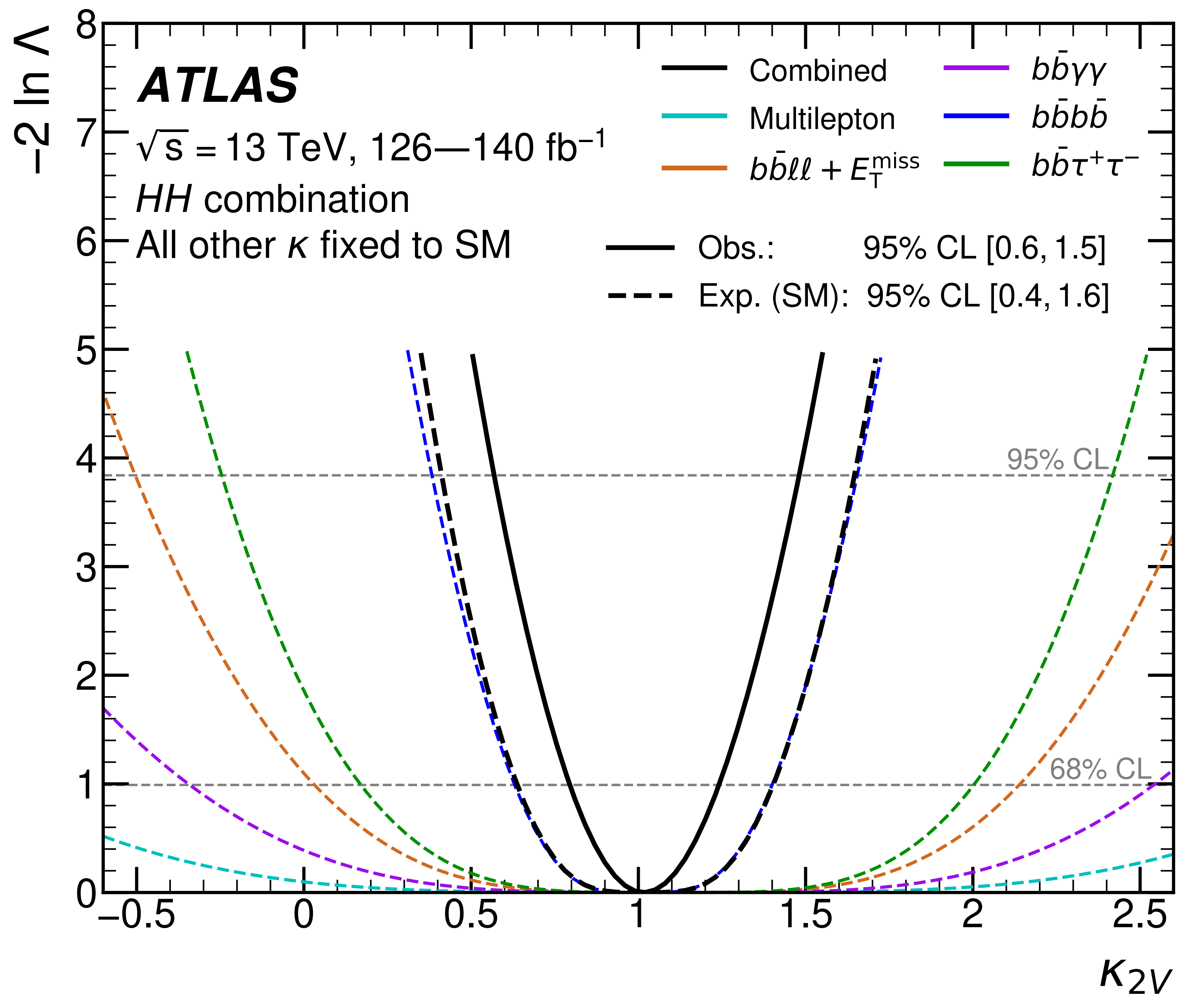
CERN-THESIS-2021-218



Observed : 0.7 < κ_{2V} < 1.4

κ_{2V} = 0 excluded at 6.6σ

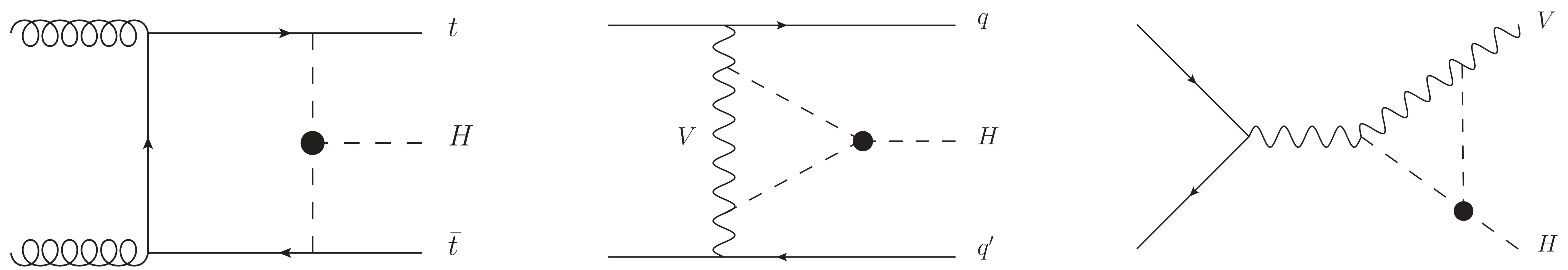
assuming other interactions at the SM



Observed : 0.6 < κ_{2V} < 1.5

Expected : 0.4 < κ_{2V} 1.6

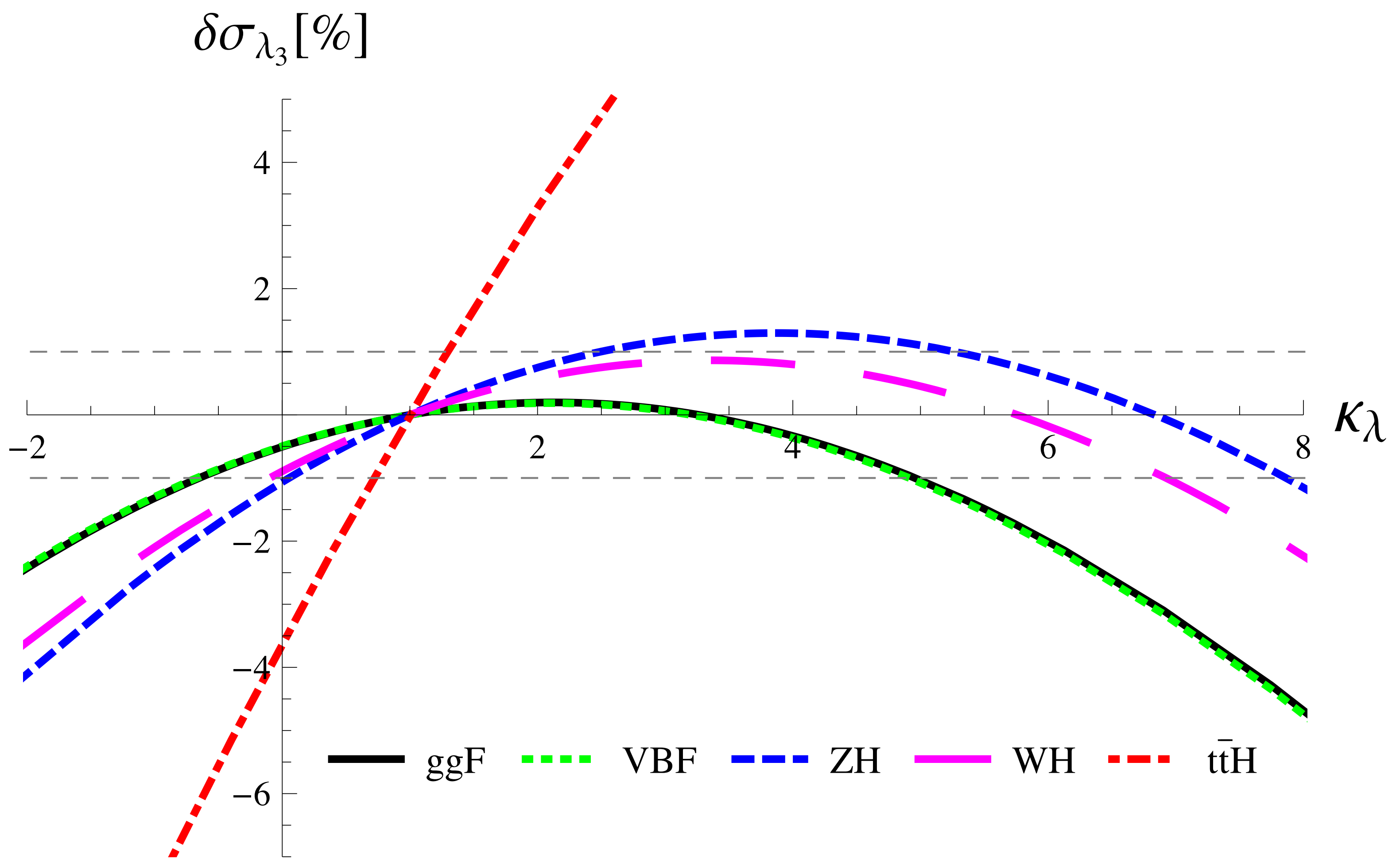
Indirect constraints on λ

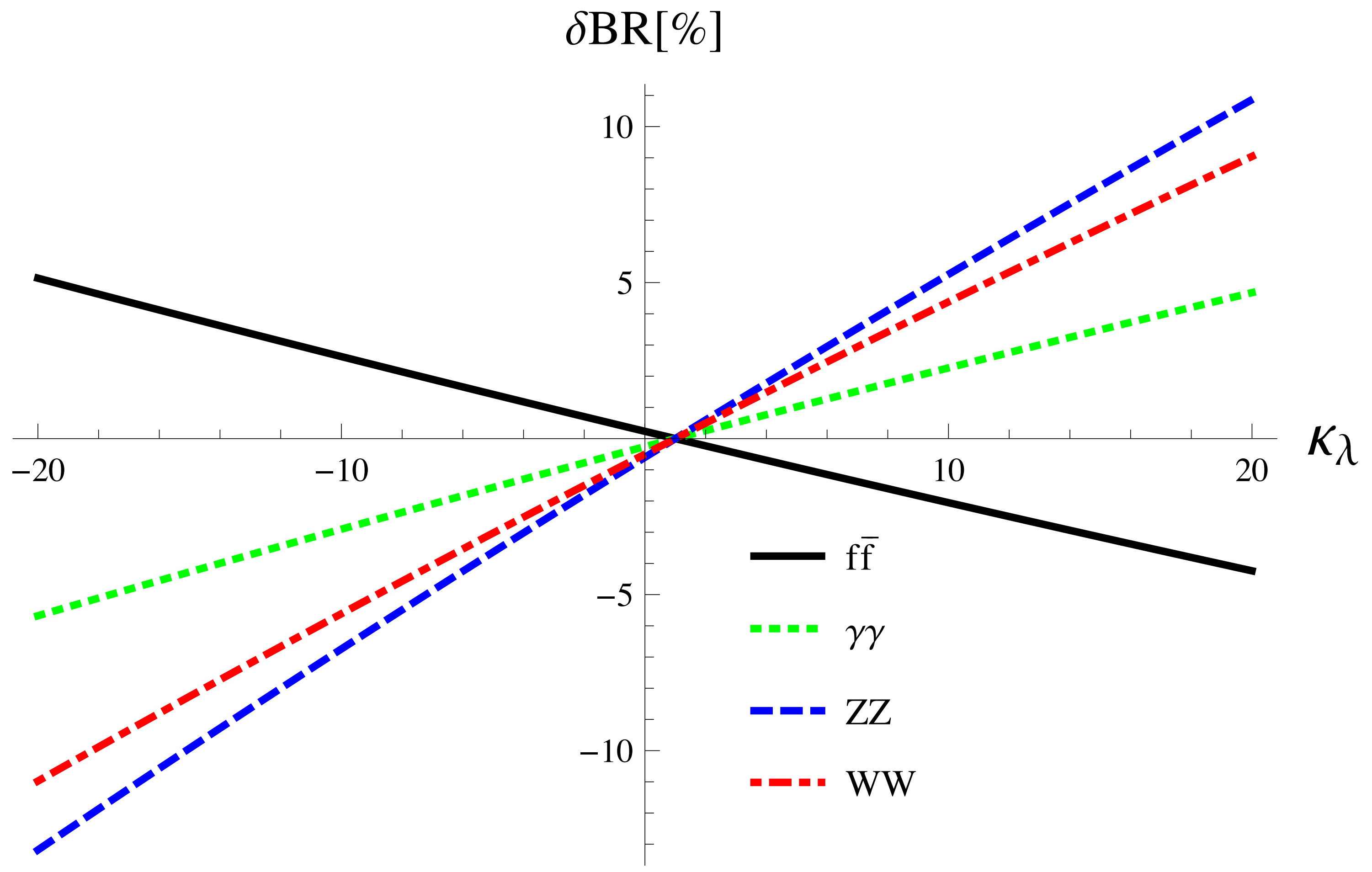


Single H production as a precision tool to look for NLO effects from λ_{HHH}

Simplified template XS single H measurements used as input

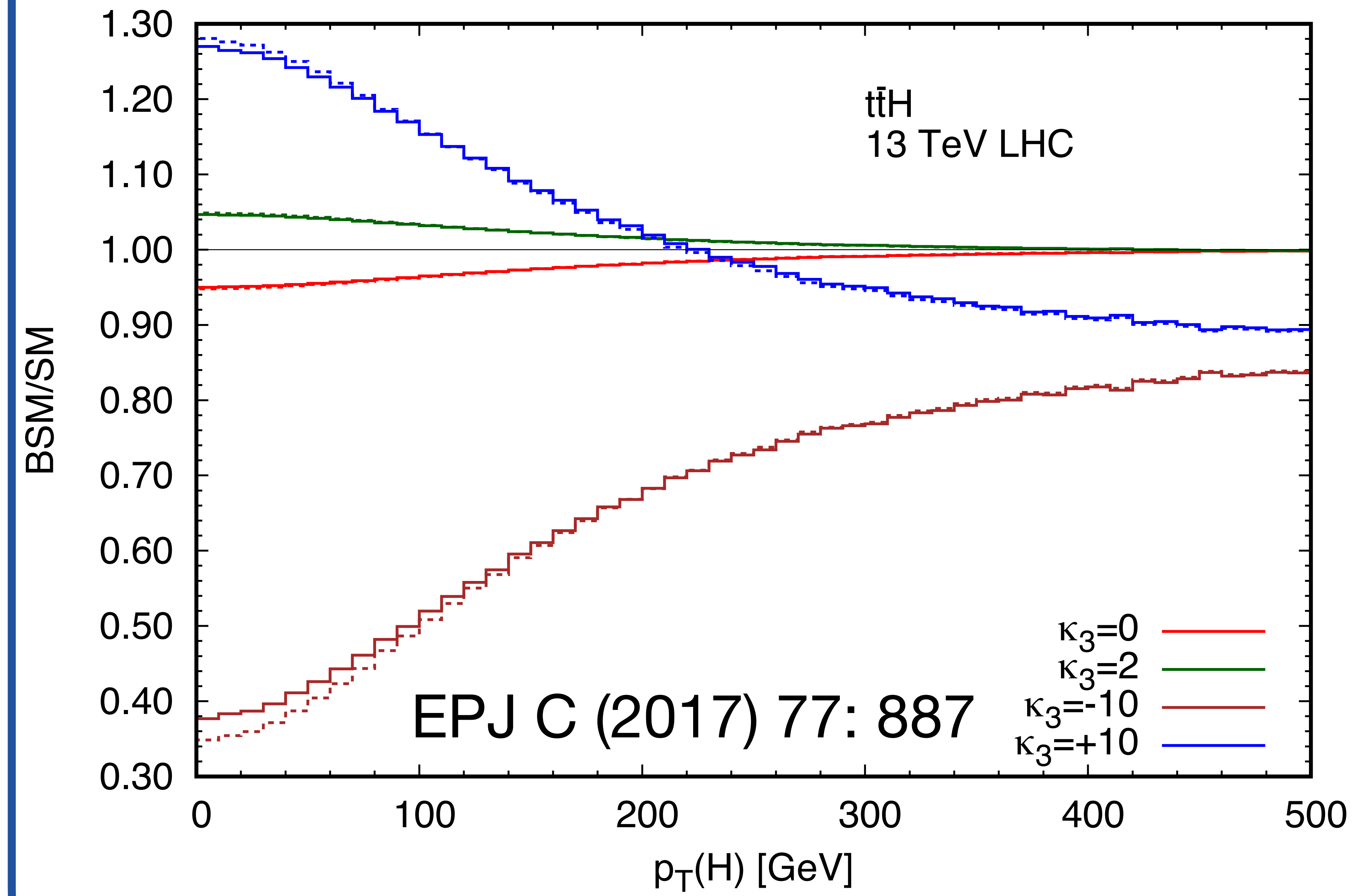
Production xs and decay BR





JHEP 1612, 080 (2016)

Differential distributions

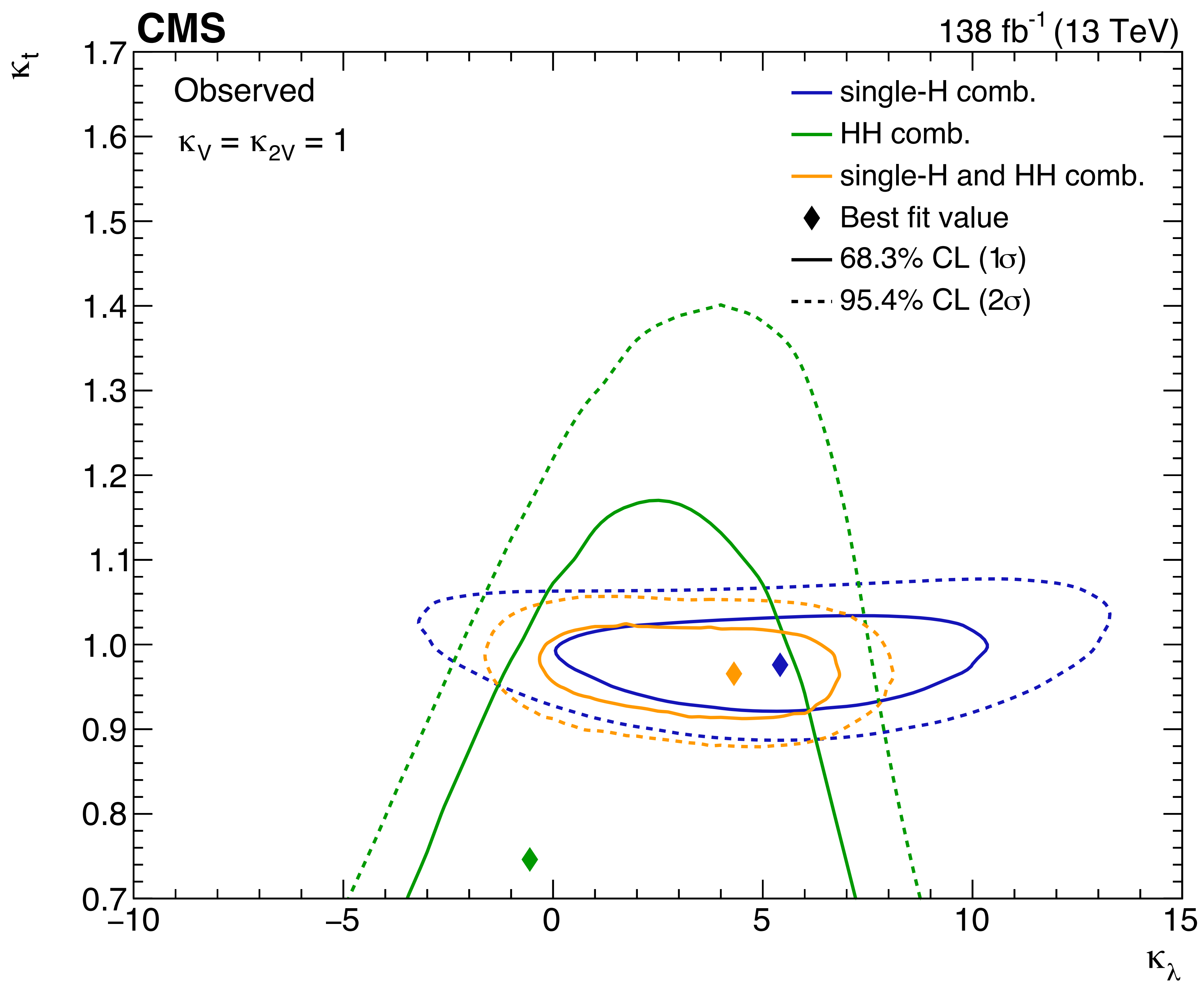


EPJ C (2017) 77: 887

H+HH combination results

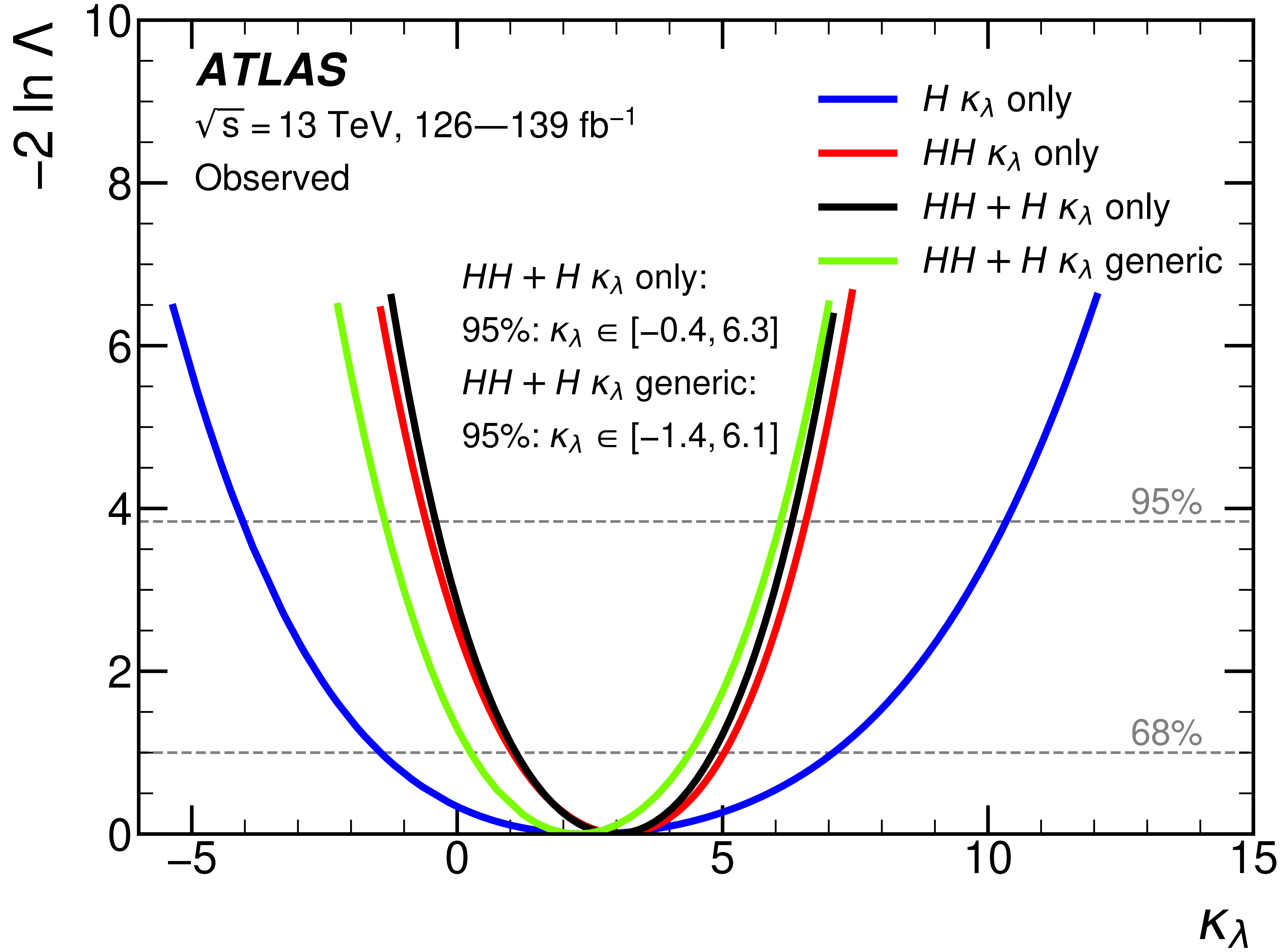
PLB 843 (2024) 137745
arXiv:2407.13554 (sub. to PLB)

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



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

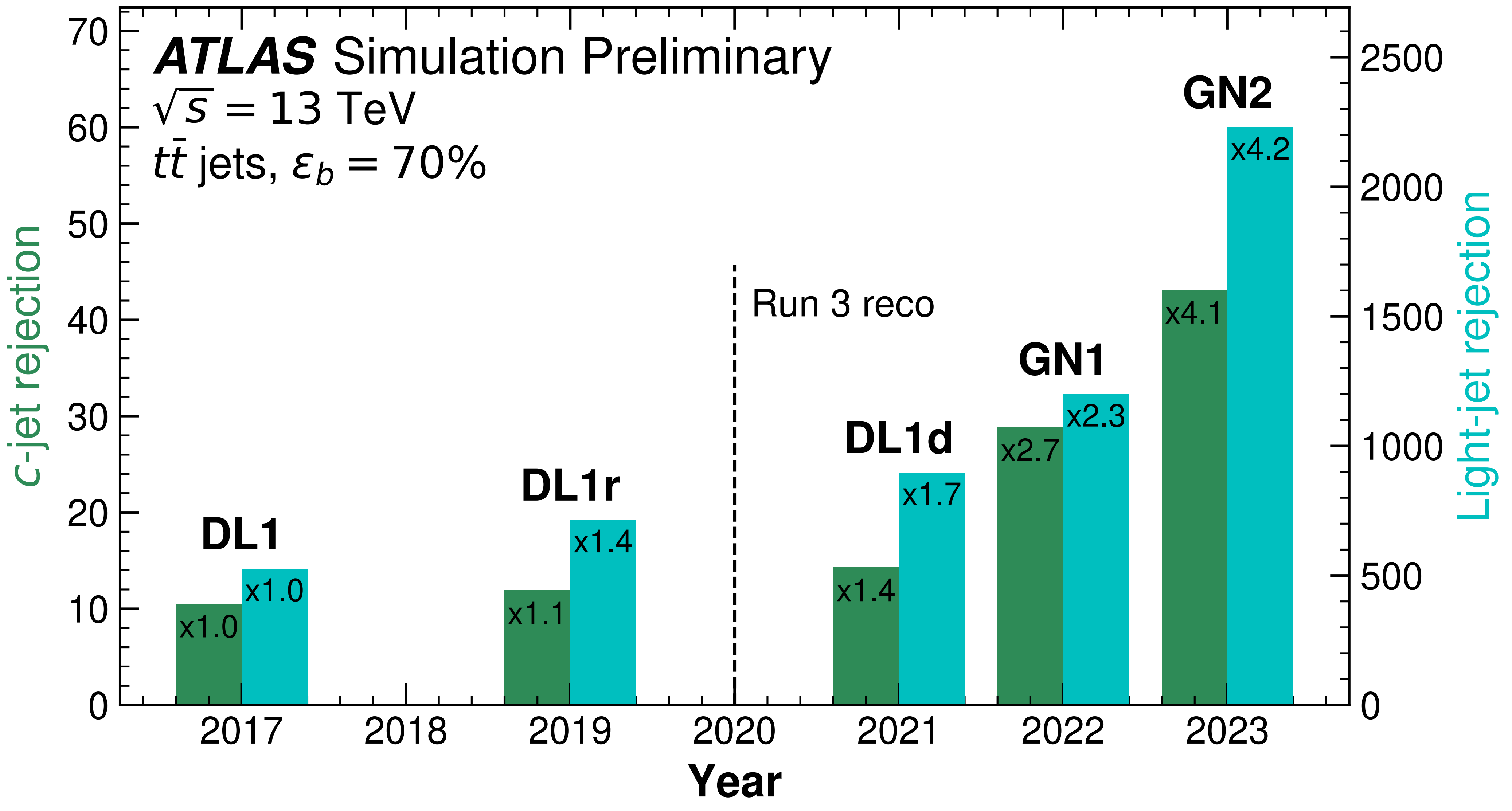
κ_λ effects in single H standalone cannot be disentangled from other couplings



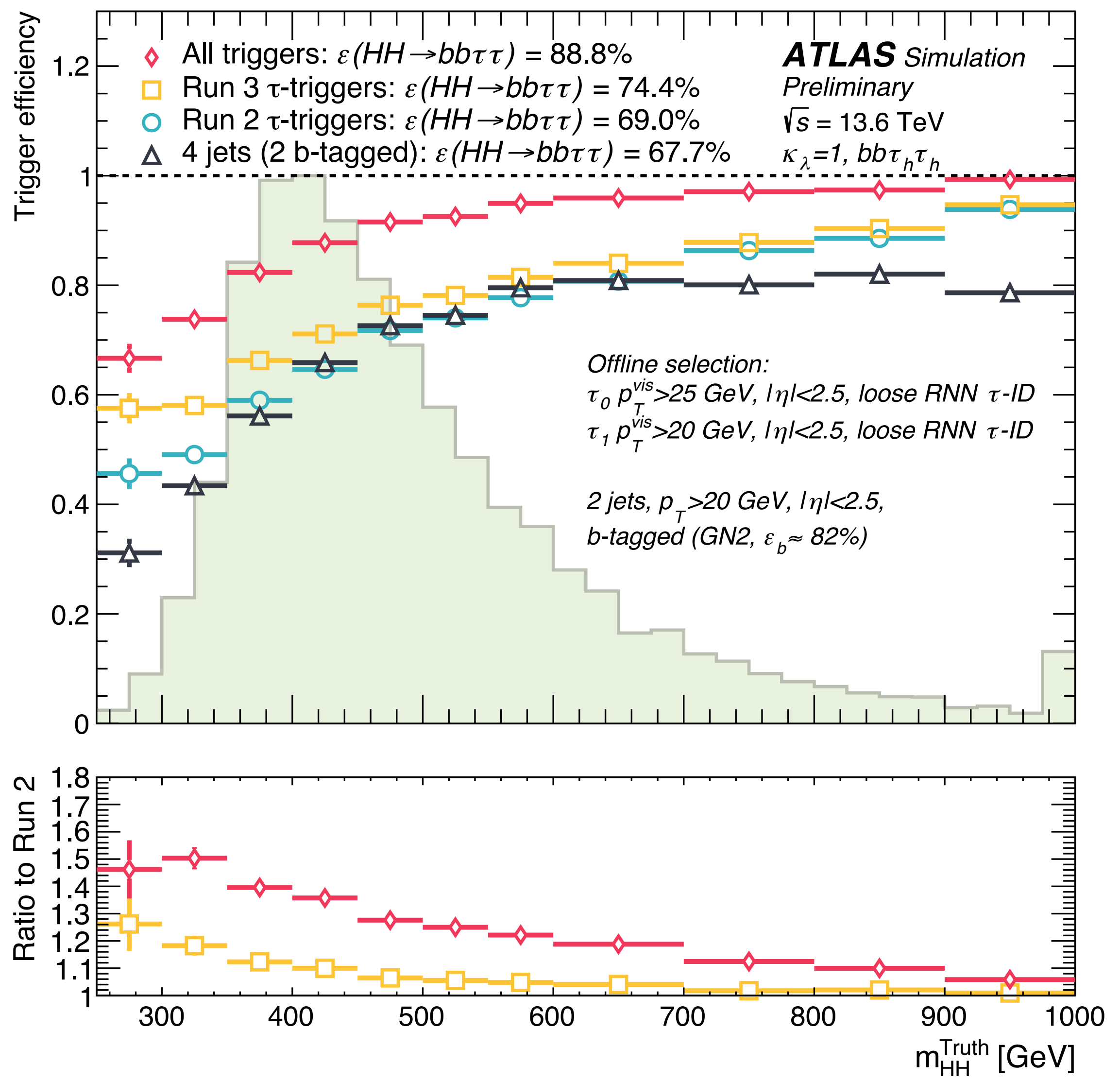
Degeneracy with κ_V, κ_f in single H lifted thanks to combined κ_λ constraint

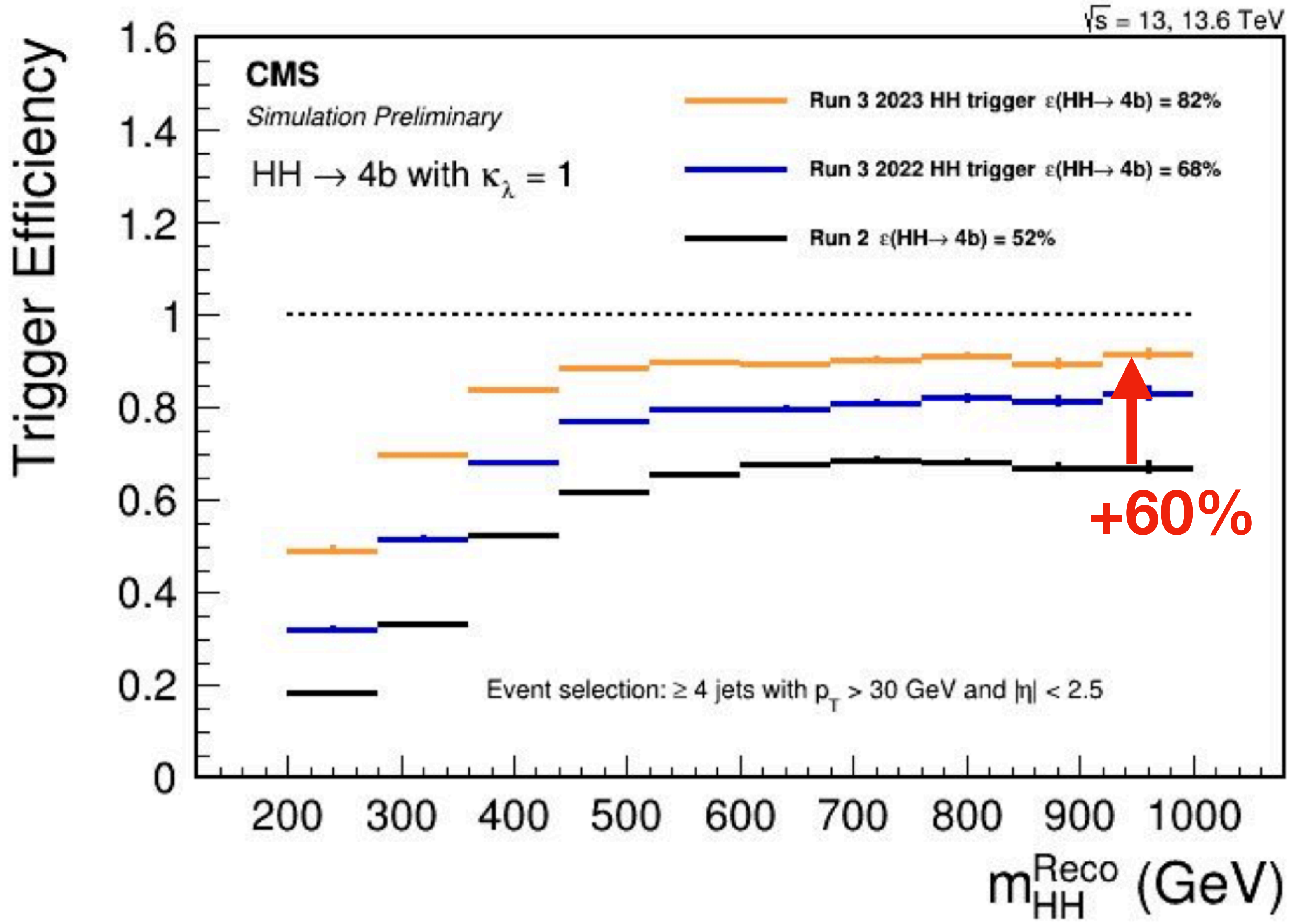
LHC Run 3 prospects

ATL-COM-DAQ-2023-100-a
CMS-DP-2023-050



Improved object identification leveraging on modern machine learning methods





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

- Will at least double the data set with at Run 3
- Opportunity to maximise the analysis sensitivity (triggers, object reconstruction, analysis techniques)

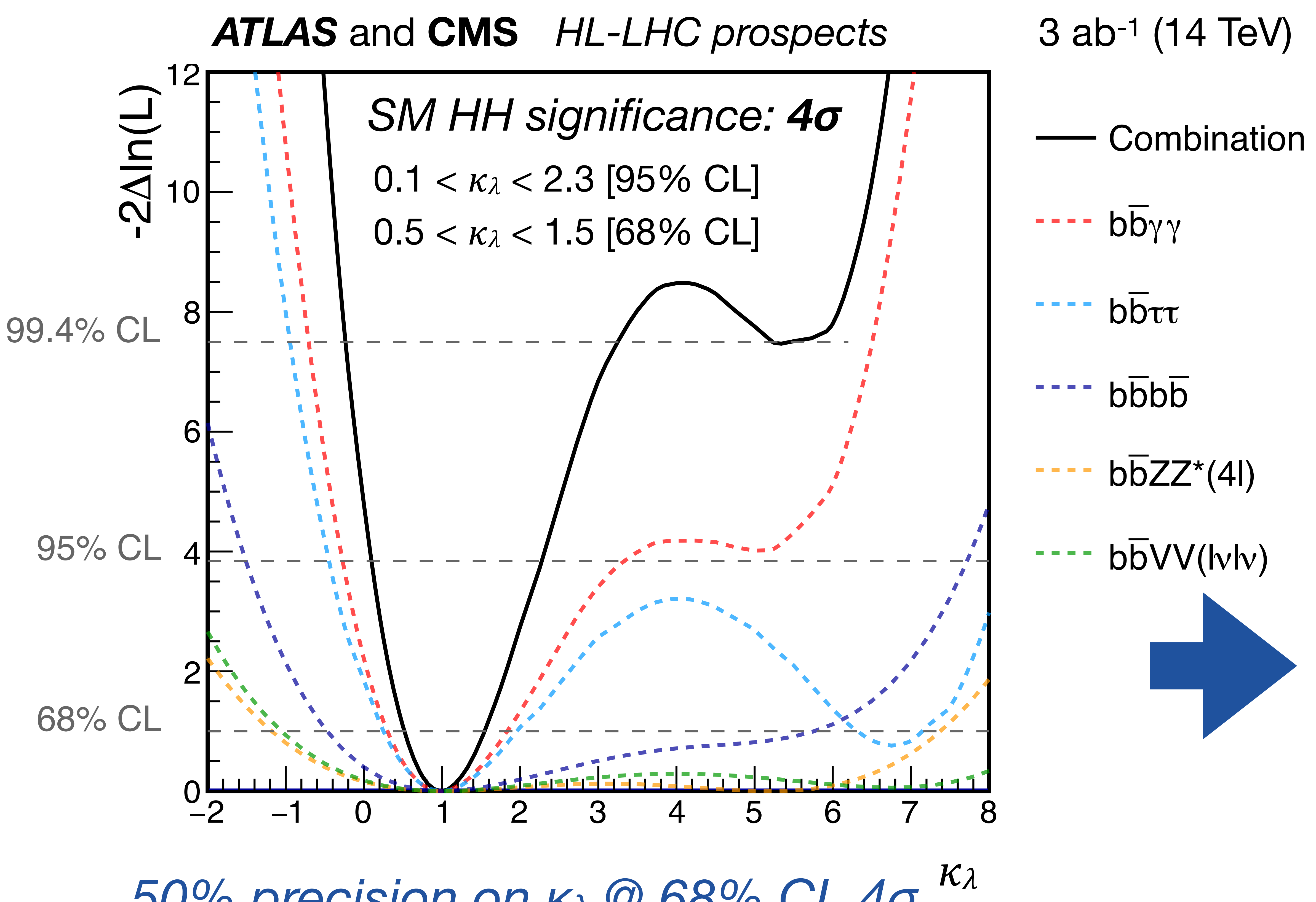
95% CL UL @ Run 2 : ~2.4 × SM per experiment
→ 1.4 × SM / experiment (Run 2 + 3 lumi scaling)
→ 1 × SM ATLAS+CMS (Run 2 + 3 lumi scaling)
→ analysis improvements : **HH evidence @ Run 3?**

Exciting opportunities for HH physics at Run 3

HL-LHC prospects

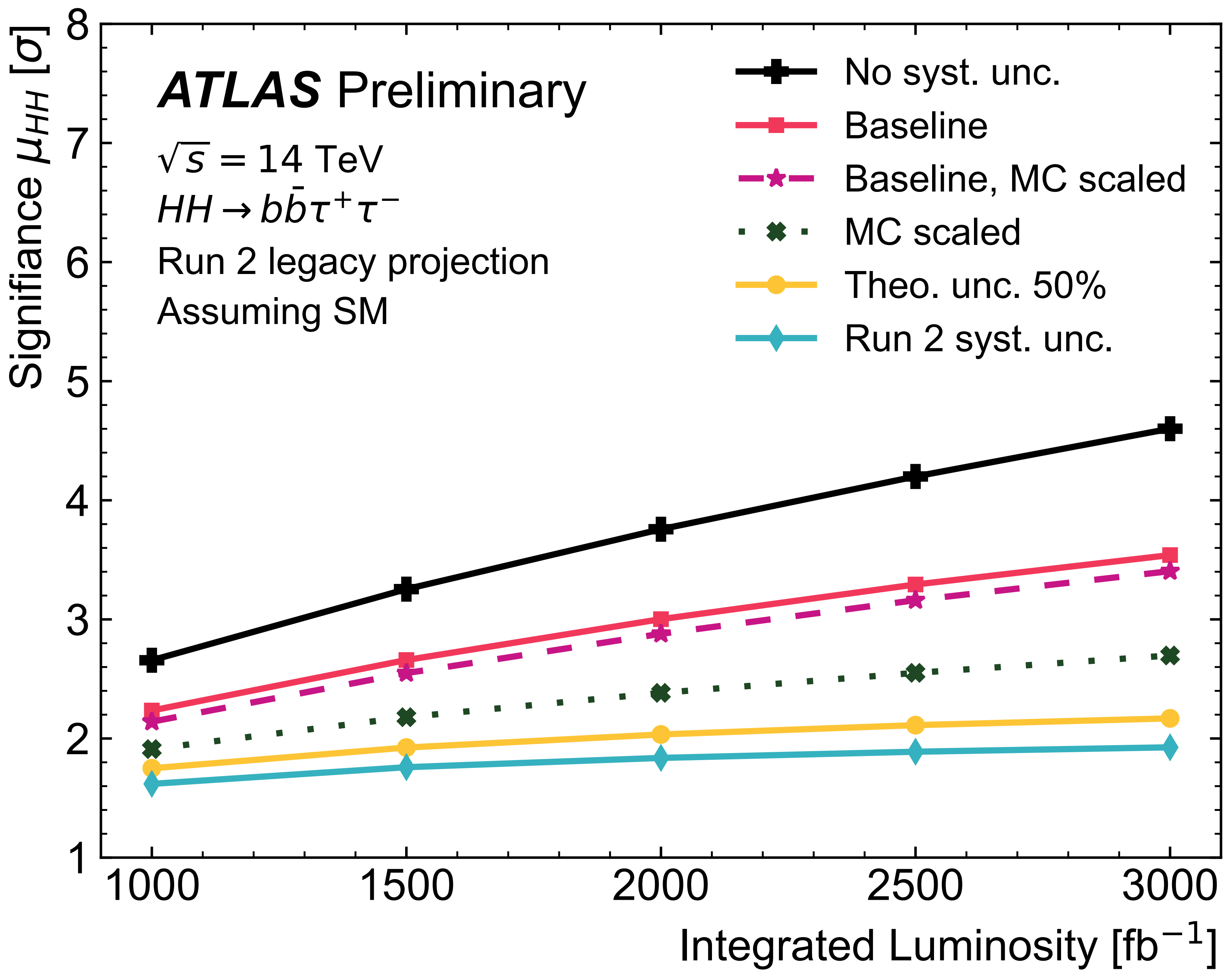
CERN-LPCC-2018-04
ATL-PHYS-PUB-2024-016

2018 European Strategy



50% precision on κ_λ @ 68% CL 4σ significance (ATLAS+CMS)

New projection from the legacy $bb\tau\tau$ Run 2 analysis!



3.5σ significance in $bb\tau\tau$ ATLAS alone in realistic scenario

- Current projections based on 36 fb^{-1} Run 2 analyses extrapolation / parametric simulation
- Ongoing update effort for the next European Strategy

Combination of channels and experiments is crucial to observe HH | **Major HL-LHC legacy**

Conclusions

- HH is a fundamental process to probe the electroweak symmetry breaking mechanism
  - access to the self-coupling HHH → shape of the scalar potential
  - access to the quartic coupling VVHH → electroweak Higgs doublet structure
- ATLAS and CMS conducted a broad programme of analyses with the full Run 2 data set
  - several channels covered
  - comprehensive study of ggF and VBF production modes
  - combined constraint from H and HH data
- Possibility of combined evidence at the Run 3 with a long-term observation at HL-LHC at reach