

Higgs coupling to Fermion measurements at LHC

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The Discovery of Higgs boson

Quarks

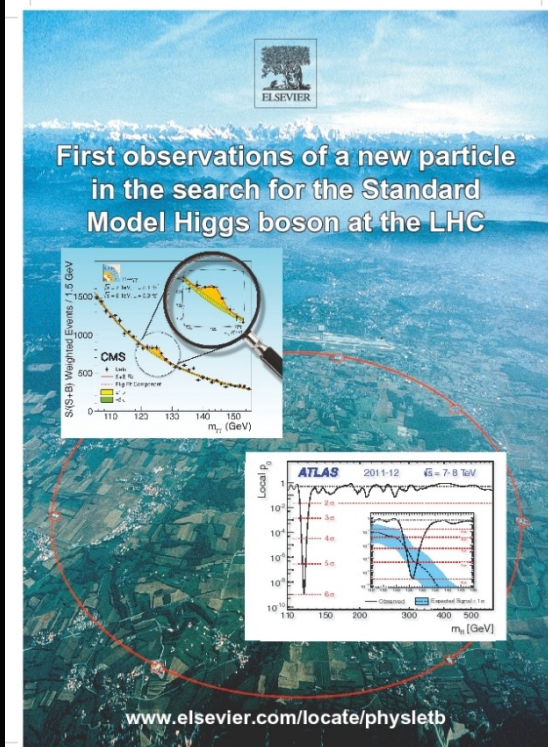


Leptons

Forces

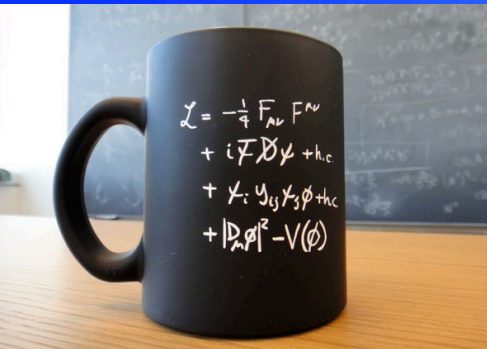


Last element of SM



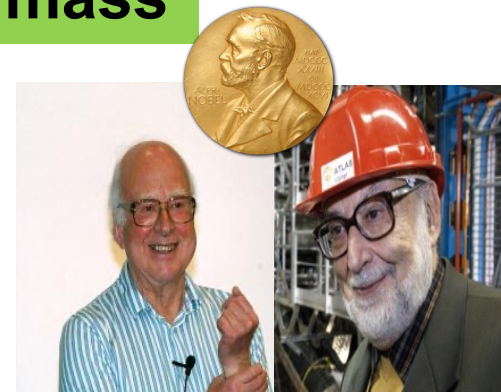
Higgs Physics: Measurement of interactions

Higgs Boson: The origin of mass

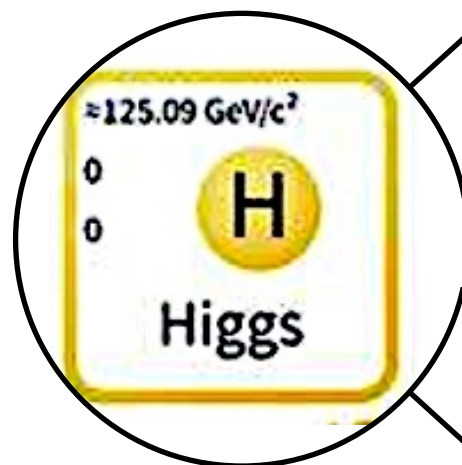


Coupling to V-bosons

➤ Higgs Mech.
➤ Discovered in 2012



2013 Nobel Prize



Coupling to Fermions

➤ **Fifth force?**
➤ Observed Coup. to 3'd generation

Radius of atom, , stability of vacuum (fate of our universe)...

Self-coupling

➤ **Sixth force?**
➤ HL-LHC

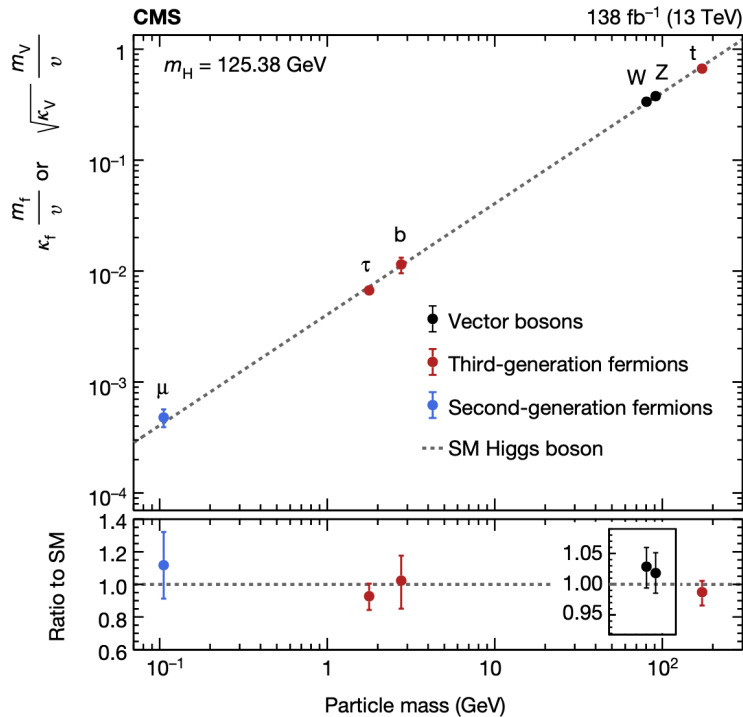
Phase-transition

Precision Challenge at LHC

Hongkong



Higgs coupling to Fermions



$$\mathcal{L}_{Yuk} = - \sum_{m,n=1}^{F'} \left[\Gamma_{mn}^u \bar{q}_{mL}^0 \tilde{\phi} u_{nR}^0 + \Gamma_{mn}^d \bar{q}_{mL}^0 \phi d_{nR}^0 \right. \\
 \left. + \Gamma_{mn}^e \bar{l}_{mn}^0 \phi e_{nR}^0 + \Gamma_{mn}^\nu \bar{l}_{mL}^0 \tilde{\phi} \nu_{nR}^0 \right] + h.c.,$$

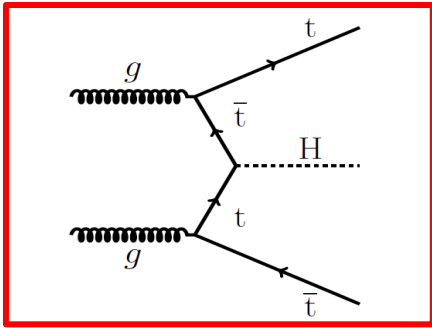
$$-\mathcal{L}_{Yuk} = \sum_i m_i \bar{\psi}_i \psi_i \left(1 + \frac{g}{2M_W} H \right) = \sum_i m_i \bar{\psi}_i \psi_i \left(1 + \frac{H}{v} \right)$$

$$m_F = \frac{v g_F}{\sqrt{2}}$$

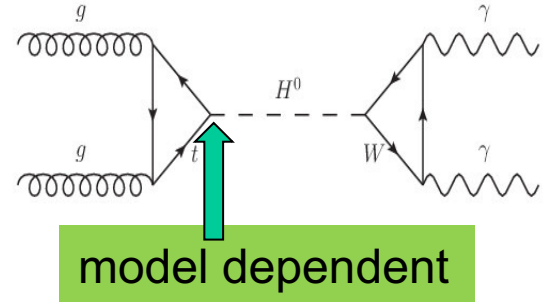
- Give mass to fermions (quarks/lepton)
- Coupling strength variations with a factor of $\sim 10^6$:
 - Only few measurable at LHC
- Unknown questions: CP properties of Yukawa interactions
- Different measurement strategies used at LHC (see next slides)

Higgs Coupling to top quark: largest coupling

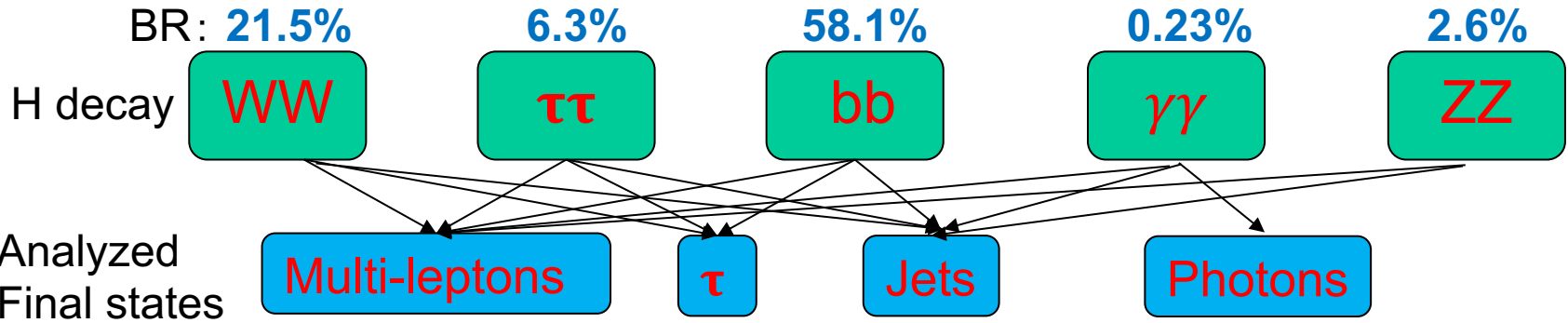
- Direct meas. use ttH ; indirect constrains in loop effects



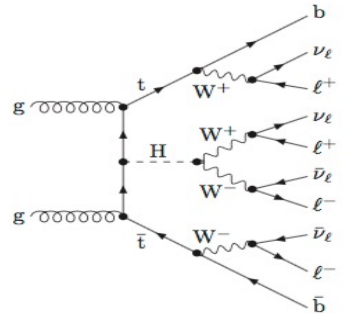
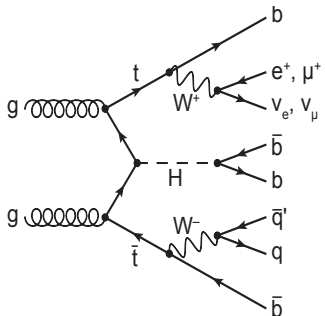
$\sim 1\%$ of total Higgs
 $\sim 0.06\%$ of $ttbar$
 $\sim 1/10^{11}$ of total interaction



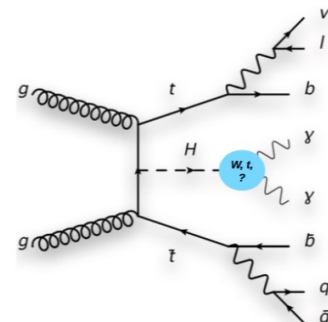
model dependent



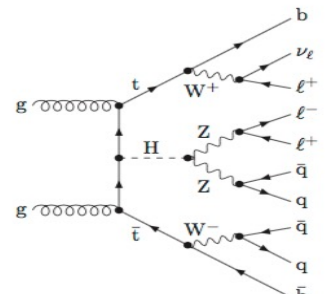
Higher cross-section ←



→ Higher purity

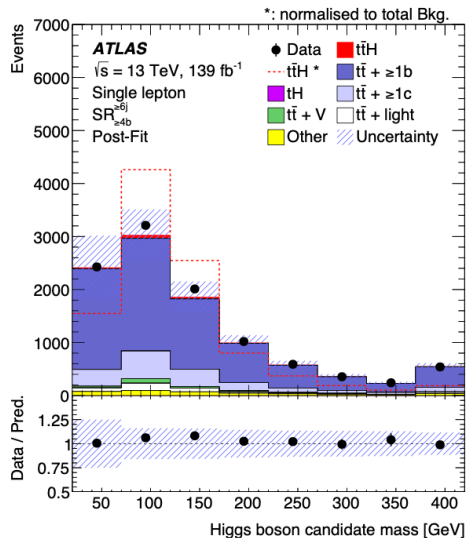
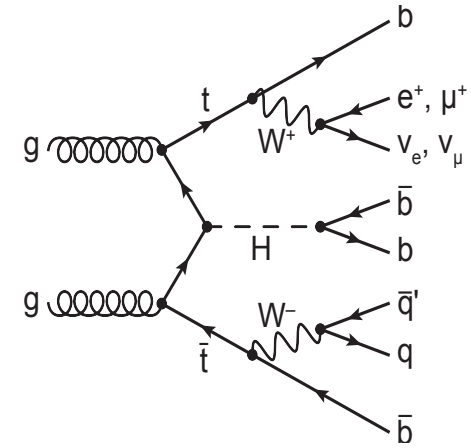


Higher purity

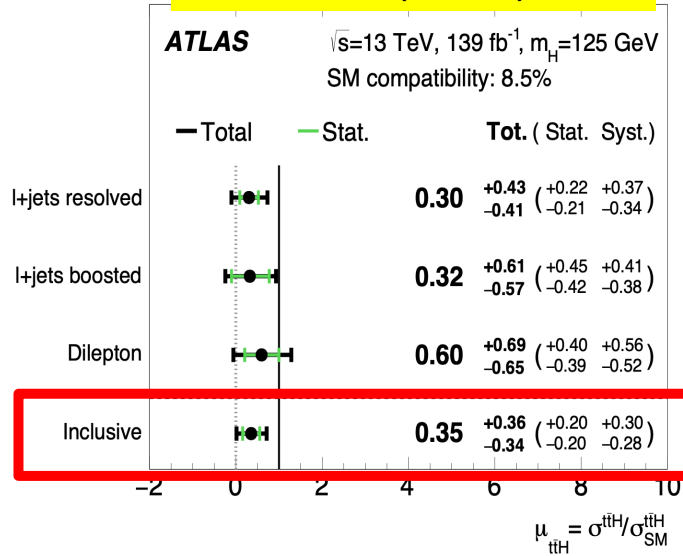


ttH, H → bb

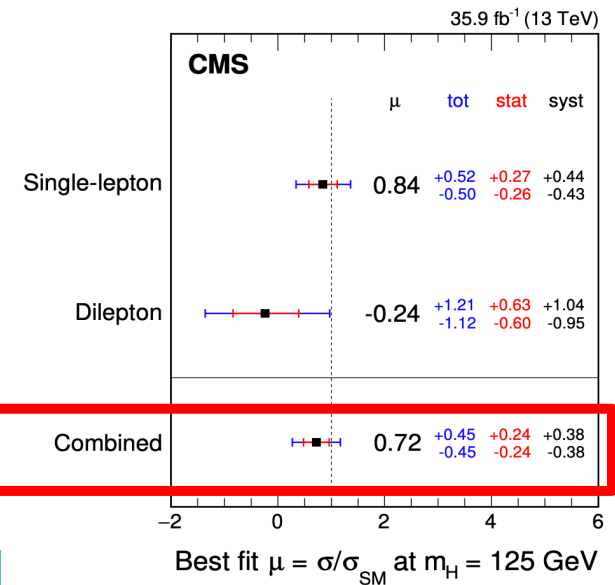
- Higgs coupling to fermions only
 - Either top quark or bottom quark
- Largest signal compared to other ttH FS
- ttHbb: l+jets, dilepton, full hadronic, boosted analyzed
- Analysis using DNN, BDT, MEM
- Major background from tt+jets
- Main uncertainties from tt+hf theory, jet tagging etc.
 - Systematics dominated already



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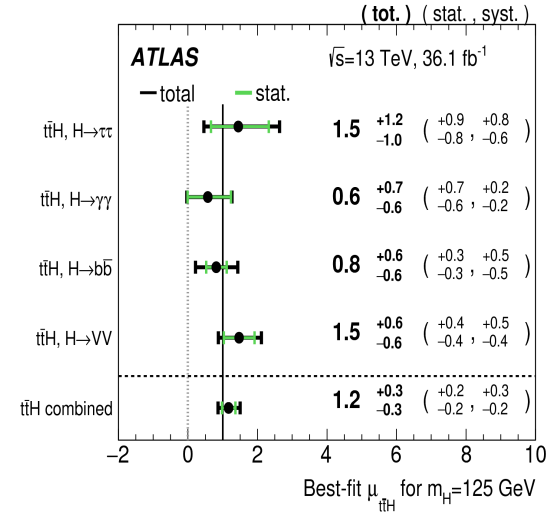
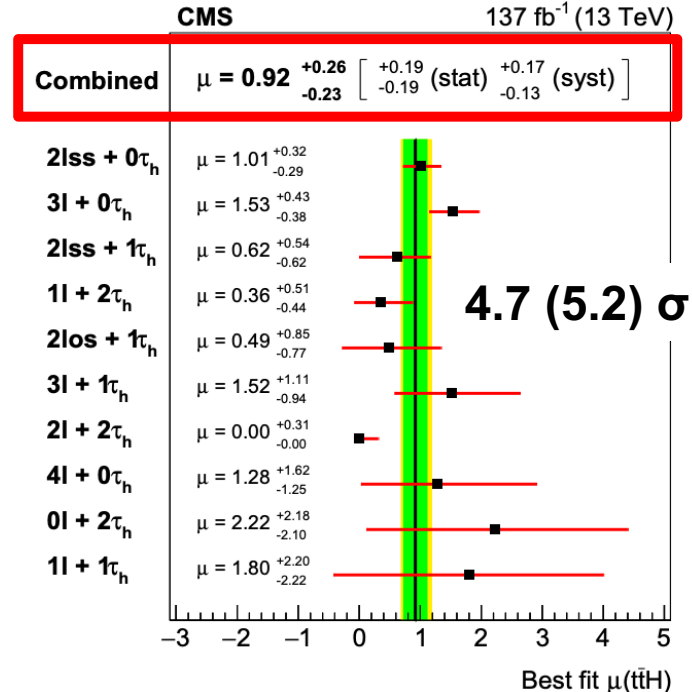
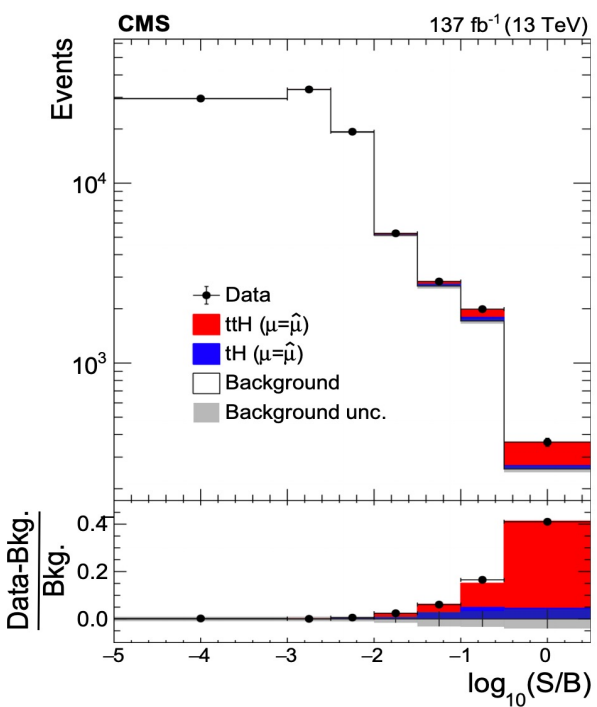
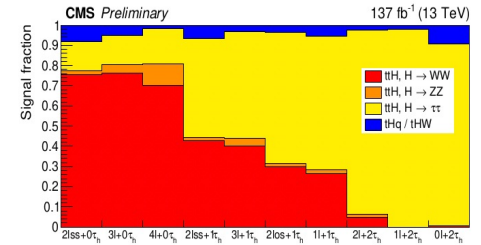
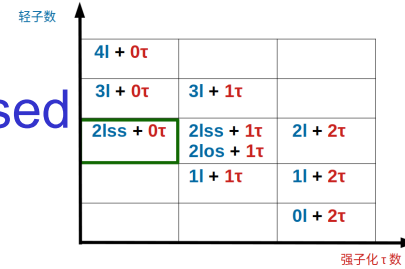


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ttH multi-lepton

- Most sensitive channel at run2
- Can not reco. the higgs system: ML used
- Tag jets from Higgs decays
 - based on relations to other obj.
- Fake lepton contribution estimated from data



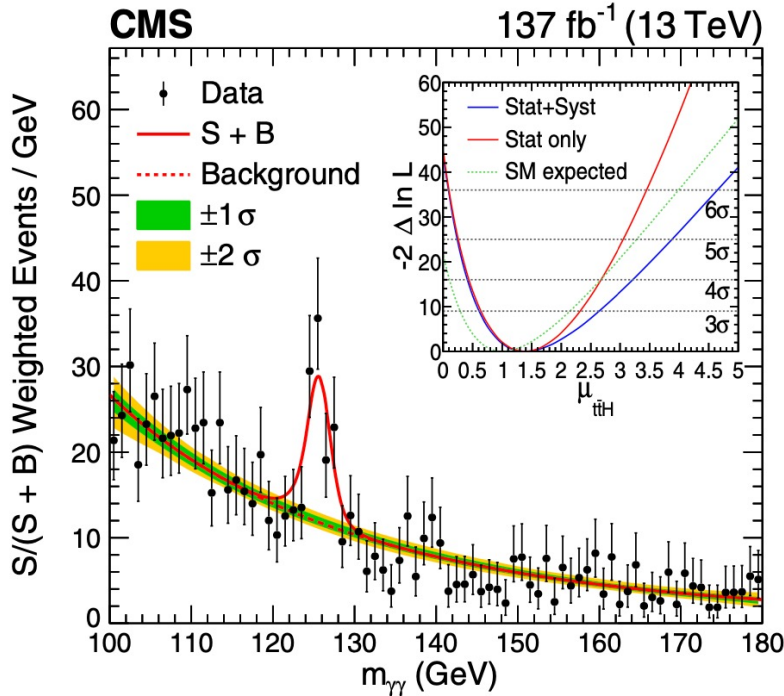
EPJC 81 (2021) 378

PRD 97 (2018) 072003

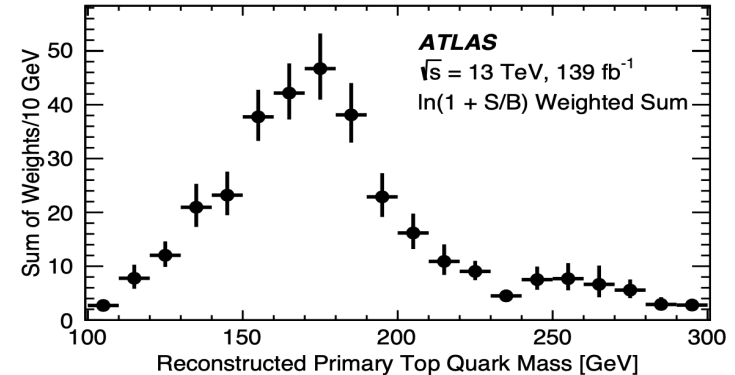
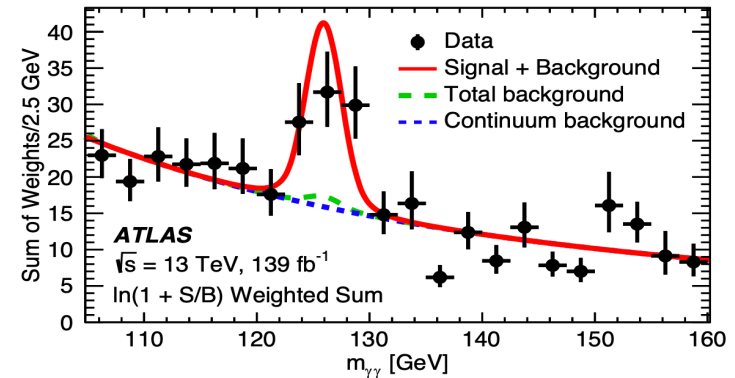
ttH, H → γγ

- Very good higgs mass resolution
- Good S/B with (background suppressed by presence of tt)
- Based on ttbar decays, divided into Lep and Had region
- Further categorization based on BDT Scores

$$\sigma_{t\bar{t}H} \mathcal{B}_{\gamma\gamma} = 1.56^{+0.34}_{-0.32} \text{ fb}$$

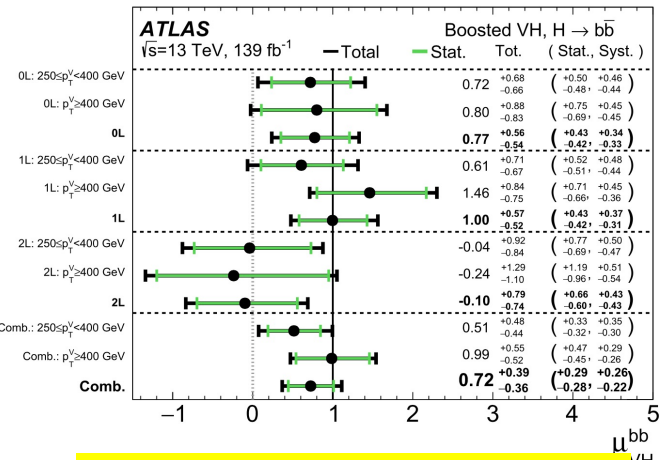
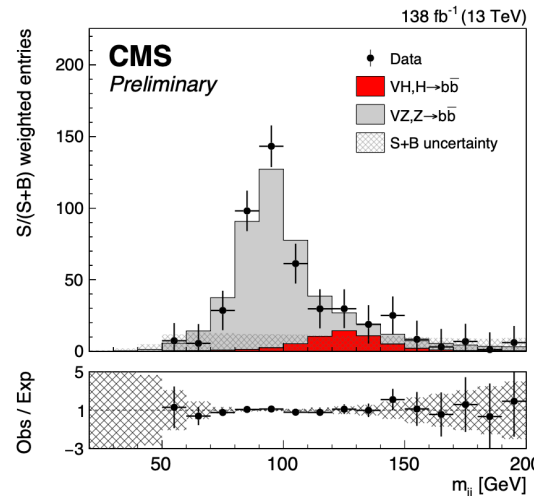
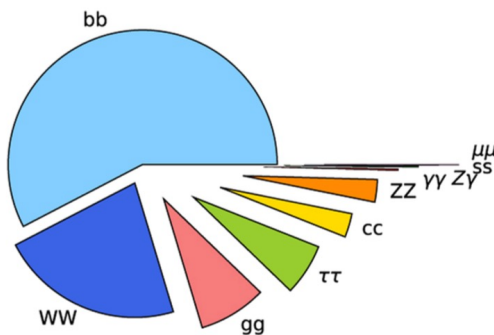
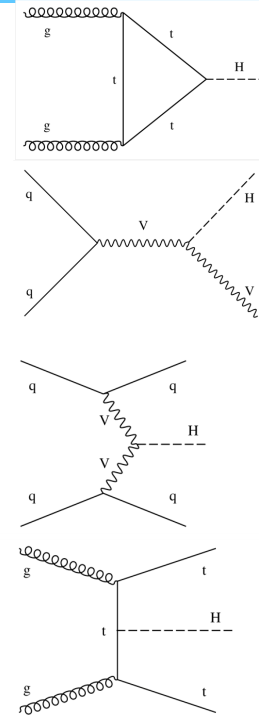


$$\sigma_{t\bar{t}H} \times \mathcal{B}_{\gamma\gamma} \text{ is } 1.64^{+0.38}_{-0.36} (\text{stat})^{+0.17}_{-0.14} (\text{sys}) \text{ fb}$$



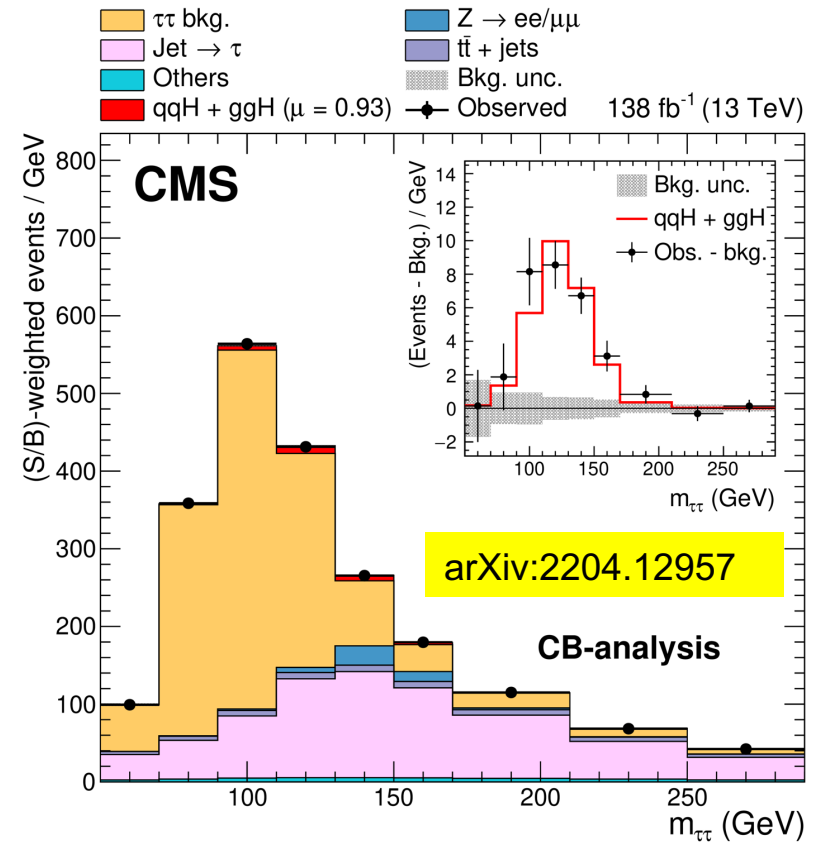
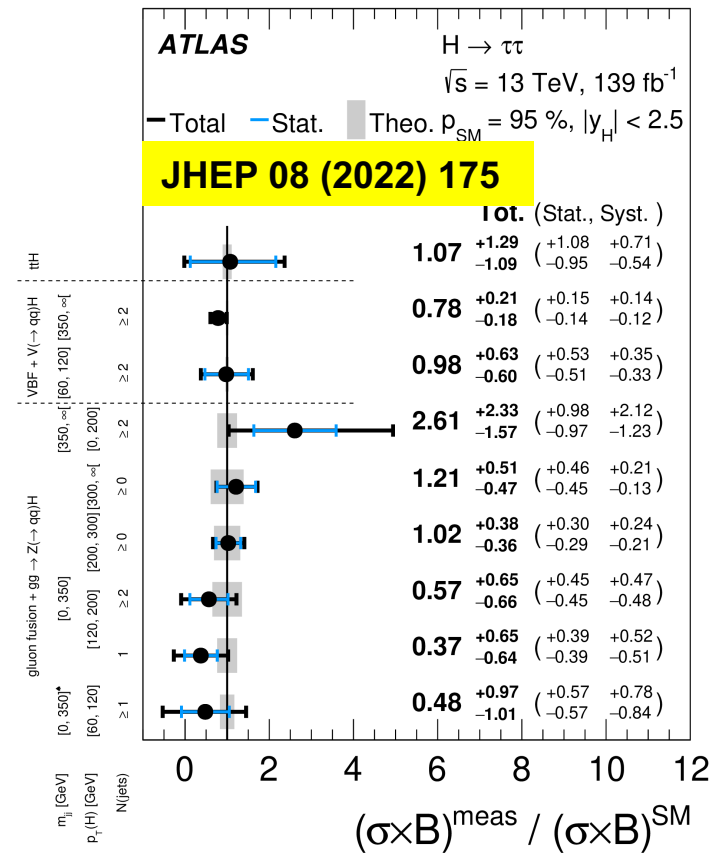
Higgs Coupling to bottom quark: $H \rightarrow bb$

- Higgs largest decay mode
- Reconstruct higgs system using 2 b-tagged jets
- Search with 4 productions modes
 - $VH, H \rightarrow bb$; Most sensitive
 - $ttH+tH, H \rightarrow bb$; Smallest XS, fair S/B
 - VBF H, $H \rightarrow bb$; Smaller XS, large bkg.
 - ggF H, $H \rightarrow bb$: largest XS, challenge bkg; use boosted $H \rightarrow bb$
- Both resolved and boosted signature, differential XS



Higgs Coupling to τ lepton: $H \rightarrow \tau\tau$

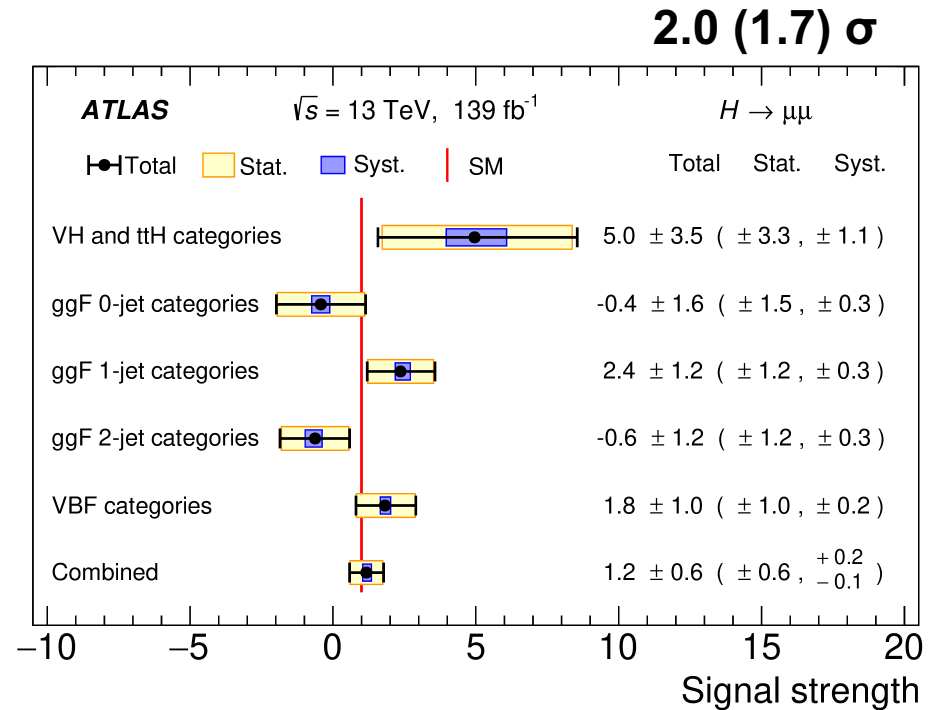
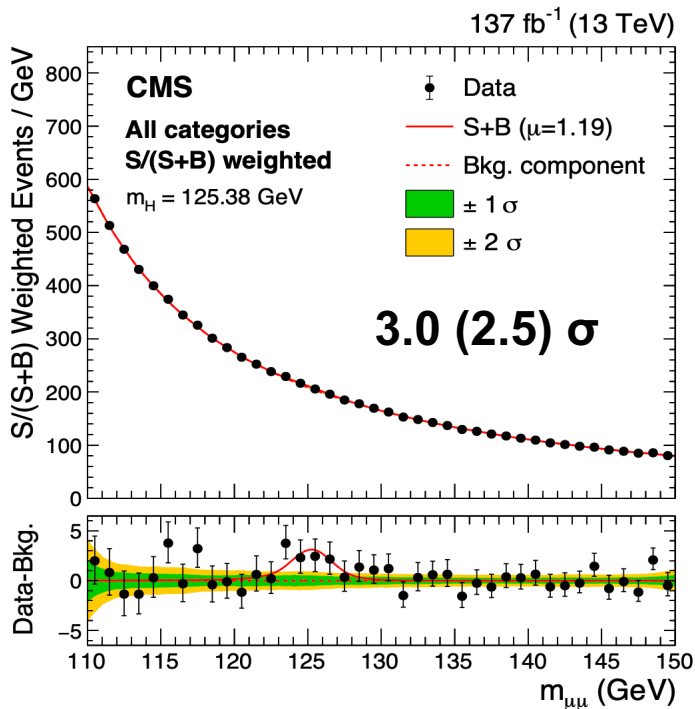
- Strong (relatively to other leptons) coupling to Higgs
- Large background dominated by $Z \rightarrow \tau\tau$
- Search $H \rightarrow \tau\tau$ in the production mode of $ggH, VBF, VH(ttH)$
- First observation by combine run1 ATLAS and CMS: precision meas. now



Hig ATLAS $\sigma_{\text{incl}} \mathcal{B}(H \rightarrow \tau\tau) = 2.94 \pm 0.21(\text{stat})_{-0.32}^{+0.37}(\text{syst}) \text{ pb}$

Higgs Coupling to μ lepton: $H \rightarrow \mu\mu$

- Next question: Higgs coupling to 2nd generation?
- Very small decay BR (0.02%)
- Overwhelming by DY background (cat. And BDT used)
- Excellent mass resolution
- Evidence observed, statistically unc. dominated

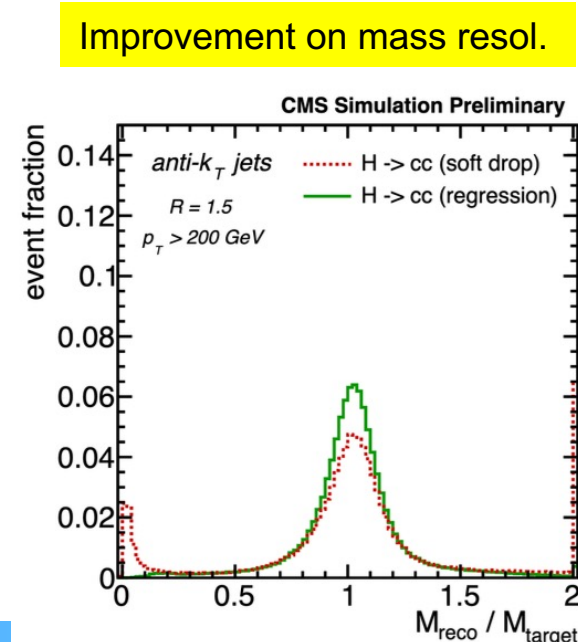
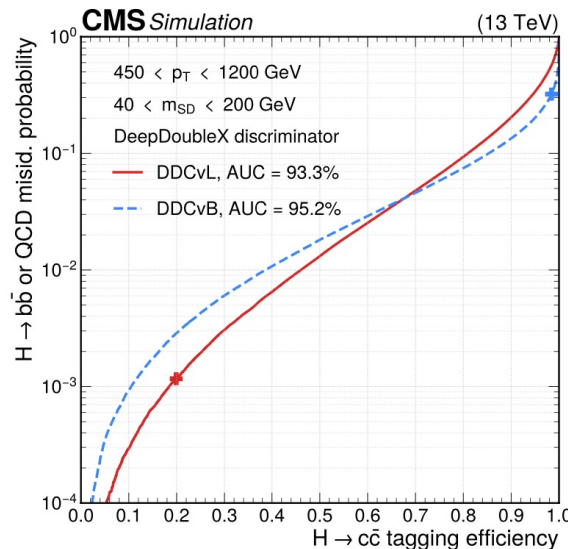
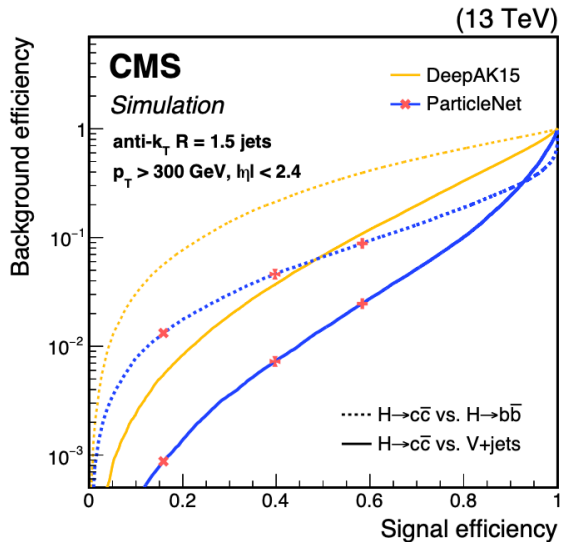


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PLB 812 (2021) 135980

Higgs Coupling to charm quark (1)

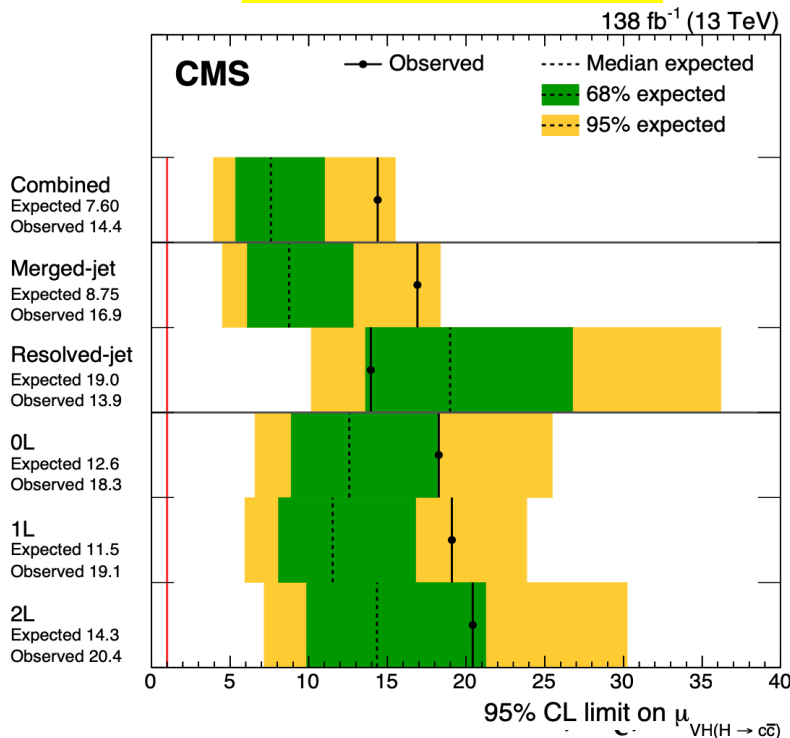
- Hunting for higgs coupling to charm quark:
 - $H \rightarrow cc$, both resolved and boosted EPJC 82(2022)717, arXiv:2211.14181; 2205.05550
 - Indirect constrain by studying Higgs Pt arXiv:2207.08615, CMS-PAS-HIG-21-009
 - $H \rightarrow J/\psi \gamma$, $H \rightarrow \psi(nS) \gamma$ arXiv:2208.03122
- More challenging to tag c-quark (than b-quark)
 - Median quark mass; median lifetime...
 - Advance technique like particleNet, Deep Learning used



Higgs Coupling to charm quark (2)

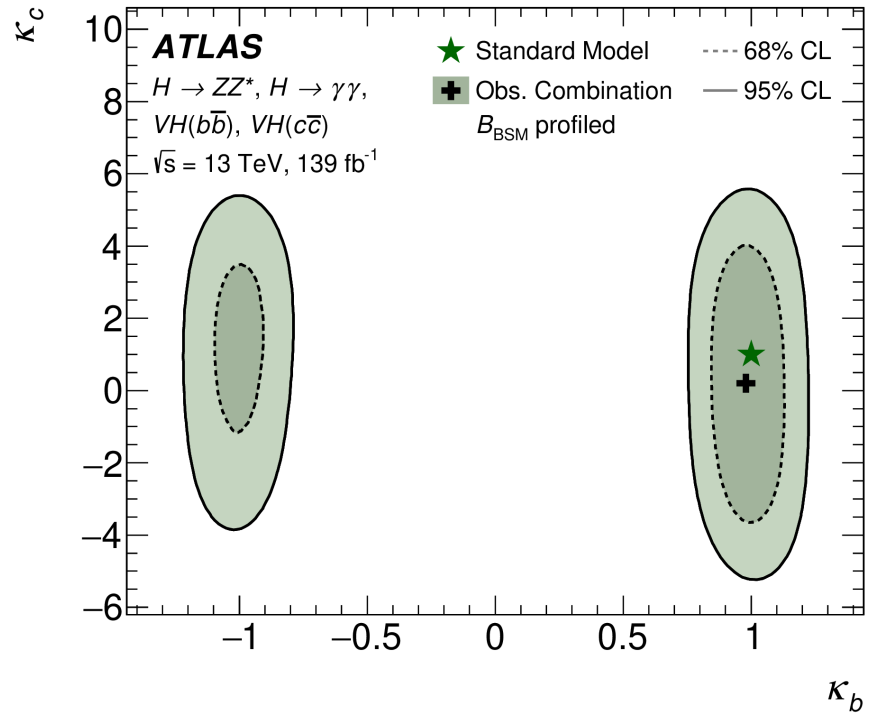
- No evidence yet
 - VH, H→cc direct search obs(exp.) limit < 14.4(7.6)*SM @ 95CL
- Higgs boson pT provide indirect constraint on charm Yukawa coupling that is comparable to direct VH, H→cc search

arXiv:2205.05550



$$1.1 < |\kappa_c| < 5.5 \quad (|\kappa_c| < 3.4)$$

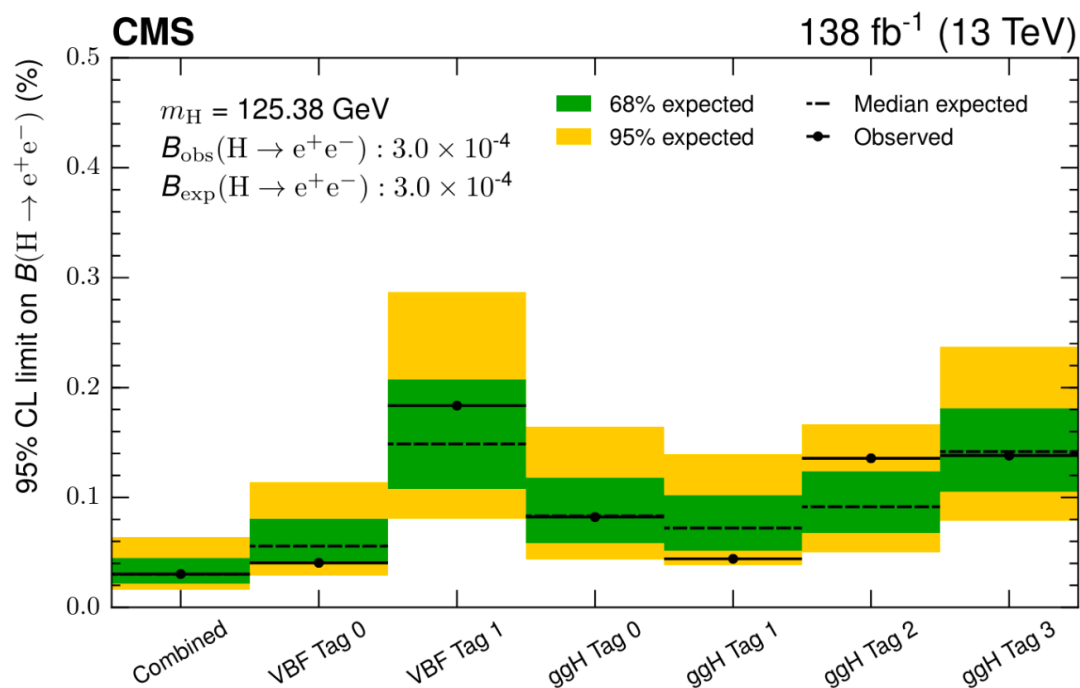
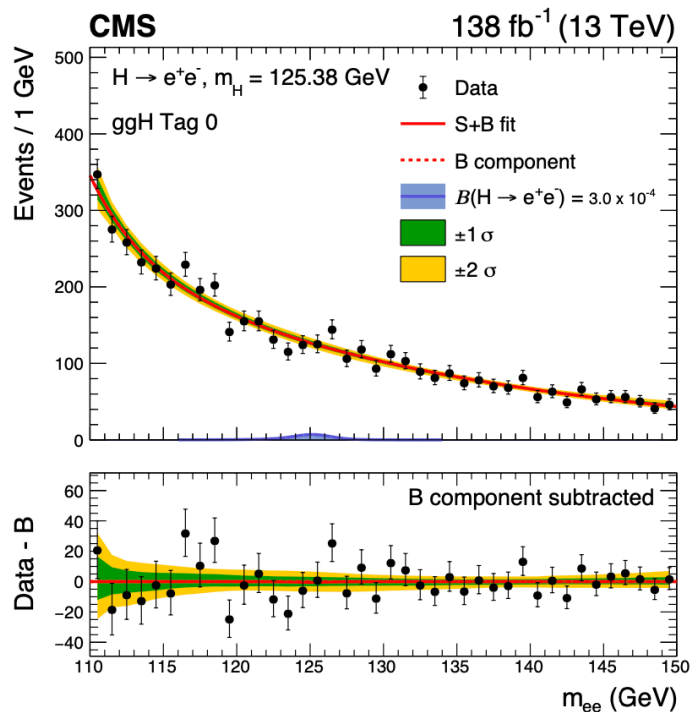
arXiv:2207.08615



$$-4.46 < \kappa_c < 4.81$$

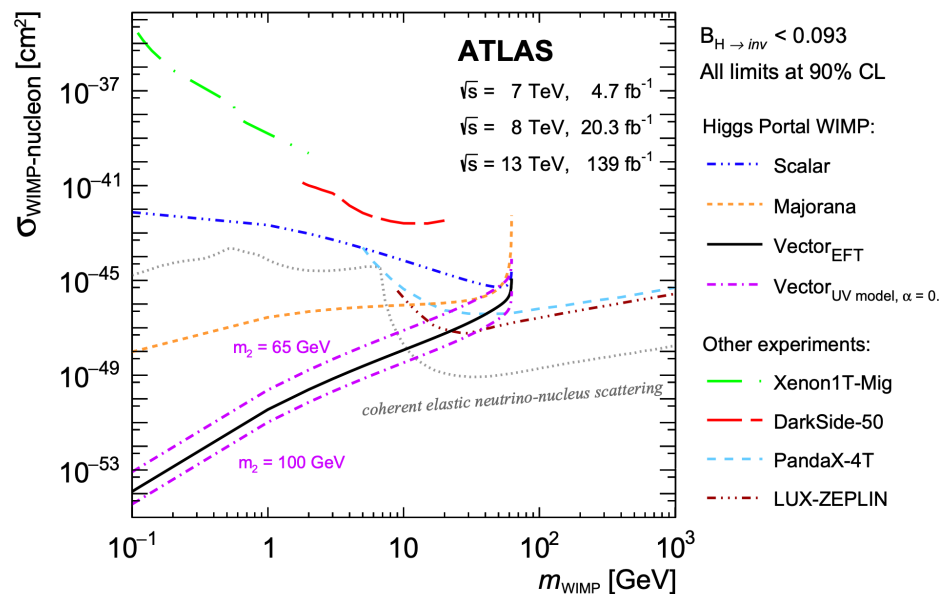
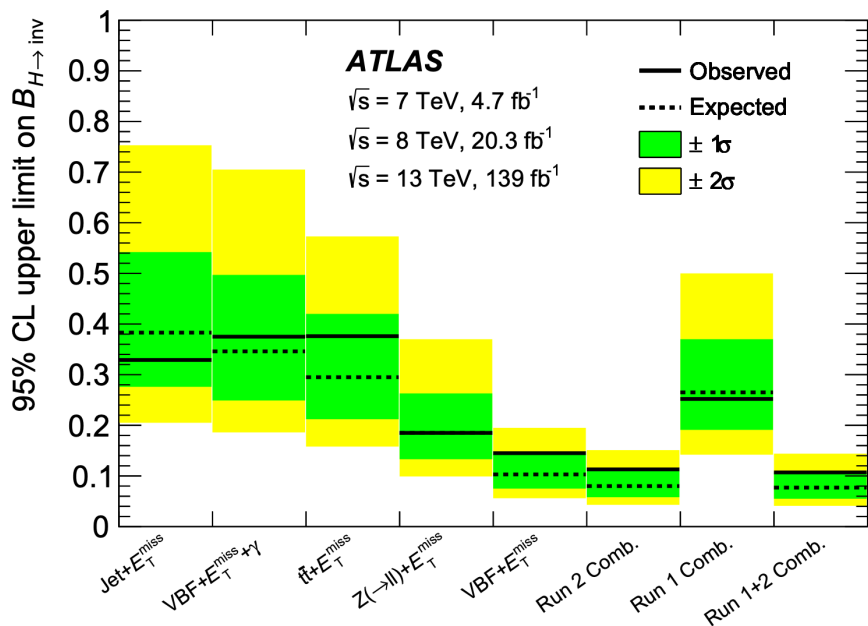
Higgs Coupling to e lepton: $H \rightarrow ee$

- Higgs couples to 1st generation? Tried $H \rightarrow ee$
- Smallest BR? ($5 \cdot 10^{-9}$)
- Fit to $m(ee)$ distribution in different event categories:
 - 4 targeting gluon fusion, 2 targeting VBF production
- Best Obs.(exp.) BR limit assume SM: $3.0 \cdot 10^{-4}$ ($3.0 \cdot 10^{-4}$) @95%



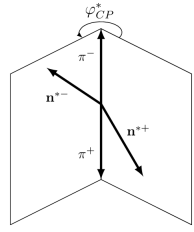
Search for $H \rightarrow \text{inv.}$

- SM pred. $H \rightarrow \text{inv.}$ Br: $< 0.1\%$
- Enhanced from BSM, ex: DM
- Searching using ggF, VBF, ttH, VH, VBF+gamma channels
- Set combined obs.(exp.) upper limit of $\text{Br} < 0.107$ (0.077) @ 95%

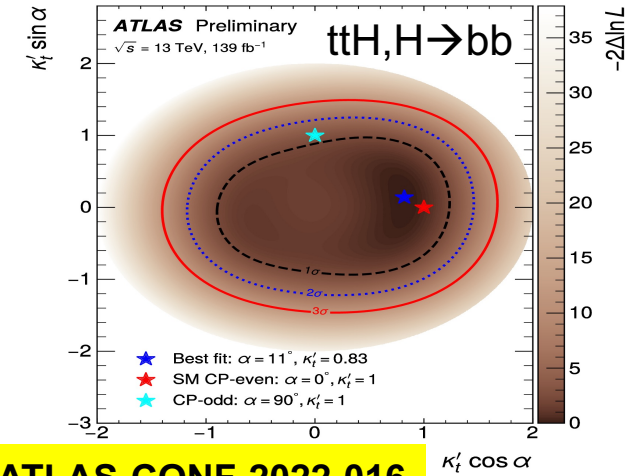


arXiv:2301.10731

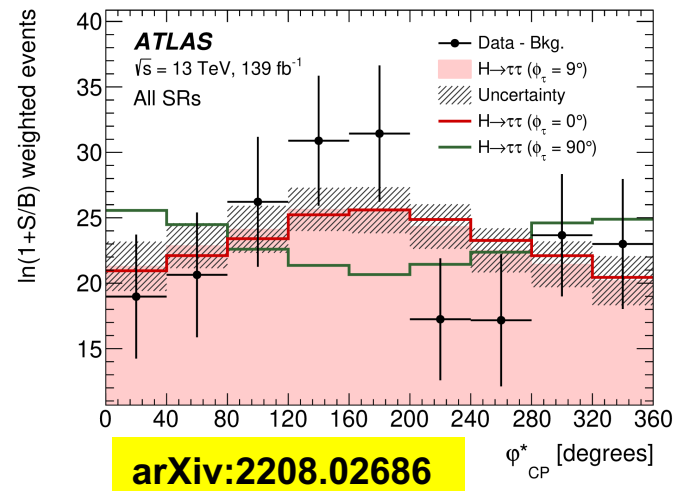
CP property of higgs-fermion coupling



- Yukawa coupling involving CP: $\mathcal{L}_f = -\frac{m}{v}\kappa_f(\cos(\alpha)\bar{f}f + i\sin(\alpha)\bar{f}\gamma_5 f)H$
- Direct measure of CP in top-higgs and tau-higgs at LHC
 - Compatible to SM prediction

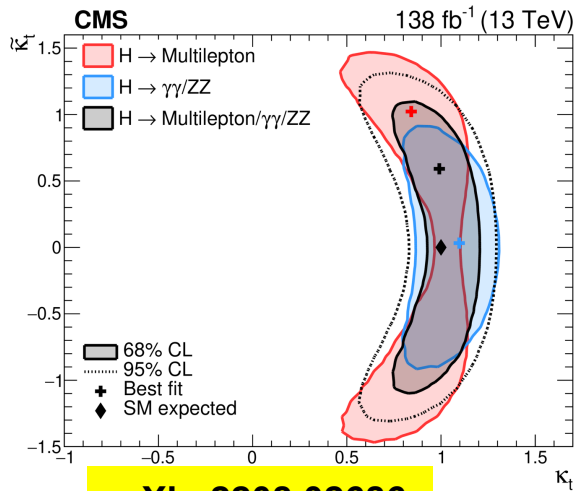


ATLAS-CONF-2022-016

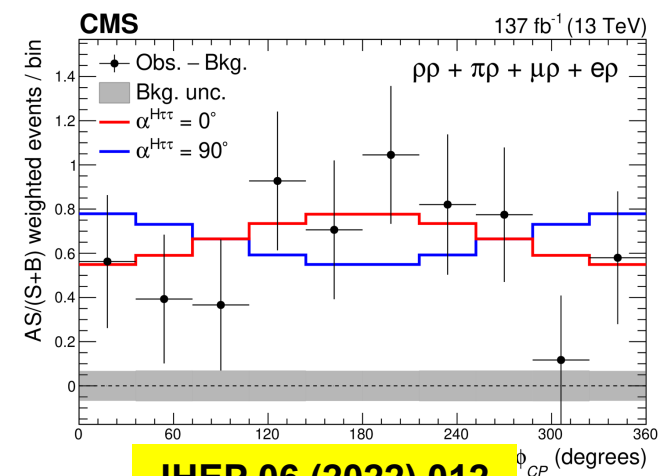


arXiv:2208.02686

Data agrees with SM higgs CP in both H-top and H-tau coupling



arXiv:2208.02686

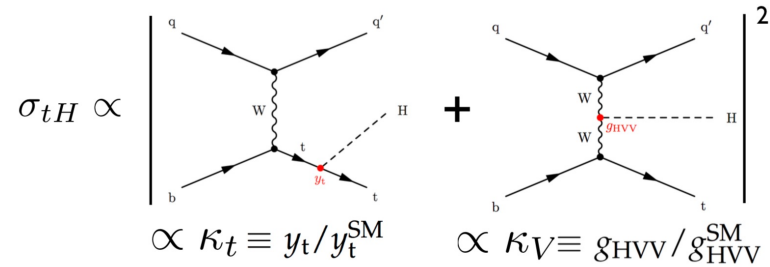


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H. Zhang@HongKong

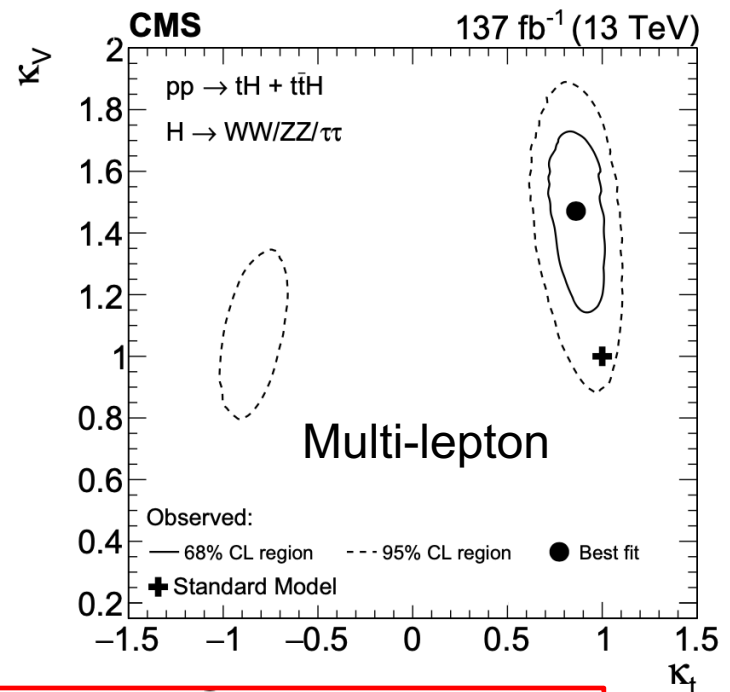
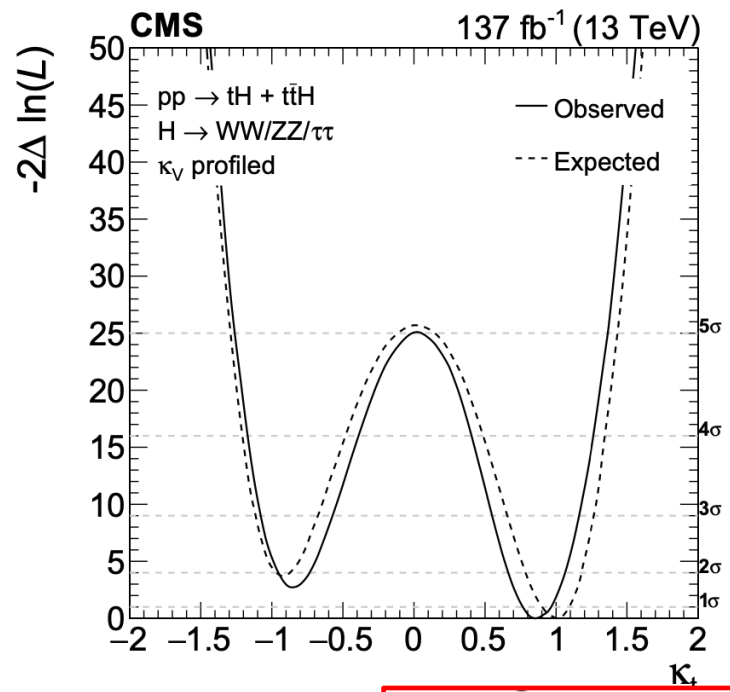
H-t and H-W coupling interference phase: tHq

- tHq: Sensitive to Y_t/g_{HVV} int.
- Search tHq in $H \rightarrow \text{multi-lepton}/bb/\gamma\gamma$
 - Combine with ttH studies



Destructive interference in SM

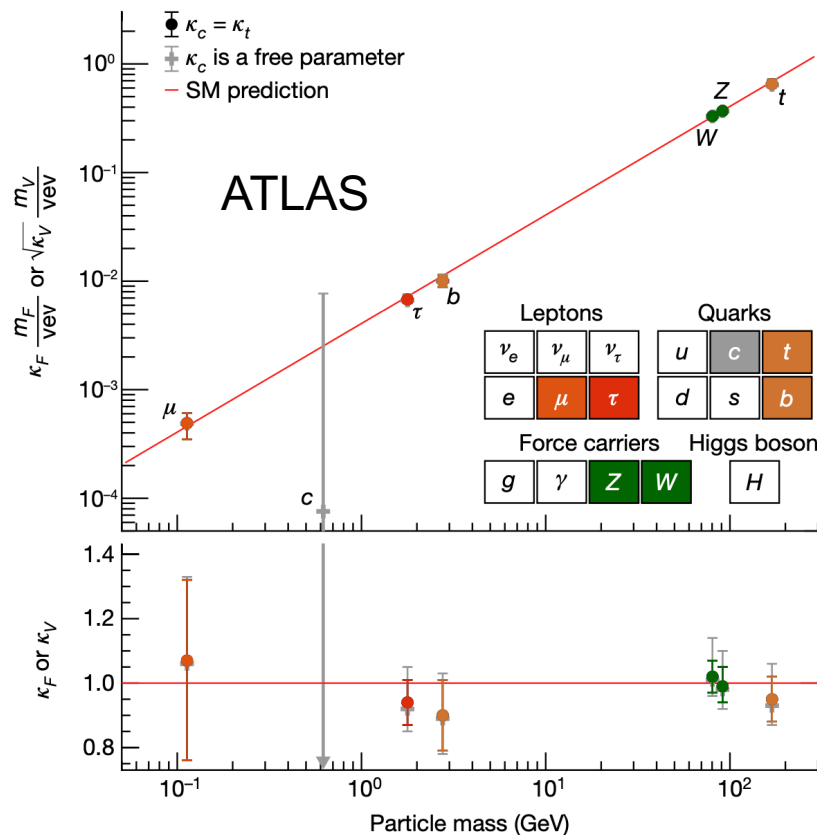
arXiv:2208.02686



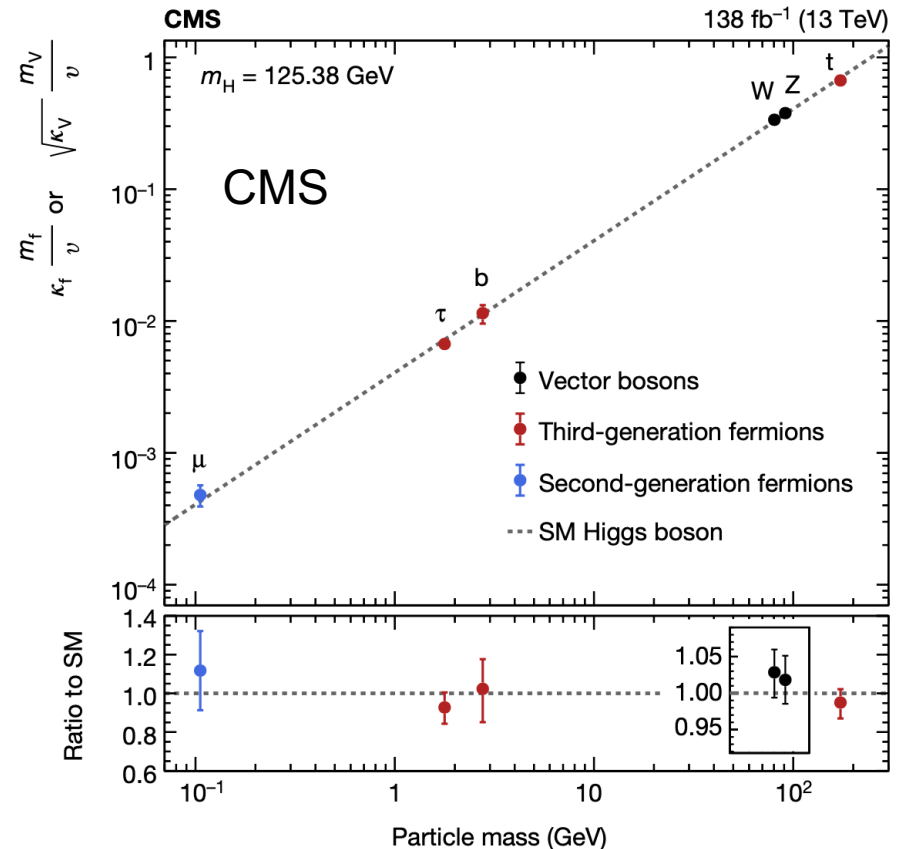
95%CL allow: $-0.9 < \kappa_t < -0.7$ and $0.7 < \kappa_t < 1.1$

Combined measurement of Higgs-Fermion coupling

- In memory of 10 years after Higgs discovery
- Combine all production and decay channels analyzed at LHC
- Higgs-Fermion coupling is part of this combination



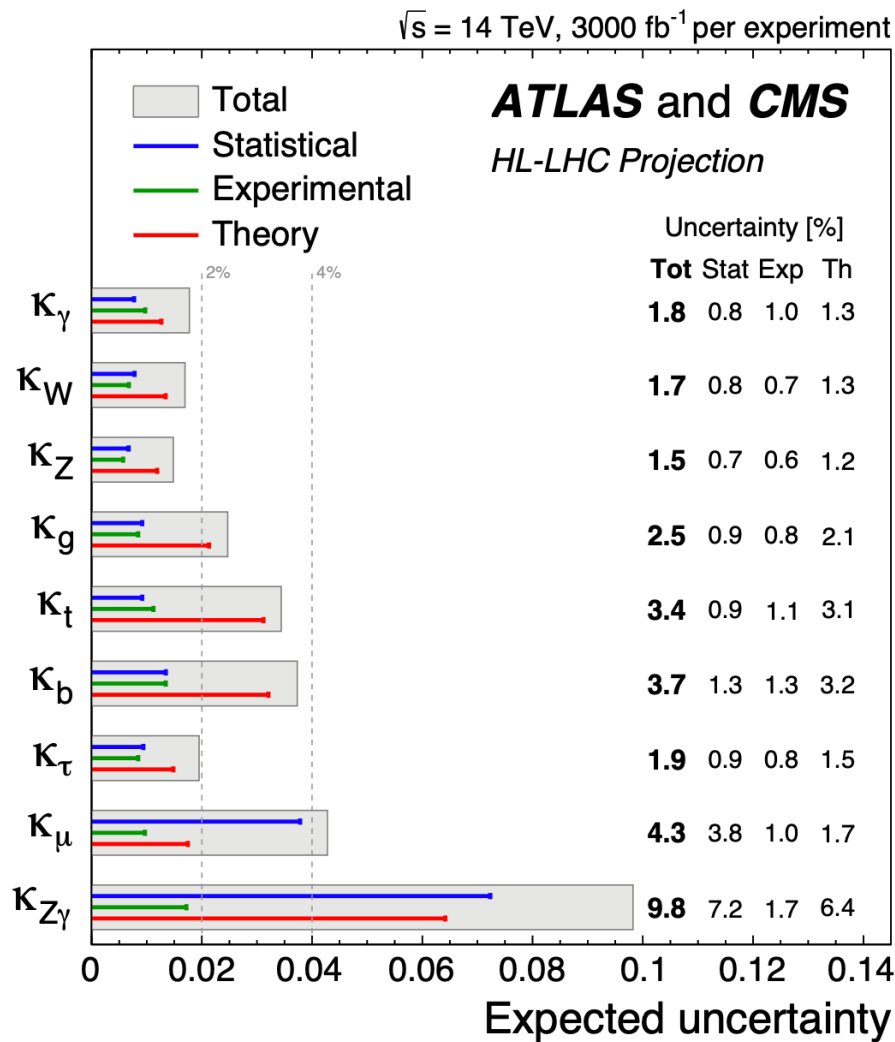
Nature 607 (2022) 52–59



Nature 607 (2022) 60–68

Higgs-Fermions coupling at HL-LHC

- ~10 time more luminosity
- Acc. Could reach <5%
 - Top-Higgs coupling
 - Bottom-Higgs coupling
 - Tau-Higgs coupling
 - μ -Higgs coupling
- Better constrains
 - Charm-Higgs coupling
 - Electron-Higgs coupling
- Better understanding of
 - Higgs-Fermion coupling CP
 - Higgs-top, Higgs-V interference phase



arXiv: 1902.00134

Summary

- Chasing Higgs Coupling to Fermions at LHC
 - Observed 3'd generation couplings:
 - Precision study including CP properties on going
 - Chasing 2'd generation coupling now (except H-s)
 - Huge challenge for testing 1st generation coupling at LHC
 - Set stringent limit of Higgs coupling to fermion DM
- The Higgs is more and more SM like
 - Still room for new physics
 - Future e+e- collider helps (ex. Abs Br. Meas.)
- Can all SM Higgs-Fermion coupling be measured?
 - New experiments? New methods?
 - Or can we leave them with extrapolation from “theory”?
- Latest results at:
 - ATLAS: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults>
 - CMS: <https://cms-results-search.web.cern.ch/>

