Probing Higgs Couplings with H and HH measurements in ATLAS

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Motivation

More than 10 years of the Higgs Boson discovery at LHC:

- Measurements of the Higgs Boson properties with increased precision
- **Single Higgs (H) combination analyses** allows to test the Higgs sector and constrain the strength of the interaction between the Higgs and the SM particles

Searches for double Higgs (HH) shed a light on the SM Higgs potential

- **Direct dependency on Higgs boson self-coupling (κ_λ) at LO**
  - crucial insights into the mechanisms of electroweak spontaneous symmetry breaking and the generation of particle masses

Statistical combination of H and HH

- To test κ_λ by relaxing the assumptions on Higgs boson couplings with other SM particles

Credit: CERN webpage

CERN 10 years HIGGS boson discovery

Higgs Symposium at CERN for 10 years discovery

Higgs couplings to SM particles: analysis input channels

NEW RESULT - - ATLAS-CONF-2025-006

Analysis channel	Production mode	Luminosity (fb-1)	STXS stage	Improv. Wrt Nature
H->yy	All	140	1.2	-
H->ZZ*->4l	All	140	1.2	-
H->tautau	All	140	1.2	**Reanalysis**
H->WW*->lnulnu	ggF, VBF	140	1.2	**Reanalysis**
H->WW*->lnulnu	VH	140	1.2	**Full Run2**
H->bb	VBF	126	1.2	-
H->bb,cc	VH	140	1.2	**Reanalysis**
H->multileptons	ttH	36.1	1.2	-
H->bb	ttH	140	1.2	**Reanalysis**
H->tautau	VH	140	0	**New analysis**
H->Zy (*)	All	140	0	-
H->mumu (*)	All	140	0	-

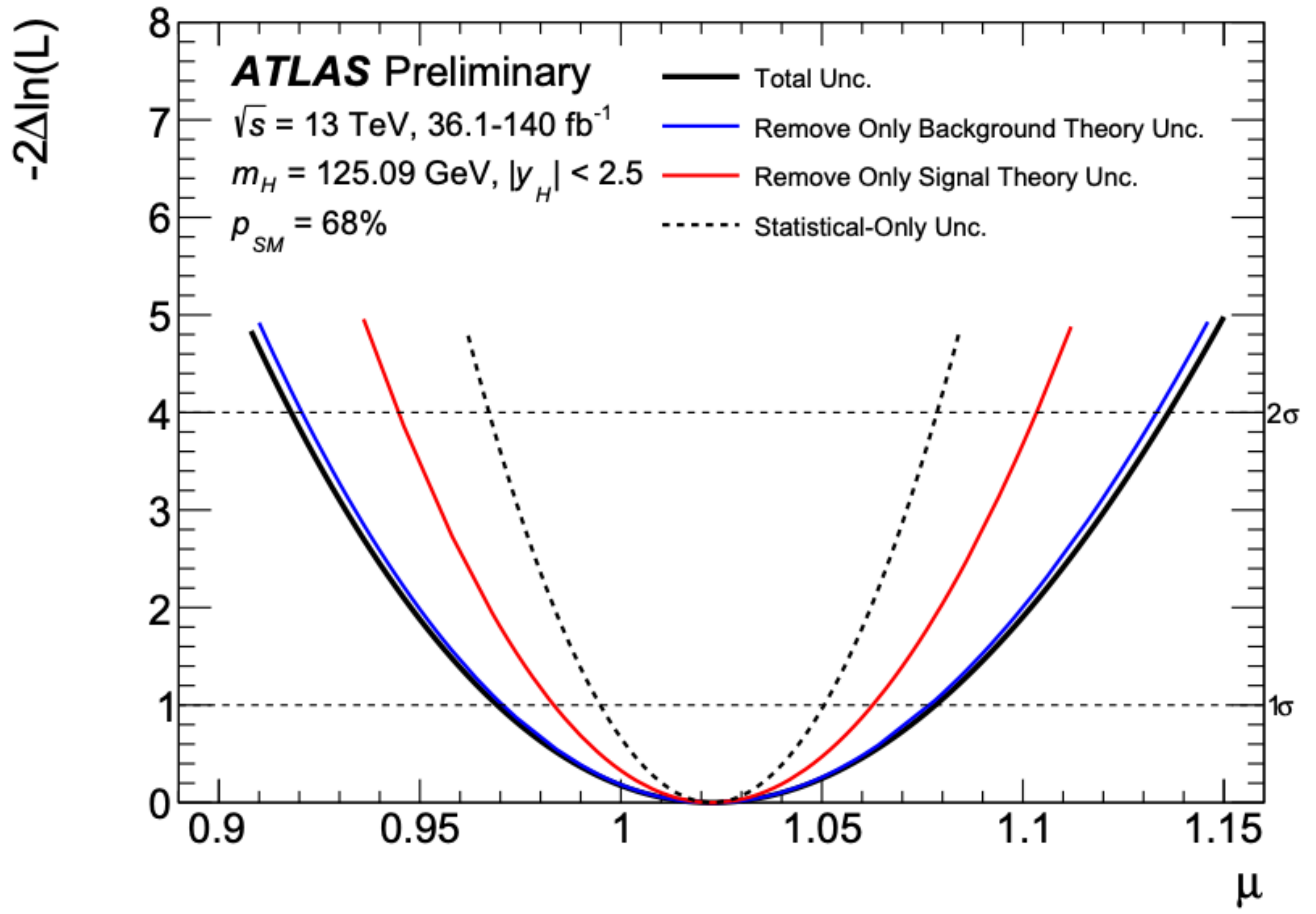
(*) new results including Run 3 dataset

See Guoqiang's and Hongtao's talks

Global Signal strength (μ)

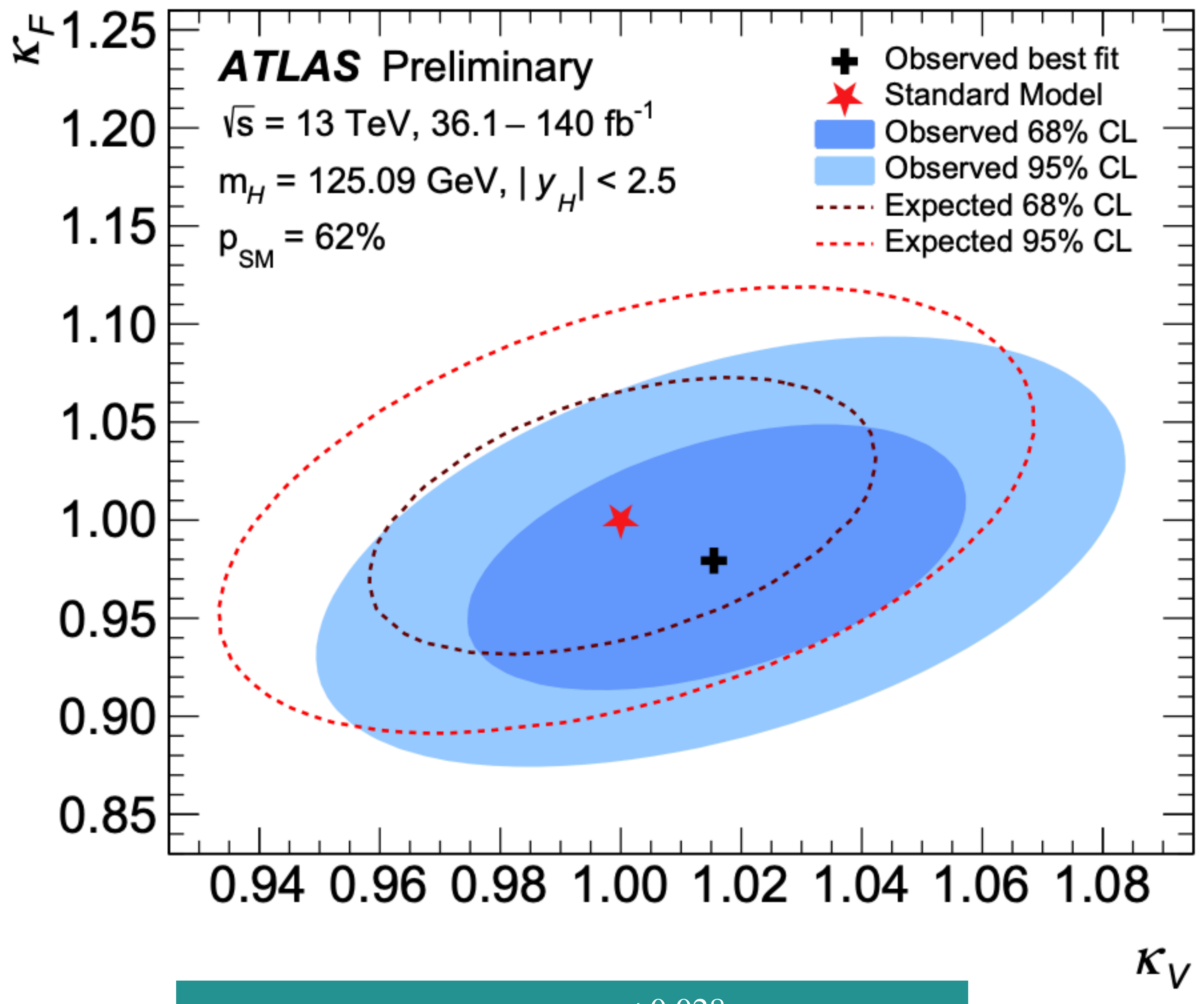
- Rate of Higgs boson production and decay processes:

- $$\mu_{if} = \frac{(\sigma_i \times B_f)}{(\sigma_i^{SM} \times B_f^{SM})} = 1.023 \pm 0.028\,(\text{stat.})\,^{+0.026}_{-0.025}\,(\text{exp.})\,^{+0.039}_{-0.036}\,(\text{sig. theo.})\; \pm 0.012\,(\text{bkg. theo.})$$



- Around 10% reduction in the total uncertainty with respect to Nature result (1.05 ± 0.06)
- Measurement in good agreement with respect to SM:
  - P-value compatibility at 68%

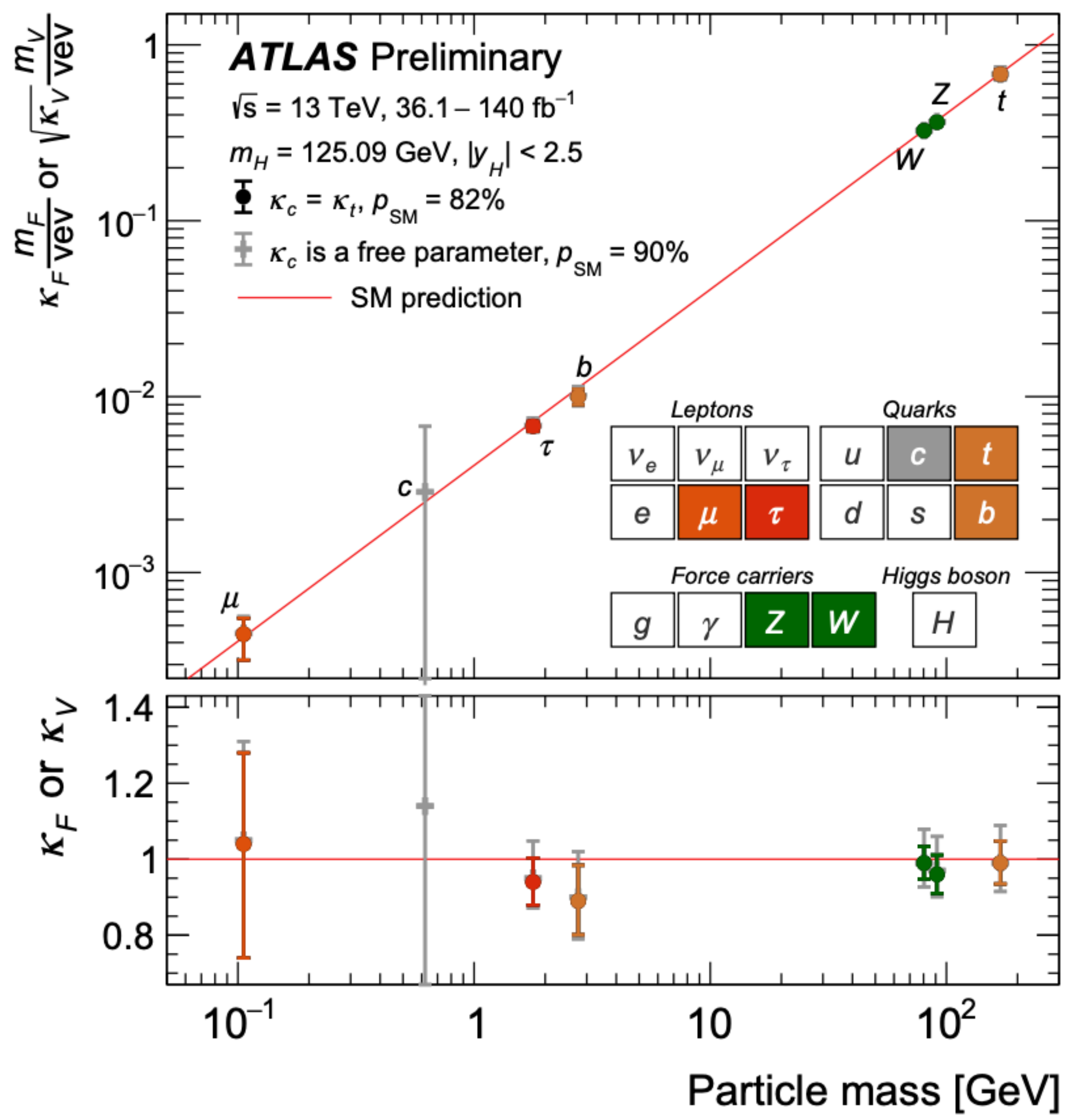
Higgs Boson coupling measurements



$\kappa_V = 1.015^{+0.028}_{-0.027}$

$\kappa_F = 0.979^{+0.044}_{-0.045}$

Compatible with SM predictions (p-value 62%)

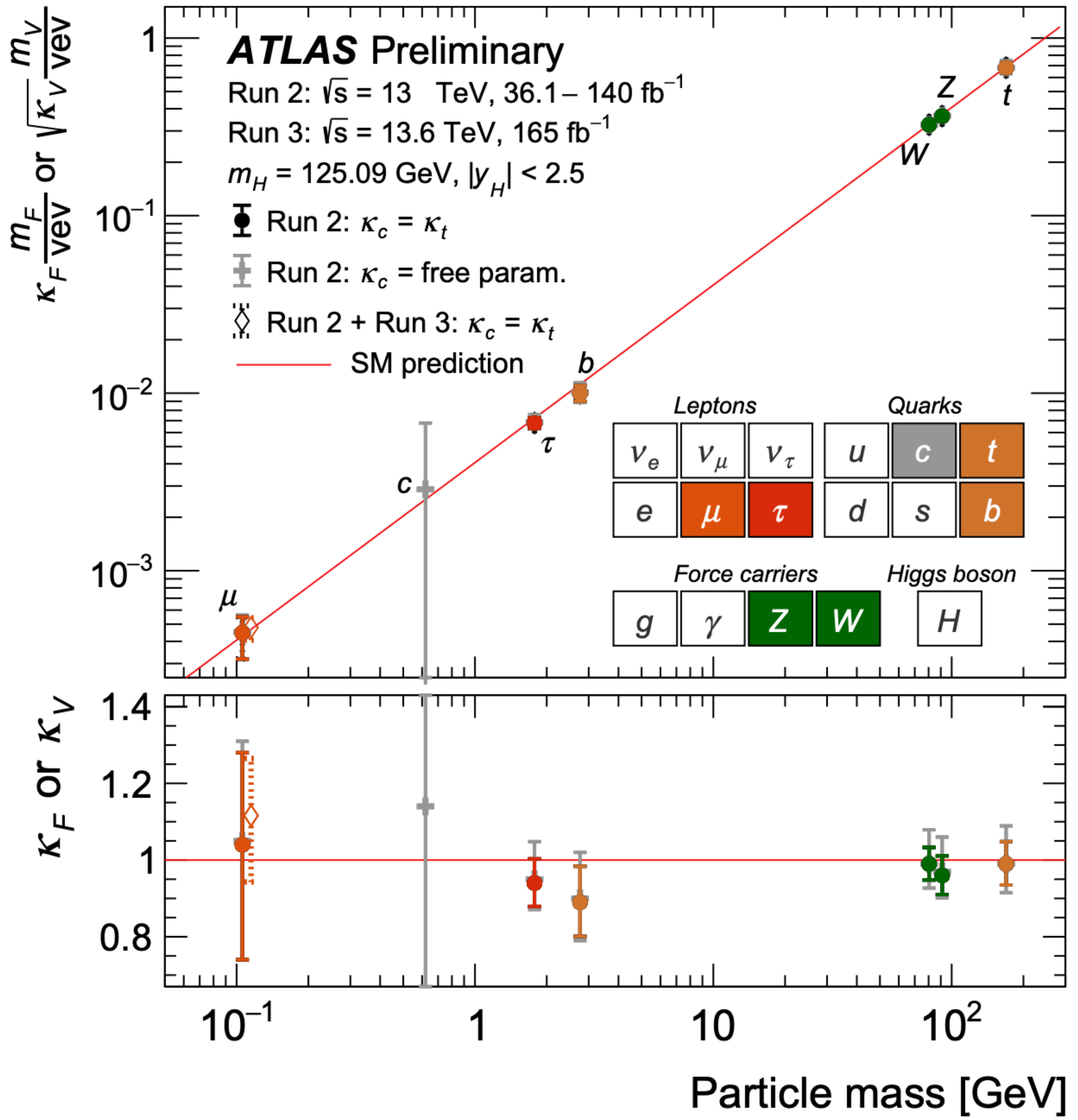


Compatible with SM predictions (p-value 90%) for resolved parametrization

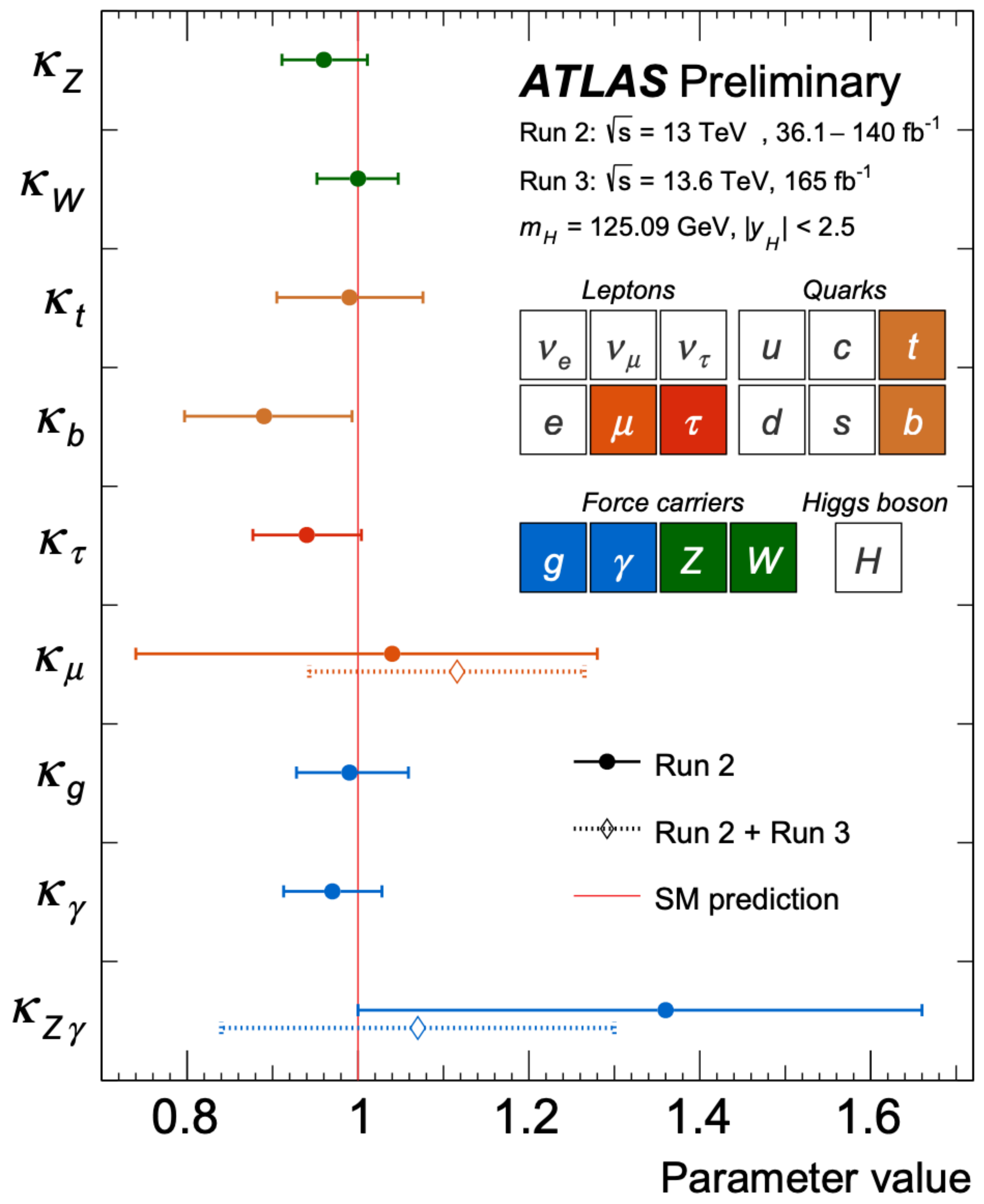
Improvements: VH, H(WW*) with lower kV and ttH(bb), with higher kF

Improved VH, H(cc) constraints halved uncertainty on κ_c; uncertainty on κ_t improved 15% (vs. Nature).

Run 2 + Run 3 Coupling modifiers



Addition of Run3 data significantly reduces total uncertainty for κ_μ wrt Run2



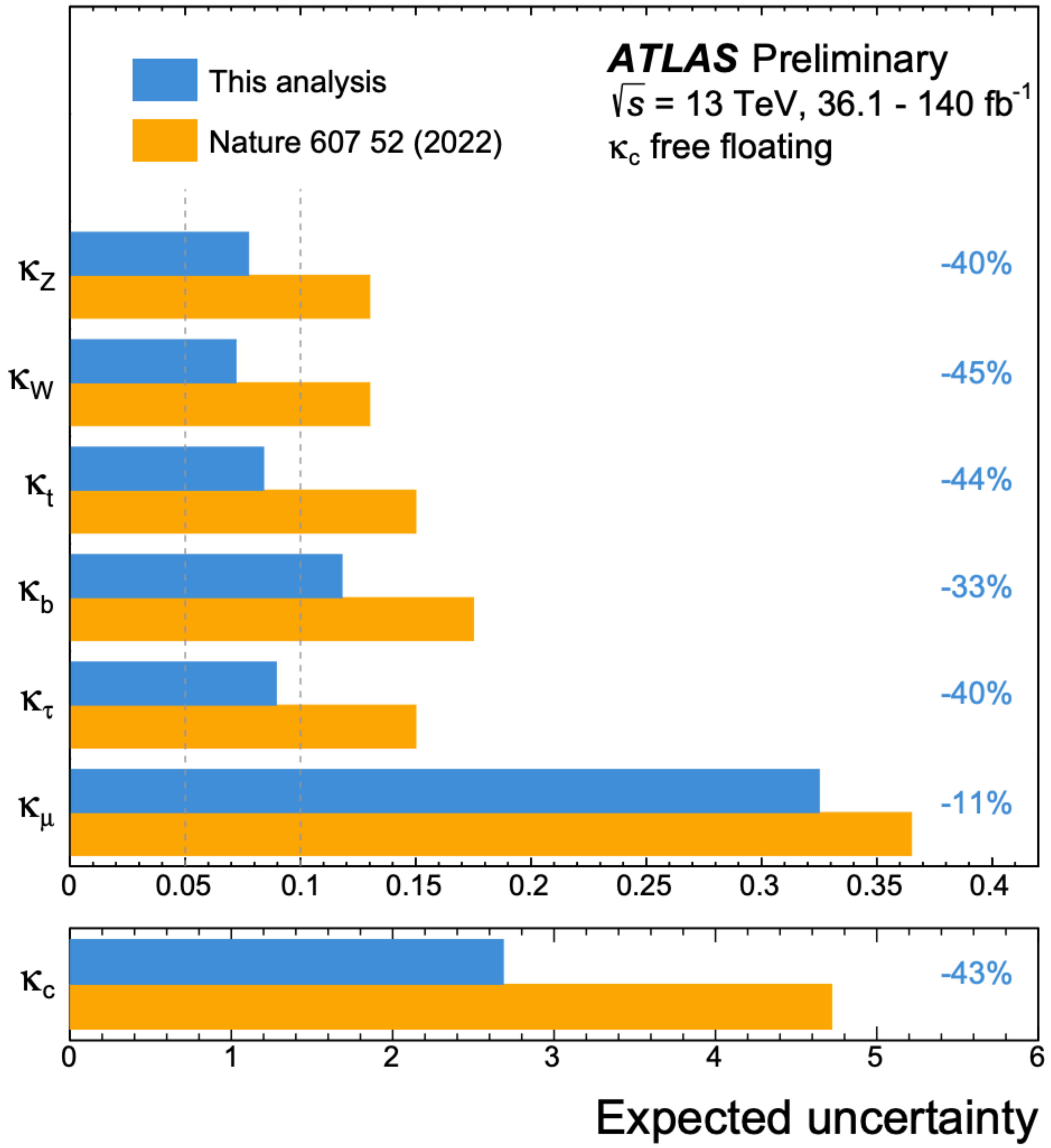
Effective parametrization

Rel. improvement on the precision of κ_μ (~38%) and $\kappa_{Z\gamma}$ (~30%) adding Run3 data wrt Run2 measurements

Coupling modifiers: expected uncertainties

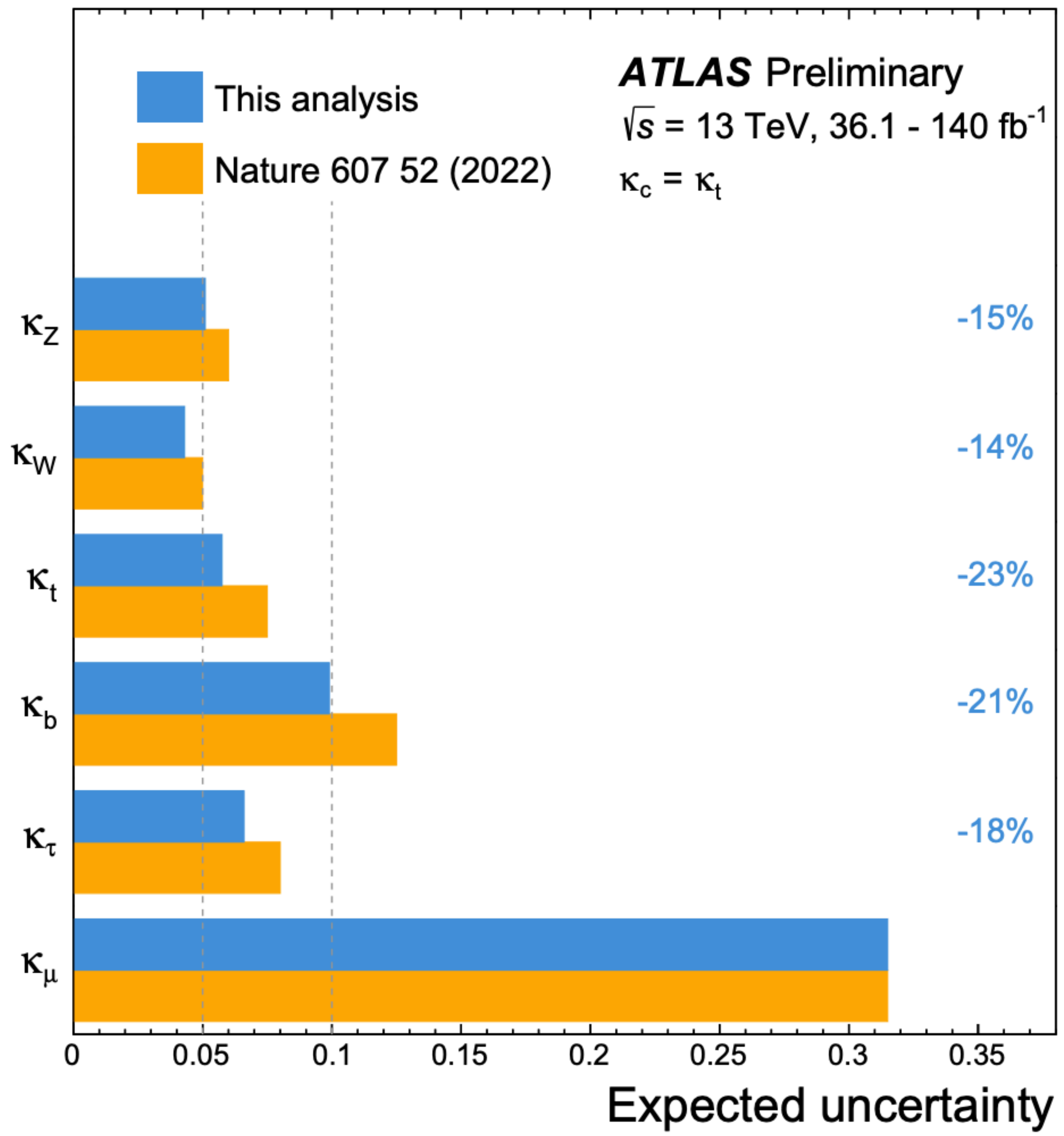
Resolved parametrization

κ_c as fit parameter



Reduction of 43% on exp. κ_c uncertainty (improved VH, H(cc) constraints)

Assuming $\kappa_c = \kappa_t$

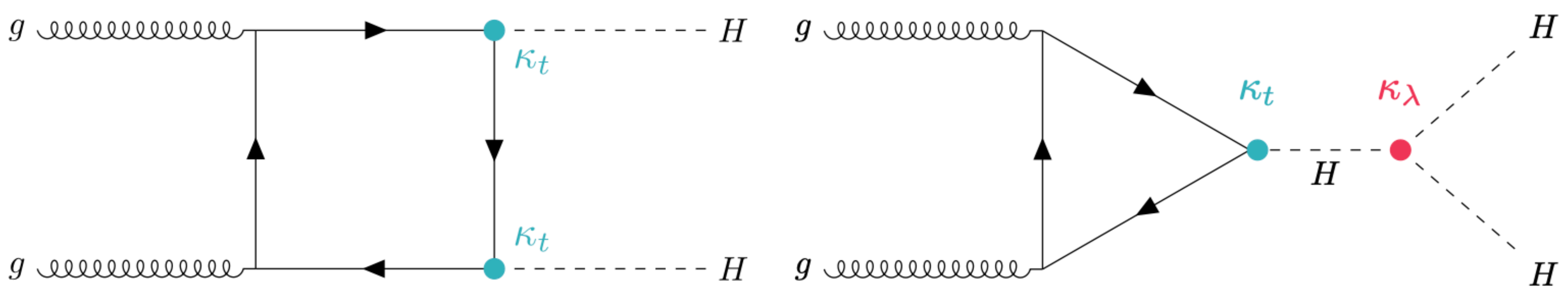


Reduction of 23% on exp. κ_t uncertainty

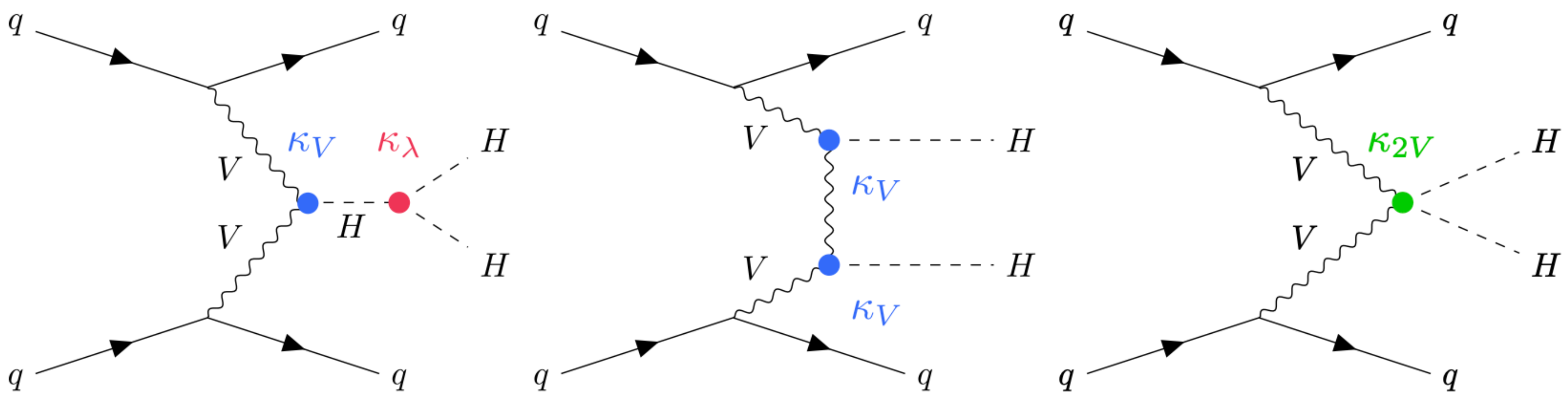
HH searches: illuminating the Higgs self-coupling

- HH processes are rare:
  - ~1000× smaller cross section than single-H production
    - Destructive interference between the box and triangle production diagrams
  - Vast amount of data and well designed analysis are needed:
    - large integrated lumonosity and highly optmized analysis techniques to suppress overwhelming background sources

ggF HH production mode



VBF HH production mode



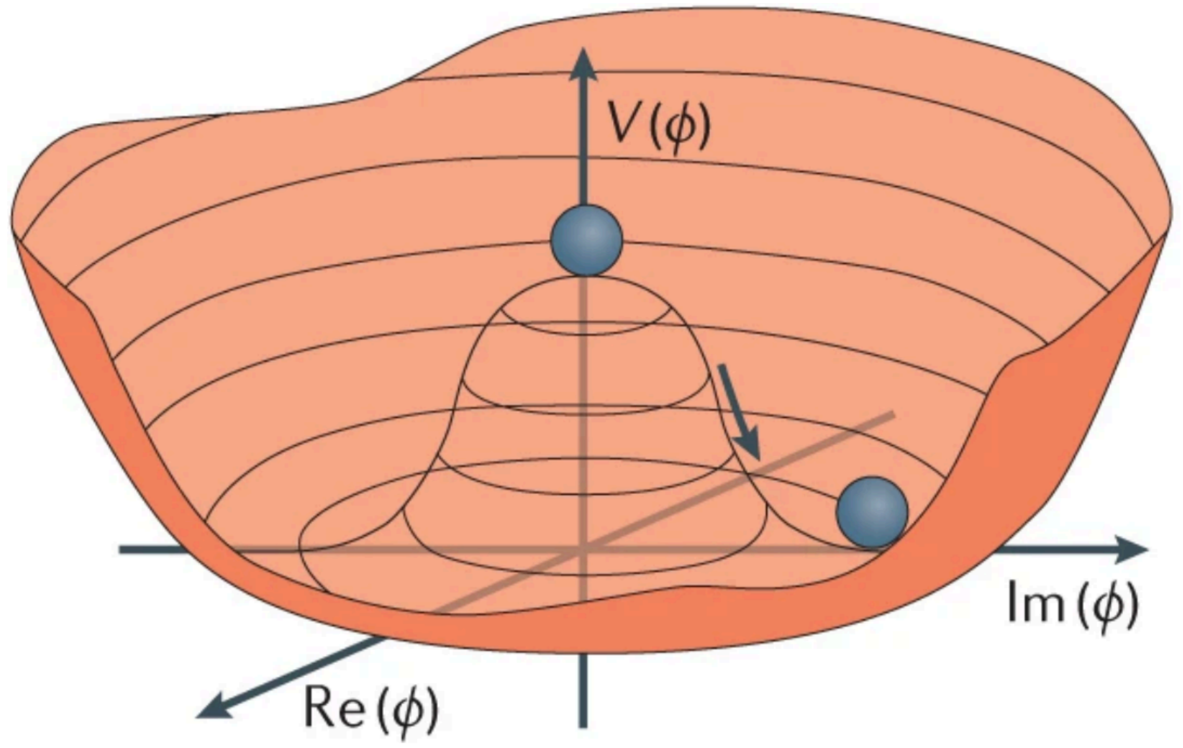
- Measure of the HH production is crucial give it provides direct probe to the Higgs boson self-coupling (κ_λ)
  - **Determines the shape of the Higgs potential**

Higgs potential expanded around its minimum:

$$V(H) = \frac{1}{2}m_H^2 + \lambda_{HHH}\nu H^3 + O(H^4) + \ldots$$

Self-coupling term: $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$

Quartic term



See Yizhou's and Yanping's talks

HH decay modes

3 Most Sensitive Channels

- **bbbb (34%):**
  - Most abundant final state, but also largest SM background (Multi-jet events)
- **bb$\tau\tau$ (7.3%):**
  - Moderate mass resolution and background contamination
- **bb$\gamma\gamma$ (0.26%):**
  - High trigger efficiency and excellent $m_{\gamma\gamma}$ resolution

- **bbll+MET (2.9%):**
  - H(bb)H(WW/ZZ/$\tau\tau$ -> ll+MET)
  - Signal and background separation in ggF (DNN) and VBF (BDT) categories
  - Major backgrounds estimated from CRs (ttbar, Z+HF and Wt)
- **Multi-leptons (6.5%):**
  - Complementary HH probing channel with multiple light leptons and taus in the final state and diphoton final states with up to two additional light leptons and/or hadronic taus
  - BDT score as fit variable, except for yy channels, where $m\gamma\gamma$ is used

New channels added to the combination

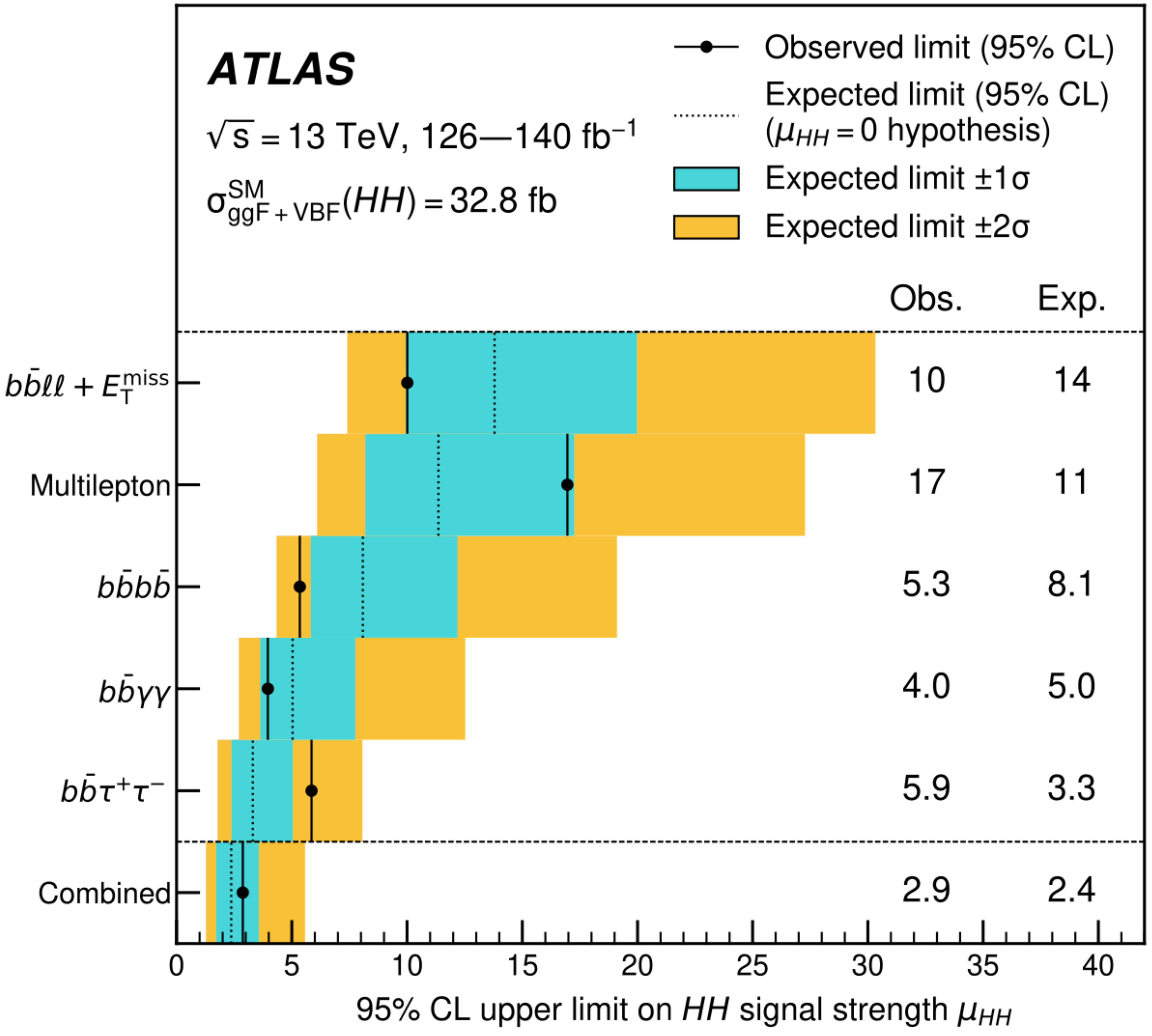
Large Decay Fraction

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

Clean Final State

Double Higgs combination: signal strength

PHYSICAL REVIEW LETTERS 133, 101801 (2024)



Upper Limits at 95%CL:

- $\mu_{HH} < 2.9$ (obs.)
- $\mu_{HH} < 2.4$ (exp.)
- Upward fluctuation on observed upper limits wrt exp (slightly excess of events)
- Smaller contribution from multi-lepton and bbll+MET

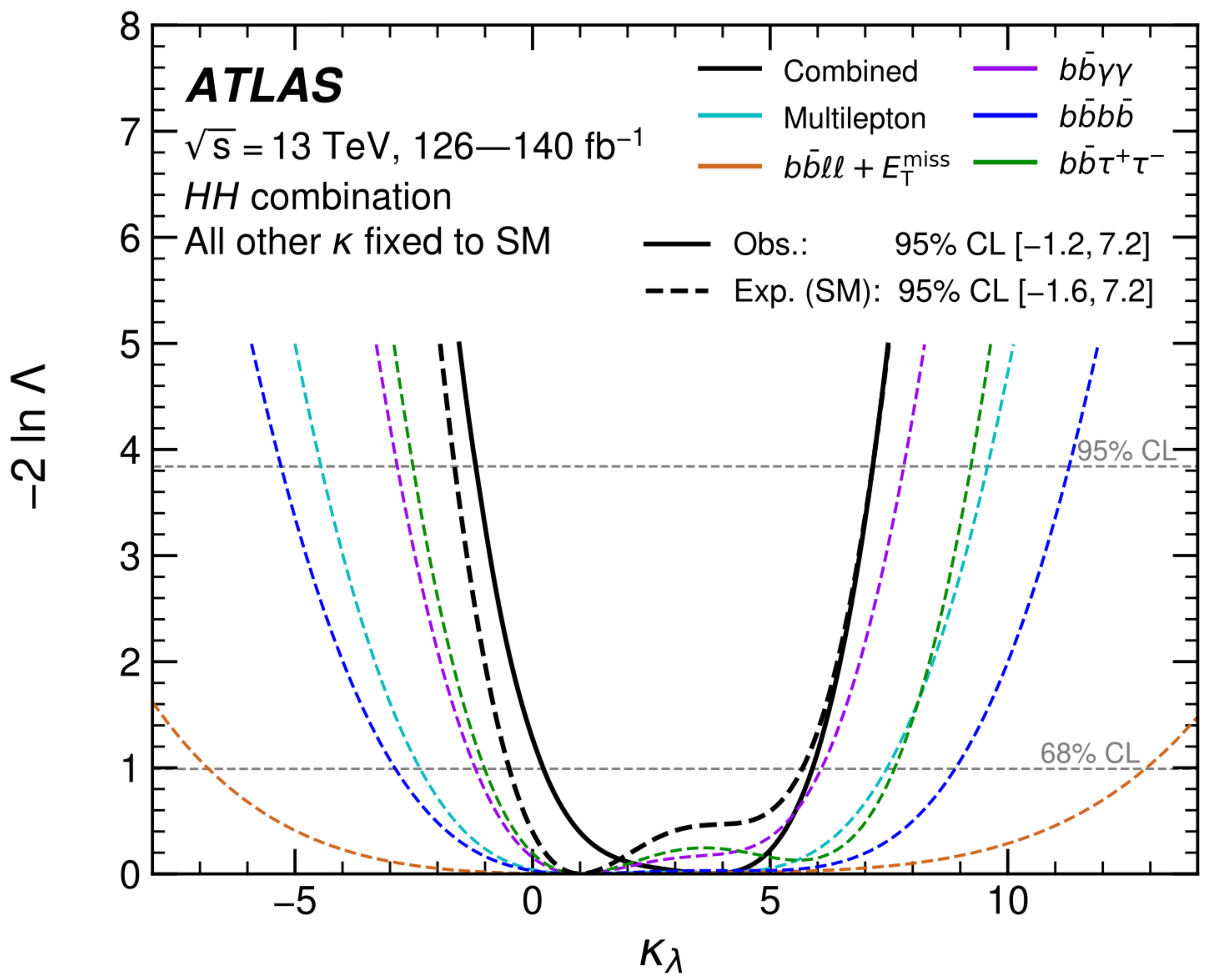
Upper Limits at $\sigma_{ggF+VBF}(HH)$ at 95% CL:

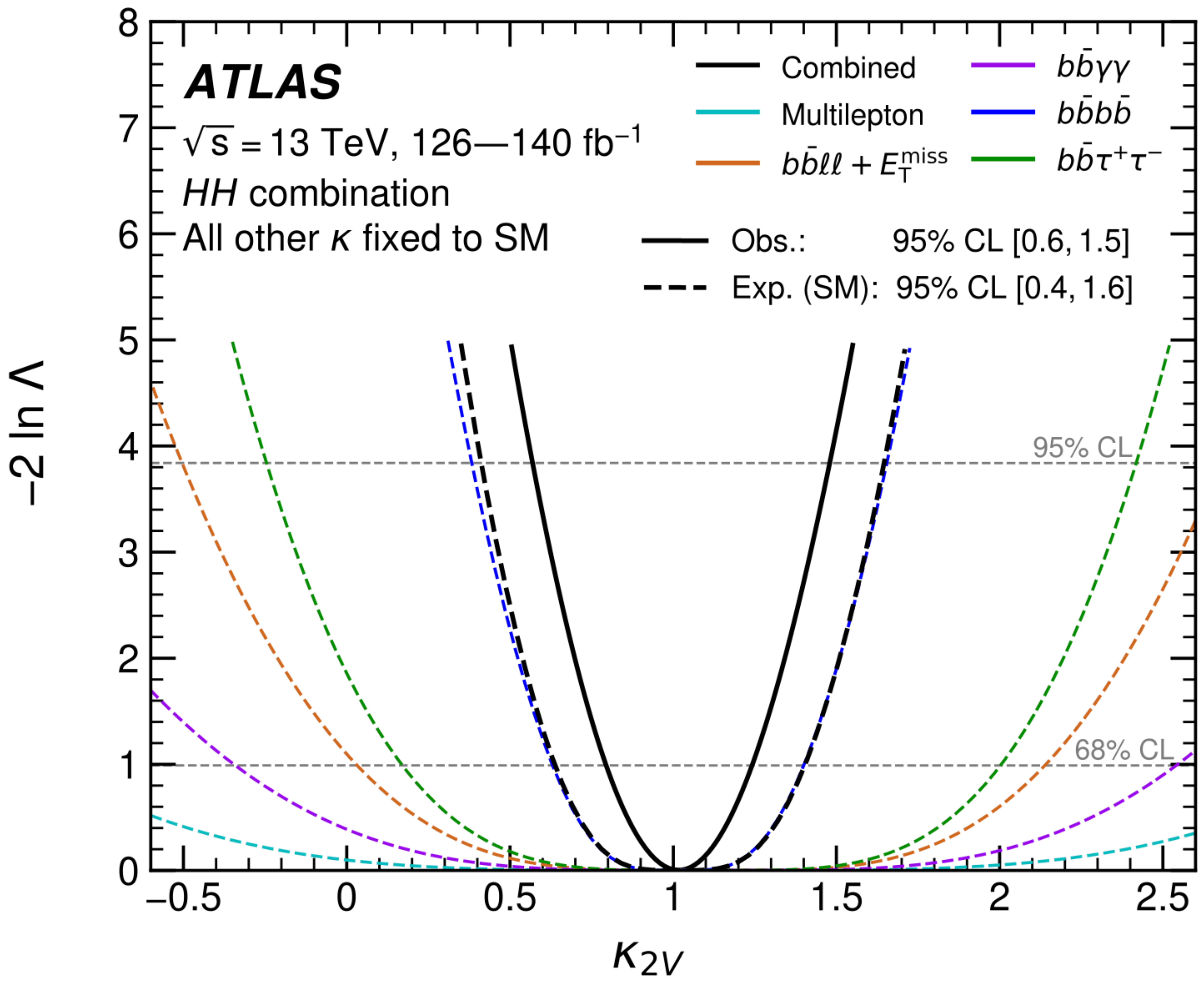
- $\sigma_{ggF+VBF}(HH) < 86$ fb (obs)
- $\sigma_{ggF+VBF}(HH) < 71$ fb (obs)

Important systematic uncertainties:

- Modelling the radiation of additional heavy-flavour jets in ggF single Higgs boson

Double Higgs combination: constraints on κ_λ and κ_{2V}



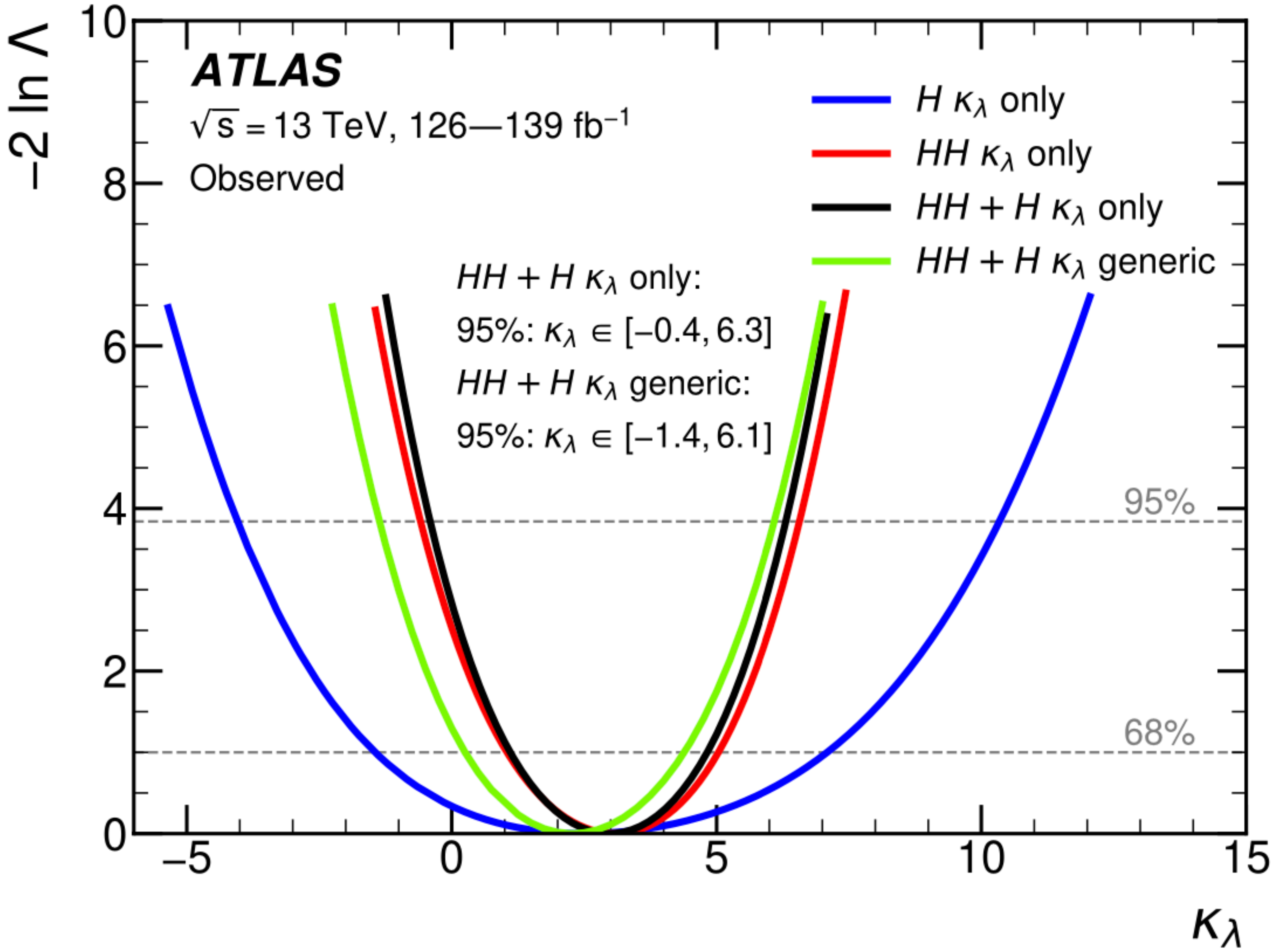


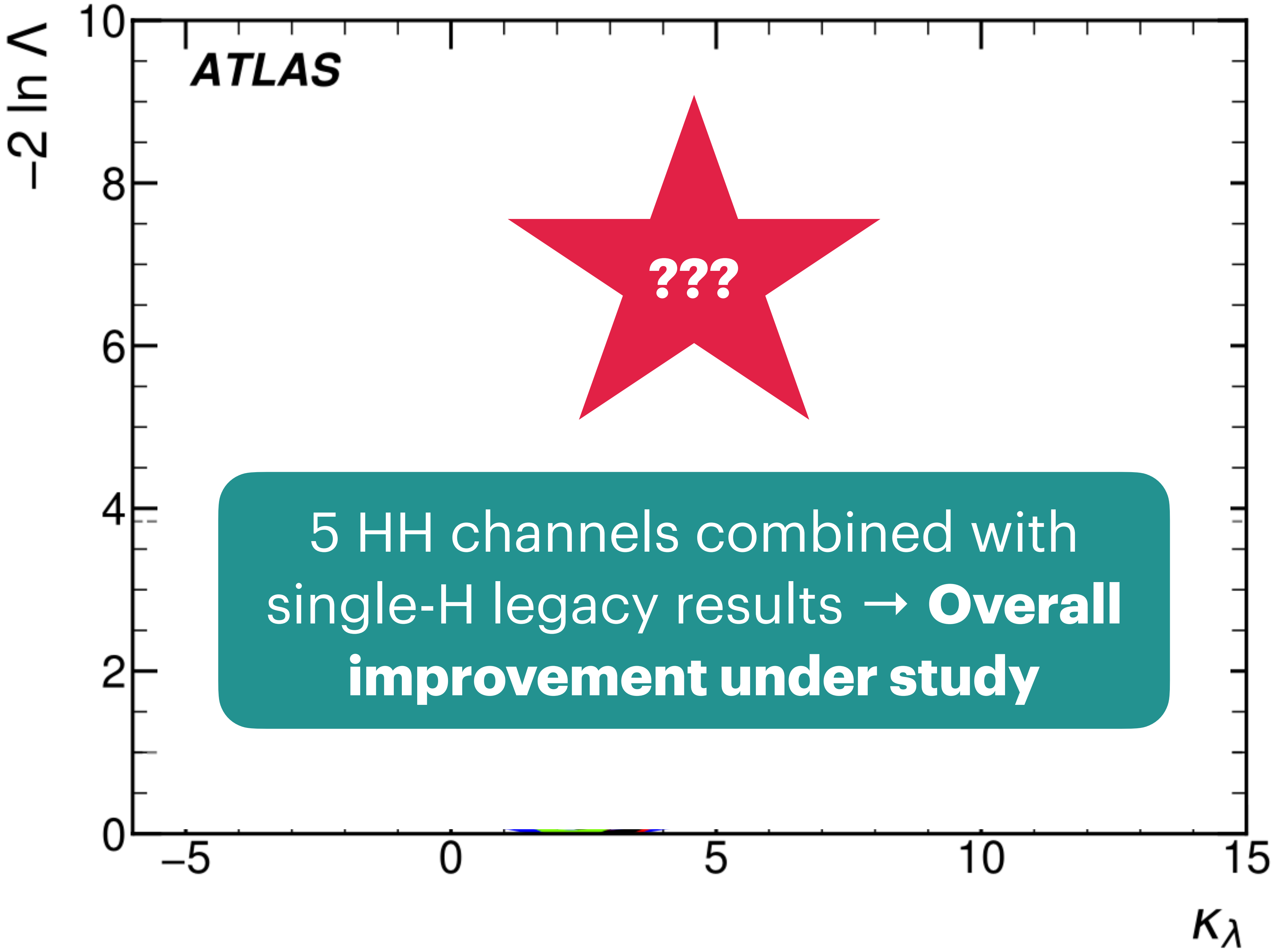
- **Obs limit at 95%CL: [-1.2,7.2]**
- Tighest upper bound on positive side from $bb\gamma\gamma$
- Tightest lower bound on negative side from $bb\tau\tau$

- **Obs limit at 95%CL: [0.6,1.5]**
- Best sensitivity from bbbb, driven by the boosted channel

Single and double Higgs combination

Phys. Lett. B 843 (2023) 137745





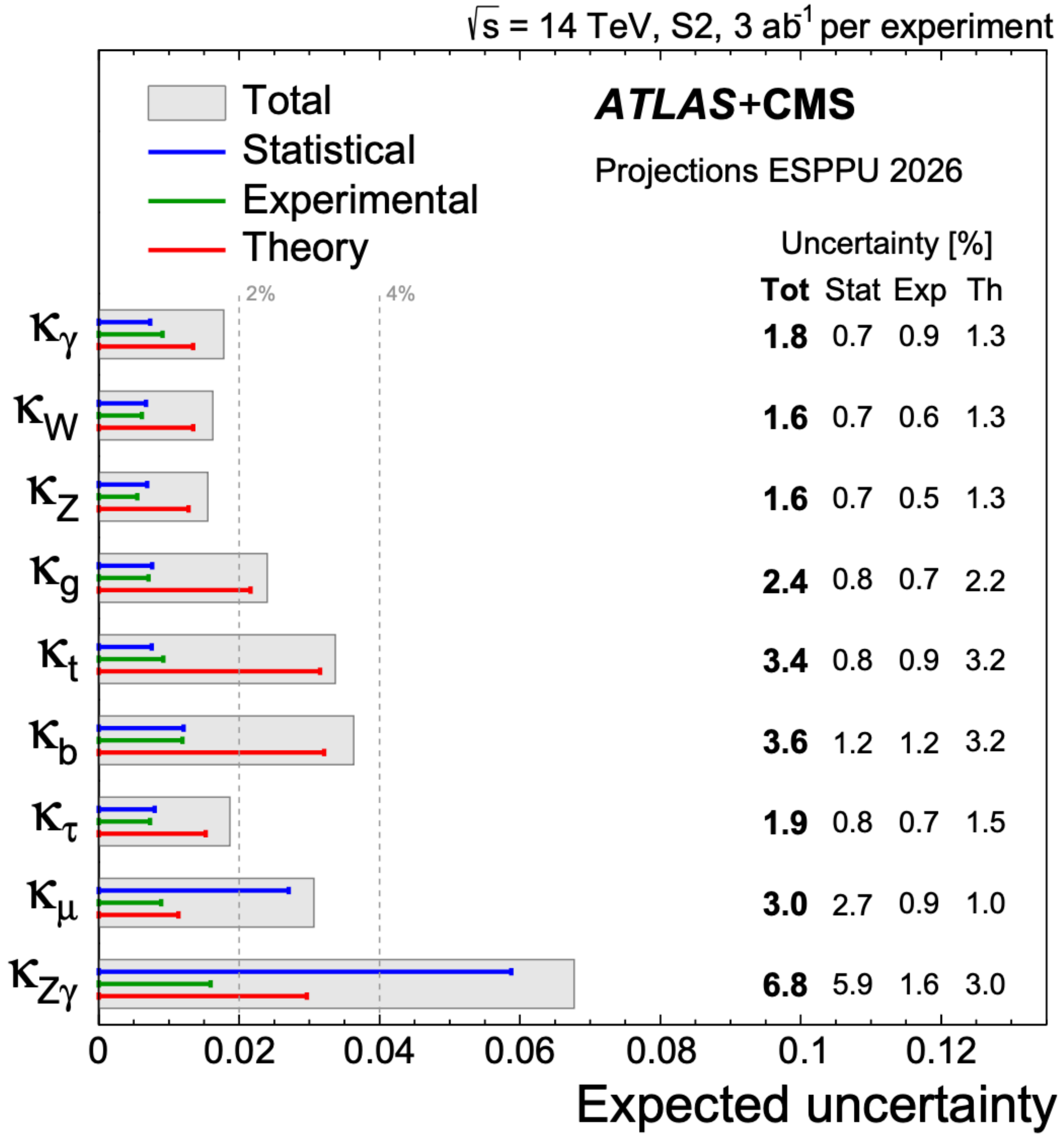
5 HH channels combined with single-H legacy results → **Overall improvement under study**

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	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

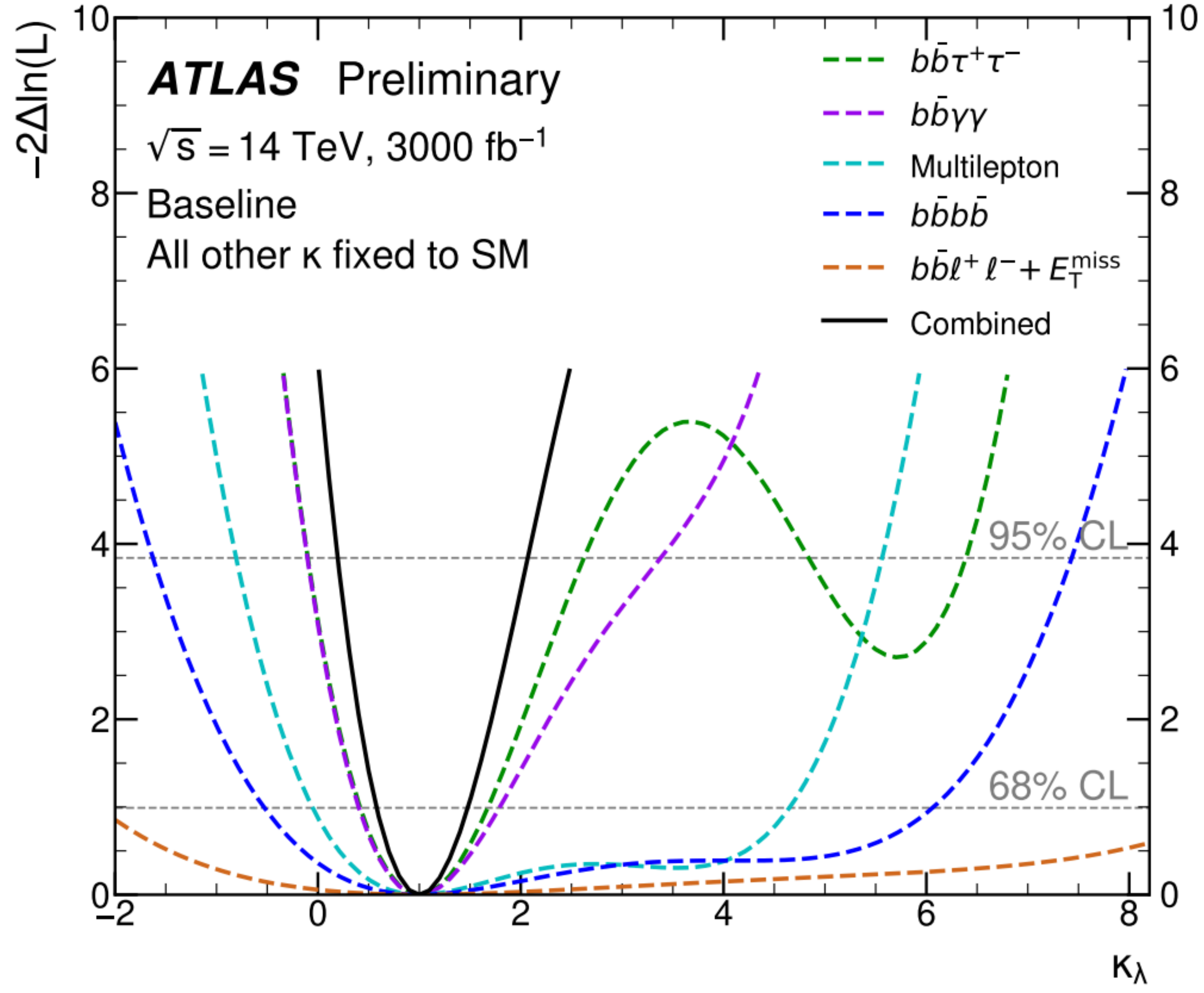
- Constraint on κ_λ mainly from HH combination;
- 7% improvement by adding single H combination
- Relaxed assumption on other couplings by adding single H combination to the HH combination

H and HH coupling projections at HL-LHC

arXiv:2504.00672



Projections considering different systematic uncertainties scenarios



- Projection on μ for rare decays H → Zγ and H → $\mu\mu$:
    - 14% and 6%, respectively
- Improvement by 30% on precision of κ_μ and $\kappa_{Z\gamma}$ wrt HL-LHC projection

- Sensitivity on κ_λ measurement dominated by bbττ and bbγγ channels
- ATLAS+CMS: Uncertainty on κ_λ below 30% and expected significance around 7.6

Summary

- **The single H combination has been *updated* with the LHC Run 2 dataset:**
  - *All measurement show excellent agreement with the SM predictions*
  - *Uncertainty reduction of the order of 10% for the signal strength and as 43% for the expected uncertainty on κ_c*
- **Searches for HH production and its combination at ATLAS:**
  - *provide unique access to Higgs potential shape*
  - *best expected constraints to date on κ_λ [-1.6, 7.2] at ATLAS*
- **A combination of H +HH measurements:**
  - *Contraints on κ_λ dominated by HH, with some gain from adding single H channels; relaxed assumptions on others couplings*
- **Prospects for HL-LHC (14 TeV, 3ab-1):**
  - Significant reduction on uncertainty of μ for rare decays;
  - ATLAS+CMS combination projection: expected significance around 7.6

Run 3 data-taking is on-going! There are much more to come!
Stay tuned!

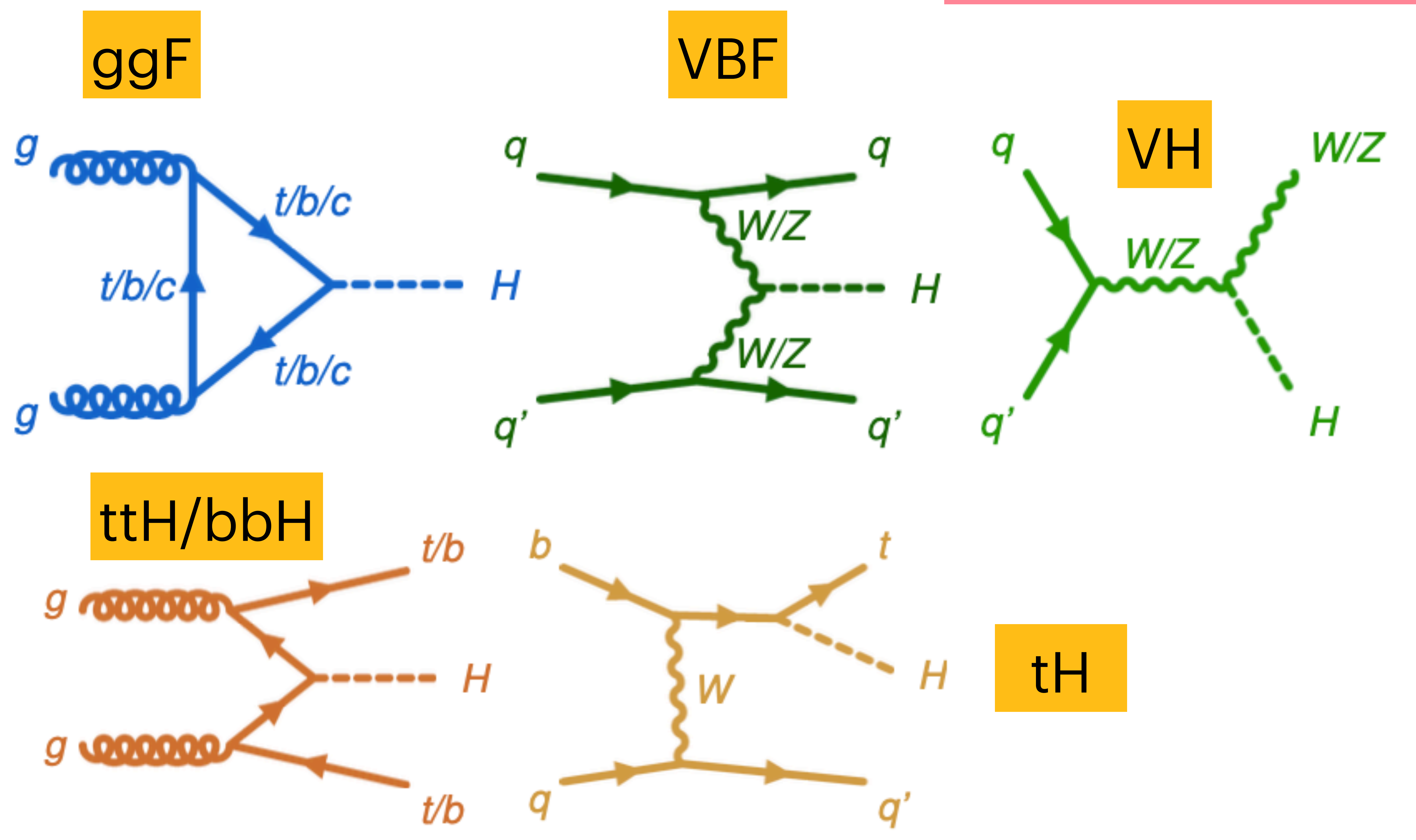
Back-up slides

Higgs Boson production and decay at LHC

Nature, vol. 607, 52-59 (2022)

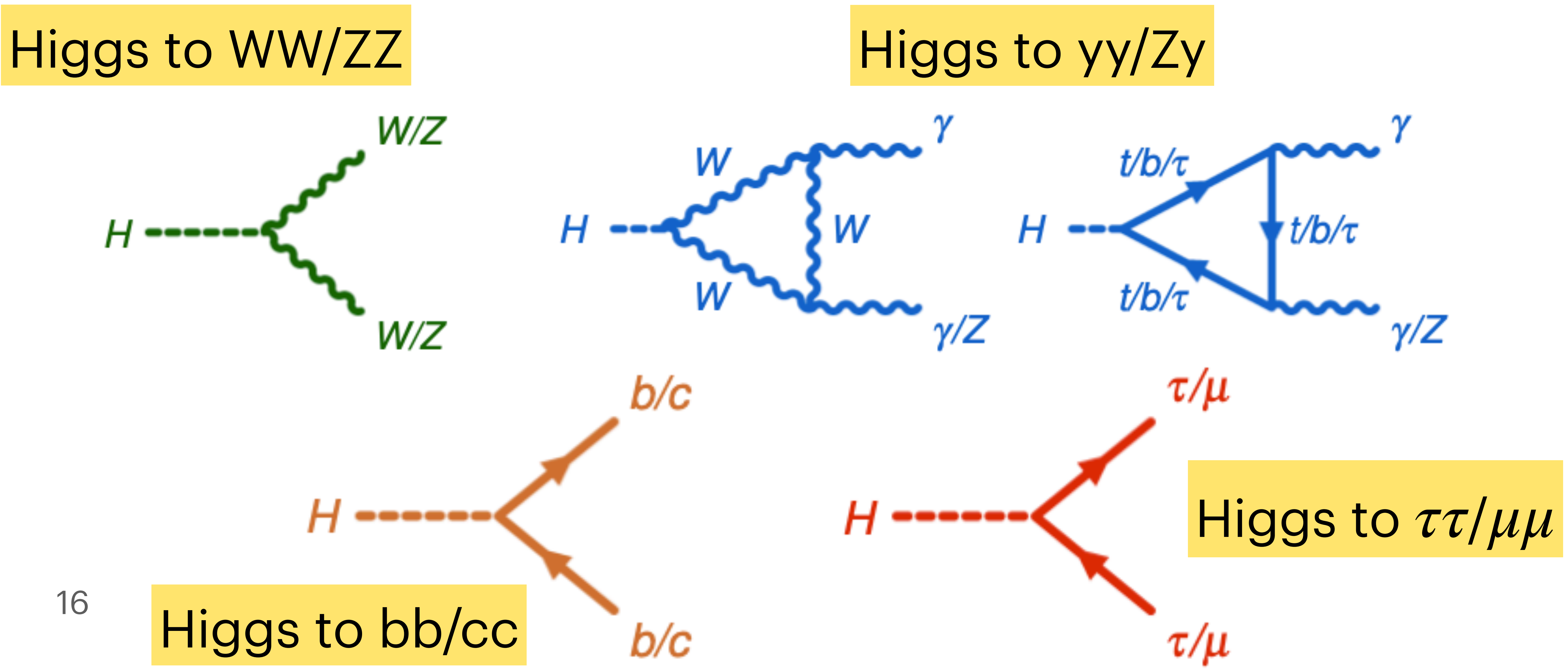
Higgs Production processes:

- Gluon-gluon fusion (ggF) (*dominant production mode*)
- Vector-boson fusion (VBF)
- Association with a vector boson (VH)
- Association with top and bottom quark pair (ttH/bbH)



Higgs Decay channels:

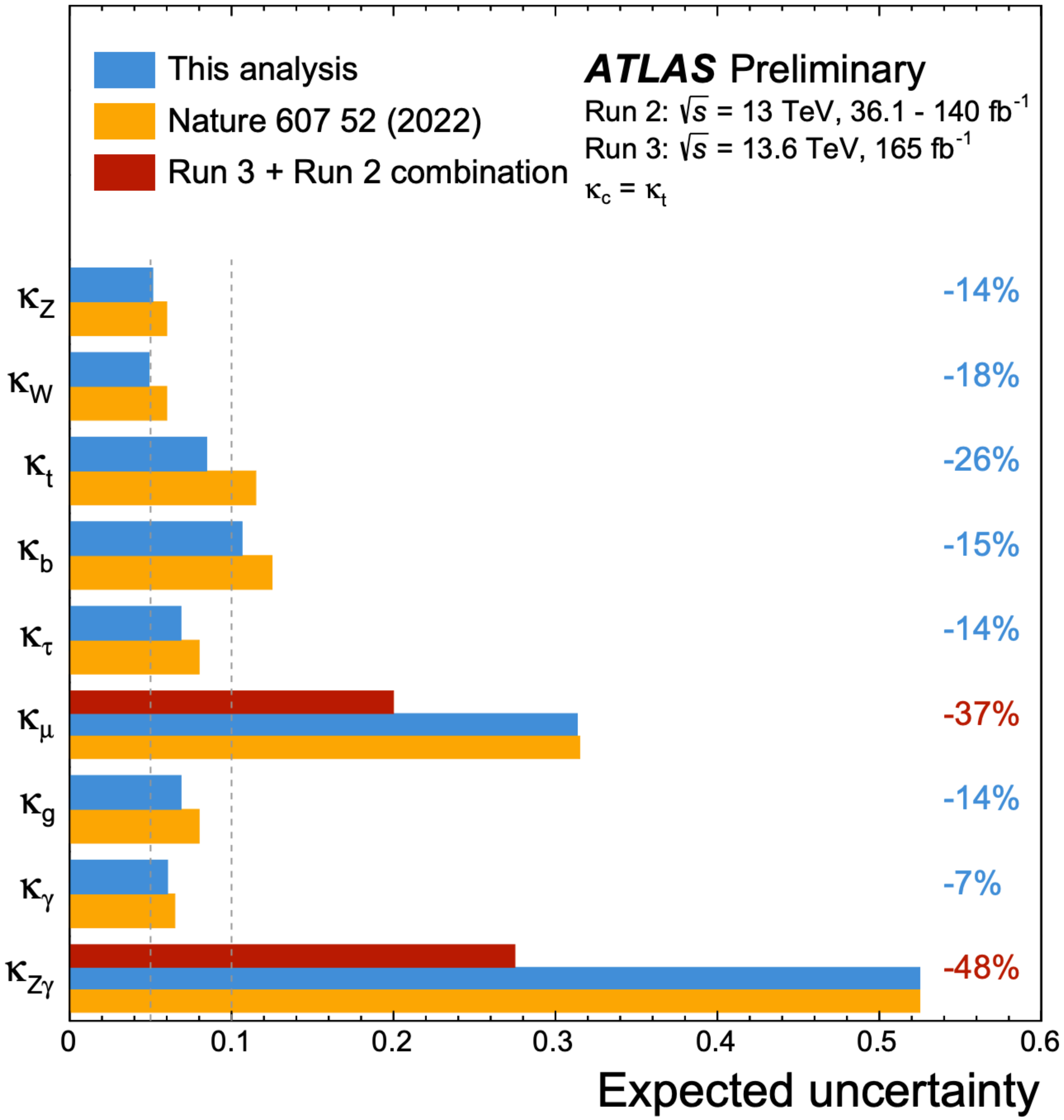
- $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$
  - Low BR and high mass resolution
- $H \to b\bar{b}, H \to W^{\pm}W^{\mp}, H \to \tau^{+}\tau^{-}$ and $H \to c\bar{c}$
  - High BR and low mass resolutions
- Rare decays: $H \to \mu^{+}\mu^{-}$ and $H \to Z\gamma$



Run 2 + Run 3 Expected Uncertainties

Effective parametrization

- Run3 dataset (2022, 2023 and 2024 = 165 fb-1) is used for analysis of H($\mu\mu$) and H($Z\gamma$)
- **Reduction on the expected uncertainty for κ_μ of about 37% while 48% reduction is expected for $\kappa_{Z\gamma}$**



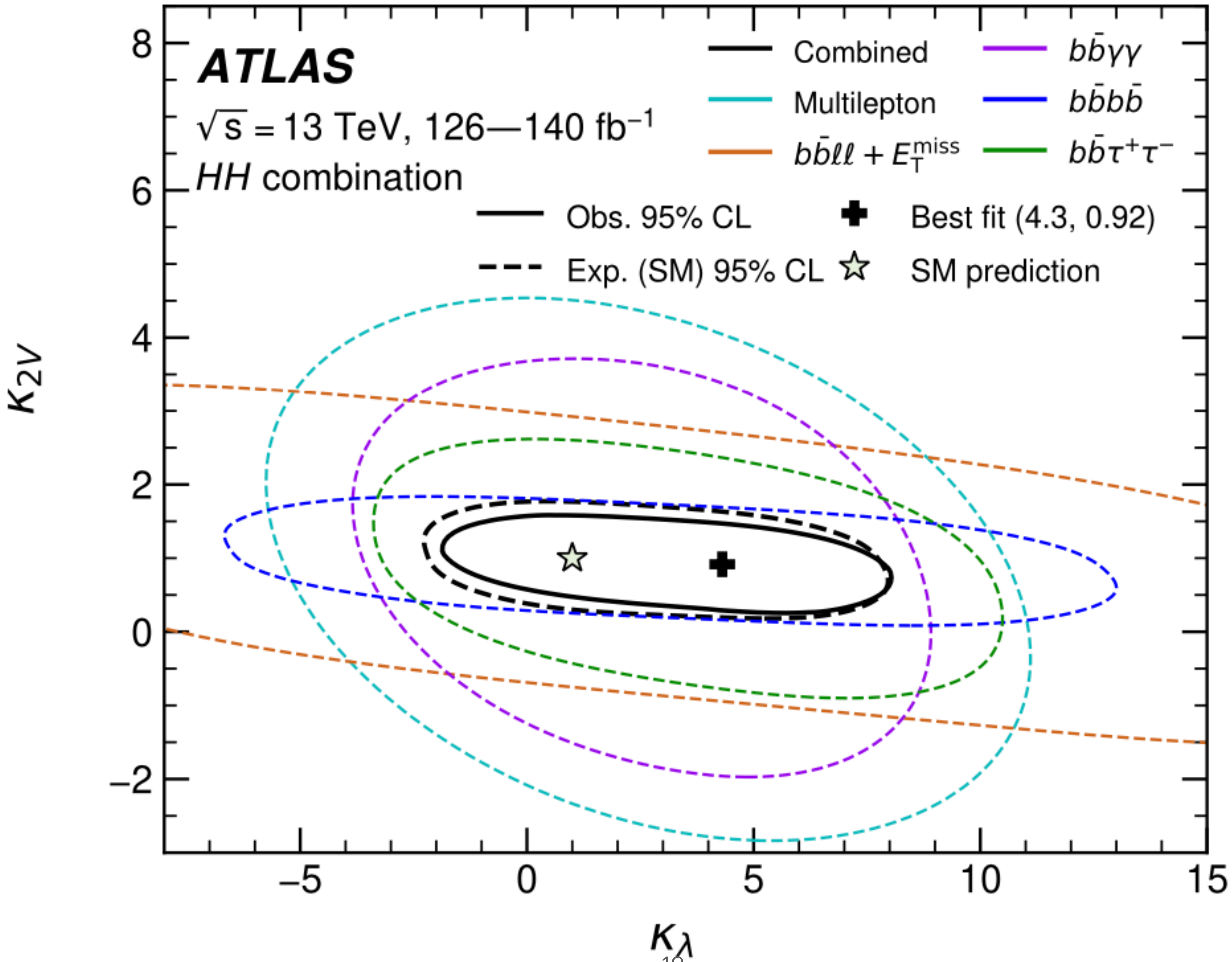
Resolved and effective parametrization

Higgs boson coupling modifiers

Parameter	Resolved $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$		Effective $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$
	Free κ_c	$\kappa_c = \kappa_t$	$\kappa_c = \kappa_t$
κ_Z	$0.97^{+0.09}_{-0.07}$	0.96 ± 0.05	0.96 ± 0.05
κ_W	$0.99^{+0.09}_{-0.06}$	0.99 ± 0.04	1.00 ± 0.05
κ_t	$0.99^{+0.10}_{-0.08}$	$0.99^{+0.06}_{-0.05}$	0.99 ± 0.09
κ_b	$0.90^{+0.12}_{-0.11}$	0.89 ± 0.09	$0.89^{+0.10}_{-0.09}$
κ_c	$1.1^{+1.6}_{-3.8}$	—	—
κ_τ	$0.95^{+0.10}_{-0.08}$	0.94 ± 0.06	0.94 ± 0.06
κ_μ	$1.05^{+0.25}_{-0.31}$	$1.04^{+0.24}_{-0.30}$	$1.04^{+0.23}_{-0.30}$
κ_g	—	—	$0.99^{+0.07}_{-0.06}$
κ_γ	—	—	0.97 ± 0.06
κ_{Z/γ^*}	—	—	$1.36^{+0.30}_{-0.36}$

- Observed coupling modifiers
- **Resolved parametrization:**
  - κ_g, κ_γ and $\kappa_{Z\gamma}$ are are expressed as a function of the other modifiers.
- **Effective parametrization:**
  - Effective modifierd as independent parameters

HH combination: κ_{2V} and κ_λ



HH combination: correlation scheme

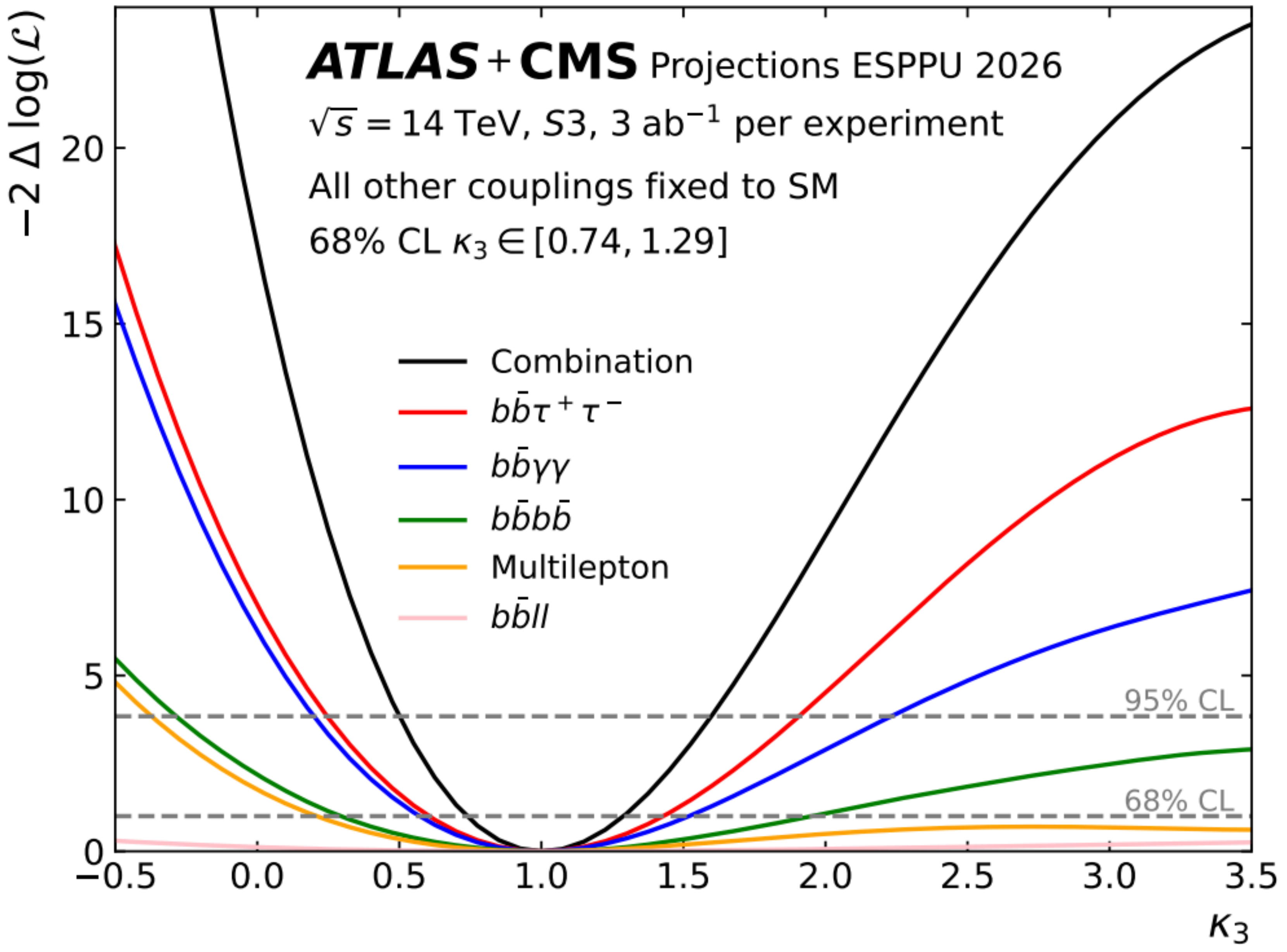
- Correlations between uncertainties across different searches are studied
  - **Correlated uncertainties include:**
    - **Data-taking related uncertainties:**
      - **Integrated luminosity** (except for the resolved bbbb analysis, which uses a different calibration).
      - **Pile-up modeling** (mismodeling of multiple pp interactions per bunch crossing).
    - **Physics-object related uncertainties** when objects are common to multiple searches.
    - **Theoretical uncertainties** affecting simulated signal and background, such as:
      - QCD scale variations,
      - Parton distribution functions (PDFs),
      - Higgs boson decay branching fractions.
  - **Uncorrelated uncertainties:**
    - Systematic uncertainties that are significant within an individual search but are strongly constrained or pulled by its fit — to avoid propagating their effect to others.
- **A check confirmed that treating these as correlated or uncorrelated has a negligible impact on the combined result.**

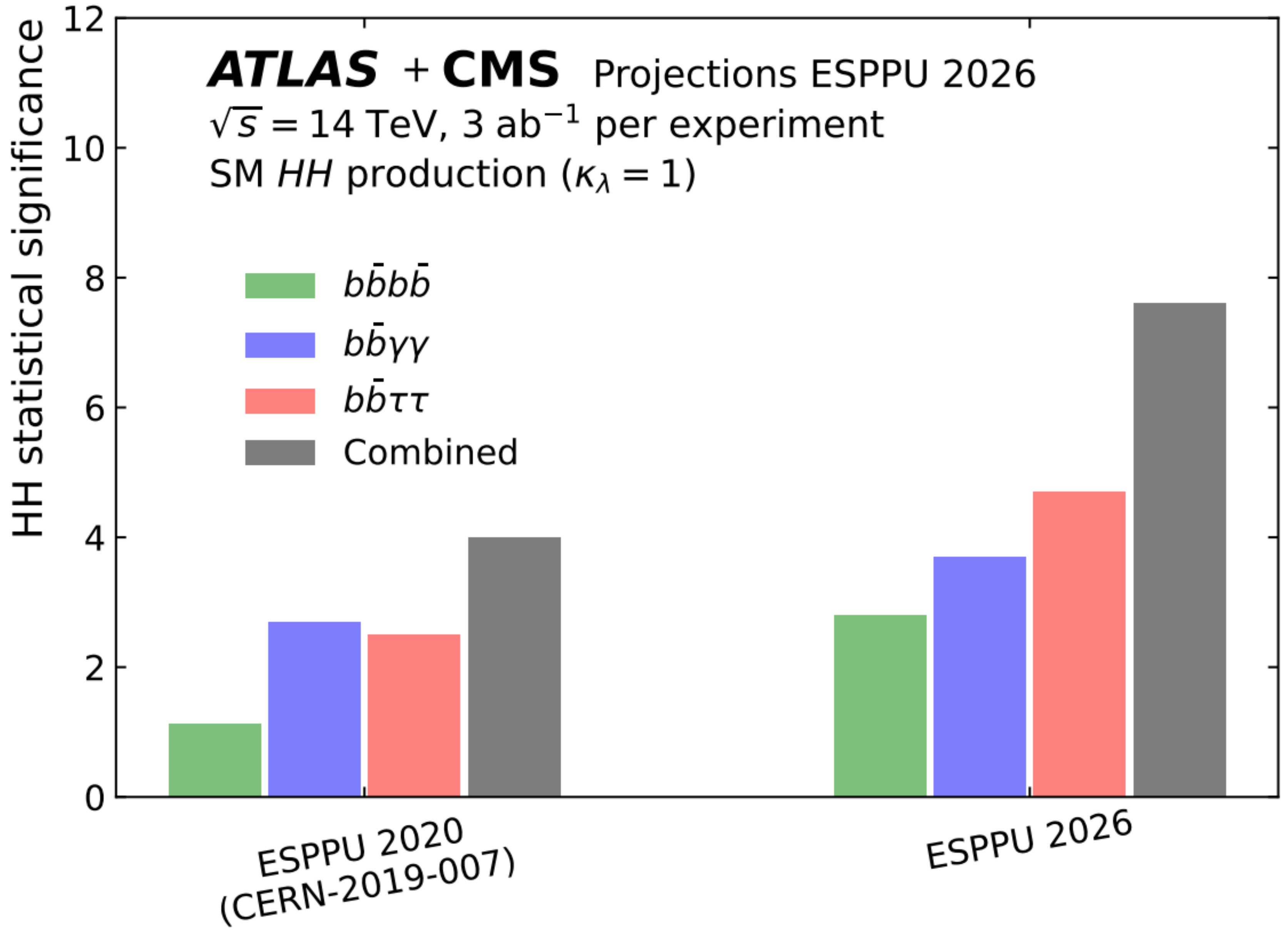
Projections at 14 TeV (3ab-1)

Highlights of the HL-LHC physics projections by ATLAS and CMS

- **S2 Scenario (Reduced Systematic Uncertainties)**
  - This scenario, named S2 for backward compatibility with previous European strategy naming, assumes **reduced systematic uncertainties in most cases**.
  - **Theoretical Systematic Uncertainties** are halved (1/2).
  - Contributions from limited MC event counts are assumed to be **negligible**.
  - **Experimental Systematic Uncertainties:** The "scaling" of these uncertainties **depends on the physics object** and accounts for their origin (e.g., statistics of calibration samples, modeling of Standard Model processes in calibration).
- **S3 Scenario (Further Improvements)**
  - This is an additional scenario (S3) that evaluates the impact of recent improvements in specific object reconstruction relative to the S2 scenario.
  - The S3 projections are presented **only when relevant** for the discussion, meaning it applies to specific studies, while S2 is the more general reduced systematics case.

Projections at 14 TeV (3ab-1)





	2 ab^{-1} ($S2$)		3 ab^{-1} ($S2$)		3 ab^{-1} ($S3$)	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
HH statistical significance						
$b\bar{b}\tau^+\tau^-$	3.0†	1.9	3.5†	2.4	**3.8**†	**2.7**
$b\bar{b}\gamma\gamma$	2.1†	2.0†	2.4†	2.4†	**2.6**†	**2.6**†
$b\bar{b}b\bar{b}$ resolved	0.9	1.0†	1.0	1.2†	**1.0**	**1.3**†
$b\bar{b}b\bar{b}$ boosted	–	1.8†	–	2.2†	–	**2.2**†
Multilepton	0.8†	–	1.0†	–	**1.0**†	–
$b\bar{b}\ell^+\ell^-$	0.4†	–	0.5†	–	**0.5**†	–
Combination	3.7	3.5	4.3	4.2	**4.5**	**4.5**
ATLAS+CMS	6.0		7.2		**7.6**	
κ_3 68% confidence interval						
$b\bar{b}\tau^+\tau^-$	[0.3, 1.8]†	[0.1, 3.0]	[0.4, 1.7]†	[0.2, 2.2]	**[0.5, 1.6]**†	**[0.3, 2.0]**
$b\bar{b}\gamma\gamma$	[0.3, 2.0]†	[0.2, 2.3]†	[0.4, 1.8]†	[0.3, 2.0]†	**[0.5, 1.7]**†	**[0.4, 1.9]**†
$b\bar{b}b\bar{b}$ resolved	[−0.7, 6.3]	[−0.6, 7.6]†	[−0.5, 6.1]	[−0.3, 7.3]†	**[−0.5, 6.1]**	**[−0.3, 7.2]**†
$b\bar{b}b\bar{b}$ boosted	–	[−0.6, 8.5]†	–	[−0.4, 8.2]†	–	**[−0.4, 8.2]**†
Multilepton	[−0.2, 4.9]†	–	[−0.1, 4.7]†	–	**[−0.1, 4.7]**†	–
$b\bar{b}\ell^+\ell^-$	[−2.4, 9.3]†	–	[−2.2, 9.2]†	–	**[−2.1, 9.1]**†	–
Combination	[0.6, 1.5]	[0.4, 1.7]	[0.6, 1.5]	[0.5, 1.6]	**[0.6, 1.4]**	**[0.6, 1.5]**
ATLAS+CMS uncertainty	−32% / +37%		−27% / +31%		**−26% / +29%**	

† *used in the ATLAS+CMS combination*

HH (ATLAS and CMS)