Higgs self-coupling measurement @ LHC

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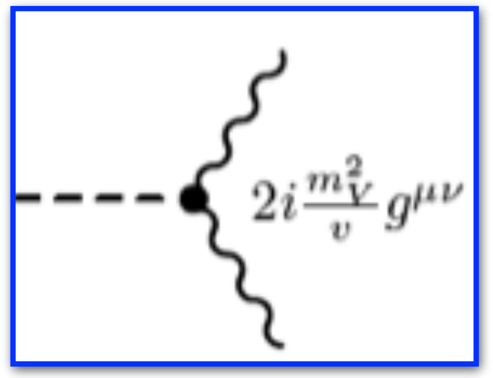
Introduction

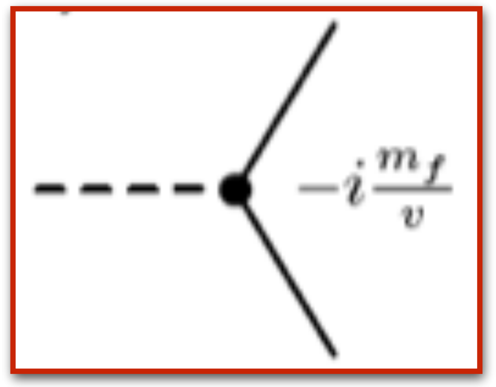
Higgs self-coupling is crucial to understand the EW symmetry breaking mechanism

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

Gauge coupling



Yukawa coupling



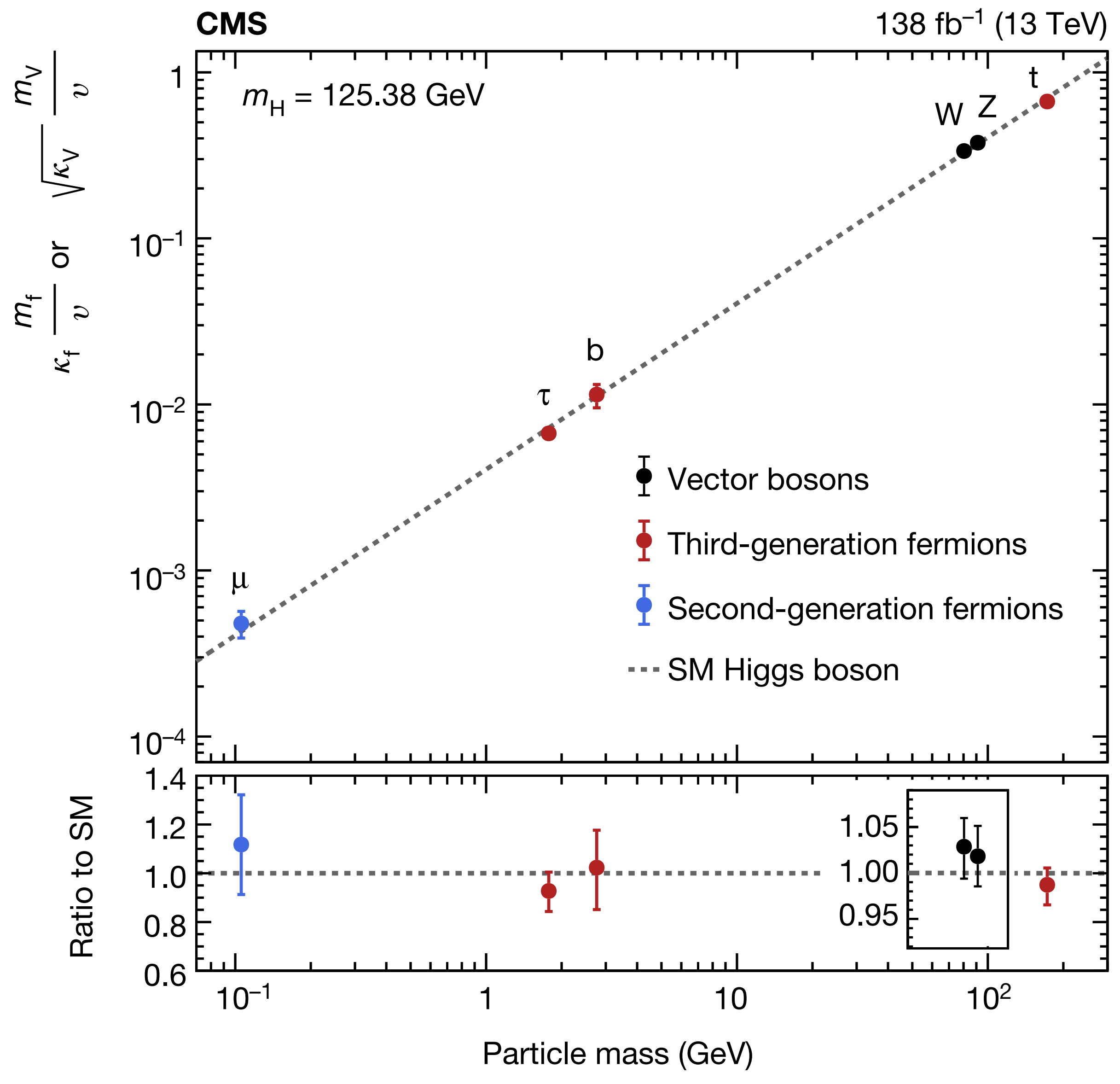
Higgs potential approximation:

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

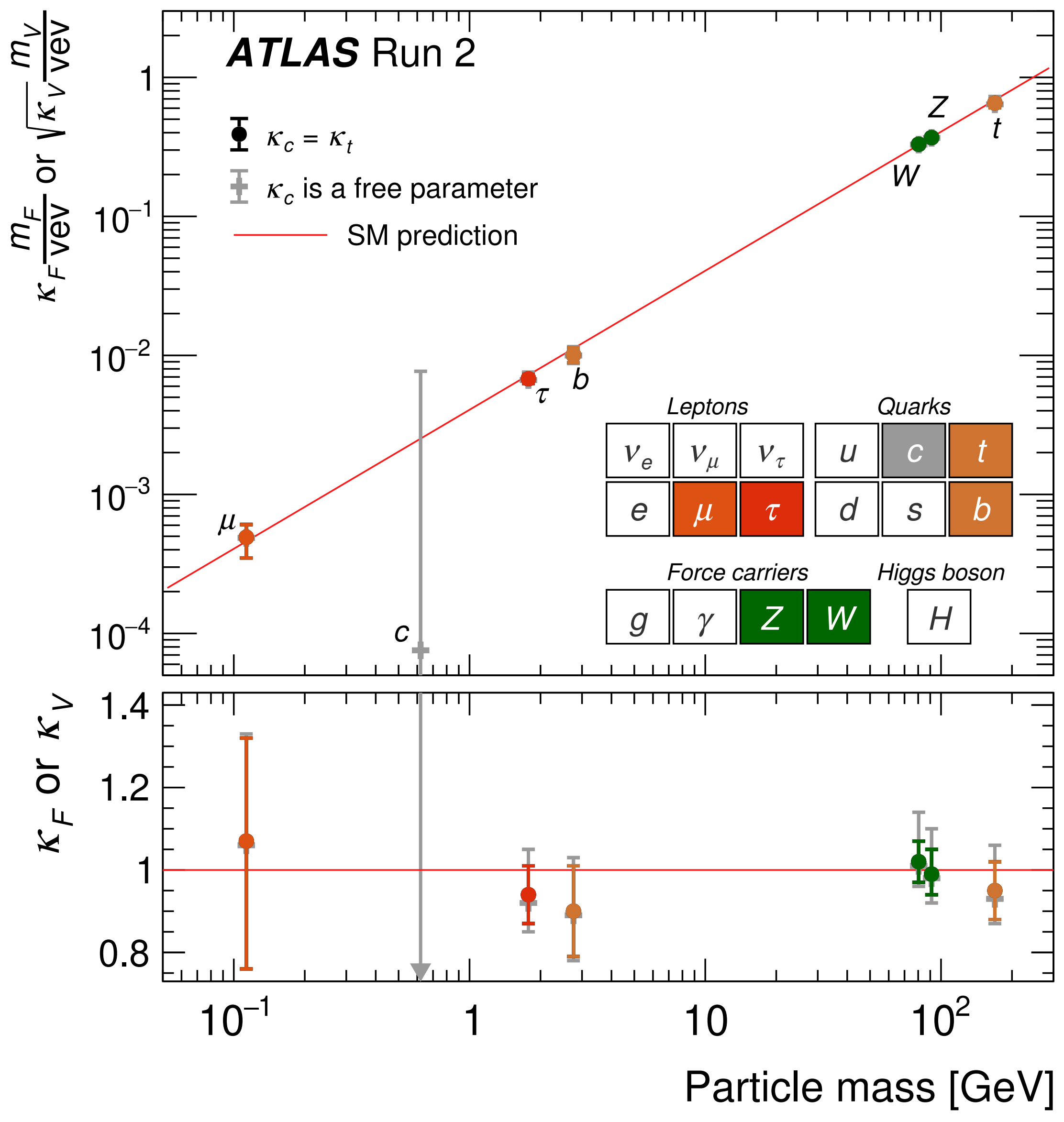
Expand about the minimum:

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

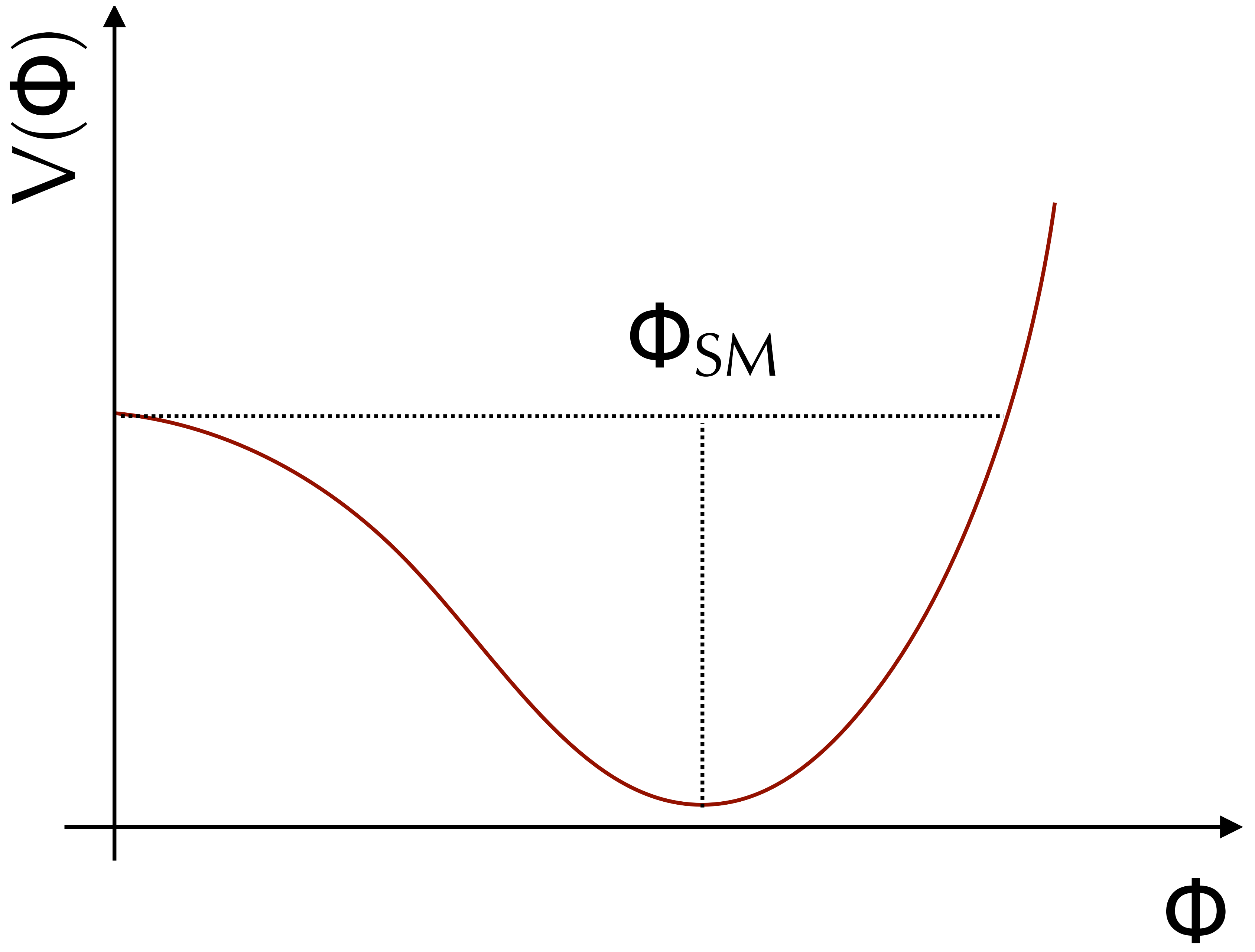
$$\text{with} \quad \lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2v^2}$$



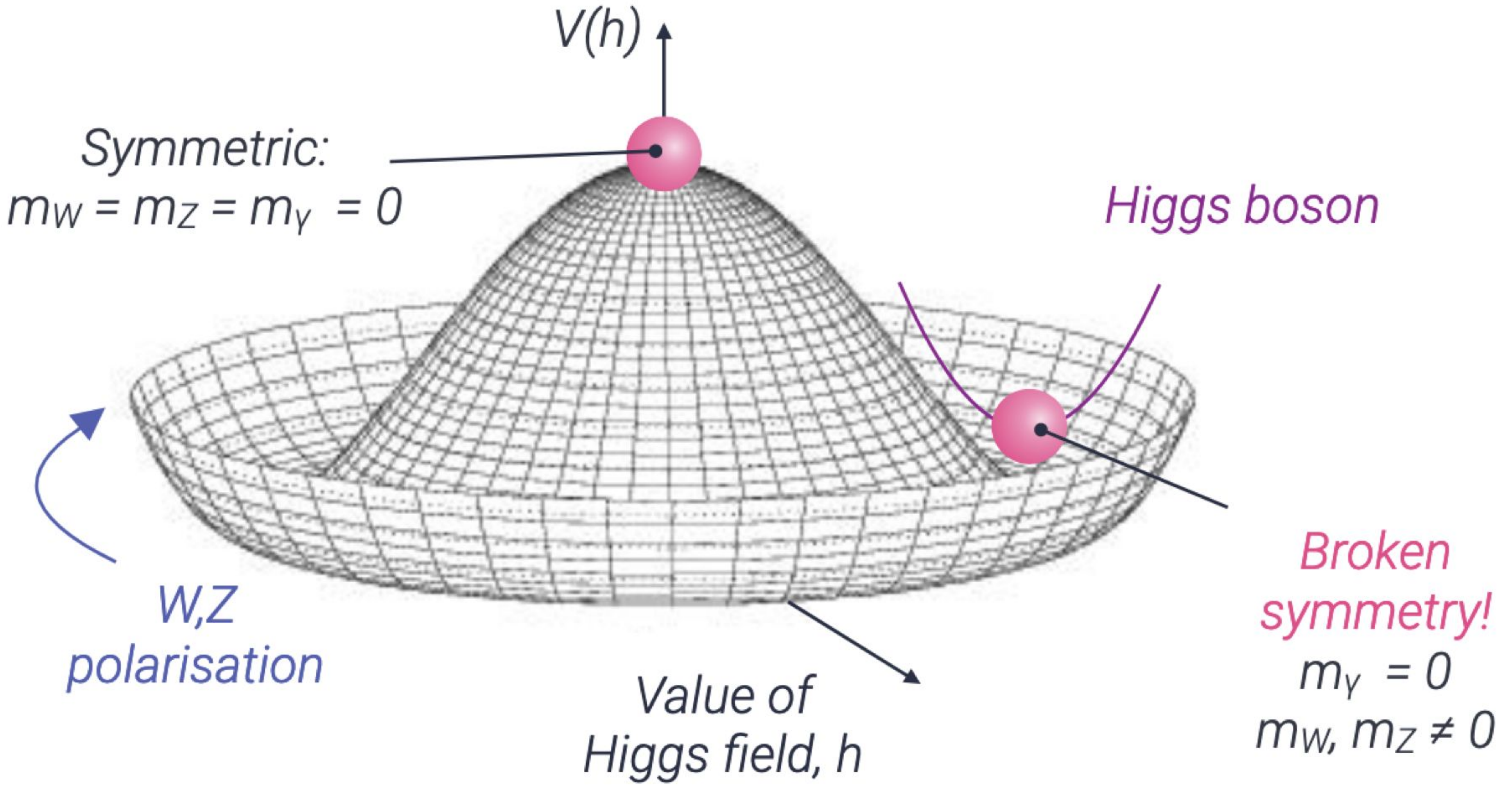
Nature 607(2022) 60-68

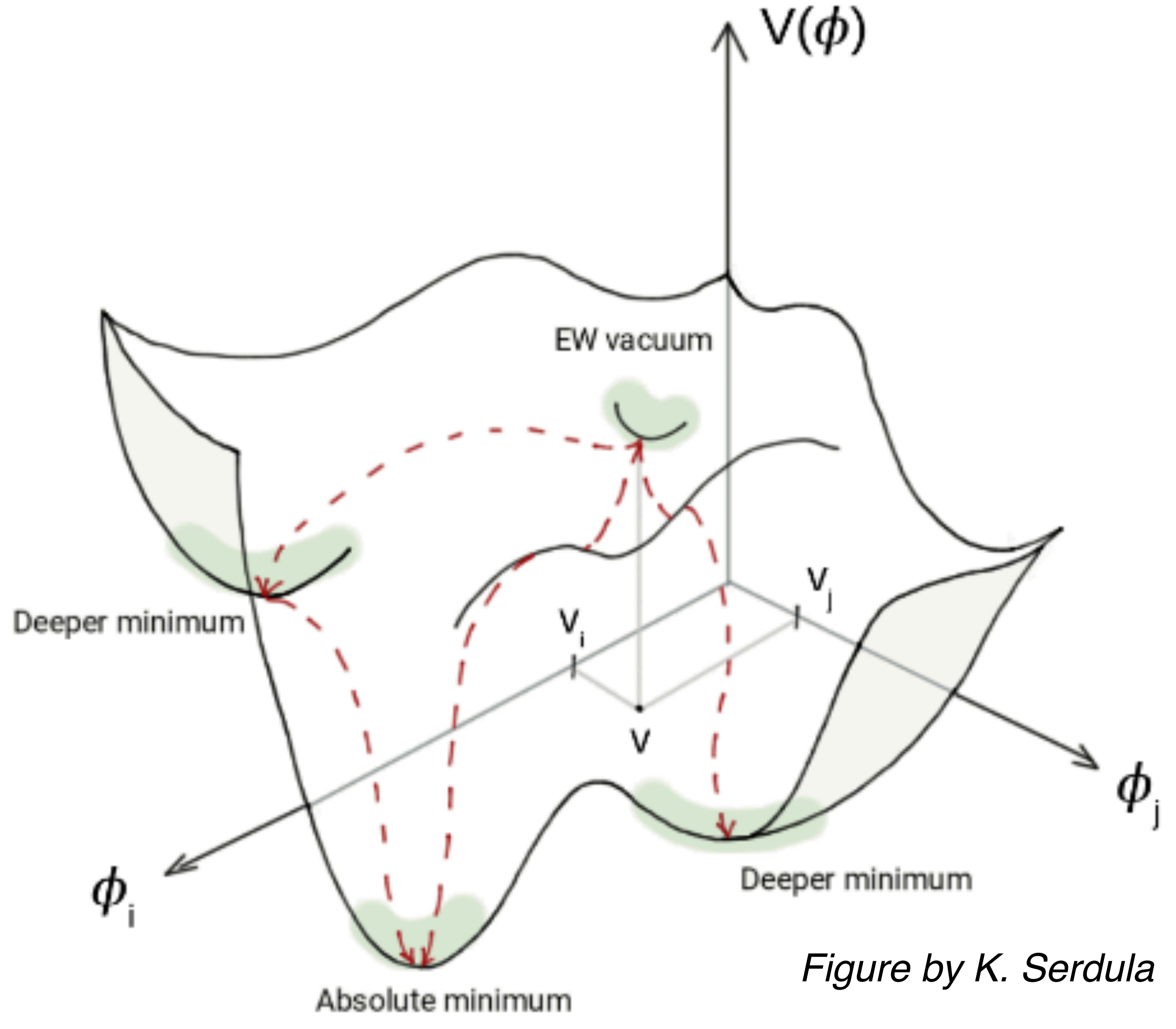


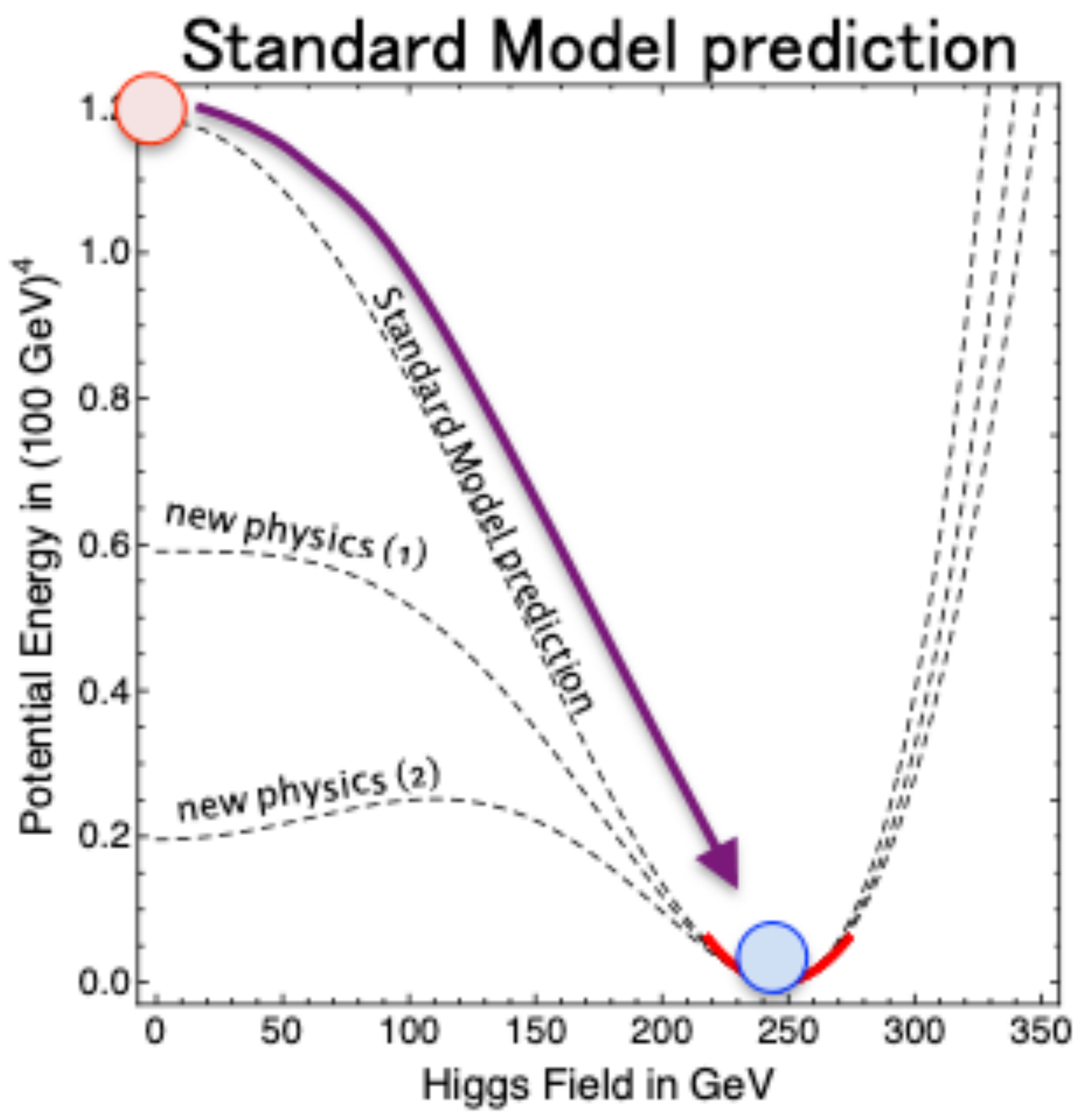
Nature 607(2022) 52-59



The Higgs Boson potential

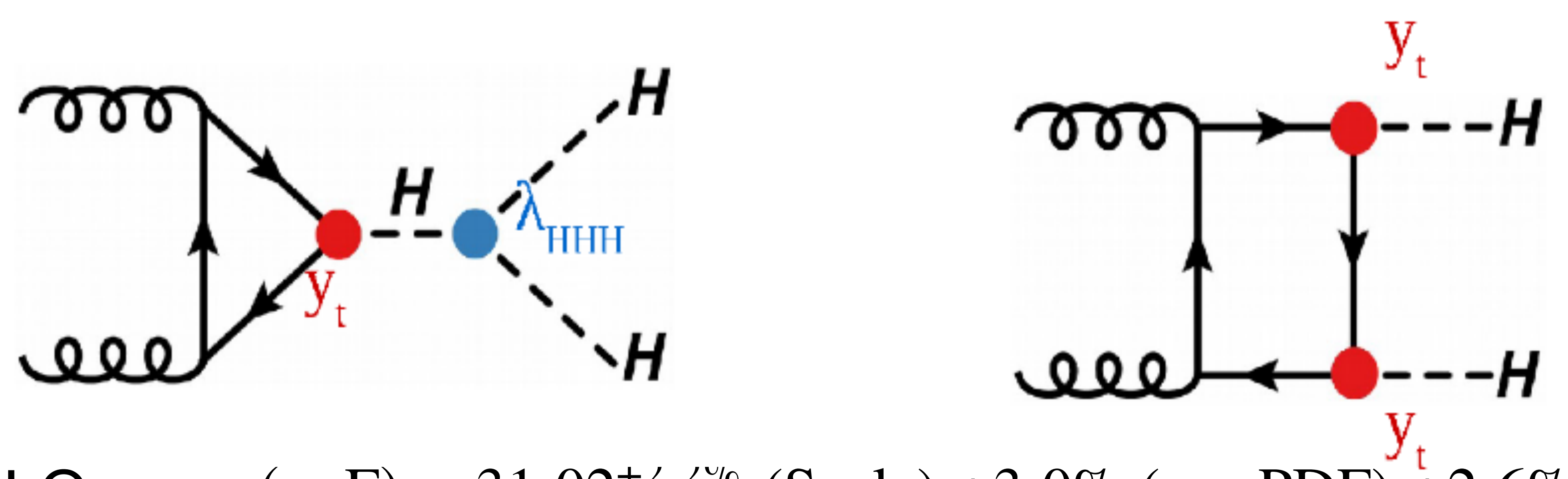




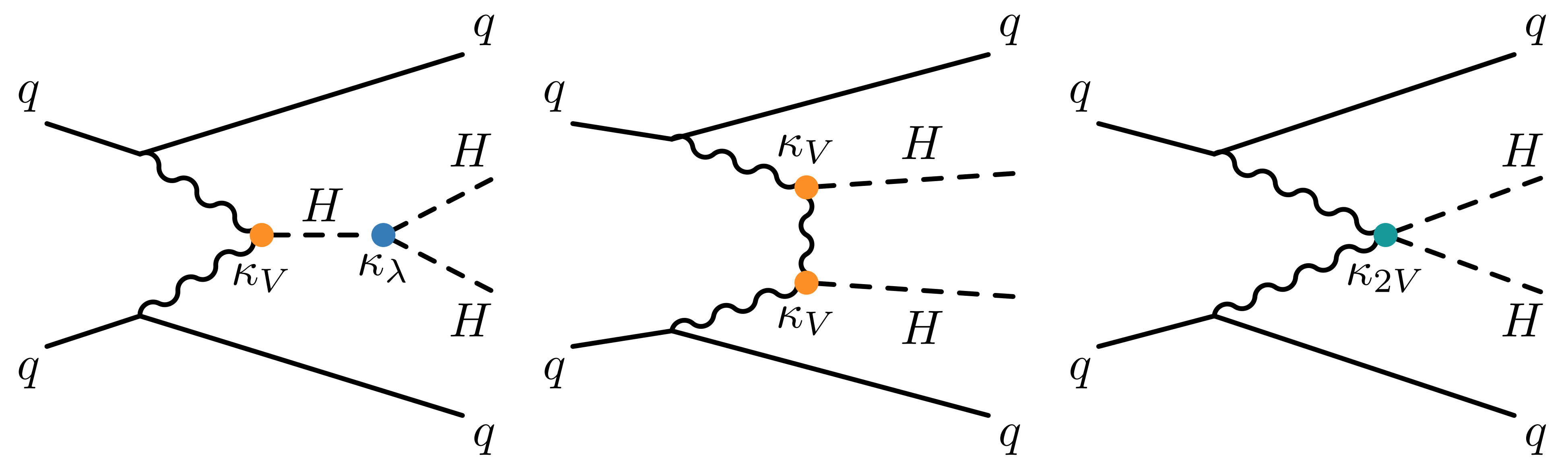


- Is the current minimum the True minimum?
- Is there another, deeper minimum elsewhere?
- Is there new physics for the deformation of potential shape?
- …

Higgs self-coupling measurement with HH production

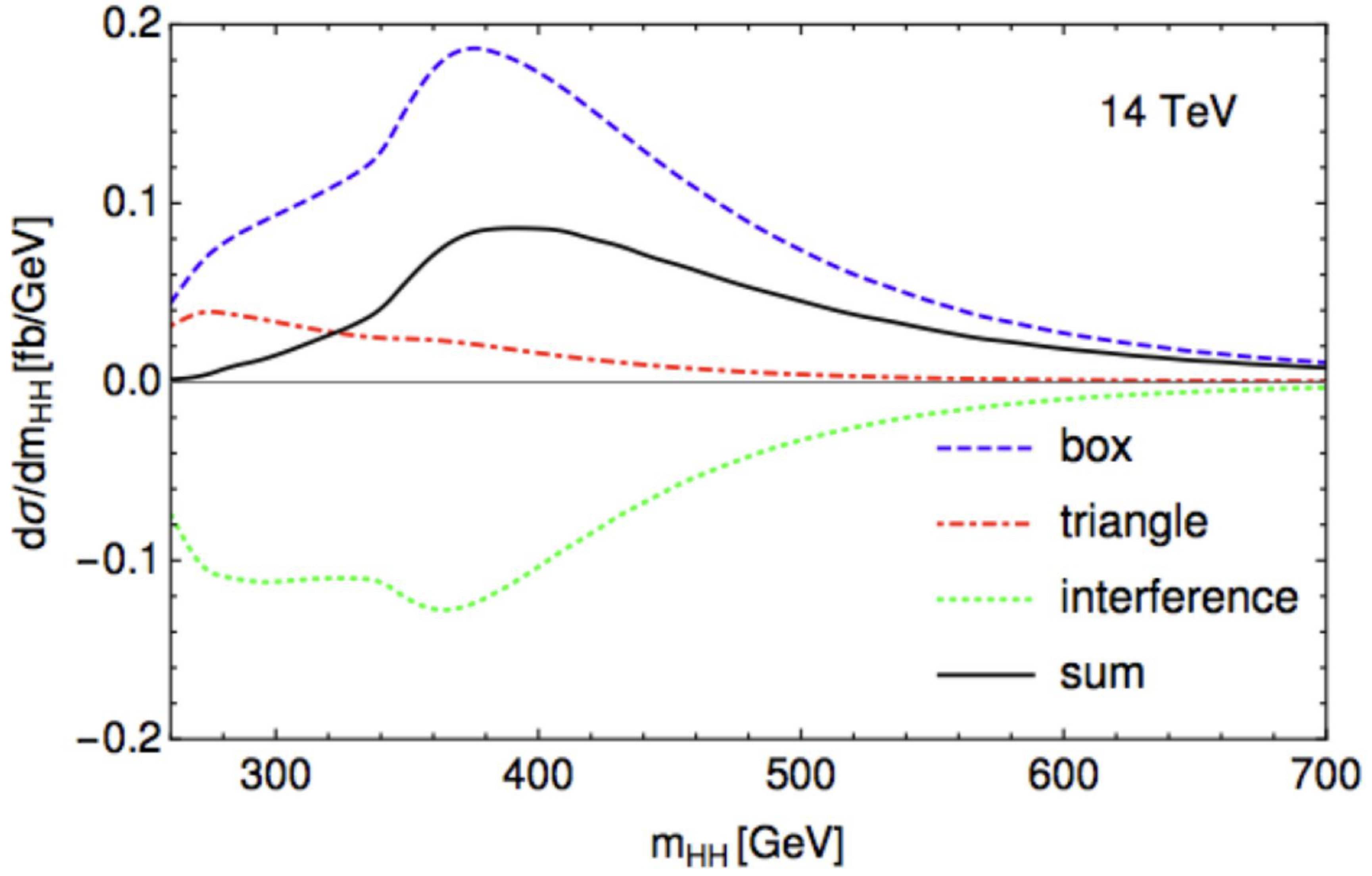


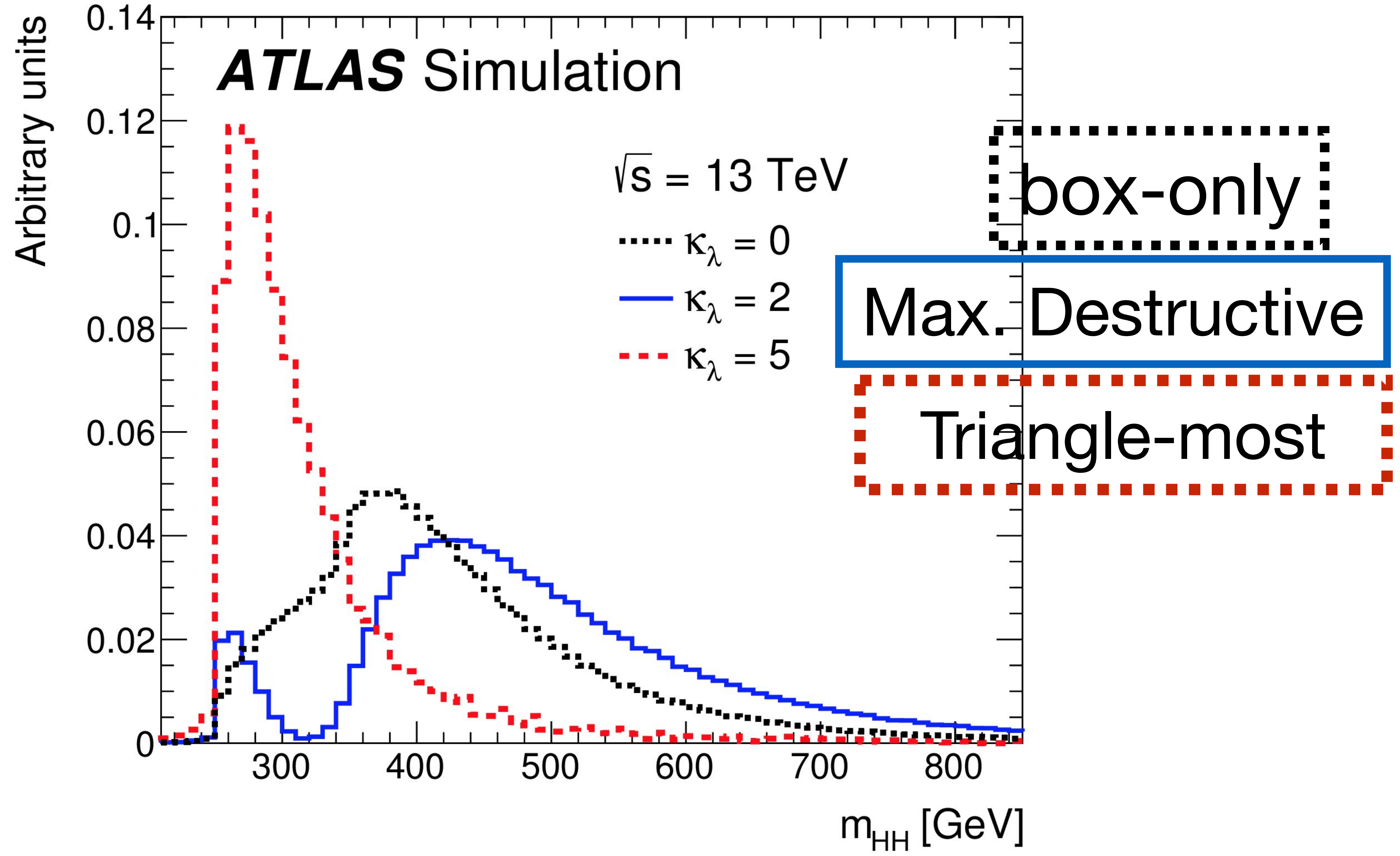
NNLO $\sigma_{HH}(\text{ggF}) = 31.02^{+2.2\%}_{-5.0\%}$ (Scale) $\pm 3.0\%$ (α_s+PDF) $\pm 2.6\%$ (m_{top}) fb



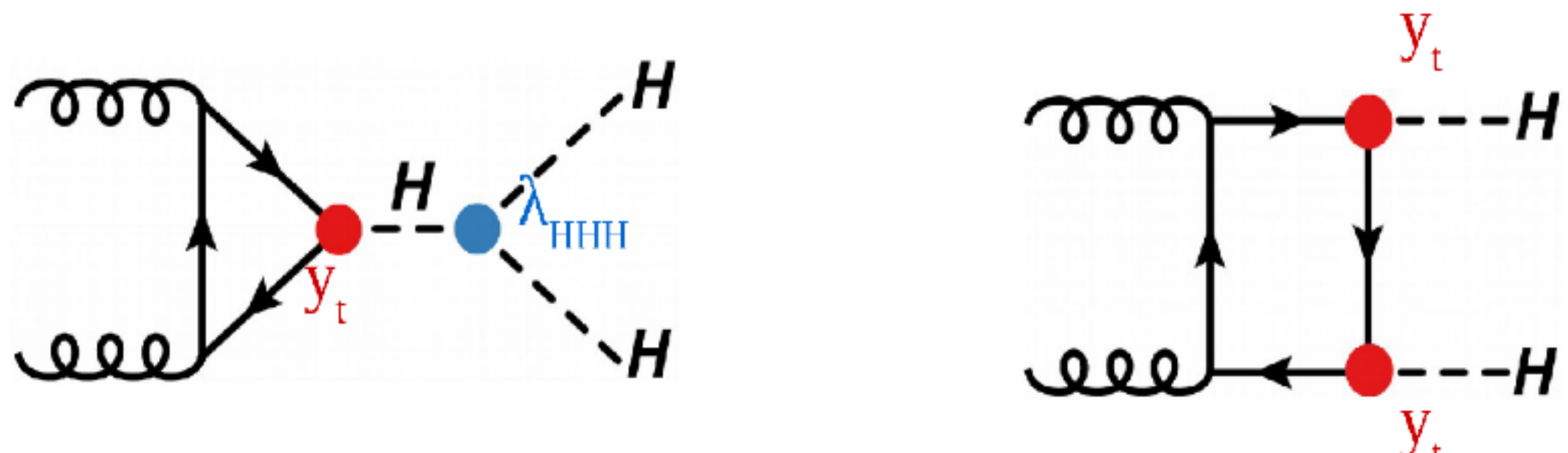
N3LO $\sigma_{HH}(\text{VBF}) = 1.72^{+0.03\%}_{-0.04\%}$ (Scale) $\pm 2.1\%$ (α_s+PDF) fb

- **HH production → direct determination of Higgs trilinear coupling λ_{HHH}**
- **Second dominant mode (VBFHH) open a window for VVHH couping (C_{2V})**
- **Challenge: rare production rate with σ(gg→HH) ~ 0.1%×σ(gg→H)**





Higgs self-coupling measurement via HH production



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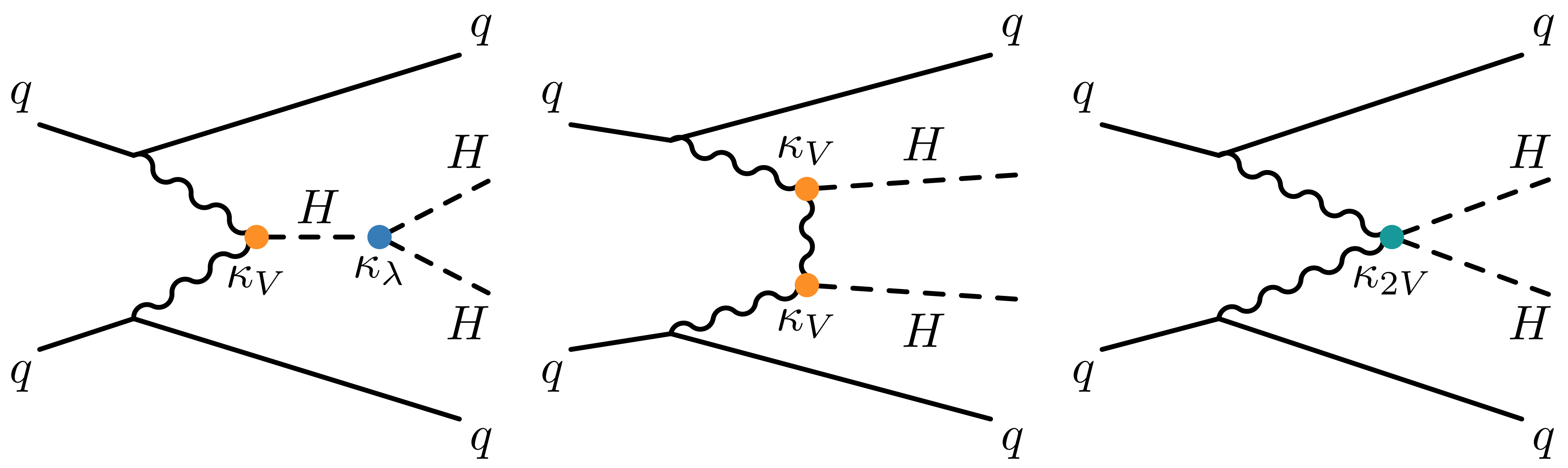

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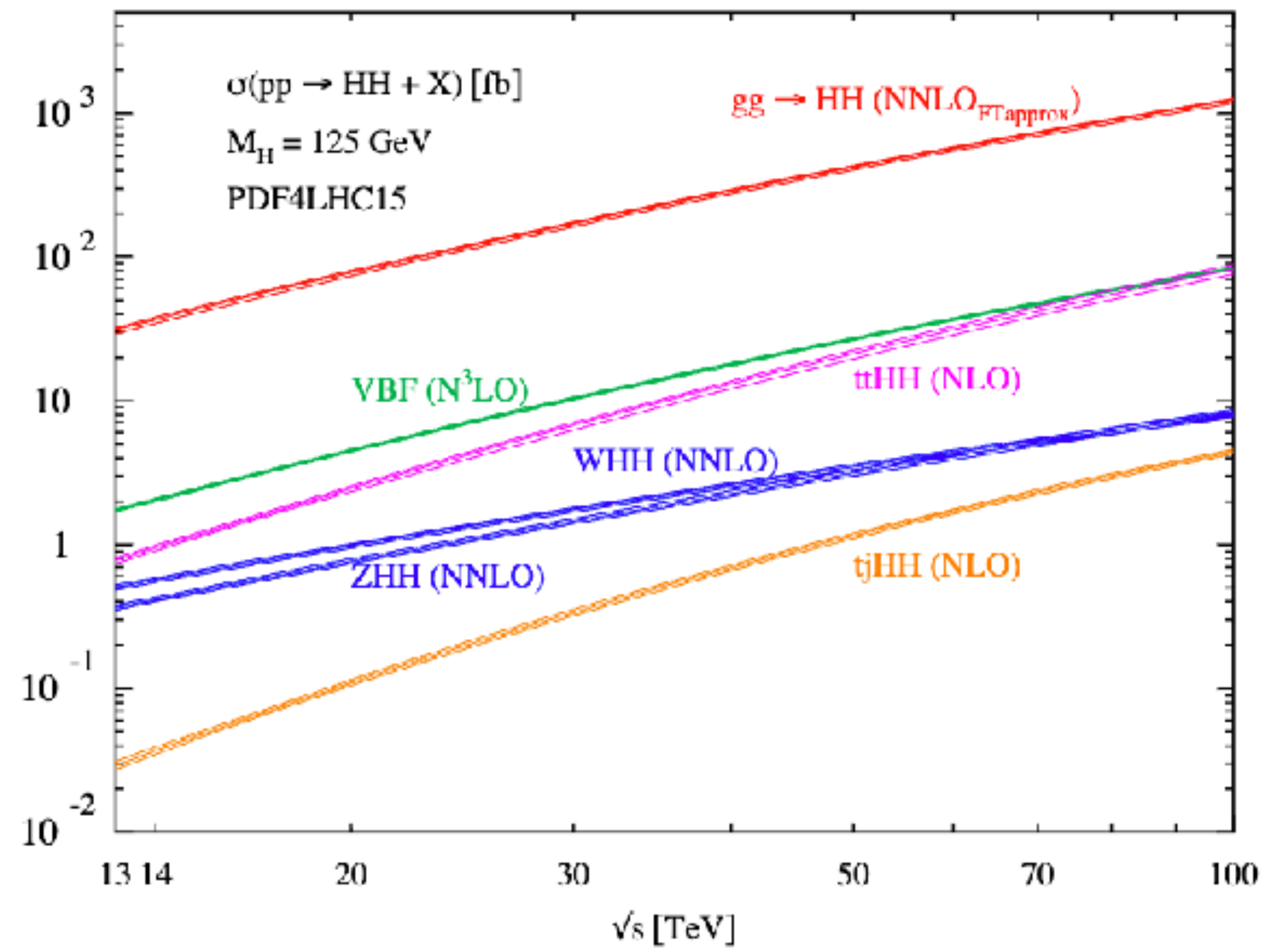
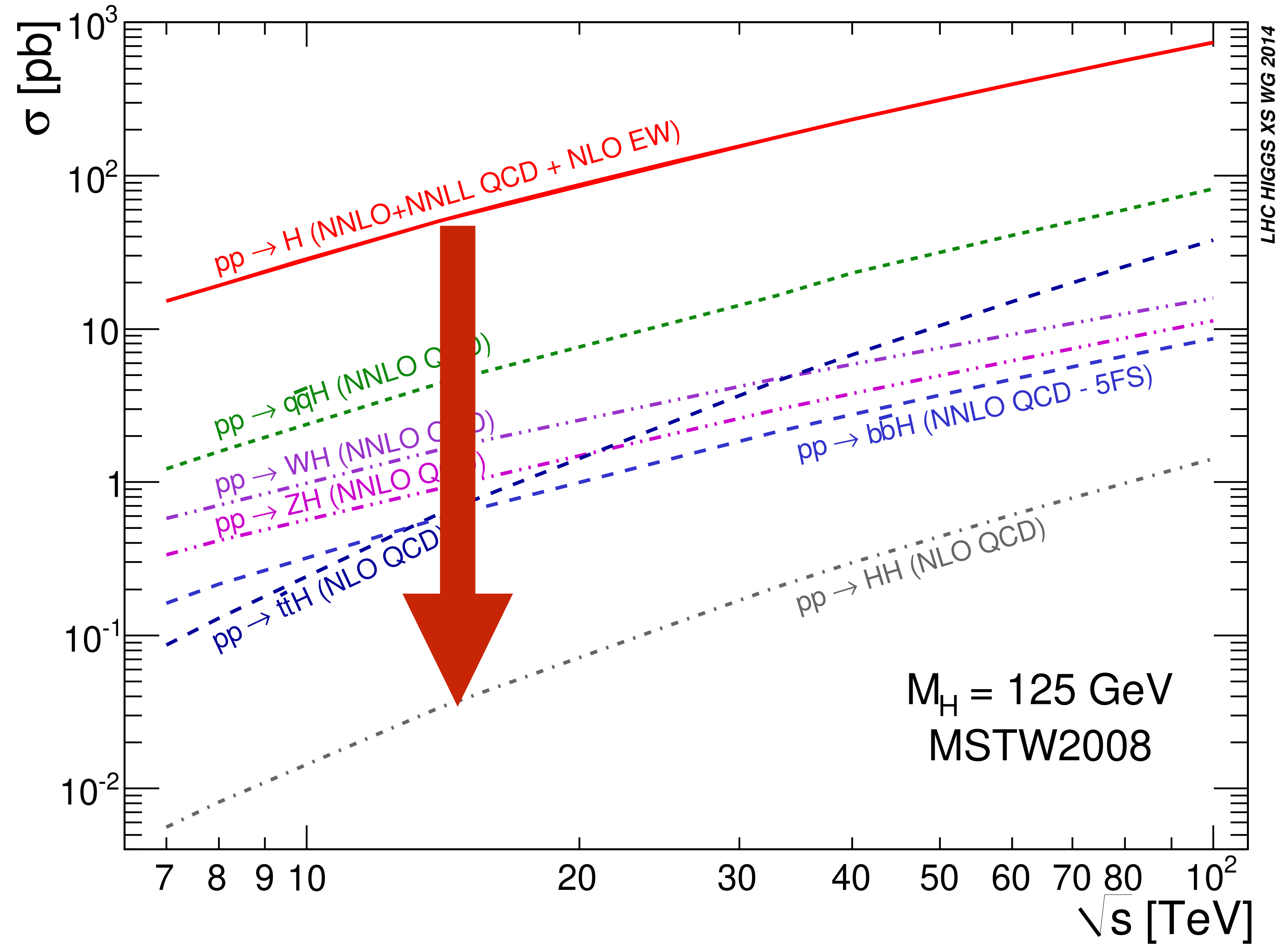
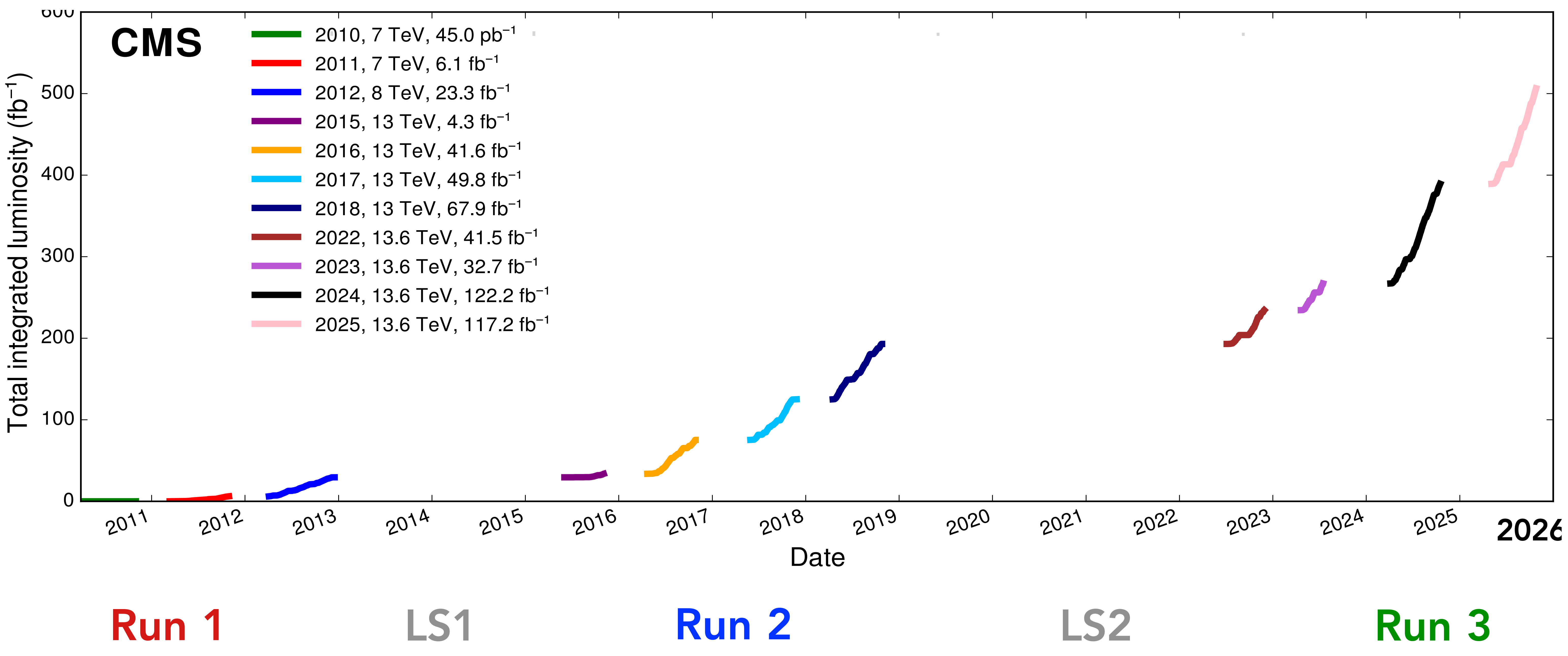
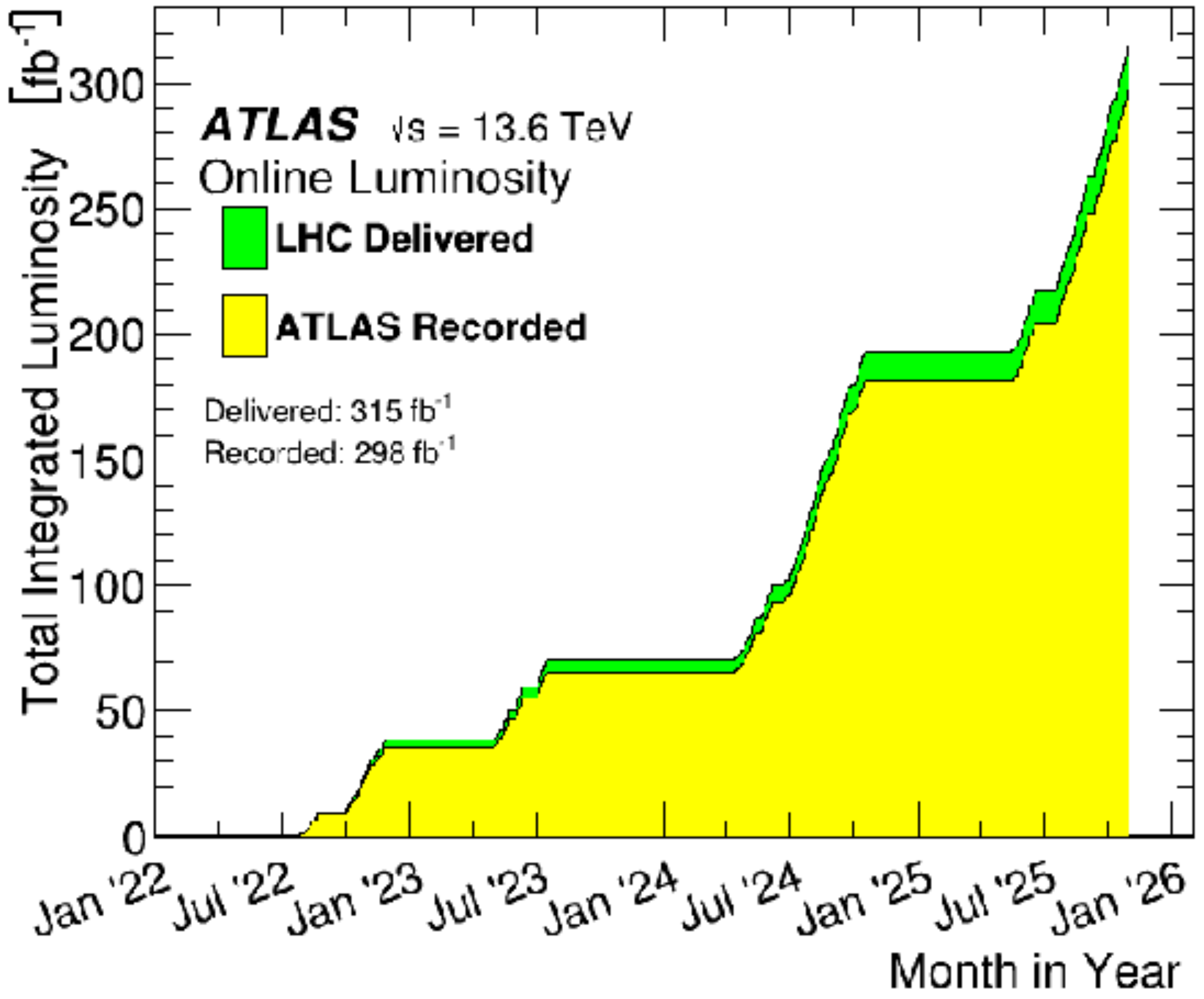
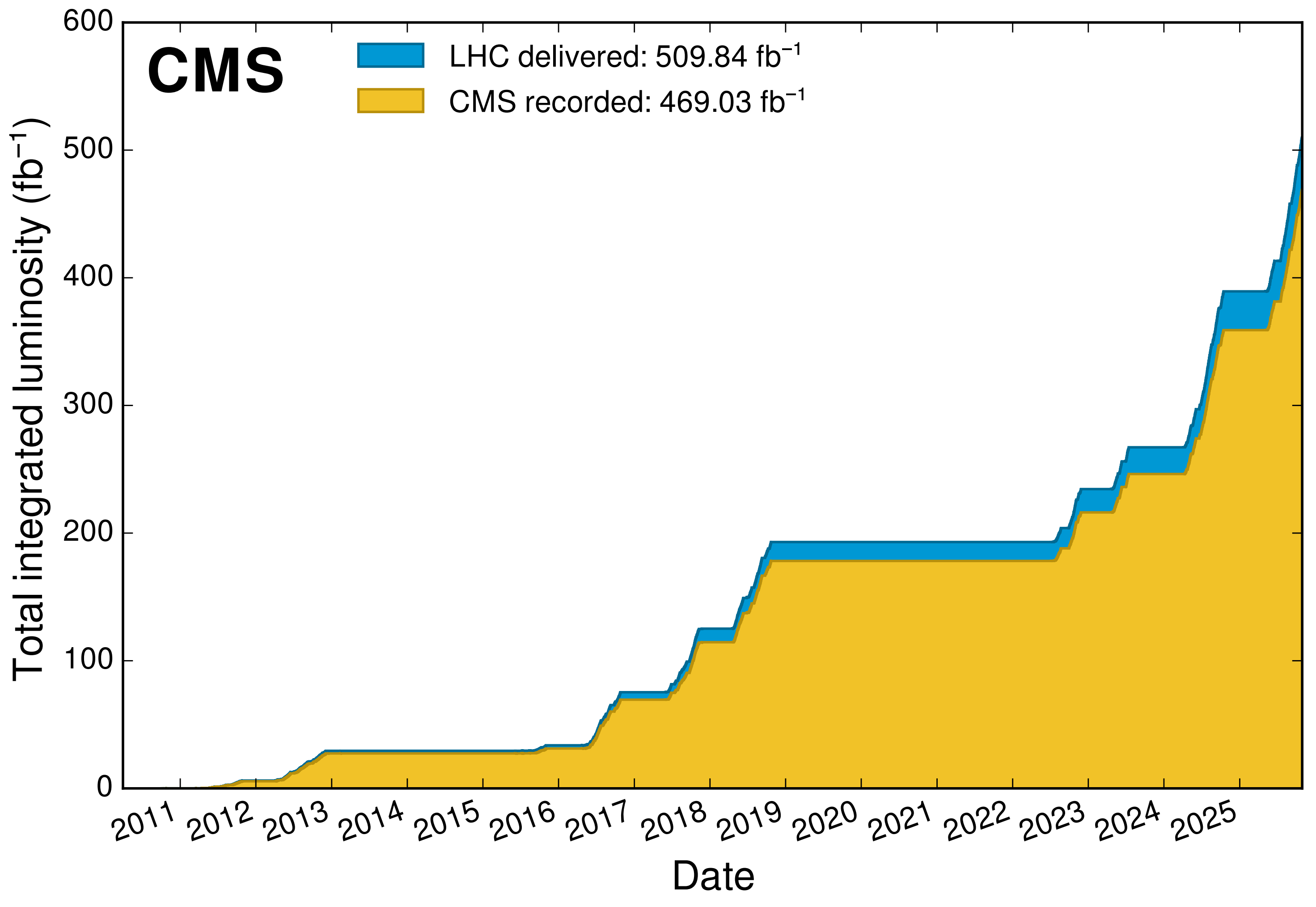




ATLAS/CMS data







HH Decays

bbbb

Highest branching fraction

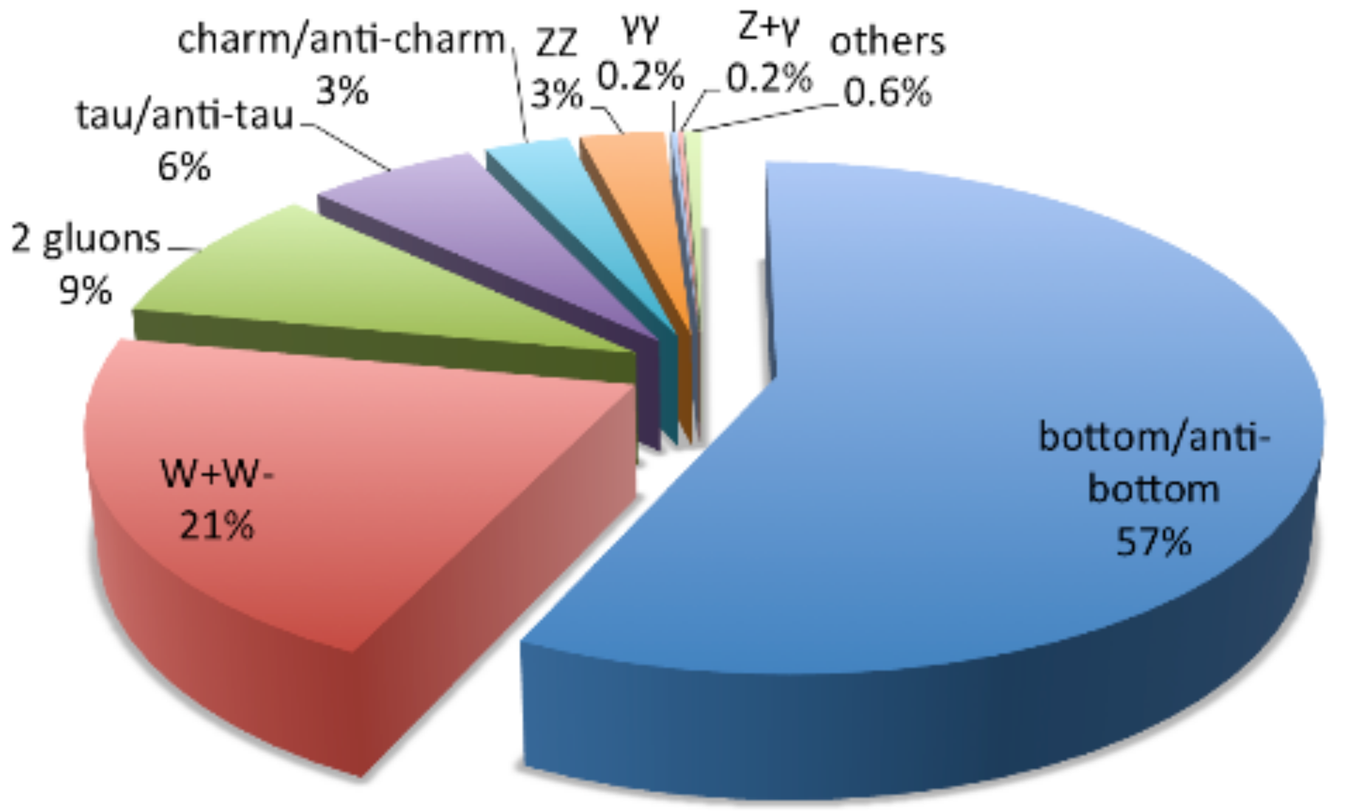
Large multi-jet background

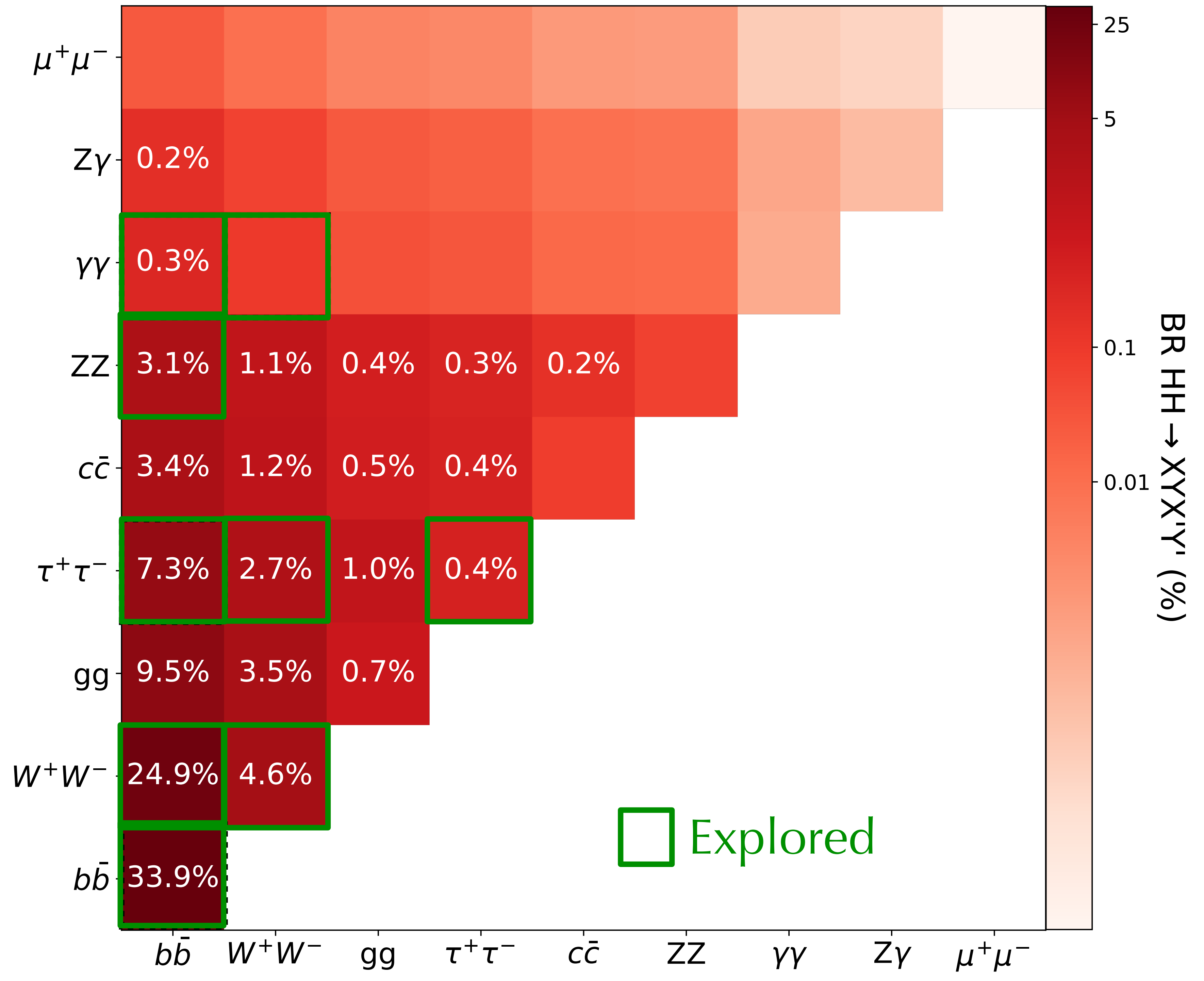
bb$\gamma\gamma$

Very small branching fraction
Clean signal due to the good photon resolution

bb$\tau\tau$

Very small branching fraction
Cleaner signal due to dedicated τ construction





bbWW (bbVV)

Second branching fraction

Large background, but cleaner with at least one lepton

WW$\gamma\gamma$

Clean $\gamma\gamma$ peak, leptonic final state or jet

$\tau\tau\gamma\gamma$

Clean $\gamma\gamma$ and $\tau\tau$ but small BR

Multilepton

Many different signatures of WWWW, WW$\tau\tau$ and $\tau\tau\tau\tau$

Clean leptonic final states

Public HH results

CMS

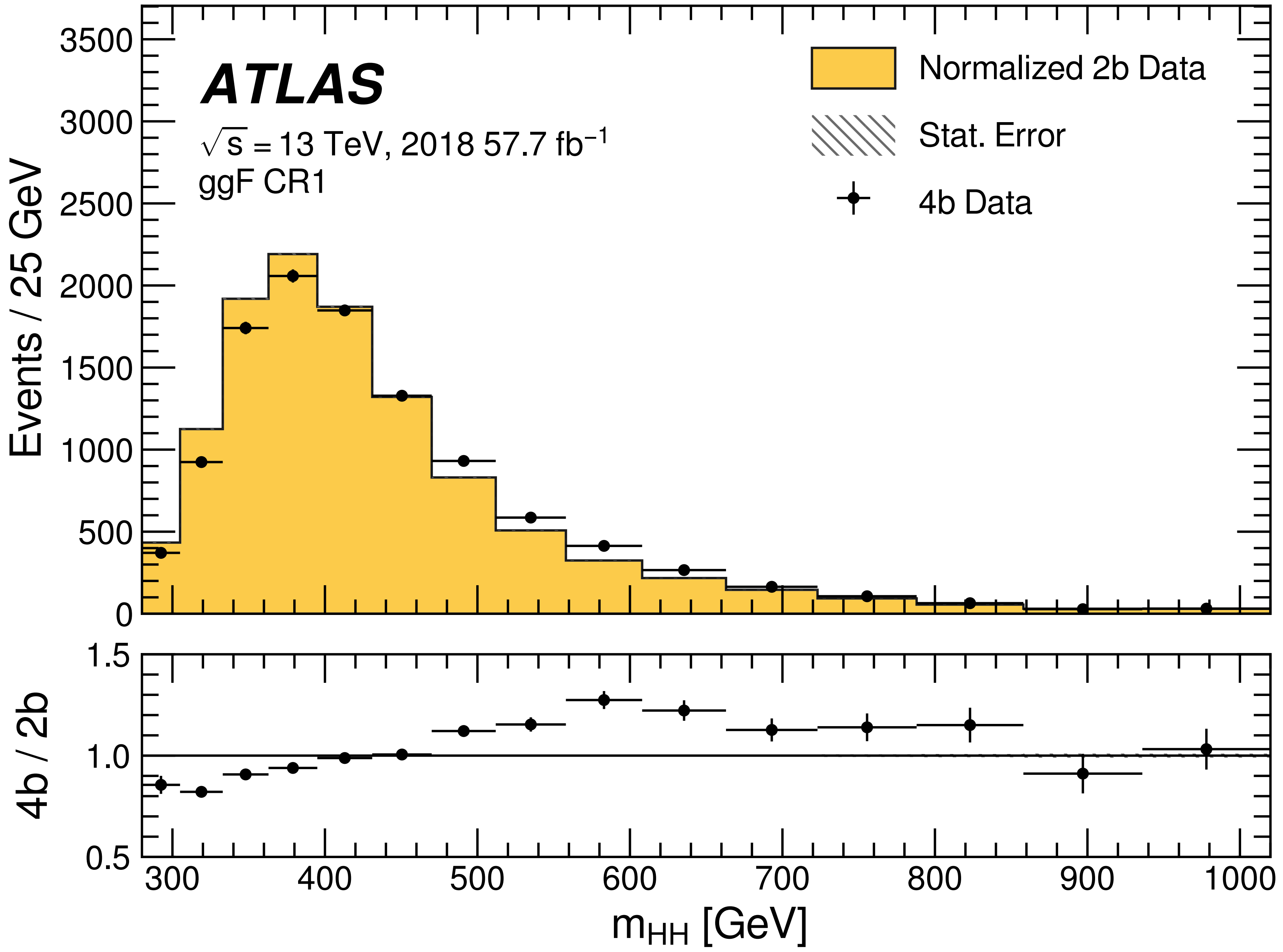
- $HH \to b\bar{b}b\bar{b}$: Phys. Rev. Lett. 129.081802; Latest results: PAS HIG-24-010
- $HH \to b\bar{b}b\bar{b}$ (boosted ggF and VBF): Phys. Rev. Lett. 131.041803
- $HH \to b\bar{b}\tau\tau$: Phys. Rev. Lett. 842 (2023) 137531
- $HH \to b\bar{b}\gamma\gamma$: JHEP03(2021)257; Latest results: PAS HIG-25-007
- $HH \to b\bar{b}ZZ(4\ell)$: JHEP06(2023)130
- $HH \to WWW^*W^*, WW\tau\tau, \tau\tau\tau\tau$ (multi-leptons): JHEP07(2023)095
- HH anniversary combinations: Nature vol. 607, pages 60–68 (2022)
- $HH \to b\bar{b}WW$: JHEP07(2024)293 and $VHH \to b\bar{b}b\bar{b}$: JHEP10(2024)061
- $HH + H$ 2023 combination: Phys. Lett. B 861 (2025) 139210
- $HH \to WW\gamma\gamma$: CMS-PAS-HIG-21-014 (not published yet)
- $HH \to b\bar{b}WW(WW \to 4b)$: CMS-PAS-HIG-23-012
- $HH \to \gamma\gamma\tau\tau$: arXiv:2506.23012 (submitted to JHEP)

ATLAS

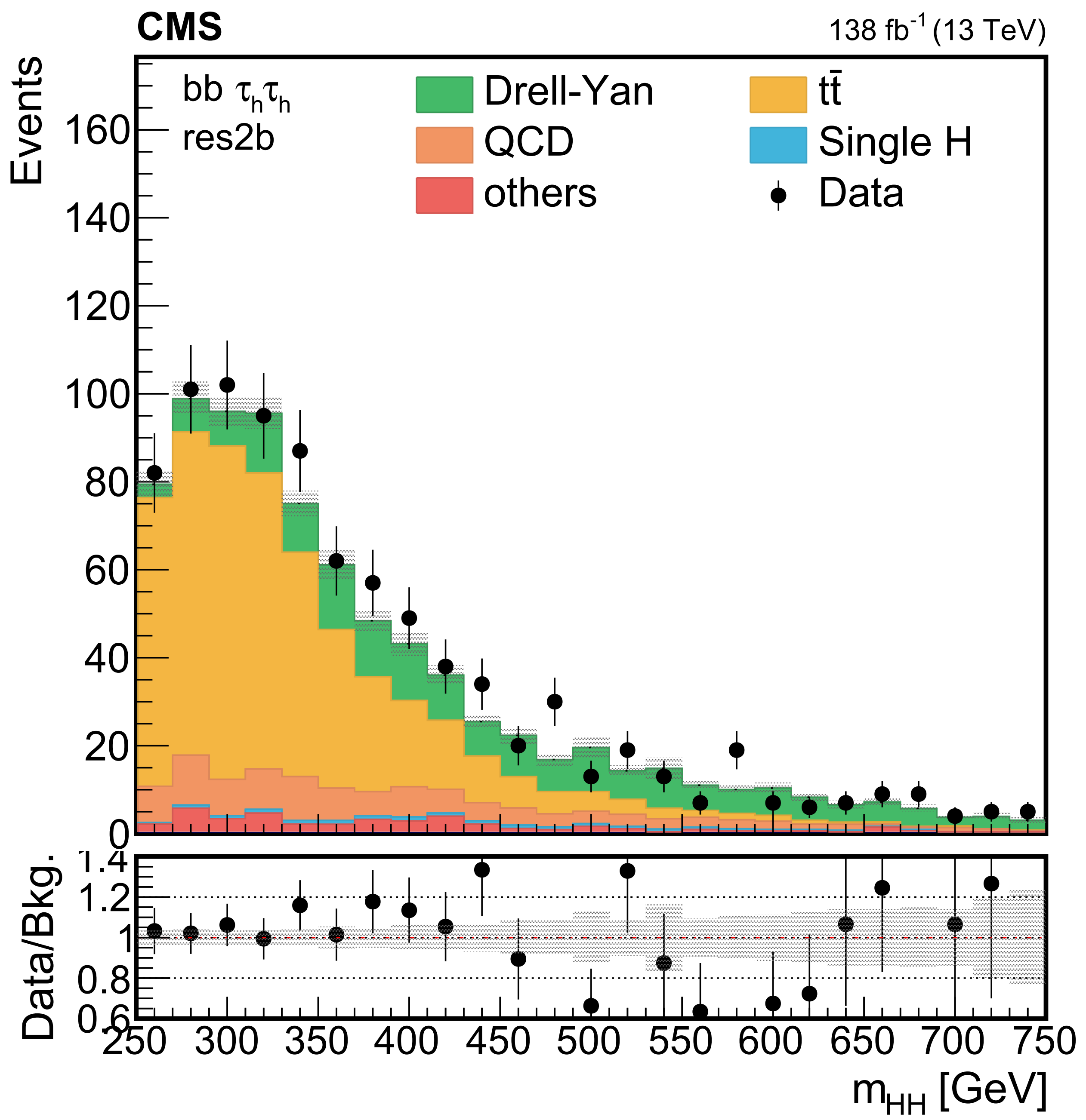
- Run 2 $HH \to b\bar{b}b\bar{b}$ (Resolved): Phys. RevD. 108.052003
- Run 2 $HH \to b\bar{b}b\bar{b}$ (Boosted VBF): Phys. Lett. B 858 (2024) 139007
- Run 2 $HH \to b\bar{b}\ell\ell + \mathrm{MET}$: JHEP02(2024)037
- Run 2 Legacy $HH \to b\bar{b}\gamma\gamma$: JHEP01(2024)066
- Run 2 Legacy $HH \to b\bar{b}\tau\tau$: Phys. RevD. 110.032012
- Run 2 $HH \to b\bar{b}ZZ,\ 4W,\ 4Z,\ VV\tau\tau,\ 4\tau,\ \gamma\gamma VV,\ \gamma\gamma\tau\tau$ (multi-leptons): JHEP08(2024)164
- HH 2022 combination: Phys. Rev. Lett. 133.101801
- Run 2 $VHH \to \nu\nu 4b, \ell\nu 4b, \ell\ell 4b$: Eur. Phys. J. C 83 (2023) 519
- Run 2 + partial Run 3 $HH \to b\bar{b}\gamma\gamma$: arXiv:2507.03495
- Run 2 + partial Run 3 $t\bar{t}HH \to 1\ell, b\bar{b}\gamma\gamma$, multi-leptons: (Just HIGP Approved)

HH search @ Run2

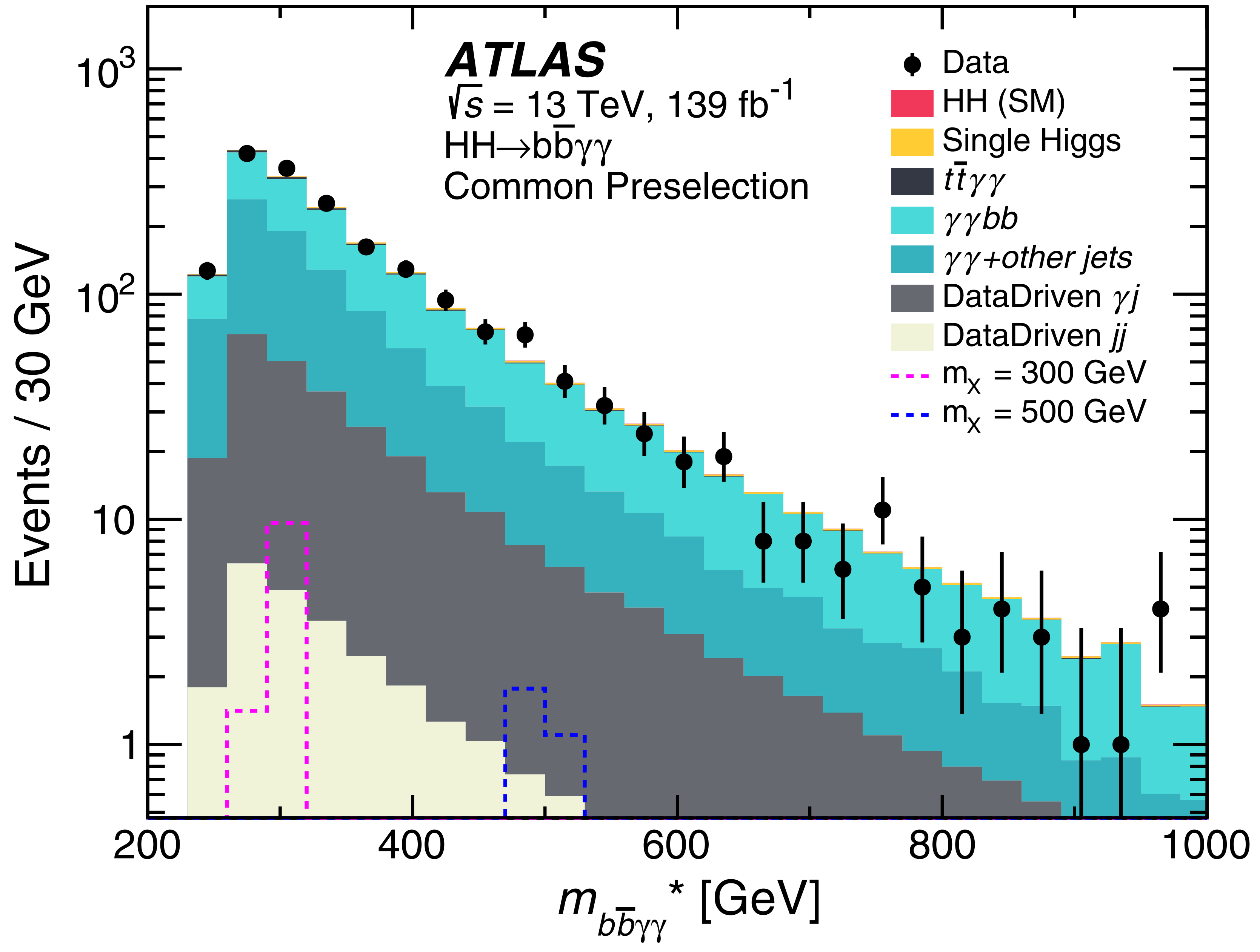
$HH \rightarrow bbbb$



$HH \rightarrow bb\tau\tau$



$HH \rightarrow bb\gamma\gamma$

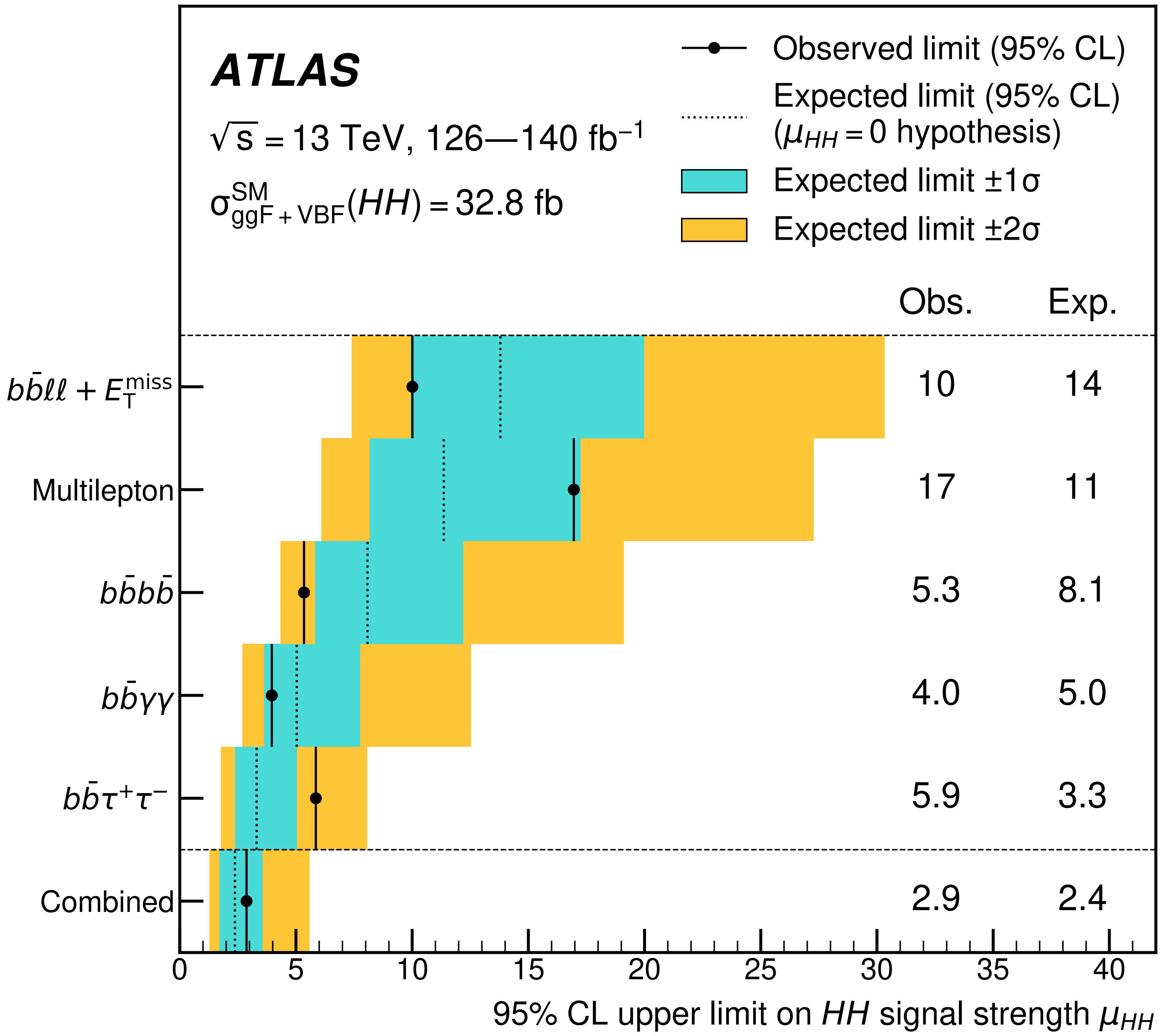


- **Orthogonal Analyses**
- **Trigger with low pt threshold for the lower m_{HH} region (sensitive to κ_λ)**
- **State-of-the art object reconstruction and identification**
- **Sensitivity optimization and background estimation with different MLs**

Run2 HH combination

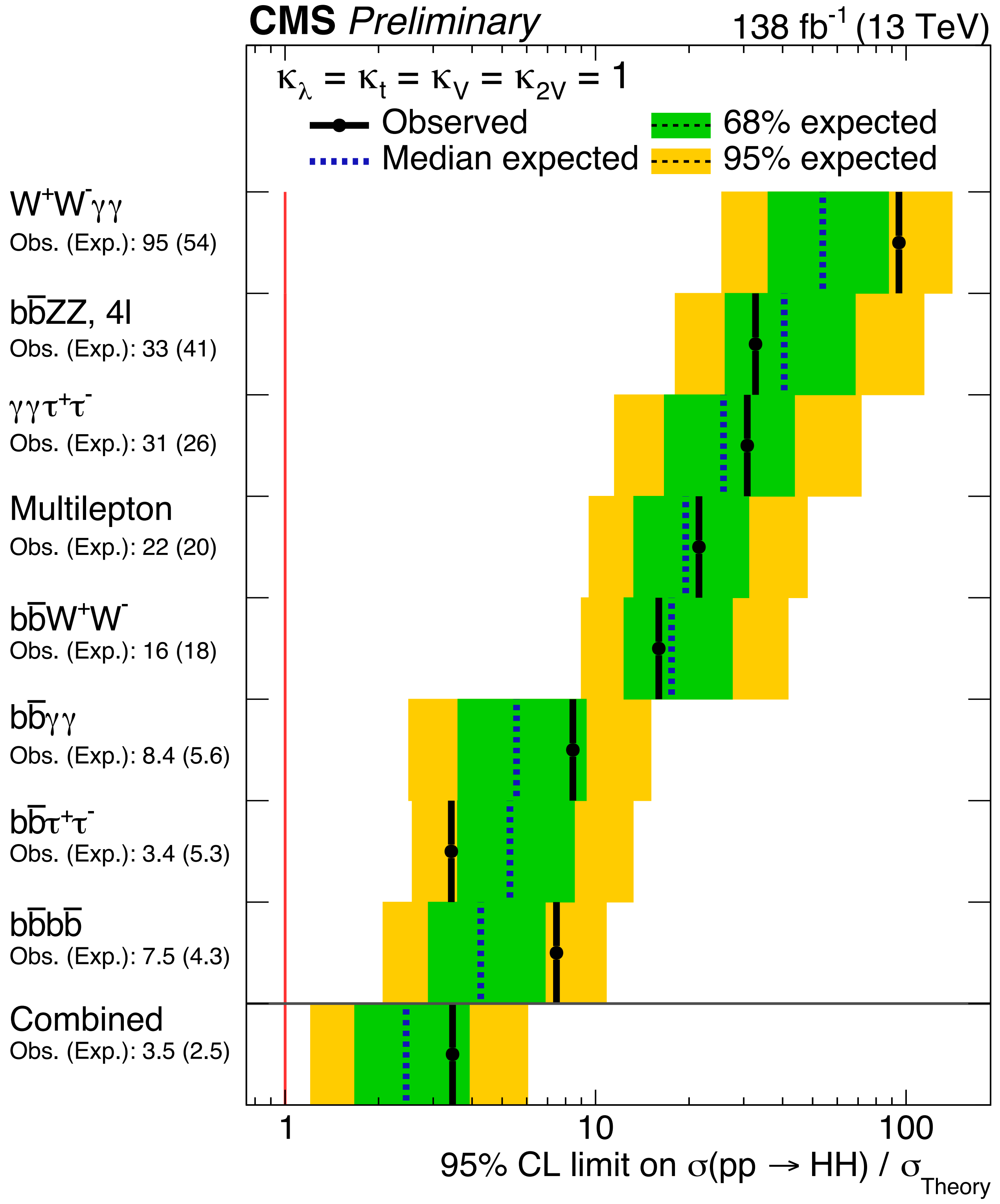
Limit on inclusive HH cross section assuming no Higgs Boson pair production

PRL 133 (2024) 101801



ATLAS Obs. (exp): 2.9× SM (2.4× SM)

PAS HIG-20-011



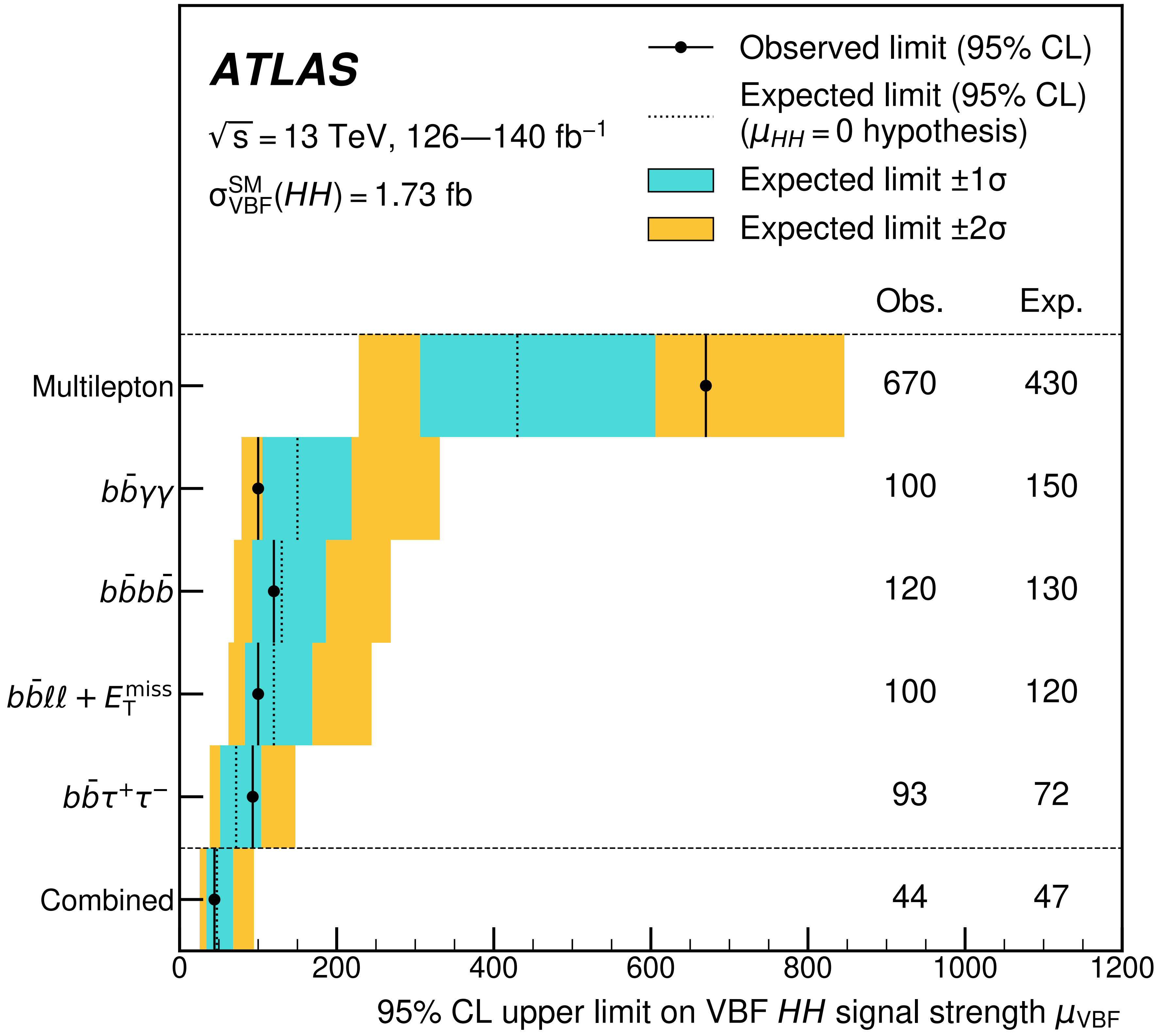
CMS Obs. (exp): 3.5× SM (2.5× SM)

Run2 "legacy" expected significance of μ_{HH} ~1.0 standard deviations for each experiment

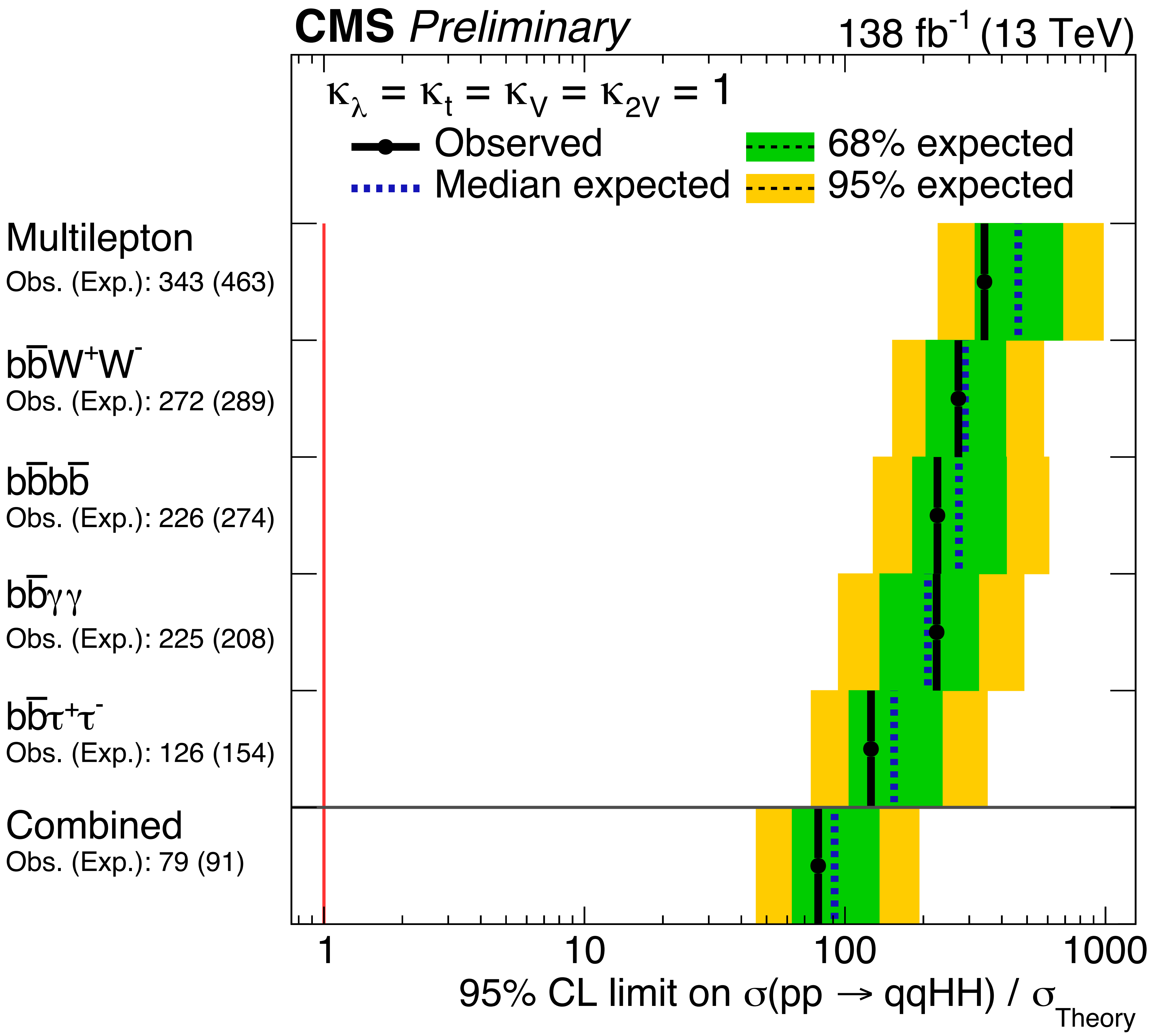
Run2 HH combination

Limit on VBFHH cross section

PRL 133 (2024) 101801



PAS HIG-20-011



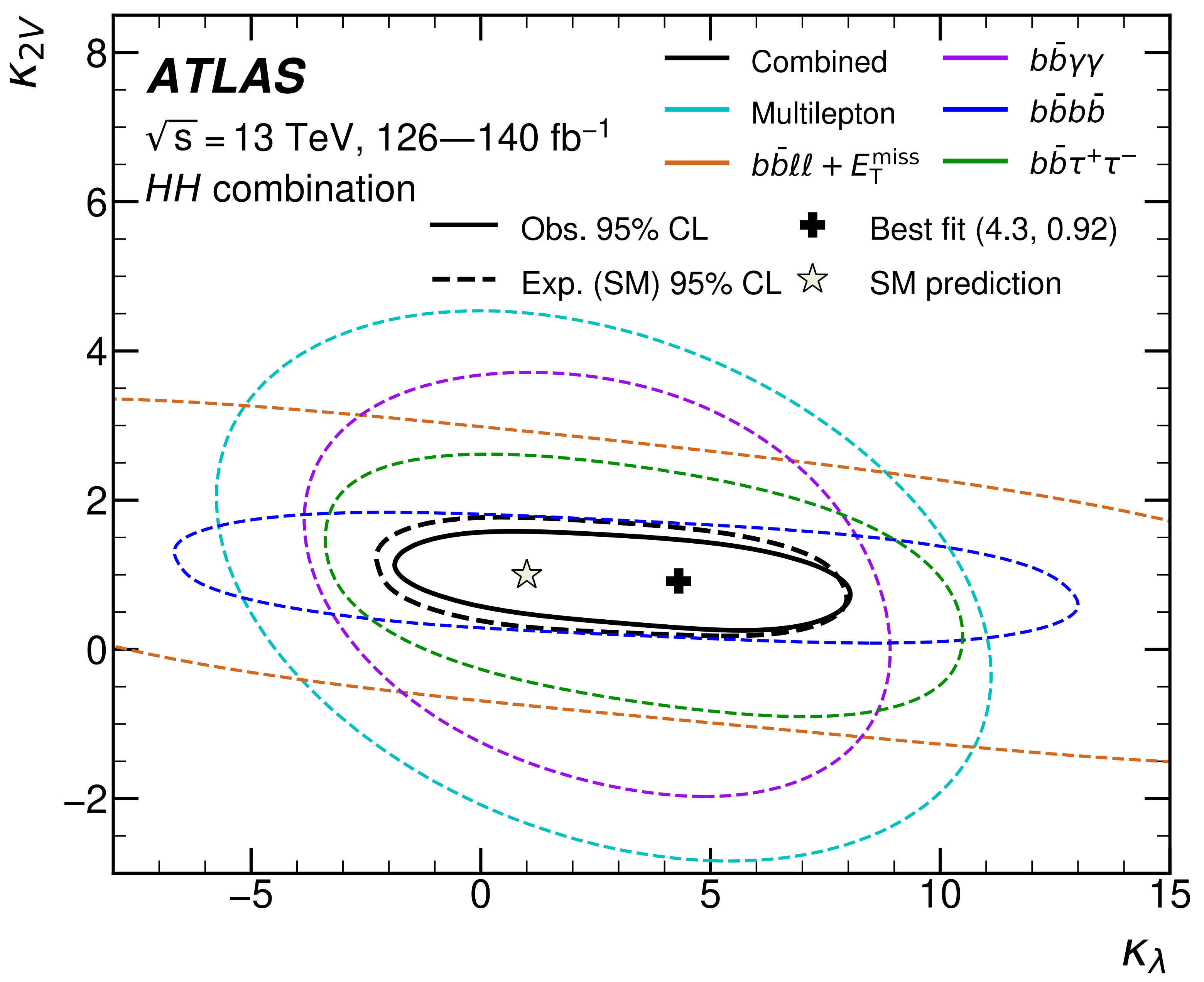
ATLAS Obs. (exp): 44× SM (47× SM)

CMS Obs. (exp): 79× SM (91× SM)

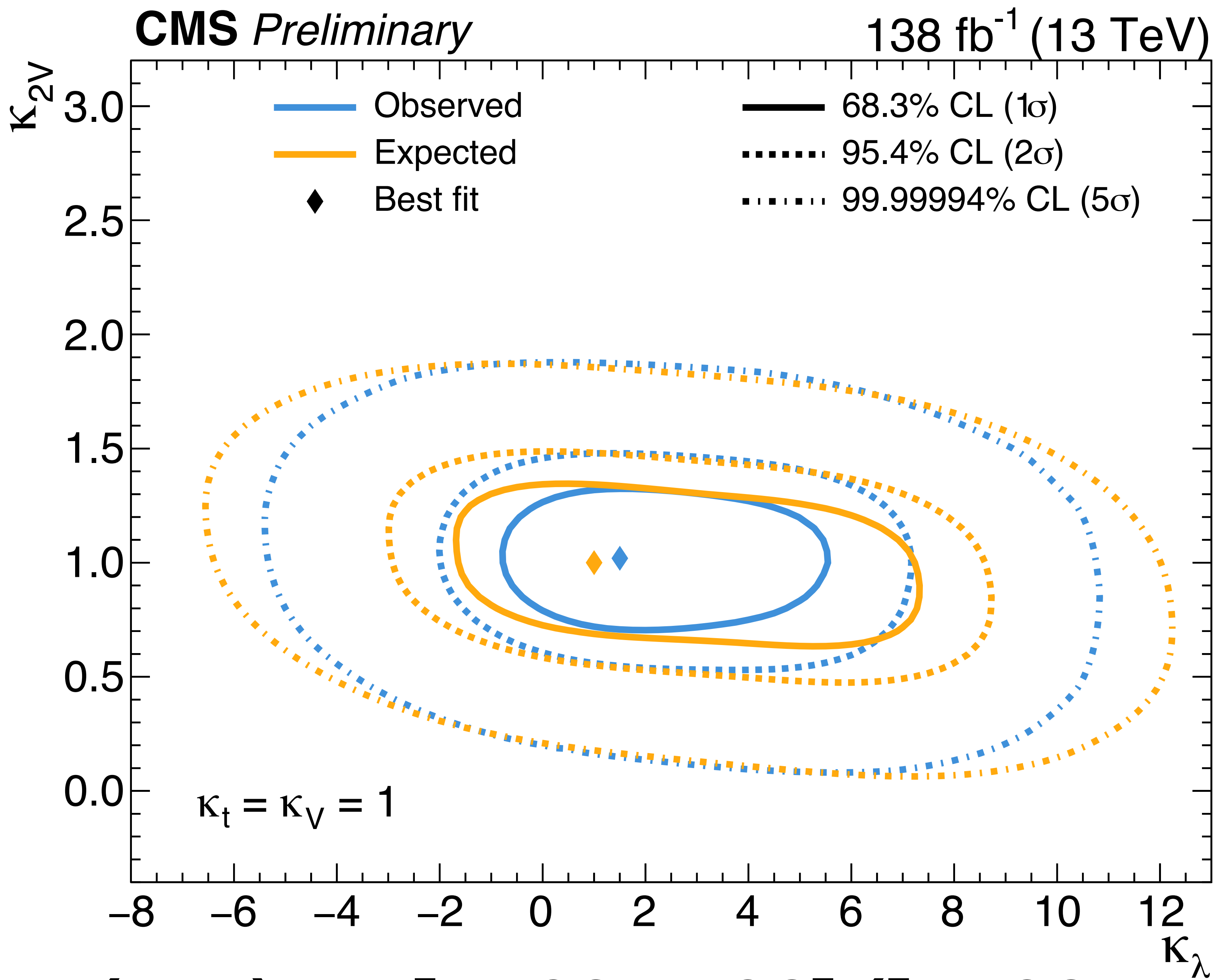
Run2 HH combination

Limit on κ_λ-κ_{2V} plane

PRL 133 (2024) 101801



PAS HIG-20-011



ATLAS Obs. (exp) κ_λ: [-1.2, 7.2] ([-1.6, 7.2])
κ_{2V}: [0.6, 1.5] ([0.4, 1.6])

CMS Obs. (exp) κ_λ: [-1.39, 7.02] ([-1.02, 7.19])
κ_{2V}: [0.62, 1.42] ([0.69, 1.35])

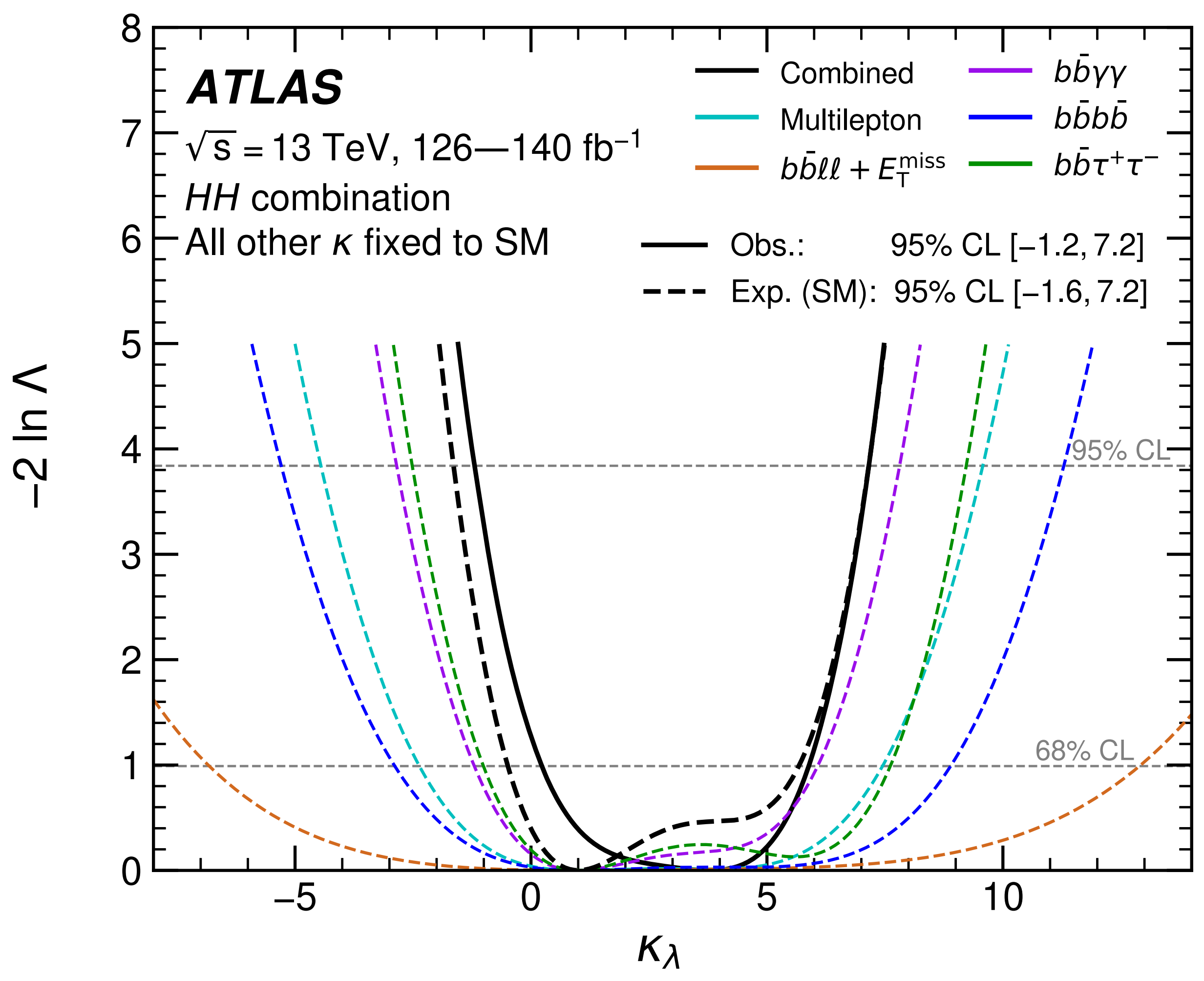
- **κ_λ limit dominated by $HH \to bb\gamma\gamma$ and $HH \to bb\tau\tau$**
- **κ_{2V} limit dominated by 4b boosted signature, $\kappa_{2V} = 0$ excluded at $> 4\sigma$**

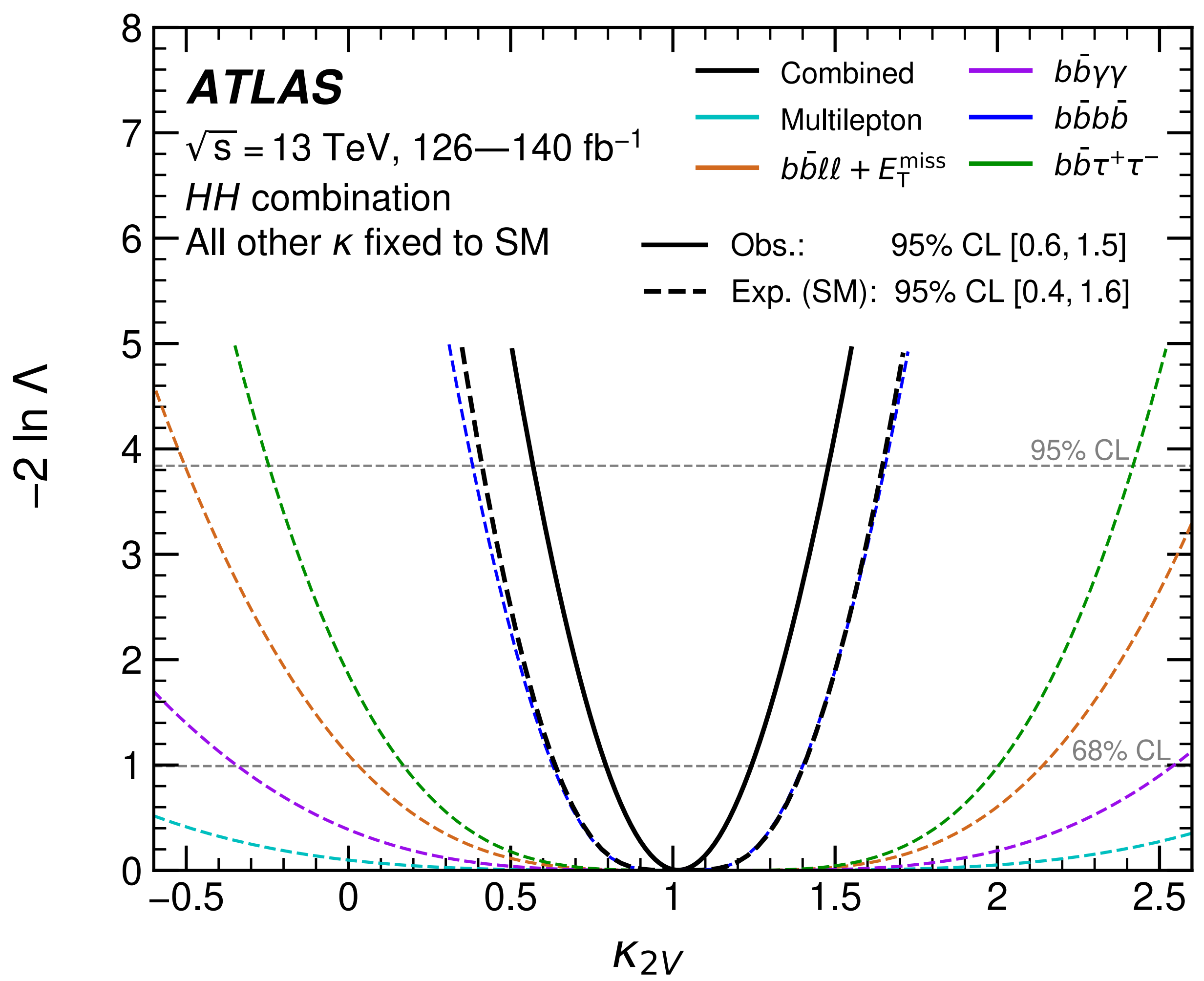
Run2 HH combination

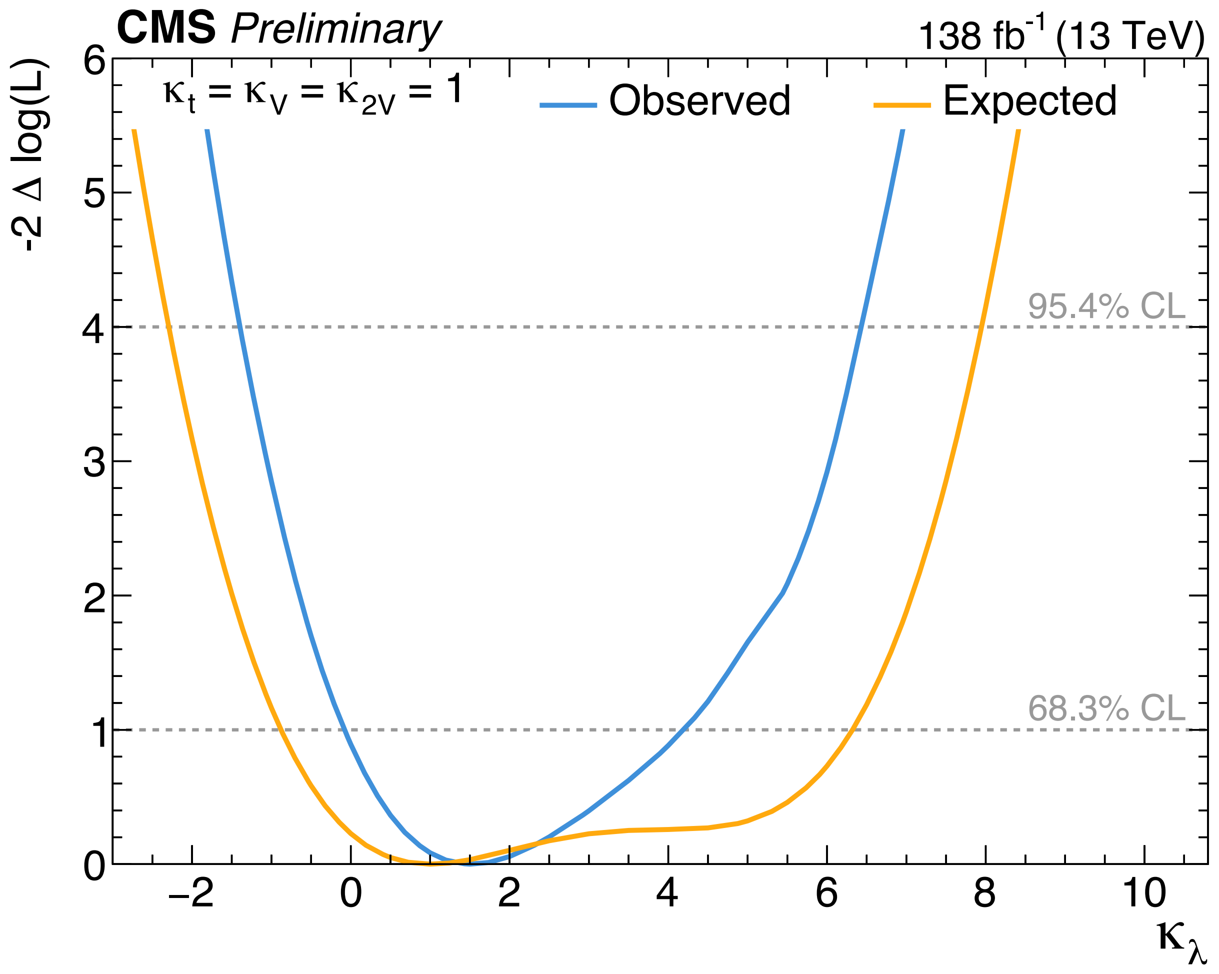
Limit on κ_λ-κ_{2V} plane

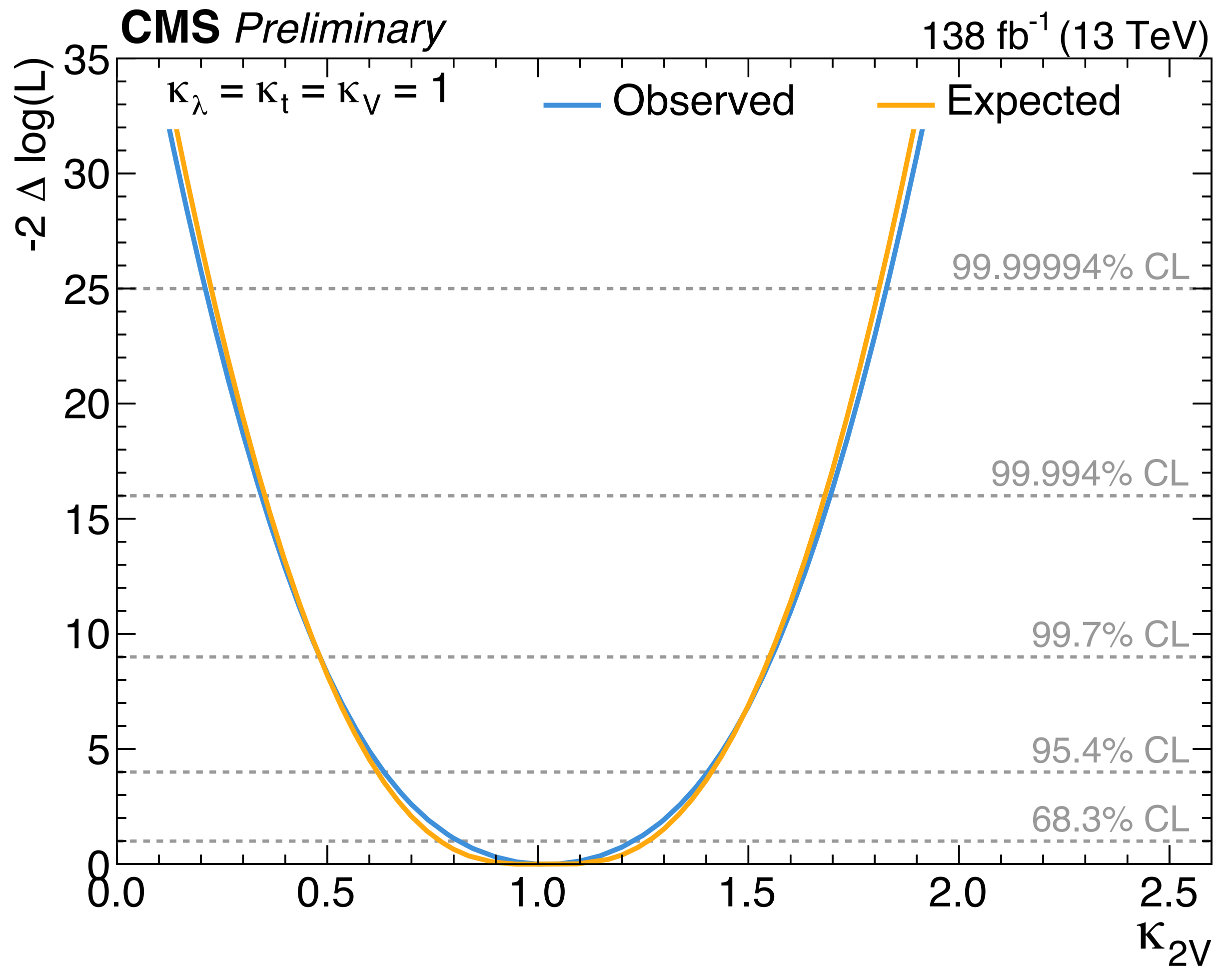
PRL 133 (2024) 101801

PAS HIG-20-011









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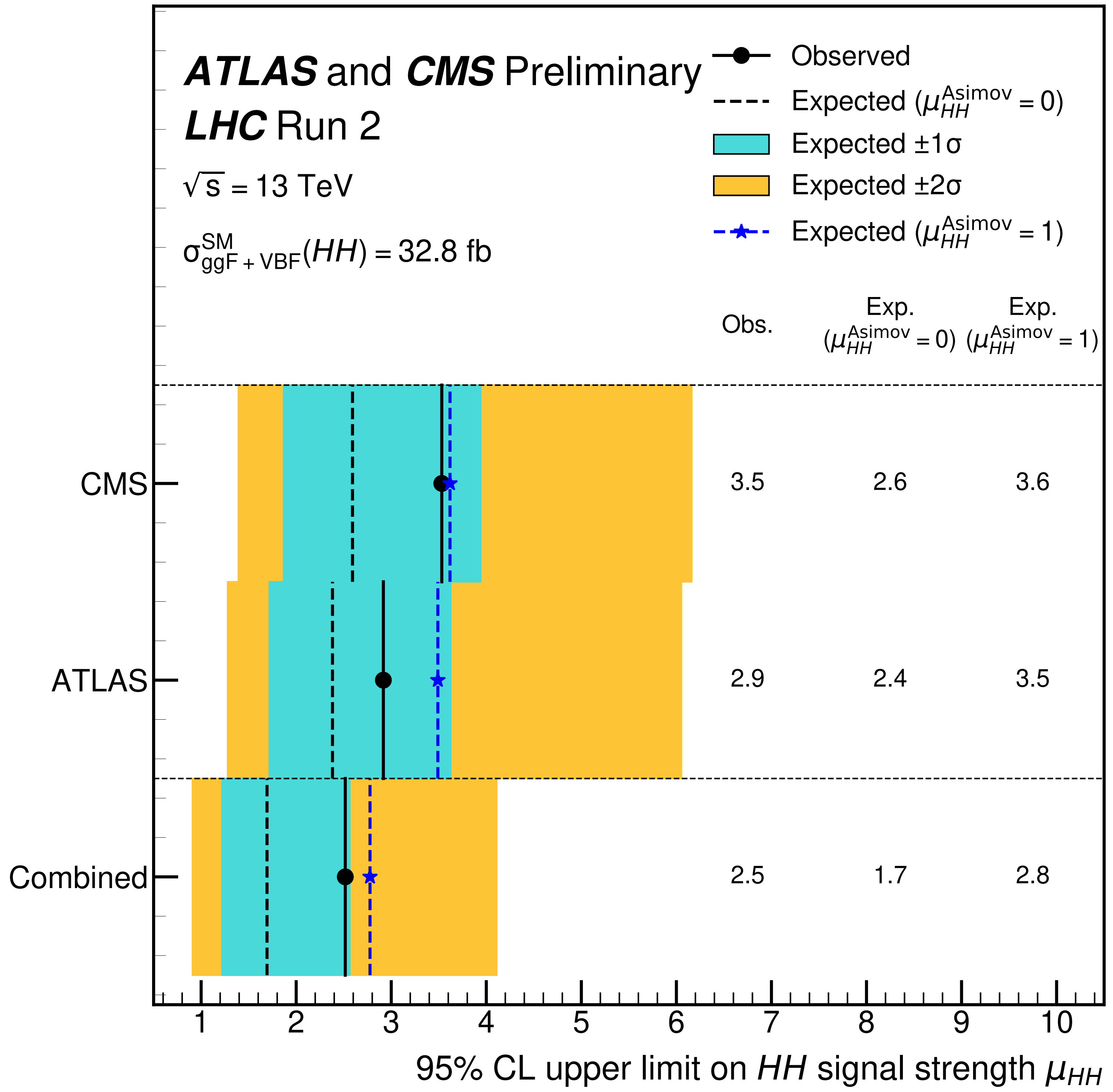
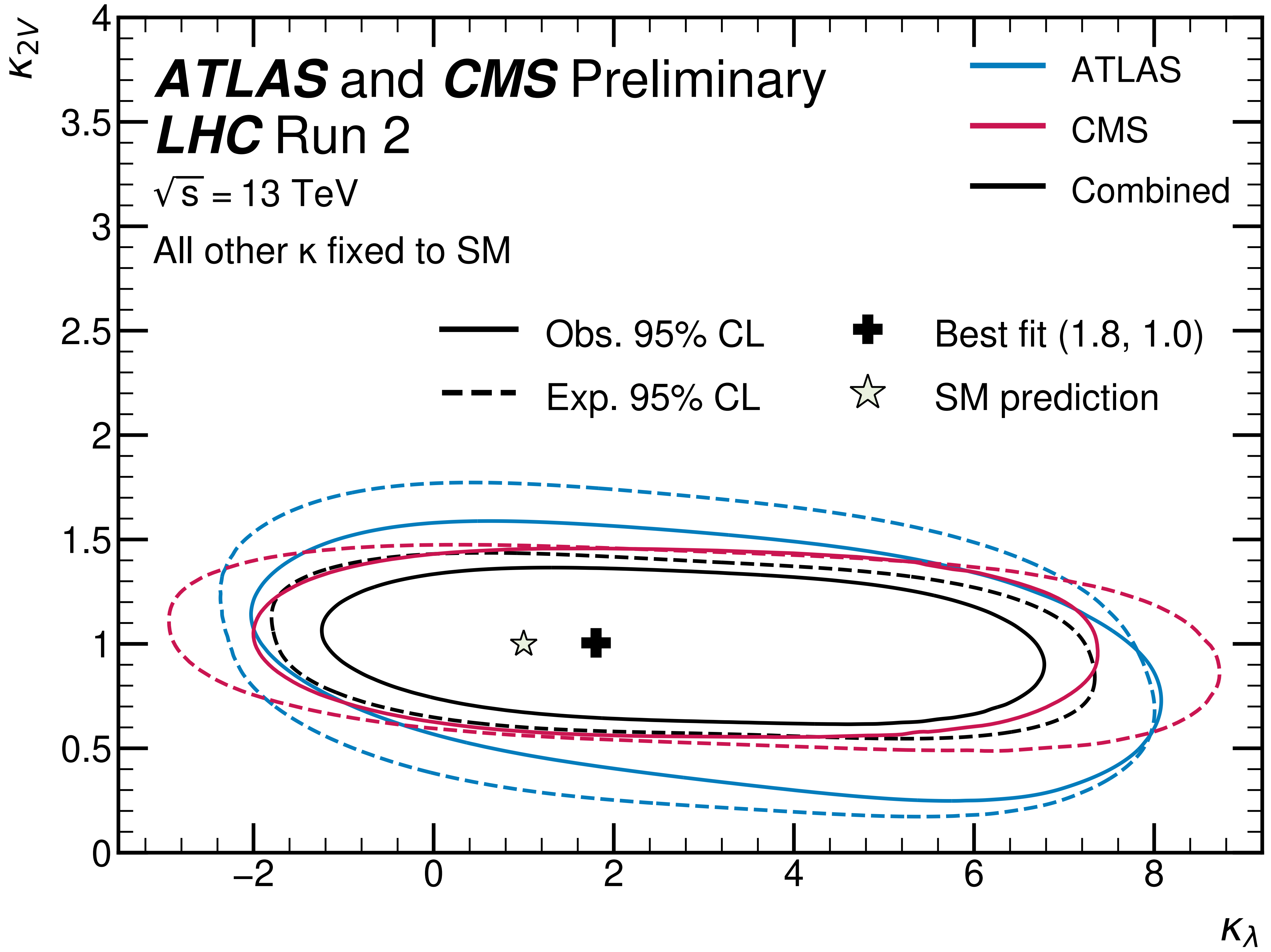
ATLAS-CMS di-Higgs "legacy" Run2 combination

ATLAS-CONF-2025-012

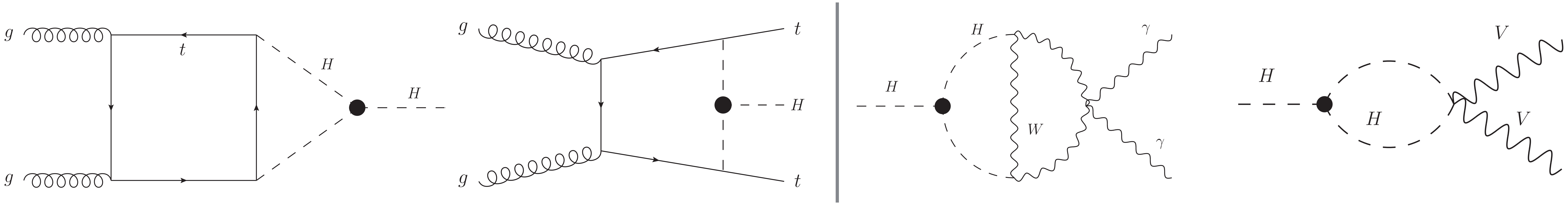




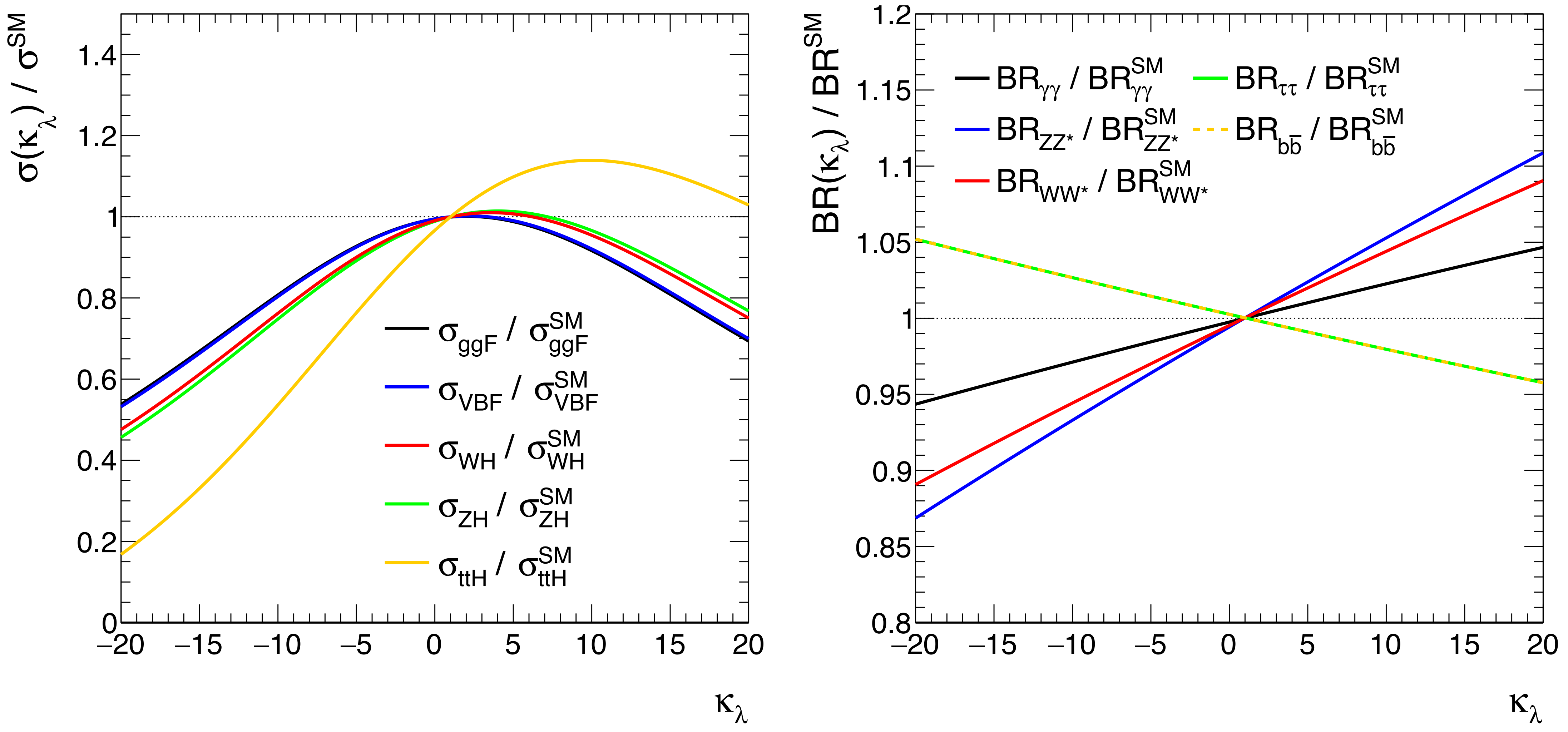
- **ATLAS-CMS obs. (exp) HH: 2.5× SM (1.7× SM w.o SM HH/ 2.8× SM w SM HH)**
- **Obs. (exp) significance: 1.1σ (1.3σ)**
- **Obs. (exp) κ_λ: [-0.71, 6.1] ([-1.3, 6.7]) with sensitivity improvement of 10%**
  κ_{2V}: [0.73, 1.3] ([0.66, 1.4]) with sensitivity improvement of 8%

Indirect self-coupling constraint via single Higgs

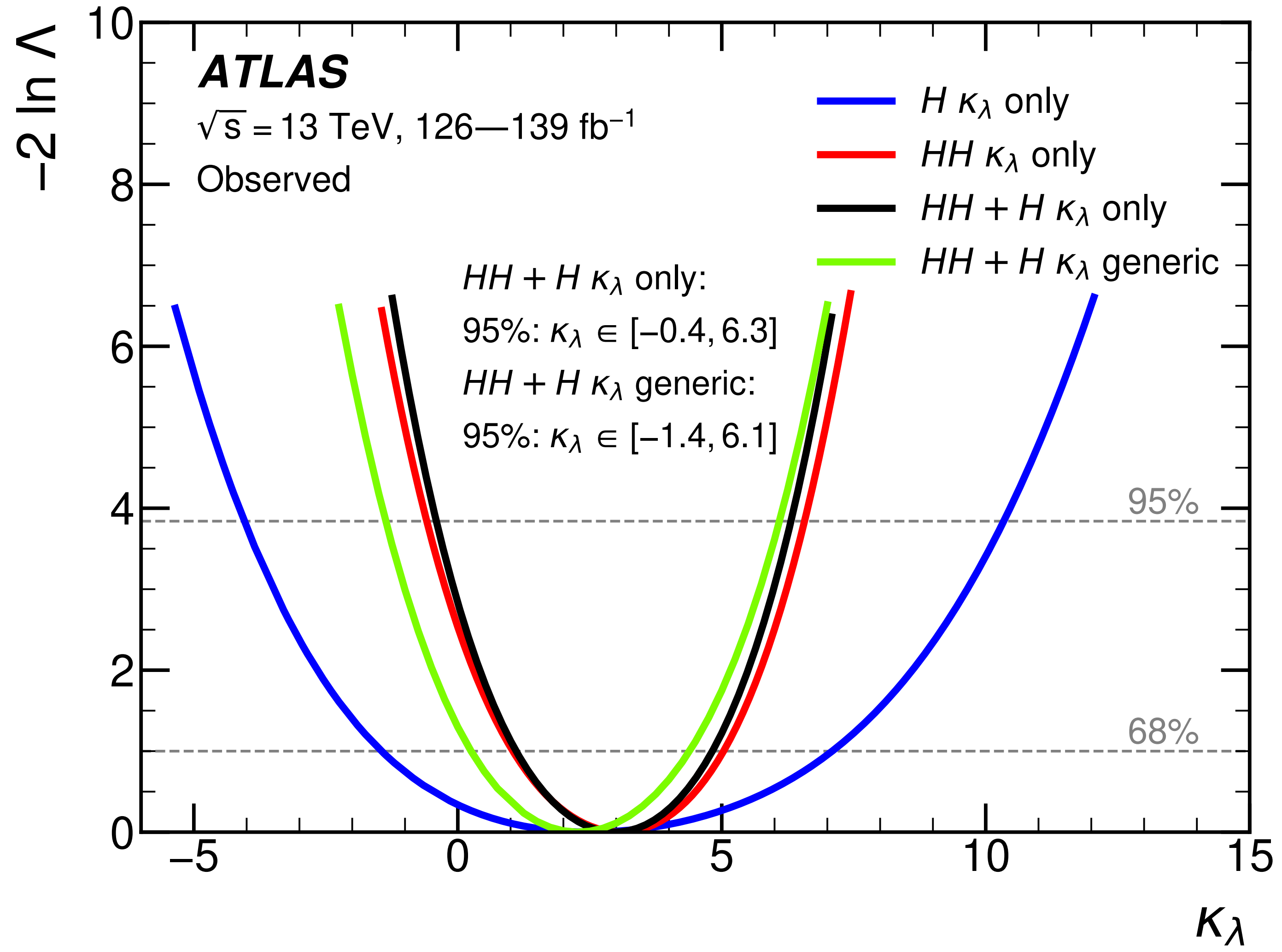
All the single Higgs production and decay processes are affected by an anomalous trilinear (**not quartic**) Higgs self coupling, parametrized by κ_λ.

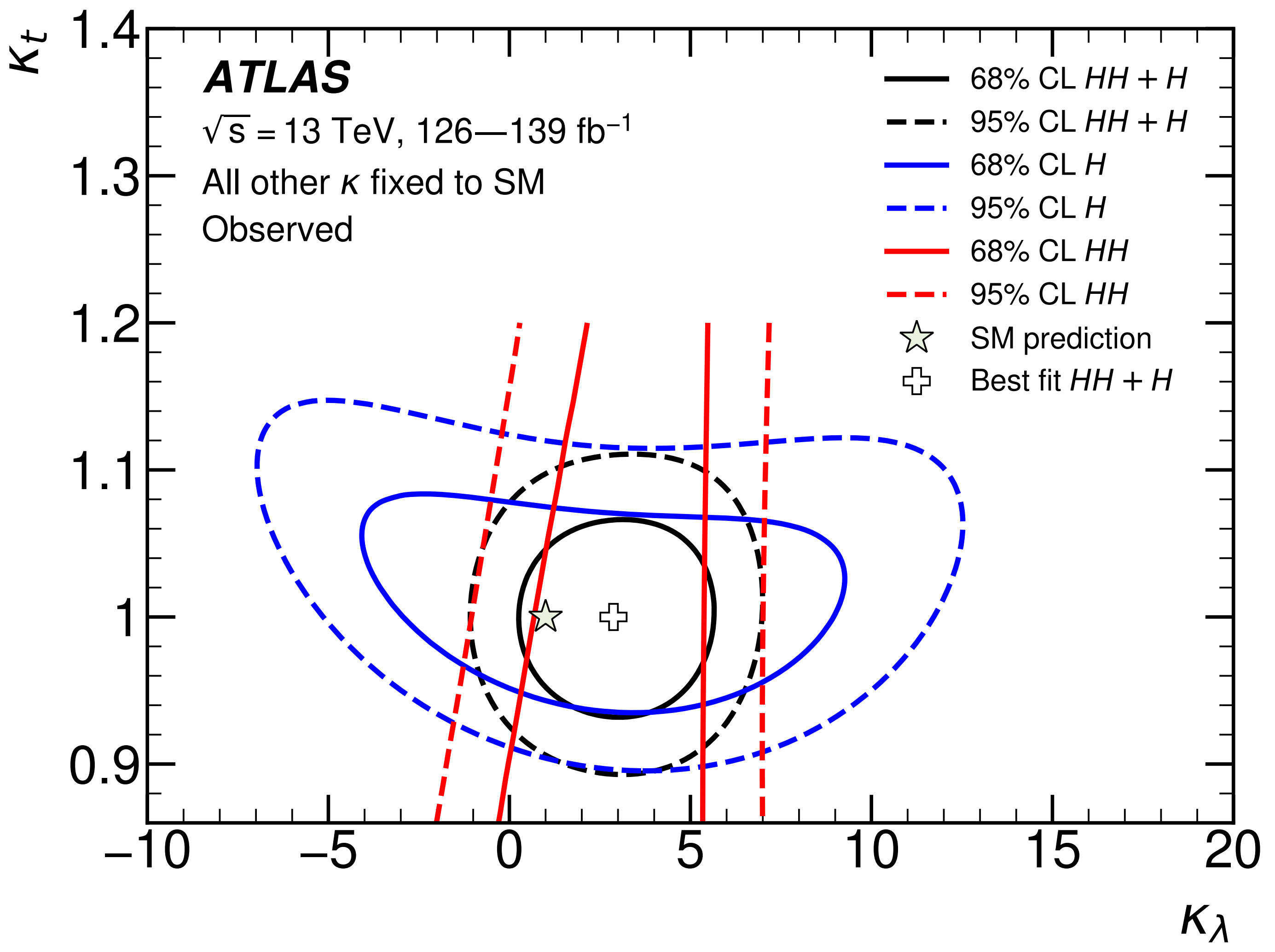


All the different signal strengths μ_i^f have a different dependence on a single parameter κ_λ, which can thus be constrained via a global fit.

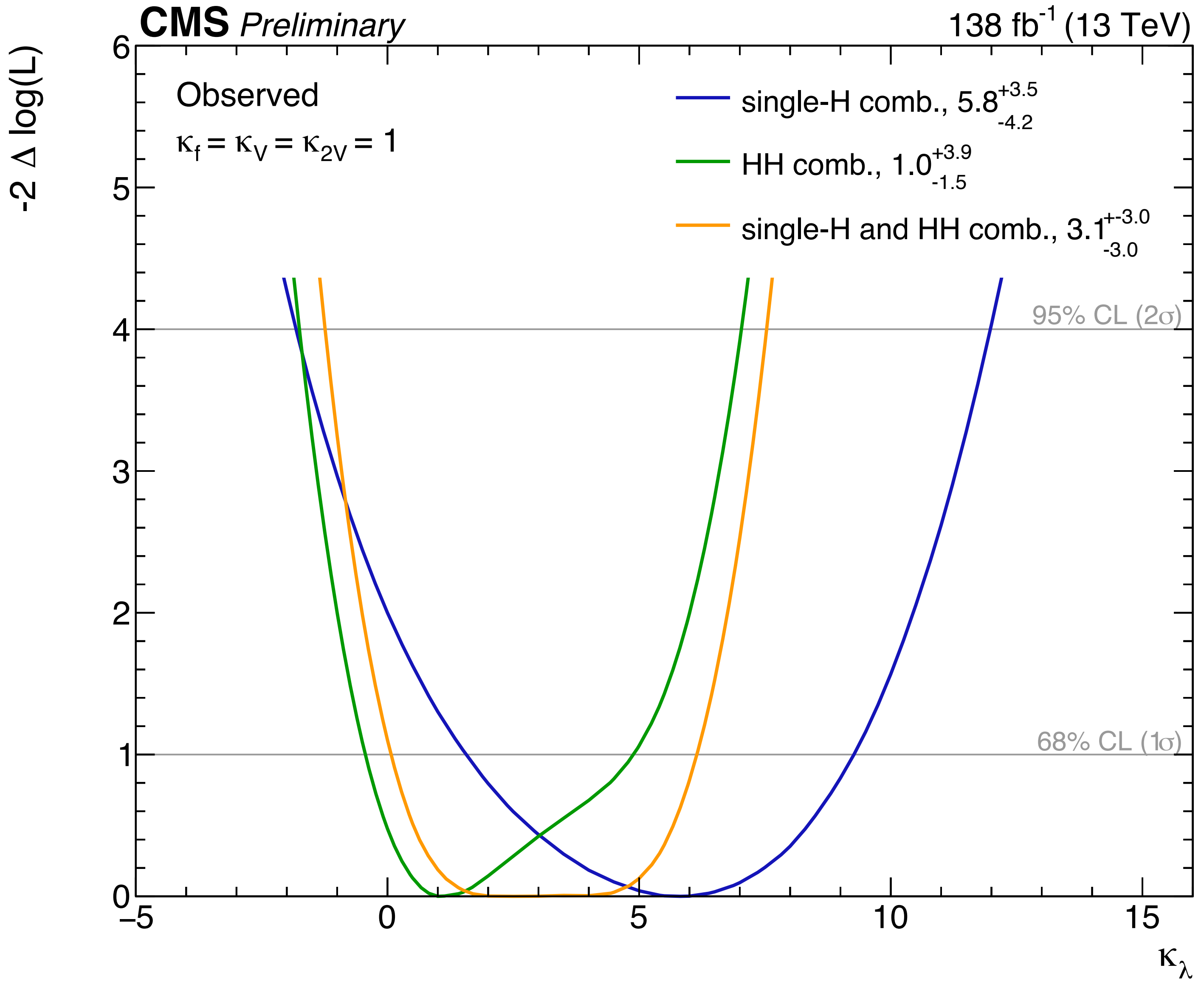


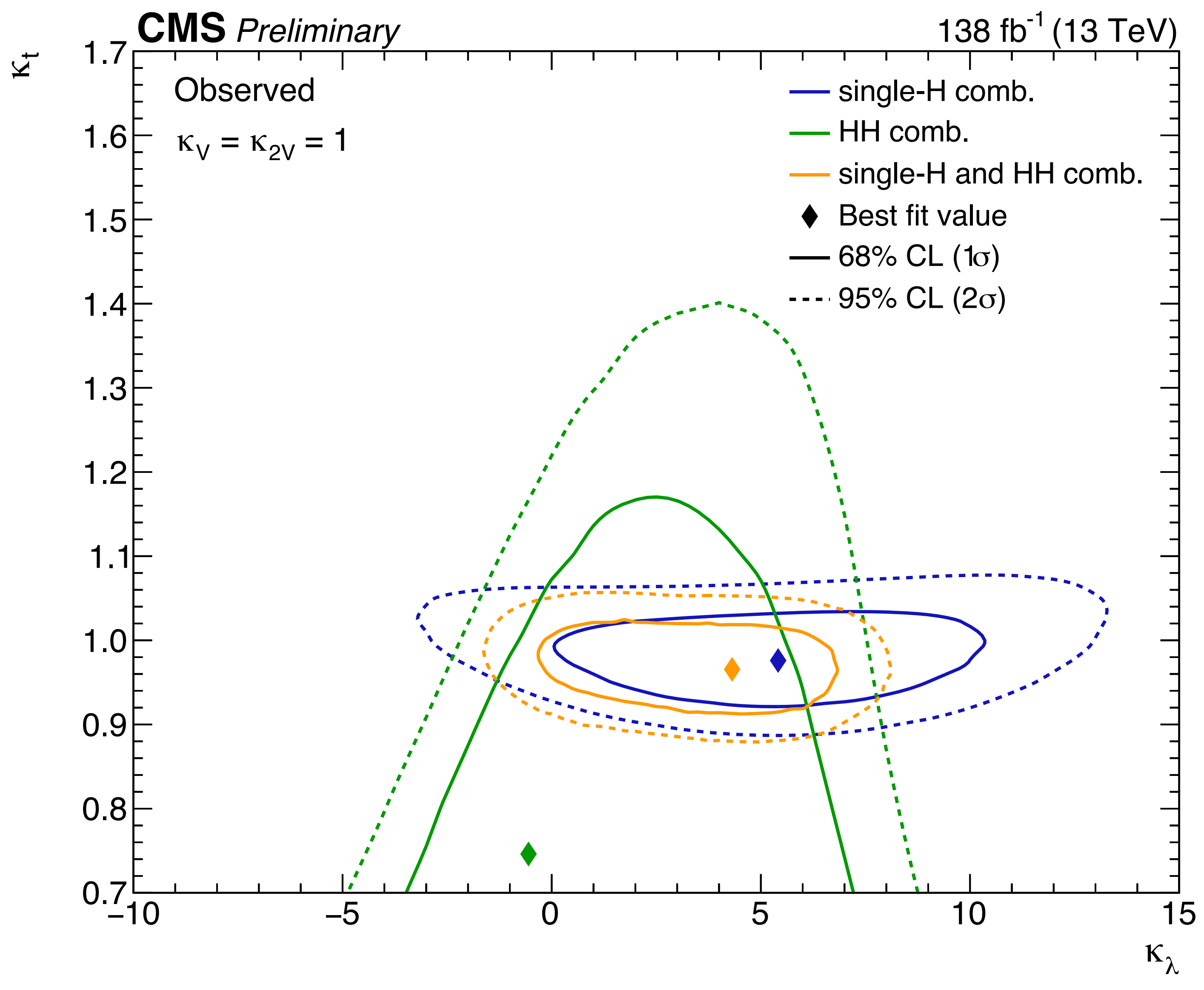
Higgs self-coupling constraint from H+HH combination





PLB 843 (2023) 137745



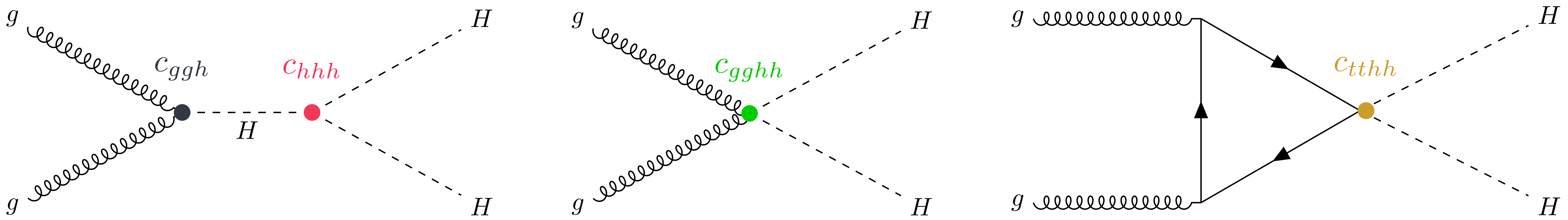


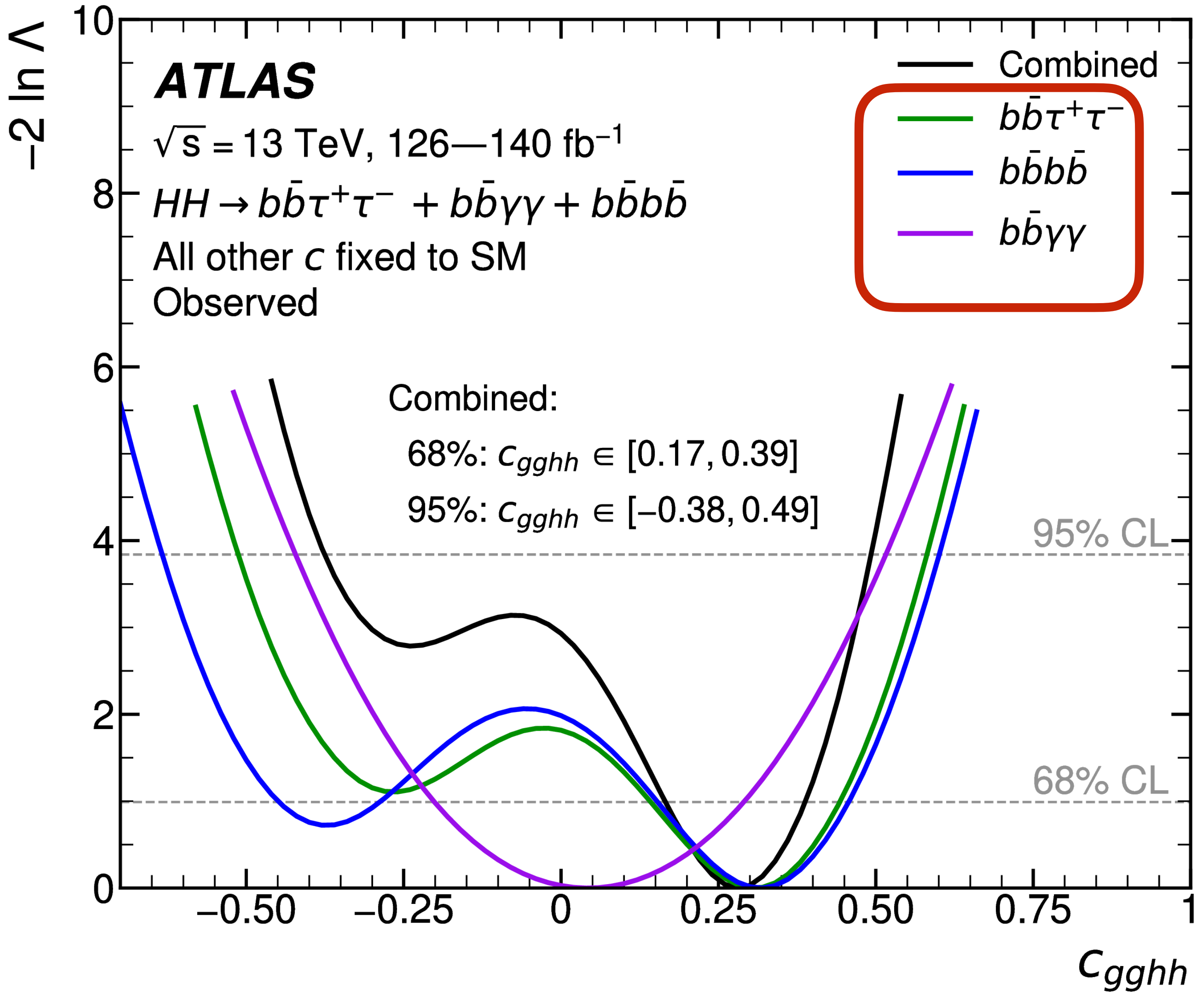
PAS HIG-23-006

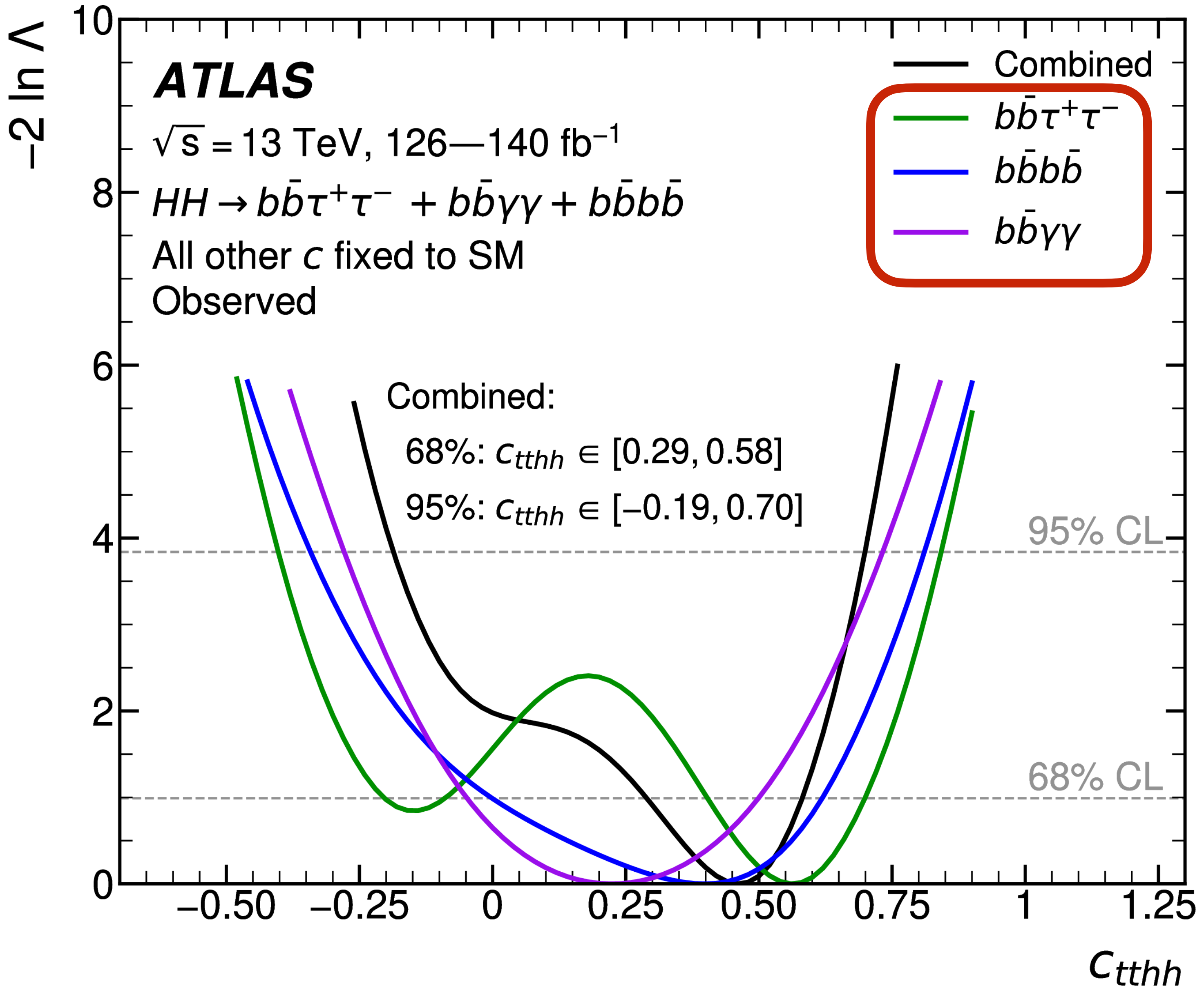
- **Complementarity** of the constraints on the Higgs Boson couplings
- Single Higgs STXS measurements brings a **~5-7% improvement** on κ_λ constraint
- **Lessen the assumptions** with simultaneous constraint of Higgs couplings to ferminons and vector bosons

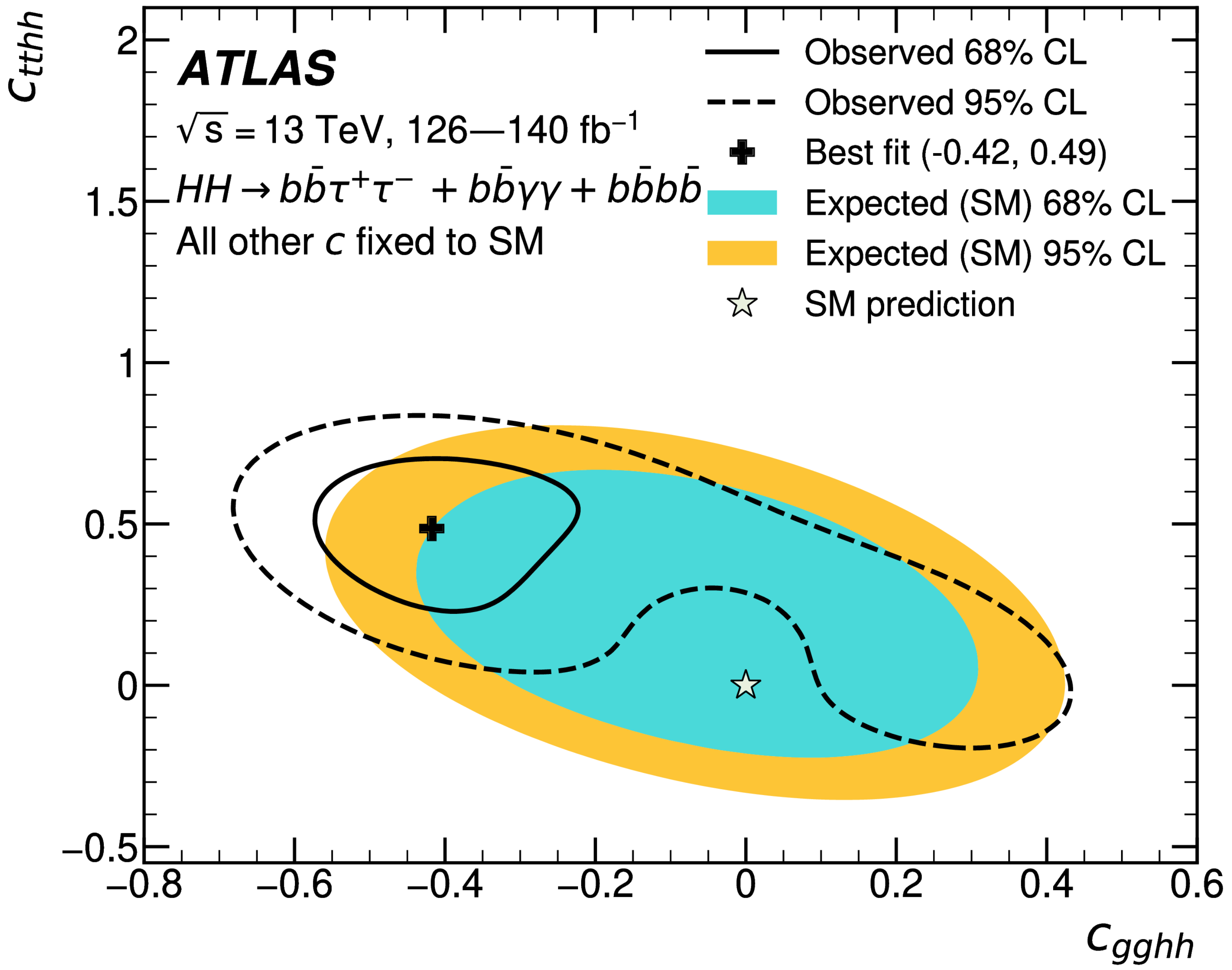
HH anomalous coupling with EFT interpretation

HEFT framework: anomalous single-Higgs and HH coupling separately









- ◈ The results are compatible with the SM predictions (p(C_{gghh})=0.087 and p(C_{tthh})=0.16)
- ◈ Due to insufficient sensitivity, strong correlations among C_{hhh}, C_{tthh} and C_{gghh}

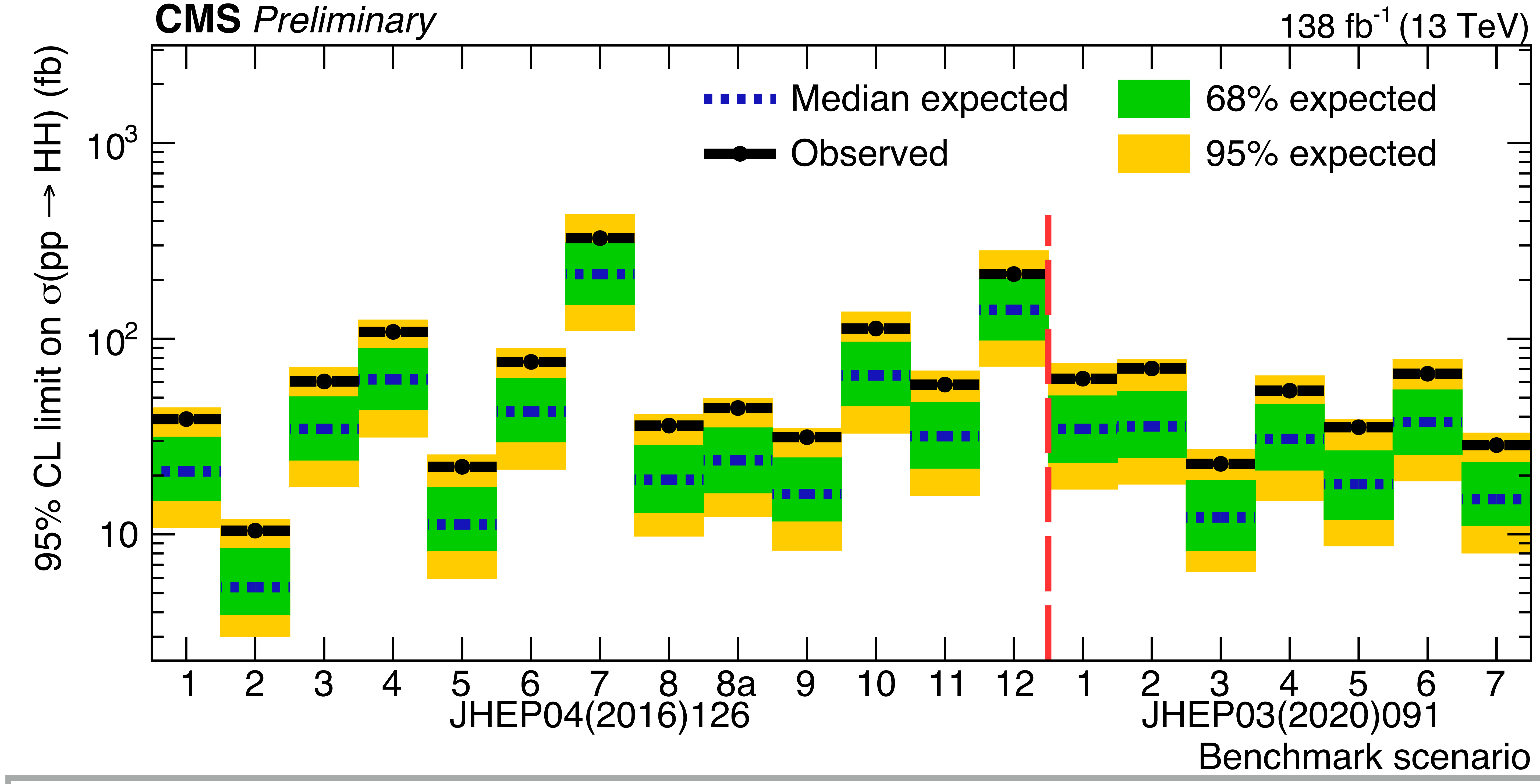
HH anomalous coupling with EFT interpretation

HEFT benchmark I

	1	2	3	4	5	6	7	8	9	10	11	12	8a
κ_λ	7.5	1.0	1.0	−3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0	1.0
κ_t	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0
c_2	−1.0	0.5	−1.5	−3.0	0.0	0.0	0.0	0.0	1.0	−1.0	0.0	1.0	0.5
c_g	0.0	−0.8	0.0	0.0	0.8	0.2	0.2	−1.0	−0.6	0.0	1.0	0.0	$\frac{0.8}{3}$
c_{2g}	0.0	0.6	−0.8	0.0	−1.0	−0.2	−0.2	1.0	0.6	0.0	−1.0	0.0	0.0

HEFT benchmark 2

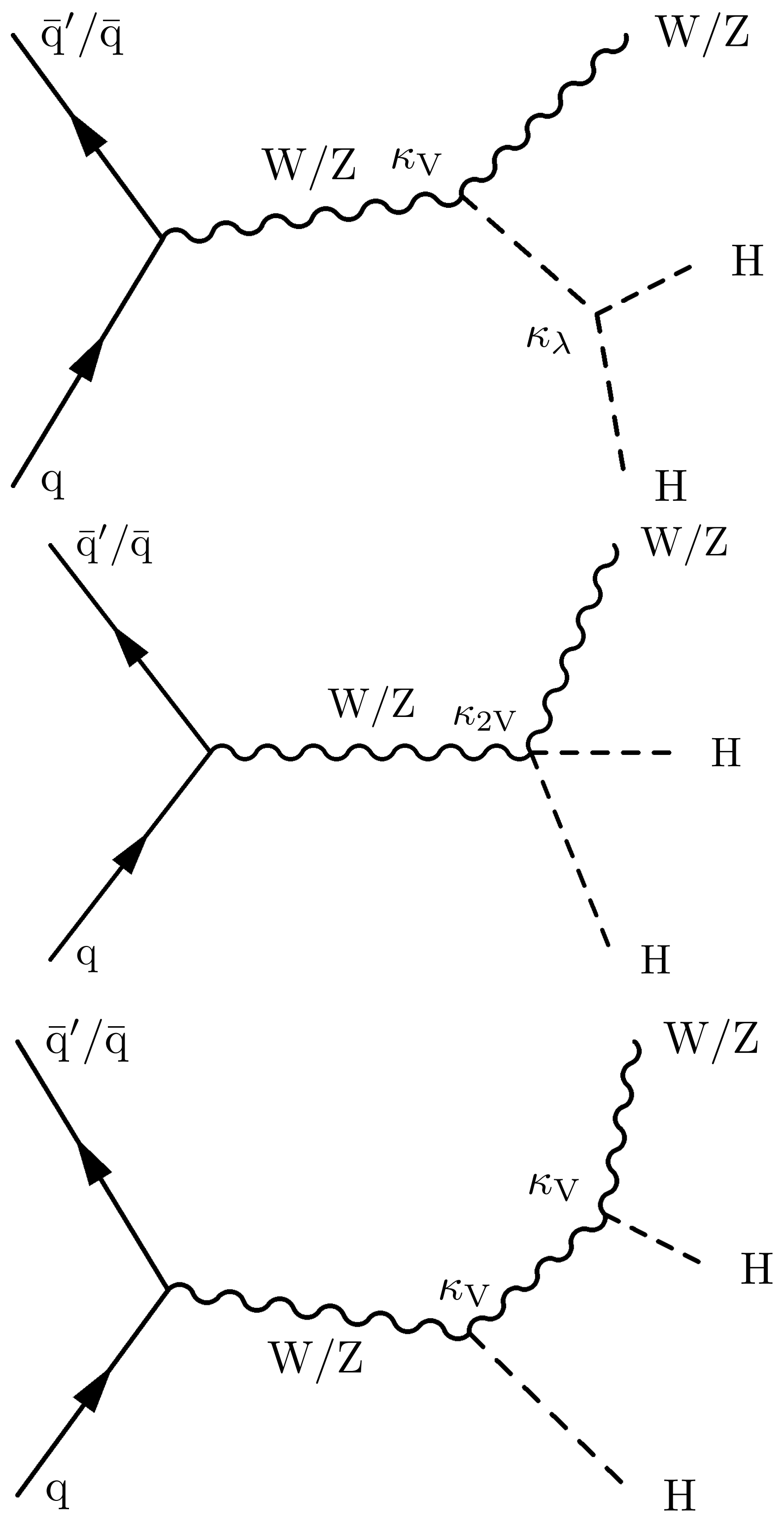
	1	2	3	4	5	6	7
κ_λ	3.94	6.84	2.21	2.79	3.95	5.68	−0.10
κ_t	0.94	0.61	1.05	0.61	1.17	0.83	0.94
c_2	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	1.0
c_g	0.5×1.5	0.0	0.5×1.5	-0.5×1.5	$\frac{1}{6} \times 1.5$	-0.5×1.5	$\frac{1}{6} \times 1.5$
c_{2g}	$\frac{1}{3} \times -3$	$-\frac{1}{3} \times -3$	0.5×-3	$\frac{1}{6} \times -3$	-0.5×-3	$\frac{1}{3} \times -3$	$-\frac{1}{3} \times -3$



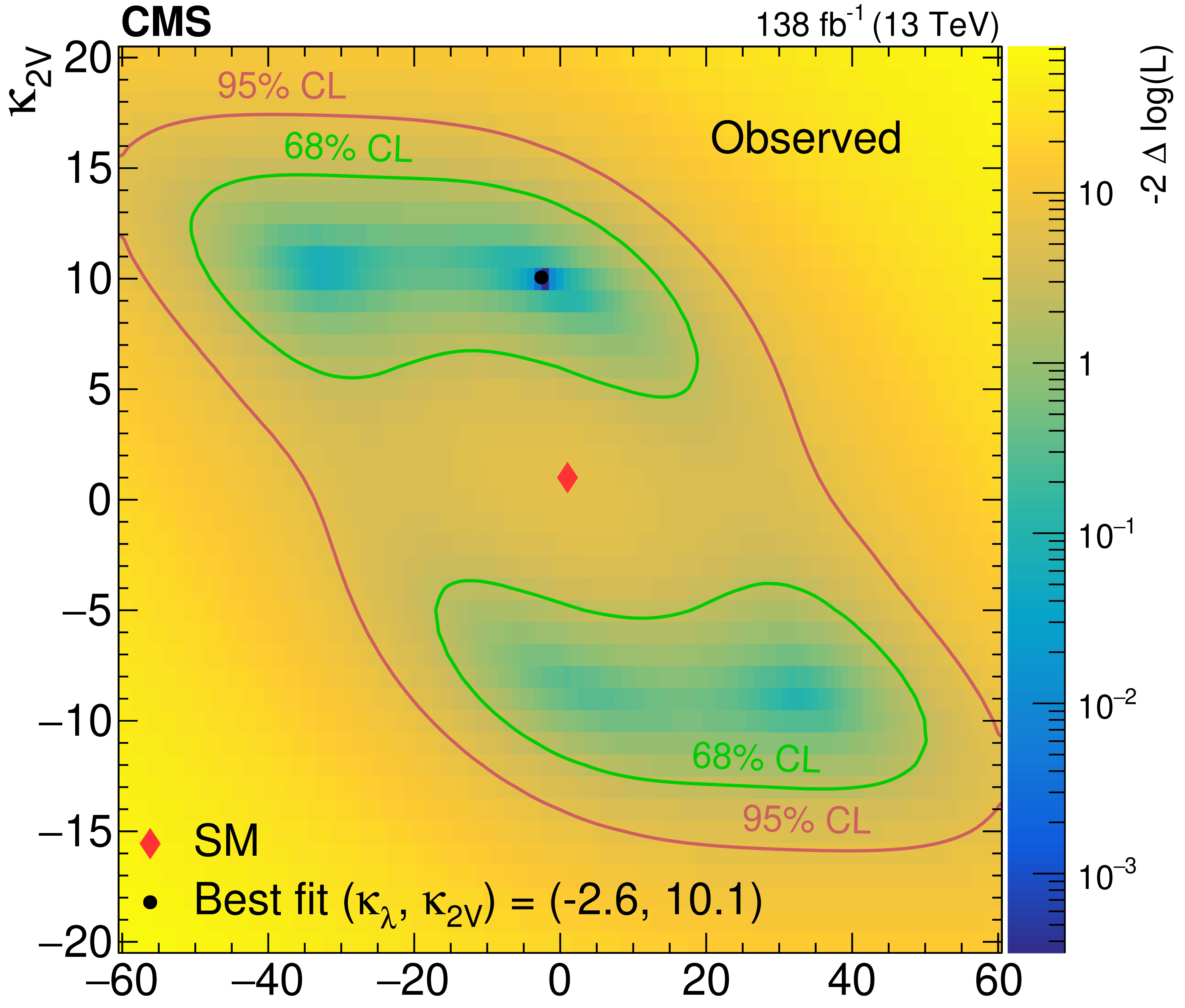
- No significant deviations from expectations
- overall excess in all benchmarks between 1σ and 2σ

VHH production with $HH \to bbbb$

In SM, $\sigma_{VHH} = 0.865$ fb

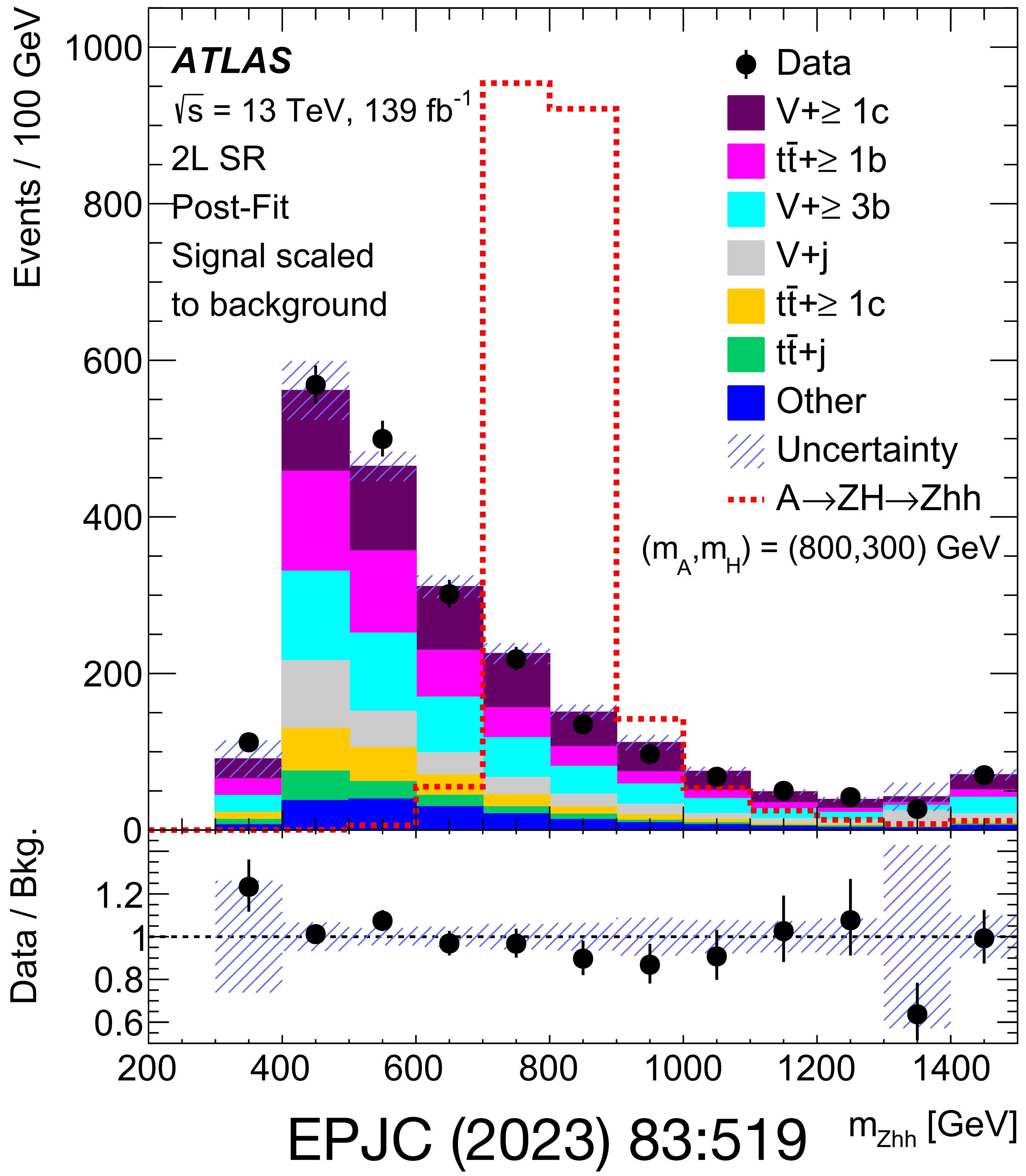


V hadronic and leptonic decays



JHEP10(2024)061

V leptonic decays



EPJC (2023) 83:519

Obs. (exp) VHH: 294× SM (124× SM)

κ_3: [-37.3, 37.2] ([-30.1, 28.9])

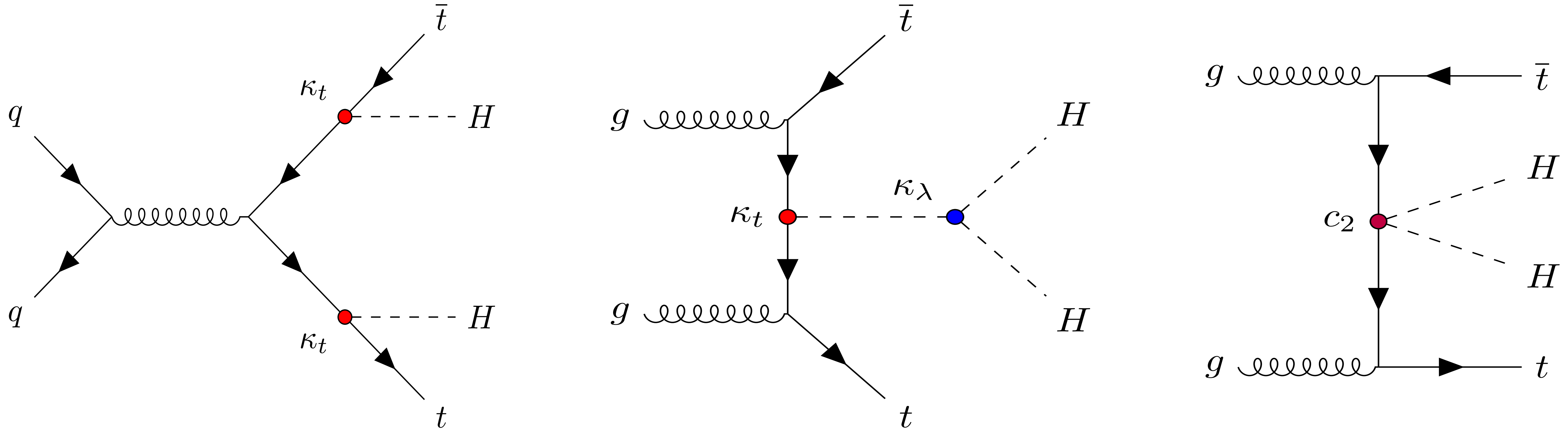
κ_{2V}: [-12.2, 13.5] ([-7.2, 8.9])

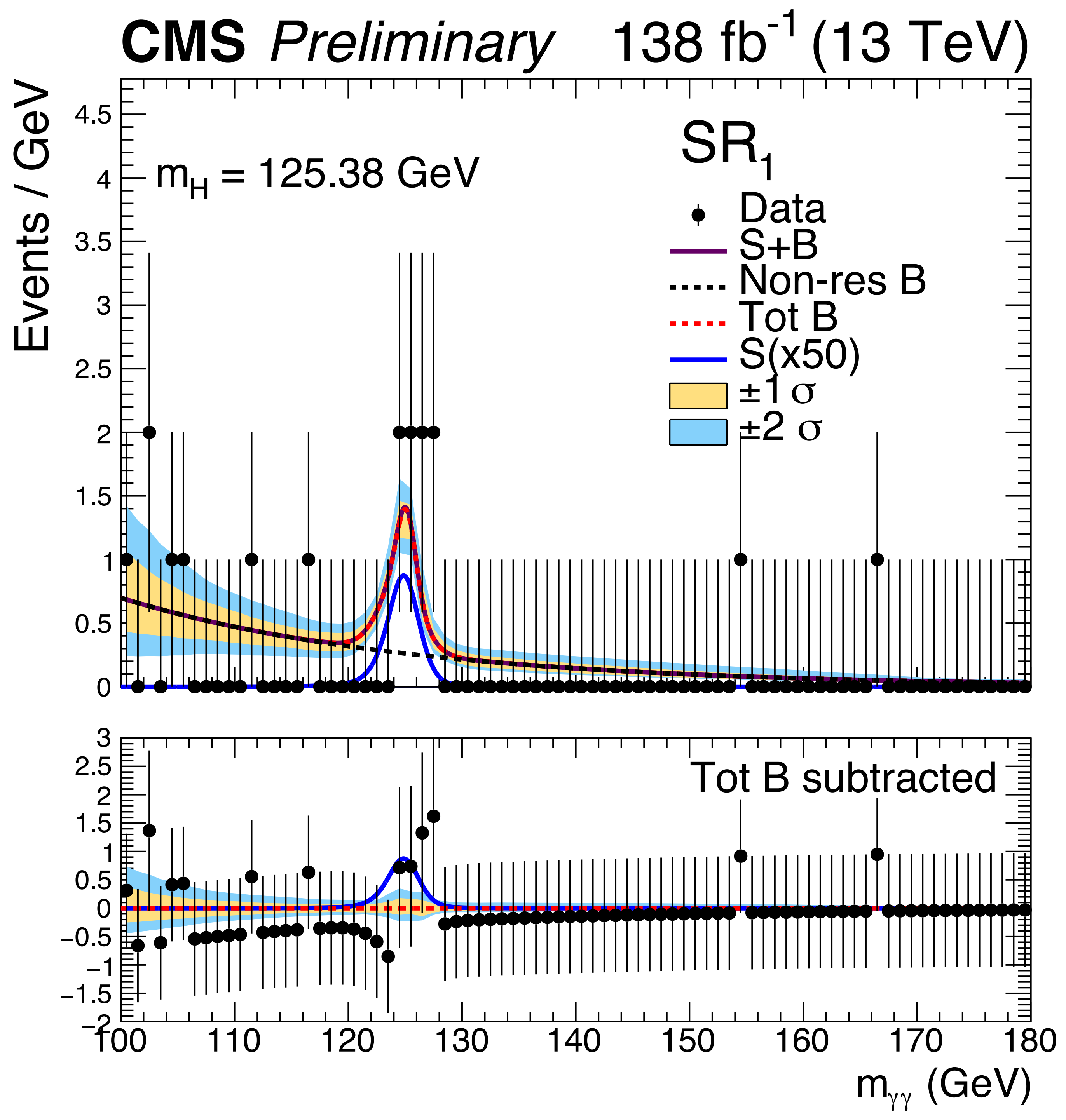
Obs. (exp) VHH: 183× SM (87× SM)

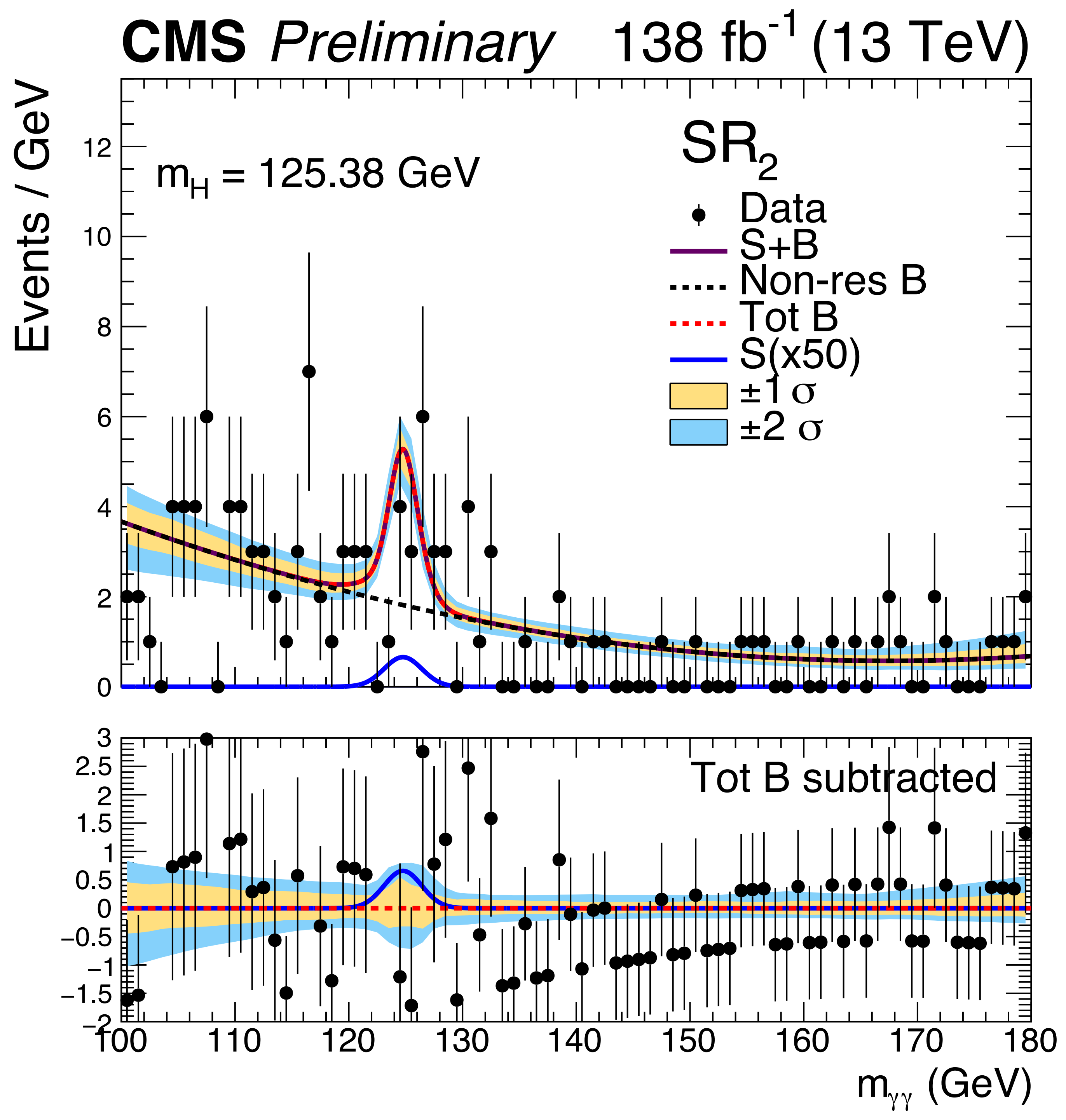
κ_3: [-34.4, 33.3] ([-24.1, 22.9])

κ_{2V}: [-8.6, 10.0] ([-5.7, 7.1])

ttHH production with $HH \to \gamma\gamma + b\bar{b}/WW/\tau\tau$





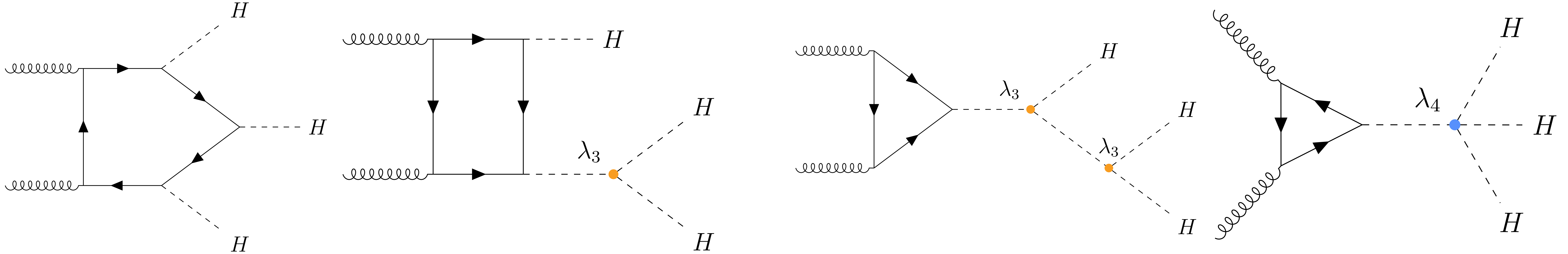


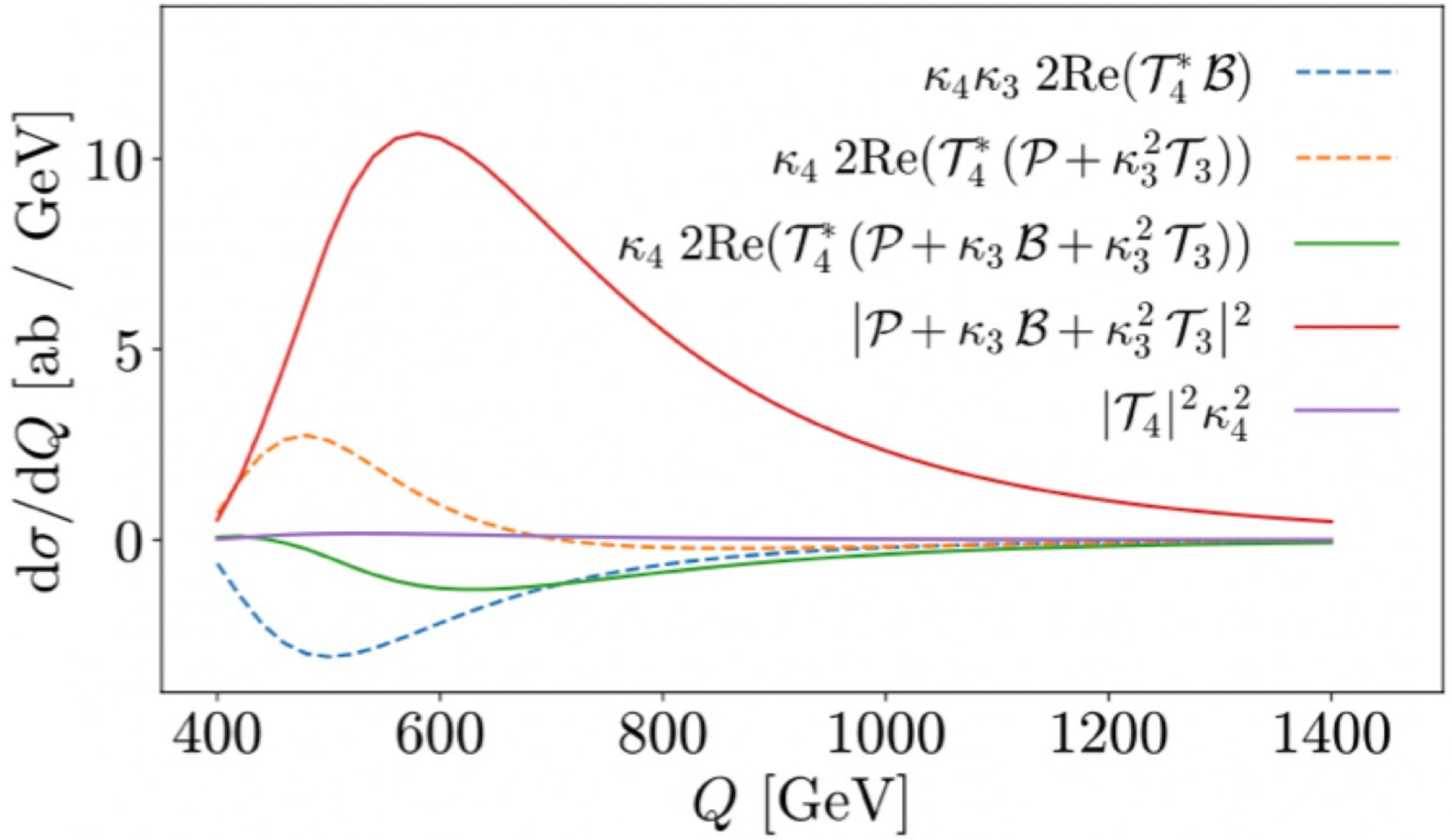
PAS-HIG-23-004

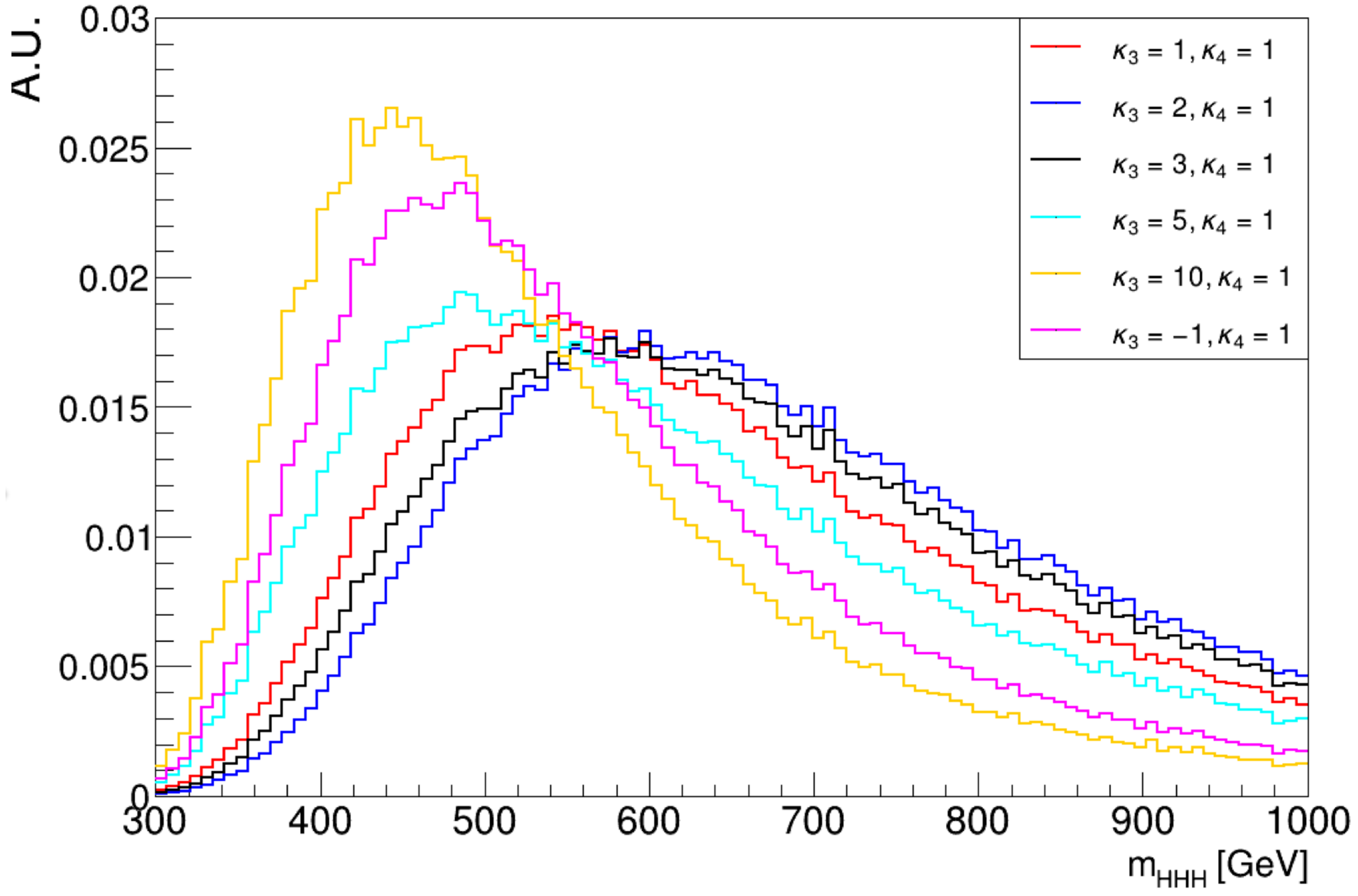
- σ_{ttHH} in the SM **0.775fb** @13TeV
- Obs. (exp) ttHH: **2.9× SM (2.4× SM)**

HHH production

HHH (0.079fb): directly probe quartic coupling κ_4 and complementary to trilinear coupling κ_3



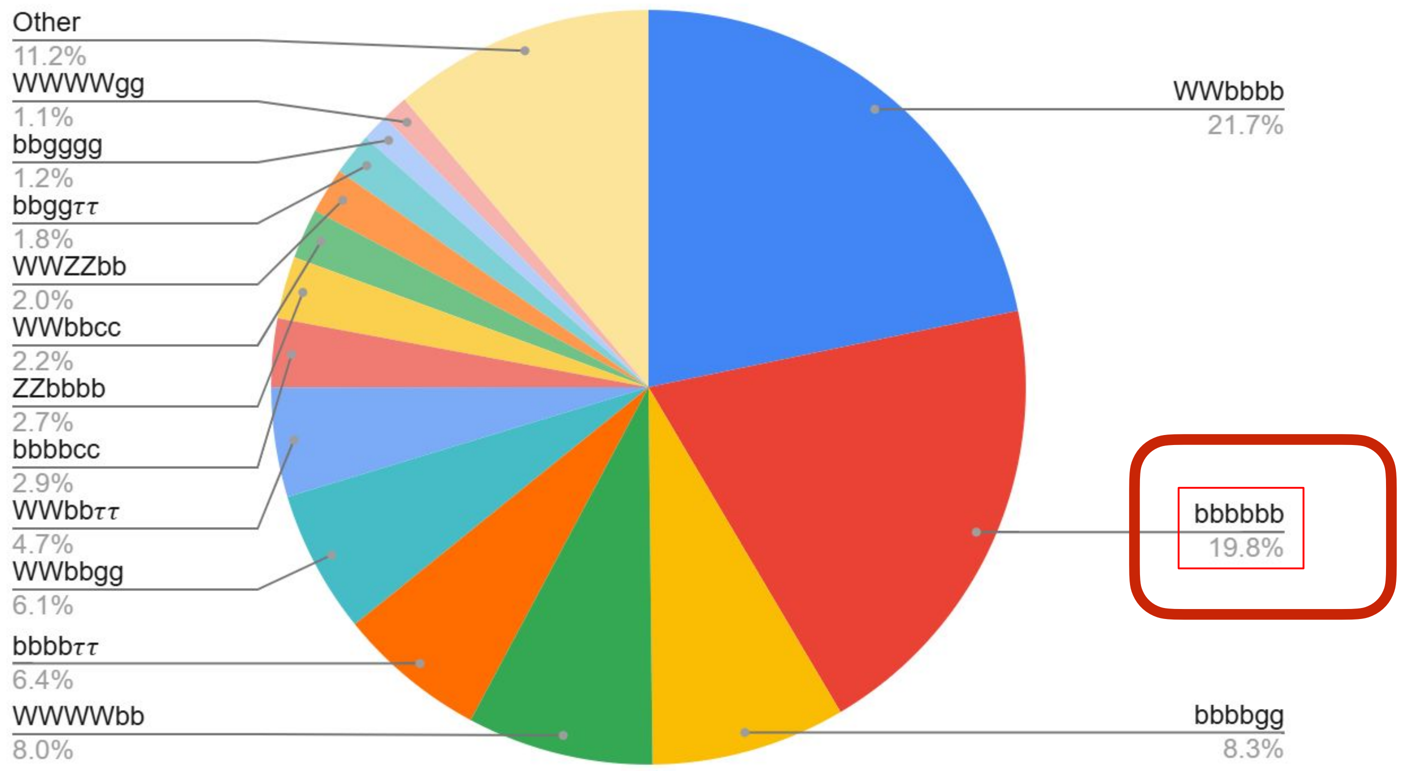


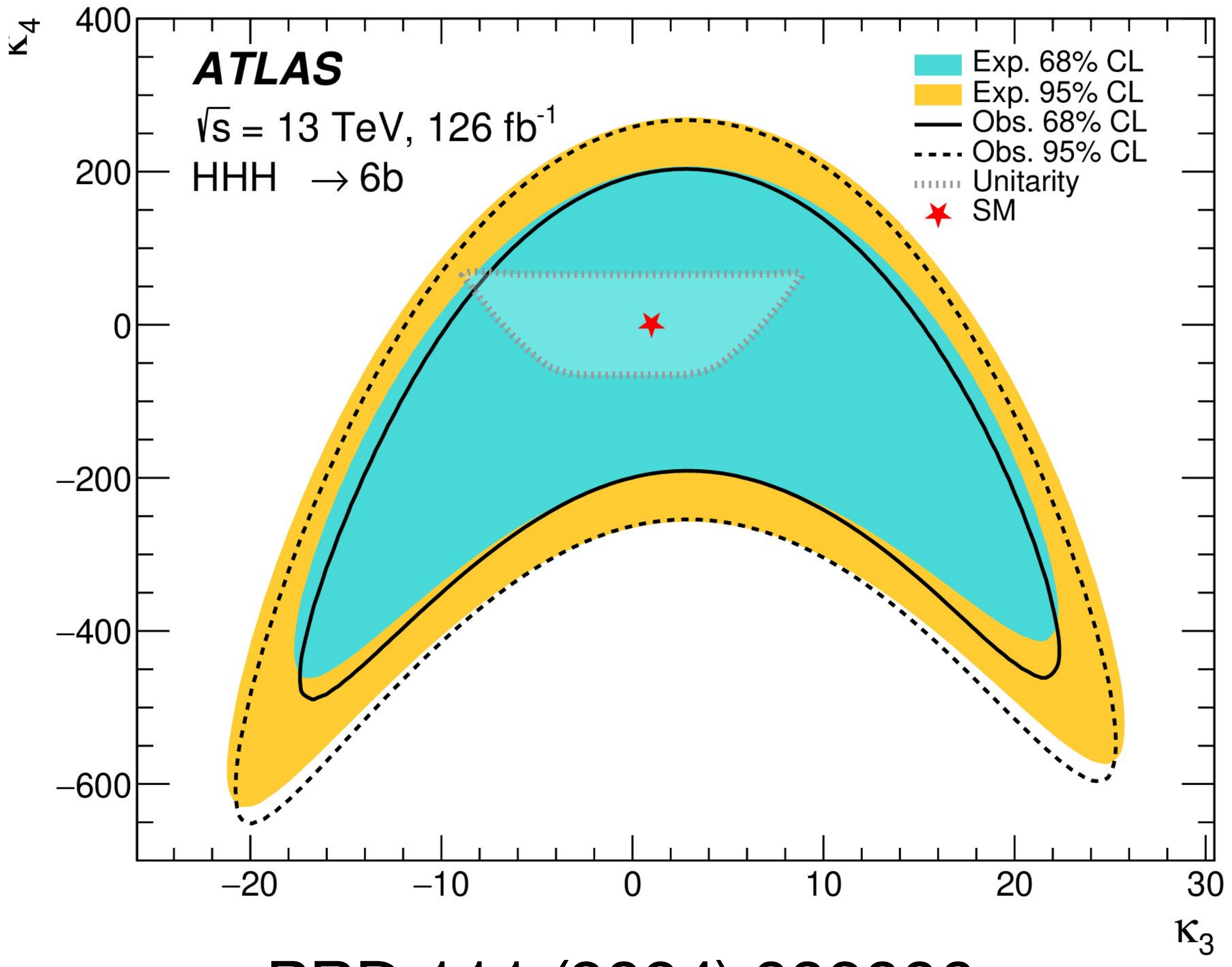


Various interference terms between κ_3 and κ_4

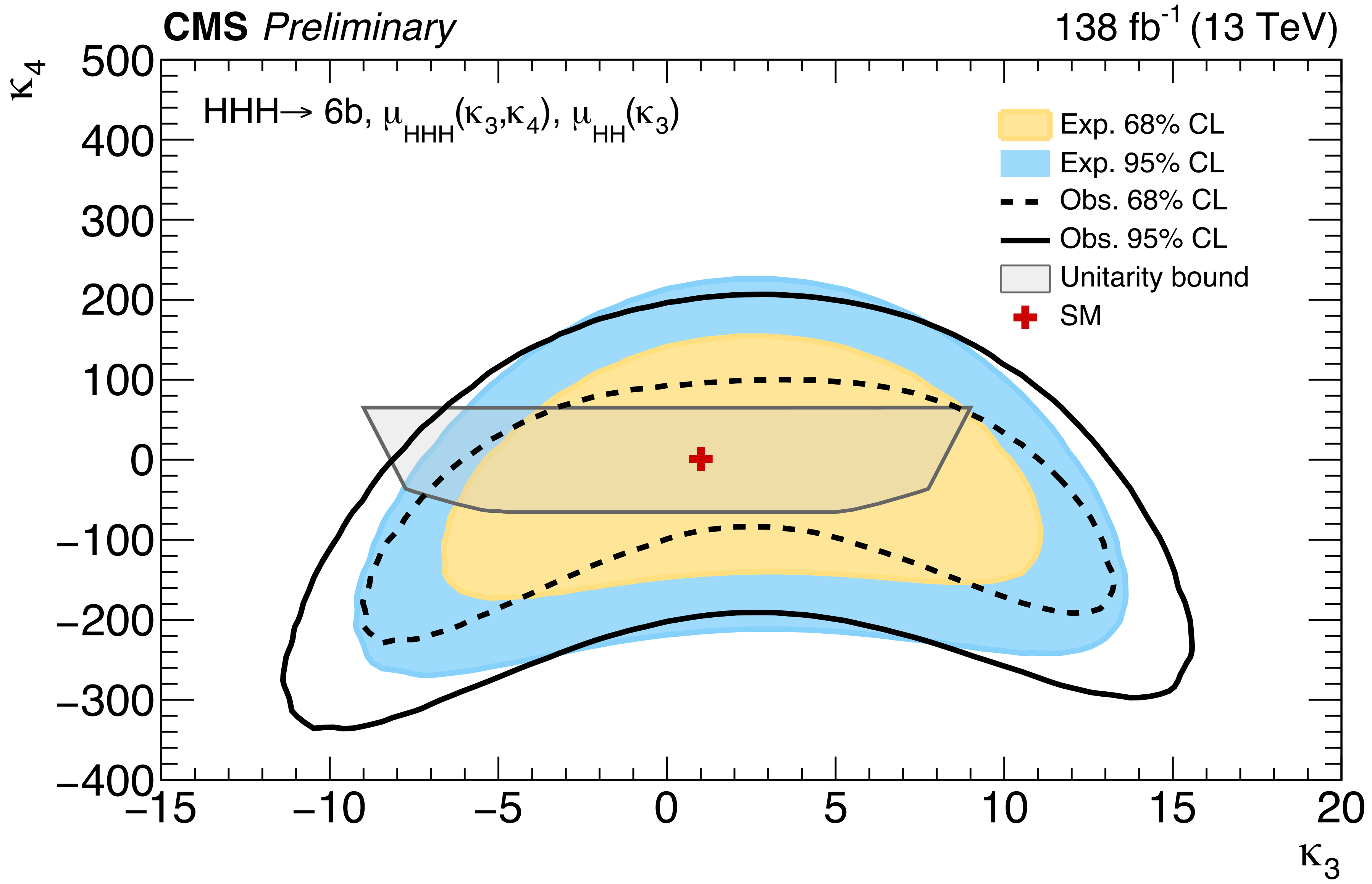
M_{HHH} distribution variations on κ_3 and κ_4

HHH → $6b$





PRD 111 (2024) 032006



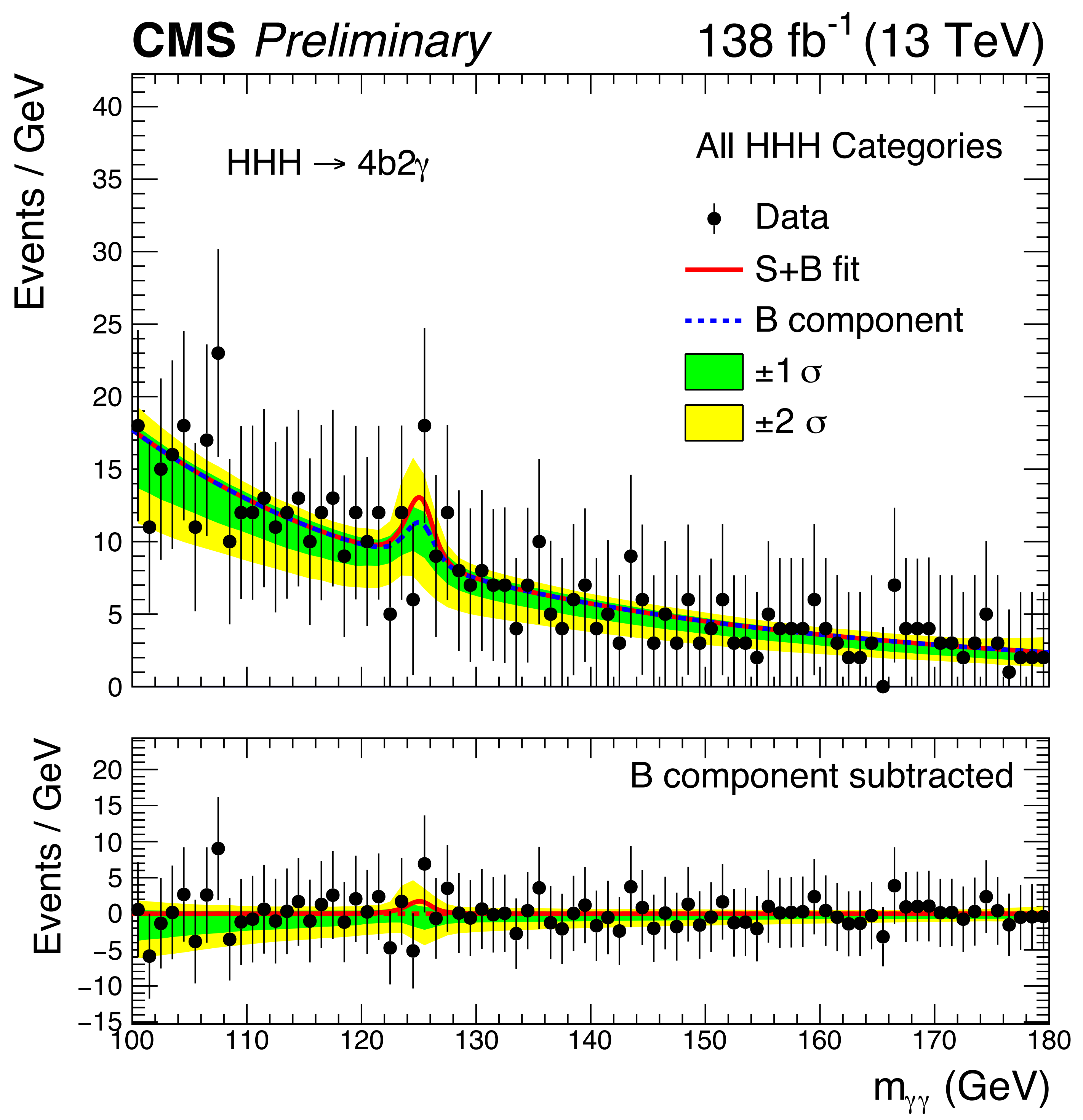
PAS-HIG-24-012

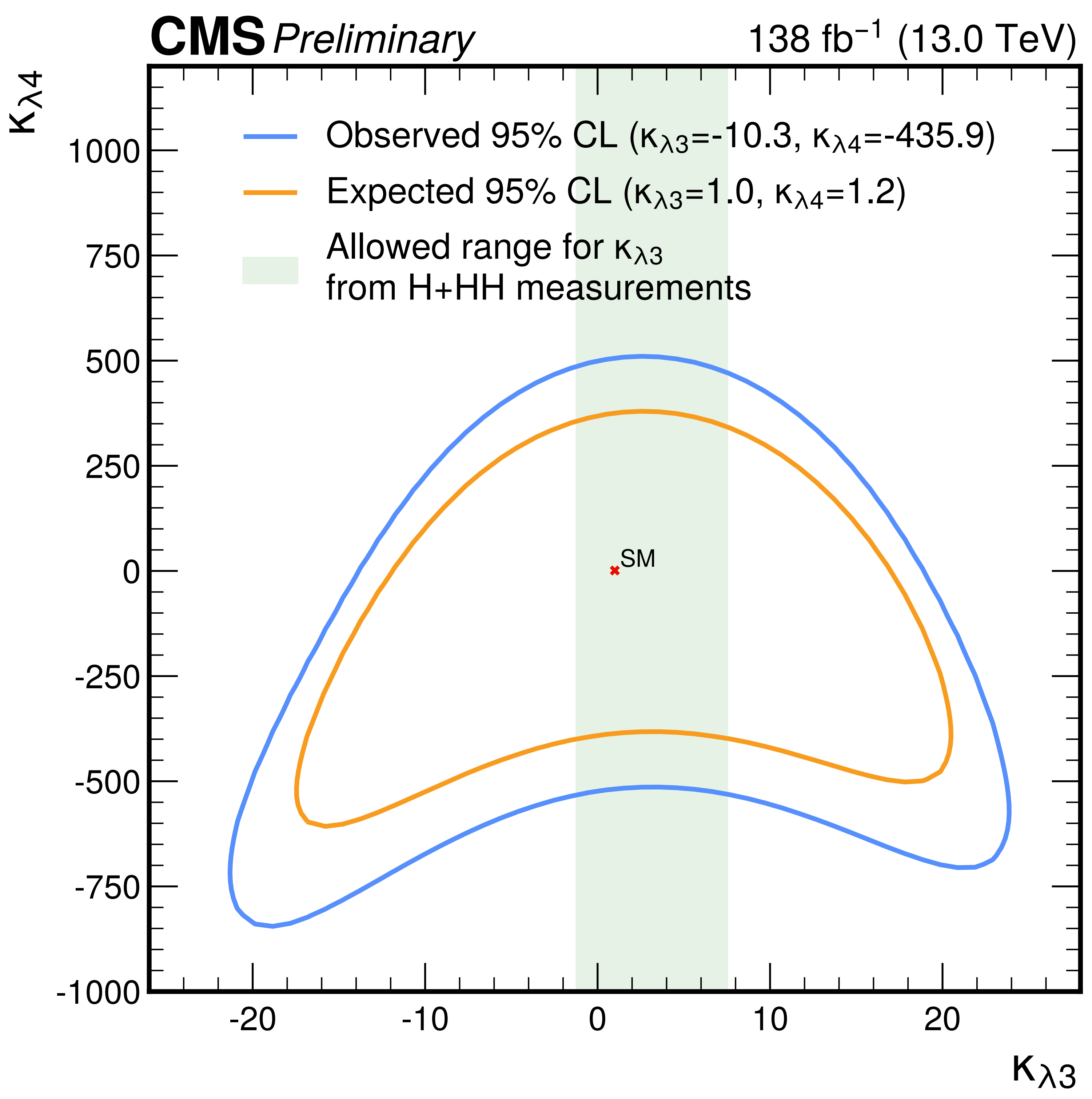
Obs. (exp) HHH: 760× SM (750× SM)
κ_3: **[-11, 17] ([-11, 17])**
κ_4: **[-230, 240] ([-230, 240])**

Obs. (exp) HHH: 588× SM (572× SM)
κ_3: **[-7, 12] ([-6, 11])**
κ_4: **[-190, 190] ([-190, 190])**

Constraints that exclude regions of phase space by perturbative unitarity bound

HHH → $4b2\gamma$



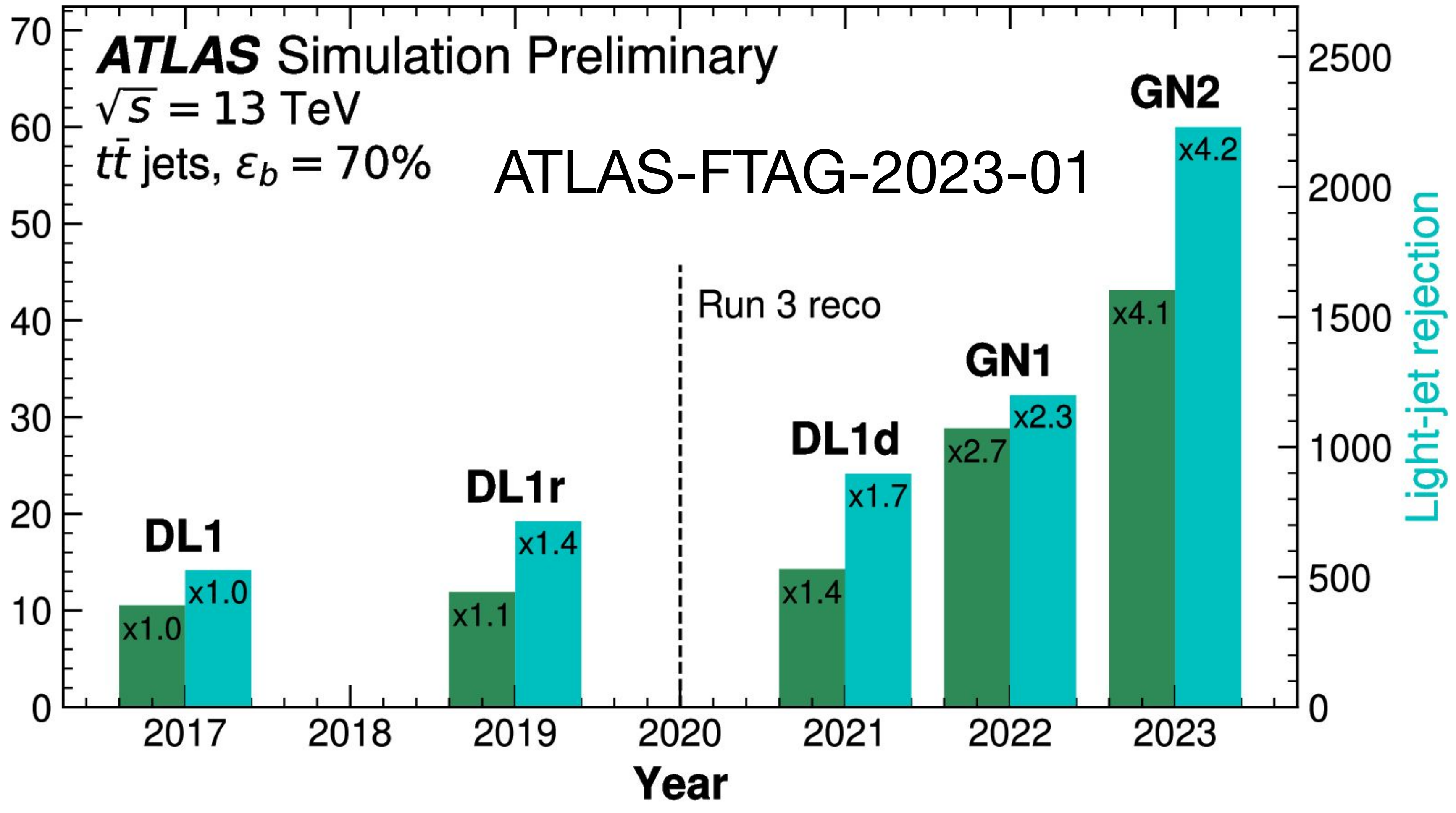


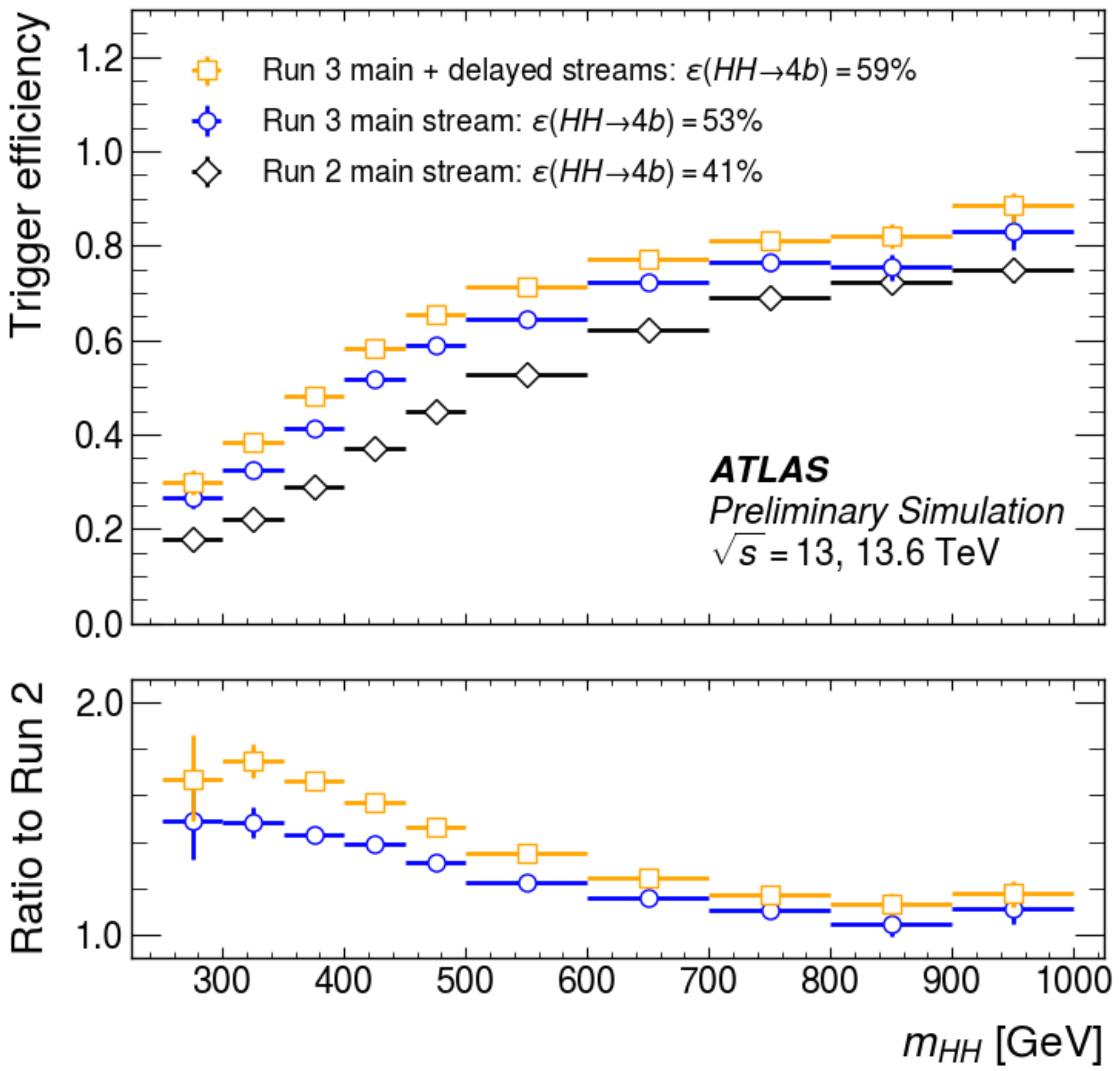
Obs. (exp) HHH: 3400× SM (2086× SM)

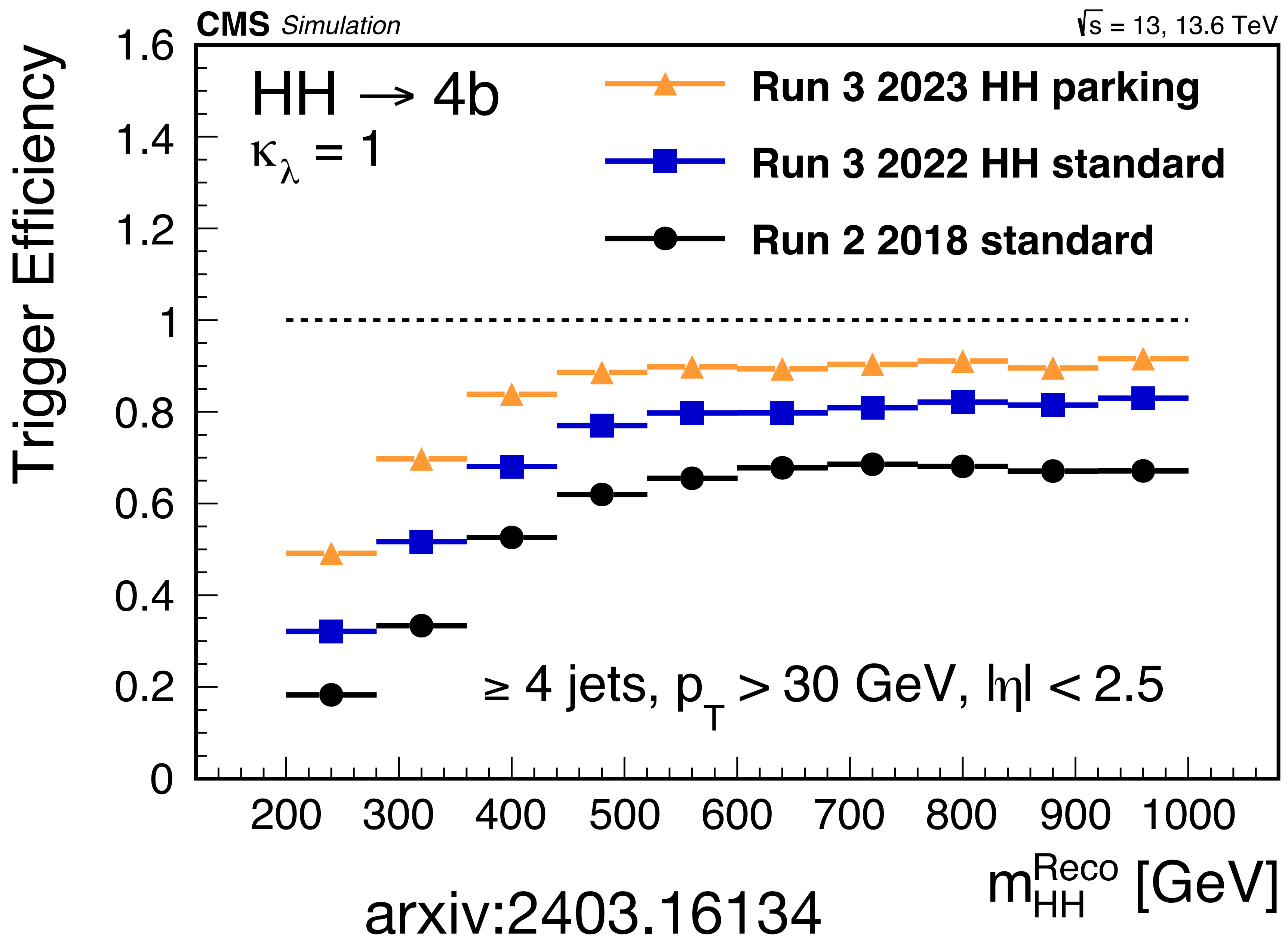
κ_3: [-16.1, 20.2] ([-13.8, 18])

κ_4: [-533, 541] ([-397, 406])

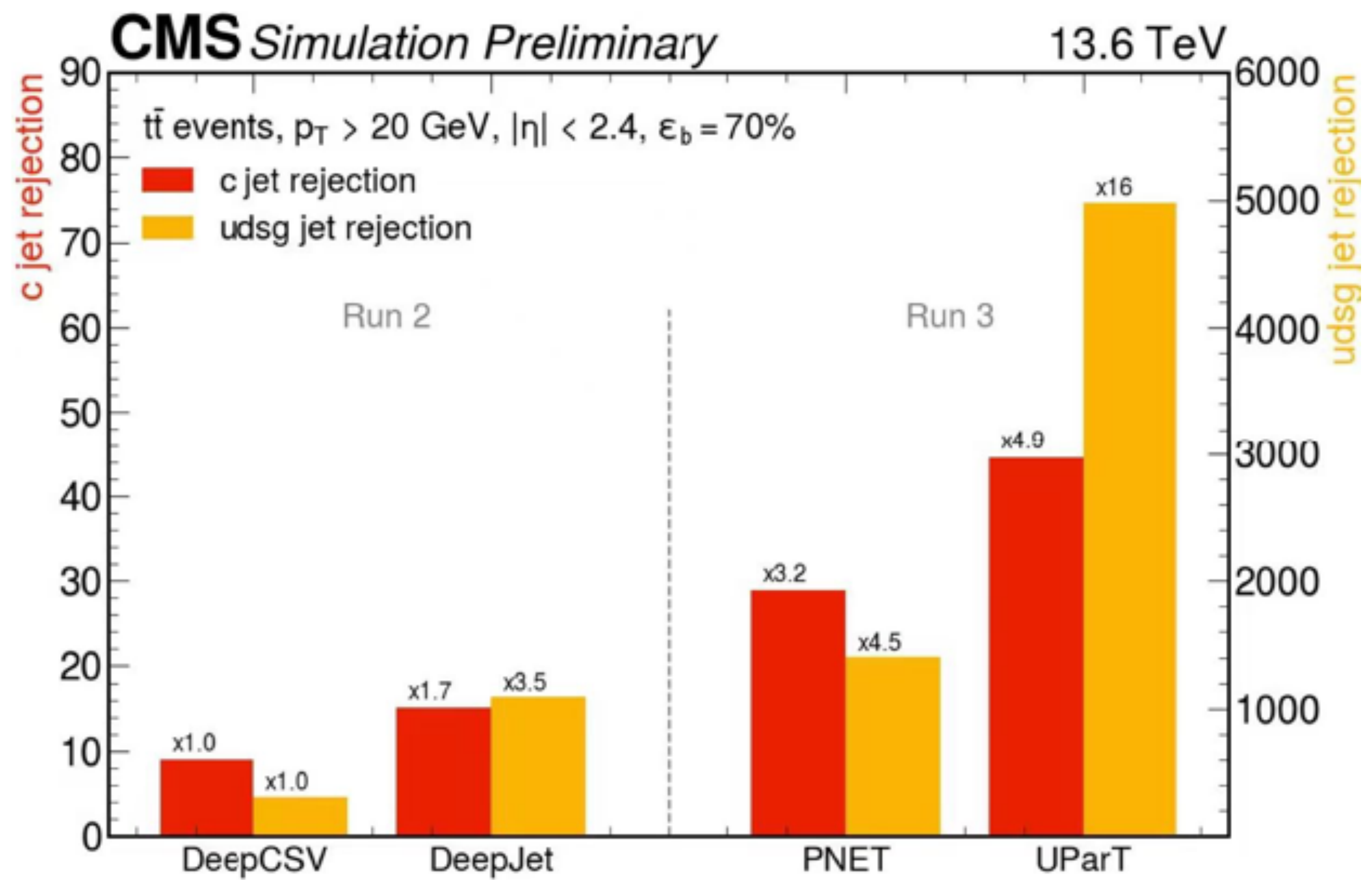
How Higgs Pair Production in Run3?





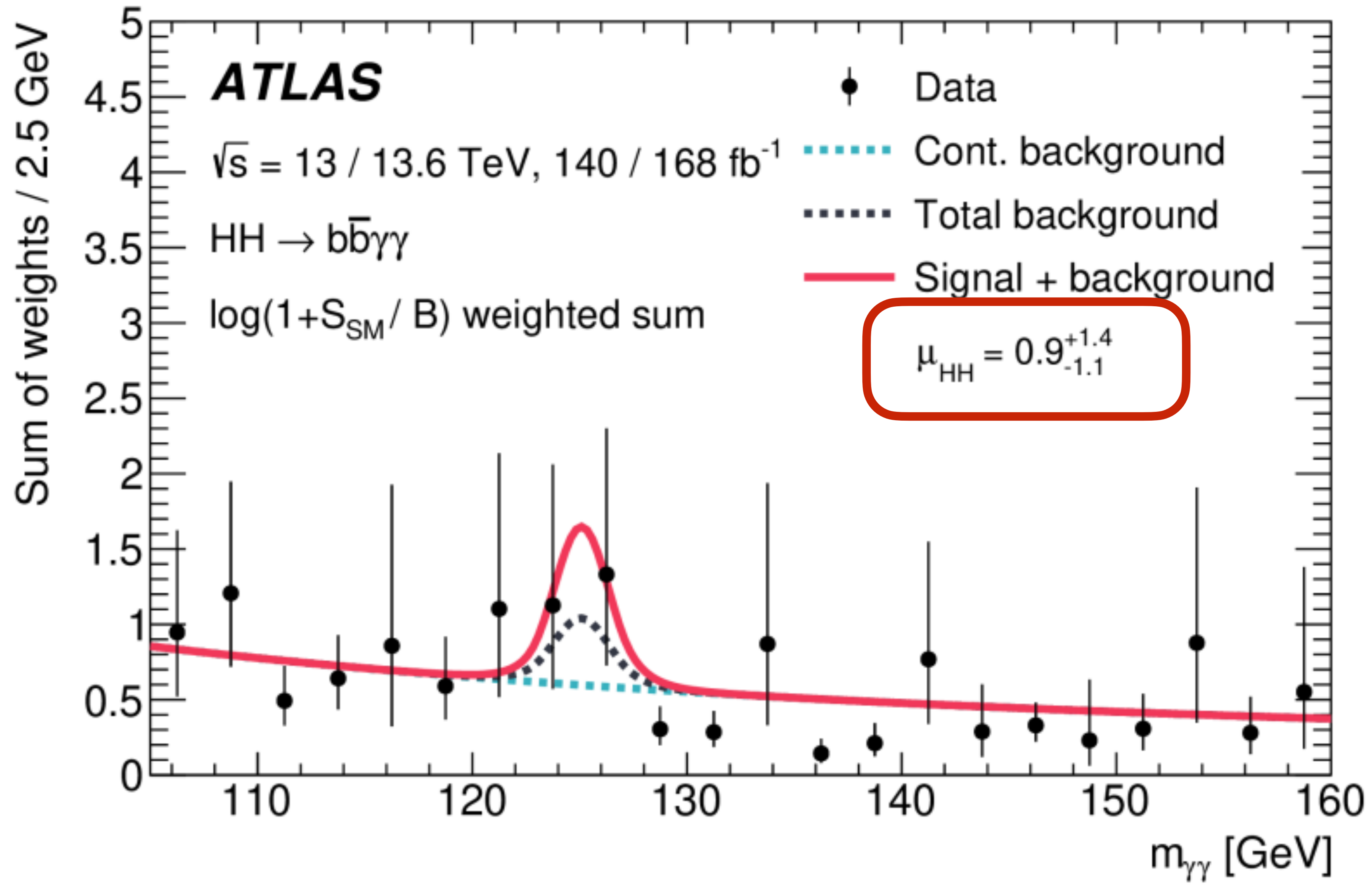


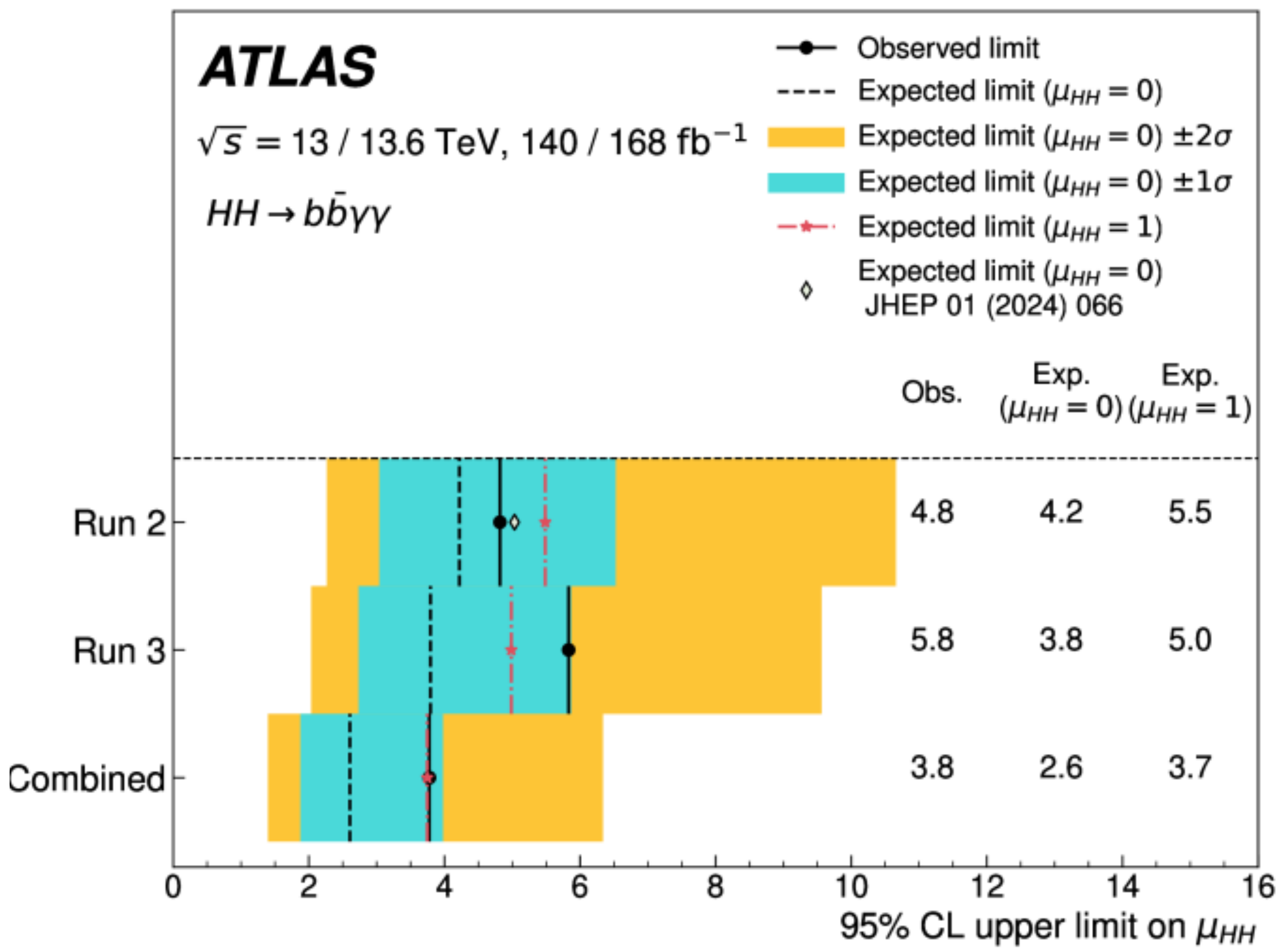
arxiv:2403.16134



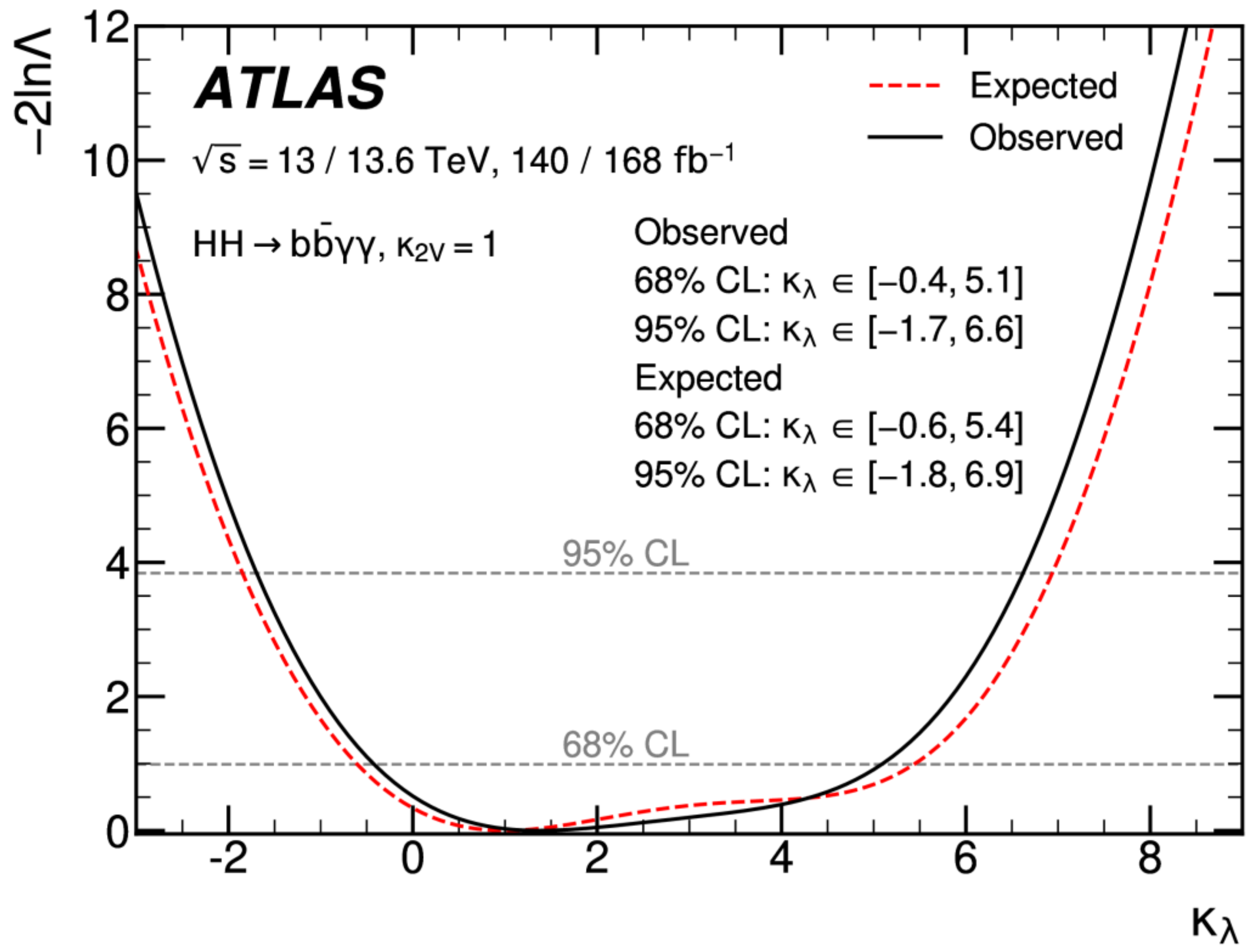
- ◈ Signal XS improvement (~1.7) and more data (~2)
- ◈ Improved object reconstruction and identification
- ◈ Higher trigger efficiency
- ◈ More Advanced ML

Run2 + Partial Run3 $HH \rightarrow bb\gamma\gamma$ @ ATLAS





arxiv:2507.03495

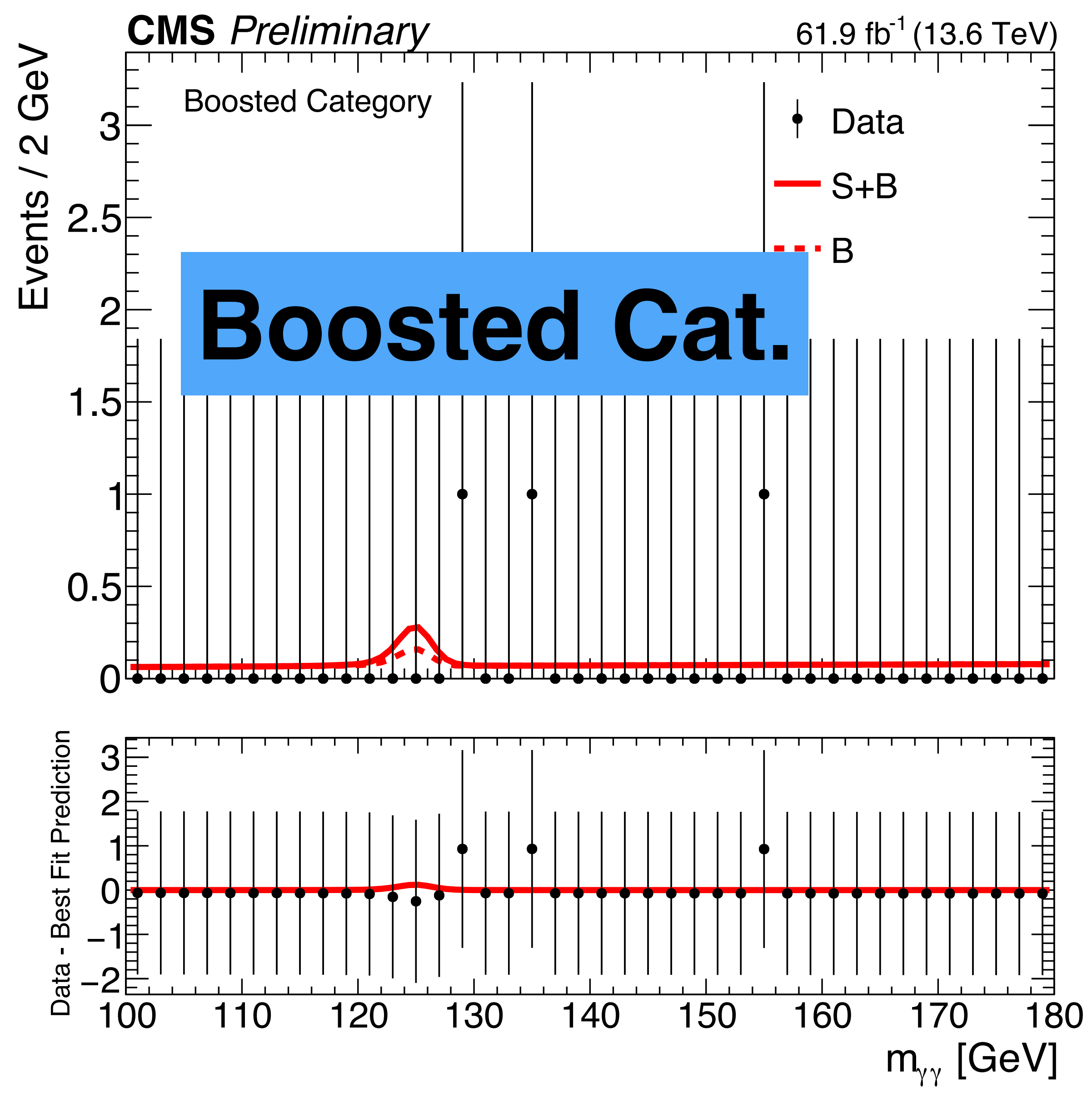


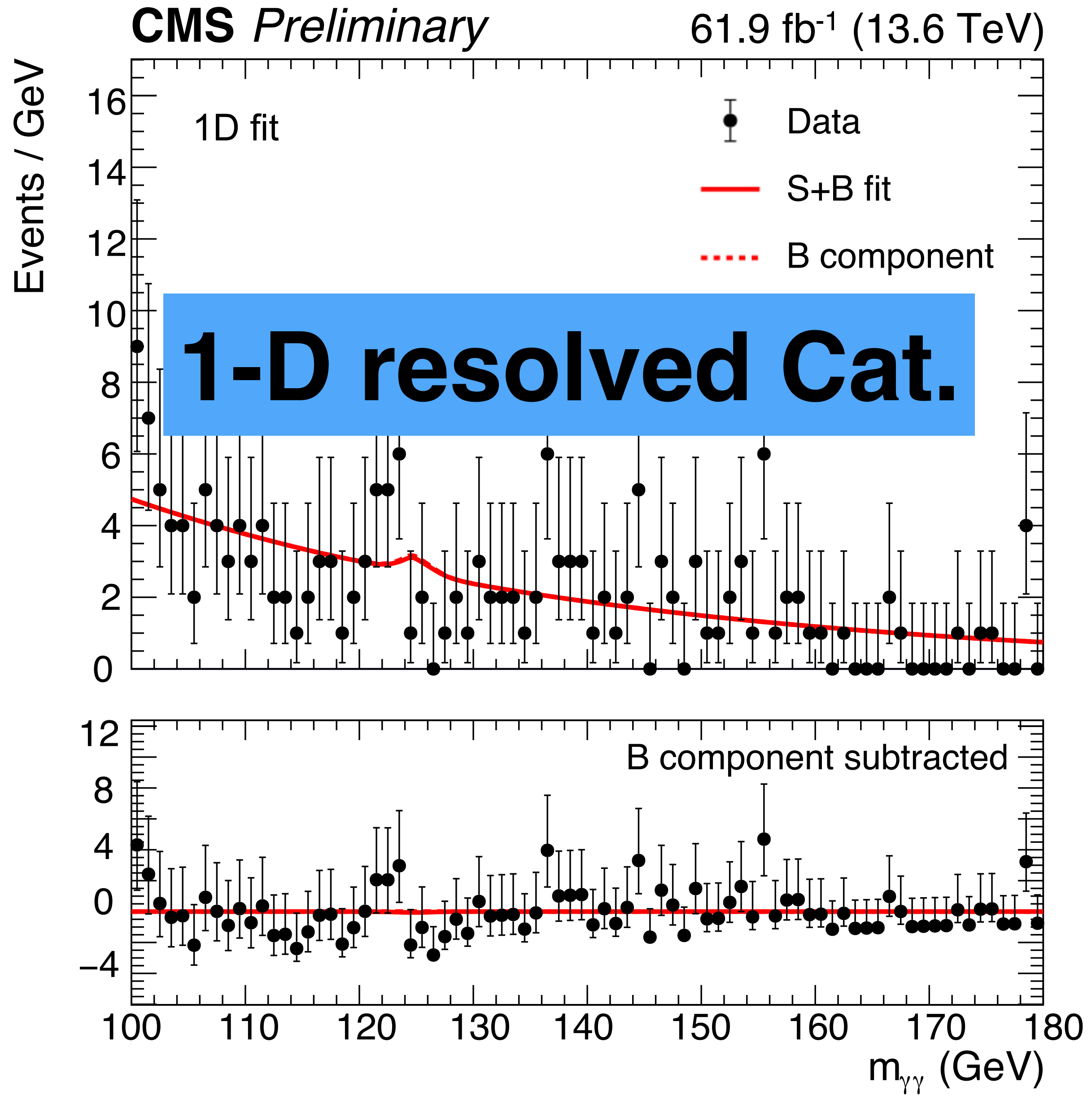
- **First HH results to reach 1σ expected significance!**
- **Obs. (exp) signal strength: 3.8× SM (2.6× SM)**
- **Limits set on Higgs self-coupling κ_λ: [-1.7, 6.6], competitive with the Run2 legacy HH combination [-1.2,7.2]**

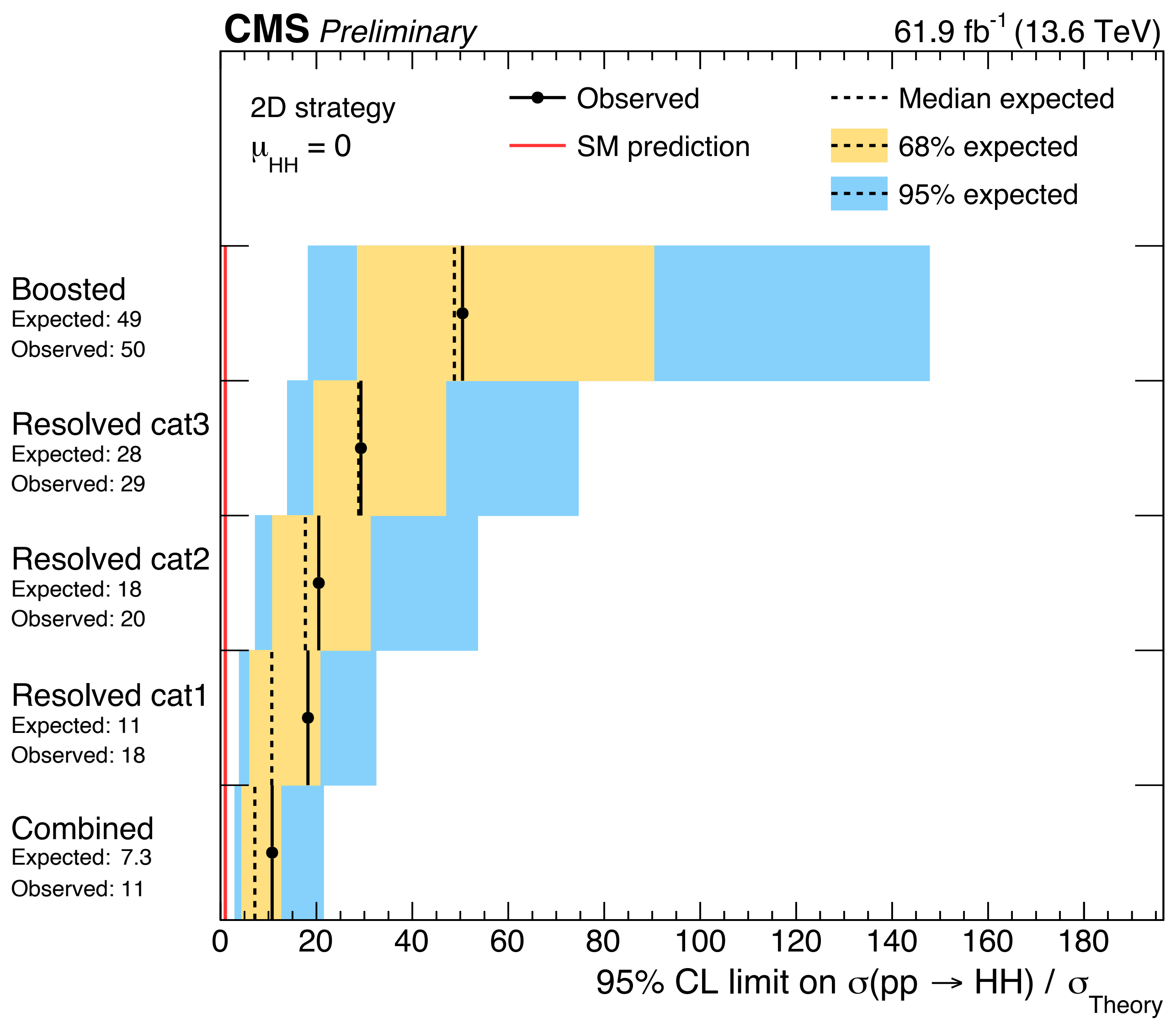
Main improvements over Run2 legacy

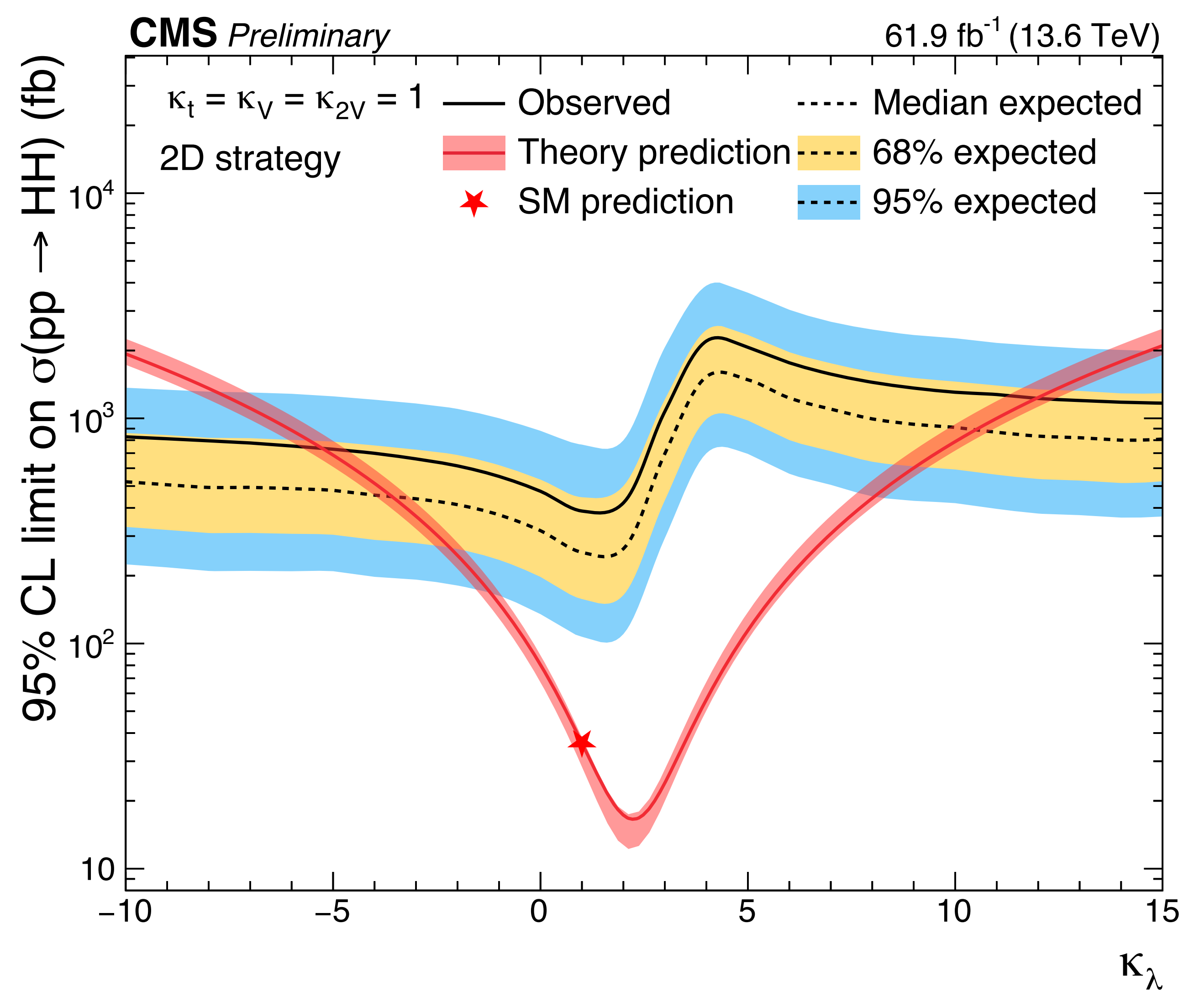
- **More data! 140 fb-1 → 308fb-1 (50%)**
- **New GNN-based tagger GN2 (20%)**
- **Correlation between Run2 and Run3 events in BDT and category optimization (10%)**
- **Kinematic Fit for m_{bb} resolution improvement (5%)**

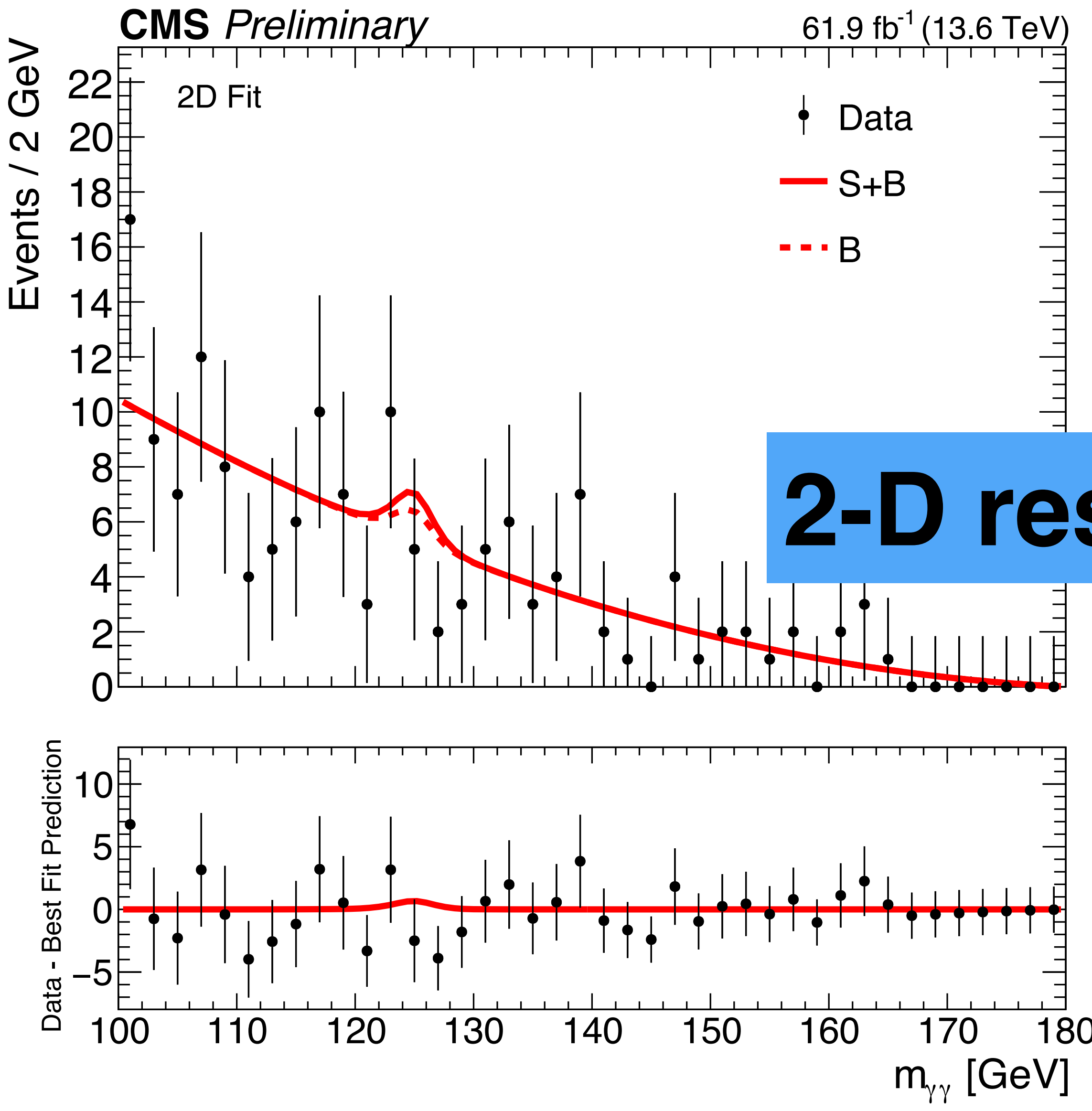
Partial Run3 $HH \rightarrow bb\gamma\gamma$ @ CMS

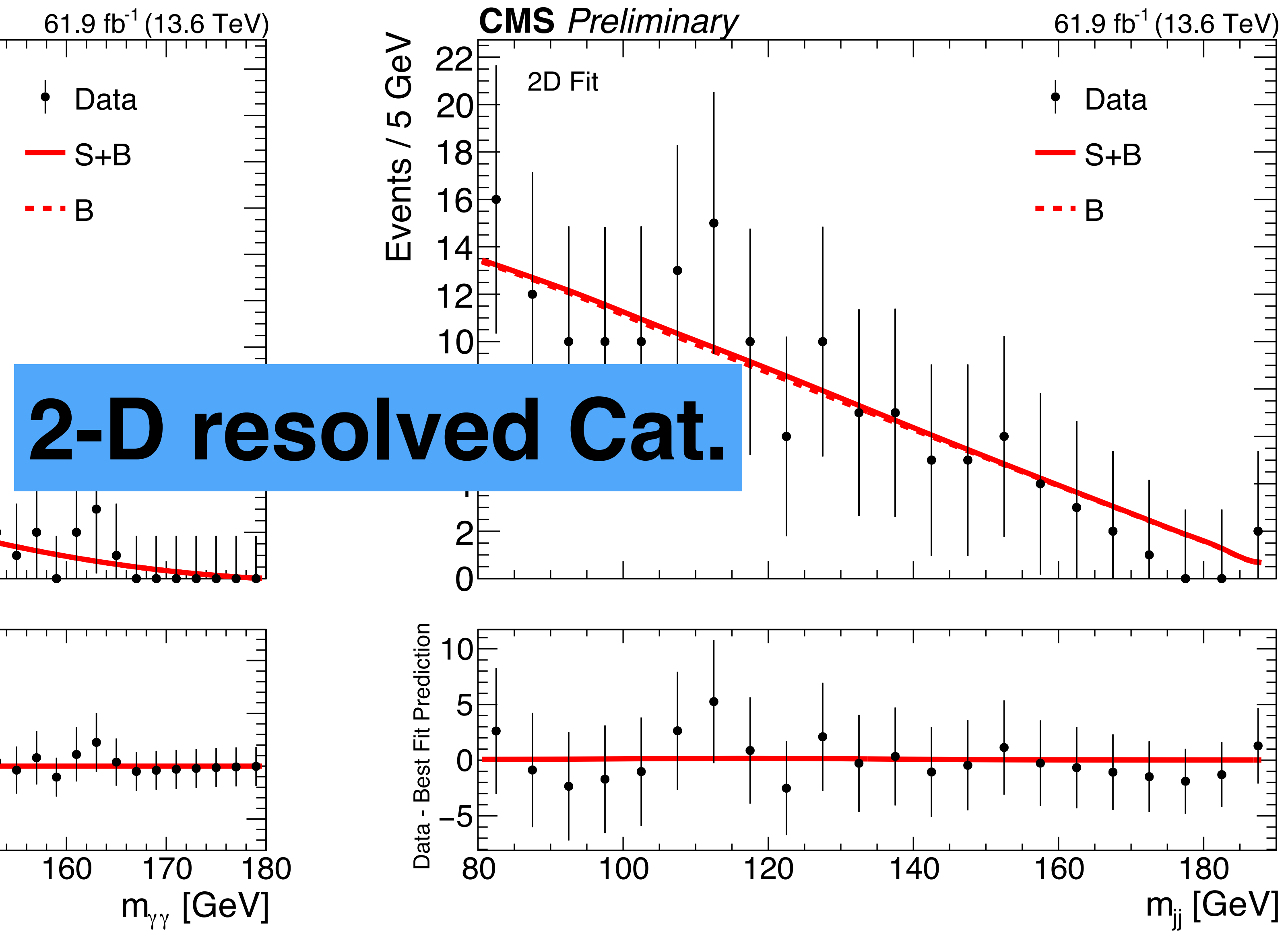












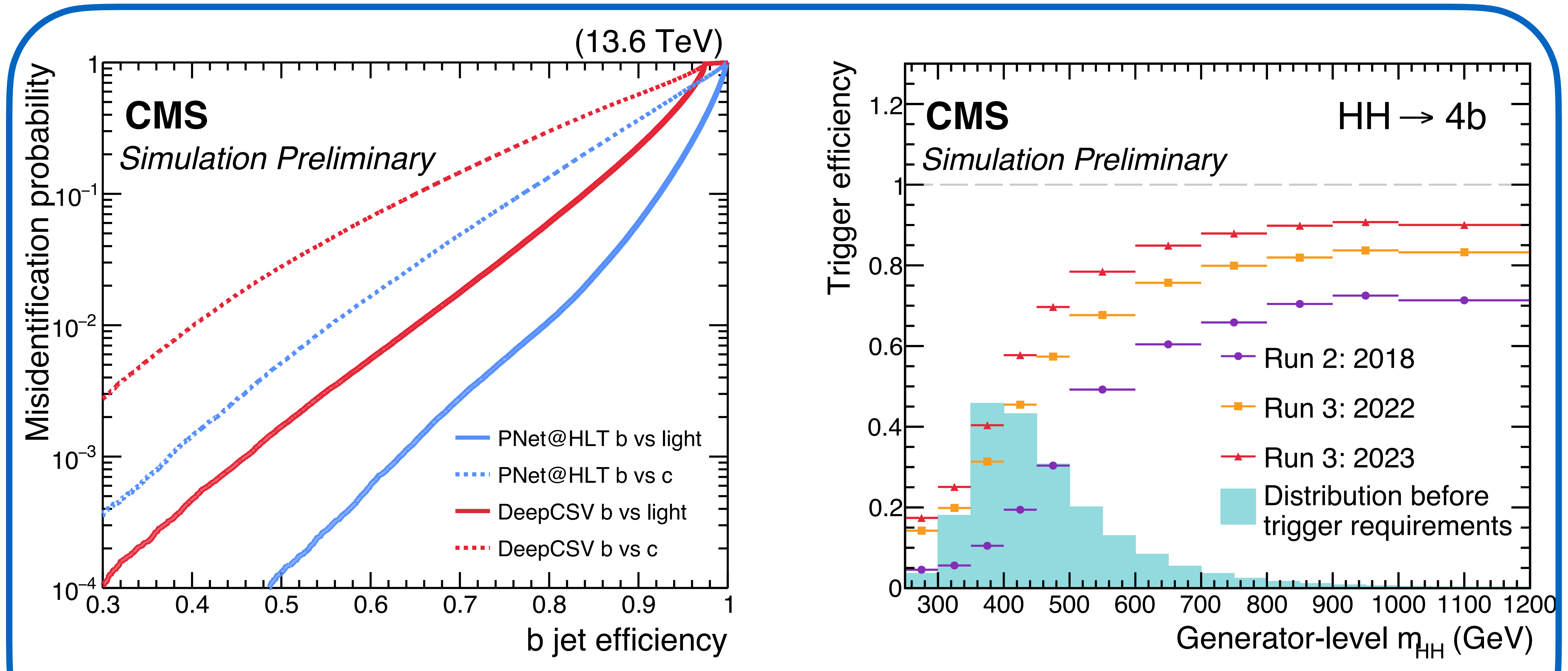
Obs. (exp) HH: 11× SM (7.3× SM)

Obs. (exp) κ_λ: [-3.6, 10.5] ([-5, 12])

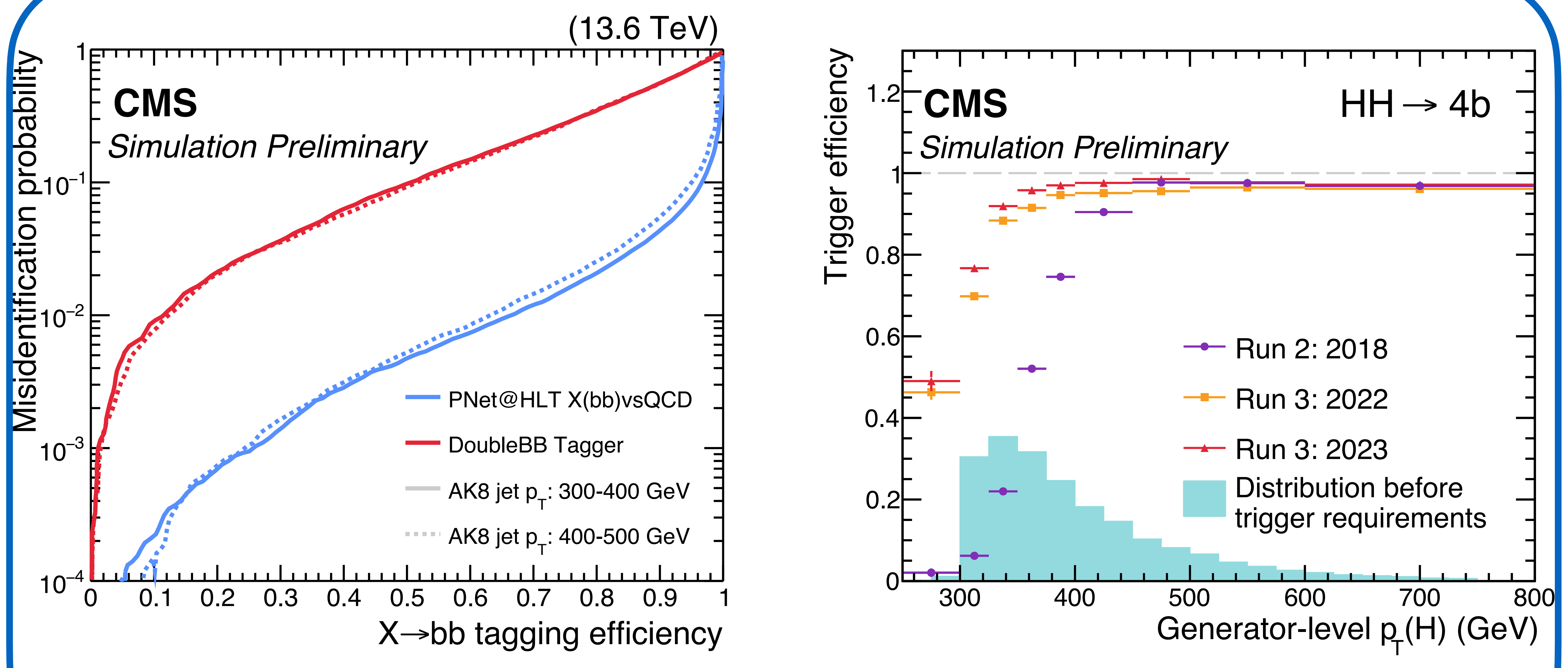
- A special boosted category is defined
- Two different and complementary analysis strategies (1-D fit on $m_{\gamma\gamma}$ and 2-D fit on $m_{\gamma\gamma}$-m_{jj}) result in consistent results
- More sensitive version is 2-D fit

PAS-HIG-25-007

$HH \to bbbb$ @ CMS



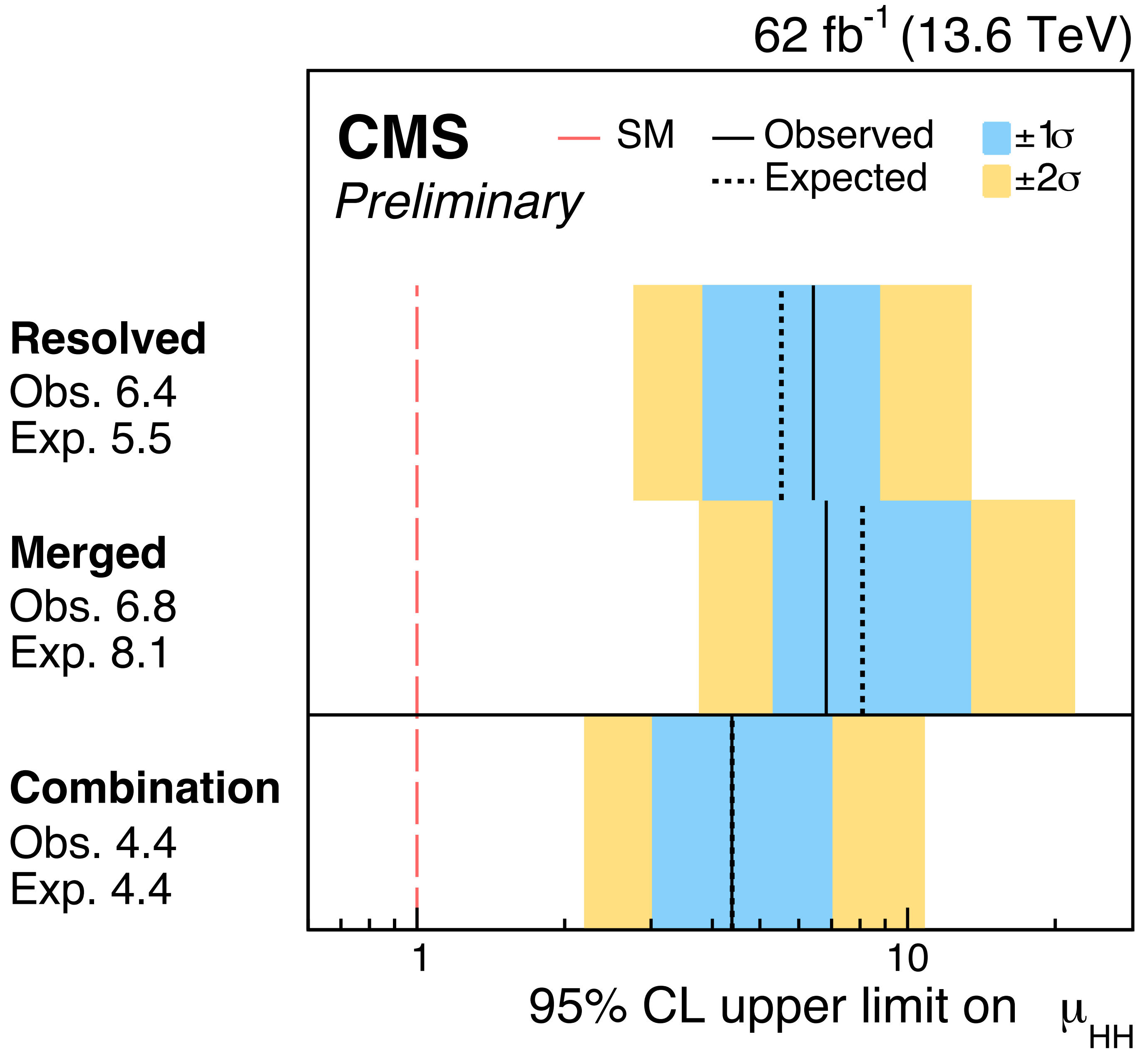
resolved

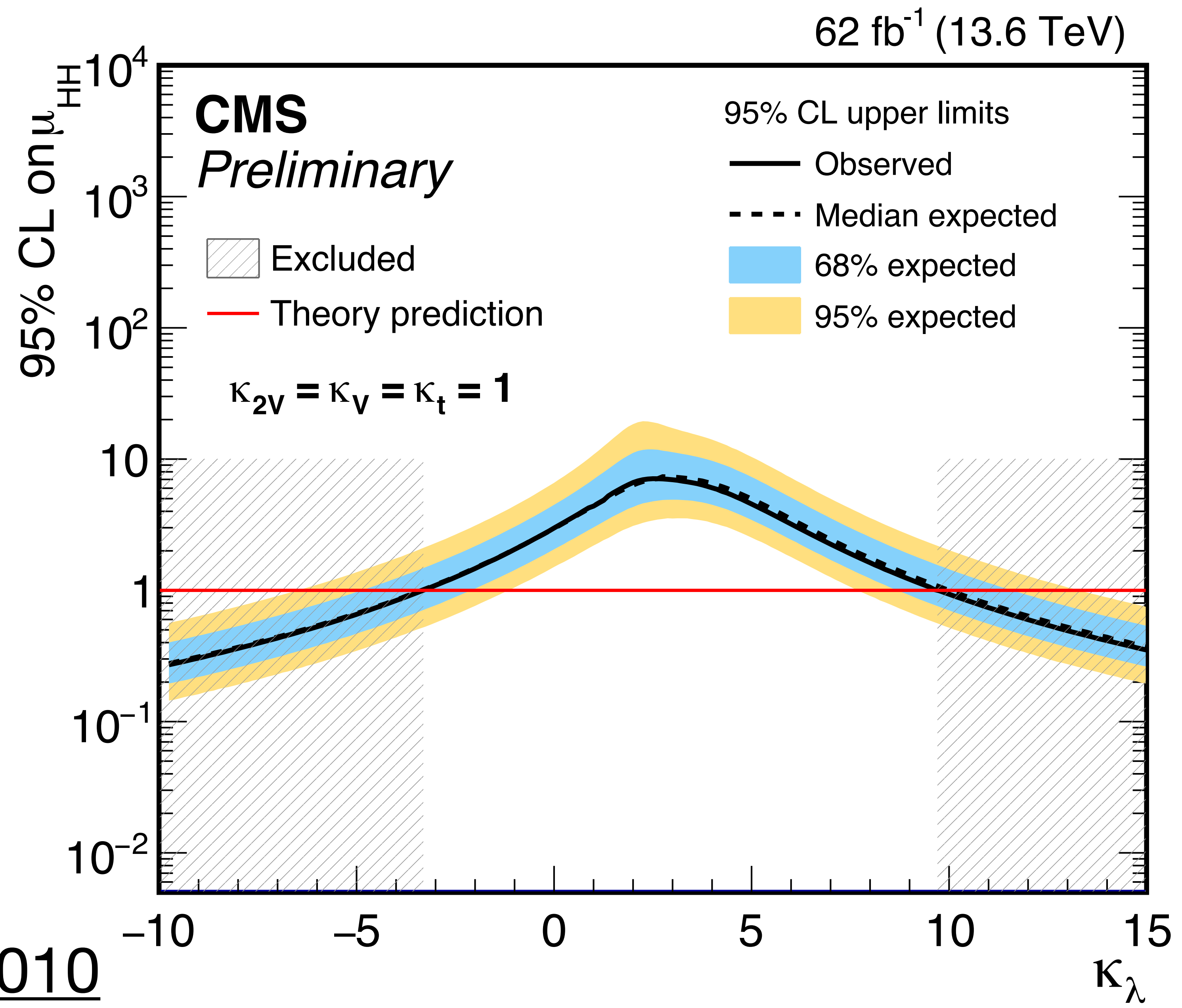


merged

- Upper limits on non-resonance HH productions using 22+23 data: **improved by more than a factor of two with an equivalent integrated luminosity**
  - Significance improvement on b-tagging and trigger for both resolved/merge cases
  - Obs. (exp) signal strength: **4.4× SM (4.4× SM)**
  - Limits set on Higgs self-coupling κ_λ: [-3.3, 9.7]([-3.4,10.0])
- Re-analysis-Run2 results: **improvement of ~25%**
  - Obs. (exp) signal strength: 10× SM (5.9× SM)

HH → bbbb @ CMS





PAS-HIG-24-010

- Upper limits on non-resonance HH productions using 22+23 data: **improved by more than a factor of two with an equivalent integrated luminosity**
  - Significance improvement on b-tagging and trigger for both resolved/merge cases
  - Obs. (exp) signal strength: **4.4× SM (4.4× SM)**
  - Limits set on Higgs self-coupling κ_λ: [-3.3, 9.7]([-3.4,10.0])
- Re-analysis-Run2 results: **improvement of ~25%**
  - Obs. (exp) signal strength: 10× SM (5.9× SM)

HL-LHC

Detector upgrades and advanced reconstruction technique to achieve better performance at ~200PU

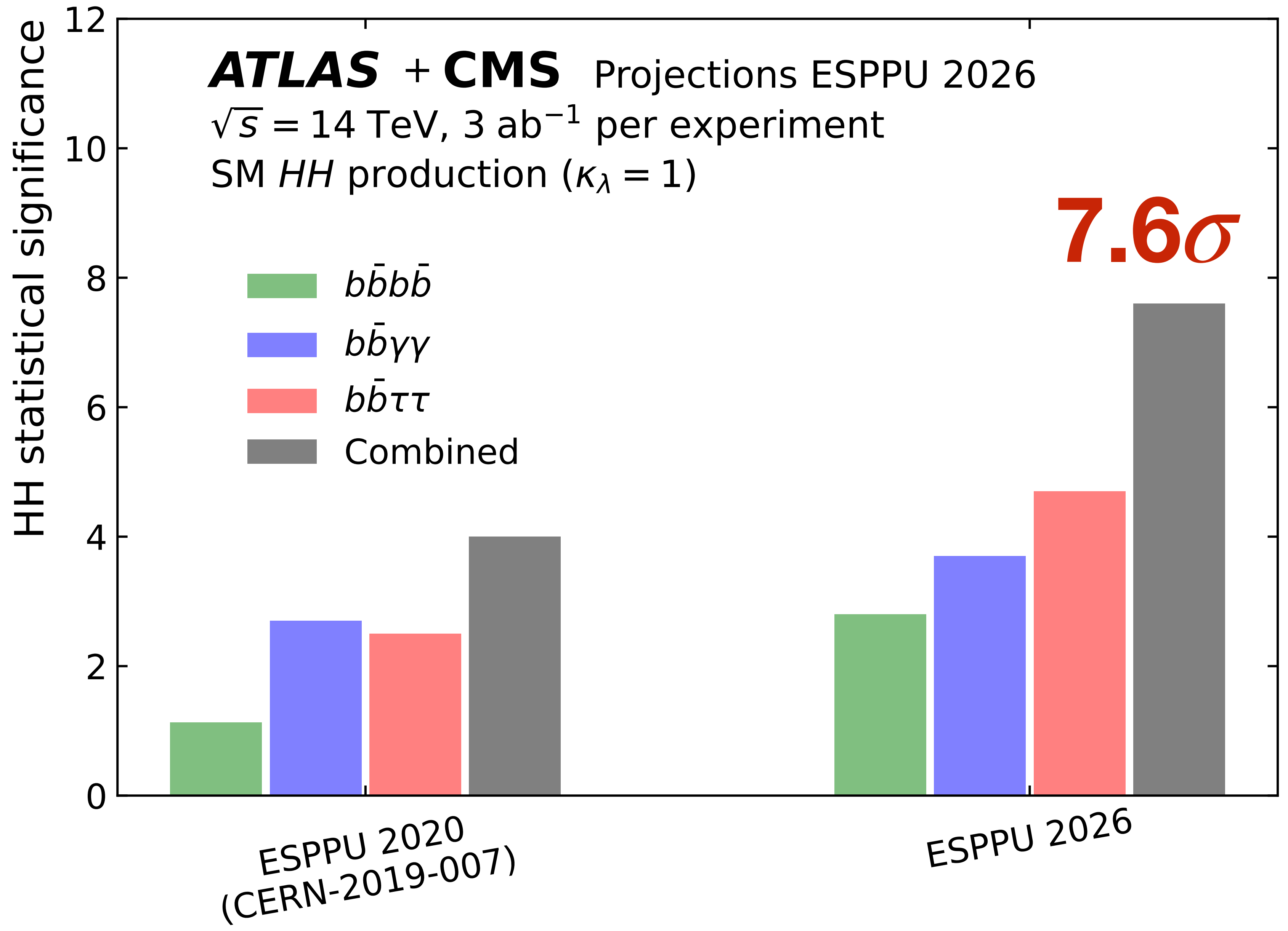
HH Projection @ HL-LHC

2 different systematic scenarios

- **S2: reduced systematic uncertainty with theoretical un. halved**
- **S3：5% improvement for b-tagging and τ rec. eff. (recent improvement evaluation)**

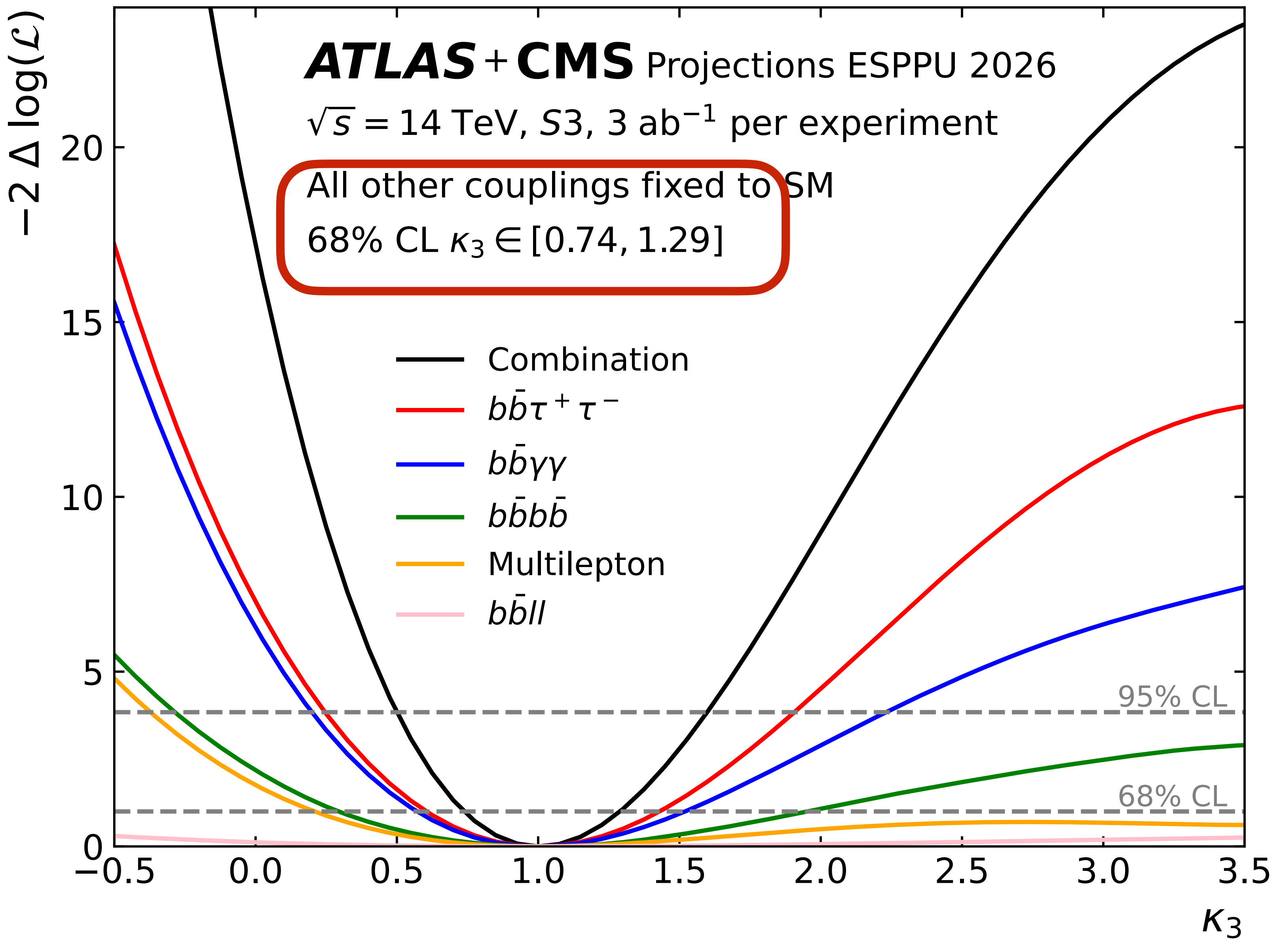
	2 ab^{-1} ($S2$) ATLAS	2 ab^{-1} ($S2$) CMS	3 ab^{-1} ($S2$) ATLAS	3 ab^{-1} ($S2$) CMS	3 ab^{-1} ($S3$) ATLAS	3 ab^{-1} ($S3$) CMS
			HH statistical significance			
$b\bar{b}\tau^+\tau^-$	$3.0^\dagger$	1.9	$3.5^\dagger$	2.4	$\mathbf{3.8}^\dagger$	**2.7**
$b\bar{b}\gamma\gamma$	$2.1^\dagger$	$2.0^\dagger$	$2.4^\dagger$	$2.4^\dagger$	$\mathbf{2.6}^\dagger$	$\mathbf{2.6}^\dagger$
$b\bar{b}b\bar{b}$ resolved	0.9	$1.0^\dagger$	1.0	$1.2^\dagger$	**1.0**	$\mathbf{1.3}^\dagger$
$b\bar{b}b\bar{b}$ boosted	–	$1.8^\dagger$	–	$2.2^\dagger$	–	$\mathbf{2.2}^\dagger$
Multilepton	$0.8^\dagger$	–	$1.0^\dagger$	–	$\mathbf{1.0}^\dagger$	–
$b\bar{b}\ell^+\ell^-$	$0.4^\dagger$	–	$0.5^\dagger$	–	$\mathbf{0.5}^\dagger$	–
Combination	3.7	3.5	4.3	4.2	**4.5**	**4.5**
ATLAS+CMS	6.0		7.2		**7.6**	

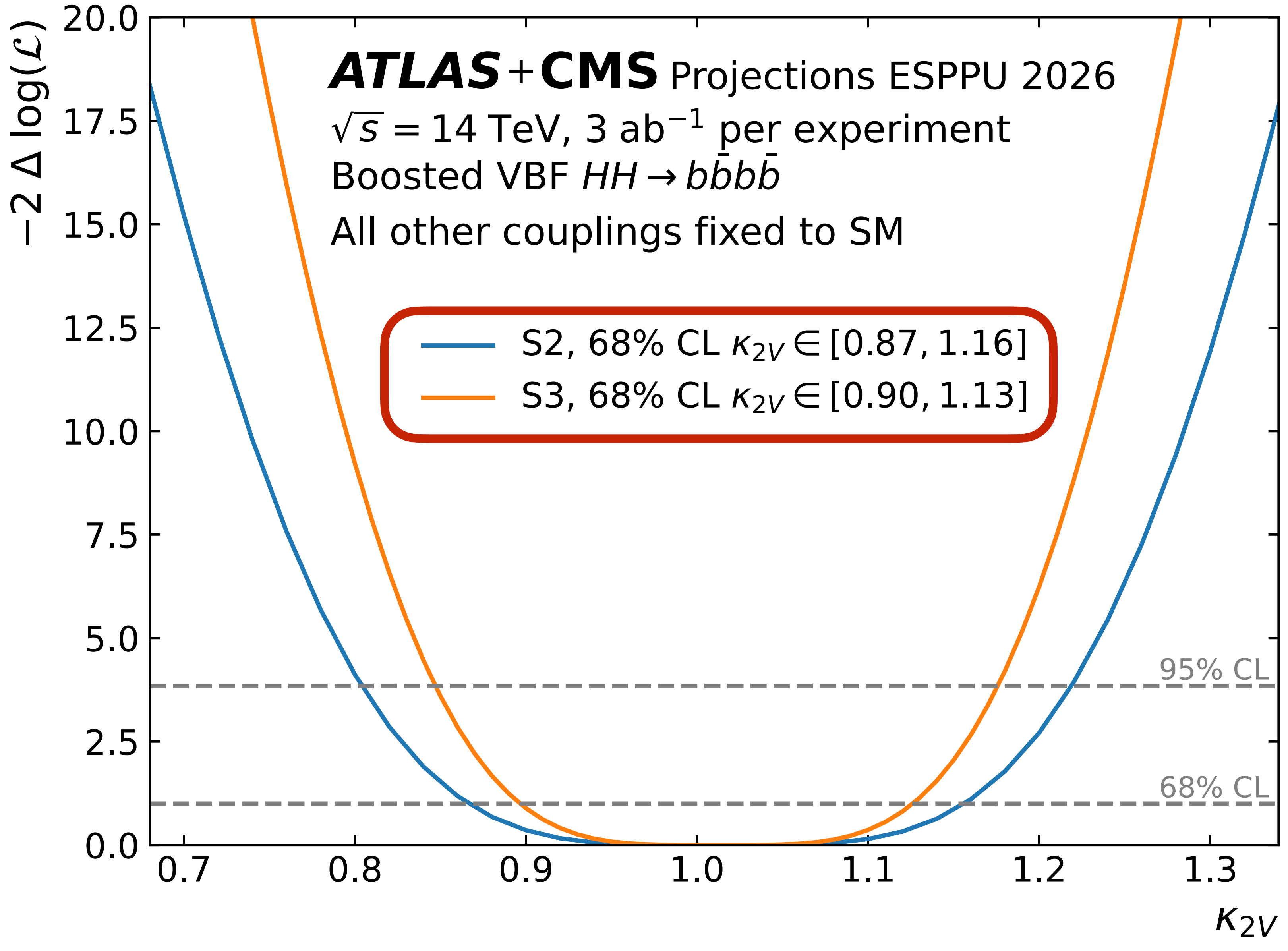
20% **5%**

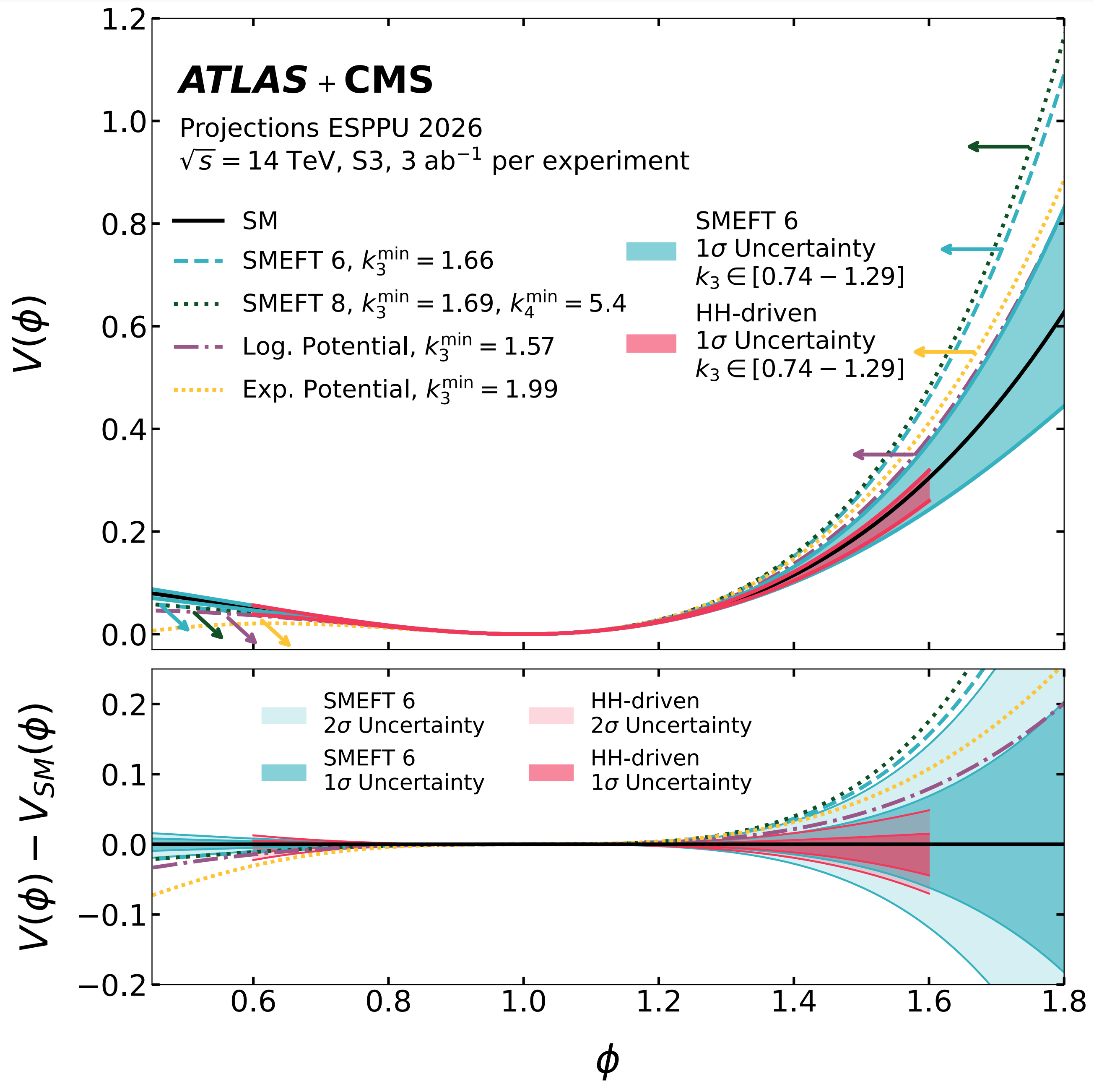


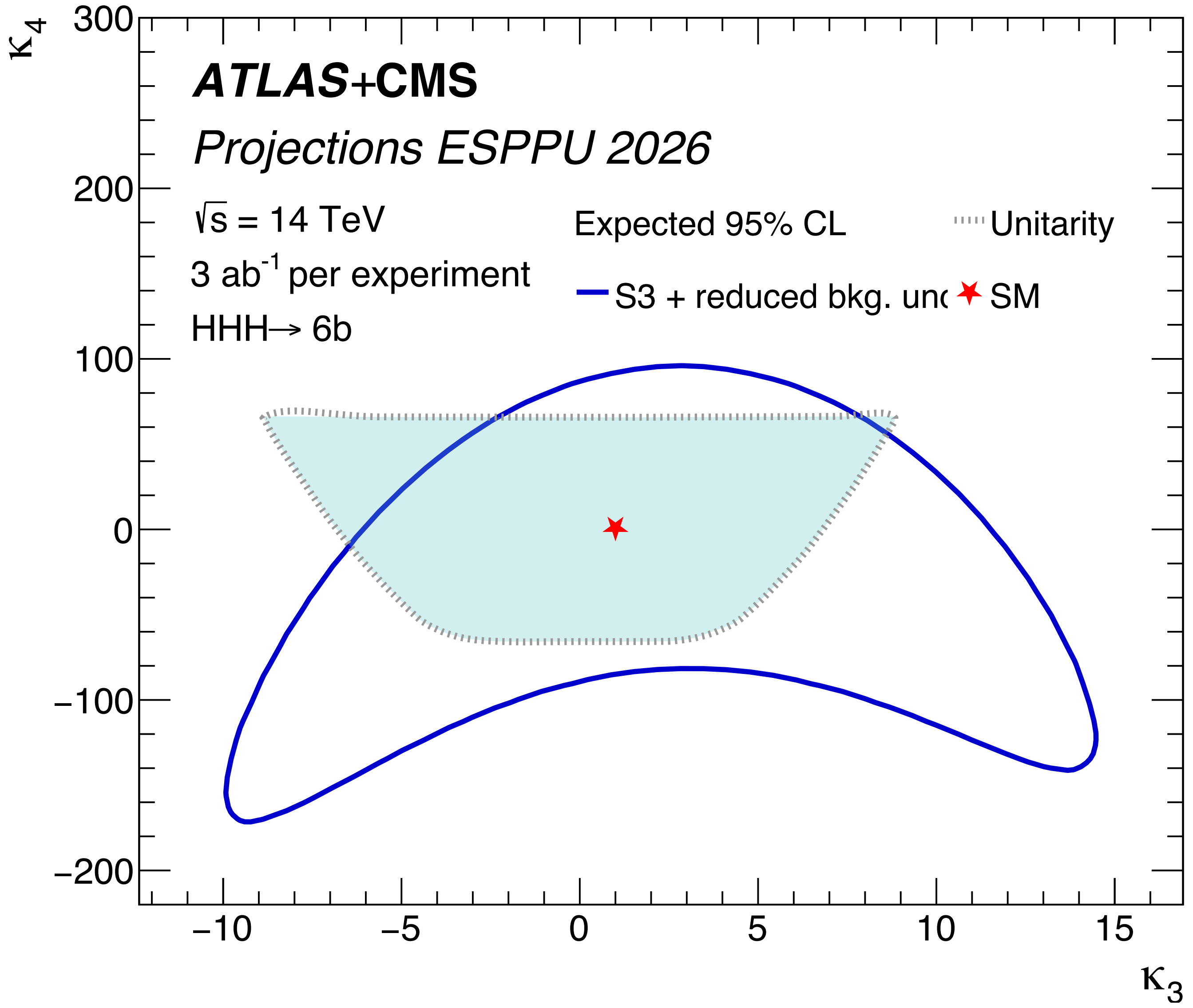
- **ATLAS+CMS expected significance >5σ with 2ab^{-1} in S2**
- **From S2 to S3: 5% gain in precision**
- **From 2ab^{-1} to 3ab^{-1}: 20% gain in precision**

Higgs self-coupling Projection @ HL-LHC









- LHC constraints from HH can only **determine κ_3 close to the minimum**
- Well exclude **alternative BSM scenarios** with strong first-order phase transition (FOPT) in the early universe
- Exp HHH: **86× SM** which can exclude portions of unitarity bound region

Summary

- ATLAS and CMS have wide investigations of HH (ggHH, VBFHH, VHH,ttHH) @ Run2 and start new studies of HHH @ Run2 and HH @ Run3
- More room for further sensitivity improvement: more data, better reconstruction/identification/trigger, novel deep learning techniques
- Question: **is evidence of SM HH production possible in Run3?**

Direct observation of $H \to HH$ interaction is a "guaranteeable" discovery that HEP is aiming for