State-of-the-art of HH and multi-Higgs searches in ATLAS and CMS

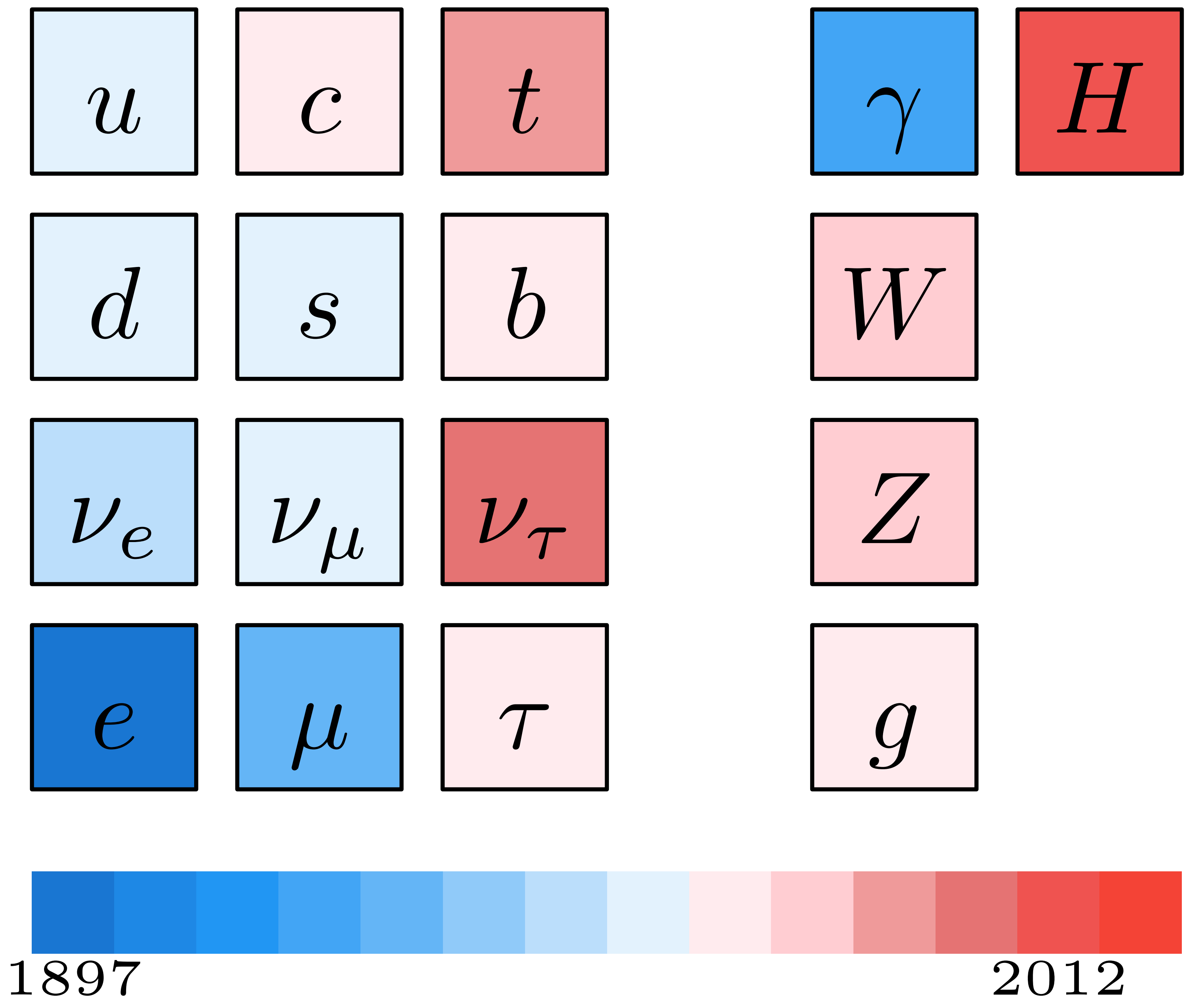
Petar Bokan
First general meeting of the COMETA COST Action
Izmir, February 28 - March 01, 2024

CERN

CMS Compact Muon Solenoid

ATLAS EXPERIMENT

The Higgs boson



Standard Model particles: discovery timeline

The Higgs field is necessary in the Standard Model for realising spontaneous electroweak symmetry breaking

$$m_W, m_Z \neq 0; \;\; m_\gamma = 0$$

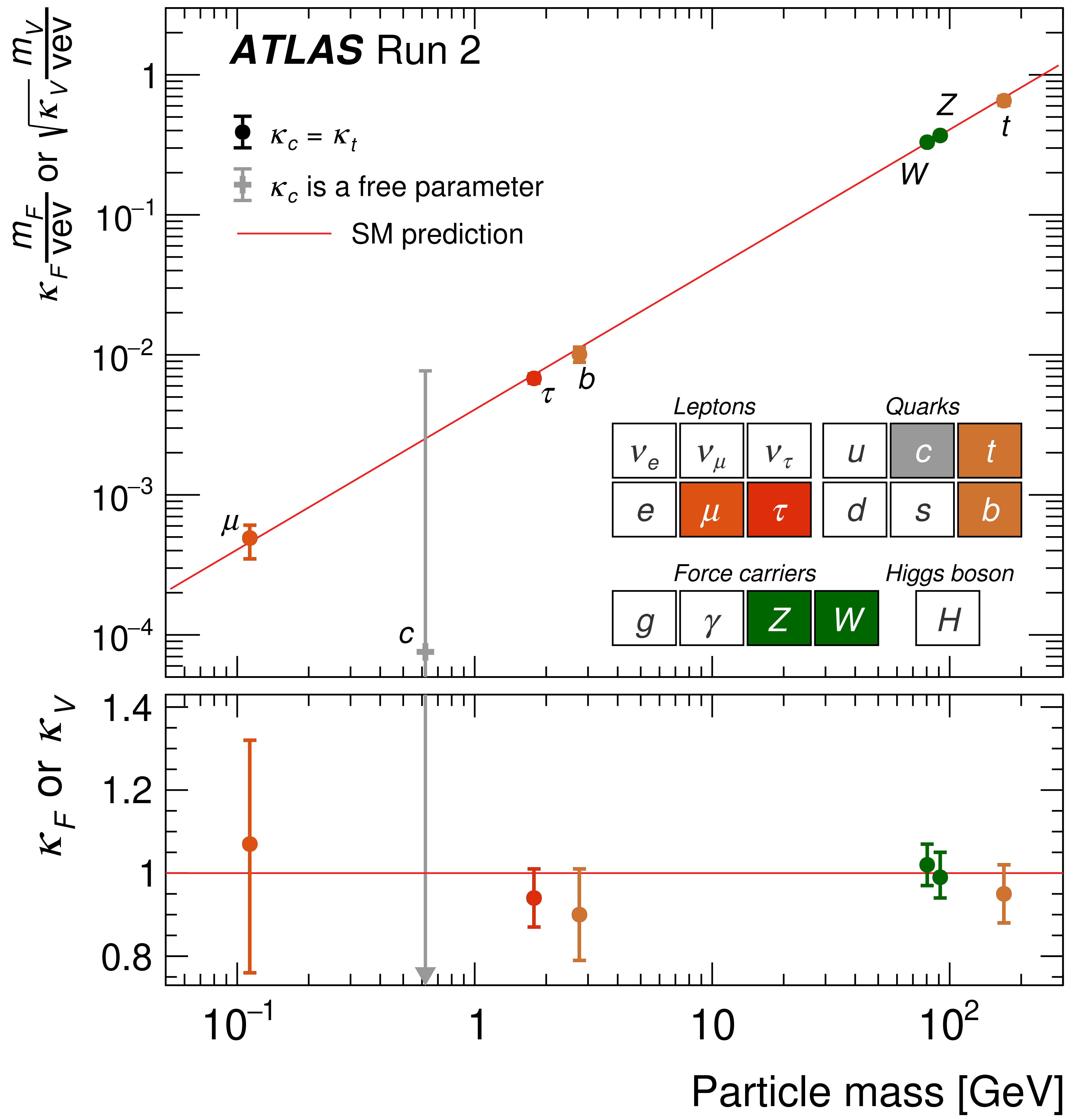
The Higgs boson interactions

Observed Higgs boson remarkably consistent with the SM theory!

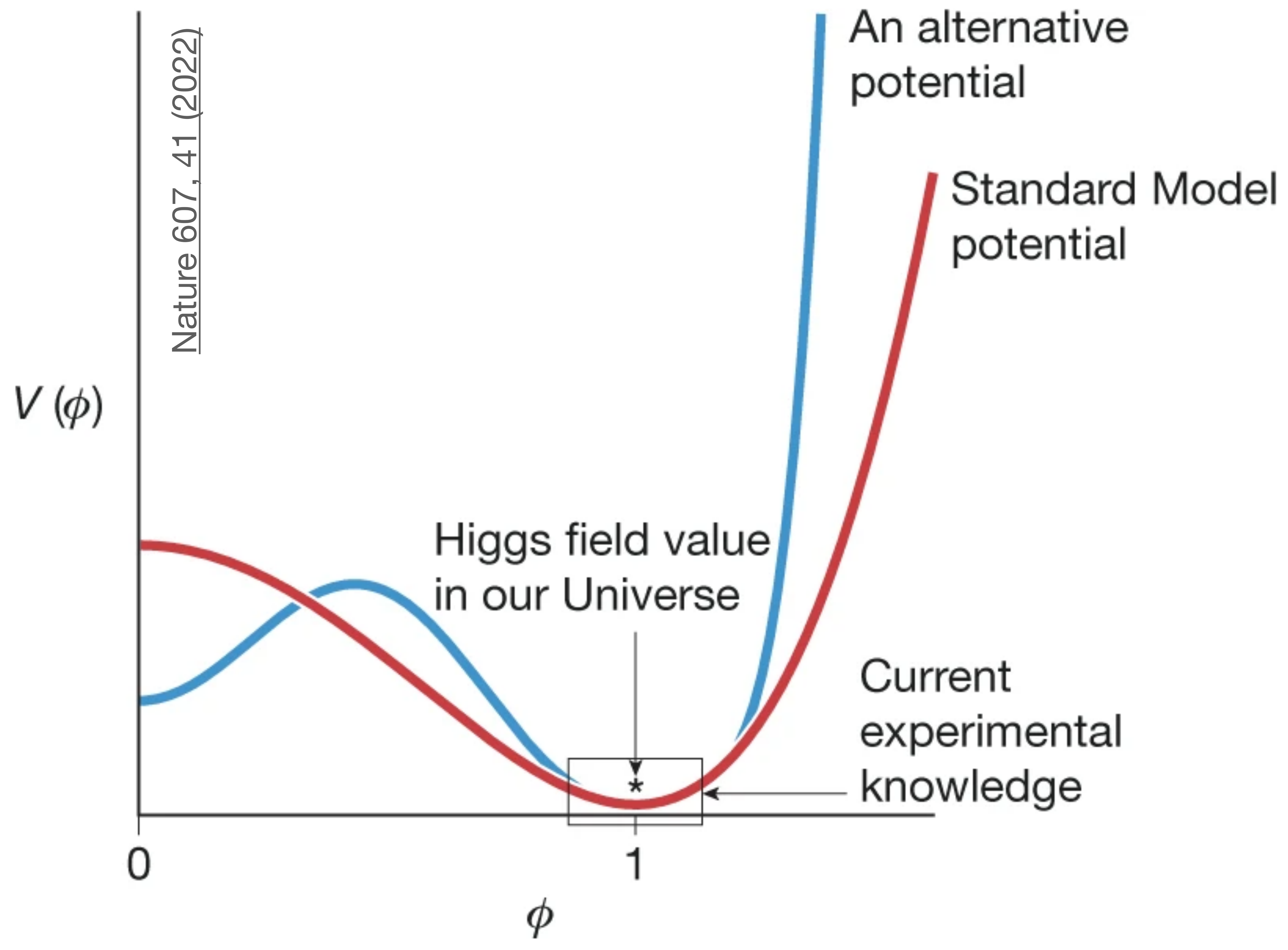
Interactions

- Gauge interactions (*W*, *Z* observed)
- Yukawa interactions (t, b, τ observed, evidence for μ)
- **Self-interaction?**
- **Beyond-the-SM interactions?**

Nature 607, 52 (2022)



Higgs potential and Higgs boson self-coupling



Measured: $m_H \approx 125$ GeV, $\nu \approx 246$ GeV

SM: $\mathscr{L}_{Higgs} = \ldots -\lambda v^2 H^2 - \lambda v H^3 - \frac{1}{4}\lambda H^4$

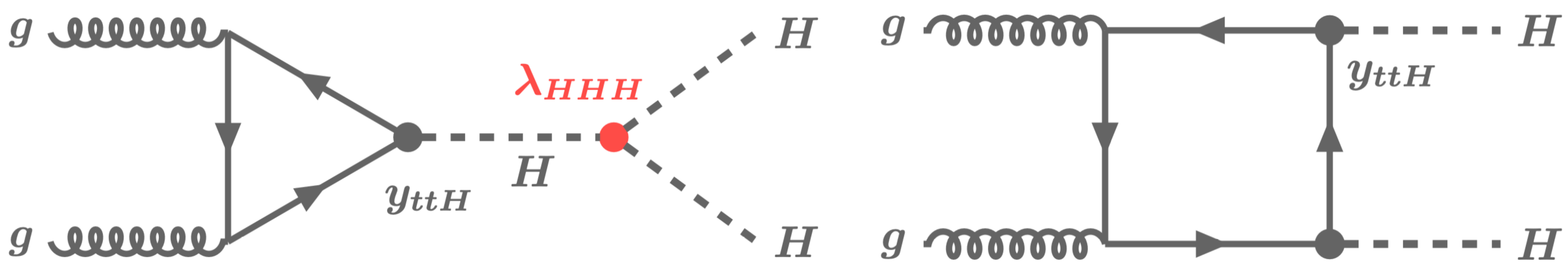
→ $\lambda = m_H^2/2\nu^2$ not verified experimentally!

→ $\lambda_{HHH} = \lambda\nu$ trilinear Higgs self-coupling constant (can be probed through *HH* production)

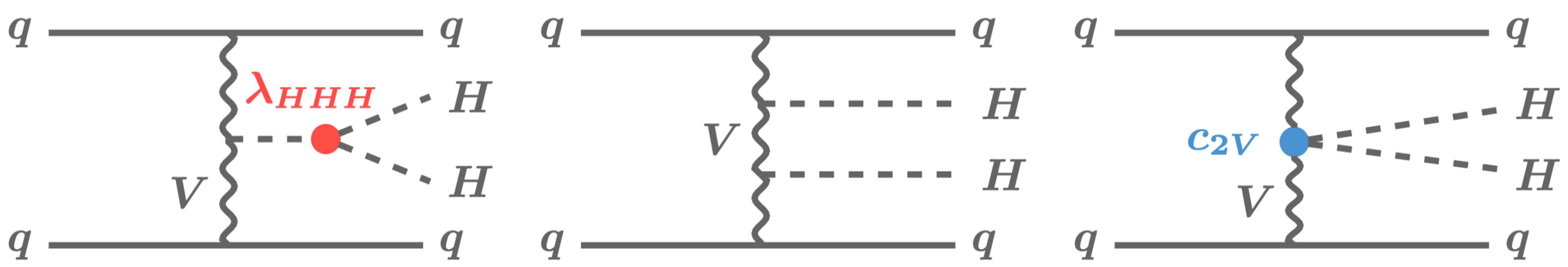
Measurement of λ could help answer questions about:

- Vacuum stability
- Dynamics of electroweak phase transition (connection to electroweak baryogenesis)
- Connection between the SM and a more complex world of particles
- …

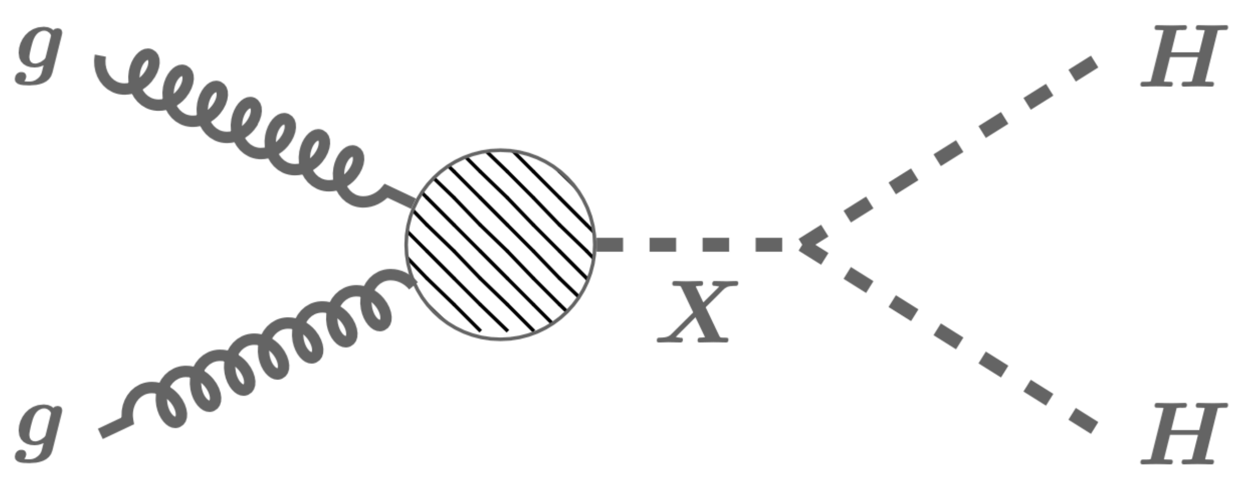
HH production at the LHC



gluon-gluon fusion (ggF)
$\sigma_{ggF} = 31.05$ fb



vector boson fusion (VBF)
$\sigma^{SM}_{VBF} = 1.72$ fb



Resonant HH production

VHH production covered in Matteo's talk

Processes parameterised using coupling modifiers:

$\kappa_\lambda = \lambda_{HHH}/\lambda^{SM}_{HHH}$

$\kappa_{2V} = c_{2V}/c^{SM}_{2V}$

Searches for non-resonant *HH* production

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0053%

HH branching ratios

Most recent ATLAS results

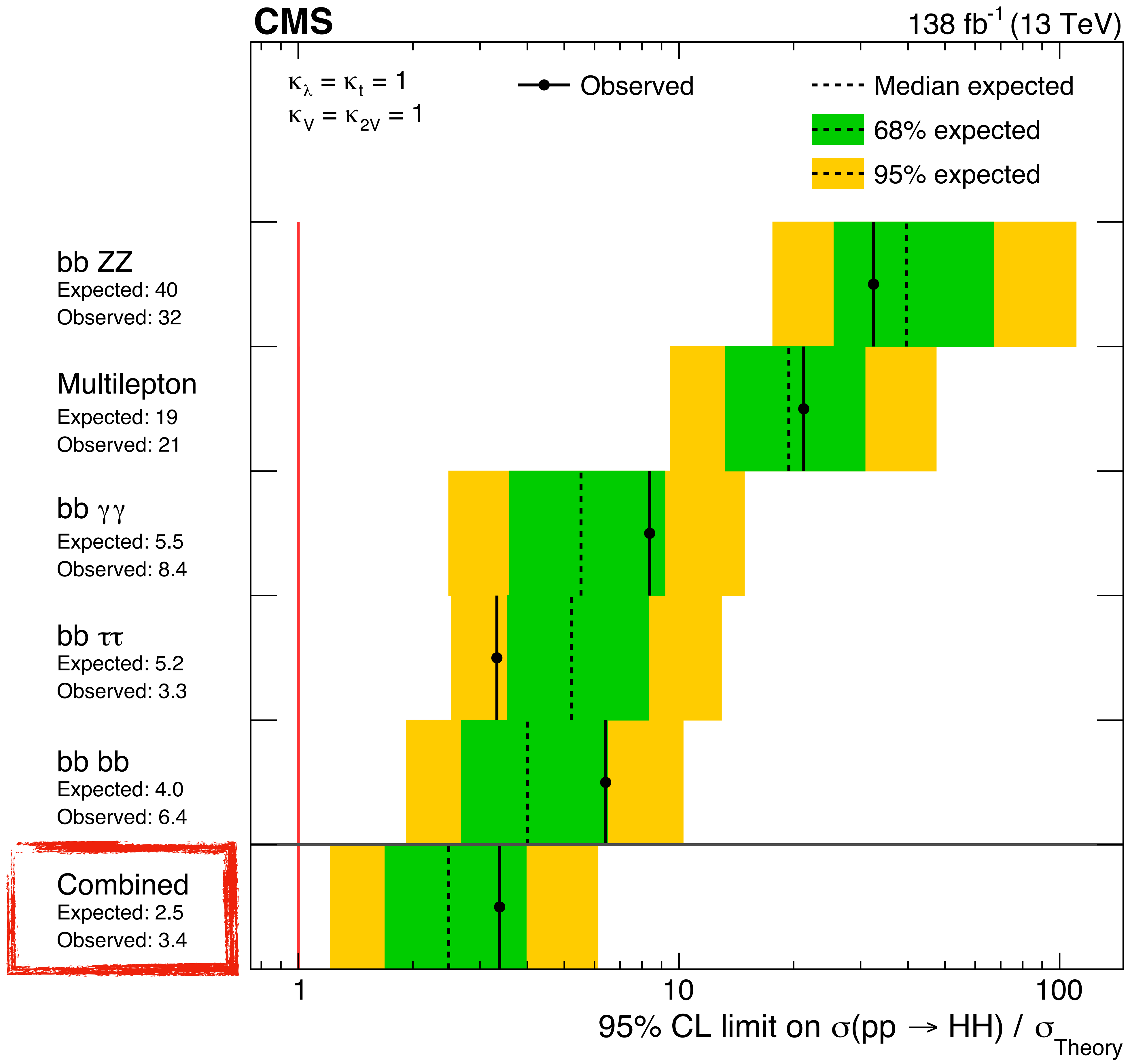
ATLAS-CONF-2023-071 ($bb\tau\tau$)
PRD 108 (2023) 052003 ($b\bar{b}b\bar{b}$)
JHEP 01 (2024) 066 ($b\bar{b}\gamma\gamma$)
arXiv:2310.11286 ($b\bar{b}\ell\ell$)
PLB 843 (2023) 137745 (*H* + *HH* combination)
ATL-PHYS-PUB-2022-053 (HL-LHC projections)

Most recent CMS results

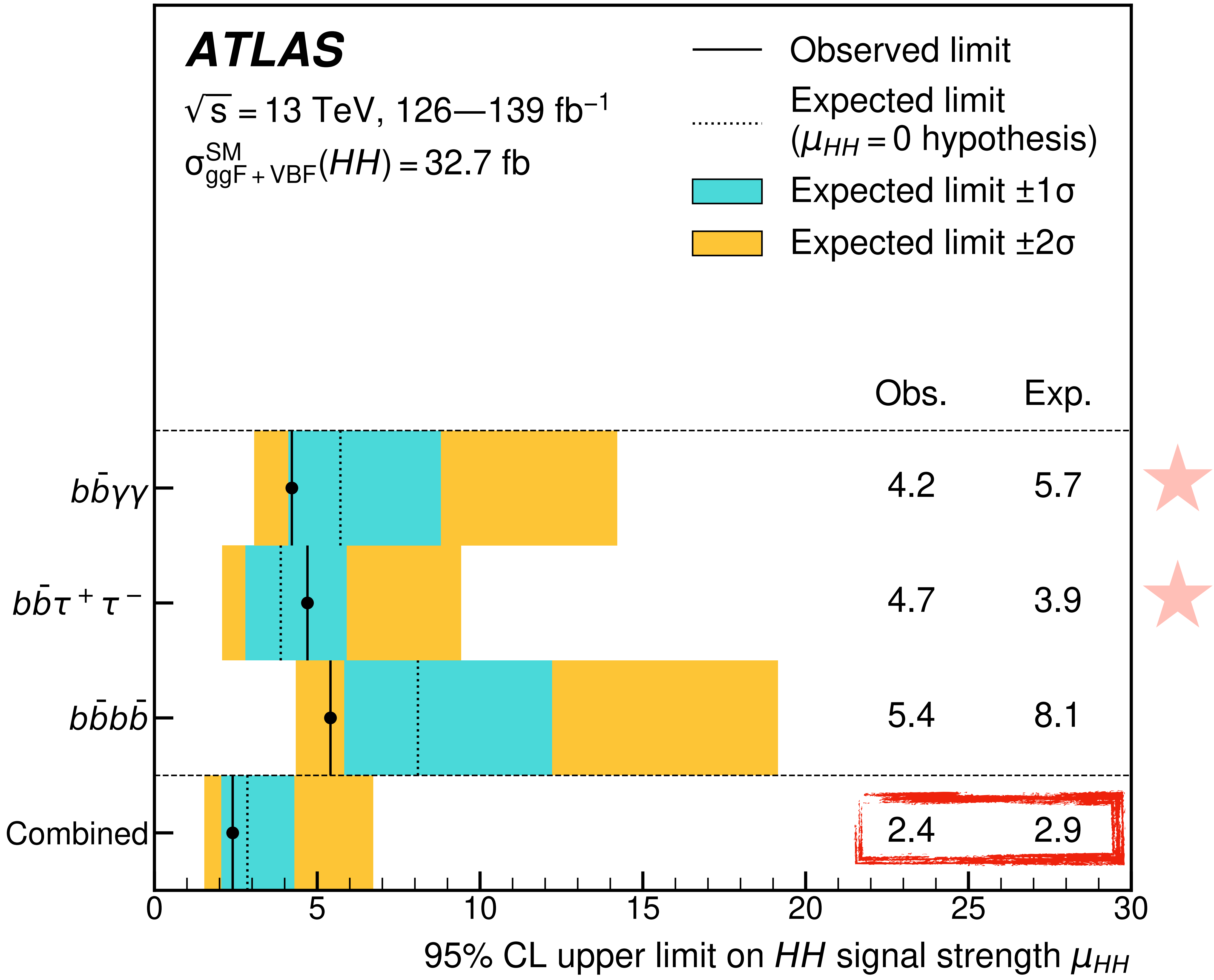
PRL 129 (2022) 081802 ($b\bar{b}b\bar{b}$ resolved)
PRL 131 (2023) 041803 ($b\bar{b}b\bar{b}$ boosted)
PLB 842 (2023) 137531 ($b\bar{b}\tau\tau$)
JHEP 07 (2023) 095 (multilepton)
JHEP 03 (2021) 257 ($b\bar{b}\gamma\gamma$)
JHEP 06 (2023) 130 ($b\bar{b}ZZ$)
CMS-PAS-HIG-21-005 ($b\bar{b}WW$)
CMS-PAS-HIG-21-014 ($WW\gamma\gamma$)
Nature 607 (2022) 60 (Comb, HL-LHC projections)
CMS-PAS-HIG-23-006 (*H* + *HH* combination)
CMS-PAS-HIG-22-006 (*VHH*, $b\bar{b}b\bar{b}$)

Combined results: *HH* signal strength limit

Nature 607 (2022) 60



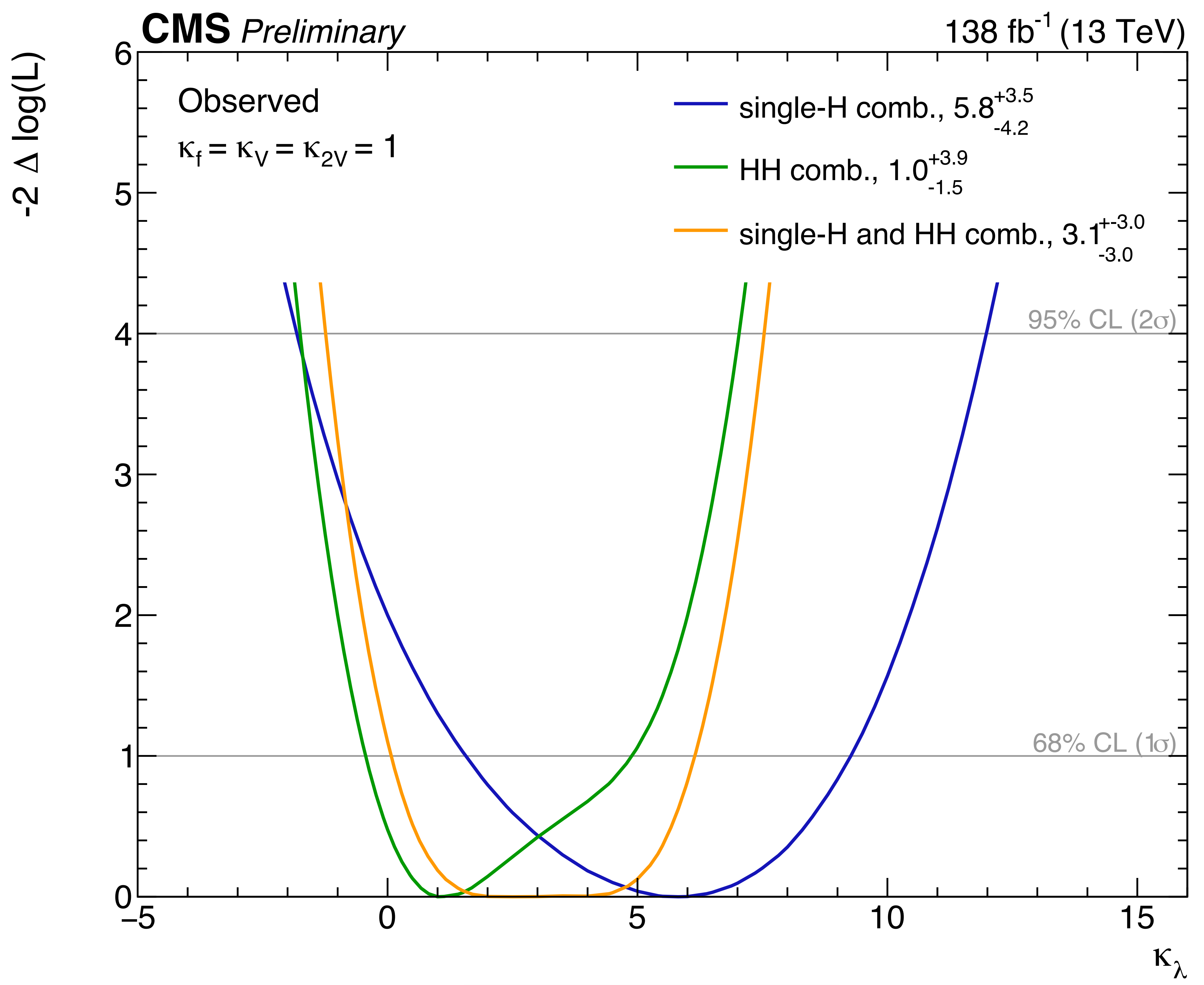
PLB 843 (2023) 137745



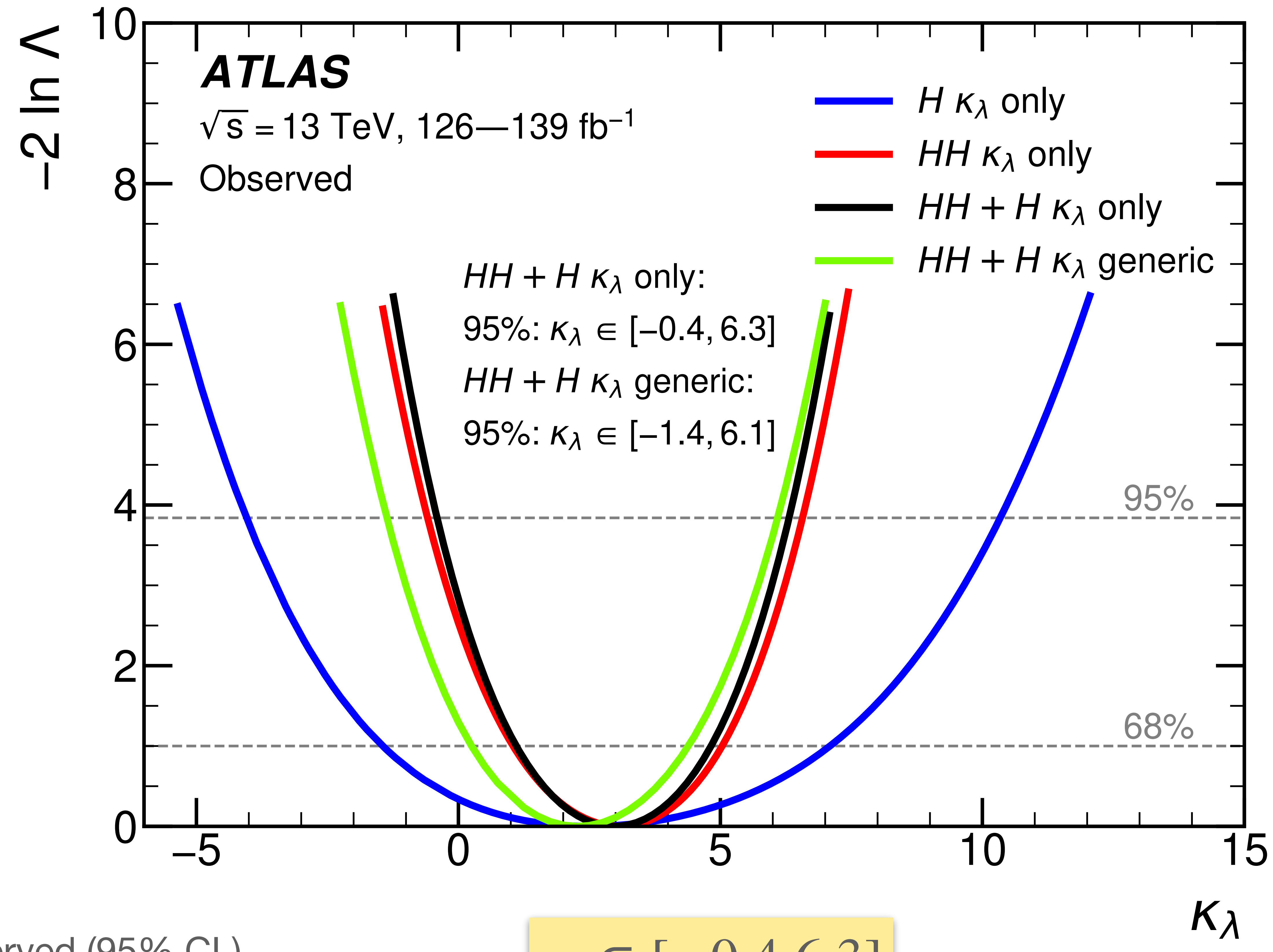
- Several individual results have been updated since these combinations ★
- Comparable sensitivities between ATLAS and CMS (3.5 - 5 times better than the 36 fb^{-1} combinations)

Combined results: Constraints on self-coupling

CMS-PAS-HIG-23-006



PLB 843 (2023) 137745



CMS		ATLAS
$\kappa_\lambda \in [-1.2, 7.5]$	Observed (95% CL)	$\kappa_\lambda \in [-0.4, 6.3]$
$\kappa_\lambda \in [-2.0, 7.7]$	Expected (95% CL)	$\kappa_\lambda \in [-1.9, 7.6]$

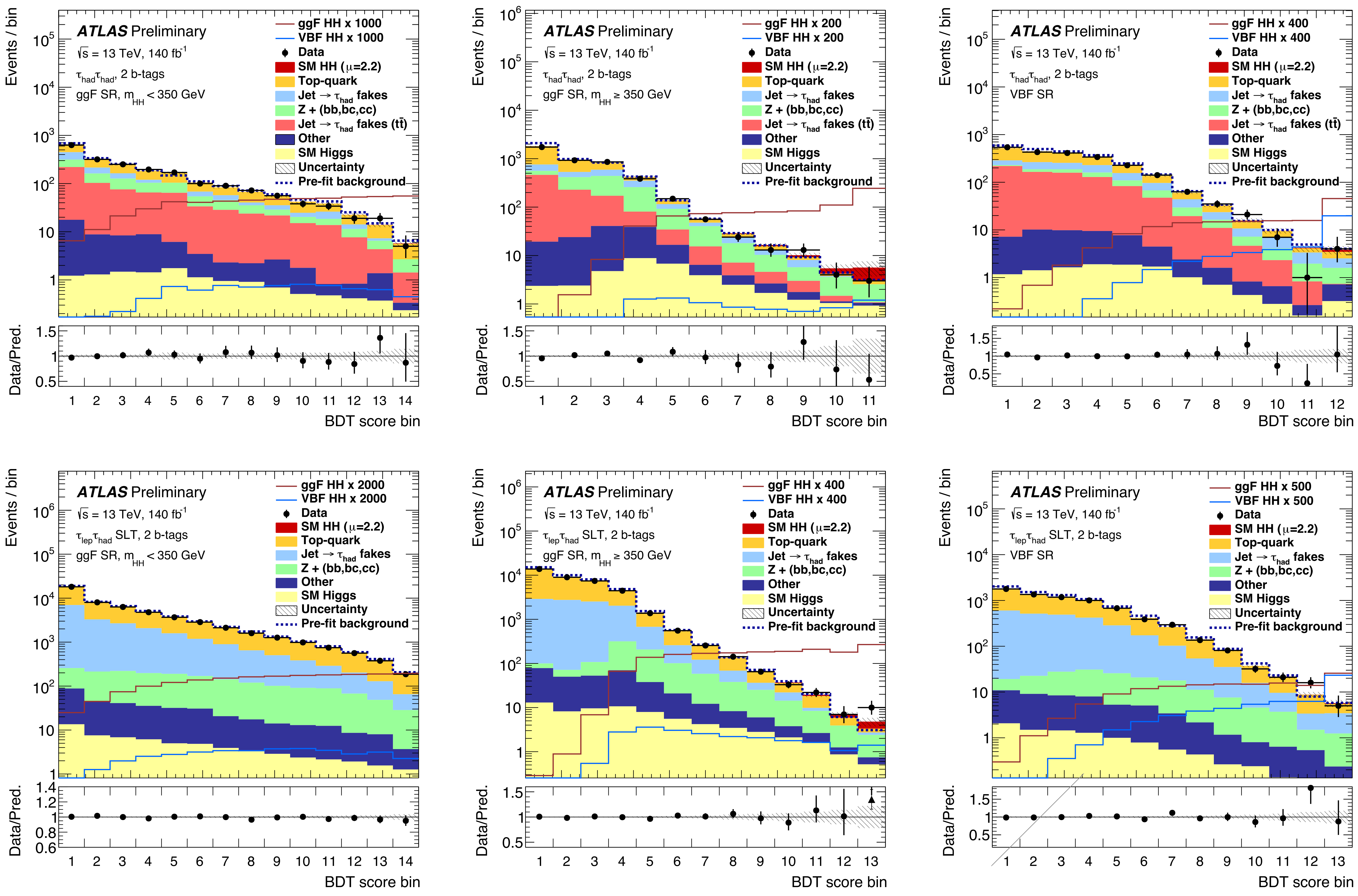
- **Quoted limits** are based on the assumption that all other couplings are as predicted by the SM
- More **generic limits** 6% (CMS) and 18% (ATLAS) less stringent $\leftarrow \kappa_V, \kappa_t, \kappa_b, \kappa_\tau$ $(+\kappa_{2V}, \kappa_\mu$ for CMS) profiled

State-of-the-art: ATLAS $HH \to b\bar{b}\tau\tau$

ATLAS-CONF-2023-071

$bb\tau_{had}\tau_{had}$

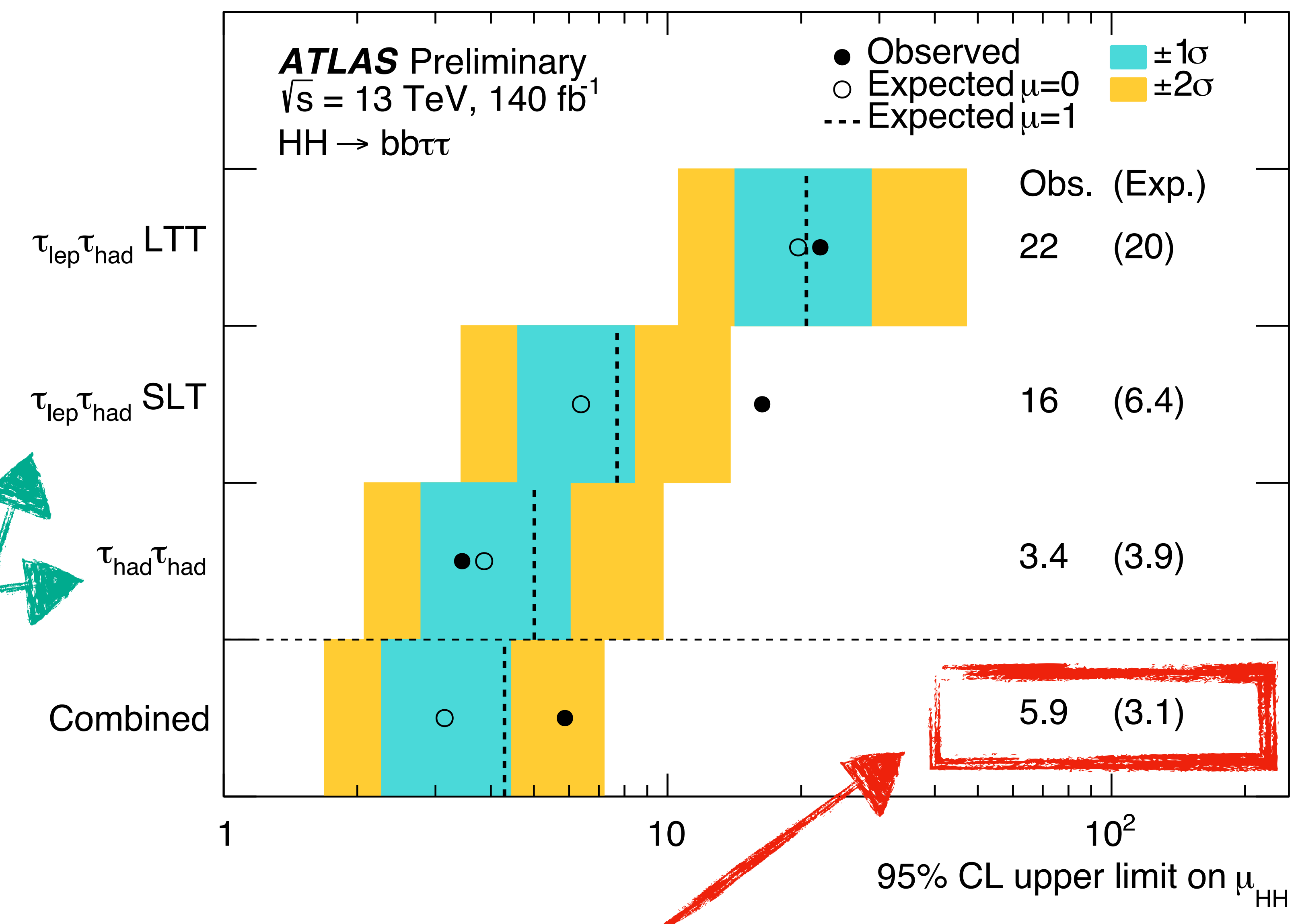
$bb\tau_{lep}\tau_{had}$



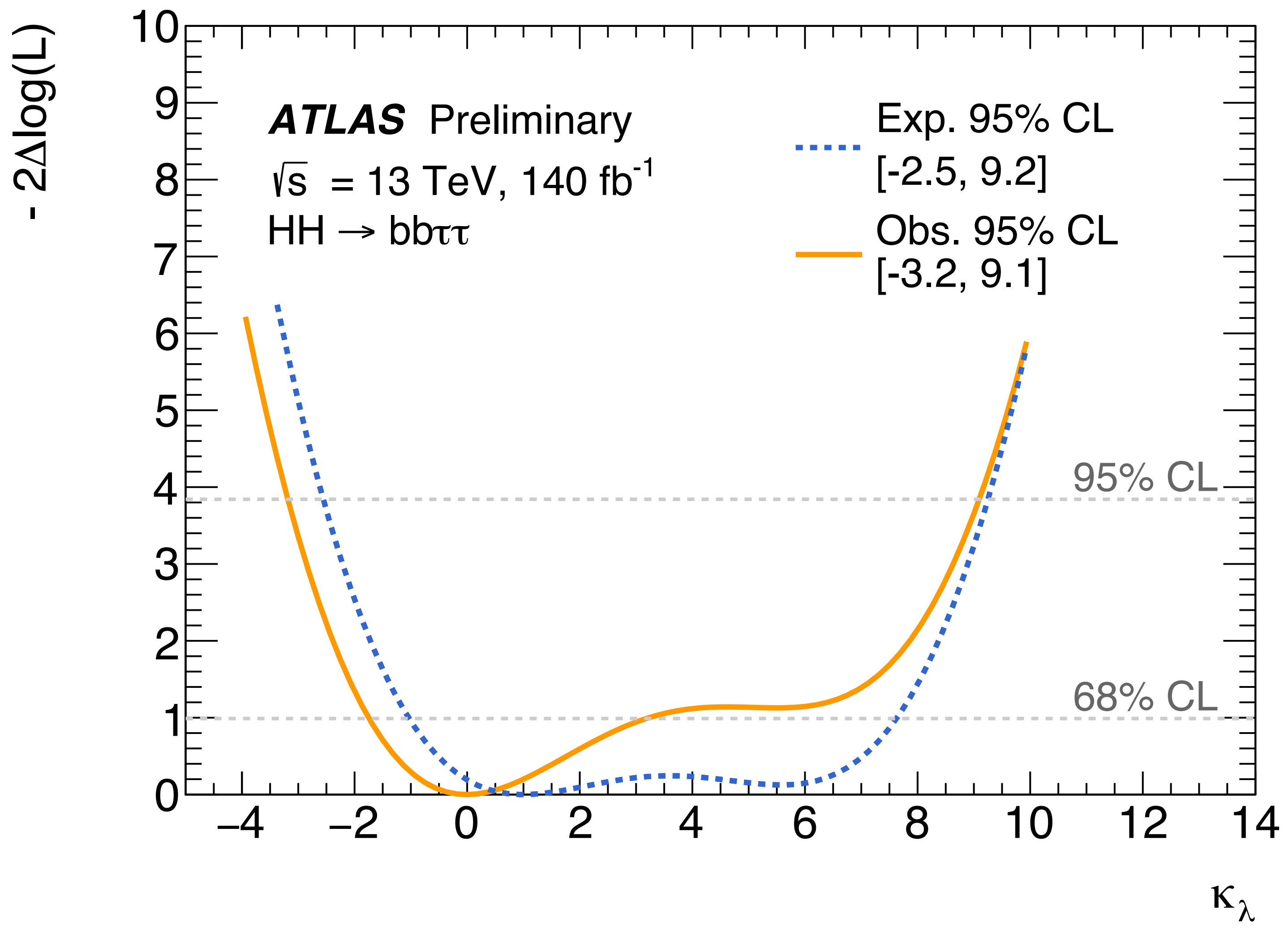
ggF, $m_{HH} < 350$ GeV

ggF, $m_{HH} < 350$ GeV

VBF SR



20% improvement in the expected result

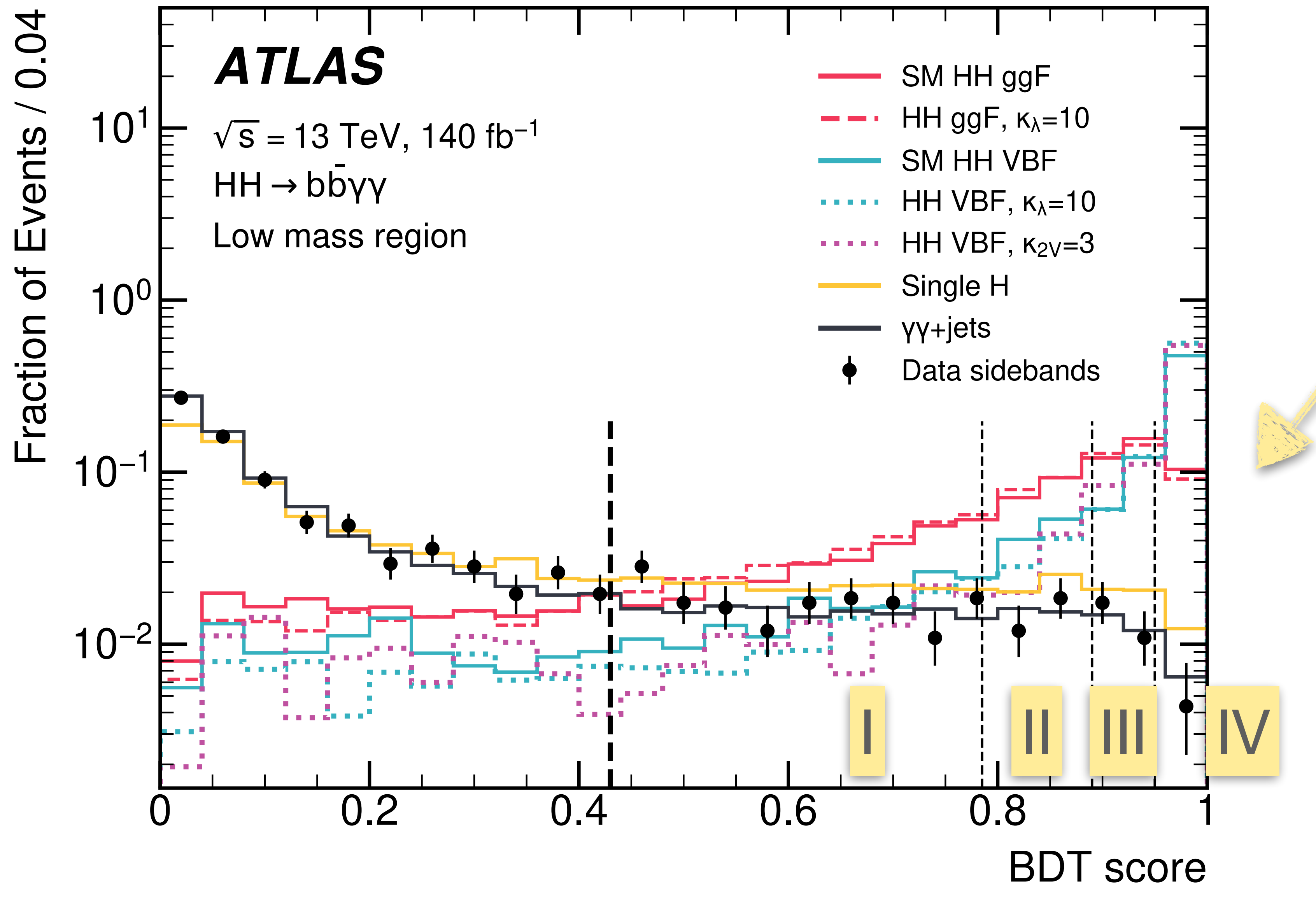


BDT classifier used to separate ggF and VBF categories; Low m_{HH} region to enhance sensitivity to κ_λ

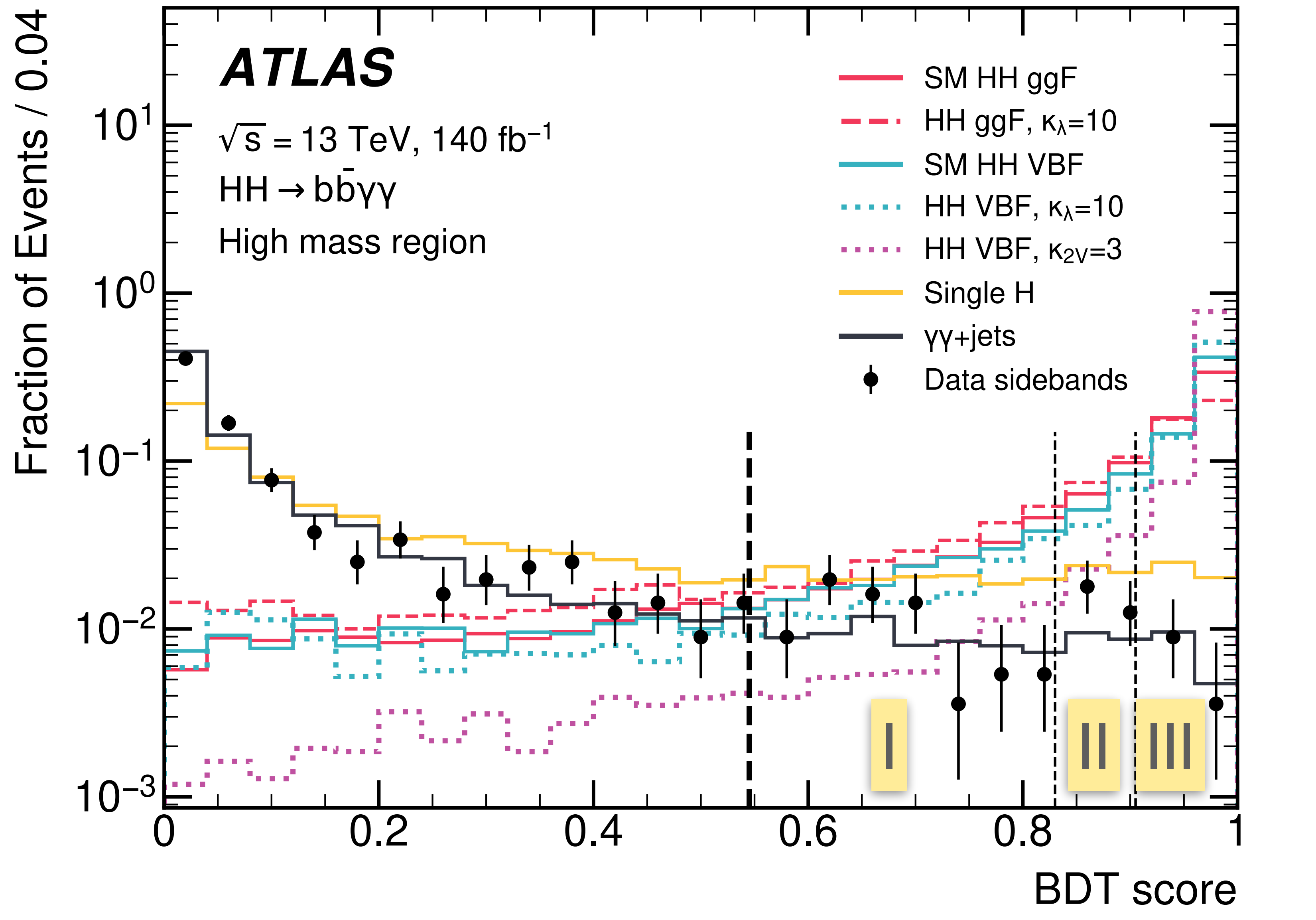
State-of-the-art: ATLAS $HH \rightarrow b\bar{b}\gamma\gamma$

JHEP 01 (2024) 066

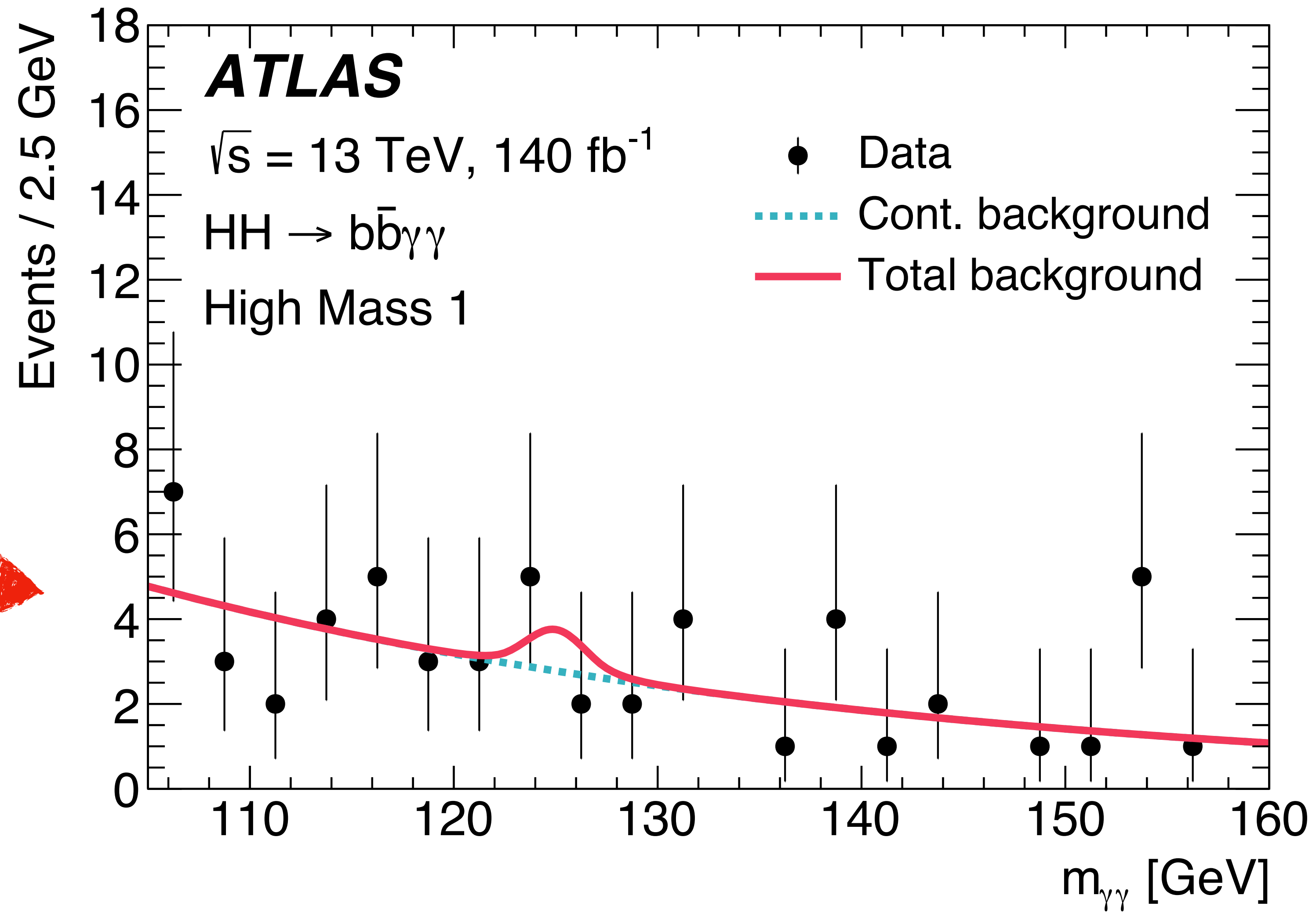
$m^*_{bb\gamma\gamma} < 350$ GeV

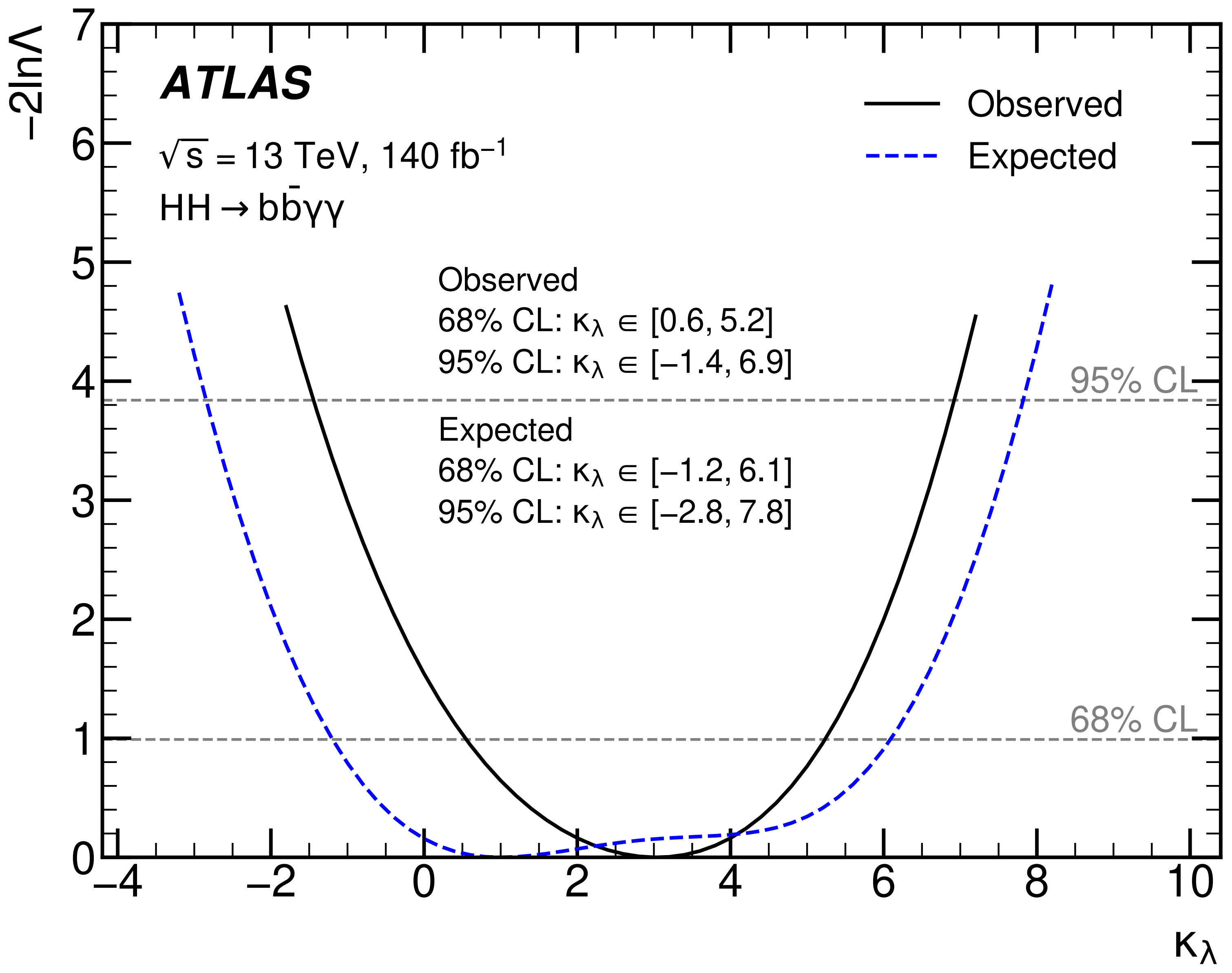


$m^*_{bb\gamma\gamma} > 350$ GeV



- BDT and $m^*_{bb\gamma\gamma}$ used to classify events into 7 SRs
- $m_{\gamma\gamma}$ final discriminants
- Example (high $m^*_{bb\gamma\gamma}$, SR I):



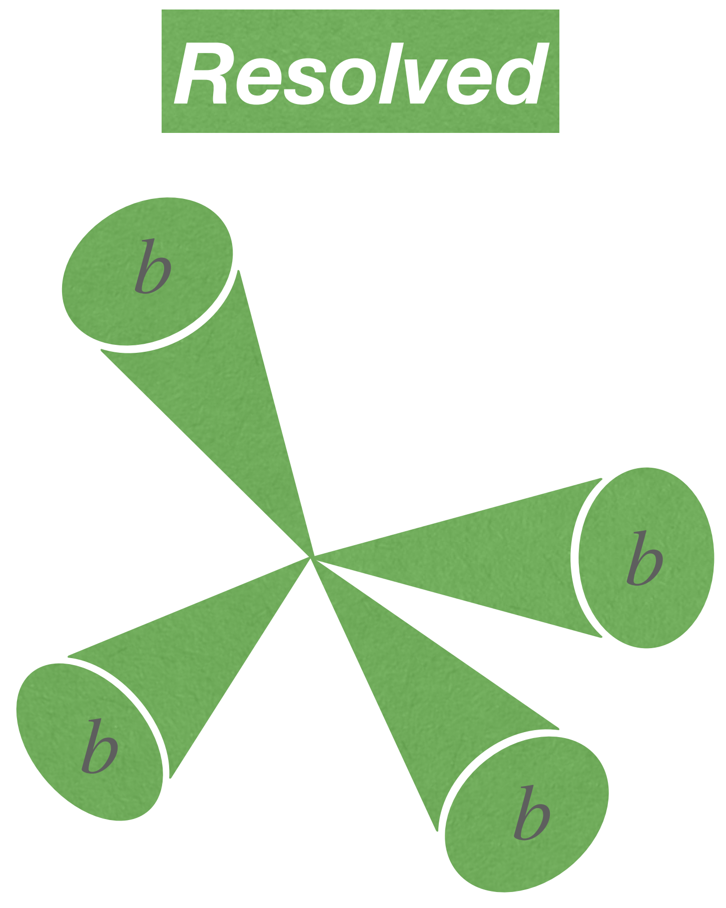


Observed (expected) 95% CL limit on μ_{HH}: 4.0 (5.0)

12% improvement in the expected result

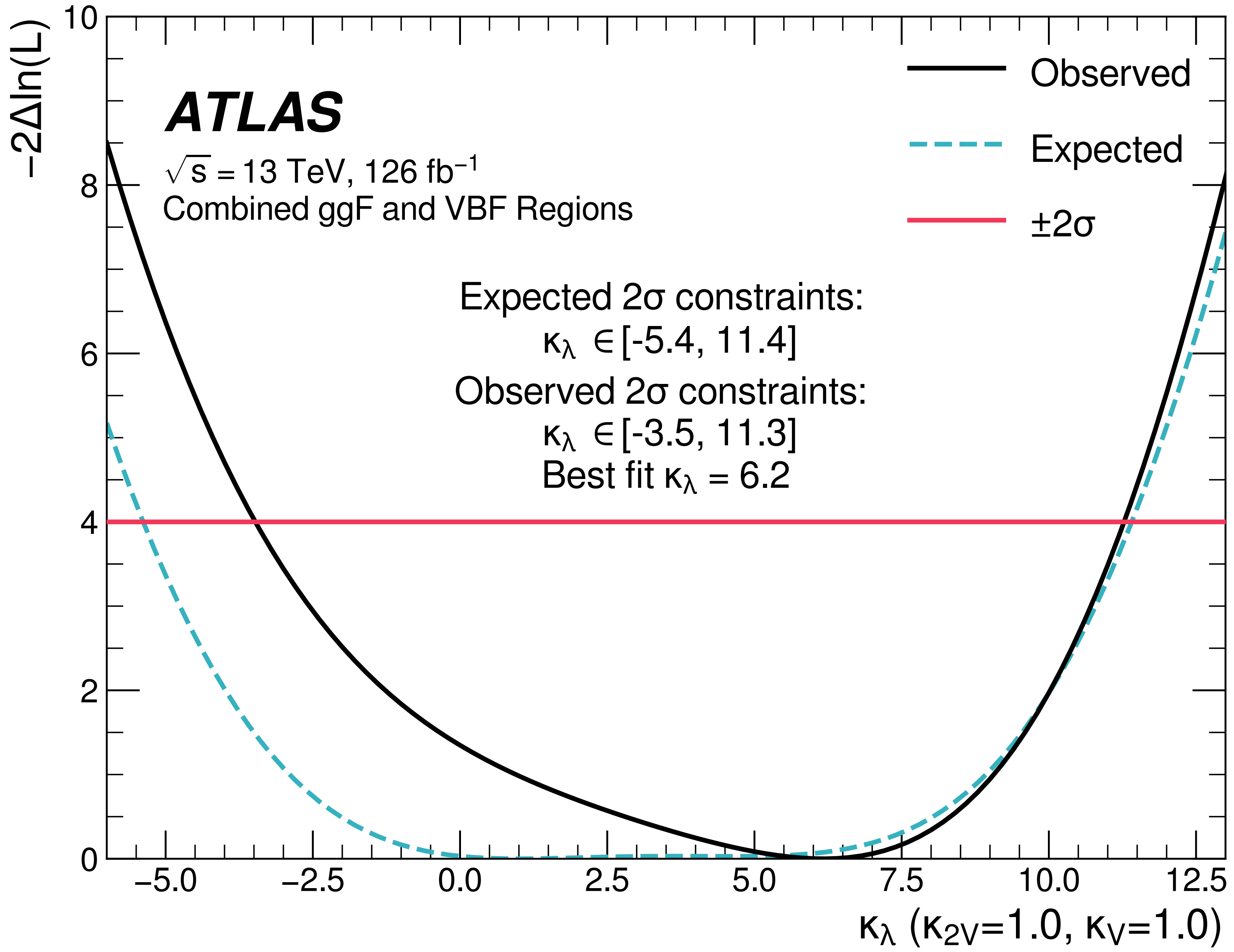
Sensitivity comparable with CMS

State-of-the-art: Resolved $HH \to b\bar{b}b\bar{b}$

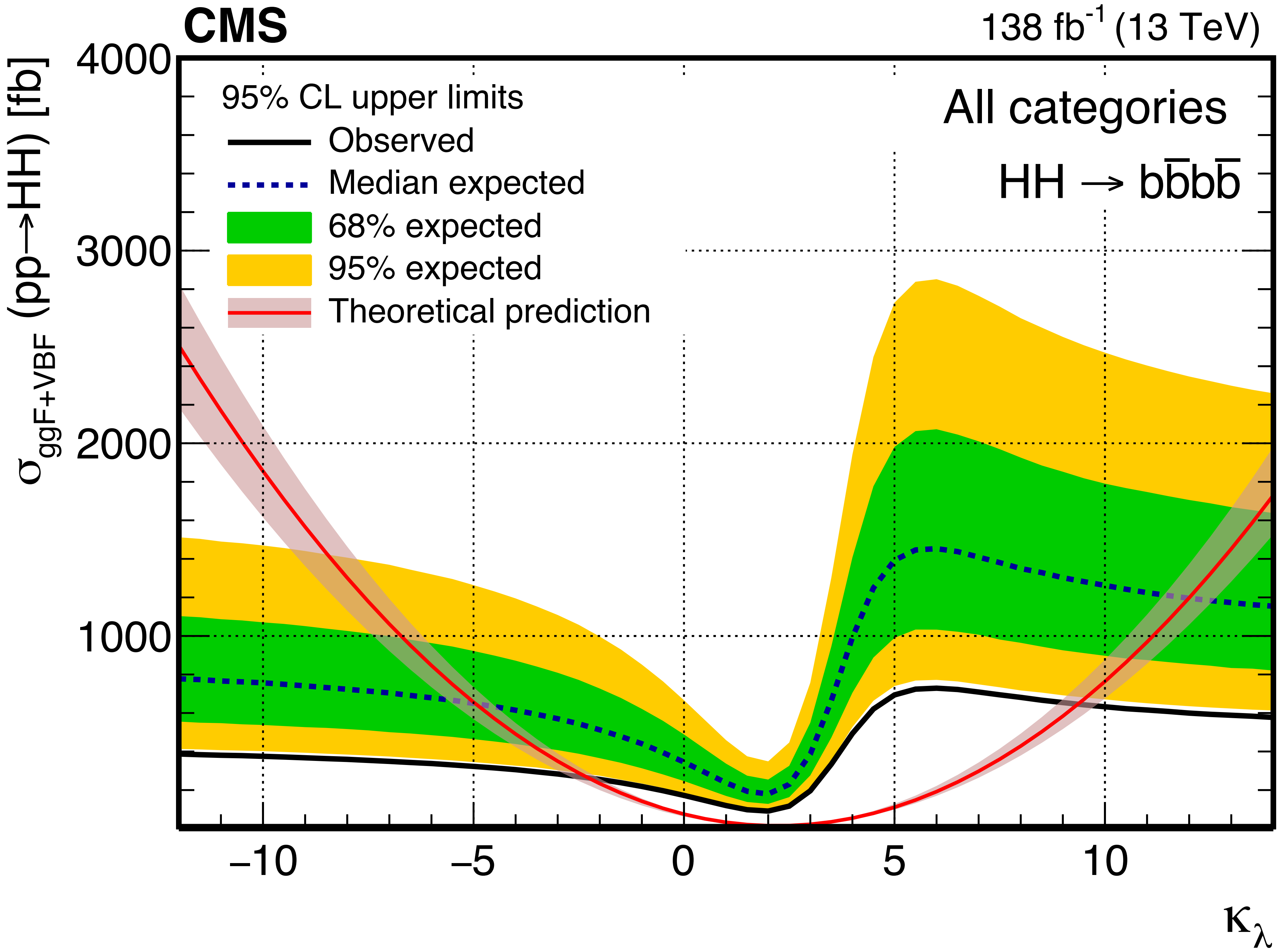


small-radius jets ($R = 0.4$)

PRD 108 (2023) 052003



PRL 129 (2022) 081802



ATLAS analysis

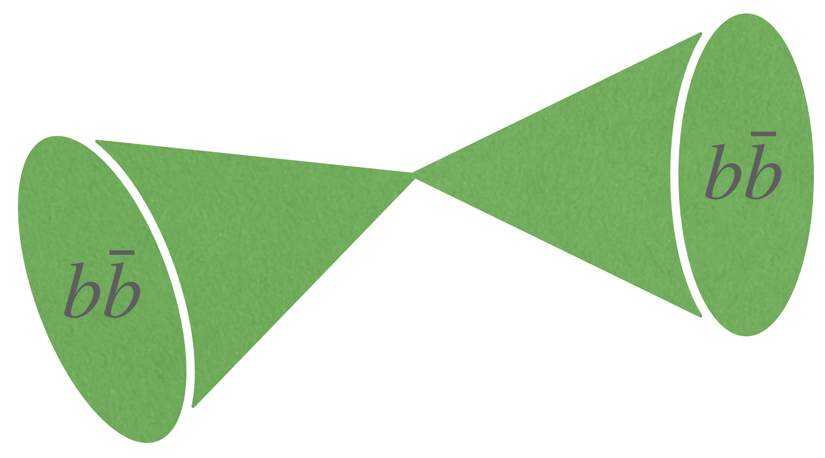
- b-jet pairing based on $\Delta R(b, b)$
- Data-driven background estimation
- 6 ggF + 2 VBF SRs based on $\Delta\eta_{HH}$ and $X_{HH} = f(m_{H1}, m_{H2})$
- 95% CL observed (expected) limit on μ_{HH}: 5.4 (8.1)

CMS analysis

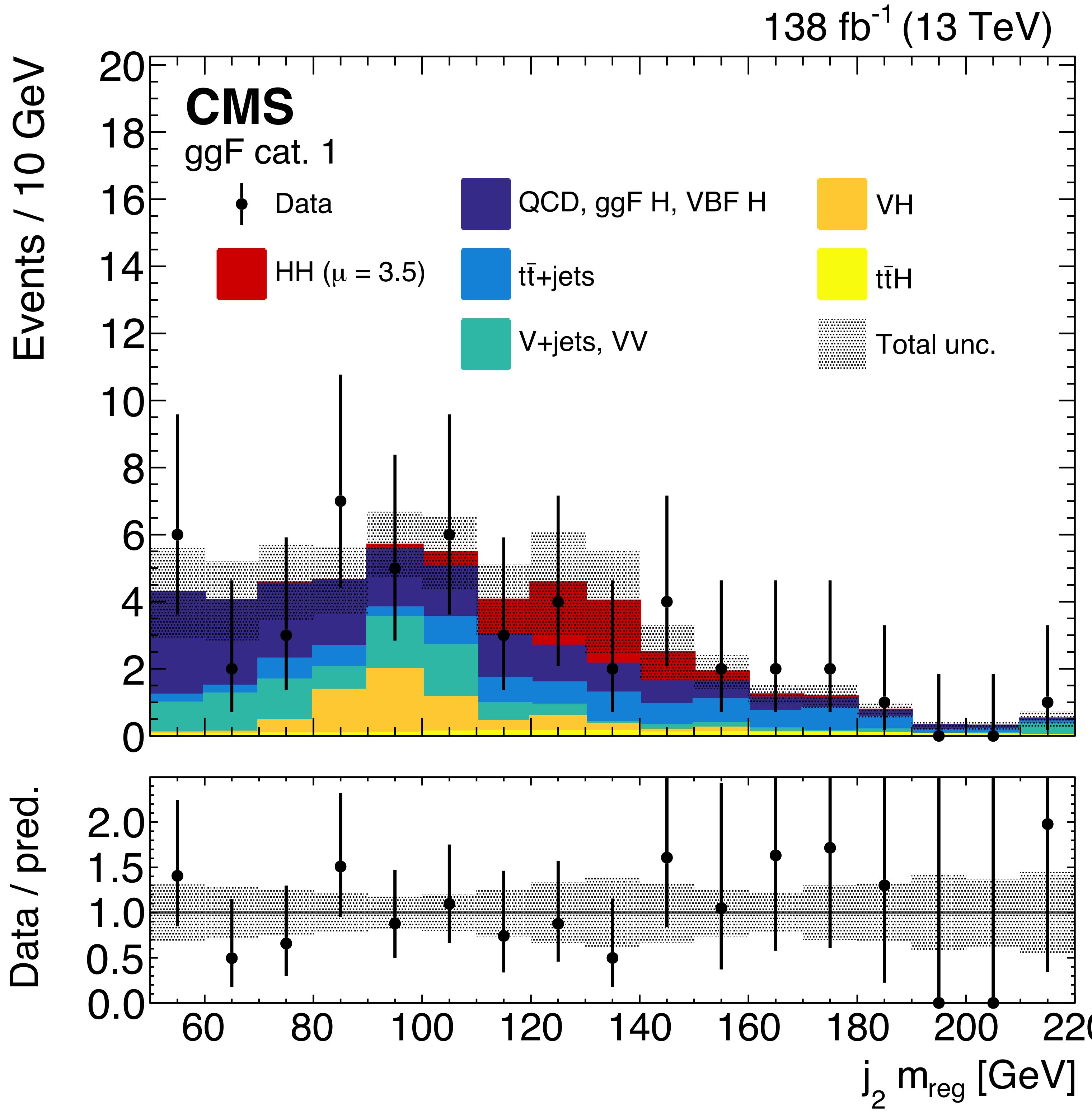
- b-jet pairing based on m_{H1}, m_{H2} plane information
- Data-driven background estimation
- ggF and VBF categories split based on a BDT classifier
- ggF categories further split into low and high m_{HH} region
- 95% CL observed (expected) limit on μ_{HH}: 3.9 (7.8)

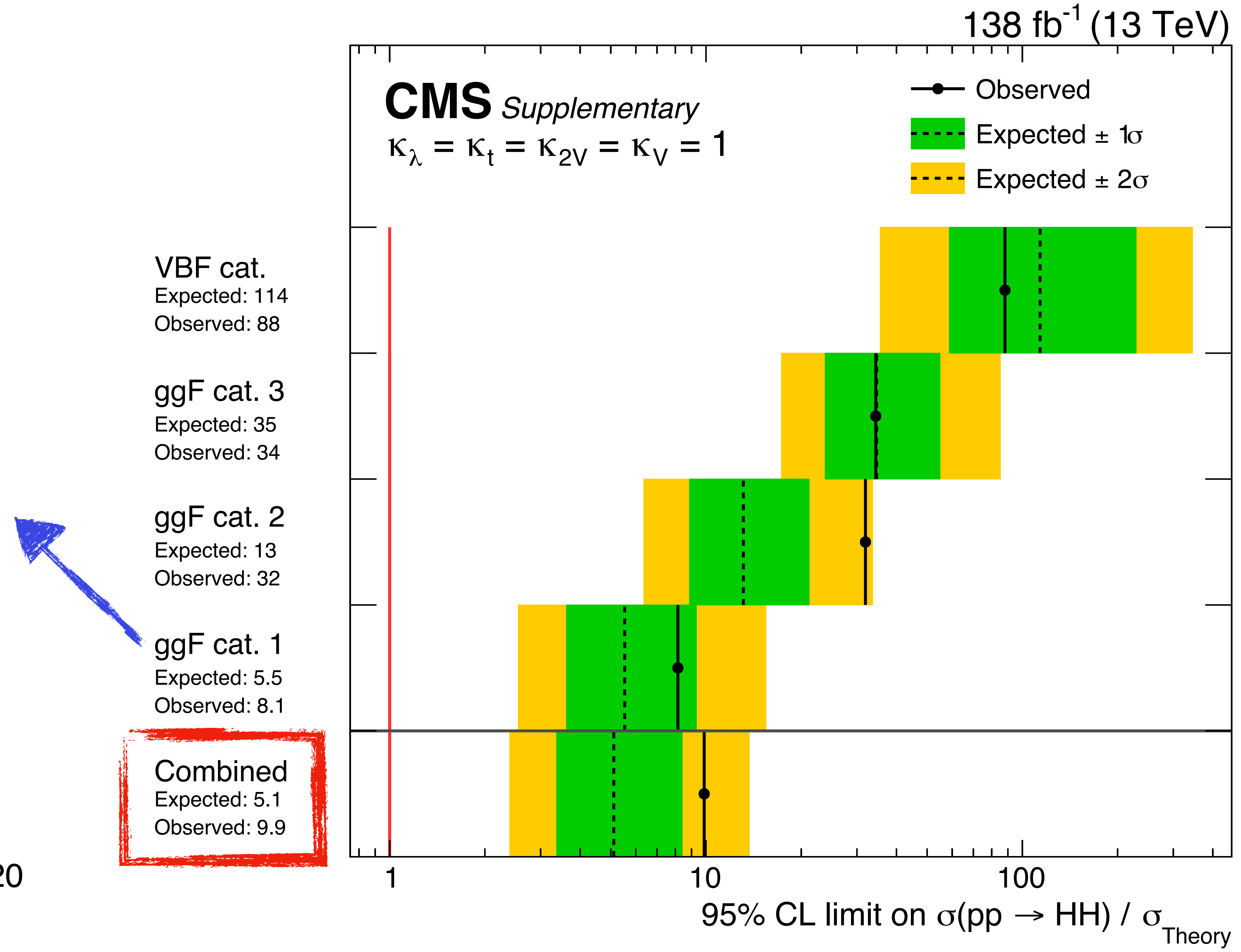
State-of-the-art: CMS boosted $HH \to b\bar{b}b\bar{b}$

PRL 131 (2023) 041803



large-radius jets ($R = 0.8$)
for $p_{T,H} > \sim 300$ GeV
(merged b-jets $\Delta R \sim 2m_H/p_{T,H}$)





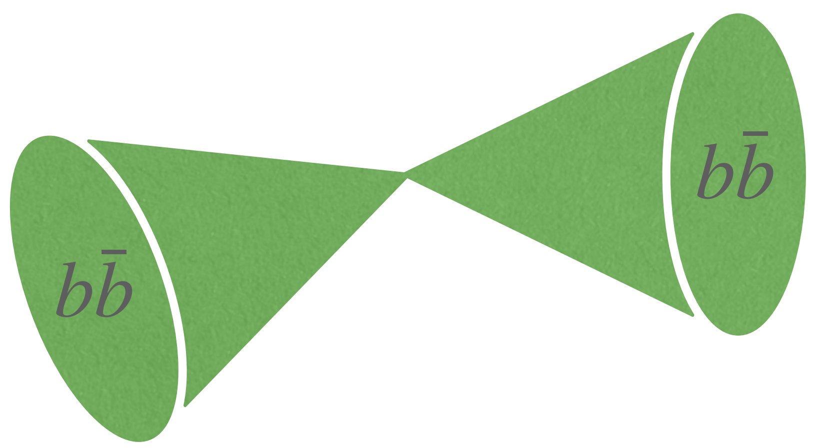
Strategy

- ParticleNet GNN $H \to b\bar{b}$ tagger used to identify the $b\bar{b}$-initiated large-radius jets
- Mixture of several triggers, challenging turn-on modelling
- ggF and VBF categories based on the kinematics of non-central jets in the event
- Three ggF SRs defined based on the ParticleNet scores and large-radius jets masses (obtained using a GNN regression)

30 x better than previous result

Expected sensitivity to κ_λ similar to the resolved analysis

State-of-the-art: CMS boosted $HH \to b\bar{b}b\bar{b}$ (κ_{2V})



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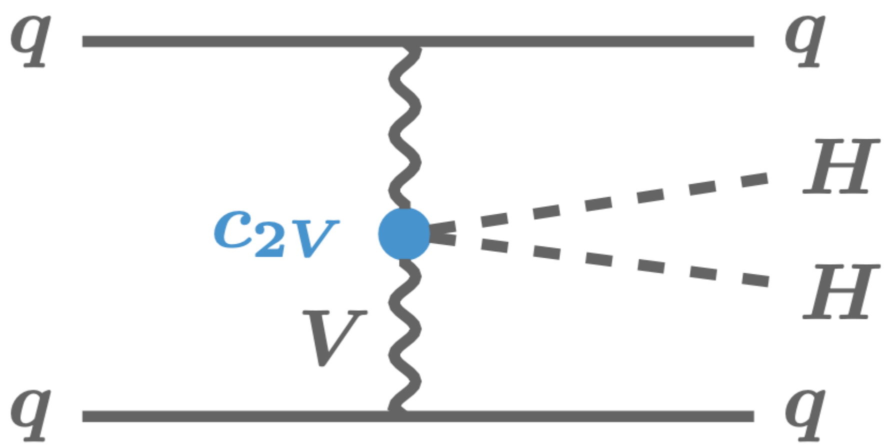
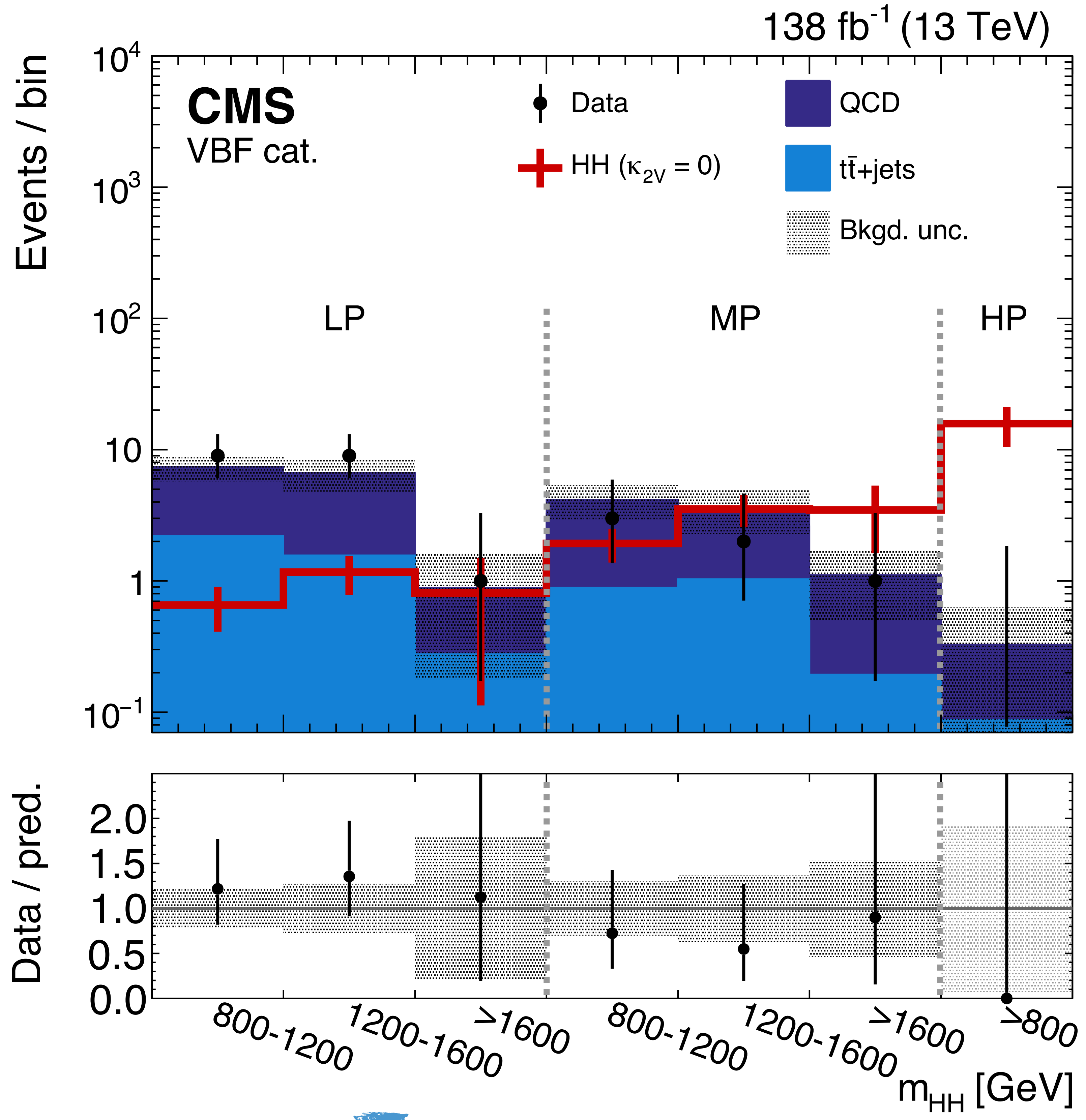
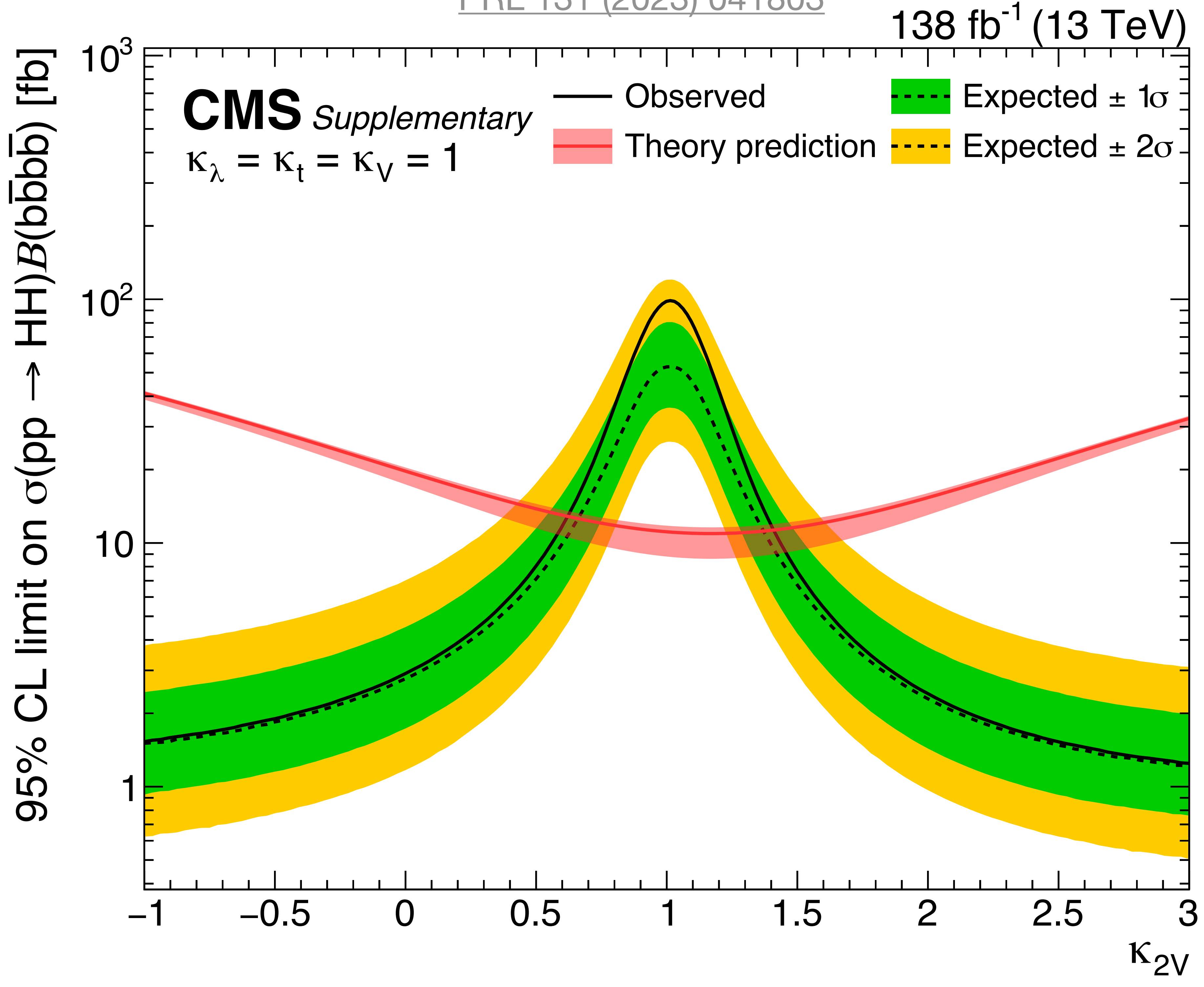




PRL 131 (2023) 041803



VBF categories:

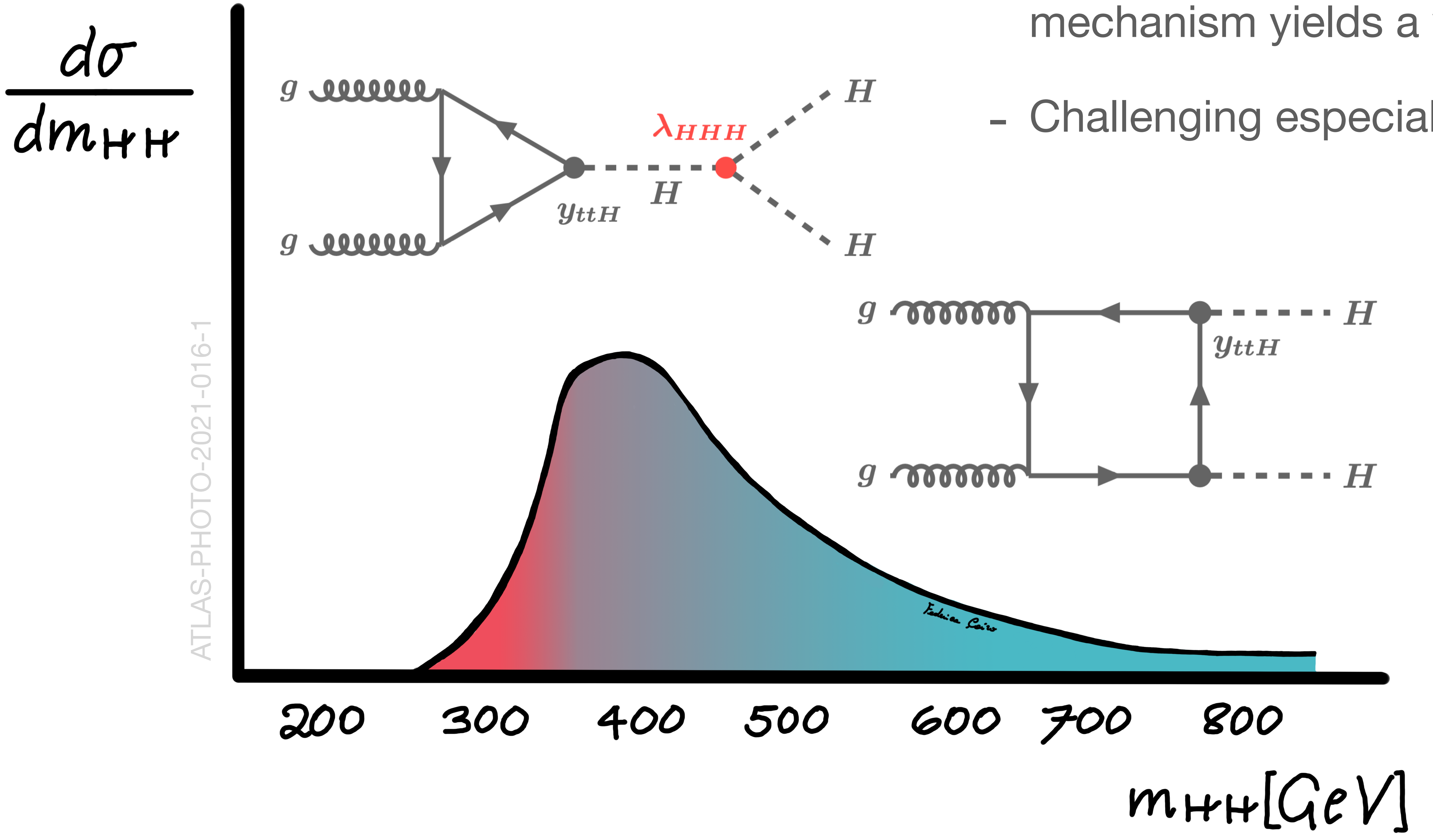
- Boosted analysis provides excellent sensitivity to variations in c_{2V}
- VBF categories defined according to ParticleNet scores and m_{HH}

Obs: $\kappa_{2V} \in [0.62, 1.41]$ at 95% CL

Exp: $\kappa_{2V} \in [0.66, 1.37]$at 95% CL

$\kappa_{2V} = 0$ excluded at 6.3σ
(Assuming all other couplings to be as in the SM)

Trigger challenges

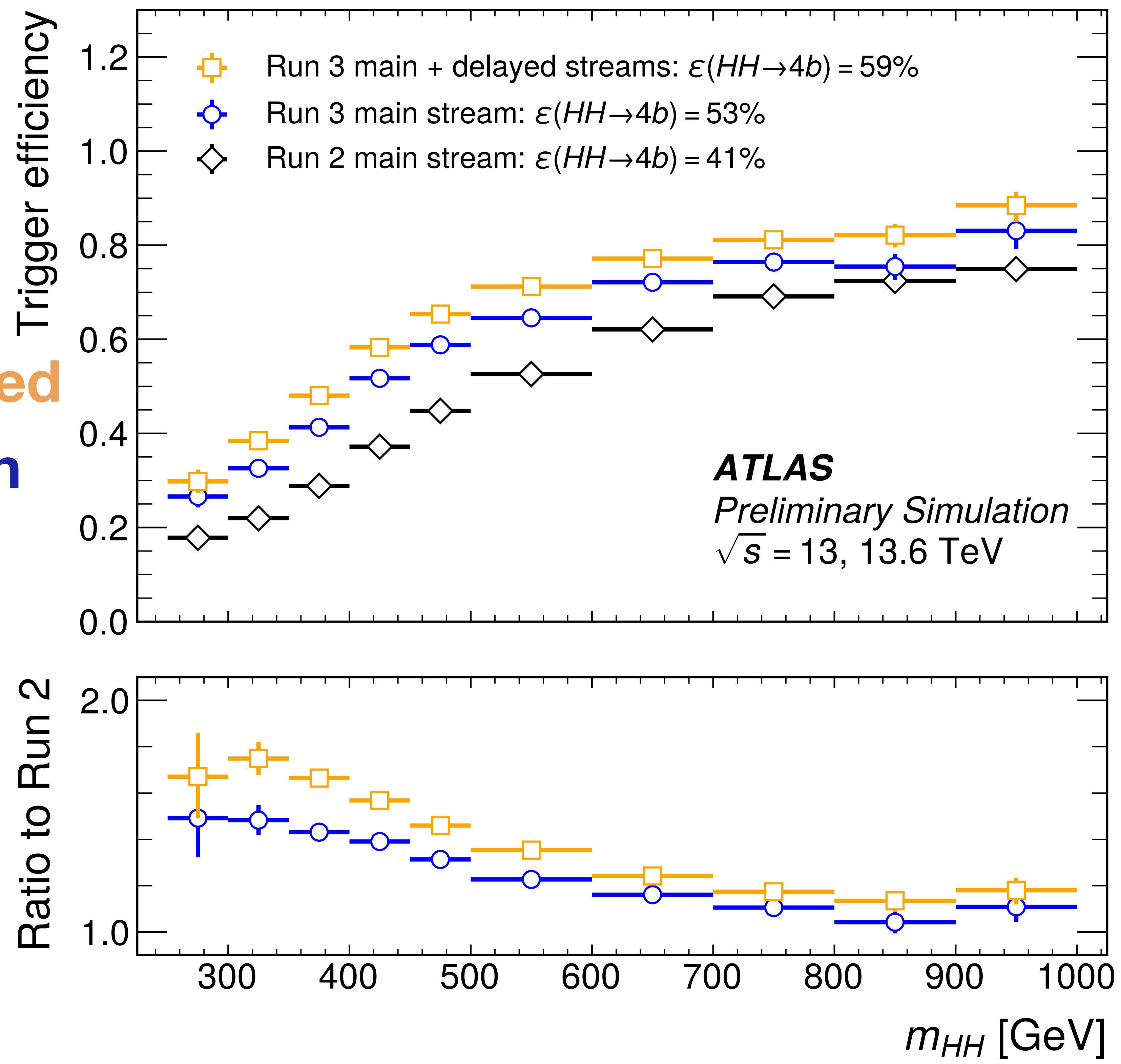


- ggF *HH* production via the Higgs self-coupling mechanism yields a very soft p_T^H spectrum
- Challenging especially for $b\bar{b}b\bar{b}$ and $b\bar{b}\tau_{\text{had}}\tau_{\text{had}}$

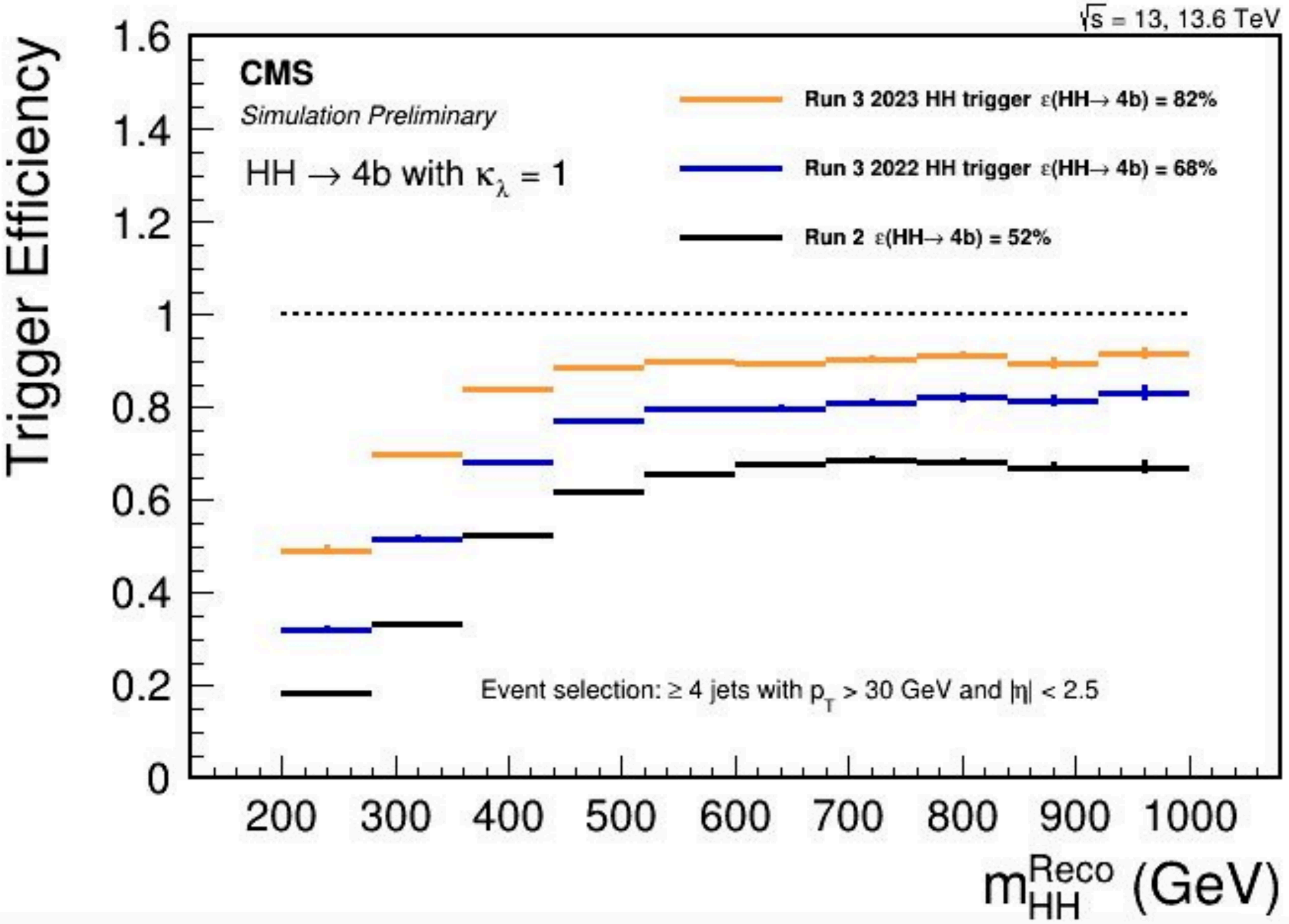
Trigger developments for Run 3: $HH \rightarrow b\bar{b}b\bar{b}$

BJetTriggerPublicResults

2022 delayed
2022 main
Run 2



CERN-CMS-DP-2023-050



2023
2022
Run 2

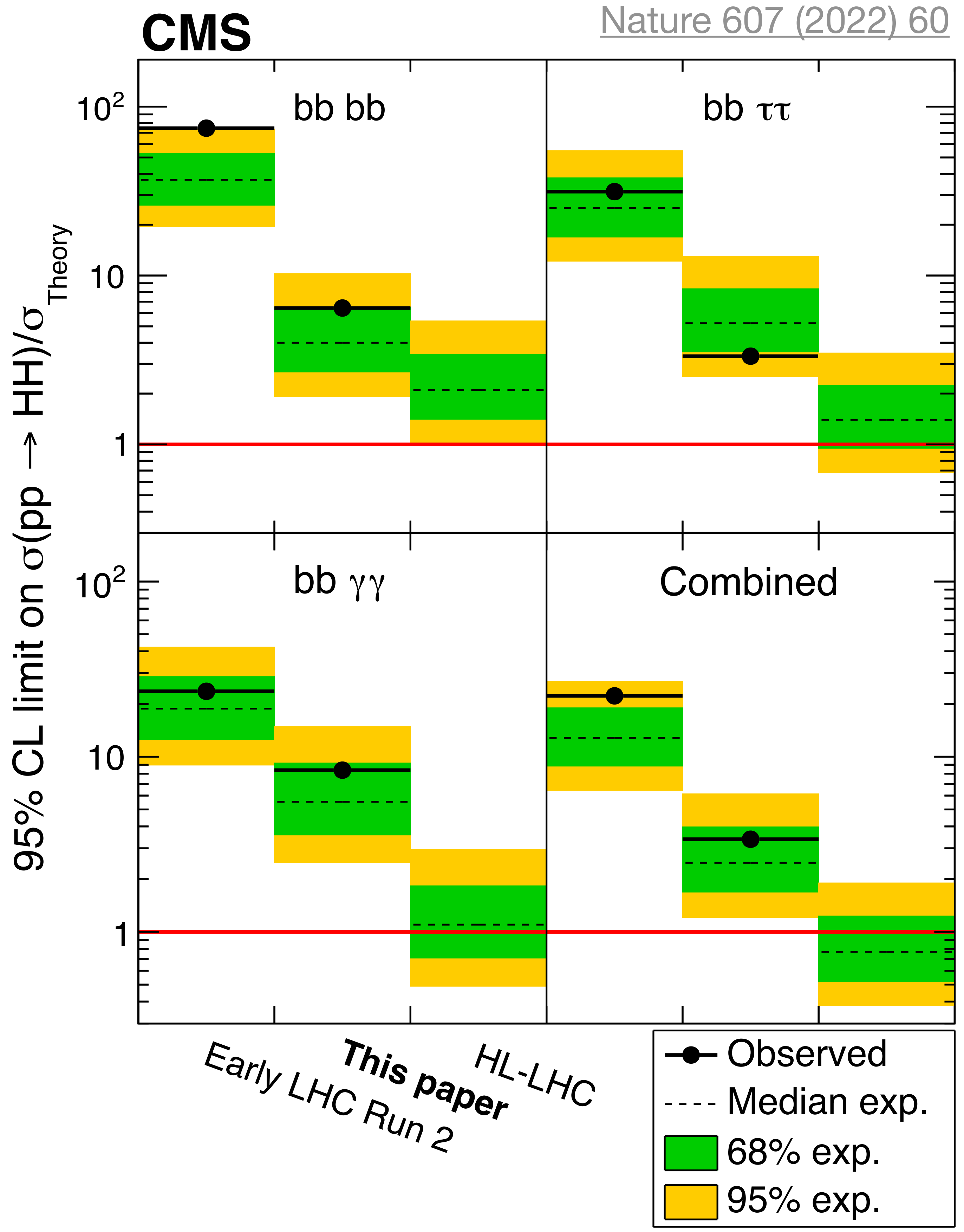
Improvements w.r.t. Run 2 in ATLAS

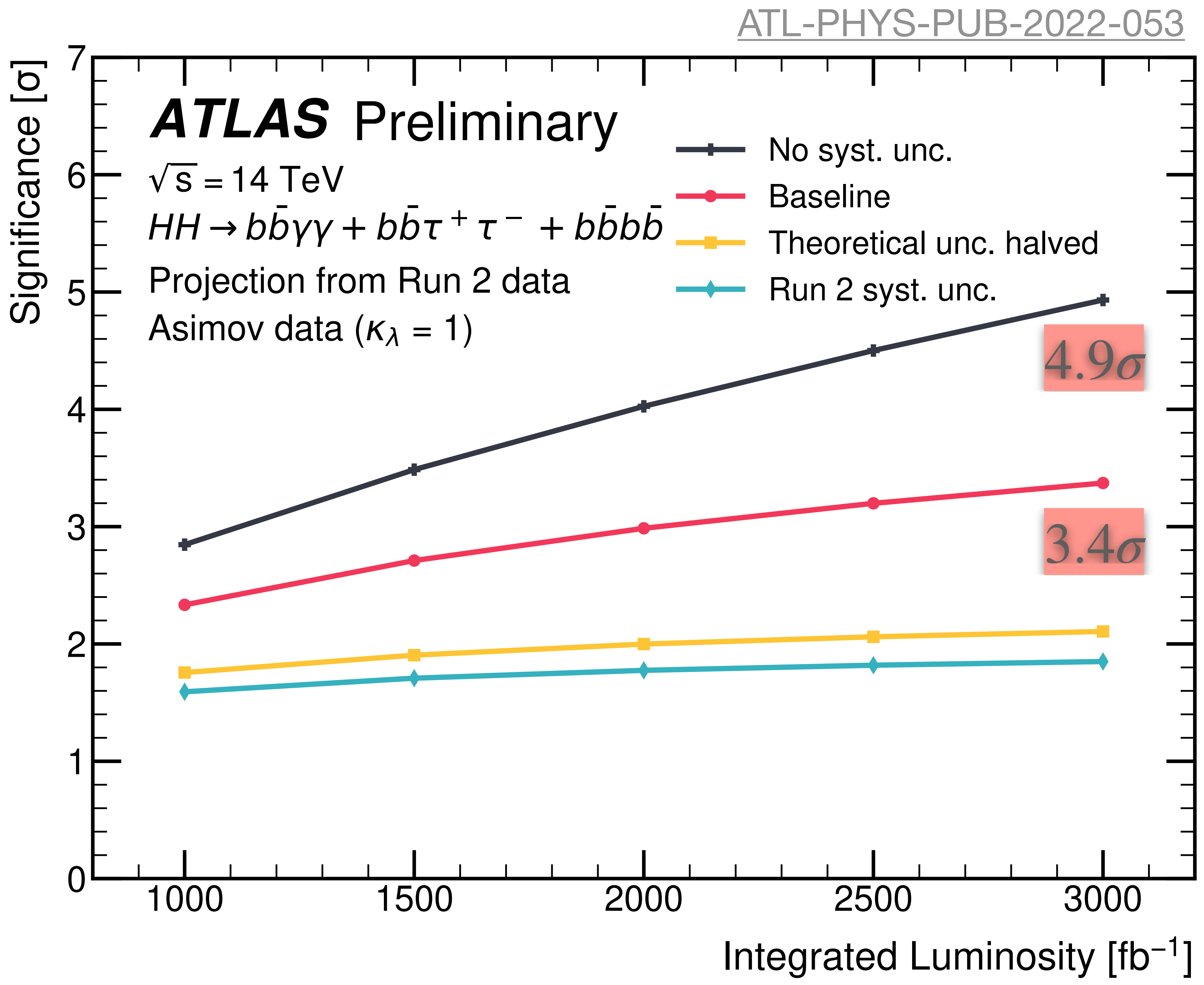
- 3-b-jet triggers with **asymmetrical p_T thresholds**
- 2-b-jet triggers with asymmetrical p_T thresholds in the **"Delayed trigger stream"**
- **GN2 *b*-tagging** at the trigger level (added in 2023)
- Similar developments for $HH \rightarrow b\bar{b}\tau\tau$

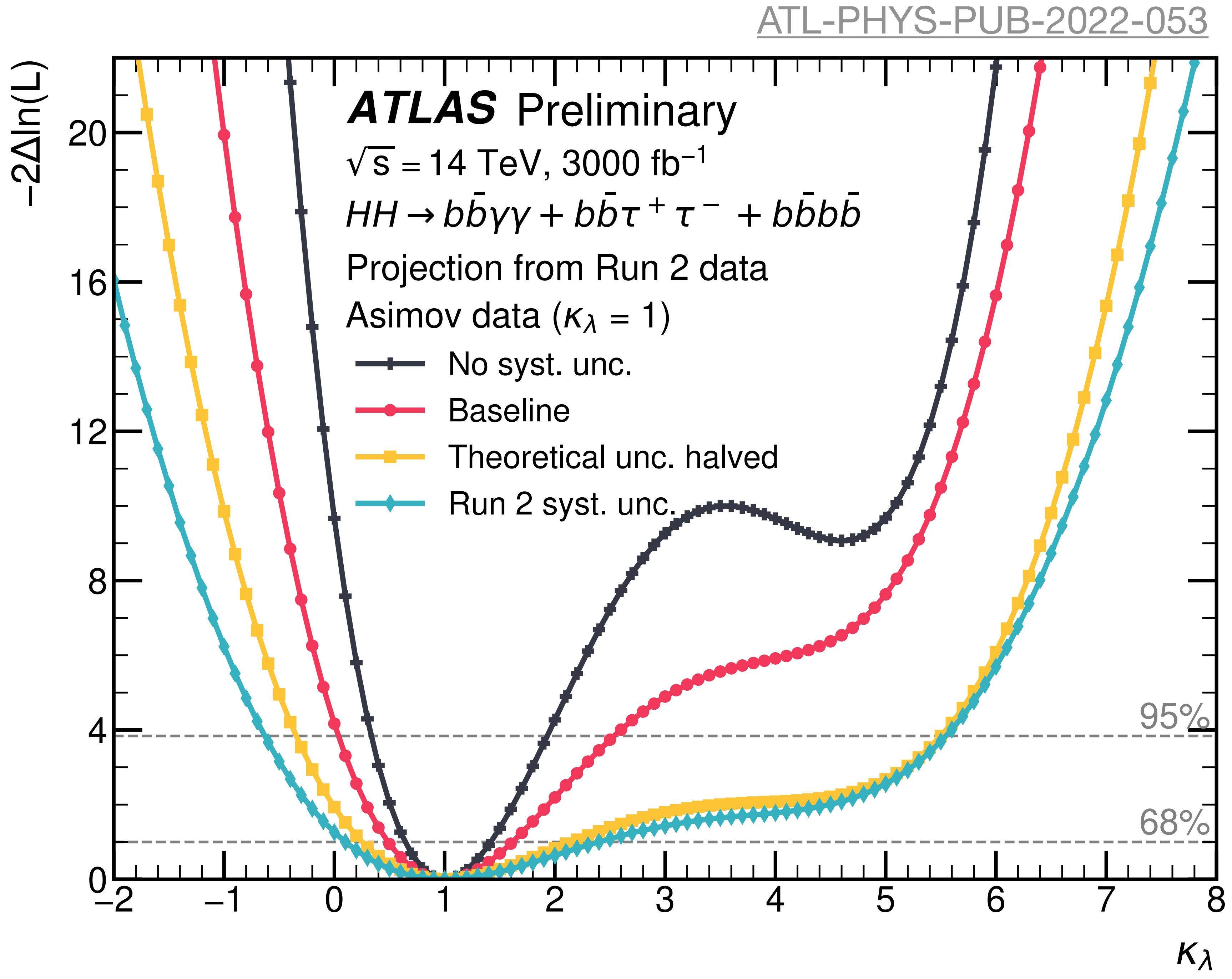
Improvements w.r.t. Run 2 in CMS

- **ParticleNet *b*-tagging** at the trigger level
- Lowered threshold on the scalar sum of jet transverse momenta in the event from 360 to 280 GeV using the "**Data Parking**" strategy

HL-LHC projections







ATLAS

Expected discovery significance in the baseline scenario for the evolution of systematic uncertainties, assuming SM signal: 3.4σ

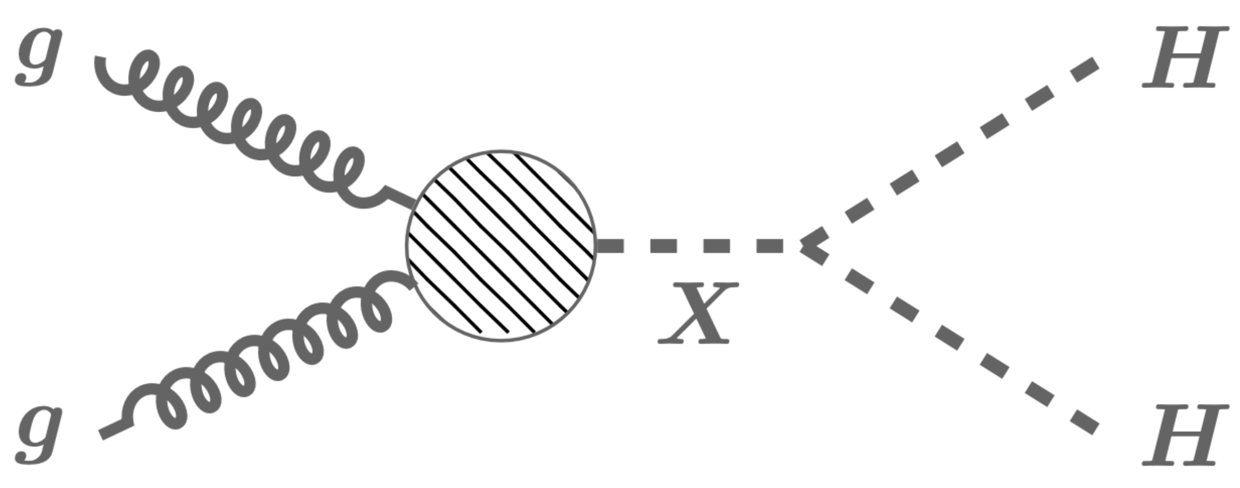
In the same scenario: $\kappa_\lambda = 1^{+0.5}_{-0.6}$

ATLAS + CMS combination could potentially yield 5σ

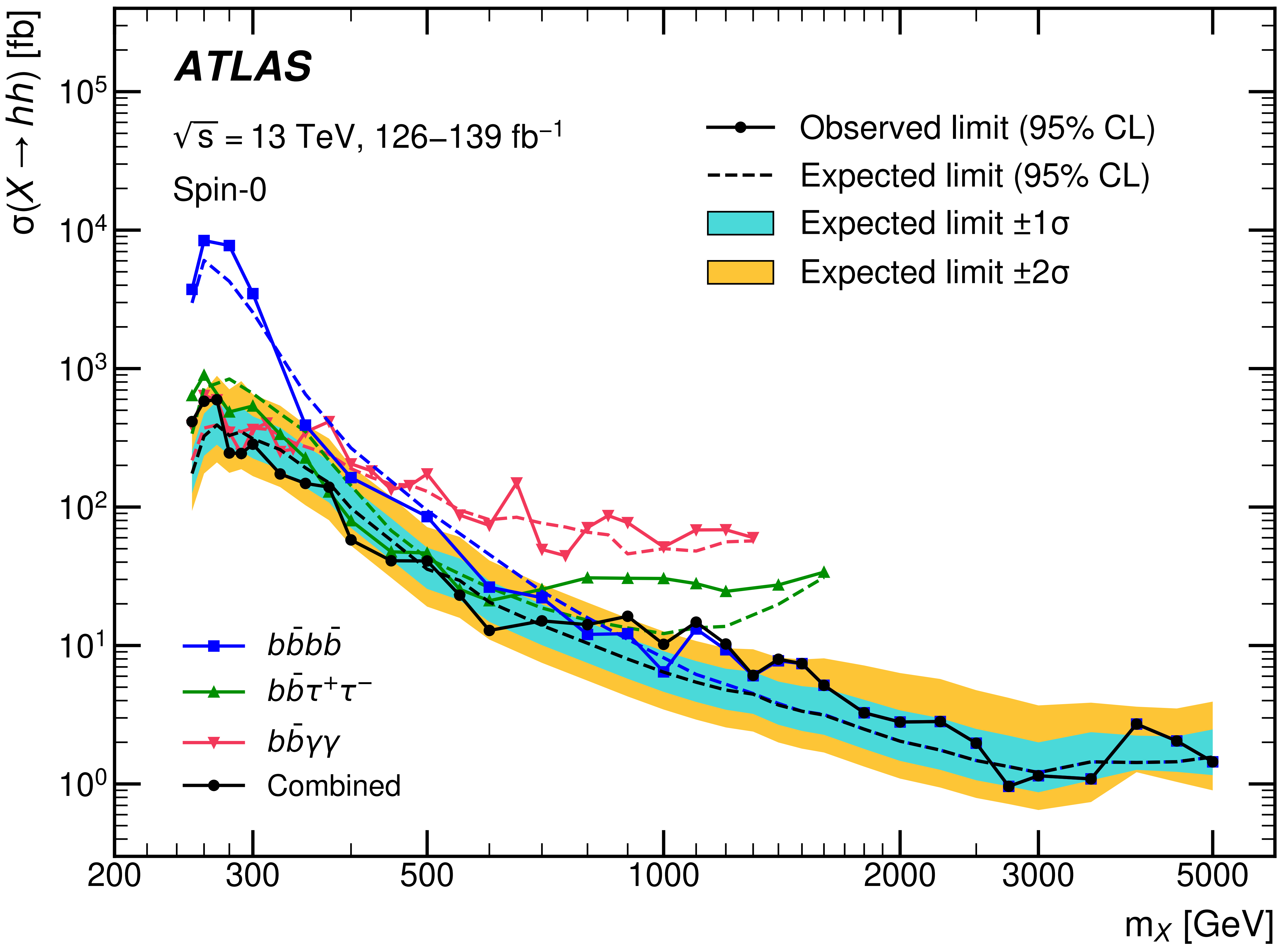
CMS

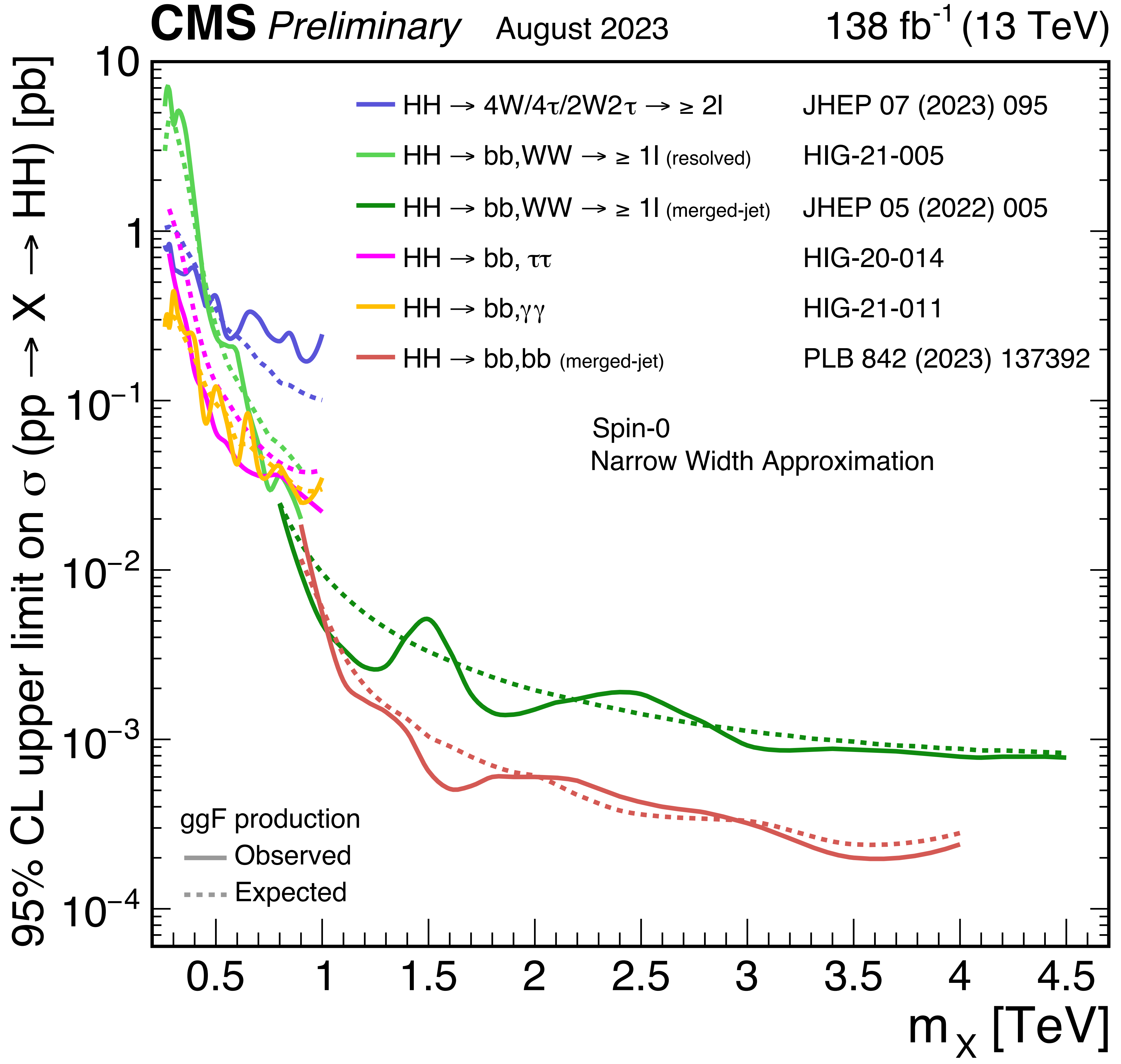
Assuming no HH production, projections show it would be excluded

Resonant *HH* production



Resonant *HH* production





ATLAS

Excess observed at 1.1 TeV. Local (global) significance 3.3 (2.1) σ

$b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$ most sensitive at low, intermediate, high m_{HH}

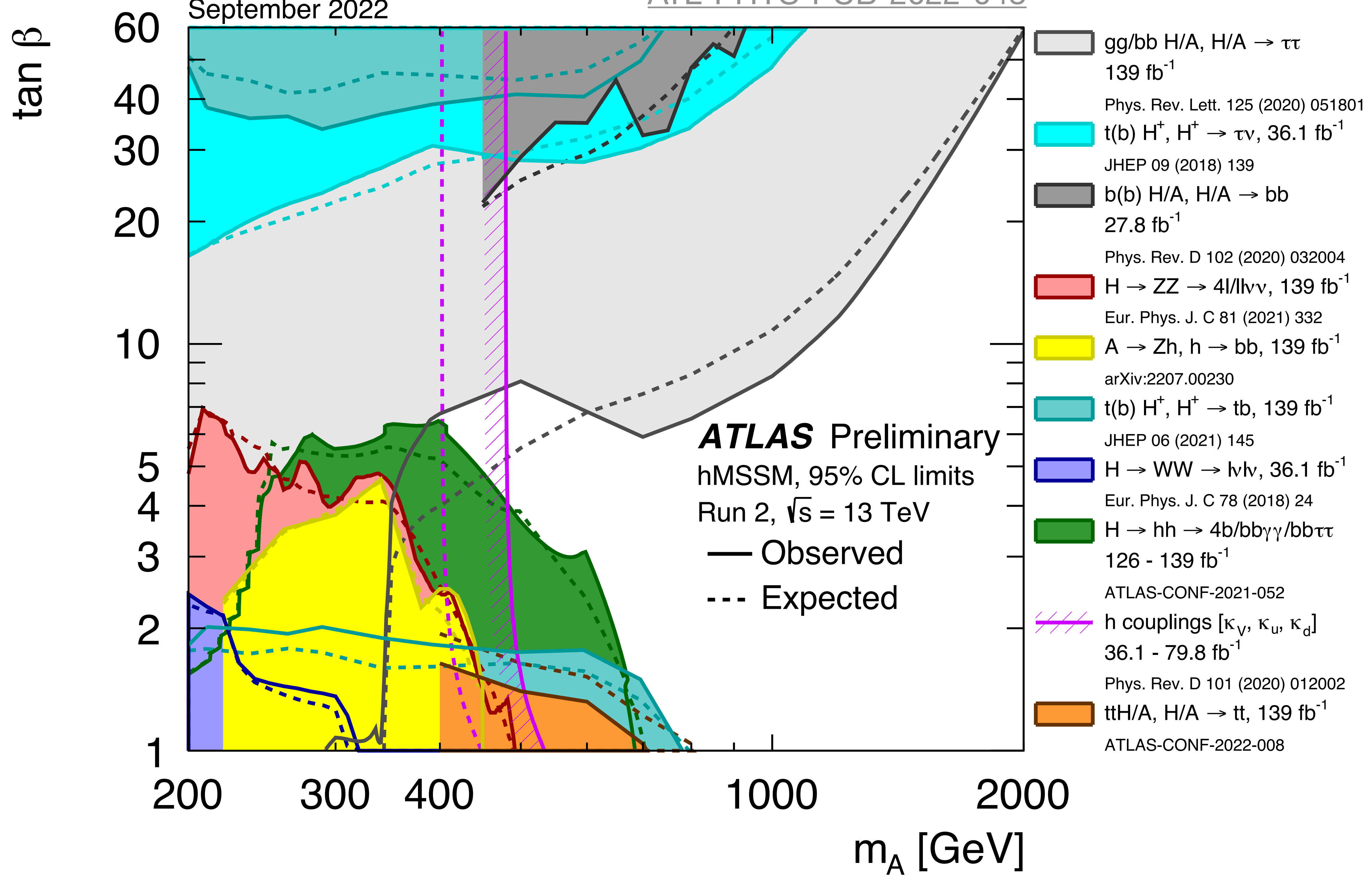
CMS

No excess

$b\bar{b}\gamma\gamma$, $b\bar{b}WW$, $b\bar{b}b\bar{b}$ most sensitive at low, intermediate, high m_{HH}

Interpretations, $X \to HY$ searches

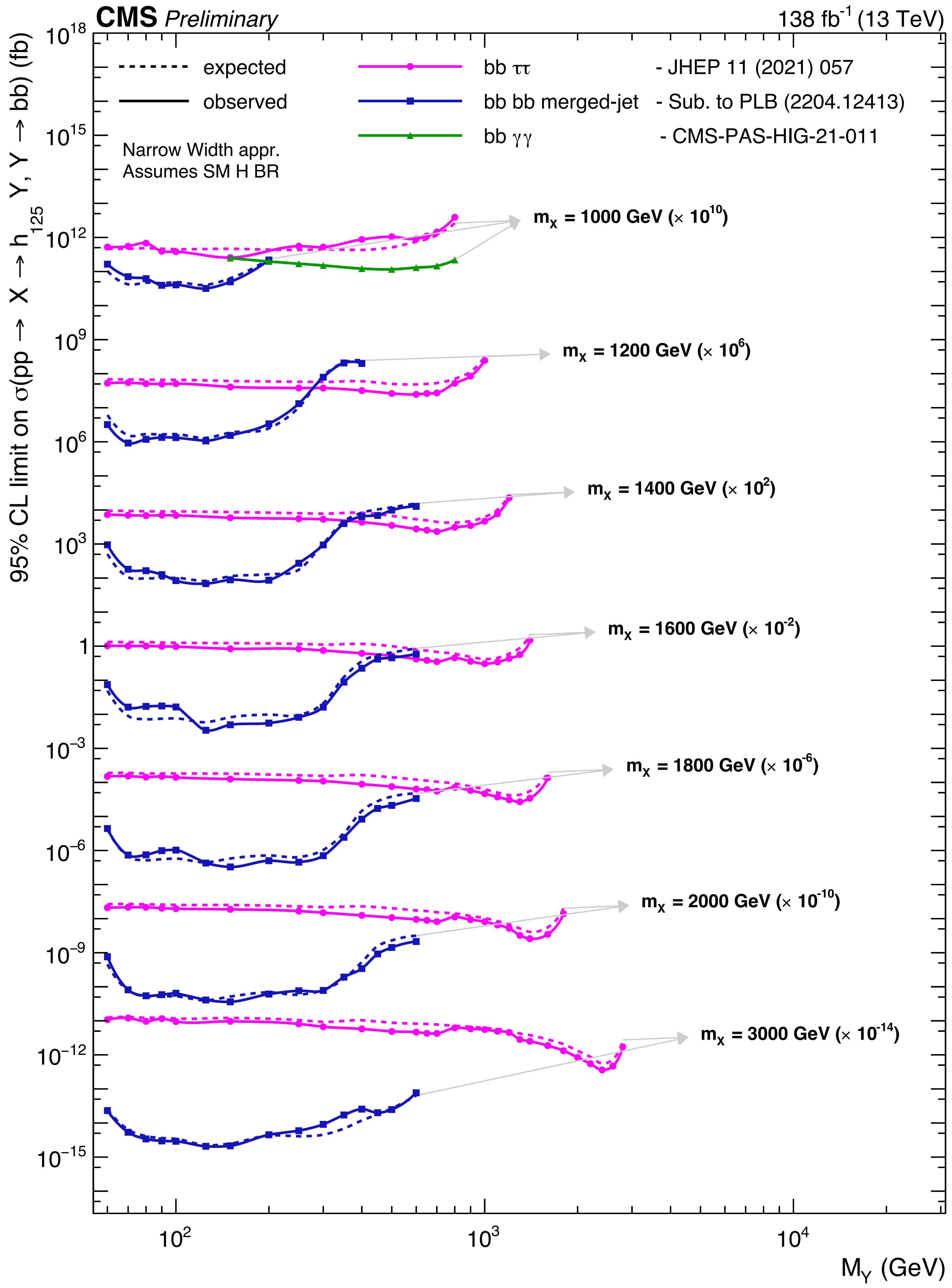
ATL-PHYS-PUB-2022-043

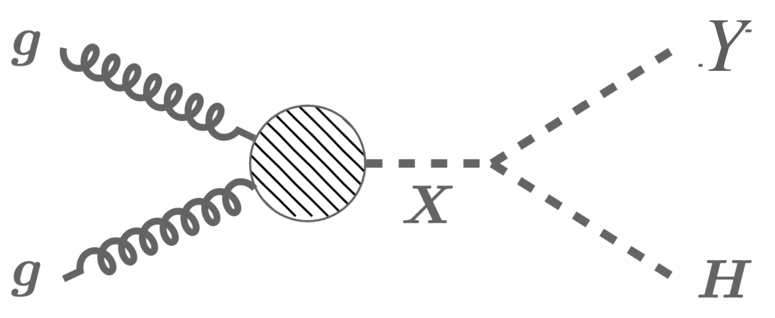


MSSM constraints - resonant HH searches

most sensitive analysis for intermediate tanβ

CMSSummaryResultsHIG





Combined limits on
$X \to HY$ searches
(extended Higgs sectors)

ATLAS results:

$b\bar{b}$+ hadronic Y decays
PRD 108 (2023) 052009

$\tau\tau$ + $Y \to VV$
JHEP 10 (2023) 009

Summary and outlook

Impressive Run 2 limits on μ_{HH}

- ATLAS: 2.4 (exp. 2.9) + updates from $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$
- CMS: 3.4 (exp. 2.5)

Allowed κ_λ ranges

- ATLAS: [-0.4, 6.3] (exp. [-1.9, 7.6]) + updates from $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$
- CMS: [-1.2, 7.5] (exp. [-2.0, 7.7])

Allowed κ_{2V} ranges

- ATLAS: [0.1, 2.0] (exp. [0.0, 2.1]) + updates
- CMS: [0.62,1.4] (exp. [0.66, 1.37]) (boosted $HH \rightarrow b\bar{b}b\bar{b}$)

Run 3 prospects

- Improvements expected due to new triggers, tagging algorithms and further improvements of the analyses

Resonant *HH* and extended Higgs sector

- Many interesting searches with a discovery potential

Quartic Higgs boson self-coupling much more difficult to probe.

Experiments, however, started considering probing HHH production

CERN-CMS-DP-2023-050