Higgs couplings to fermions and bosons at the LHC

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Standard model physics at the TeV scale

Standard Model Higgs boson couplings

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SM predictions for Higgs couplings:

- Couples to all massive SM fermions f, vector bosons V and itself
- Coupling strength increases with particle mass
- All couplings CP-even

$$\mathcal{L} = -\frac{m_f}{v}\bar{f}f\,H + \frac{2m_W^2}{v}W_\mu W^\mu H + \frac{m_Z^2}{v}Z_\mu Z^\mu H + \frac{m_V^2}{v^2}V_\mu V^\mu H^2 + \frac{m_H^2}{2v}H^3 + \frac{m_H^2}{8v^2}H^4$$

How to test these at the LHC?

Standard Model Higgs boson couplings

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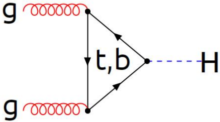
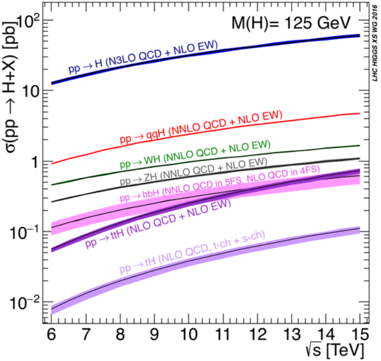
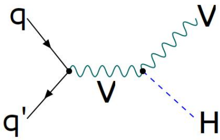
How to test these at the LHC?

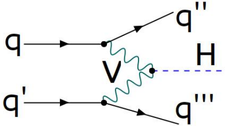
- Study Yukawa and vector-boson couplings in single-Higgs events
- Study quartic vector-boson coupling and trilinear self-coupling in di-Higgs events
- So far, no sensitivity to quartic self-coupling

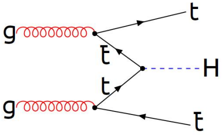
Single-Higgs production









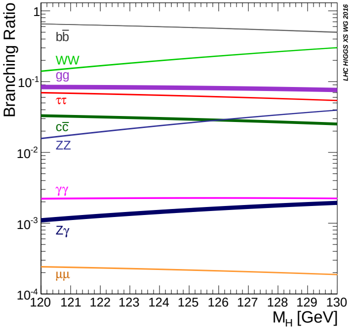


Couplings to heavier particles stronger

⇒ Production mainly facilitated by weak bosons and 3rd generation quarks

Branching ratios

SM prediction:



Experimentally observed decay channels:

- Low branching ratio: $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$
- High branching ratio: $H \to bb$, $H \to \tau\tau$, $H \to WW^* \to \ell\nu\ell\nu$

Different experimental challenges $\Rightarrow$ Final states accessed in separate analyses

In the following, show selection of analyses:

- in different final states
- probing different properties of Higgs couplings

$H \to \tau\tau$ final state

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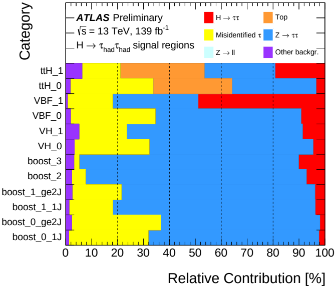
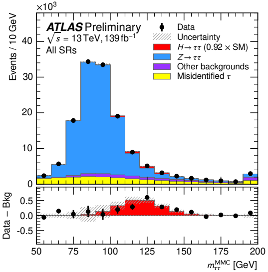
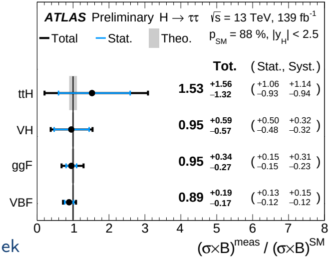
Start with measurement in already observed channel for general strategy

- Multiple analysis regions targeting different Higgs production mechanisms
- Conduct fit to di-τ invariant mass
  $\Rightarrow$ Can measure cross-section for each production mode

For more detailed measurement, go beyond xsec per production mode







Simplified template cross-sections

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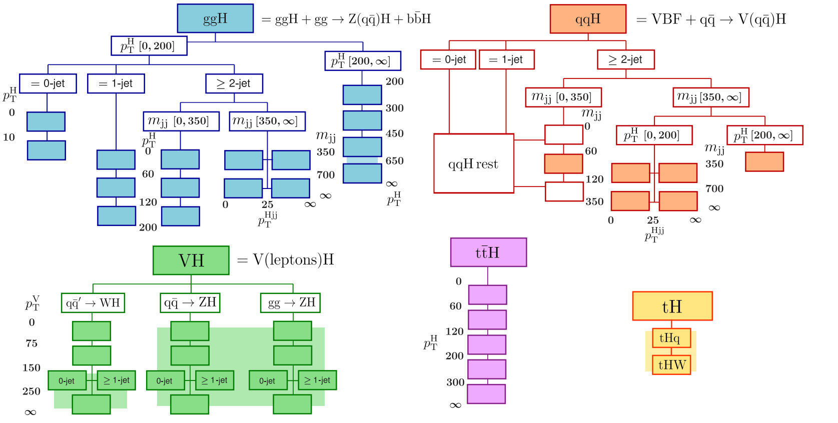
Short description of STXS approach:

- Separate phase-space regions targeting different production modes
- Processes split into "bins" based on event kinematics



⇒ Reduces impact of theoretical uncs and gives kinematic information

STXS results

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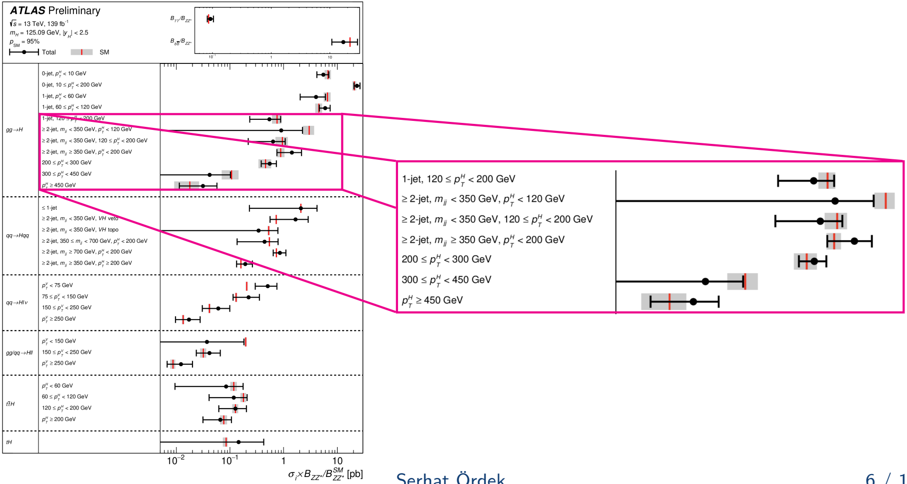
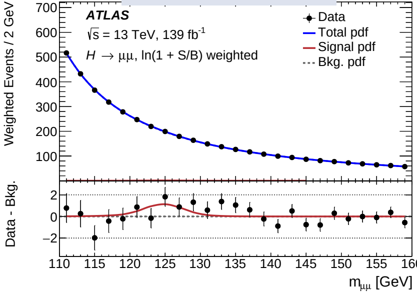
- Combined measurements in $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$ and $H \to bb$
- High-p_T^H ggF bins enhanced in many BSM scenarios
- No significant deviation from SM expectation found



$H \to \mu\mu$ measurements

- Now move from observed processes to searches
- In 2nd generation, most sensitive to $\mu\mu$ due to well-reconstructed final state
- Fitting $m_{\mu\mu}$ in dedicated SRs for the four main production mechanisms (exception: CMS VBF region uses multivariate classifier)

Phys. Lett. B 812 (2021) 135980



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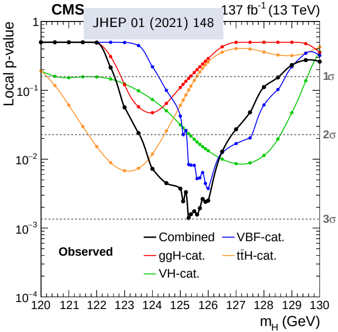

- ATLAS: 2.0 (1.7)σ observed (expected) significance
- CMS: 3.0 (2.5)σ observed (expected) for $m_H = 125.38$ GeV
- First reported evidence of $H\mu\mu$ Yukawa coupling

Coupling modifier measurement
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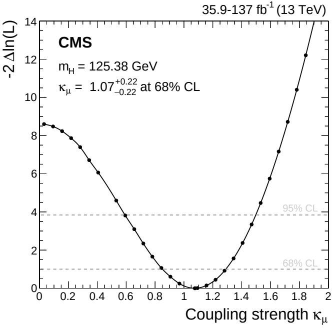
Interpret measurements using κ framework:

- Use SM cross-sections and decay widths as reference
- Introduce factors $\boldsymbol{\kappa}$ for each production/decay mode that modify these:

$$\kappa_j^2 = \frac{\sigma_j^{\text{Obs}}}{\sigma_j^{\text{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j^{\text{Obs}}}{\Gamma_j^{\text{SM}}} \quad \Rightarrow \text{SM expectation: } \kappa_j = 1$$

$\Rightarrow$ κ parameters act as linear modifiers to H coupling strengths

Most recently, modifier κ_μ of $H\mu\mu$ coupling was measured:



Coupling vs mass

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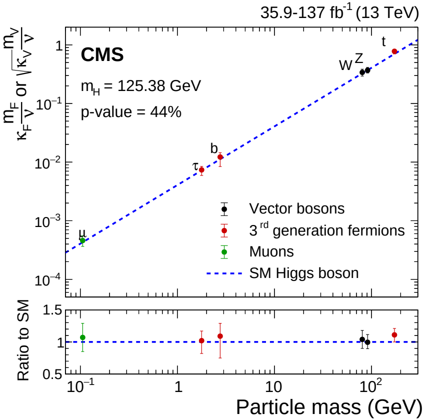


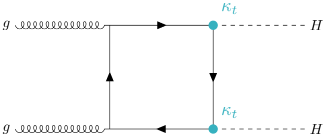
- Combine κ, particle mass and vev $\Rightarrow$ "observed coupling strength"
- Collected for all couplings with experimental evidence

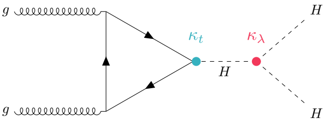
$\Rightarrow$ Very SM-like over 3 orders of magnitude

These are all the confirmed couplings, now showing searches for others

Di-Higgs production
ATL-PHYS-PUB-2021-031

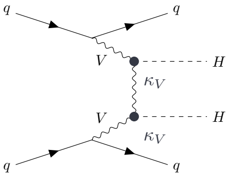
To access further Higgs couplings, need to study di-Higgs events.
LO diagrams of ggF HH production, highest-xsec process:

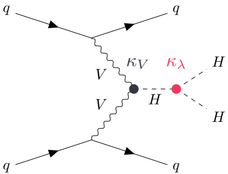


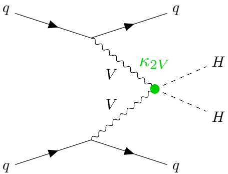


- Affected by κ_t and κ_λ
- Easier to constrain κ_t in single-Higgs events, but κ_λ best measured here

Di-Higgs production in VBF:







- Affected by κ_V and κ_λ
- Also sensitive to κ_{2v} modifier of *HHVV* coupling

$HH \to bb\gamma\gamma$ final state

- Relatively low background in $bb\gamma\gamma$
  $\Rightarrow$ Probe low-m_{HH} region, sensitive to κ_λ
- 95% C.L. obs (exp) limit on xsec:
  7.7 (5.2) [CMS], 4.1 (5.5) [ATLAS]
- Scan κ_λ values, compare limit to xsec
- 95% C.L. limit on κ_λ:
  $[-3.3, 8.5]$ ($[-2.5, 8.2]$) [CMS],
  $[-1.5, 6.7]$ ($[-2.4, 7.7]$) [ATLAS]

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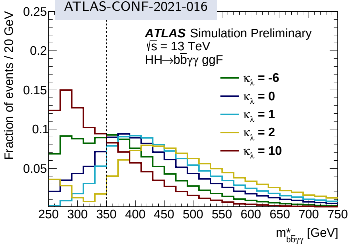

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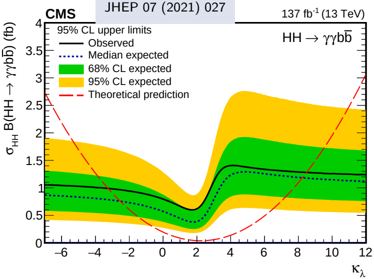

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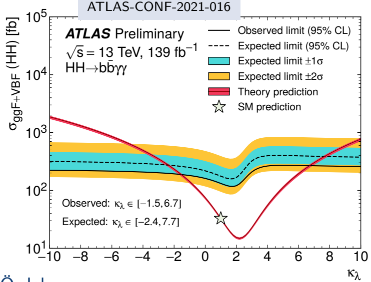

$HH \to bb\tau\tau$ and $HH \to 4b$

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- Higher BR than $bb\gamma\gamma$, lower low-m_{HH} signal acceptance
- 95% C.L. obs (exp) limit on SM xsec: 4.7 (3.9) [ATLAS $bb\tau\tau$], 3.6 (7.3) [CMS $4b$]
- 95% C.L. obs (exp) limits from CMS $4b$:
  $\kappa_\lambda \in [-2.3, 9.4]$ ($[-5.0, 12.0]$)
  $\kappa_{2V} \in [-0.1, 2.2]$ ($[-0.4, 2.5]$)

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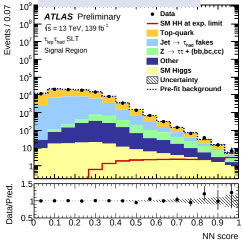

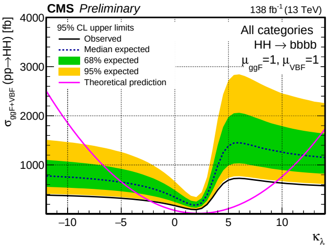

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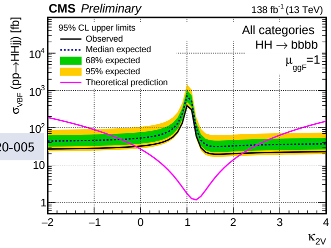

⇒ Constrained *HHH* and *HHVV* coupling strengths, only *HHHH* not covered

CP test in *ttH*

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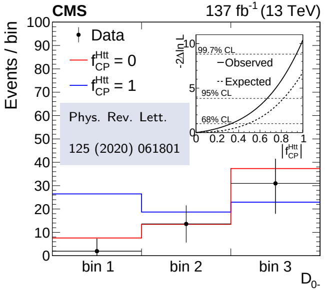
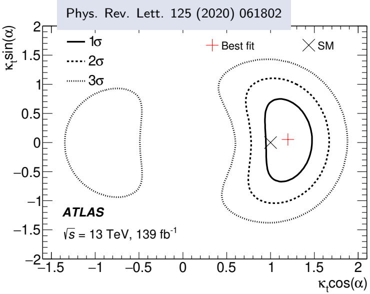
In last part of talk, focusing on BSM couplings

- SM prediction: Higgs couplings purely CP-even
- Searches for CP-odd contribution to top Yukawa coupling in *ttH* production
- In Higgs Characterization model: (SM: $\alpha = 0$, $\kappa_t = 1$)

$$\mathcal{L} = -\frac{m_t}{\nu}\left(\bar{\psi}_t \kappa_t \left[\underbrace{\cos(\alpha)}_{\text{CP-even}} + \underbrace{i\sin(\alpha)\gamma^5}_{\text{CP-odd}}\right] \psi_t\right) H$$

$ttH \to \gamma\gamma$: Fit $m_{\gamma\gamma}$ in regions with different CP compositions of signal





CP test in $H \to \tau\tau$

CMS-PAS-HIG-20-006

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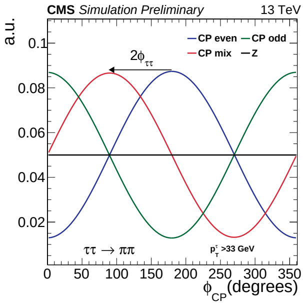
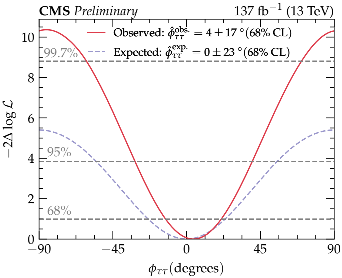
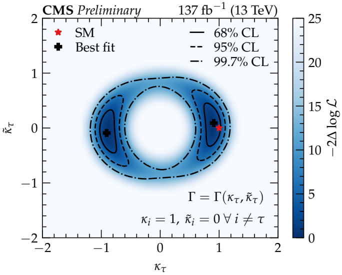
- Similar measurement for τ Yukawa coupling
- Angle between τ decay planes $\Leftrightarrow$ CP mixing angle
- Mixing angle: $\phi_{\tau\tau} = (4 \pm 17)^\circ$ (exp: 0 ± 23)
- Simultanous measurement of odd and even coupling prefers even coupling
  $\Rightarrow$ No sign of CP violation in top or τ Yukawa coupling







EFT interpretations

Use EFT approach to study CP-even BSM Higgs couplings

- EFT Lagrangian: $\mathcal{L} = \mathcal{L}_{SM} + \sum_i^{N_6} \frac{c_i}{\Lambda^2} O_i^{(6)} + \ldots$
- One Wilson coefficient c_i introduced per BSM coupling
- Measured in combination of multiple final states

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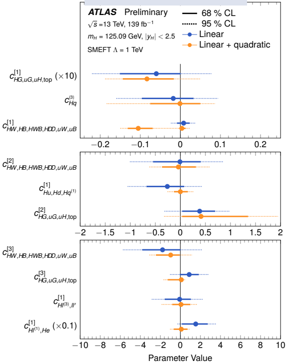

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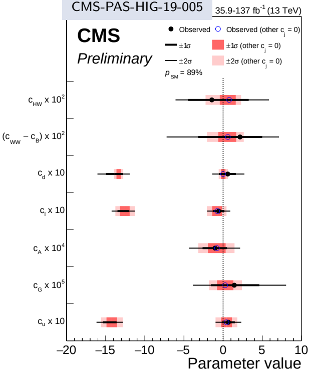

No significant deviation from 0 for any c_i ⇒ no BSM couplings found

Conclusion

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- Presented overview of recent measurements of Higgs boson couplings
- STXS measurements in agreement with SM
- Evidence for muon Yukawa coupling recently reported
- Limits from di-Higgs measurements quickly improving
- No sign of CP-odd or BSM CP-even Higgs couplings found yet