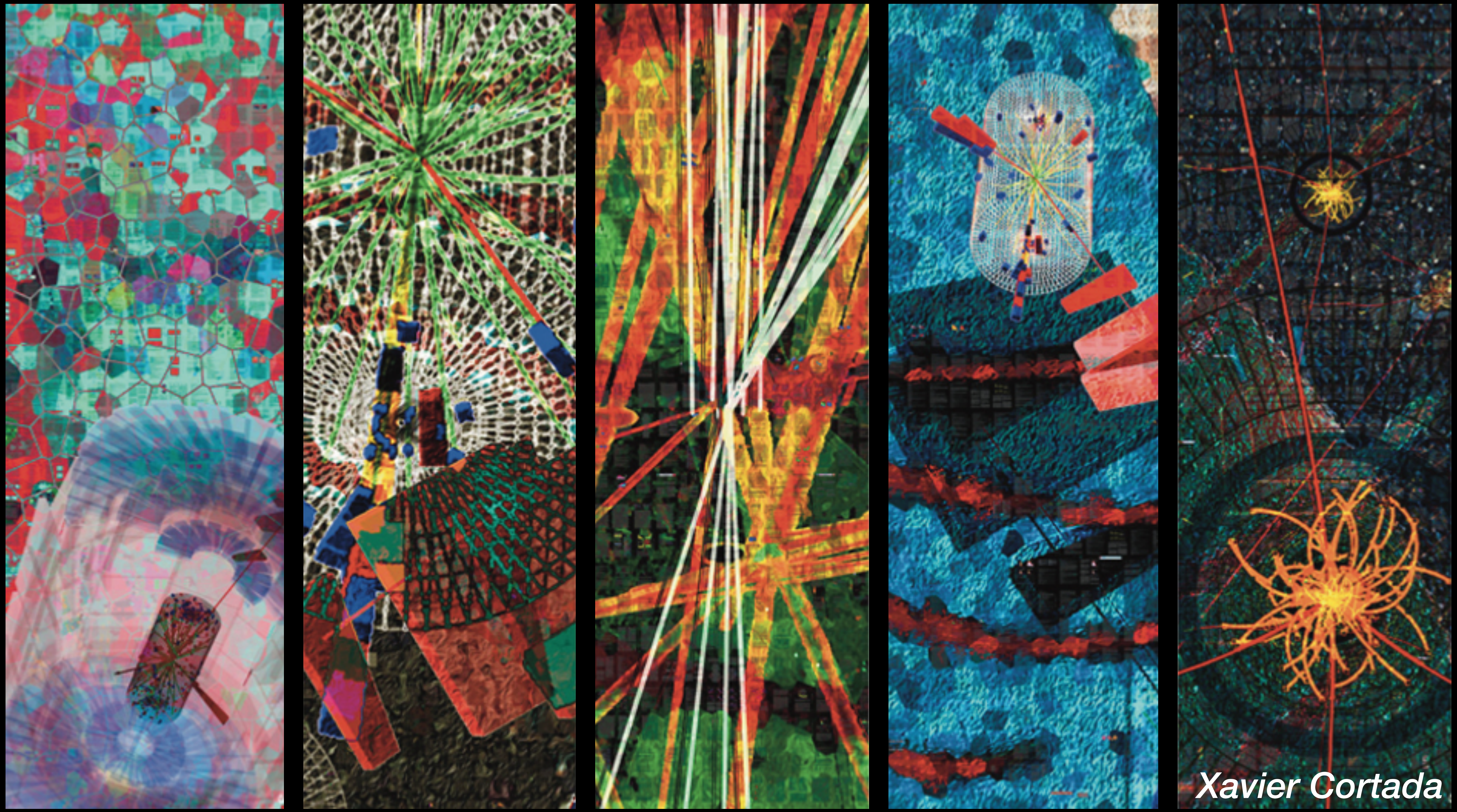
Mapping the Higgs Potential with ATLAS and CMS

Latest non-resonant Run 3 HH results and combinations, single H constraints, HHH searches, and HL-LHC projections.

SM@LHC 2026



Cédrine Hügli, DESY
On behalf of the ATLAS and CMS Collaborations

ATLAS EXPERIMENT

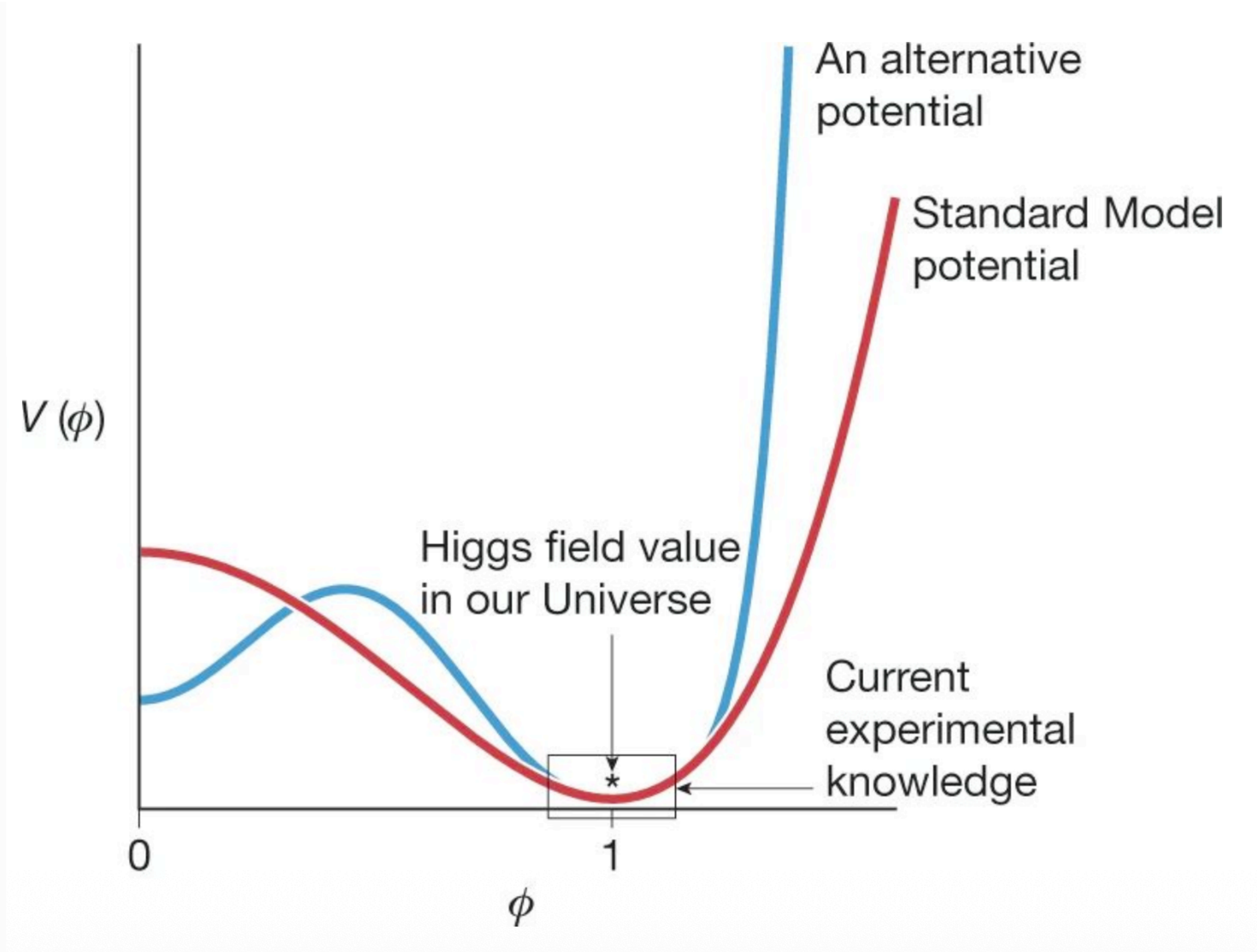
CMS

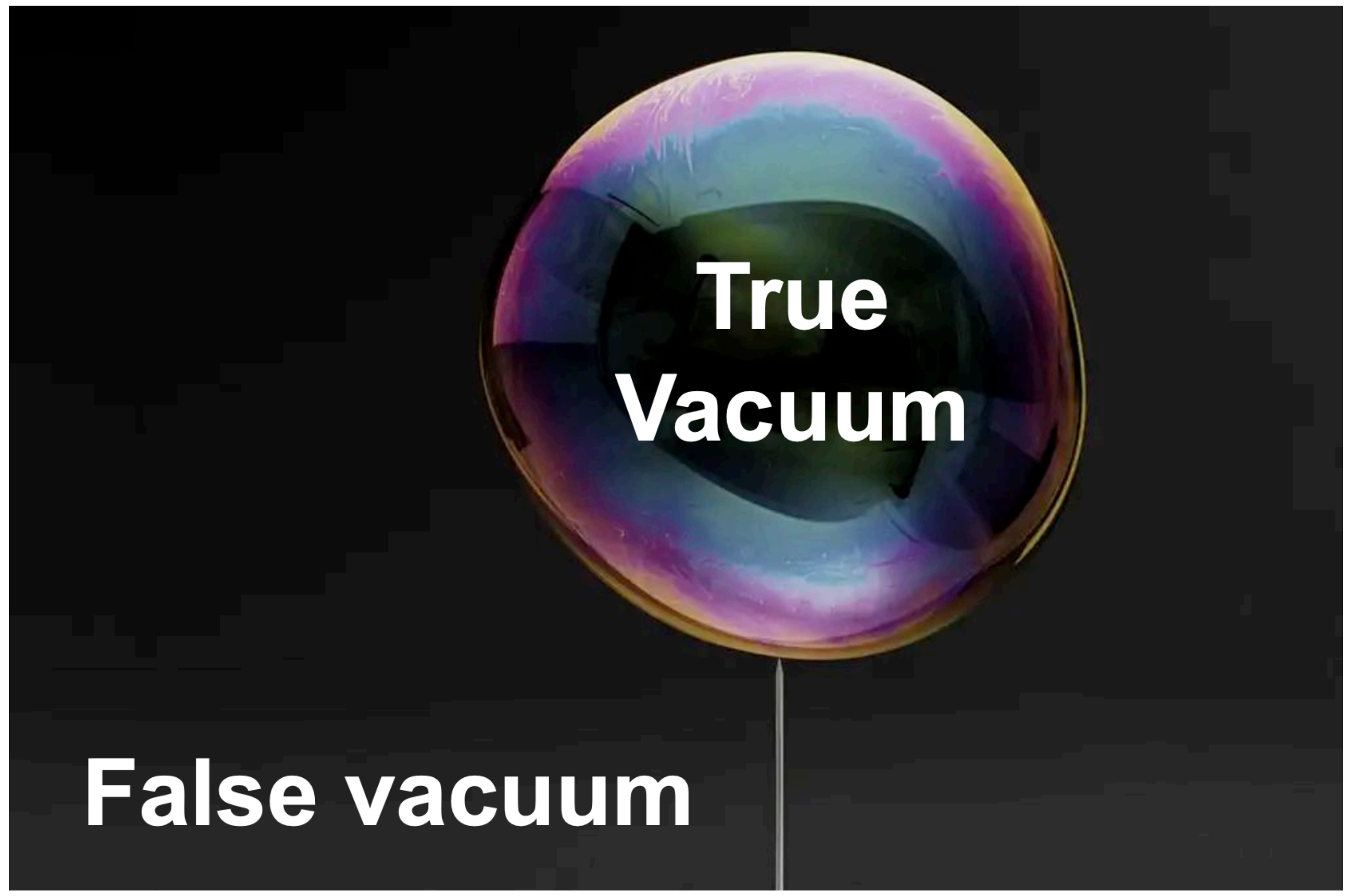
Content

- Introduction
- Higgs self-coupling search
  - diHiggs (HH)
  - triple Higgs (HHH)
  - single Higgs (H)
- HL-LHC projections

The importance of the Higgs potential

- non-SM coupling may provide a mechanism for first order (EW) phase transition
  - key requirement for matter-antimatter asymmetry (EW Baryogenesis)

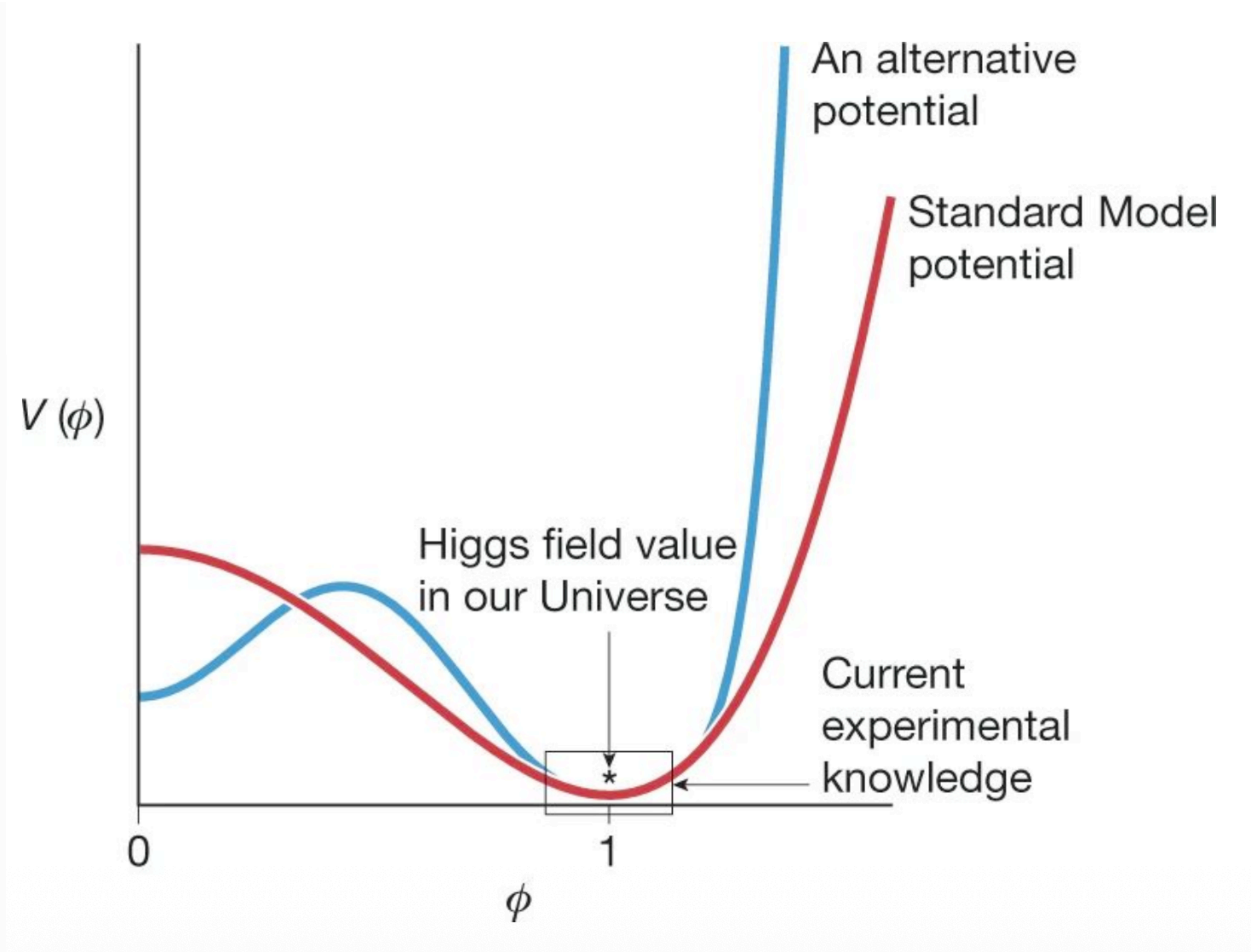


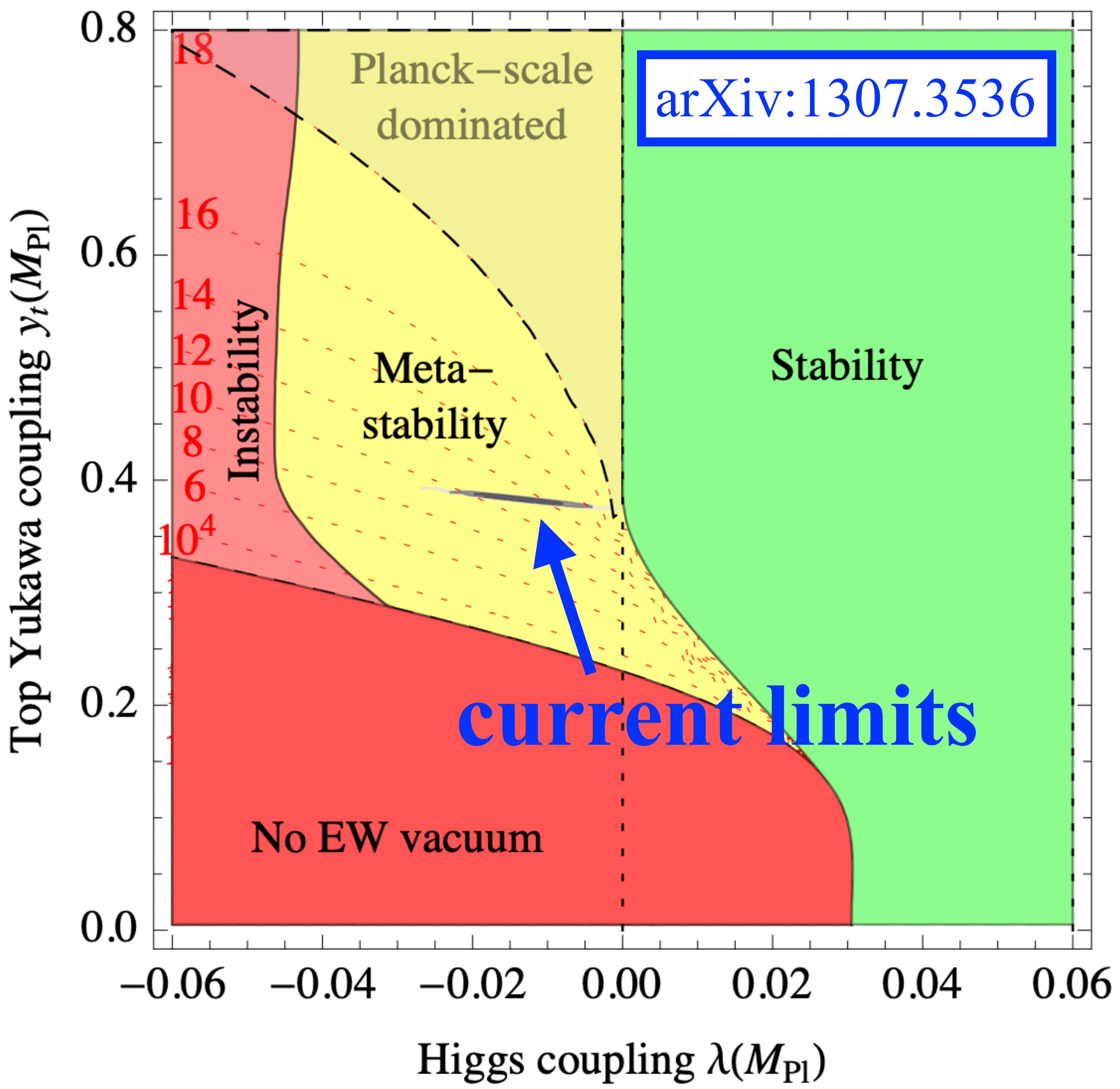


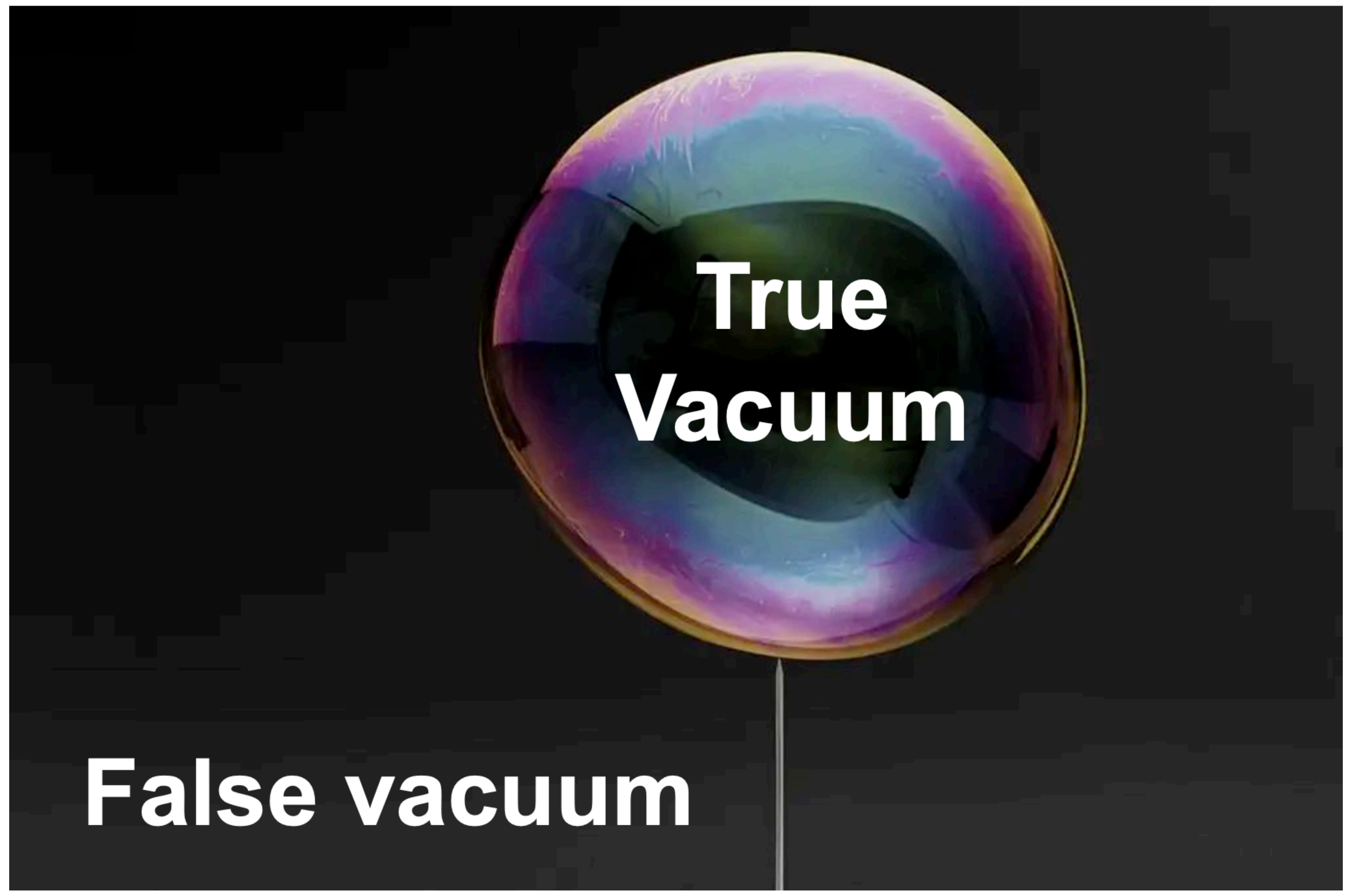
The importance of the Higgs potential

- non-SM coupling may provide a mechanism for first order (EW) phase transition
  - key requirement for matter-antimatter asymmetry (EW Baryogenesis)
- vacuum stability of the universe

Higgs boson self-coupling governs the shape of Higgs potential







Theory and nomenclature

The Higgs potential is given by

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

in the SM we assume: $\lambda_{SM} = \lambda_3 = \lambda_4 = \frac{m_H^2}{2v^2}$.

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However, we could have $\lambda_3 \neq \lambda_4$ in BSM.

We often define

$$\kappa_\lambda = \kappa_3 = \frac{\lambda_3^{\text{obs.}}}{\lambda_3^{\text{SM}}} \text{ and } \kappa_4 = \frac{\lambda_4^{\text{obs.}}}{\lambda_4^{\text{SM}}}$$

Ways to access the Higgs boson self-coupling

1 pb = 1000 fb

$$\mu_X = \frac{\sigma_X^{\text{obs.}}}{\sigma_X^{\text{SM}}} = \textit{signal strength}$$

DiHiggs (HH)

$$\sigma^{\text{SM, 13 TeV}}_{\text{ggF, HH}} = 30.8^{+2.0}_{-7.1}\ \text{fb}$$

- large sensitivity to κ_3
- no sensitivity to κ_4
- upper limit μ_{HH}

Triple Higgs(HHH)

$$\sigma^{\text{SM, 13 TeV}}_{\text{HHH}} = 0.079^{+0.012}_{-0.013}\ \text{fb}$$

- low sensitivity to κ_3
- sensitivity to κ_4
- upper limit μ_{HHH}

Single Higgs (H)

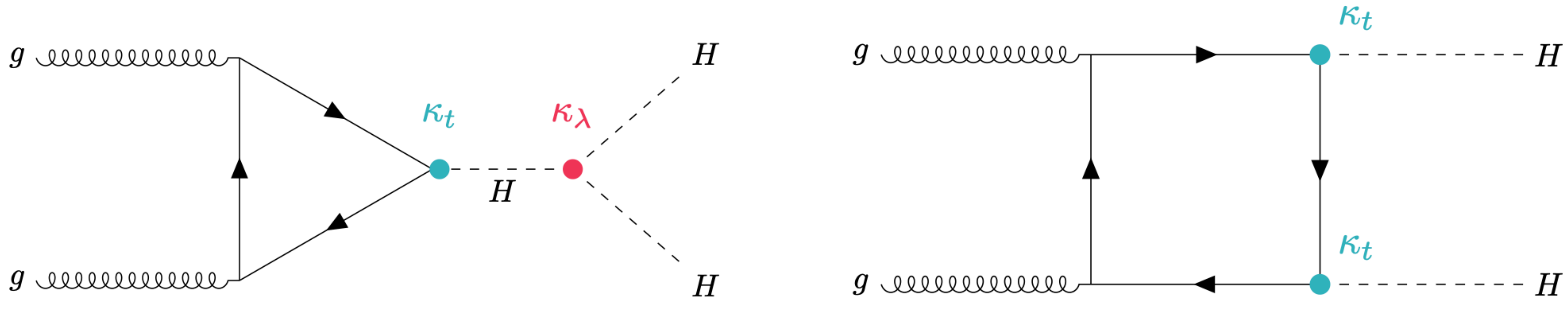
$$\sigma^{\text{SM, 13 TeV}}_{\text{total, H}} = 59.3 \pm 5.7\ \text{pb}$$

- κ_3 sensitivity through NLO EW corrections to single Higgs production
- no sensitivity to κ_4

Higgs boson pair production

HH production modes at the LHC

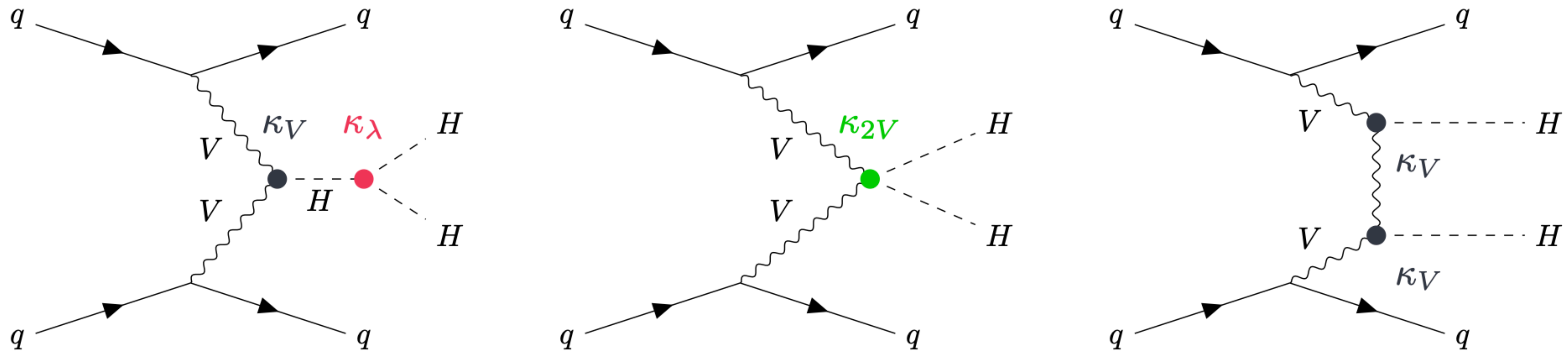
ggF production



(a) Trilinear coupling

(b) Box diagram

VBF production



(a) Trilinear coupling

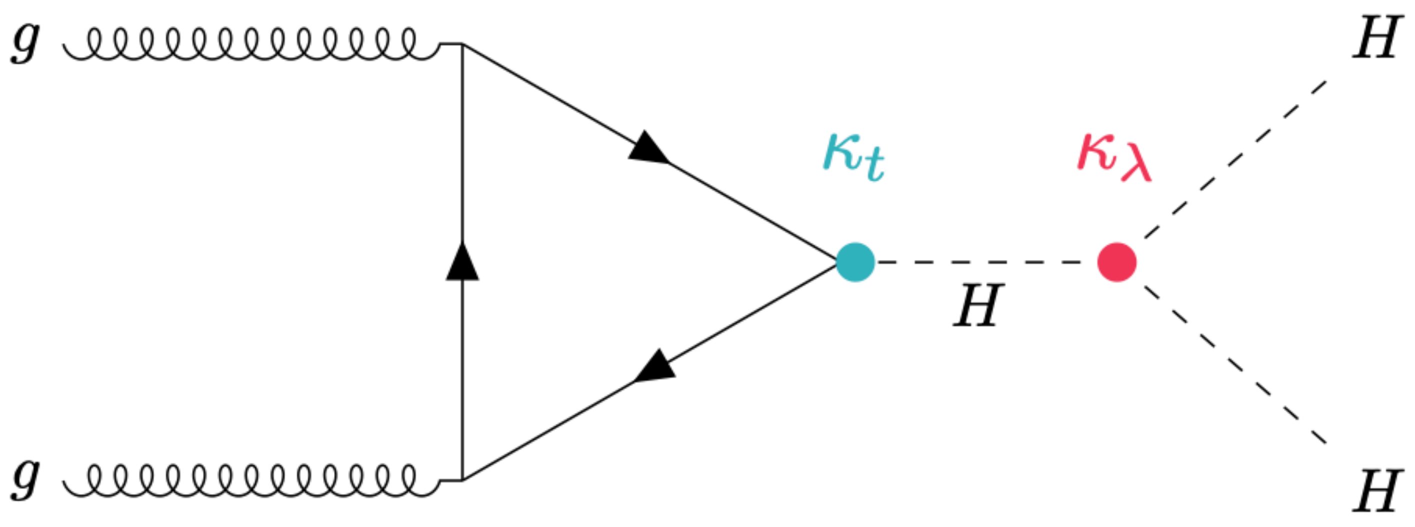
(b) *HHVV* vertex

(c) *VVH* Production mode

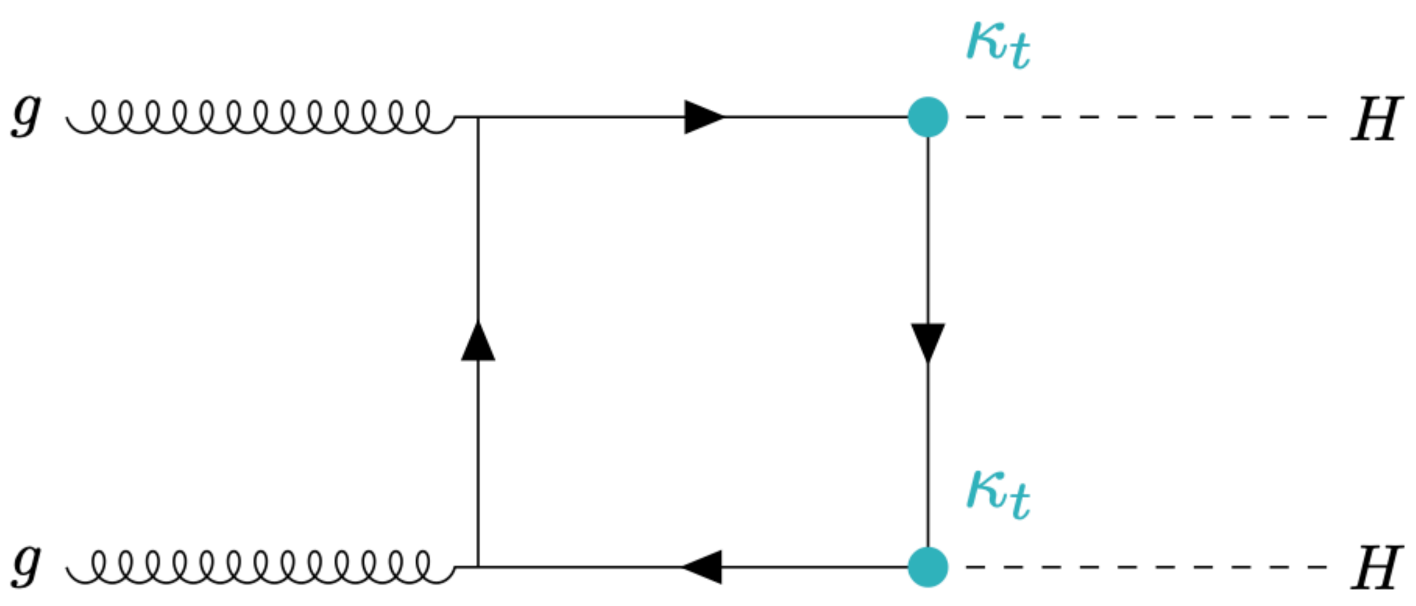
arXiv:1910.00012

HH production modes at the LHC

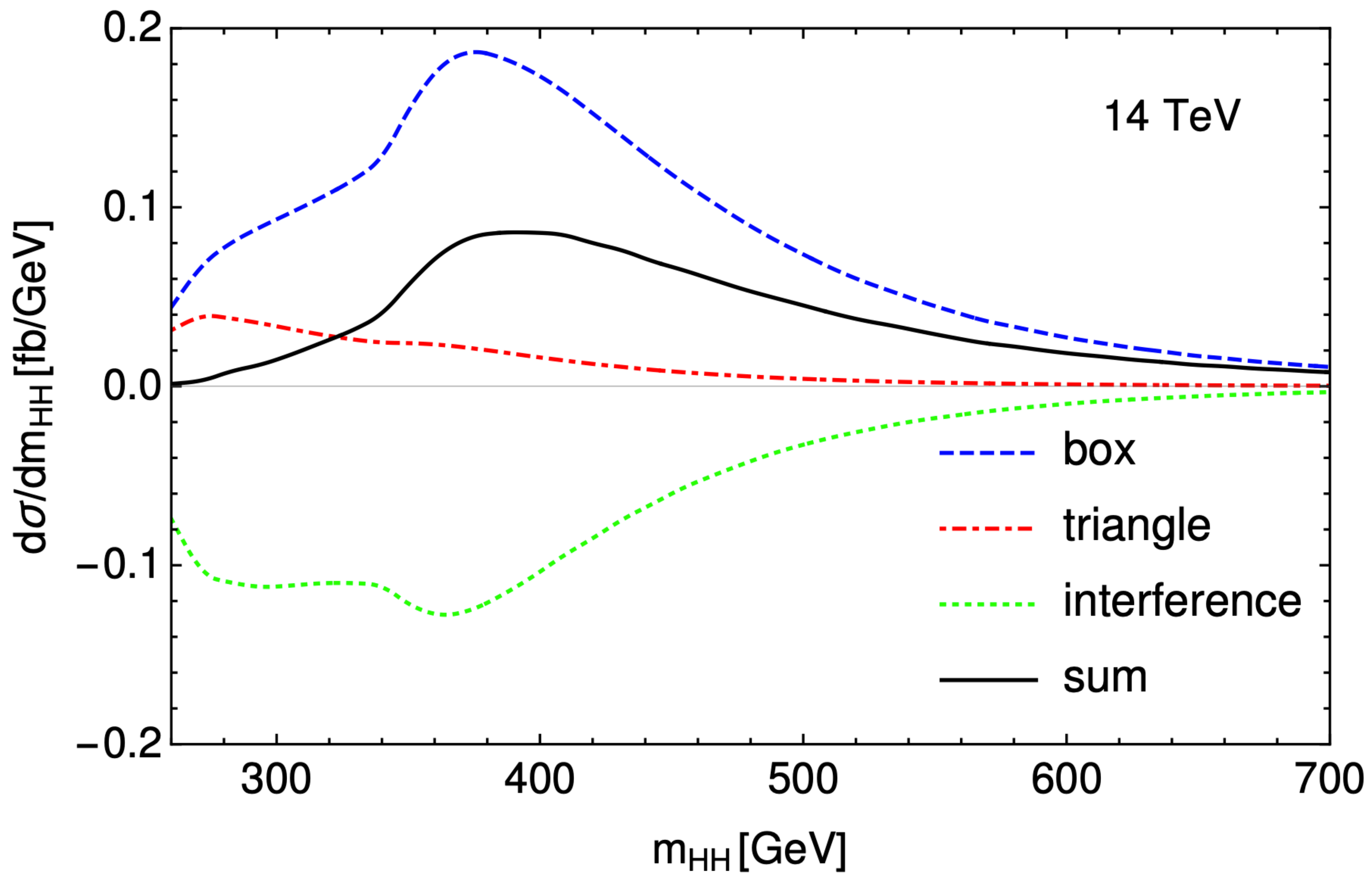
ggF production



(a) Trilinear coupling



(b) Box diagram



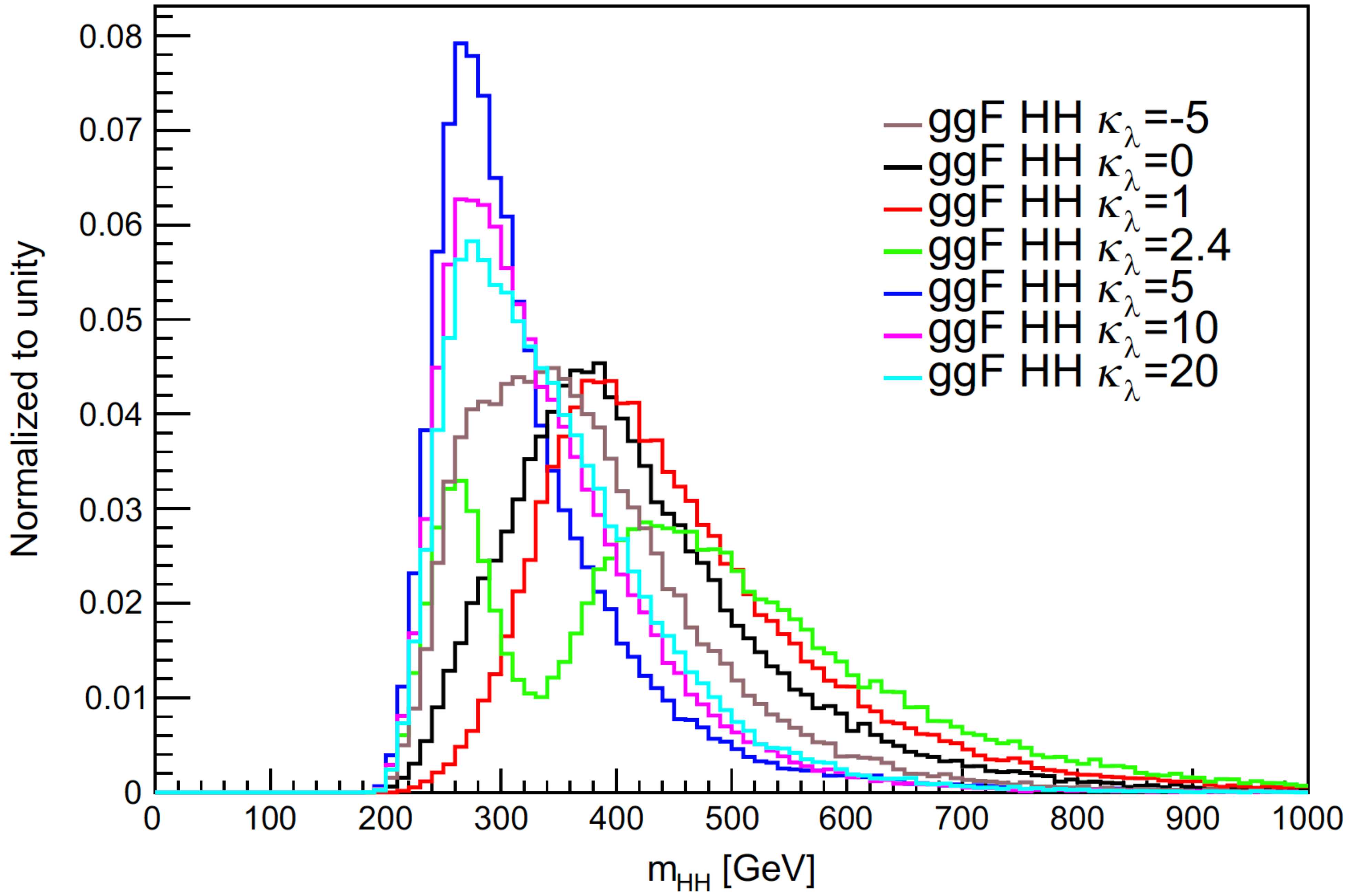
Destructive interference

arXiv:1910.00012

HH methodology concept

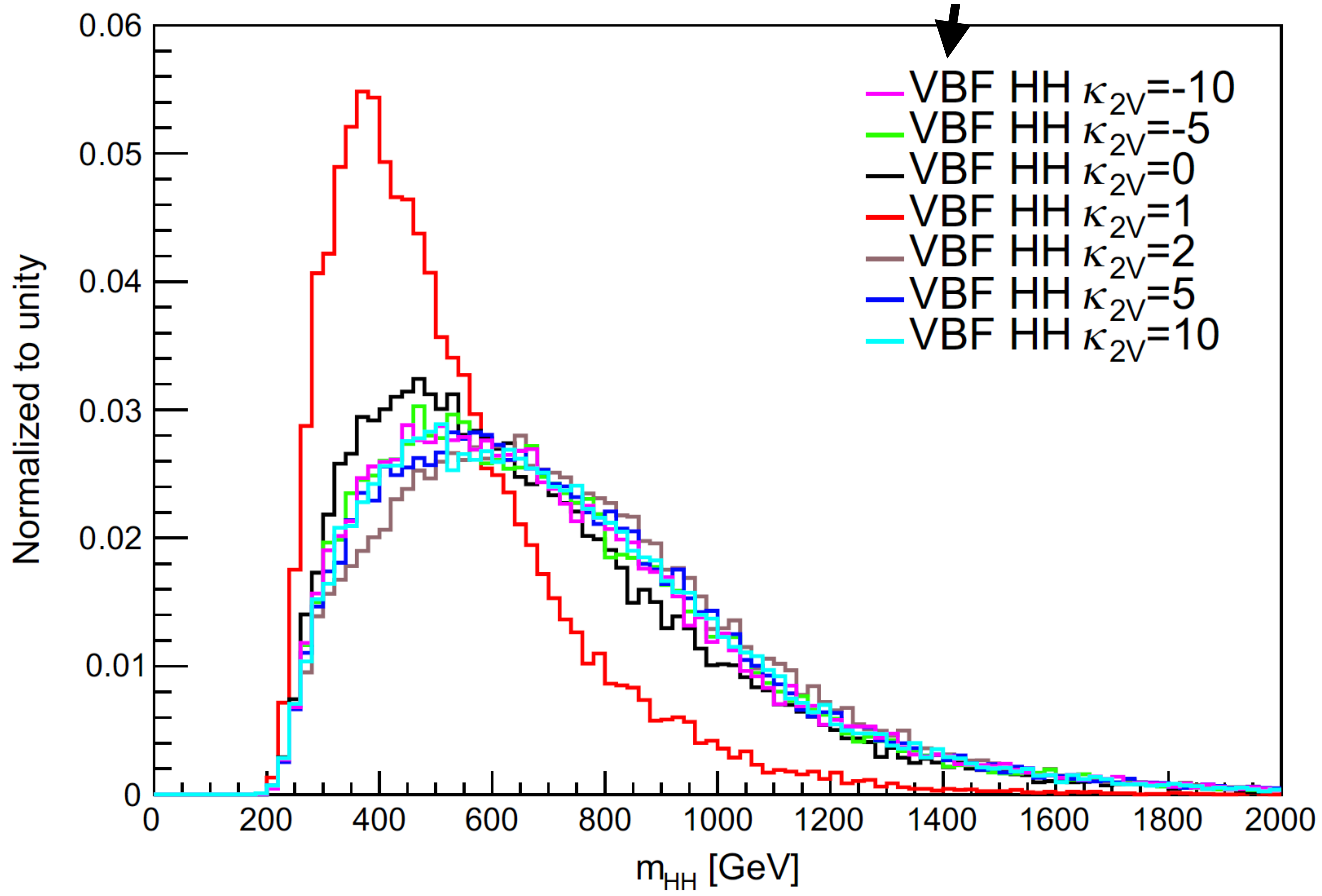
κ_{2V} can only be measured in the VBF production mode!

m_{HH} distribution for different κ_3 values



κ_3 sensitivity in the low m_{HH} region

m_{HH} distribution for different κ_{2V} values



κ_{2V} sensitivity in the high m_{HH} region

arXiv:1910.00012 PHYSICAL REVIEW D 107, 034014 (2023)

Input analyses for the latest ATLAS + CMS combination

ATLAS

- *bbbb*: **Phys. Rev. D 108 (2023) 052003**, **Phys. Lett. B 858 (2024) 139007**
- $bb\tau\tau$: **Phys. Rev. D 110 (2024) 032012**
- $bb\gamma\gamma$: **JHEP 01 (2024) 066**
- $bbll + E_{\mathrm{T}}^{\mathrm{miss}}$ ($bbWW$, $bbZZ$ and $bb\tau\tau$): **JHEP 02 (2024) 037**
- Multilepton (everything else): **JHEP 08 (2024) 164**

CMS

- *bbbb*: **Phys. Rev. Lett. 129 (2022) 081802**, **Phys. Rev. Lett. 131 (2023) 041803**
- $bb\tau\tau$: **Phys. Lett. B 842 (2023) 137531**
- $bb\gamma\gamma$: **JHEP 03 (2021) 257**
- $bbWW$: **JHEP 07 (2024) 293**
- Multilepton ($WWWW$, $WW\tau\tau$, $\tau\tau\tau\tau$): **JHEP 07 (2023) 095**

arXiv:2602.23991v2

Input analyses for the latest ATLAS + CMS combination

ATLAS

- *bbbb*
- $bb\tau\tau$
- $bb\gamma\gamma$
- $bbll + E_T^{miss}$: *bbWW*, *bbZZ* and $bb\tau\tau$
- Multilepton: everything else

	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%

CMS

- *bbbb*
- $bb\tau\tau$
- $bb\gamma\gamma$
- *bbWW*
- Multilepton: *WWWW*, $WW\tau\tau$, $\tau\tau\tau\tau$

	bb	WW	ττ	ZZ	γγ
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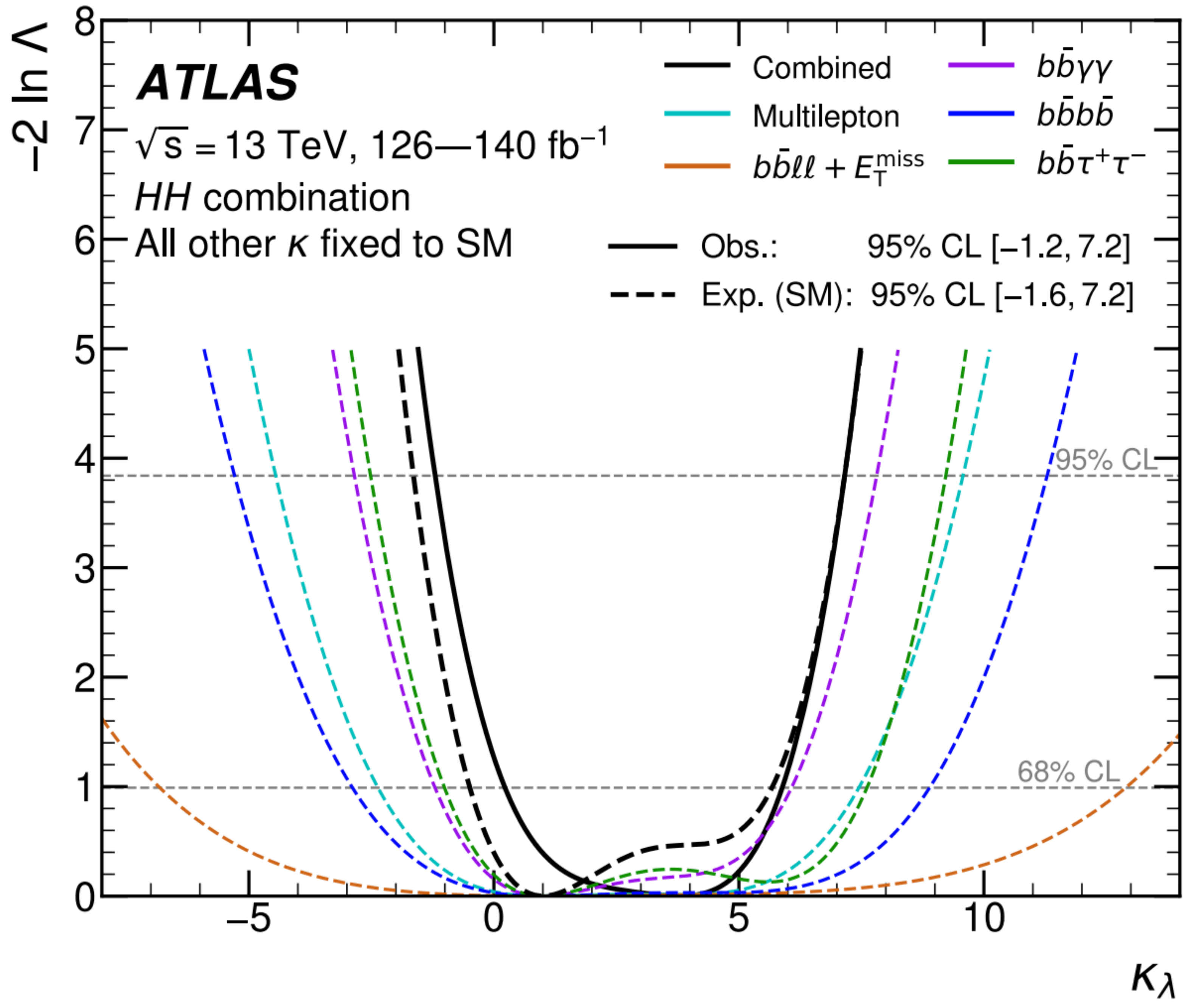
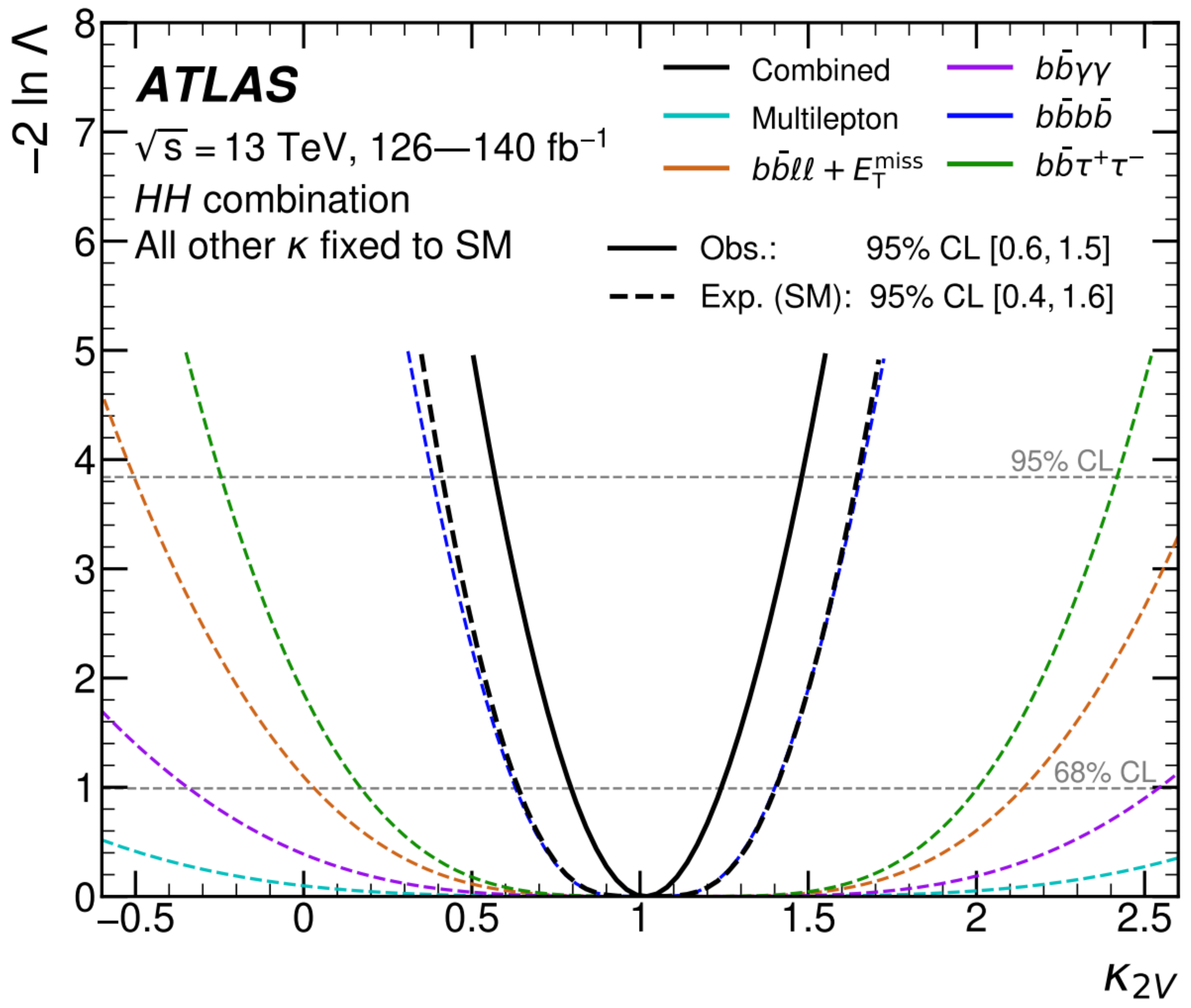
Strength comes from the combination!

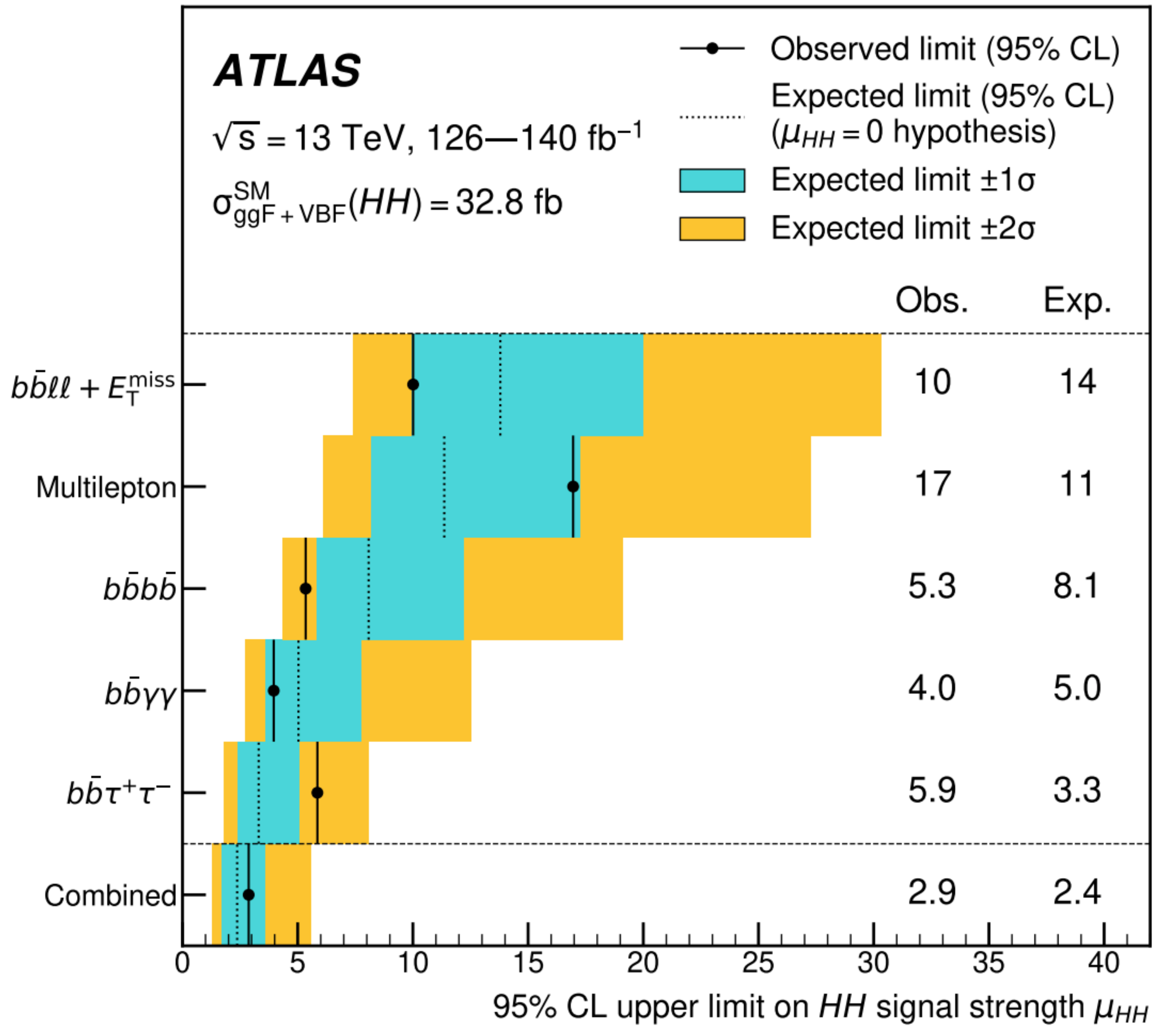
ATLAS Run 2 HH combination



Most sensitive channels are $bb\gamma\gamma$ and $bb\tau\tau$



Most sensitive channel is $bbbb$



Best expected upper limit comes from $bb\tau\tau$

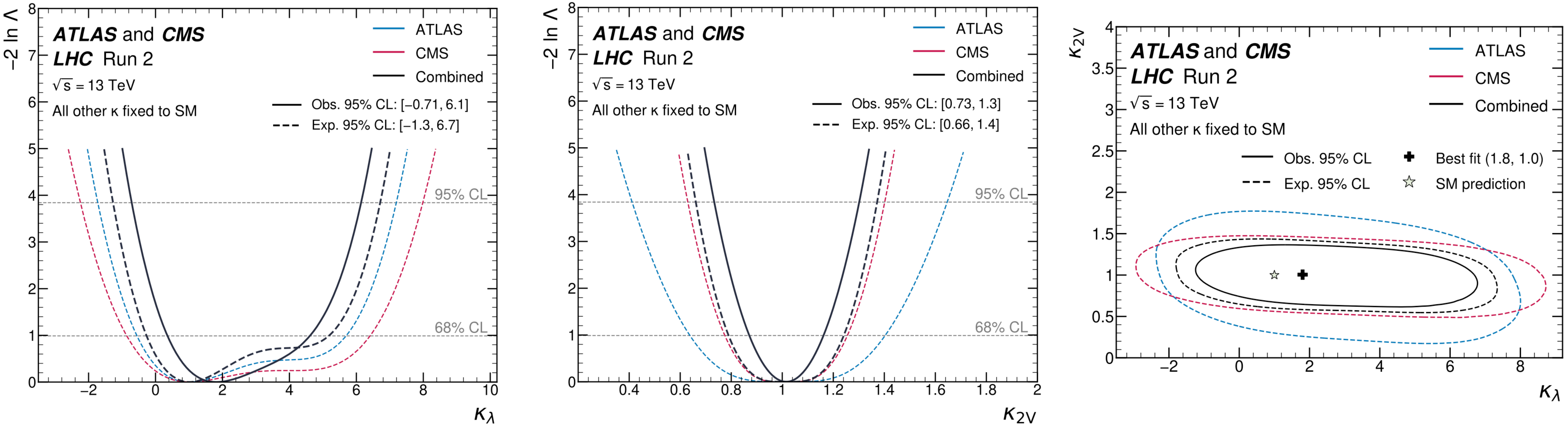
The power of the HH measurements lies in their combination: there is no golden channel

arXiv:2406.09971

HH ATLAS + CMS combination results

Run 2

All the other Higgs boson couplings are fixed to their SM predictions



	κ_3	κ_{2V}
ATLAS	$[-1.3, 7.2]$	$[0.57, 1.5]$
CMS	$[-1.4, 6.6]$	$[0.66, 1.4]$
ATLAS+CMS	$[-0.71, 6.1]$	$[0.73, 1.3]$

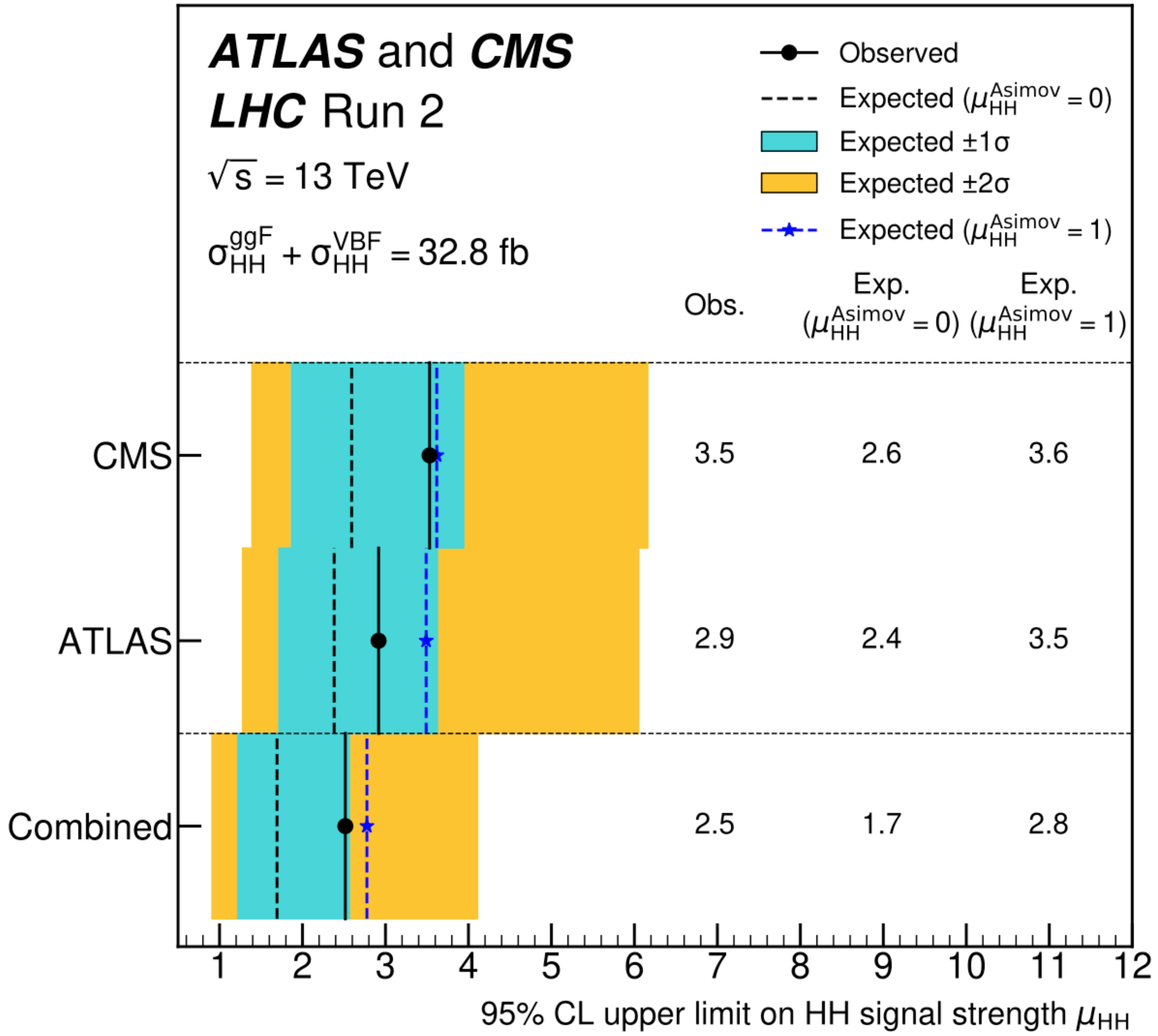
The combination improved the interval width by **~20%** compared to ATLAS and by ~ **15%** compared to CMS combinations alone

arXiv:2602.23991v2

HH ATLAS + CMS combination results

Run 2

	κ_3	κ_{2V}	μ_{HH}
ATLAS	$[-1.3, 7.2]$	$[0.57, 1.5]$	< 2.9
CMS	$[-1.4, 6.6]$	$[0.66, 1.4]$	< 3.5
ATLAS+CMS	$[-0.71, 6.1]$	$[0.73, 1.3]$	< 2.5



The combination improved the upper limit on the signal strength by **~16%** compared to ATLAS and by ~ **40%** compared to CMS combinations alone

arXiv:2602.23991v2 arXiv:2507.03495

Current HH partial Run 3 results

- ATLAS *bbγγ*: **arXiv:2507.03495** Run 2 + 2022-2024, **2024 data included**
- CMS *bbγγ*: **CMS PAS HIG-25-007**, only 2022-2023, **2D fit $m_{\gamma\gamma}$ vs. m_{jj}**
- CMS *4b*: **CMS PAS HIG-24-010**, only 2022-2023
- ATLAS *ttHH*: **arXiv:2603.13113**, Run 2 + 2022-2023

ATLAS HH most stringent single channel limits to-date

non-resonant $HH \rightarrow bb\gamma\gamma$ Run 2 + partial Run 3

2022-2024

first analysis including 2024 data !!!

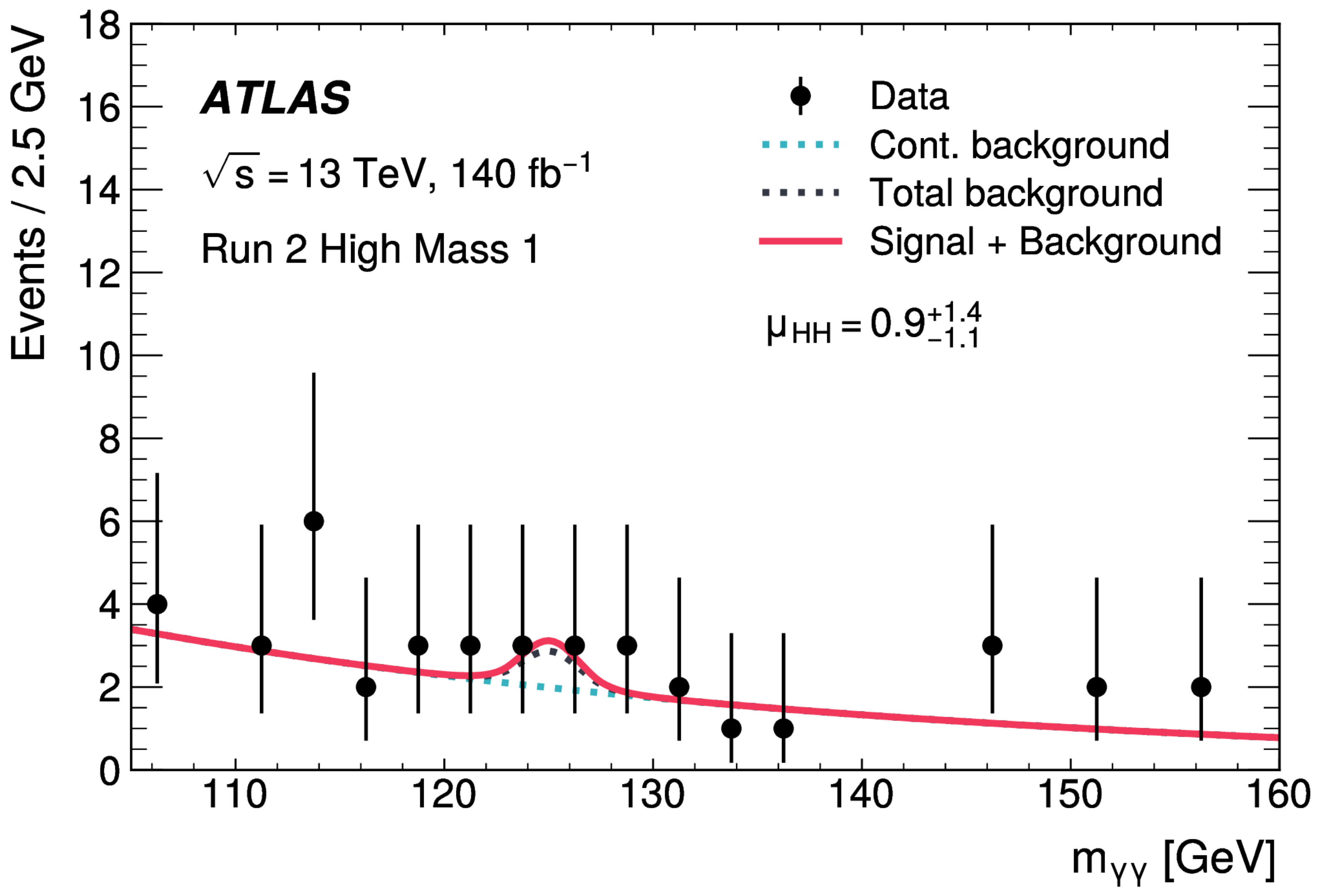
+168 fb^{-1} !!!

arXiv:2507.03495

ATLAS HH most stringent single channel limits to-date

non-resonant $HH \rightarrow bb\gamma\gamma$ Run 2 + partial Run 3

- Split into high mass region and low mass region
- Train Boosted Decision Trees (BDTs) to distinguish signal from backgrounds
- Make categories based on the BDTs outputs
- Make simultaneous fits to $m_{\gamma\gamma}$



fit B → $\kappa_3 = \frac{\lambda_3^{obs.}}{\lambda_3^{SM}}$

fit A → $\mu = \frac{\sigma_{obs.}}{\sigma_{SM}}$

arXiv:2507.03495

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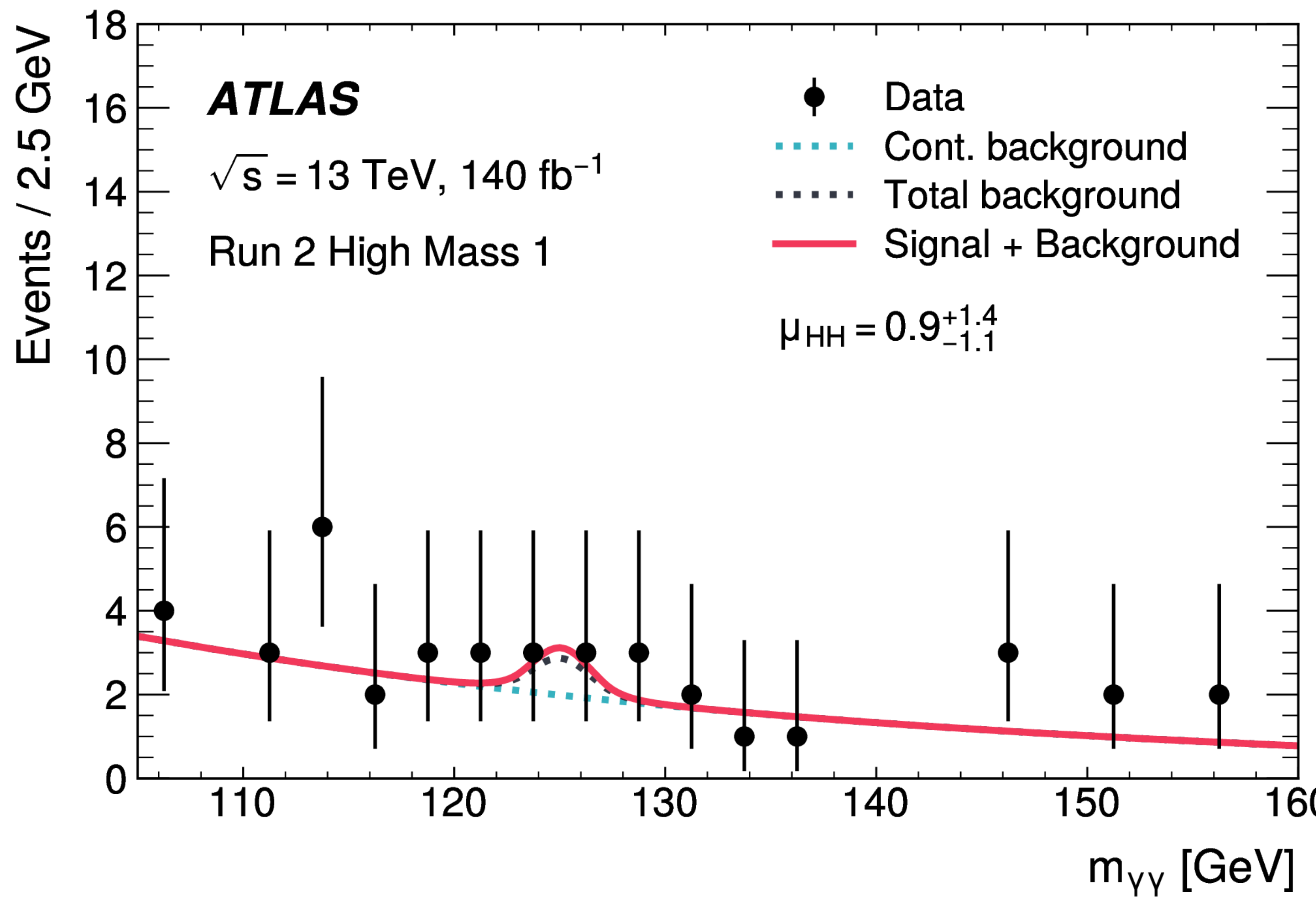

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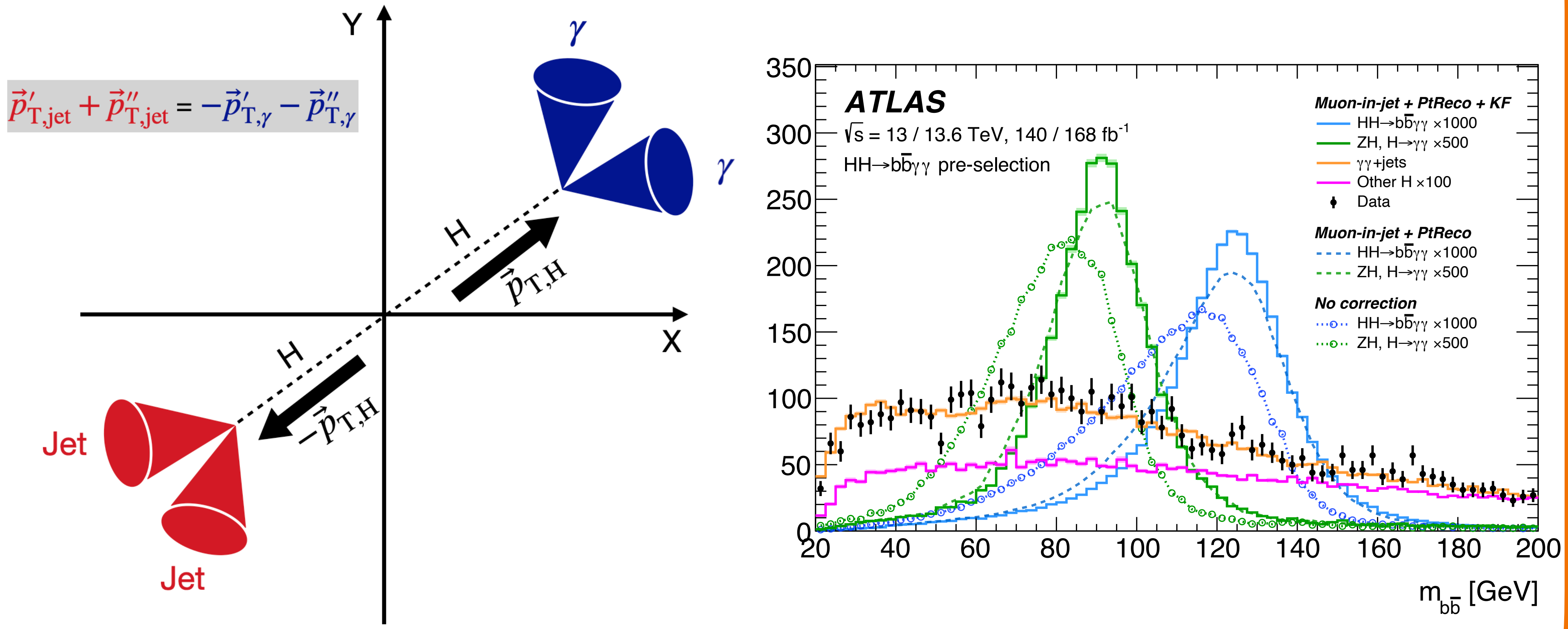
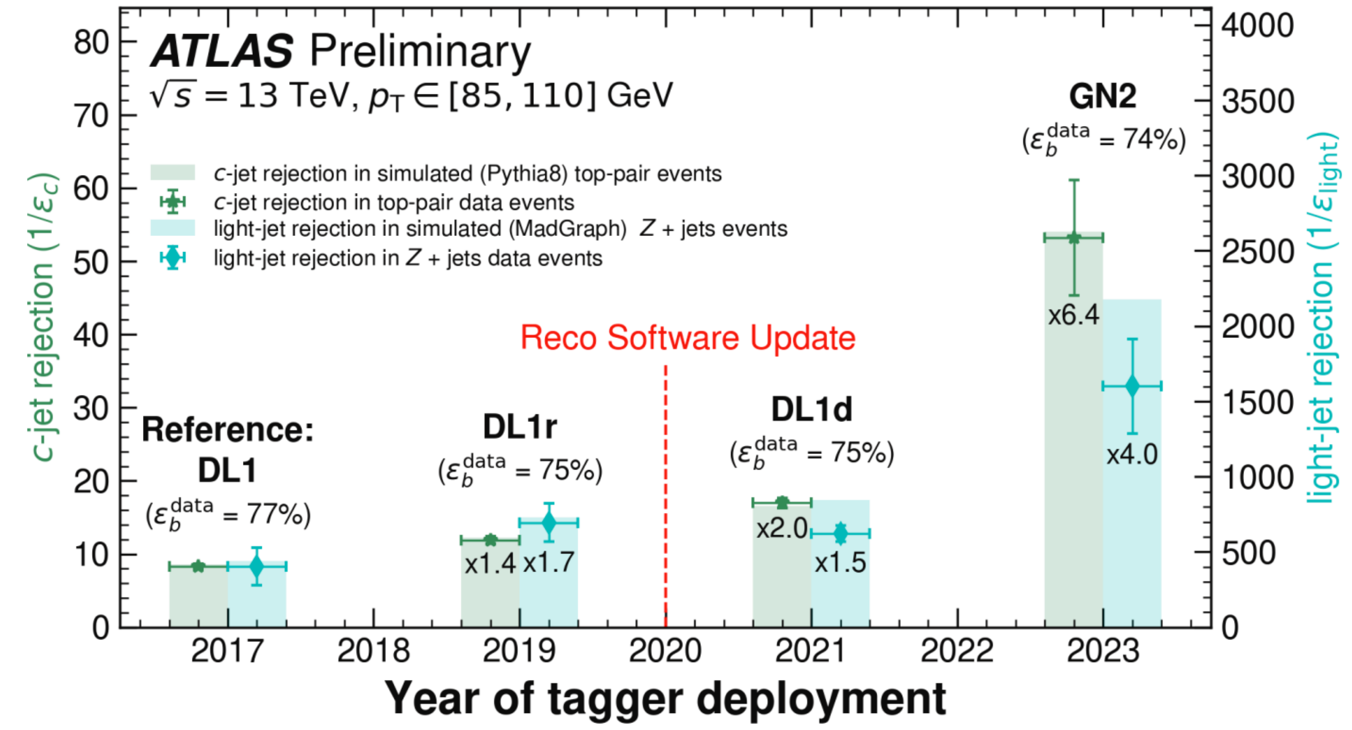
arXiv:2507.03495

Kinematic fit



μ_{HH} **improved by ~ 5%**

Flavour tagging improvements



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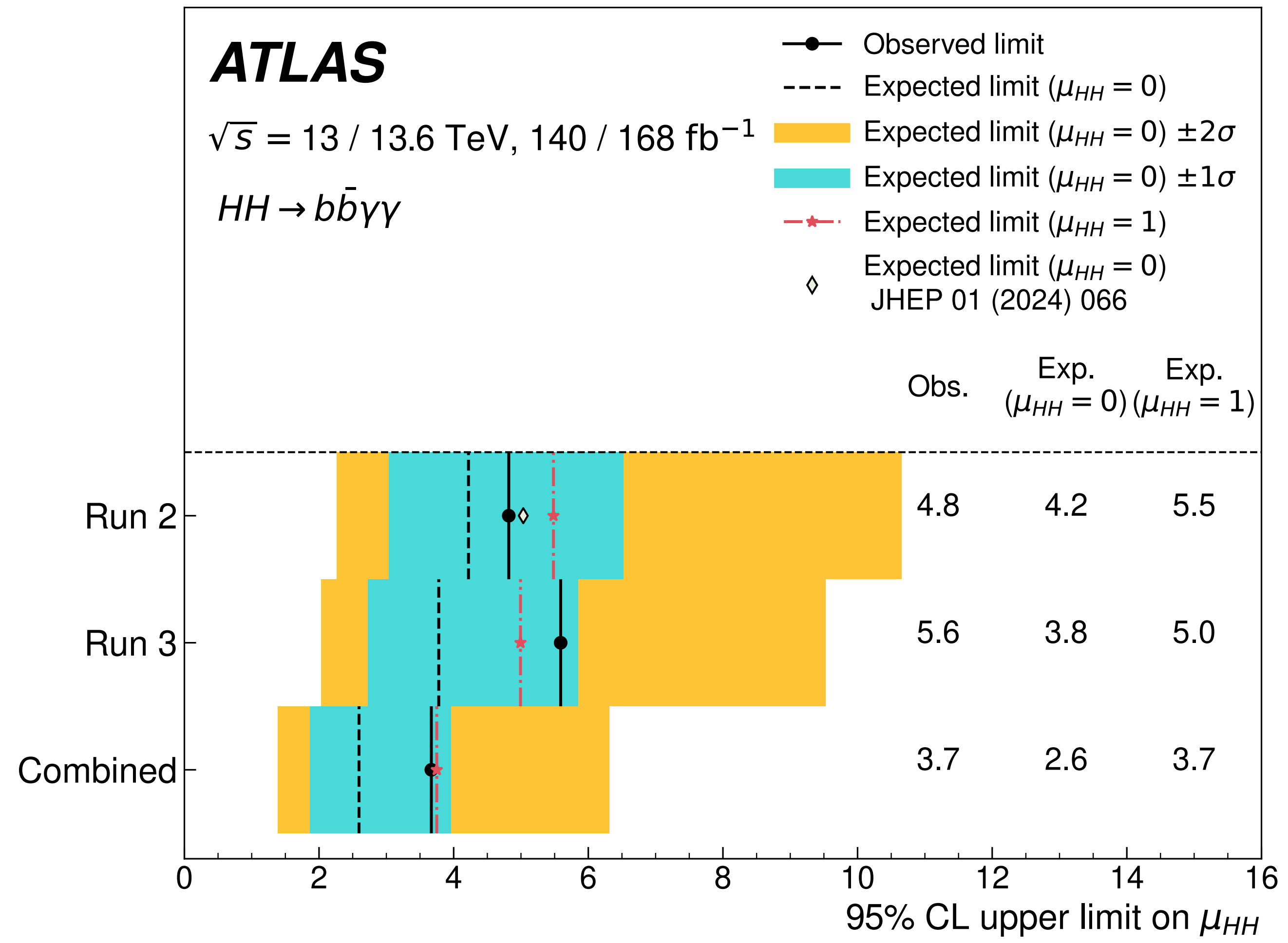
Current HH partial Run 3 results



- ATLAS $bb\gamma\gamma$: **arXiv:2507.03495** Run 2 + 2022-2024, **2024 data included**

$$\mu_{HH} < 3.7, \kappa_3 \in [-1.6, 6.6]$$

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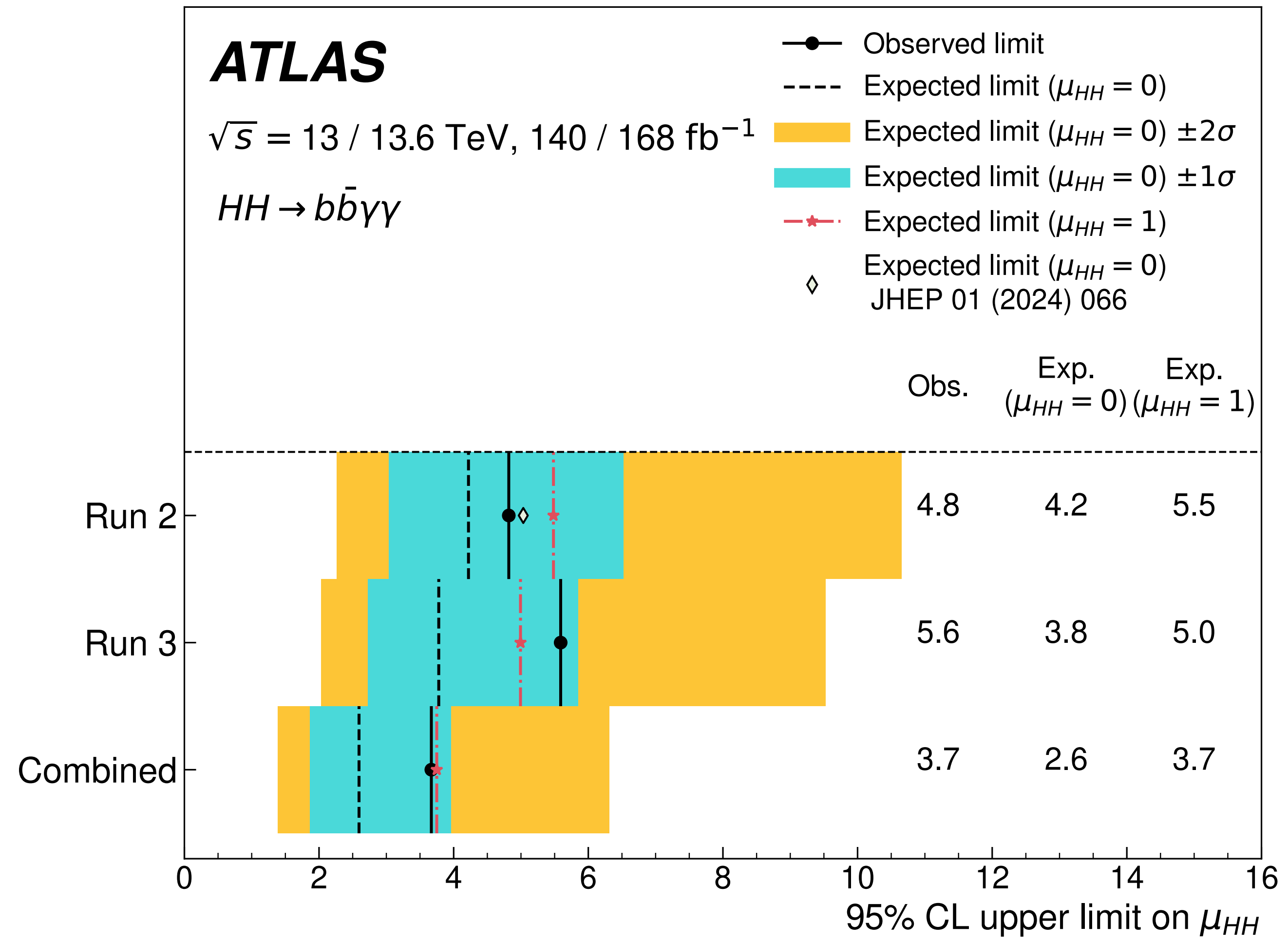
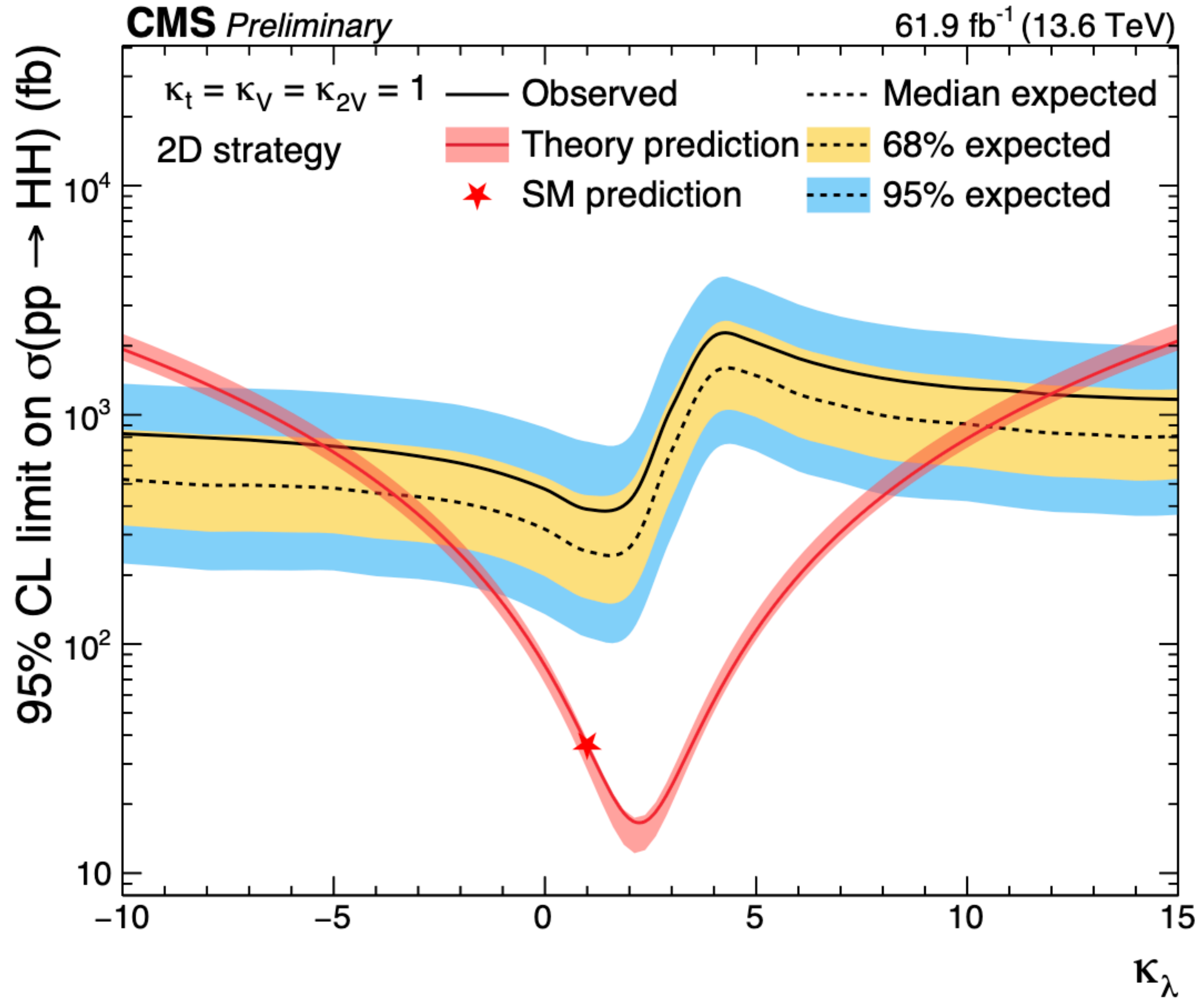


$$\mu_{HH} < 3.7,\ \kappa_3 \in [-1.6, 6.6]$$

- CMS $bb\gamma\gamma$: CMS PAS HIG-25-007, only 2022-2023, **2D fit $m_{\gamma\gamma}$ vs. m_{jj}**



1D fit: $\kappa_3 \in [-3.9, 10.4]$

2D fit: $\kappa_3 \in [-5, 12]$

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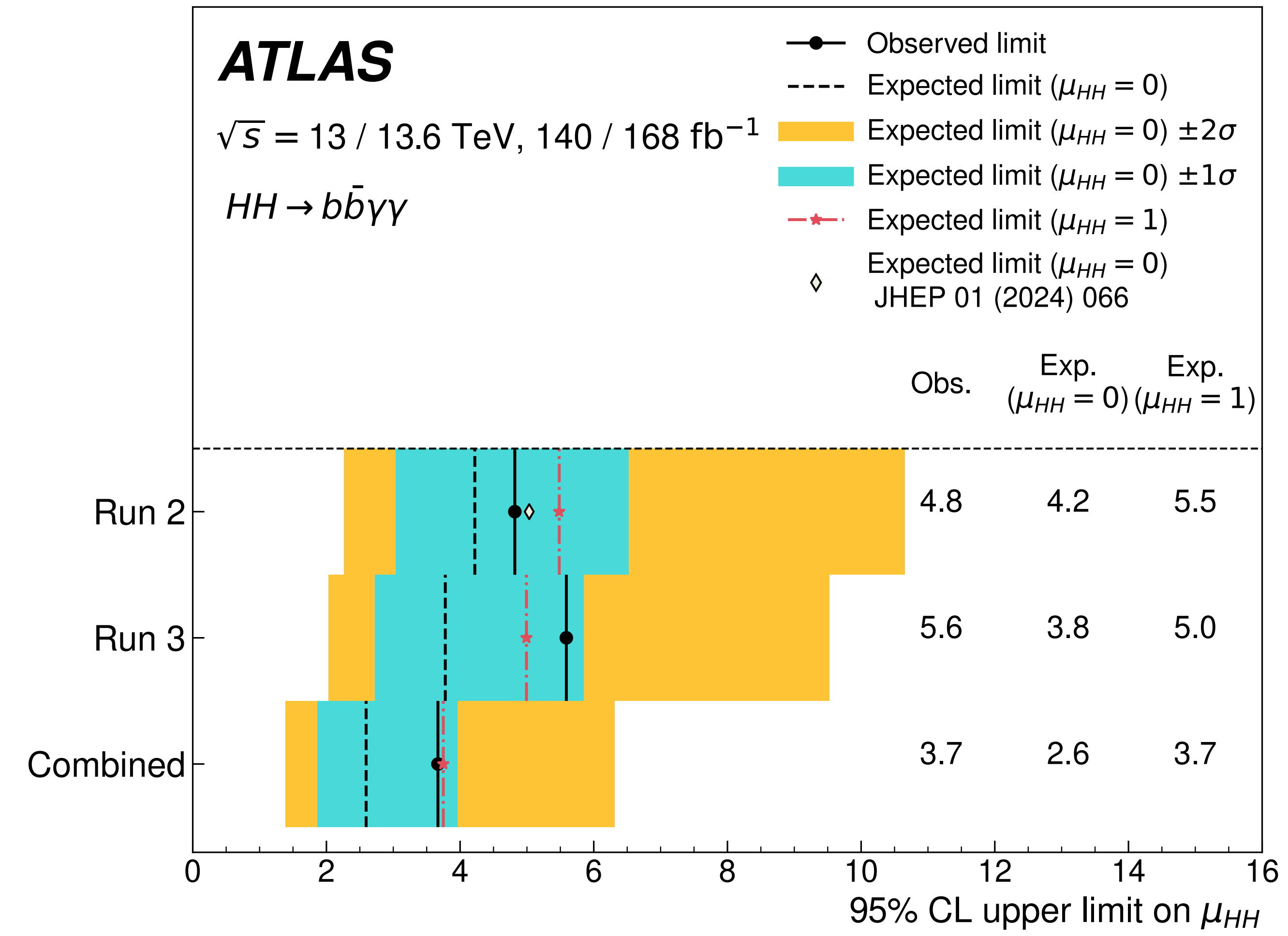

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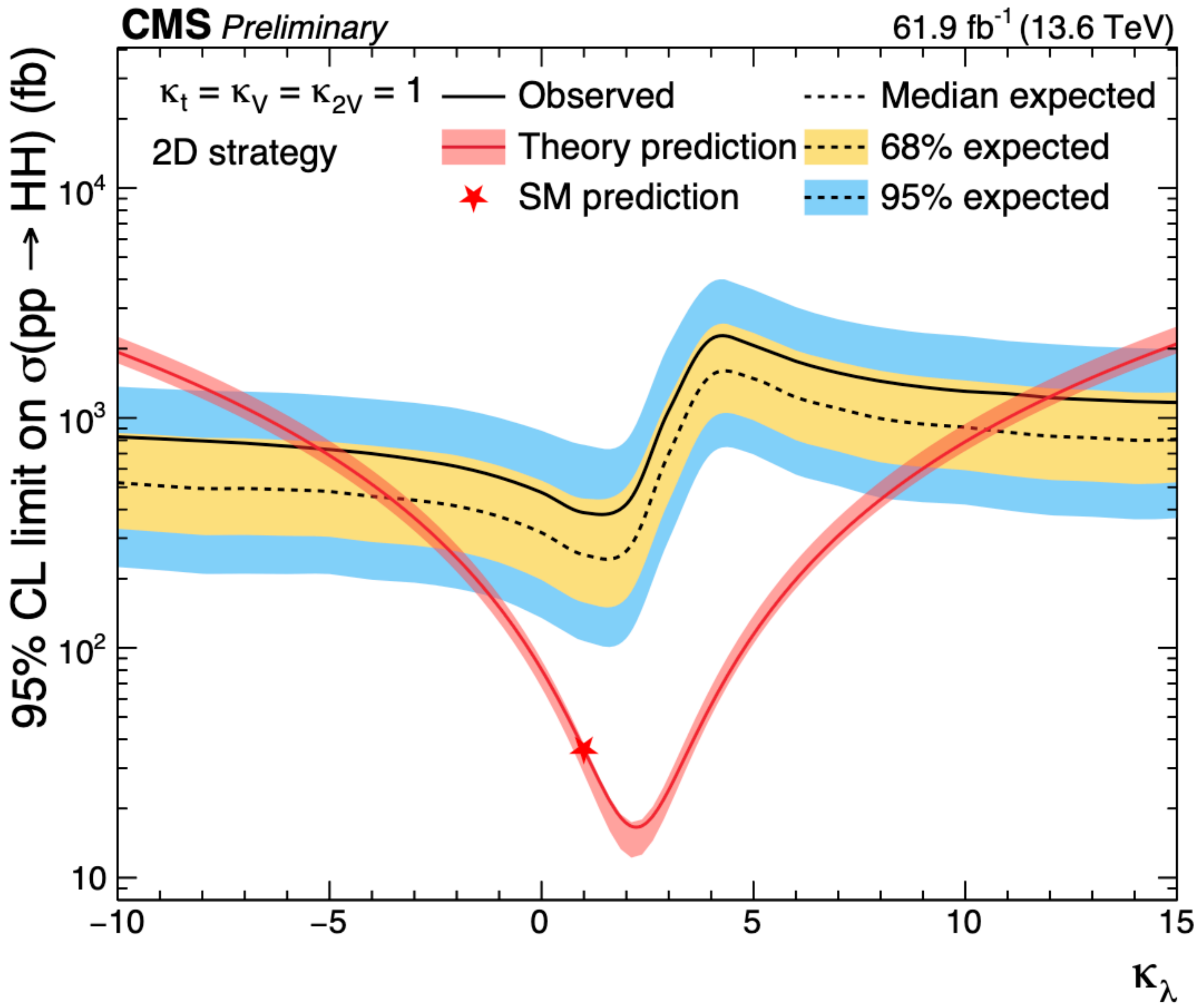
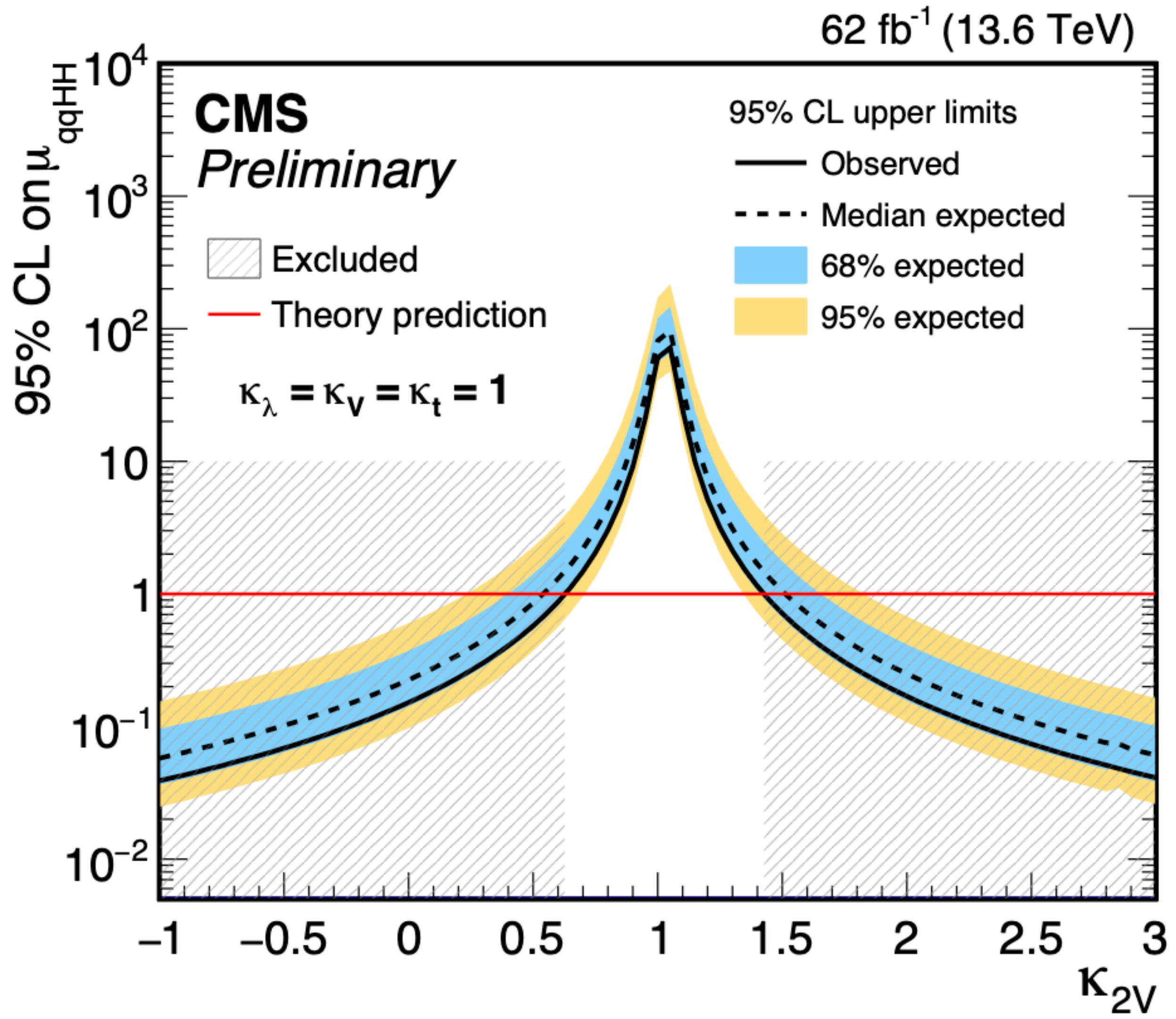


1D fit: $\kappa_3 \in [-3.9, 10.4]$

2D fit: $\kappa_3 \in [-5, 12]$

- CMS *4b*: CMS PAS HIG-24-010, only 2022-2023

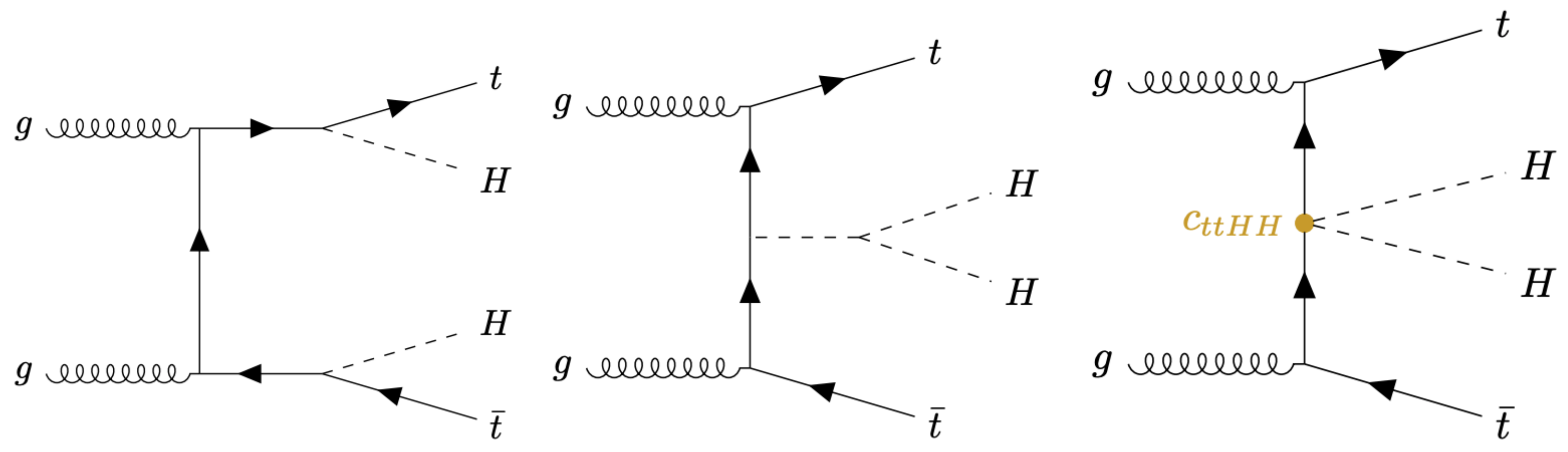
$$\kappa_{2V} \in [0.63, 1.43]$$

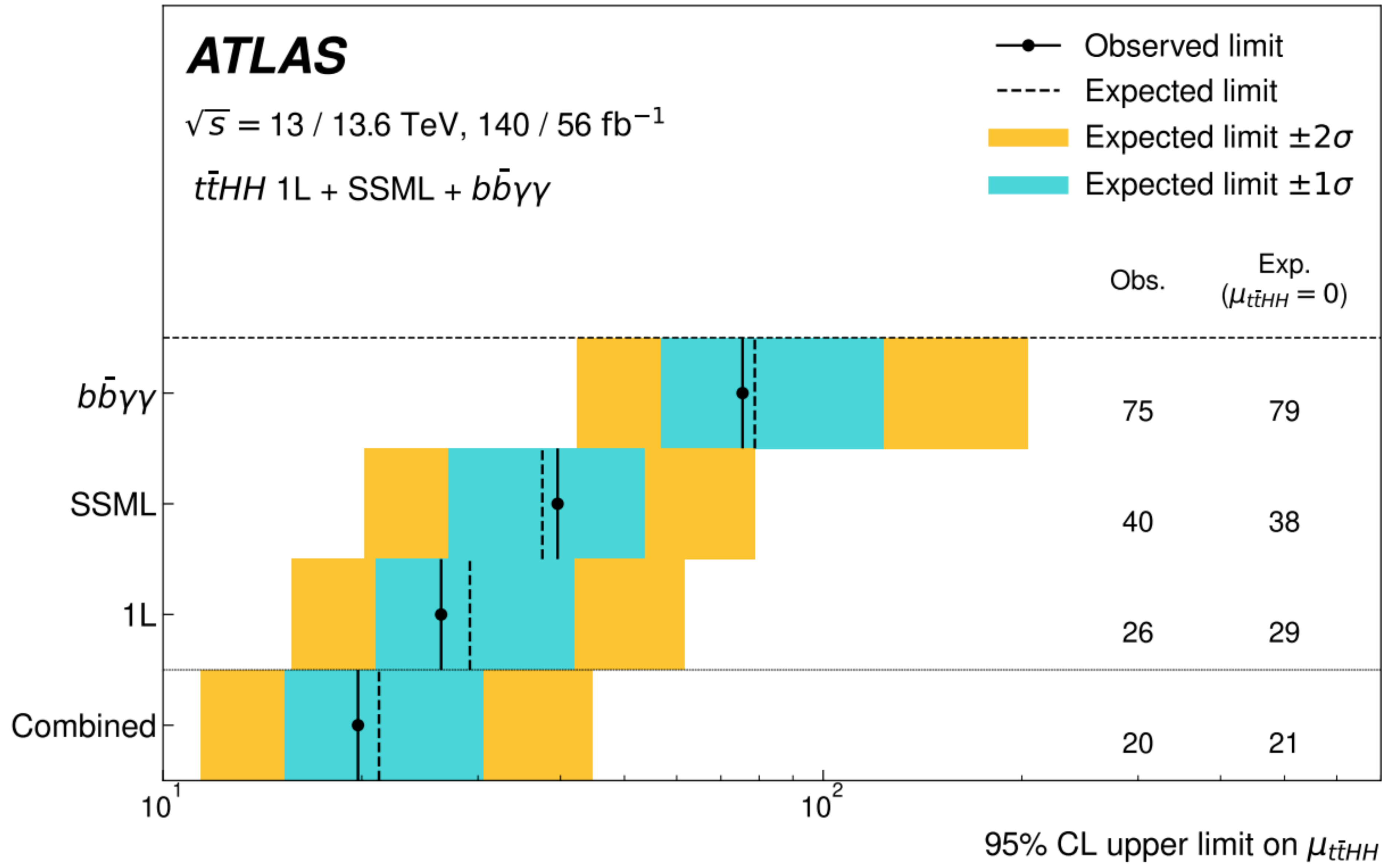


- ATLAS *ttHH*: arXiv:2603.13113, Run 2 + 2022-2023

ATLAS ttHH - Run 2 + partial Run 3

- Run 2 + pRun 3 = 196 fb^{-1}
- targets 3 final states:
  - 1L: $1\ell + \geq 5$b-jets
  - SSML: ≥ 2b-jets + (2ℓ(SS) or $> 2\ell$)
  - $bb\gamma\gamma$: ≥ 2b-jets + 2γ
- 3 final states → different analysis strategies:
  - 1L and SSML: transformer to distinguish signal from bkg, MC and data for bkg estimation, fit to transformer output and selected variables in bkg CRs
  - $bb\gamma\gamma$: very similar strategy as $HH \to bb\gamma\gamma$ fit to $m_{\gamma\gamma}$
- HEFT interpretation: $-3.9 < c_{t\bar{t}HH} < 3.3$ (95% CL)



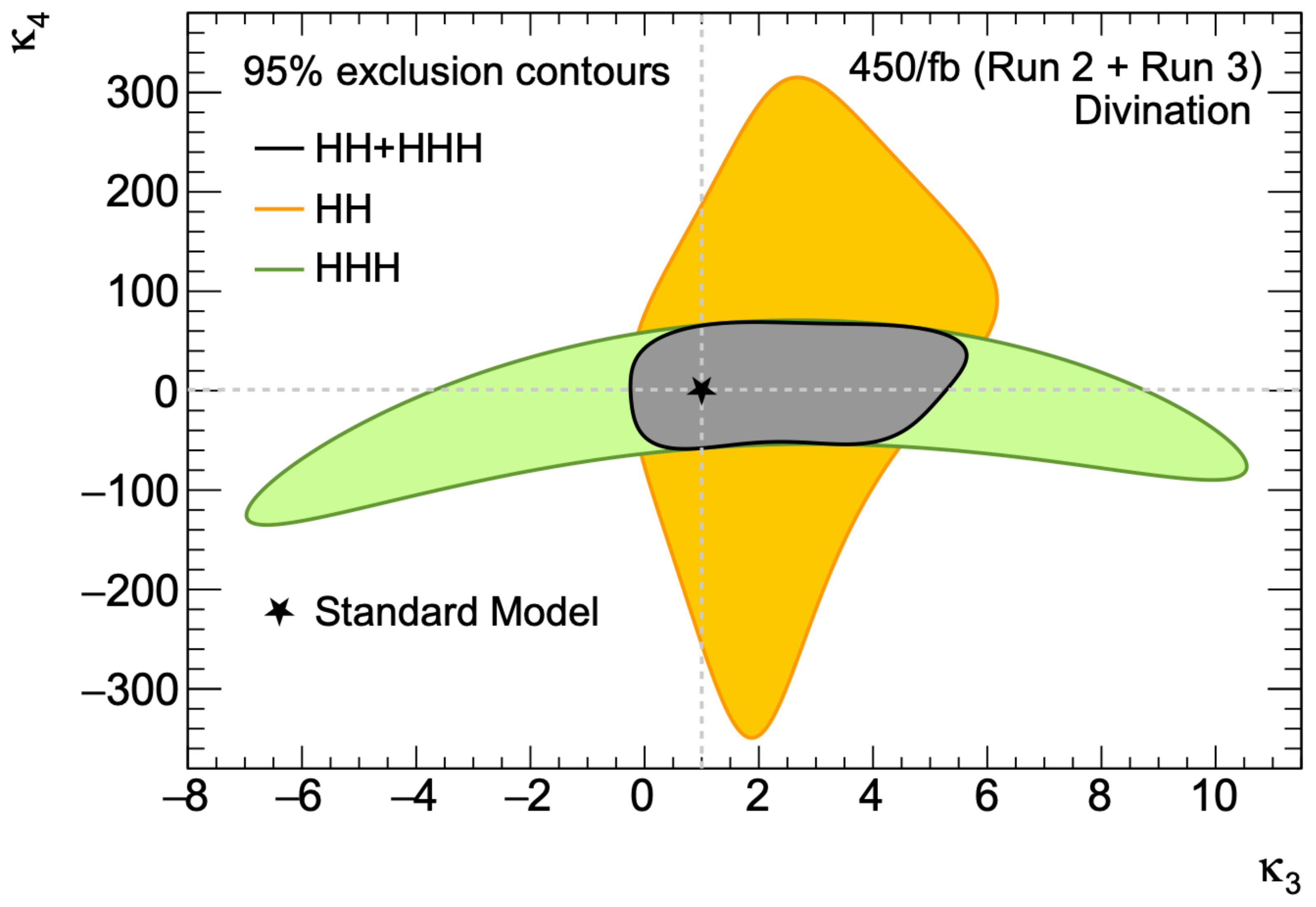


$\mu_{t\bar{t}HH} < 20$ (95% CL)

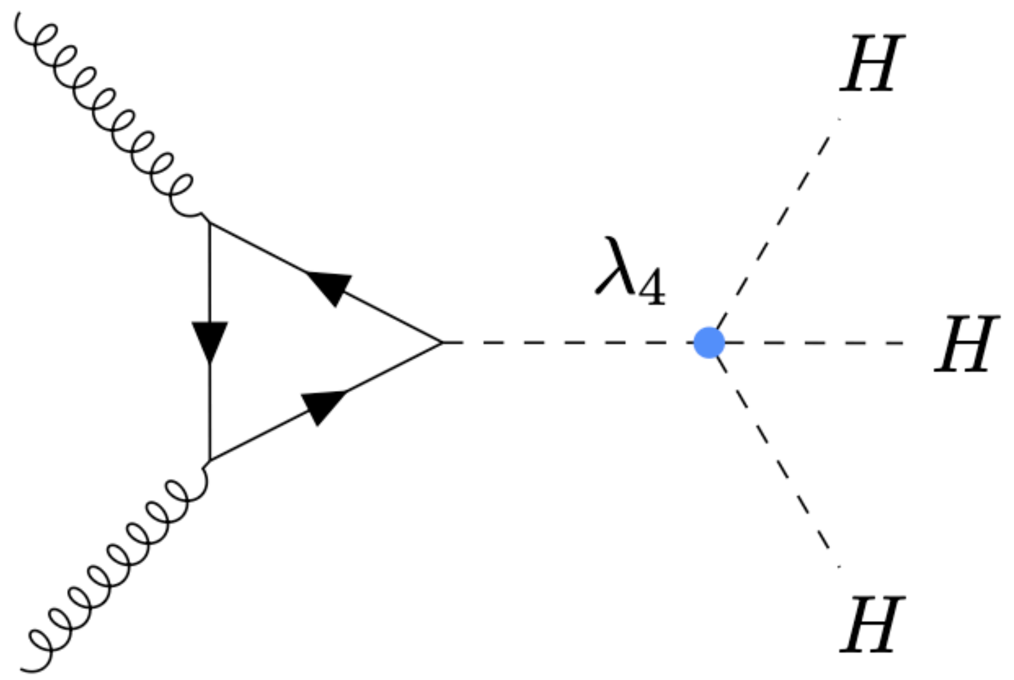
arXiv:2603.13113 *CMS ttHH: [CMS-PAS-HIG-23-004](), only Run 2*

Triple Higgs Boson production

HHH methodology concept



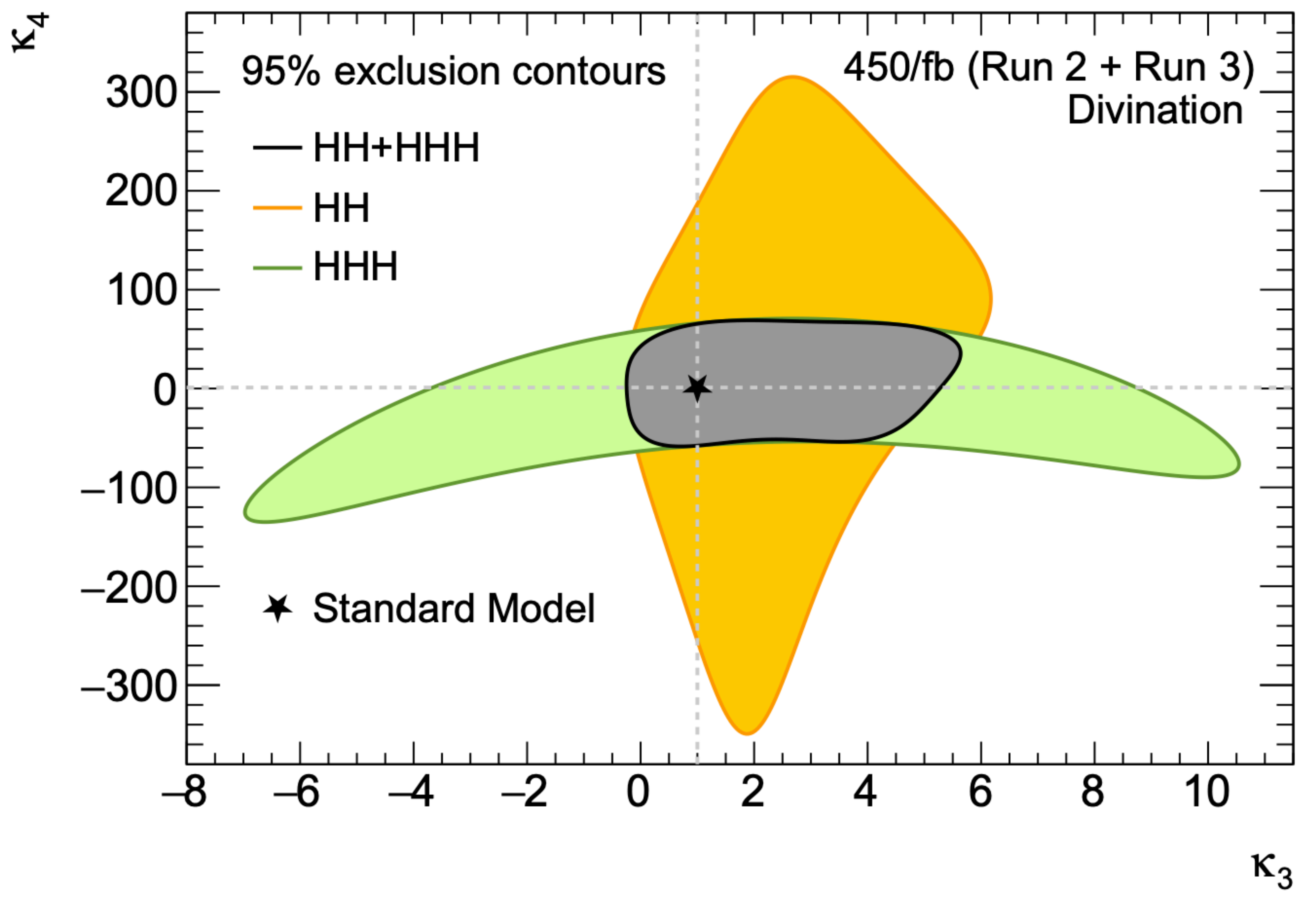
- HHH is complementary to HH searches
- HHH is uniquely suited to access κ_4

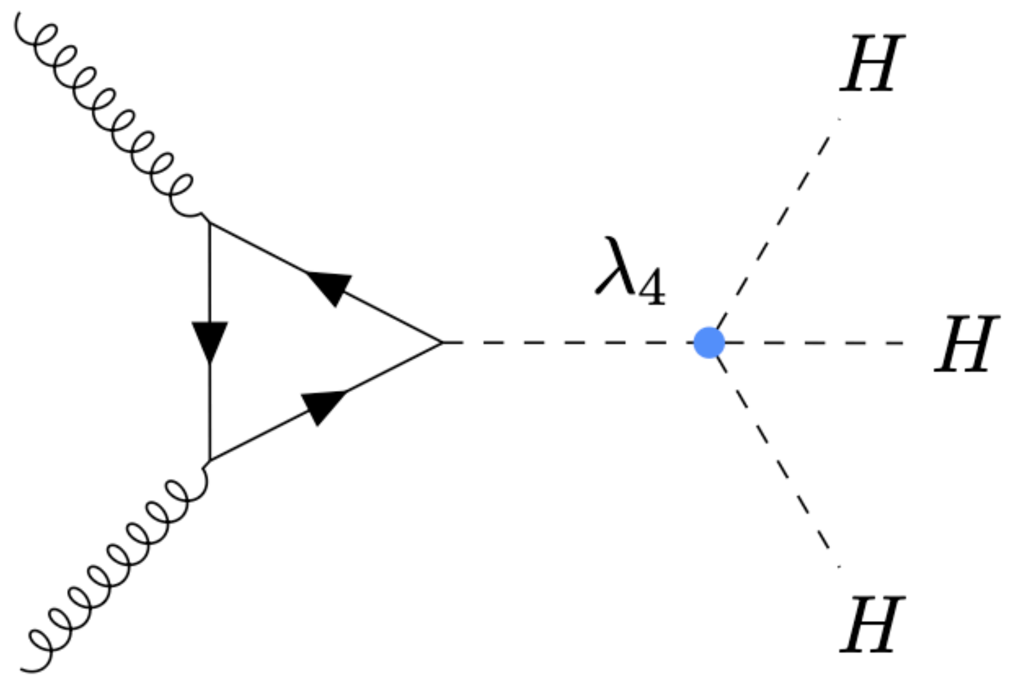


arXiv:2407.03015

HHH methodology concept

- HHH is complementary to HH searches
- HHH is uniquely suited to access κ_4
- 3 most promising channels to explore are:
  - $HHH \to 6b$
  - $HHH \to 4b2\gamma$
  - $HHH \to 4b2\tau$





BR(HHH → bb xx yy) [%]

$m_H = 125.25$ GeV

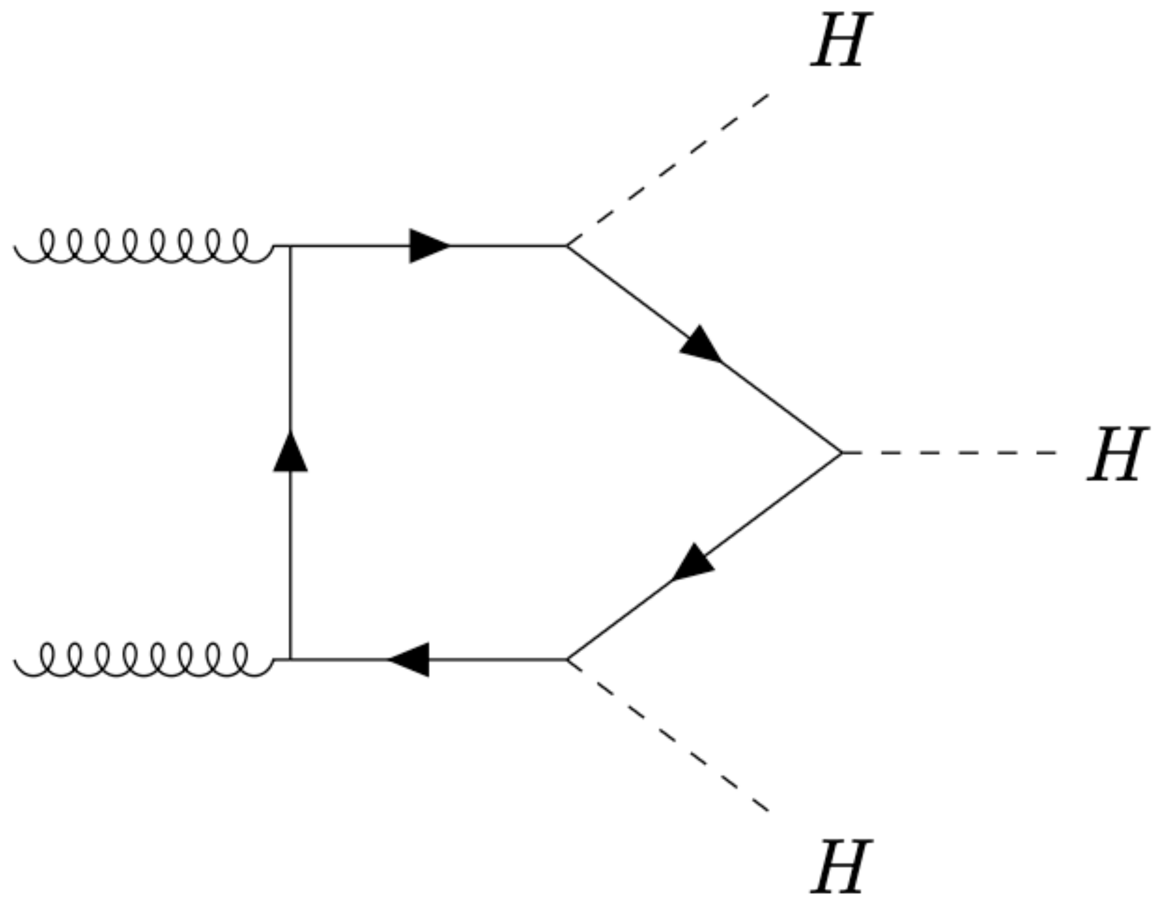
	bb	WW	gg	ττ
bb	19.3%			
WW	21.8%	8.2%		
gg	8.2%	6.2%	1.2%	
ττ	6.2%	4.7%	1.8%	0.7%
ZZ	2.7%	2.0%	0.8%	0.6%
yy	0.2%	0.2%	0.1%	0.0%

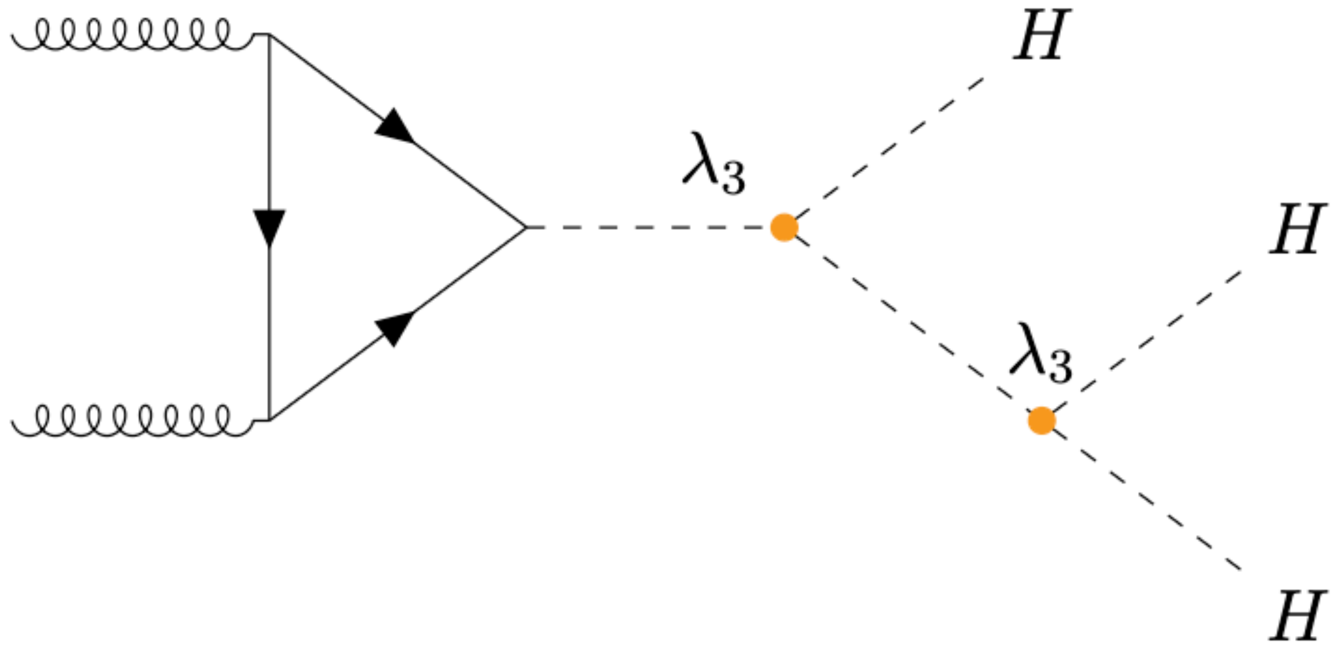
arXiv:2407.03015

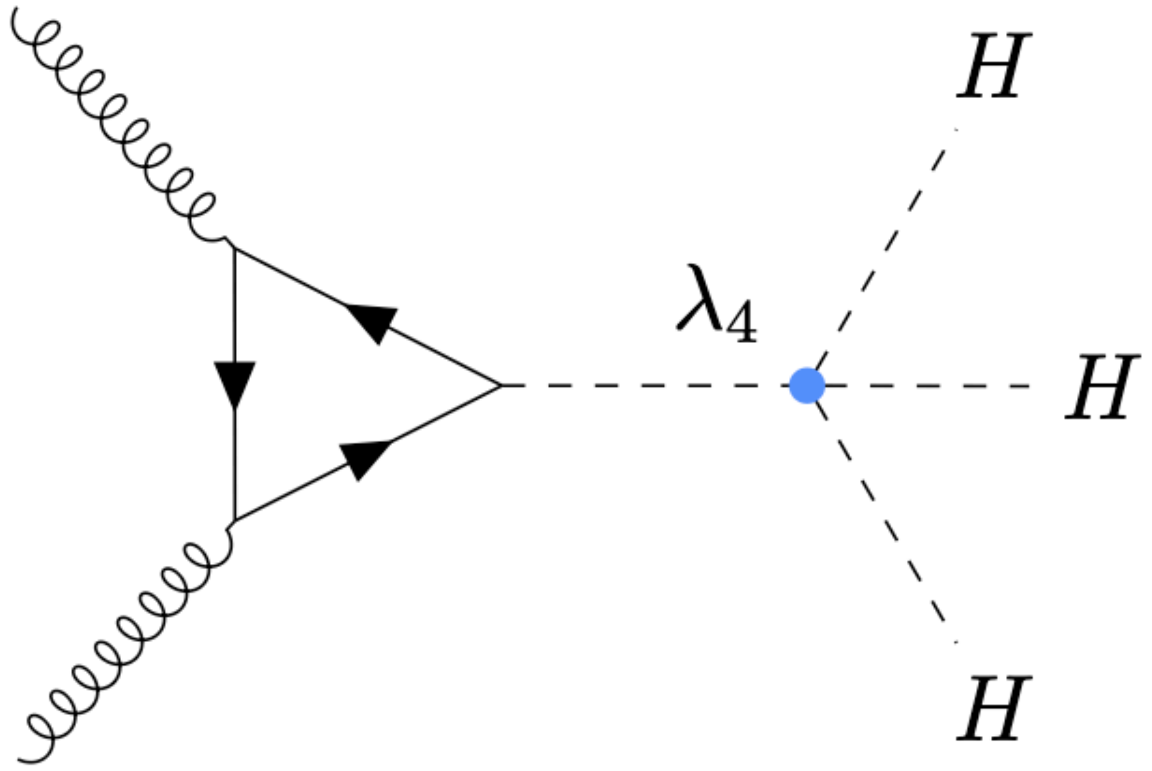
Current triple Higgs boson production landscape

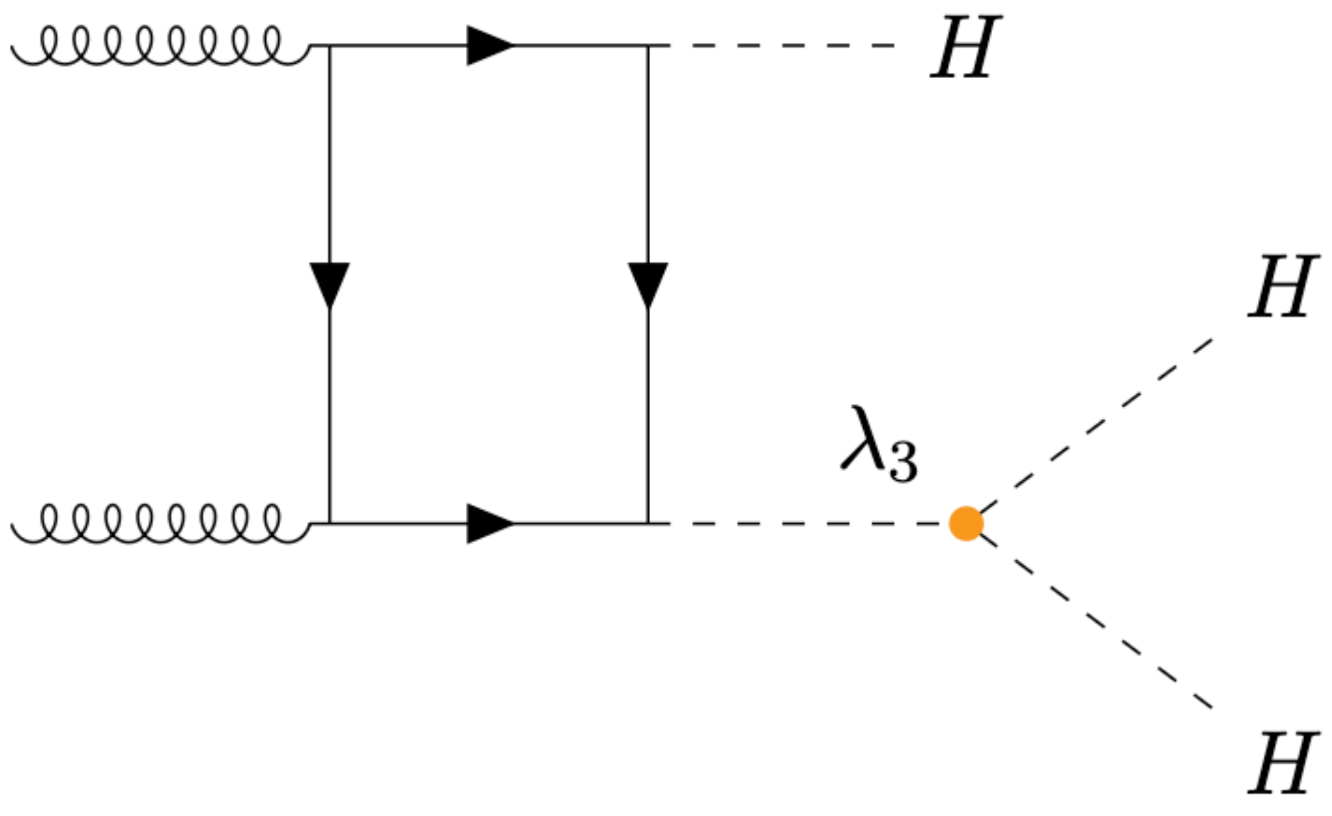
Only 3 searches have been published looking into triple Higgs boson production:

- ATLAS $HHH \rightarrow 6b$: **Phys. Rev. D 111, 032006**
- CMS $HHH \rightarrow 6b$: **CMS PAS HIG-24-012**
- CMS $HHH \rightarrow 4b2\gamma$: **CMS PAS HIG-24-015**





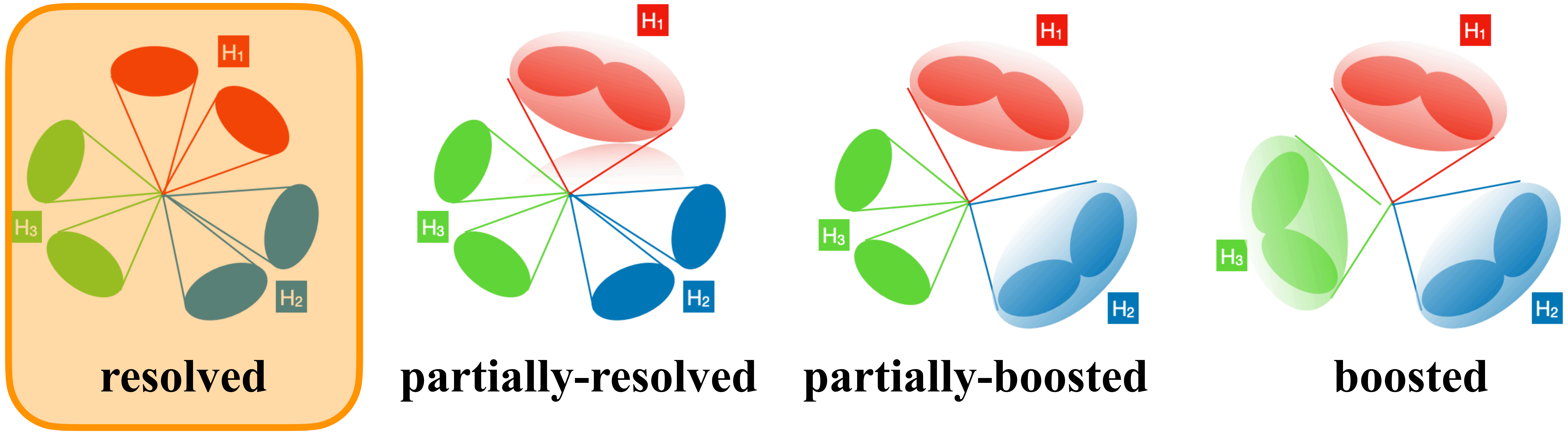




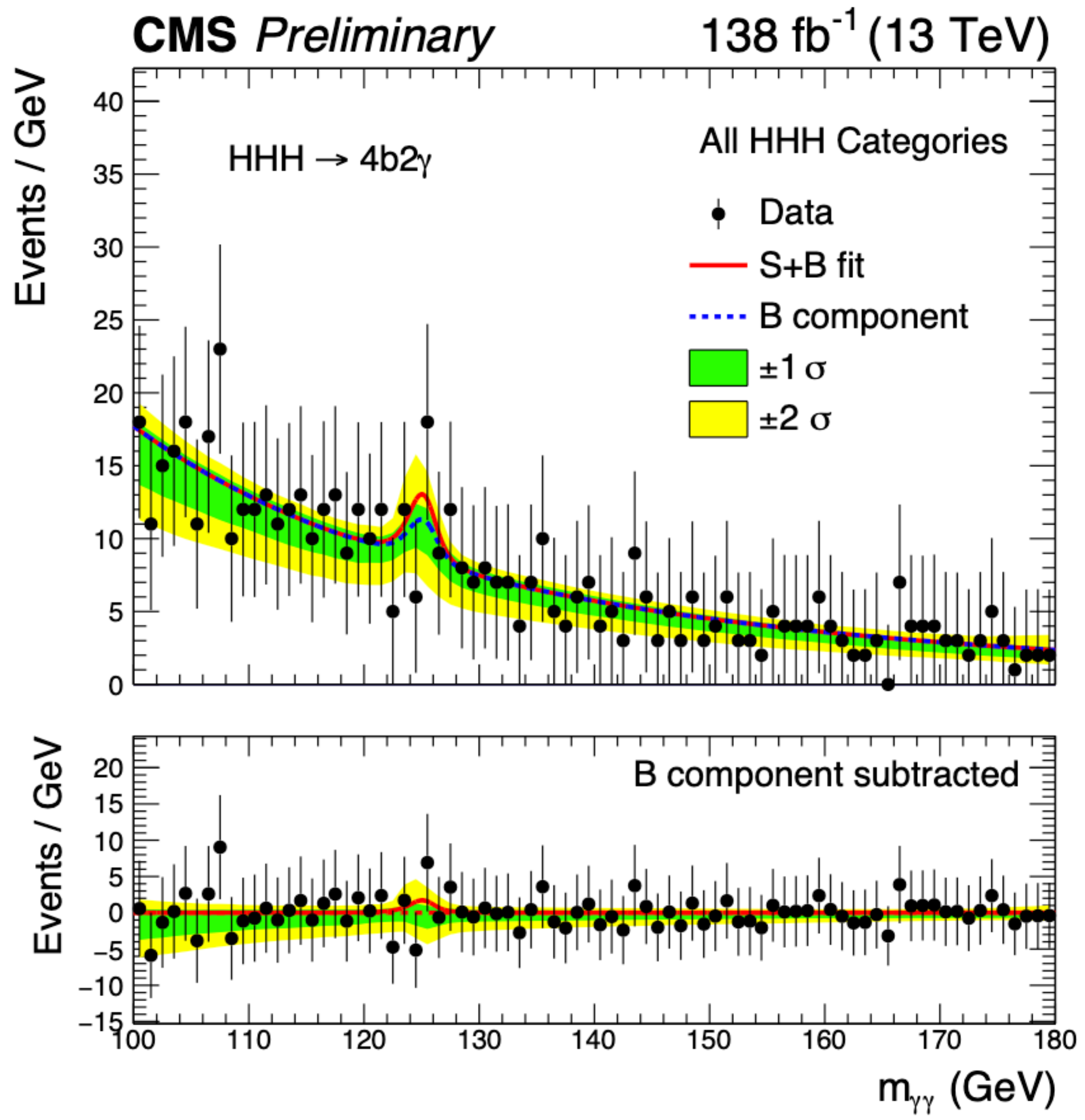
CMS PAS HIG-24-015

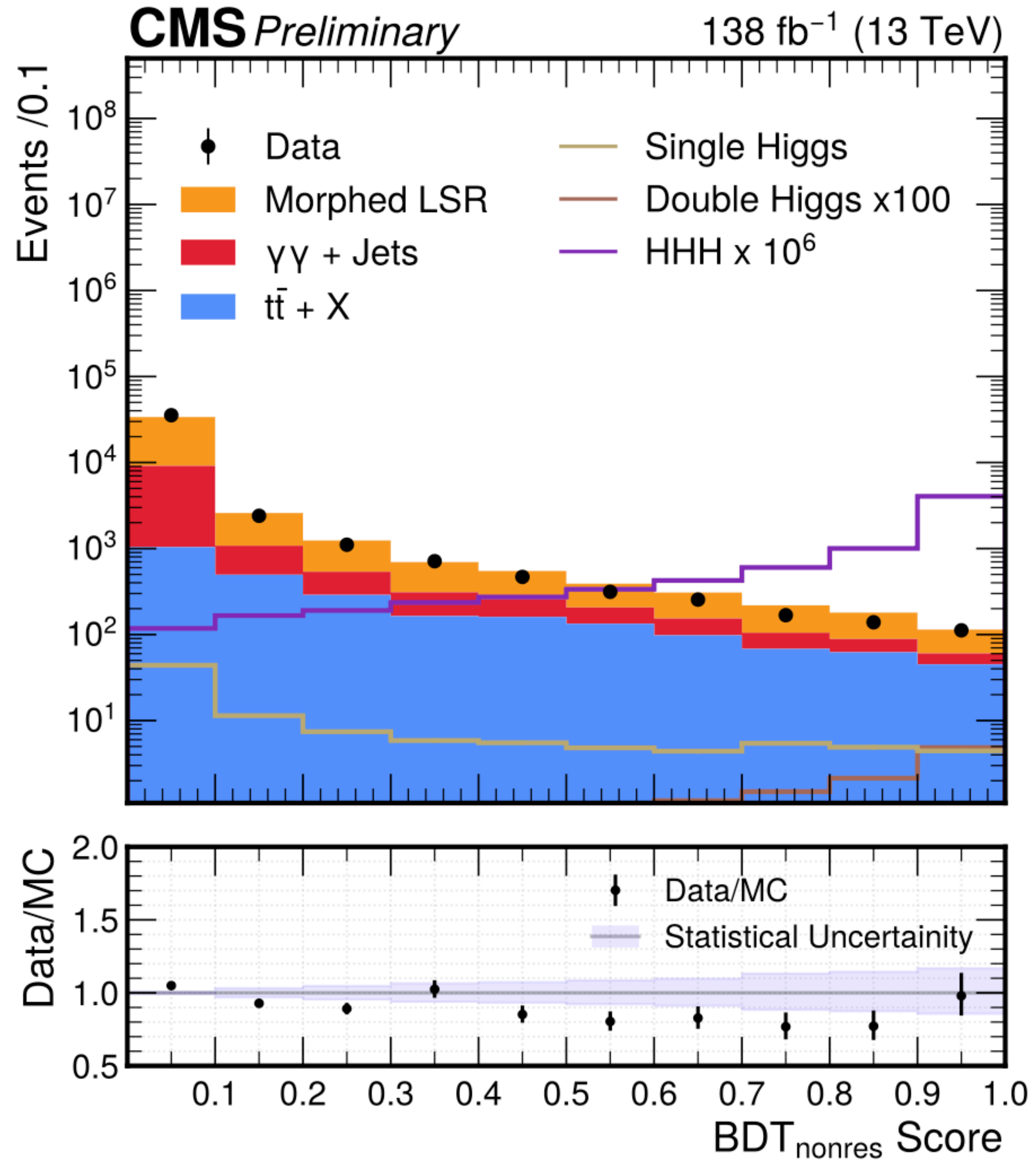
CMS $HHH \to 4b2\gamma$ analysis - Run 2

- only resolved topology is considered



- A BDT is used to separate signal from background
- The final result is extracted via a 2D Fit (or simultaneous fit) of the $m_{\gamma\gamma}$ distribution and the BDT output scores



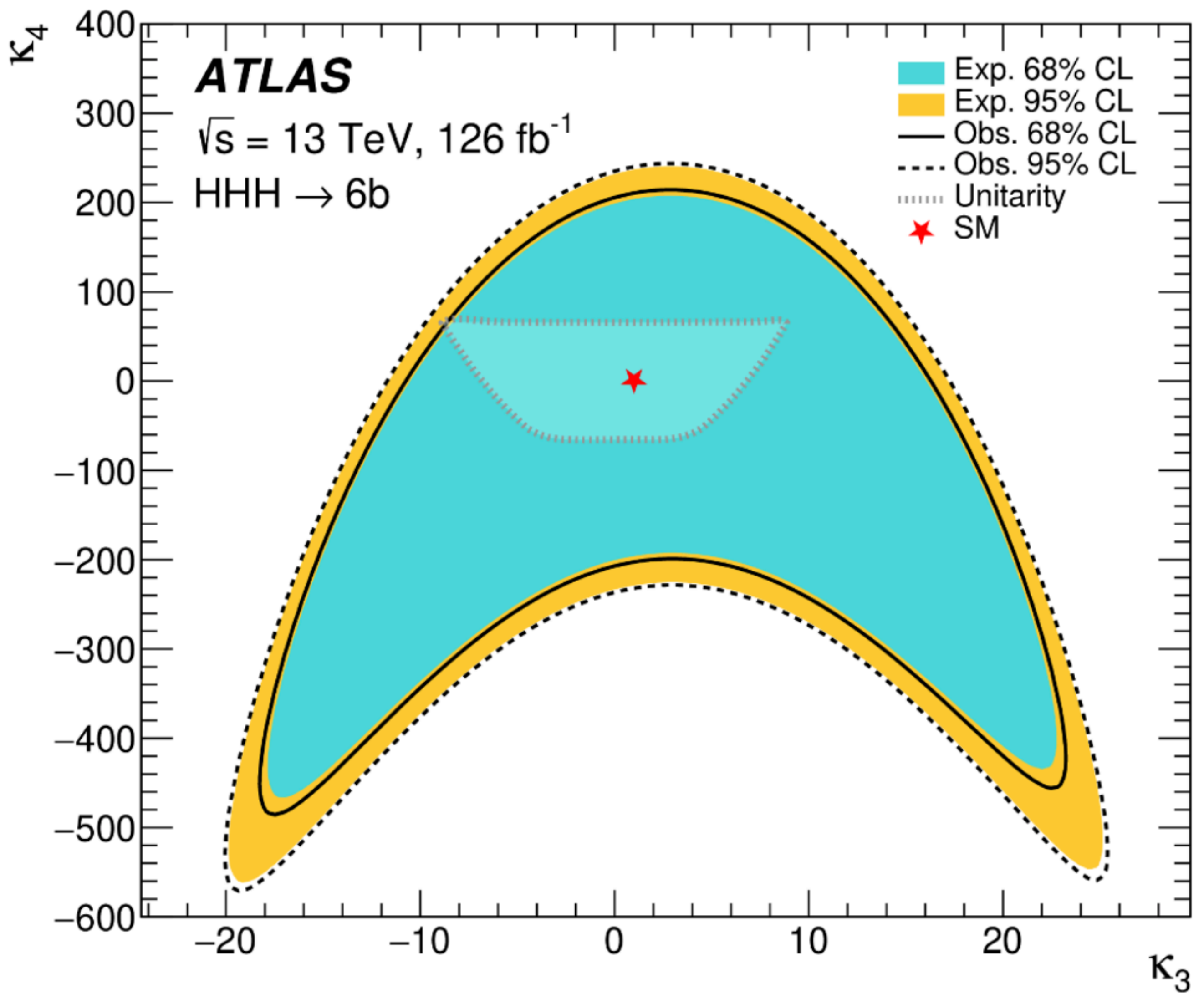


CMS PAS HIG-24-015

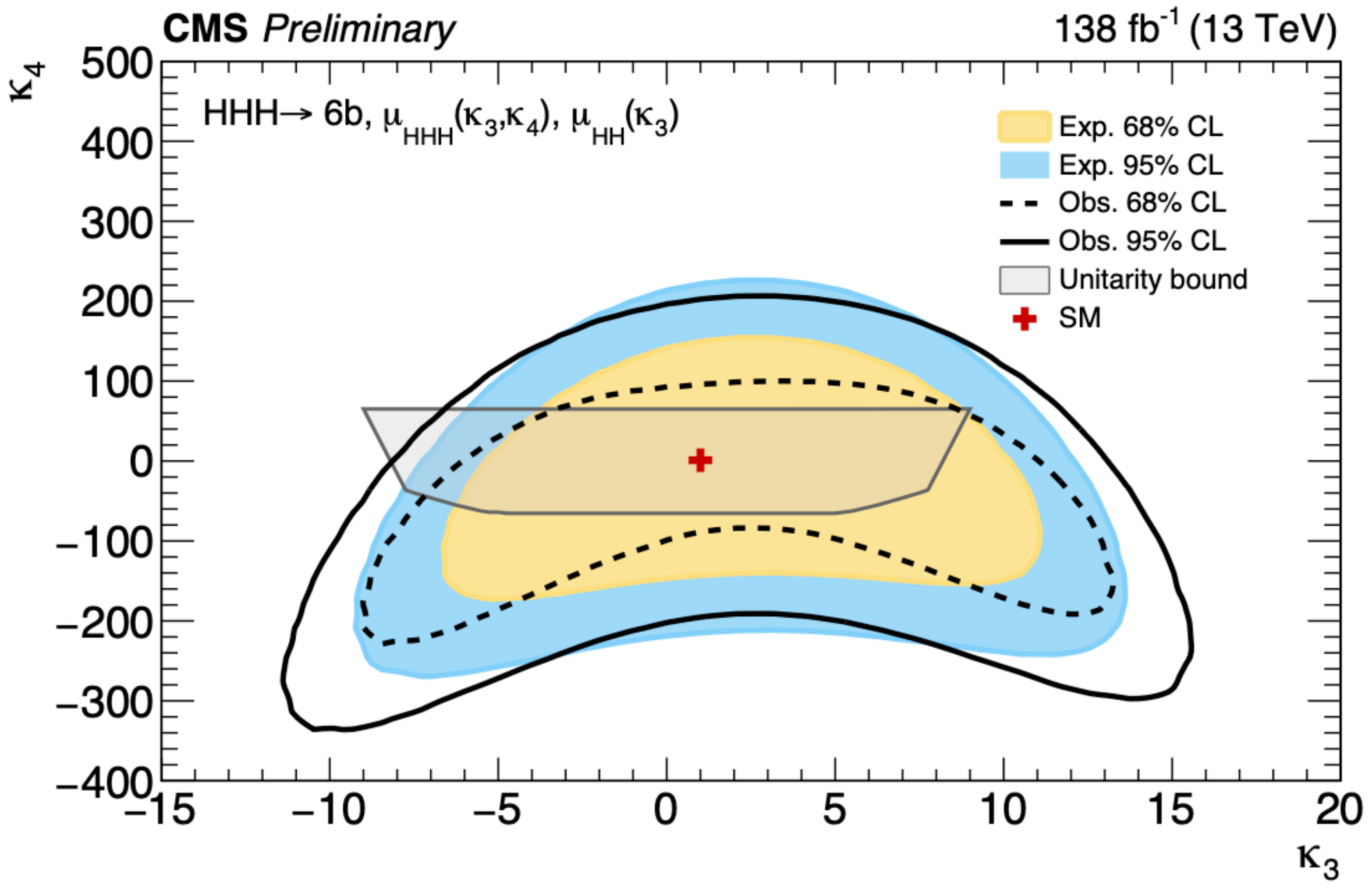
HHH summary of results

Run 2

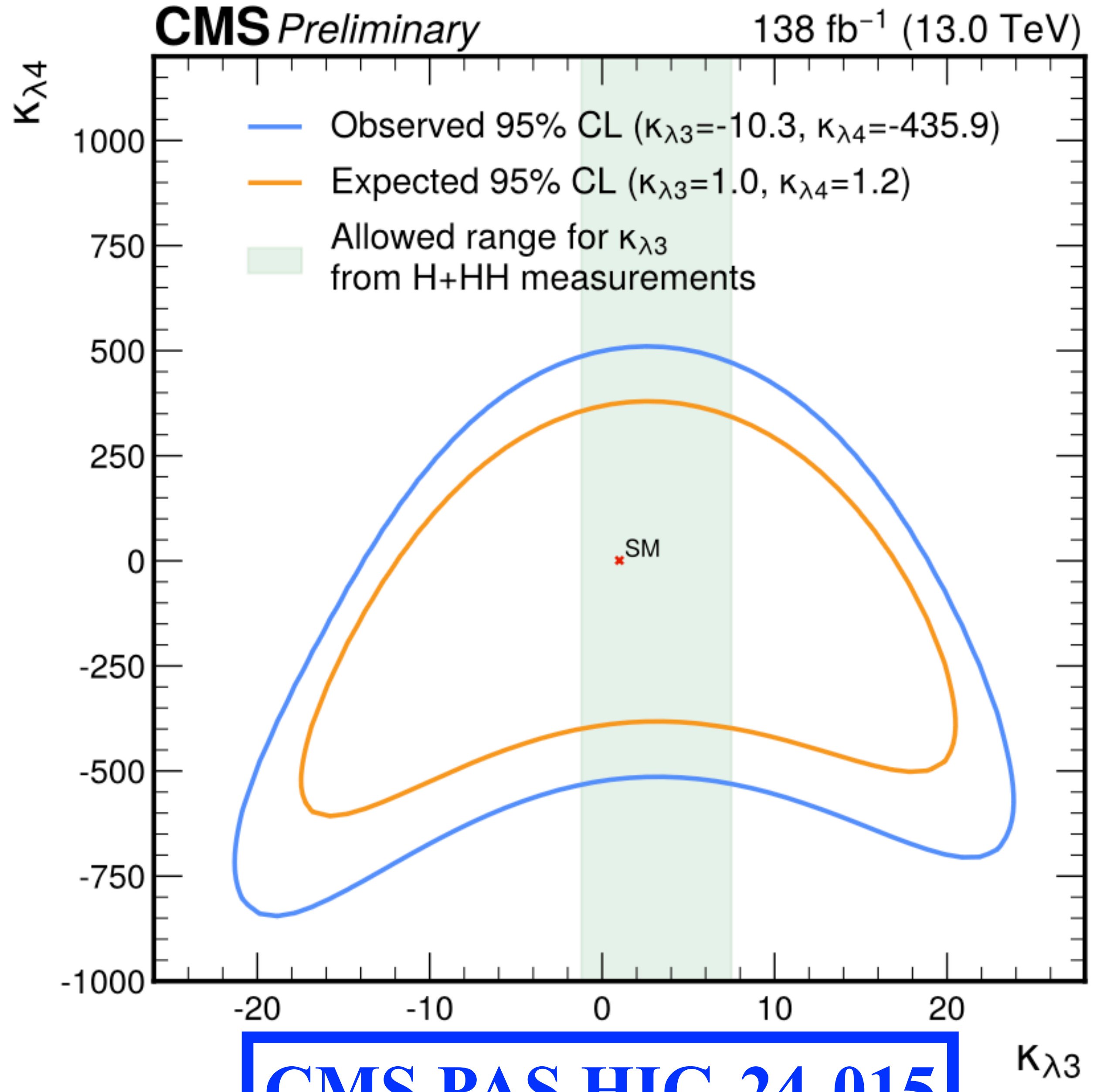
- ATLAS $HHH \to 6b$: $\kappa_3 \in [-11,17]$ and $\kappa_4 \in [-230,240]$, $\mu_{HHH} < 760$
- CMS $HHH \to 6b$: $\kappa_3 \in [-7,12]$ and $\kappa_4 \in [-190,190]$, $\mu_{HHH} < 588$
- CMS $HHH \to 4b2\gamma$: $\kappa_3 \in [-16,20]$ and $\kappa_4 \in [-533,541]$, $\mu_{HHH} < 3400$



Phys. Rev. D 111, 032006



CMS PAS HIG-24-012



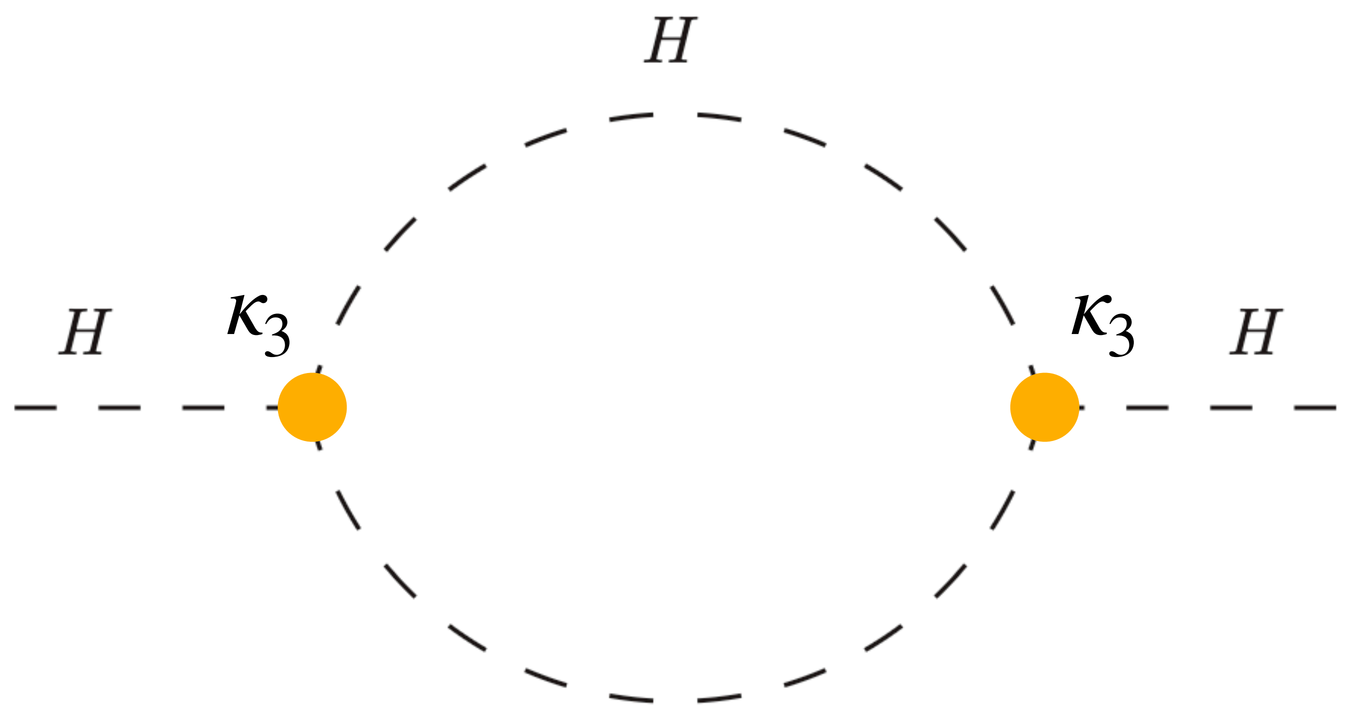
CMS PAS HIG-24-015

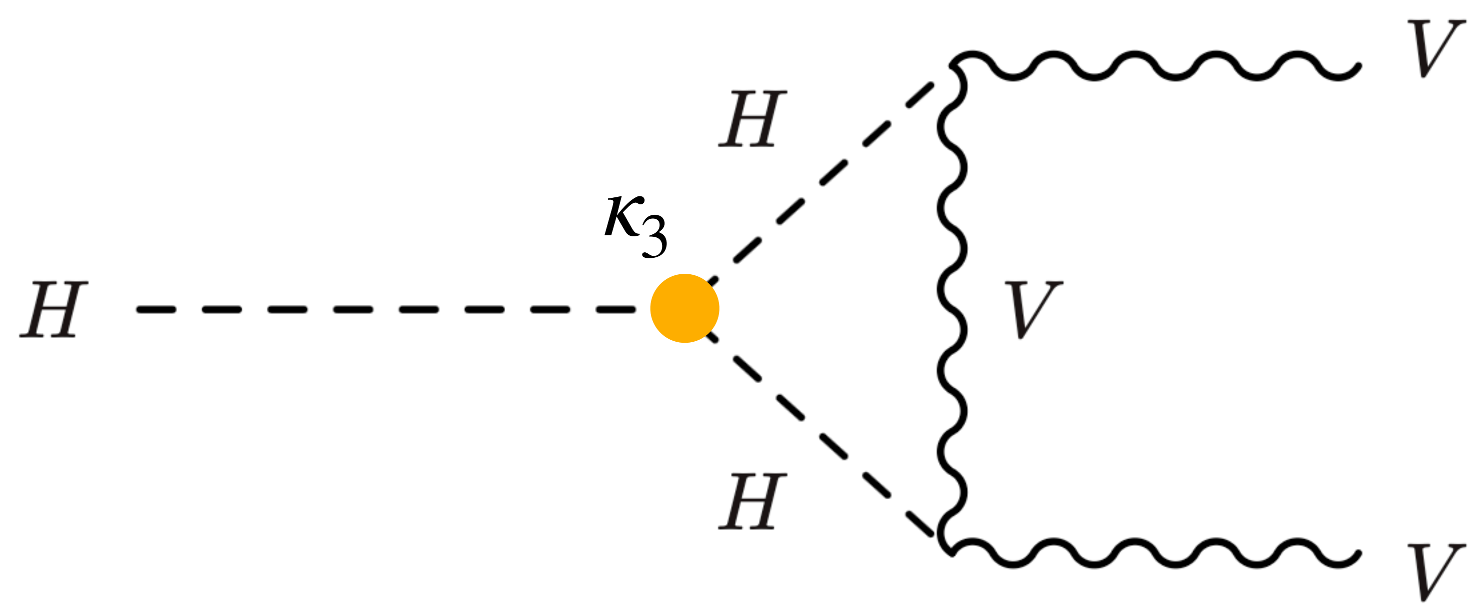
Cédrine Hügli (DESY), SM@LHC 2026, Higgs potential at the LHC

Single Higgs boson constraints

Single Higgs boson methodology concept

- κ_3 dependence enters at **NLO EW:**





- **inclusive cross-sections are sensitive to** κ_3, but some contributions cancel each other out
- **differential cross-section** measurements have a larger sensitivity to κ_3
- VH and ttH productions have the best differential sensitivity to κ_3

arXiv:1607.04251v3

CMS latest result - H combination

Run 2

This round of combination has new input analyses in particular:

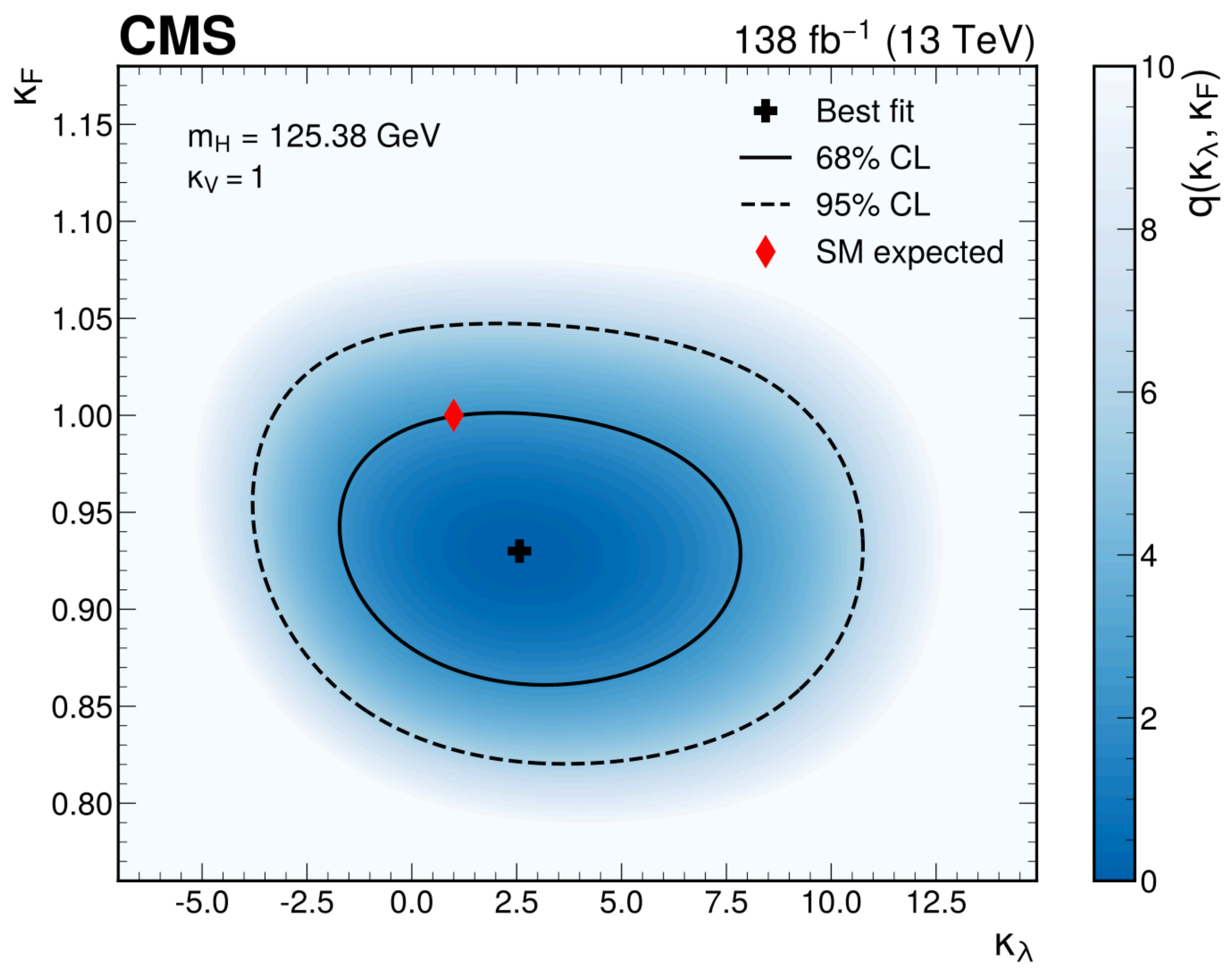
most notably the VH ($H \to bb$) and ttH ($H \to bb$) channels

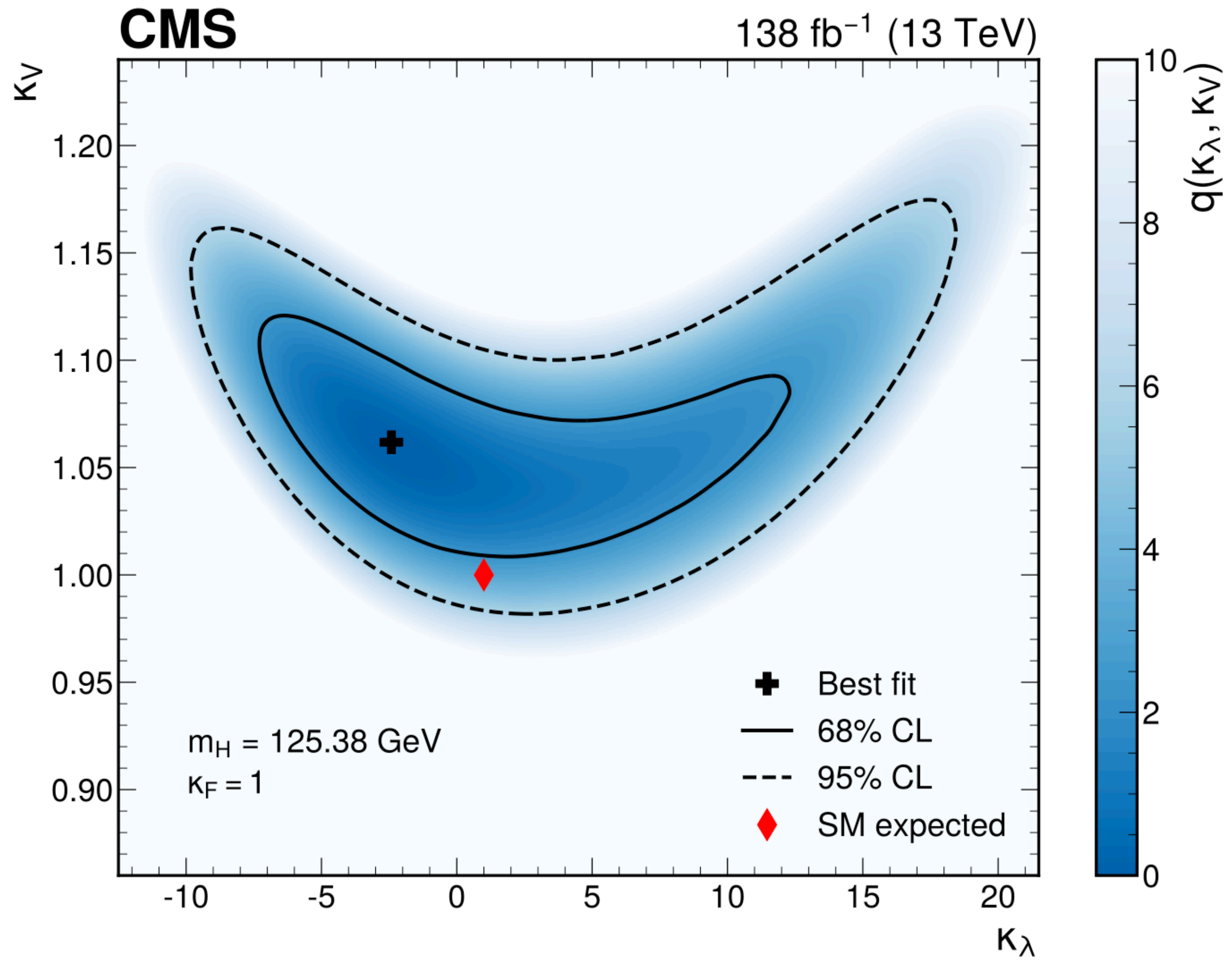
$\kappa_3 = 2.1^{+4.0}_{-3.2}$ (κ_V, κ_F fixed)

$\kappa_3 = 0.1^{+6.3}_{-6.0}$ (κ_V, κ_F floating)

slight improvement compared to [arXiv:2407.13554]

The analysis does not provide 95% CL intervals





arXiv:2602.18611v1

Cédrine Hügli (DESY), SM@LHC 2026, Higgs potential at the LHC

Current self-coupling results summary

Run 2

DiHiggs (HH)

$\sigma^{\text{SM, 13 TeV}}_{\text{ggF, HH}} = 30.8^{+2.0}_{-7.1}$ fb

- large sensitivity to κ_3
- no sensitivity to κ_4
- upper limit μ_{HH}

$\kappa_3 \in [-0.71, 6.1]$

$\kappa_{2V} \in [0.73, 1.3]$

$\mu_{HH} < 2.5$

Triple Higgs(HHH)

$\sigma^{\text{SM, 13 TeV}}_{\text{HHH}} = 0.079^{+0.012}_{-0.013}$ fb

- low sensitivity to κ_3
- sensitivity to κ_4
- upper limit μ_{HHH}

$\kappa_4 \in [-190, 190]$

$\mu_{HHH} < 588$

Single Higgs (H)

$\sigma^{\text{SM, 13 TeV}}_{\text{total, H}} = 59.3 \pm 5.7$ pb

- κ_3 sensitivity through NLO EW corrections to single Higgs production
- no sensitivity to κ_4

+7% improvement to κ_3 constraints

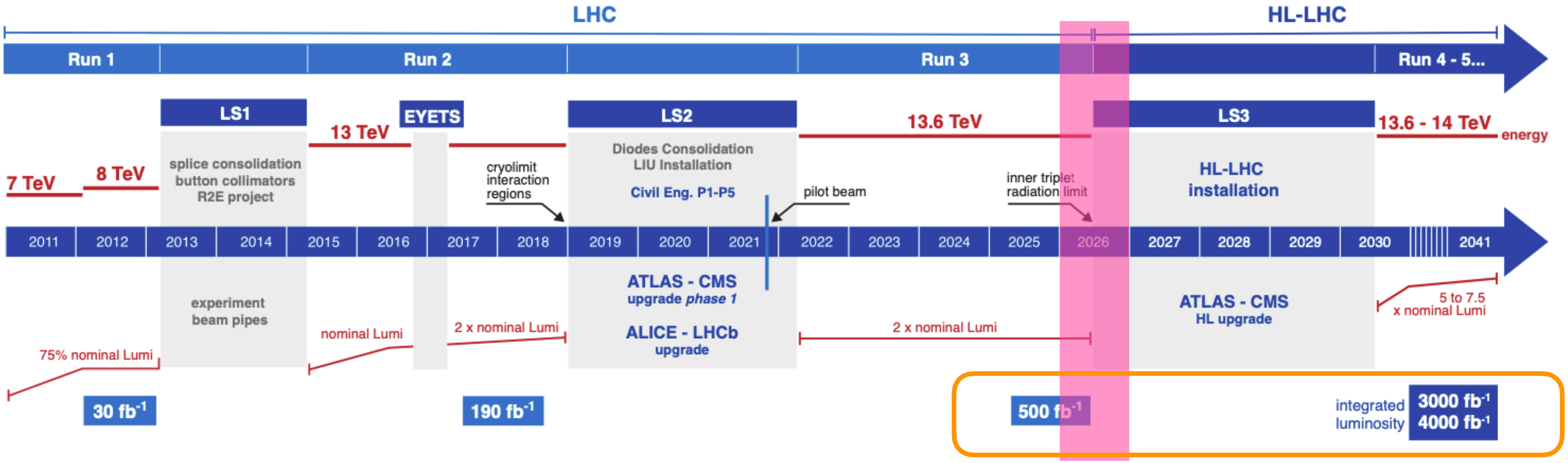
We are closing in on HH production and κ_3 values!

Still pretty far from HHH production and κ_4 values….

arXiv:2602.18611 | Phys. Lett. B 843 (2023) 137745 | Phys. Rev. D 111, 032006 | CMS PAS HIG-24-012 | arXiv:2602.23991v2

HL-LHC projections

HL-LHC



The HL-LHC era is about to start with the Long Shutdown 3

HL-LHC data-taking (Run 4) should start in 2030

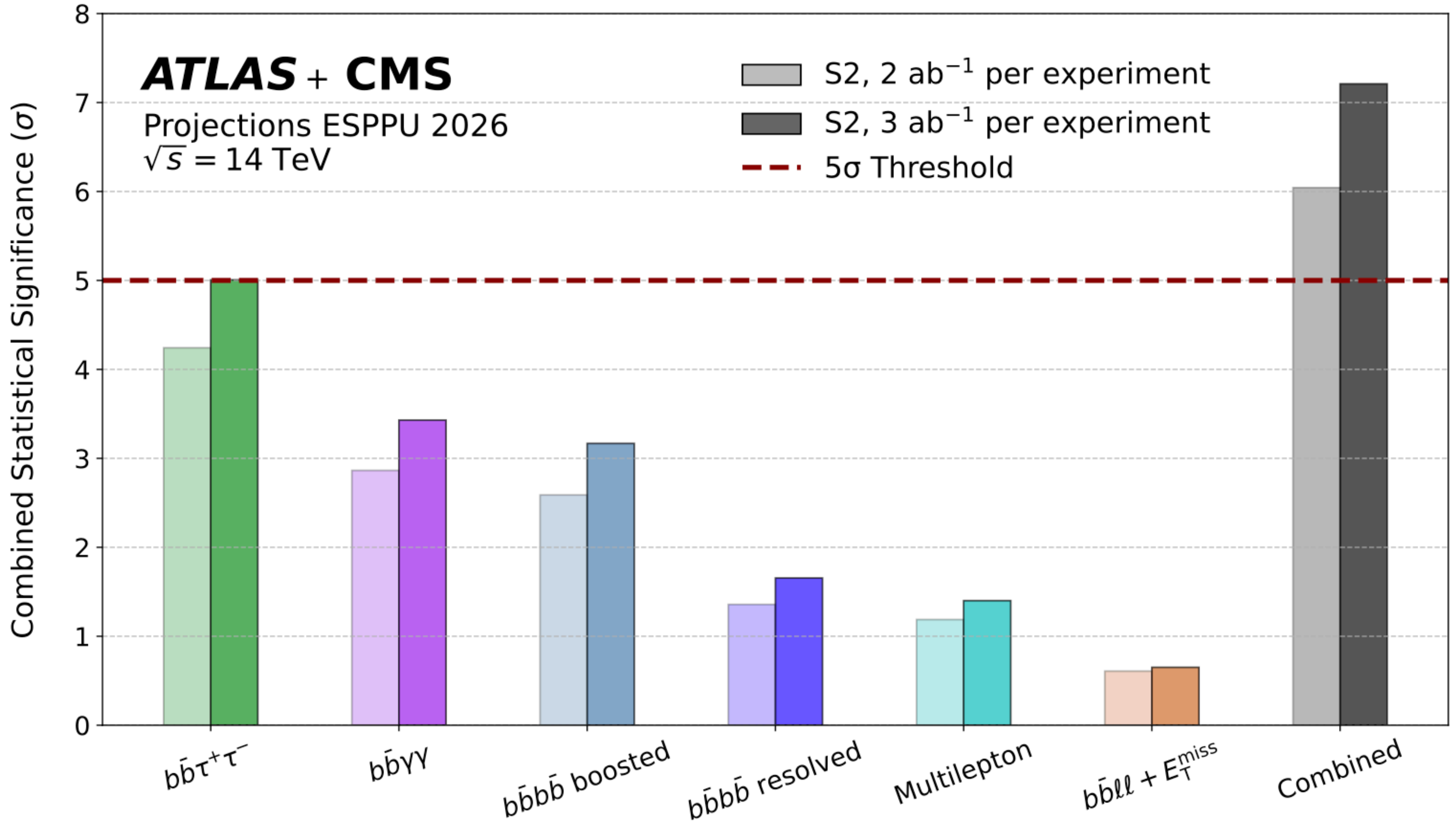
arXiv:2505.03535

Key points about HL-LHC

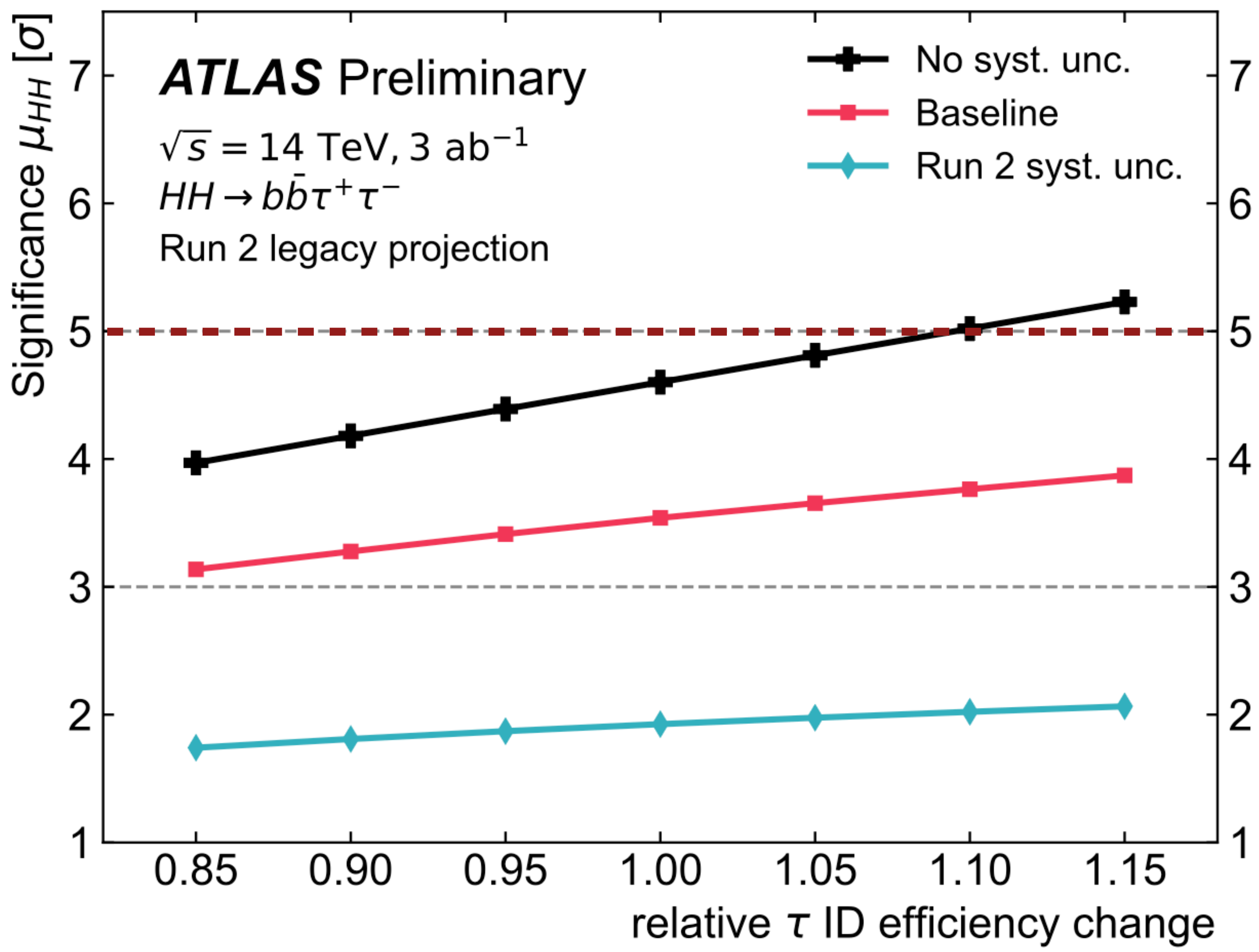
- 13.6 TeV or 14 TeV
- collect 3 ab^{-1} (intermediate 2 ab^{-1})
- systematic scenarios:
  - **S2 - Reference Scenario:** A conservative projection where theoretical uncertainties are halved and experimental systematic errors scale down based on the increased volume of data ($1/\sqrt{L}$).
  - **S3 - Optimized Scenario:** A more realistic projection that includes all **S2** improvements plus a **5% boost** in performance for identifying specific particles (like b-jets and taus) due to better hardware and AI algorithms.
- **Increase pileup is not taken into account**: assumption the increase in pileup is compensated by the improvements in detector technology and recording as well as data processing improvements

ATLAS + CMS HL-LHC projections significance

$2\ \text{ab}^{-1}$ vs $3\ \text{ab}^{-1}$



ATLAS $bb\tau\tau$ projections

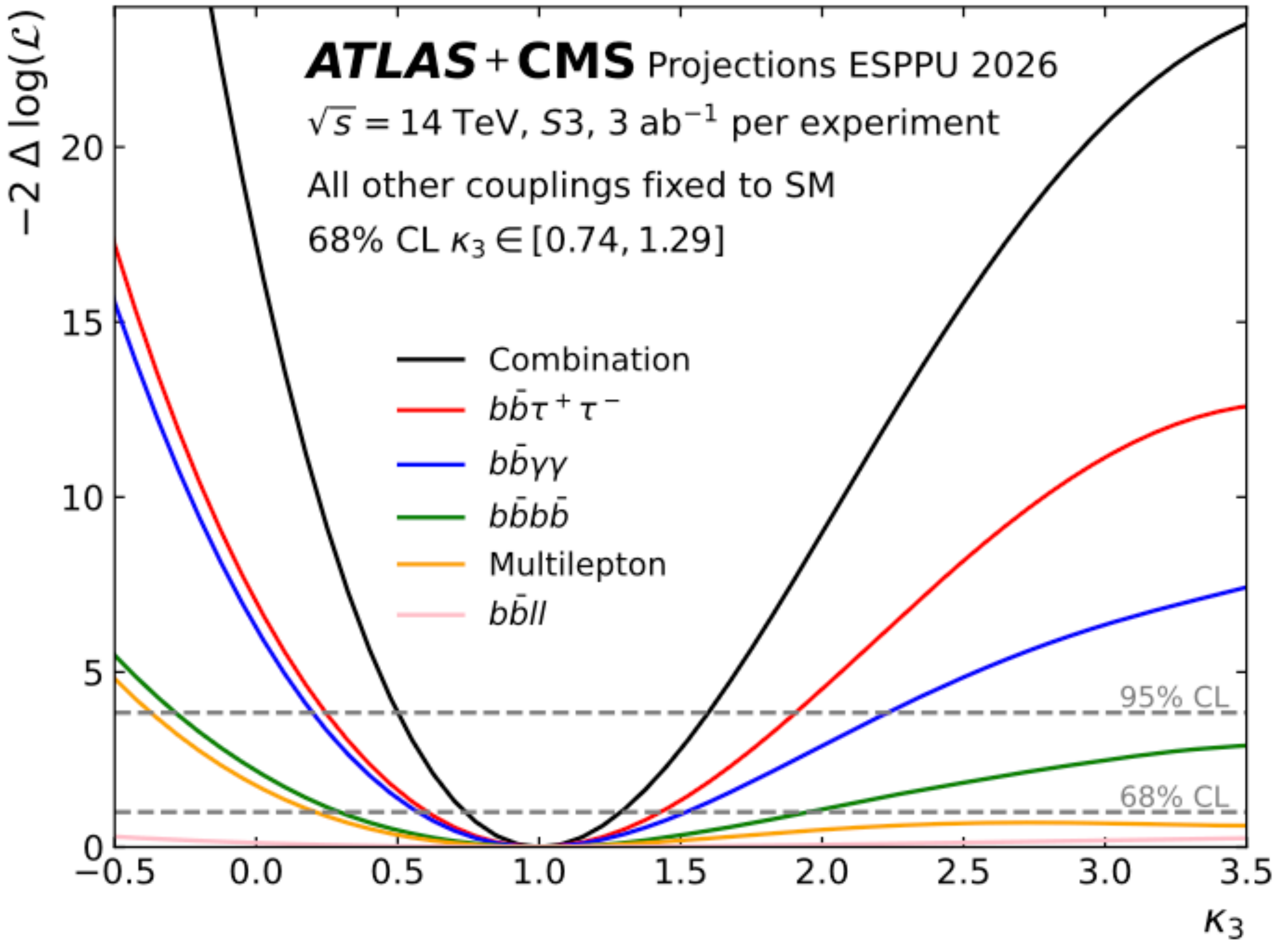


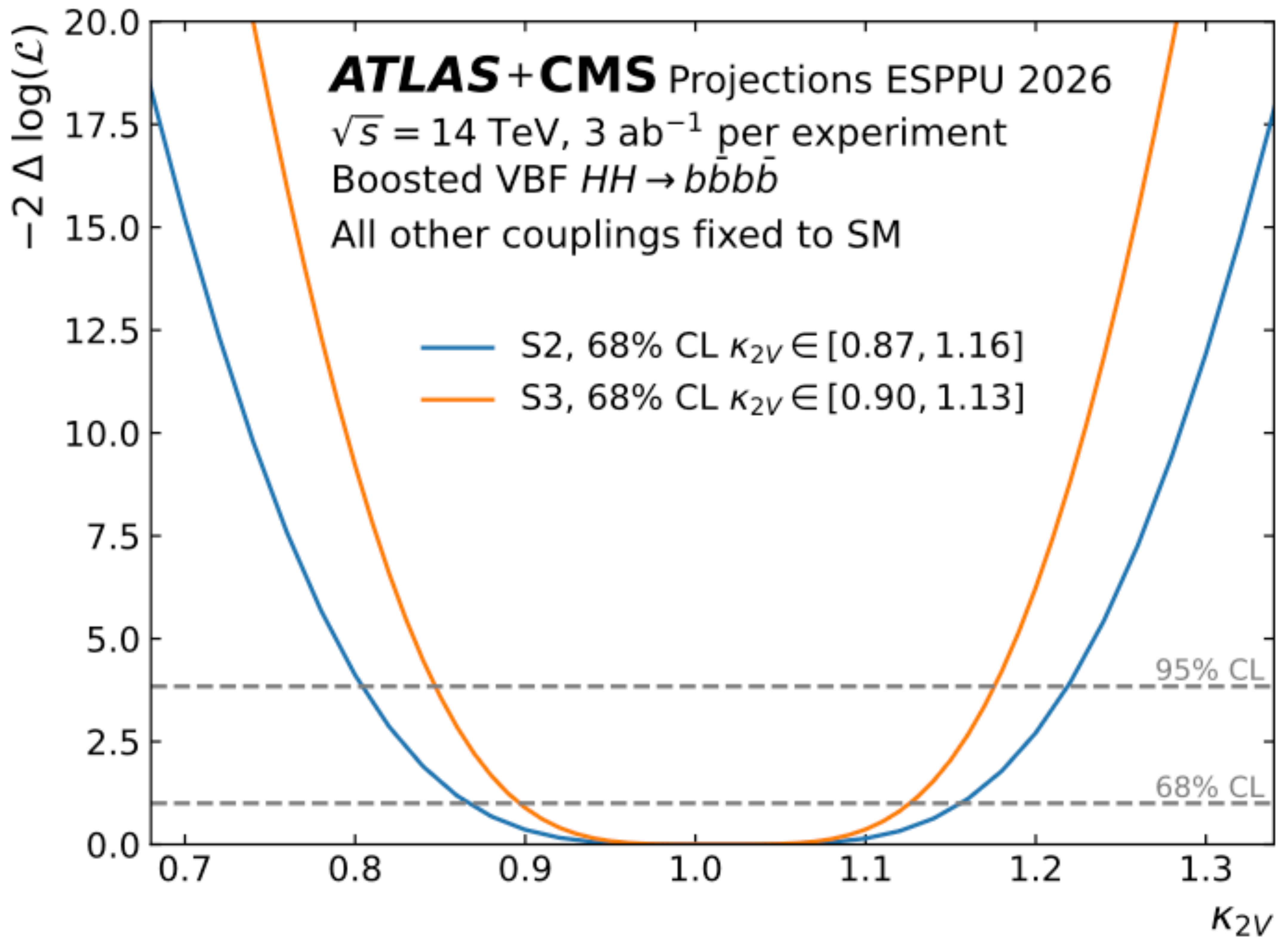
While a single-experiment observation is unlikely at $2\ \text{ab}^{-1}$, it's possibly in reach at $3\ \text{ab}^{-1}$, also in view of further analysis optimisations: $bb\tau\tau$ is the most sensitive channel for discovery

A significance 7.6σ can be achieved in the ATLAS+CMS HL-LHC combination

arXiv:2504.00672 | ATL-PHYS-PUB-2025-006 | ATL-PHYS-PUB-2024-016

ATLAS + CMS HL-LHC projections



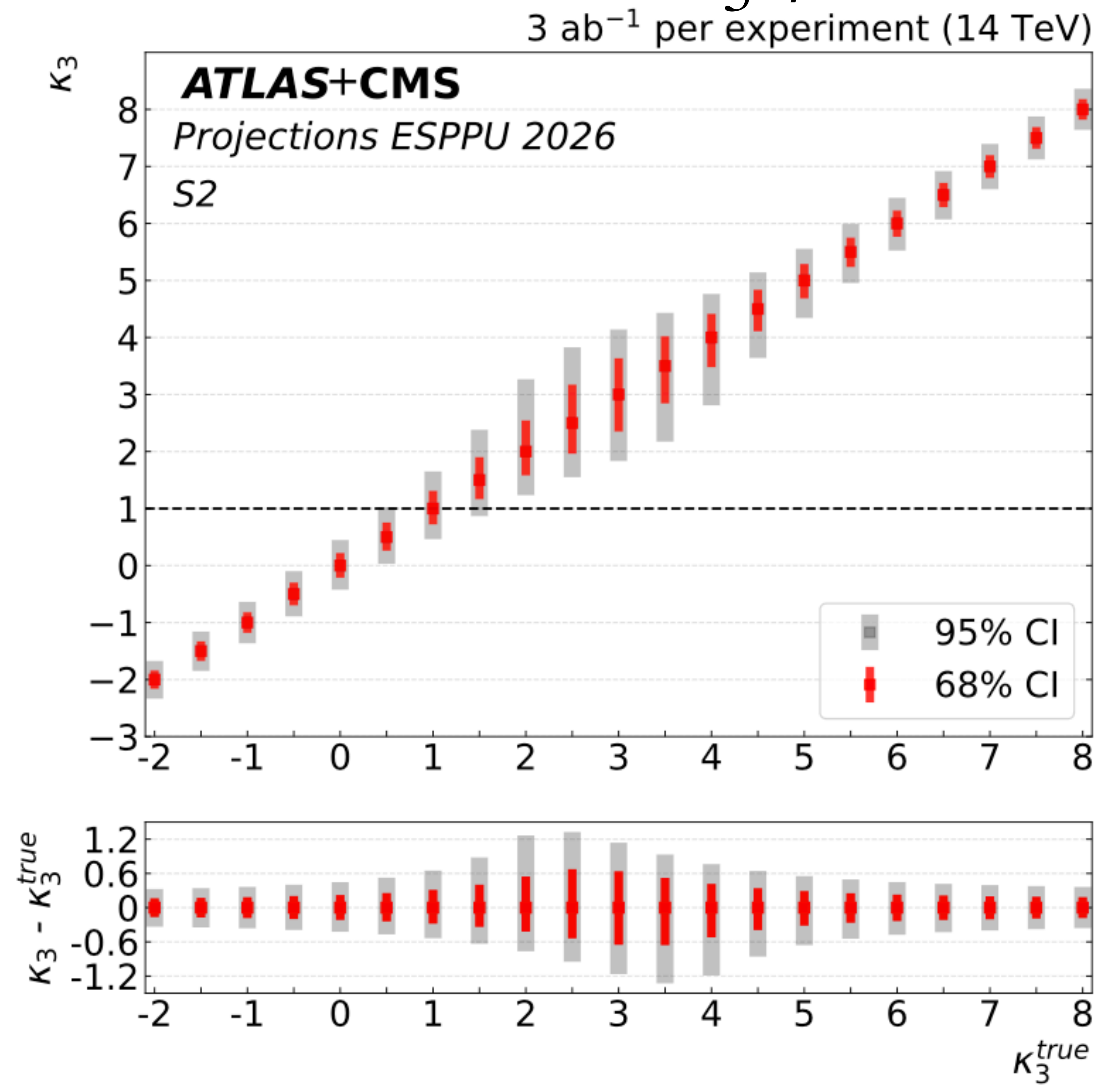


κ_3 uncertainty of $^{+29\%}_{-26\%}$ can be achieved with 3 ab^{-1} (S3)

arXiv:2504.00672

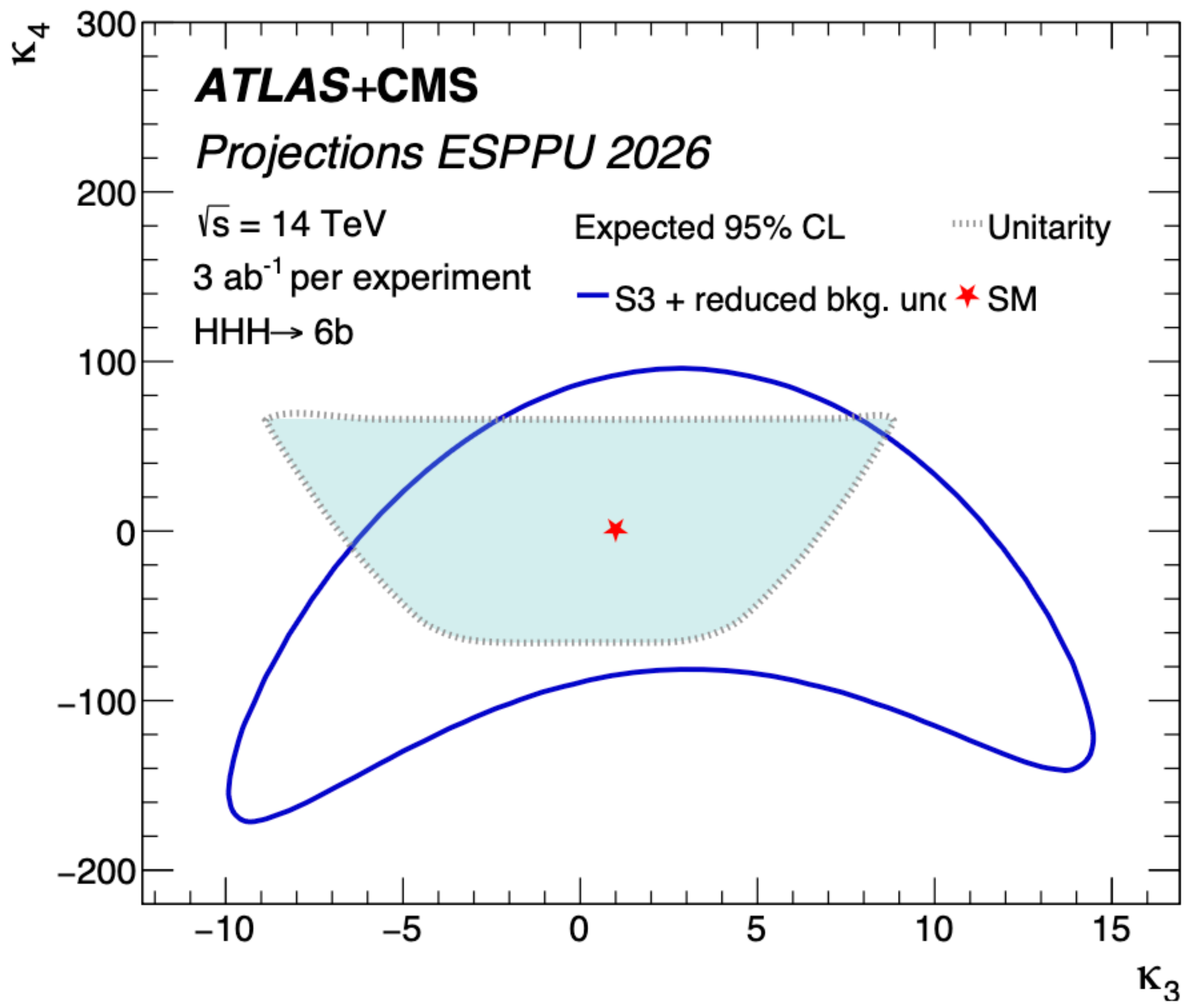
ATLAS + CMS HL-LHC projections $\kappa_3 \neq 1$ and κ_4

In case $\kappa_3 \neq 1$



Largest uncertainty = largest interference

Triple Higgs production

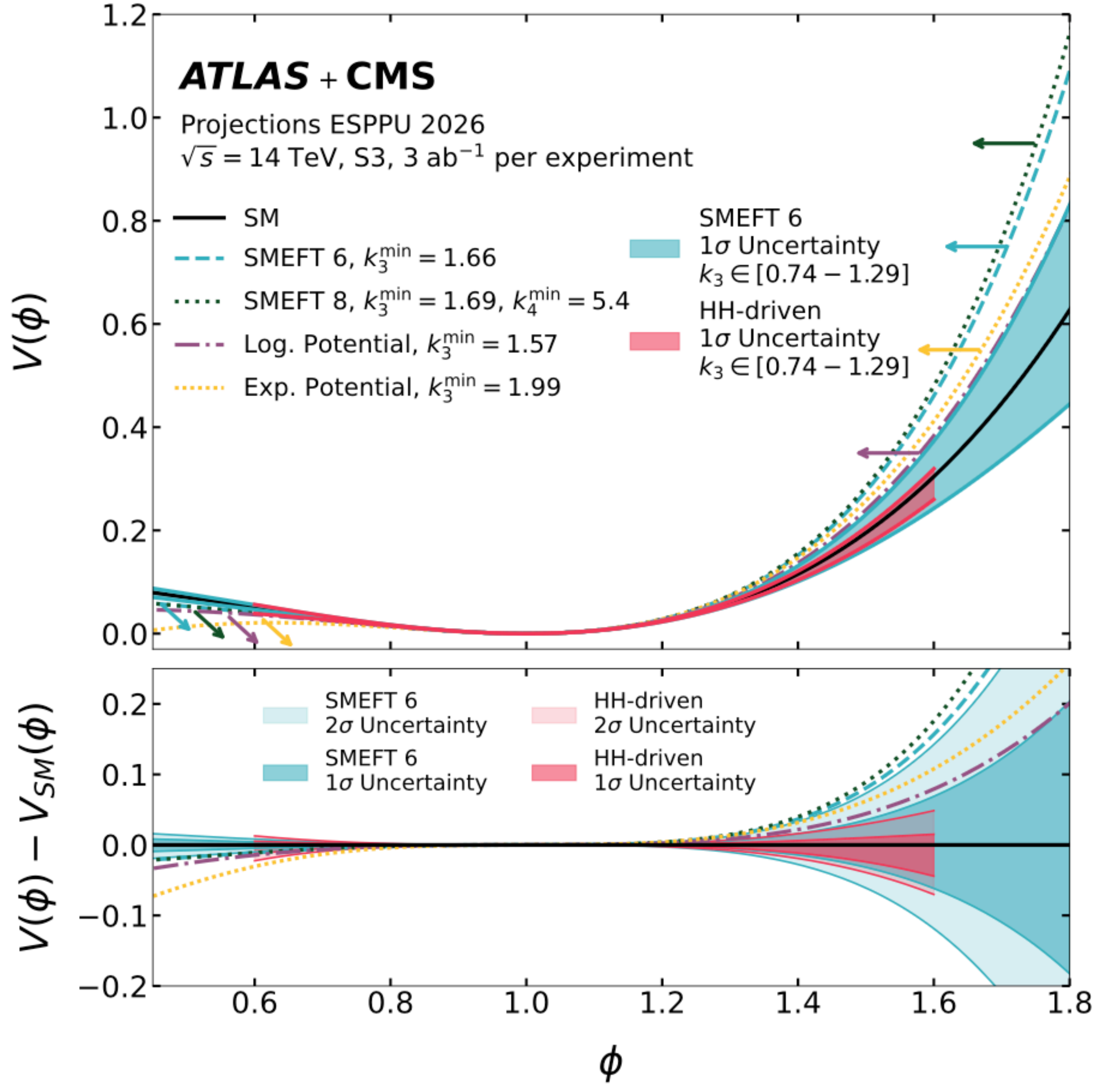


Expected upper limit on $\mu_{HHH} < 86$ (S3 scenario)

arXiv:2504.00672

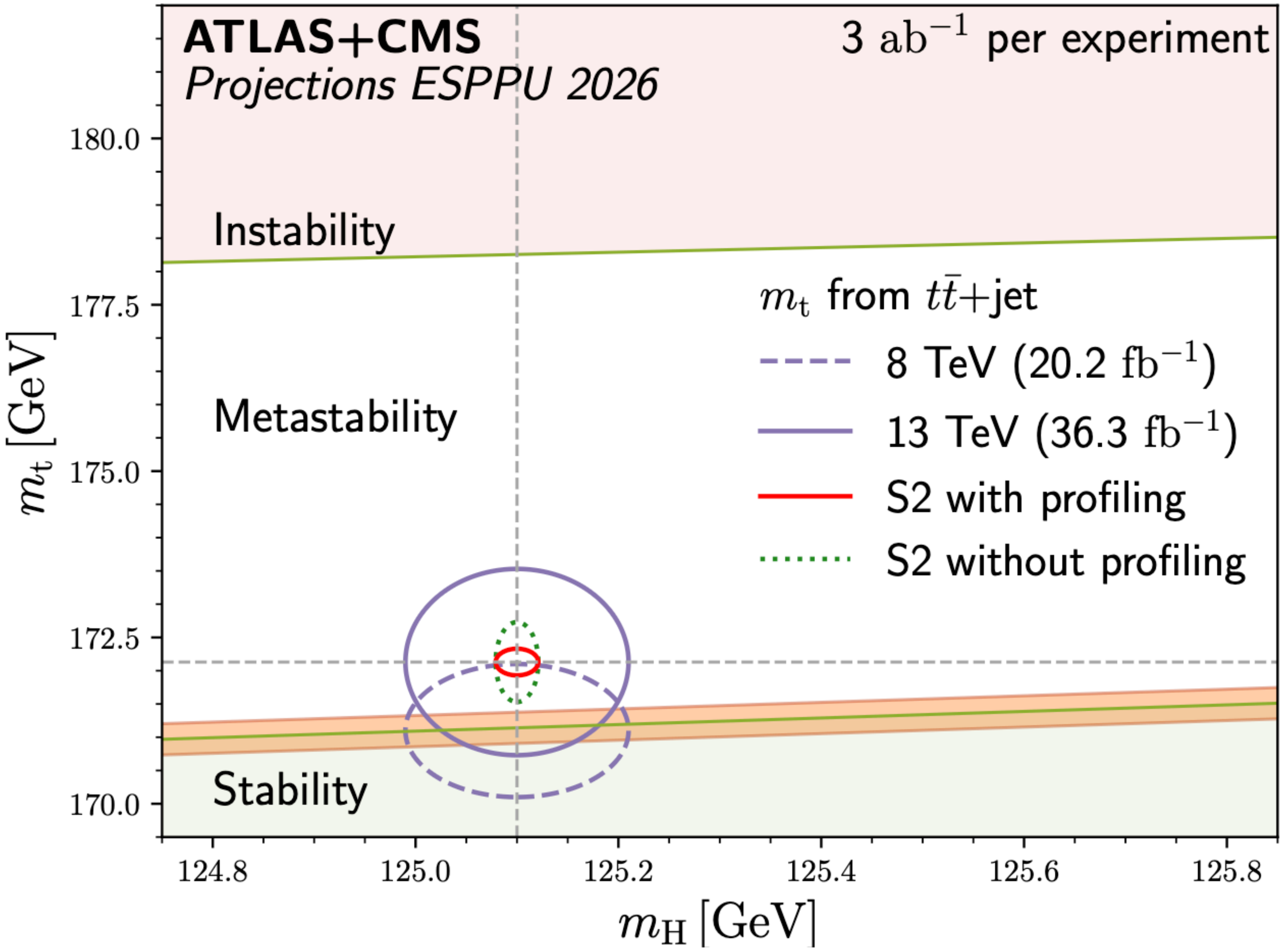
Strong first order phase transition

- **Goal:** investigating a Strong First-Order Phase Transition (FOPT) in the early universe(not possible in the SM).
- **Method:** analysis of four alternative BSM Higgs potential shapes predicting a FOPT
- **Results:**
  - **2 ab^{-1}:** some FOPT scenarios remain possible
  - **3 ab^{-1}:** the 95% CL sensitivity (red band) excludes nearly all strong-FOPT hypotheses



arXiv:2504.00672

Vacuum stability



Assumption: the central values of the two masses remain the same as measured at present

May be able to make a conclusive statement on the stability of the vacuum assuming the SM is valid up to the Planck scale, depending on the central value of m_t

arXiv:2504.00672

Conclusion

- The Higgs self-coupling can be accessed through HH and HHH measurements, and single H EW NLO corrections
- HH ATLAS+CMS combination (Run 2 only) puts the most stringent limits on κ_3 to-date: $\mu_{HH} < 2.5$, $\kappa_3 \in [-0.71, 6.1]$ and $\kappa_{2V} \in [0.73, 1.31]$
- HHH production: total of 3 public analyses: best limits obtained by CMS $HHH \to 6b$ $\kappa_4 \in [-190, 190]$, $\mu_{HHH} < 588$
- Single H can measure κ_3: can improve HH result alone by up to 7%
- HL-LHC is gonna be exciting!
  - HH discovery (7.6σ expected)
  - κ_3 measurement with a $\pm 30\,\%$ uncertainty expected

Thank you for listening! Questions?