Combined measurements of Higgs boson cross sections and couplings at CMS

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On behalf of the CMS Collaboration

Higgs 2023 conference
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Introduction

Run 1	discovery
Run 2 / Run 3 and beyond	H coupling to 2^{nd} and 3^{rd} generation fermions
HL-LHC	H self-coupling

- The profile of Higgs boson becomes clearer
- Still several puzzles
  - Naturalness of H mass, stability of the universe, …
- The Higgs boson
  - a natural probe for many BSM scenarios
  - **Combinations** of its measurements are powerful
- This talk will focus on **the latest Higgs combinations at CMS**
  - Signal strengths
  - Couplings

The Procedure for the Combinations

- CMS from the beginning developed a coherent effort on the tool called combine
- In Run 1: Started to be evident that many channels share a similar excess
- In Run 2: Increased analyses' **complexity**
  - Simplified templates cross section (STXS) in many final states
  - Larger and lager sensitivity to differential observables
  - HH combinations
- Need **more effort** to work on the complexity

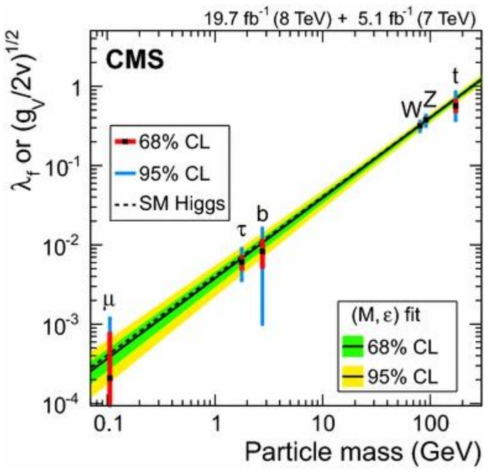
→ see A.C.Marini's talk

Procedure for the LHC Higgs boson search combination in Summer 2011

The ATLAS Collaboration
The CMS Collaboration
The LHC Higgs Combination Group

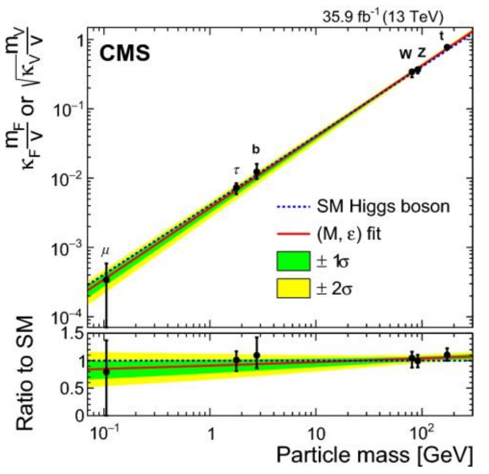
CMS-NOTE-2011-005; ATL-PHYS-PUB-2011-11

Run 1 combination



Eur. Phys. J. C 75 (2015) 212

Run 2 combination



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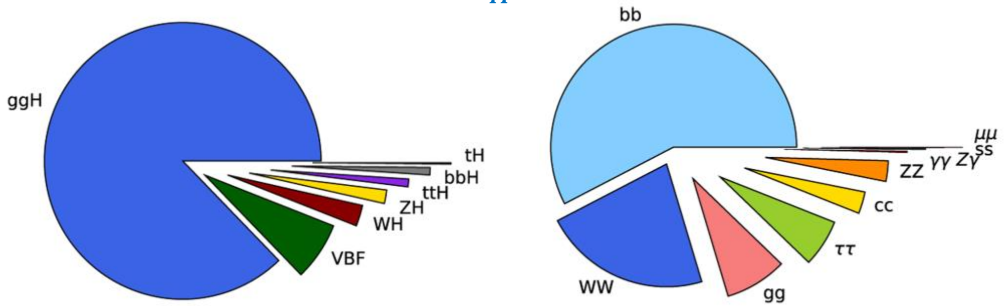
Measurements of the Higgs Couplings

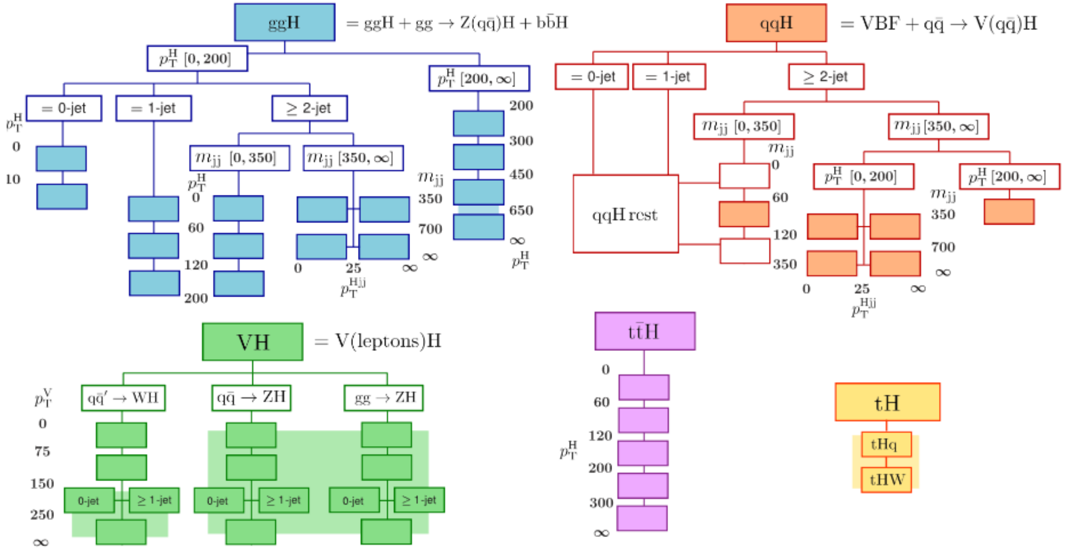
[Nature 607 (2022) 60-68]

- 6 main production modes **(ggH, VBF, WH, ZH, ttH, tH)** ×
  7 decay channels **(ZZ, WW, bb, $\tau\tau$, $\gamma\gamma$, γZ, $\mu\mu$)**
  - We can have 42 possible combinations
- **Signal Strengths μ:**
  - precise measurement of H production XS and decay BR
  - Check compatibility with the SM
- **Coupling modifiers κ-framework:**
  - Probe the deviations from the SM
- **Cross Section**
  - Total and differential cross section
  - **S**implified **T**emplates Cross Section (STXS): Extract production mode cross sections in exclusive phase space regions

Production & decay modes
at 13 TeV for m_H=125.38 GeV



Stage1.2



CMS-HIG-19-0015
[JHEP 07 (2021) 027]

Signal Strengths μ in Production and Decay modes

- **Good agreement** with the SM
  - 5 production XS (ggH, VBF, WH, ZH, ttH)
  - 5 decay BR (ZZ, $\gamma\gamma$, WW, $\tau\tau$, bb)
- **Hints of excesses** in rare production (tH) and decay ($\mu\mu, Z\gamma$) modes
  - More information about them in Run 3
- Overall signal strength

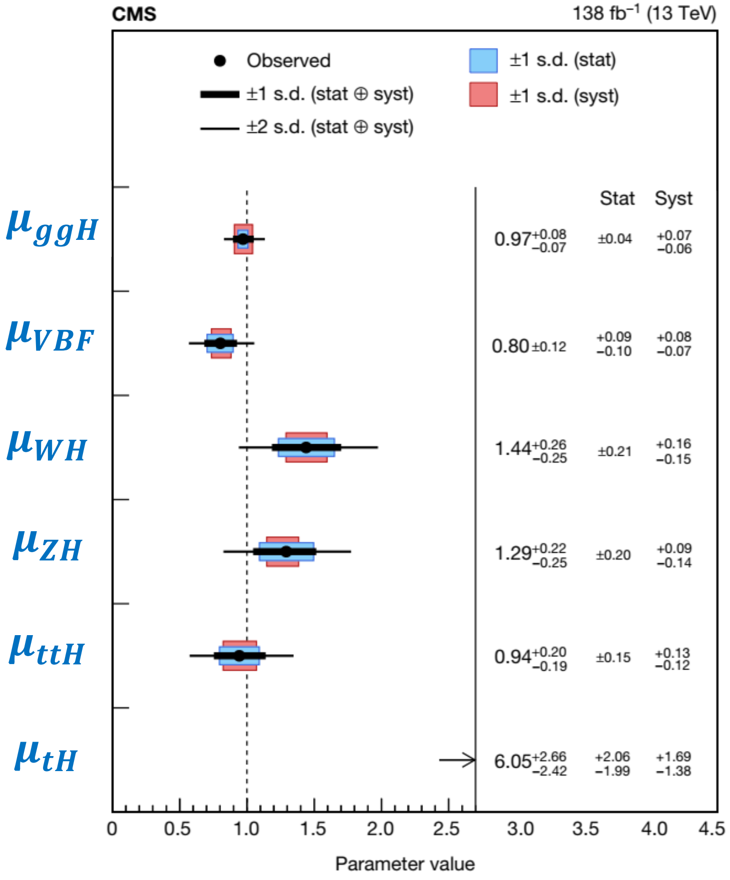
$$\mu = 1.002 \pm 0.057$$

$$[\pm 0.037(\text{theory}) \pm 0.033(\text{expt.}) \pm 0.029(\text{stat.})]$$

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\text{SM}}}, \qquad \mu^f = \frac{B^f}{(B^f)_{\text{SM}}}$$

Production Mode

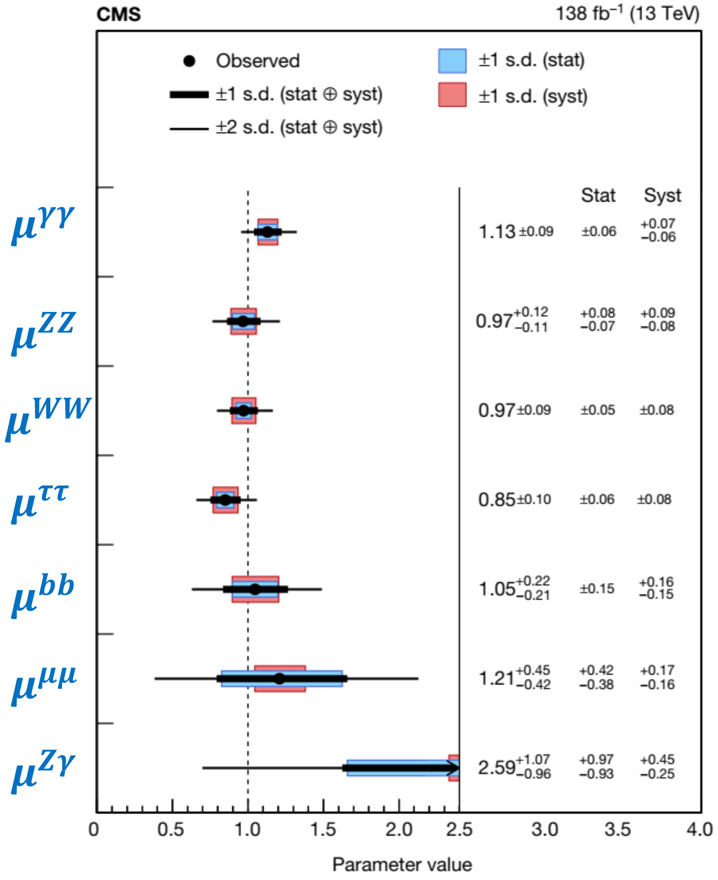
Signal Strengths μ_i



Assuming $B^f = (B^f)_{SM}$

Decay Mode

Signal Strengths μ^f



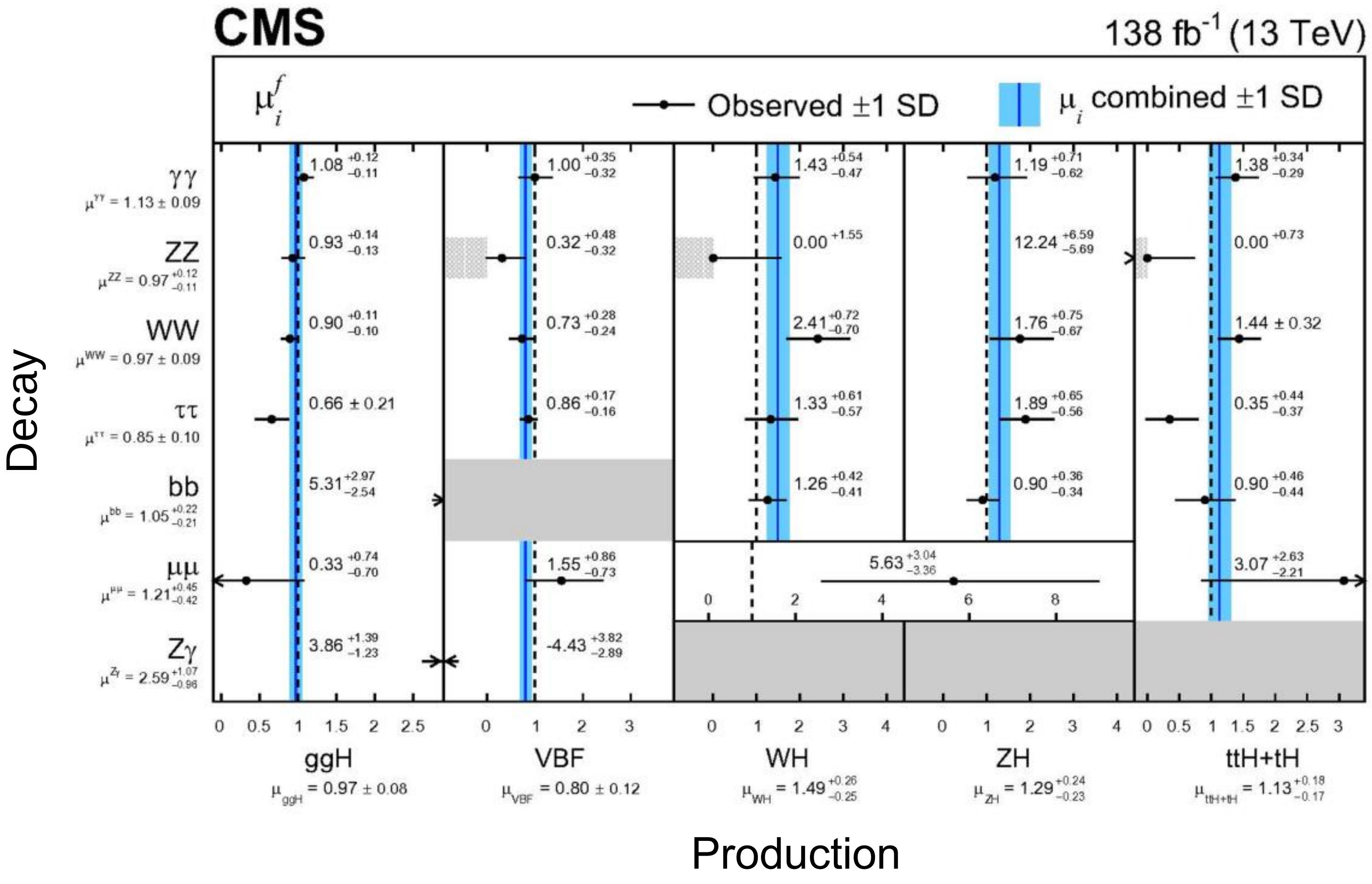
Assuming $\sigma_i = (\sigma_i)_{SM}$

Nature 607 (2022) 60-68

Signal Strengths μ Overall Agreement with the SM

- CMS combination matrix
- **Good compatibility** in most channels combination with the SM
- Few discrepancies in channels with limited **statistical** precision
  - To be improved with more data

$$\mu_i^f = \frac{\sigma_i \times B^f}{(\sigma_i)_{SM} \times (B^f)_{SM}} = \mu_i \times \mu^f$$



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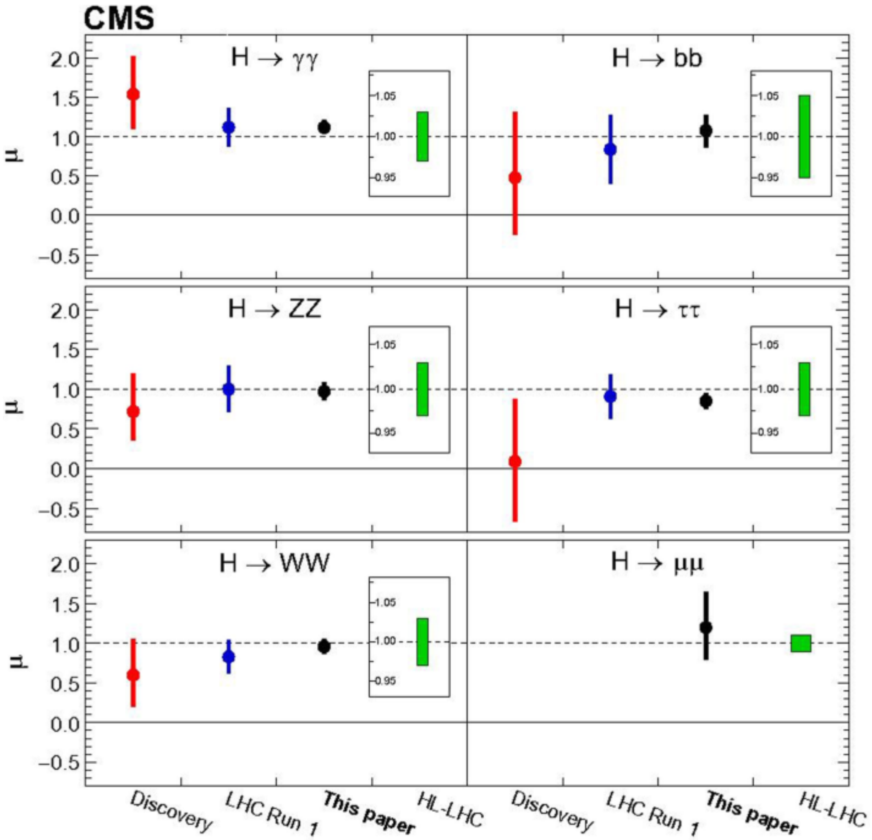
Time Evolution of μ Measurements

- Higgs discovery
  - 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV
  - $\boldsymbol{\mu = 0.87 \pm 0.23}$ **[dominated by statistic uncertainty]**
- Run 1 combination
  - 5.1 fb^{-1} at 7 TeV and 19.7 fb^{-1} at 8 TeV
  - $\boldsymbol{\mu = 1.00 \pm 0.13[^{+0.08}_{-0.07}(theory) \pm 0.07(exp.) \pm 0.09\ (stat)]}$
- Run 2 combination
  - 138 fb^{-1} at 13 TeV
  - $\boldsymbol{\mu = 1.002 \pm 0.057[\pm 0.037(\mathrm{theory}) \pm 0.033(\mathrm{expt.}) \pm 0.029(\mathrm{stat.})]}$
- Experimental statistical uncertainty **comparable** to systematics and theory
  - Approaches need to be improved for smaller experimental uncertainties
  - Improved precision on theory production would help improve results



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Coupling Modifier κ-Framework

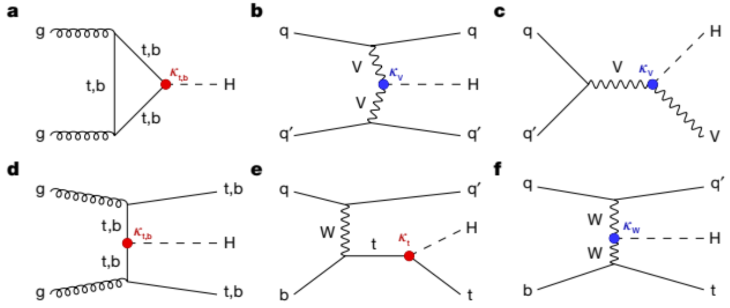
- Simply parameterize **the deviations from the SM**
  - Easy interpretation of possible deviations
  - Easy reinterpretation on other models
- The quantities σ_i, Γ^f and Γ_H, computed from the SM predictions are scaled by $\boldsymbol{\kappa_i^2}$
- **Coupling compatibility tests:**
  - $\boldsymbol{\kappa}$ relative to SM & ratio $\boldsymbol{\lambda}$ of coupling modifiers κ
  - Example: For the $gg \to H \to \gamma\gamma$ process:

$$\frac{\sigma(gg \to H) \times BR(H \to \gamma\gamma)}{\sigma(gg \to H)_{SM} \times BR(H \to \gamma\gamma)_{SM}} = \kappa_g^2 \kappa_\gamma^2 / \kappa_H^2$$

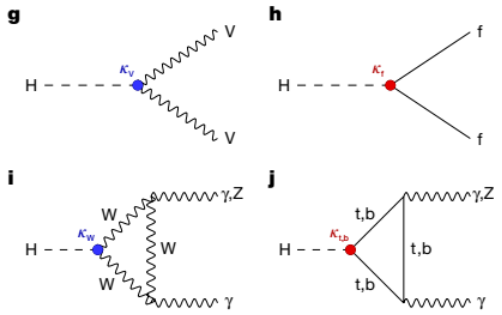
- $\boldsymbol{\kappa_V}$ and $\boldsymbol{\kappa_f}$ scale the H couplings to massive gauge bosons and to fermions respectively

$$g_F = \kappa_F \frac{\sqrt{2} m_F}{v} \qquad g_V = \frac{\kappa_V 2 m_V^2}{v}$$

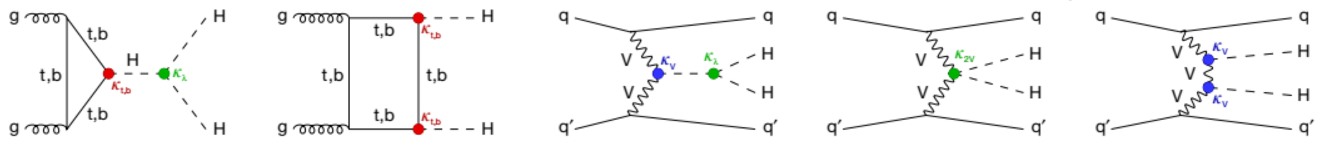
H boson production modes



H boson decay channels



H boson pair production



$$\sigma_i \sim \kappa_i^2 \sigma_i^{SM} \qquad \Gamma_f \sim \kappa_f^2 \Gamma_f^{SM} \qquad \sigma_i B^f = \left(\frac{\sigma_i \Gamma_f}{\Gamma_H}\right)_{SM} \cdot \kappa_i^2 \kappa_f^2 / \kappa_H^2$$

$$\Gamma_H = \sum \Gamma_f(\kappa) / (1 - B_{inv.} - B_{Undet.})$$

LHCHXSWG-2012-001

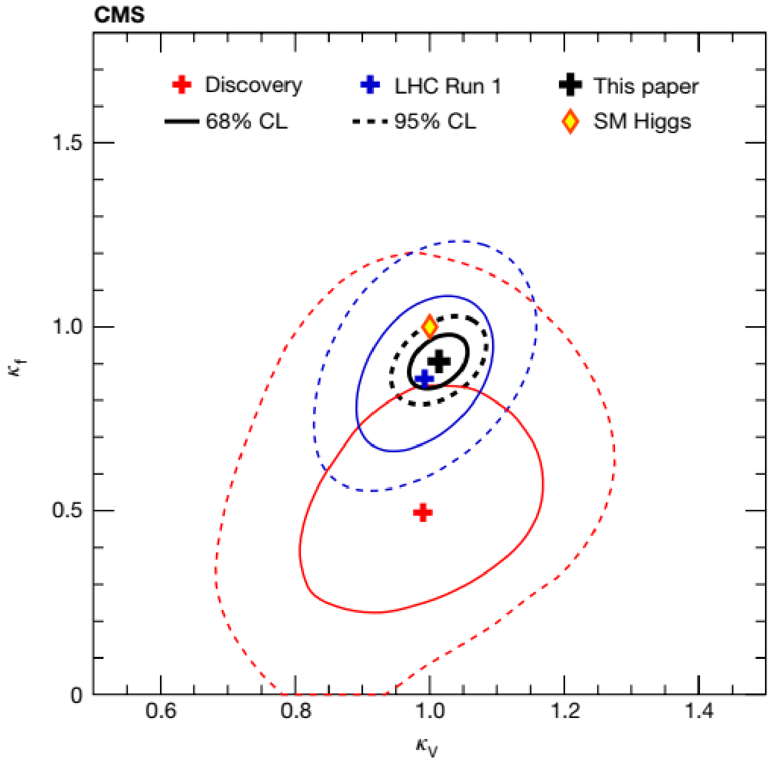
H Couplings to Fermions and Vector Bosons

- Couplings to boson and 3rd generation particles are now known at **~10% level**, with no significant deviations from the SM predictions

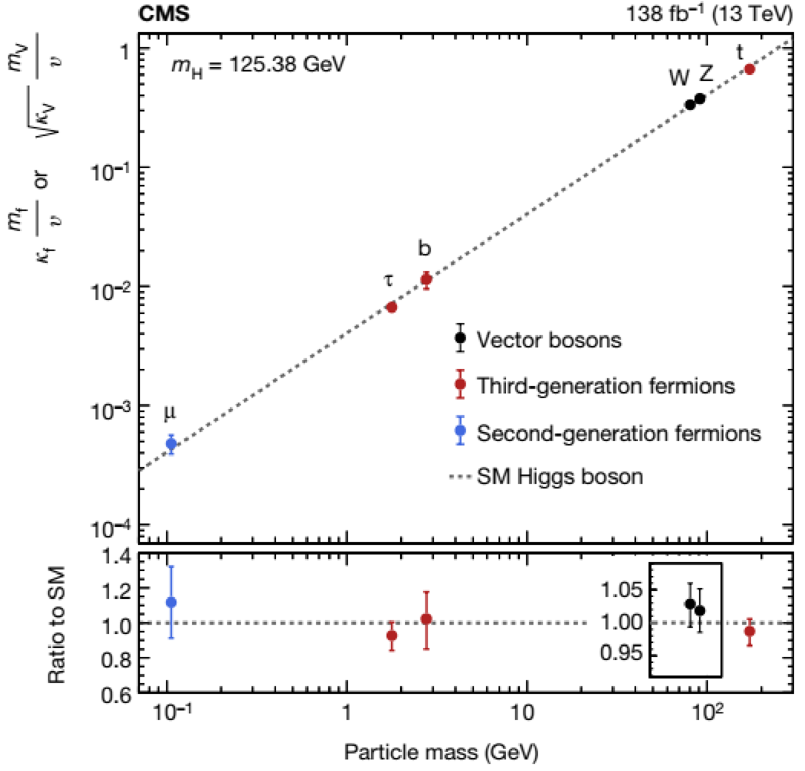
- Higgs couplings test across **3 orders of magnitude** in particle mass
  - A remarkable agreement with the predictions of BEH mechanism

- Starting to probe the 2nd generation

κ_f vs κ_V from Discovery to Run1 to Full Run2



H couplings vs **particle mass**



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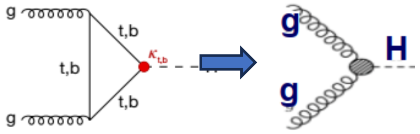
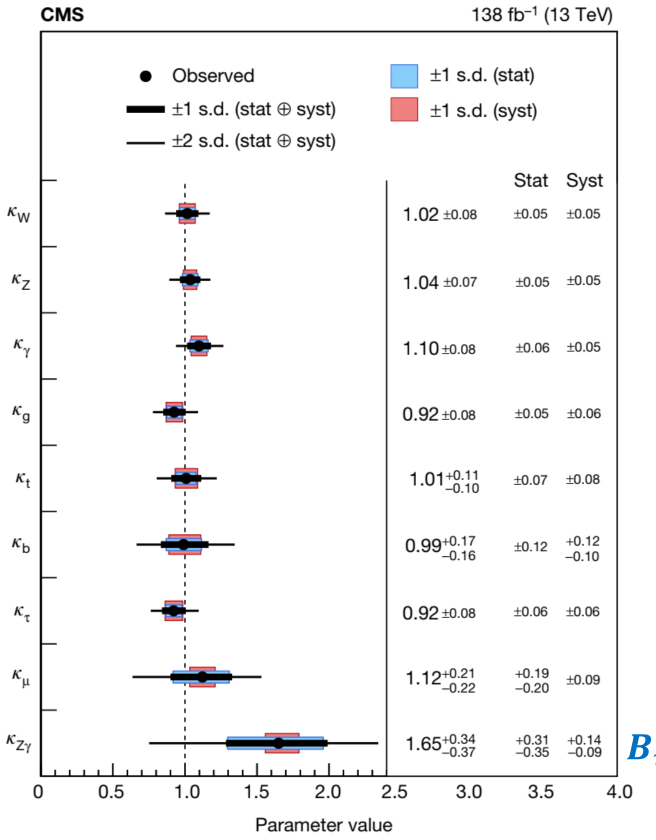
H Couplings with Different Assumptions

- Assumption: no invisible and undetected decays
  - Single narrow resonance, SM tensor structure
  - No new physics in loops (gg→H, H→ $\gamma\gamma$, H→Zγ)
  - No BSM decays (invisible, not observed)
  - Statistical and systematics uncertainties **contribute at the same level** to all measurements except for κ_μ and $\kappa_{Z\gamma}$

- Assumption: allowing for invisible and undetected decays
  - Require $|\kappa_W| < 1$ & $|\kappa_Z| < 1$
  - $\boldsymbol{\kappa_W, \kappa_Z}$ **imposed upper bound to the SM value**
  - Both invisible and undetected BR's **compatible with zero**

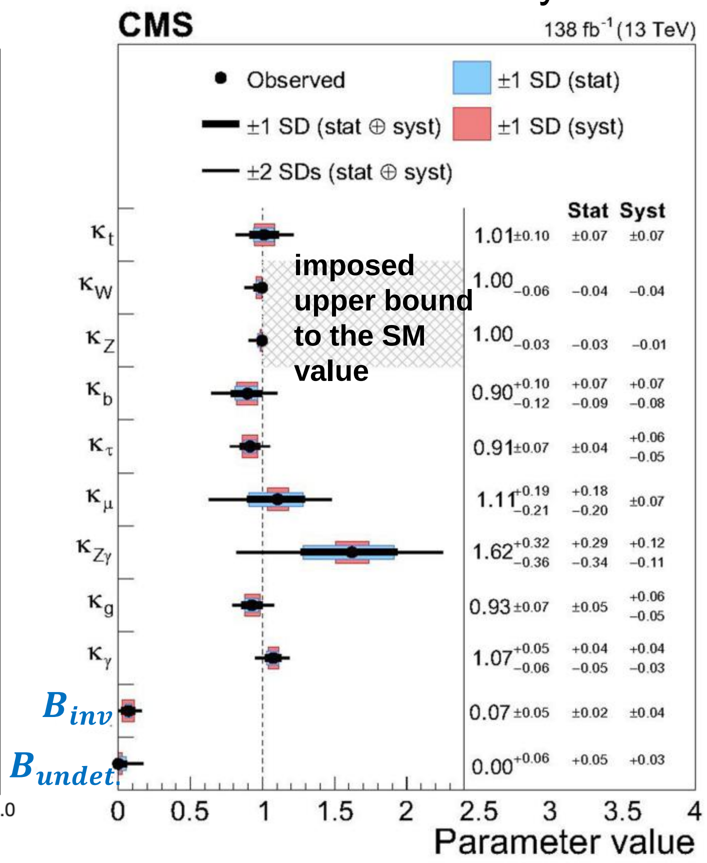


Assuming no invisible and undetected decays



p-value SM: 28%

Assuming invisible and undetected decays



p-value SM: 33%

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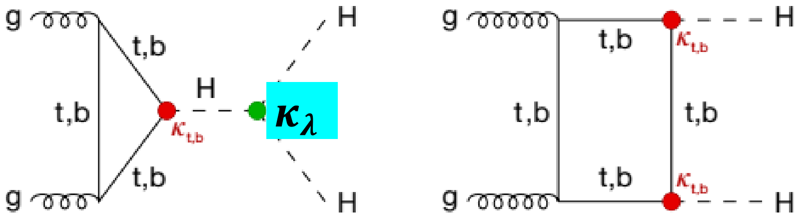
H Self-Coupling Measurement

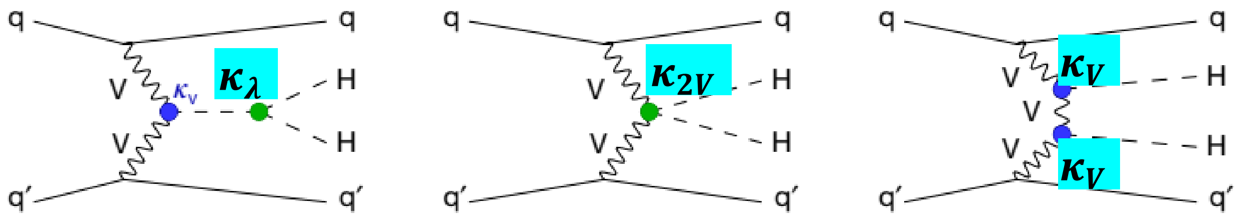
- Higgs self-coupling probes the nature of the Higgs potential:
    - $V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4$
- **Trilinear coupling λ_3** can be probed via two ways:
    - Directly from HH production
        - probe λ_3 **extremely challenging** at LHC, but accessible at HL-LHC
    - Indirectly from H measurement
        - H self-coupling κ_λ affects the single H production XS through electroweak corrections
        - **Possible to extract limits** on the $\boldsymbol{\kappa_\lambda}$ by combining several channels together

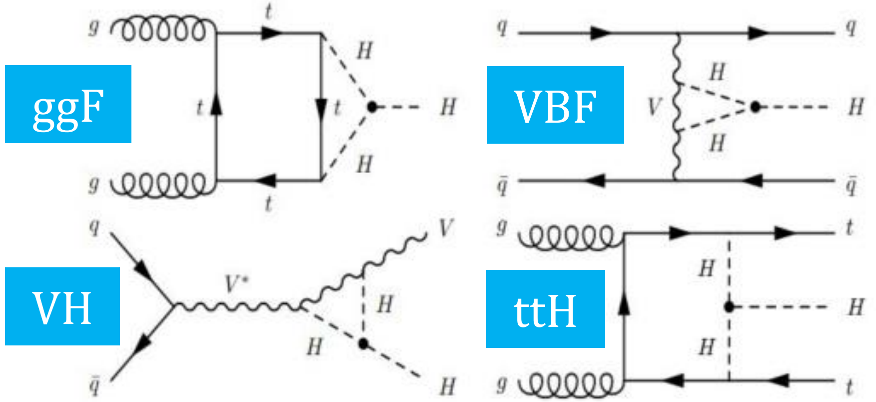
$$\boldsymbol{\kappa_\lambda = \lambda/\lambda_{SM}}$$

Main production mode **ggF** ~31.05 fb @NNLO



Sub-leading **VBF** ~1.73 fb @13 TeV N3LO QCD

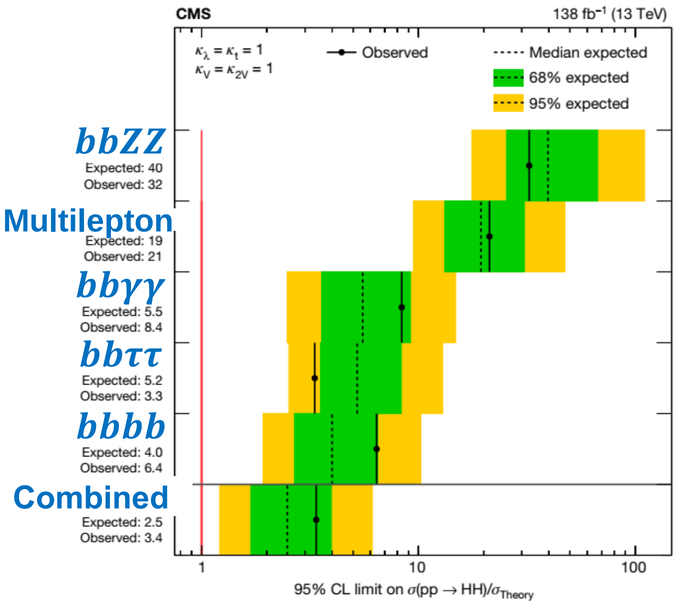




H Self-Coupling: Inclusive HH Searches

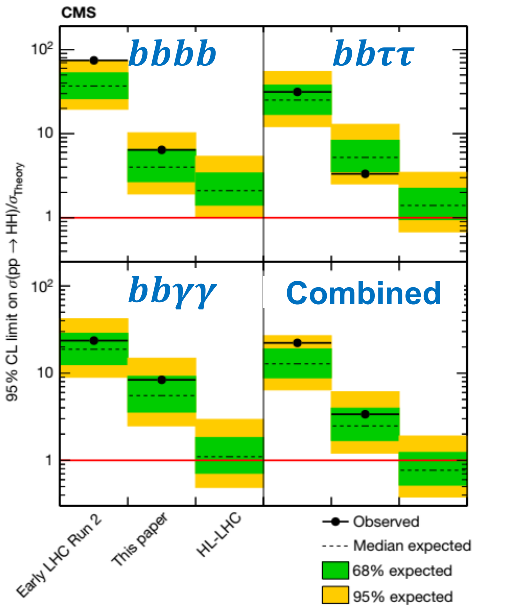
- Using the different final states **(HH → bbVV, bb$\gamma\gamma$, bb$\tau\tau$, bbbb)** and their combination
- Ratios of measured **HH production cross section** and the expectation from the SM
  - Combined observed (expected) 95% CL Upper limits: $\mathbf{3.4}$ $(\mathbf{2.5})$
  - **Significant improvement** comparing to early Run 2 results (35.9 fb^{-1})
  - Sensitivity in HL-LHC (3000 fb^{-1}) sufficient to establish the existence of the SM HH production

$\boldsymbol{\sigma/\sigma_{SM}}$ 95% CL Limit Nonresonant



Assuming $\boldsymbol{\kappa_\lambda = \kappa_t = 1}$
$\boldsymbol{\kappa_V = \kappa_{2V} = 1}$

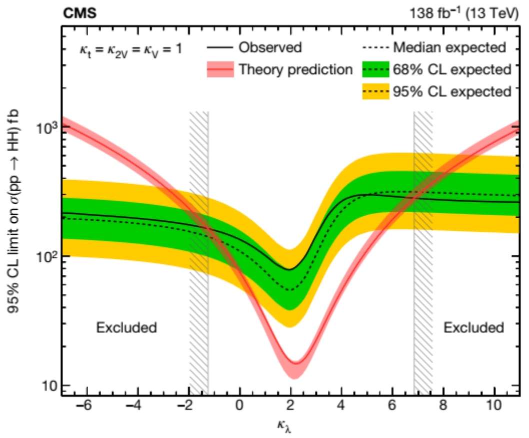
Evolution: Early Run2 to Now to HL-LHC



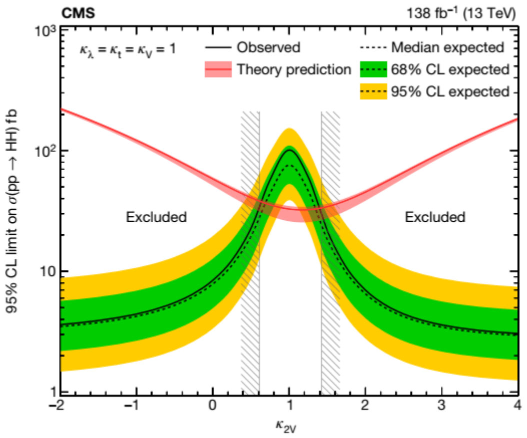
H Self-Coupling: Inclusive HH Searches

- 95% CL interval for H self-interaction coupling modifier
  - κ_λ: **[-1.24, 6.49]**
- 95% CL interval for quartic coupling modifier
  - κ_{2V}: **[0.67, 1.38]**
  - $\boldsymbol{\kappa_{2V} = 0}$ **is excluded** with a significance of 6.6σ, assuming $\kappa_\lambda = \kappa_V = \kappa_t = 1$, establishing the existence of VVHH
- HH and single-H have comparable sensitivities to κ_λ
- **HH and single-H combination** including κ_λ have potential for higher precision → See Yihui's talk

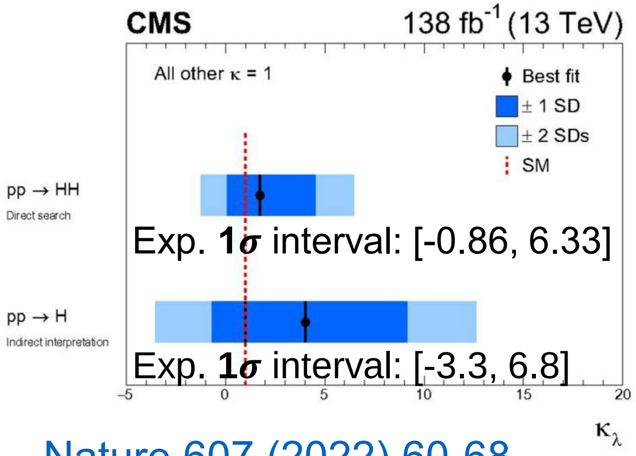
95% CL Limit on $\sigma(HH)$ (fb) vs **self-coupling κ_λ**



95% CL Limit on $\sigma(HH)$ (fb) vs **self-coupling κ_{2V}**



κ_λ measurement **from HH** vs **from single-H**



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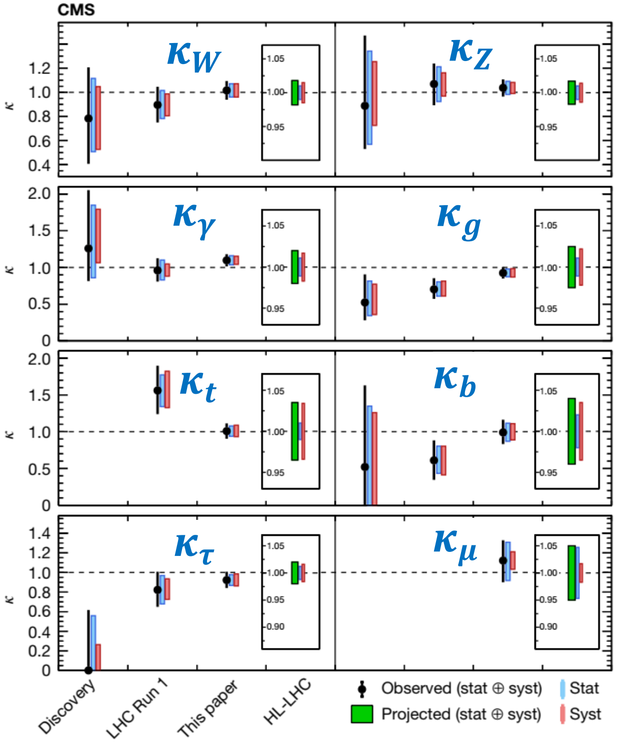
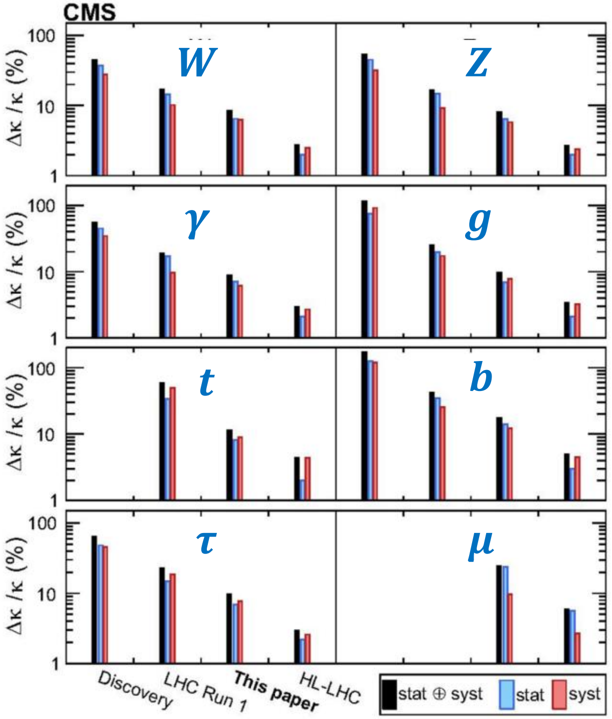
The Improvement on Higgs Couplings





[Nature 607 (2022) 60-68]

- **Impressive improvement** on Higgs couplings over the years
  - The current dataset enables the establishment of **rare decays channels** (H→ $\mu\mu$, H→ $Z\gamma$)
- **At HL-LHC** high precision tests of the SM
  - **Expected precision below 5%** for all the couplings

Summary

- Combinations of Higgs boson experimental measurements are extremely powerful to shed the light on the Higgs sector
- **Combined measurement of Higgs couplings with Run 2 data at CMS**
  - Higgs signal-strengths and single-H couplings measurement
  - Higgs self-coupling measurement
  - Overall agreement with the SM is extremely good
- **Impressive progress** on precisions have been achieved in Run 2
- Stay tuned for future results
  - HVV anomalous couplings
  - H-HH combinations

Thank you!

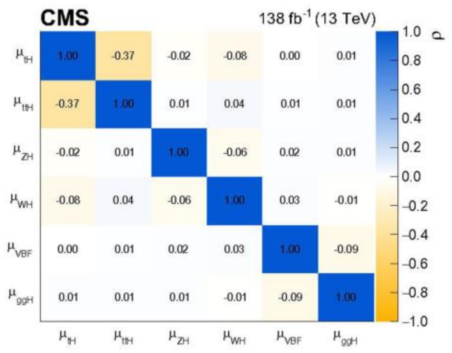
Back up

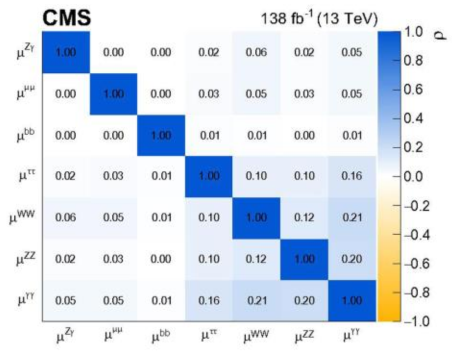
The Journey to Higgs Combination

[Nature 607 (2022) 60-68]

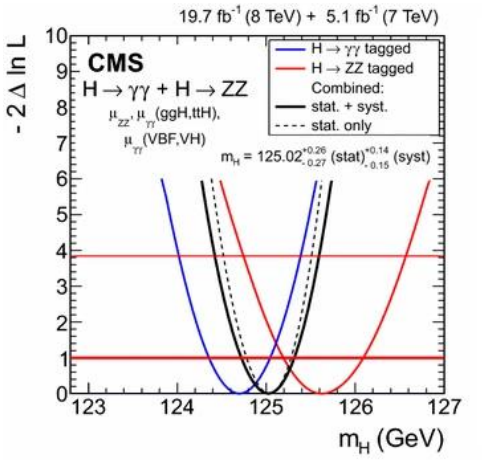
- Weighted average
  - Neglects all correlations between parameters
- Average + correlation matrix
  - Considers correlations between uncertainties
  - But neglects more subtle effects
- Likelihood Scan
  - Not so easy to reinterpret
- Full combination
  - Take into account full correlation between parameters
  - The best sensitivity achieved by exploiting the full power of recorded data
  - But complex input analyses imply a more complex combined model

Correlations between different couplings

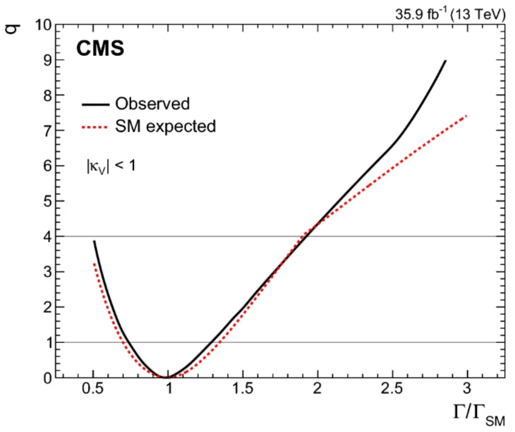




Run 1 combination



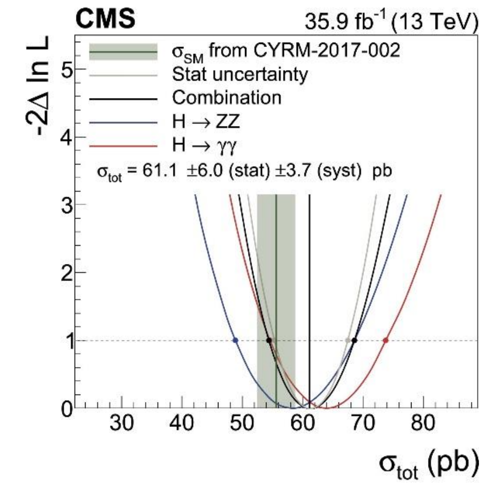
Run 2 combination

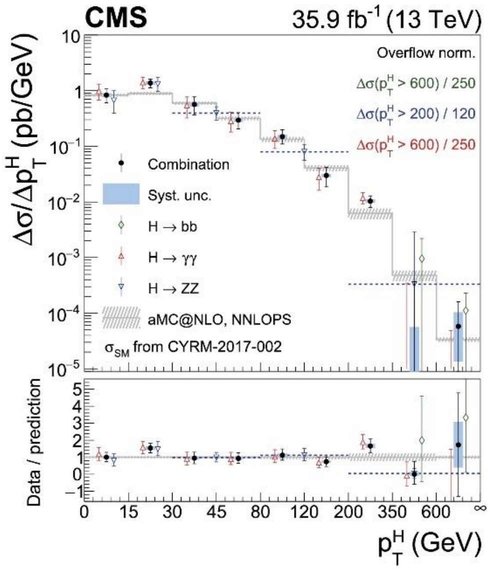


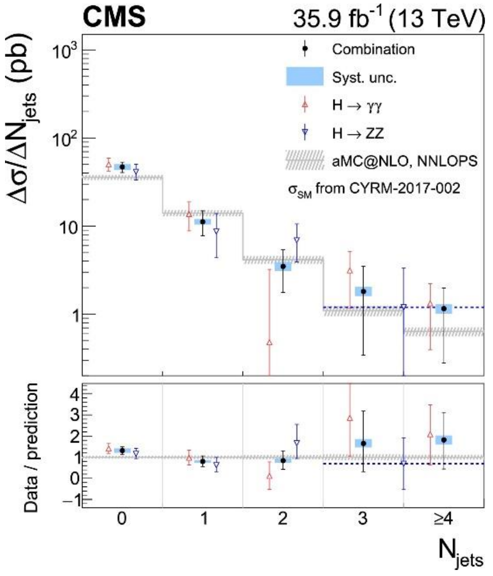
[Eur. Phys. J. C 75 (2015) 212] [Eur. Phys. J. C 79 (2019) 421]

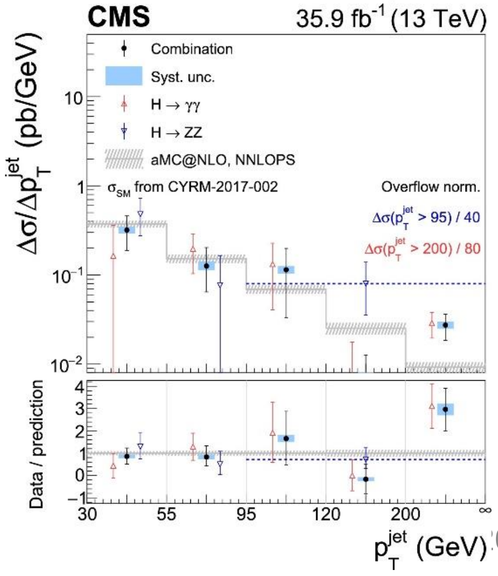
Total and Differential Cross Sections

[Phys. Lett. B 792 (2019) 369]









- Using early Run 2 dataset (36fb^{-1}) by CMS
- Based on a combination of channels: H→ $\gamma\gamma$, H→ZZ, H→bb
- The measured total cross section for Higgs boson production is $61.1 \pm 6.0(stat) \pm 3.7(syst)$ pb
- The combination result agrees with the SM value of 55.6 ± 2.5 pb
- Combined measurement of differential cross sections for few specific observables ($p_T^H, N_{jet}, p_T^{jet}$)
  - No significant deviations from the SM are observed

Event Categories in the Analyses Included

Analysis	CADI-line	Main production tags
$H \to \gamma\gamma$	HIG-19-015	ggH, VBF, ttH
$H \to ZZ$	HIG-19-001	ggH, VBF, VH, ttH
$H \to WW$	HIG-20-013	ggH, VBF, VH hadronic, WH leptonic, ZH leptonic
$H \to Z\gamma$	HIG-19-014	ggH, VBF
$H \to bb$	Boosted ggHbb: HIG-19-003	ggH
	ttH(bb): HIG-17-022, HIG-17-026	ttH
	VH(bb): HIG-16-044, HIG-18-016	WH leptonic, ZH leptonic
$H \to \tau\tau$	HIG-19-010	ggH, VBF, VH
ttH multilepton	HIG-19-008	ttH
$H \to \mu\mu$	HIG-19-006	ggH, VBF
$H \to$ inv.	HIG-20-003, EXO-20-004, EXO-19-003	ggH, VBF, VH hadronic, ZH leptonic

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Event Categories in the Analyses Included

- The analyses in the H to invisible are only included in models that allow for invisible decay modes of the Higgs boson.
- In some cases, the referenced analysis includes combinations with the Run-1 and 2015 datasets but those datasets are not included in either of the combinations in this paper.
- For the single Higgs analyses, most analyses target STXS binning stage 1.2. This additional kinematic information is not used for the standard LO kappa framework interpretations but is used when constraining the Higgs boson self-coupling from NLO electroweak interactions in single Higgs production/decay.

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Models for Interpretations – Higgs Self-coupling

- The rates for the dominant single Higgs boson production modes μ_i, relative to their SM predictions, are parameterized as

$$\mu_i(\kappa_V, \kappa_F, \kappa_\lambda) = Z_H^{BSM}(\kappa_\lambda)\left[S_i(\kappa_V, \kappa_F) + \frac{C^i}{K_{EW}^i}(\kappa_\lambda - 1)\right]$$

  - $Z_H^{BSM}(\kappa_\lambda) = \left(1 - \left(\kappa_\lambda^2 - 1\right)\delta Z\right)^{-1}$, $\delta Z = -1.536 \times 10^{-3}$

- The parametrization of the branching ratios mf is given by

$$\mu^f(\kappa_V, \kappa_F, \kappa_\lambda) = \frac{S_f(\kappa_V, \kappa_F) + (\kappa_\lambda - 1)C^f}{\sum_d \Gamma_d^{SM}(S_d(\kappa_V, \kappa_F) + (\kappa_\lambda - 1)C^d)}$$

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Statistical Procedure

- A profiled likelihood ratio q is used as test statistics to estimate the parameters of interest (POIs) $\vec{\alpha}$ of the model and their associated confidence interval, taking into account the systematic uncertainties as individual nuisance parameters $\vec{\theta}$:

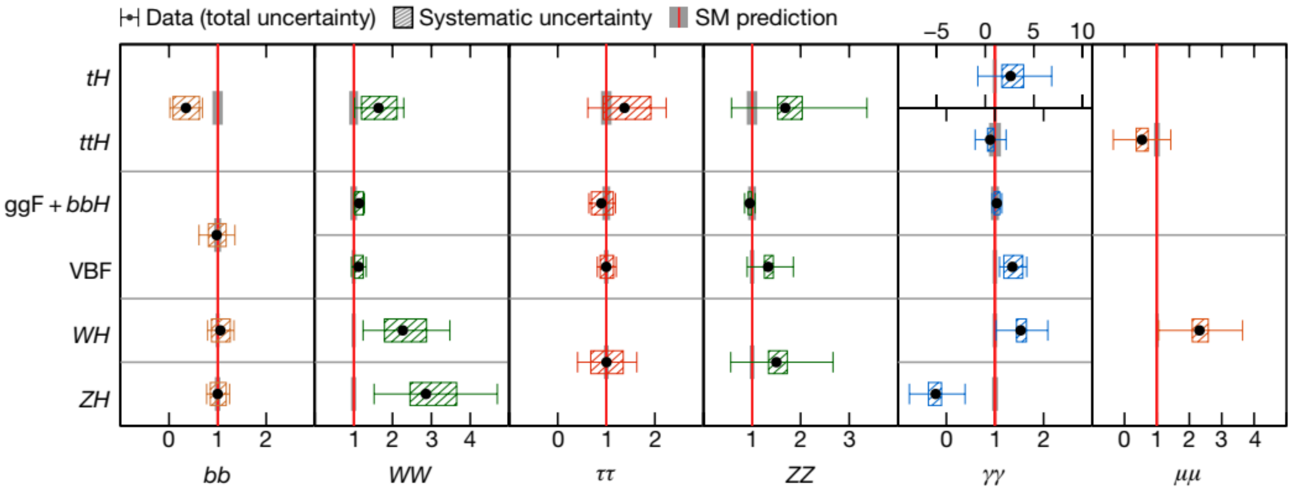
$$q(\vec{\alpha}) = -2\ln\left(\frac{L\left(\vec{\alpha}, \hat{\hat{\vec{\theta}}}\right)}{L\left(\hat{\vec{\alpha}}, \hat{\vec{\theta}}\right)}\right)$$

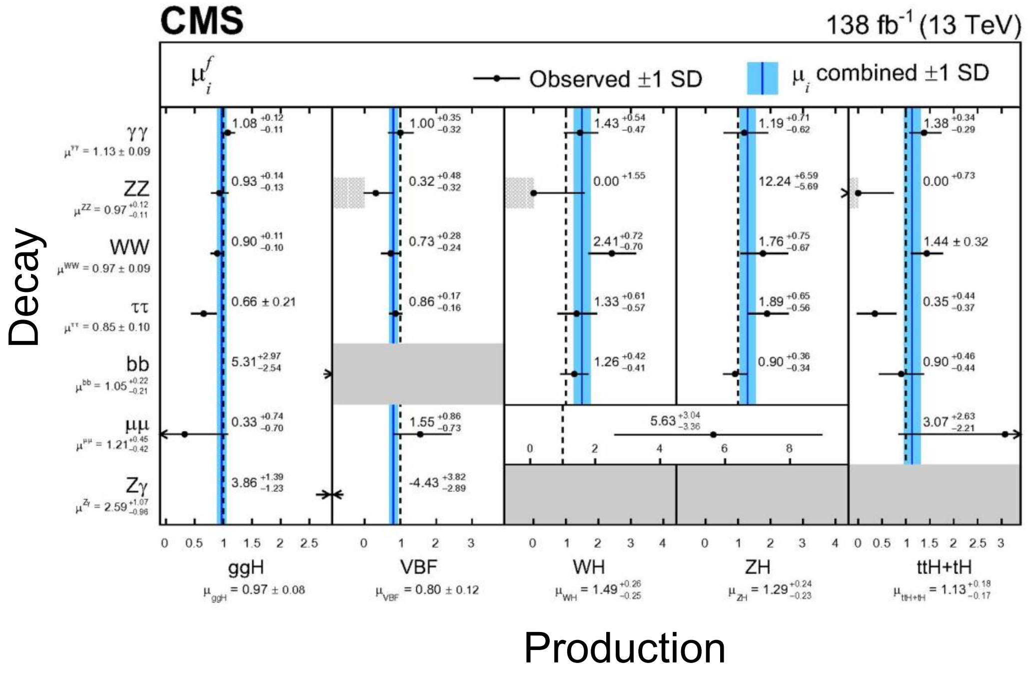
- L is the likelihood function, which is built as the product of the likelihoods of the respective input analyses, multiplied by constraint terms on the nuisance parameters

[Nature 607 (2022) 60-68]

Compared with ATLAS

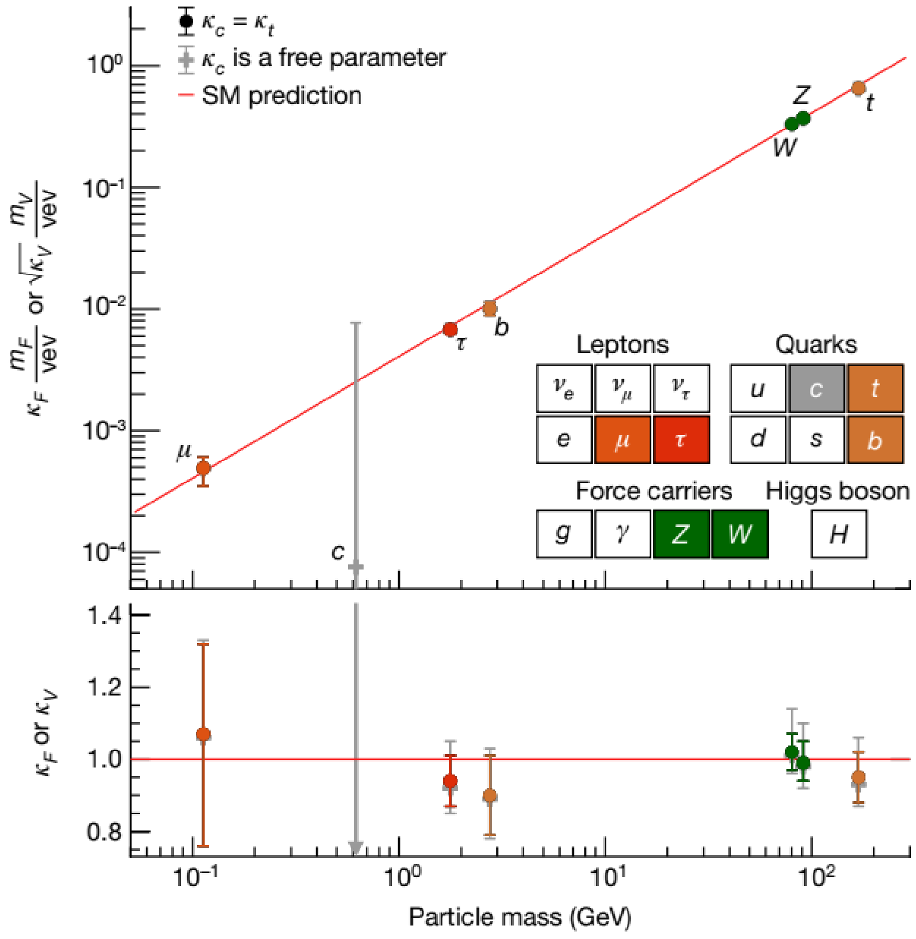
- Signal strengths μ_i^f overall agreement with the SM

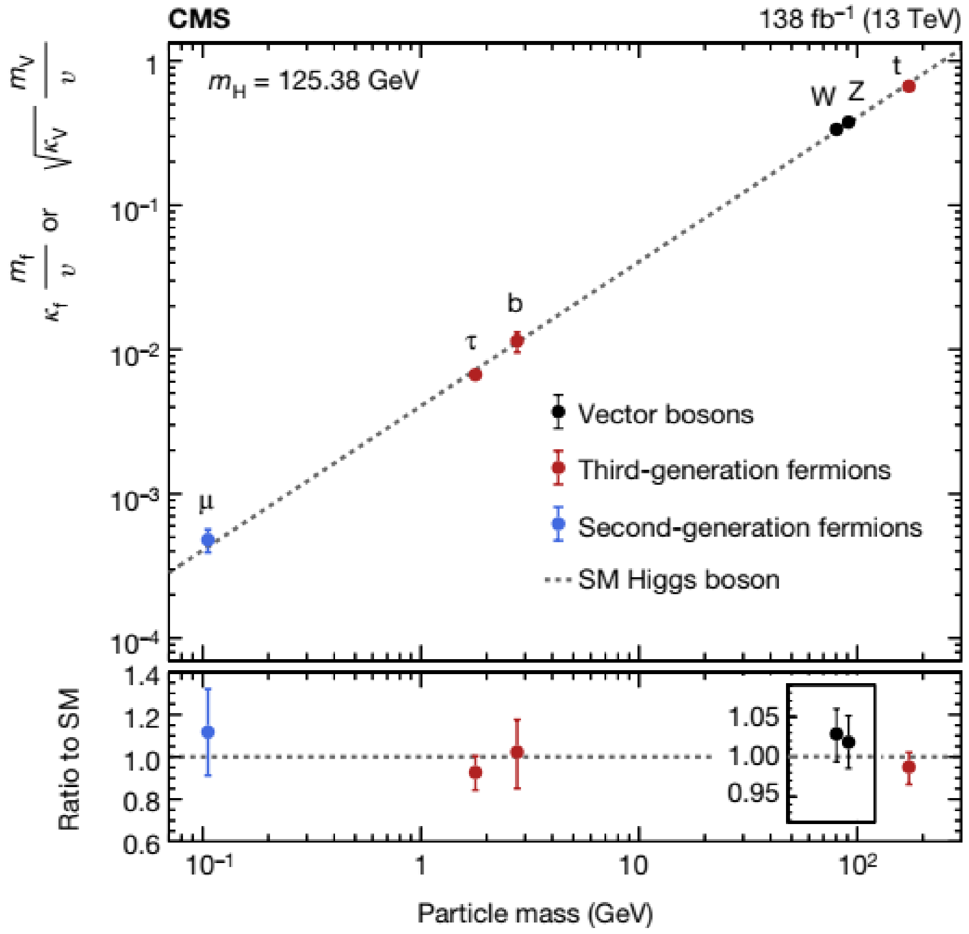




Compared with ATLAS

- **H couplings** vs **particle mass**





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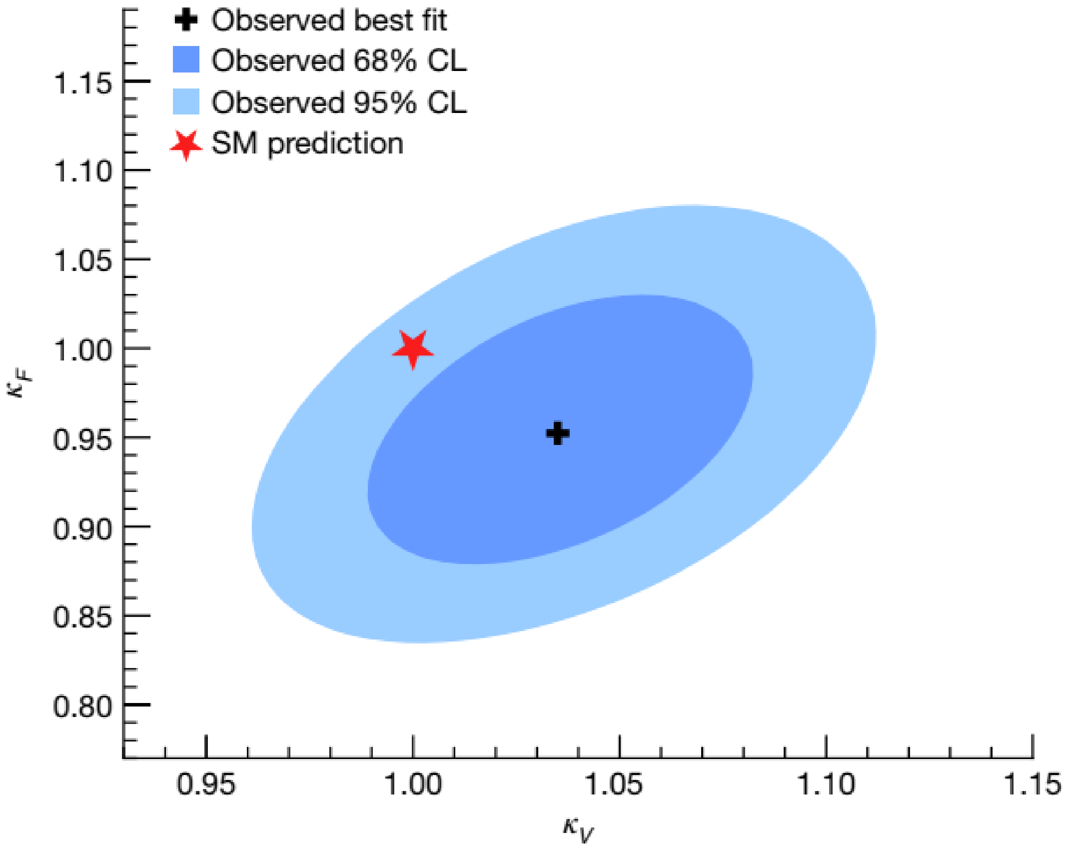
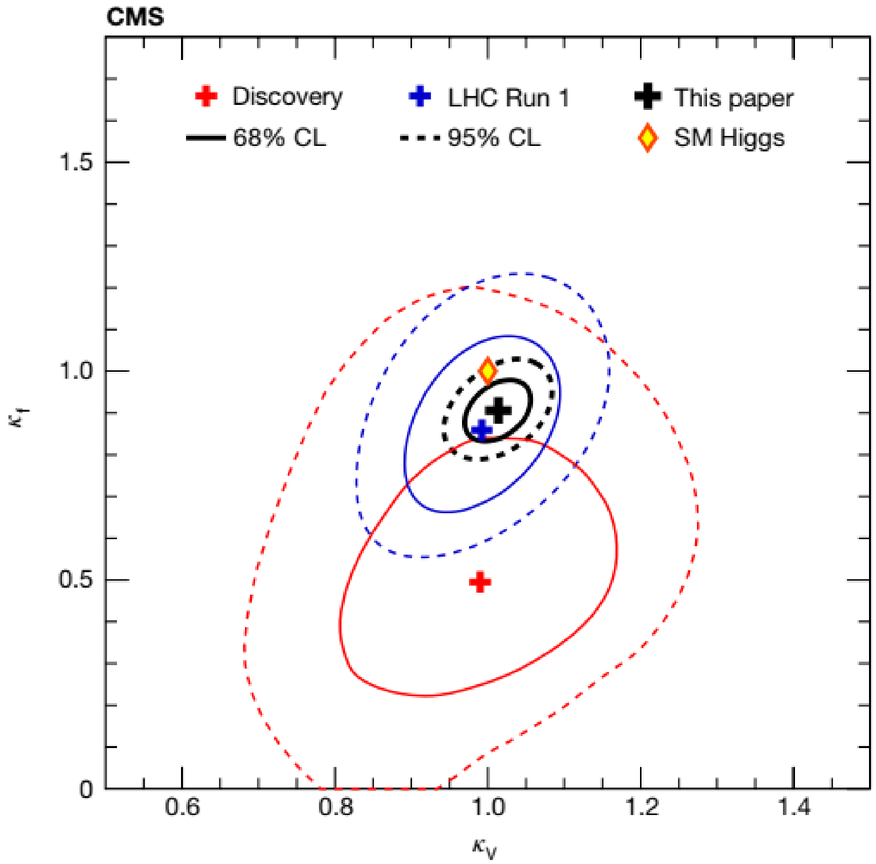
Compared with ATLAS

- κ_f vs κ_V from Discovery to Run1 to Full Run2





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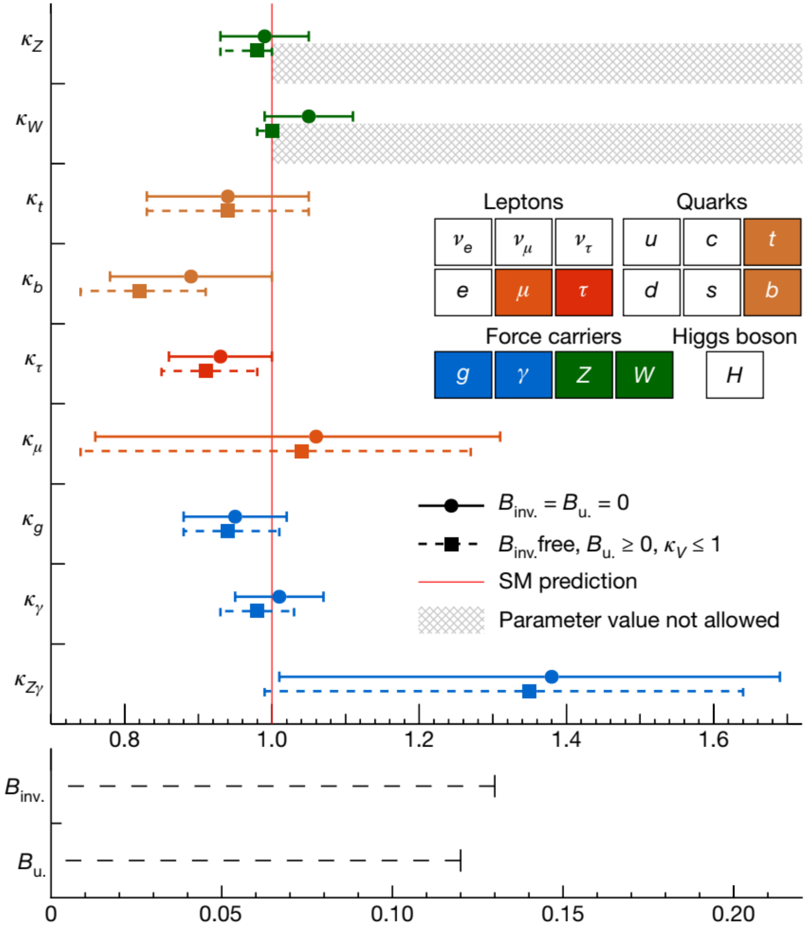
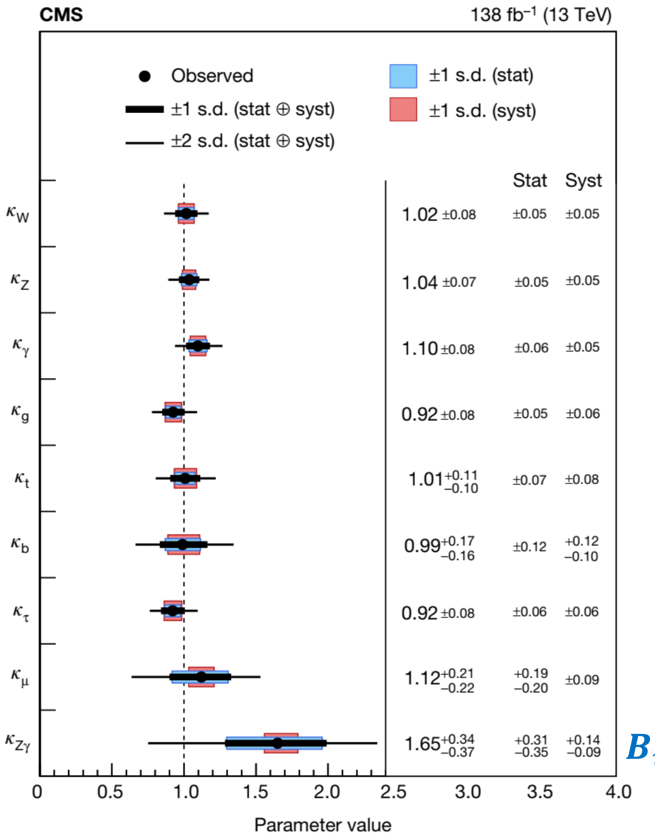
Compared with ATLAS

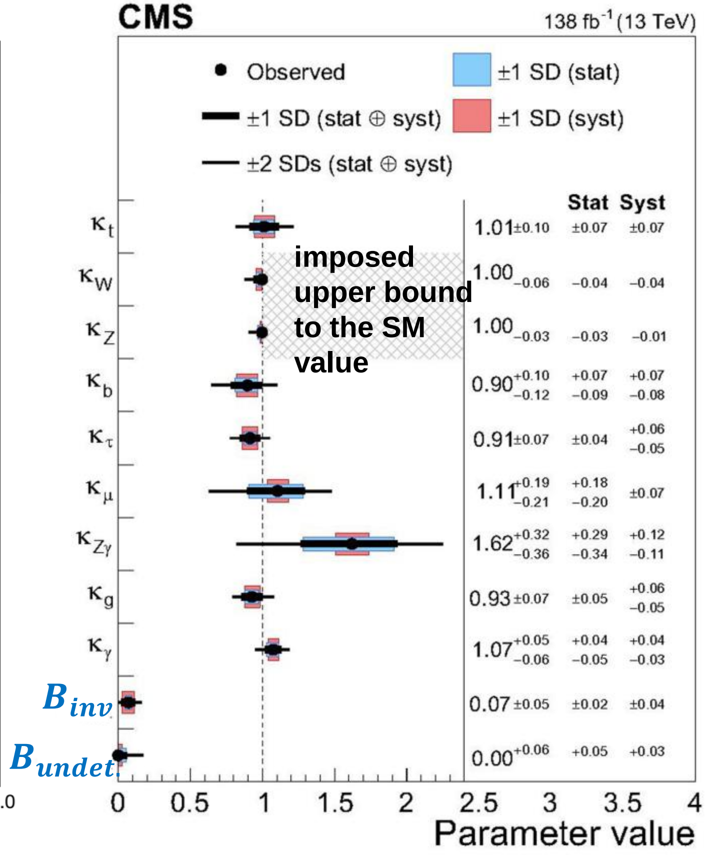
- Coupling modifiers κ_i



Assuming no invisible and undetected decays



Assuming invisible and undetected decays



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