Status and prospects for Higgs physics at the LHC

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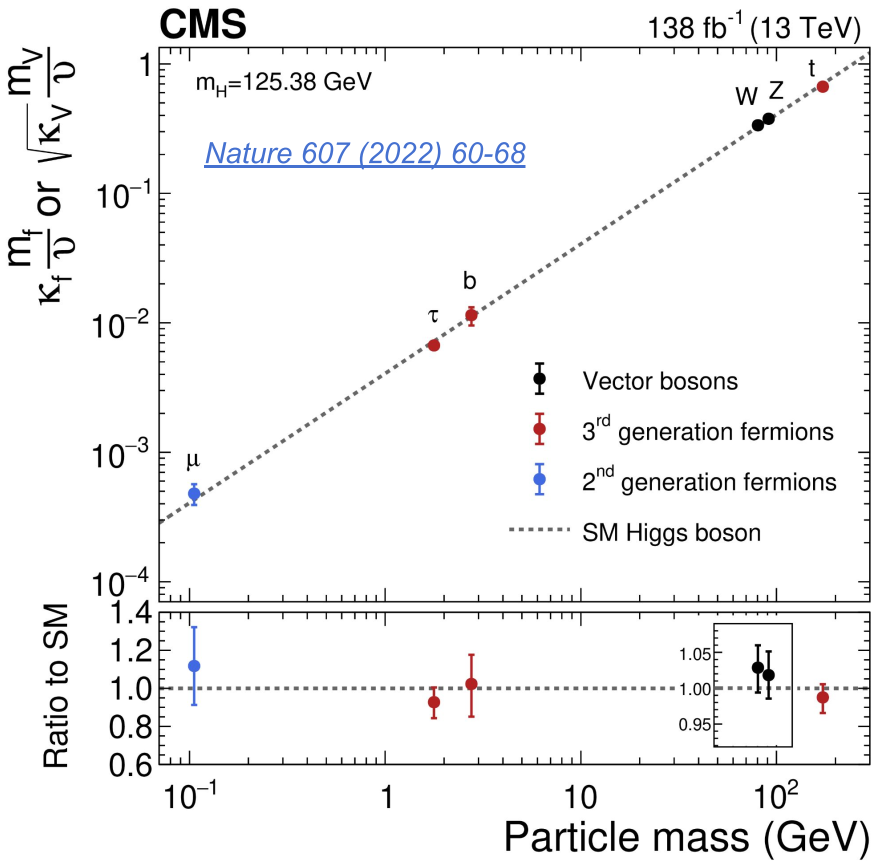
17/9/2024

Outline

- Current status of art
- New Run2 Results: Single Higgs
- New Run2 Results: Double Higgs and self couplings
- New Results: Run3 measurements
- Few slides on the future

Current status of art

Current status-of-art: **Higgs boson couplings**



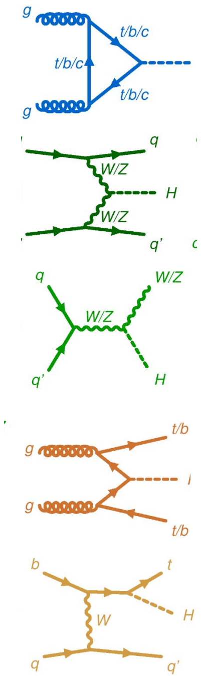
Reached precision per experiment:

Boson Sector (W,Z,γ,g): **7-8%**

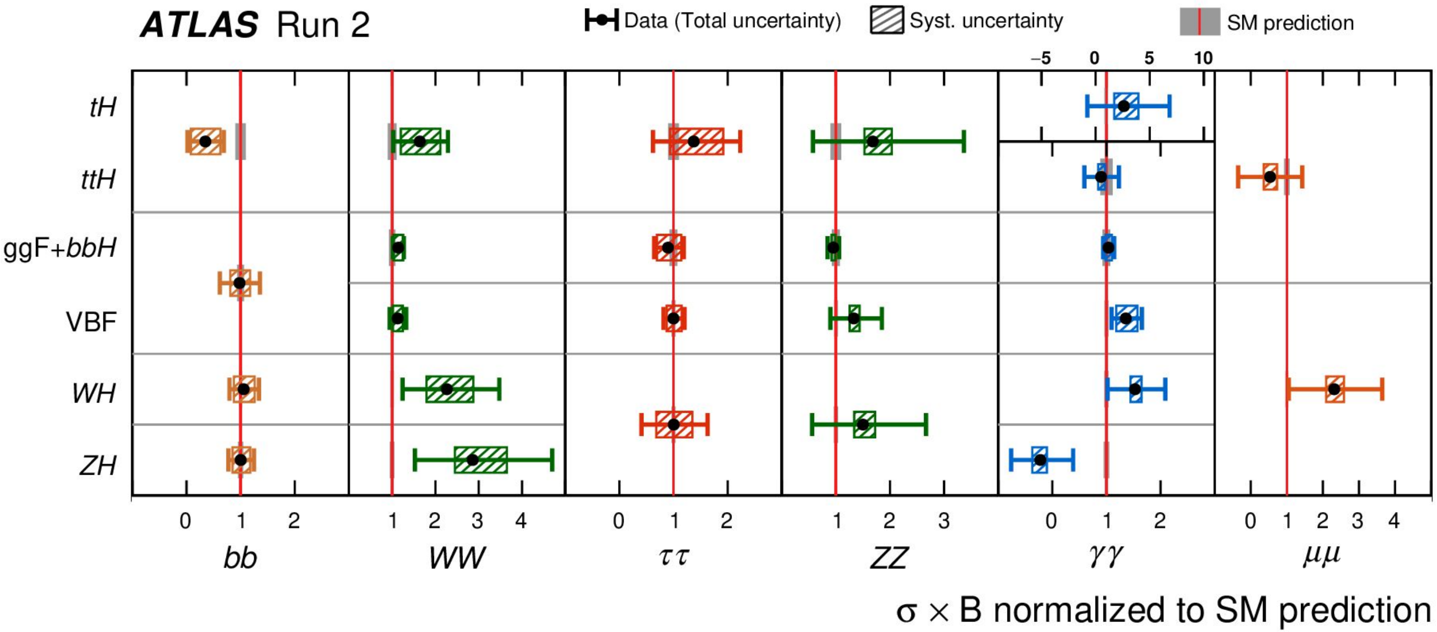
Fermion Sector:

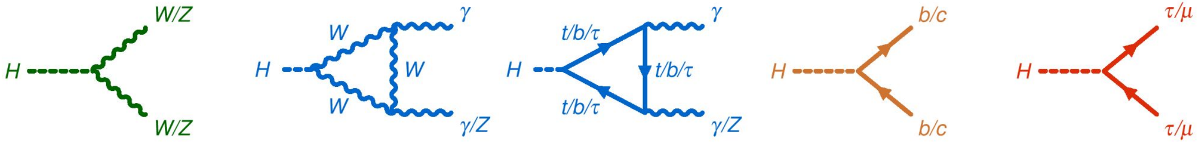
- Quarks : **10%(b) 15%(t)**
- Leptons: **8%(τ), 20%(μ)**

Current status-of-art: **Production and decay modes**



[Nature 607 52 (2022)](https://doi.org/10.1038/s41586-022-04893-w)





Very good agreement with the SM Higgs boson!

Current status-of-art: **Higgs boson mass**

CMS: using $H \to ZZ^* \to 4l$:

$$m_H = 125.08 \pm 0.10\ (\text{stat}) \pm 0.05\ (\text{syst})\ \text{GeV}$$

CMS-PAS-HIG-21-019

most precise single measurement!

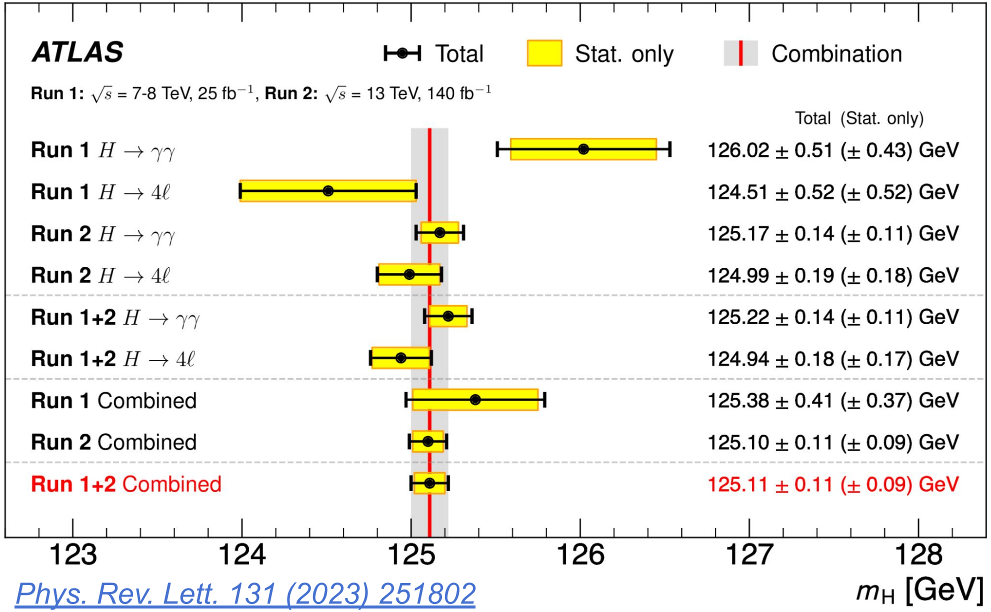
ATLAS: combining $H \to 4l + H \to \gamma\gamma$:

$$m_H = 125.11 \pm 0.11\ \text{GeV}\ (\text{syst: } 0.09\ \text{GeV})$$

Phys. Rev. Lett. 131 (2023) 251802

most precise measurement up to date

$H \to \gamma\gamma$ mass resolution systematics reduced by factor 4!



Phys. Rev. Lett. 131 (2023) 251802

Current status-of-art: **Higgs boson width**

SM Prediction: $\Gamma_H^{SM} = 4.1\ \mathrm{MeV}$

Indirect measurement through the on-shell and off-shell measurement

$$\sigma^{\text{on-shell}} \propto \frac{g_p^2 g_d^2}{\Gamma_H} \propto \mu_p \Rightarrow \sigma^{\text{off-shell}} \propto g_p^2 g_d^2 \propto \mu_p \Gamma_H,$$

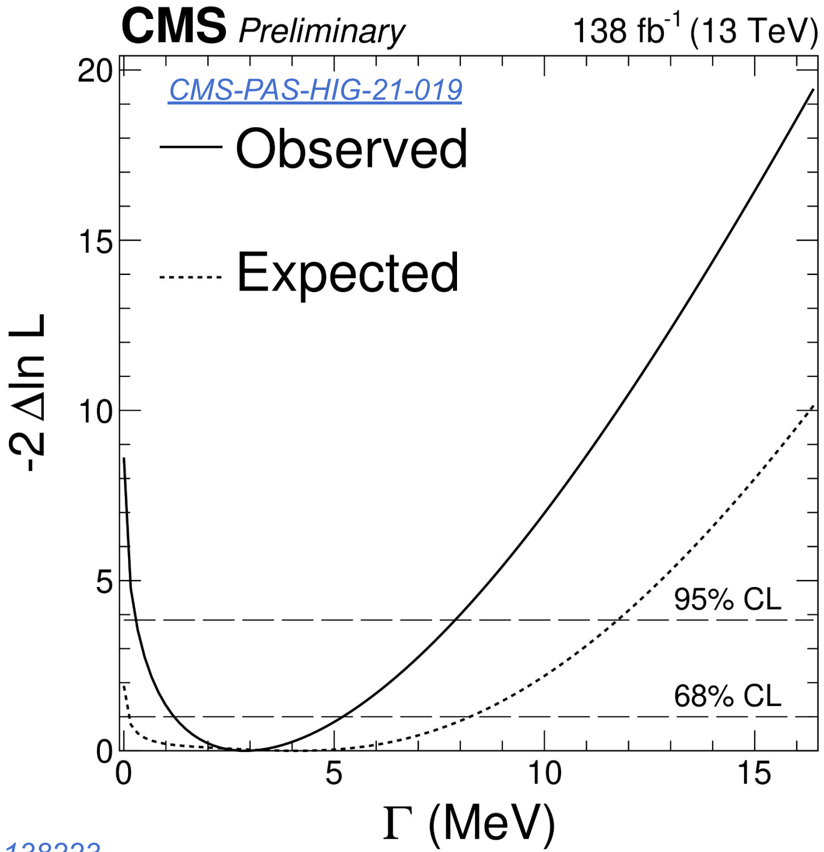
Assumes that Higgs production follows SM prediction

CMS: using H→ZZ*→4l:

$$\Gamma_H = 2.9^{+2.3}_{-1.7}\ \mathrm{MeV}$$ CMS-PAS-HIG-21-019

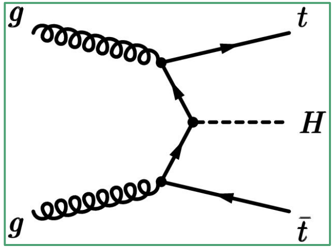
ATLAS: combining H→4l +H→2l2v:

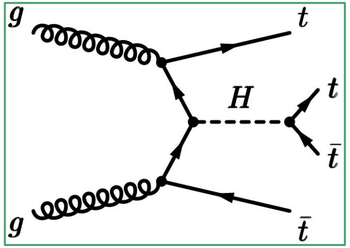
$$\Gamma_H = 4.5^{+3.3}_{-2.5}\ \mathrm{MeV}$$ Phys. Lett. B 846 (2023) 138223



Current status-of-art: **Higgs boson width**

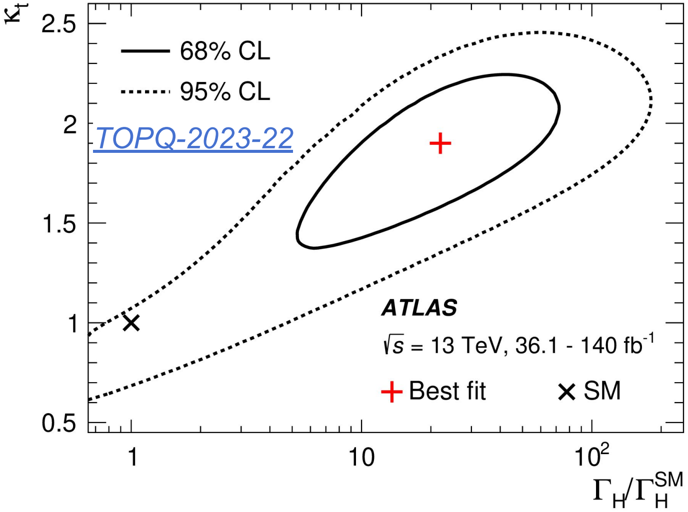
Top with on-shell and off-shell Higgs:





Use full Higgs combination to constrain the other couplings.

ttH is a tree level process,
no BSM in the loop
=> complementary to the ZZ channel



$$\Gamma_H < 110\,\Gamma_{\rm H}^{SM}\ (95\%\ \mathrm{CL})$$

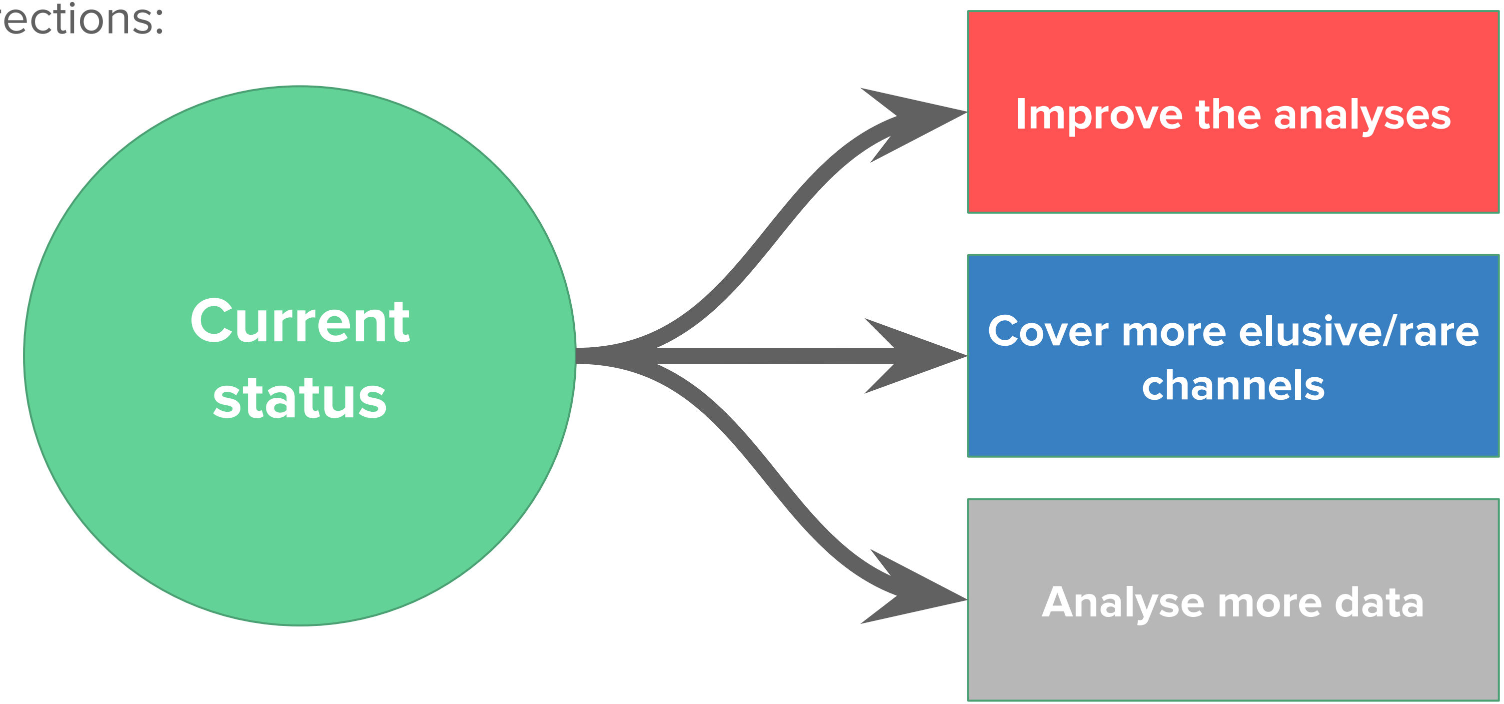
Expected: $\Gamma_H < 18\,\Gamma_{\rm H}^{SM}\ (95\%\ \mathrm{CL})$
(small excess of 4t on data)

(some) open questions

- Are there anomalies in the interaction of the Higgs boson with:
  - the W and Z bosons?
  - the fermion sector?
  - itself?
- Does the Higgs boson decay into pairs of different flavour fermions?
- Are there CP violating Higgs decays?
- Are there new modes of the Higgs boson decay?
- Is the Higgs boson width consistent with the SM prediction?
- Can the Higgs boson act as a portal for an hidden sector?
- Is there an extended Higgs sector?
- ... and many more!

(some) open questions

Directions:

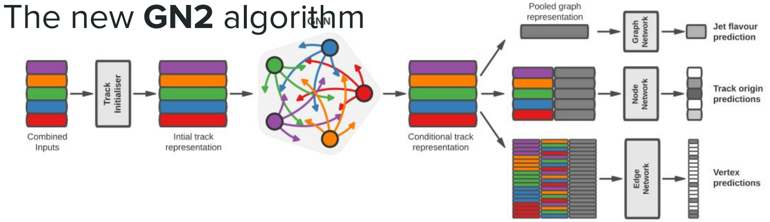


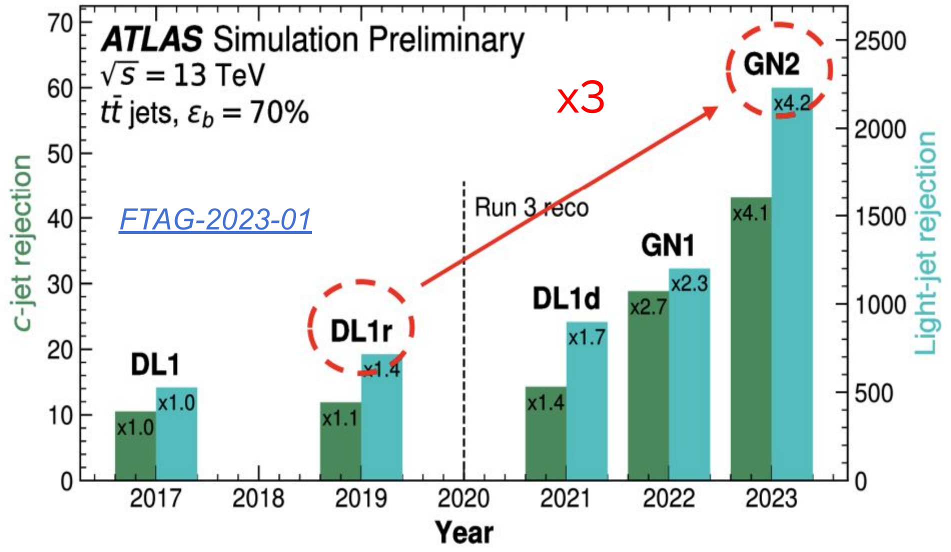
An example of improvements in experimental techniques

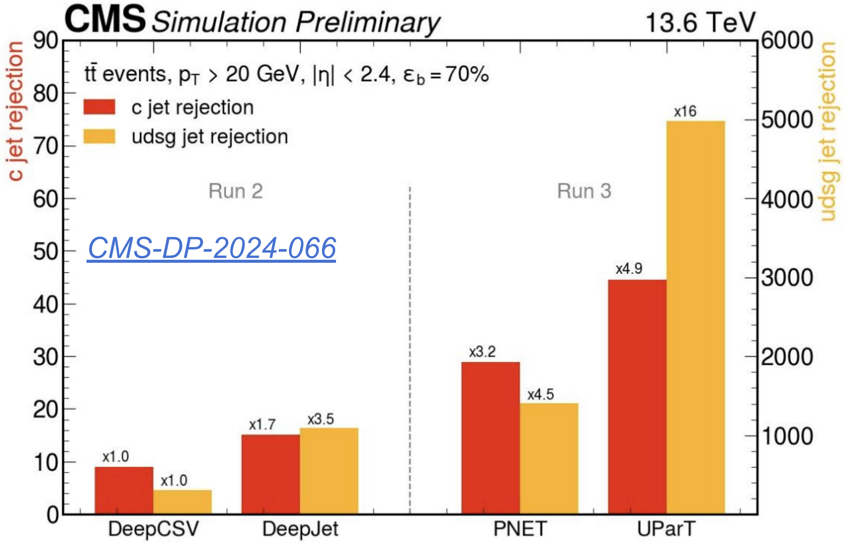
Rapid progress in techniques:

- **BDT => DNN => GNN,Transformers, etc.**

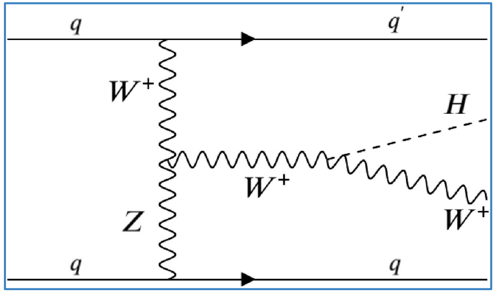
The new **GN2** algorithm

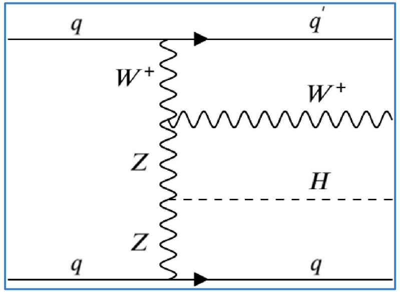


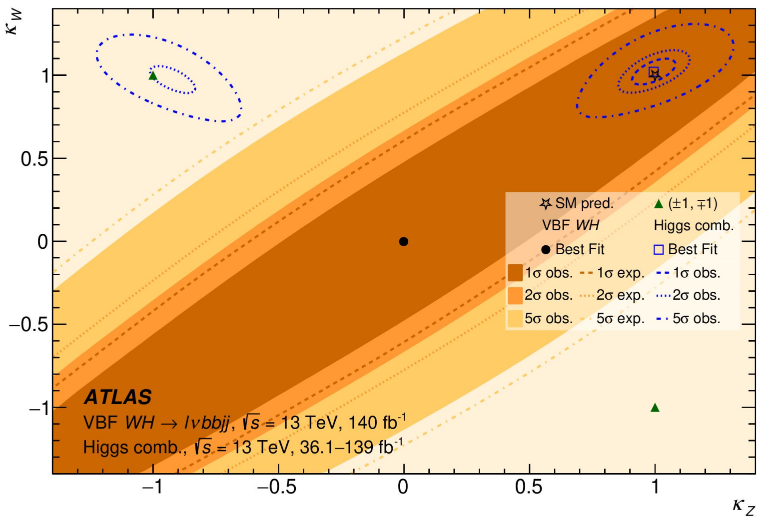




An elusive/rare channel: WH produced via VBF







HIGG-2021-21
accepted by PRL - Editor selection

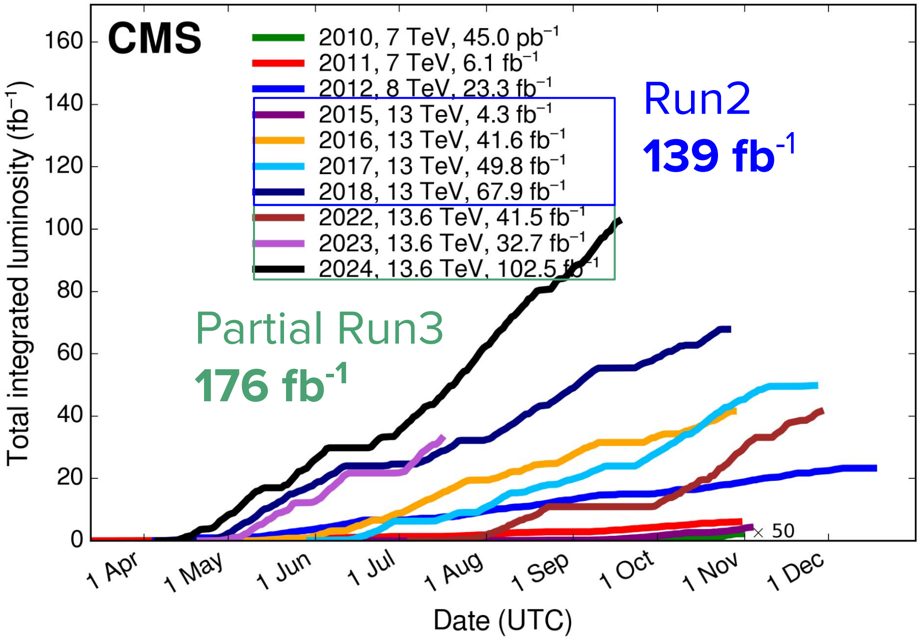
Thanks to the interference in the VBF WH production, we can determine the relative sign of κ_W and κ_Z.

Different relative sign excluded with > 5 σ

Similar results from CMS

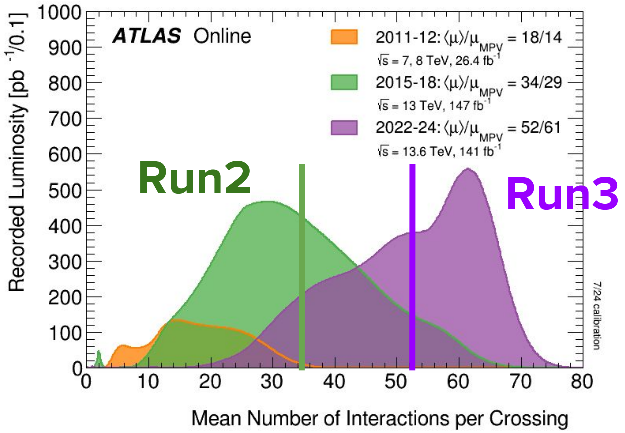
CMS-HIG-23-007

The data we can use



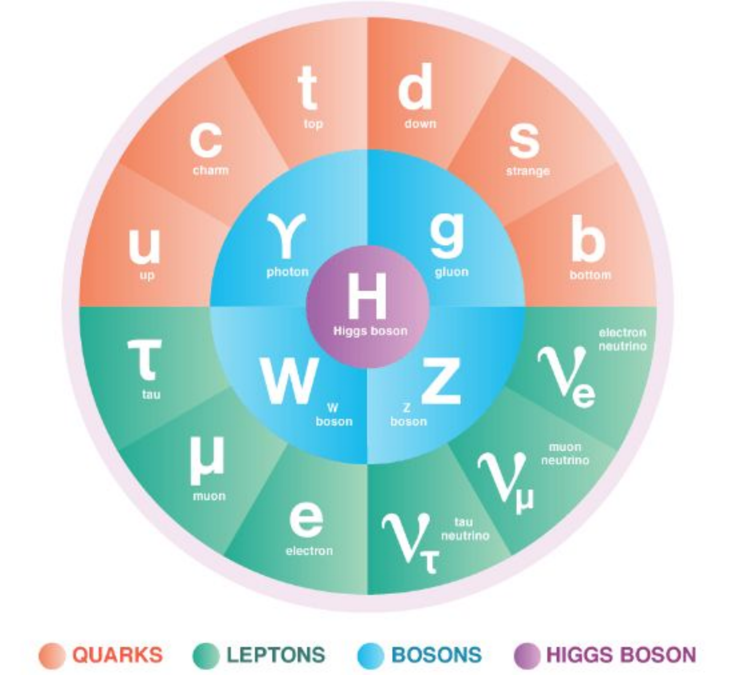
[CMS Luminosity Public Results]

- Run3: **2022 - 2025 (?)**
- More integrated luminosity than Run2+Run1
- Almost twice the number of interactions per bunch crossing

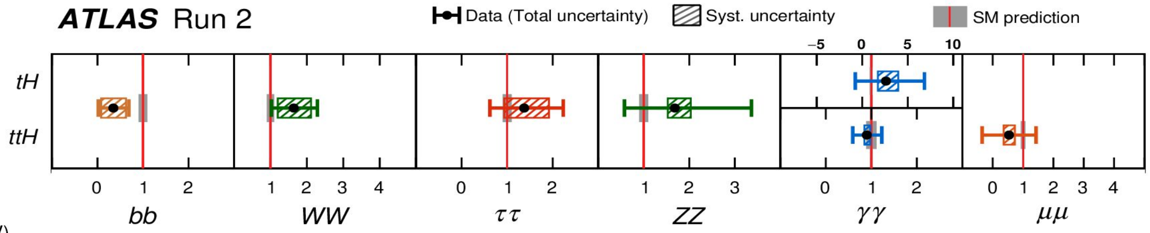


[ATLAS Public Luminosity Results]

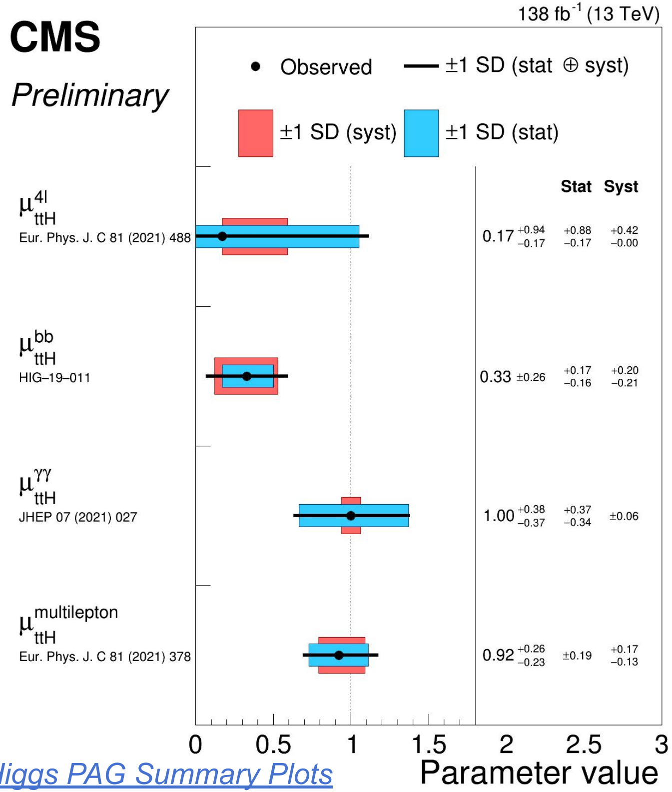
New Run2 results: Single Higgs



Higgs-top coupling



Nature 607 52 (2022)



Higgs PAG Summary Plots

ttH ⇒ tree-level Higgs-top coupling

⇒Exploit the different decay channels.

Precisions per experiments in Run2 :

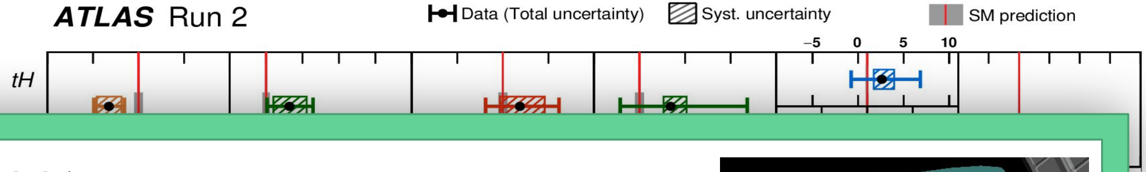
- H→γγ: ~35%
- H→ML: ~25%
- H→bb: ~26-27%,

H→bb has the largest Higgs BR (58%)

BUT: it is a complex signature:
4b + 2 W (1 or 2 leptons (e|μ))

Can we do better?

Higgs-top coupling



CM

Pre

μ^{4l}_{ttH} Eur. Ph

μ^{bb}_{ttH} HIG–19

$\mu^{\gamma\gamma}_{ttH}$ JHEP (

μ^{mu}_{ttH} Eur. Ph

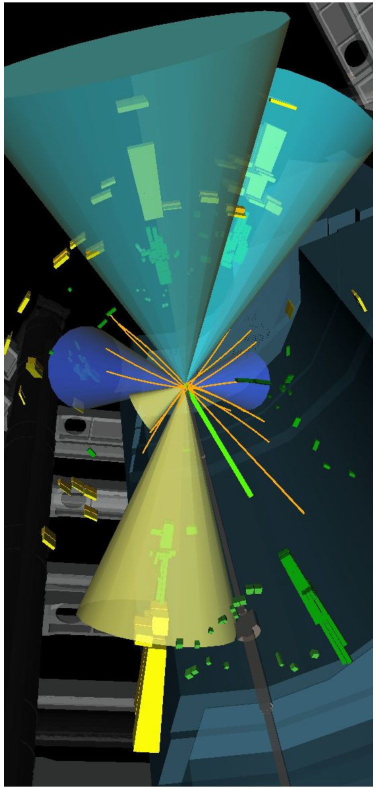
- Improved b-tagging (DL1r)
- Improved modeling of backgrounds (tt+b(b)…),
- Looser selection for better control.
- Use of transformer networks to separate signal and background, reconstruct $p_T(H)$

Overall uncertainty improved by factor 1.8,

4.6σ observed

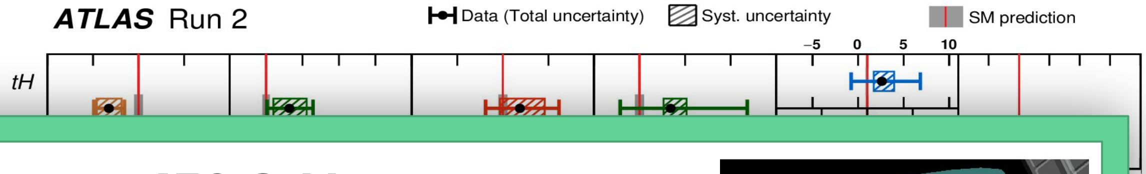
$$\mu_{ttH} = 0.81 \,^{+0.22}_{-0.19} \left(^{+0.20}_{-0.16} \text{ syst.} \right)$$

HIGG-2020-24



Parameter value

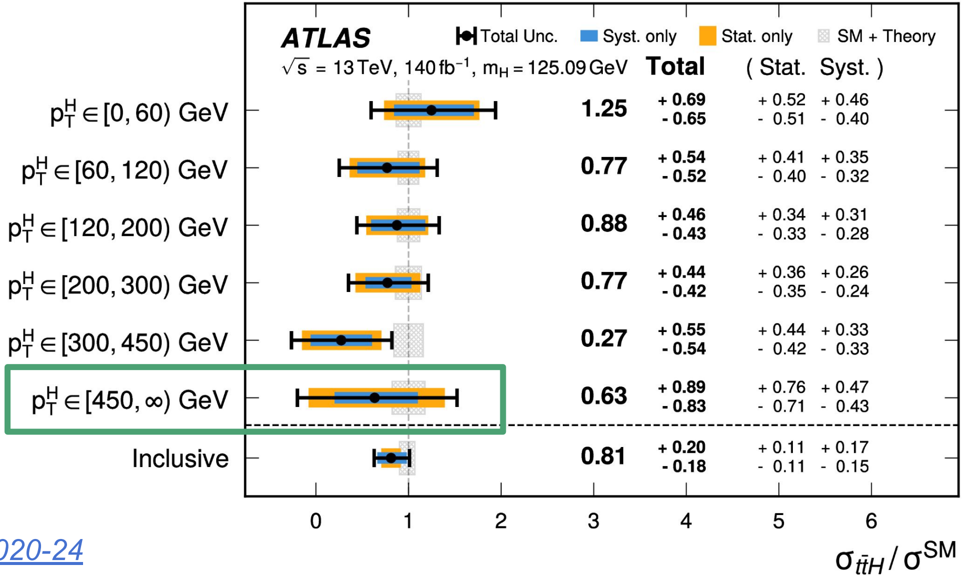
Higgs-top coupling

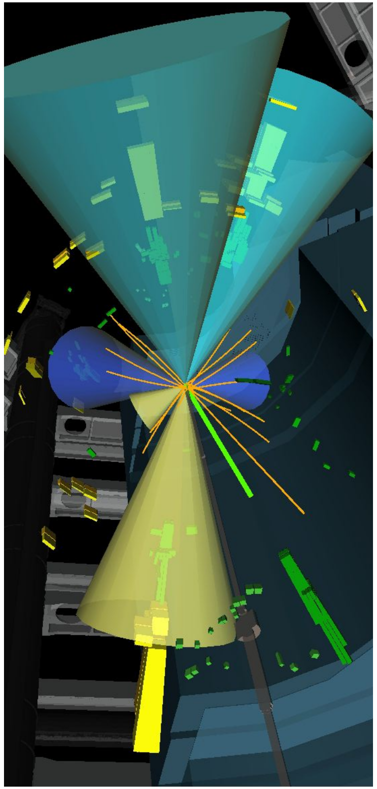


Measure $\sigma_{tt}(H)$ in $p_T(H)$ bins **up to 450 GeV.**

Best single measurement to date.

⇒ Test SM in extreme phase-space





HIGG-2020-24

Parameter value

Higgs-charm coupling

H→bb largest Higgs BR (58%)

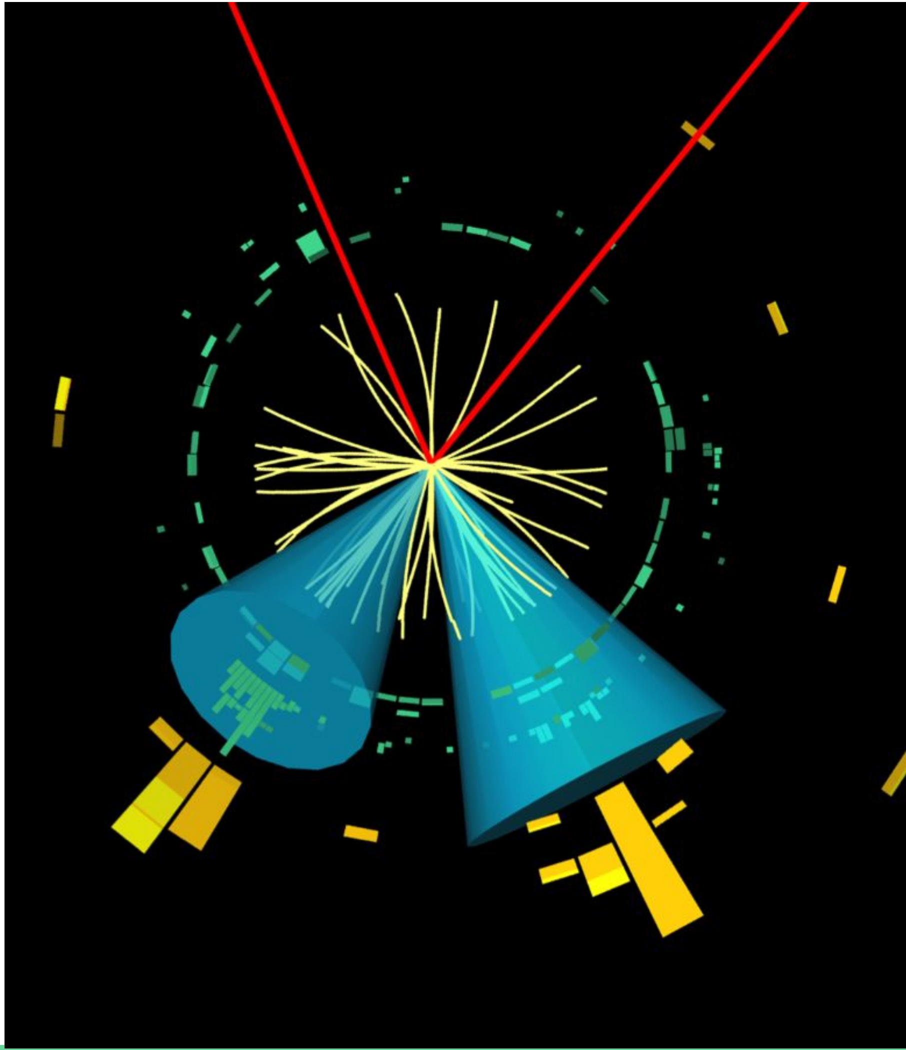
H→cc largest BR to 2nd gen. fermions (2.9%)

(V→lep)H most sensitive mode to access both.

Require b-jets or c-jets,

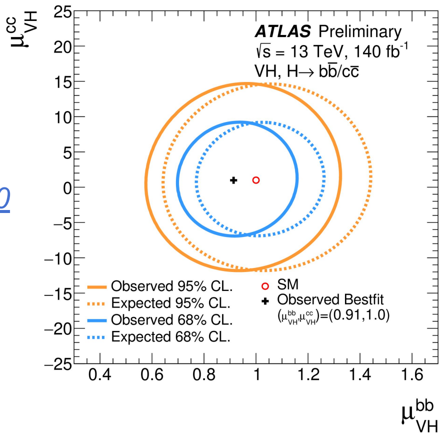
split signal in $N_{leptons}$:

- 0 (Z→νν),
- 1 (W→lν)
- 2 (Z→ll)



Higgs-charm coupling

ATLAS



ATLAS-CONF-2024-010

Simultaneous fit with VH→bb

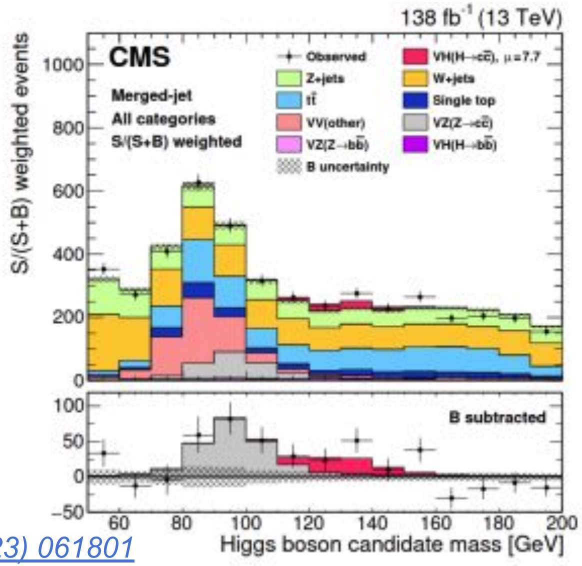
Best limit to date

Factor 2.5 improv. over previous limit !

⇒ |κc| < 4.2 @ 95% CL

X2 improvement over previous

CMS



[PRL 131 (2023) 061801](PRL 131 (2023) 061801)

With boosted H→cc (p_T(H) >300 GeV)

Best expected sensitivity

⇒ 1.1 < |κc| < 5.5

First observation of Z→cc in had. coll.

ATLAS-CONF-2024-010

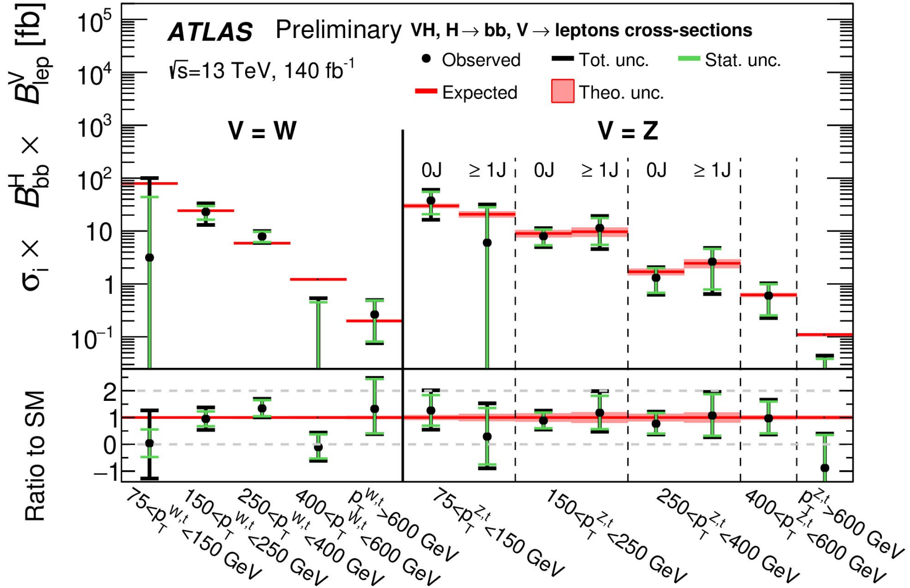
Higgs-bottom coupling

Uncertainties reduced by ~20%,

First observation of WH→bb (5.3σ)

$$\mu_{WH} = 0.95 \,^{+0.21}_{-0.19} \left(\,^{+0.15}_{-0.13} \text{ syst.} \right)$$

$$\mu_{ZH} = 0.87 \,^{+0.23}_{-0.20} \left(\,^{+0.18}_{-0.14} \text{ syst.} \right)$$

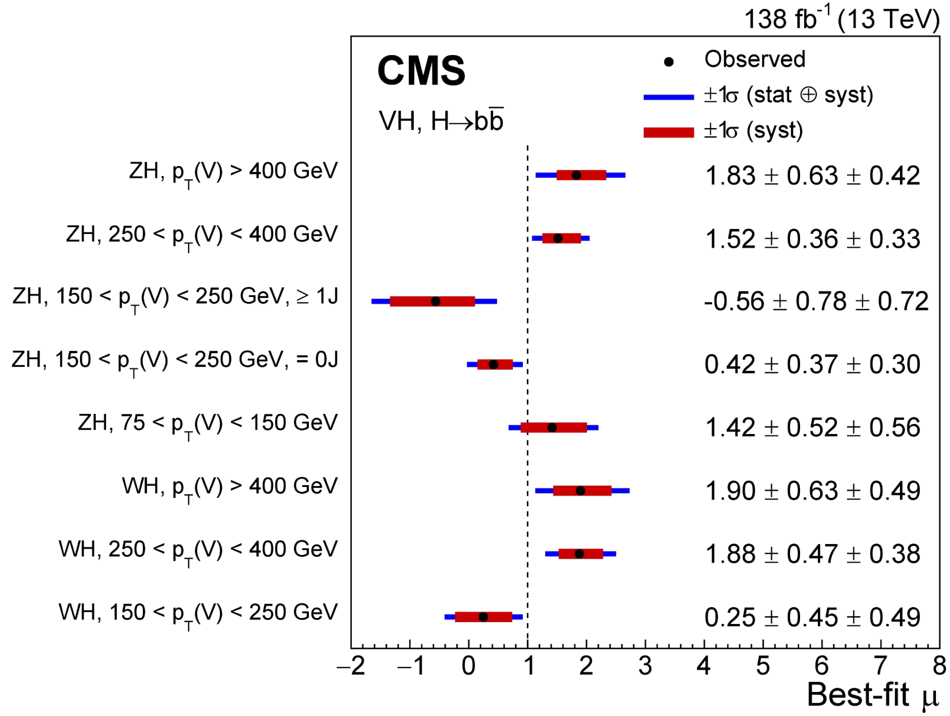


Phys. Rev. D 109 (2024) 092011

Results compatible with SM

$$\mu_{WH} = 1.31 \pm 0.24 \pm 0.26$$

$$\mu_{ZH} = 1.07 \pm 0.17 \pm 0.17$$



ATLAS-CONF-2024-010

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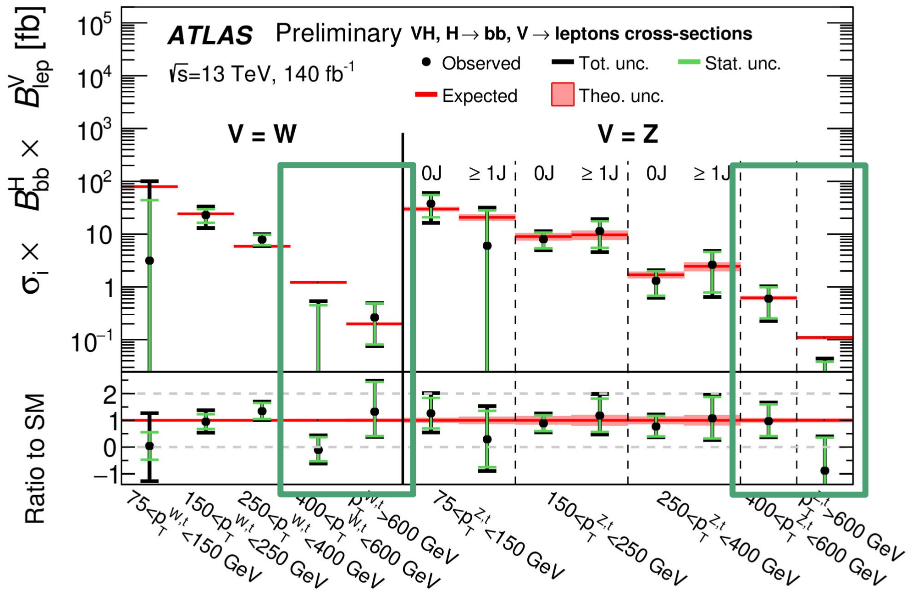

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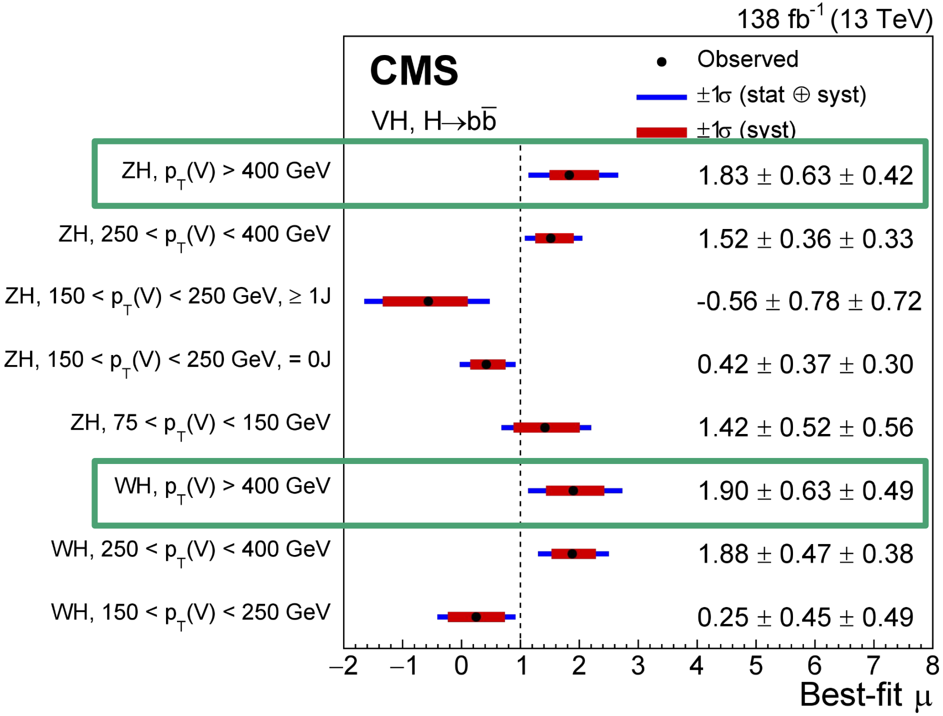
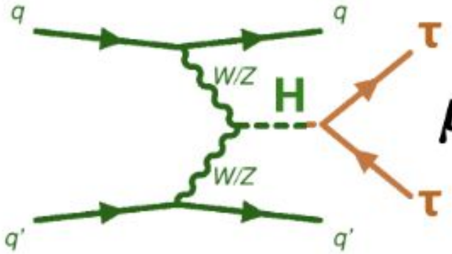


Higgs-tau coupling

HIGG-2022-07

$H \rightarrow \tau\tau$ largest BR to leptons (6%)

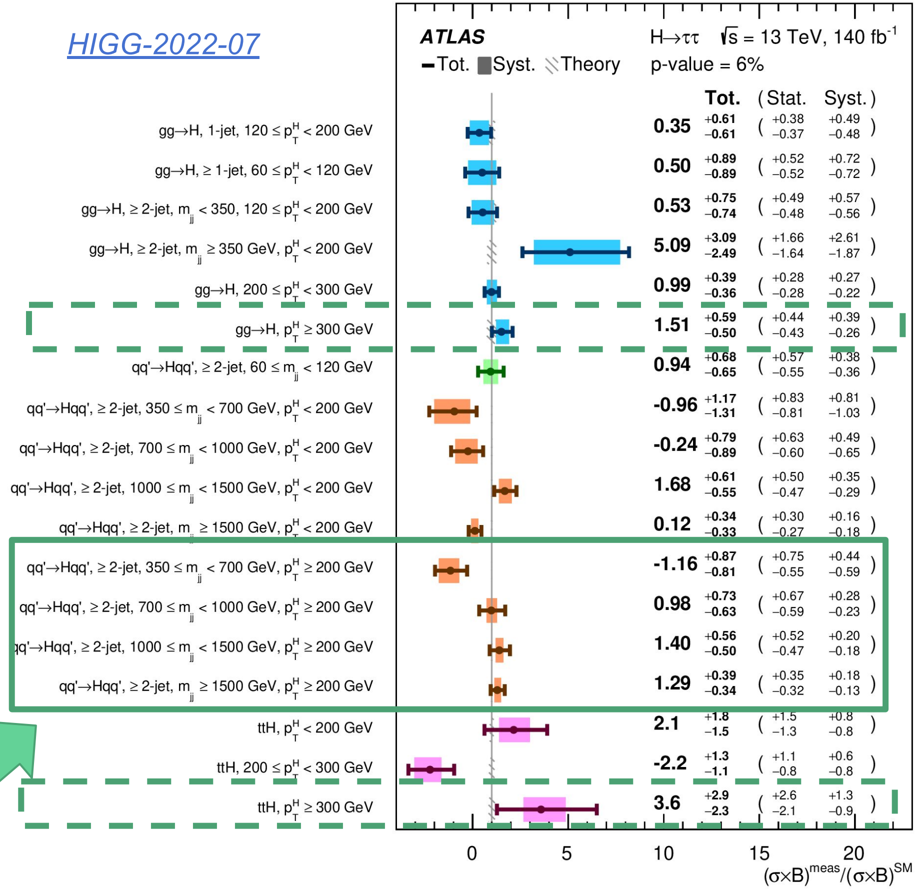
Sufficient statistics and low enough backgrounds for precise measurements for **VBF**:



$$\mu_{\mathrm{VBF}} = 0.93\,^{+0.17}_{-0.15}$$

Most precise measurement to date

First measurement in multiple m_{jj} bins for the higher $p_T(H)$



Higgs-tau coupling

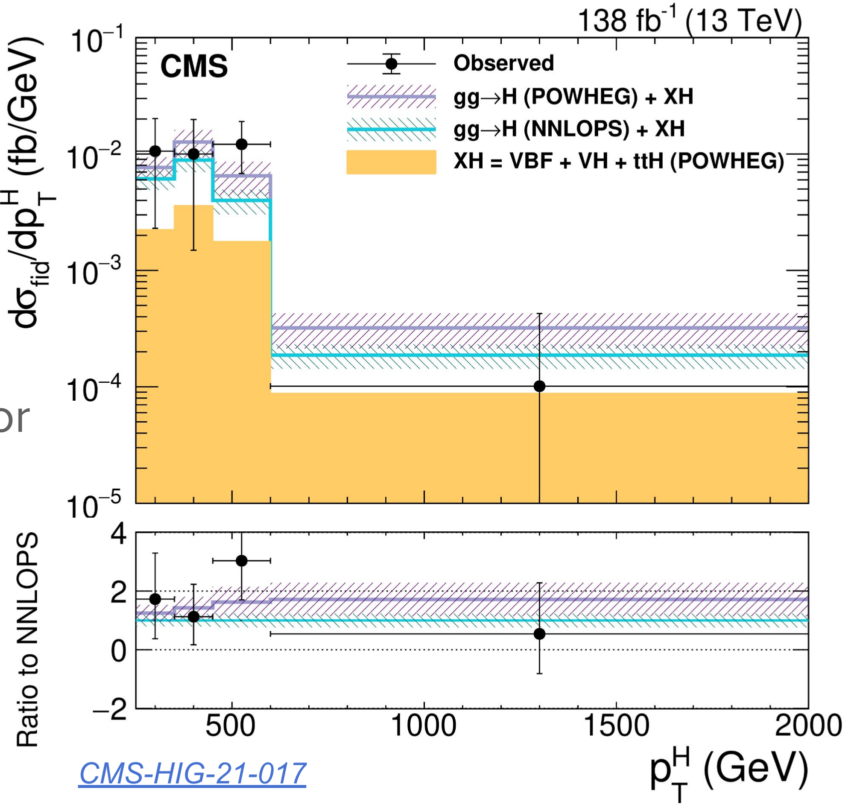
HIGG-2022-07

Sufficient statistics and low enough backgrounds for precise measurements at **high p_T(H)**:

First measurement of boosted high p_T(H) using the H → ττ

Dedicated reconstruction algorithm for the boosted ττ topologies

Among the most precise measurements in the p_T(H) regime



CMS-HIG-21-017

Differential measurements

Combine measurements using

- **H→γγ**
- **H→ZZ*→4l**
- **H→WW***
- **H→ττ**
- **H→ττ boosted**

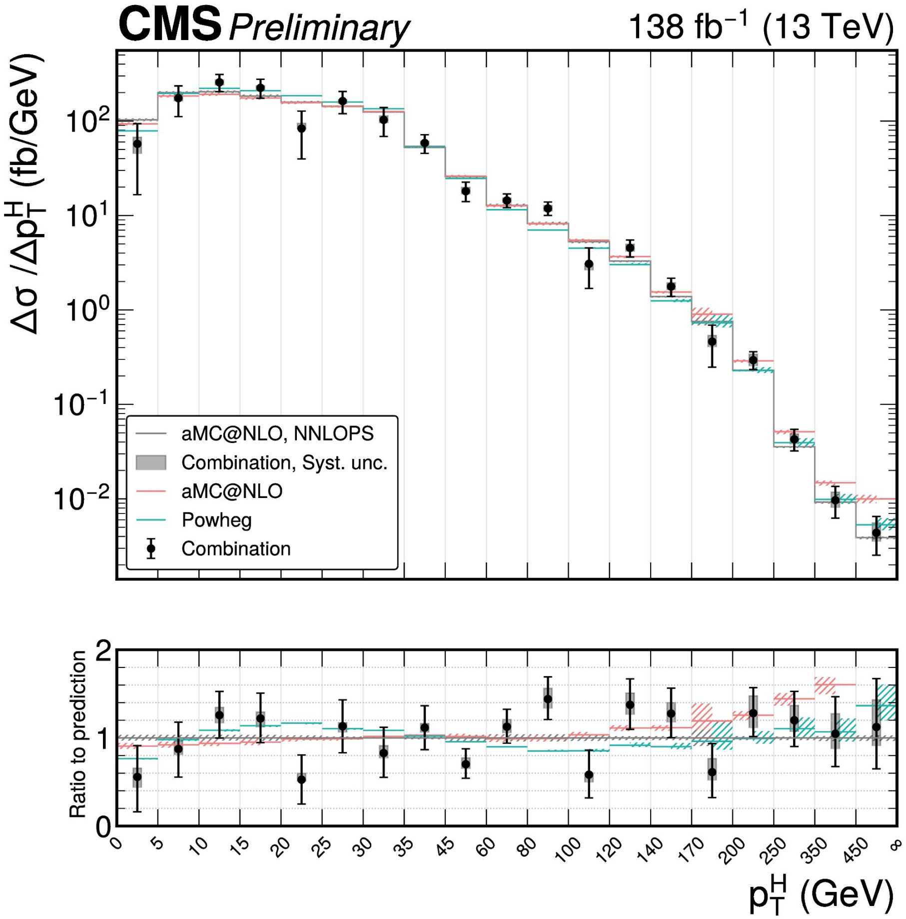
High-precision channels (H→γγ, H→ZZ*→4l)

Sensitive to high-p_T^H region (H→ττ, H→ττ boosted)

Test of the SM over a wide $p_T(H)$ range.

Also N_{jets}, $p_T(j_1)$, $\Delta\varphi_{jj}$, …

Good agreement of the distributions with the SM



CMS-PAS-HIG-23-013

Differential measurements

Combine measurements using

- **H→γγ**
- **H→ZZ*→4l**
- **H→WW***
- **H→ττ**
- **H→ττ boosted**

High-precision channels (H→γγ, H→ZZ*→4l)

Sensitive to high-p_T^H region (H→ττ, H→ττ boosted)

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Also N_{jets}, $p_T(j_1)$, $\Delta\varphi_{jj}$, ...

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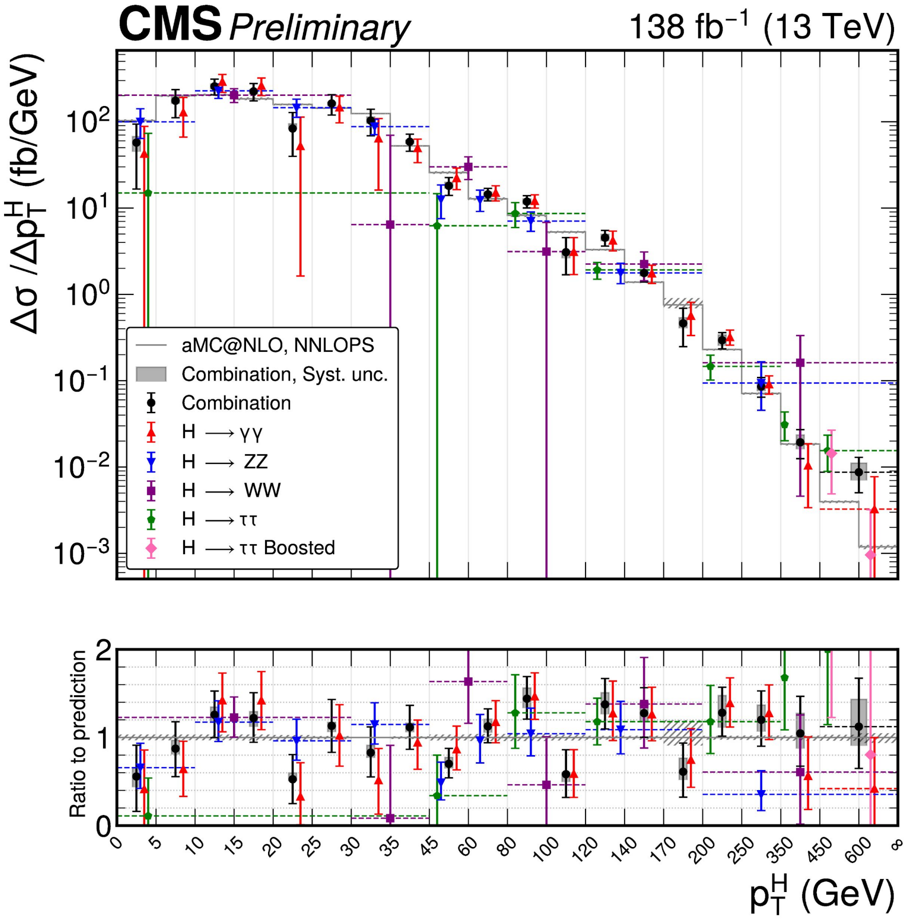
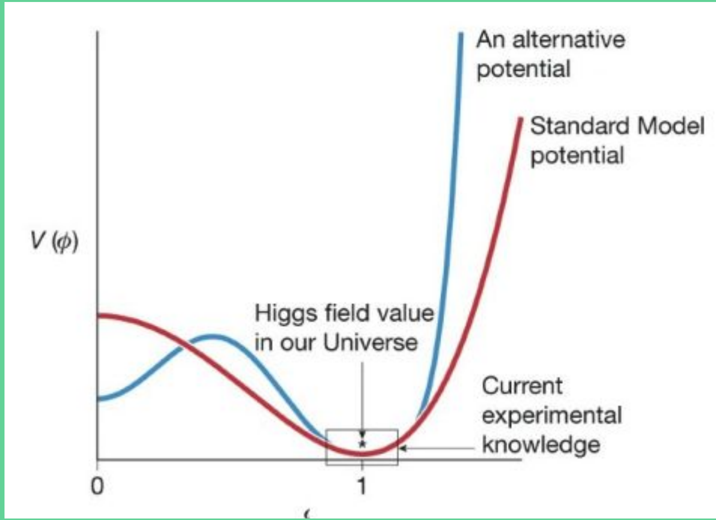


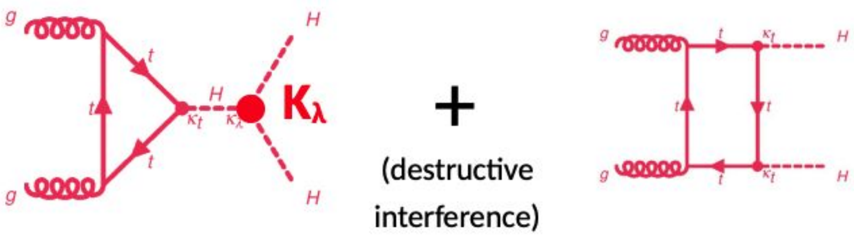
CMS-PAS-HIG-23-013

New Run2 results: Double Higgs and self couplings



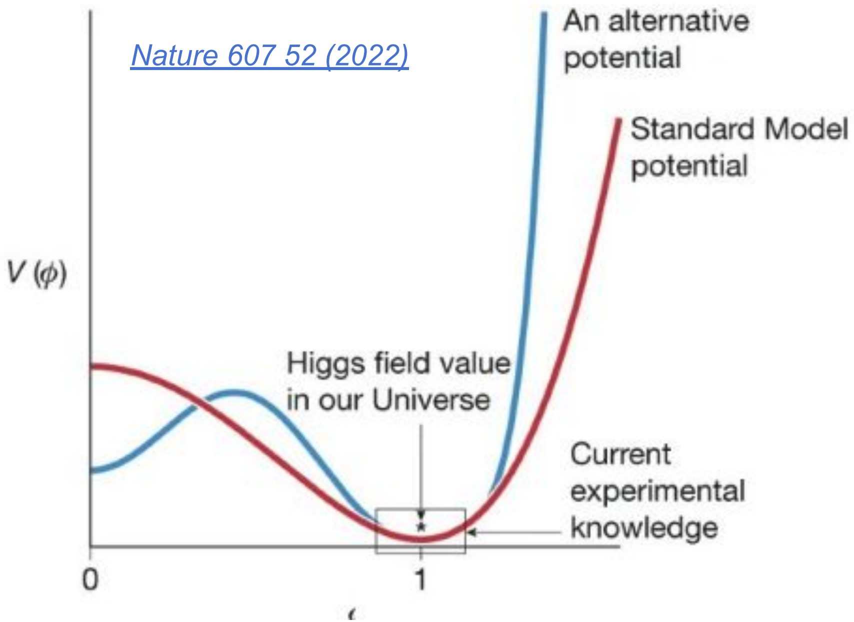
Higgs pairs at LHC

pp→HH : 1000× smaller than pp→H

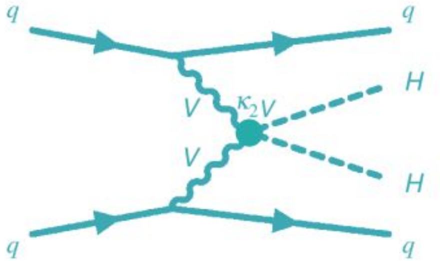


Access the triple Higgs boson coupling (κ_λ)

⇒Probe the shape of the Higgs potential



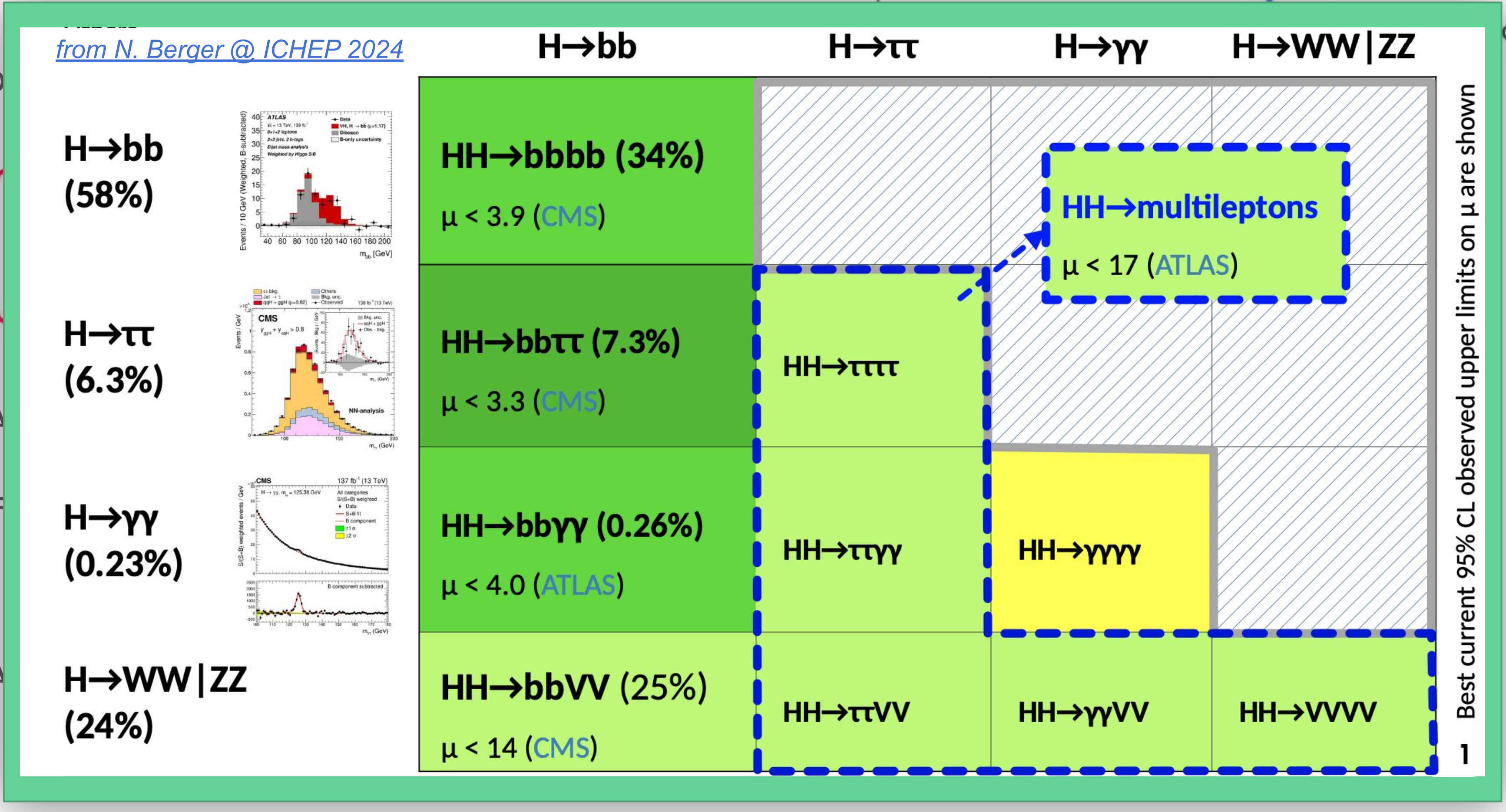
Also accesses other interactions, e.g. VVHH (κ_{2V})



Higgs pairs at LHC

An alternative potential

del



ATLAS Run 2 combinations

Combine HH→bbττ + bbγγ + bbbb + multileptons + bbll+MET:

$$\mu_{HH} = 0.5\,^{+1.2}_{-1.0}\left(\,^{+0.7}_{-0.6}\ \text{syst.}\right)$$

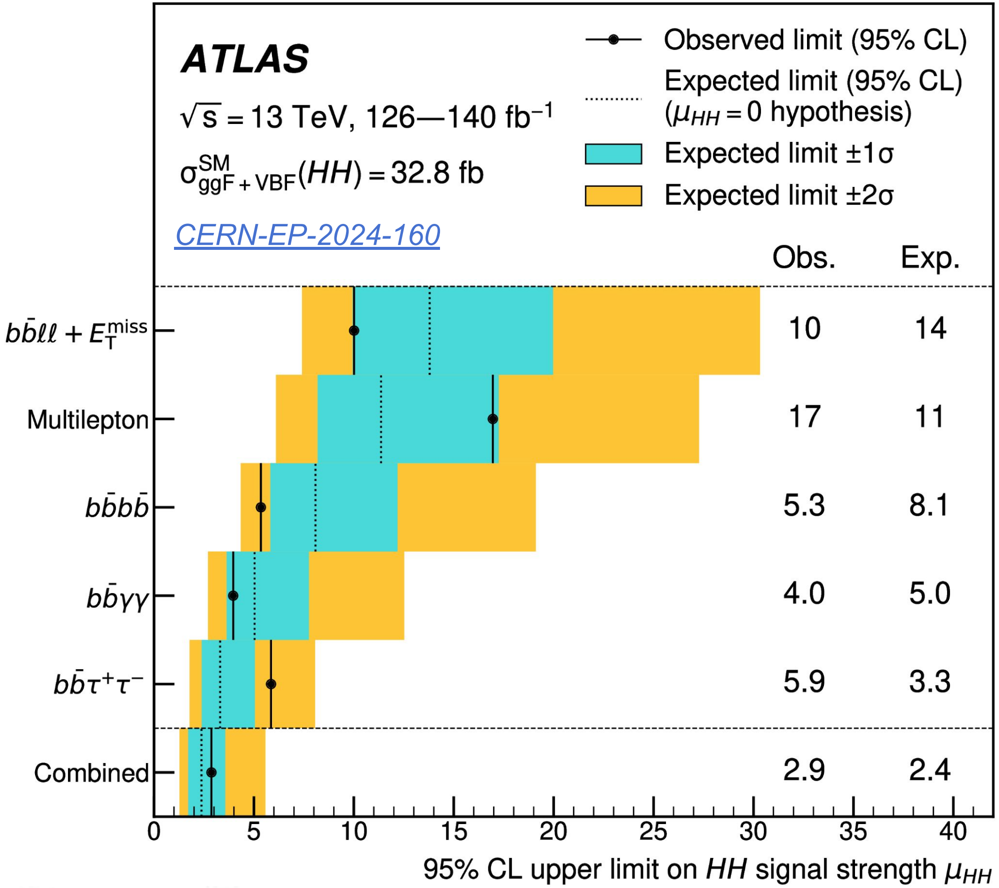
Uncertainty comparable to SM signal!

-1.2 < κ$_\lambda$ < 7.2 @ 95% CL

Dominated by γγbb + ττbb Best constraint to date on λ3 coupling!

0.6 < κ$_{2V}$ < 1.5 @ 95% CL

Dominated by VBF HH→bbbb Best constraint from CMS: **0.67 < κ$_{2V}$ < 1.38 @ 95% CL**



CMS HH Combination results:
Nature 607 (2022) 60-68

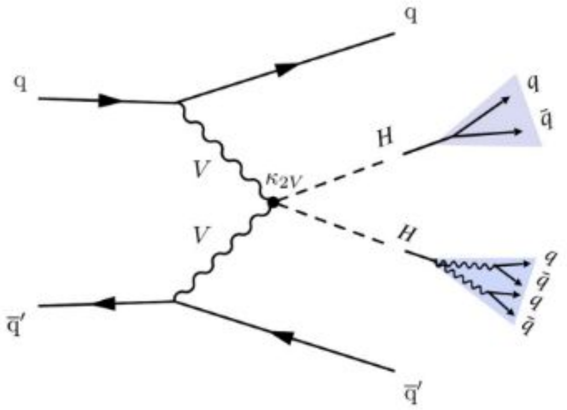
CMS VBF HH→bbVV

CMS-PAS-HIG-23-012

Search for VBF HH→bbVV production

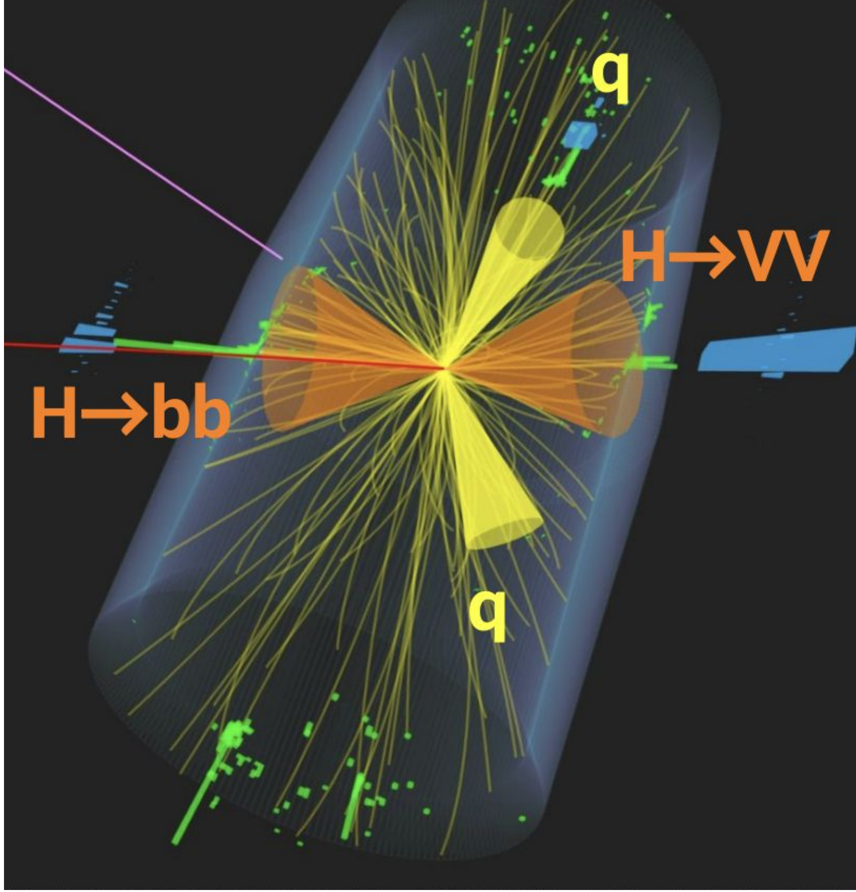
Consider collimated hadron decays:

H→bb tagger and H→VV tagger



Observe μ_{HH} < 142 (69 exp.)

and $-0.04 < \kappa_{2V} < 2.05$ @ 95% CL



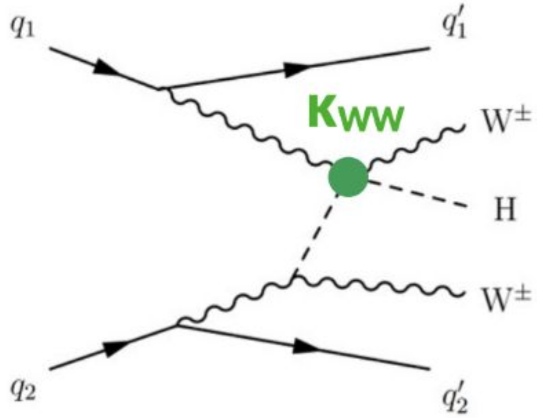
ATLAS VBF HH→4b results: HDBS-2022-02

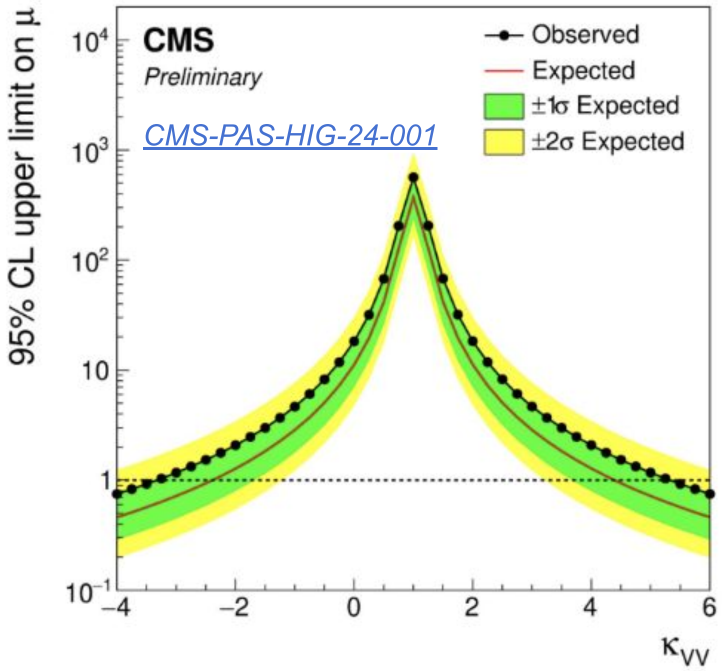
$0.55 < \kappa_{2V} < 1.49$ @ 95% CL

CMS Search for WWH(bb) in VBS

Analysis of H(bb) + $W^{\pm}W^{\pm}(l^{\pm}\nu l^{\pm}\nu)$ produced in Vector Boson Scattering (VBS)

Sensitive to κ_{2W}

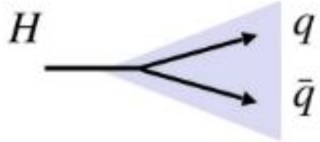




$-3.33 < \kappa_{WW} < 5.33$ @ 95% CL

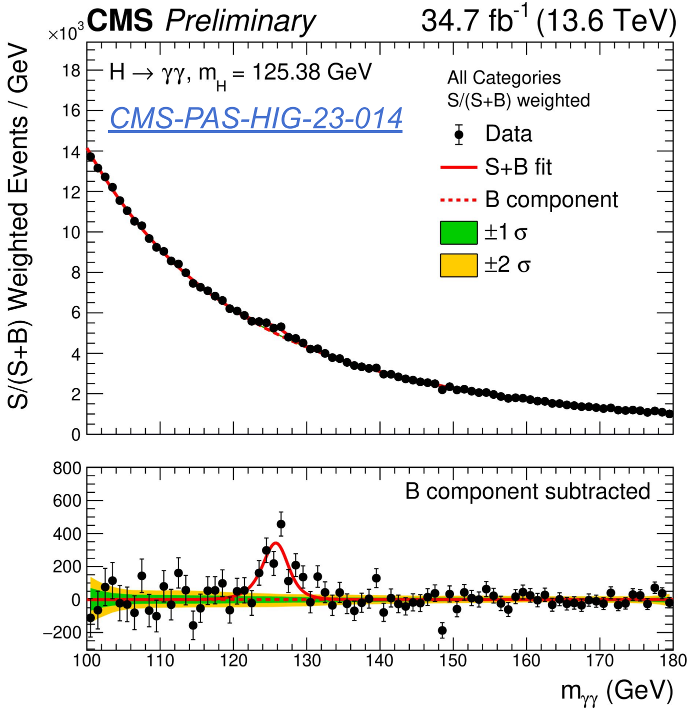
First analysis targeting κ_{2W} using single H

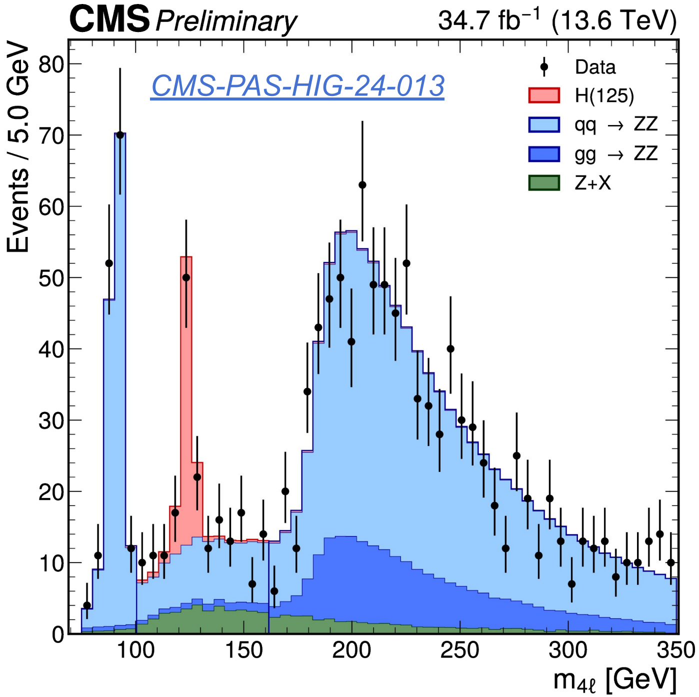
H(bb) reconstructed as a single Large-R jet



New results:
Run3 measurements

CMS Run3 Hγγ and H4l at 13.6 TeV





Measure Hγγ and H4l in Run3 data (34.7 fb-1 collected in 2022).

Fiducial x-sect.:

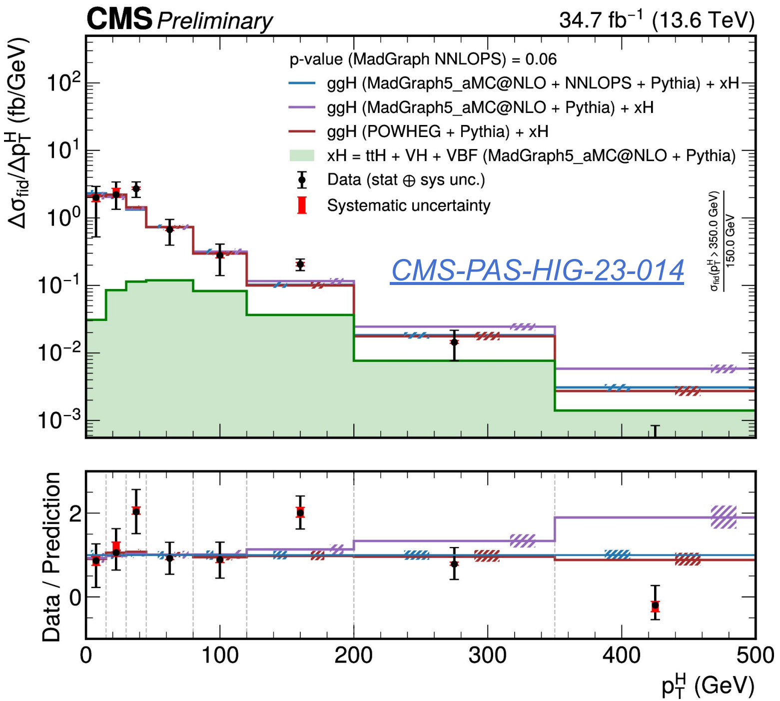
$$\sigma_{\mathrm{fid},\gamma\gamma} = 78 \pm 11\ (\mathrm{stat.})\ ^{+6}_{-5}\ (\mathrm{syst.})\ \mathrm{fb}\ (\mathrm{SM:}\ 67.8 \pm 3.4\ \mathrm{fb})$$

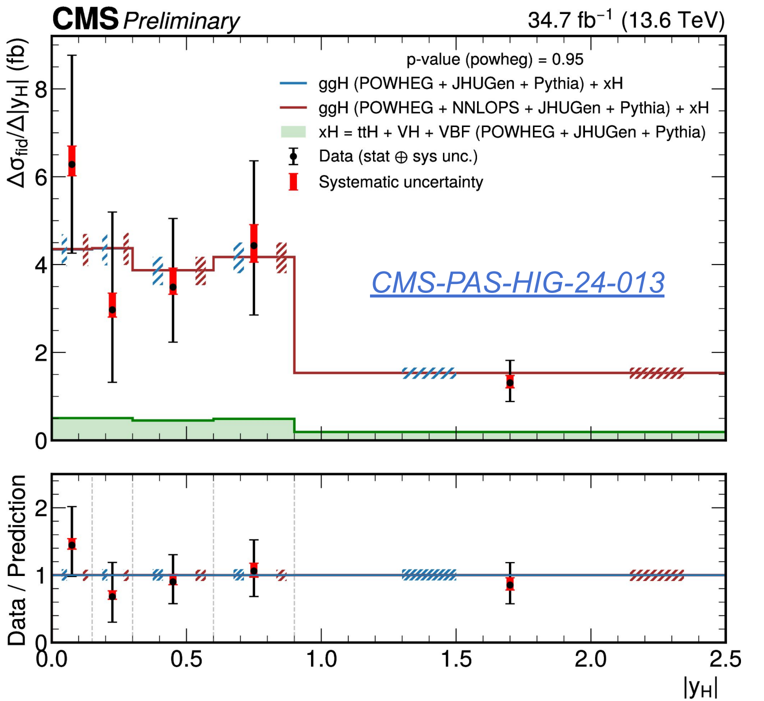
$$\sigma_{\mathrm{fid},4l} = 2.94^{+0.53}_{-0.49}\ (\mathrm{stat.})\ ^{+0.29}_{-0.22}\ (\mathrm{syst.})\ \mathrm{fb}\ (\mathrm{SM:}\ 3.09^{+0.39}_{-0.31}\ \mathrm{fb})$$

Similar results from ATLAS:

Eur. Phys. J. C 84 (2024) 78

CMS Run3 Hγγ and H4l at 13.6 TeV





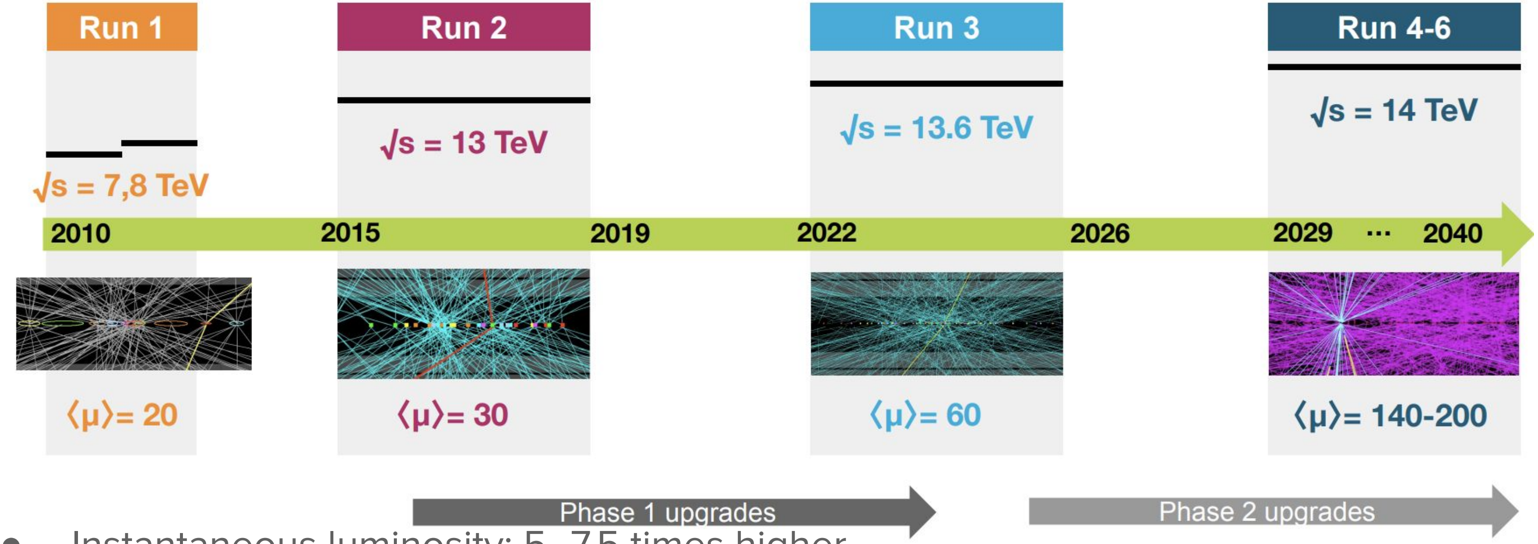
Measure Hγγ and H4l in Run3 data (34.7 fb-1 collected in 2022).

Differential cross sections in $p_T(H)$, N_{jets}, … in agreement with predictions

Few slides on the future

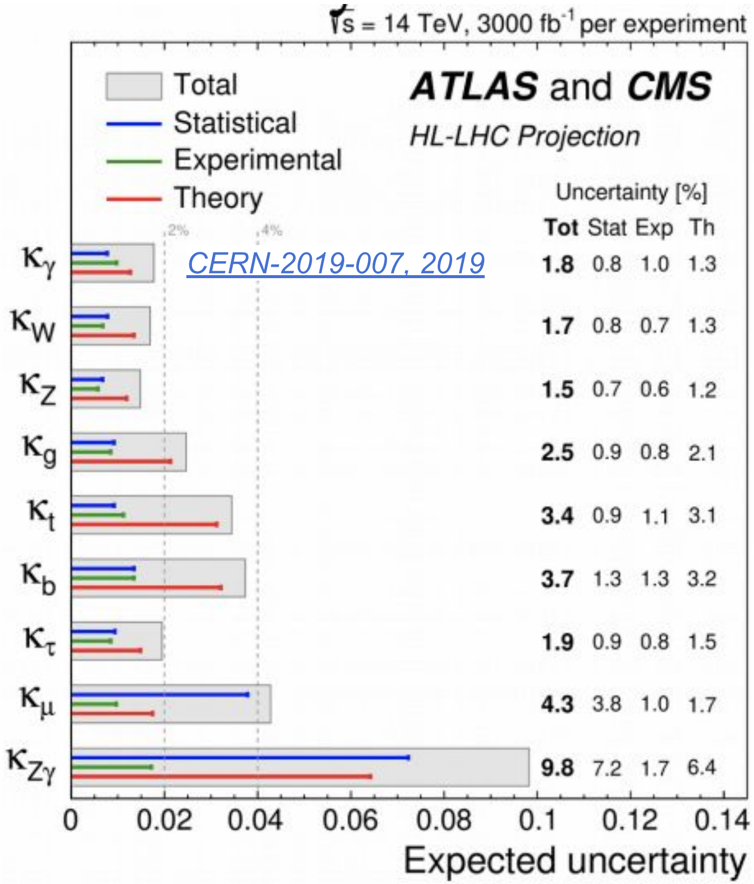
LHC schedule

From Liza's Brost slides



- Instantaneous luminosity: 5–7.5 times higher
  - Pile up will increase from 60 (now) to 140-200 (levelled)
  - Beam induced cavern background increases linearly
  - Much larger radiation to detectors
  - Larger data sample: big challenges for computing and data storage
- Require improvements for experiments in all areas
  - Detectors, Electronics & Trigger, Software and computing

Projections: Higgs couplings



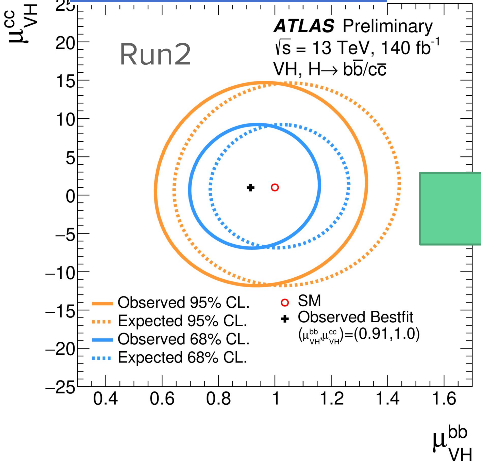
CERN-2019-007, 2019

Higgs couplings move into precision regime

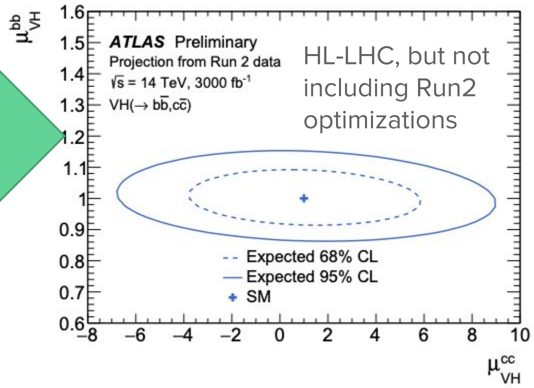
- Bosons and τ: <2% level
- 3rd generation quarks: 3.5%

Most of them dominated by theory uncertainties

ATLAS-CONF-2024-010

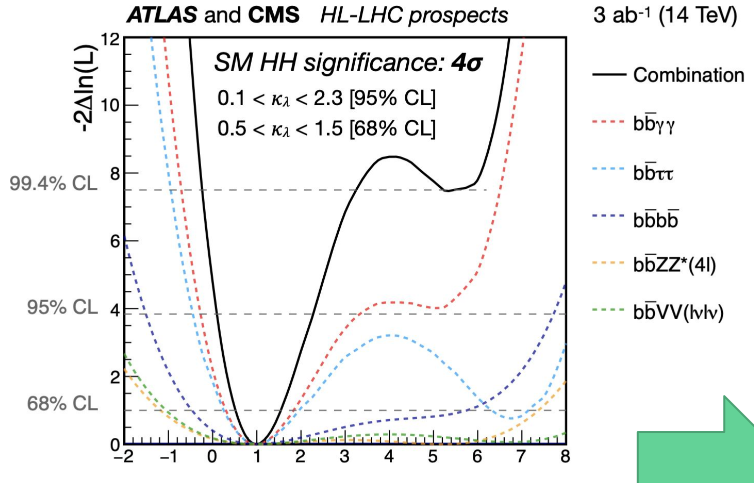


ATLAS: ATL-PHYS-PUB-2021-039
CMS: PRL 131 (2023) 061801



Do we already know we can do better?

Projections: Higgs self-coupling



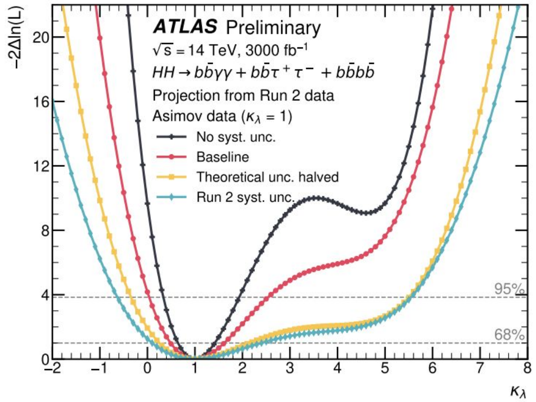
[CERN-2019-007, 2019](#)

European Strategy (2018)

Combination of 5 HH channels, based on partial Run2 results

50% precision in self coupling

4σ for SM HH (ATLAS + CMS)



[ATL-PHYS-PUB-2022-053](#)

Snowmass+ (2022)

ATLAS Updated bbbb, bbγγ, and bbττ, CMS updated bbγγ, γγWW, γγττ, ttHH

Likely 5σ from back of the envelope estimations

and today?

Conclusions

Conclusions

Very broad physics program on the Higgs boson at the LHC.

- Reaching an unforeseen level of precision for the amount of data we analysed!

- Significant reduction of uncertainties on all the couplings,
  - Second generation fermions are not anymore beyond our reach

- Di-Higgs is already reaching the SM sensitivity with Run2 data
  - And we have more Run3 collisions already on our disks!

- Completing the Run2 physics program
  - Final Run2 Combinations between LHC experiments

- Run3 offers us a unique opportunity to improve the precision of our measurements,
  - and surprises can always come….