ATLAS HH combination and EFT interpretation

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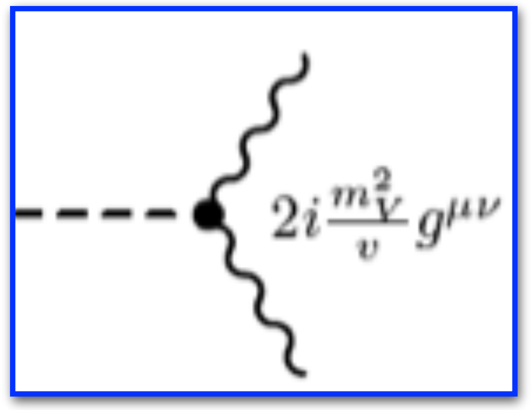
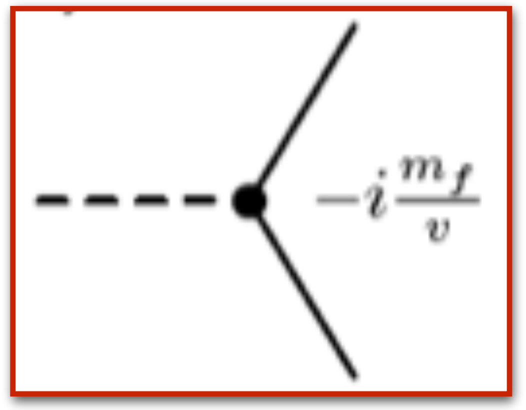
Higgs Self-coupling

The Higgs particle is responsible for the masses of elementary particles

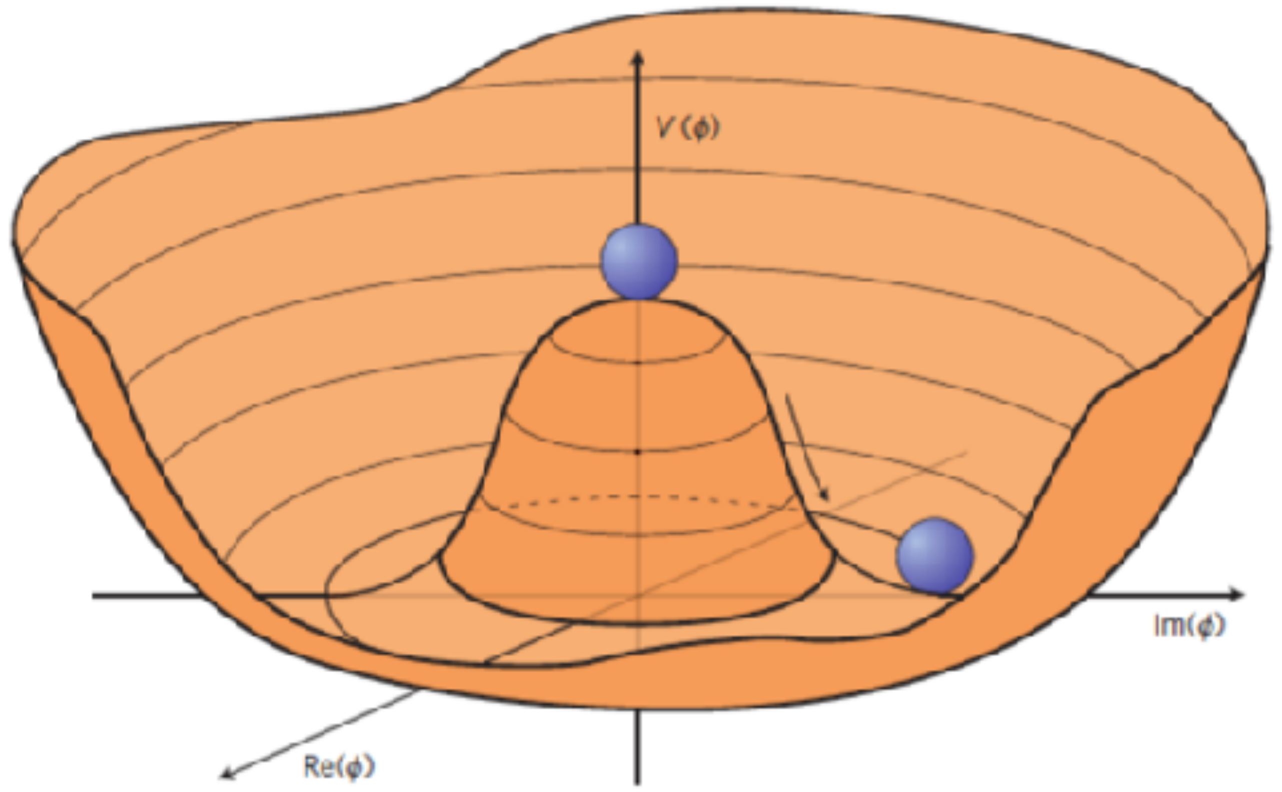
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$



Gauge coupling



Yukawa coupling



◈ **Higgs potential approximation:**

$$V(h) = \frac{1}{2}m_H^2h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

Self-coupling

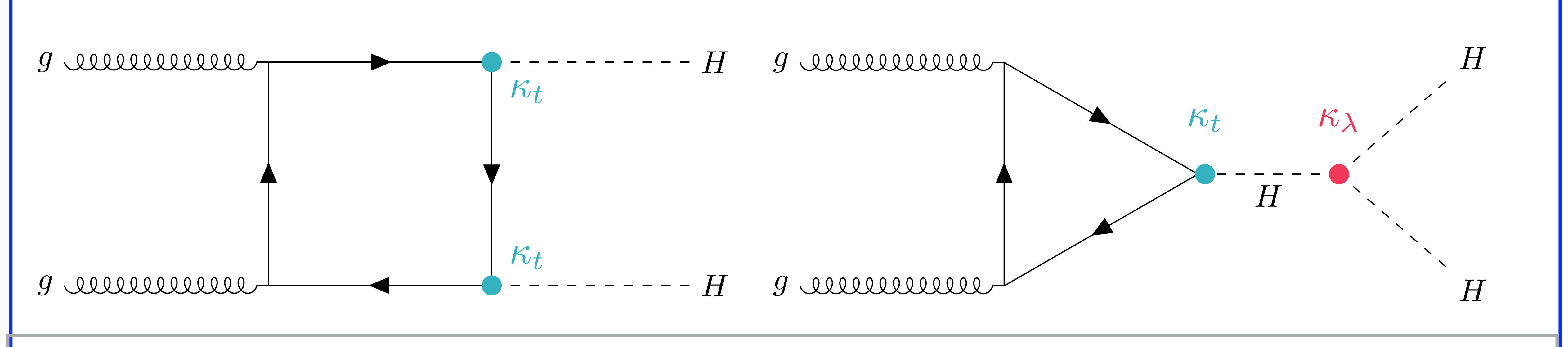
with $\lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2v^2}$ $\kappa_\lambda = \kappa_3 = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$

◈ **Understanding Non-trivial Structure to the Higgs potential**

◈ **Understanding the stability of the universe**

Di-Higgs production @ LHC

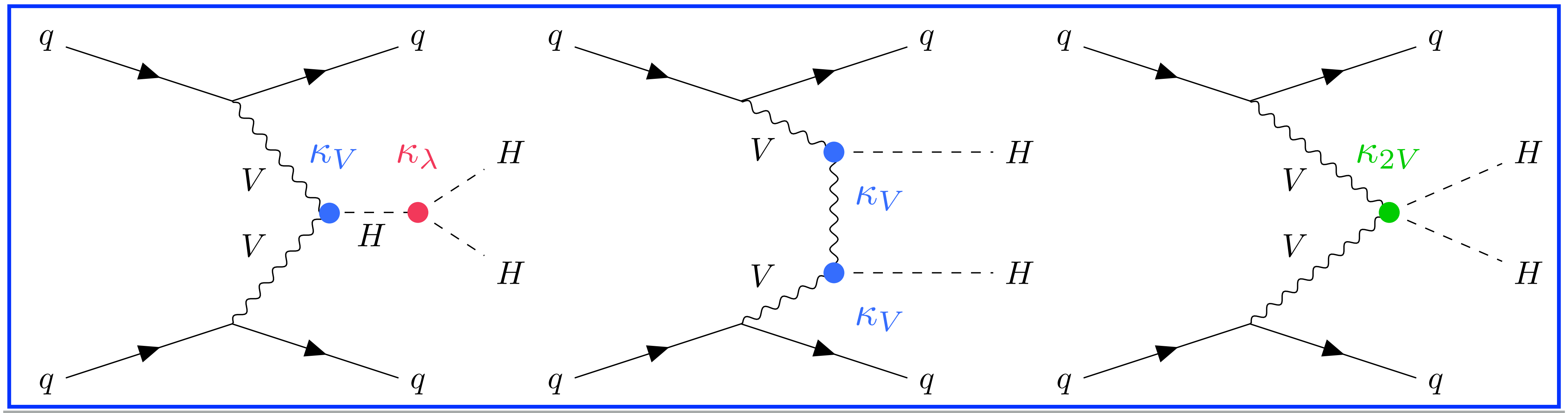
Directly sensitive to Higgs self-coupling at LO



Dominant mode: $\sigma_{ggF}(HH) = 31.0^{+2.1}_{-7.2}$ fb@13TeV

Destructive interference between the two diagrams

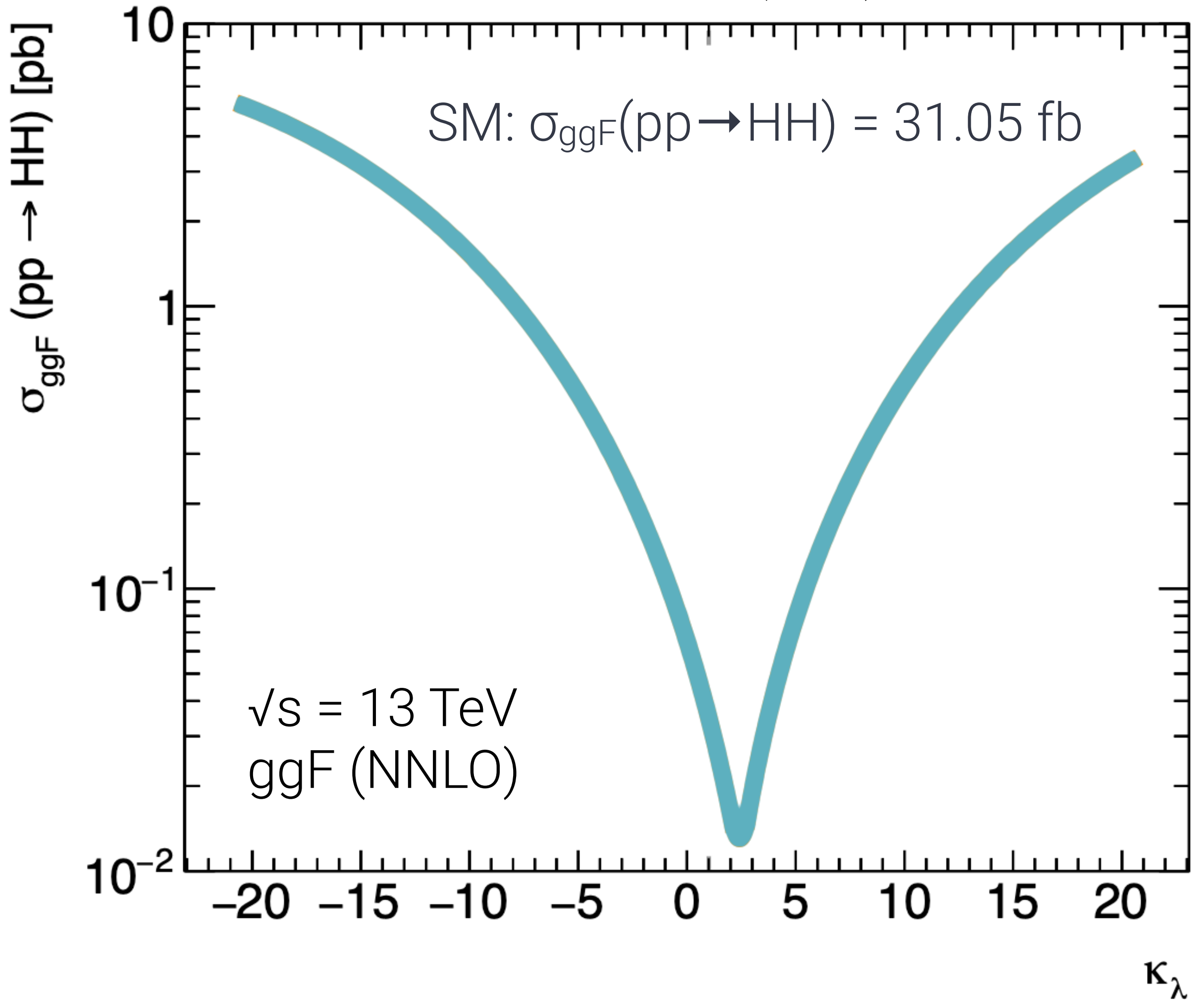
Dependent on κ_λ and κ_t



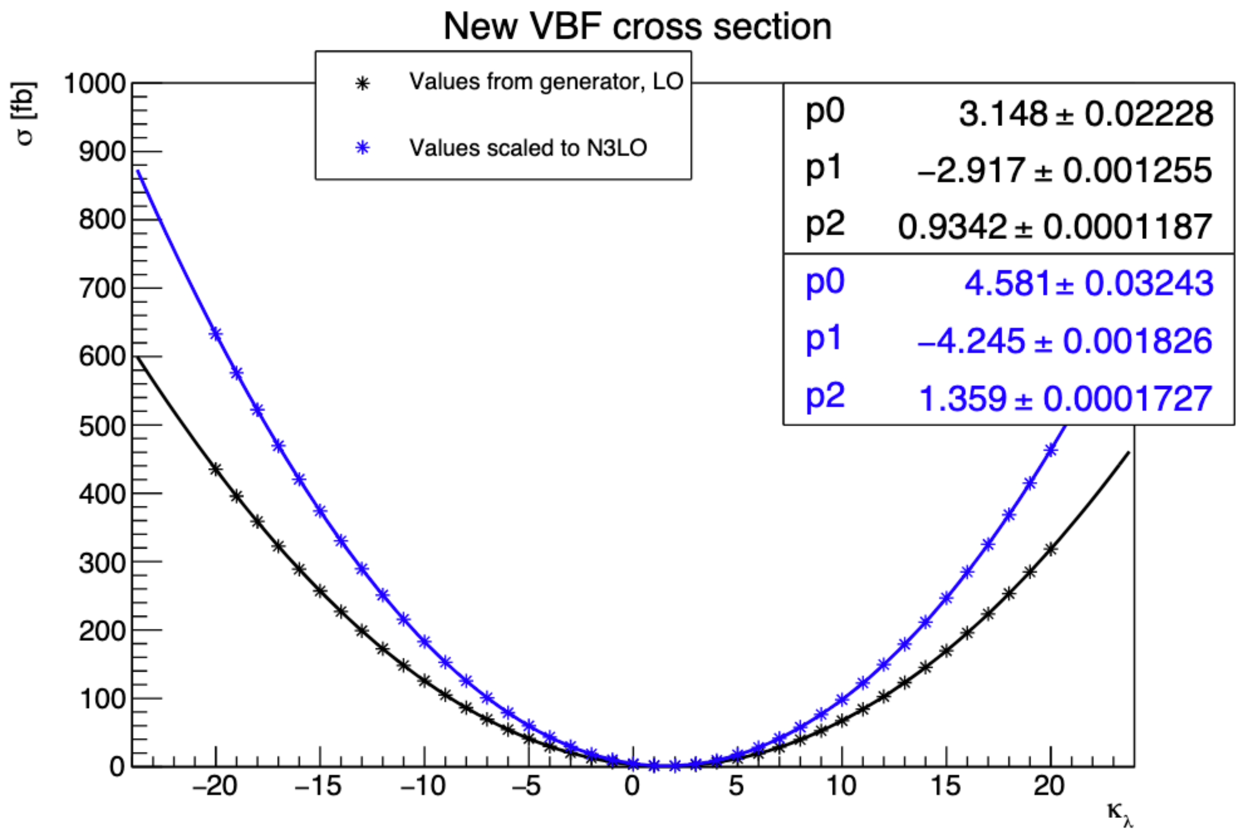
Second abundent mode: $\sigma_{VBF}(HH)$= 1.72±0.04fb@13TeV

Dependent on κ_λ , κ_V and κ_{2V}

JHEP 05 (2018) 059 and others



$$\frac{d\sigma_{ggF}}{d\Phi}(\kappa_\lambda,\kappa_t) = \kappa_t^2\left[\left(\kappa_t^2+\frac{\kappa_\lambda^2}{20}-\frac{399}{380}\kappa_\lambda\kappa_t\right)\times\frac{d\sigma_{ggF}}{d\Phi}(0,1) + \left(\frac{40}{38}\kappa_\lambda\kappa_t-\frac{2}{38}\kappa_\lambda^2\right)\times\frac{d\sigma_{ggF}}{d\Phi}(1,1) + \left(\frac{\kappa_\lambda^2-\kappa_\lambda\kappa_t}{380}\right)\times\frac{d\sigma_{ggF}}{d\Phi}(20,1)\right]$$



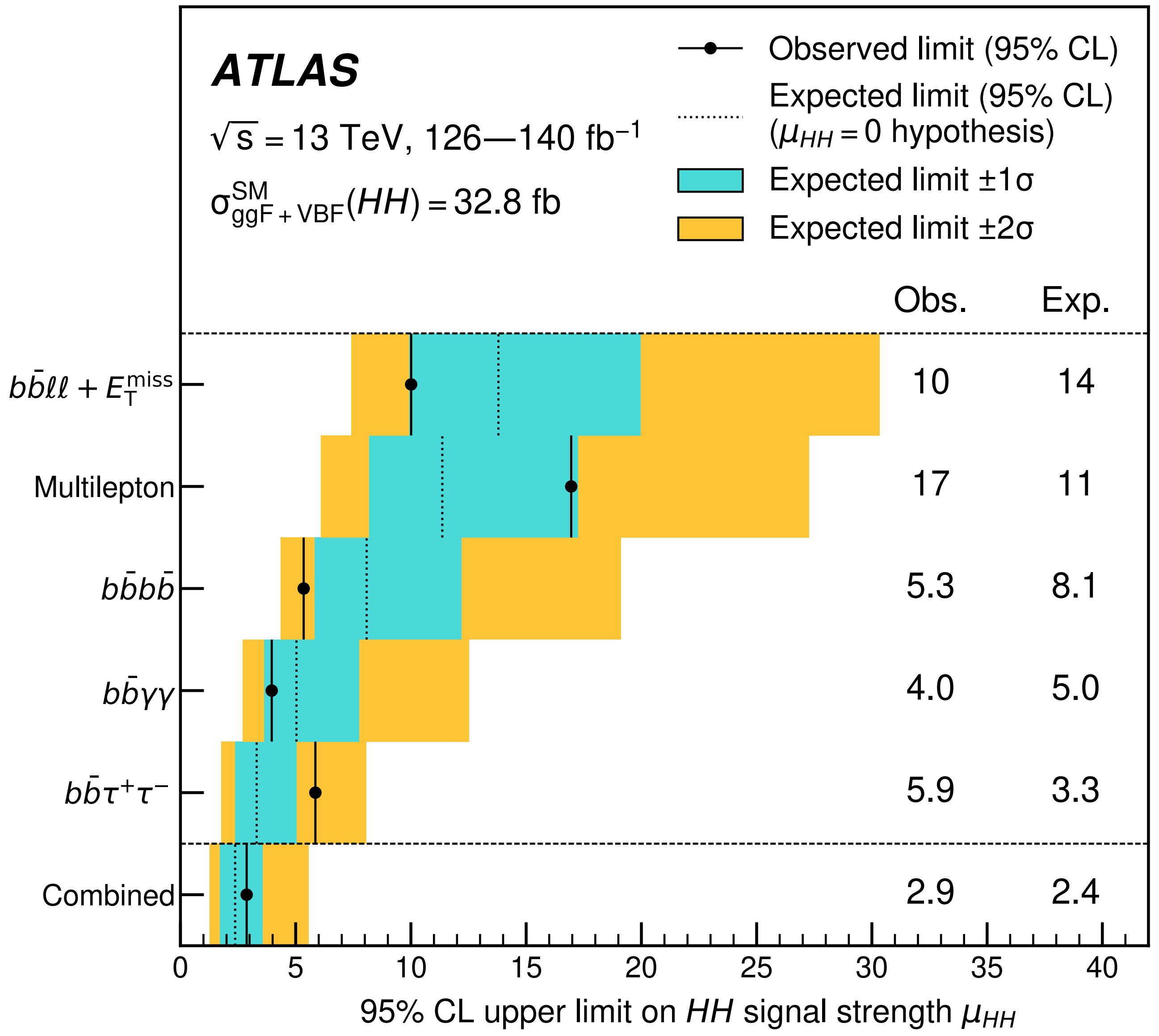
$$\frac{d\sigma_{VBF}}{d\Phi}(\kappa_\lambda,\kappa_{2V},\kappa_V) = \left(\frac{68\kappa_{2V}^2}{135} - 4\kappa_{2V}\kappa_V^2 + \frac{20\kappa_{2V}\kappa_V\kappa_\lambda}{27} + \frac{772\kappa_V^4}{135} - \frac{56\kappa_V^3\kappa_\lambda}{27} + \frac{\kappa_V^2\kappa_\lambda^2}{9}\right)\times\frac{d\sigma_{VBF}}{d\Phi}(1,1,1)$$
$$+\left(-\frac{4\kappa_{2V}^2}{5} + 4\kappa_{2V}\kappa_V^2 - \frac{16\kappa_V^4}{5}\right)\times\frac{d\sigma_{VBF}}{d\Phi}(1,1.5,1)$$
$$+\left(\frac{11\kappa_{2V}^2}{60} + \frac{\kappa_{2V}\kappa_V^2}{3} - \frac{19\kappa_{2V}\kappa_V\kappa_\lambda}{4} - \frac{53\kappa_V^4}{30} - + \frac{13\kappa_V^3\kappa_\lambda}{6} - \frac{\kappa_V^2\kappa_\lambda^2}{8}\right)\times\frac{d\sigma_{VBF}}{d\Phi}(2,1,1)$$
$$+\left(-\frac{11\kappa_{2V}^2}{140} + \frac{11\kappa_{2V}\kappa_V\kappa_\lambda}{216} + \frac{13\kappa_V^4}{270} - \frac{5\kappa_V^3\kappa_\lambda}{54} + \frac{\kappa_V^2\kappa_\lambda^2}{72}\right)\times\frac{d\sigma_{VBF}}{d\Phi}(10,1,1)$$
$$+\left(\frac{88\kappa_{2V}^2}{45} - \frac{16\kappa_{2V}\kappa_V^2}{3} + \frac{4\kappa_{2V}\kappa_V\kappa_\lambda}{9} + \frac{152\kappa_V^4}{45} - \frac{4\kappa_V^3\kappa_\lambda}{9}\right)\times\frac{d\sigma_{VBF}}{d\Phi}(1,1,0.5)$$
$$+\left(\frac{8\kappa_{2V}^2}{45} - \frac{4\kappa_{2V}\kappa_V\kappa_\lambda}{9} - \frac{8\kappa_V^4}{45} + \frac{4\kappa_V^3\kappa_\lambda}{9}\right)\times\frac{d\sigma_{VBF}}{d\Phi}(-5,1,0.5)$$

Parametrization with 3 independent samples (κ_λ, κ_t)

Parametrization with 6 independent samples (κ_λ ,κ_V, κ_{2V})

HH combination with different di-Higgs decays

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%



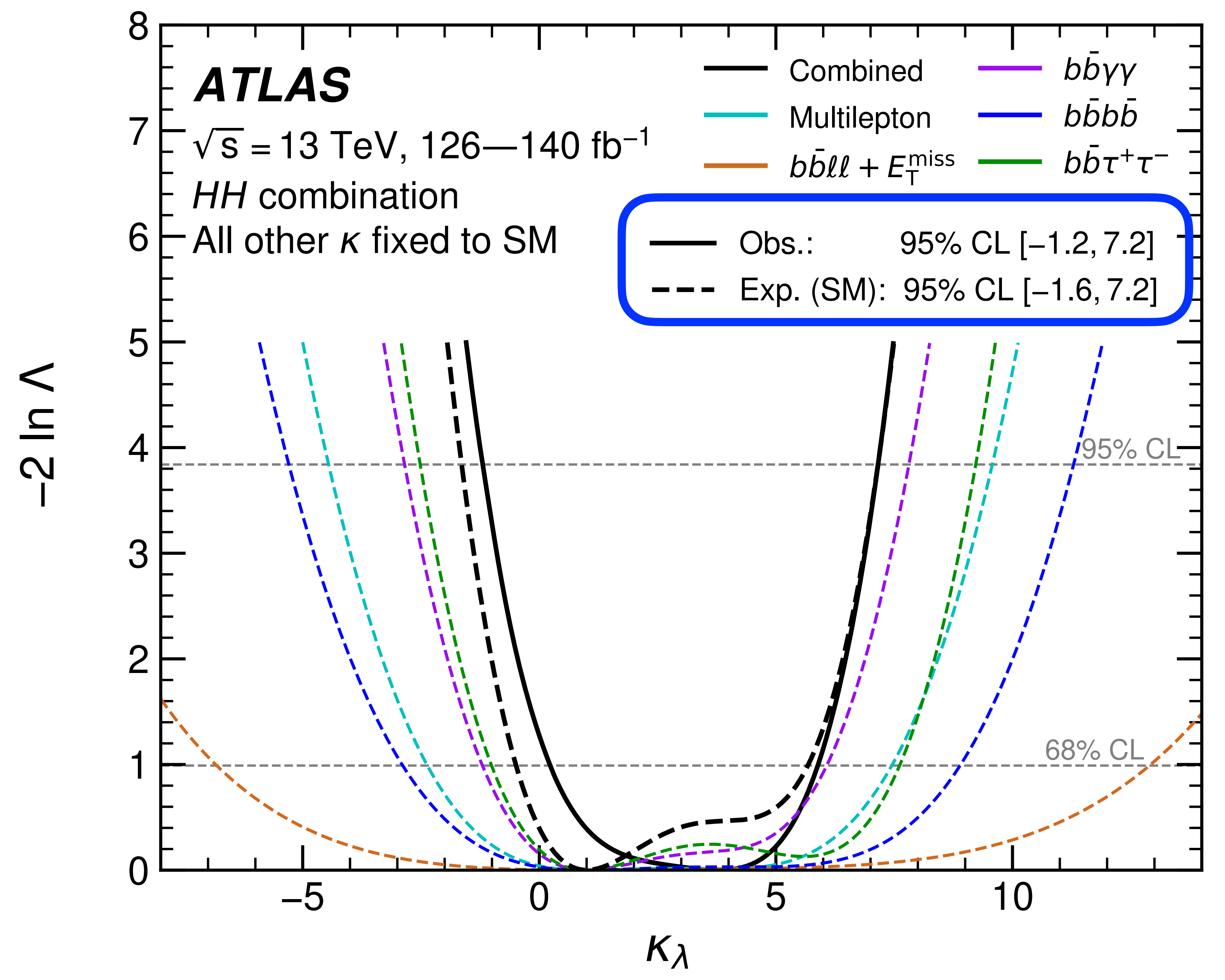
All channels have trade-offs between branching ratio vs final state

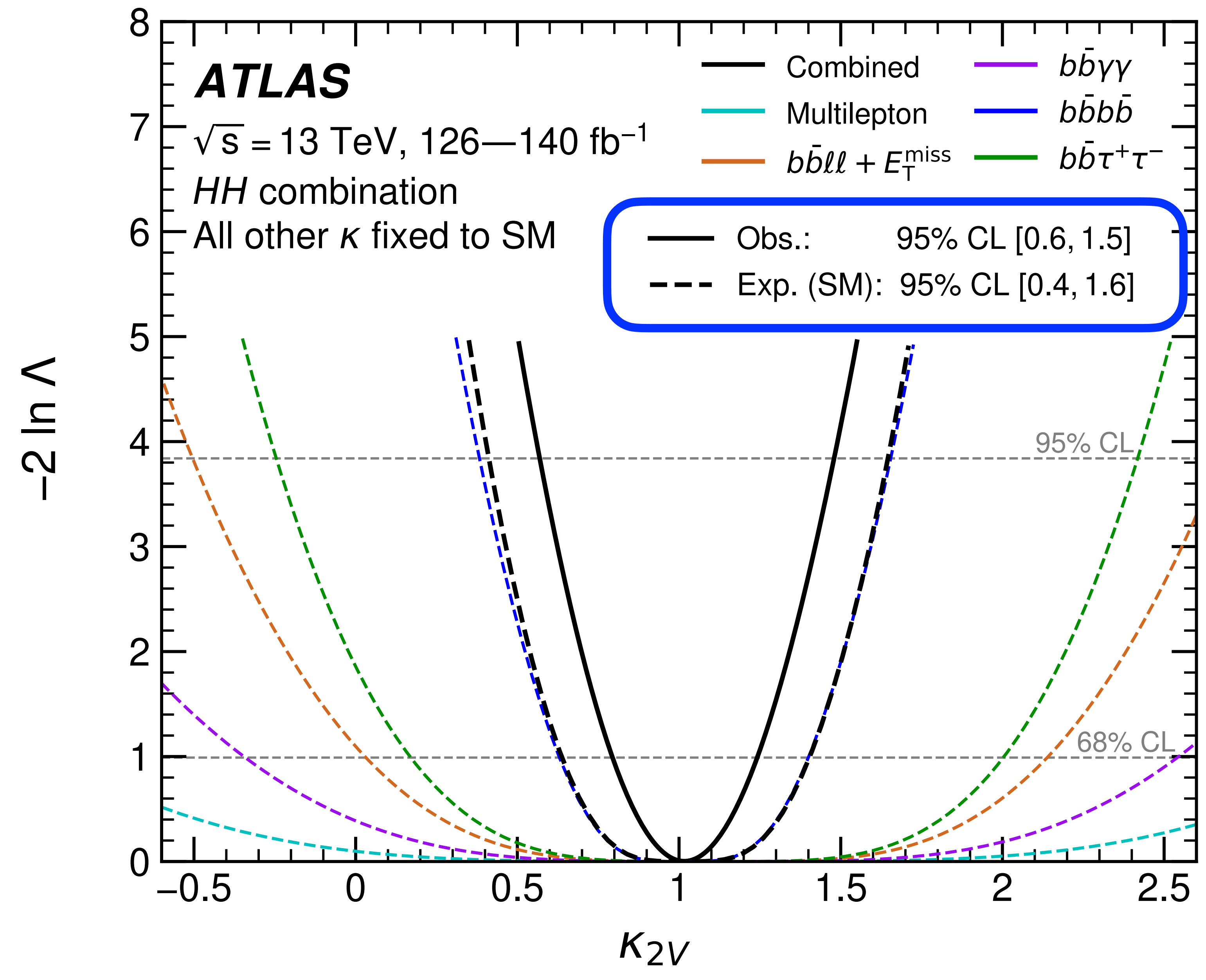
- HH→bbbb: Largest BR; but large QCD (multi-jet) background, difficult to pair jet into Higgs candidates
- HH→bbττ: Moderate BR, Presence of hadronic taus effective at rejecting multi-jet backgrounds; EW and top background mimic signal
- HH→bbγγ: Small BR; very clean final state, excellent di-photon mass resolution

Channel	Production mode	Lumi	Journal reference
$HH \rightarrow bb\ell\ell + E_{T,miss}$	ggF + VBF	140 fb^{-1}	JHEP 02 (2024) 037
$HH \rightarrow$ Multilepton	ggF + VBF	140 fb^{-1}	JHEP 08 (2024) 164
$HH \rightarrow bbbb$	ggF + VBF VBF	126 fb^{-1} 140 fb^{-1}	PRD 108 (2023) 052003 PLB 858 (2024) 139007
$HH \rightarrow bb\gamma\gamma$	ggF + VBF	140 fb^{-1}	JHEP 01 (2024) 066
$HH \rightarrow bb\tau\tau$	ggF + VBF	140 fb^{-1}	PRD 110 (2024) 032012
Combination	ggF + VBF	126-140 fb^{-1}	PRL 133 (2024) 101801

Latest Run2 HH combination: expected limit improved from 2.9 to 2.4 from previous ATLAS HH combination

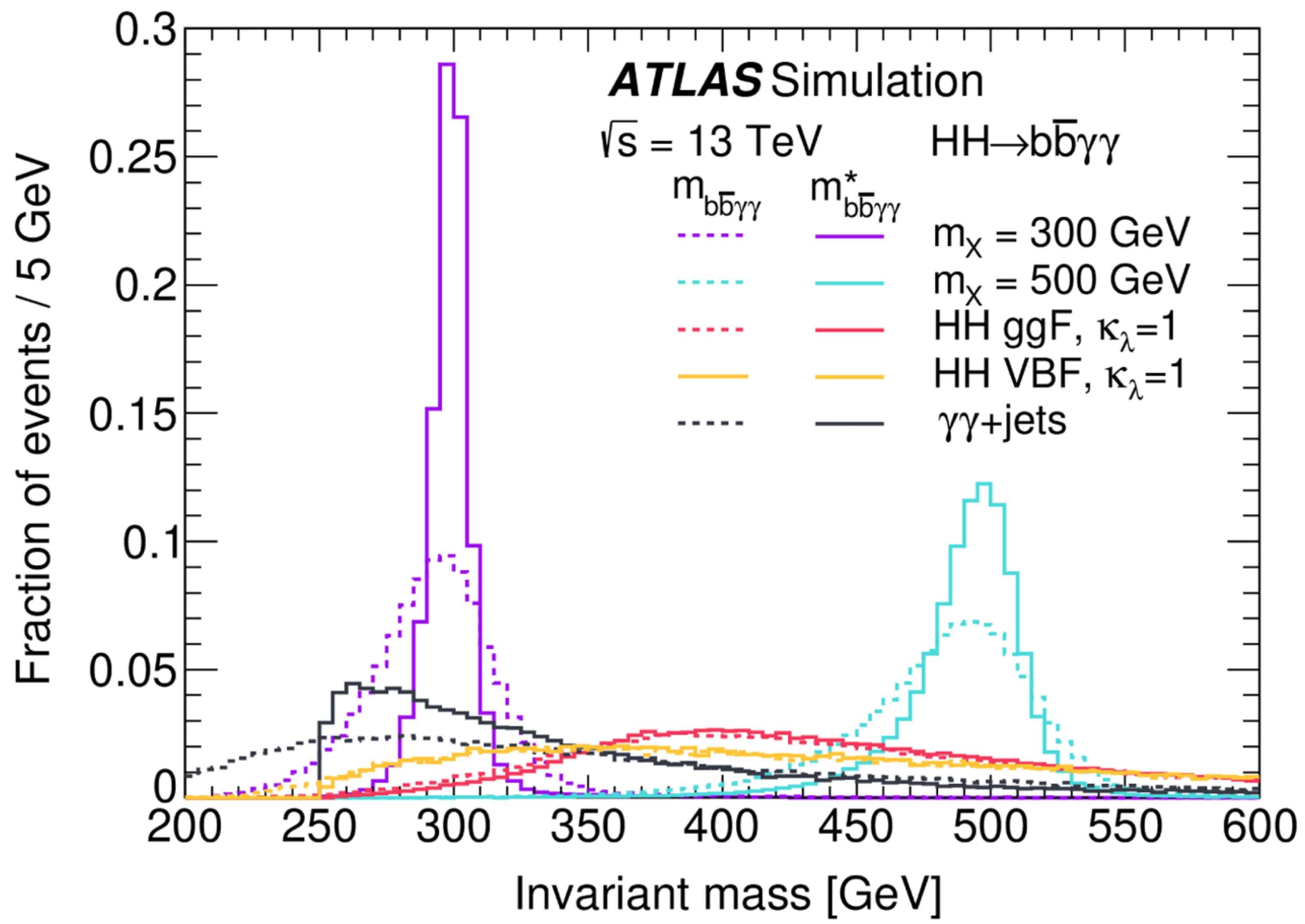
Constraint on κ_λ and κ_{2V} from HH combination

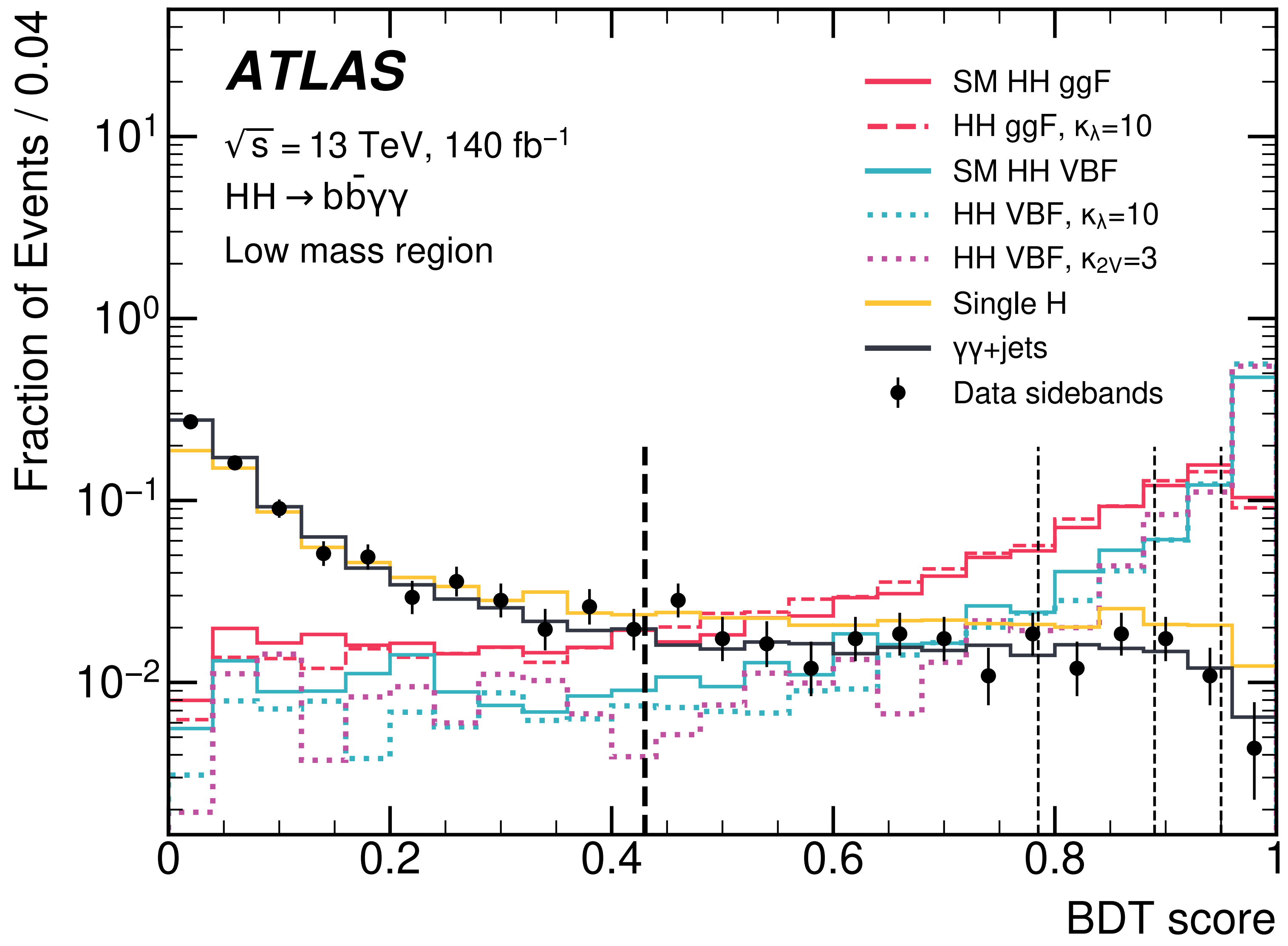


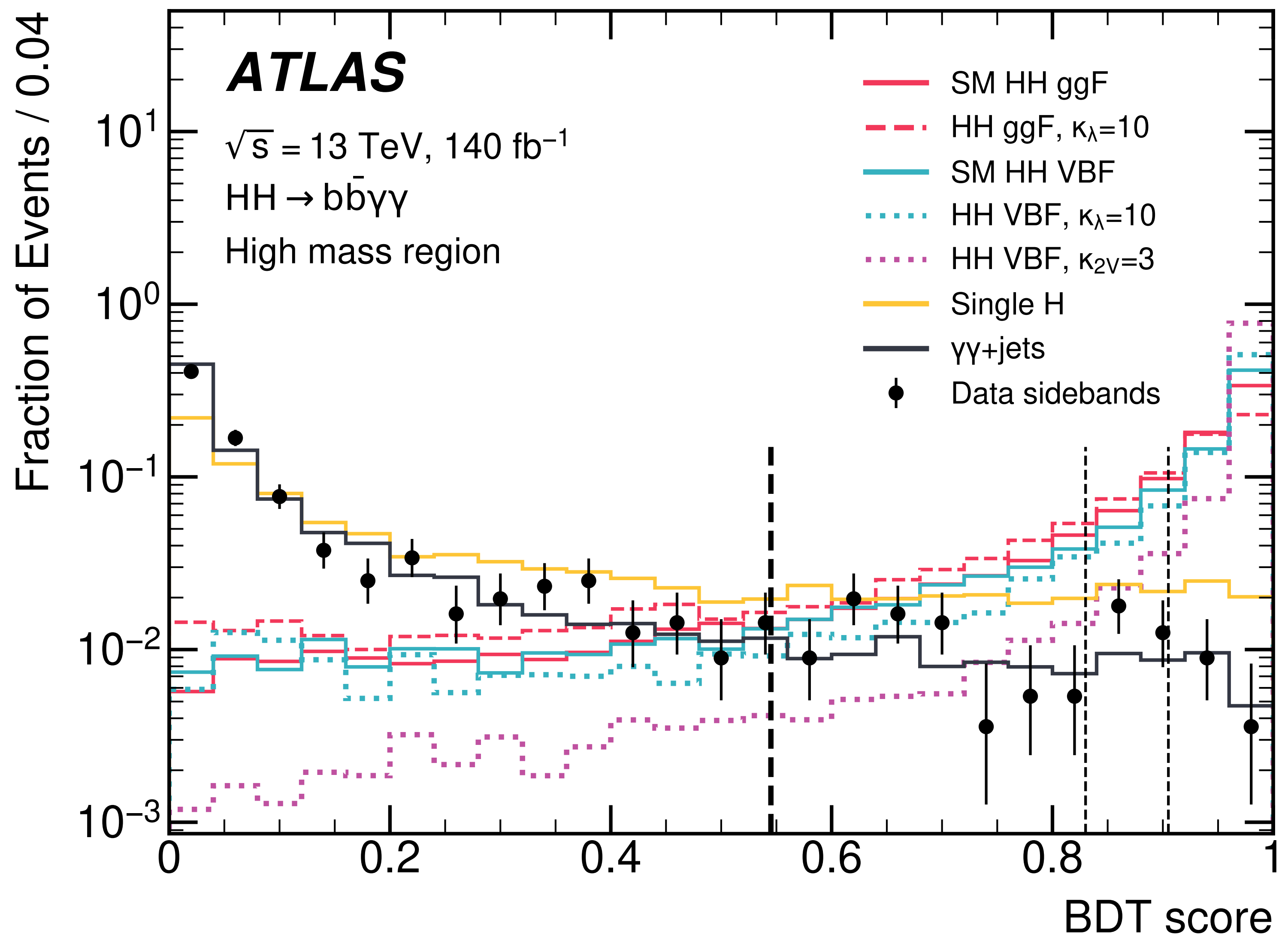


Best constraint on κ_λ from $HH \rightarrow bb\gamma\gamma$ and κ_{2V} from $HH \rightarrow bbbb$

Updates on $HH \to bb\gamma\gamma$

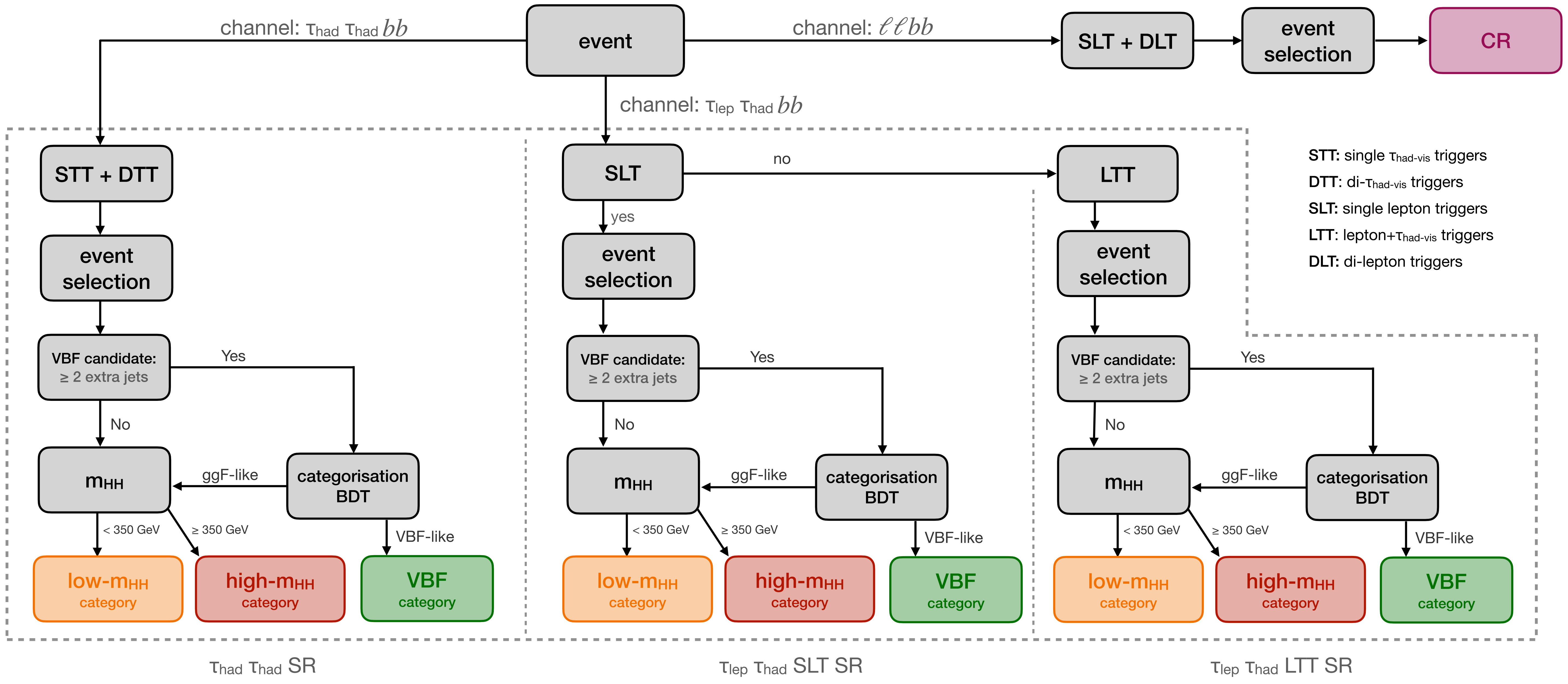


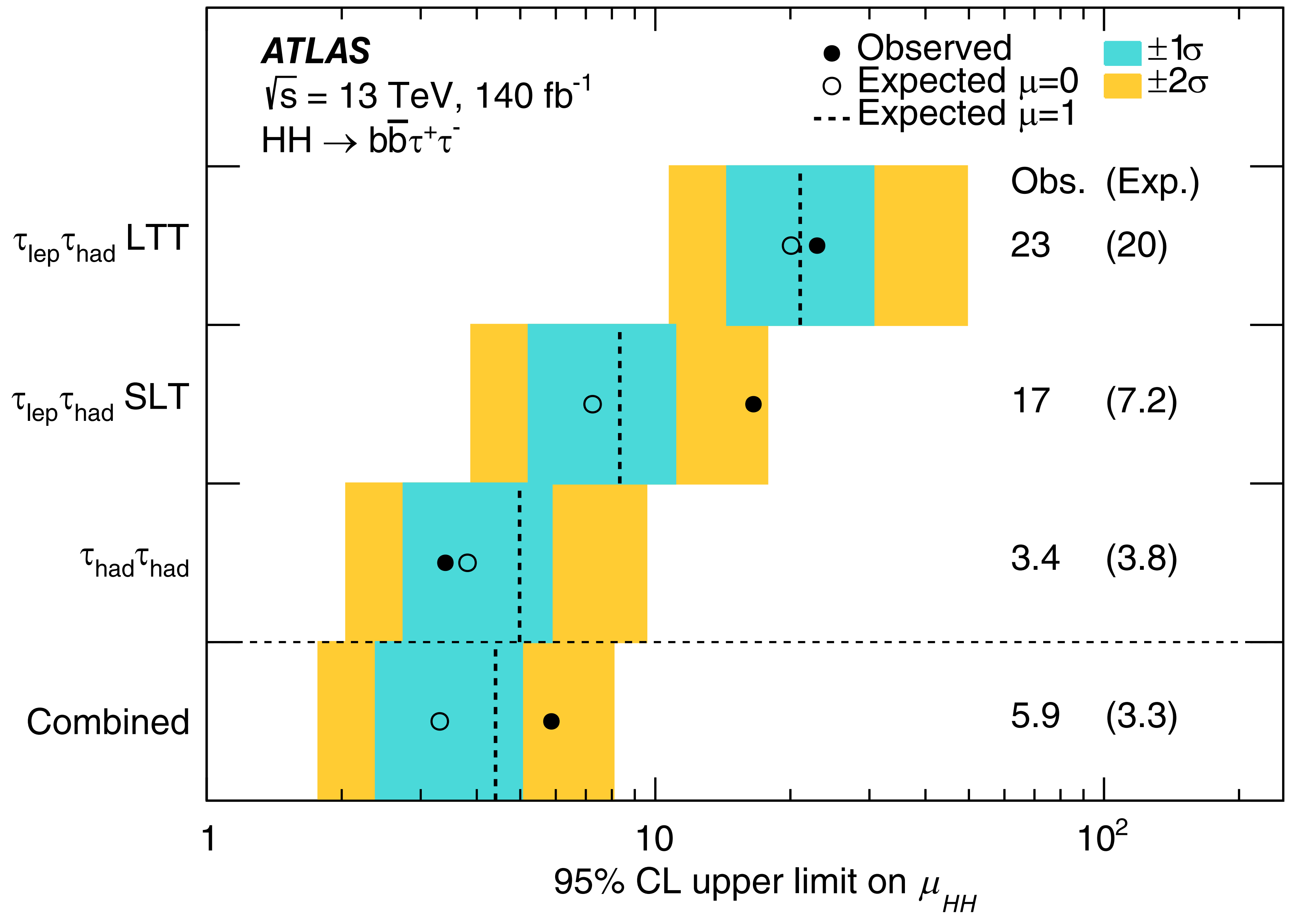




- 4-body mass definition for resolution cancellation: $m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250$
- 7 optimized categories based on the tuning on training sample mixture and hyperparameters
- HH signal strength with 12% reduction in latest results:
  - $\mu_{obs(exp)} < 4.2(5.7)$ @ 95% CL (PRD 106 (2022) 052001)
  - $\mu_{obs(exp)} < 4.0(5.0)$ **@ 95% CL (JHEP 01 (2024) 066)**

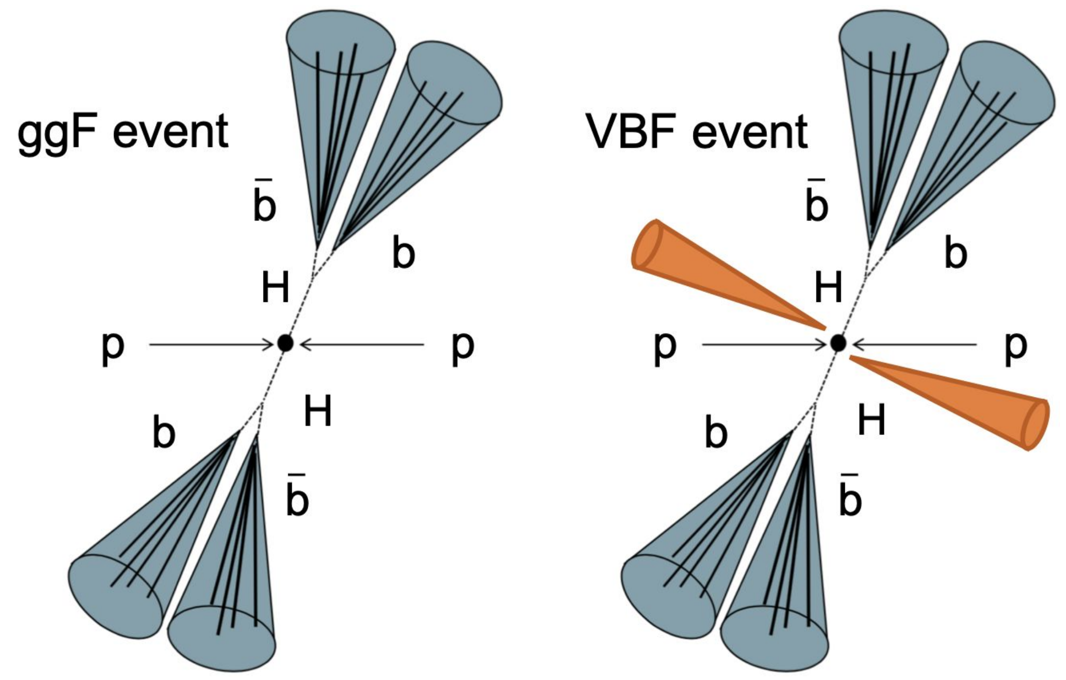
Updates on $HH \rightarrow bb\tau\tau$

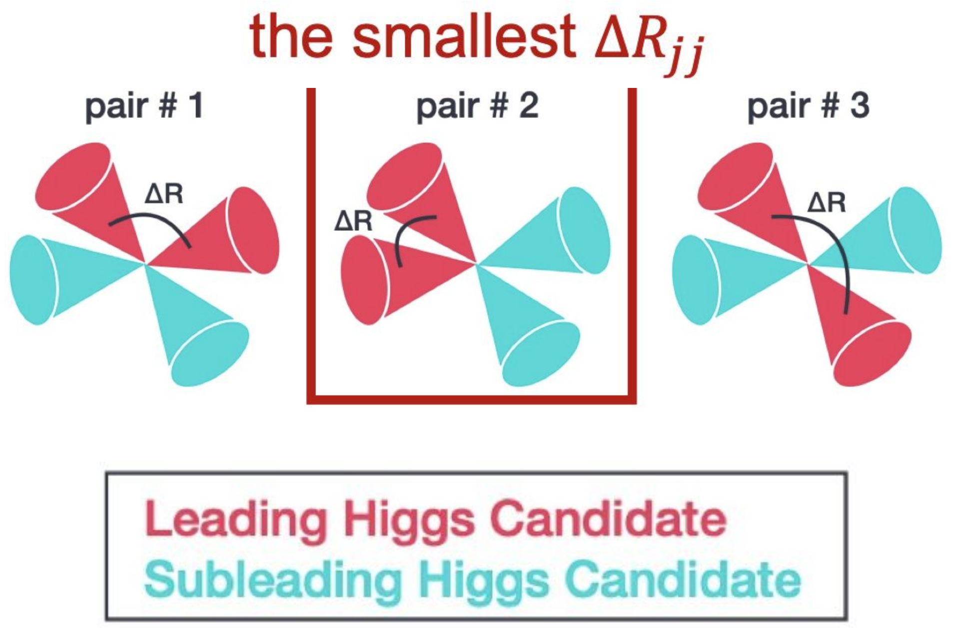


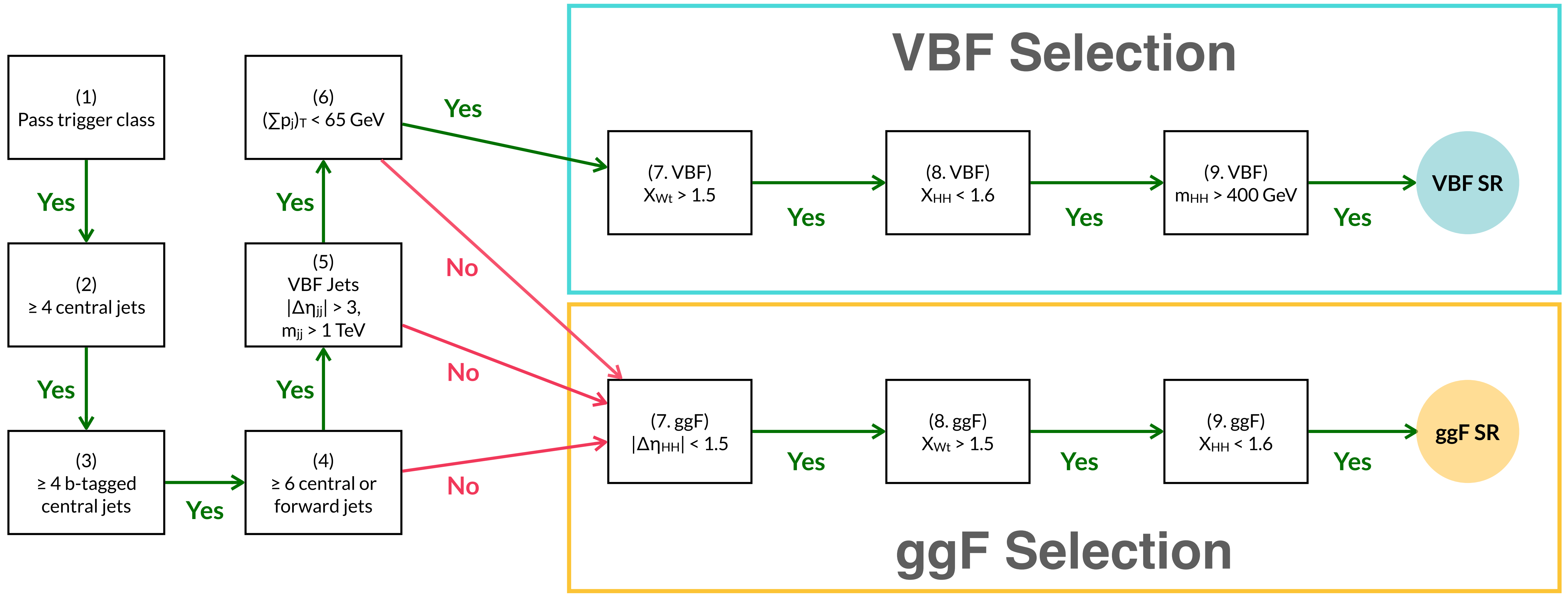


- Three SRs: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$ (SLT) and $\tau_{lep}\tau_{had}$ (LTT)
- Three categories in each SR: low-mHH, high-mHH and VBF category
- BDT score used as the discriminant for each SR
- HH signal strength with 15% reduction in latest results:
  - $\mu_{obs(exp)} < 4.7(3.9)$ @ 95% CL (JHEP 07 (2023) 040)
  - $\mu_{obs(exp)} < 5.9(3.3)$ **@ 95% CL (PRD 110 (2024) 032012)**

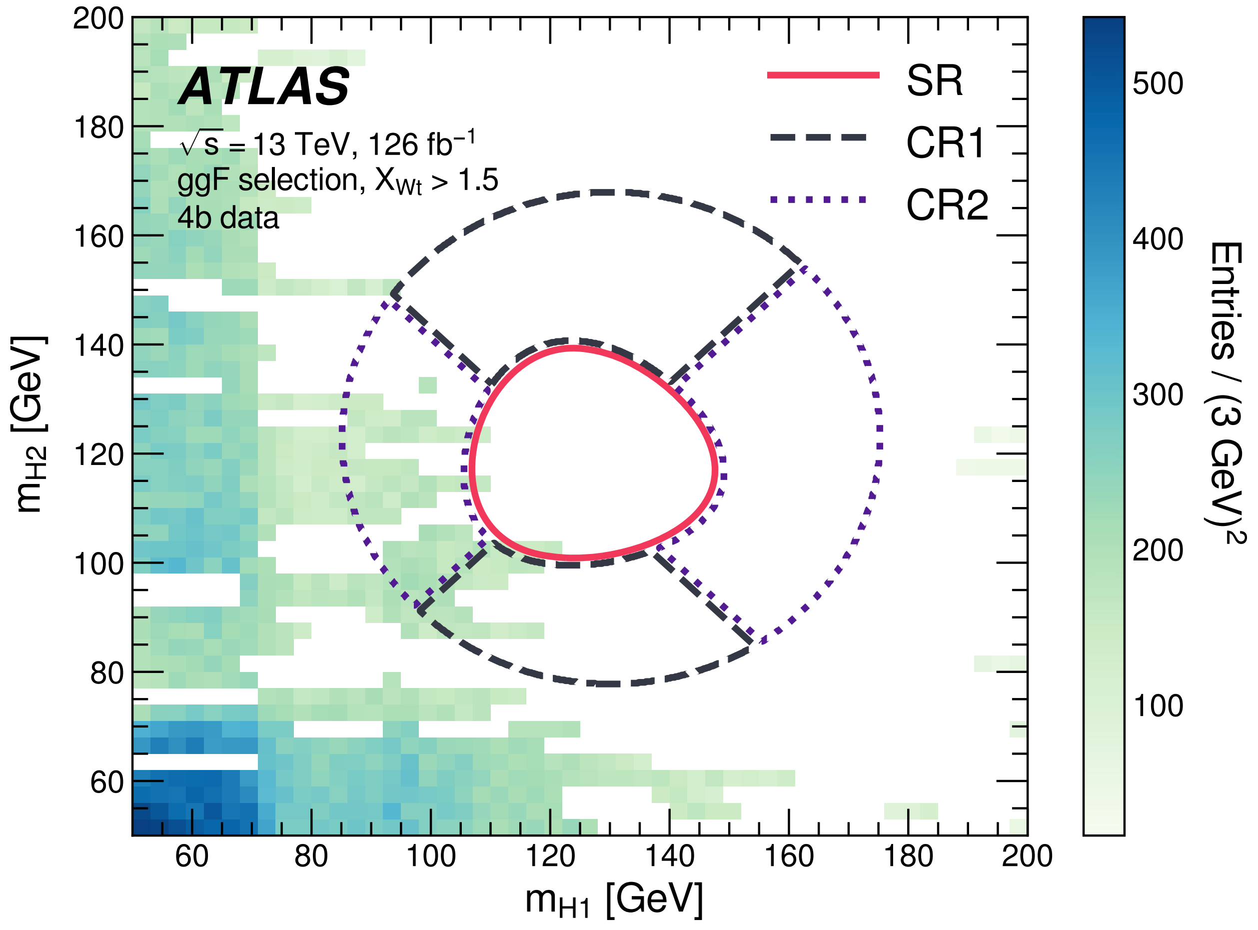
Updates on $HH \to b\bar{b}b\bar{b}$

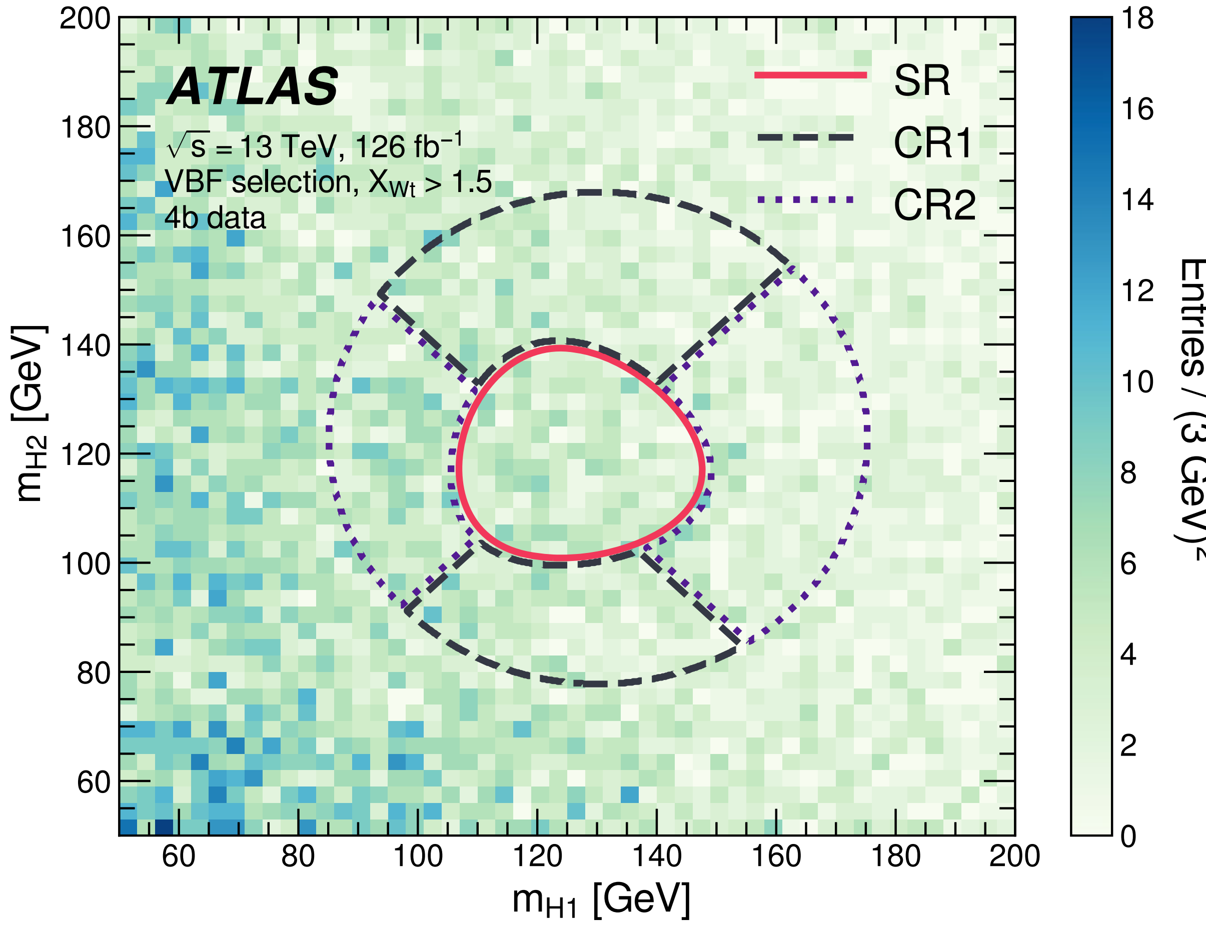




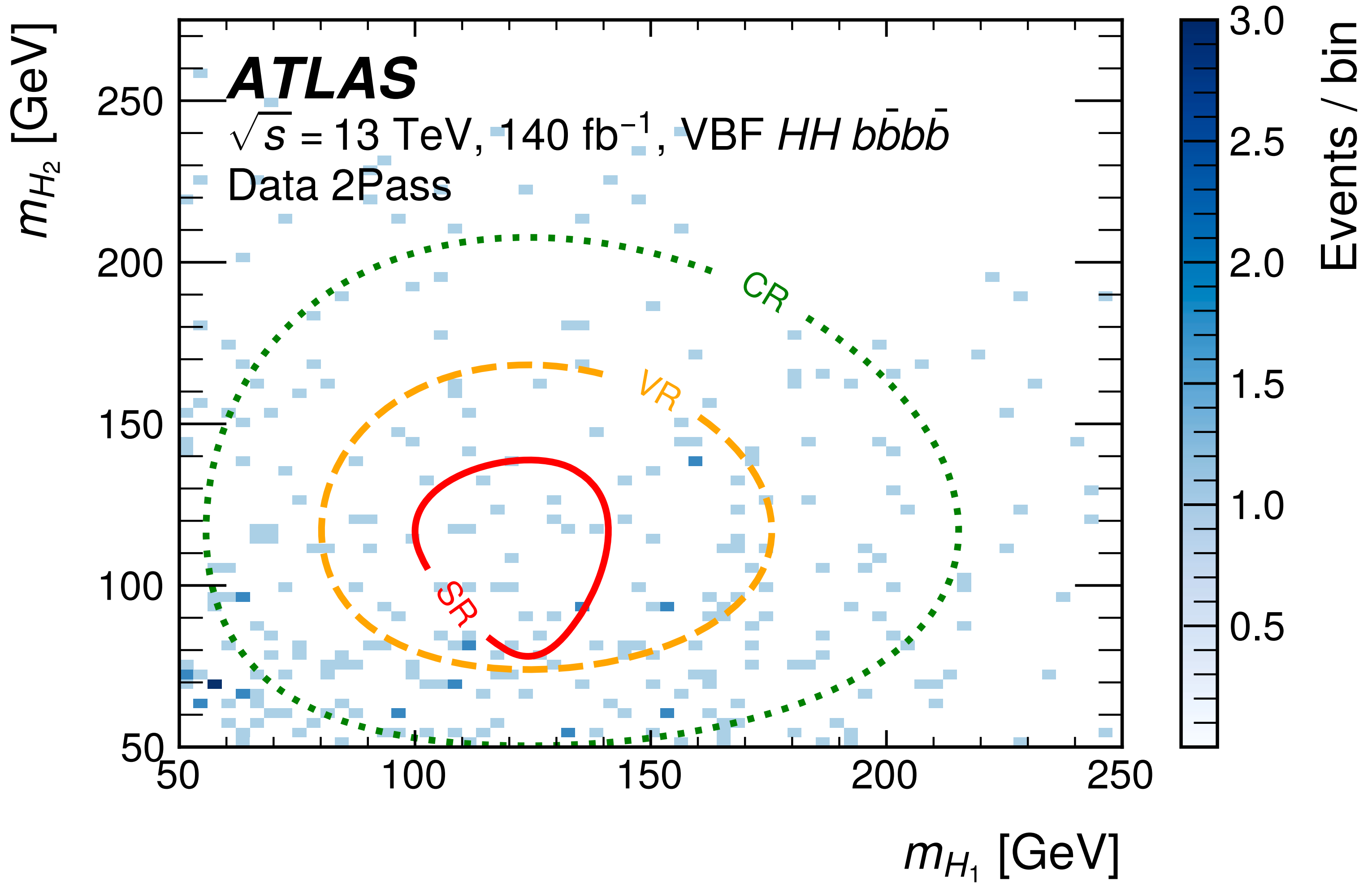


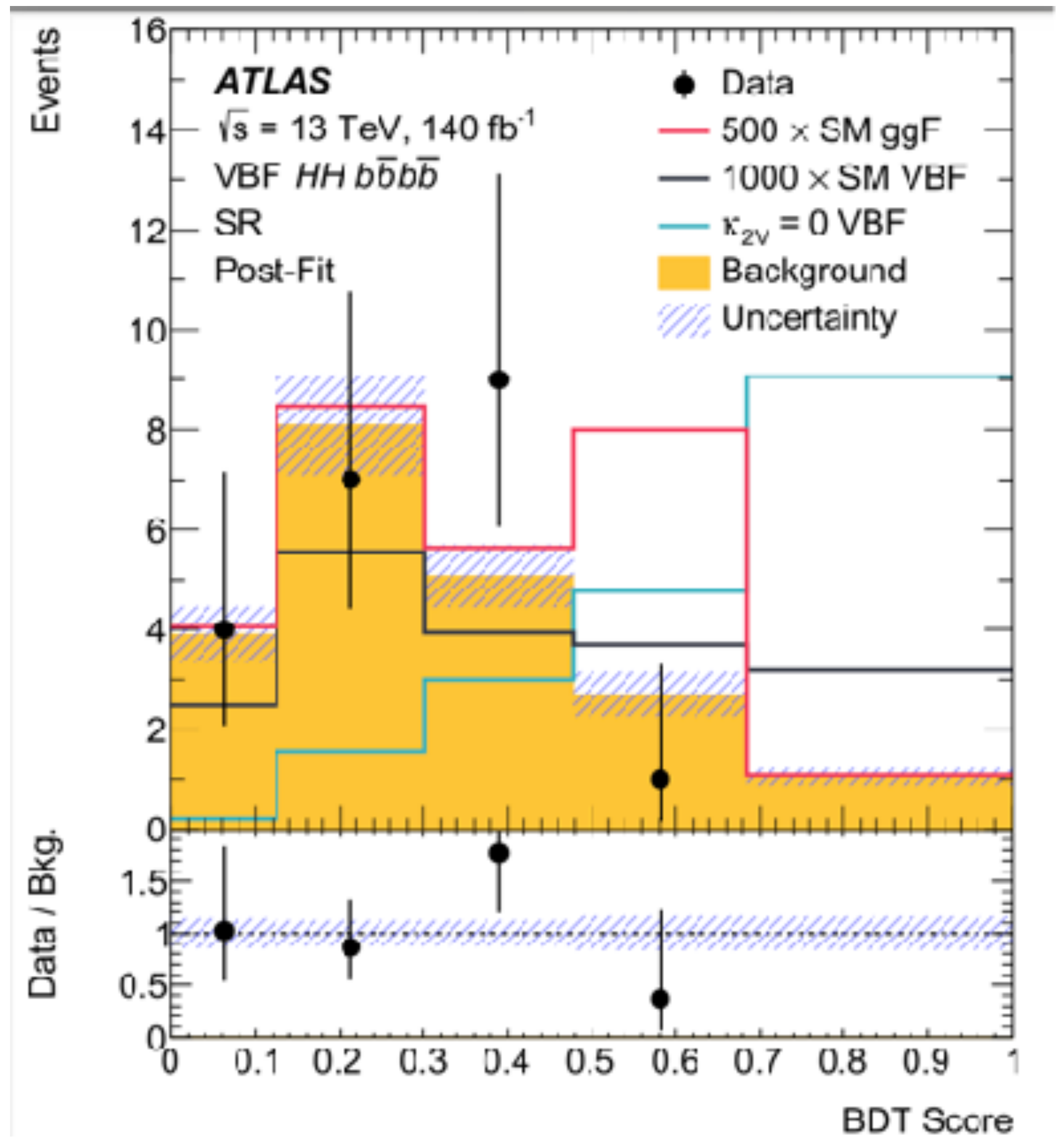
- Two orthogonal selections targeting ggF and VBF
- HH pairing decision: higher-pT jet pair with smallest ΔR separation has 90% correct rate
- Fully data-driven background estimation using a neural network to estimate multijet background
- DiHiggs mass used as the discriminant for each SR
- With full Run2 data, HH signal strength is $\mu_{obs(exp)} < 5.4(8.1)$ @ 95% CL

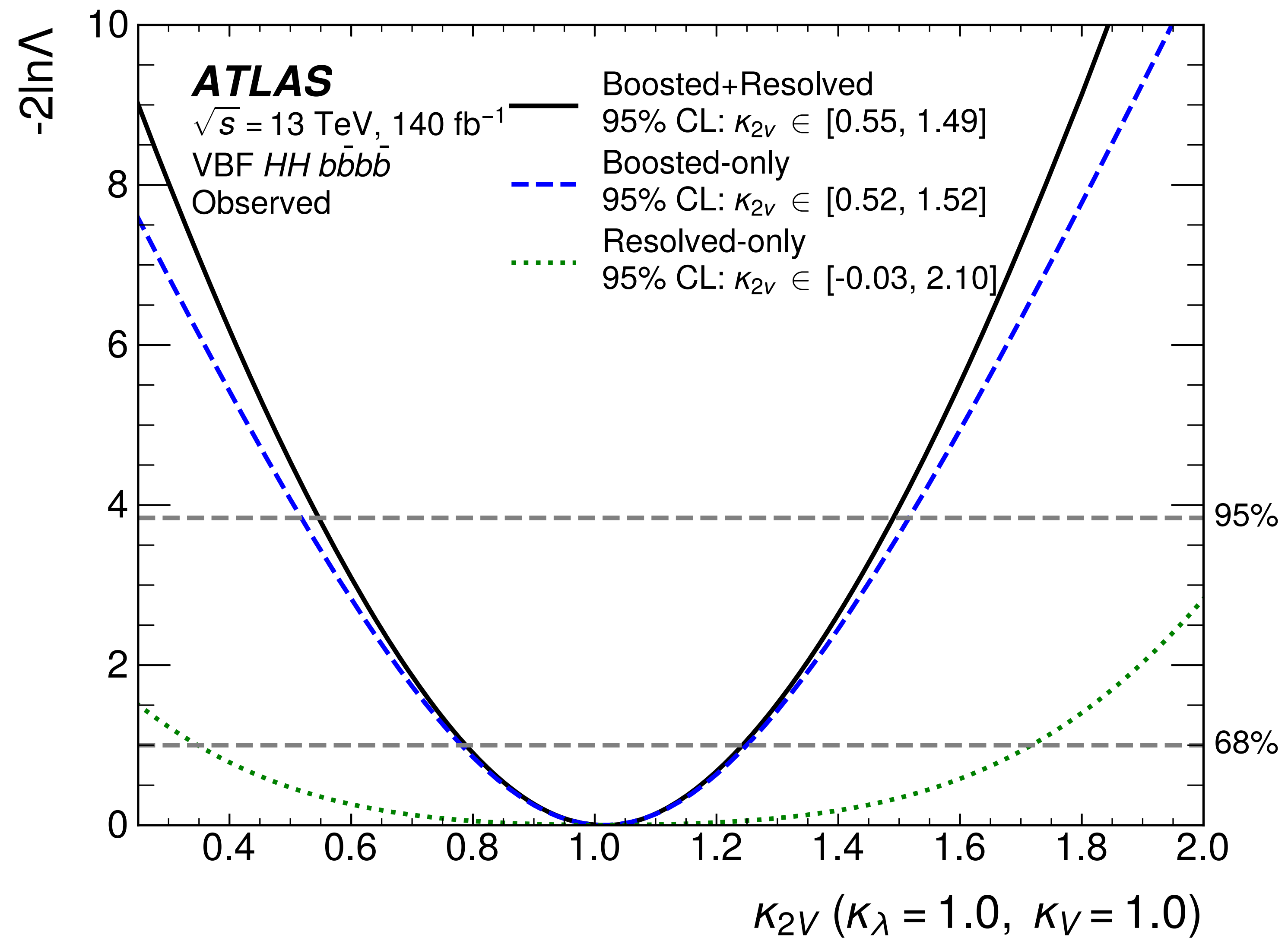




Boosted $HH \to b\bar{b}b\bar{b}$



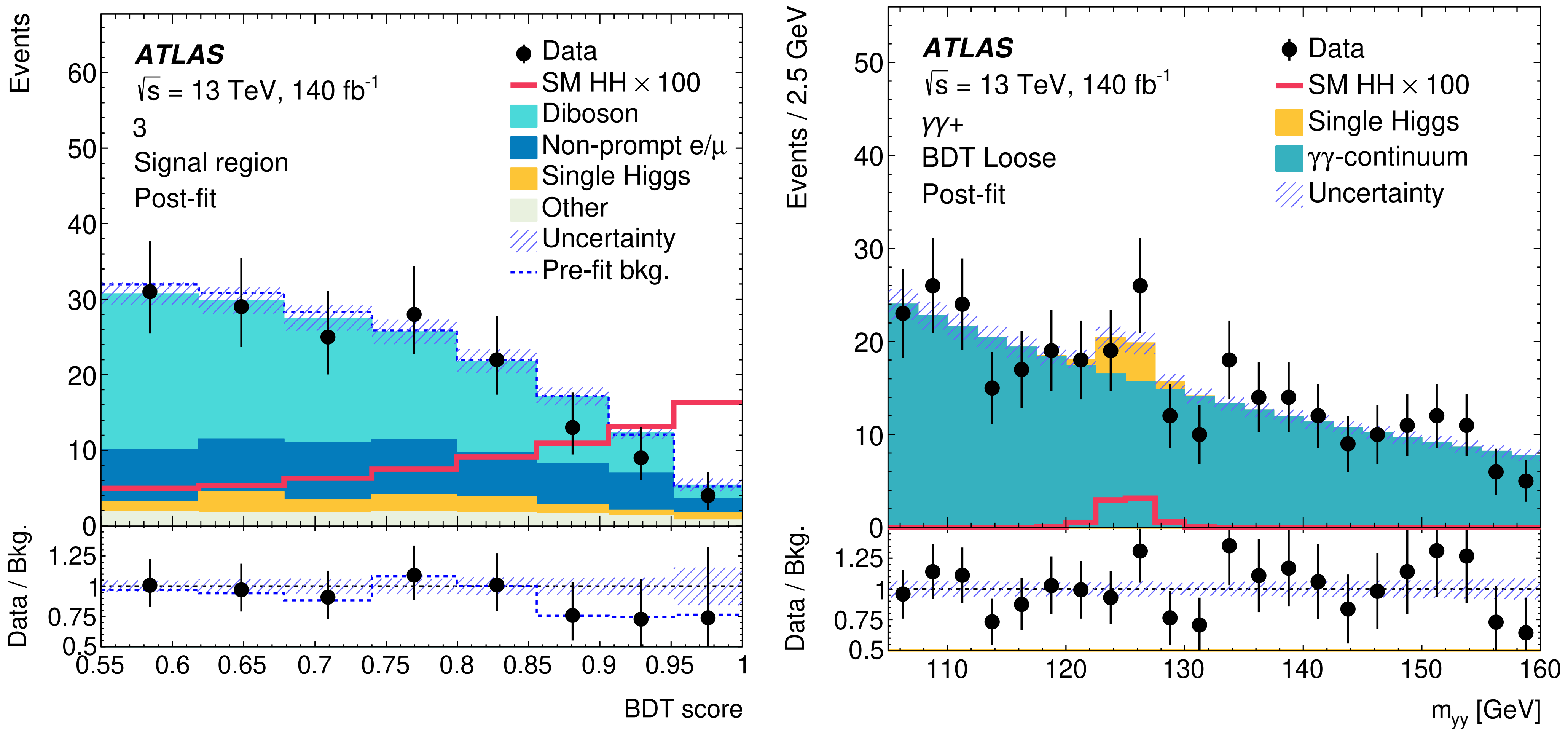


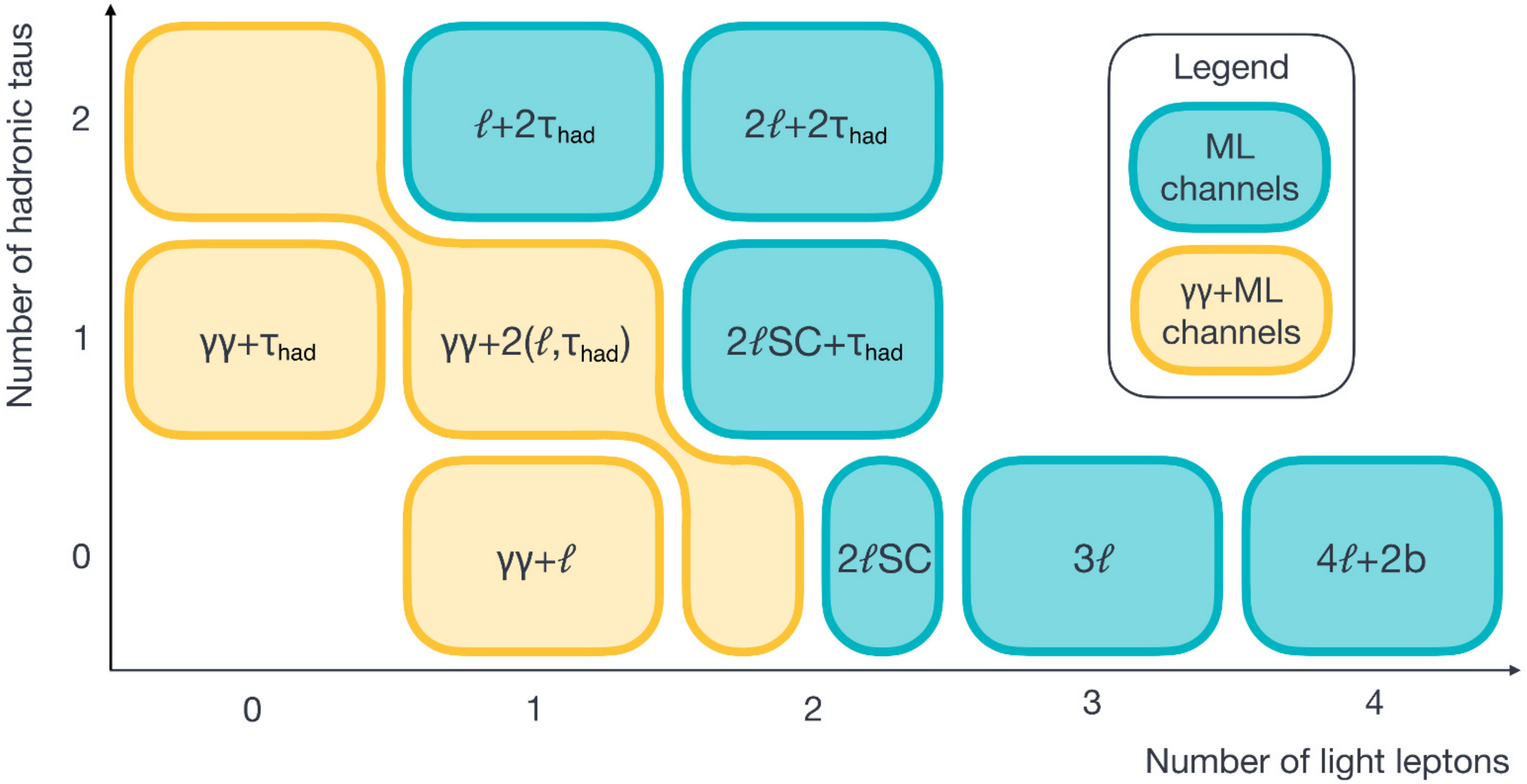


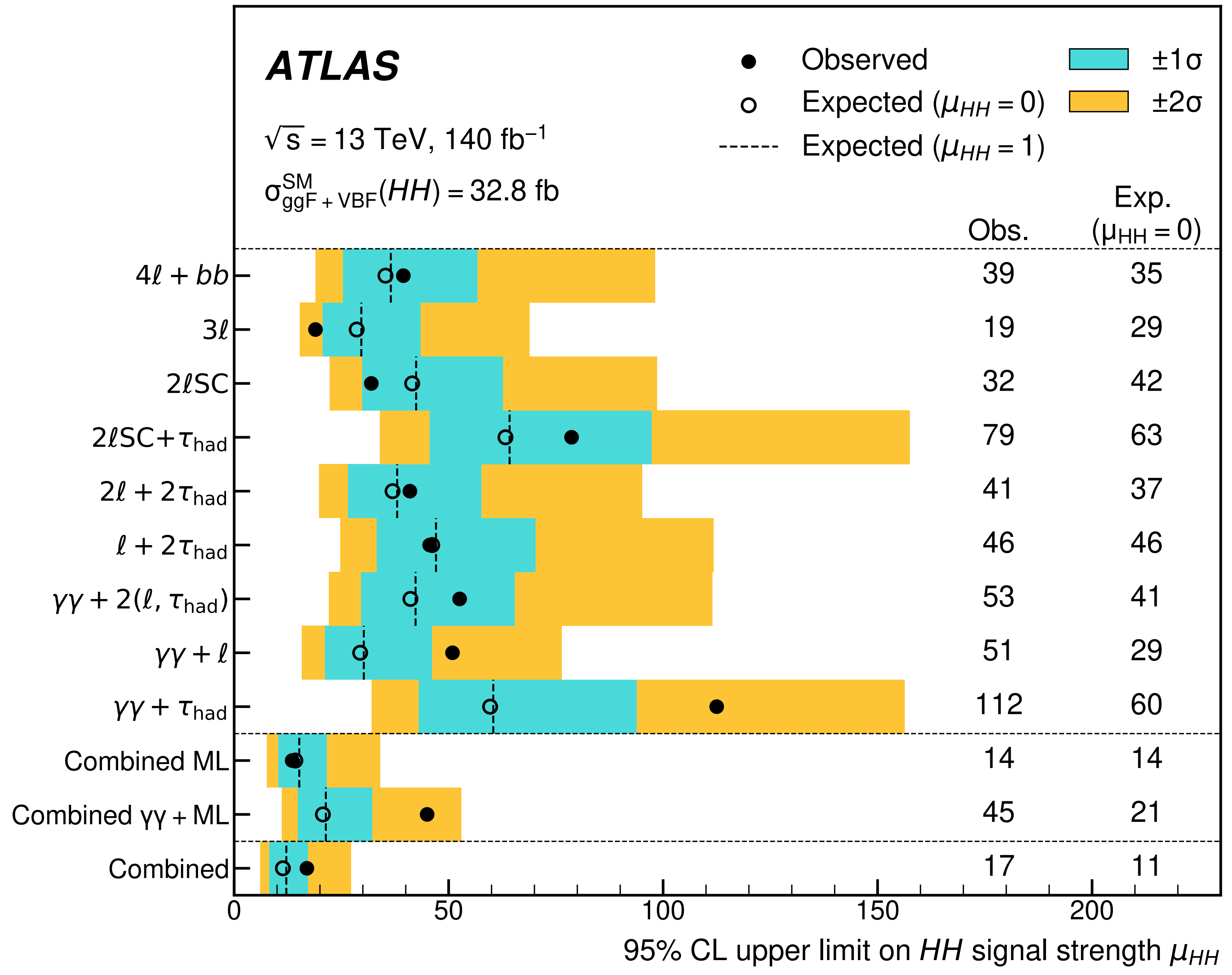
- Particularly sensitive to κ_{2V} with the boosted construction：
  - HH system reconstructed with 2 large-R (R=1.0)jets
  - VBF signature from 2 resolved small-R(R=0.4) jets
- BDT score as the discriminant for the signal and background separation
- With boosted and resolved search combination: $0.55 < \kappa_{2V} < 1.49(0.37 < \kappa_{2V} < 1.67)$ @ 2σ
- κ_{2V} =0 is excluded with an significance of 3.4σ (2.9σ)

$HH \rightarrow$ Multilepton

- Final states from
  $HH \rightarrow bbZZ^*/VV^*VV^*/VV^*\tau^+\tau^-/\tau^+\tau^-\tau^+\tau^-/\gamma\gamma VV^*/\gamma\gamma\tau^+\tau^-$ (6.5% BR)
- Two types of categories: $\gamma\gamma + ML$ and ML with the final discriminants of $m_{\gamma\gamma}$ and BDT score, respectively
- Obs. (Exp) HH signal strength<17 (11) @95% CL

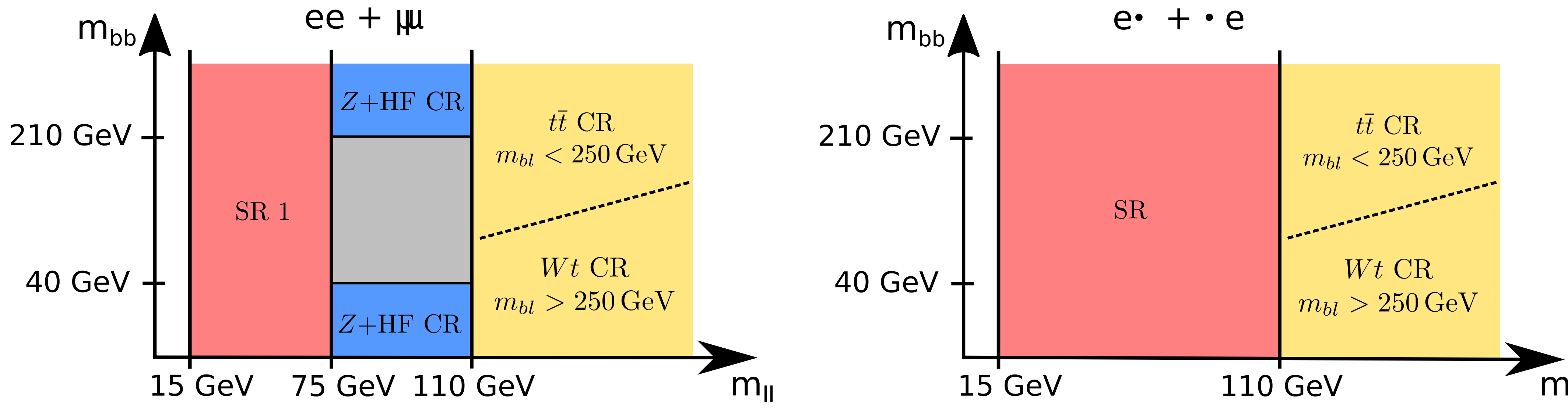


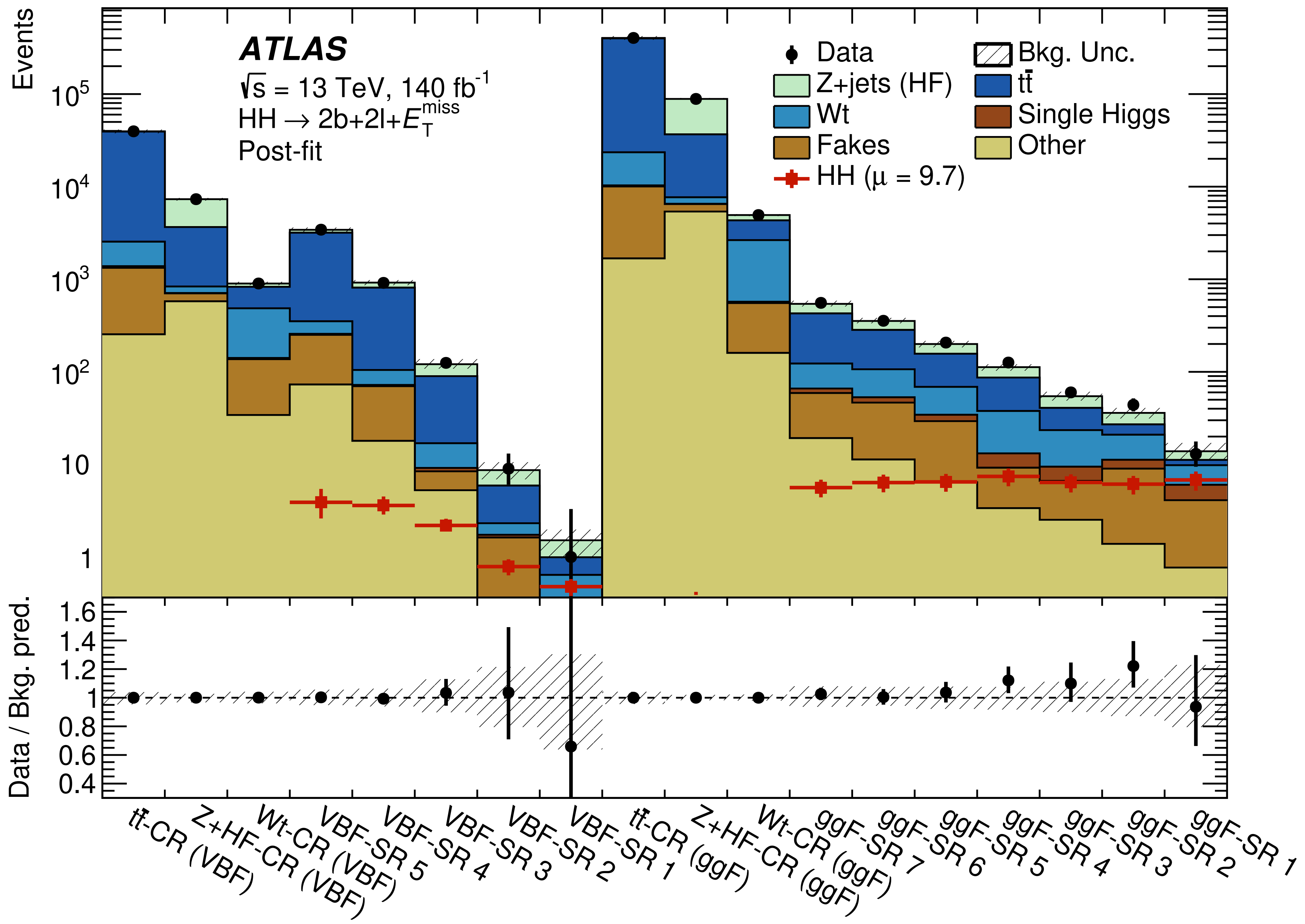


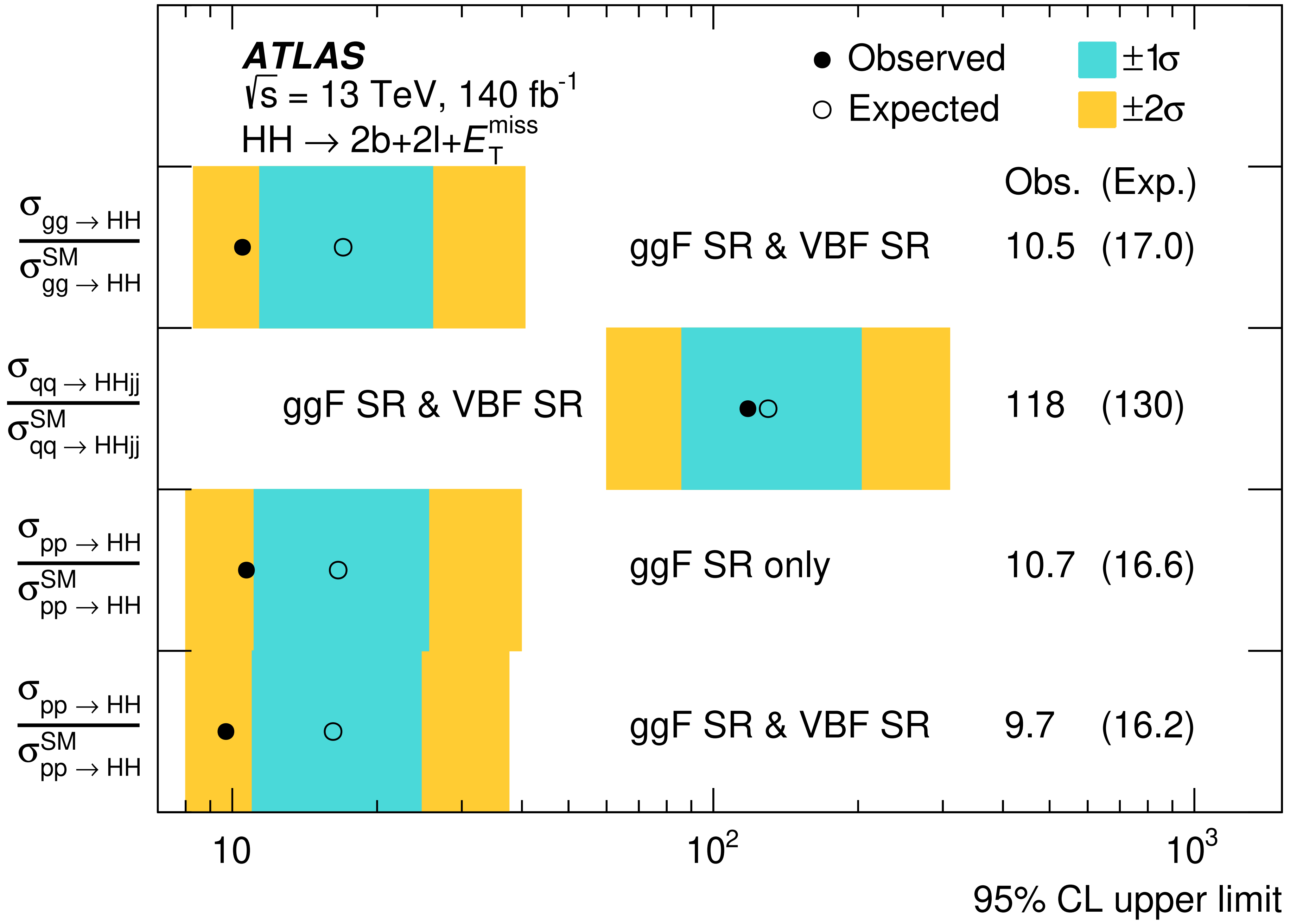


$HH \to$ bbll + $E_{T,miss}$

- Final states from $HH \to bb + WW^*/ZZ^*/\tau^+\tau^- \to bb + l^+l^- + n\nu$
- Two orthogonal selections targeting ggF and VBF
- MVA to separate signal from background
  - DNN discriminant for ggF
  - BDT discriminant for VBF
- Obs. (Exp) HH signal strength<17 (11) @95% CL

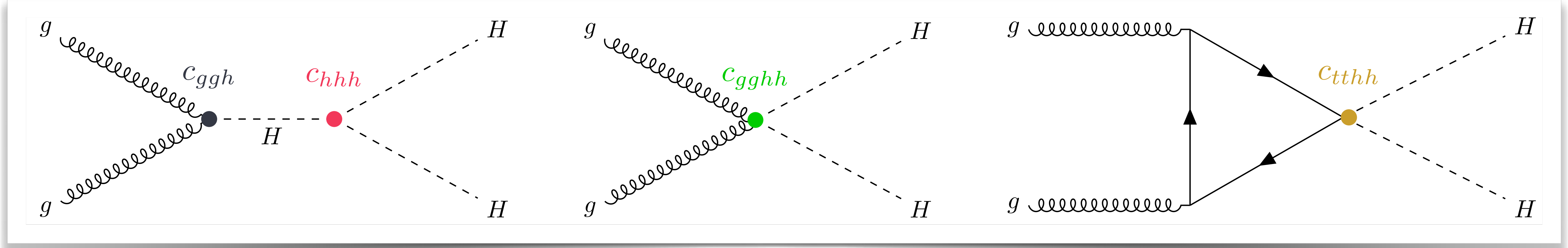






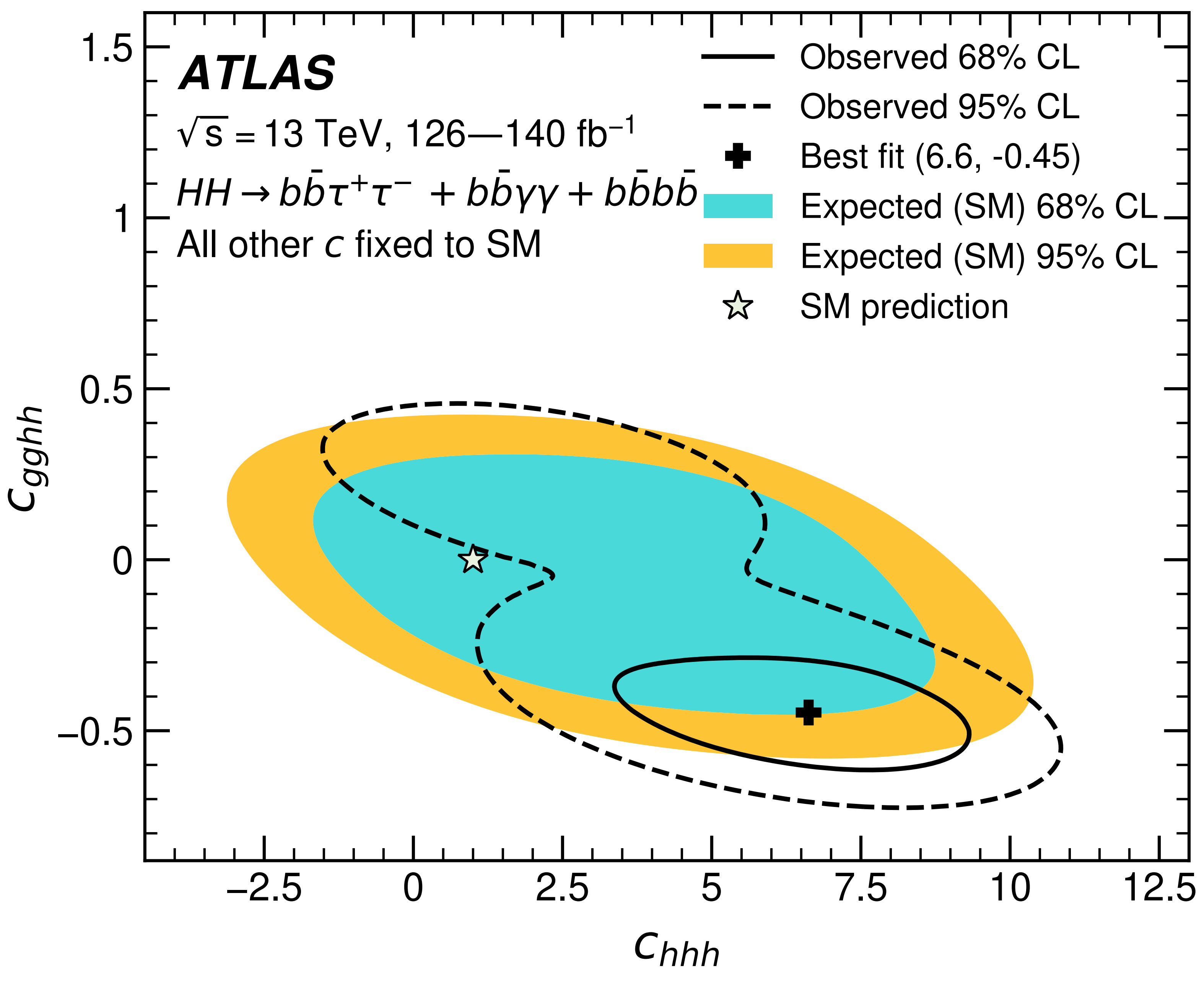
EFT interpretations from HH combination

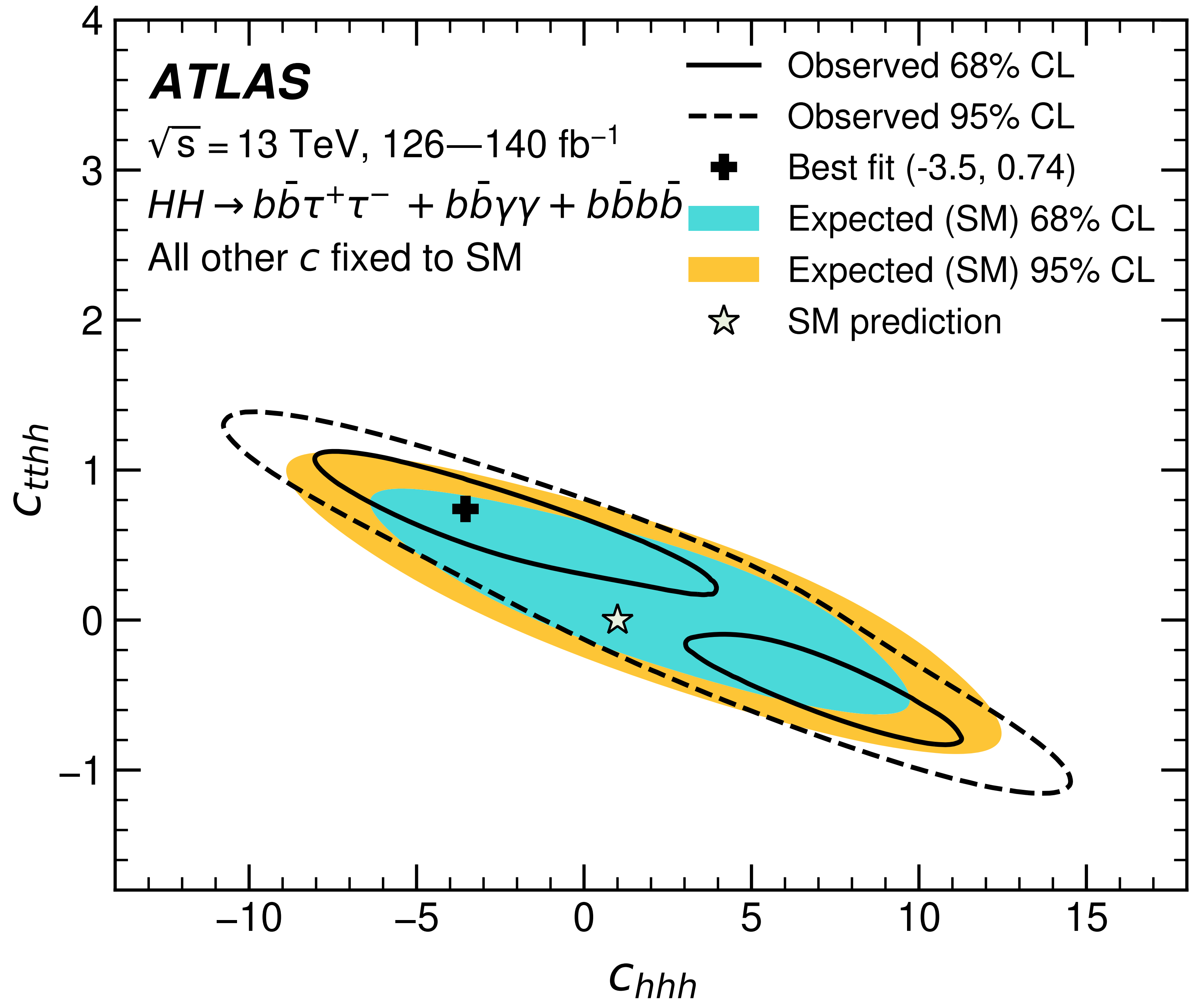
- HEFT used in latest HH combination: separate anomalous single-Higgs and HH couplings and described by LO Wilson Coefficients
- Only include the 3 most sensitive HH decays: $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$ and $b\bar{b}b\bar{b}$
- Reweight methods on LO particle-level mHH distributions for alternative WC
- Most stringent constraints on c_{gghh} and c_{tthh}

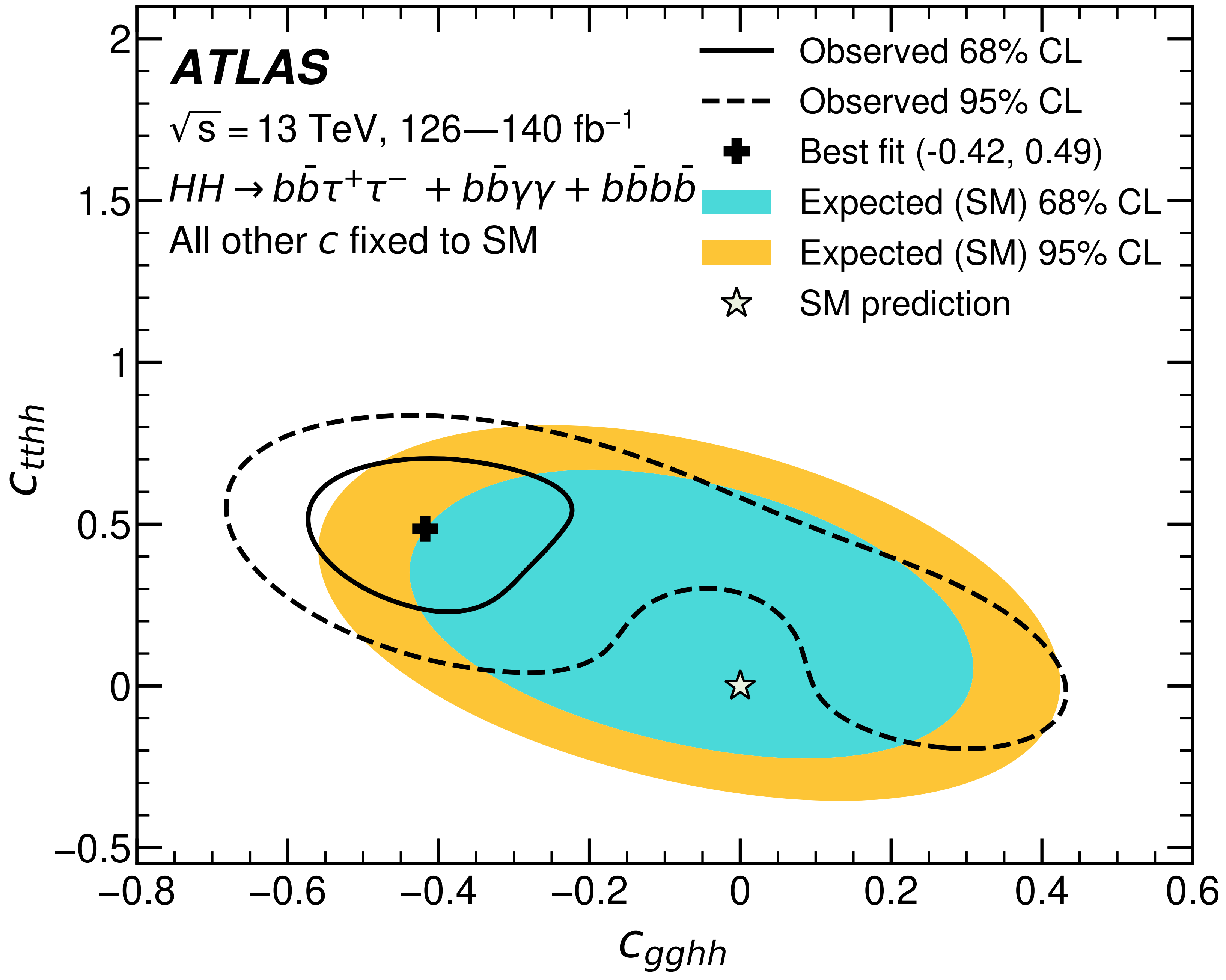


$$-0.38 < c_{gghh} < 0.49(-0.36 < c_{gghh} < 0.36)@95\%\,CL$$

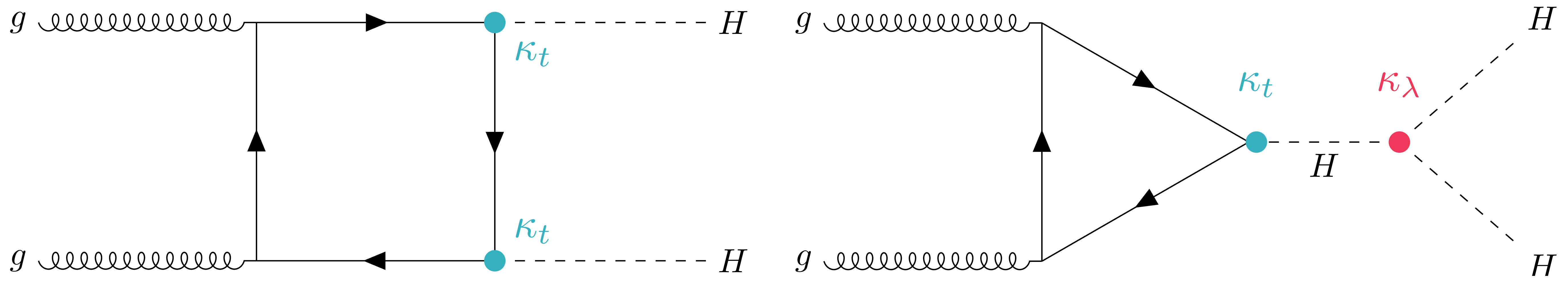
$$-0.19 < c_{tthh} < 0.70(-0.27 < c_{tthh} < 0.66)@95\%\,CL$$



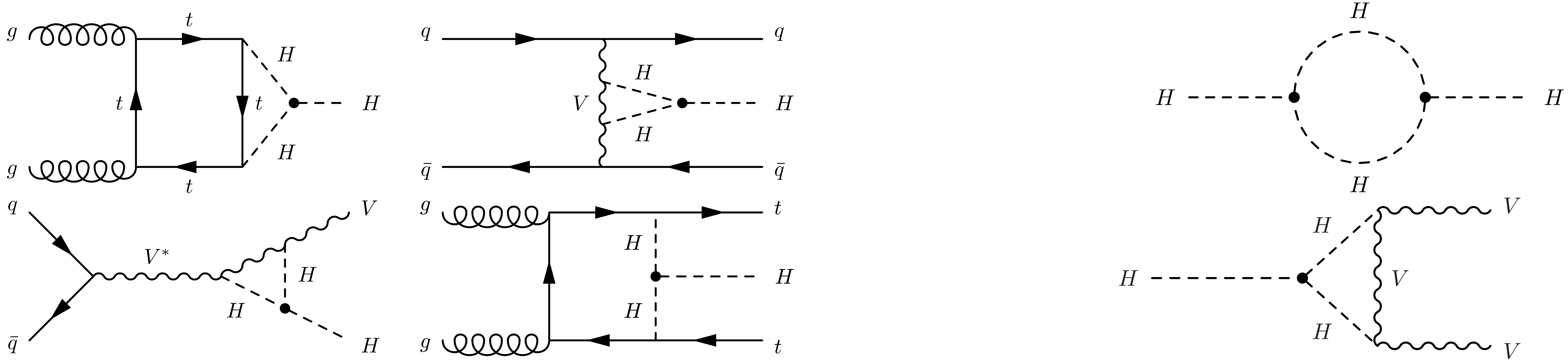




Degeneracy between κ_λ and κ_t in the HH-only measurement



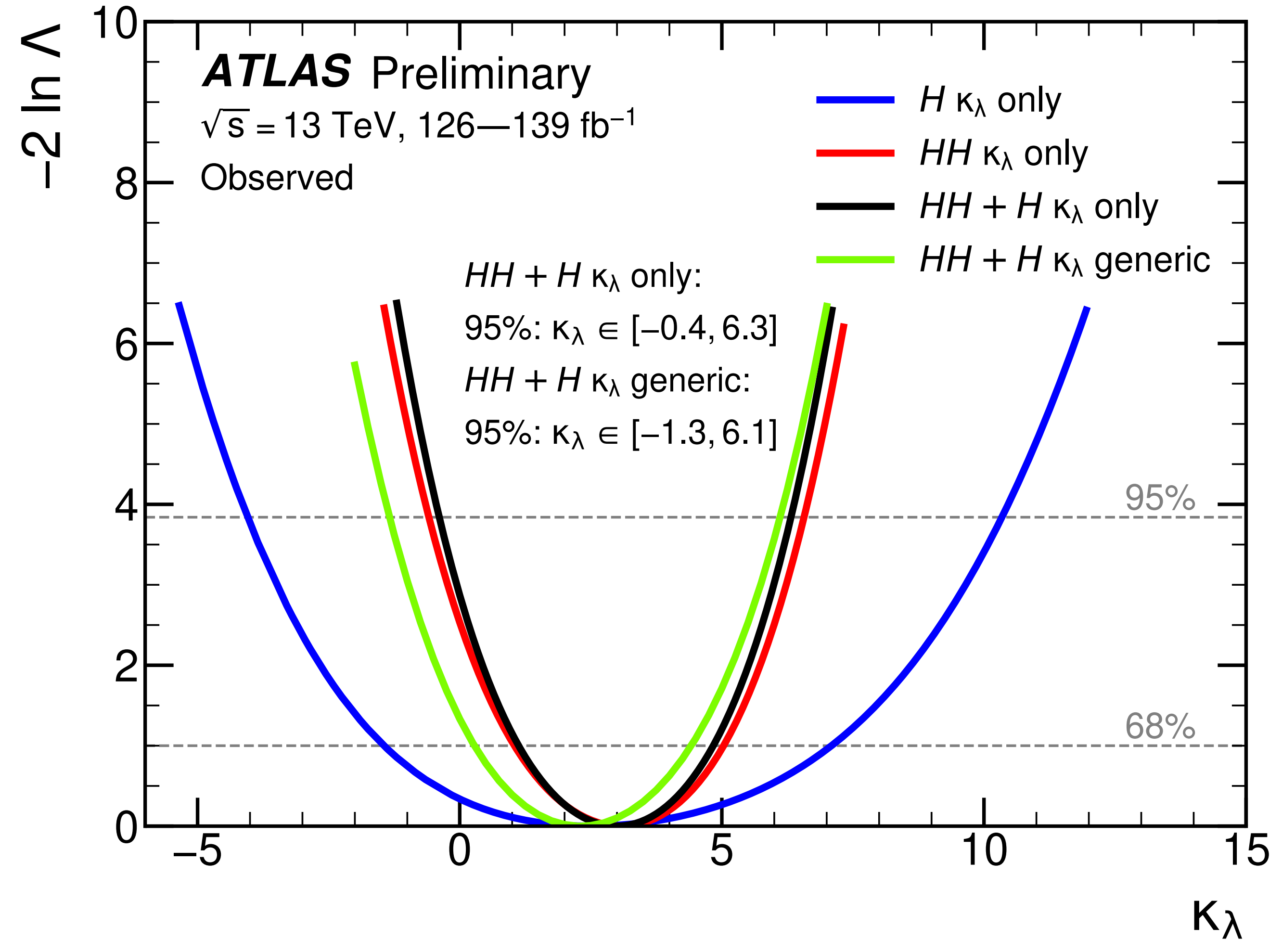
All the single Higgs production and decay processes are affected by an anomalous trilinear (**<u>not quartic</u>**) Higgs self coupling, parametrized by κ_λ.

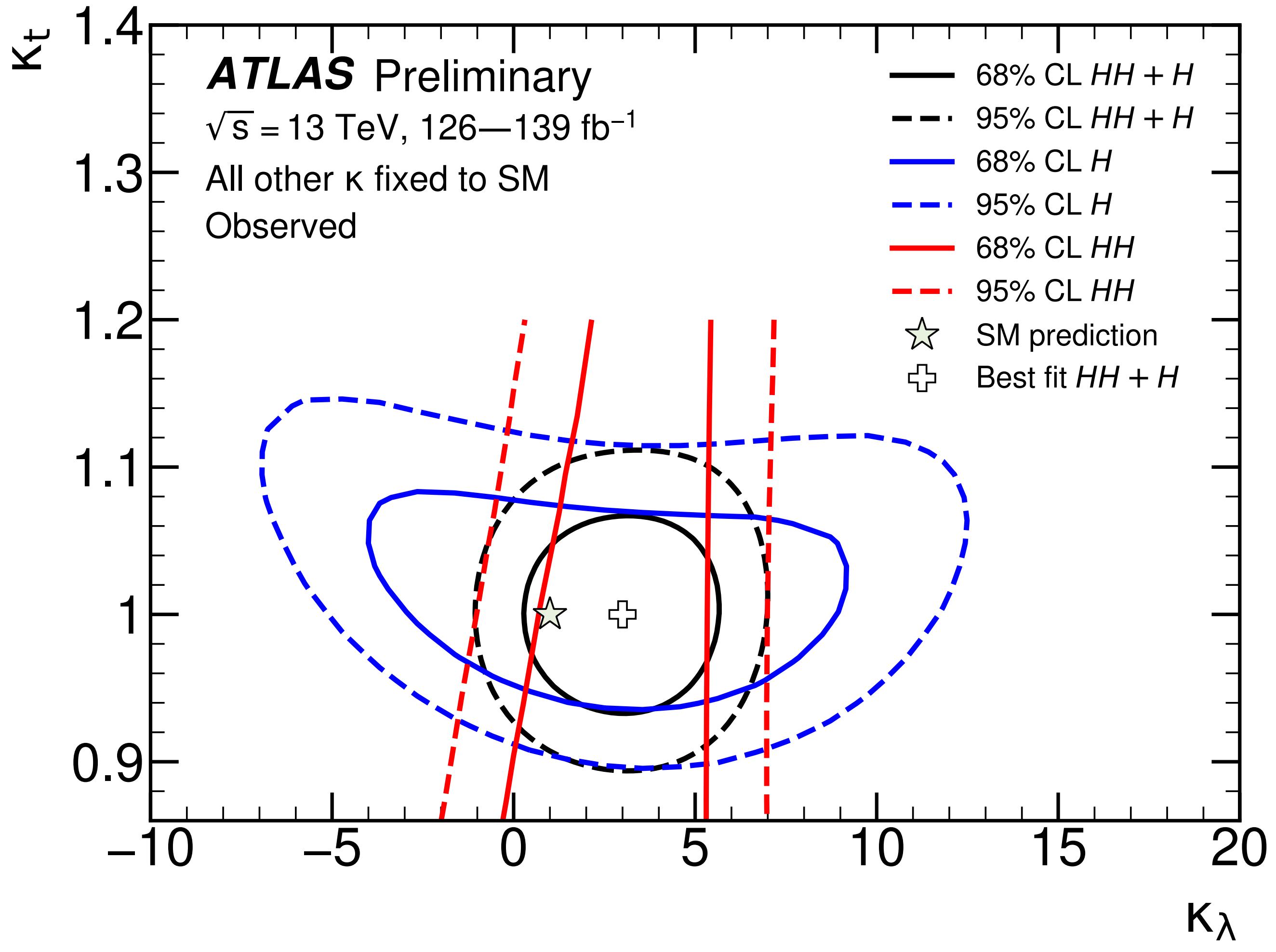


With the NLO-EW correction for single-H processes, complementary for the HH approach and less model dependent

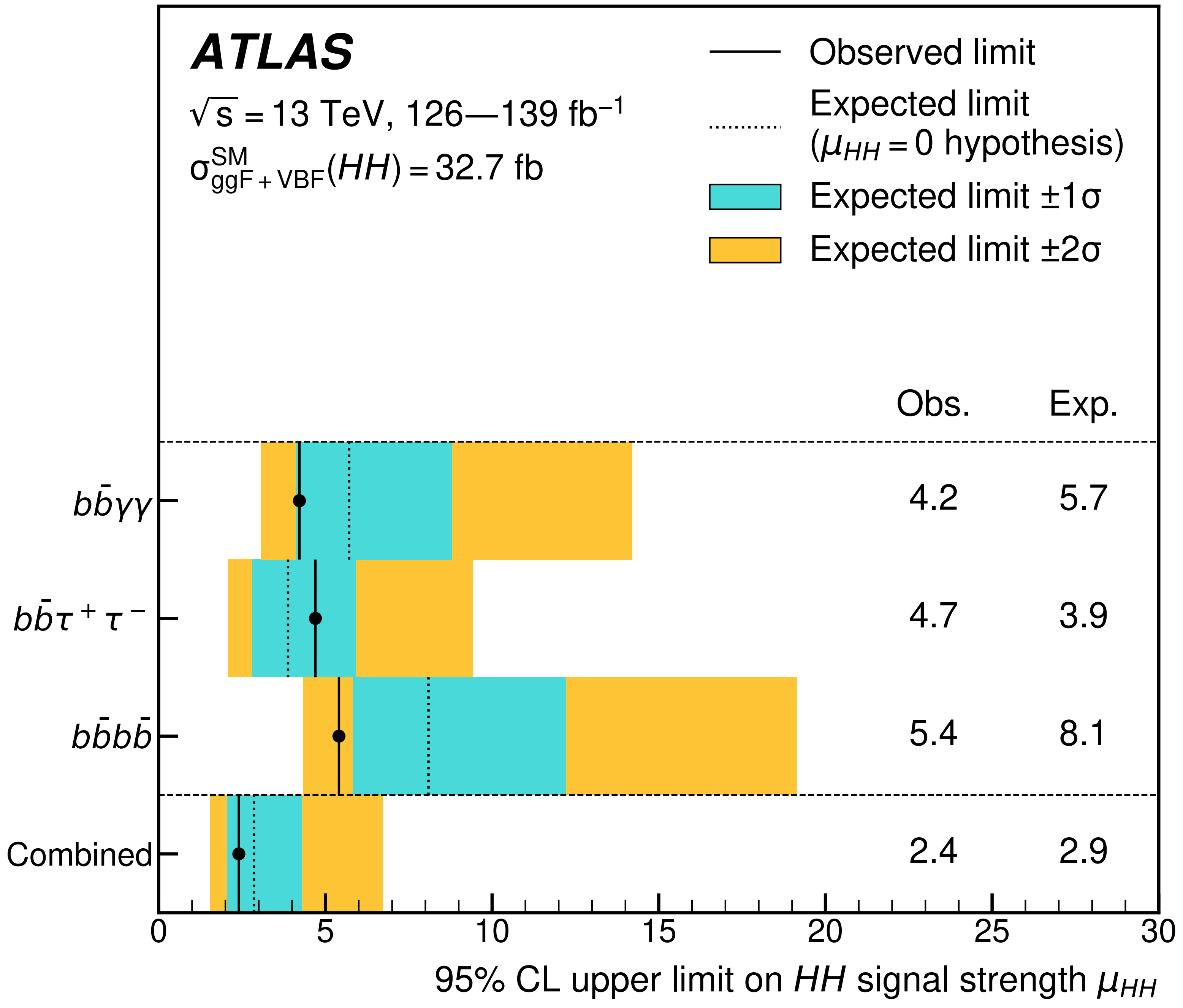
H+HH Combination

Analysis channel	Integrated luminosity [fb^{-1}]
$HH \to b\bar{b}\gamma\gamma$	139
$HH \to b\bar{b}\tau^+\tau^-$	139
$HH \to b\bar{b}b\bar{b}$	126
$H \to \gamma\gamma$	139
$H \to ZZ^* \to 4\ell$	139
$H \to \tau^+\tau^-$	139
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)	139
$H \to b\bar{b}$ (VH)	139
$H \to b\bar{b}$ (VBF)	126
$H \to b\bar{b}$ ($t\bar{t}H$)	139



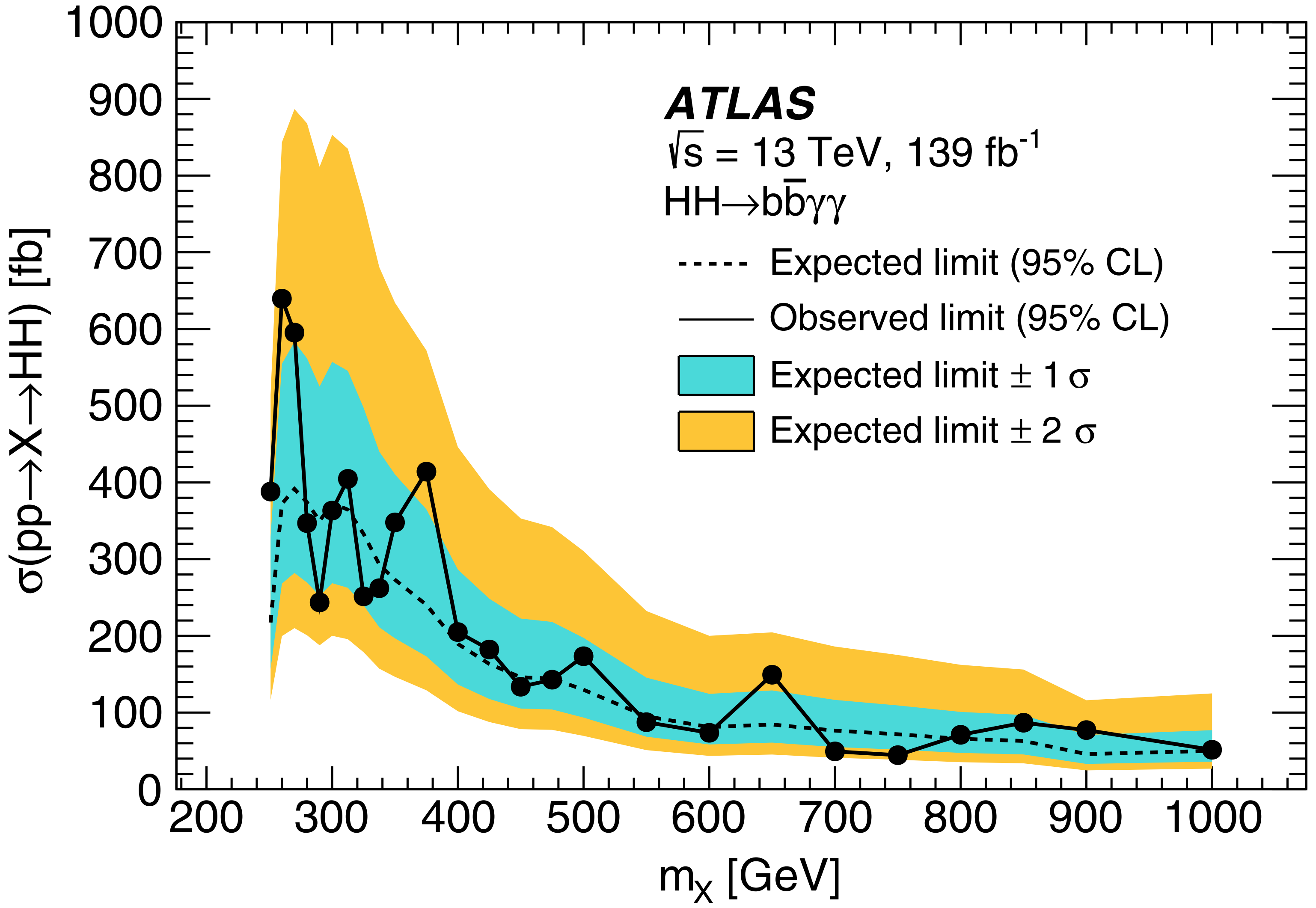


Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.5$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

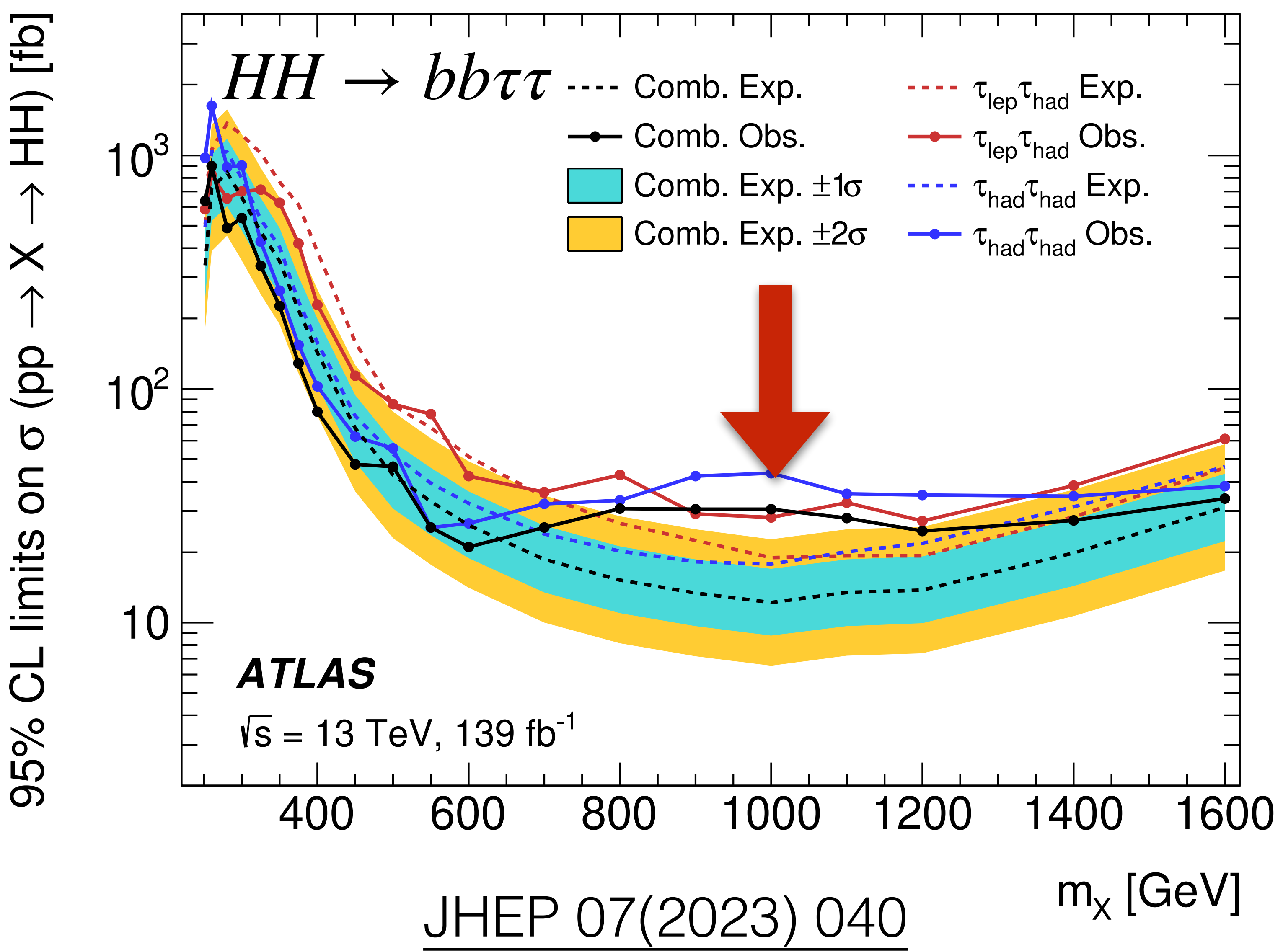


- HH-only can't constrain κ_λ and κ_t simultaneously
- H+HH combination have Exp. κ_λ limit with ~5% better than HH

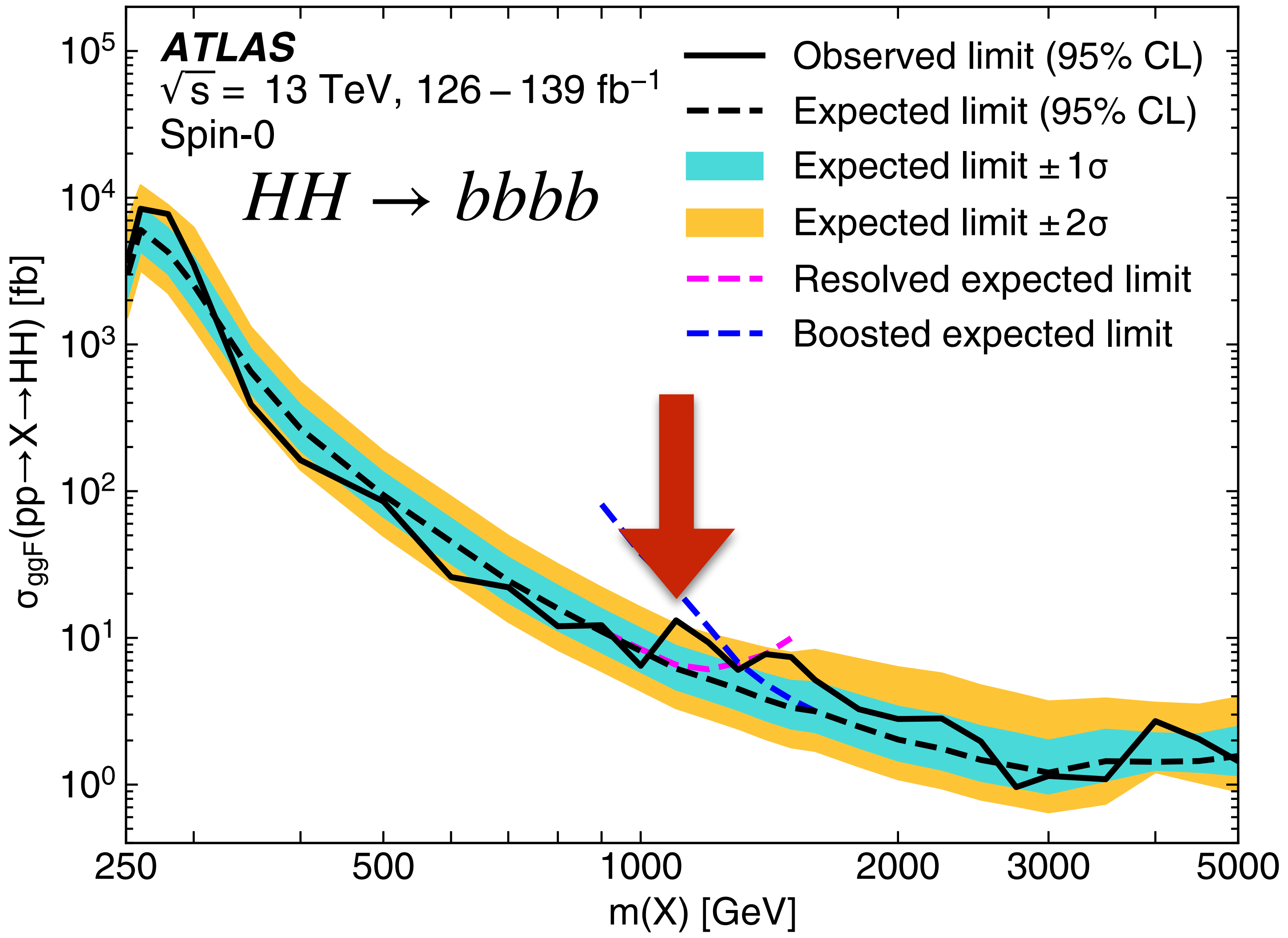
New resonance search via HH events



PRD 106 (2022)052001

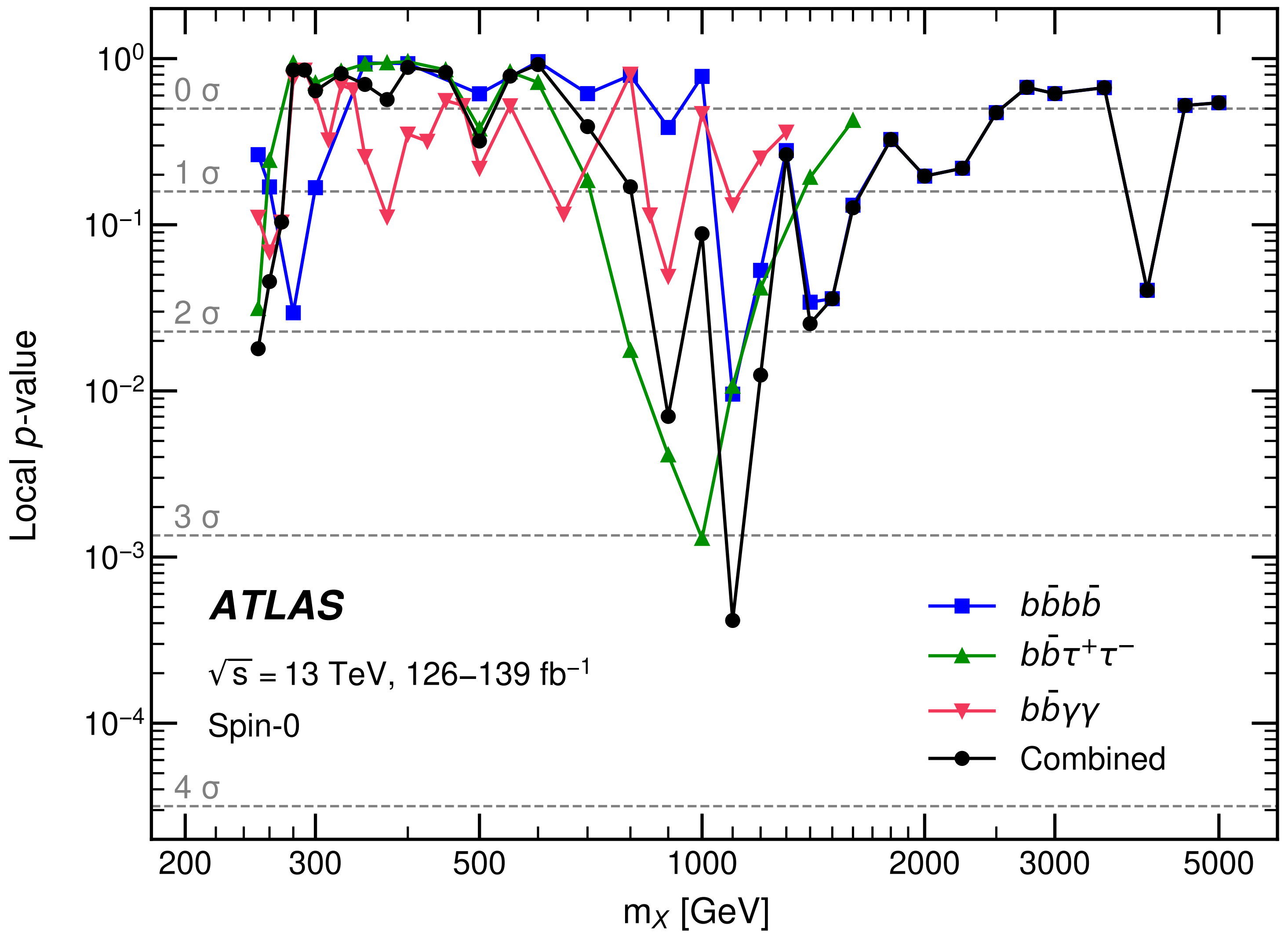


JHEP 07(2023) 040



PRD 105 (2022)092002

- ◈ Largest deviation is at 1.1TeV (Z_{local}=3.3σ , Z_{global}=2.1σ)
  - ✦ $b\bar{b}\gamma\gamma$: no significant excess
  - ✦ $b\bar{b}\tau^+\tau^-$: 3.1σ (2.0σ) at 1TeV
  - ✦ $b\bar{b}b\bar{b}$: 2.3σ (0.4σ) at 1.1TeV



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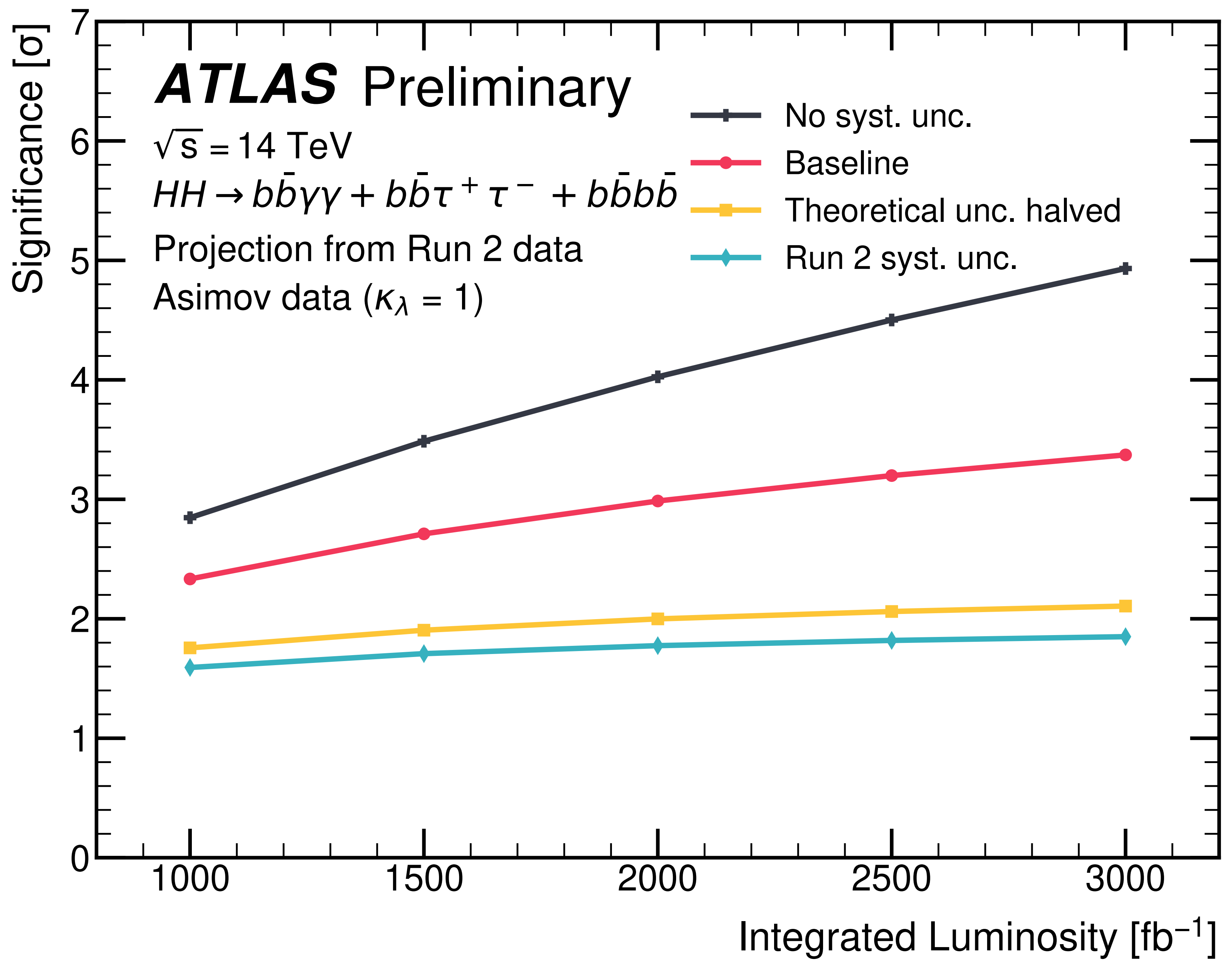
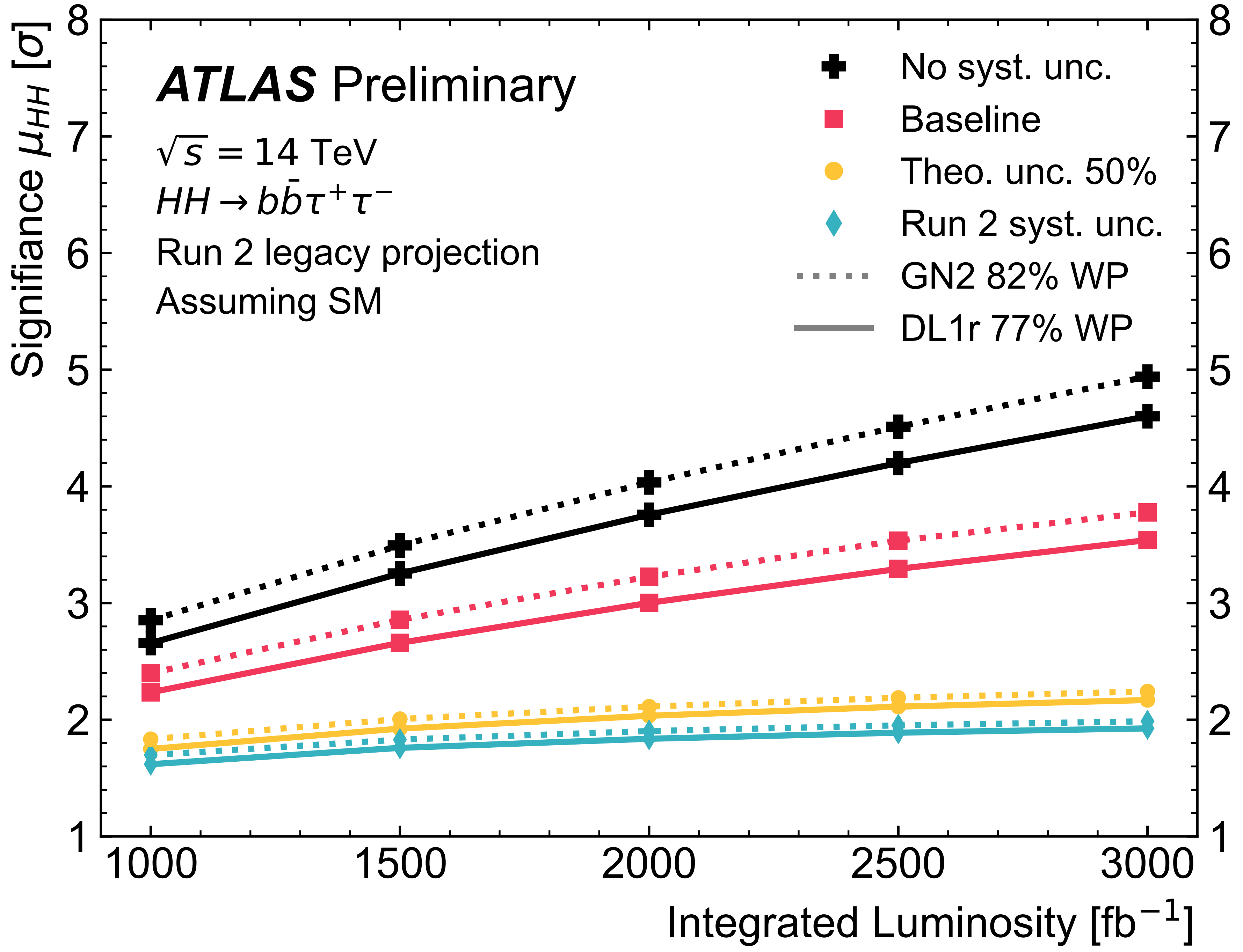
HL-LHC Prospects





- Latest ATLAS combination projection using the three most sensitive channels of $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}b\bar{b}$ [ATLAS-PHYS-PUB-2022-053]
- Updated ATLAS projection of the updated $b\bar{b}\tau^+\tau^-$channel [ATL-PHYS-PUB-2024-016]
  - Updated categorization optimization and improvements of b-tagging and τ-identification algorithms
  - Expected to observe HH with the significance of 3.8σ (4.9σ)

Summary

- Updated ATLAS *HH* combination with full Run 2 data：
  - Double-Higgs production signal strength constrainned with observed (expected) 95% CL upper limit of μ_{HH}< 2.9 (2.4)
  - Higgs boson self-coupling modifier κ_λ constrained with observed (expected) 95% CL intervals of $-1.2 < \kappa_\lambda < 7.2$ ($-1.6 < \kappa_\lambda < 7.2$)
  - Quartic *HHVV* coupling modifier κ_{2V} constrained with observed (expected) 95% CL intervals of $0.6 < \kappa_{2V} < 1.5$ ($0.4 < \kappa_{2V} < 1.6$)
- New ATLAS projections for the HL-LHC at 3000 fb^{-1} obtained, but not based on fully latest individual HH results
- More promising results with Run3 and HL-LHC