UPPSALA UNIVERSITET

UNIVERSITÄT BONN

Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS

Christina Dimitriadi (christina.dimitriadi@cern.ch)

On behalf of the **ATLAS** Collaboration

Phenomenology 2023 Symposium, Pittsburgh

8-10 May 2023

ATLAS EXPERIMENT

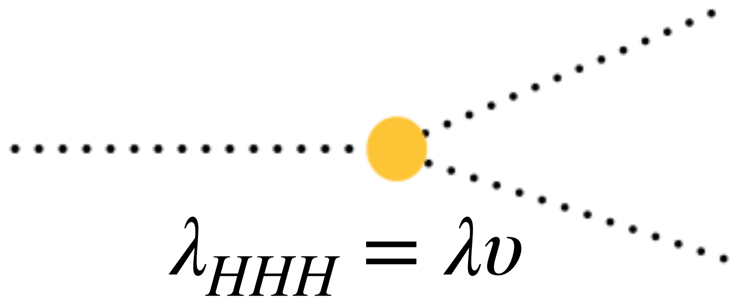
Why look for Higgs boson pairs?

- Great progress in our understanding of the **Higgs boson** since its discovery in 2012

- But still little knowledge about the **Higgs potential**

$$V(H) = \frac{1}{2} m_H H^2 + \lambda v H^3 + \ldots$$

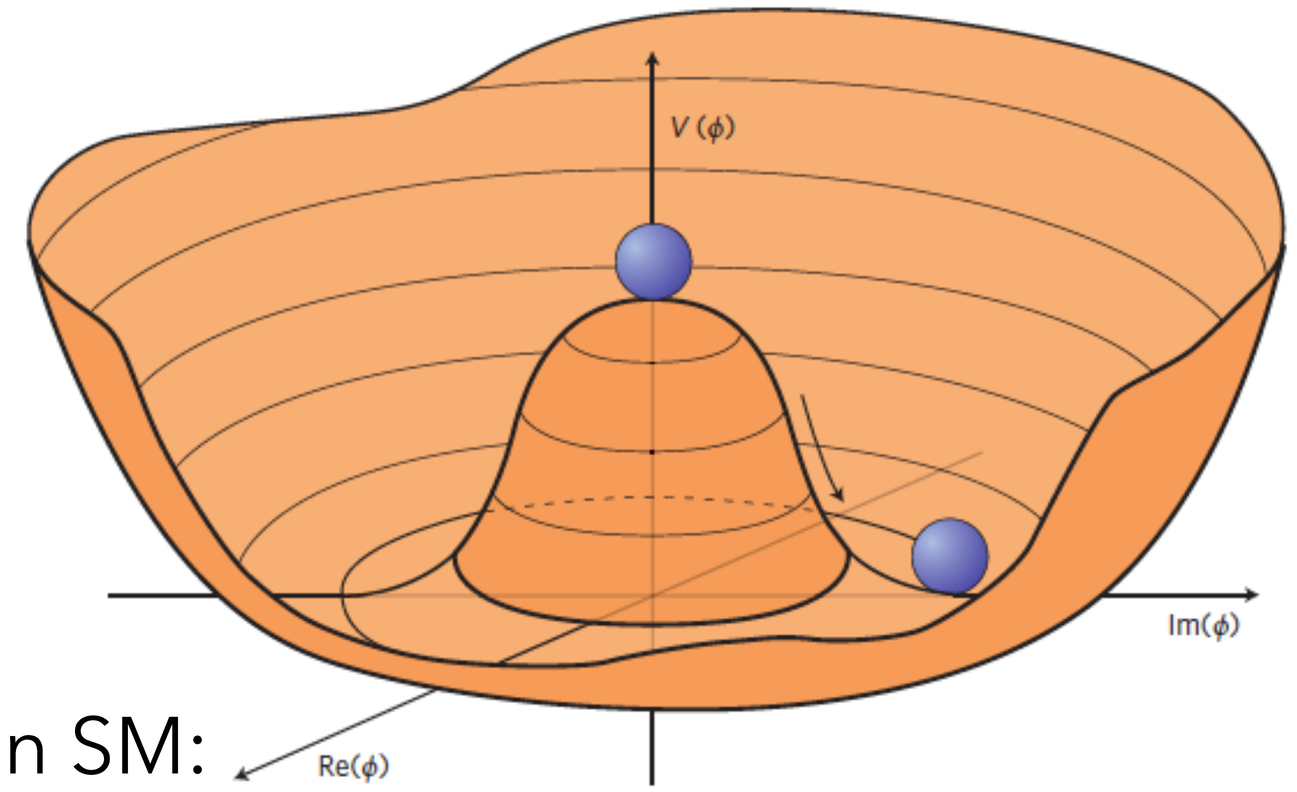
self-interaction term



$\lambda_{HHH} = \lambda v$

Vacuum expectation value in SM:

$v = (\sqrt{2} G_F)^{-1/2} = 246\,\text{GeV}$

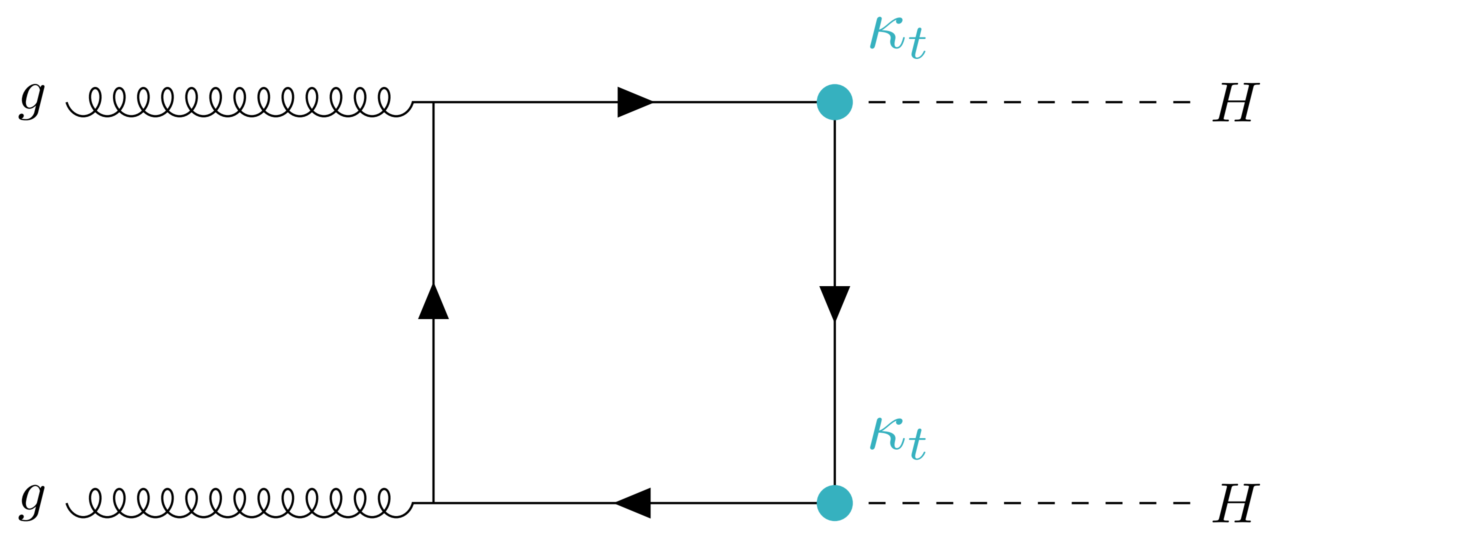


- A **measurement** of Higgs boson pair (HH) production could provide evidence of the **Higgs self-coupling**, which is a direct probe of the shape of the Higgs potential

- Any **deviation** of the self-interaction from its SM expectation is a sign of **new physics**!

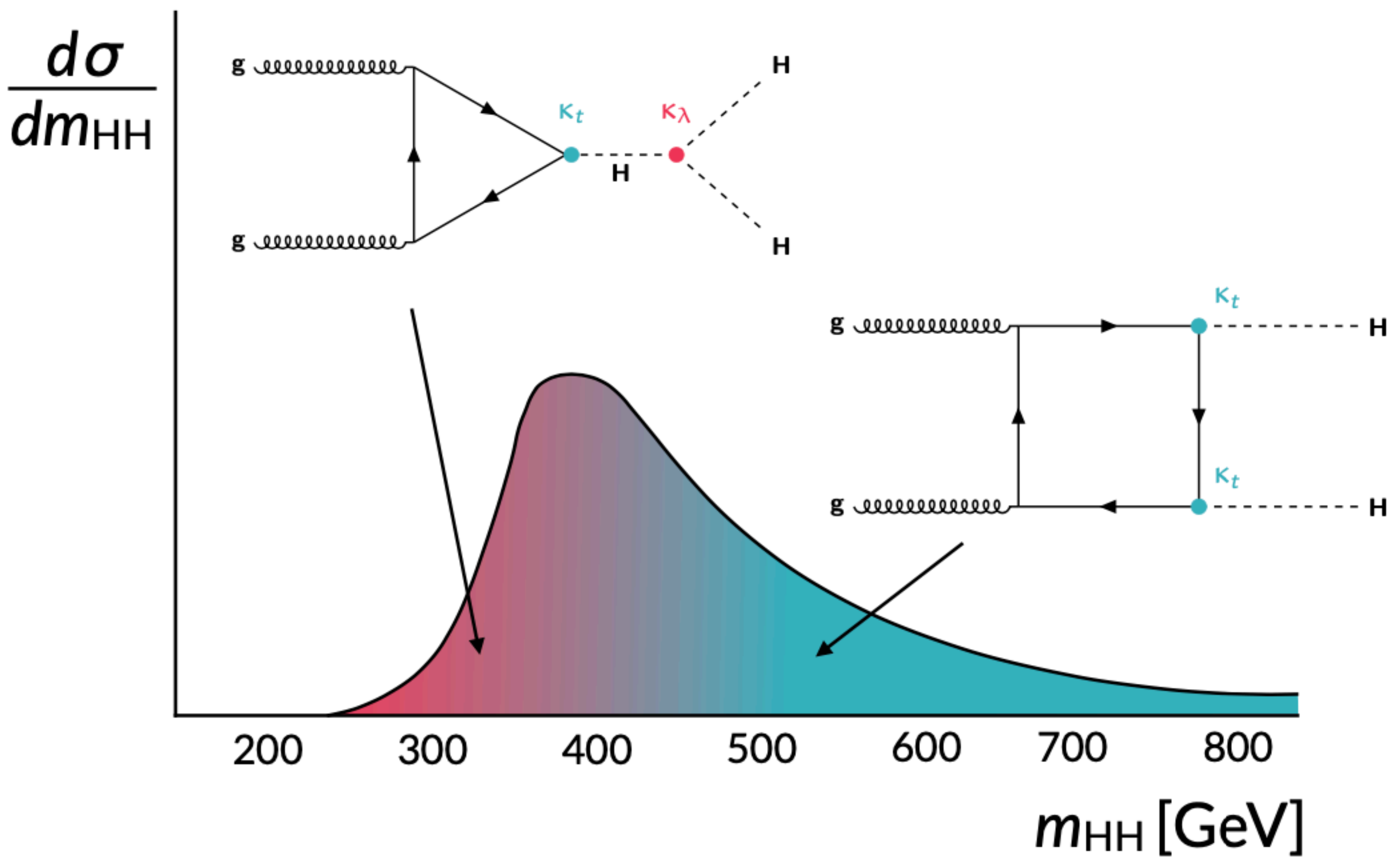
Higgs boson pair production

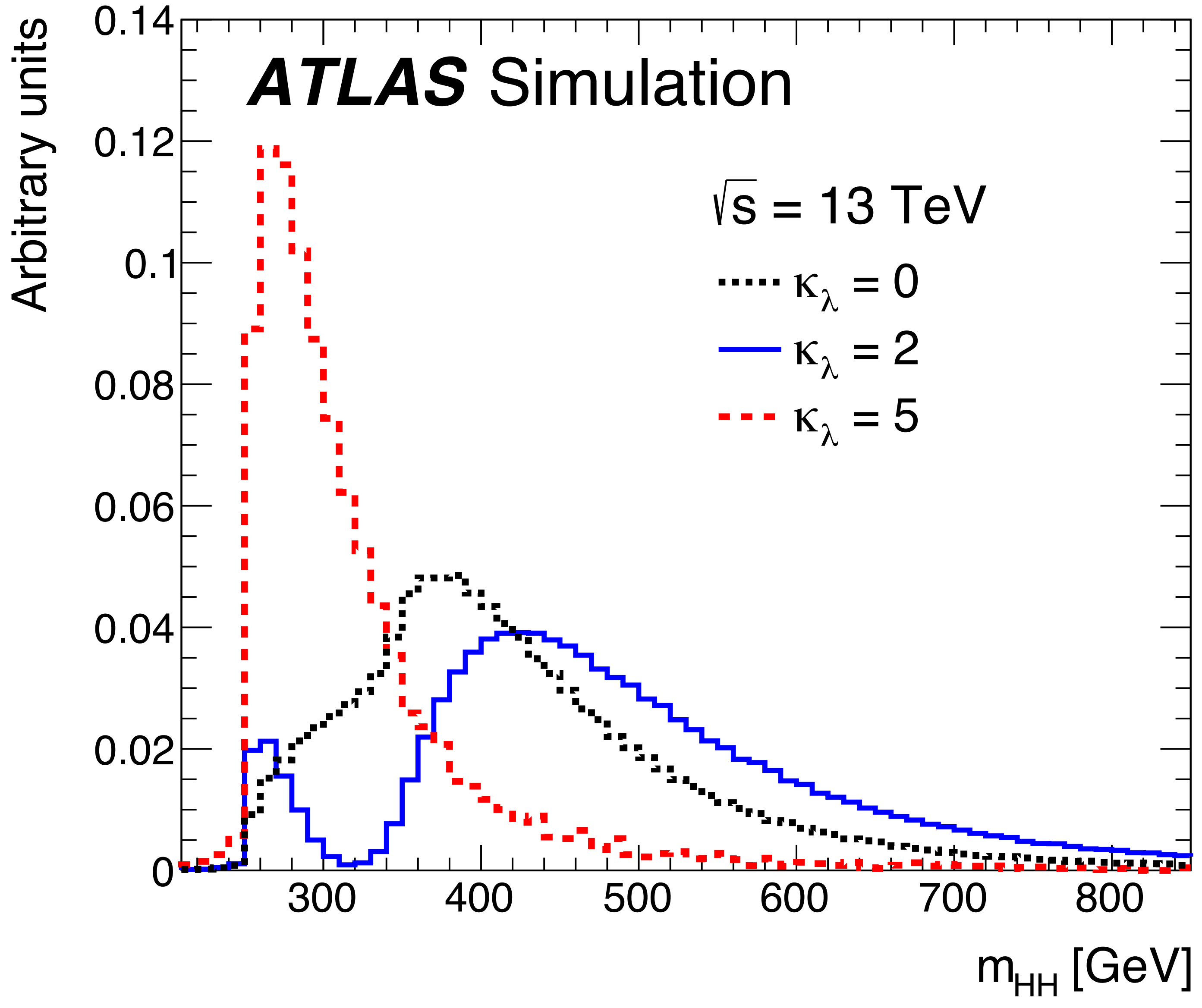
- Gluon fusion: $\sigma_{\text{ggF}}(pp \to HH) = 31$ fb at 13 TeV



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

➡ κ_λ variations modify the HH cross-section and kinematics w.r.t SM predictions

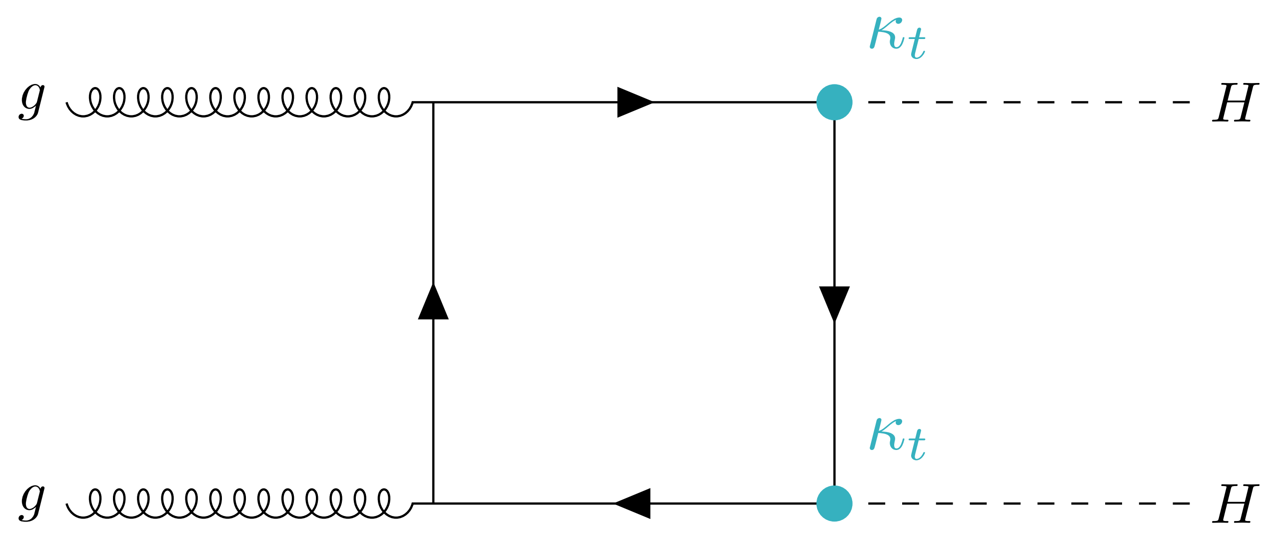


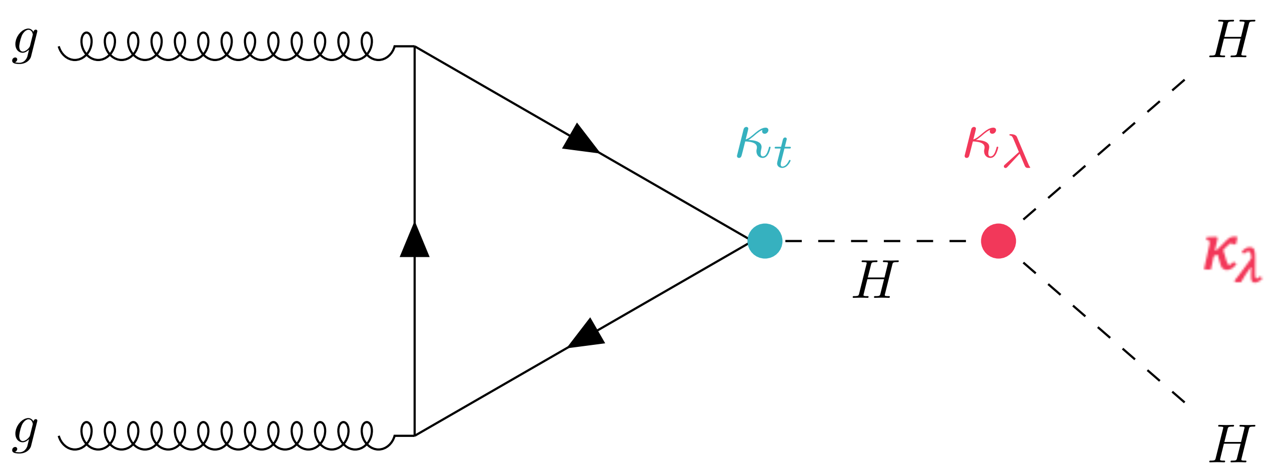


Phys. Lett. B 800 (2020) 135103

Higgs boson pair production

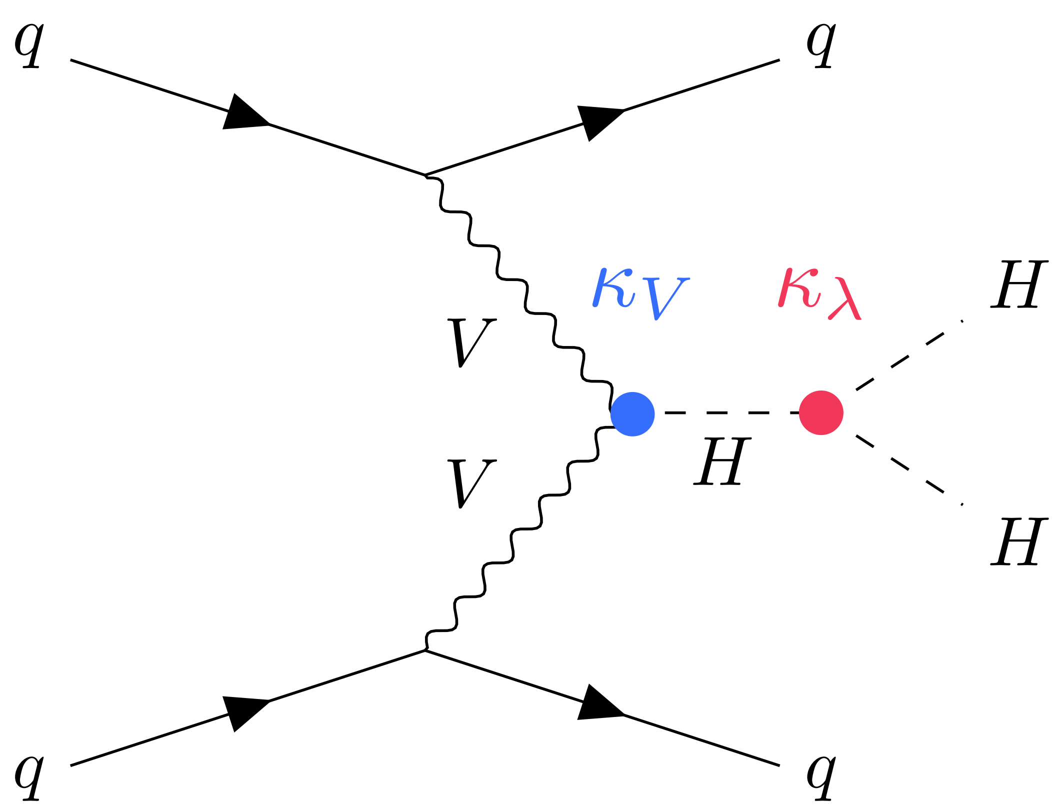
- Gluon fusion: $\sigma_{\text{ggF}}(pp \to HH) = 31$ fb at 13 TeV

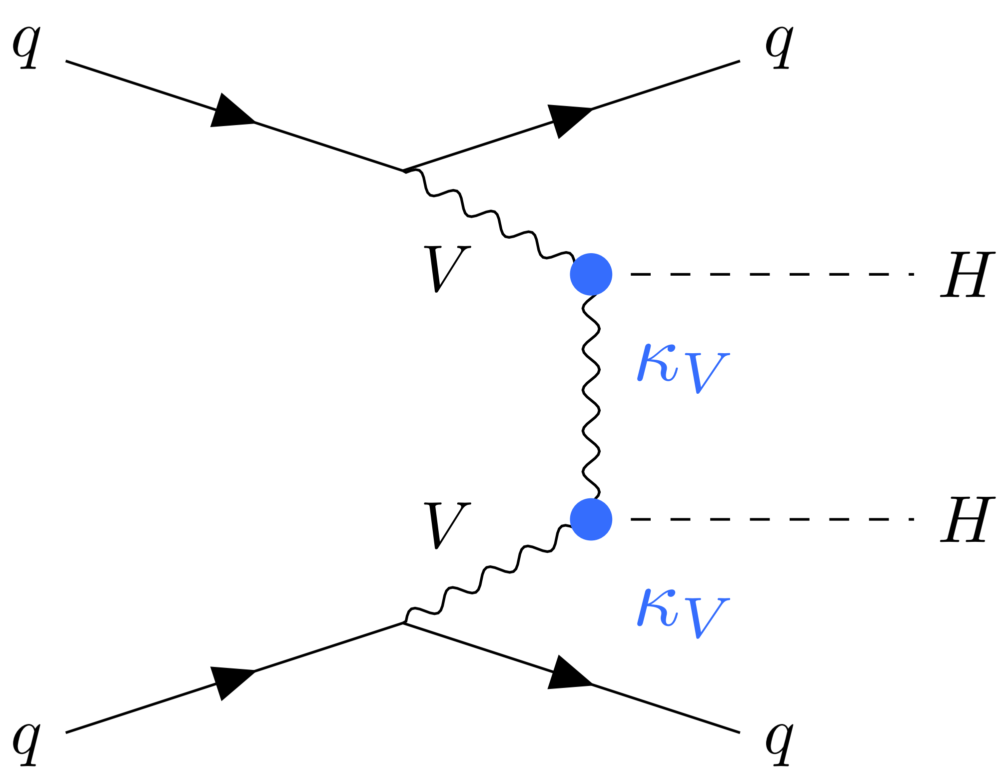


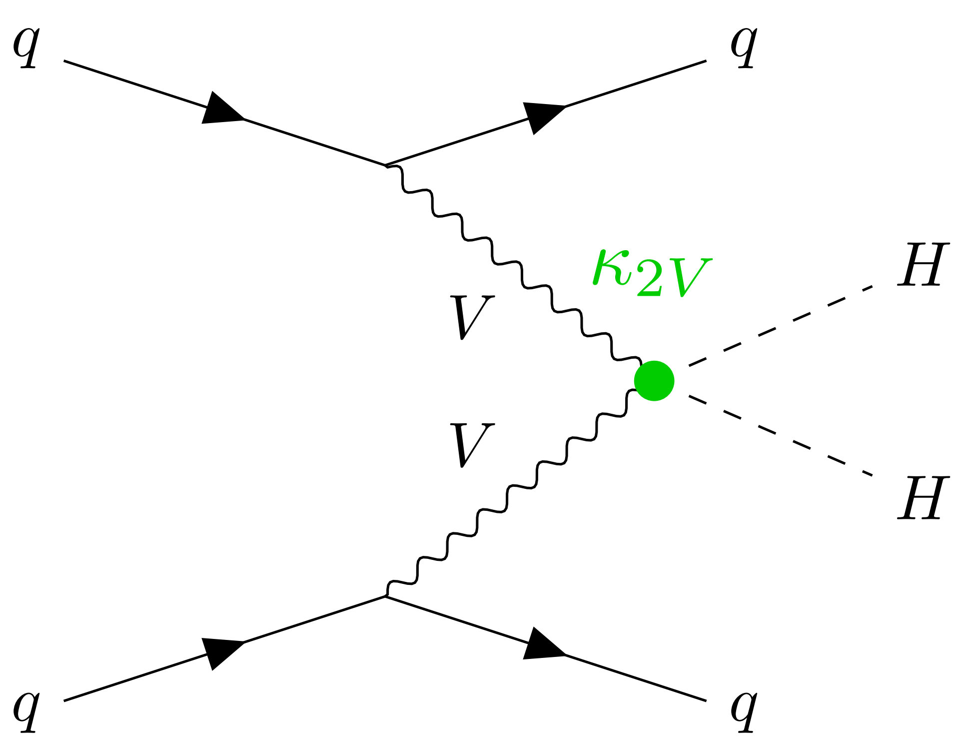


$\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$

- Vector-boson fusion: $\sigma_{\text{VBF}}(pp \to HH) = 1.7$ fb at 13 TeV







Additional sensitivity to κ_λ

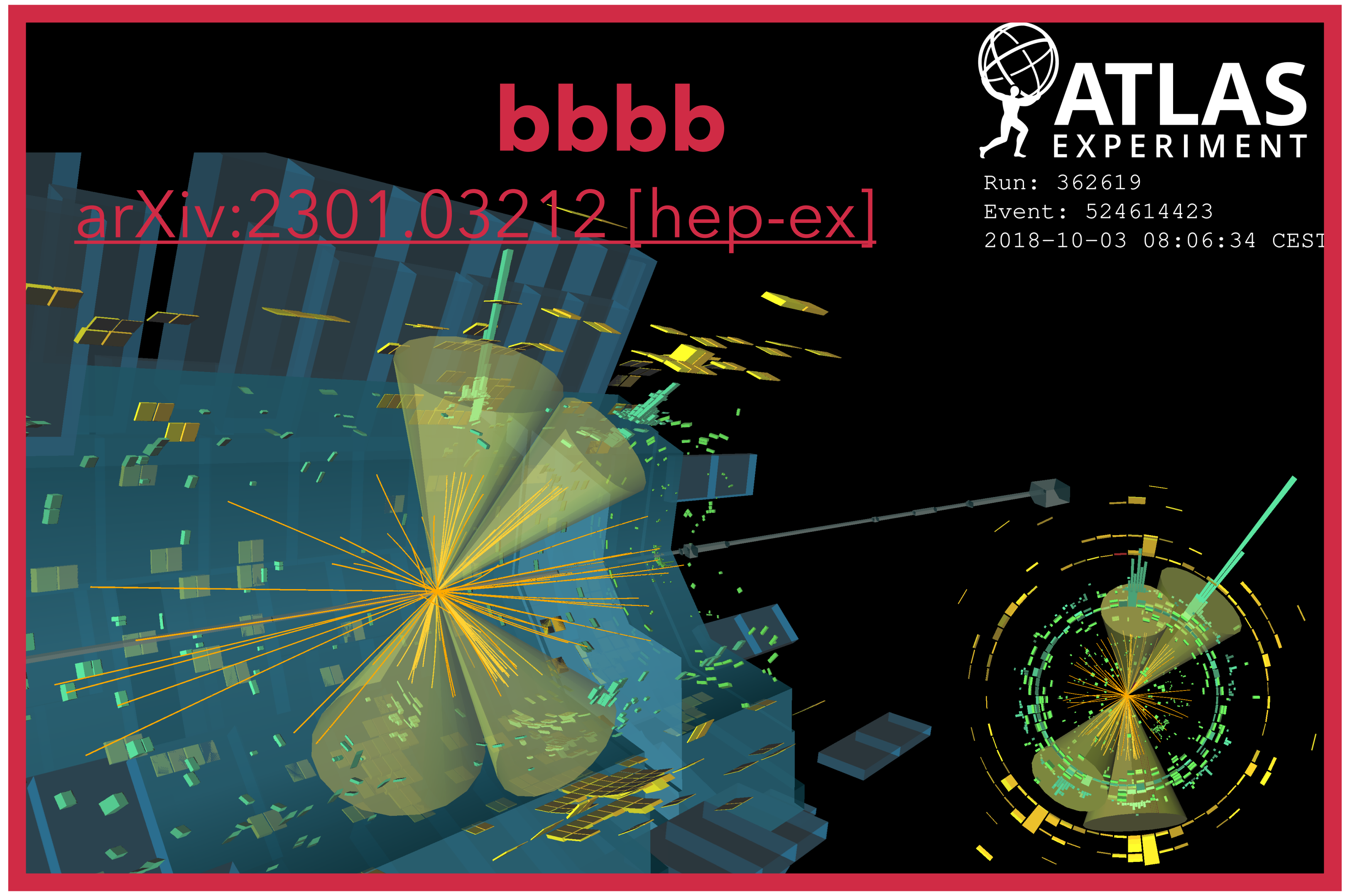
Unique probe of κ_{2V} in VBF HH searches

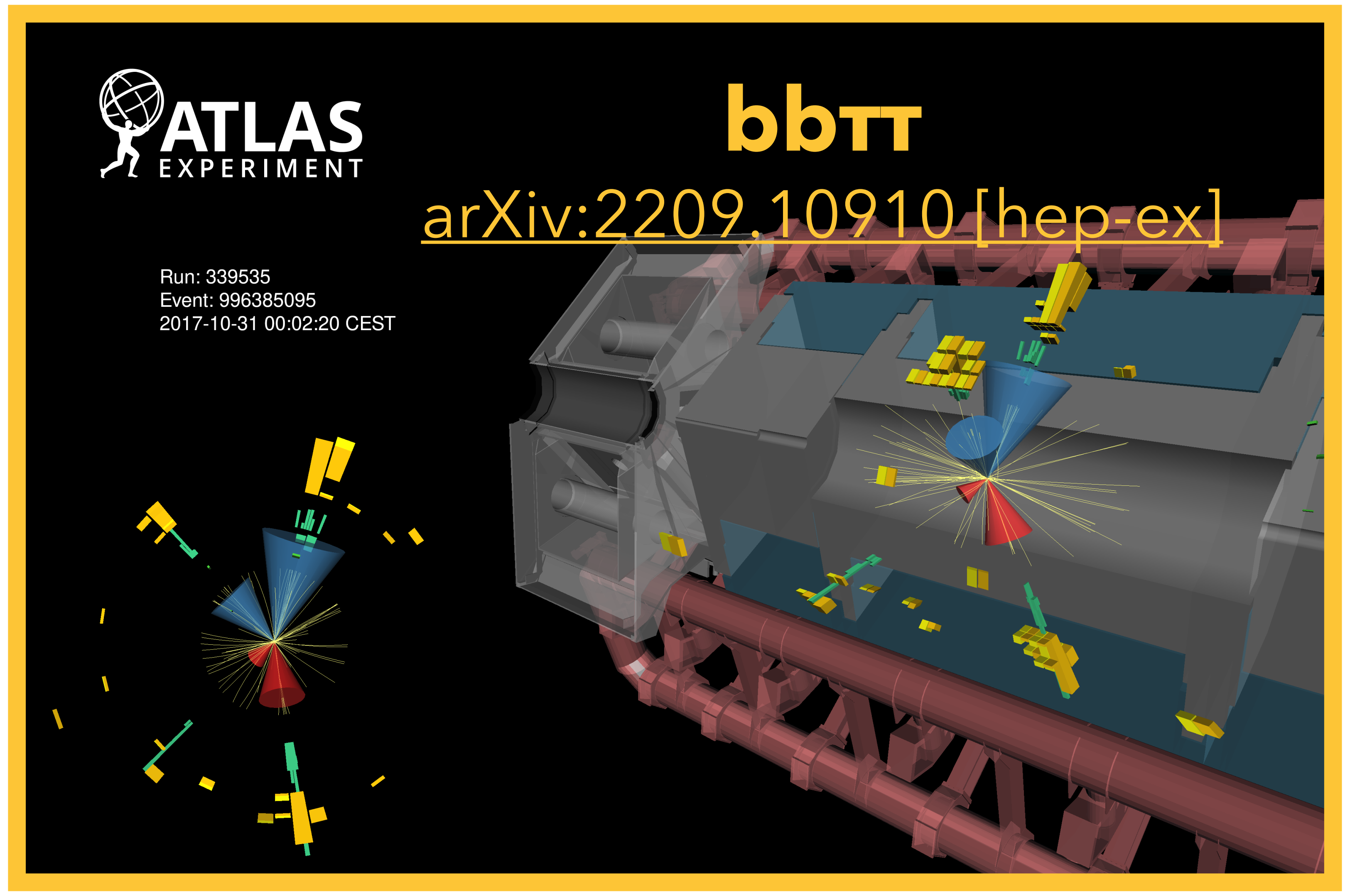
HH decay channels

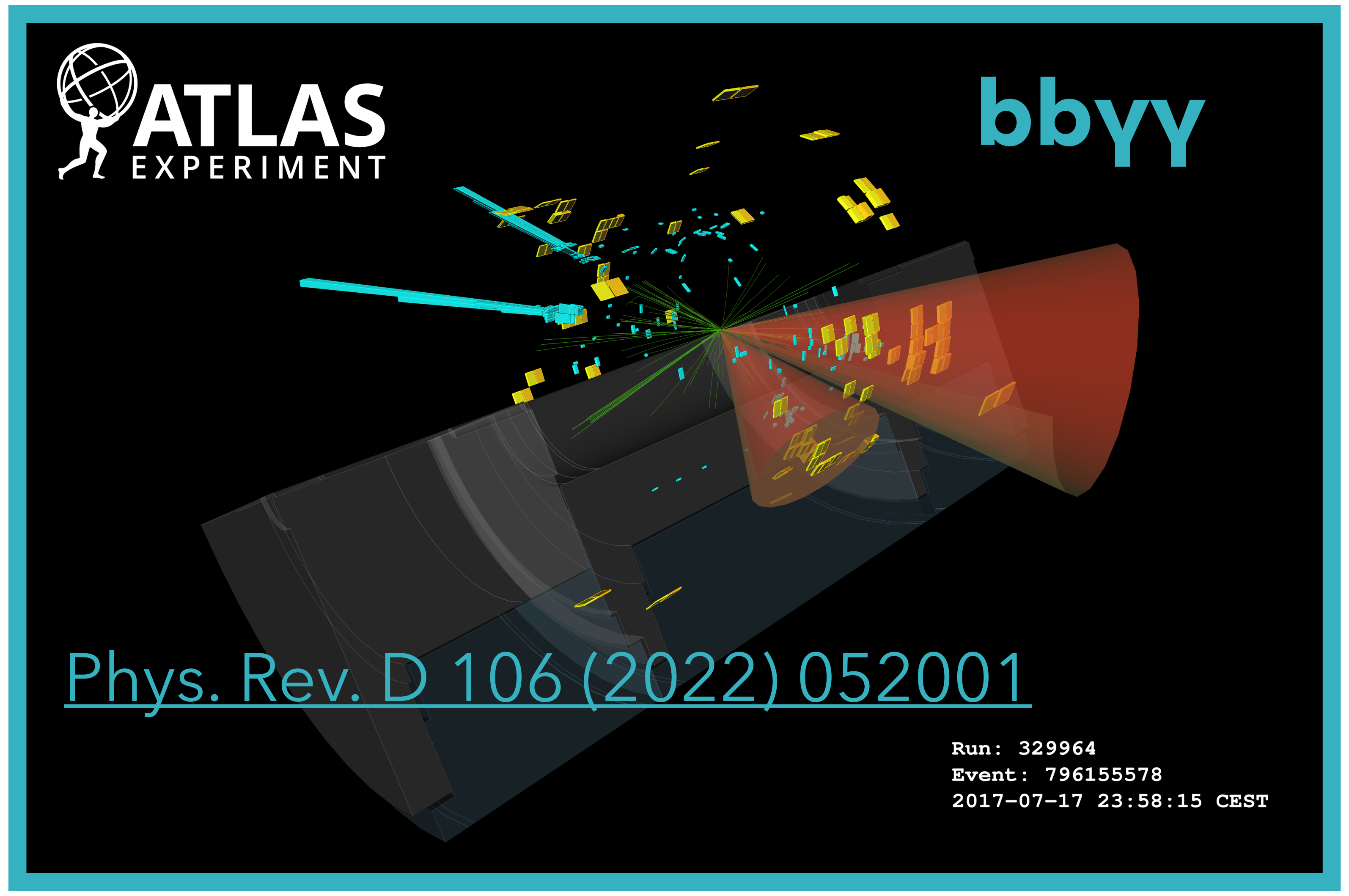
Multiple decay channels, here focus on the **3 most sensitive searches** and **their combination**:

- $HH \rightarrow bbbb$: plenty of signal 👍, but challenging multi-jet background 👎
- $HH \rightarrow bb\tau\tau$: moderate signal rate, relatively clean final state ⚖️
- $HH \rightarrow bb\gamma\gamma$: very clean signature 👍, but tiny branching ratio 👎

	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%



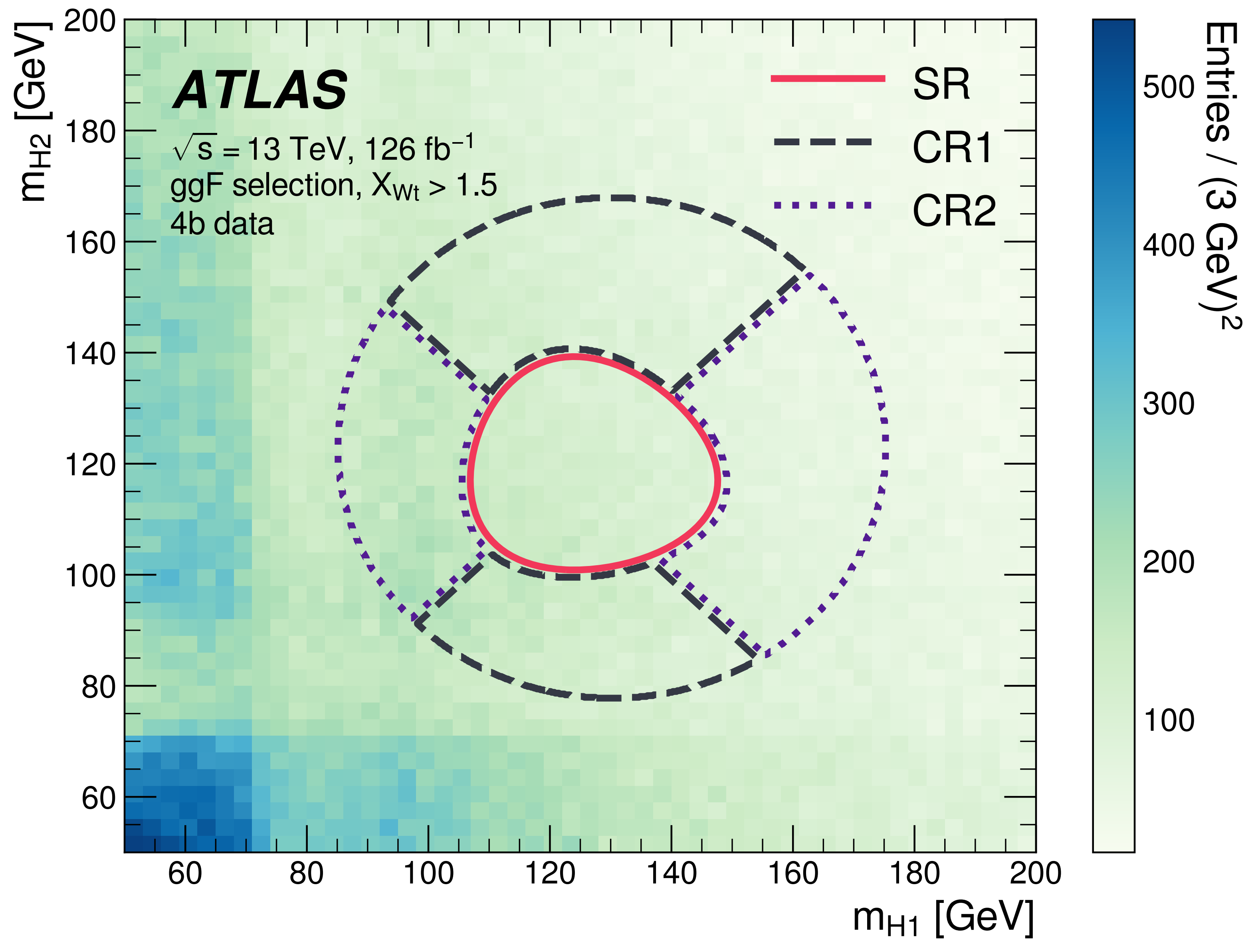


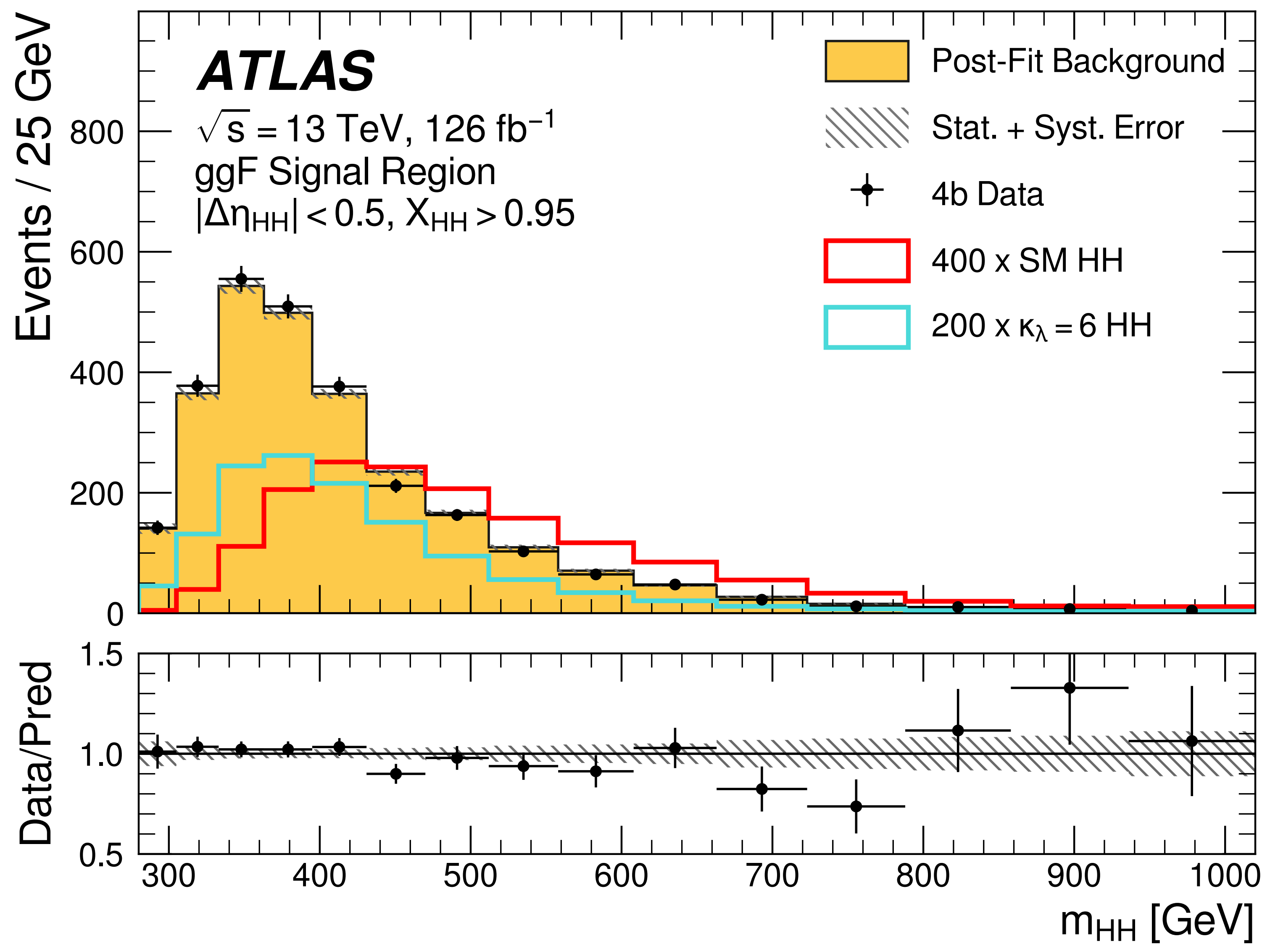


HH→bbbb search

arXiv:2301.03212 [hep-ex]

- Event selection
  - Trigger on events with at least 2 b-tagged jets
  - Two Higgs boson candidates reconstructed from 4 b-tagged jets with the smallest ΔR_{jj} pairing
  - **6 ggF and 2 VBF categories** based on forward jets and HH kinematic properties
- **Main backgrounds**: 90% multi-jet, 10% $t\bar{t}$ events
- Data-driven background estimates
  - $2b \rightarrow 4b$ event reweighting in SR (NN-based weights from CR)
- Fit m_{HH} in all categories





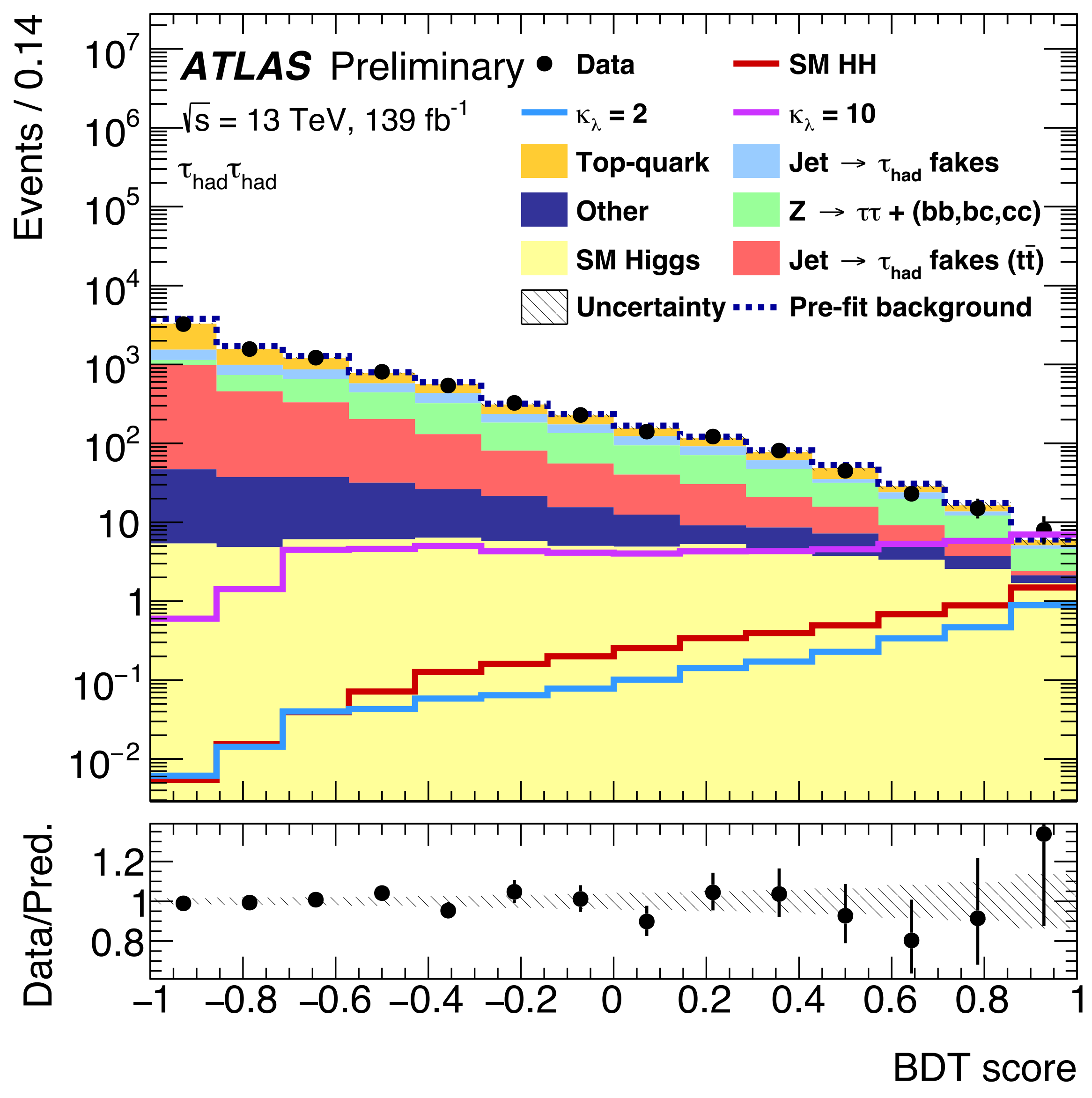
HH→bbττ search

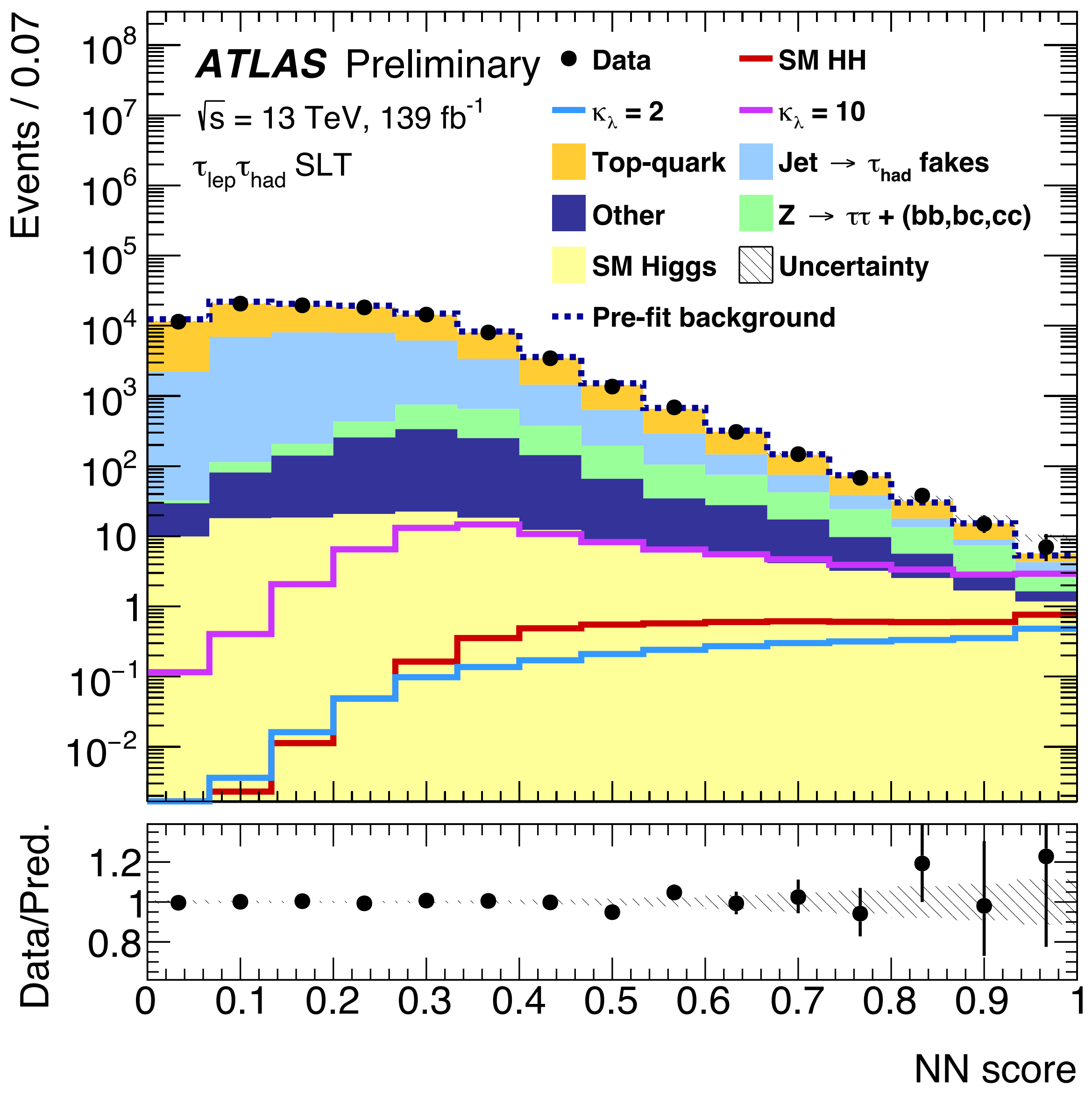
arXiv:2209.10910 [hep-ex]

- Event selection
  - 2 sub-channels split by tau decay mode, in total **3 SRs** driven by trigger
    - $b\bar{b}\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ → BDT
    - $b\bar{b}\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ SLT (single-lepton triggers) → NN
    - $b\bar{b}\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ LTT (lepton+tau triggers) → NN

MVA discriminants trained with kinematic variables

- Dominant backgrounds:
  - True taus from $t\bar{t}$ and $Z \to \tau\tau$ + HF (simulation)
  - Fake taus from multi-jet and $t\bar{t}$ processes (data-driven)
- **Fit MVA** outputs in all categories together with m_{ll} in a $Z \to ee/\mu\mu$ + HF CR



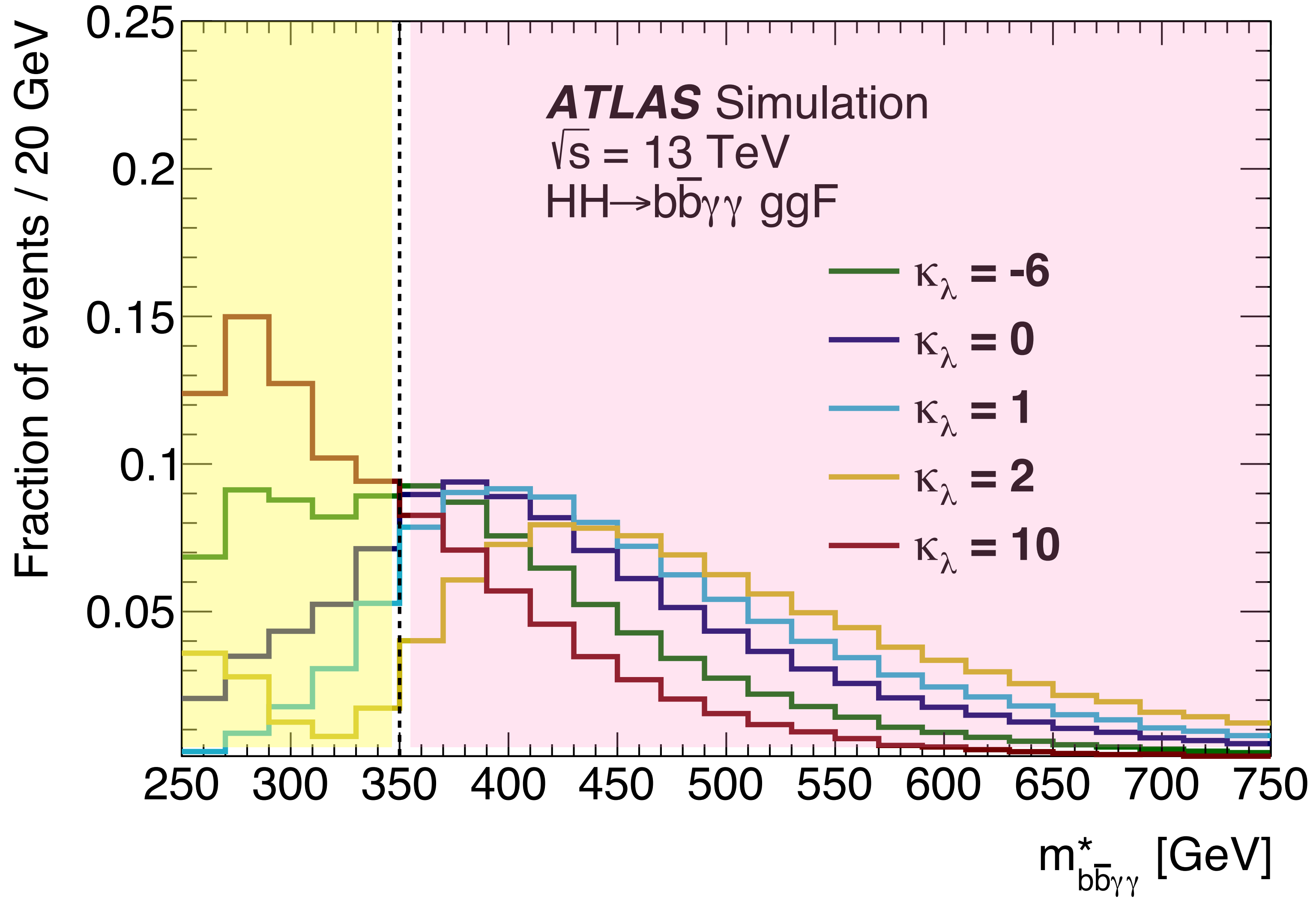


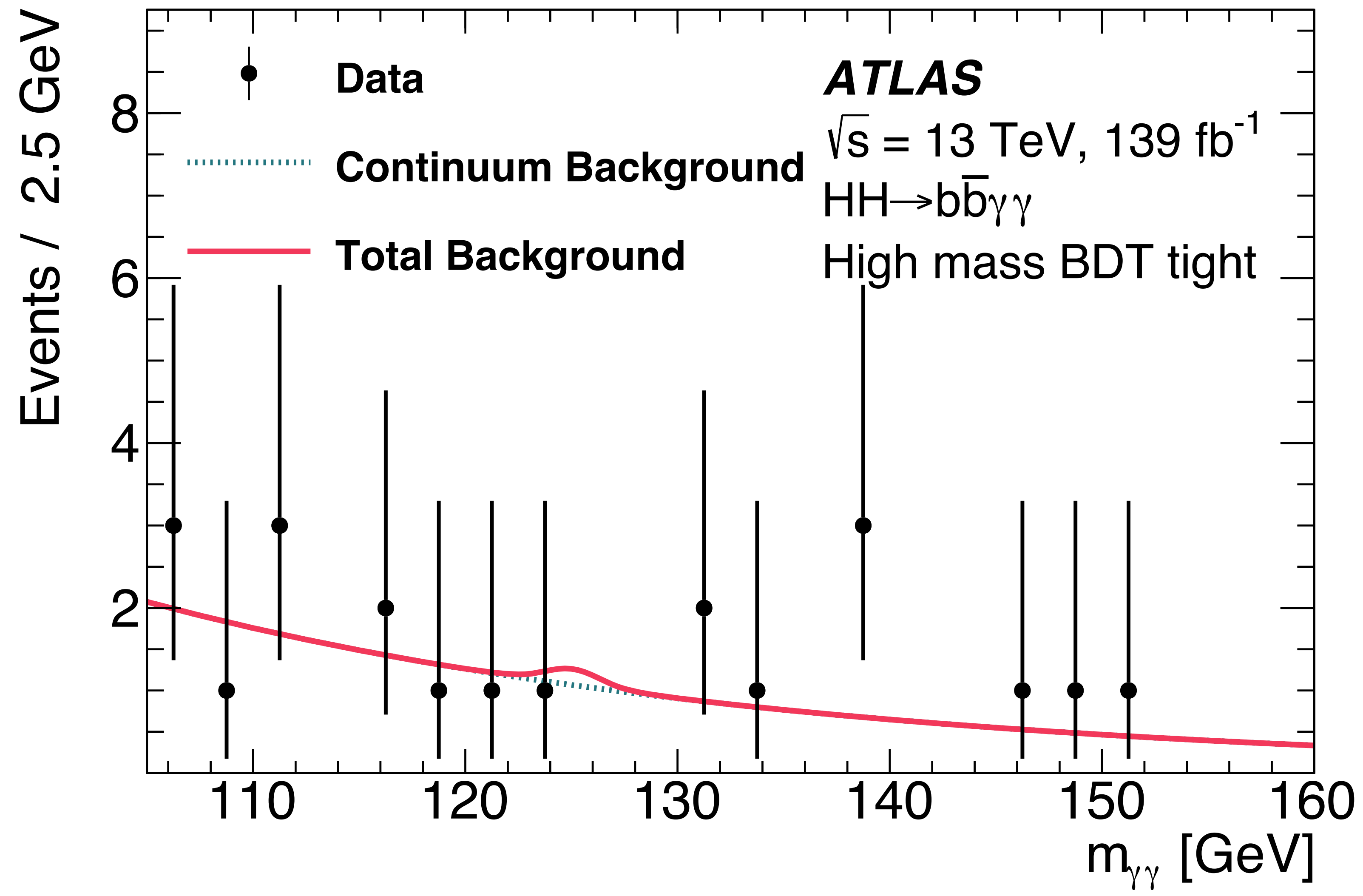
ATLAS-CONF-2021-052

HH→bbγγ search

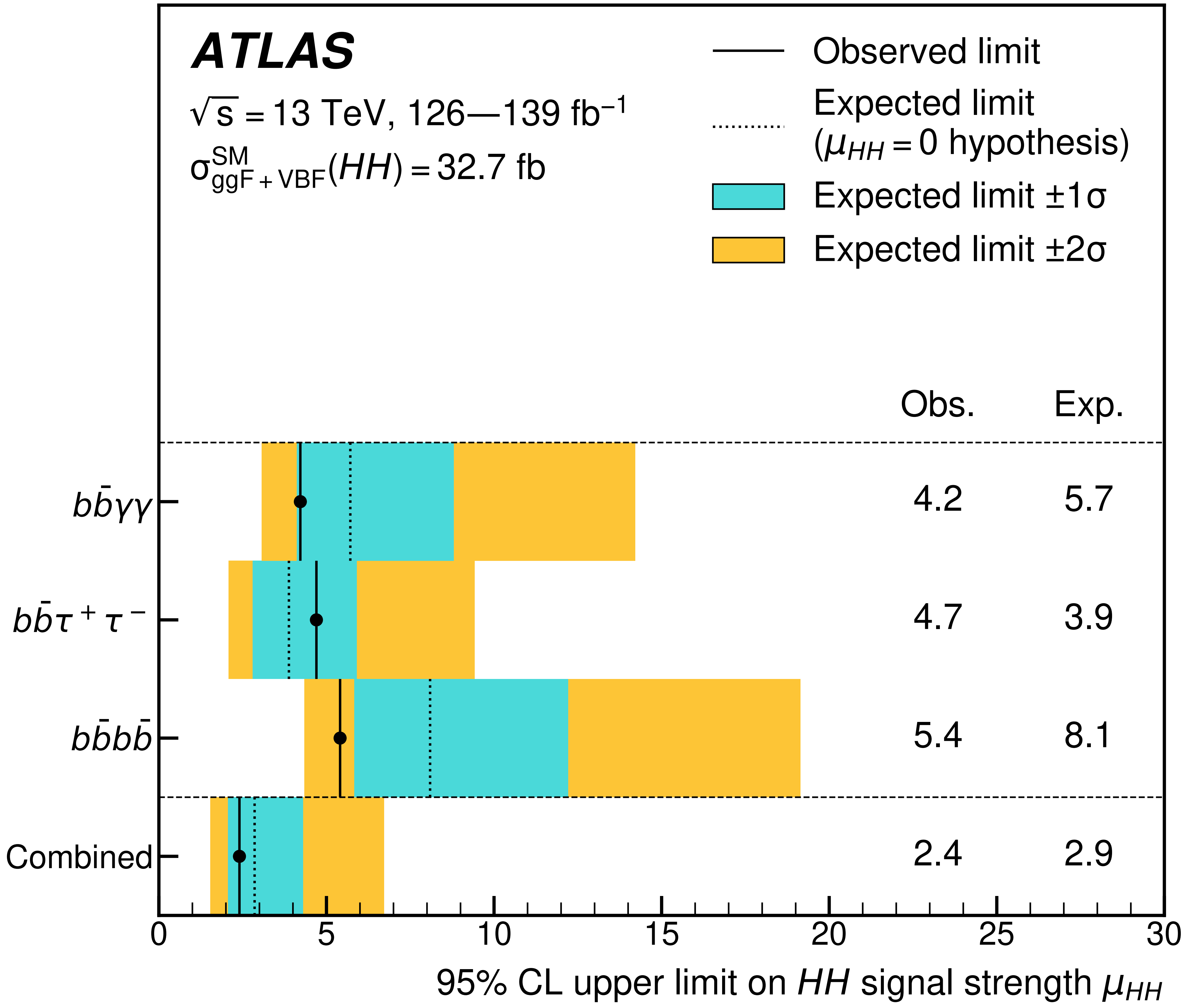
Phys. Rev. D 106 (2022) 052001

- Event selection
  - At least 2 photons and exactly 2 b-tagged jets
  - Split events into **low- and high-mass** regions to target different signal hypotheses
  - Separate BDTs in those two regions
    - Categorise into **loose- and tight-BDT SRs** for each mass region → 4 SRs in total
- **Main backgrounds:** $\gamma\gamma$ continuum and single Higgs boson
- **Fit** $m_{\gamma\gamma}$ in all categories





Combination: HH→bbbb + bbττ + bbγγ



arXiv:2211.01216 [hep-ex]

- **Statistical combination** of the three most sensitive HH decay channels (full Run-2 data)
- Yielded the **best** observed limits yet on HH production

  Observed (Expected) 95% CL limit: **2.4** (2.9) x SM prediction

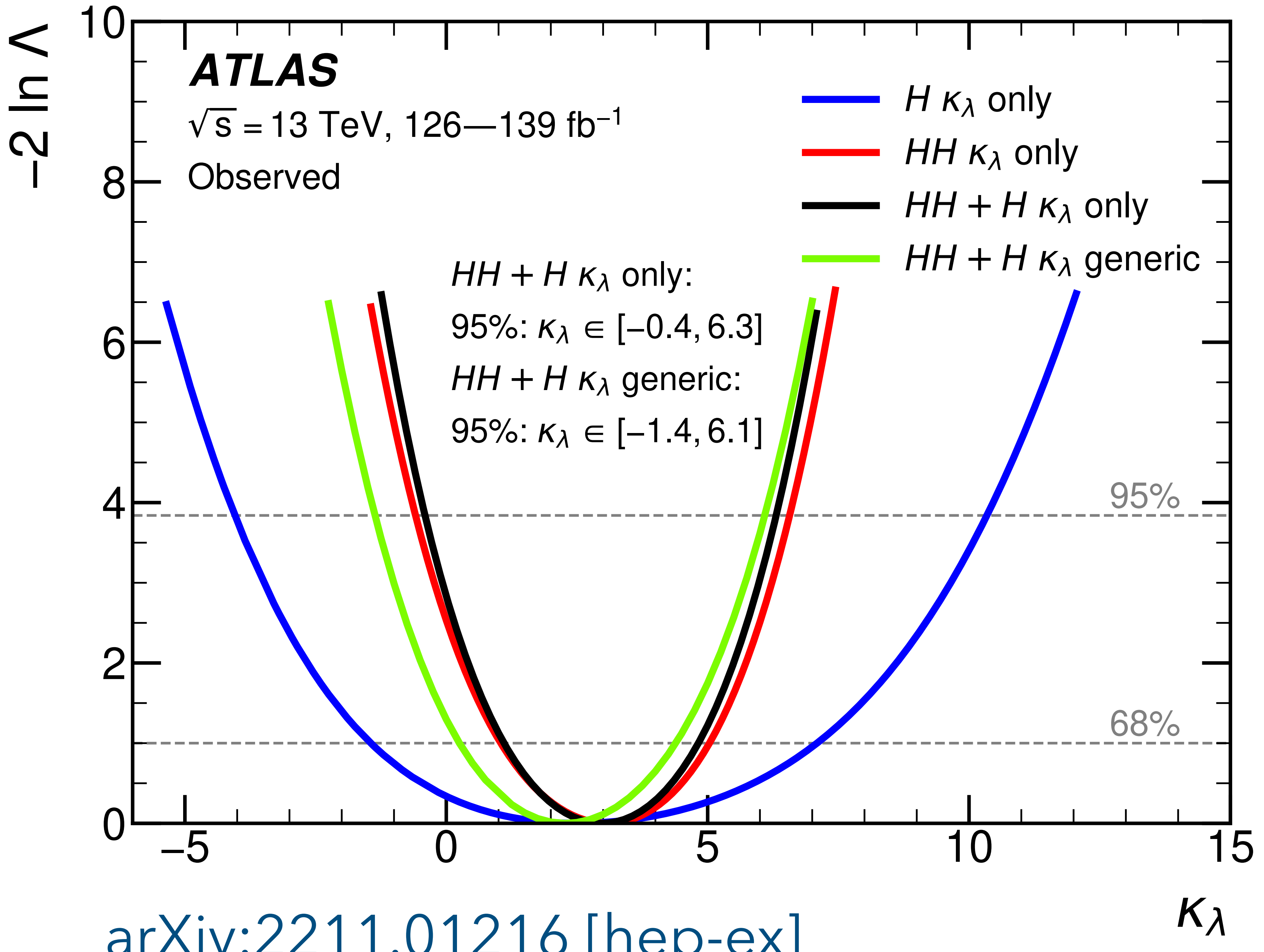
  Factor ~**3.4 improvement** compared to 36 fb^{-1} results (Phys. Lett. B 800 (2020) 135103)

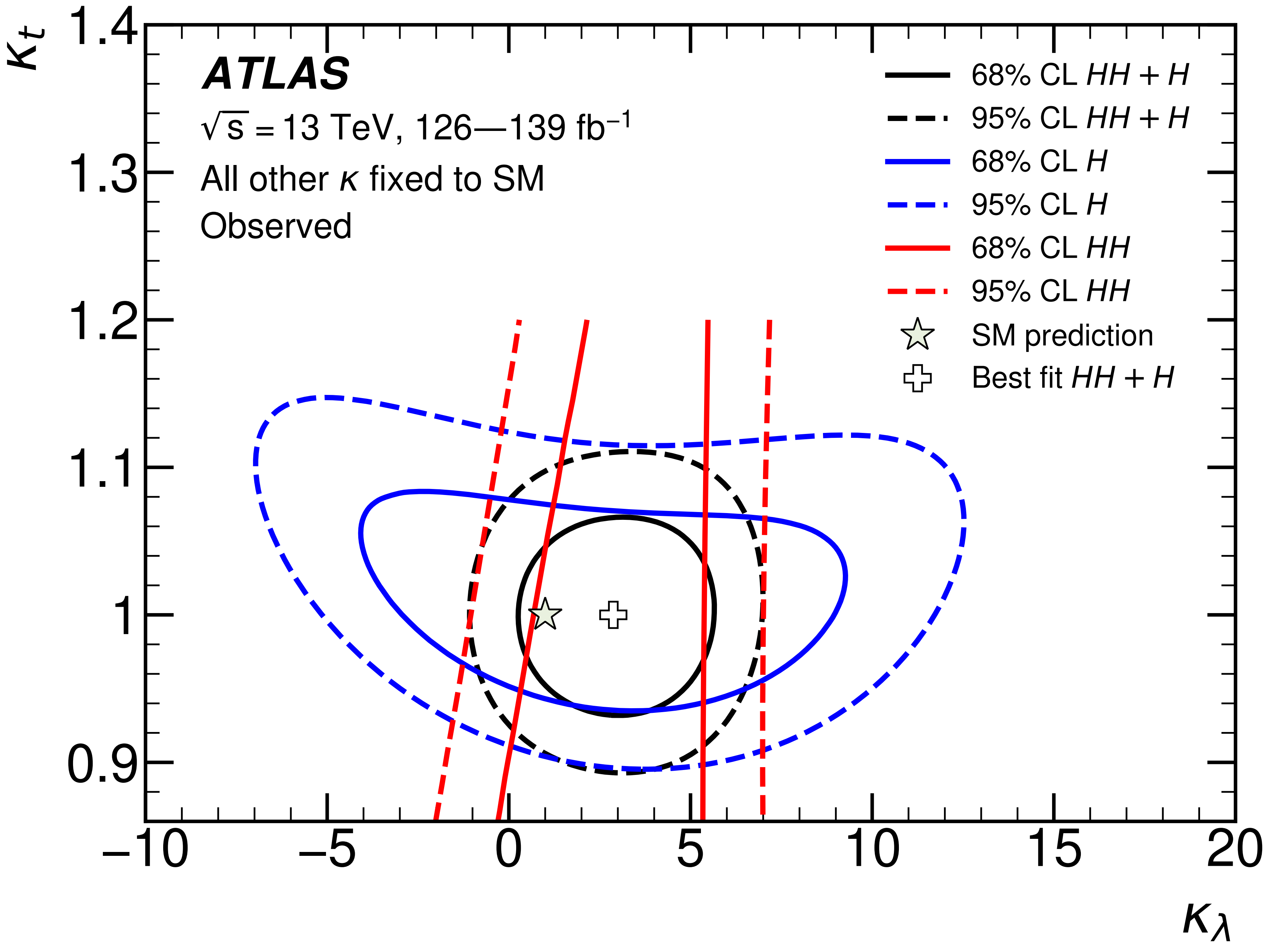
  → improved analysis design, object reconstruction & identification

HH+H constraints

- Single Higgs boson processes also sensitive to κ_λ through NLO electroweak loop corrections

- Better constraints achieved from the combination of $HH + H$ searches
  - Combination with single-Higgs allows for a less model-dependent interpretation





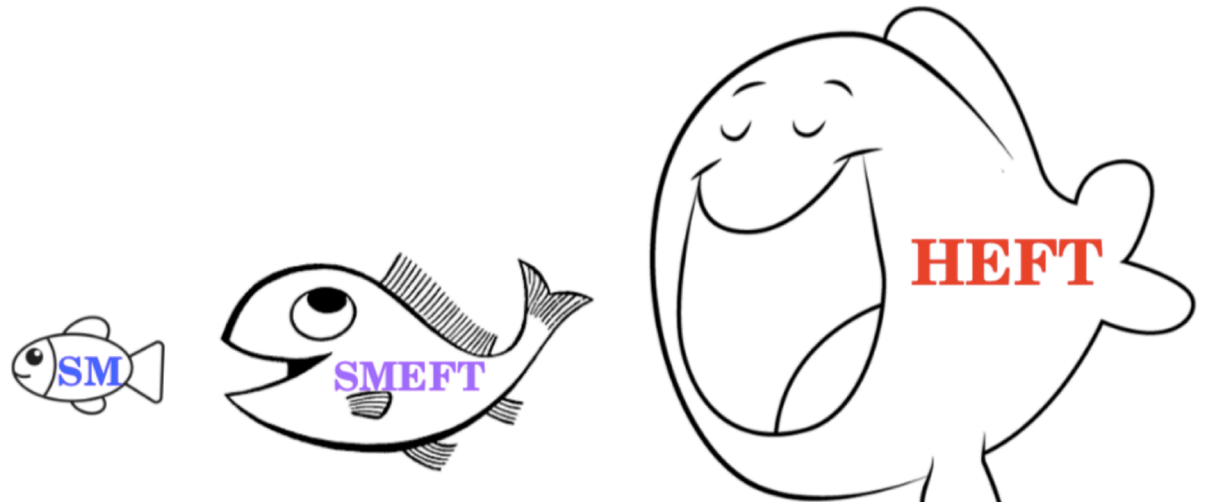
[arXiv:2211.01216 [hep-ex]]

HH in Effective Field Theories

- **New physics** effects can be parametrised without strong model-dependence by EFTs

- Two common frameworks in HH: **SMEFT** and Higgs EFT (**HEFT**)

    - Underlying different assumptions (e.g. SMEFT uses SM symmetries)



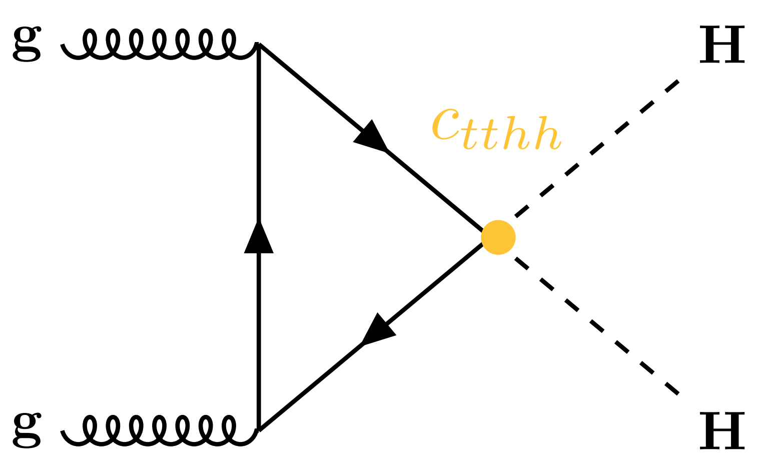
Raquel Gomez Ambrosio

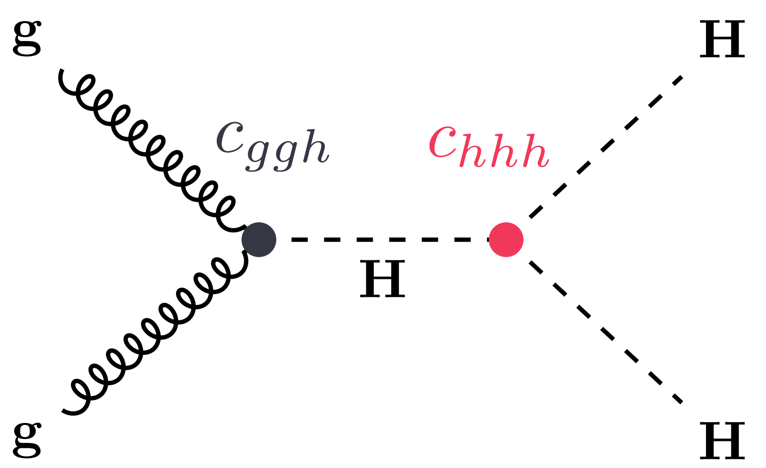
- Effective operators can modify the $gg \rightarrow HH$ production in various ways

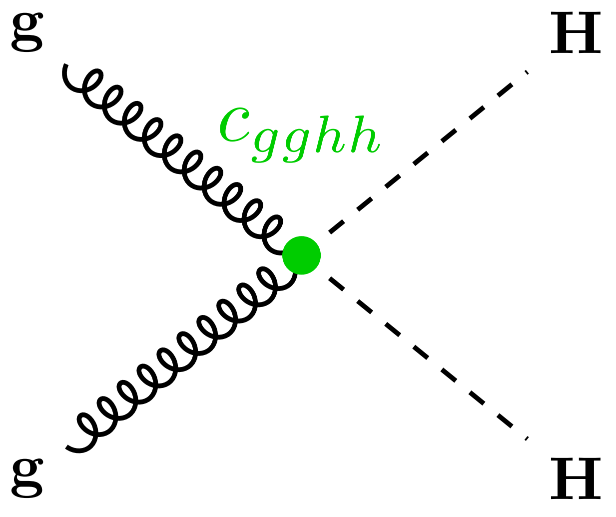
$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{n,i} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

Wilson Coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$
c_{HG}	$H^\dagger H G^A_{\mu\nu} G^{\mu\nu}_A$
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}G^A_{\mu\nu}$

$$\mathscr{L}_{\mathrm{HEFT}} \supset -m_t \left(c_{tth}\frac{h}{v} + c_{tthh}\frac{h^2}{v^2} \right) \bar{t}t - c_{hhh}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v} + c_{gghh}\frac{h^2}{v^2} \right) G^a_{\mu\nu}G^{a,\mu\nu}$$







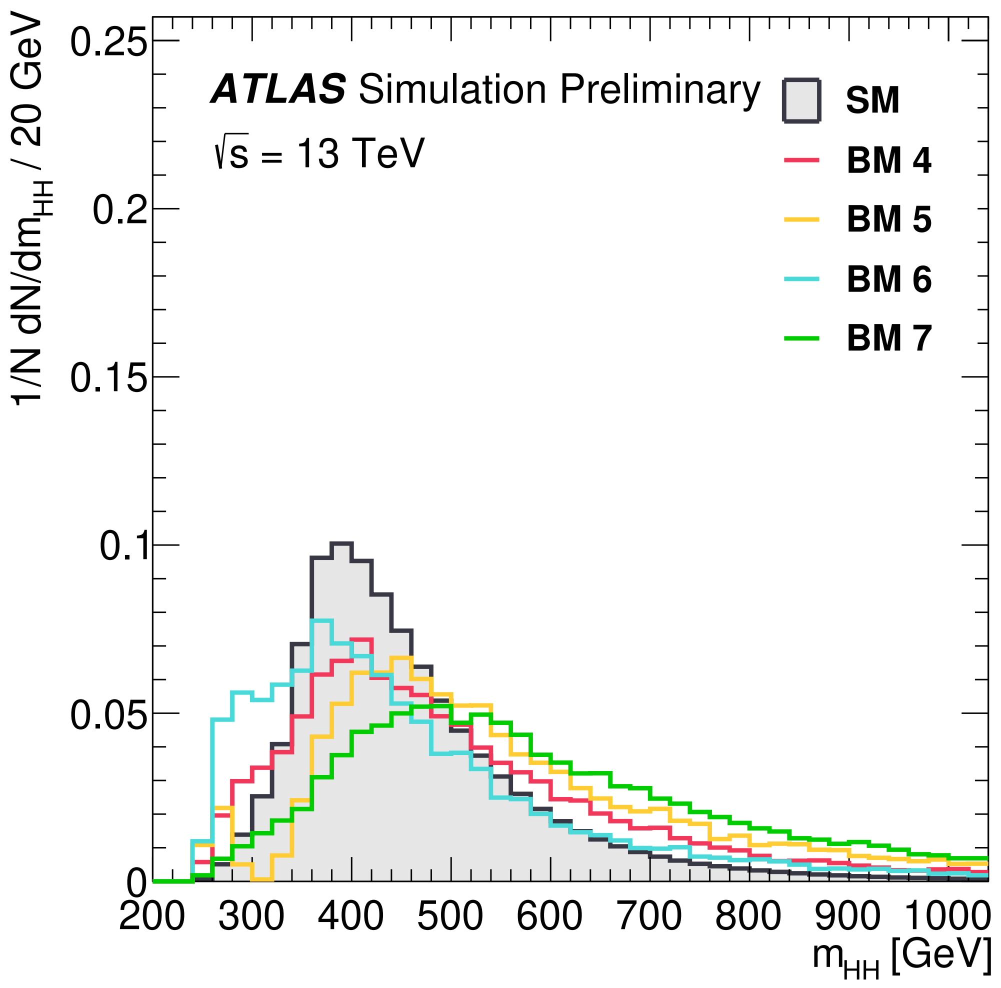
BSM diagrams

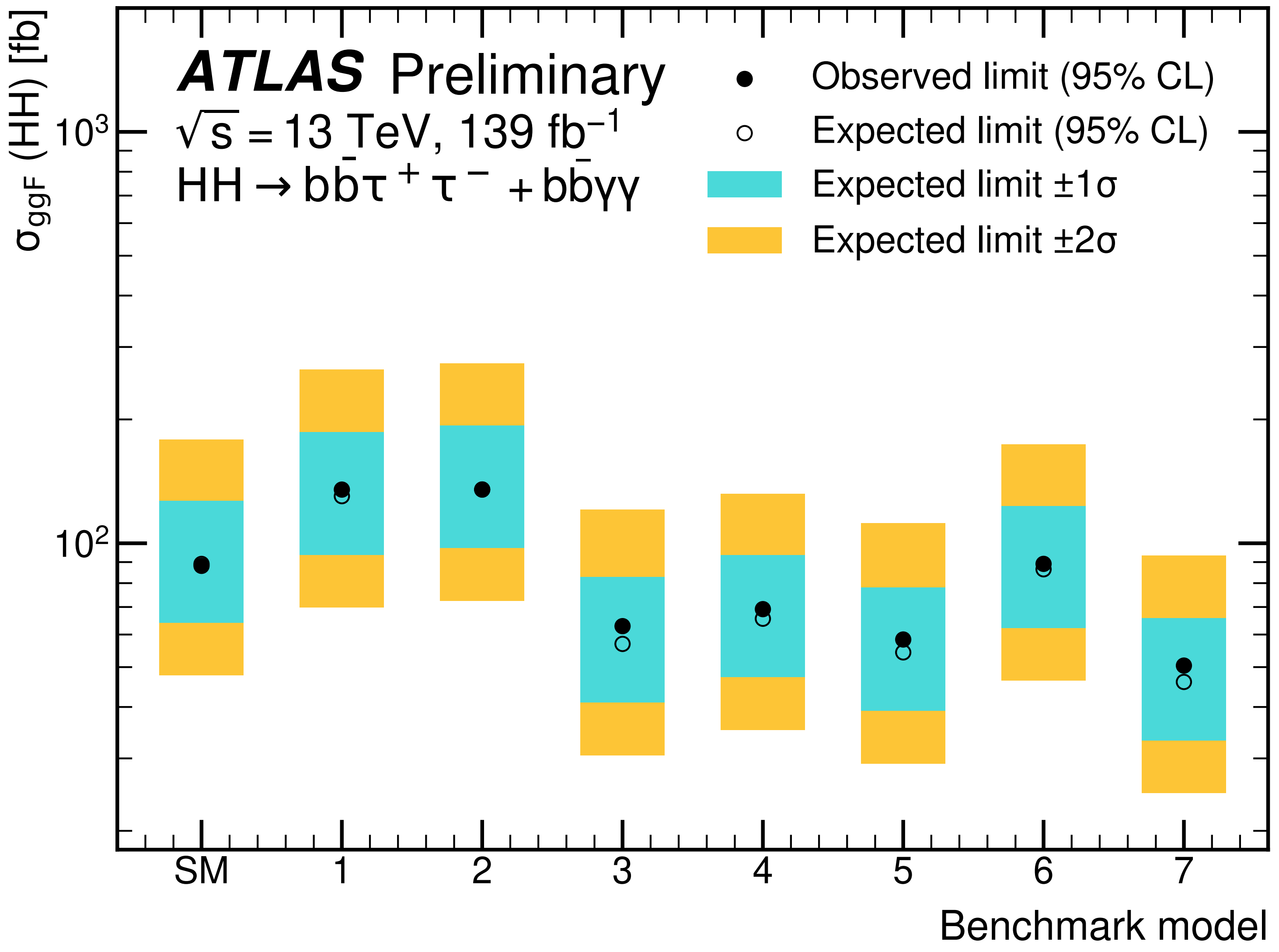
EFT re-interpretations of HH searches

- Upper limits on seven HEFT benchmarks with characteristic m_{HH} shape features

ATL-PHYS-PUB-2022-019

Benchmark model	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1	1	0	0	0
BM 1	3.94	0.94	1/2	1/3	−1/3
BM 2	6.84	0.61	0.0	−1/3	1/3
BM 3	2.21	1.05	1/2	1/2	−1/3
BM 4	2.79	0.61	−1/2	1/6	1/3
BM 5	3.95	1.17	1/6	−1/2	−1/3
BM 6	5.68	0.83	−1/2	1/3	1/3
BM 7	−0.10	0.94	1/6	−1/6	1





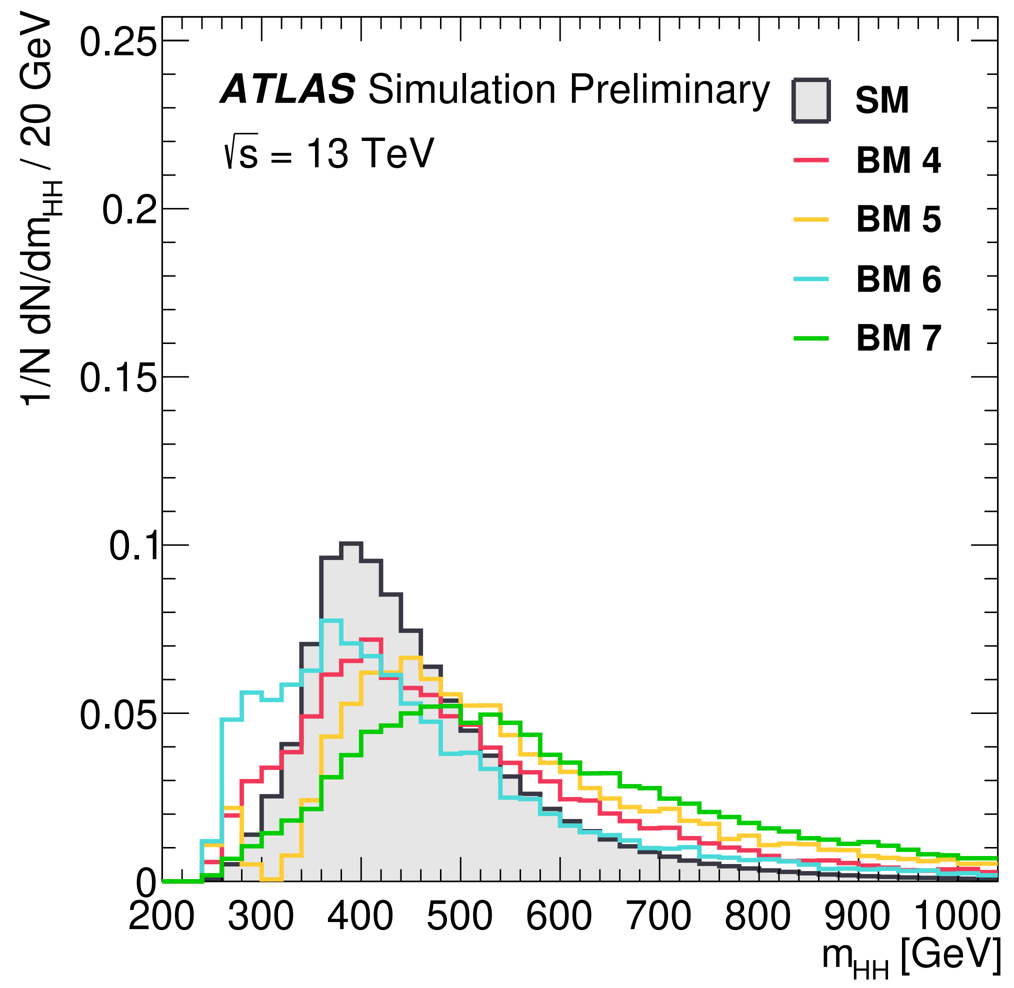
bbττ + bbγγ

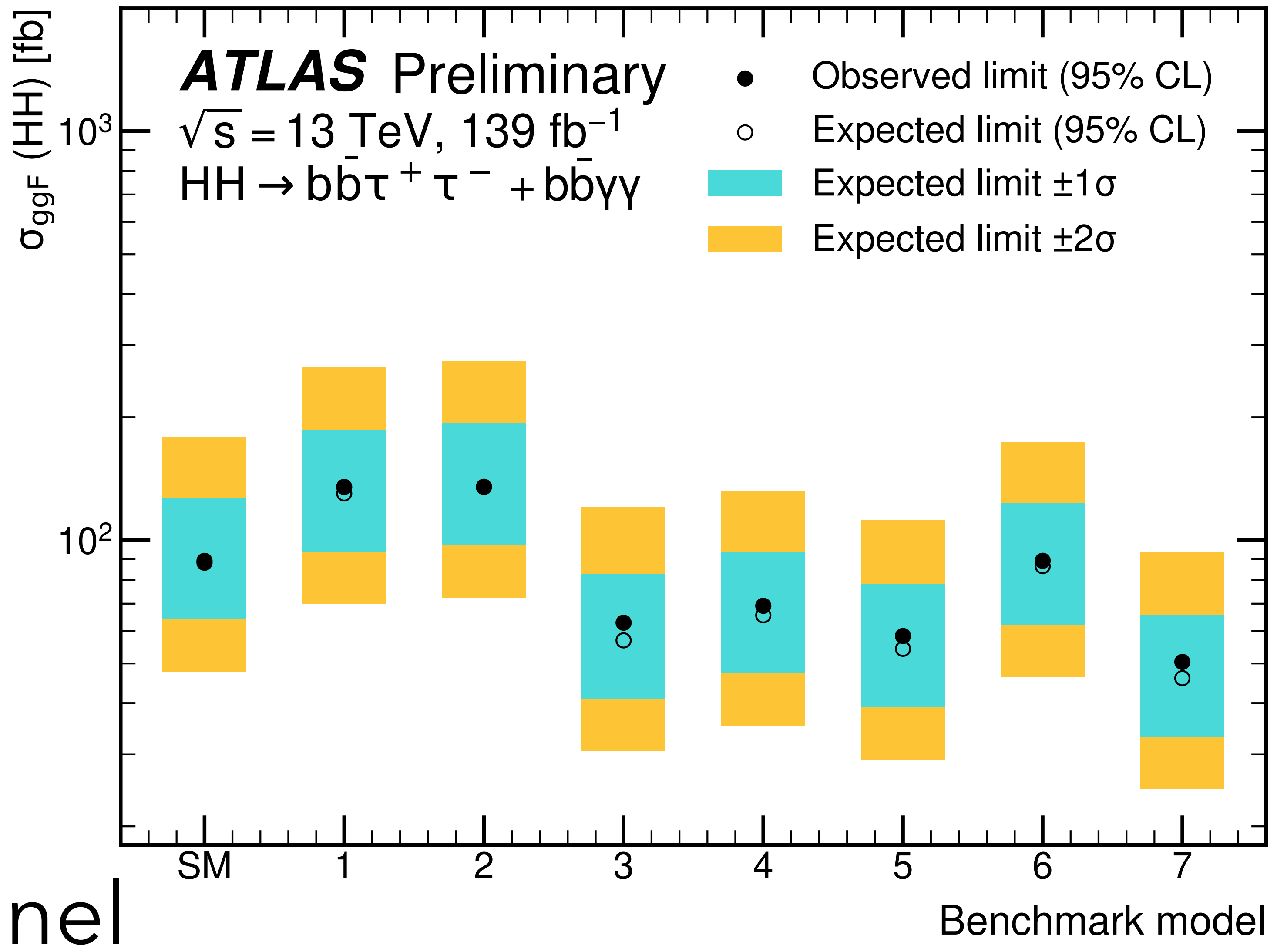
EFT re-interpretations of HH searches

- Upper limits on seven HEFT benchmarks with characteristic m_{HH} shape features

ATL-PHYS-PUB-2022-019

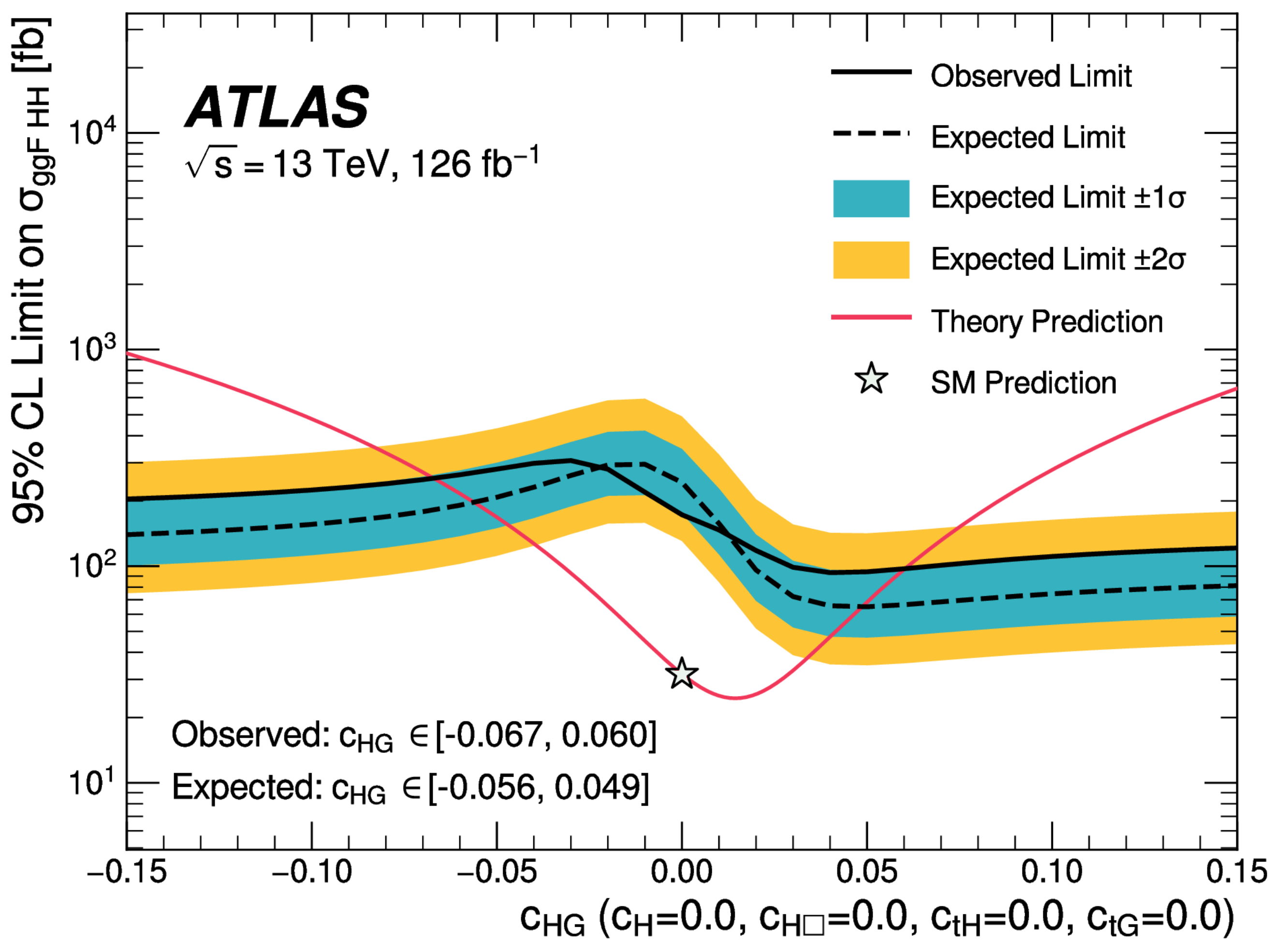
Benchmark model	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1	1	0	0	0
BM 1	3.94	0.94	1/2	1/3	−1/3
BM 2	6.84	0.61	0.0	−1/3	1/3
BM 3	2.21	1.05	1/2	1/2	−1/3
BM 4	2.79	0.61	−1/2	1/6	1/3
BM 5	3.95	1.17	1/6	−1/2	−1/3
BM 6	5.68	0.83	−1/2	1/3	1/3
BM 7	−0.10	0.94	1/6	−1/6	1

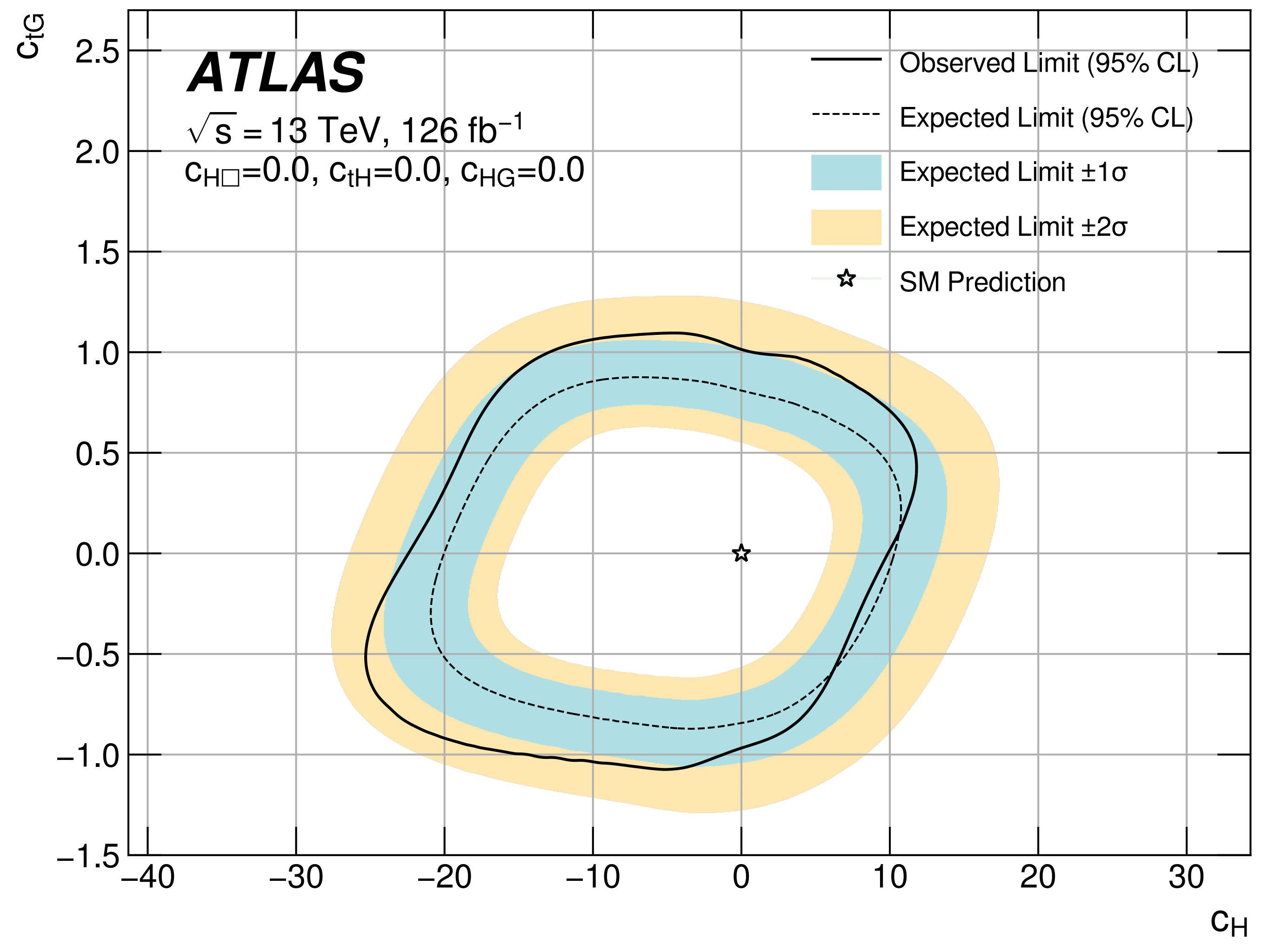




bbττ + bbγγ

- First constraints on SMEFT Wilson coefficients in the *bbbb* channel





bbbb

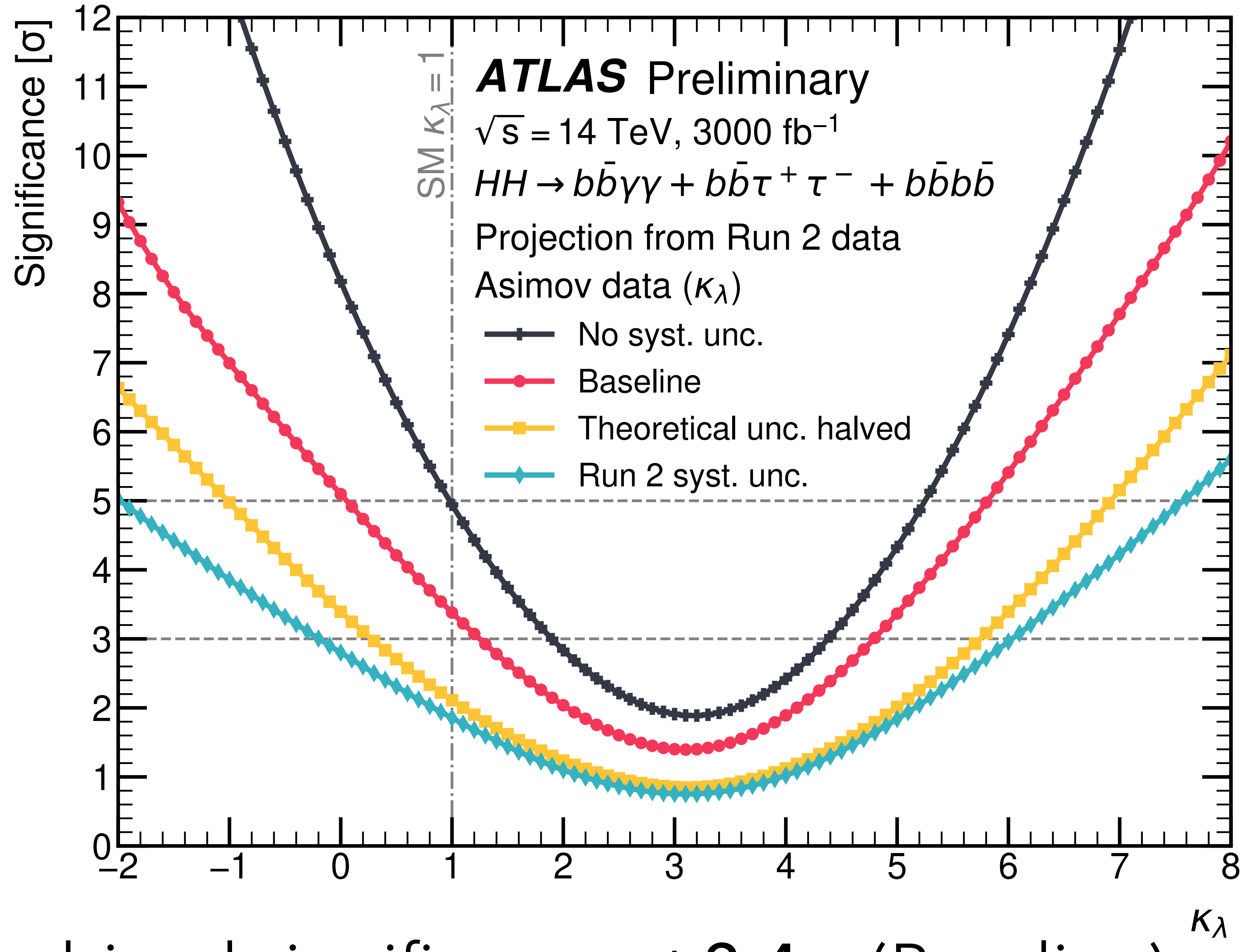
arXiv:2301.03212 [hep-ex]

Summary

- Searching for Higgs boson pairs is the ultimate probe of the shape of the Higgs potential and thereby of the nature of electroweak symmetry breaking
- No single golden channel - combinations are the key
  - 95% CL upper limit on μ_{HH} at 2.4 x SM prediction
  - $HH + H$ combination allows for more robust interpretations
- EFT interpretations becoming increasingly popular (HEFT and SMEFT results in ATLAS)
- Further studies performed in parallel (e.g. VBF κ_{2V} constraints, VHH search)
  - All public results can be found in https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HDBSPublicResults

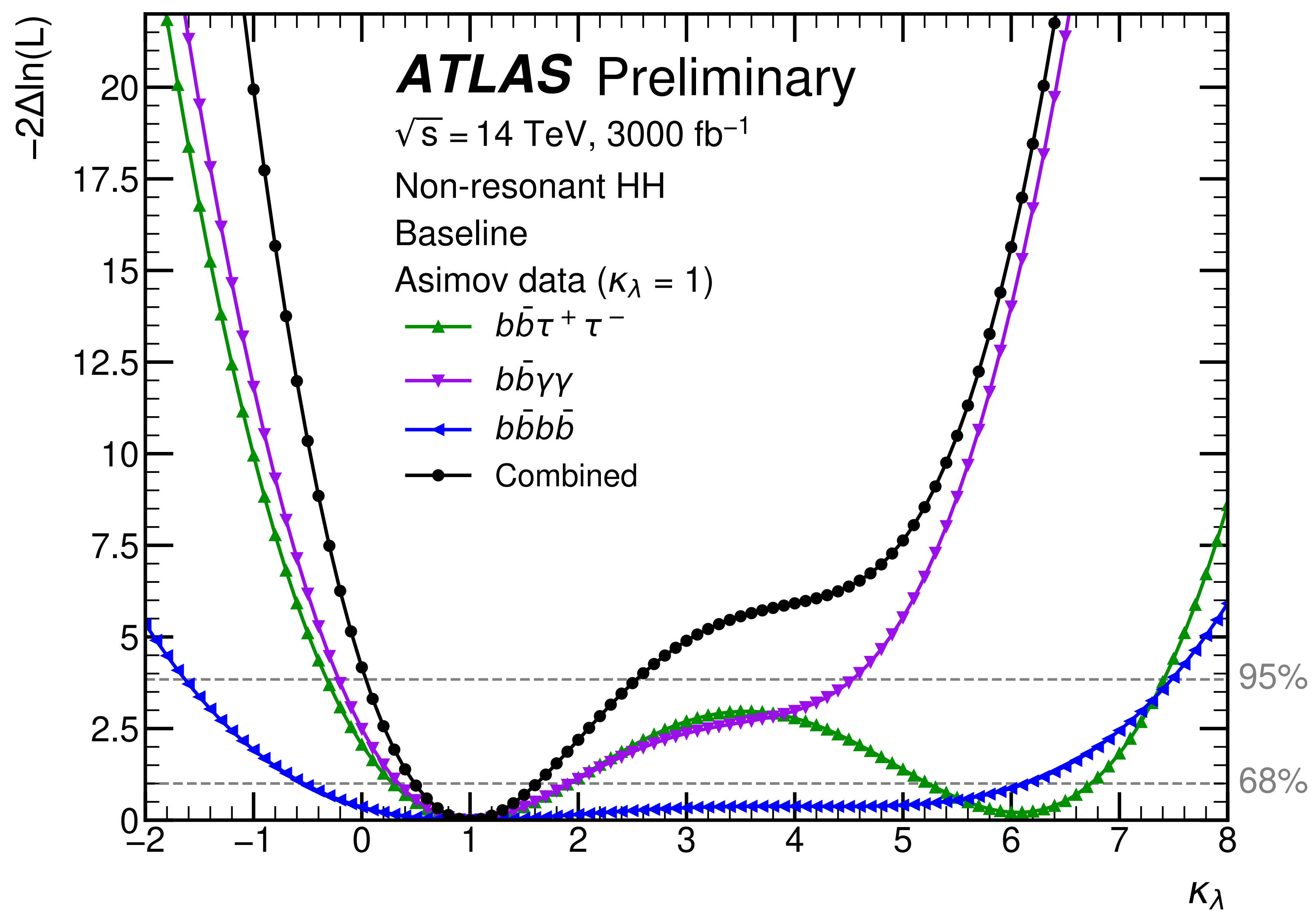
Outlook - HL-LHC prospects

- HL-LHC critical for observing and measuring low cross-section processes like HH
- Prospect studies through extrapolation of the Run-2 results to 3000 fb^{-1} and 14 TeV
- Consider different systematic uncertainty scenarios. "Baseline" → best guess of the future uncertainties



Combined significance at 3.4σ (Baseline)

Evidence is reachable!

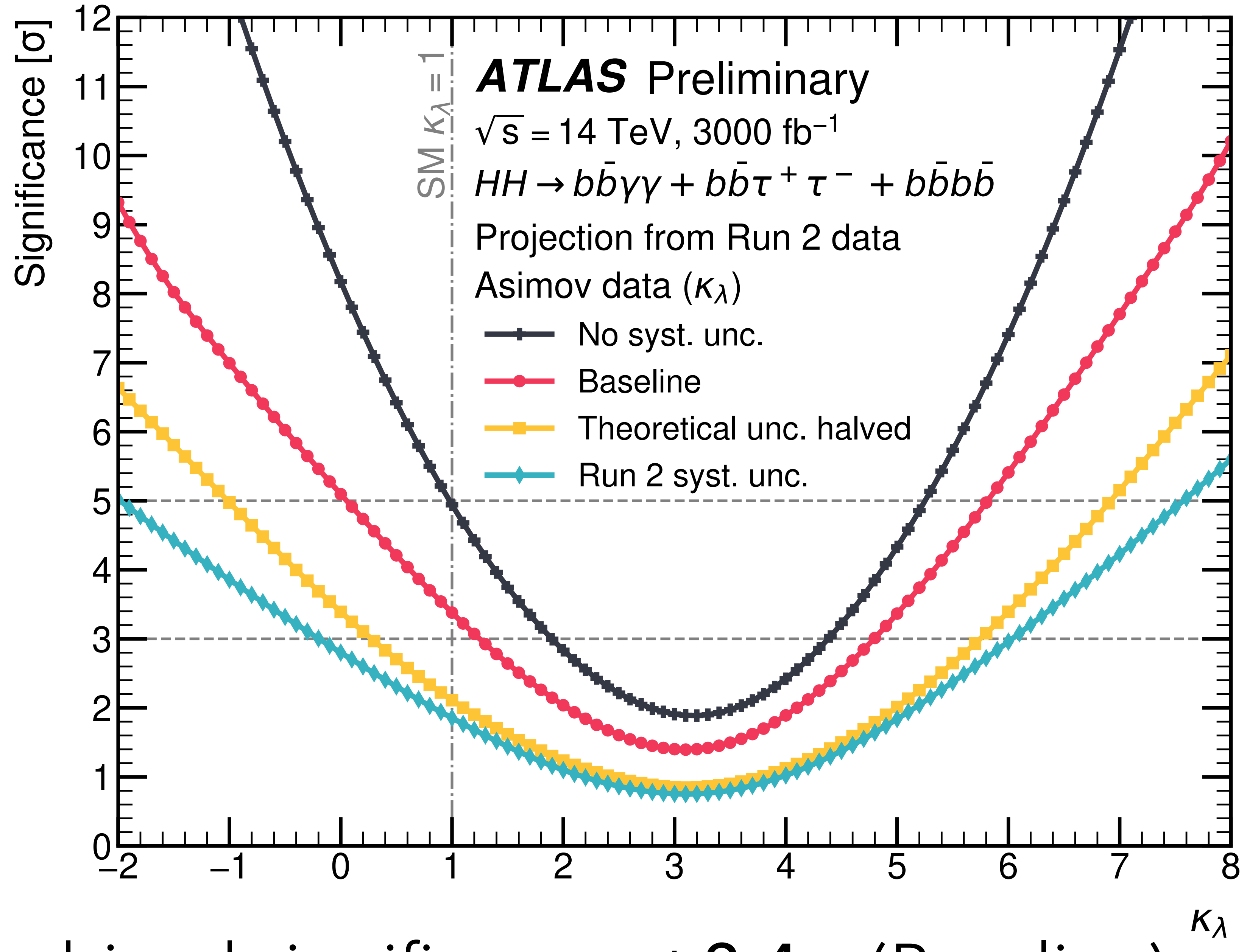


68% confidence interval for κ_λ at [0.5, 1.6] (Combined - Baseline)

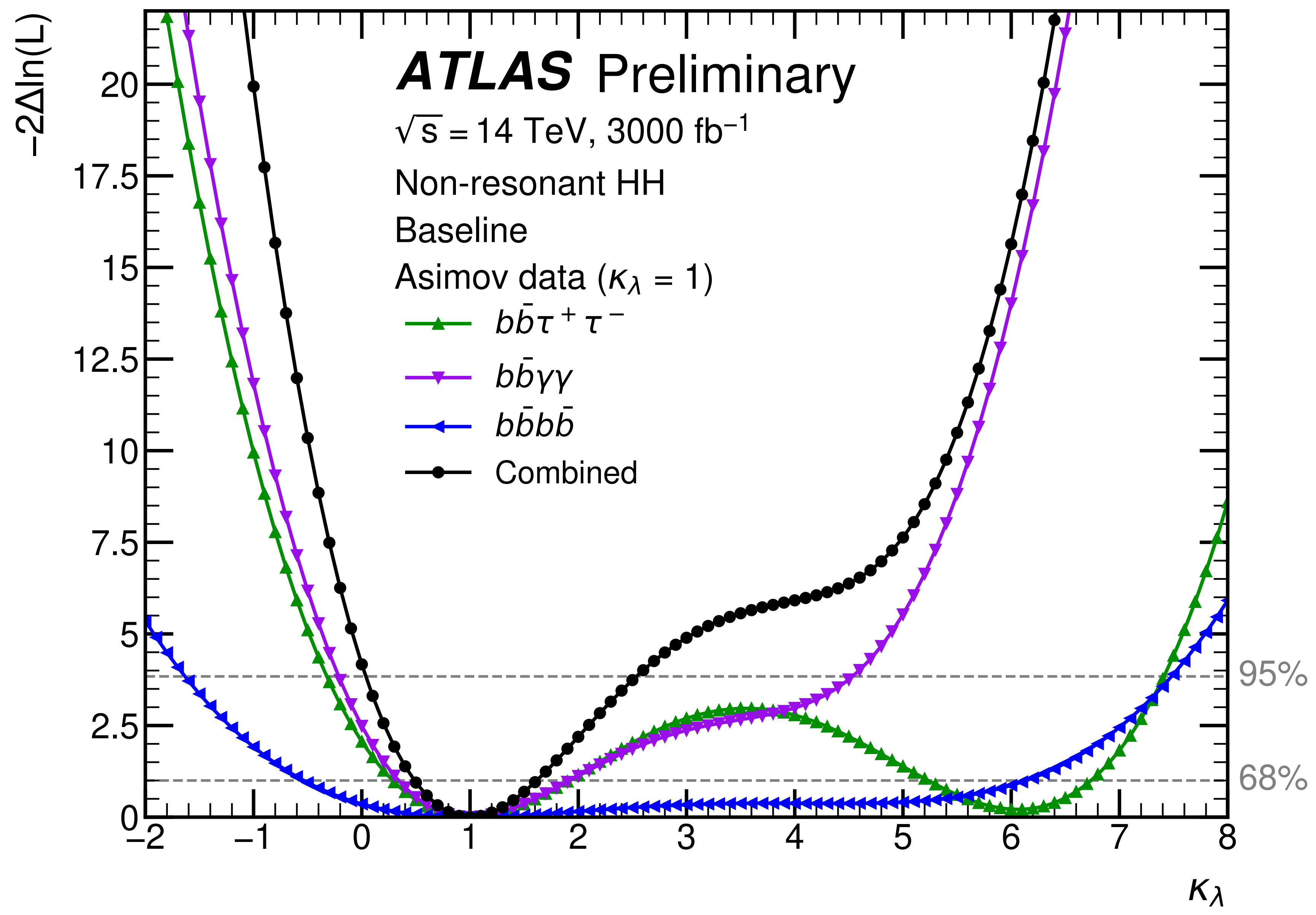
ATL-PHYS-PUB-2022-053

Outlook - HL-LHC prospects

- HL-LHC critical for observing and measuring low cross-section processes like HH
- Prospect studies through extrapolation of the Run-2 results to 3000 fb^{-1} and 14 TeV
- Consider different systematic uncertainty scenarios. “Baseline” → best guess of the future uncertainties



Combined significance at 3.4σ (Baseline)



68% confidence interval for κ_λ at [0.5, 1.6] (Combined - Baseline)

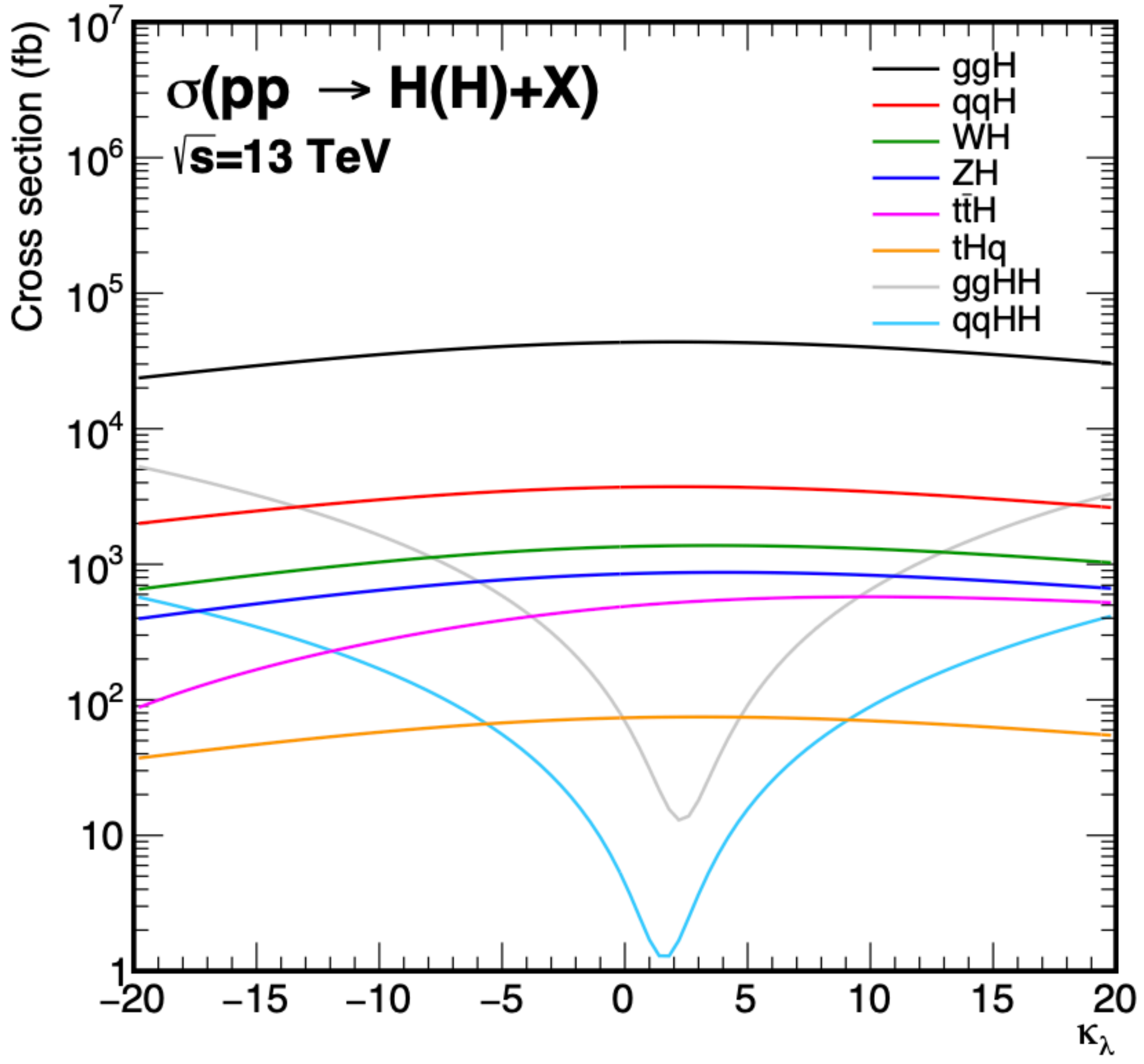
ATL-PHYS-PUB-2022-053

Evidence is reachable!

Observation is likely possible with an ATLAS + CMS combination 🎉

Back-up

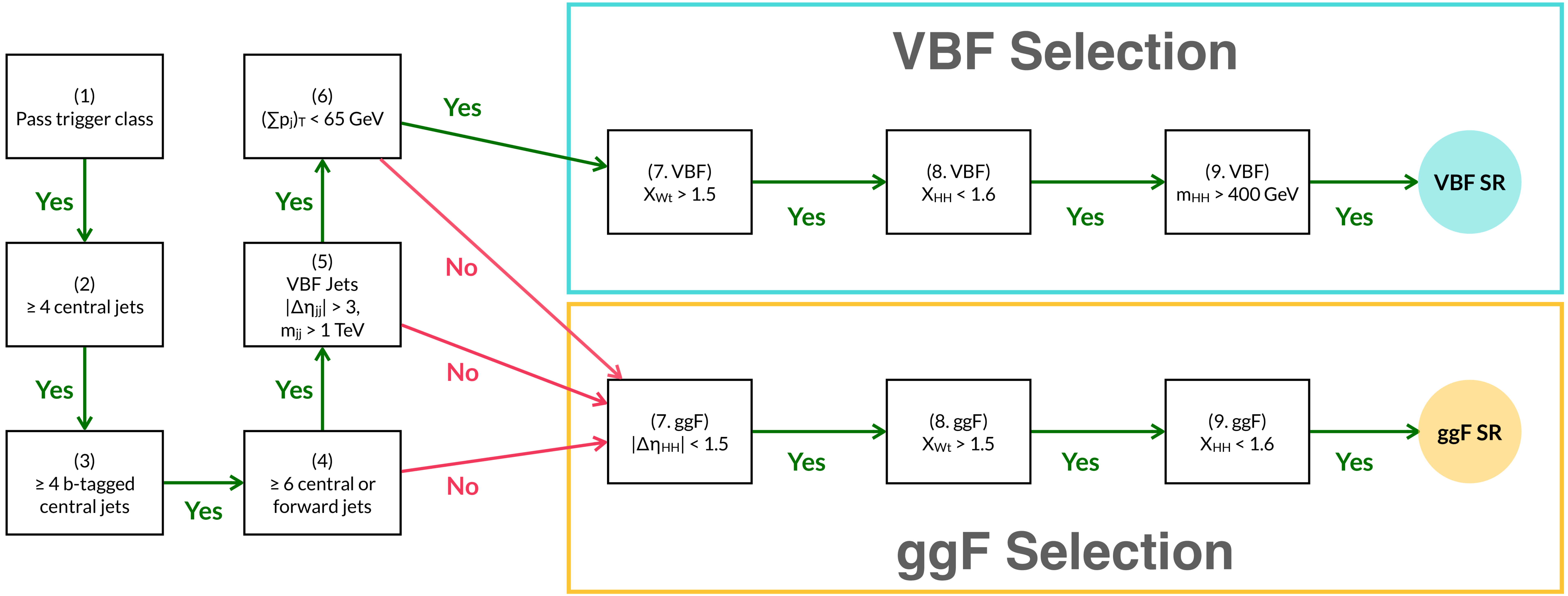
H and HH cross-sections vs. κ_λ



LHCHWG-2022-002

HH→bbbb [event selection]

arXiv:2301.03212 [hep-ex]

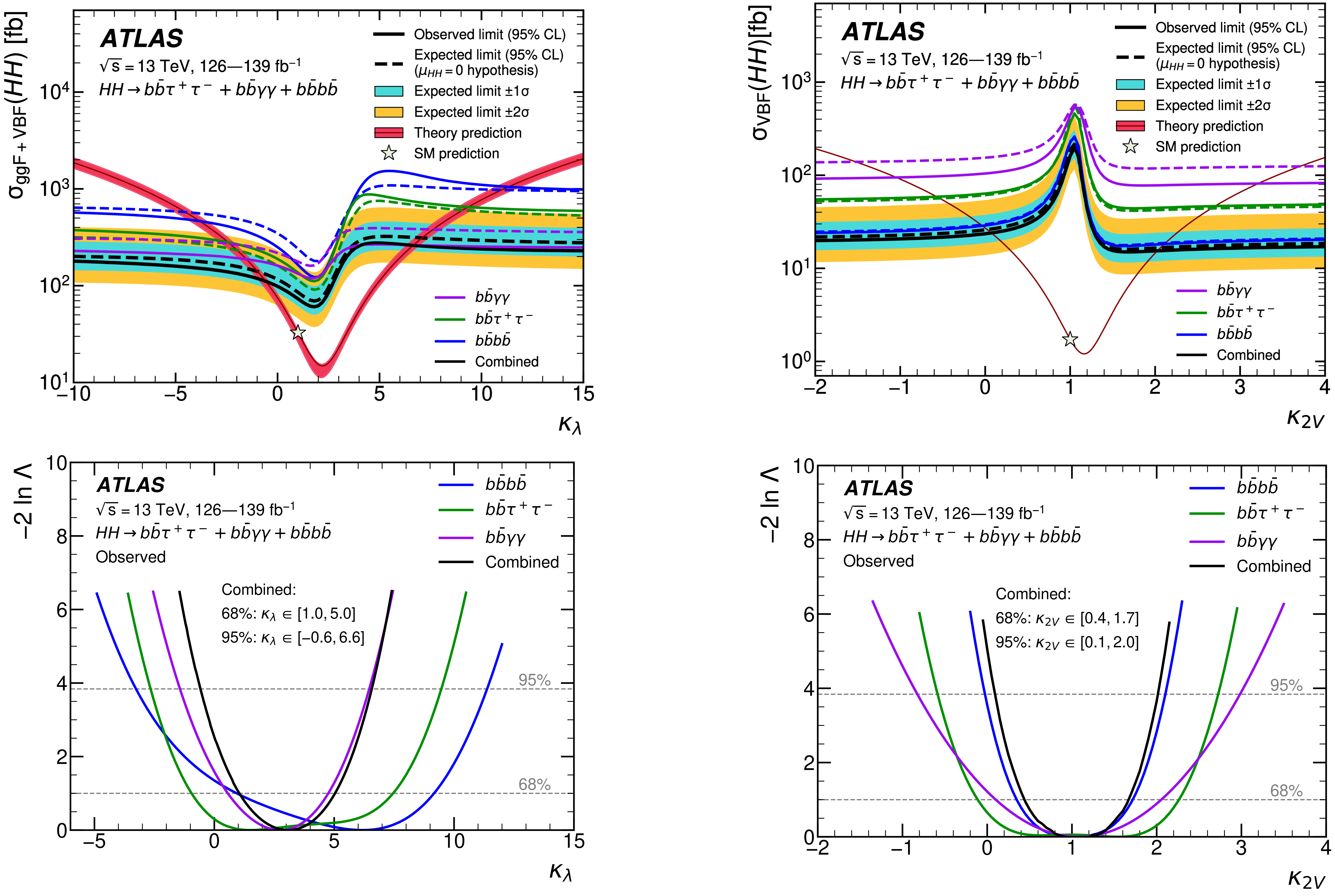


$$X_{Wt} = \min\left[\sqrt{\left(\frac{m_{jj} - m_W}{0.1 m_{jj}}\right)^2 + \left(\frac{m_{jjb} - m_t}{0.1 m_{jjb}}\right)^2}\right]$$

$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\ \mathrm{GeV}}{0.1\ m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\ \mathrm{GeV}}{0.1\ m_{H2}}\right)^2}$$

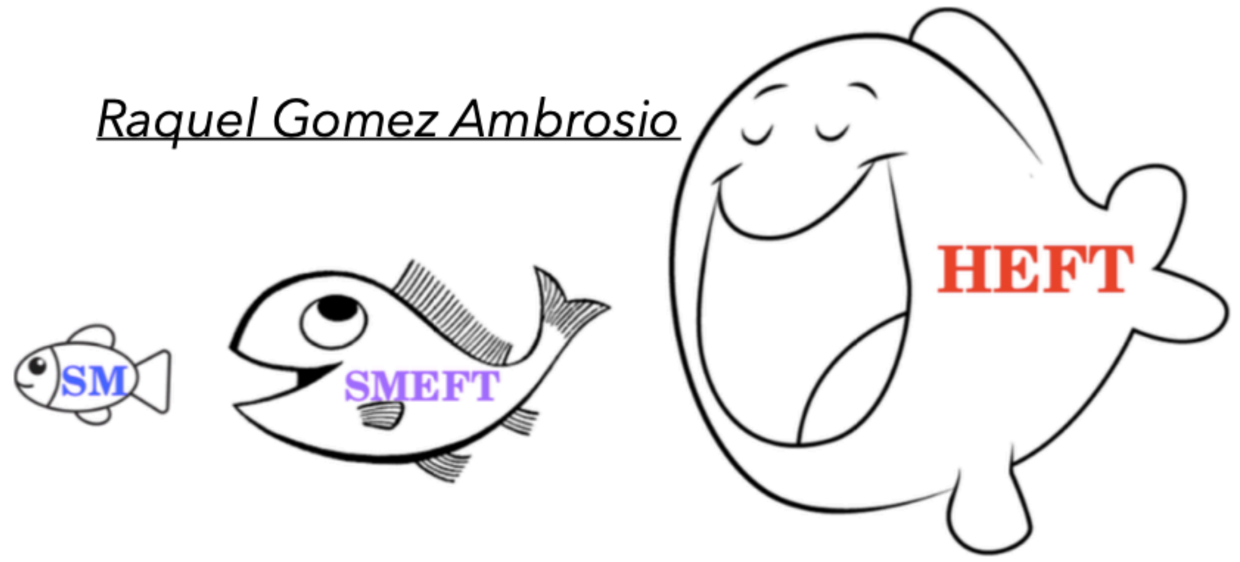
Combined results

arXiv:2211.01216 [hep-ex]



EFT frameworks

Raquel Gomez Ambrosio



SMEFT

- Canonical counting, expansion in $1/\Lambda$

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{n,i} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathscr{O}_i^{(n)}$$

- SM symmetries and fields, traditional EWSB mechanism (Higgs field: $SU(2)_L$ doublet)
- More restrictive (correlated Wilson coefficients)

HEFT

- No power-counting like in SMEFT, more similar to chiral perturbation theory

$$\mathscr{L}_{d_\chi} = \mathscr{L}_{(d_\chi=2)} + \sum_{L=1}^{\infty} \sum_i \left(\frac{1}{16\pi^2}\right)^L c_i^{(L)} O_i^{(L)}$$

- Higgs field: EW singlet
- Much more general (independent couplings)

SMEFT vs. HEFT

SMEFT

$$\Delta\mathscr{L}_{\text{Warsaw}} = \frac{C_{H,\Box}}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \frac{C_{HD}}{\Lambda^2}(\phi^\dagger D_\mu\phi)^*(\phi^\dagger D^\mu\phi) + \frac{C_H}{\Lambda^2}(\phi^\dagger\phi)^3 + (\frac{C_{uH}}{\Lambda^2}\phi^\dagger\phi\bar{q}_L\tilde{\phi}\,t_R + \text{h.c.}) + \frac{C_{HG}}{\Lambda^2}\phi^\dagger\phi G^a_{\mu\nu}G^{\mu\nu,a} + \frac{C_{uG}}{\Lambda^2}(\bar{q}_L\sigma^{\mu\nu}T^a G^a_{\mu\nu}\tilde{\phi}\,t_R + \text{h.c.})$$

$$\Delta\mathscr{L}_{\text{SILH}} = \frac{\bar{c}_H}{2v^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi) + \frac{\bar{c}_u}{v^2}y_t(\phi^\dagger\phi\,\bar{q}_L\tilde{\phi}t_R + \text{h.c.}) - \frac{\bar{c}_6}{2v^2}\frac{m_h^2}{v^2}(\phi^\dagger\phi)^3 + \frac{\bar{c}_{ug}}{v^2}g_s(\bar{q}_L\sigma^{\mu\nu}G_{\mu\nu}\tilde{\phi}\,t_R + \text{h.c.}) + \frac{4\bar{c}_g}{v^2}g_s^2\phi^\dagger\phi\,G^a_{\mu\nu}G^{a\mu\nu}$$

HEFT

$$\Delta\mathscr{L}_{\text{HEFT}} = -m_t(c_t\frac{h}{v} + c_{tt}\frac{h^2}{v^2})\,\bar{t}\,t - c_{hhh}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}(c_{ggh}\frac{h}{v} + c_{gghh}\frac{h^2}{v^2})\,G^a_{\mu\nu}G^{a,\mu\nu}$$

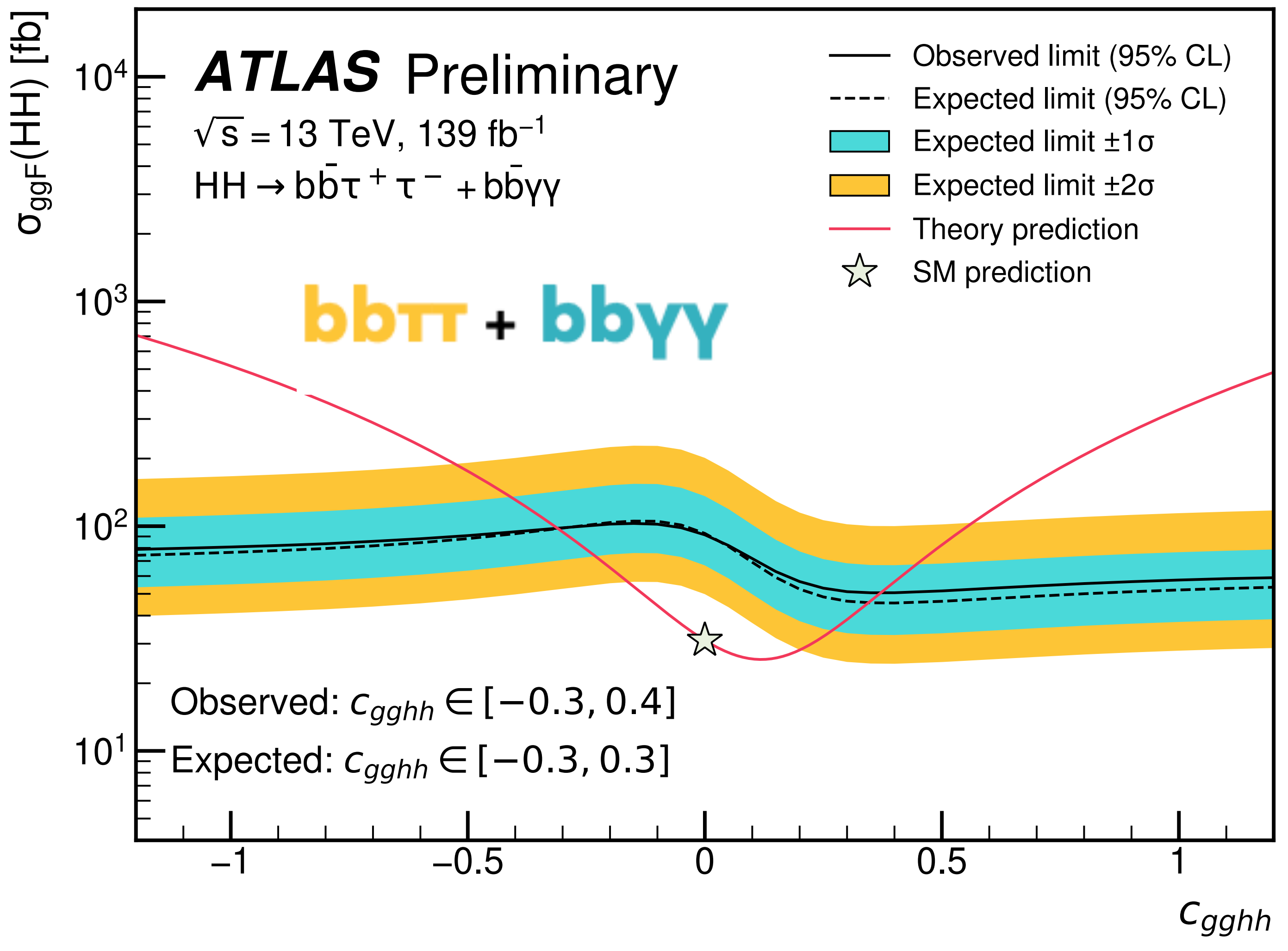
Naive translation after field redefinition up to $\mathcal{O}(\Lambda^{-2})$ in Lagrangian ($C_{H,\text{kin}} = C_{H,\Box} - \frac{1}{4}C_{HD}$)

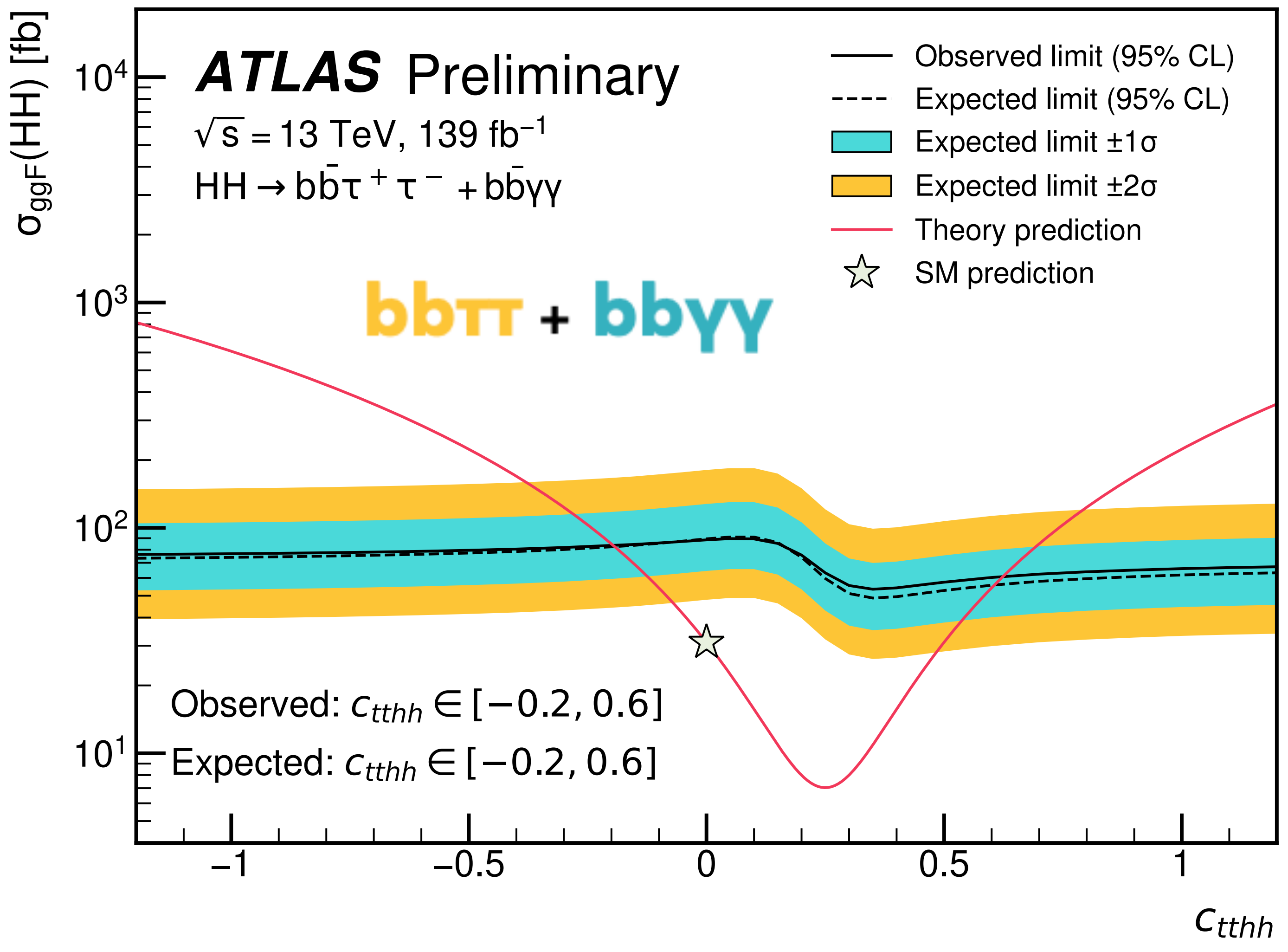
- ! Different assumptions, different EFT validity range
- ! Translation contains α_s which is a running parameter, typically evaluated at $\mu_0 = m_{hh}/2$
- ! Not generally applicable in practical calculations

HEFT	SILH	Warsaw
c_{hhh}	$1 - \frac{3}{2}\bar{c}_H + \bar{c}_6$	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2}C_H + 3\frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
c_t	$1 - \frac{\bar{c}_H}{2} - \bar{c}_u$	$1 + \frac{v^2}{\Lambda^2}C_{H,\text{kin}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t}C_{uH}$
c_{tt}	$-\frac{\bar{c}_H + 3\bar{c}_u}{4}$	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t}C_{uH} + \frac{v^2}{\Lambda^2}C_{H,\text{kin}}$
c_{ggh}	$128\pi^2\bar{c}_g$	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s}C_{HG}$
c_{gghh}	$64\pi^2\bar{c}_g$	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s}C_{HG}$

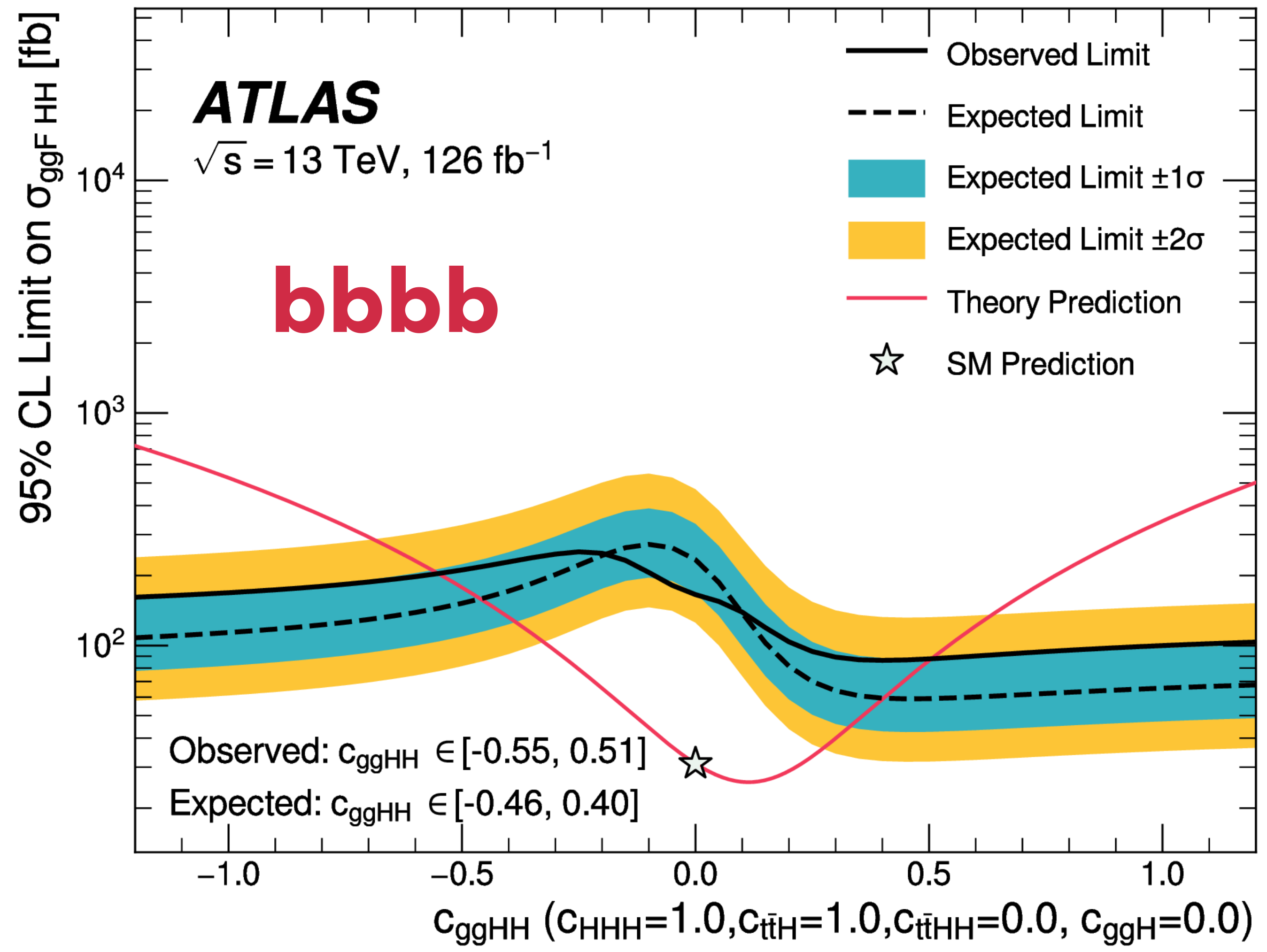
Christina Dimitriadi EFTs in *HH* production March 29, 2023 5

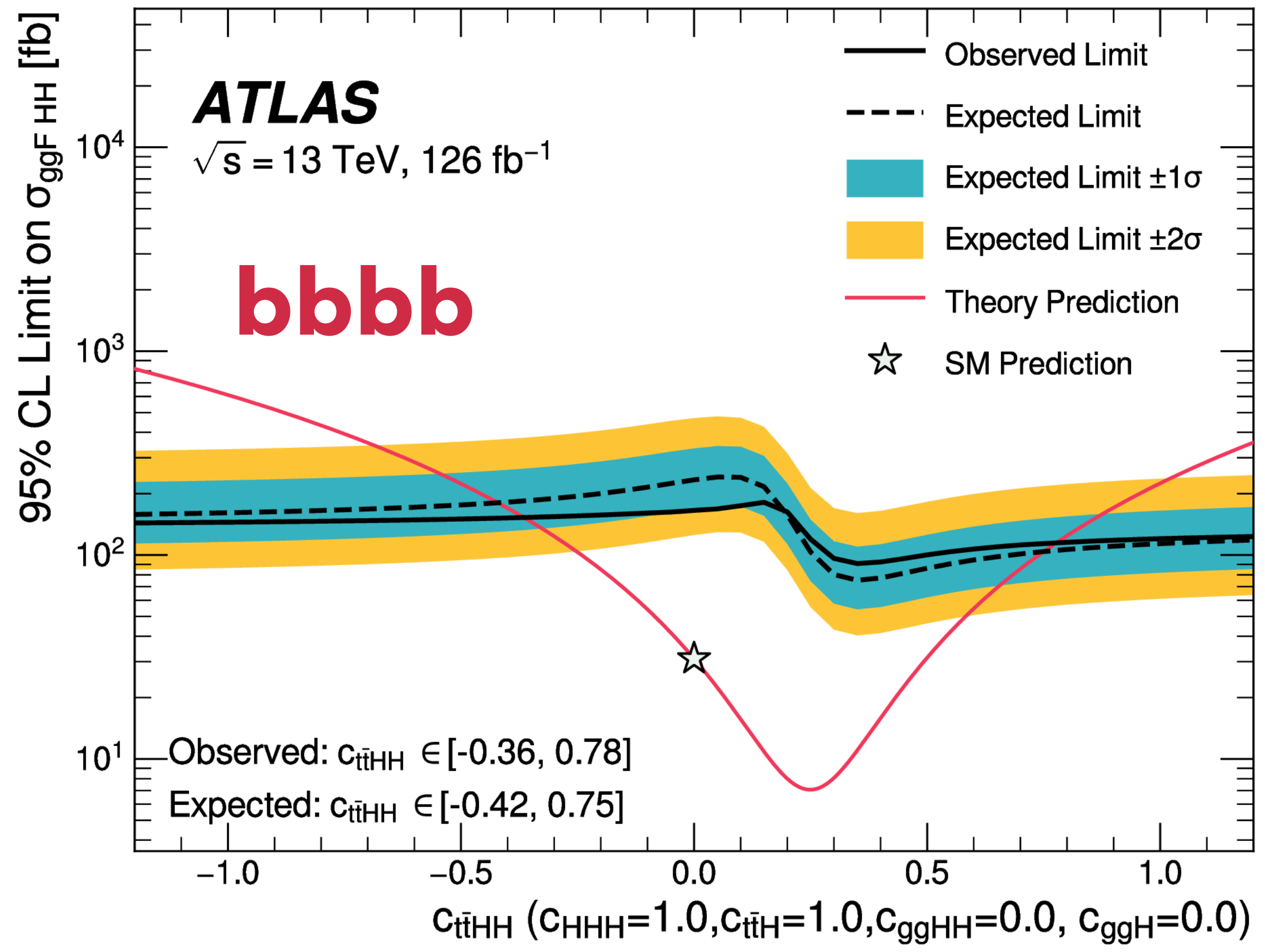
HEFT interpretations

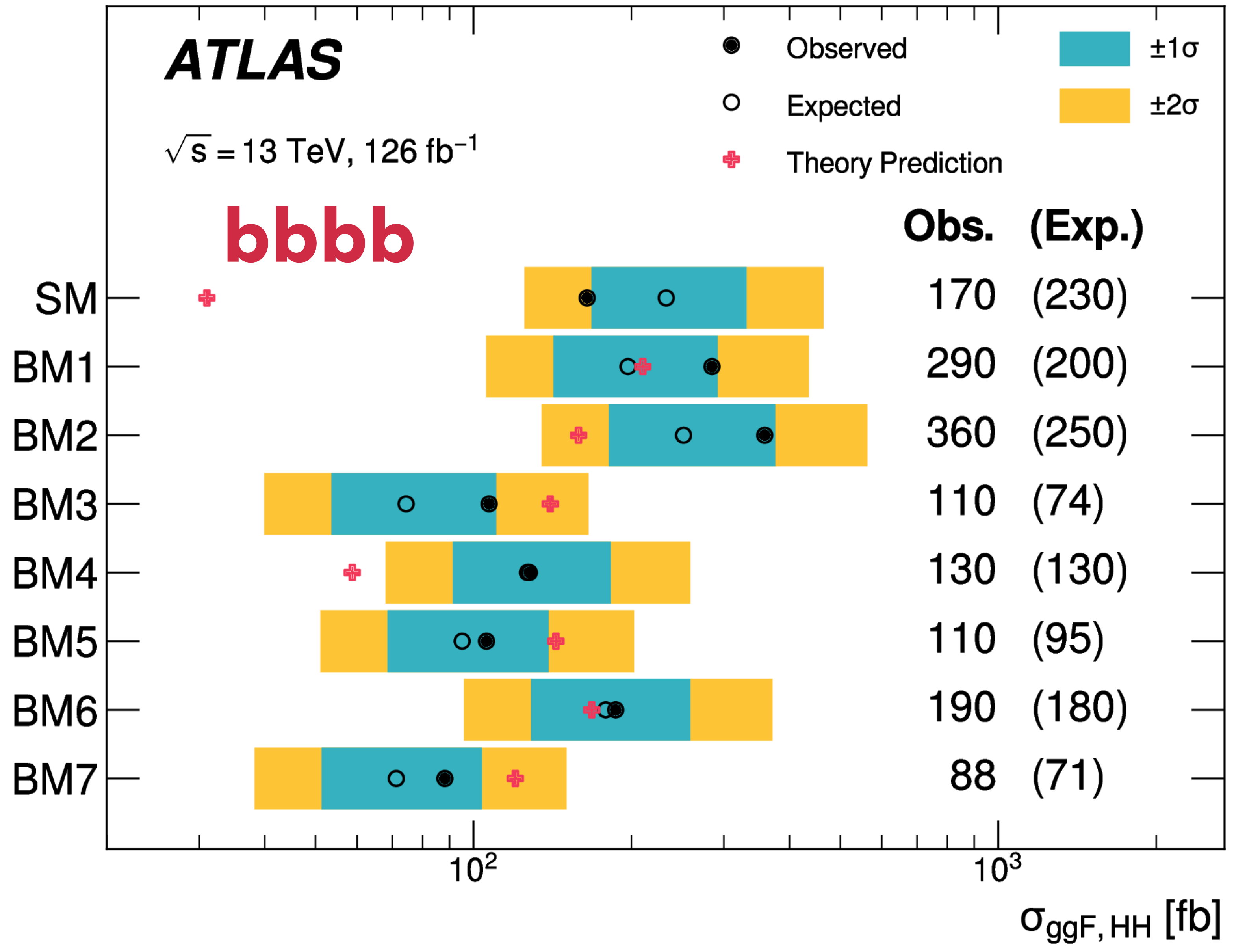




ATL-PHYS-PUB-2022-019







arXiv:2301.03212 [hep-ex]