Workshop for Tera-Scale Physics and Beyond 2025

Latest LHC physics and HL-LHC prospects (Higgs)

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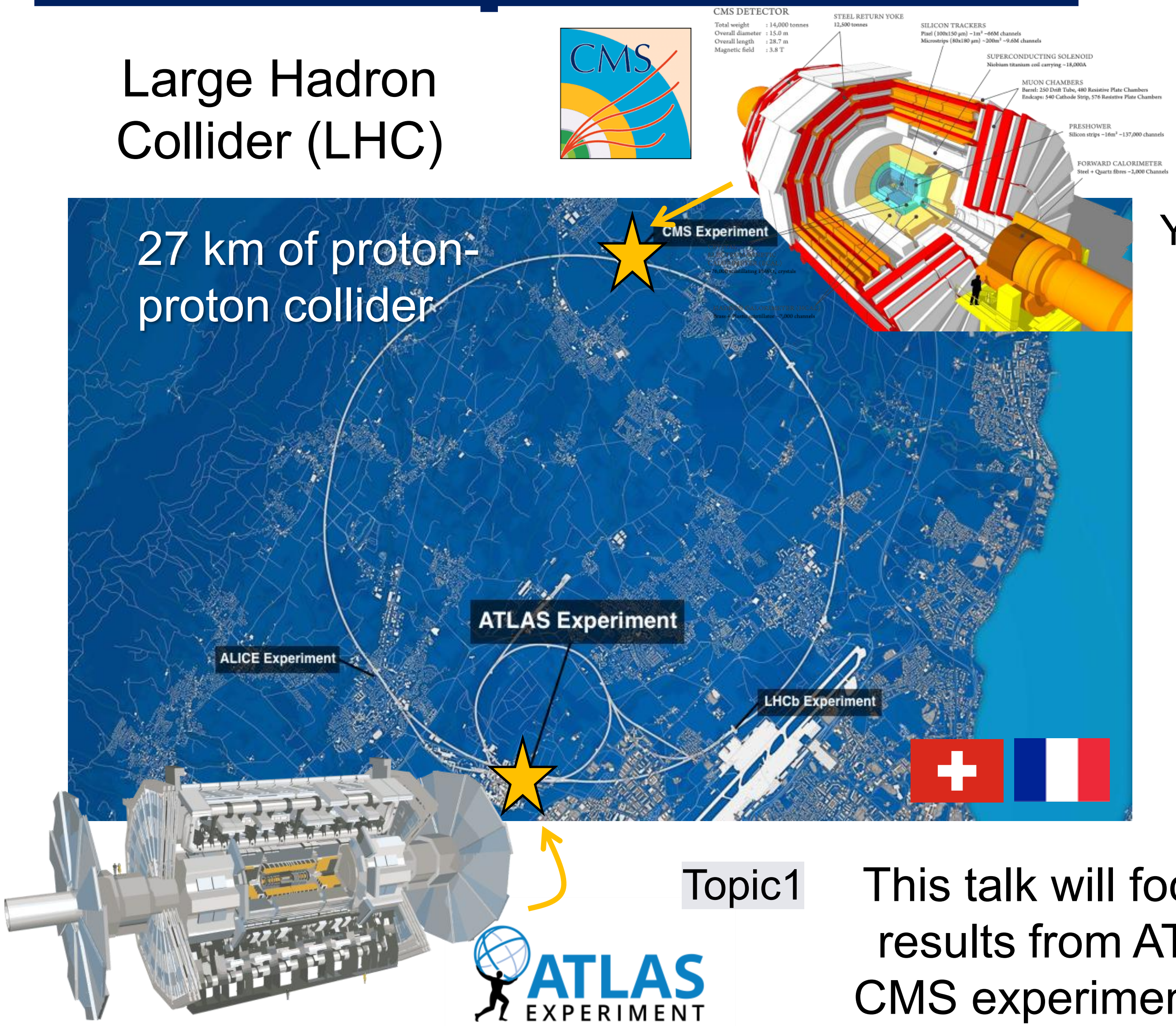
LHC experiments

Large Hadron Collider (LHC)



27 km of proton-proton collider

Operation and data-taking

	Run 1	Run 2	Run 3
Year	2011 2012	2015 2018	2022 2026.6
Center of mass energy $\sqrt{s}$		13 TeV	13.6 TeV
Peak luminosity		~10^{34} /cm^2 s	~10^{34} /cm^2 s
Integrated luminosity		147 fb^{-1}	301 fb^{-1} (Until 2025) Full Run 3 500 fb^{-1} in total

Topic1 This talk will focus on the results from ATLAS and CMS experiments in 2025

Plan from 2030

Topic2 ~3 ab^{-1} until the end of HL-LHC period

Interest: Higgs physics

- ○ Higgs boson discovery in 2012
  All elementary particles predicted by the SM have been discovered
- ○ Higgs boson measurement today CMS-PAS-HIG-21-018, ATLAS-CONF-2025-006
  - ATLAS : $\mu = 1.023 \pm 0.028(\text{stat.})^{+0.026}_{-0.025}(\text{exp.})^{+0.051}_{-0.048}\,(\text{theory})$
  - CMS : $\mu = 1.014 \pm 0.028(\text{stat.})^{+0.025}_{-0.024}(\text{exp.})^{+0.040}_{-0.039}\,(\text{theory})$

→ High-precision Higgs measurements are the next key

Is the Higgs boson we observe consistent with the Standard Model? Or are there any BSM Higgs?

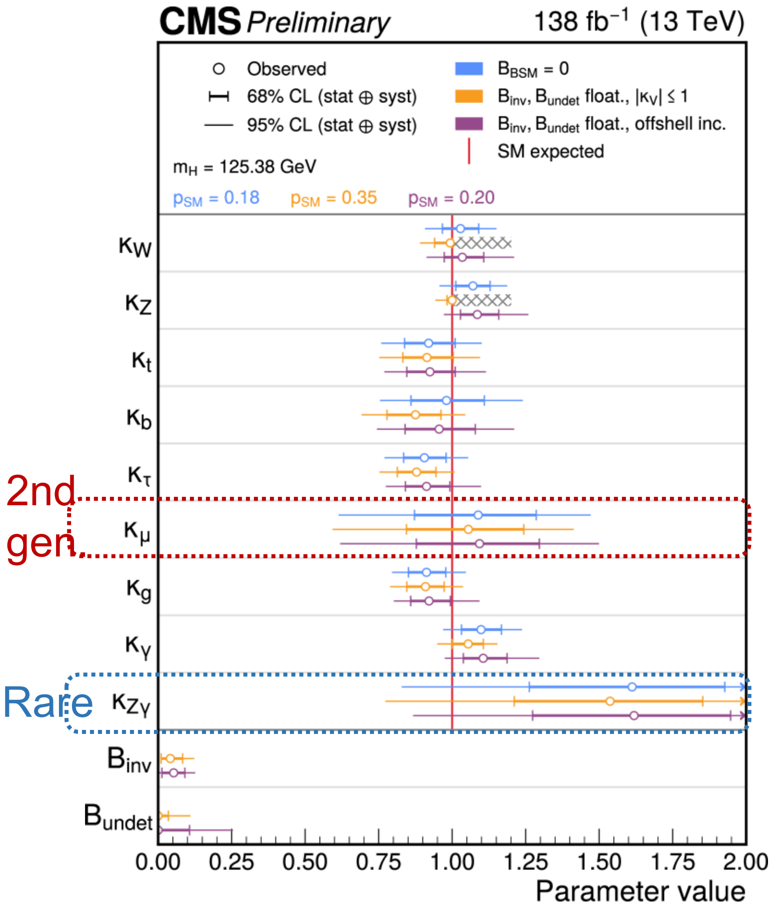
- ○ Coupling measurement is important to understand the Higgs sector of the SM
  - **Fermions**: Test of Yukawa-couplings
    Are the fermion masses proportional to their Higgs couplings?
  - **Bosons**: Test of electroweak symmetry breaking (EWSB)
  - **Self-coupling**: The direct way to probe the shape of the Higgs potential
    Understanding the structure of the vacuum

κ_F and κ_V measurement (Run 2)

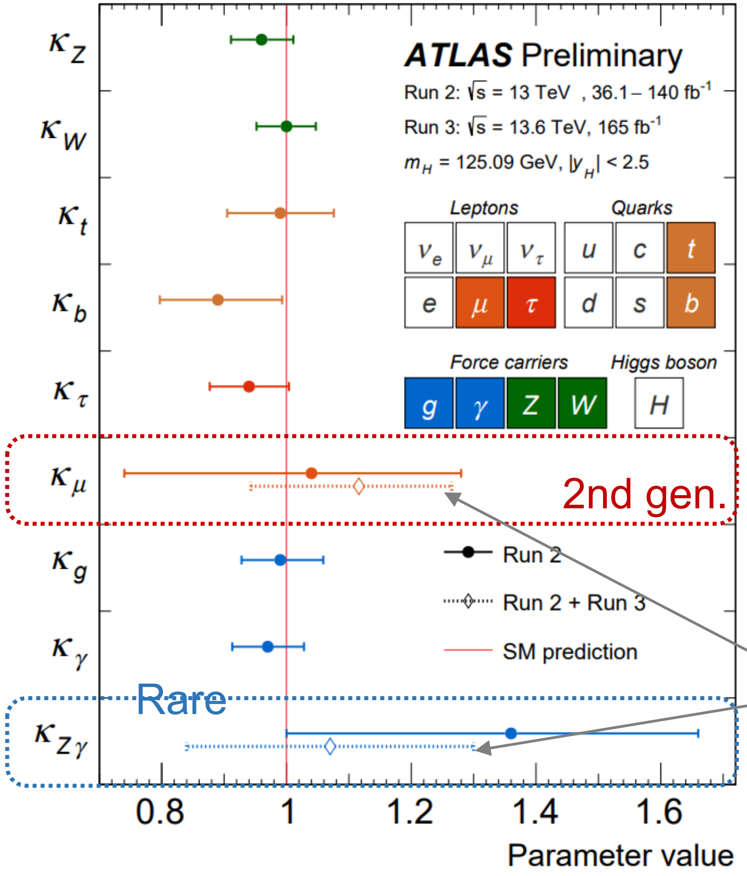
Summary of coupling measurement in Run 2

$$\kappa_i = g_i/g_i^{SM}$$

CMS-PAS-HIG-21-018



ATLAS-CONF-2025-006



The couplings to third-generation fermions and weak bosons are already constrained at the 10% level

Increased statistics in Run 3

Next steps is to measure second-generation couplings and rare processes

- New $H \to \mu^+\mu^-$ and $H \to Z\gamma$ results are released from ATLAS
- $H \to c\bar{c}$ results are released from ATLAS and CMS

$H \to \mu^+\mu^-$ at ATLAS (partial Run 3)

Phys. Rev. Lett. 135 (2025) 231802

Small branching ratio, but clean channel

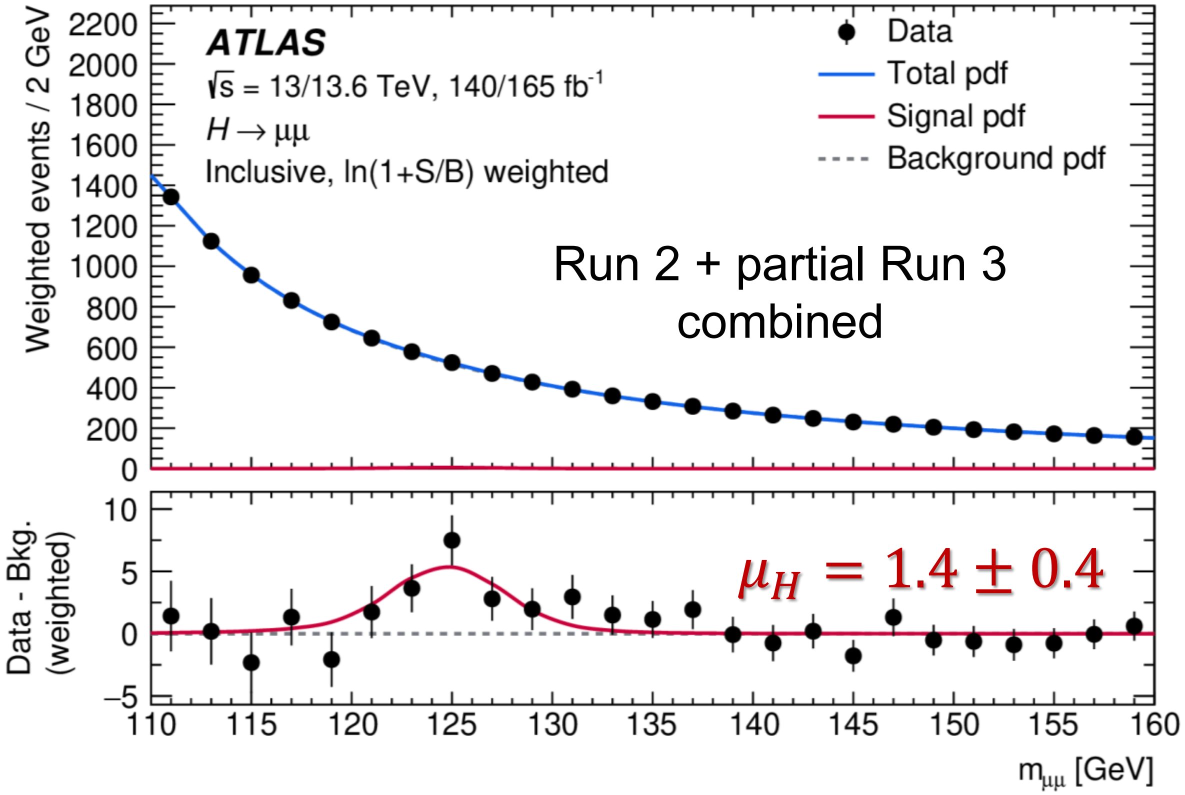
- Branching ratio: ~2x10^{-4}
- Main background is Drell-Yan ($Z \to \mu^+\mu^-$)

Analysis strategy

- Dataset: **partial Run 3 165 fb^{-1}**
- 23 categories are defined for statistical analysis
  ggF x8, VBF x8, VH x5, ttH x2

	Observed	**Expected**
Partial Run 3	2.8σ	1.8σ
Statistical combination with Run 2 analysis (Phys. Lett. B 812 (2021) 135980)	**3.4σ**	2.5σ

Evidence of $H \to \mu^+\mu^-$!



Run 2 + partial Run 3 combined

$\mu_H = 1.4 \pm 0.4$

↔ 3.0σ (2.5σ exp.) at CMS Run 2

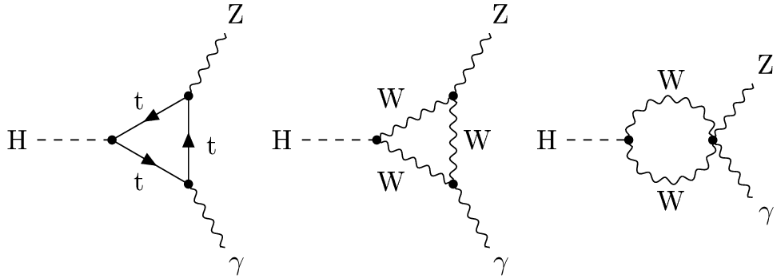
JHEP 01 (2021) 148

Consistent result

$H \rightarrow Z\gamma$ at ATLAS (partial Run 3)

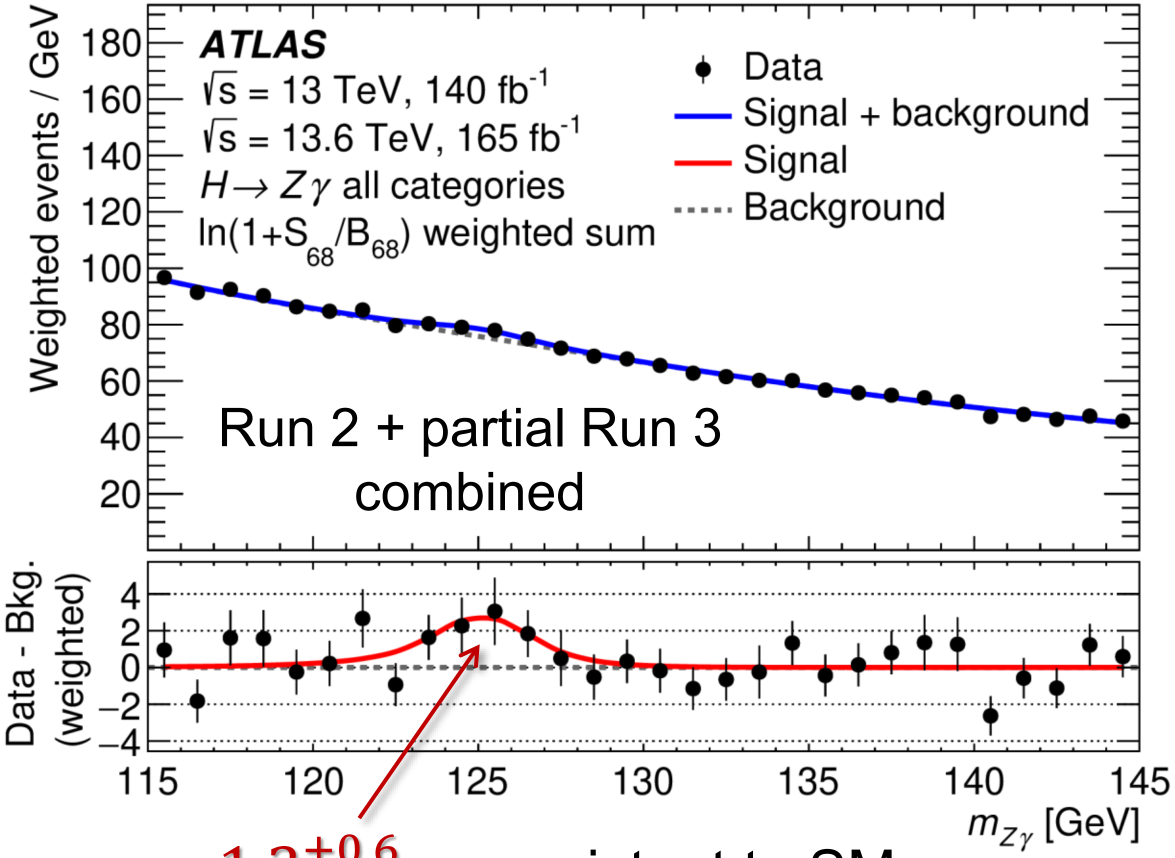
arXiv:2507.12598

- Rare process (~1.5x10^{-3})
  Loop-induced process
  : it may be sensitive to BSMs in the loop



- Analysis strategy
  - Dataset: **partial Run 3 165 fb^{-1}**
  - Only $Z \rightarrow ll$ decay is considered
  - Main background: $Z +$ jets, Diboson
    Use BDT to separate

	Observed	**Expected**
Partial Run 3	1.4σ	1.5σ
Combined with Run 2 analysis (Phys. Lett. B 809 (2020) 135754)	**2.5σ**	1.9σ



$\mu_H = 1.3^{+0.6}_{-0.5}$: consistent to SM

Previous analysis: $\mu_H = 2.0^{+1.0}_{-0.9}$ (Run 2)

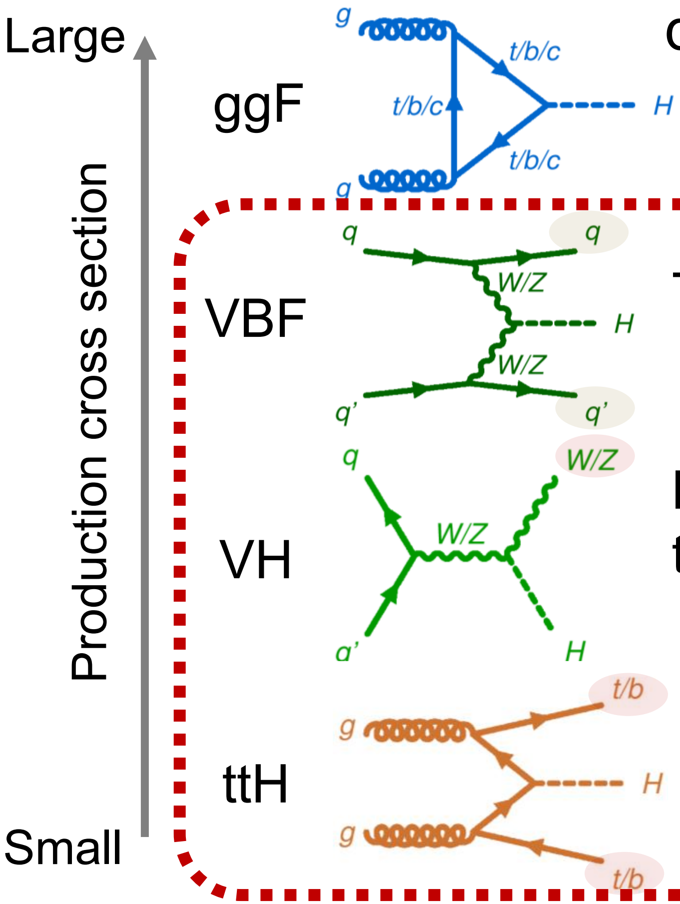
The excess over the SM prediction is reduced

$H \to c\bar{c}$

- ○ Branching ratio: 2.9% (SM)
- ○ Huge QCD multijet as background

} $H \to c\bar{c}$ is very challenging…

Strategy 1 Use a production mode with distinctive features



Two jets go forward region

VBF trigger is developed

Leptonic decay of W/Z can tag

Used as a main channel

Two tops can tag

Strategy 2 Improve *c*-jet tagger

Transformer-based tagger is introduced

- ○ ATLAS: GN2
- ○ CMS: ParticleTransformerAK4

Probability score of b-, c- and light-jets are calculated while training

Rejection factor at 50% *c*-jet efficiency

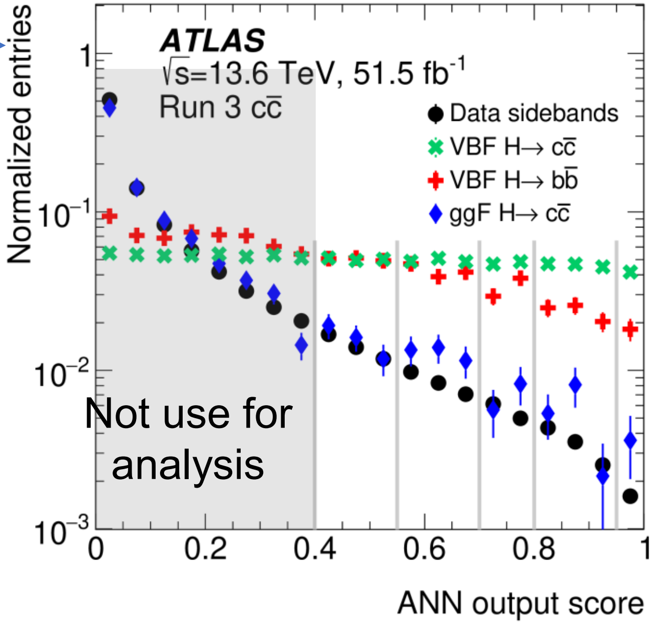
	Light-jets
ATLAS tagger (arXiv:2505.19689)	~30
CMS tagger (CMS-DP-2022-050)	~30

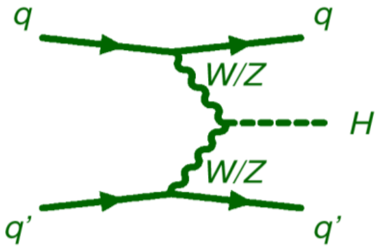
$H \to c\bar{c}$ by VBF at ATLAS

arXiv:2511.21911

- VBF process
  - Subleading production process (but small)
  - Main background: QCD multijets
- Strategy
  - ○ Datasets: Run 2 37.5 fb^{-1} + Run 3 52 fb^{-1}
  - ○ **New inclusive VBF trigger** was introduced late Run 2
  - ○ Use ANN for categorization

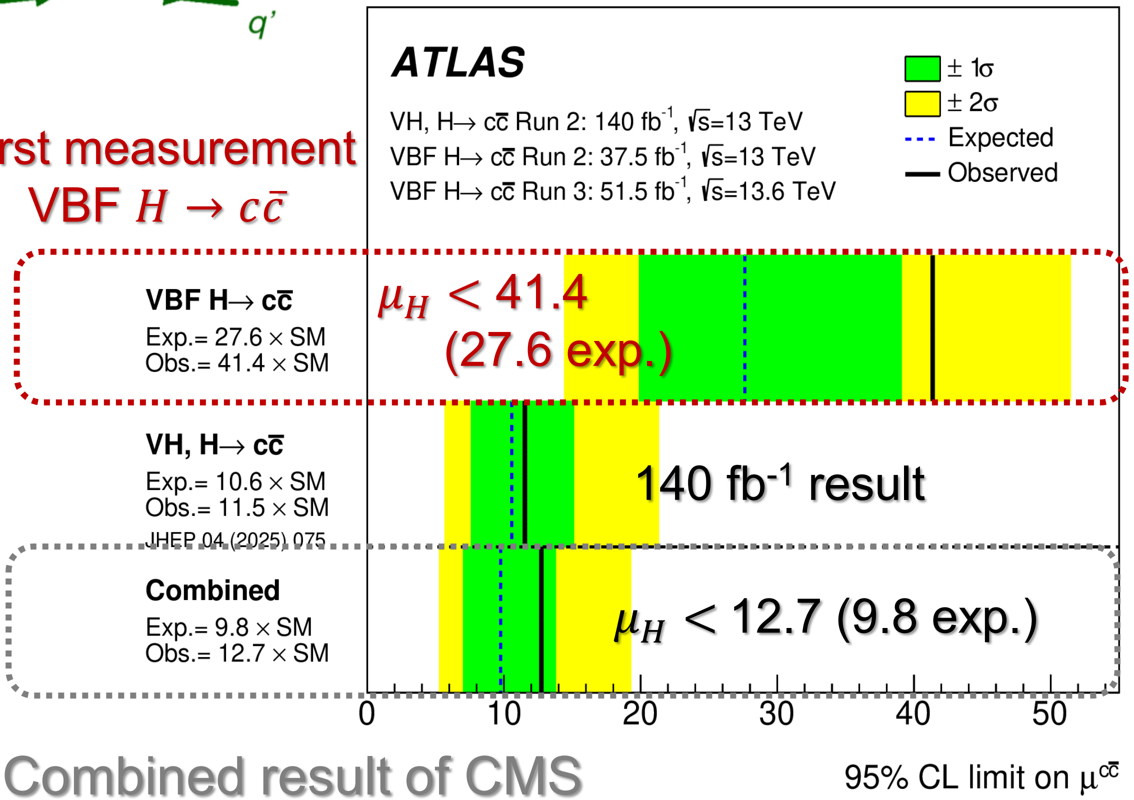
m$_H$ was decorrelated due to using final discriminant





ATLAS can start to measure with VBF process !

First measurement VBF $H \to c\bar{c}$



$\mu_H < 41.4$ (27.6 exp.)

140 fb^{-1} result

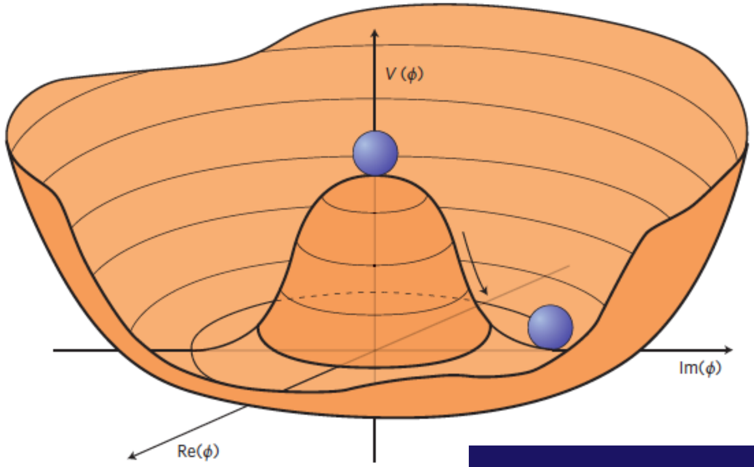
$\mu_H < 12.7$ (9.8 exp.)

Combined result of CMS ($\mu_H < 9.3$ (5.6 exp.)) is better than ATLAS

Higgs self-coupling

It is important to test the shape of Higgs potential

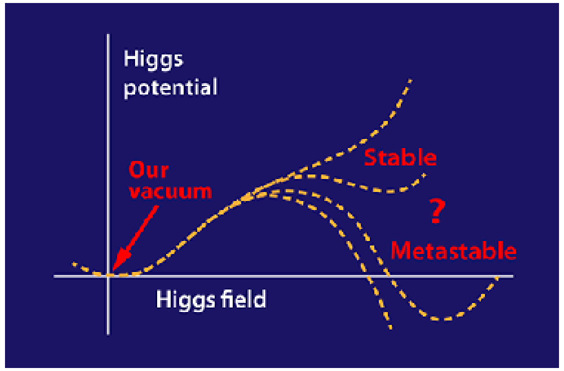
- EWSB is induced by the Higgs potential
- Determine the vacuum structure



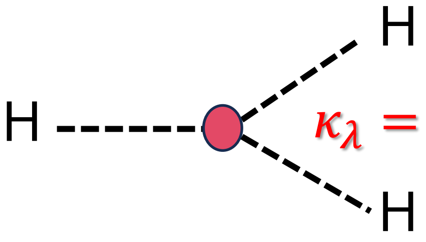
$$V(\Phi) = -\mu^2\Phi^2 + \lambda\Phi^4$$

Expand around vacuum expectation value v

$$V(h) = -\frac{\lambda}{4}v^4 + \lambda v^2 h^2 + \lambda_{HHH} v h^3 + O(h^4)$$



Trilinear coupling



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

λ determines the shape of Higgs potential

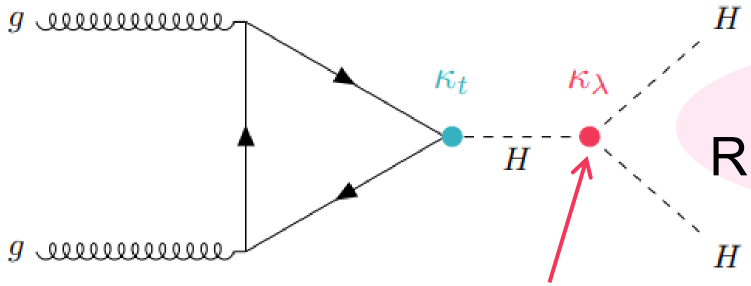
- In the SM: $\lambda_{HHH}^{SM} = \frac{m_H^2}{2v^2} \approx 0.13$
- λ can be modified if there are some BSM effects
  e.g. 2HDM model (Phys. Rev. D 101 (2020) 055032)
  κ_λ can be changed by ~100%

Production and decay modes

- Production process

Gluon-gluon fusion (ggF) $\sigma_{ggF}^{SM} = 31$ fb

($\sqrt{s} = 13$ TeV)



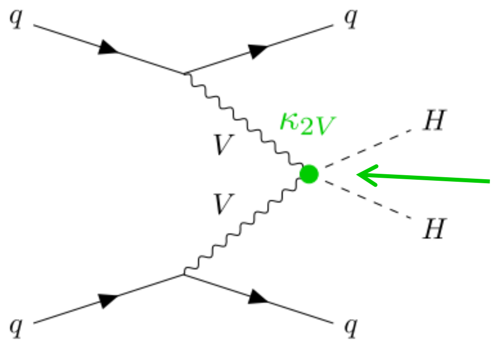
Determine the shape of Higgs potential

Rare

~9,000 events in Run 2 ATLAS + CMS

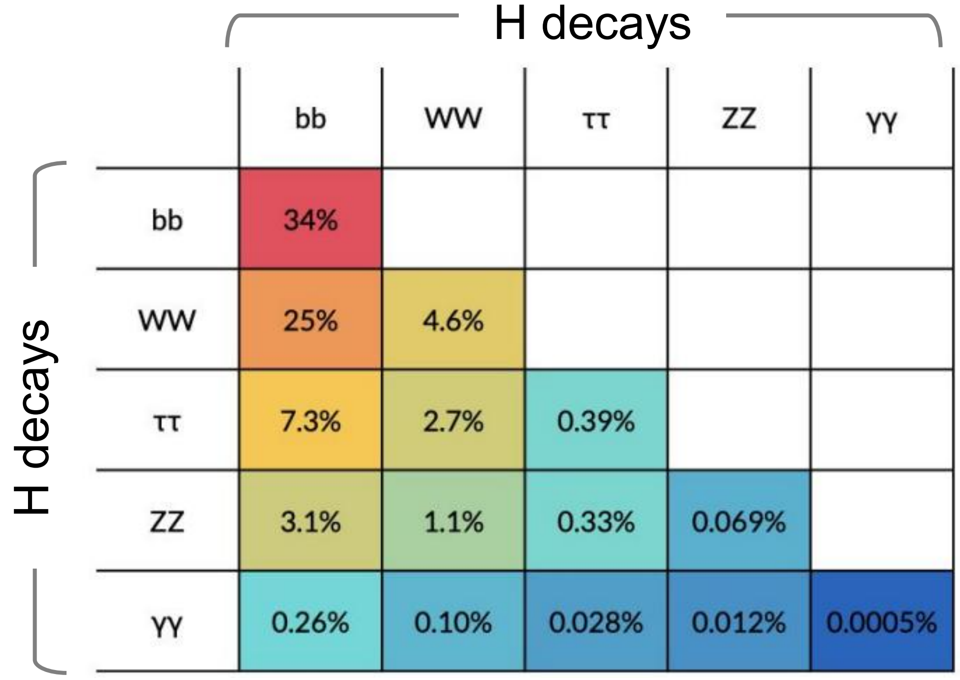
Vector boson fusion (VBF) $\sigma_{VBF}^{SM} = 1.7$ fb

($\sqrt{s} = 13$ TeV)



Sensitive to BSM

- Decay modes



	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%

Large ← Branching ratio → Small

Low ← Signal purity → High

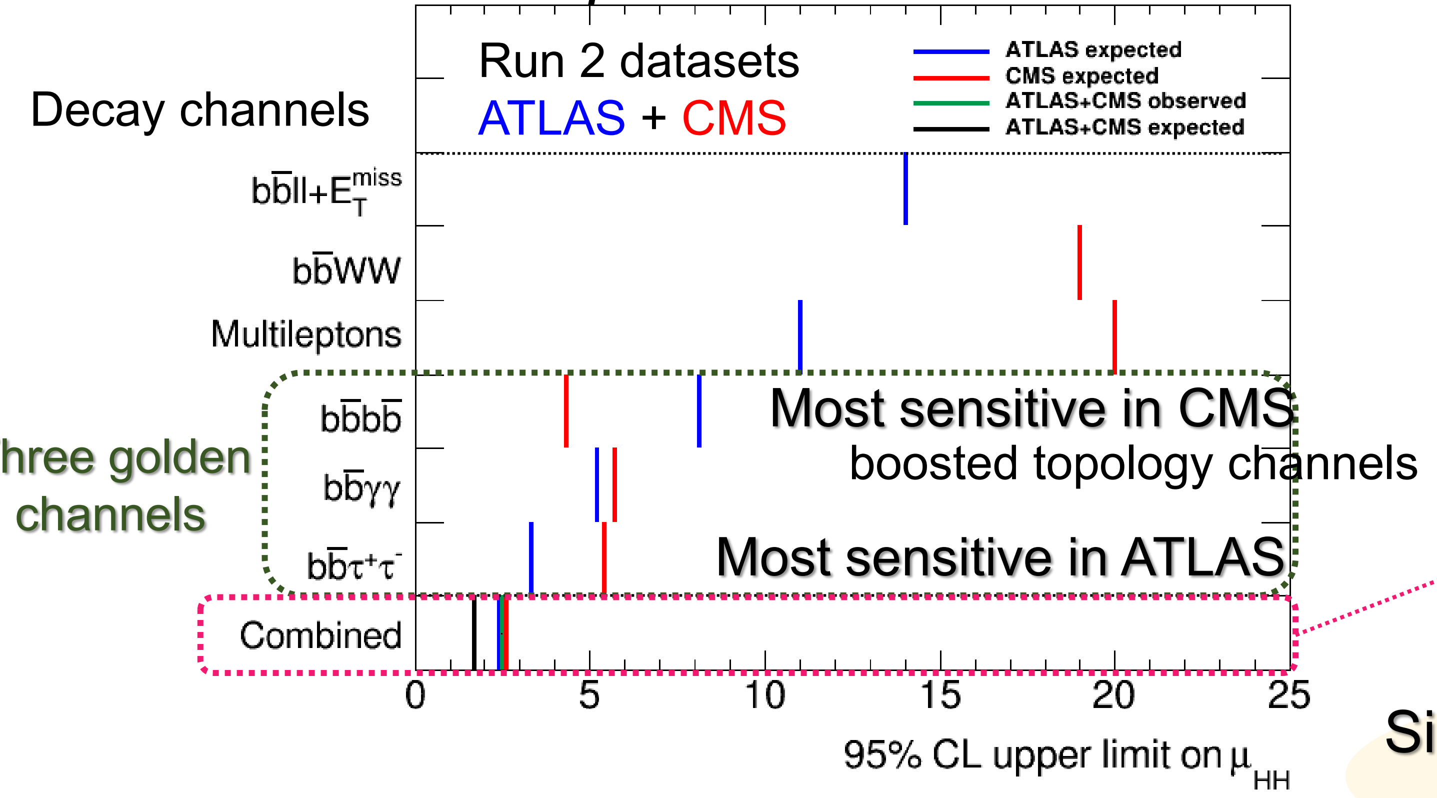
Rare production + no strong mode → HH search is challenging

Di-Higgs searches at LHC (Run 2)

ATLAS-CONF-2025-012,
CMS-PAS-HIG-25-014

- Upper limit on μ_{HH} ($\mu_{HH} = 0$ hypothesis)

Private plot



Three golden channels

Most sensitive in CMS boosted topology channels

Most sensitive in ATLAS

95% C.L. upper limit on μ_{HH}

	Obs.	Exp. ($\mu_{HH} = 0$)	Exp. ($\mu_{HH} = 1$)
CMS	3.5	2.6	3.6
ATLAS	2.9	2.4	3.5
Combined	2.5	1.7	2.8

Significance: 1.1σ (1.3σ exp)

The signal begins to exceed the 1σ level!

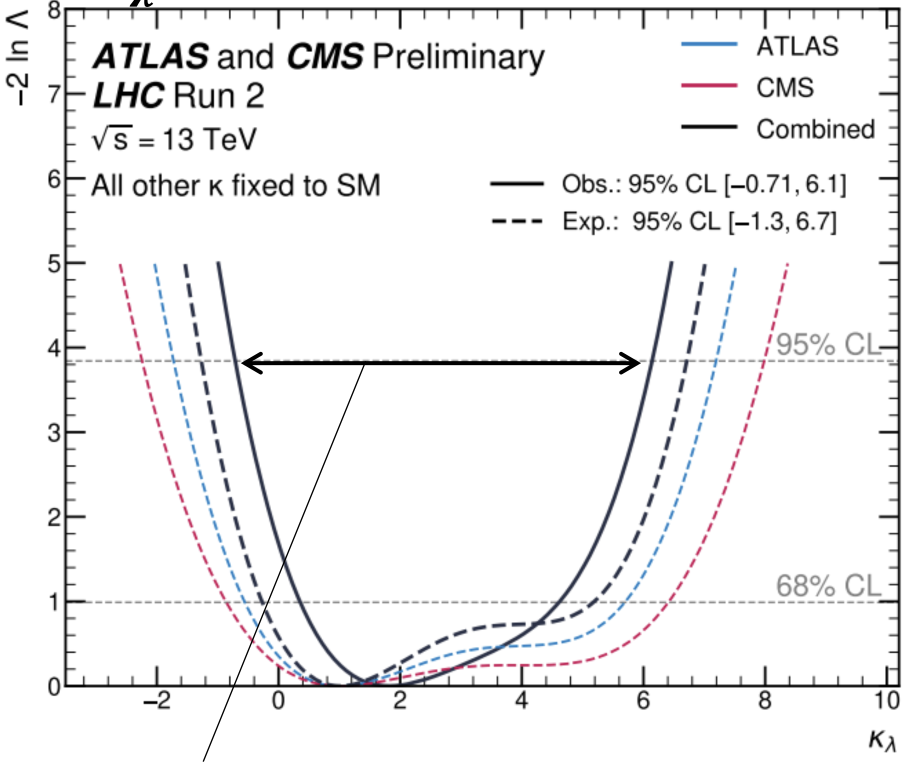
- Best fit value of signal strength $\hat{\mu}_{HH}$ (SM: $\mu_{HH} = 1$)

Observed $\mu_{HH} = 0.8^{+0.7}_{-0.6}(\text{stat.})\ ^{+0.4}_{-0.2}(\text{theory})\ ^{+0.3}_{-0.3}(\text{exp.})$ Statistical uncertainties is dominant

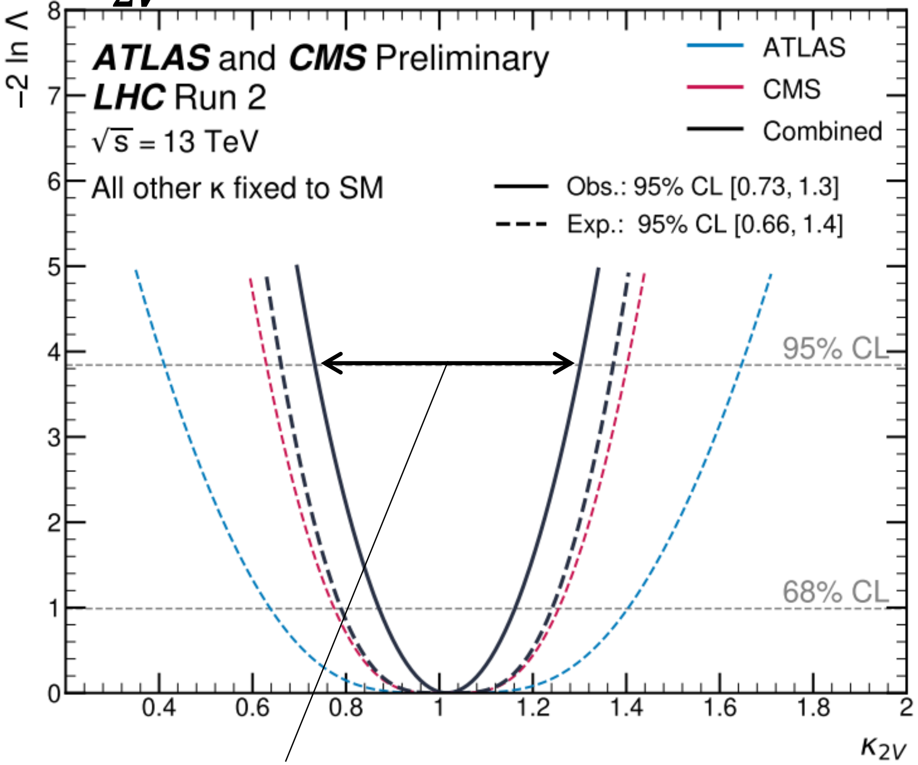
Constraint on κ_λ and κ_{2V} (Run 2)

ATLAS-CONF-2025-012, CMS-PAS-HIG-25-014

$\boldsymbol{\kappa_\lambda}$ constraint



$\boldsymbol{\kappa_{2V}}$ constraint



$\mathbf{-0.71 < \boldsymbol{\kappa_\lambda} < 6.1}$ $(-1.3 < \kappa_\lambda < 6.7\ \mathrm{exp.})$

10% better

- ○ ATLAS: $-1.3 < \kappa_\lambda < 7.2$
- ○ CMS: $-1.4 < \kappa_\lambda < 6.6$

$b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ are most sensitive channel

$\mathbf{0.73 < \boldsymbol{\kappa_{2V}} < 1.3}$ $(0.66 < \kappa_{2V} < 1.4\ \mathrm{exp.})$

8% better

- ○ ATLAS: $0.57 < \kappa_{2V} < 1.5$
- ○ CMS: $0.66 < \kappa_{2V} < 1.4$

$b\bar{b}b\bar{b}$ are most sensitive channel

$b\bar{b}\gamma\gamma$ at ATLAS (Run 2 + partial Run 3)

arXiv:2507.03495

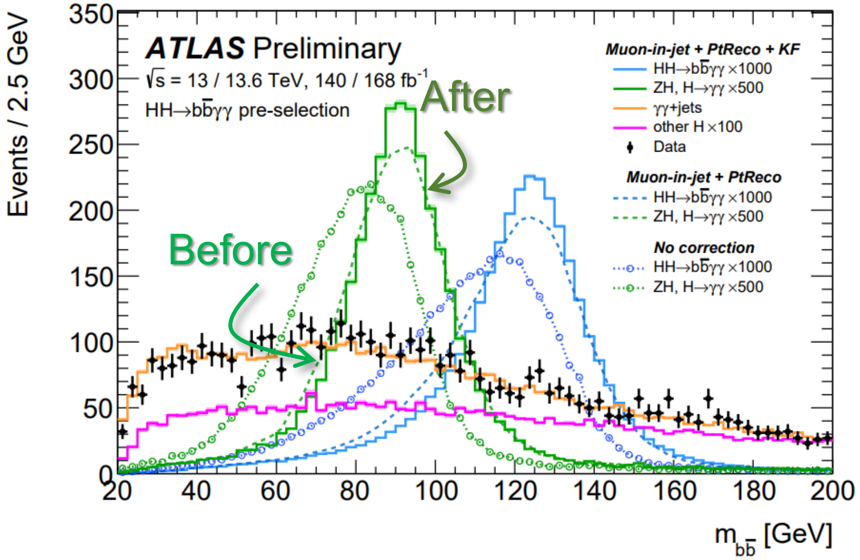
- About this channel
  - Branching ratio: 0.26%
  - Main backgrounds: $\gamma\gamma$ + jets, $H \to \gamma\gamma$

    BDT is used to separate signal and background
- New analysis strategy from Run 2 analysis (JHEP 01 (2024) 066)

Kinematic fit

Correct $\mathrm{m}_{b\bar{b}}$ using the information of $H \to \gamma\gamma$ momenta

$\mathrm{m}_{b\bar{b}}$ resolution: 13% improvement



New b-jet tagging

DL1r → GN2 (based on the transformer)

Light jet rejection: x3

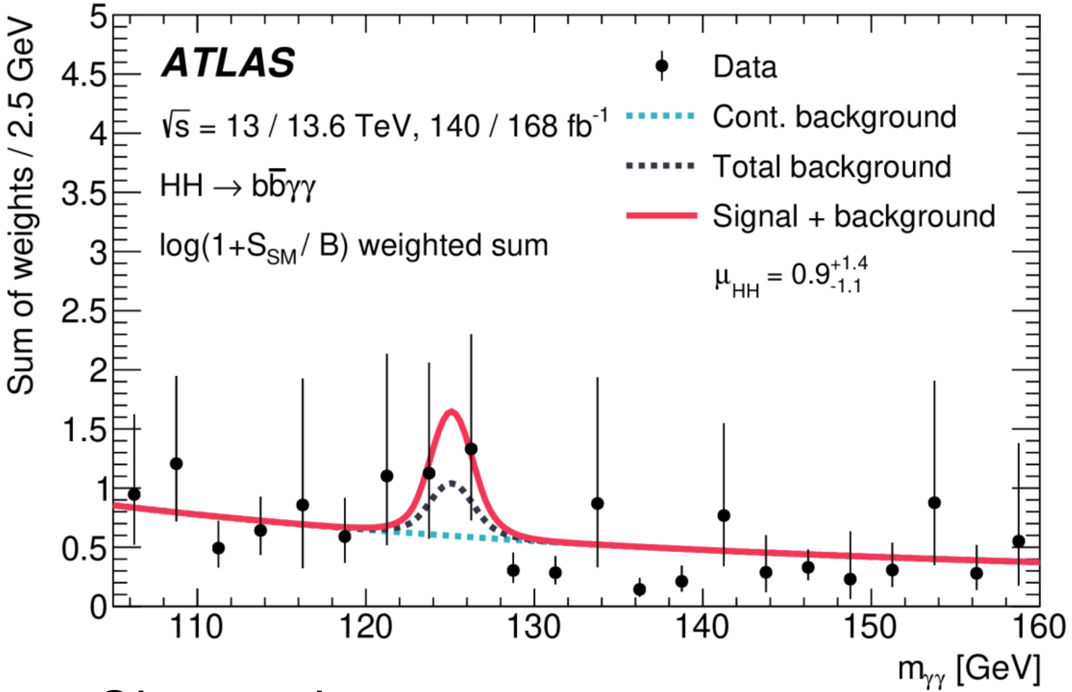
Addition of Run 3 data **(2022-2024)**

	Run 2	Run 3
ggF(VBF) cross section	30.77 (1.68) fb	**34.13 (1.87) fb**
Integrated luminosity	140 fb^{-1}	**168 fb^{-1}**
Expected number of ggF (VBF) $\mathrm{HH} \to b\bar{b}\gamma\gamma$ signals	11.2 (0.61)	12.4 (0.68)

$b\bar{b}\gamma\gamma$ at ATLAS (Run 2 + partial Run 3)

arXiv:2507.03495

- Fit result (all regions combined)



Observed

$$\mu_{HH} = 0.9^{+1.3}_{-1.0}\,(stat)\,^{+0.6}_{-0.5}\,(\text{syst})$$

Expected

$$\mu_{HH} = 1.0^{+1.3}_{-1.0}$$

Significance
0.84σ (1.01 exp.)

Previous analysis: 5.0
→ 15% improvement by only analysis strategy

- Upper limit on μ_{HH}

	Obs.	Exp. ($\mu_{HH} = 0$)	Exp. ($\mu_{HH} = 1$)
Run 2 dataset	4.8	**4.2**	5.5
Run 3 dataset	5.8	3.8	5.0
Combined	3.8	2.6	3.7

- Constraint on κ_λ

$$\mathbf{-1.7 < \kappa_\lambda < 6.6\ \ (obs.)}$$

$$\mathbf{-1.8 < \kappa_\lambda < 6.9\ \ (exp.)}$$

20% improved from previous full-Run2 analysis

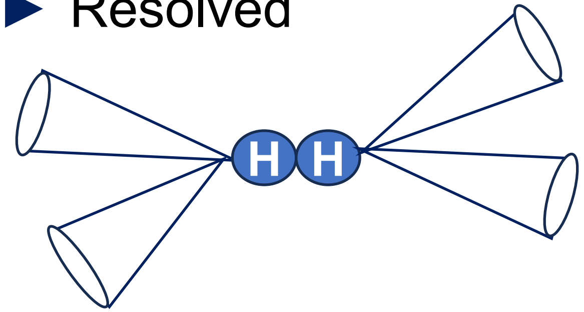
$b\bar{b}b\bar{b}$ at CMS (partial Run 3)

CMS-PAS-HIG-24-010

- About this channel
  - Highest branching ratio (34%)
  - Main background: QCD multijet

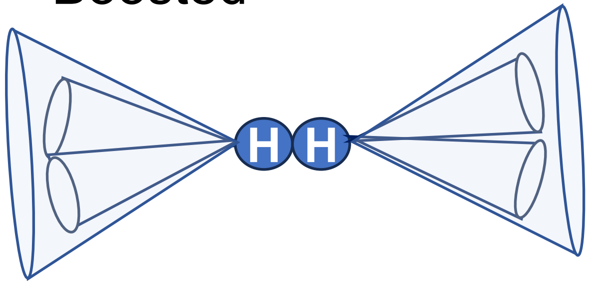
    Used data-driven estimation with reweighting by neural network
- Analysis strategy
  - Datasets: Run 3 2022+2023 **61.9 fb^{-1}**
  - Main improve: *b*-tagging
  - Two analysis topologies

▶ Resolved

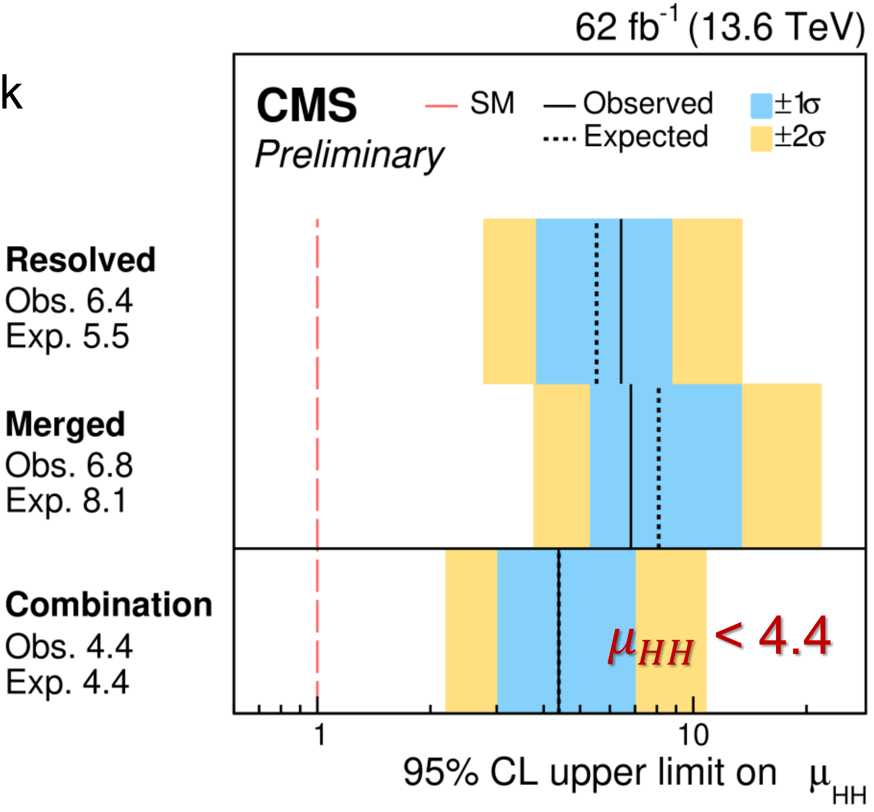


- ○ m$_H$ regression : 10-25% improve
- ○ DNN signal/background separation: 25% improve

▶ Boosted



Performed mass regression with new boosted tagger

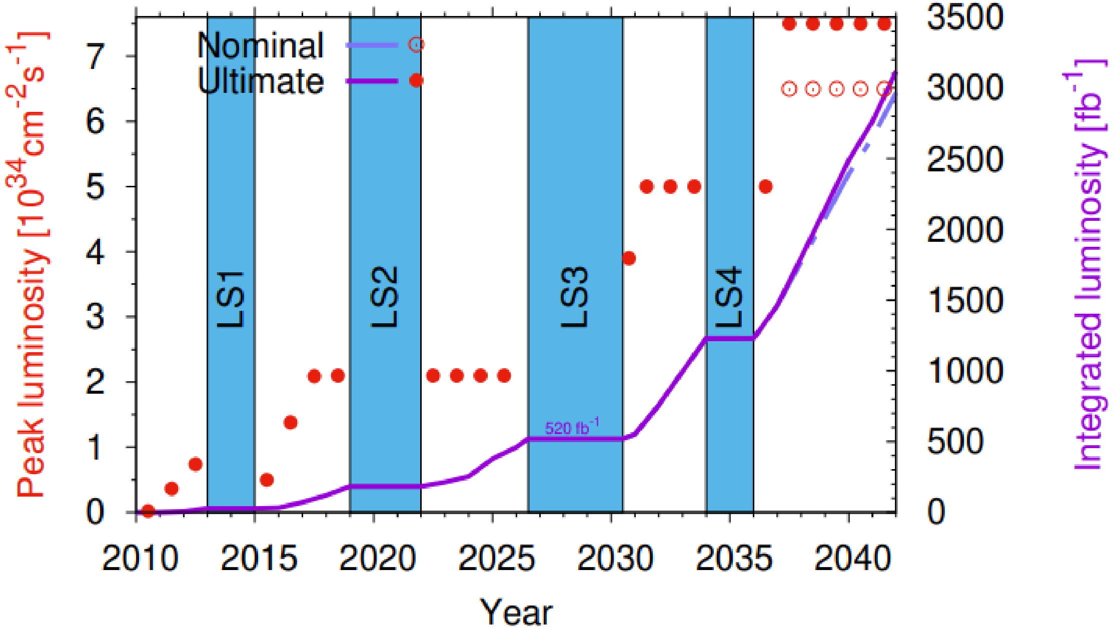


Similar sensitivity with Run 2 full analysis by only Run 3 !!

HL-LHC

▶ LHC operation plan

LHC schedule



- Start in 2030
- Pileup brings up to ~200
- Target integrated luminosity: 3 ab^{-1}

The increased statistics is expected to bring **~2.4 times** of improvement in statistical uncertainties

▶ Detector upgrades

- Tracker: replace all silicon
- Timing detector
- New muon chambers
- Trigger and DAQ updates

… and more

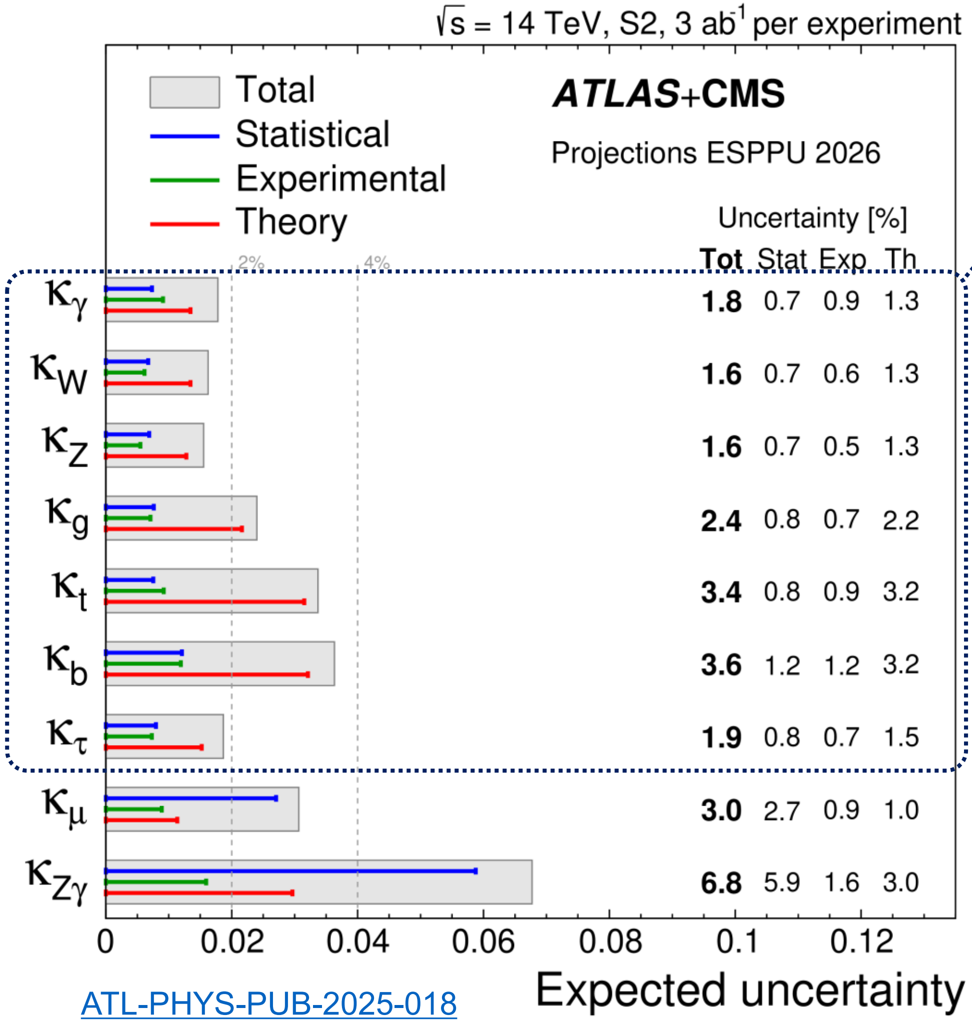
Many detector upgrades may potentially introduce improvements in analysis performance

- Improve b-/c-/tau- tagging
- Improve muon reconstruction resolution

* In the following projections, there are no new method exploiting performance of new detectors

Precision measurement at HL-LHC

Expected coupling precision measurement



ATL-PHYS-PUB-2025-018

The coupling can be measured with a precision of 3–7%

Limited by theory uncertainties

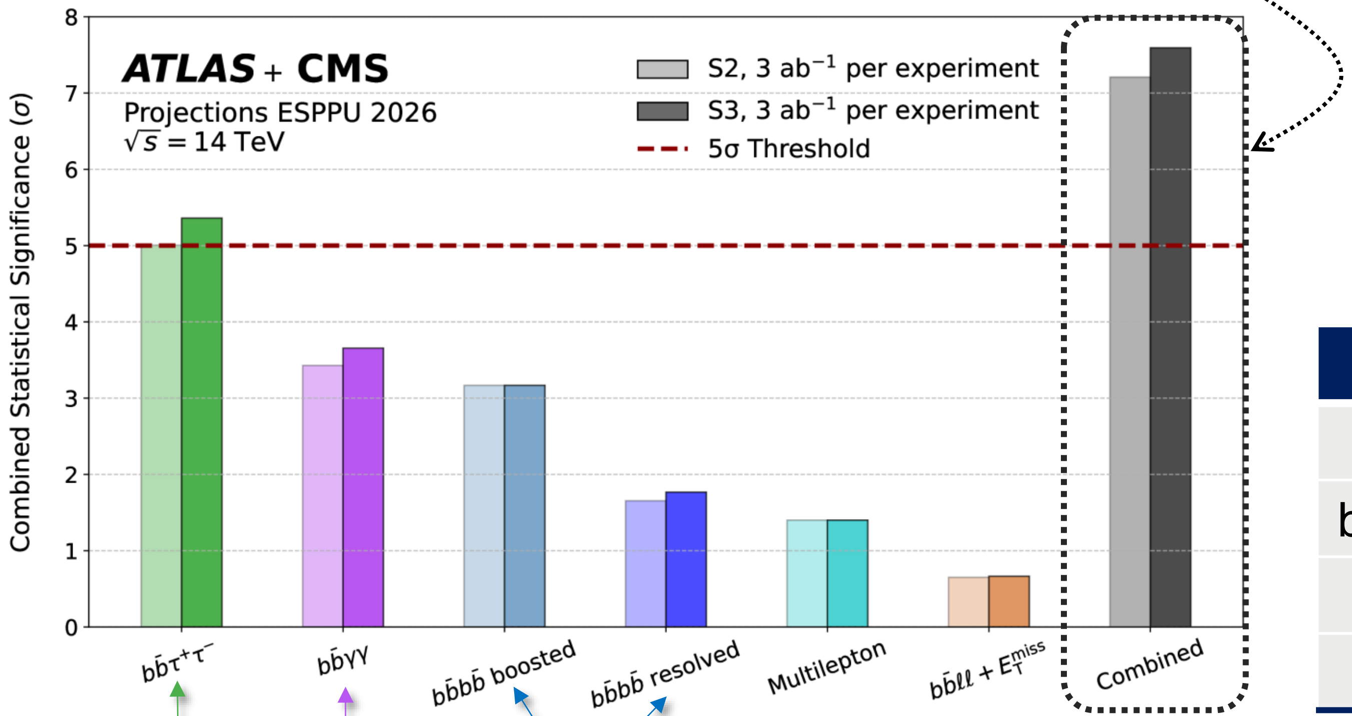
2nd generation and rare process

- $H \rightarrow \mu^+\mu^-$
  - Maximum 30% improvement by detector upgrades
- $H \rightarrow Z\gamma$
  - 5 σ @ > 2 ab^{-1}
- $H \rightarrow c\bar{c}$
  - ~1.7 σ @ 3 ab^{-1}
  - Limit on $\mu_{HH}^{SM} < 1.5$
- Analysis of other rare process will start
  - $H \rightarrow J/\psi\,\gamma,\ H \rightarrow \phi\gamma$

HH search at HL-LHC

Projection based on Run 2 result

ATL-PHYS-PUB-2025-018 Di-Higgs signal can reach ~7σ



Limit by stat.

Limit by a lot of QCD background

Comparable level with theory syst. and stat.

Effects by analysis improvement

ATLAS only projection example at 3 ab^{-1}
(Baseline scenario from ATL-PHYS-PUB-2025-006)

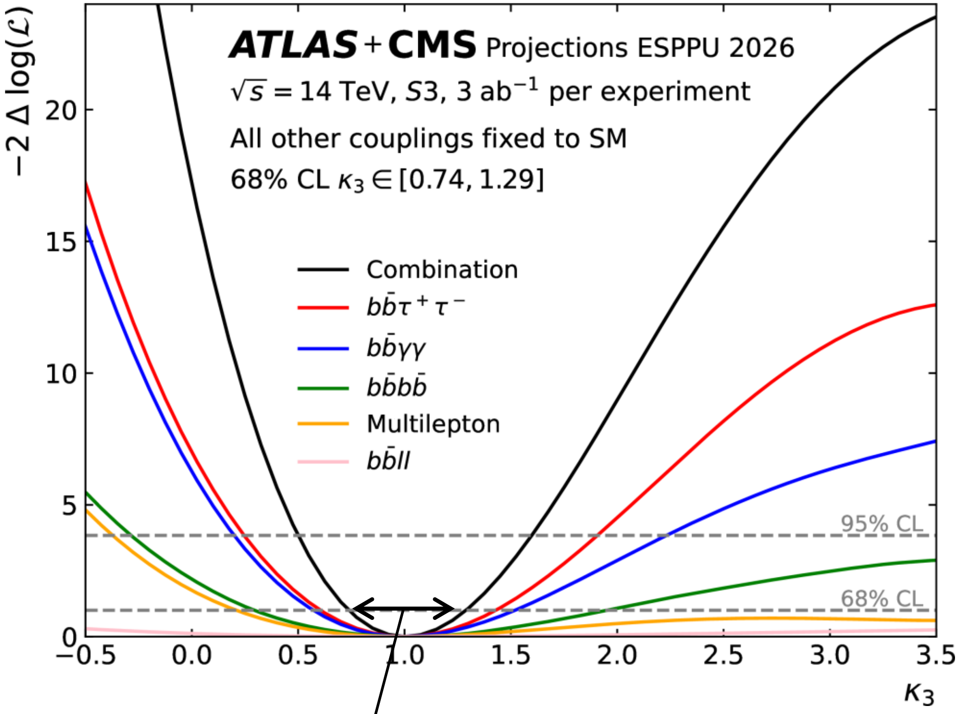
	Significance
Baseline	4.26σ
b-tagging efficiency improved by 5%	4.44σ (+ 4%)
τ_{had} ID efficiency improved by 5%	4.34σ (+ 2%)
b-tag and τ_{had} improved	4.52σ (+ 6%)

Sensitivity will be better by analysis improvements

κ_λ constraint at HL-LHC

ATL-PHYS-PUB-2025-018

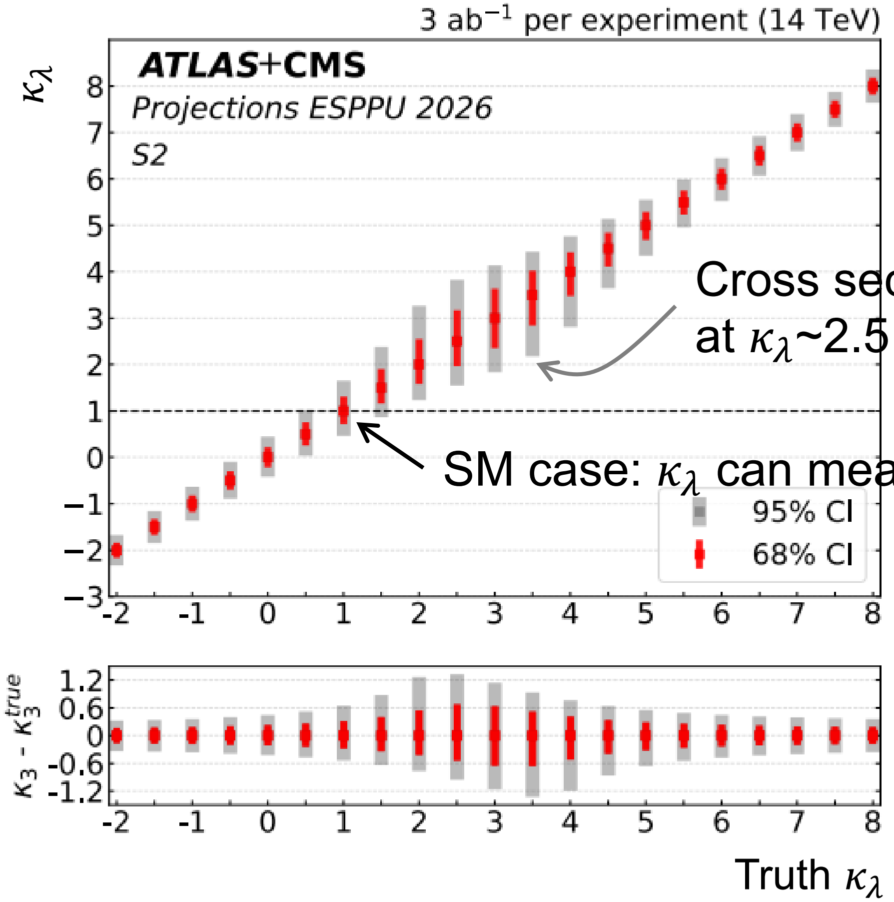
κ_λ likelihood scan



$\mathbf{0.74 < \kappa_\lambda < 1.29}$ (68% CL)

< 30% of precision measurement

How precisely κ_λ can be measured for a given assumed true value of κ_λ



Cross section is smallest at κ_λ~2.5: less precise

SM case: κ_λ can measured by 30%

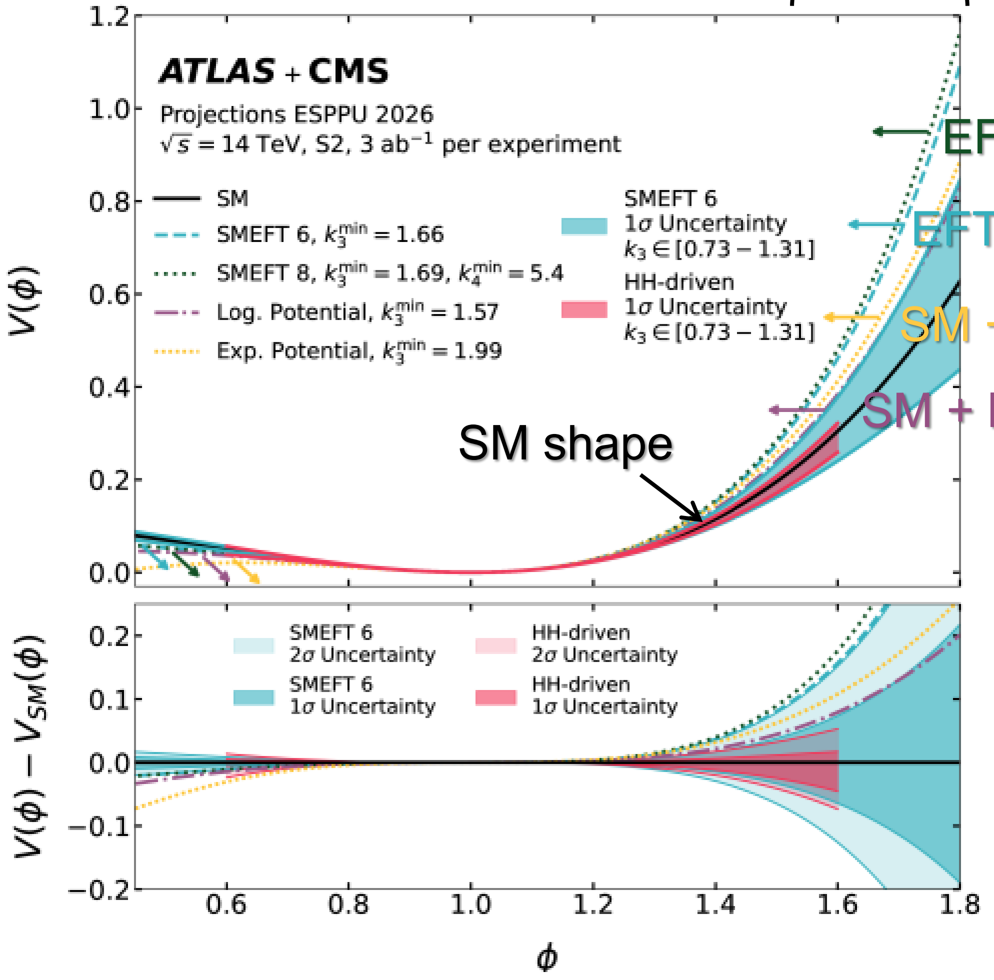
If true $\kappa_\lambda < 0.5$ or $\kappa_\lambda > 2$, SM can be excluded

Constraint on Higgs potential

ATL-PHYS-PUB-2025-018

Strong first-order phase transition is one of the necessary conditions to realize electroweak baryogenesis

Shape will change at larger ϕ



EFT Dim8

EFT Dim6

SM + exponential

SM + logarithmic term

SM shape

In case of EFT

$$V_8(\phi)=\underbrace{\frac{1}{8}(\phi^2-1)^2}_{\text{SM}}+\underbrace{\underbrace{\frac{\kappa_3-1}{16}(\phi^3-1)^3}_{\text{Dim6}}+\underbrace{\frac{\kappa_4-6\kappa_3+5}{128}(\phi^2-1)^4}_{\text{Dim8}}}_{\text{higher-energy-scale corrections}}$$

Test with various scenario

⇨ Strong first-order phase transition in $\kappa_3 > 1.4$~1.9

HL-LHC may have sensitive for the strong first-order phase transition scenario

Conclusion

- The Higgs boson has entered the era of precision measurements

  Coupling measurement helps the understanding Higgs physics

- ATLAS and CMS experiments are performing analysis
  - Adding Run 3 datasets, more sensitivity was obtained
  - Fermion coupling: moving to focus on 2nd generation and rare process
  - Self-coupling: di-Higgs production reached to ~1σ

- Prospects at the HL-LHC
  - Fermion coupling can measure with a few % of precision
  - HH can observed by 7σ
  - These projection can be improved by analysis improvements and detector upgrades

Public results link: ATLAS EXPERIMENT [ATLAS results] CMS [CMS results]

Backup