# Properties of the Higgs boson at the LHC (ATLAS+CMS)

Interplay between Particle and Astroparticle physics 2022
5th-9th September, 2022

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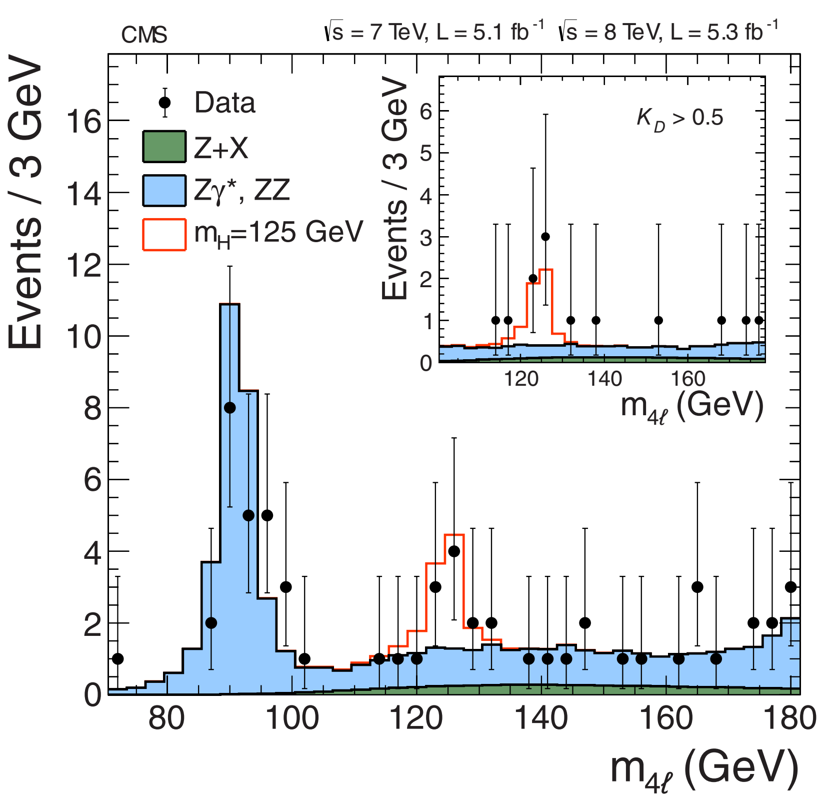
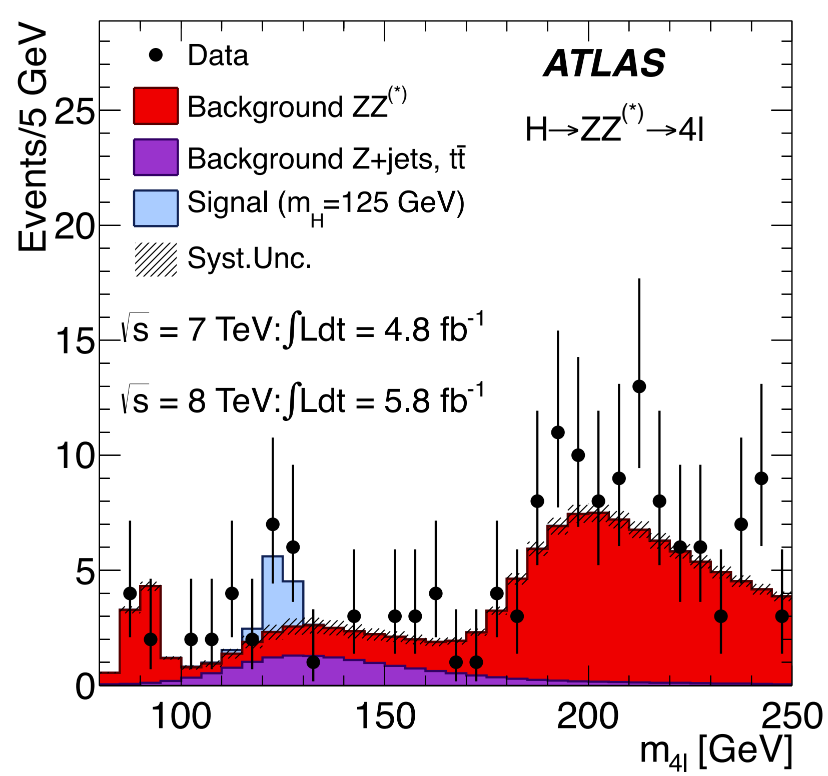
on behalf of CMS and ATLAS collaborations

Phys. Lett. B 716 (2012) 30
Phys. Lett. B 716 (2012) 1

# Introduction

- Higgs 10th year anniversary!!
- Extensive studies of its properties in the last 10 years.
- Standard model Lagrangian parameters:
  - ➡ 19 parameters in total ($g_{1,2,3}$, $\theta_{CKM}$ etc.).
  - ➡ 11 from the Higgs sector.
  - ➡ Those should be determined by experiments.



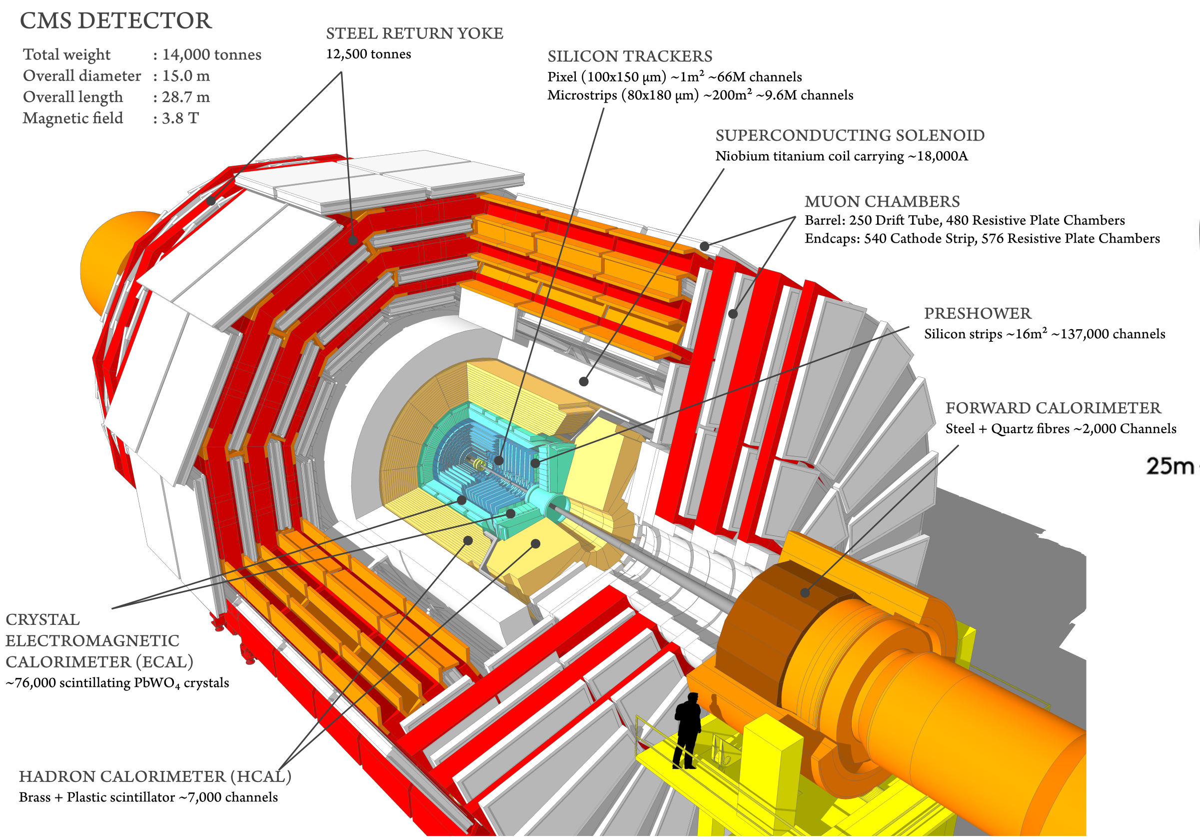



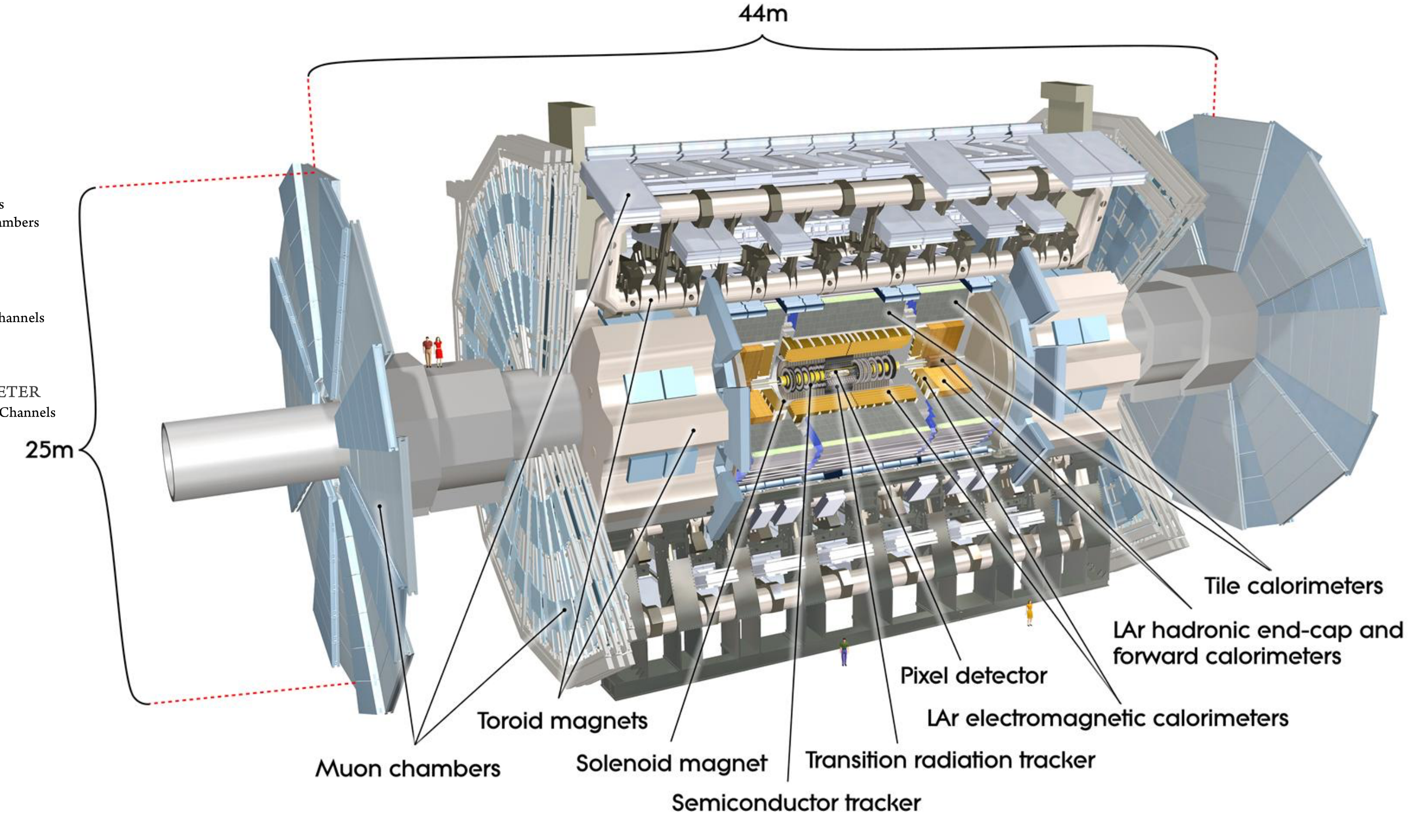

# LHC: Large Hadron Collider

- World's largest proton-proton collider built at CERN.
  - ➡ Only facility which can produce Higgs.
  - ➡ 150/fb per experiments of data recorded so far.
  - ➡ 150/fb × 2 (CMS and ATLAS) × $\sigma_H$ (50 pb) ~ 15M Higgs.
- RUN3 has been started with $\sqrt{s}$ = 13.6 TeV.

# Experiments

- CMS and ATLAS
  - ➡ General purpose collider detector.
  - ➡ Trackers, magnets, calorimeters and muon detectors.
    - ✓ Possible to detect and measure energy/momentum of particles which are produced by pp collisions.



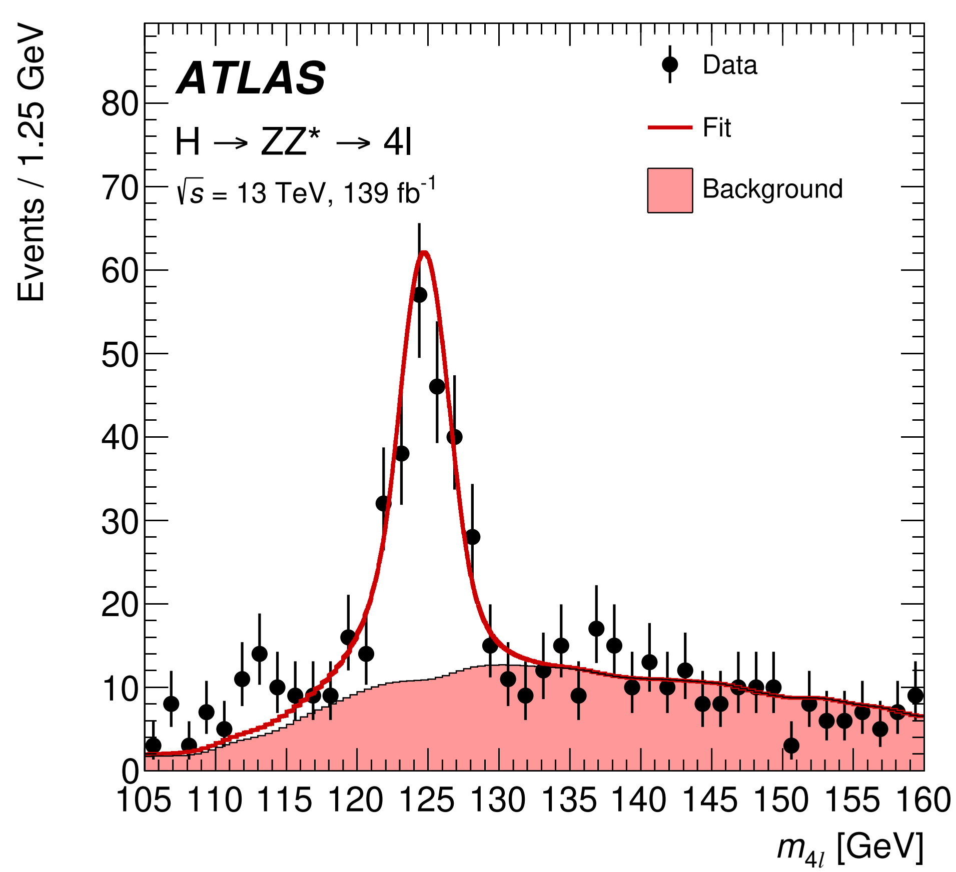

**Disclaimer: focusing only on the most recent results.**

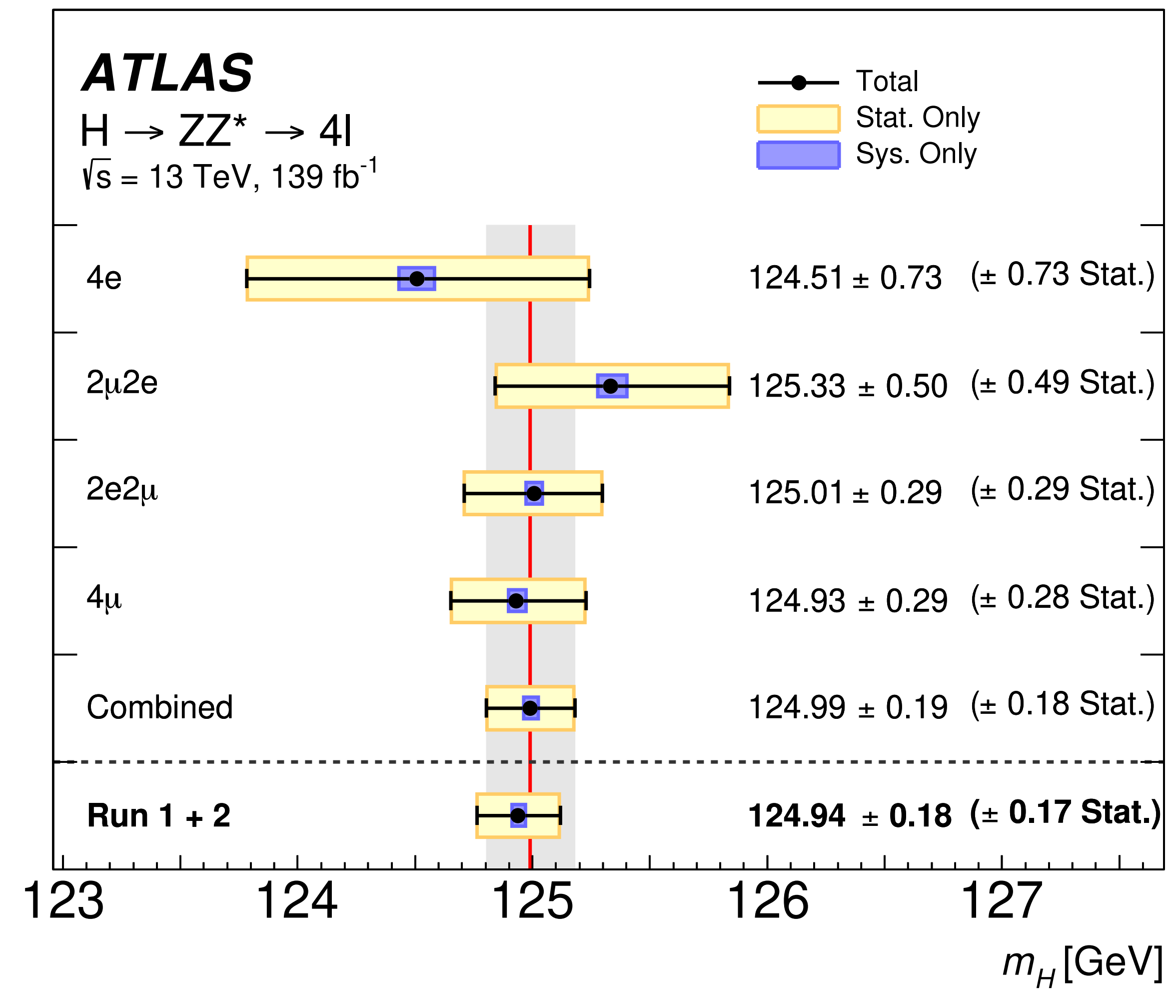
# Higgs Mass and Width

arXiv:2207.00320
Phys. Lett. B 805 (2020) 135425

# Mass

- H→ZZ*→4L
  - ➡ Cleanest channel to measure the Higgs mass.
  - ➡ Improved muon momentum calibration, new analytic model with event-by-event $m_{4l}$ resolution, and DNN for S/B discrimination.



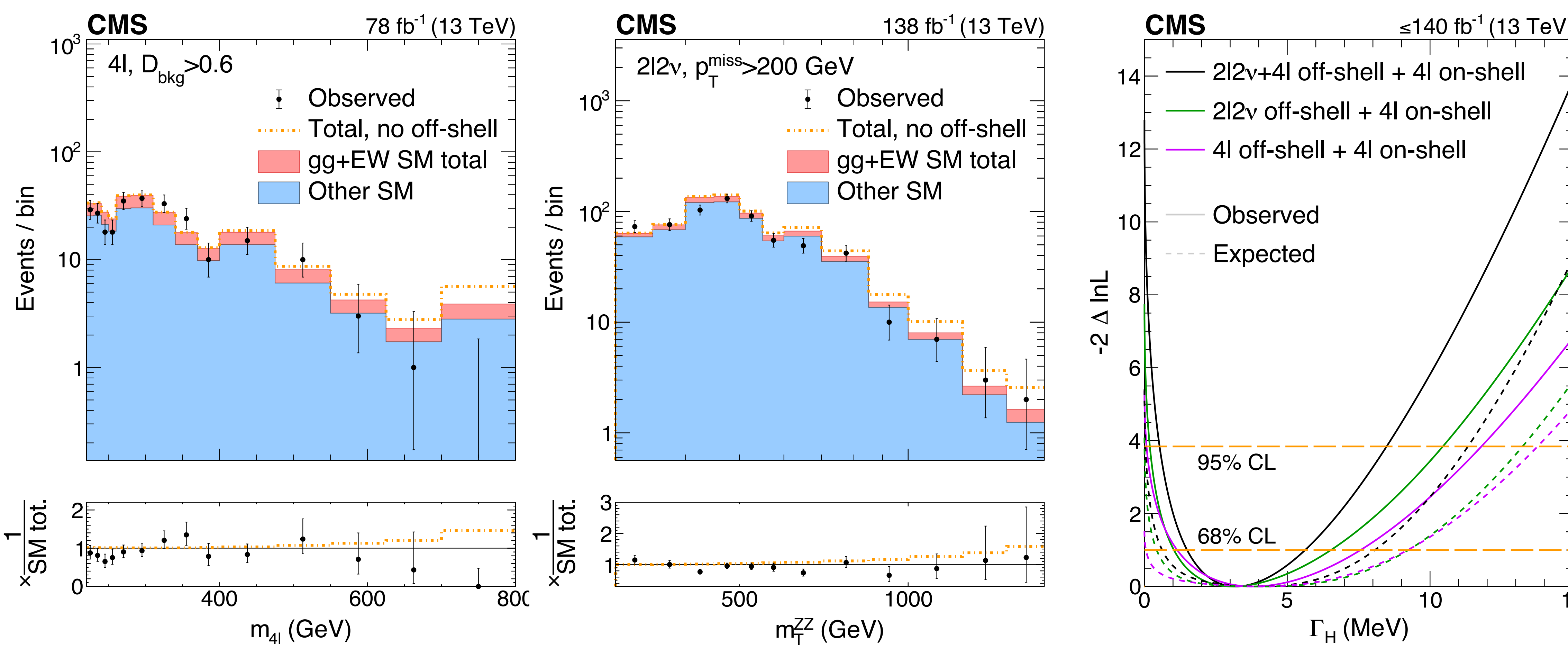




c.f. CMS latest (2020) results: 125.38 ± 0.14 GeV

arXiv:2202.06923

# Width

- The first evidence for off-shell Higgs production in $H \rightarrow ZZ^* \rightarrow 4l$ or llνν. Concentrate on the high-mass tail.
- On-shell and Off-shell ratio gives $\Gamma_H$ (SM: $\Gamma_H \sim 4.1$ MeV).
- Measured width $\Gamma_H = 3.2^{+2.4}_{-2.7}$ MeV

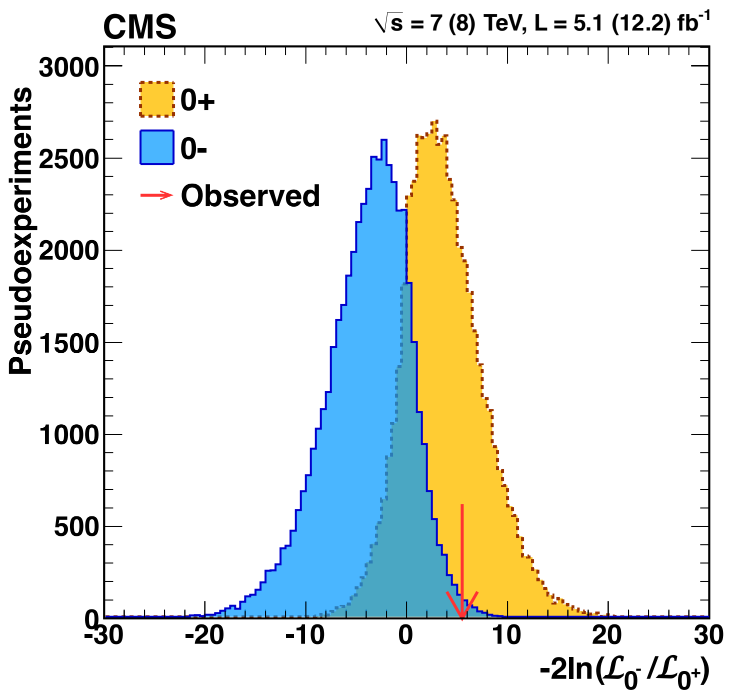


# Higgs CP structure

Phys. Rev. Lett. 110 (2013) 081803

# CP Property of Higgs

- Spin and parity of "the new boson" was immediately tested.
  - ➡ It was proven that the newly found boson has $J^P = 0^+$.
    - ✓ Done in H→γγ, H→ZZ(→4l), H→WW(→lνlν).
  - ➡ Declared the observed particle was "the Higgs boson".




- Opened a new direction to search for sources of CP violation.
  - ➡ CP-odd contributions in HVV couplings are suppressed with a $1/\Lambda^2$.
  - ➡ It is desired to test its CP nature in H→ff couplings.

**Today, focusing only on CP studies in Hff couplings**

ATLAS-CONF-2022-032
JHEP 06 (2022) 012

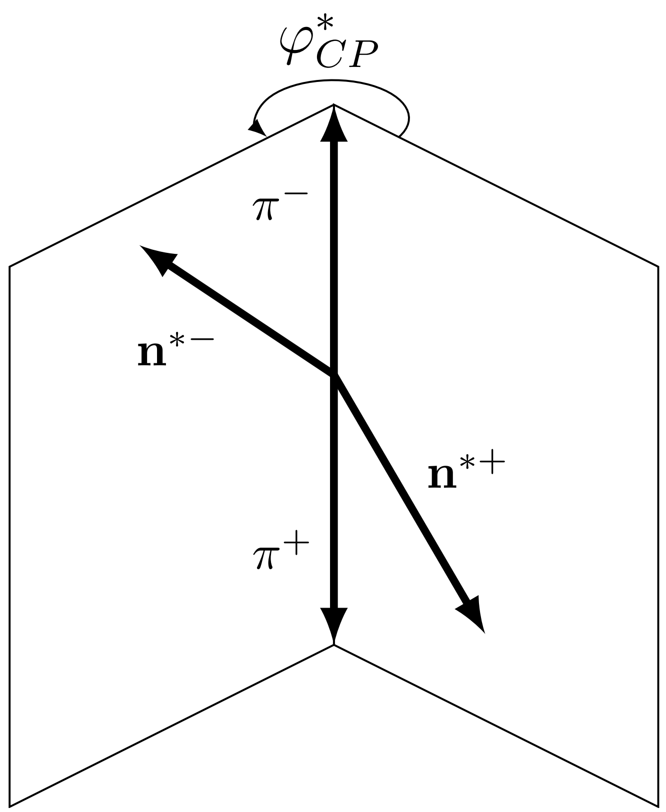
# Experimental results: Hττ

- CP structure in the Yukawa term of τ.

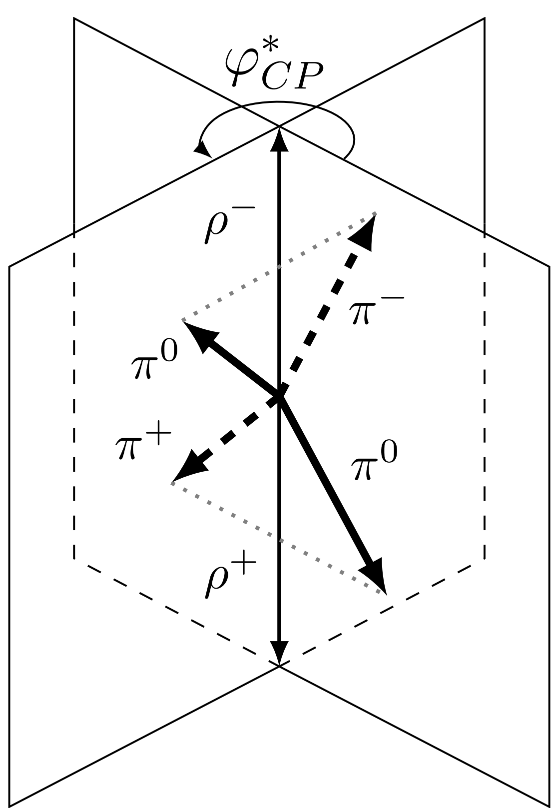
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

- Using the angular correlations btw the decay planes of $\tau$'s

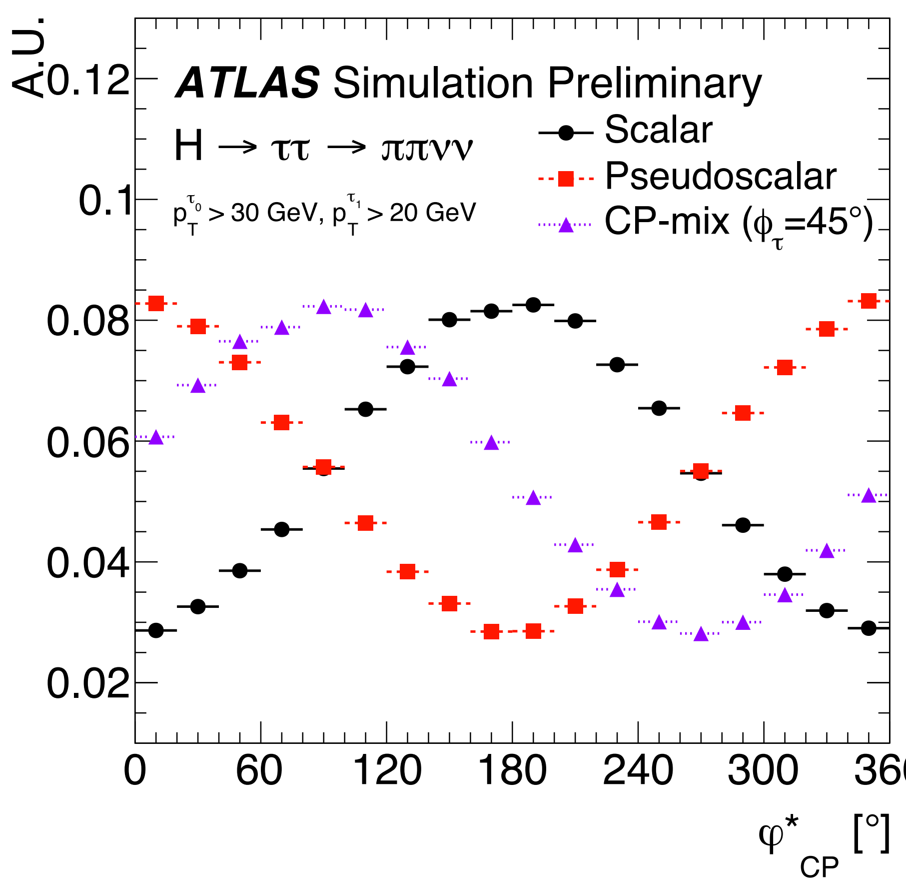
$$d\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau)$$




(a) $H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$




(b) $H \to \tau^+\tau^- \to \pi^+\pi^0\nu\pi^-\pi^0\nu$



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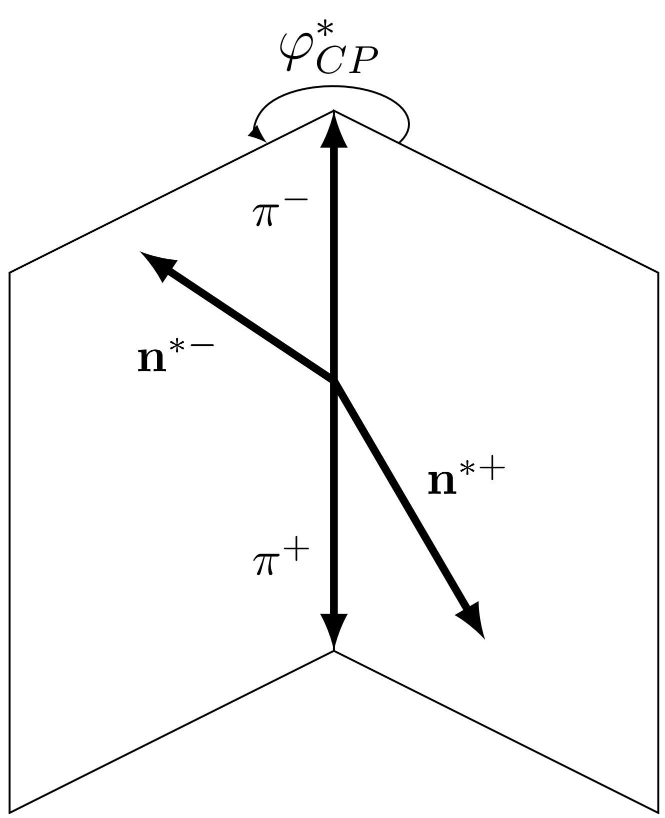


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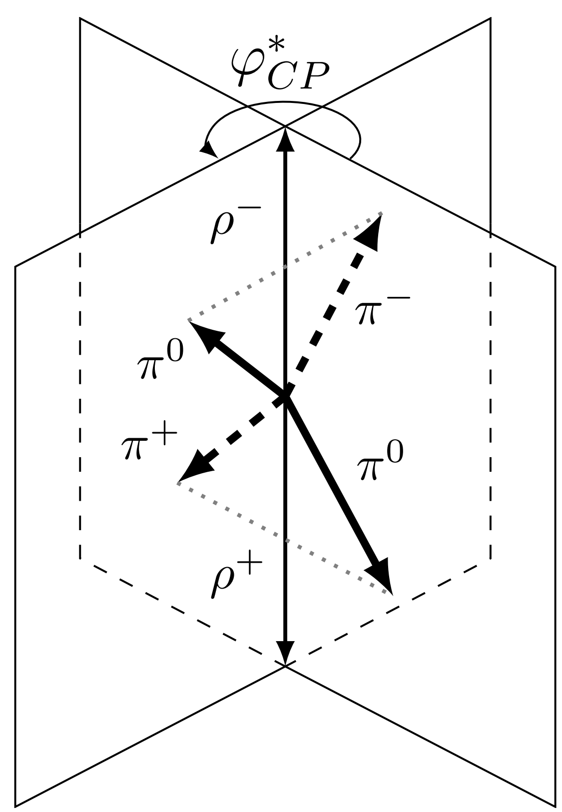


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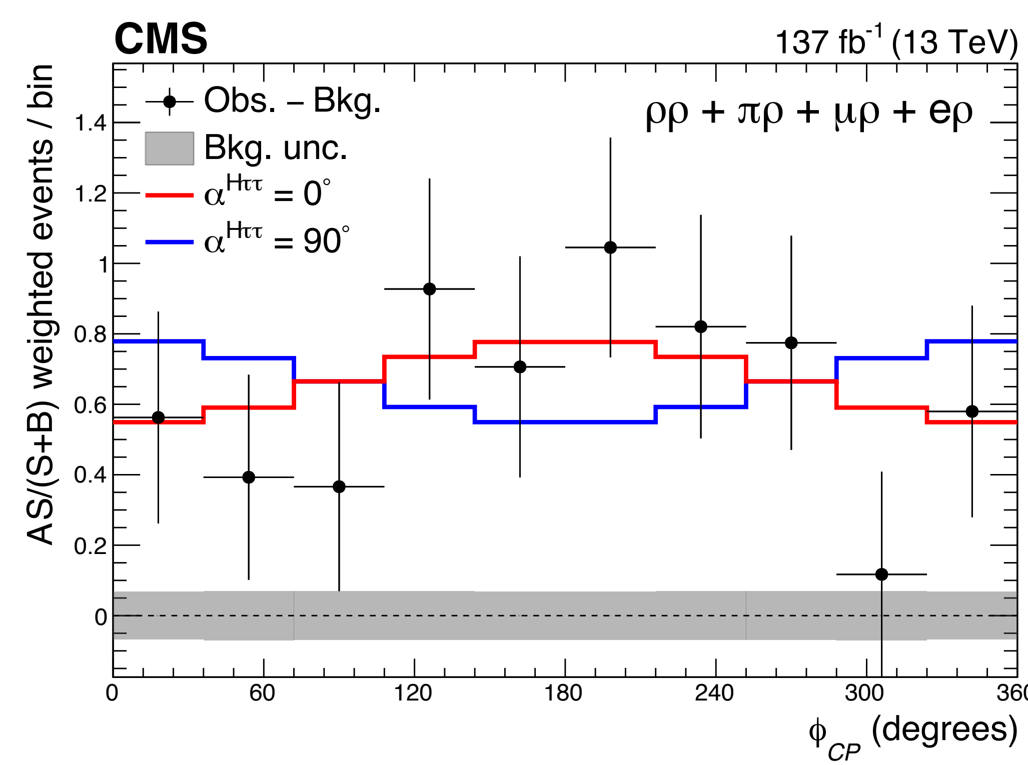

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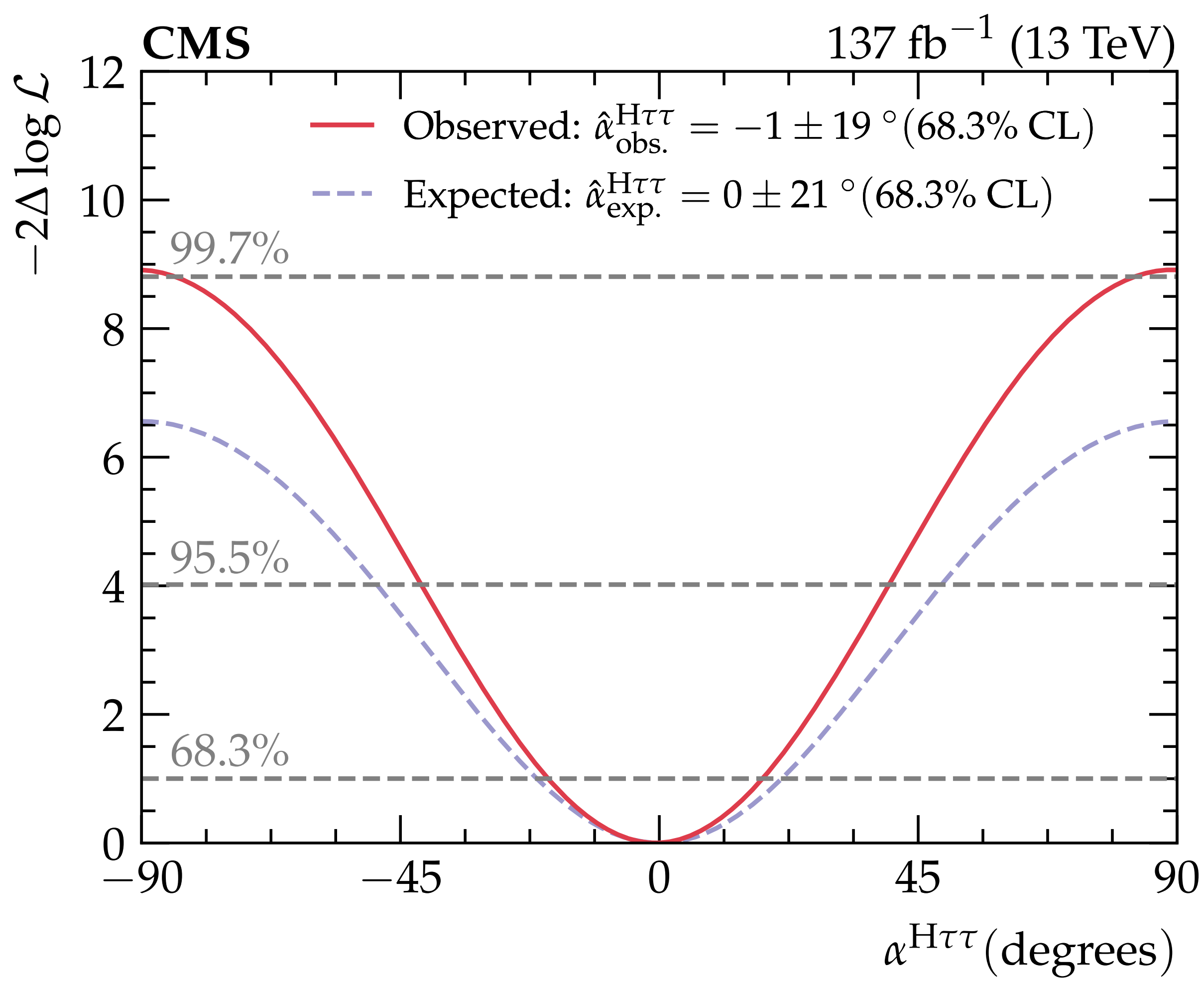
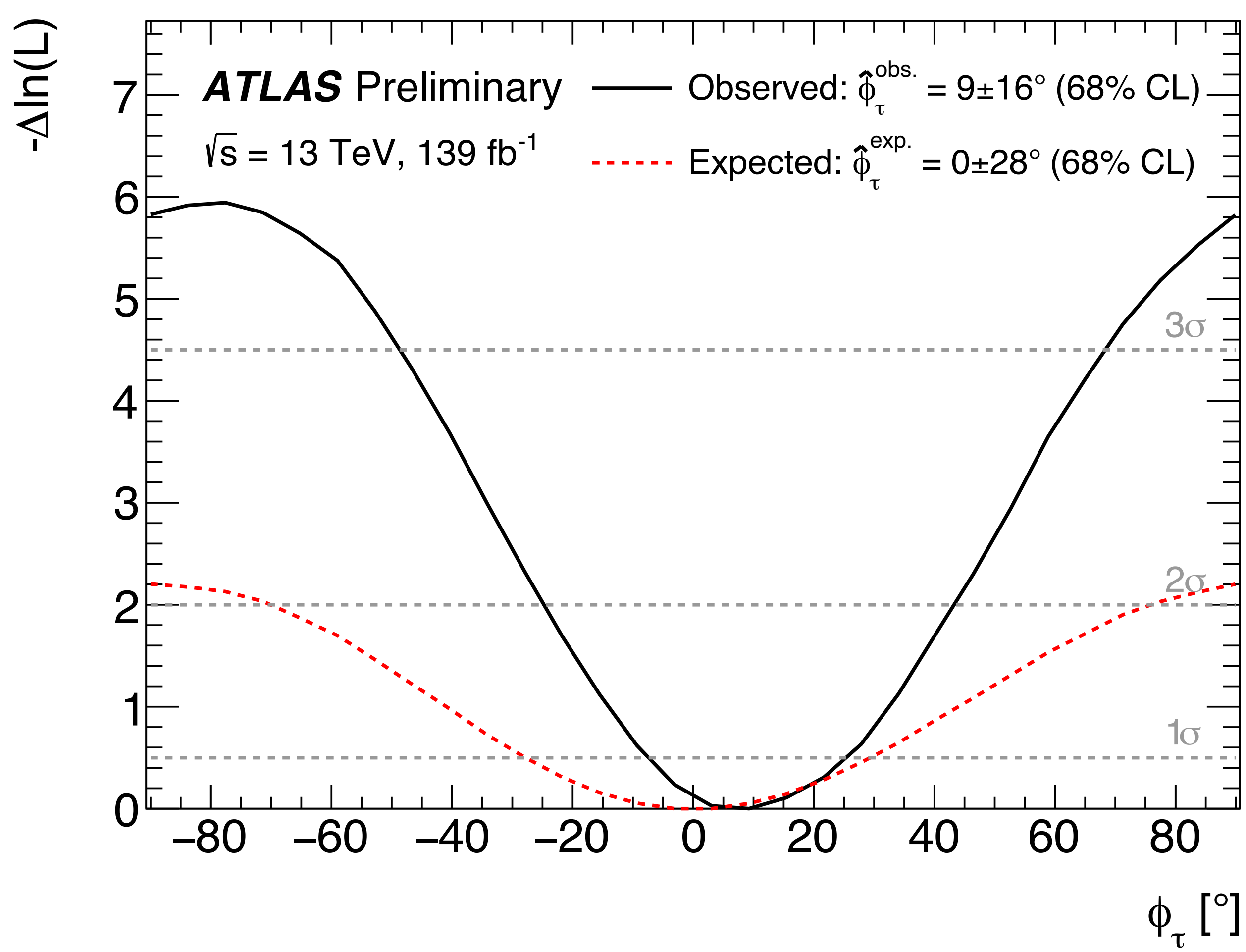
- Pure CP-odd is excluded but still admixture is possible.

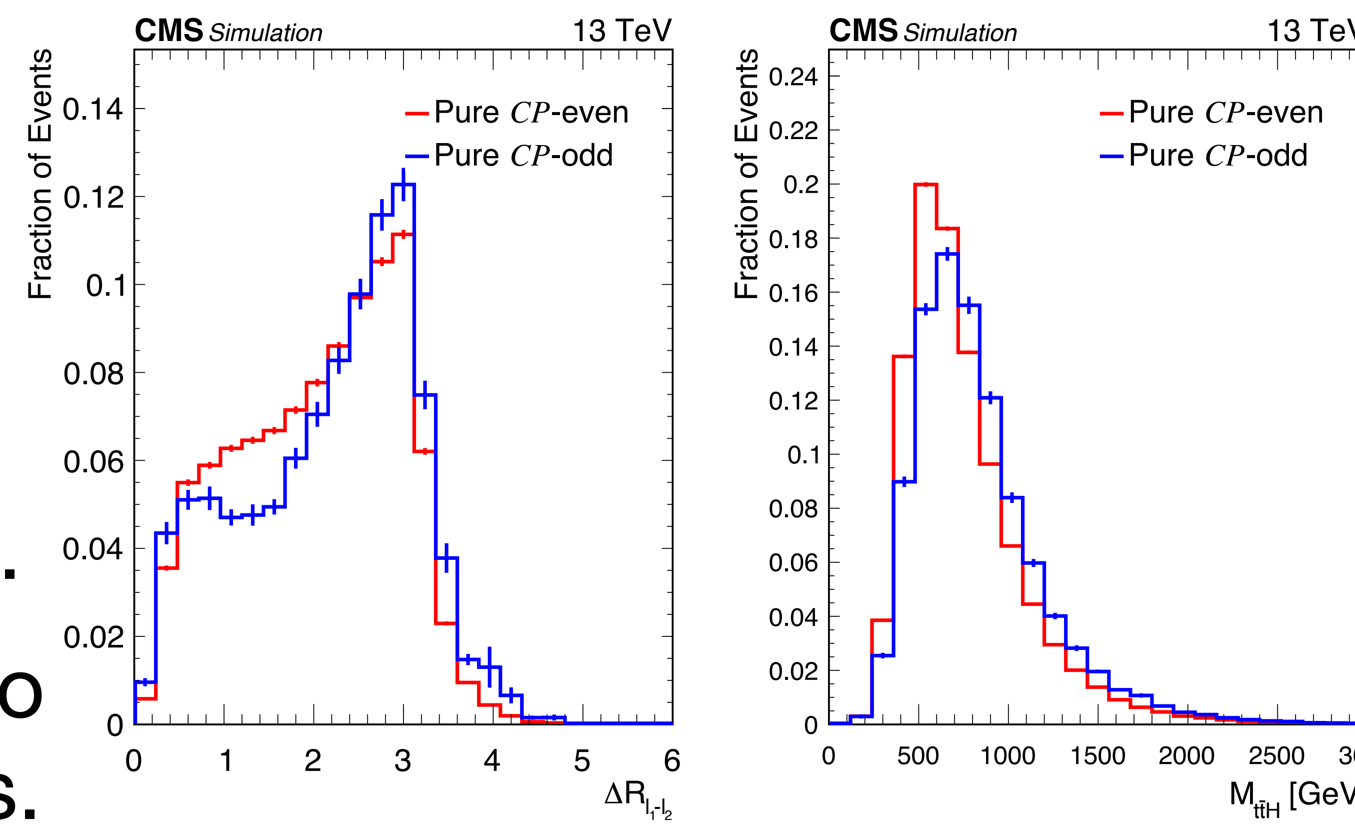


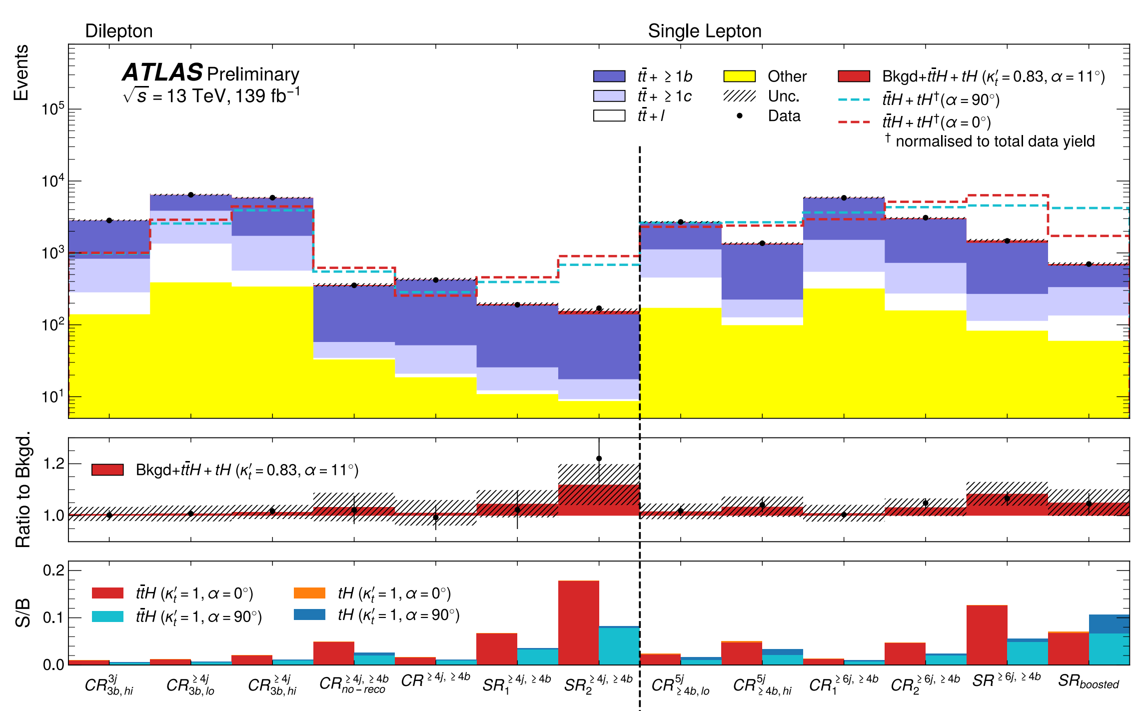



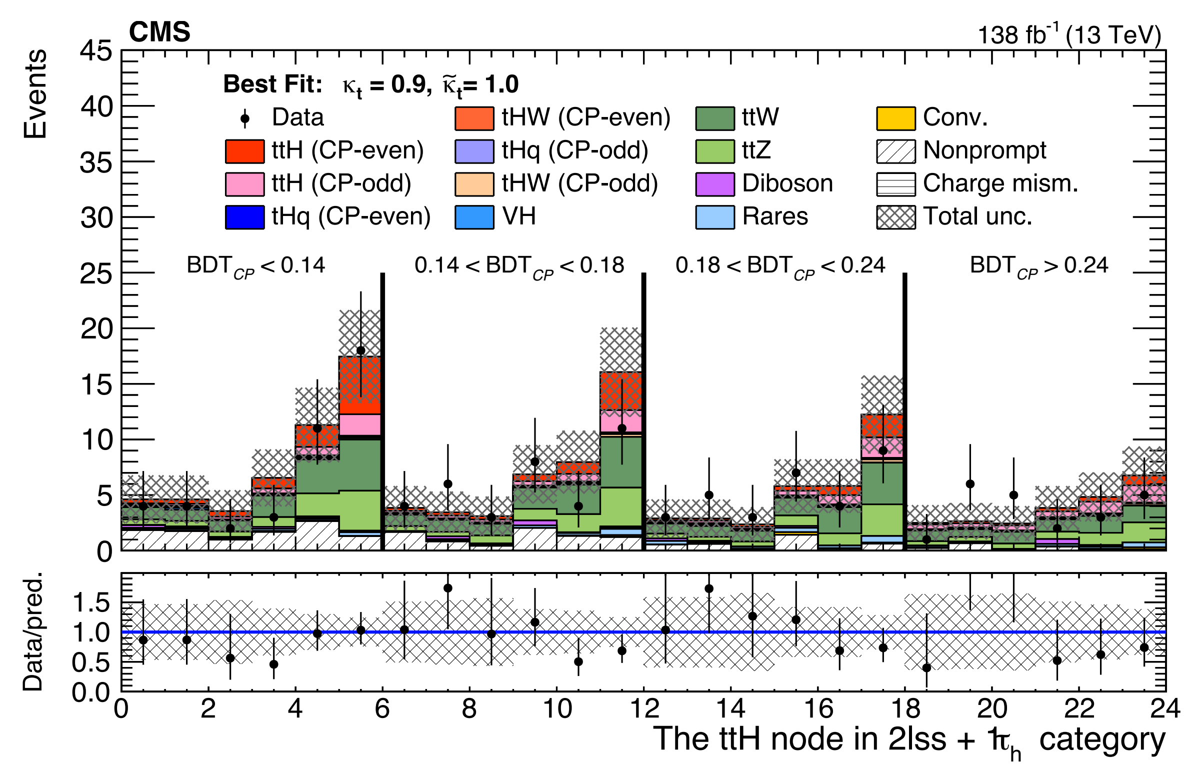
arXiv:2208.02686
ATLAS-CONF-2022-016

# Experimental results: ttH coupling

- CMS: ttH, tH→multi-lepton.
  - ➡ Same sign req. helps to suppress backgrounds.
- ATLAS: H→bb in ttH and tH.
  - ➡ Helped by large BR(H→bb).
- Machine Learning technique to separate CP-even/-odd states.



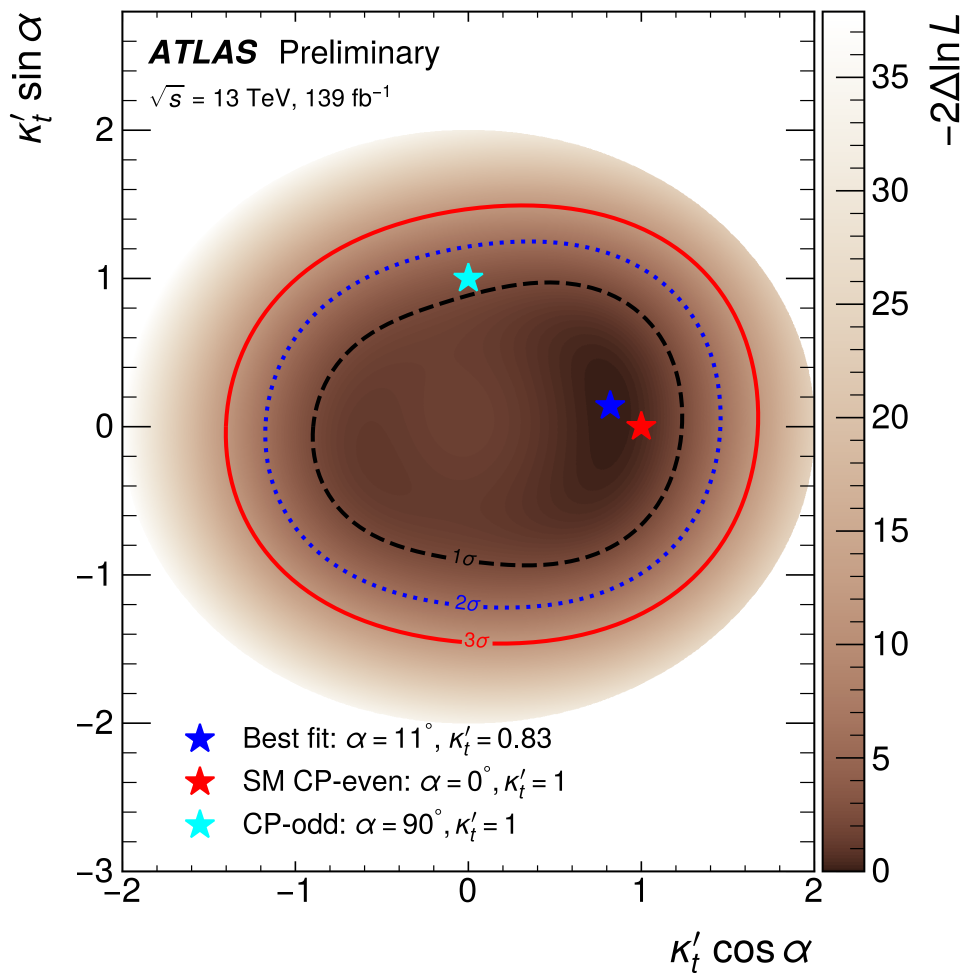
arXiv:2208.02686
ATLAS-CONF-2022-016

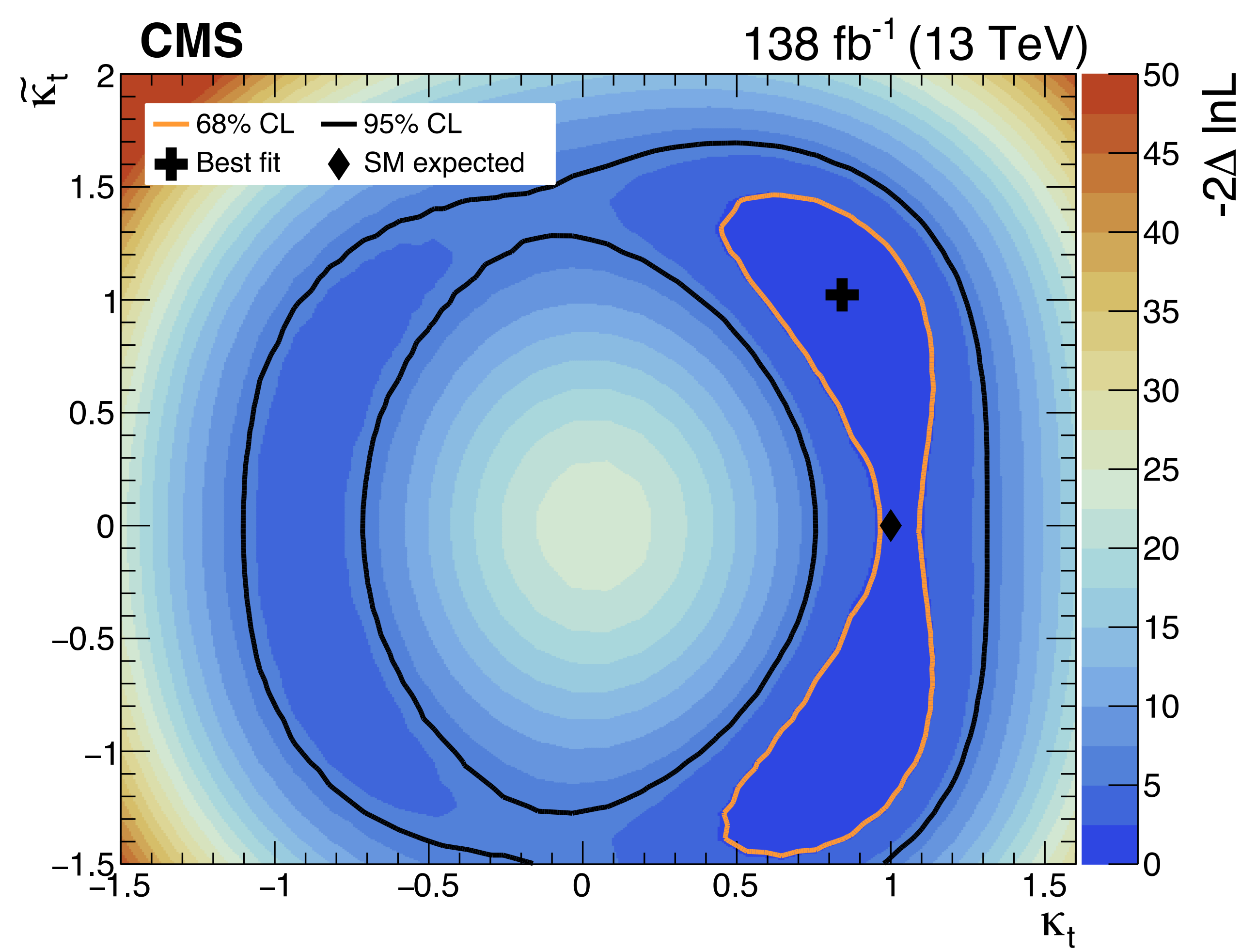
# Experimental results: ttH coupling

- Limit is set on the 2D κ plane.

$$\mathcal{L}_t = -\frac{m_t}{v}(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t)H \qquad \text{SM: } (\kappa_t, \tilde{\kappa}_t) = (1, 0) \qquad \begin{aligned} \kappa_t &= k_t \cos\alpha \\ \tilde{\kappa}_t &= k_t \sin\alpha \end{aligned}$$

- Both experiments show results consistent to the SM expectation.
  ➡ Pure CP-even was excluded by CMS.



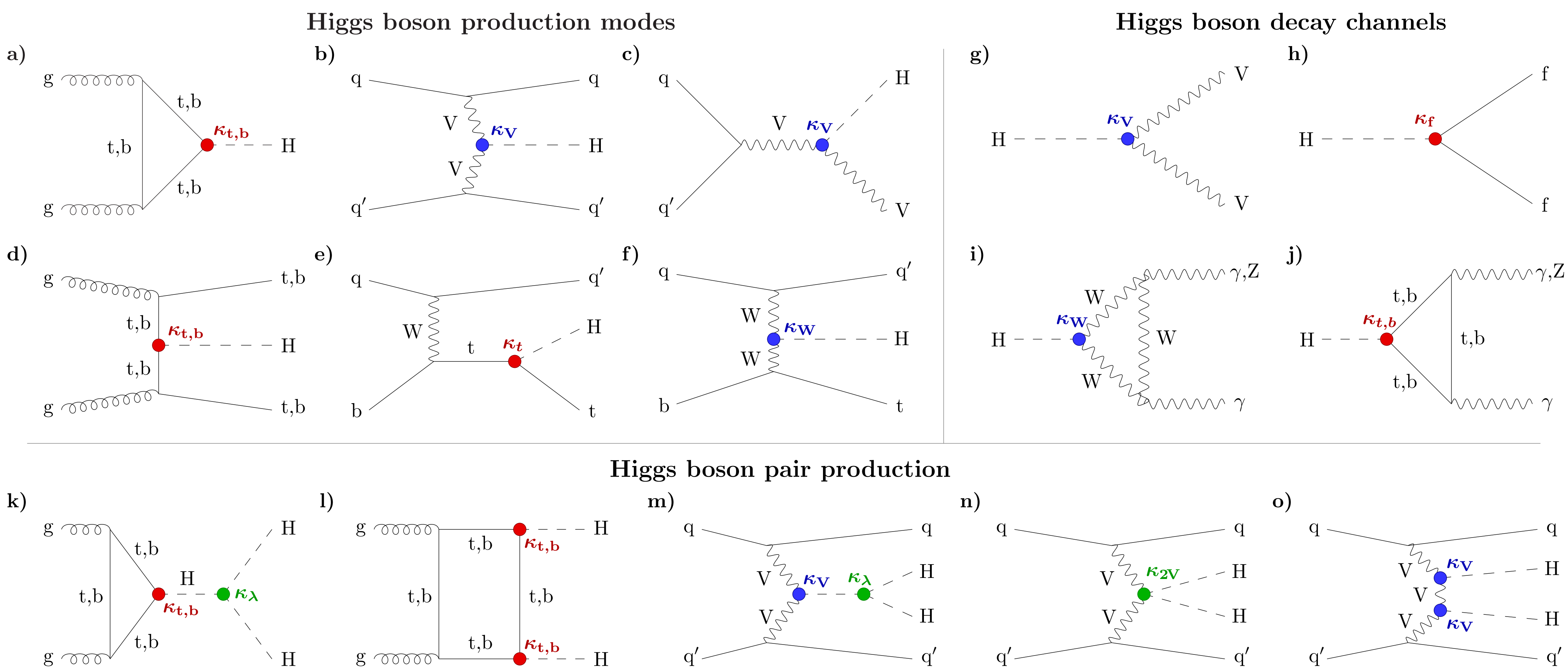



# Coupling measurements

Nature 607 (2022) 60

# Higgs couplings

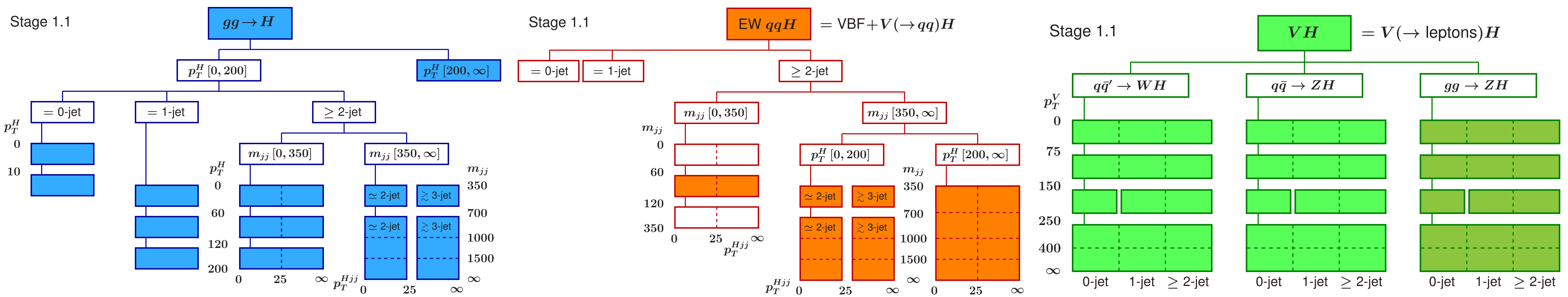
- Higgs boson is expected to couple to massive particles.
  ➡ Need to determine a coupling constant for "each".
- Plenty of (production modes)×(decay modes) requires extraction of couplings by global fitting.



arXiv:1906.02754

# STXS

- Simplified Template Cross Section
  - ➡ Adopted by the LHC experiments as a common framework.
  - ➡ Defined as several kinematic bins and production modes.
  - ➡ Advantages:
    - ✓ Reducing theoretical uncertainties.
    - ✓ Opportunities to combine measurements btw. various decay channels and btw. experiments.



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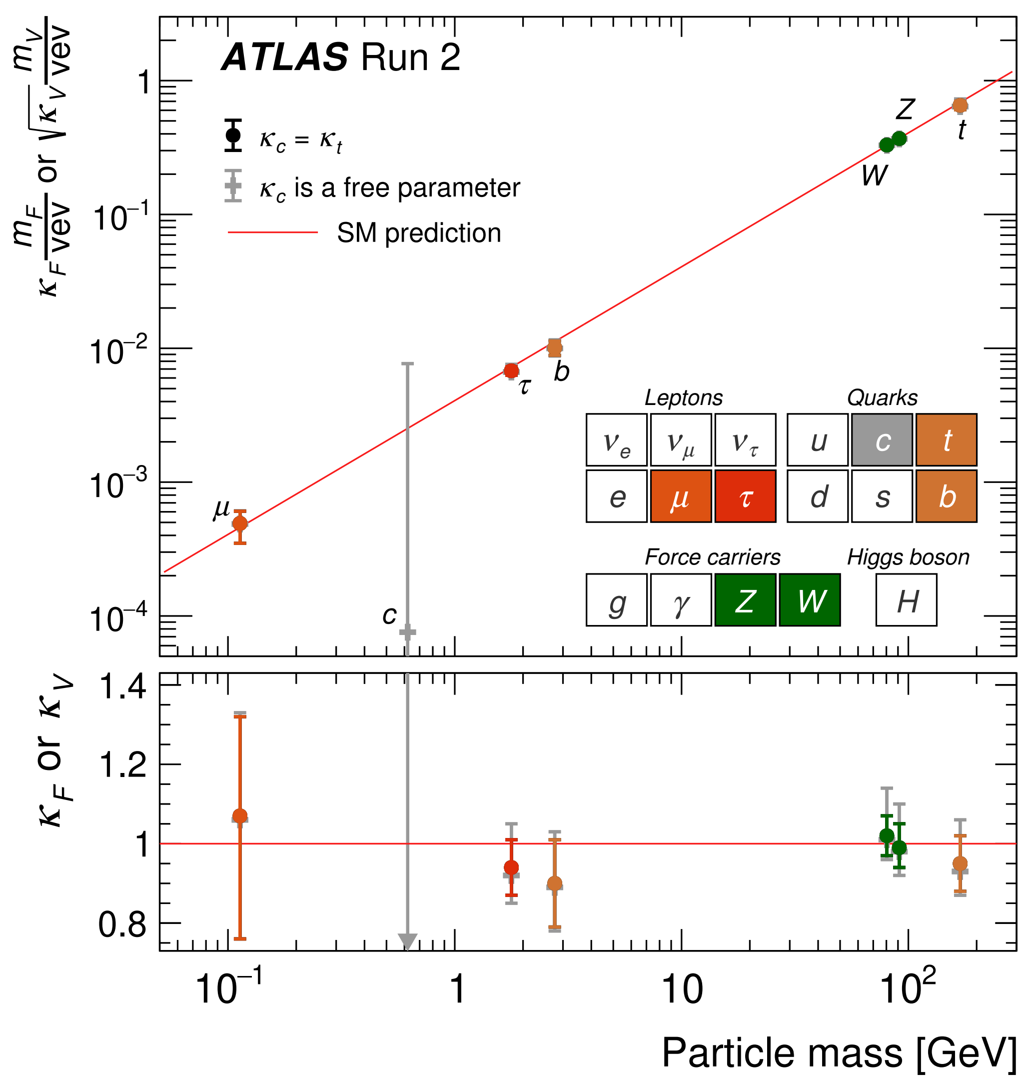
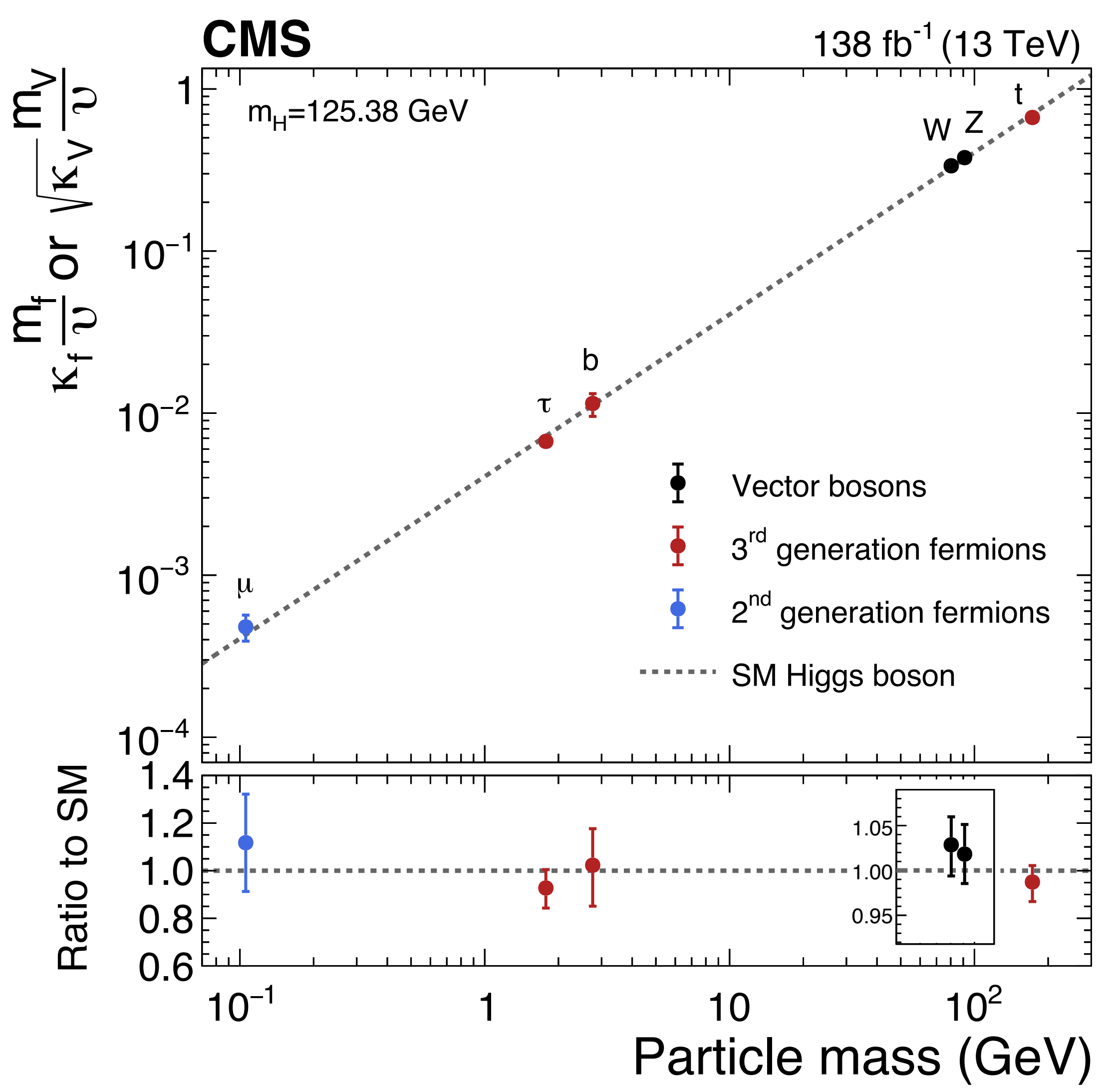
Nature 607 (2022) 52

# Couplings Overview

- Both experiments show results consistent to SM
  - ➡ 3rd gen. measured 10% level, going into 2nd gen. particles.
  - ➡ Improving precision for the diff. cross-section measurements.



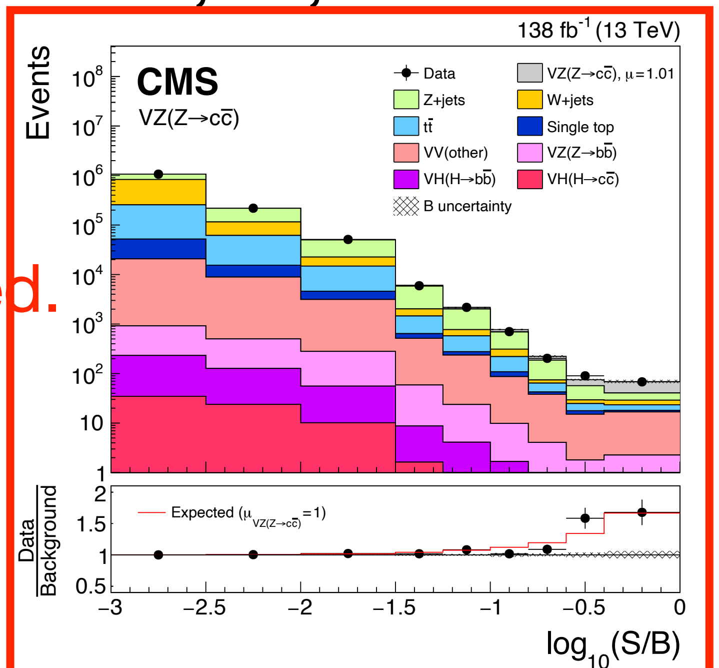



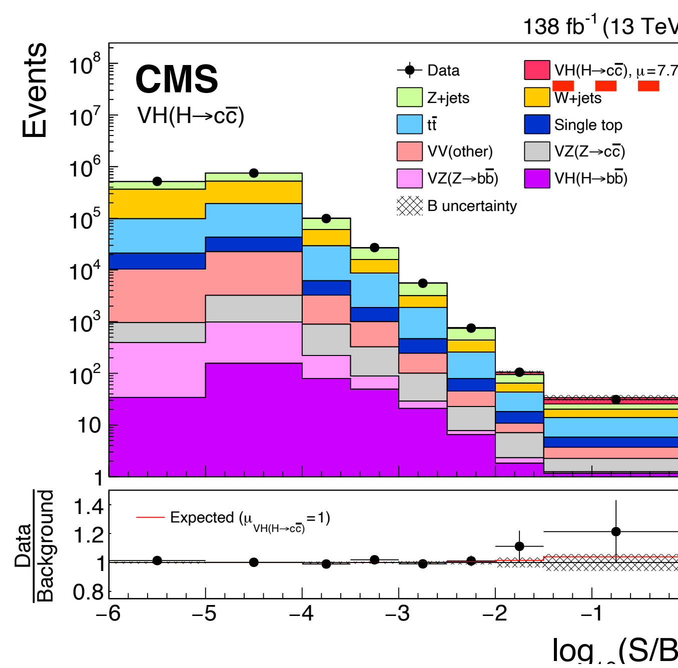
Eur. Phys. J. C 82 (2022) 717
arXiv:2205.05550

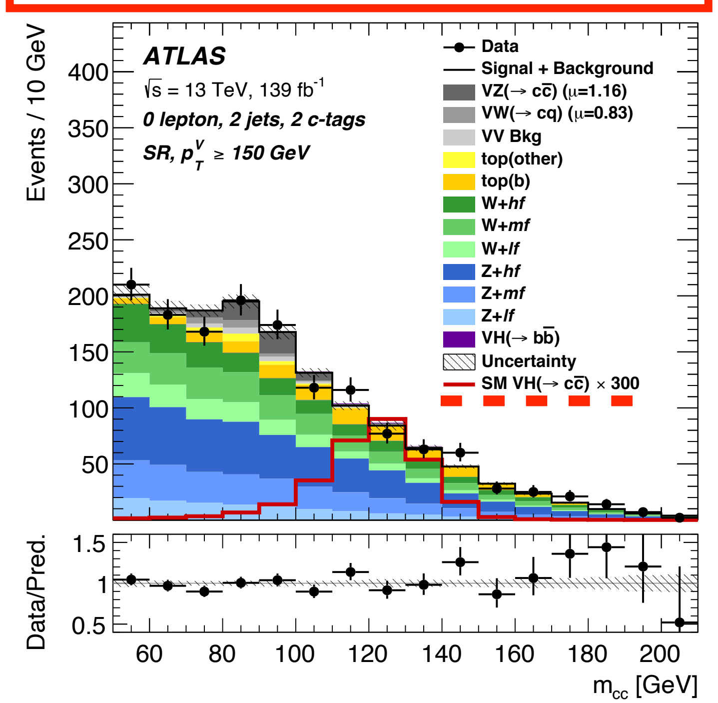
# H→2nd gen. particles: H→cc

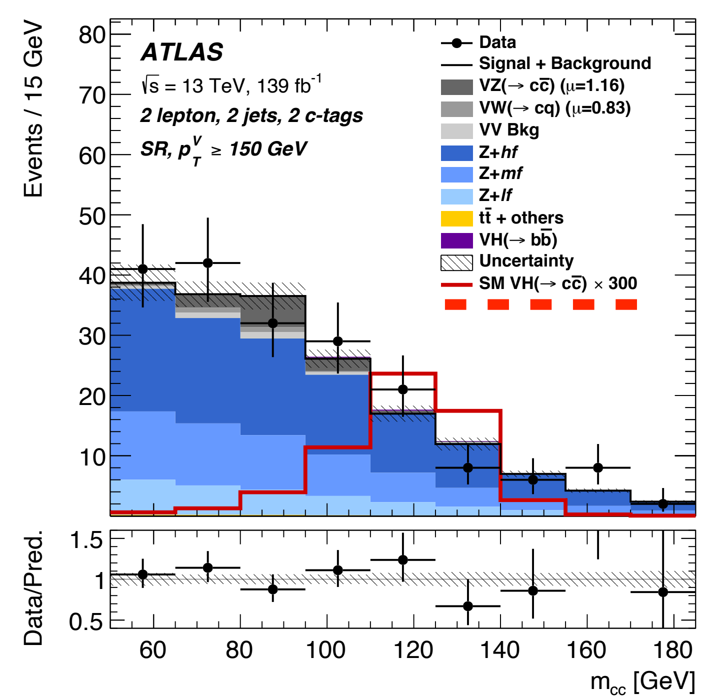
- New results published from both experiments.
  - ➡ VH with 2l, 1l, 0l final states with dedicated c-tagging algs.

VZ(→cc) is clearly observed.



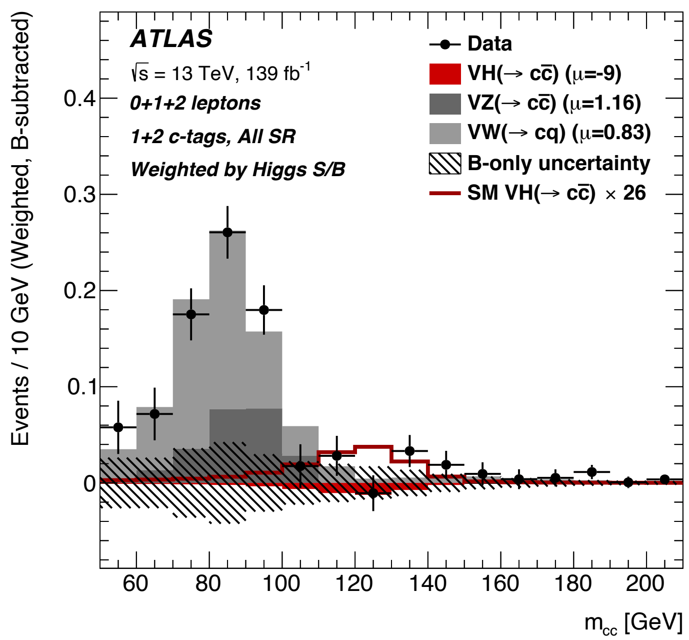



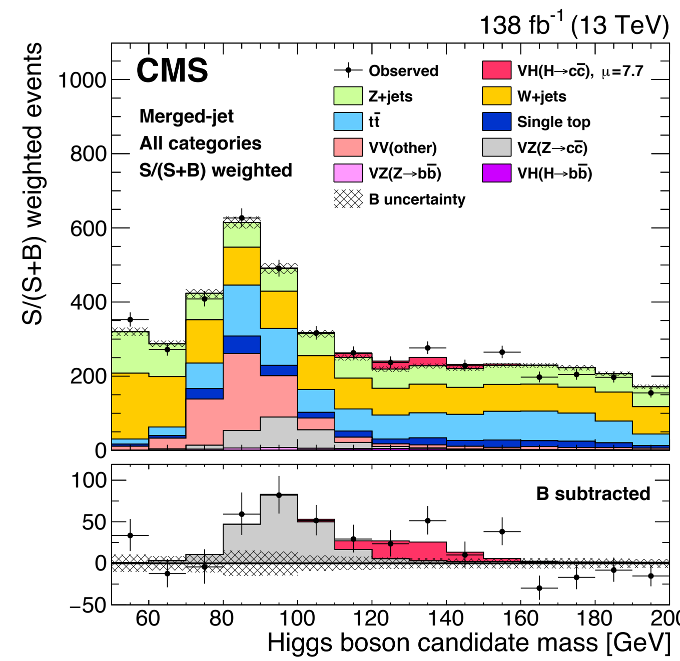



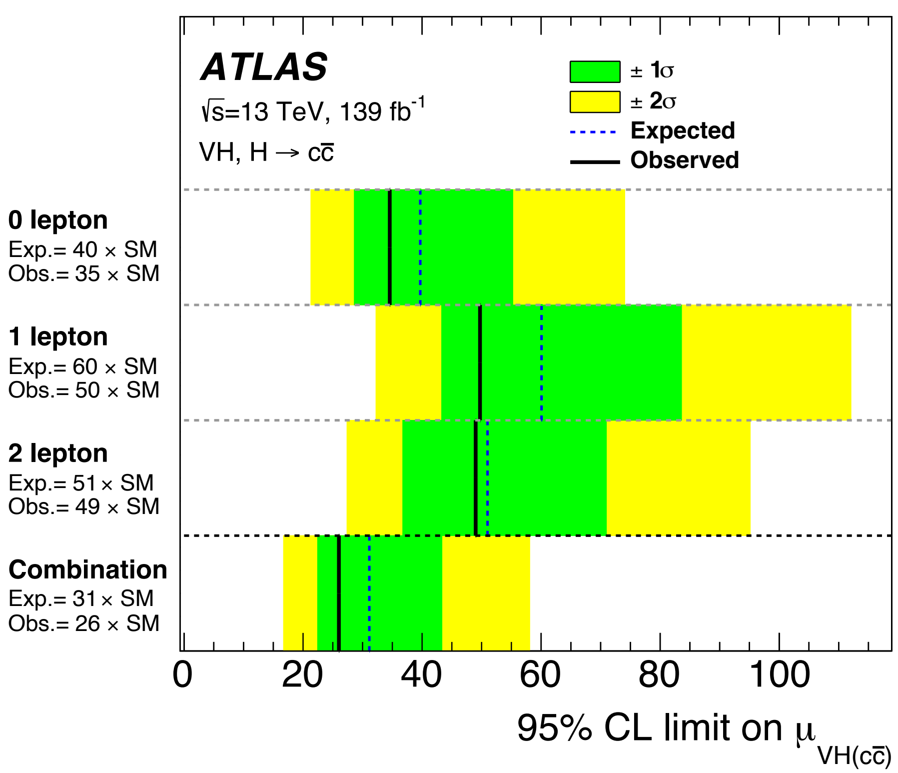
Eur. Phys. J. C 82 (2022) 717
arXiv:2205.05550

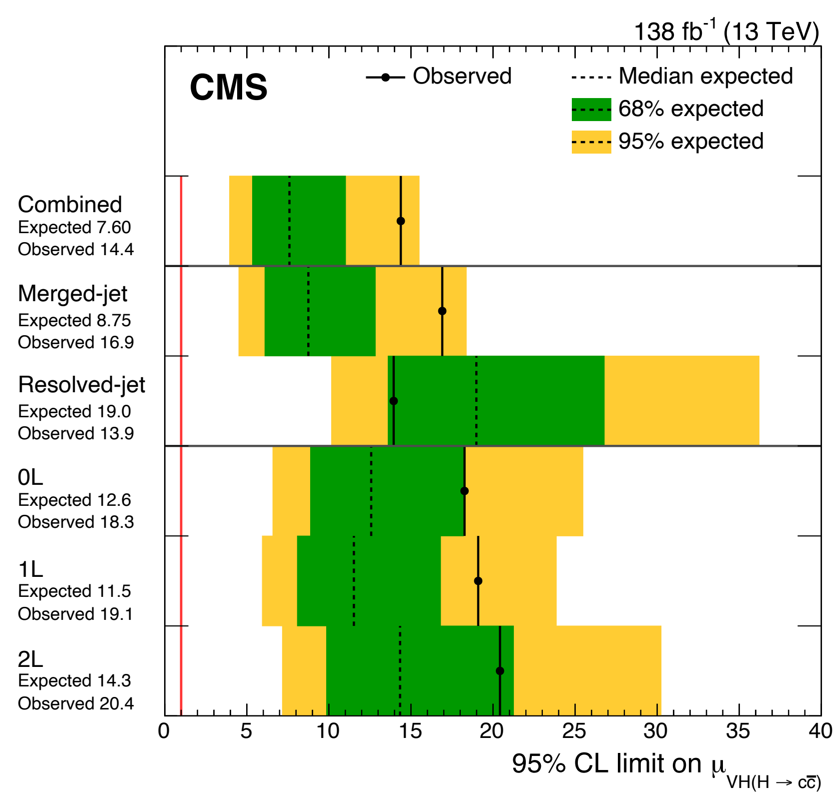
# H→2nd gen. particles: H→cc

- Upper limit on μ=($\sigma_{obs}/\sigma_{SM}$): 26 by ATLAS, 14.4 by CMS.



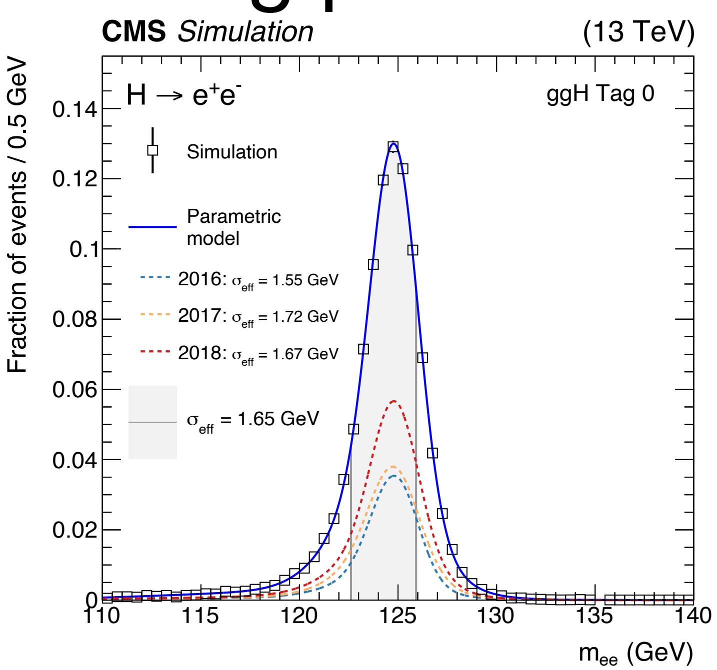



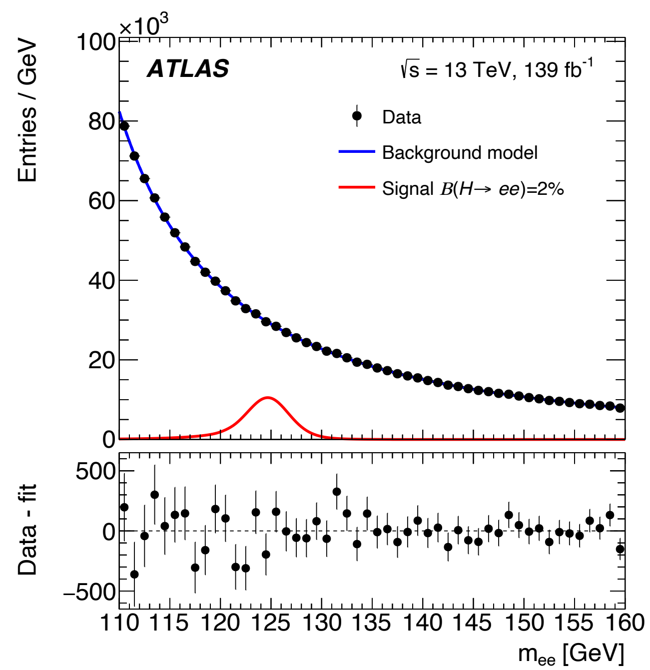
arXiv:2208.00265

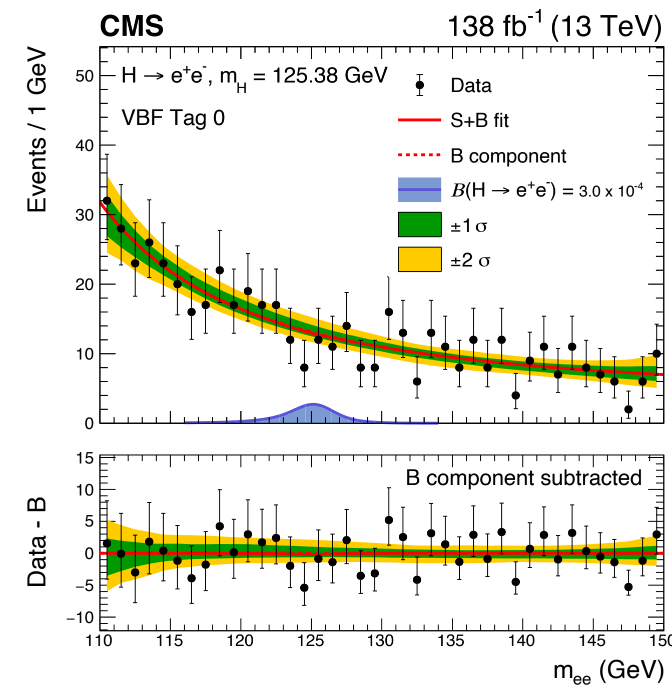
Phys. Lett. B 801 (2020) 135148

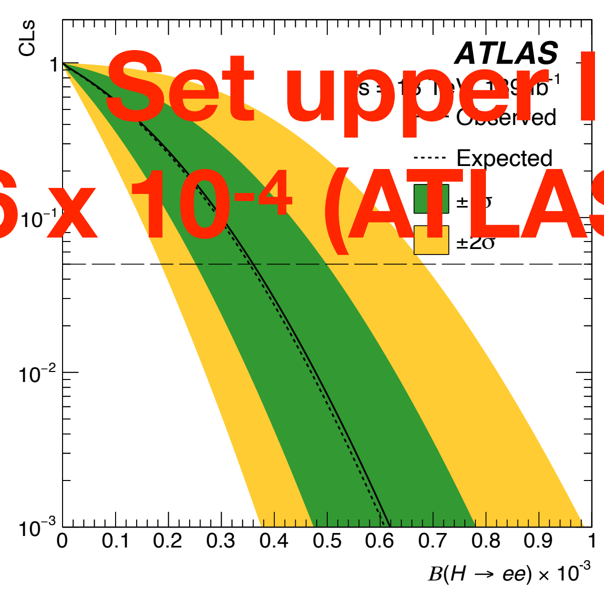
# H→1st gen. particles: H→ee

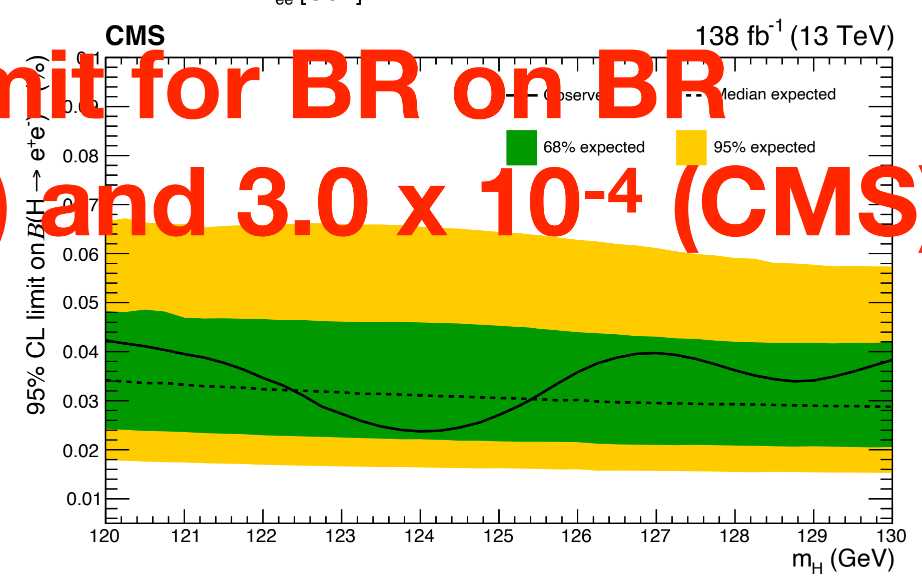
- SM expectation: BR(H→ee) = 5 x $10^{-9}$
  - ➡ Using ggH or VBFH modes categorized by BDT scores.
  - ➡ Fitting performed on $m_{ee}$ distribution.



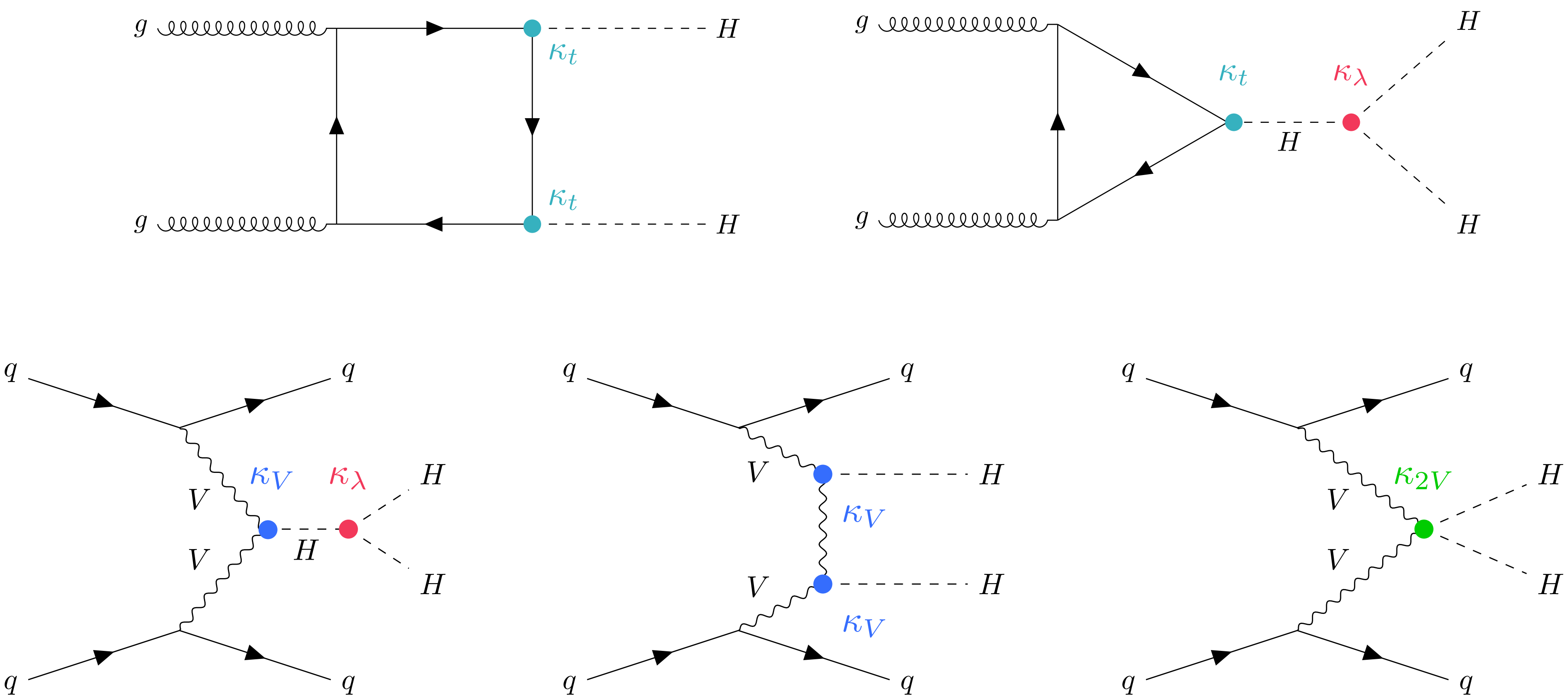

**Set upper limit for BR on BR**

**3.6 x $10^{-4}$ (ATLAS) and 3.0 x $10^{-4}$ (CMS)**

ATLAS-CONF-2022-050
Nature 607 (2022) 60

# Di-Higgs and Higgs self coupling

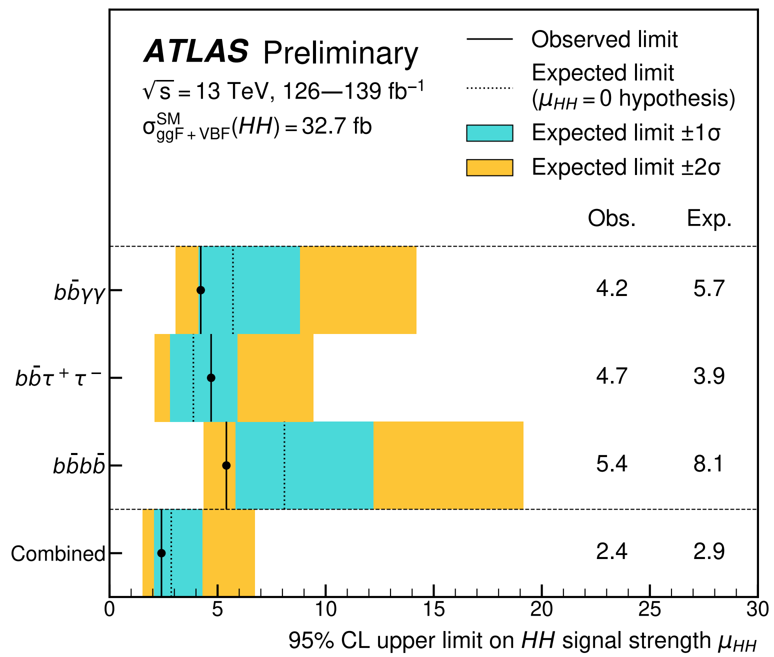
- Di-Higgs property measurement is one of challenges in LHC.
  - ➡ Many possibilities to modify σ from $\sigma_{SM}$.
  - ➡ Also, plenty of final states.
    - ✓ (Prod. modes: ggH-like, VBFH-like,,,) × (Decay modes: bb, WW, ZZ, ττ, γγ, ZZ ,,,)

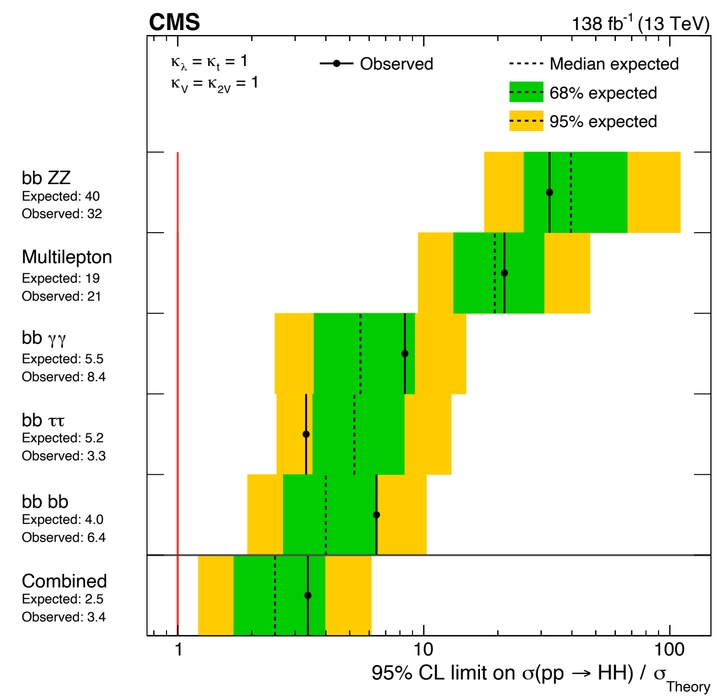


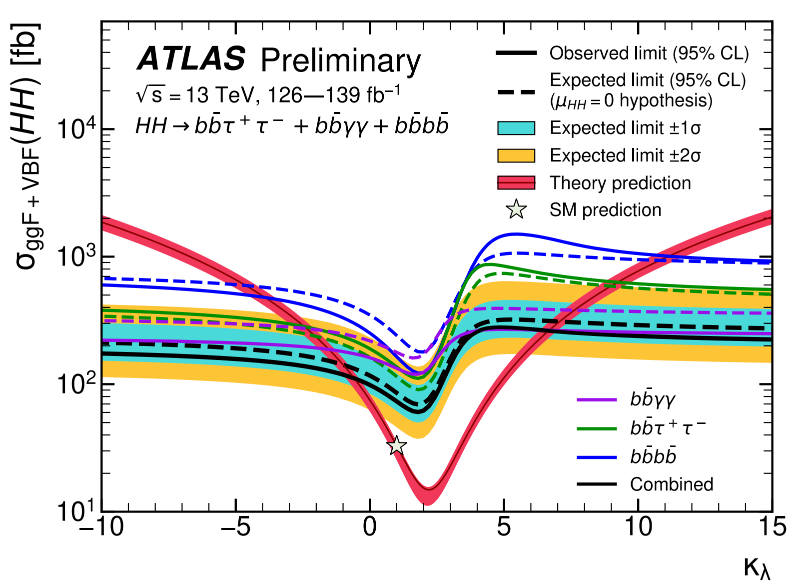
ATLAS-CONF-2022-050
Nature 607 (2022) 60

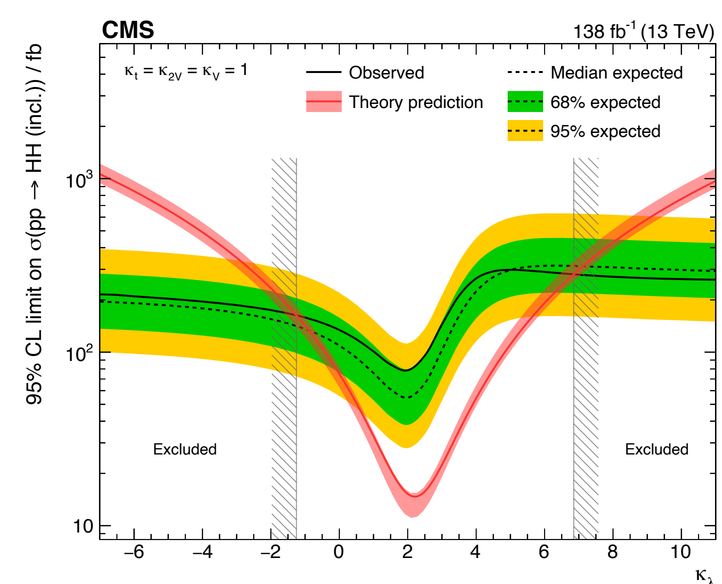
# Di-Higgs and Higgs self coupling

- Upper limit on $\mu=(\sigma_{obs}/\sigma_{SM})$: 2.4 by ATLAS, 3.4 by CMS.
- $\kappa_\lambda$ = [-0.4, 6.3] by ATLAS, [-1.24, 6.49] by CMS at 95% CL.



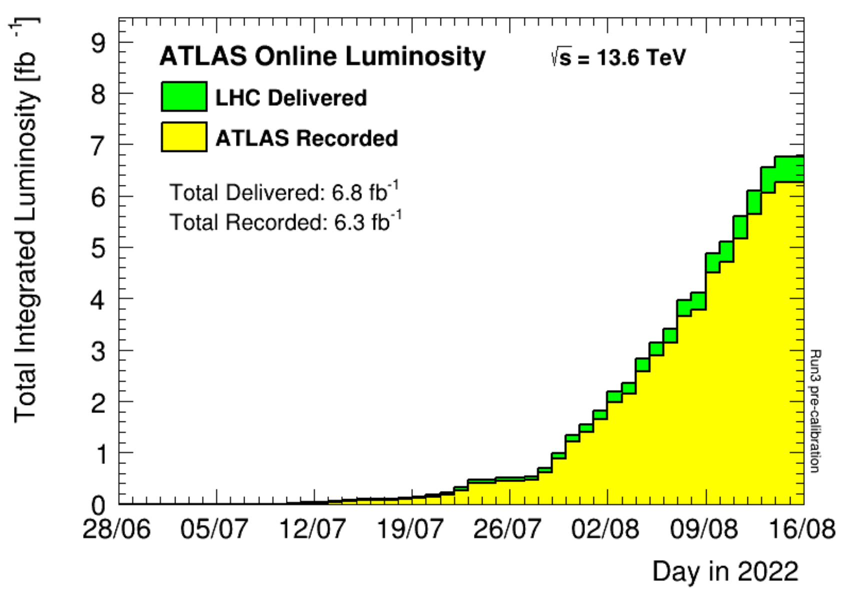



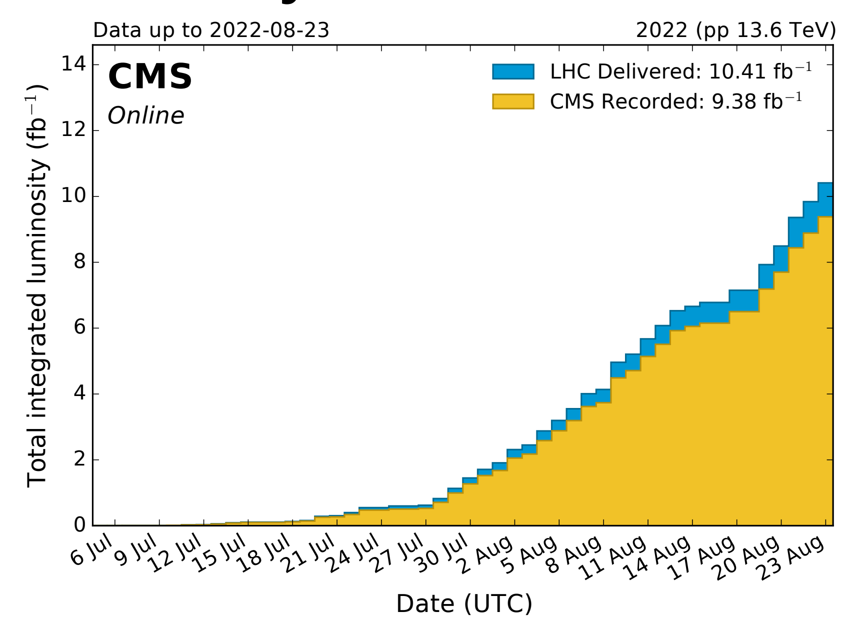



# Future improvements

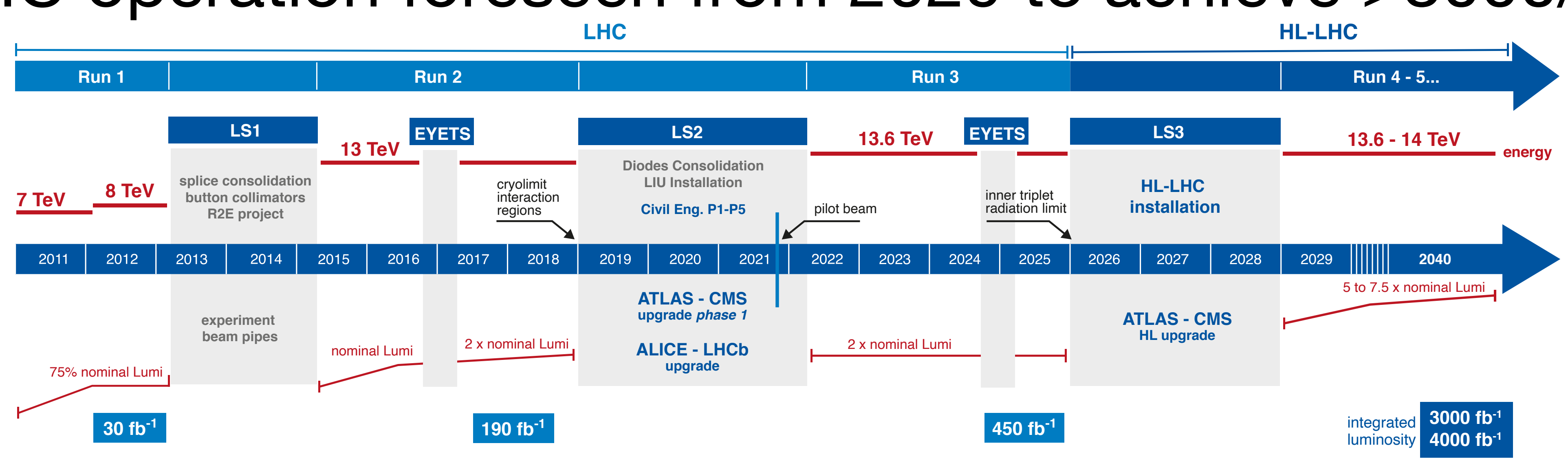
# Ongoing and future LHC Operation

- RUN3 has been started with $\sqrt{s}$ = 13.6 TeV.
  - ➡ Higgs production rate (σ*L) 7% larger than Run2.
  - ➡ Total ~50M Higgs to be produced by the end of RUN3.



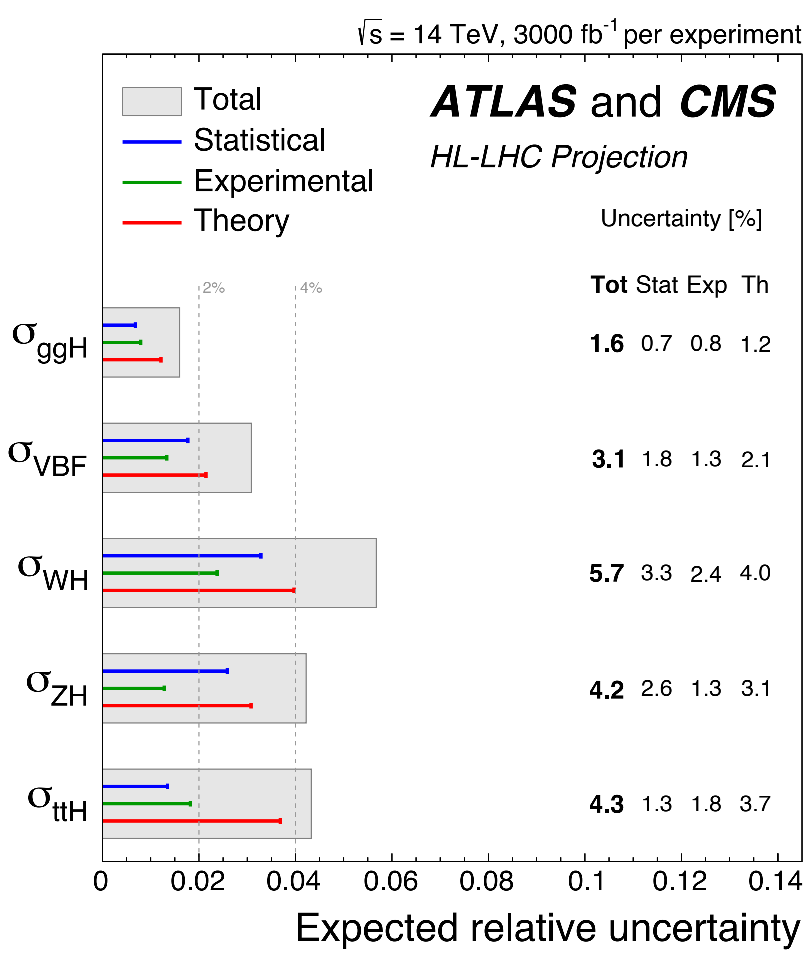



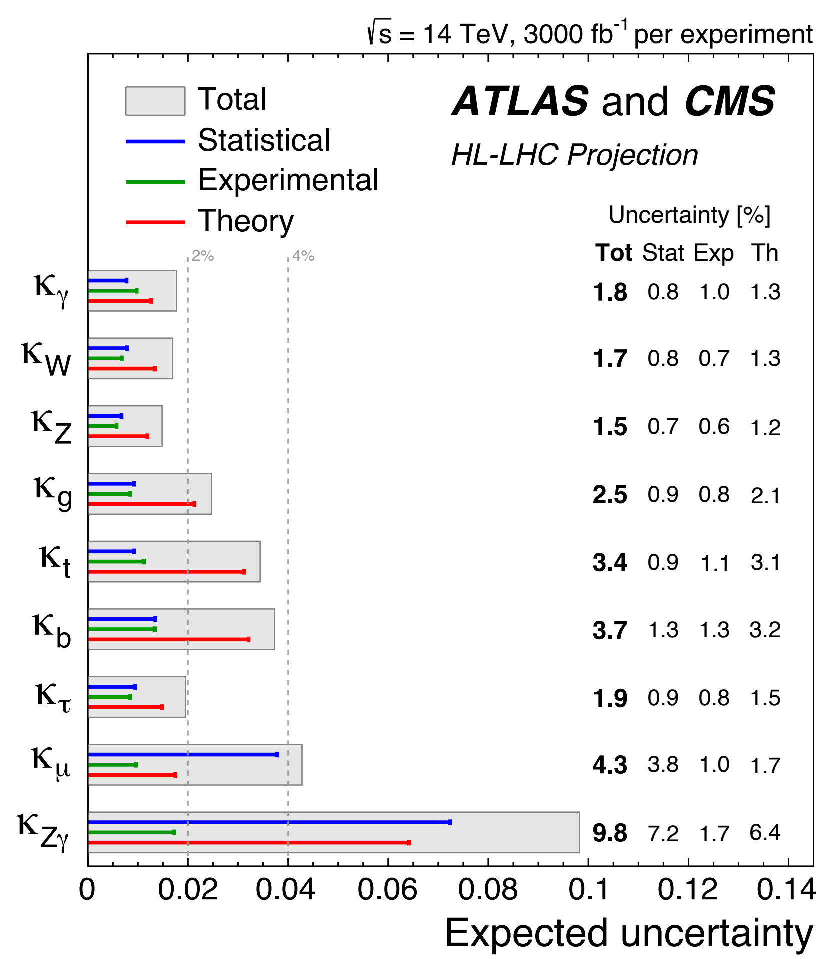

- HL-LHC operation foreseen from 2029 to achieve >3000/fb.

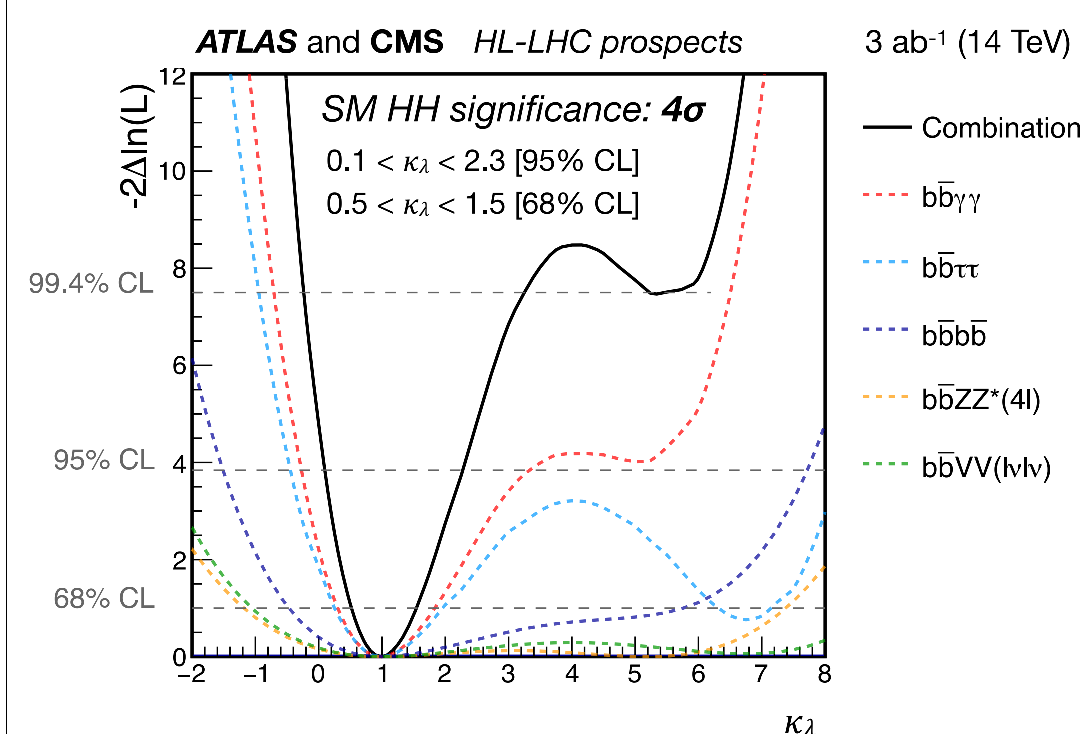


# Future improvements in HL-LHC

- Coupling measurements:
  - ➡ Precision of 2-4% possible.
  - ➡ Limited by theory uncertainties for many analysis.
- Self-coupling:
  - ➡ Could exclude $\kappa_\lambda = 0$ at the 95% CL.

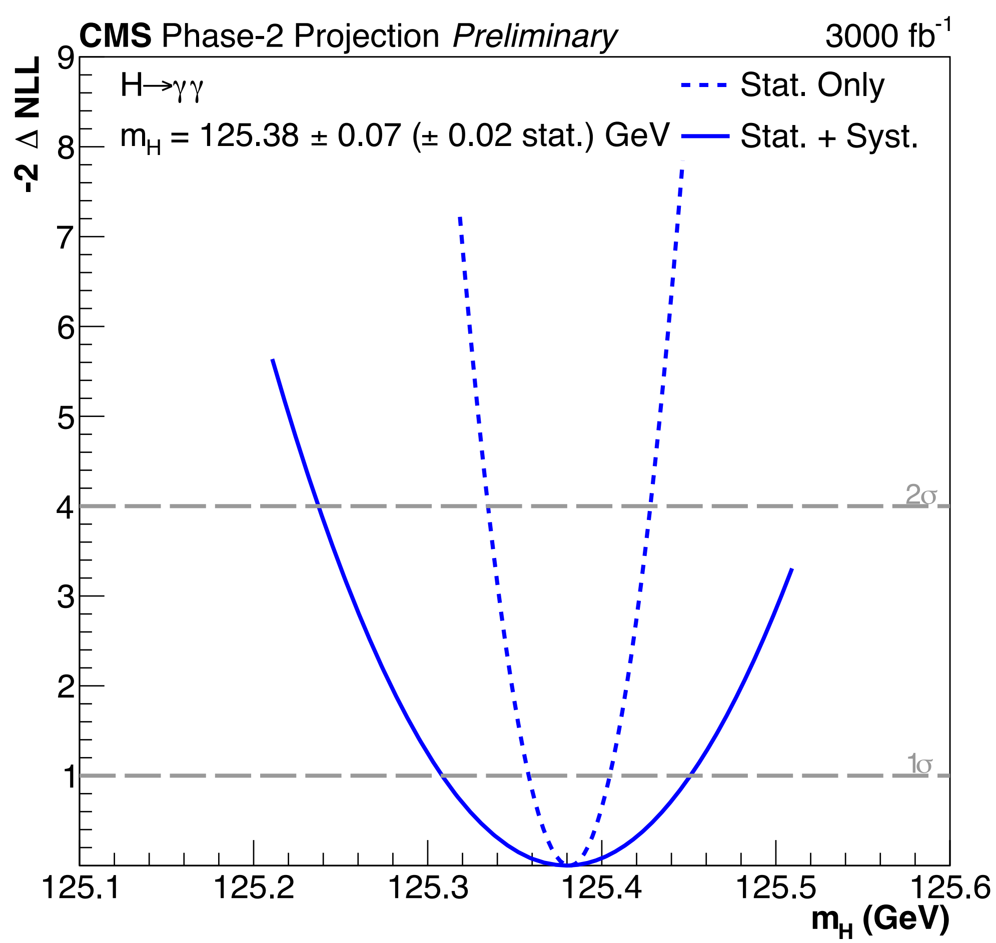


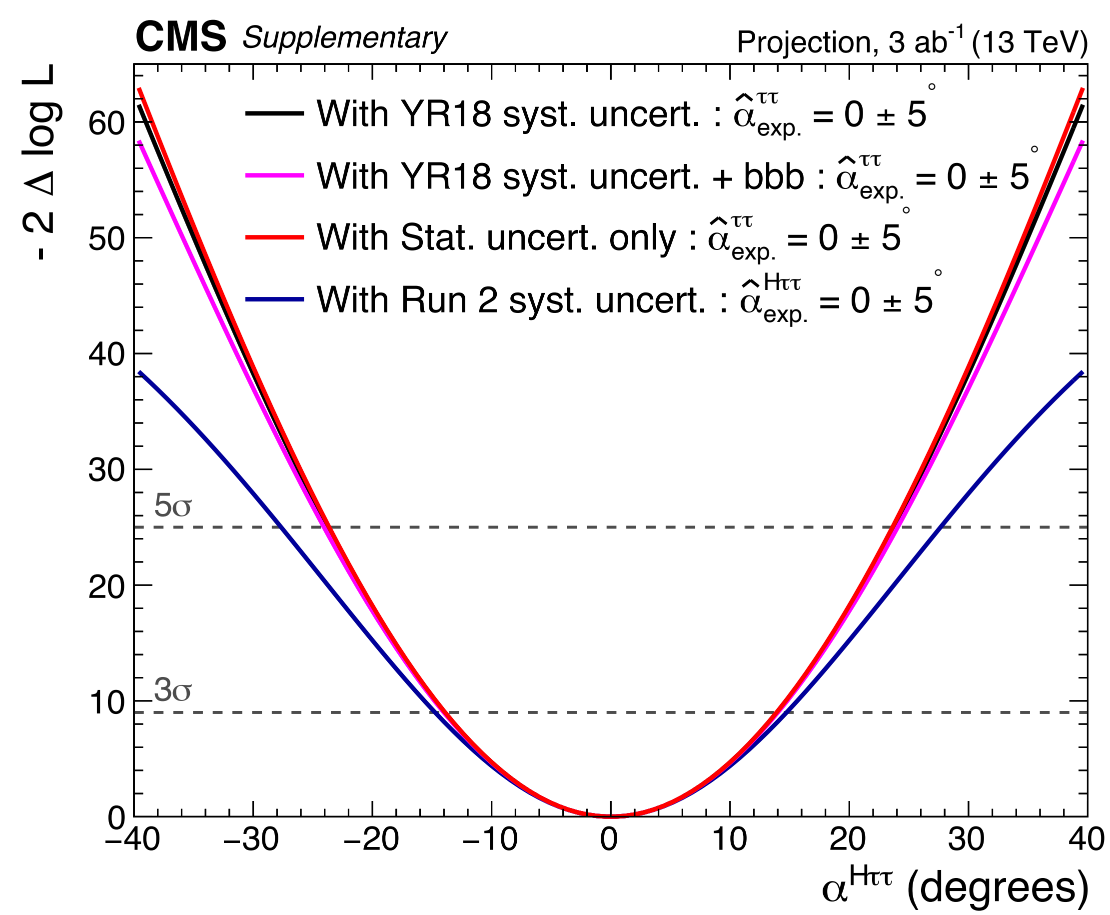



# Future improvements in HL-LHC

- Mass:
  - ➡ Precision of 0.06% would be possible.
  - ➡ Systematically limited.
- CP of the Hff coupling:
  - ✓ CP-even/-odd mixing greater than 24° could be observed.



# Conclusion

- 10 years since discovery of the Higgs boson
  - ➡ Studied intensively at ATLAS and CMS experiments.
  - ➡ With 30-times larger data recoded, its properties were measured more precisely.
- A lot of its properties have been measured.
  - ➡ Mass, Spin, Parity.
  - ➡ Couplings to other particles and Higgs itself.
- So far, everything is consistent to the SM.
  - ➡ Gave stringent constraints on many BSM physics models.
- Foreseen to improve the measurements, and pursuing the unproved parameters in the future.

# Backup

# Analysis Categories

- CP
  - ➡ H-top
    - ✓ CMS: HIG-21-006
    - ✓ ATLAS: Phys. Rev. Lett. 125 (2020) 061802
  - ➡ H-tau
    - ✓ CMS: HIG-20-007
    - ✓ CMS: JHEP 06 (2022) 012
    - ✓ ATLAS: Phys. Lett. B 805 (2020) 135426
  - ➡ H-W
    - ✓ ATLAS: Eur. Phys. J. C 82 (2022) 622
  - ➡ H-gam in VBF
    - ✓ ATLAS: 2208.02338
- Mass
  - ➡ Math, Width
    - ✓ CMS: HIG-21-013
  - ➡ Di-Higgs
    - ✓ CMS: Nature 607 (2022) 60
    - ✓ CMS HH->4L+bb: HIG-20-004
    - ✓ CMS HH->WWWW, WWtautau, tau*4: HIG-21-002
    - ✓ CMS HH->bbtautau: HIG-20-010
    - ✓ CMS HH->bbbb: HIG-20-005
    - ✓ ATLAS: ATLAS-CONF-2022-050

# Analysis Categories

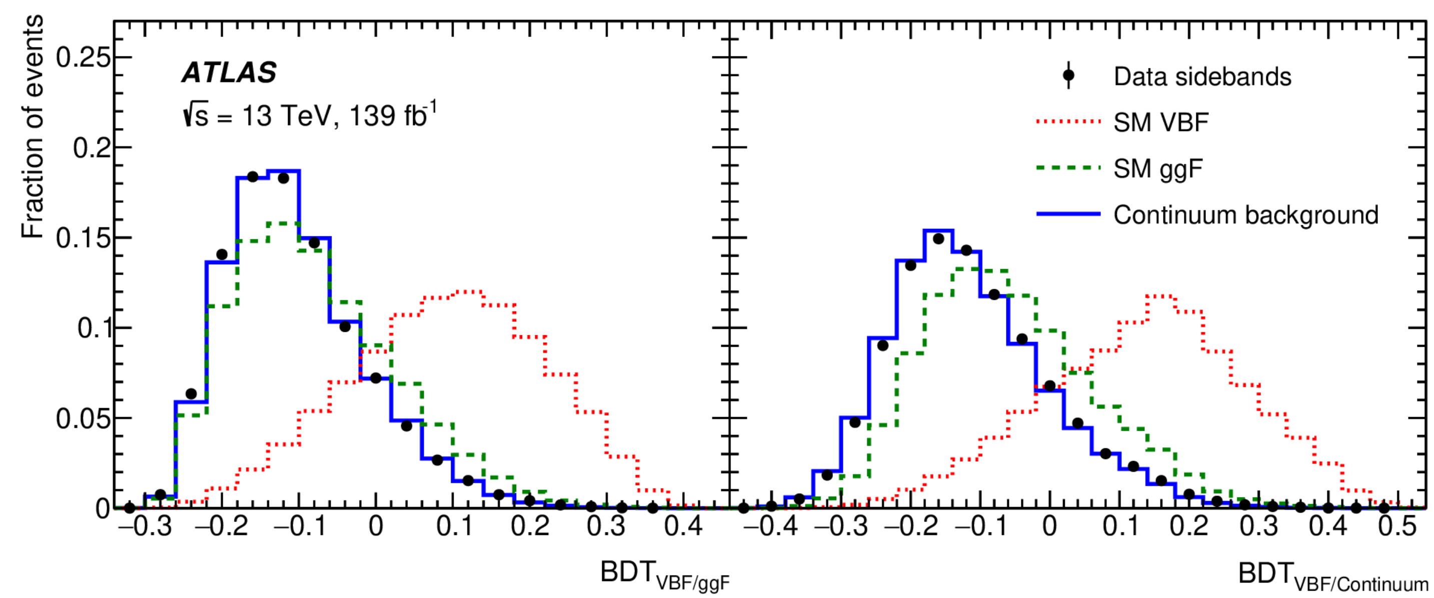
- Couplings
  - ➡ Hcc
    - ✓ ATLAS: Hcc, 2201.11428
    - ✓ ATLAS: J/Psi, 2208.03122
    - ✓ CMS: Hcc, HIG-21-008
    - ✓ CMS J/Psi, Upsiron: HIG-20-008
  - ➡ Hmumu, Hee
    - ✓ CMS: Hee, HIG-21-015

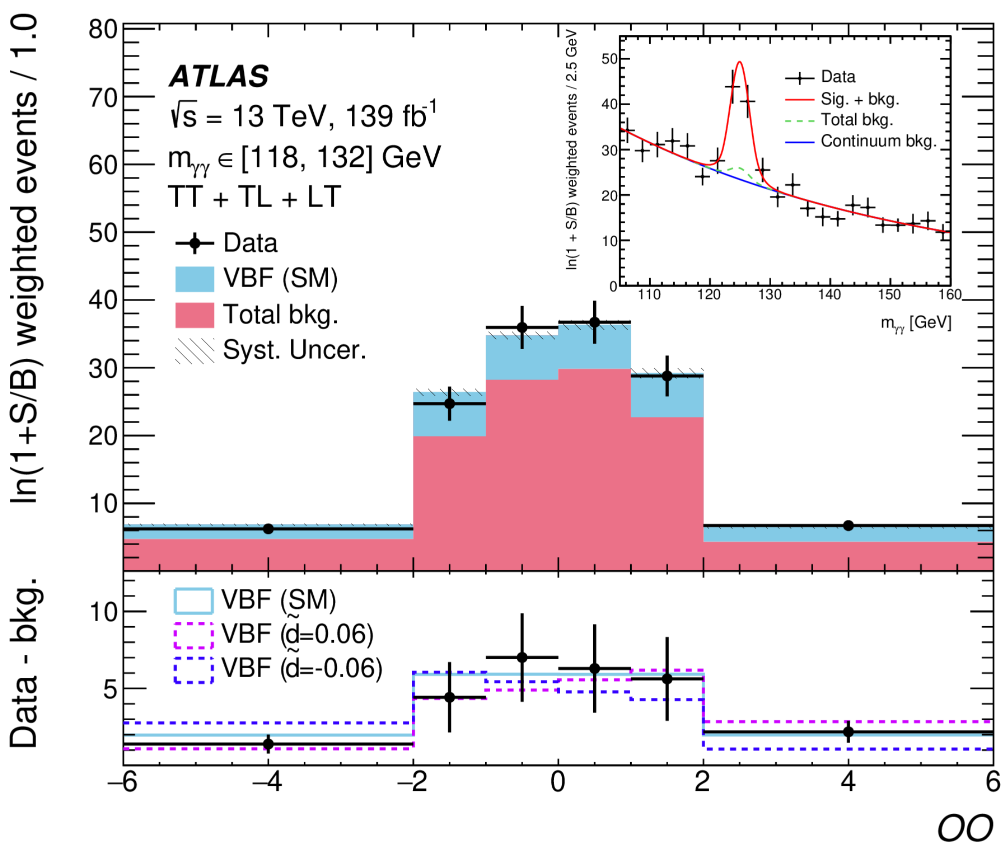
  - ➡ Hgg, HZZ differential xs
    - ✓ ATLAS: 2207.08615

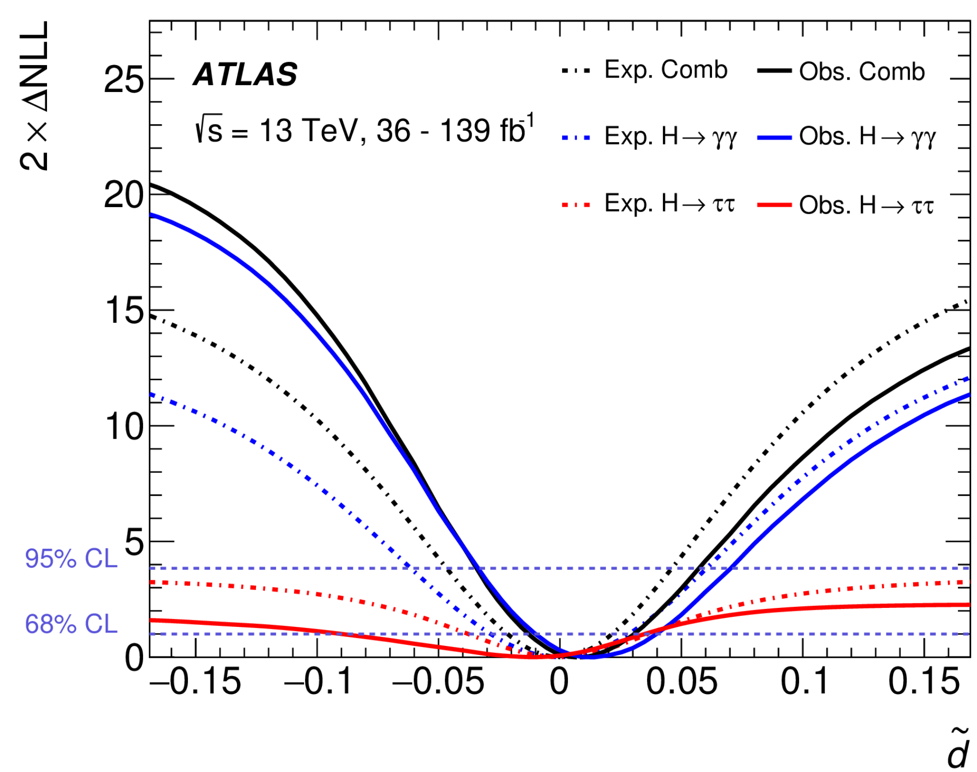
# CP in H→γγ

$$|\mathscr{M}|^2 = |\mathscr{M}_{\rm SM}|^2 + 2 \cdot c_i \cdot {\rm Re}(\mathscr{M}^*_{\rm SM}\mathscr{M}_{\rm CP\text{-}odd}) + c_i^2 \cdot |\mathscr{M}_{\rm CP\text{-}odd}|^2.$$

$$OO = 2 \cdot {\rm Re}(\mathscr{M}^*_{\rm SM} \cdot \mathscr{M}_{\rm CP-odd}) / |\mathscr{M}_{\rm SM}|^2$$



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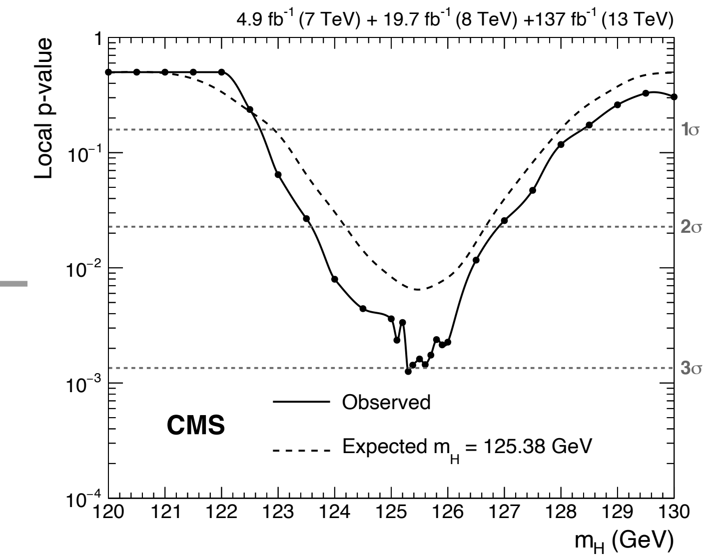
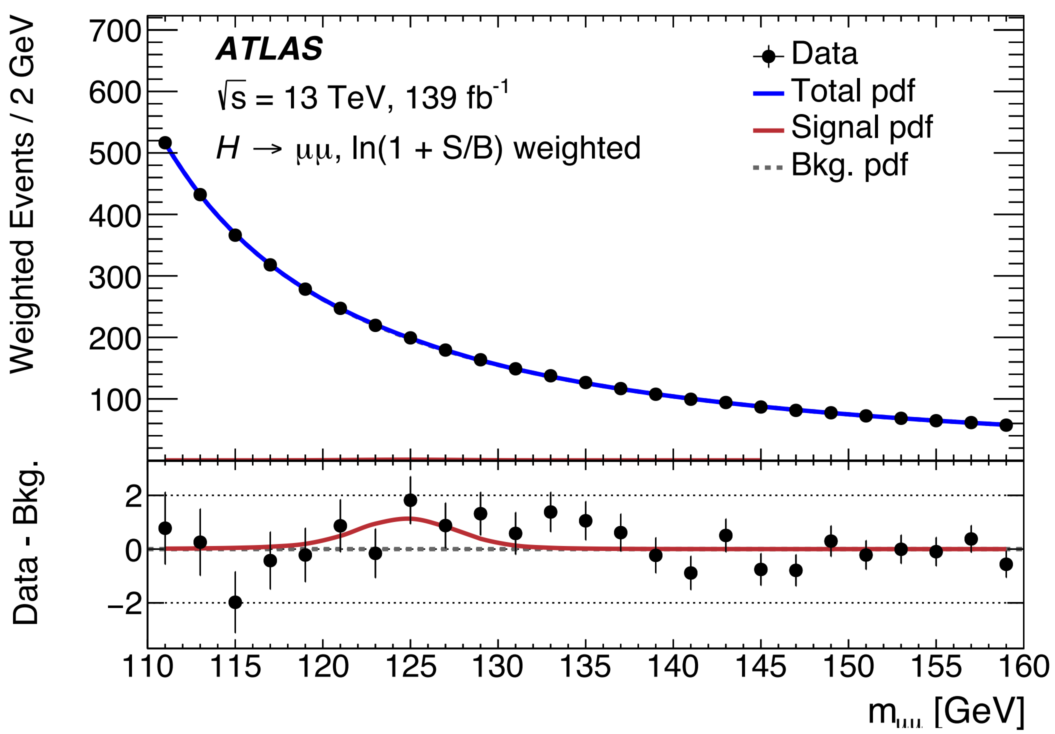
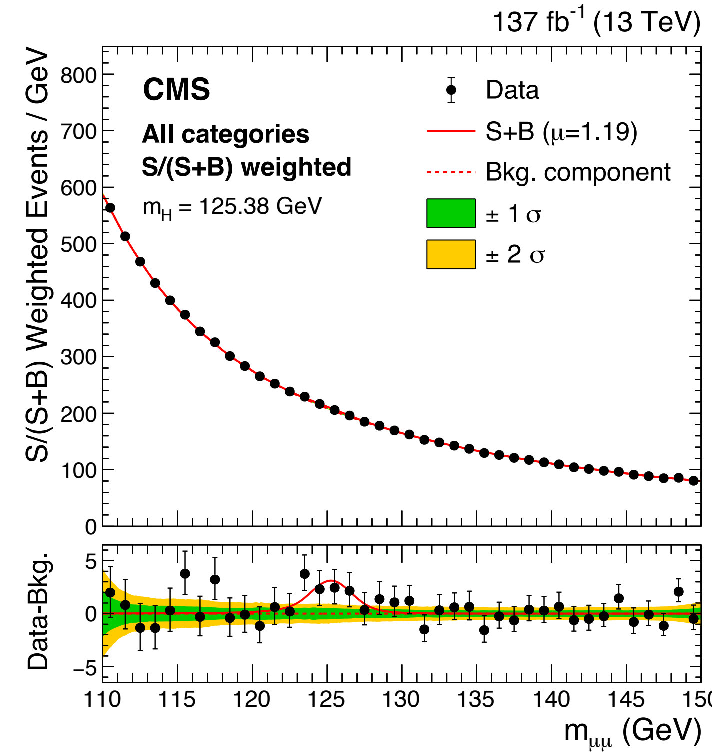
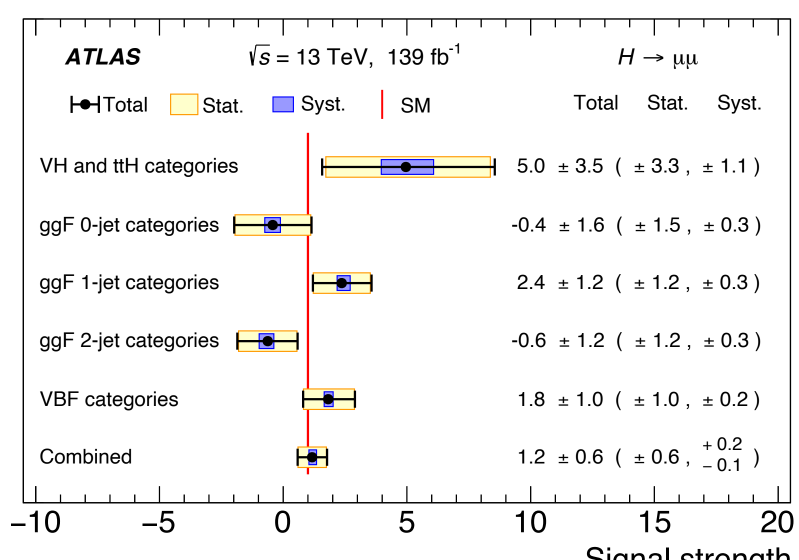
# H→2nd gen. particles: H→μμ

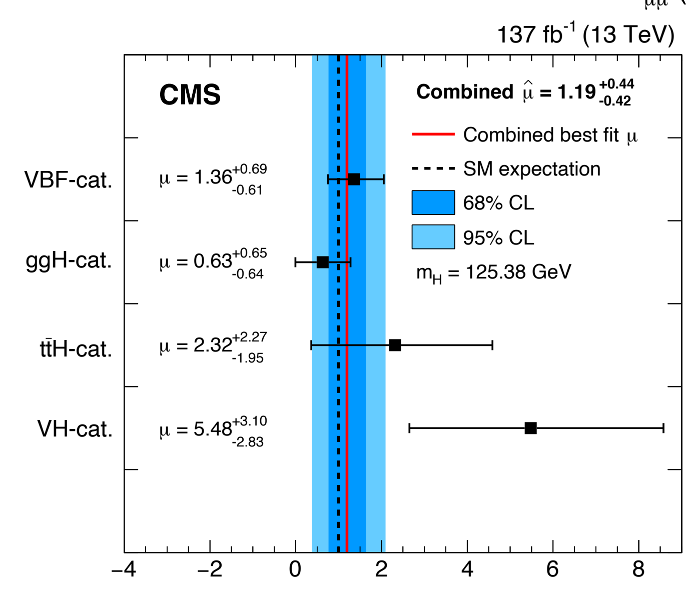
- SM expectation: BR(H->μμ) = 2 x $10^{-4}$
- No recent results. Evidence by CMS.



# CMS c-tagging algorithm