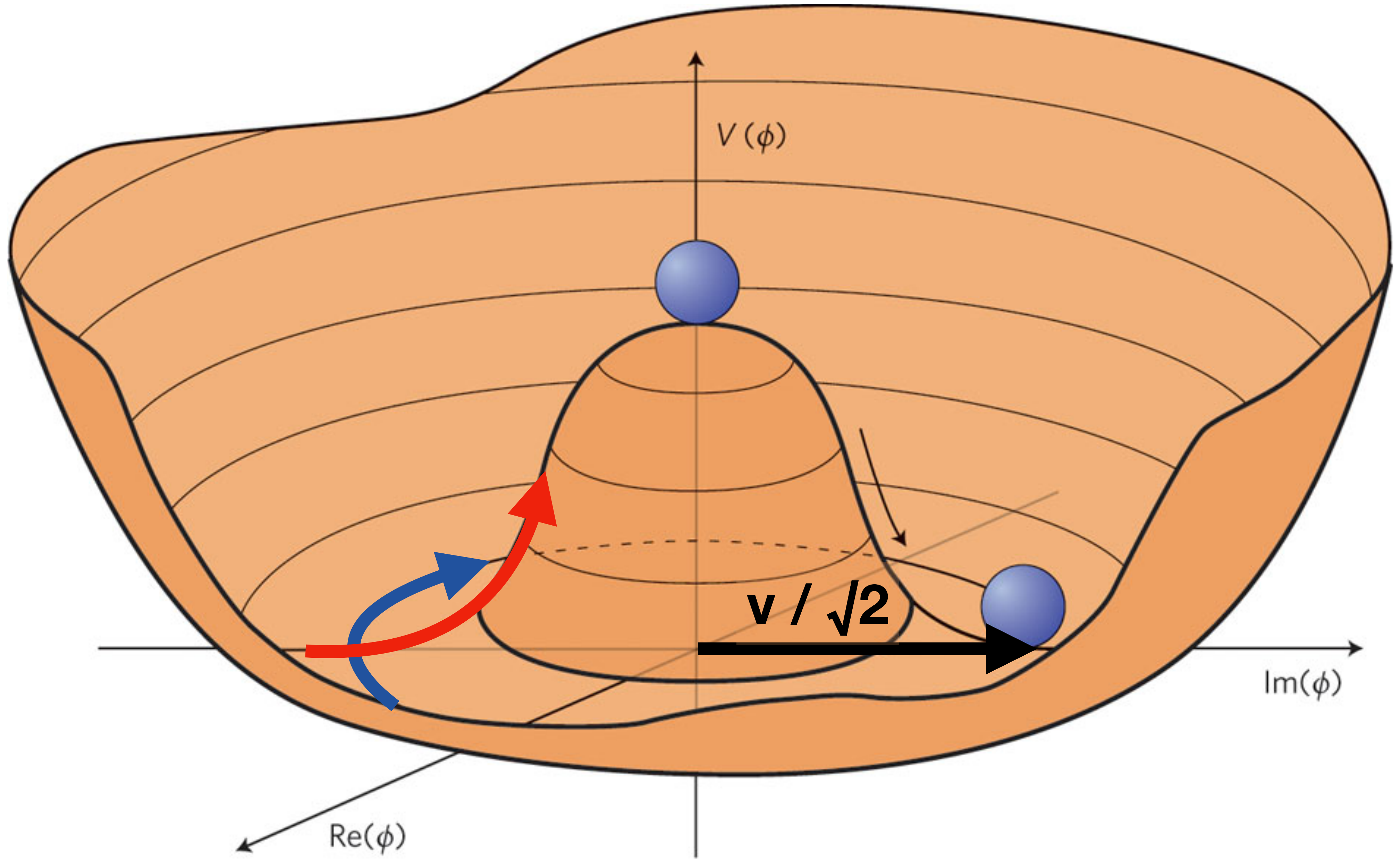
Non-resonant HH at the LHC

Luca Cadamuro

Higgs potential and BSM opportunity
August 29th, 2021

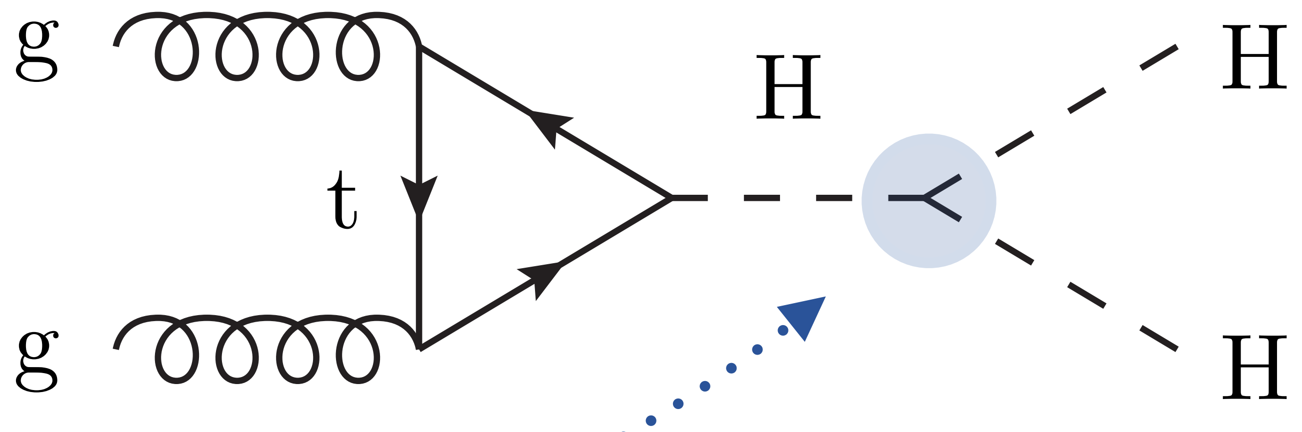
HH and the Higgs boson self-coupling



Higgs boson pair production | **A milestone in the exploration of the scalar sector**

- Scalar potential **shape** ⟹ scalar sector **properties** ⟹ self-coupling **strength**
  - $\lambda \overset{\text{SM}}{=} m_{\text{H}}^2/(2v^2) \approx 0.13$: test of the SM validity
  - unique access to BSM physics effects

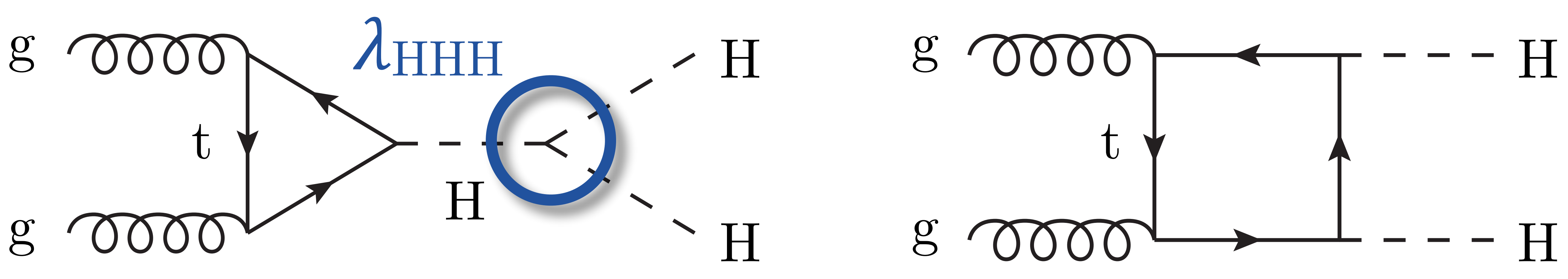
$$V(\Phi^\dagger\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

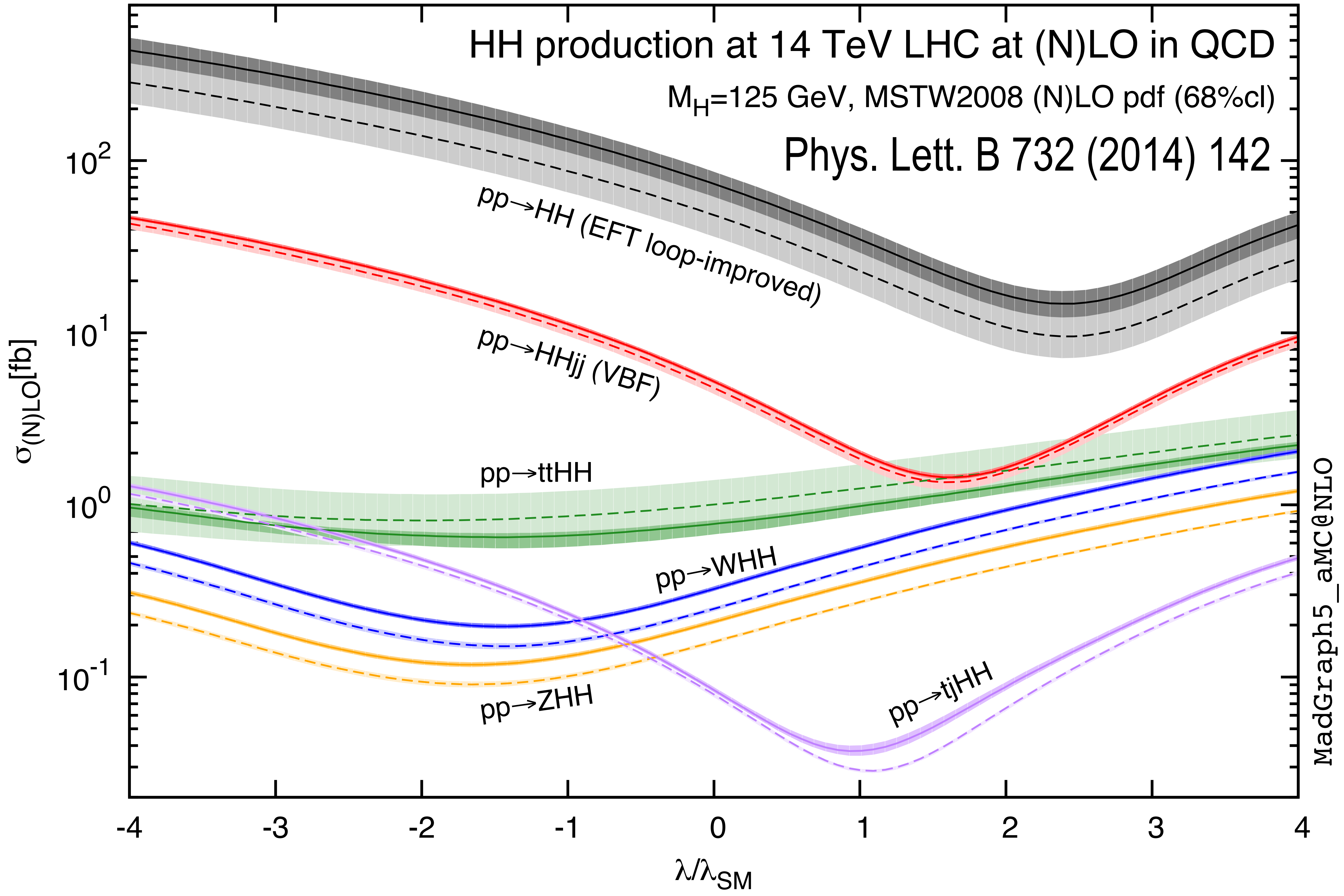


HH production modes

NNLO FT-approx
JHEP 1805 (2018) 059

$$\sigma^{SM}_{ggF} = 31.05\,\mathrm{fb}^{+6.7\%}_{-23.2\%}\ (13\,\mathrm{TeV})$$





- **Gluon fusion**: dominant production mode
  - about 4500 HH events in the Run 2 datasets
  - large destructive interference $\Longrightarrow$ tiny xs
  - self-coupling information both total and differential cross section (strong m_{HH} dependence on λ_{HHH})
- **VBF**: second production mode

HH production $\Longrightarrow$ direct determination of Higgs trilinear coupling λ_{HHH}

Which decay channels?

Full Run 2 results
focus of this talk

XX % : *current public results at sqrt(s) = 13 TeV*

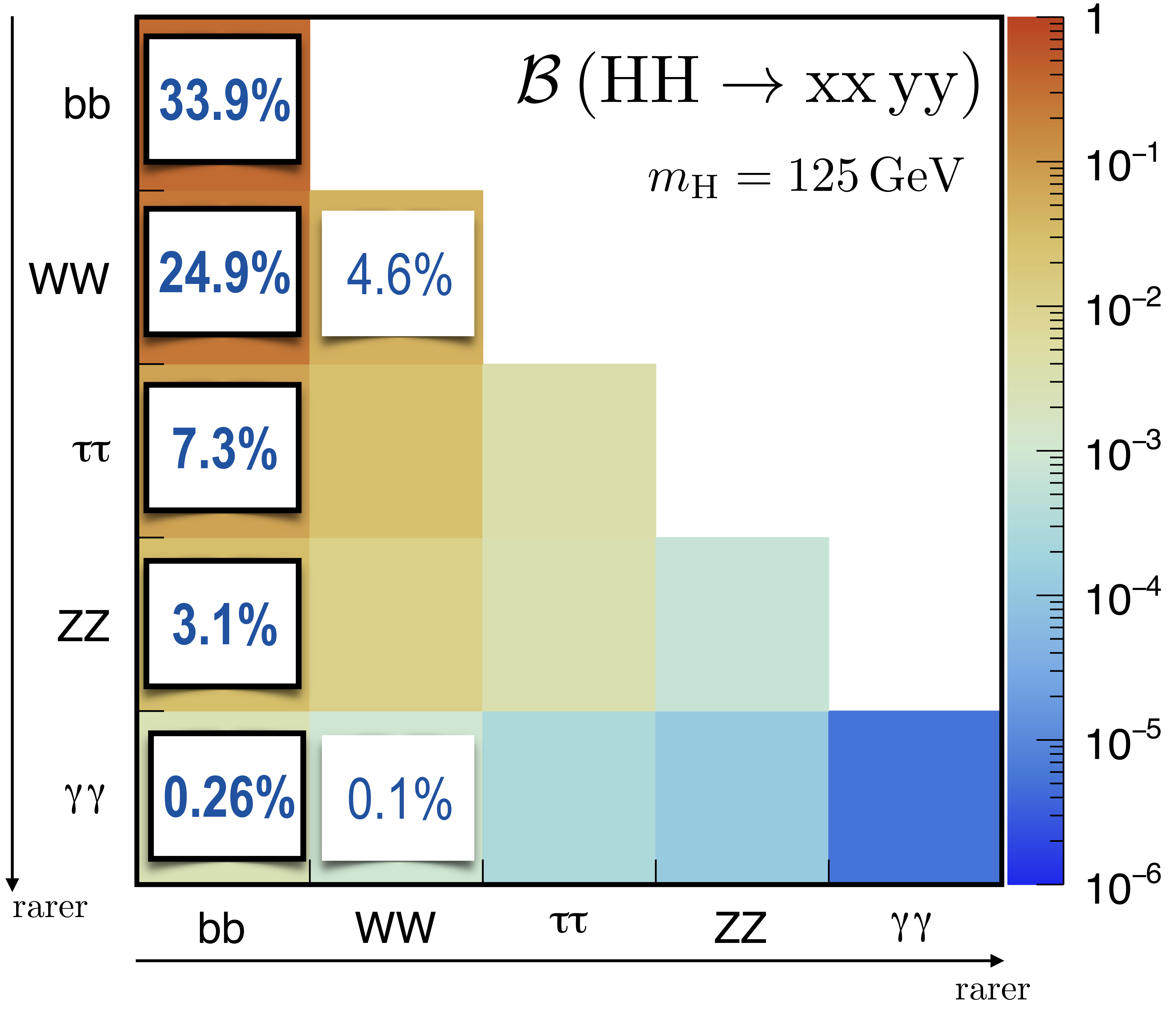
ATLAS (VBF only)
CMS

ATLAS

ATLAS (SM only)

CMS bbZZ(4ℓ)

ATLAS
CMS

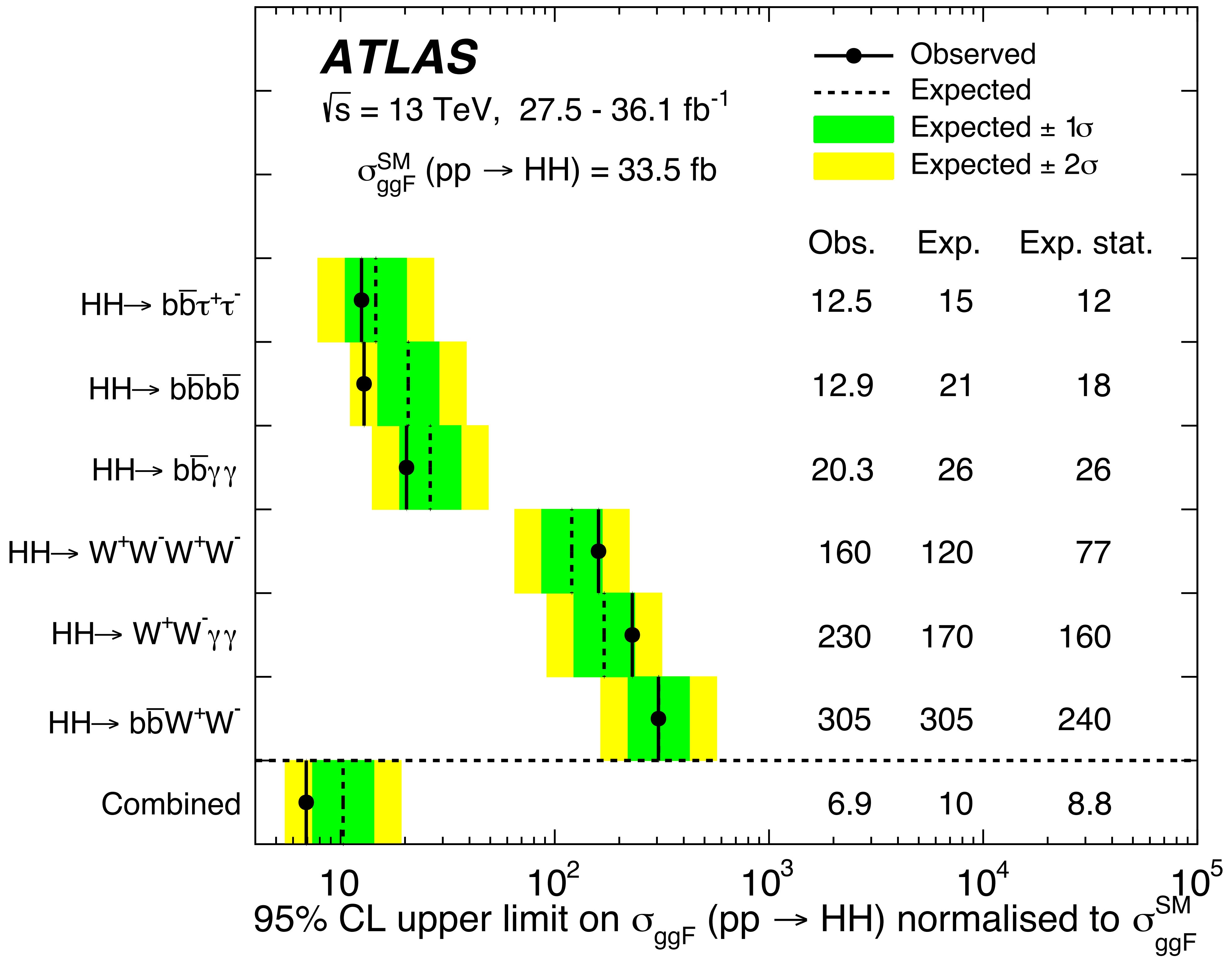


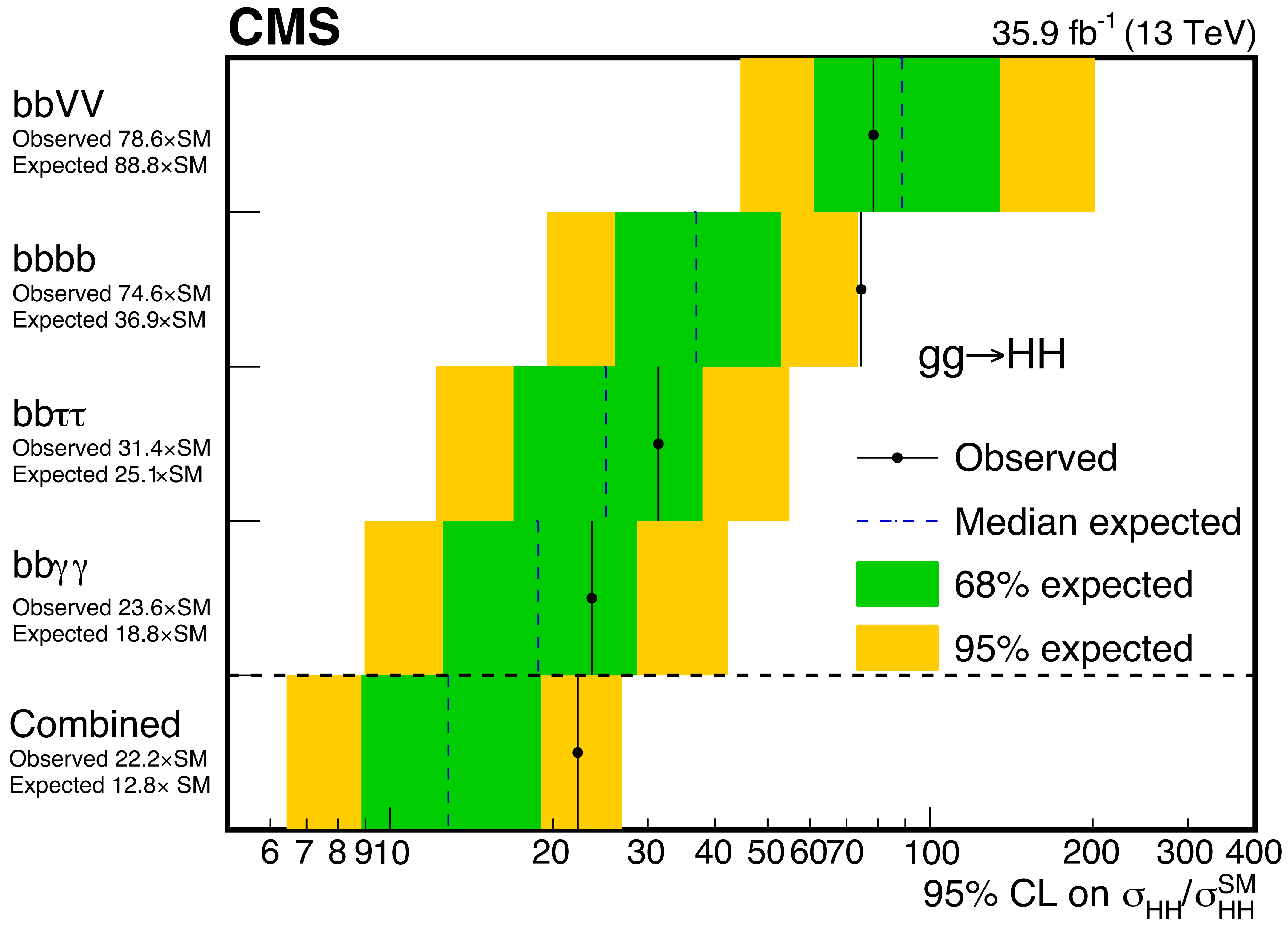
- Many final states explored at the LHC
  - progressively covering more as luminosity increases
- Several full Run 2 results available!
  - focus of this talk

No “golden channel” for the study of HH

Complementarity from the final states for SM observation and BSM study

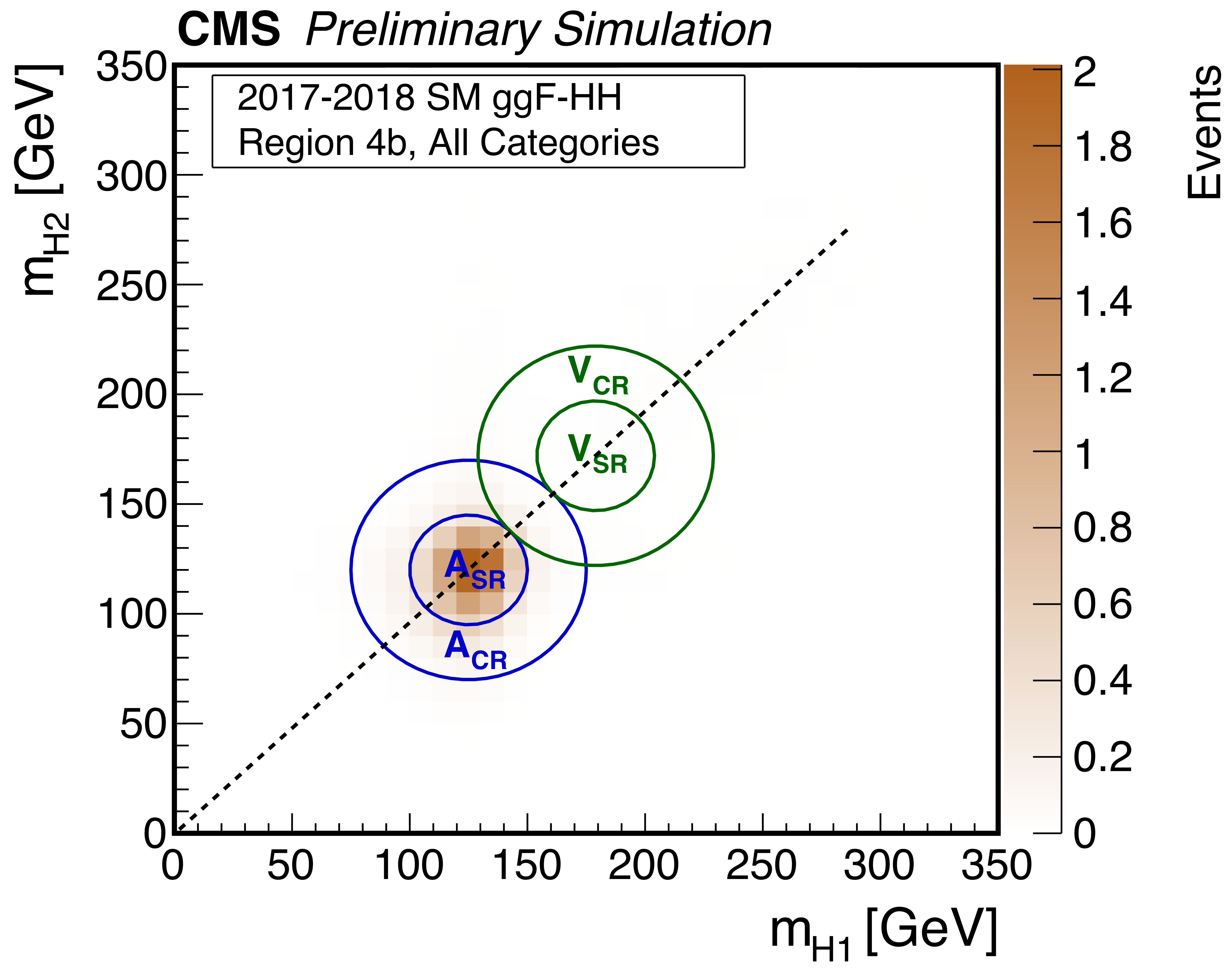
Previous measurements





- A sensitivity of ~10 x SM is set by each experiment with the 2016 dataset
  - corresponds to κ_λ in the range of about [-6, 12]
- These results clearly show the importance of exploring and combining several final states

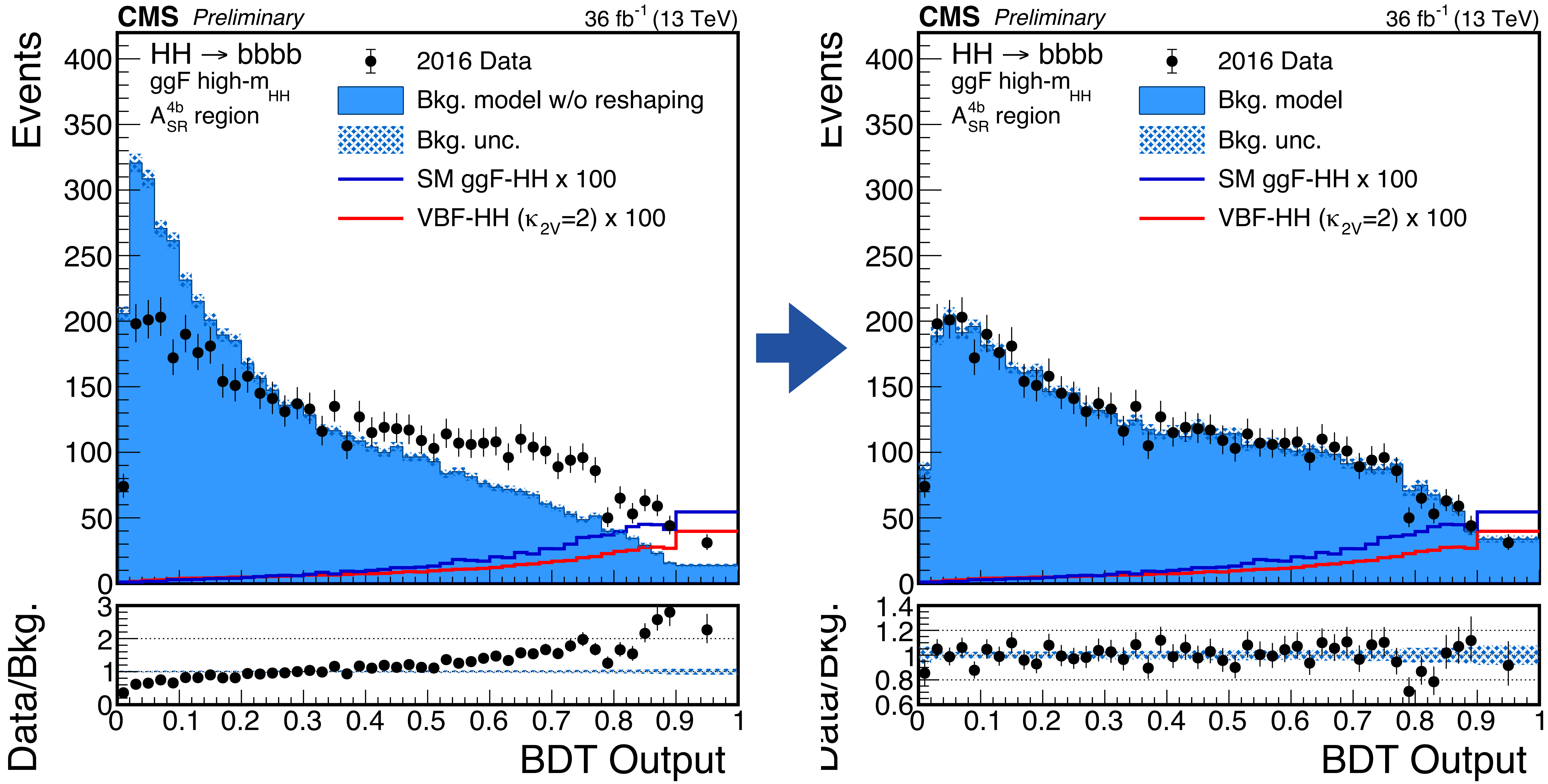
High BR, low S/B : HH→bbbb



- Events selected with ≥ 3 b jets
  - largely rely on b tag performance, also at HLT
- Signal combinatorics solved by pairing jets as "closest to diagonal"
  - minimal bias of the bkg in the signal region
  - natural definition of signal, control, and validation regions based on signal properties
- Advanced categorization of events
  - ggF - VBF discriminant to define production mode categories
  - high and low m_{HH} regions in ggF
  - SM- and BSM-like categories in VBF

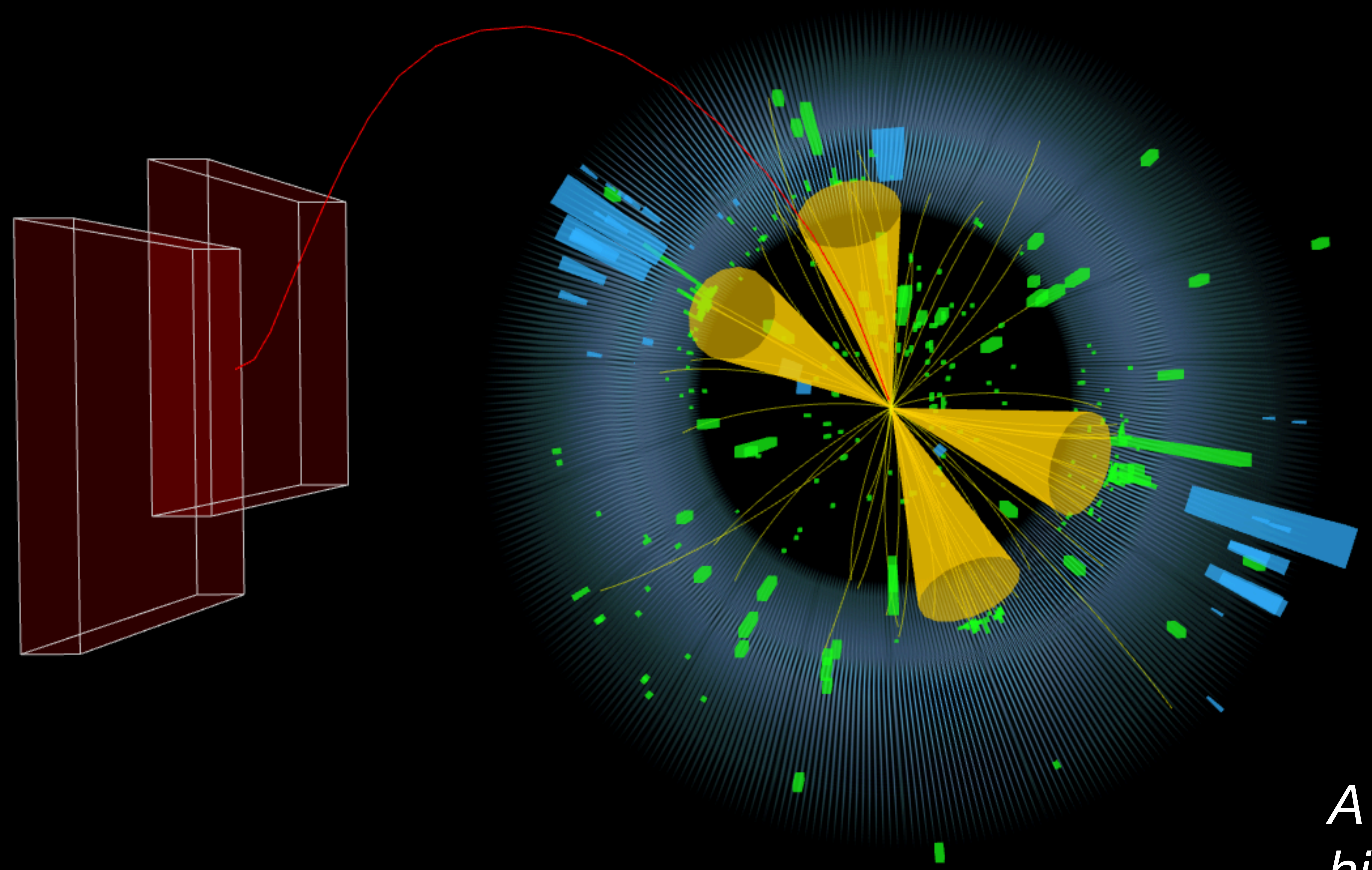
HH → bbbb : the multijet challenge

Overwhelming multijet background | **Powerful discriminants and data driven estimate**



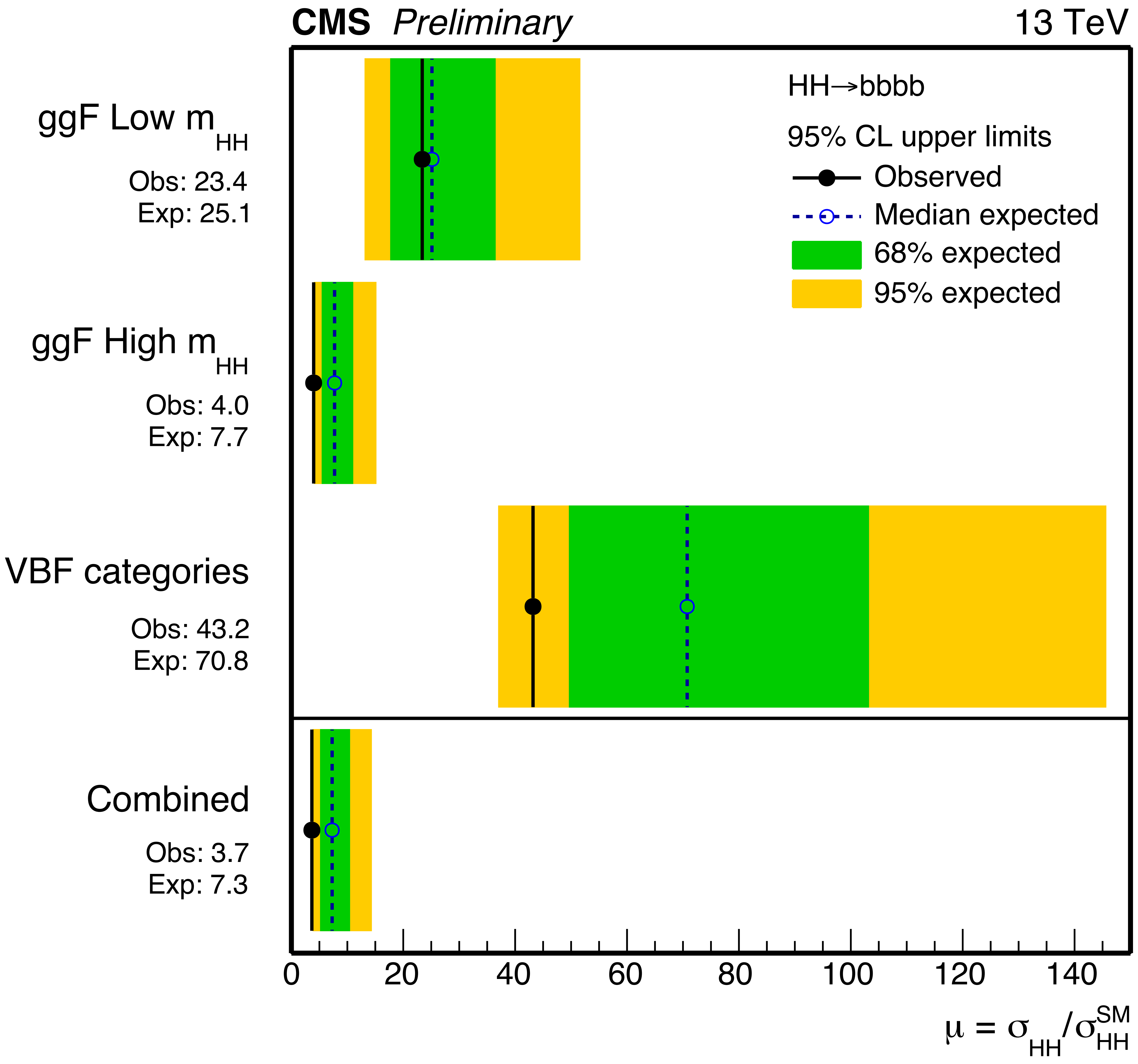
- Background from 3b region
  - 3b→4b transfer function trained with BDT reweighting method in CR
  - applied to data in the SR(3b) to model SR(4b)
  - accurate method validation in signal-free VR
- Powerful multivariate discriminant to separate background from signal in ggF

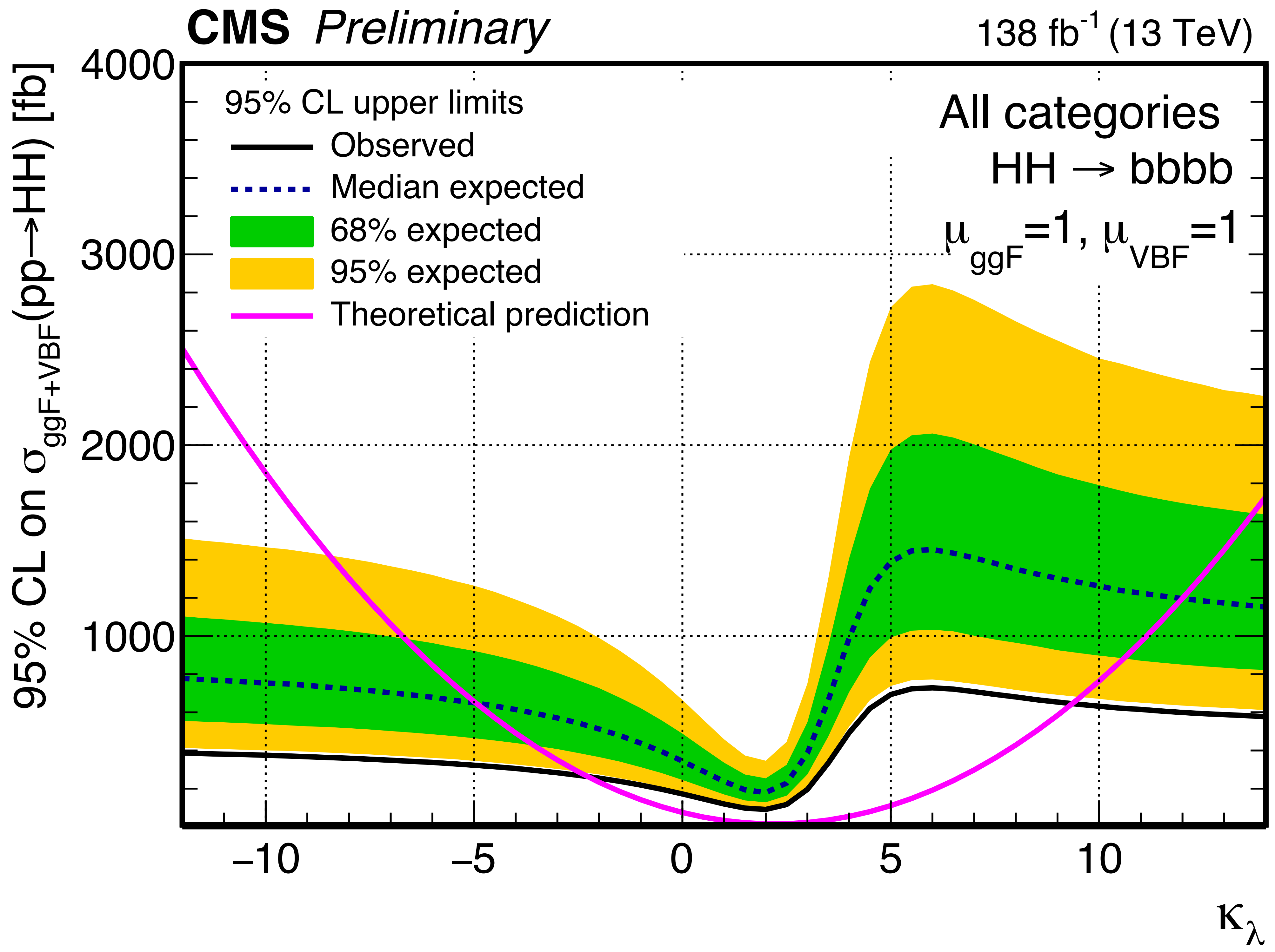
Leverage on ML techniques to boost the analysis performance



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

HH → bbbb : results

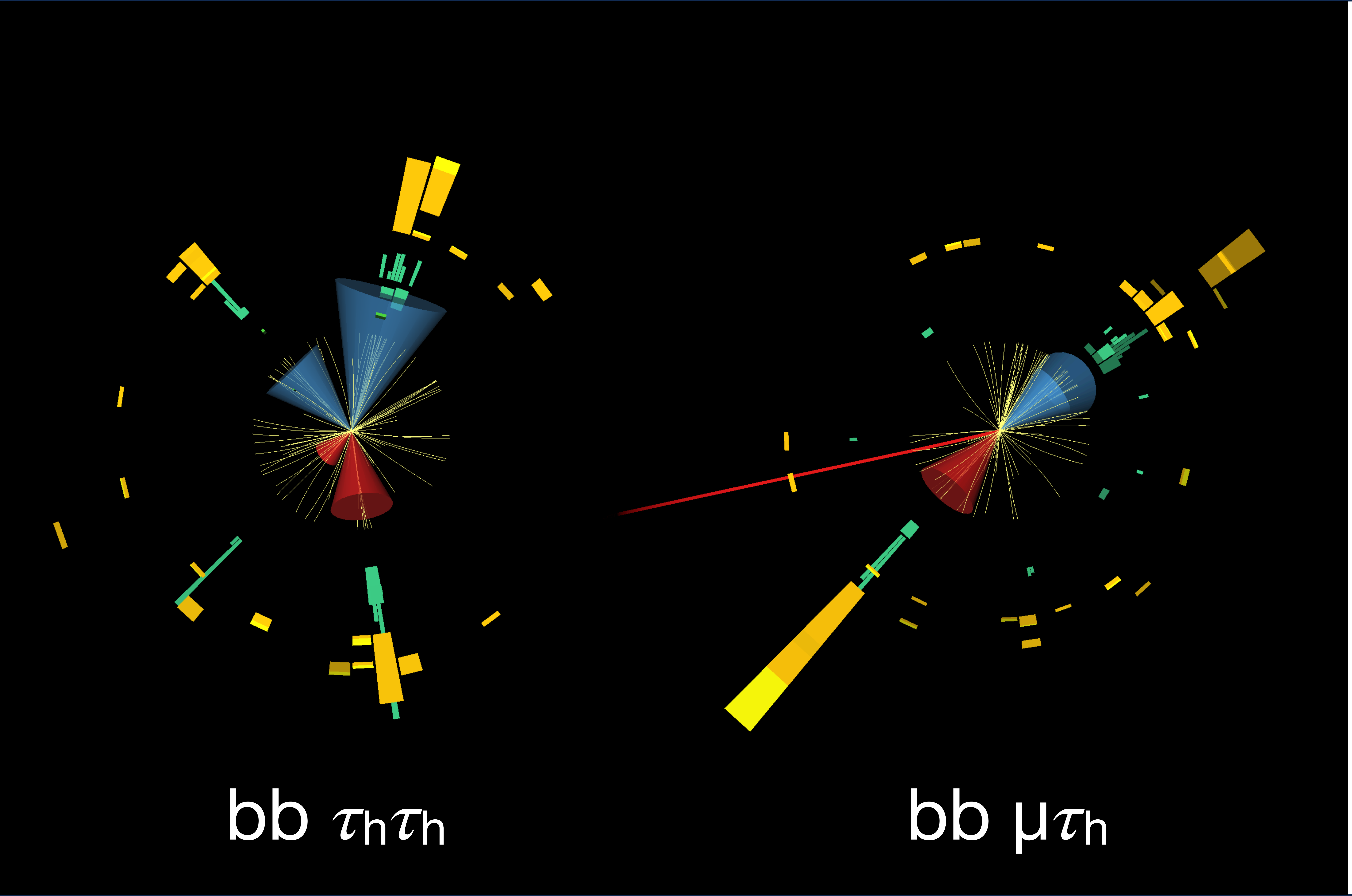




Observed (expected) 95% CL UL
3.6 (7.3) × SM
$-2.3 < \kappa_\lambda < 9.4$ $(-5 < \kappa_\lambda < 12)$

Best constraint to date on SM HH

Medium BR, medium S/B : $HH \to bb\tau\tau$

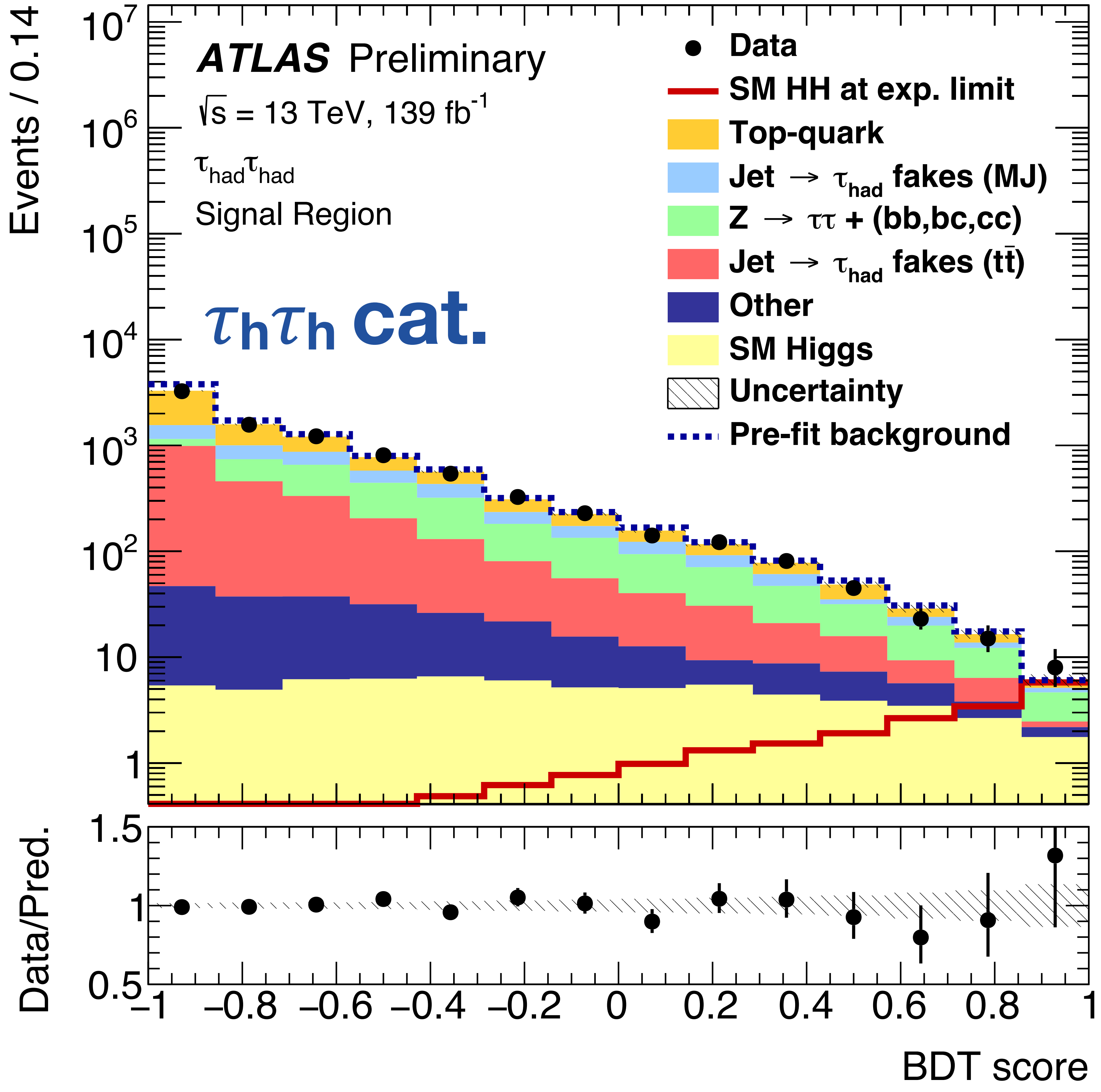


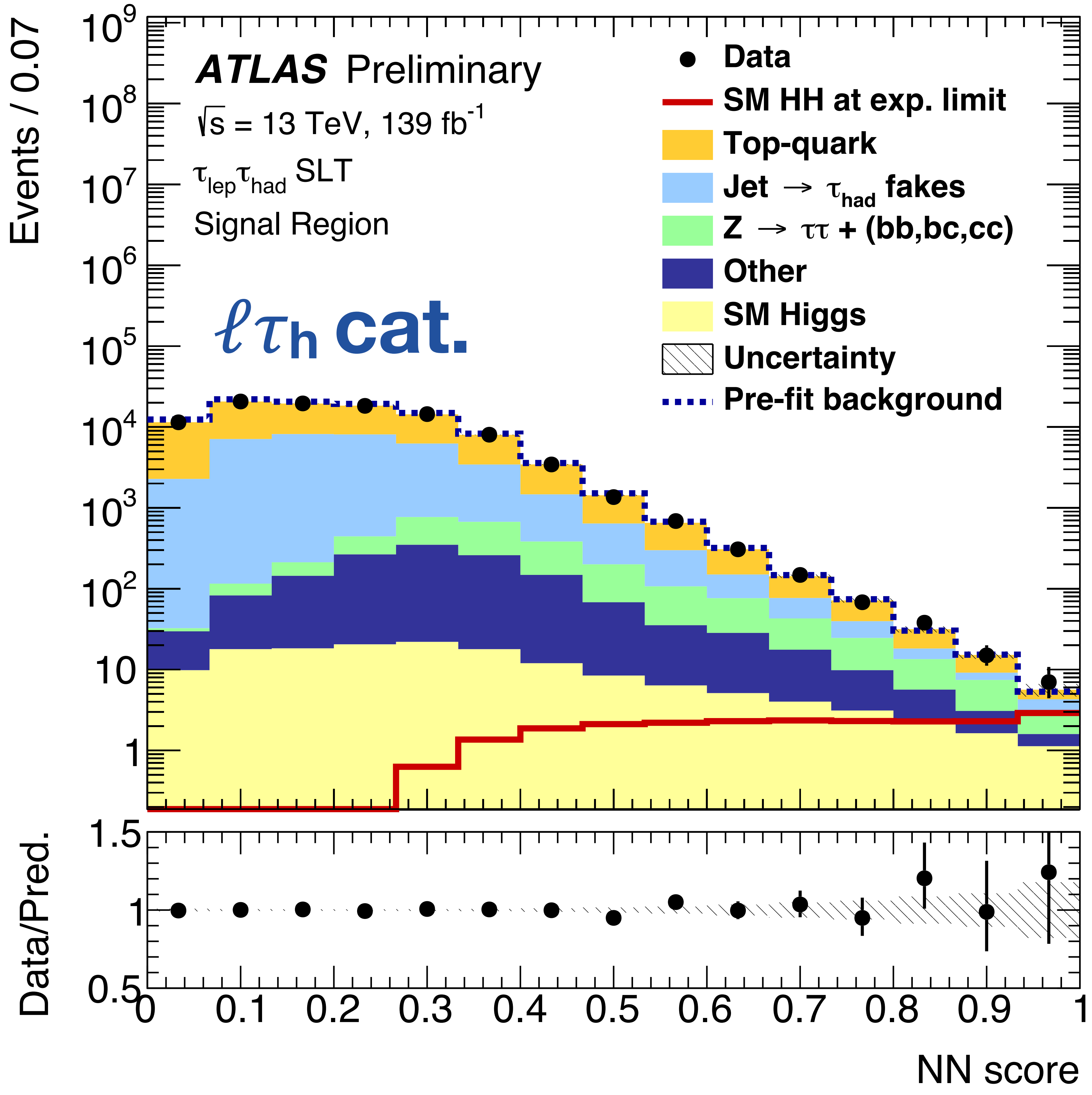
- Several final states
  - $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$: 88% of the total decays
- Incomplete reconstruction
  - use likelihood-based algorithms to estimate $m_{\tau\tau}$
- Several background processes
  - tt (irreducible): from MC
  - Z+HF: MC + data-driven normalization in ee/μμ+jets CR
  - misidentified jet→τ_h bkg. from data

Challenging decay channel

$HH \to bb\tau\tau$: looking for the signal

- Use the rich kinematic event information to separate signal from bkg with a BDT/NN
  - inputs: masses, momenta and angles between objects
- Fit the BDT/NN output
- Results dominated by the statistical uncertainty
  - leading systematic: bkg. modelling



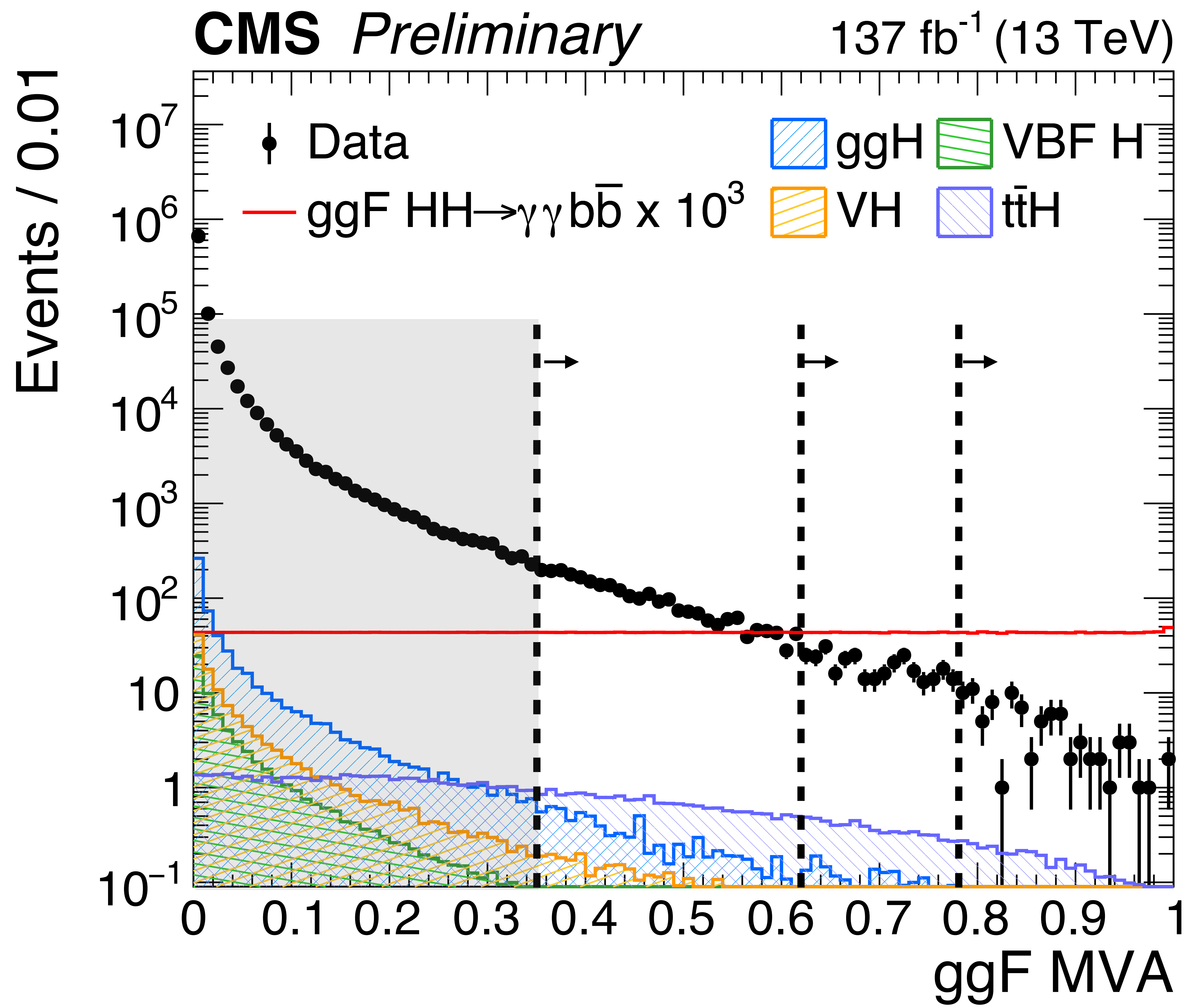


Observed (expected) 95% CL UL: 4.7 (3.9) × SM

No results yet on κ_λ constraints and on separate ggF/VBF measurements

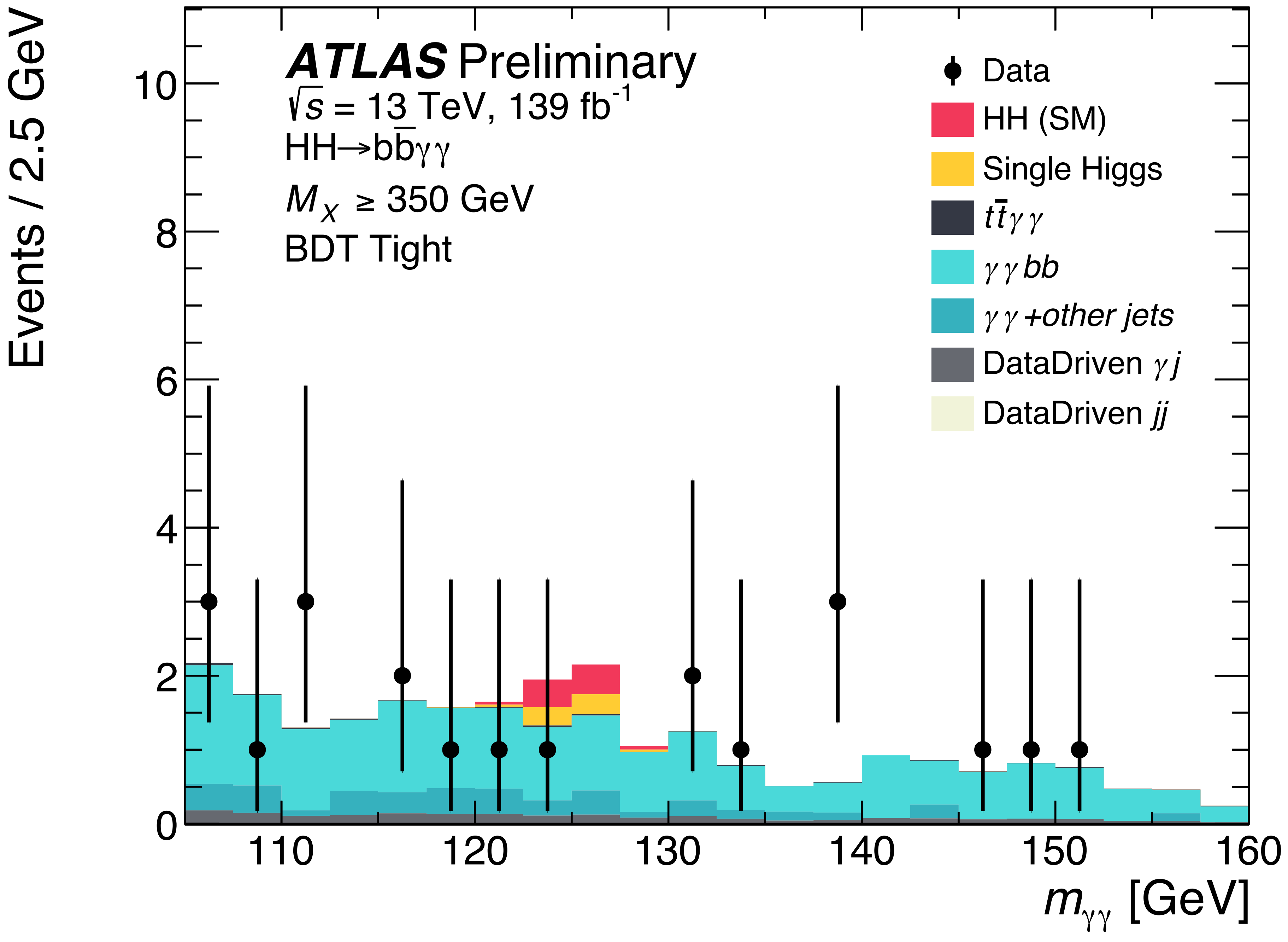
Low BR, high S/B : HH → $bb\gamma\gamma$

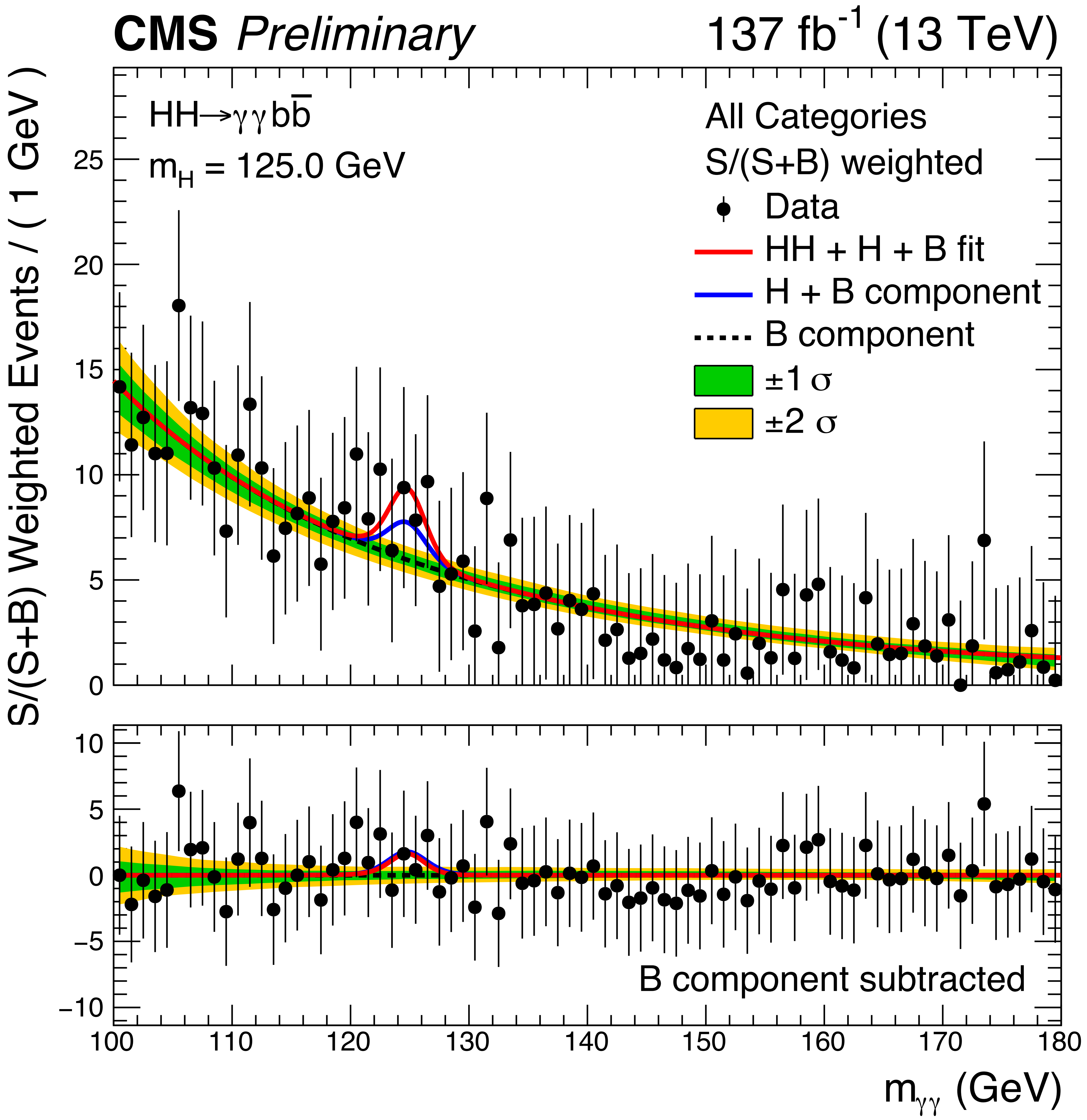
Very rare but clean channel | **Analysis targets maximal efficiency and purity**



- Dedicated MVAs for background suppression
  - CMS: feep NN against ttH + BDT against nonresonant $\gamma(\gamma)$ + jet (uses object kinematics, ID, resolution)
  - ATLAS: single bkg. discriminant
- Event classification based on the MVA purity and the HH invariant mass
  - CMS: 3 MVA categories × 4 m_{HH} categories
  - ATLAS: 2 MVA categories × 2 m_{HH} categories
  - additional VBF-specific categories and results by CMS
- m_{bb} resolution improved with multivariate regression

bb$\gamma\gamma$: signal extraction





Bkg. dominated by irreducible $\gamma\gamma$+bb in the most sensitive categories

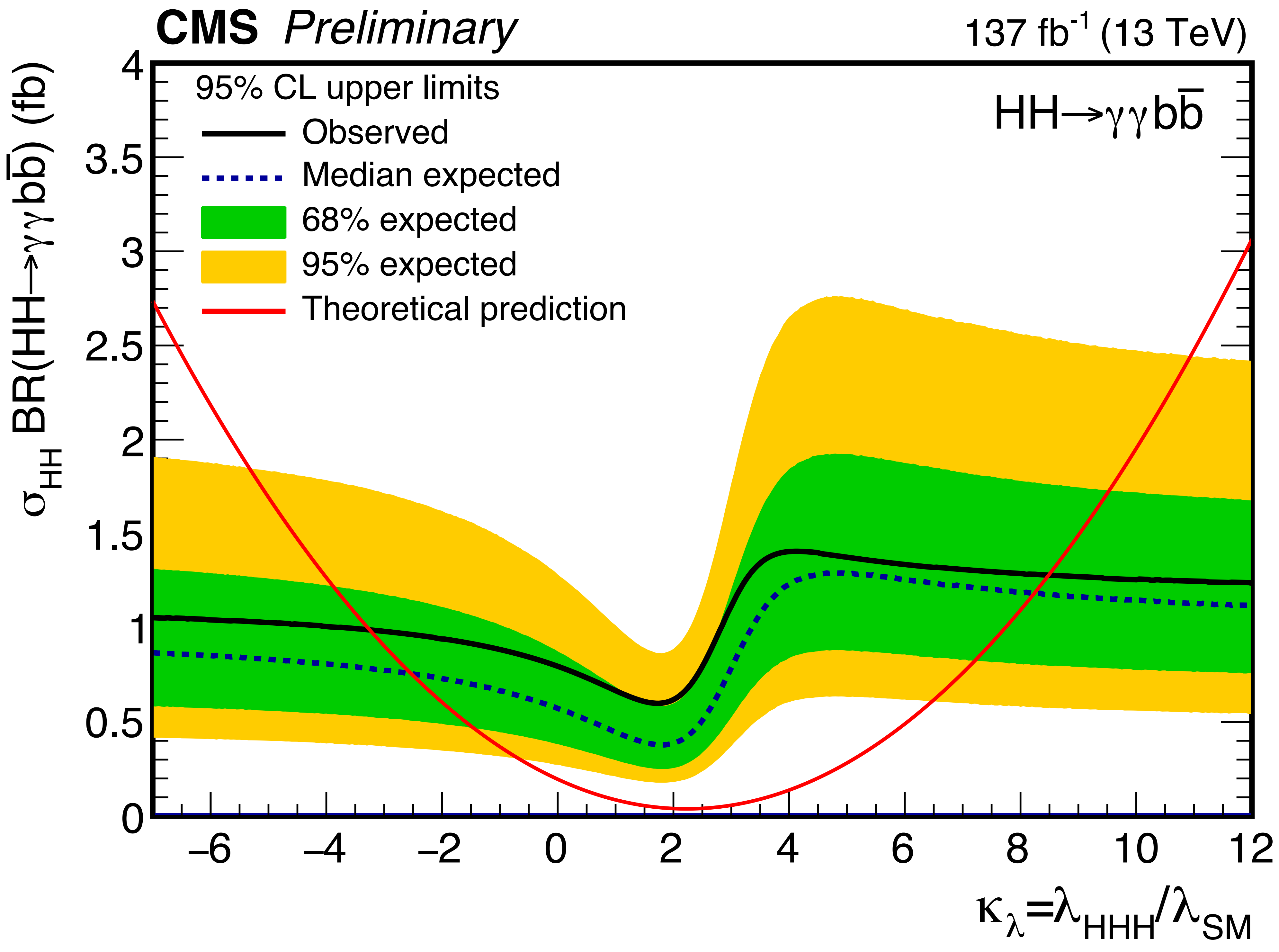
Important contribution from single H

- Signal searched as an excess in the $m_{\gamma\gamma}$ spectrum
  - CMS: 2D fit over $m_{\gamma\gamma}$ and m_{bb}
  - simultaneous fit over all analysis categories
- Results fully dominated by the statistical error

bbγγ : results

Combined constraint from ggF and VBF categories (in CMS)

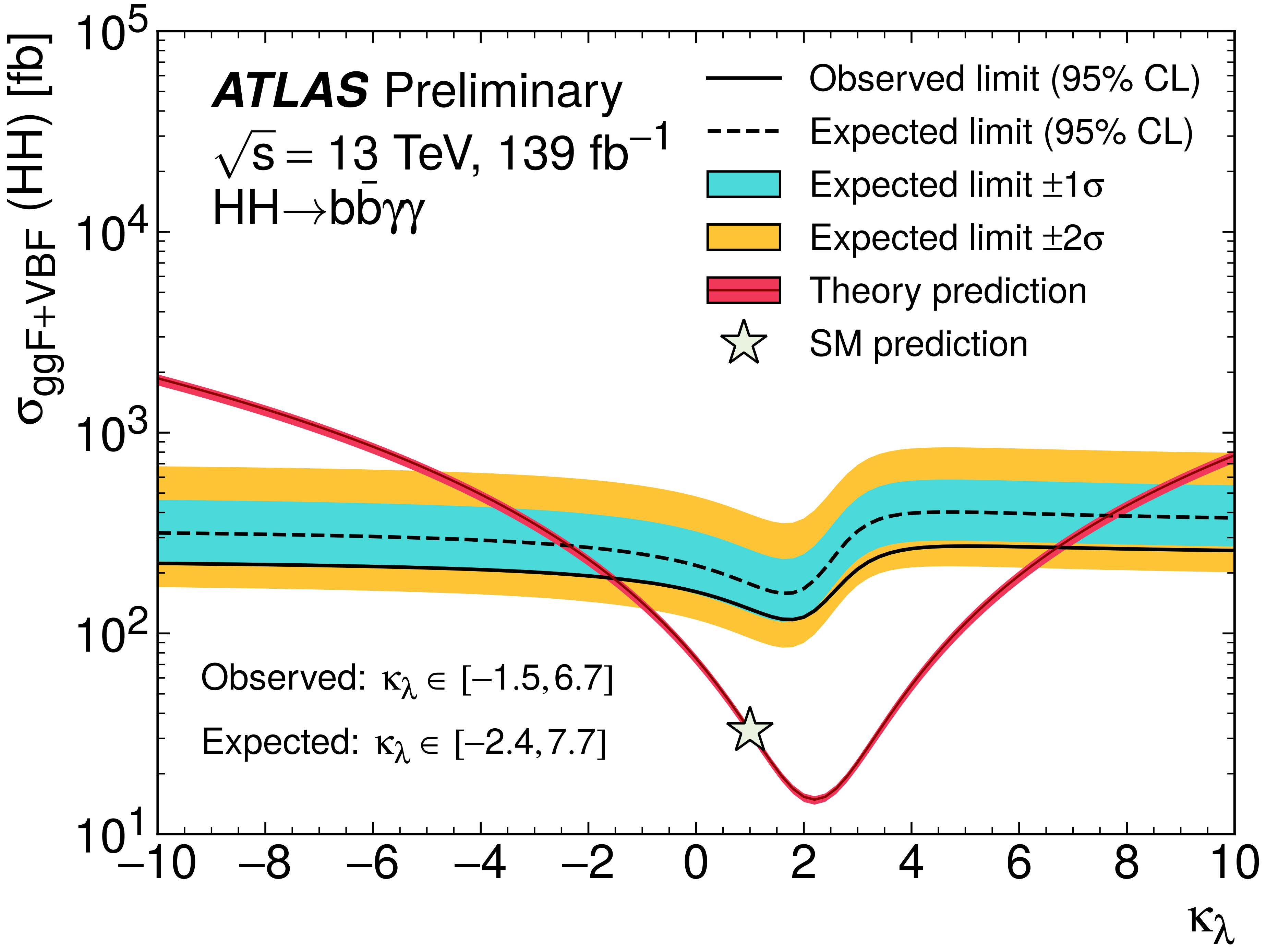
Sensitivity to κλ driven by ggF production



Observed: ***$-3.3 < \kappa_\lambda < 8.5$***

Expected: *$-2.5 < \kappa_\lambda < 8.2$*

Obs. (exp.) 7.7 (5.2) × σ_{SM} (HH)

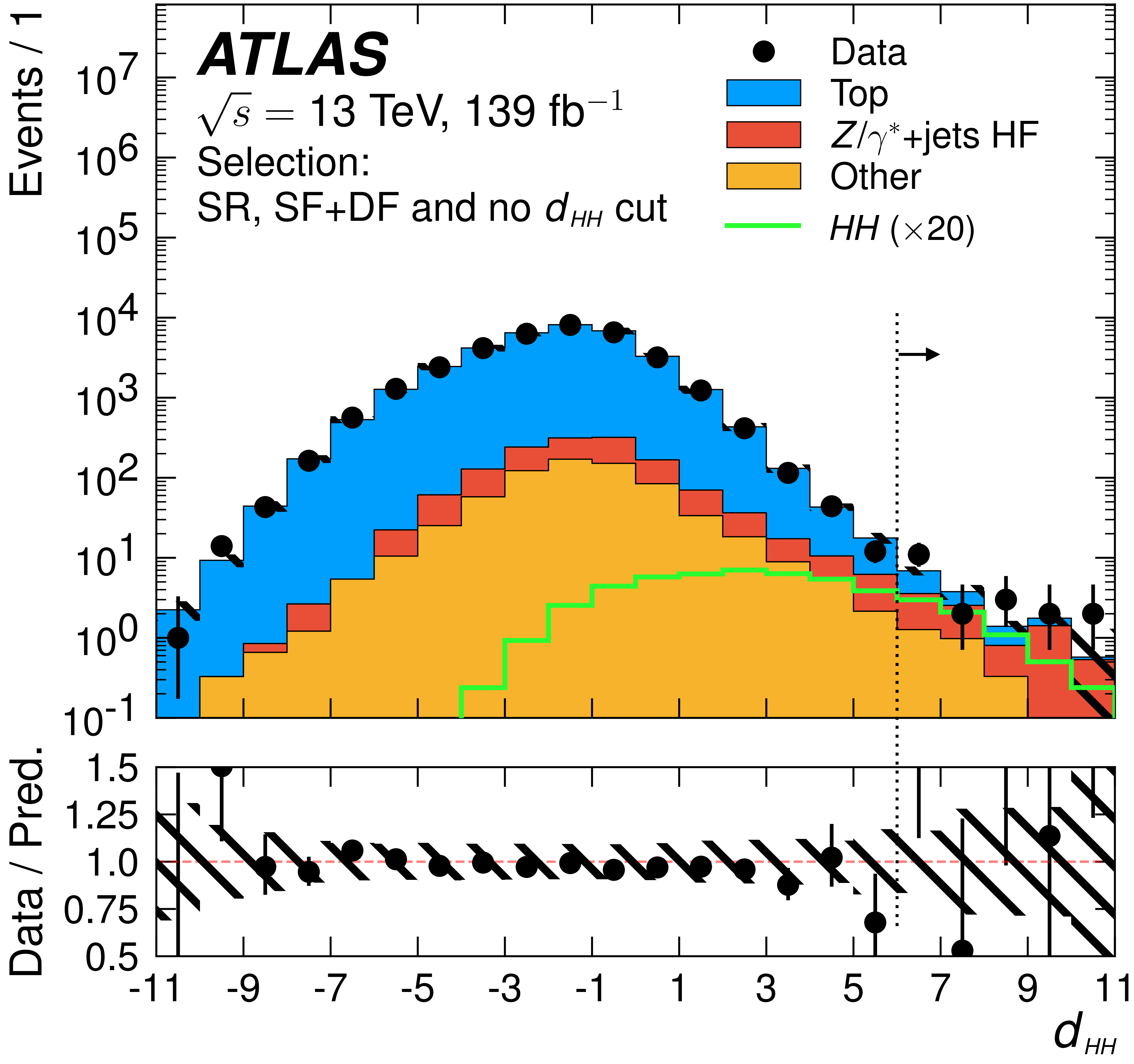


Observed: ***$-1.5 < \kappa_\lambda < 6.7$***

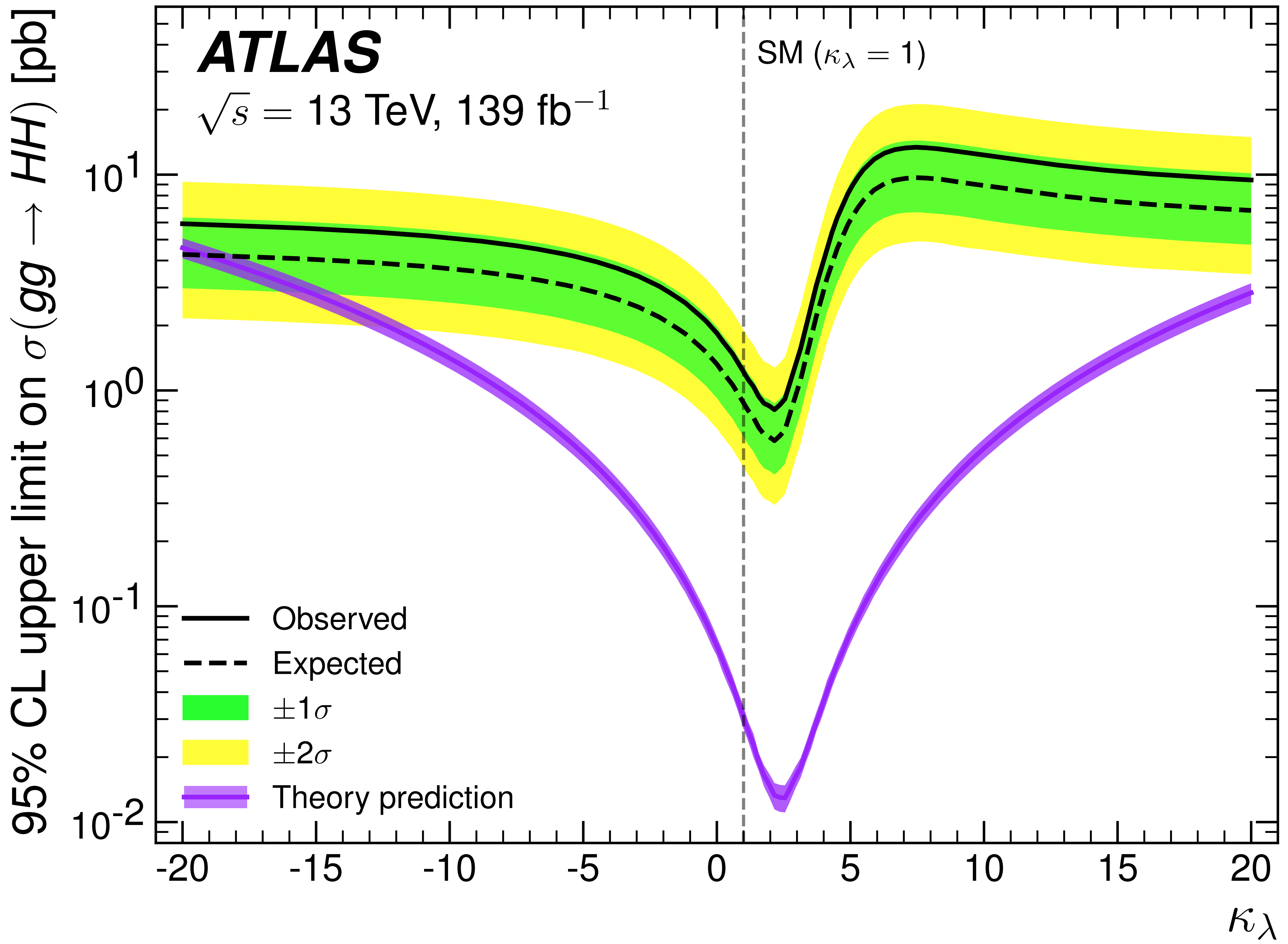
Expected: *$-2.4 < \kappa_\lambda < 7.7$*

Obs. (exp.) 4.1 (5.5) × σ_{SM} (HH)

HH → bbWW



- Fully leptonic WW→$\ell\nu\ell\nu$ final state
- Irreducible ttbar background suppressed with ML methods
  - kinematic inputs: mass, p_T, angles, multiplicities, energy sums
- Counting experiment at high NN score

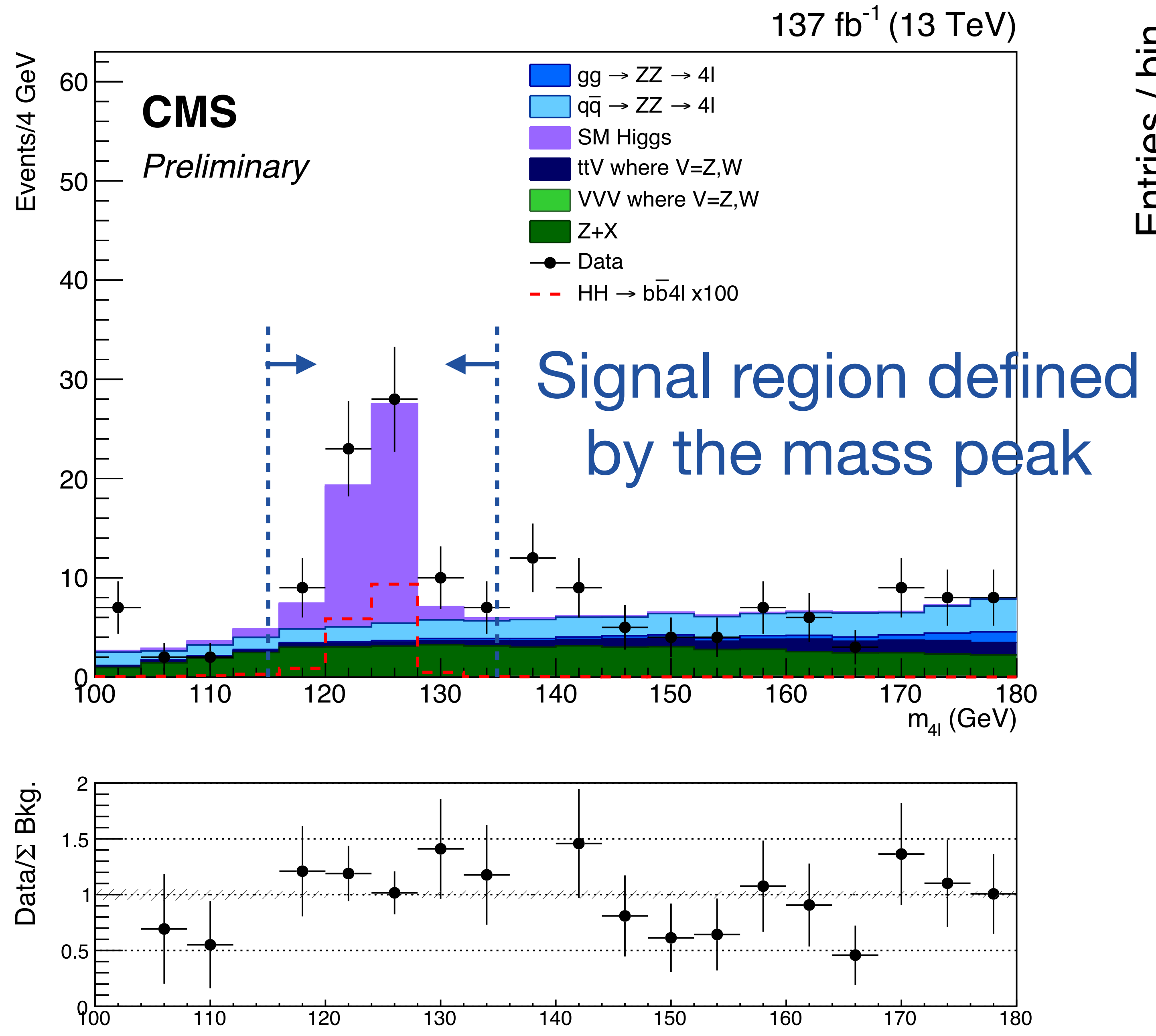


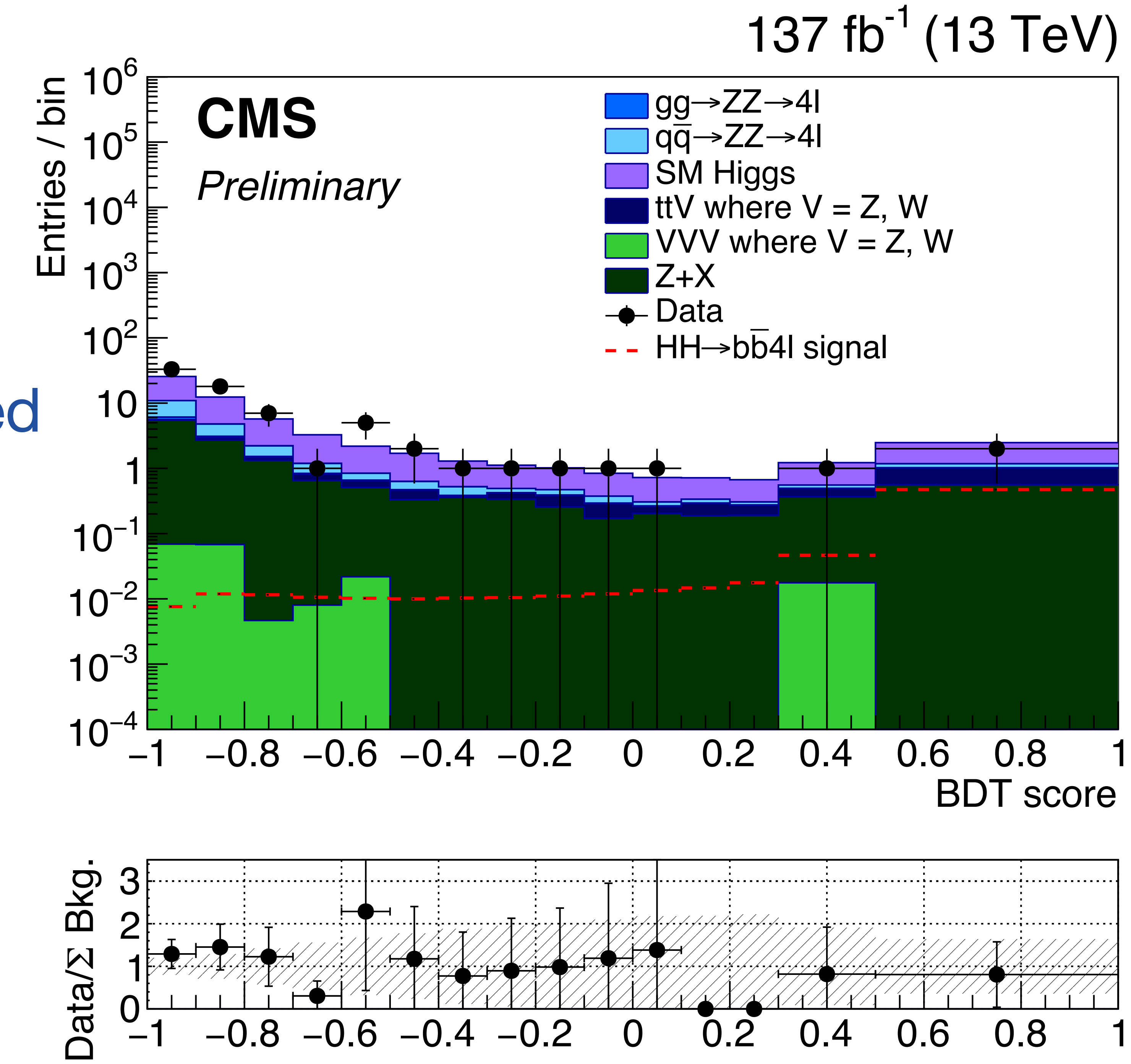
95% CL upper limit:

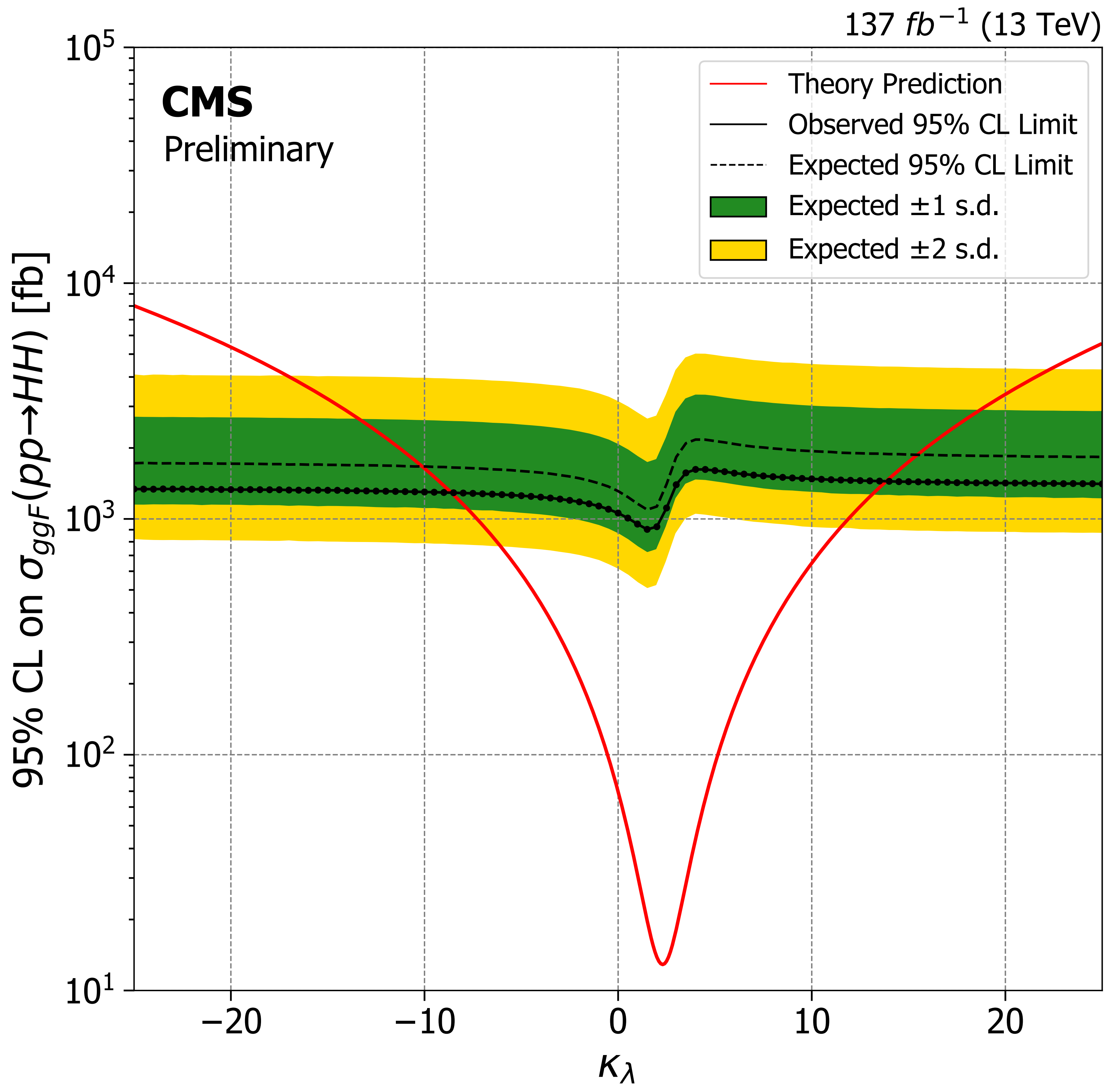
40 (29) × SM

HH → 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



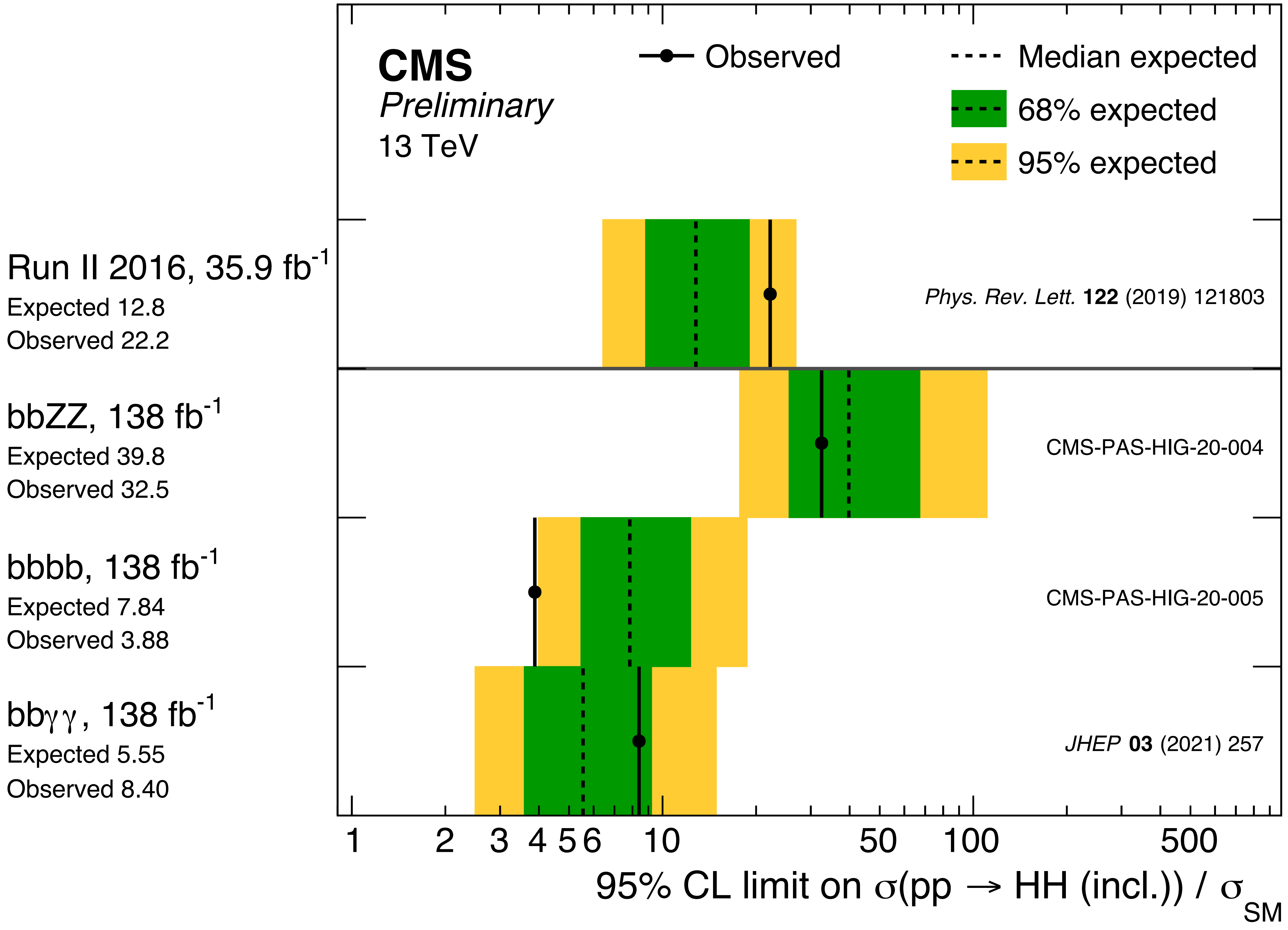


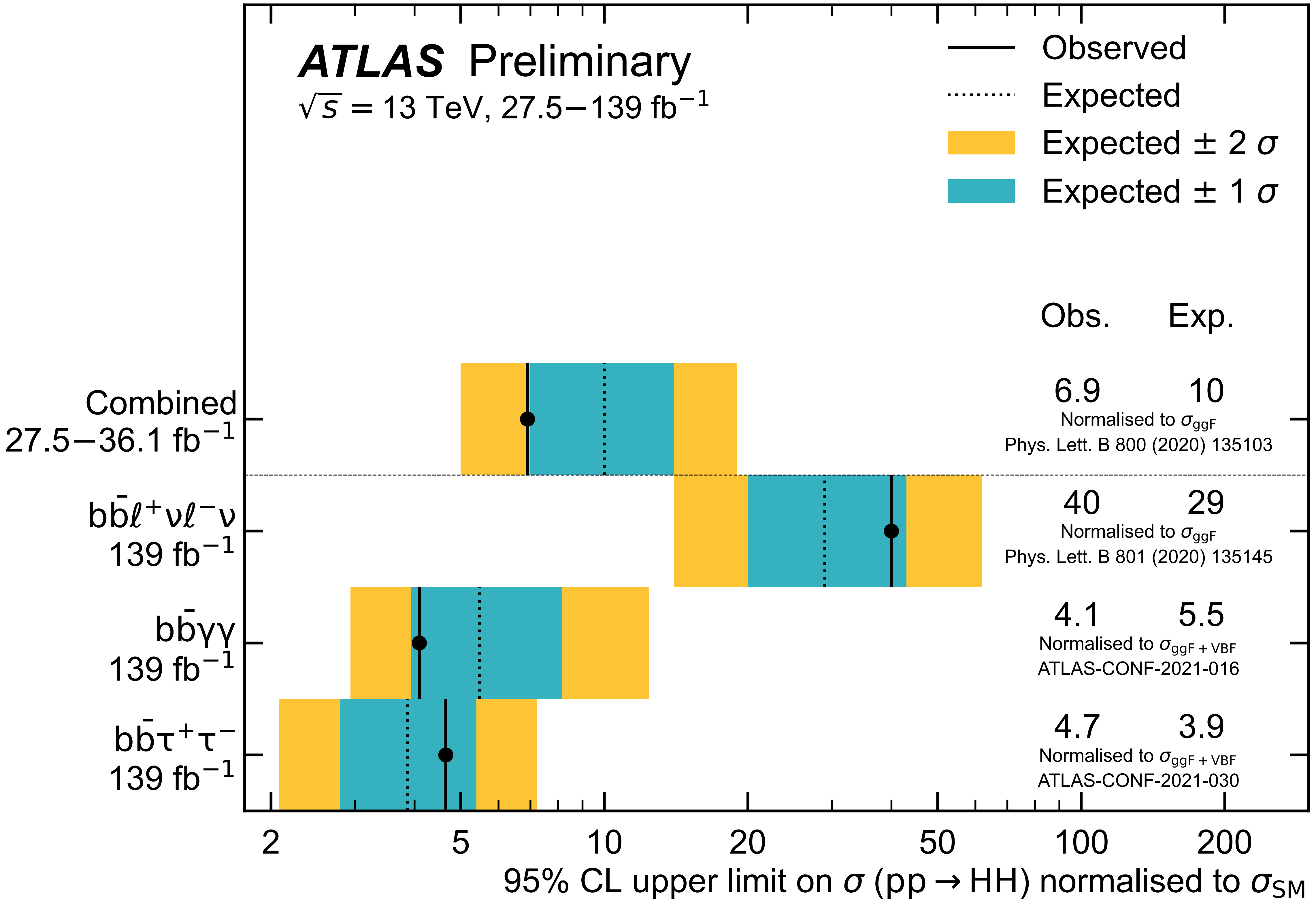


95% CL upper limit: 30 (37) × SM

Observed: –9 < κ_λ < 14

Summary of full Run 2 results





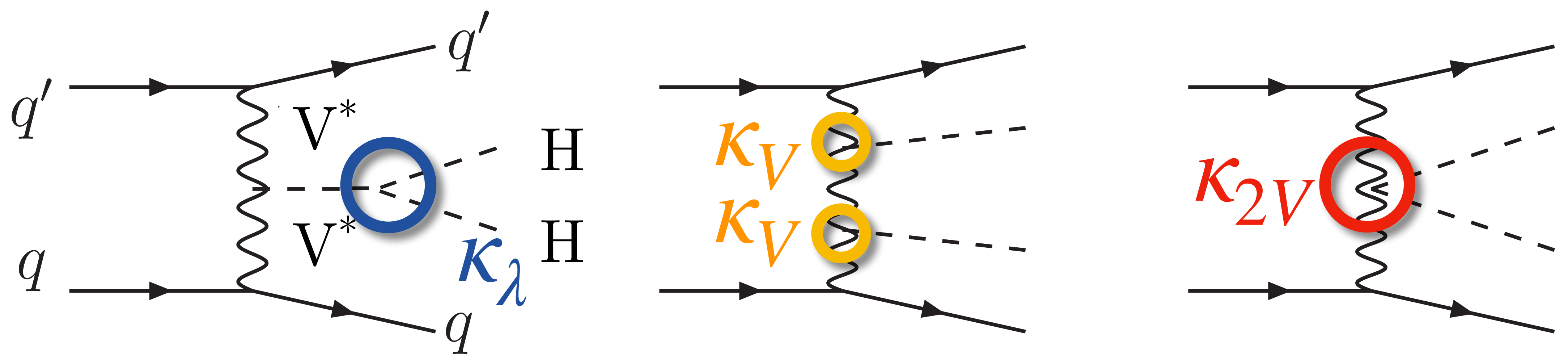
- Individual channels achieve 5-7 × SM : sensitivity improved much faster than luminosity!
  - more data → more sophisticated analysis methods

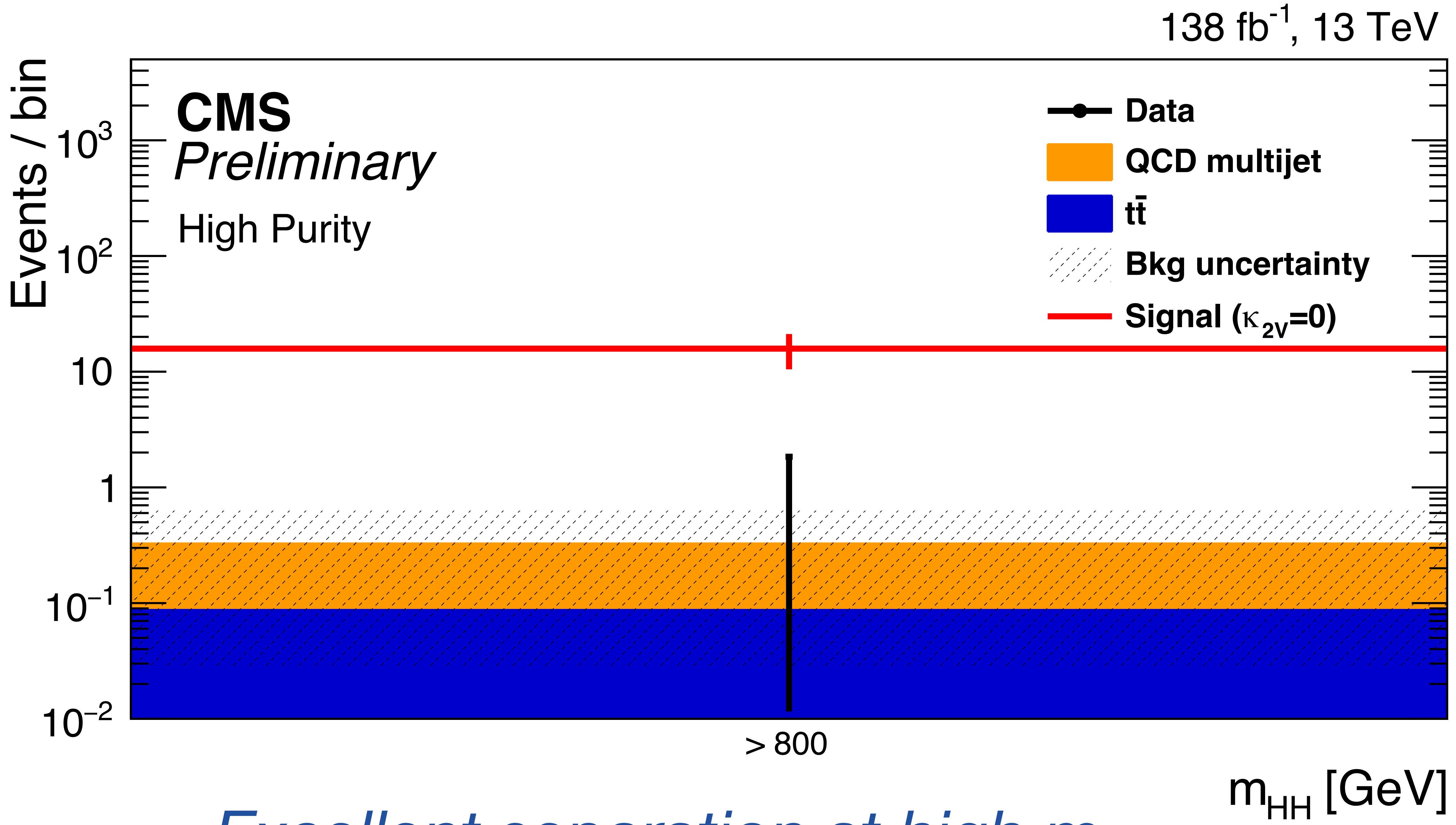
Excellent prospects for the Run 2 combination

Probing the VVHH vertex

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

  Highly sensitive to anomalous κ_{2V} !
  - O(1) κ_{2V} variation → O(10) xs increase
  - large fraction of anomalous κ_{2V} signal at high m_{HH}
    → dedicated search with boosted topologies in bbbb
- VBF HH(bbbb) : 2 AK8 (large radius) jets + 2 AK4
  - select $p_T(H)$ > 400/500 GeV
  - dedicated ParticleNet discriminant D_{bb} to identify the bb candidates
  - 3 purity categories based on D_{bb}
  - m_{bb} reconstructed with DNN regression and used to define SR

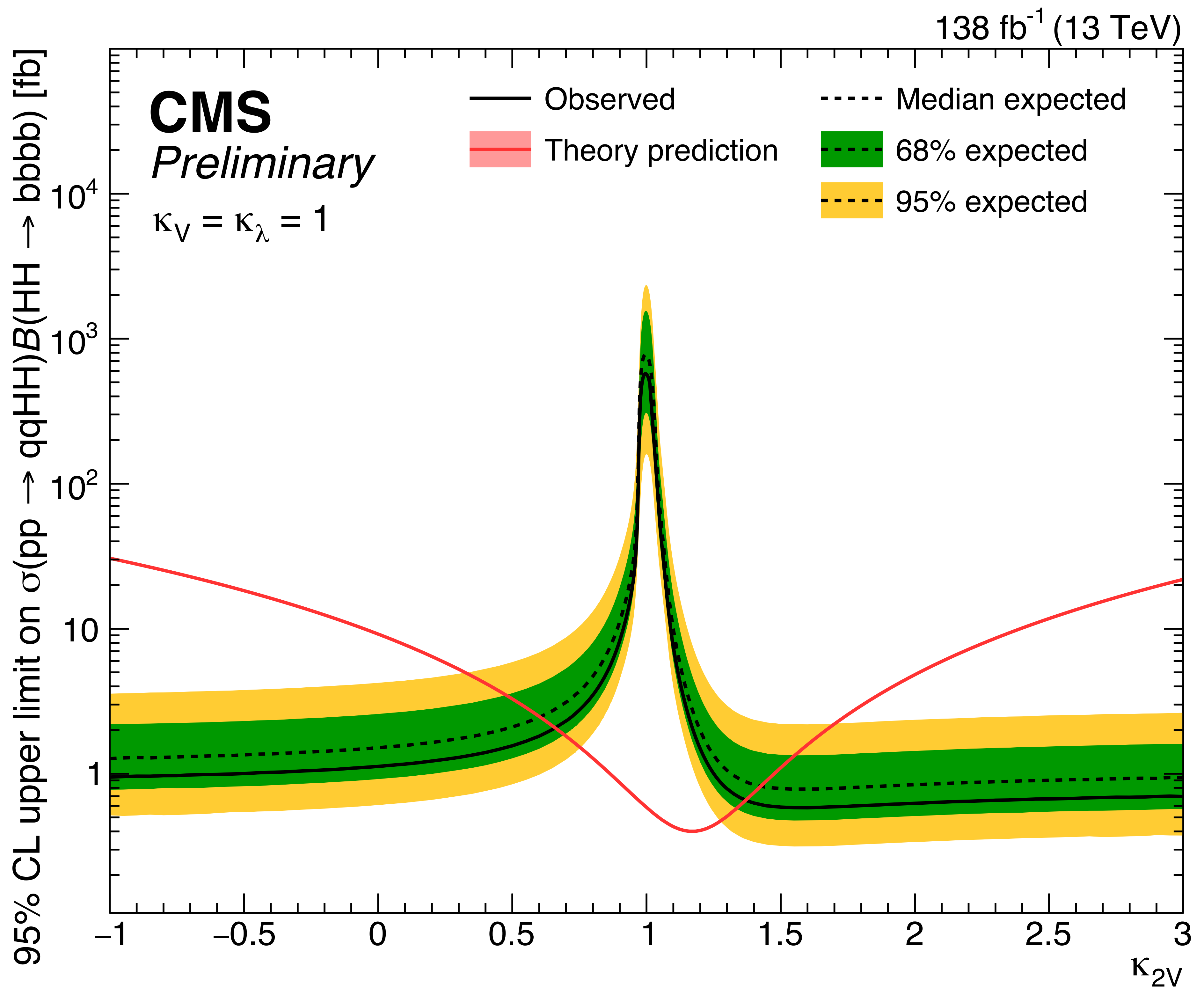


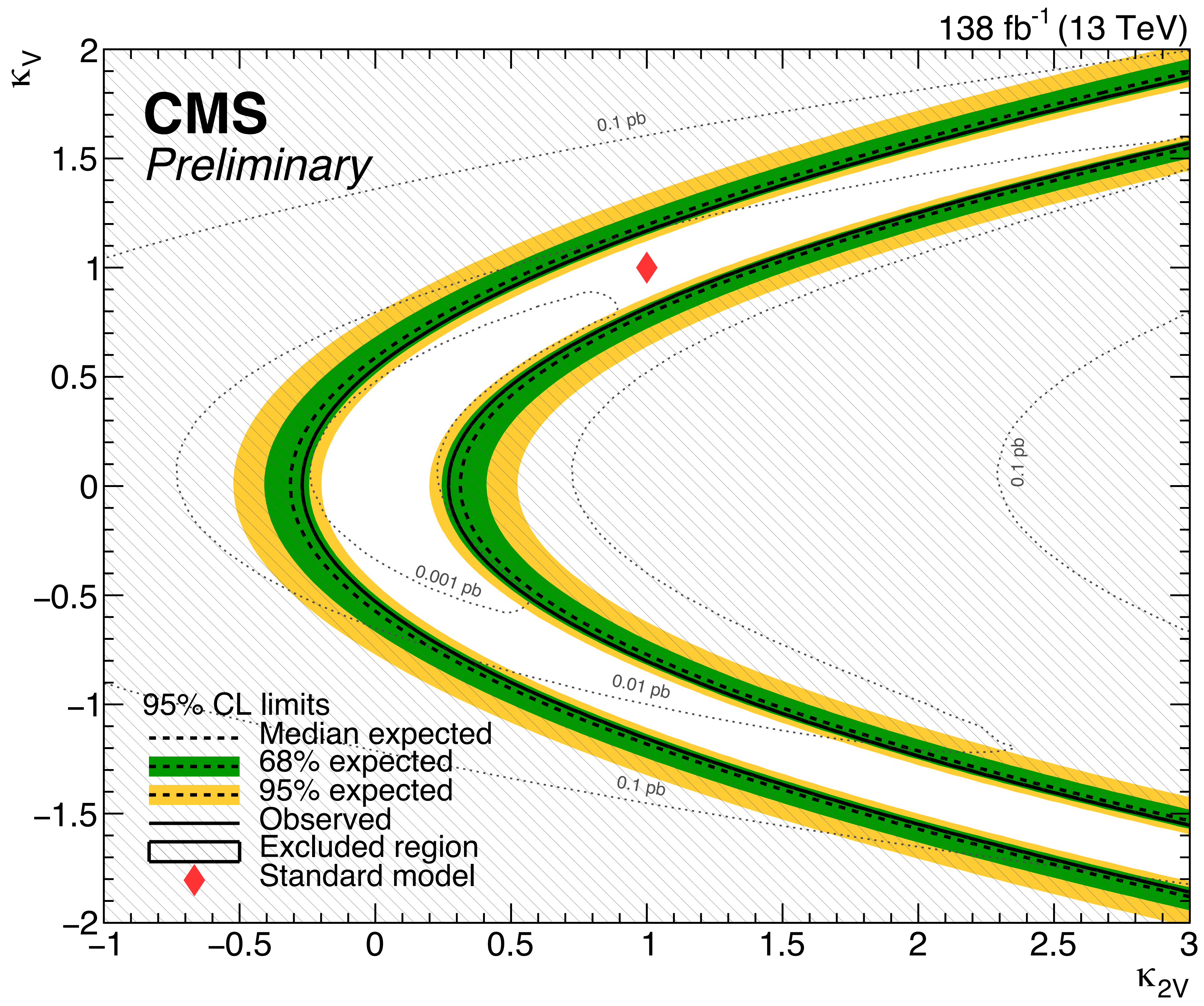


Exploit HH→bbbb at high m_{HH} with dedicated boosted analysis methods

Excellent separation at high m_{HH} leading to good S/B ratio

VBF HH at high m_{HH} : results





- Other full Run 2 VBF results set in $bb\gamma\gamma$ (CMS) and bbbb (CMS, VBF-only ATLAS analysis)

*Observed: **0.6 < κ_{2V} < 1.4***

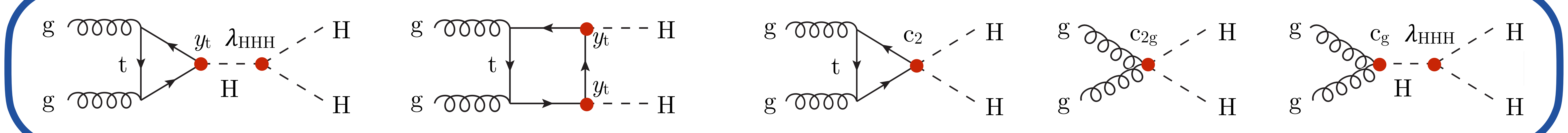
Interplay between κ_{2V} and κ_V

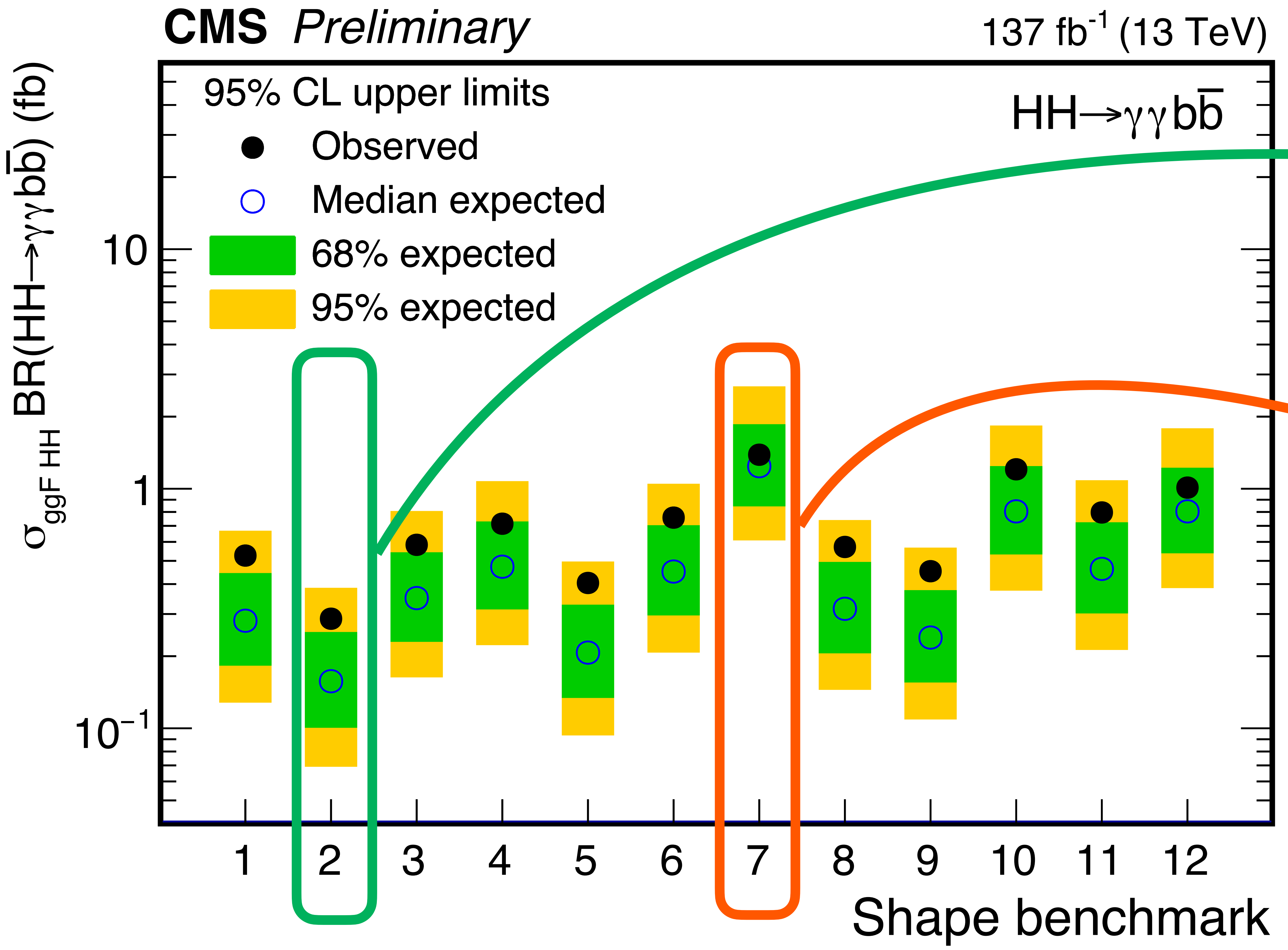
*Best sensitivity to SM production from resolved CMS analysis : **226** (412) × SM*

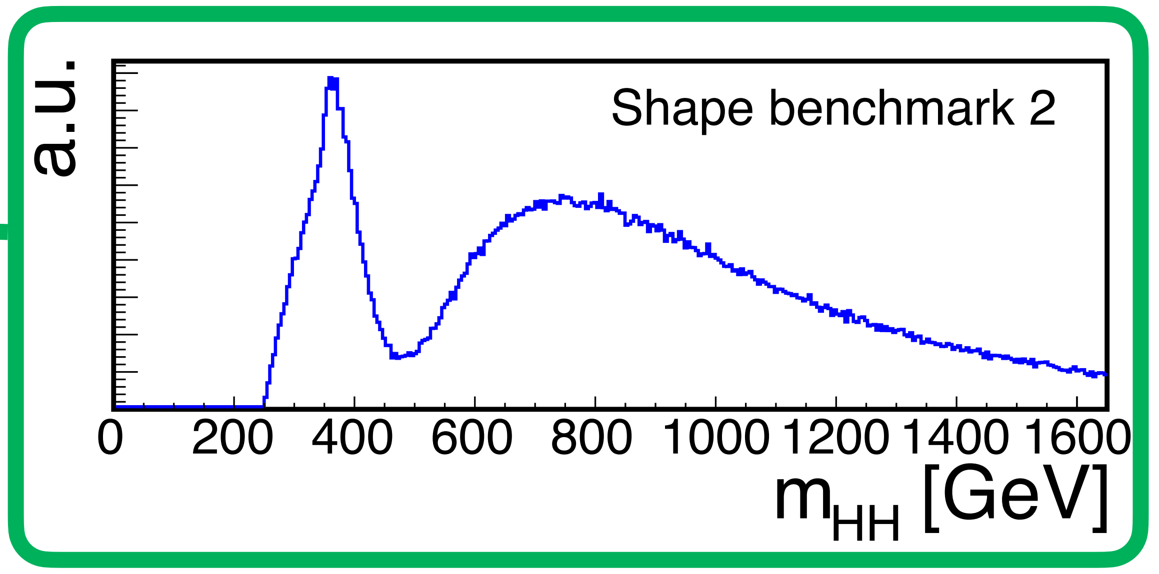
Combination with single H measurements can solve this → we can claim that the VVHH interaction exists!

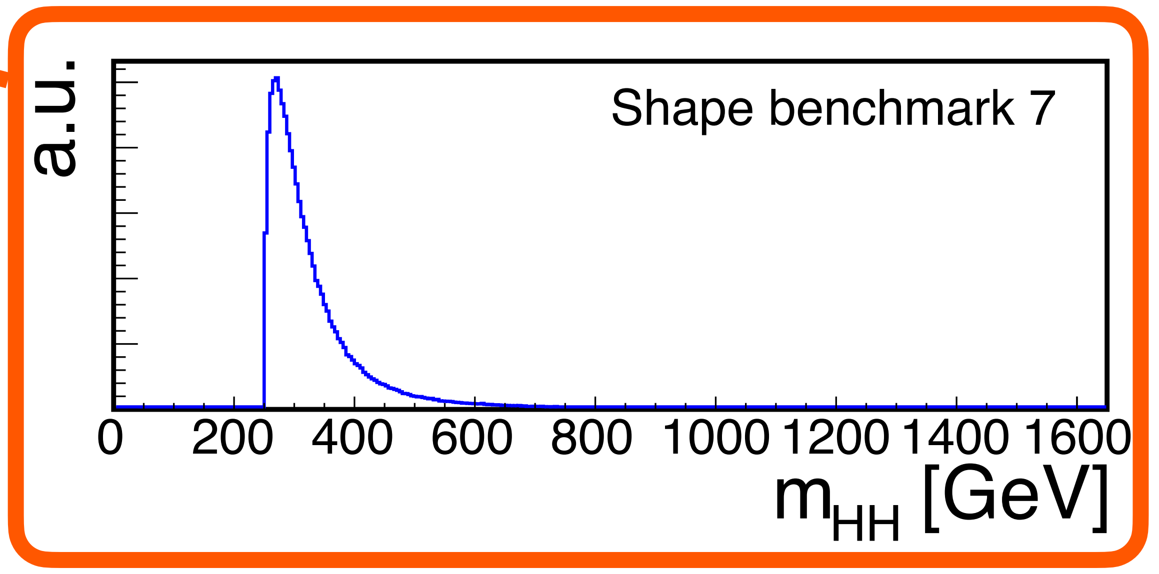
A broader BSM picture

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





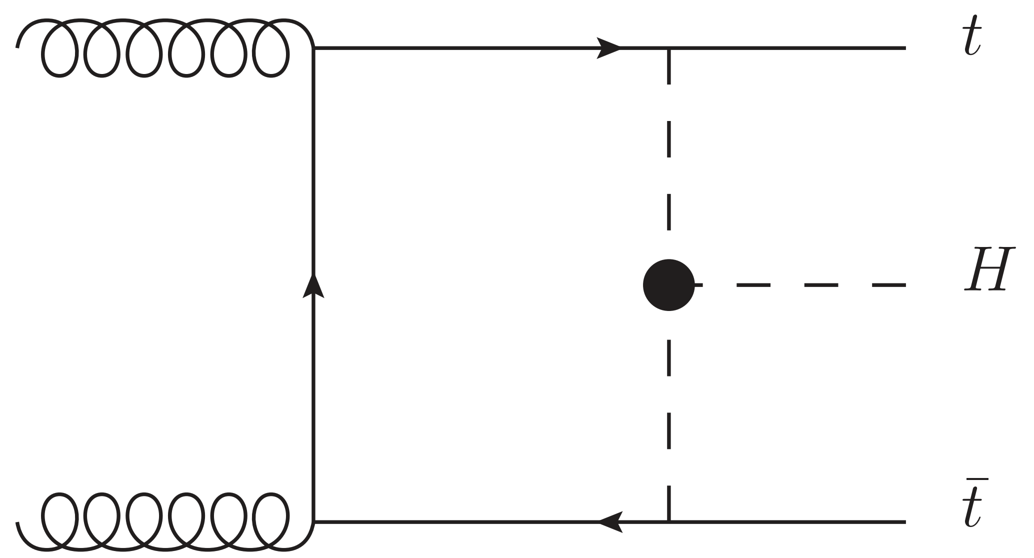




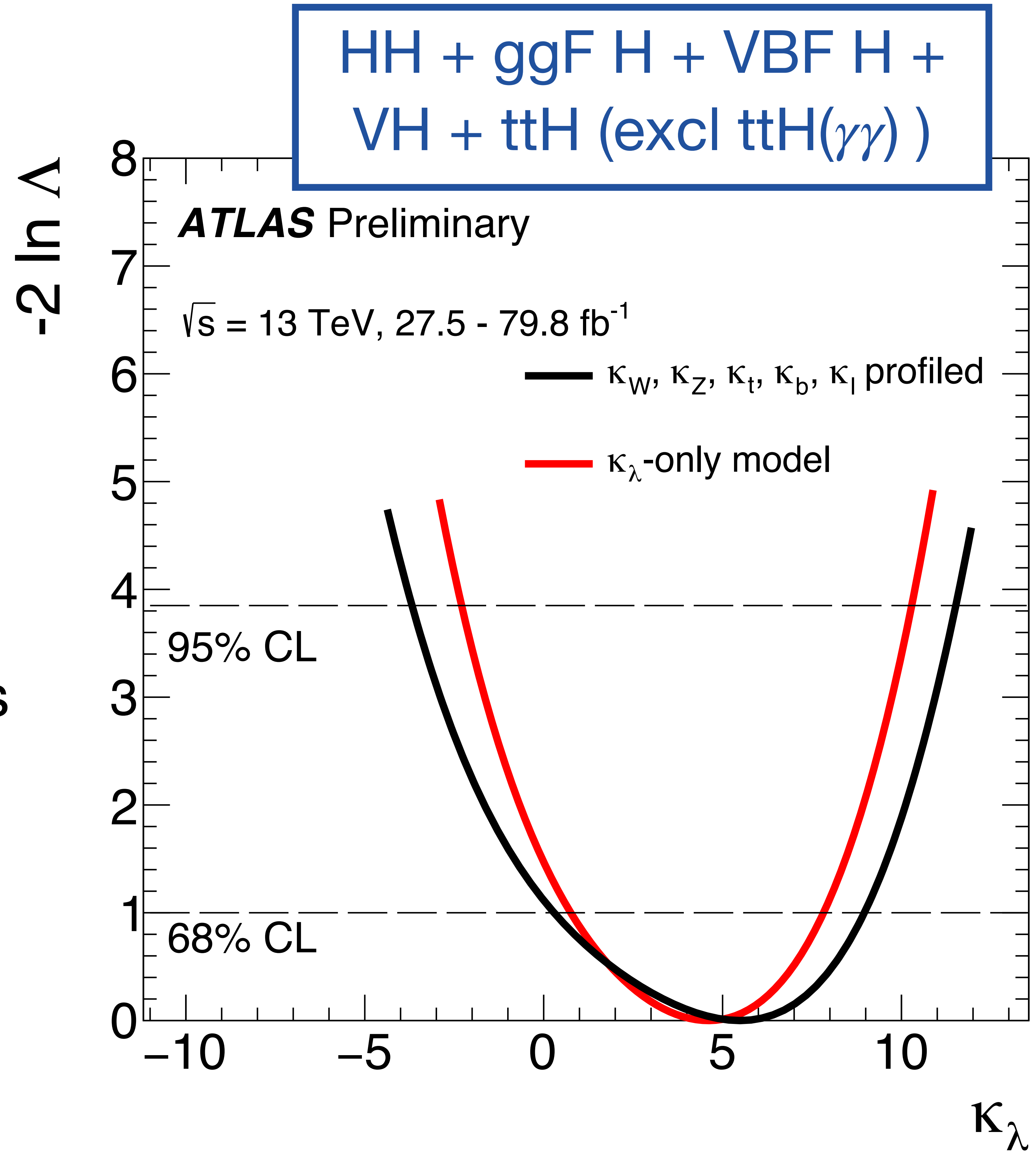
- 5D parameter space, contact interactions, large kinematic modifications
  - probed with representative signal shape benchmarks
- EFT effects become more important as the experimental sensitivity approaches the SM

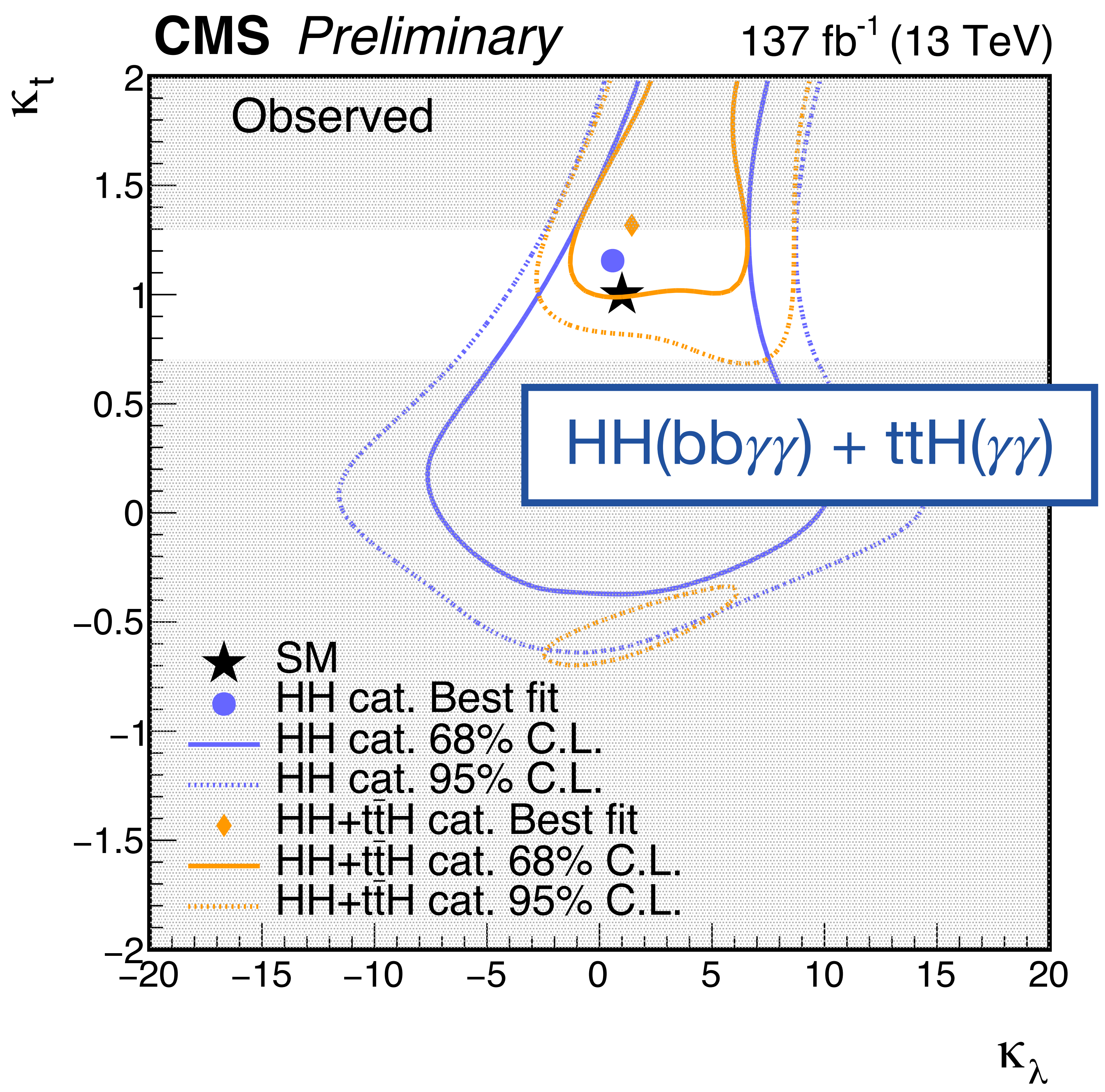
HH as a probe of high energy BSM effects | **Full EFT fit as the next step**

H + HH: combined κλ constraints



- Sensitivity to κλ from loop effects
  - total xs and BR depend on κλ
  - information from differential xs
  - note: NLO (H) vs LO (HH) κλ effects
- ~20% improvement in sensitivity to λ_{HHH} when adding all single H measurements
- Combination with single H reduces degeneracies with κ_t

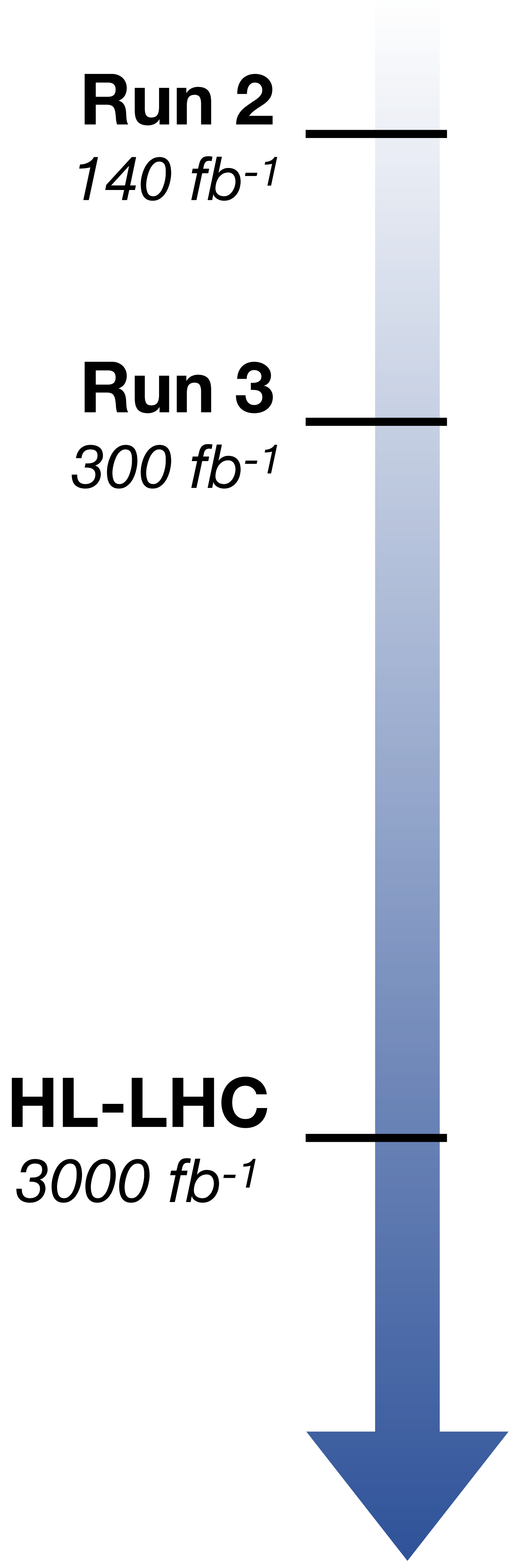




HH : key input for a combined Higgs measurement | **Need a solid theoretical framework**

5^{th} CERN Yellow Report
DOI : 10.23731/CYRM-2019-007

Which prospects for HH?



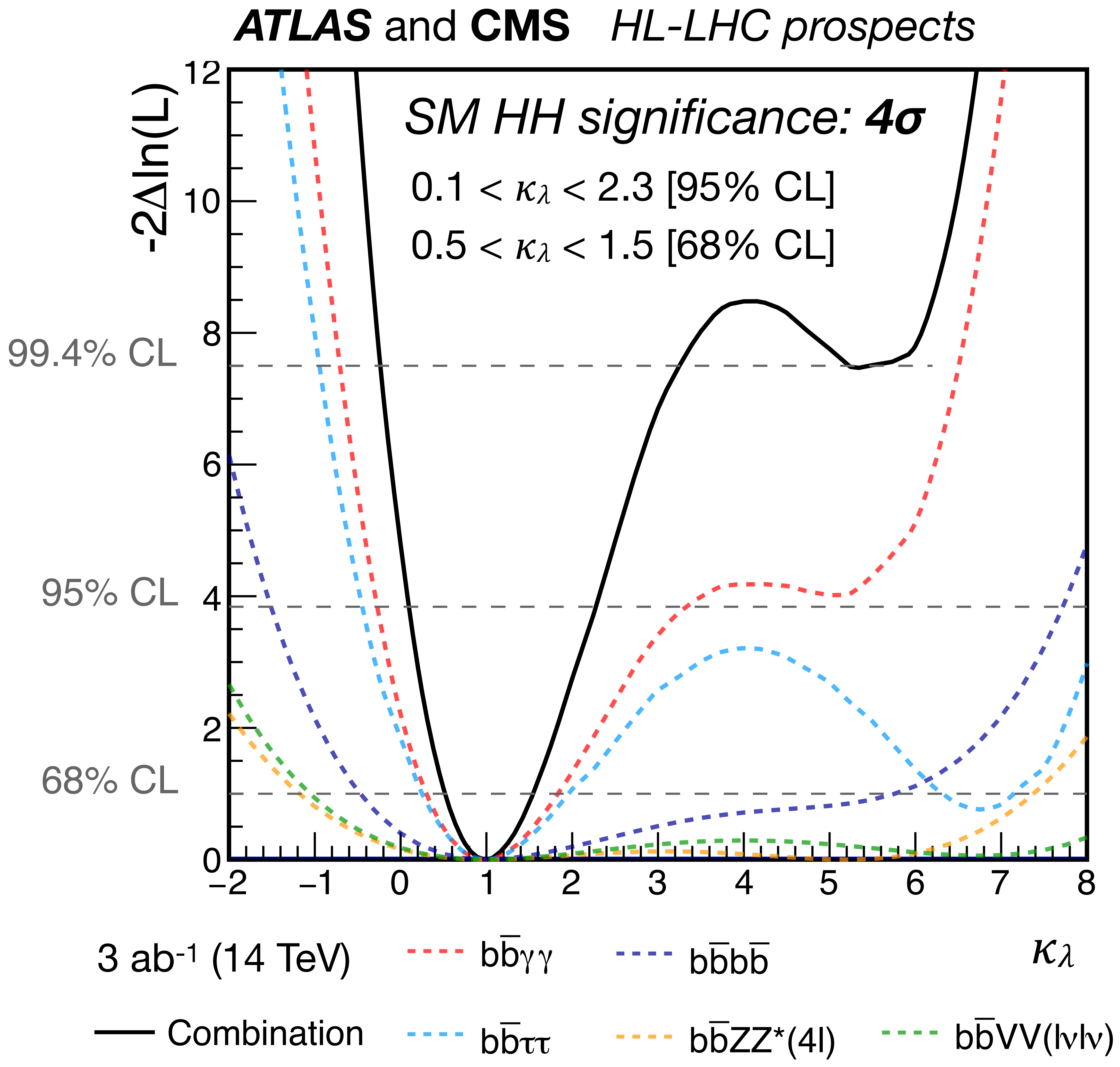
2-3 × SM sensitivity by each experiment

O(1) × SM sensitivity with ATLAS + CMS
Close to a evidence for HH production?

Observation of HH production
50% or better constraint of κ_λ

NOTE: Run 2 results quickly improving (better techniques, more sophisticated analyses)

Projections are likely conservative

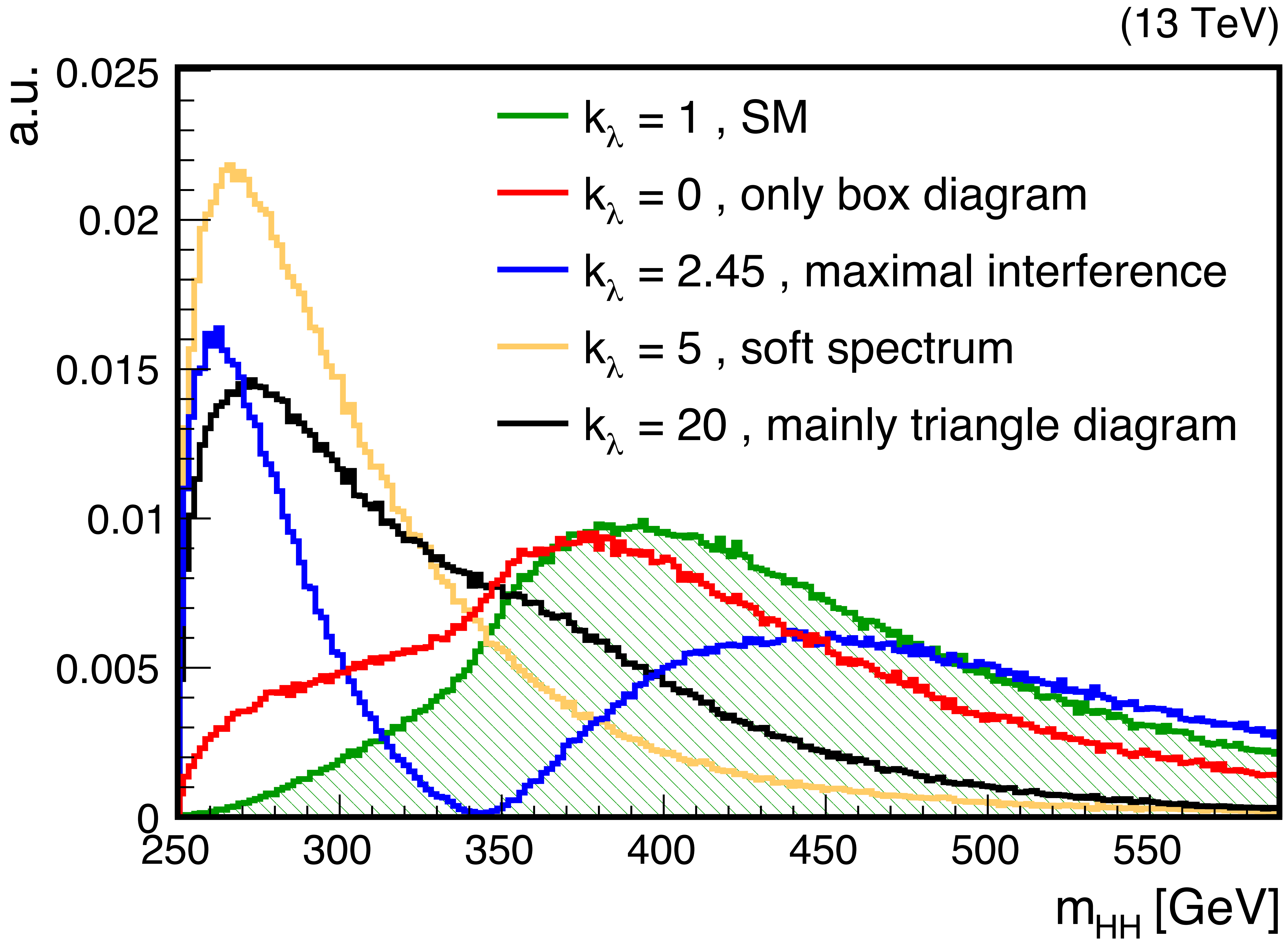


Conclusions

- ATLAS and CMS are conducting a broad program of exploration of HH physics
  - SM HH search and self-coupling determination
  - BSM effects in nonresonant production: VVHH vertex, anomalous couplings
- Full Run 2 results are now becoming public
  - largely improve over the previous 2016 results beyond lumi scaling
  - the large dataset enables the exploration of rare channels (e.g. bbZZ(4l))
- We are approaching a combined sensitivity of about 2-3 $\times\ \sigma^{SM}$
  - high-energy BSM effects become relevant $\Longrightarrow$ motivates the study of a global EFT approach
  - beneficial for the combined interpretation of single and double H measurements
- HH as a topic for HL-LHC only? Not really!
  - a lot of interesting results in the Run 2 dataset
  - more channels and more production modes to explore in the Run 3 dataset

Additional material

ggF HH production mode

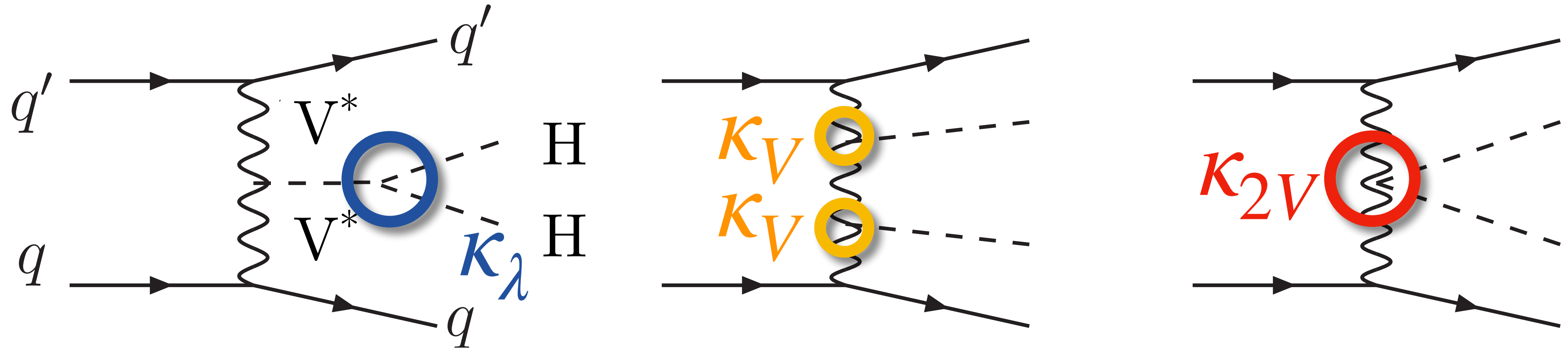


- Strong dependence of the m_{HH} distribution on κ_λ
- Challenge for analyses: need optimal performance over a broad range of kinematics

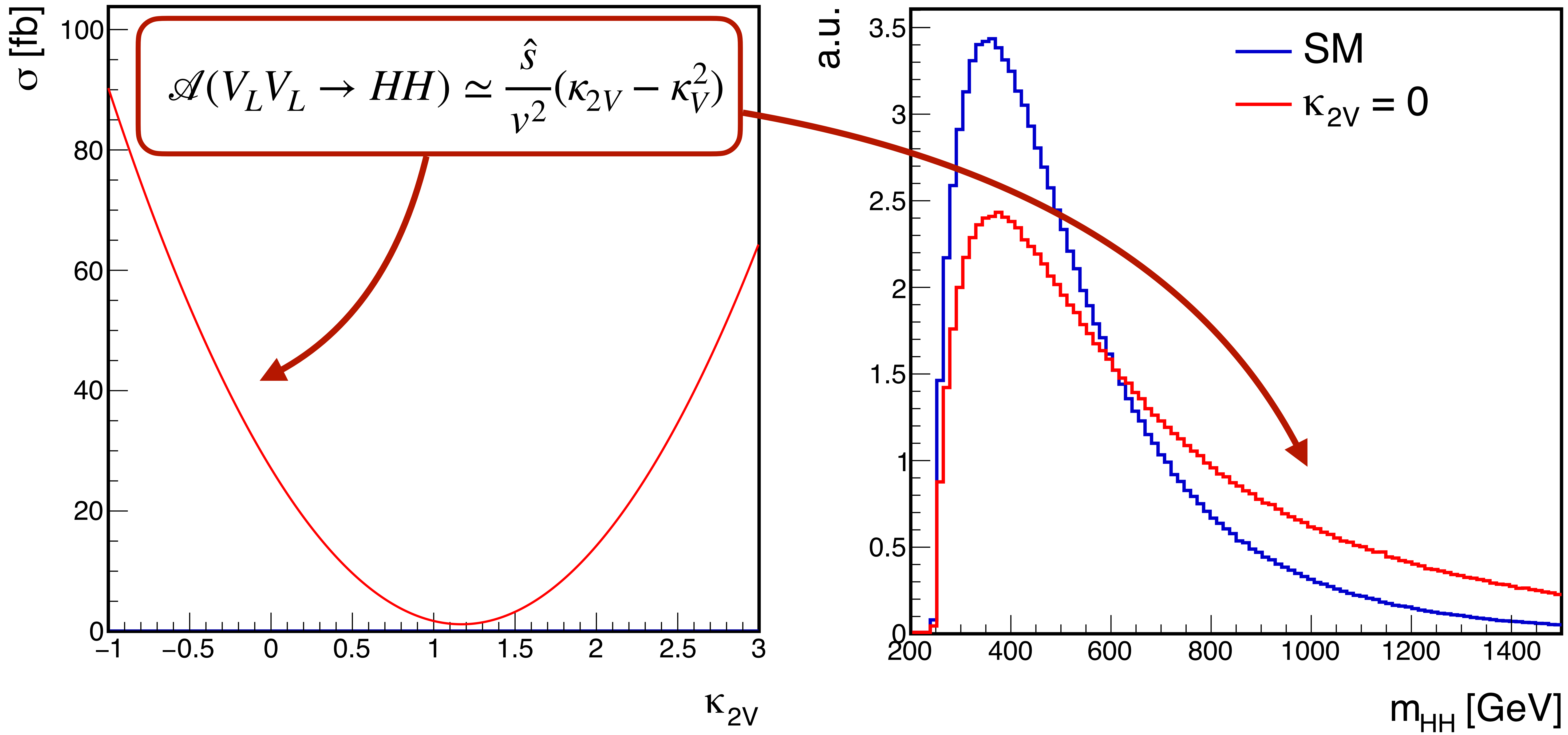
HH production: vector boson fusion

N³LO QCD
PRD 98, 114016 (2018)

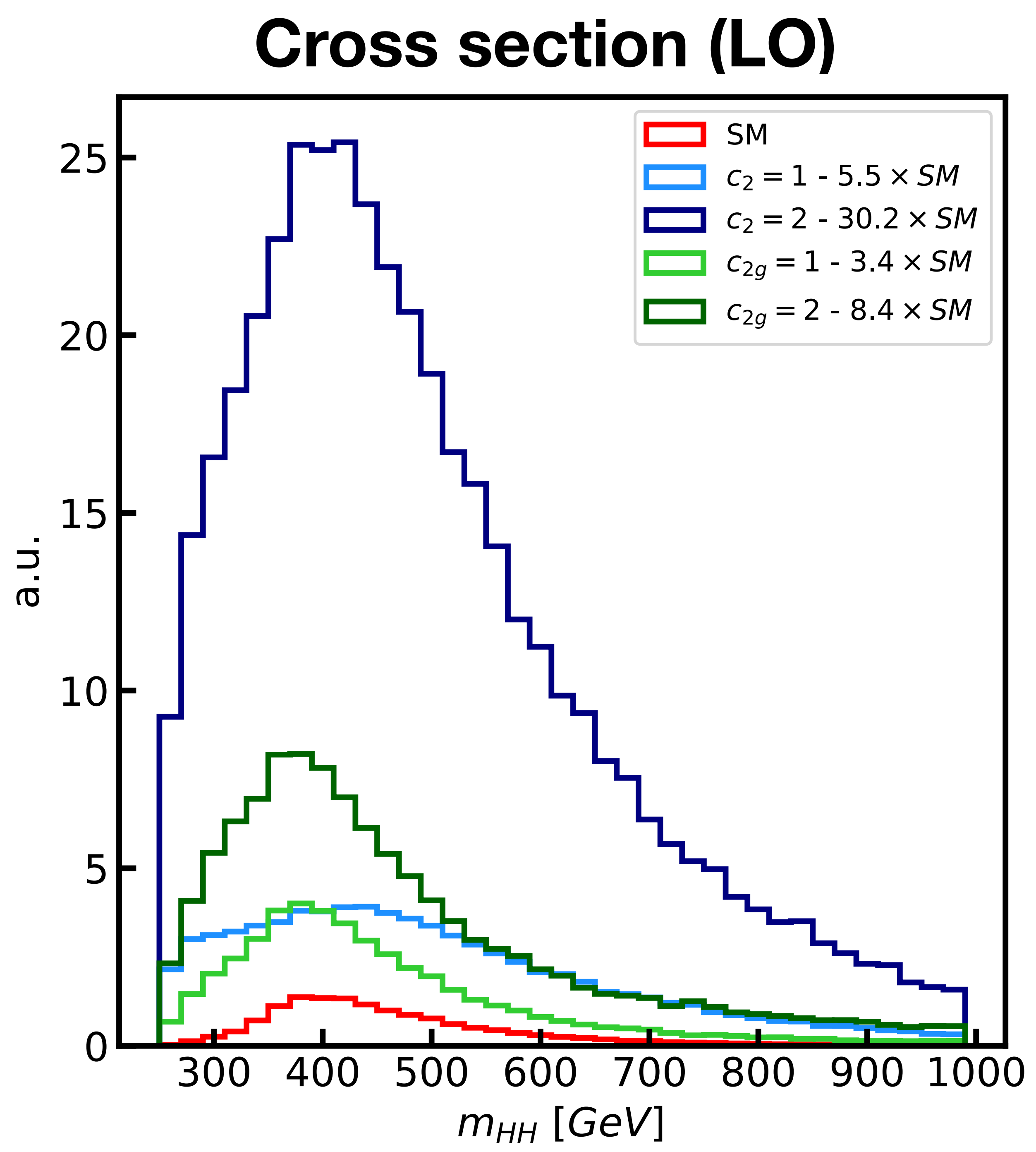
$$\sigma^{SM}_{VBF} = 1.73\ \text{fb} \pm 2.1\ \%\ \ (13\ \text{TeV})$$

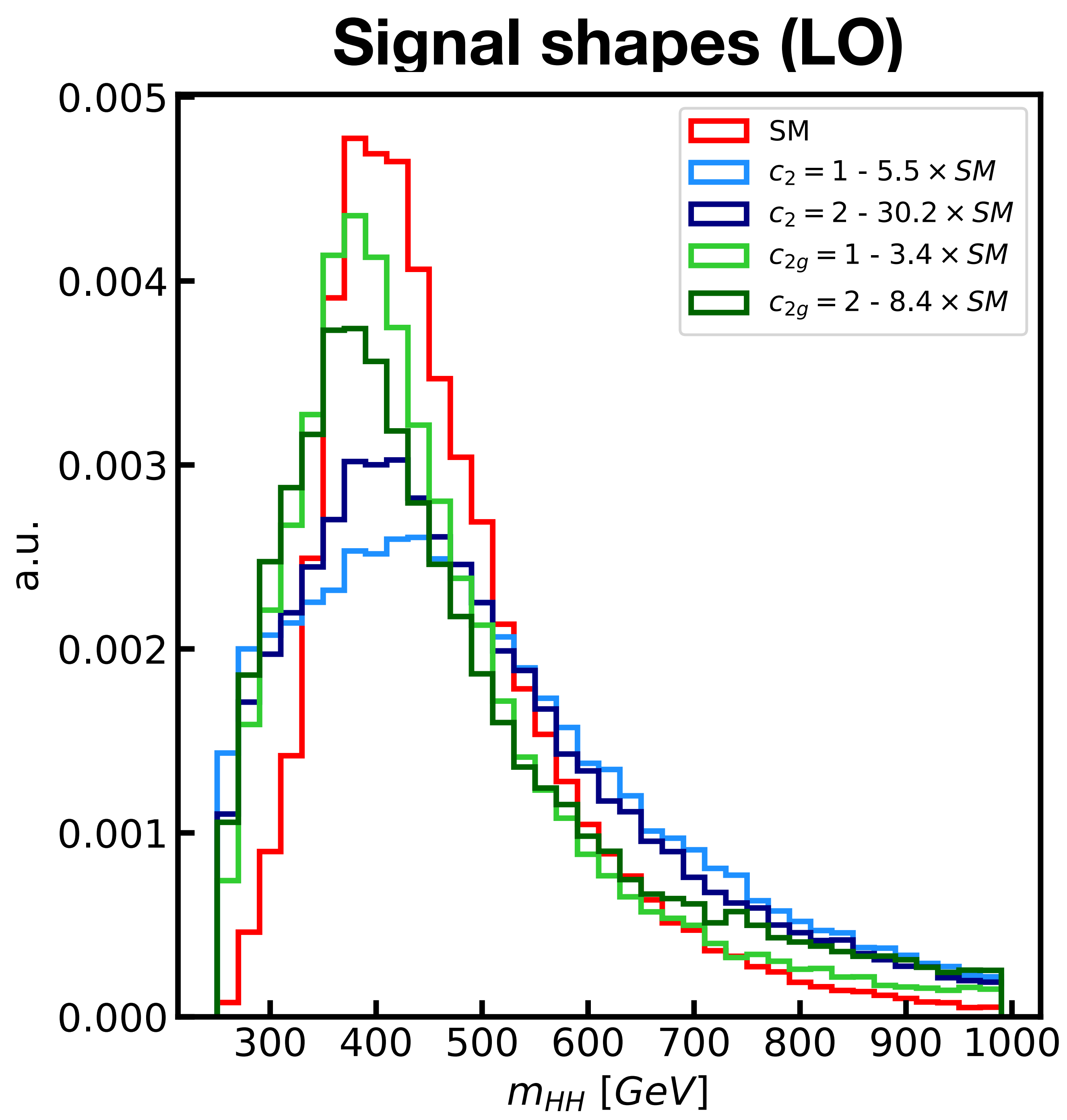


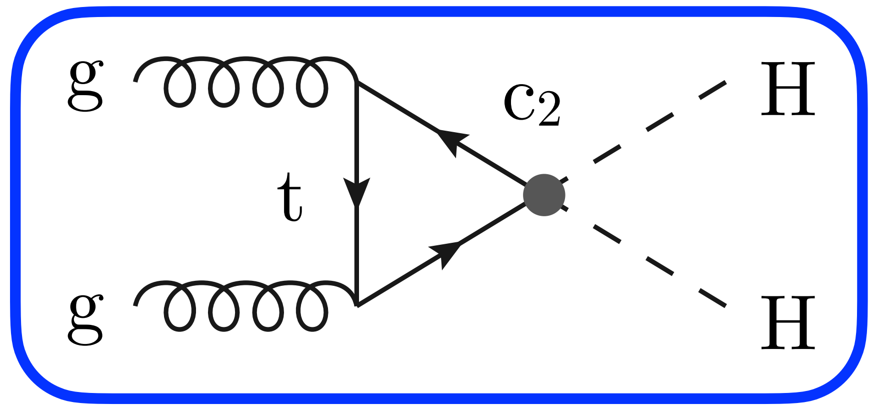
- Very rare production mode
  - moderate sensitivity to λ
- Unique sensitivity to the VVHH interaction
  - $\kappa_{2V} \neq \kappa_V$ in e.g. composite Higgs models
  - longitudinal scattering opens when $\kappa_{2V} \neq \kappa_V$ → growth of xs at high m_{HH} values

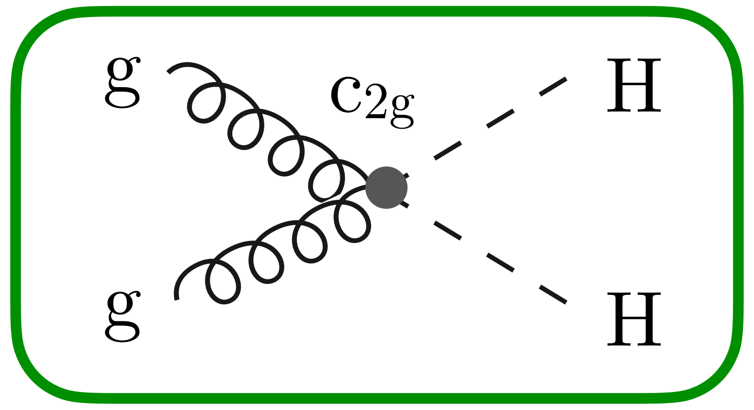


EFT effects in HH









- 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

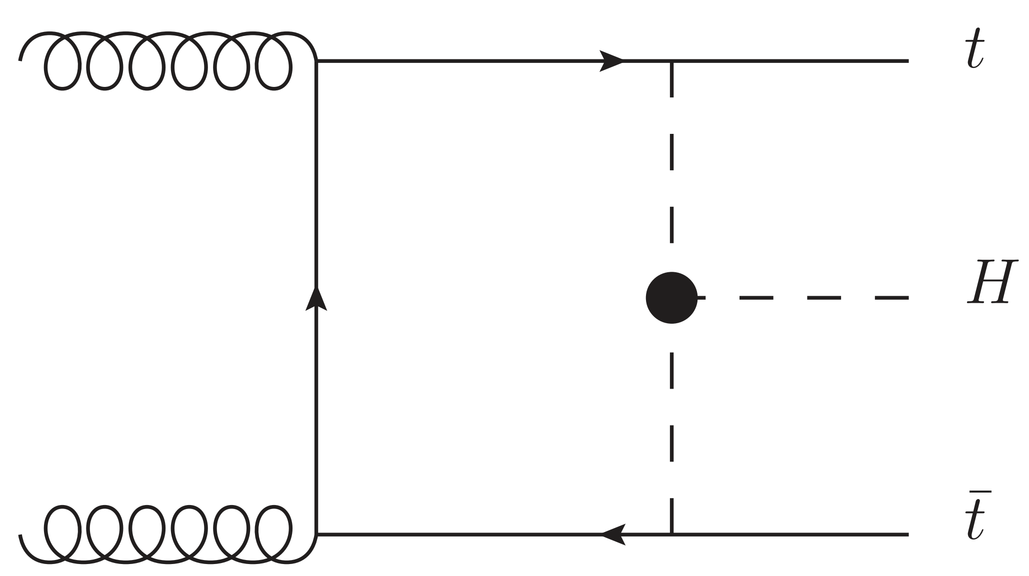
A more generic result needs to account for the effect of other contributions

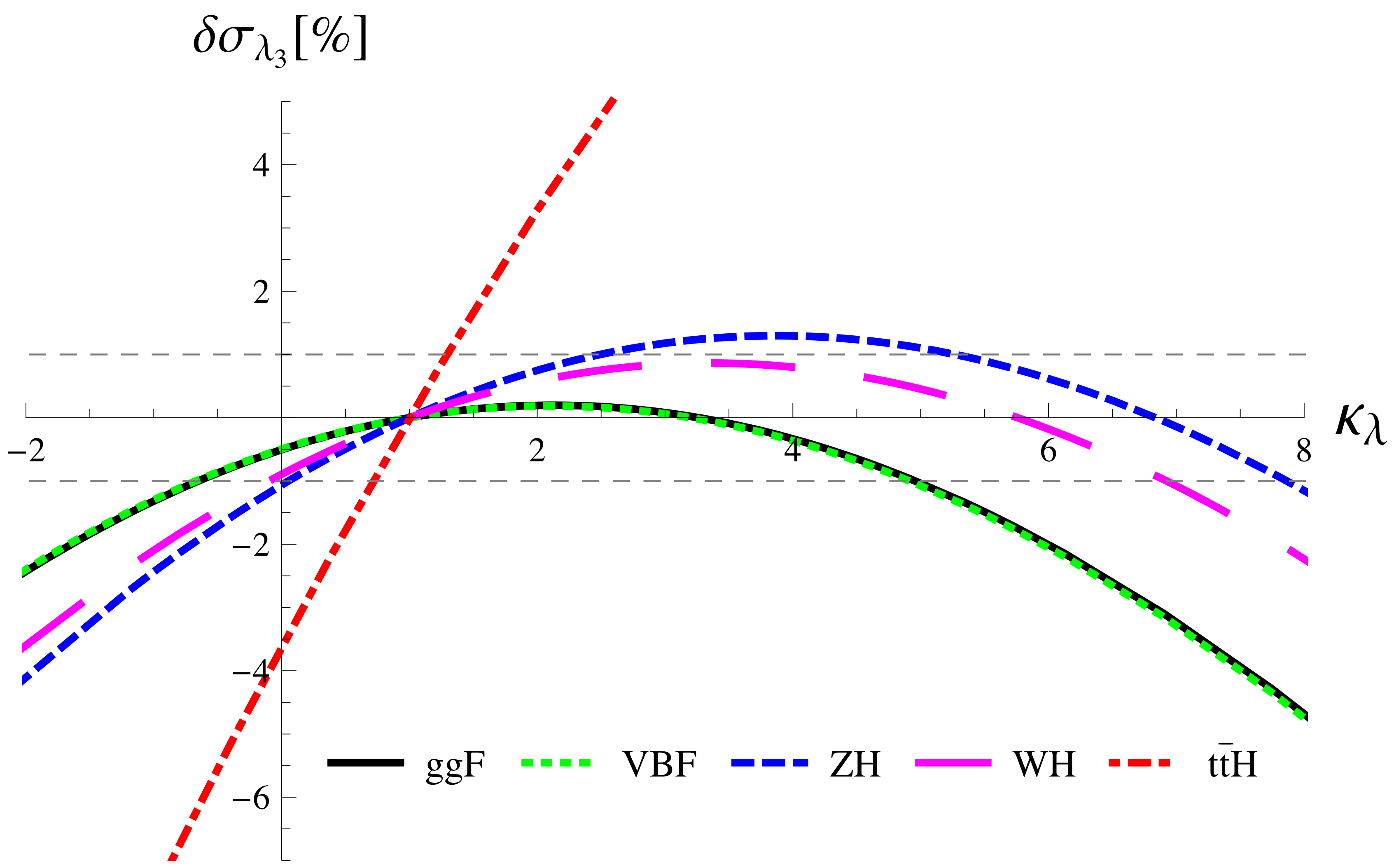
Cross sections of O(1) c_2/c_{2g} are within experimental reach

Loop effects in single H

Single H measurements provide sensitivity to λ from loop effects

- total cross section and BR changes
  - fully used by the experimental results
- differential information
  - limited usage by experiments so far (theory prediction not available in ggF, no ttH differential info from 2016 analyses)

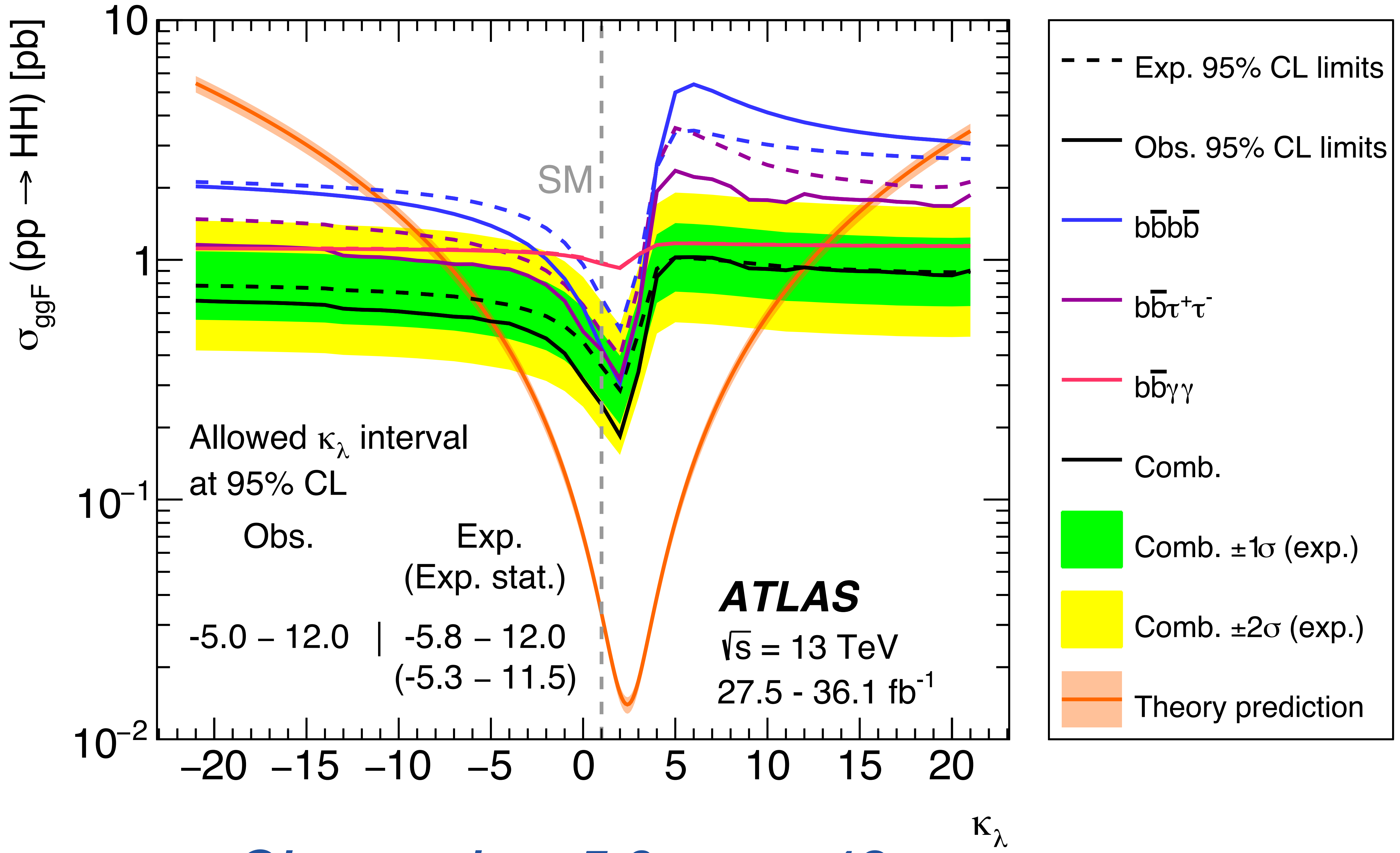




Challenges in the H + HH combination

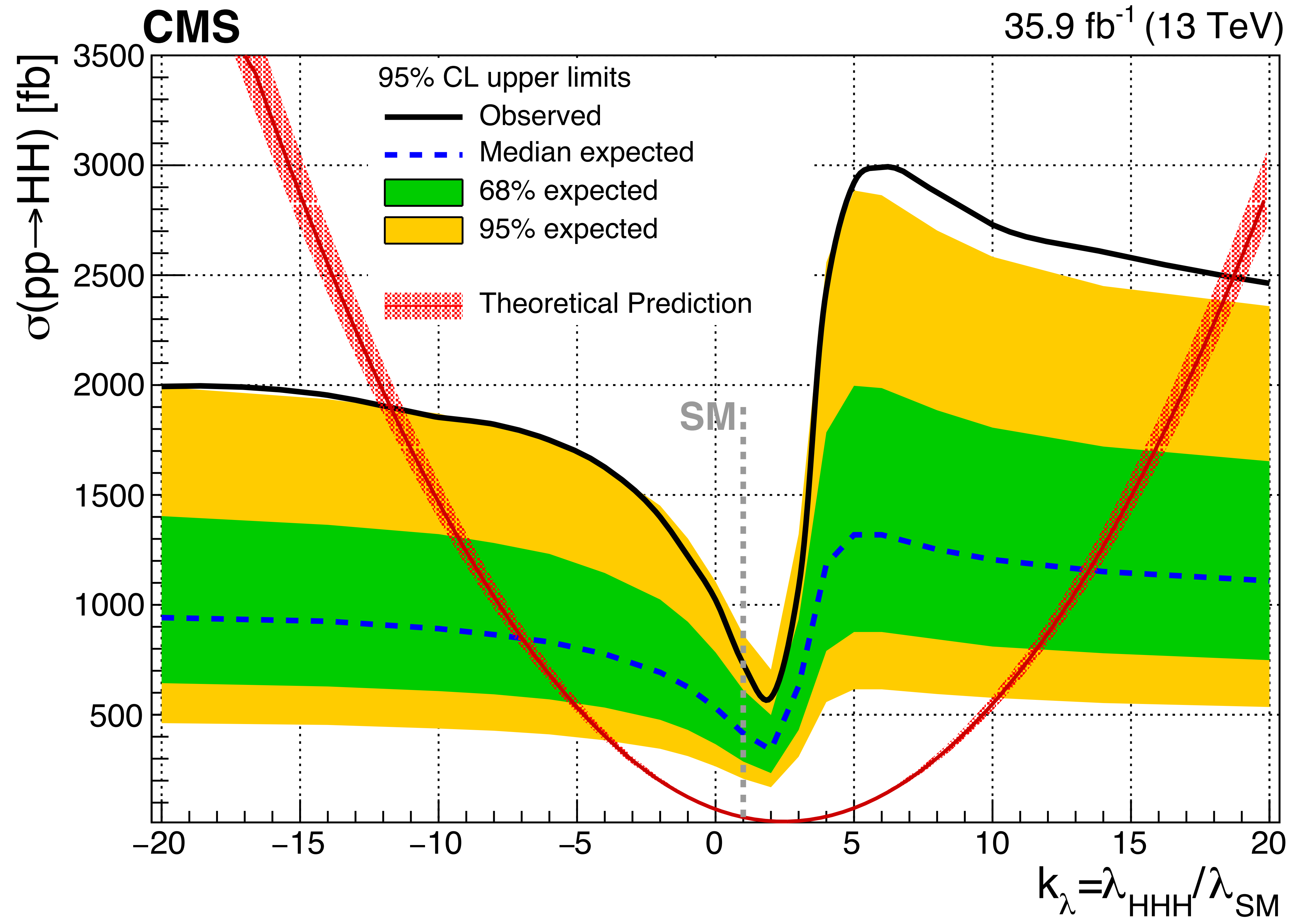
- experimental : treating overlaps between H and HH analyses
  - often similar final states, esp. with ttH and H(bb)H(XX) analyses
- theory : defining the framework to perform the combination
  - κ-framework used so far, combines LO and NLO effects in double and single Higgs
  - perfect case for a EFT interpretation

Combined 2016 sensitivity to λ



Observed: ***-5.0 < κλ < 12***

Expected: *-5.8 < κλ < 12*



Observed: ***-11.8 < κλ < 18.8***

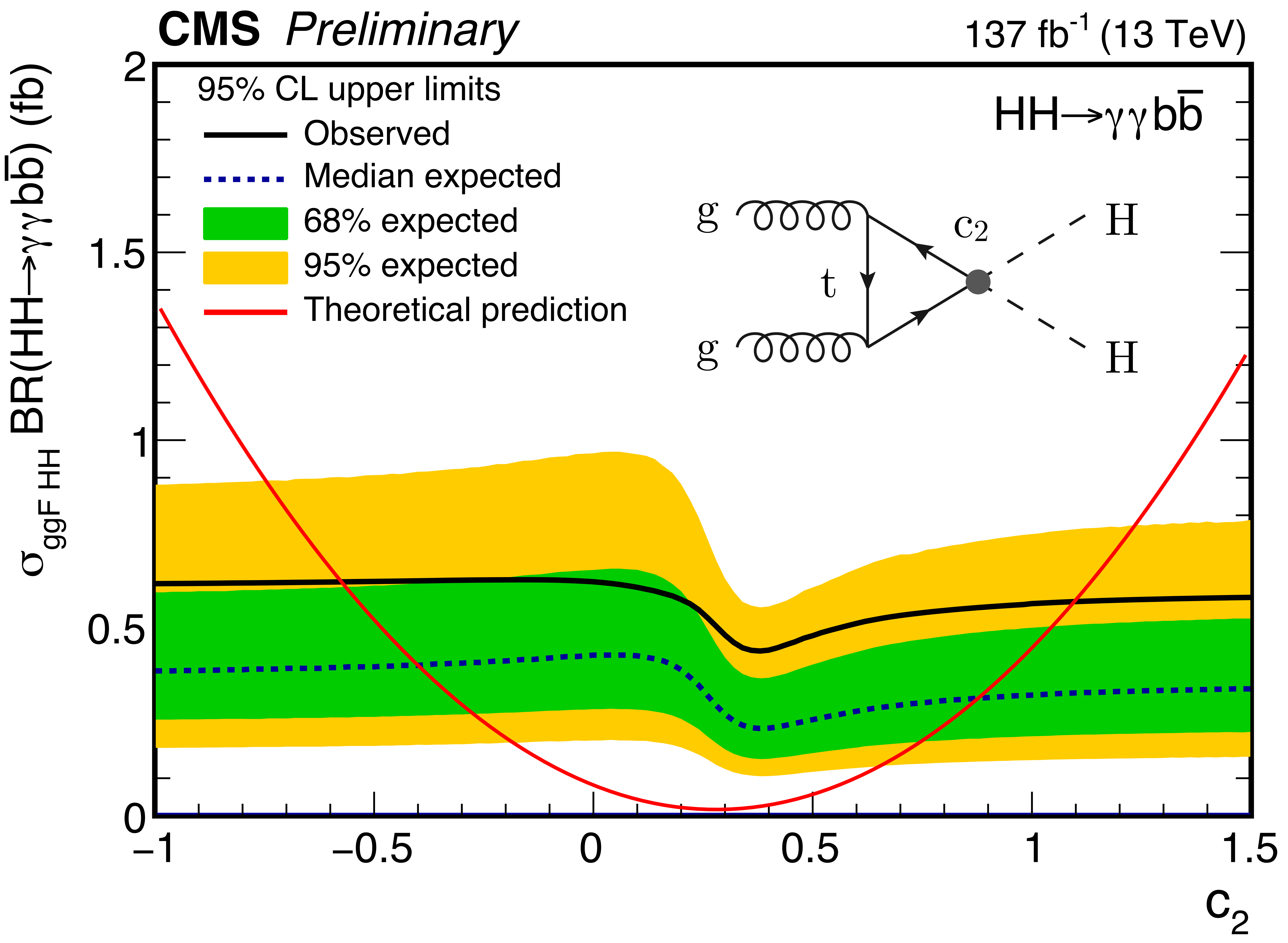
Expected: *-7.1 < κλ < 13.6*

Combined constraints based on the 2016 dataset only (36 fb^{-1})

Large room for improvement with 140 fb^{-1}

Single coupling EFT scan

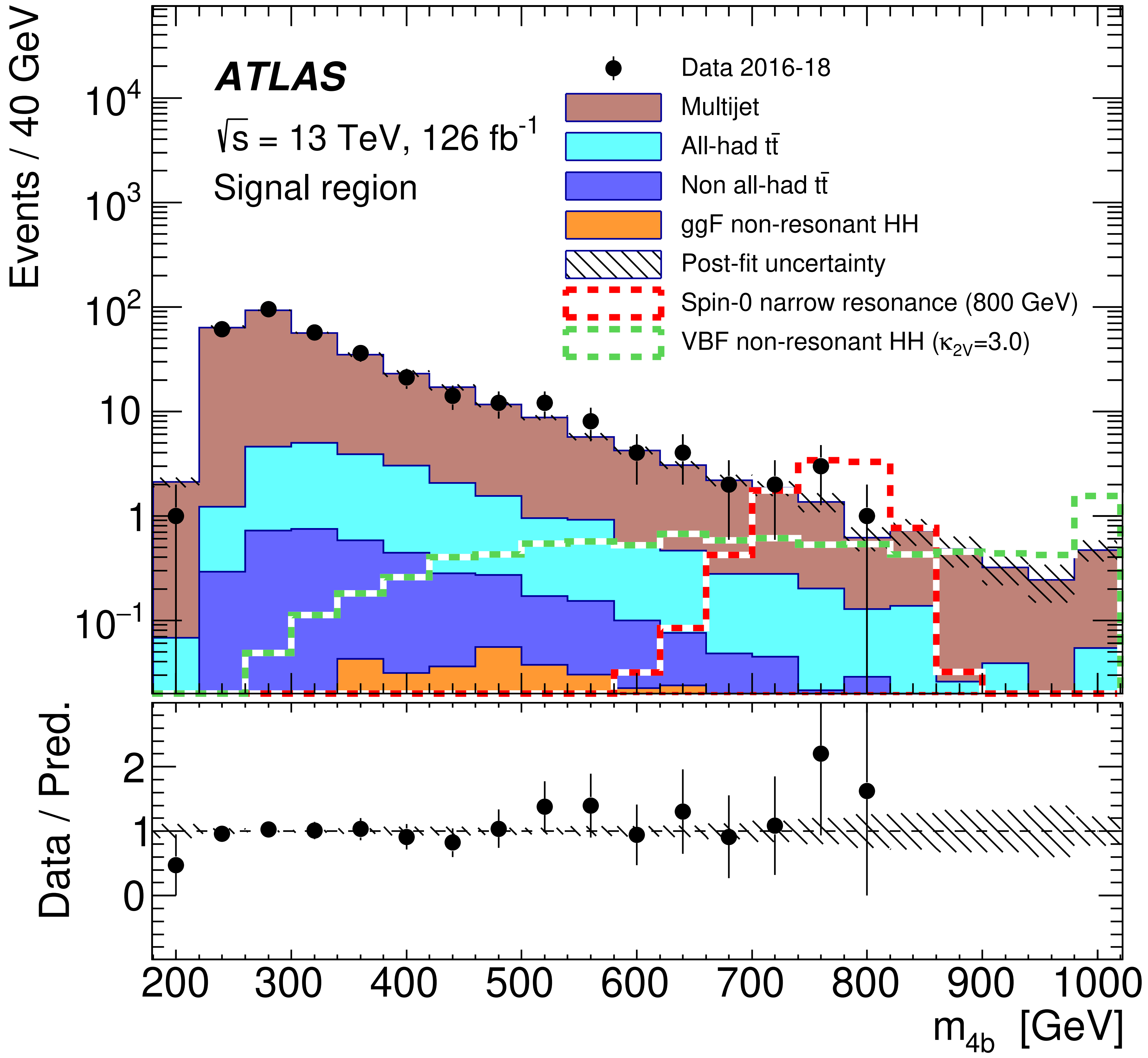
- Upper limit plot as function of c_2 from the bb$\gamma\gamma$ analysis
- Assumes that only c_2 is varied and other couplings are fixed to the SM value
- Under this assumption, observe $-0.6 < c_2 < 1.1$ (exp. $-0.4 < c_2 < 0.9$)
  - correlation with other couplings are expected to reduce the sensitivity

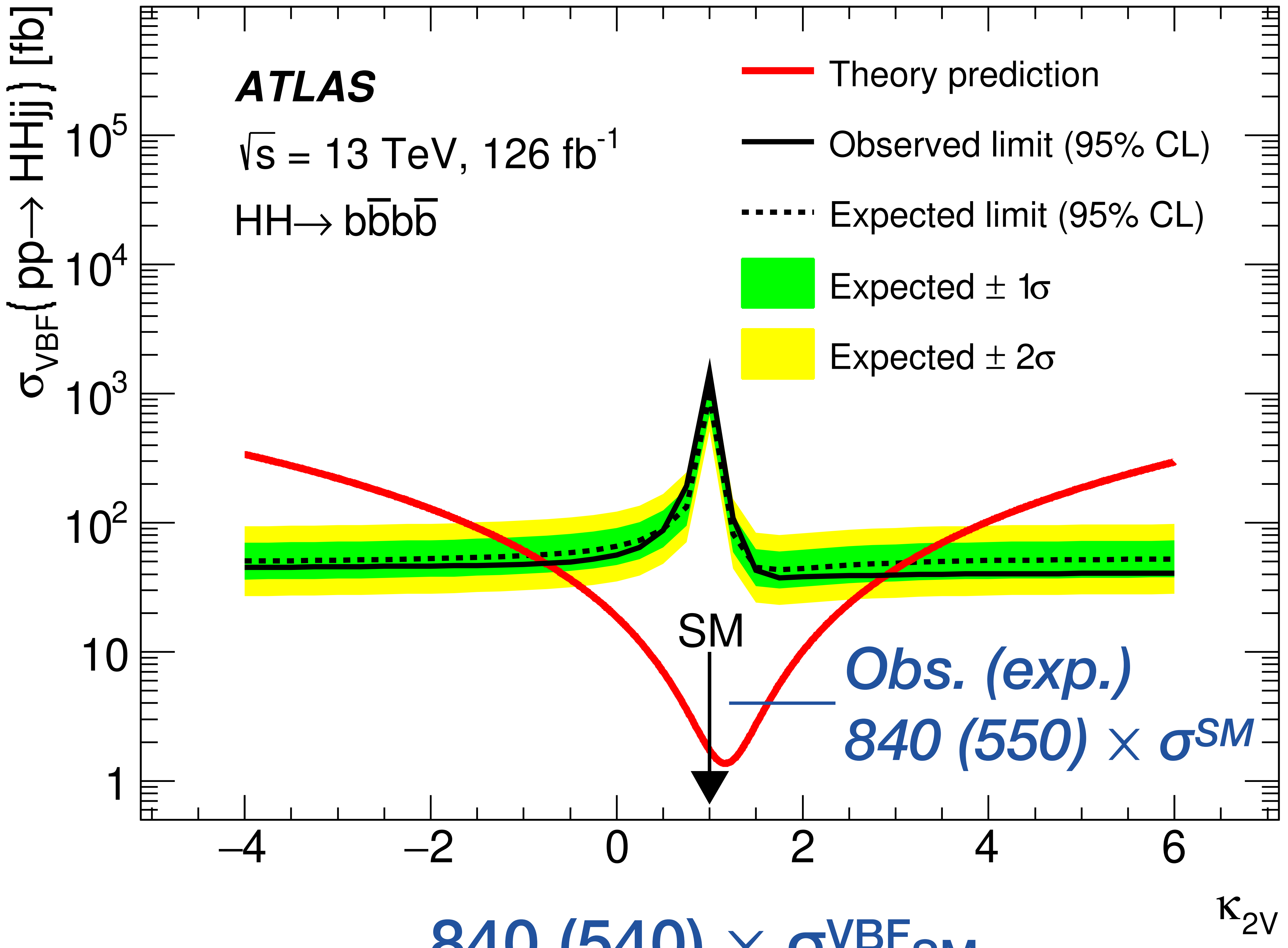


VBF HH→bbbb

- bbbb analysis extended with the two VBF jets signature ($\Delta\eta_{jj}$ > 5, m_{jj} > 100)
- Analysis based on a 4 b-tagged jet topology + 2 VBF jets
- Multijet background data-driven estimate from inverted b tag region

Rare production mode | **High BR channel + extra purity with VBF jets**





$840\ (540) \times \sigma^{VBF}_{SM}$

$-0.8 < C_{2V} < 2.9\ (-0.9 < C_{2V} < 3.1)$ allowed @ 95% CL

- Ongoing study in the LHC HH on the cross section vs c_V / c_{2V} in the fiducial analysis phase space