Experimental Higgs Studies

- a landscape -

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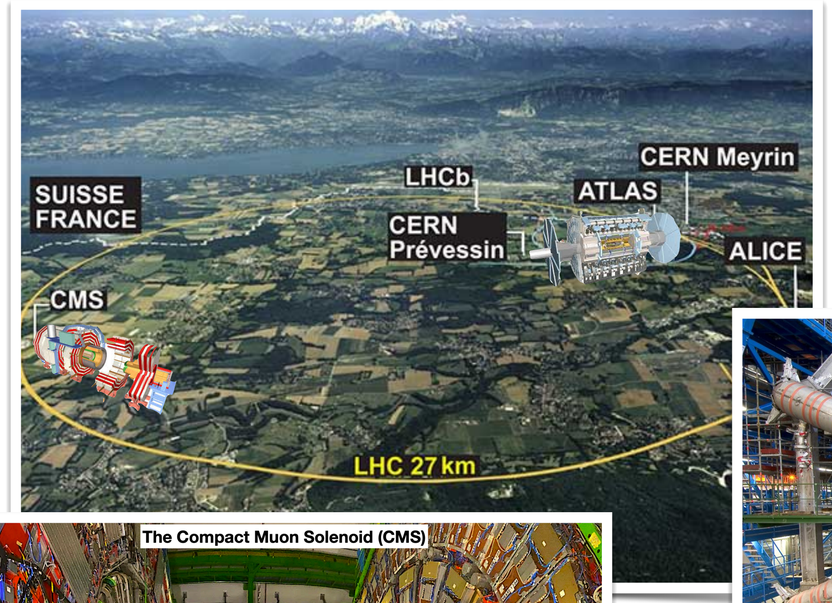
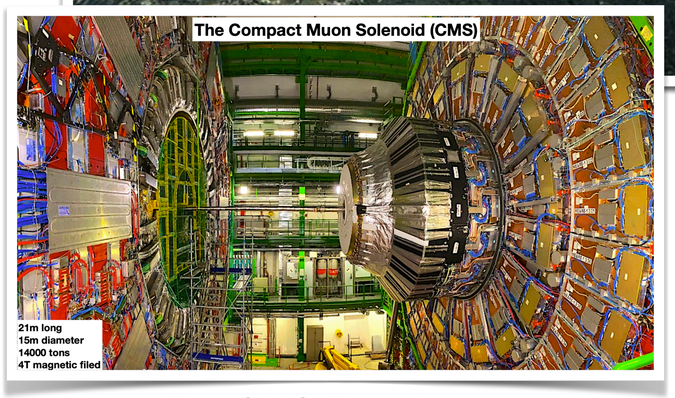
On behalf of the ATLAS and CMS collaborations

Aspen Center for Physics, March 2023

Outline

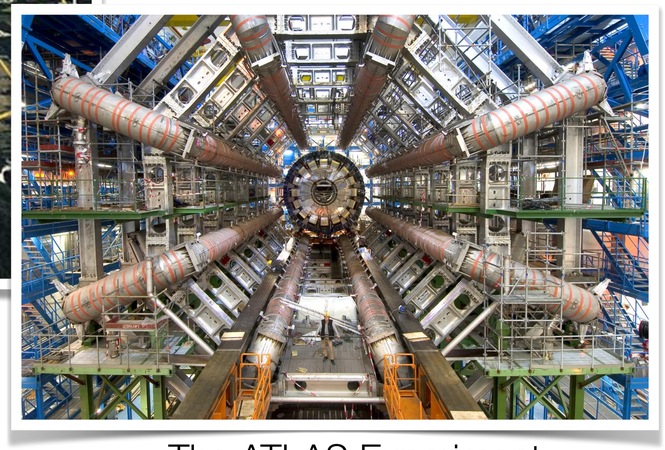
- Higgs Theory
  - See Carlos Wagner's talk :)
- The LHC landscape
  - The enablers
- Higgs Studies - a perspective
  - In a 20 min. nutshell
    - A flavor of what has been, and can be, done
      - but not all that has been done..
    - Illustrate w/ selected ATLAS and CMS results





The CMS Experiment

Nature 607, 60-68 (2022



The ATLAS Experiment

Nature 607, 52-59 (2022)

Higgs 10th Anniversary publications with legacy results from Run 2

Higgs studies include

Production
Decays
Bosons
Fermions

Self-coupling
Di-Higgs production
Resonant production
Other resonances

And more…

Mass
Width
Spin
CP

Rare Decays
Exotic decays
Invisible decays
Anomalous couplings
Multiple BSM connections

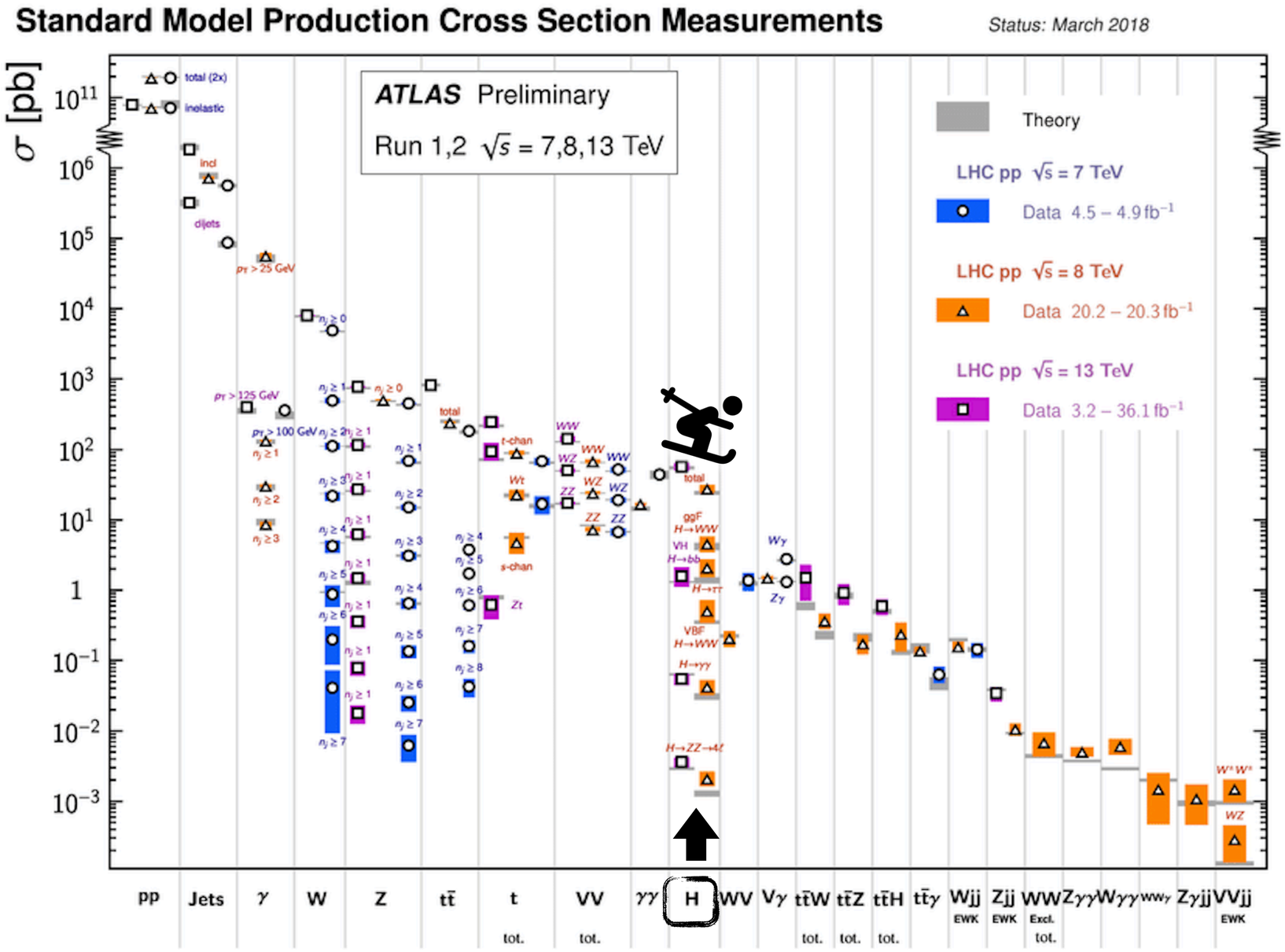
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

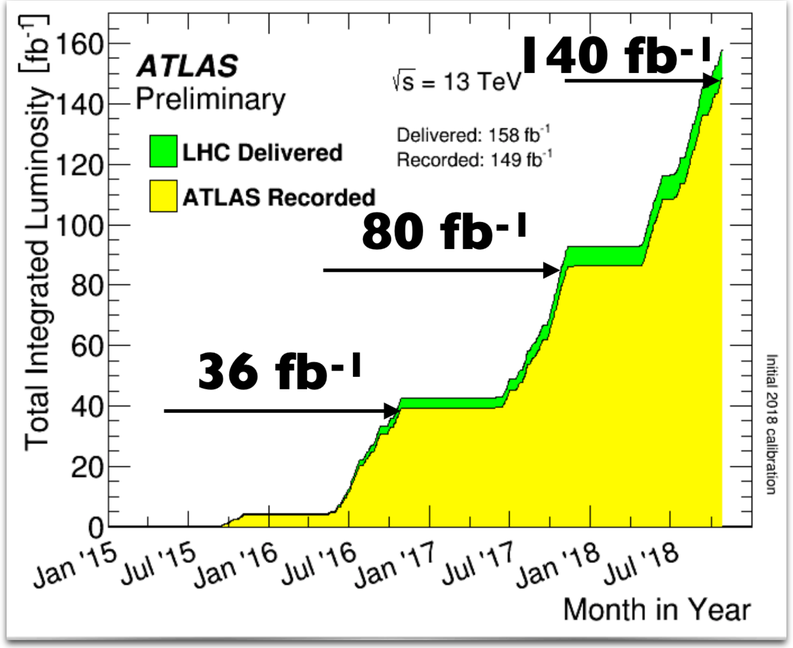
Several hundred publications !

Why can we do so much?

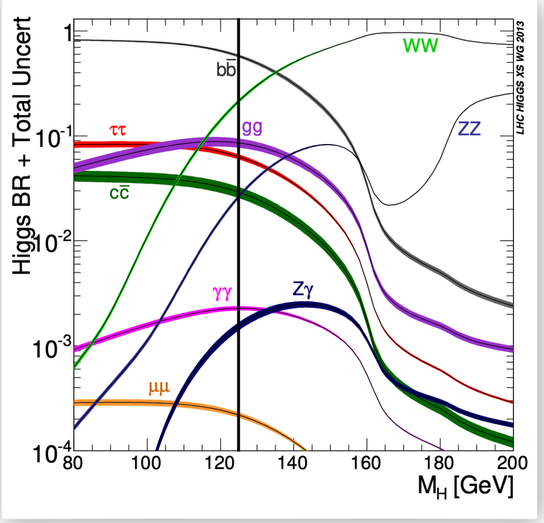
Why can we do so much?



1 Increasing LHC integrated luminosity

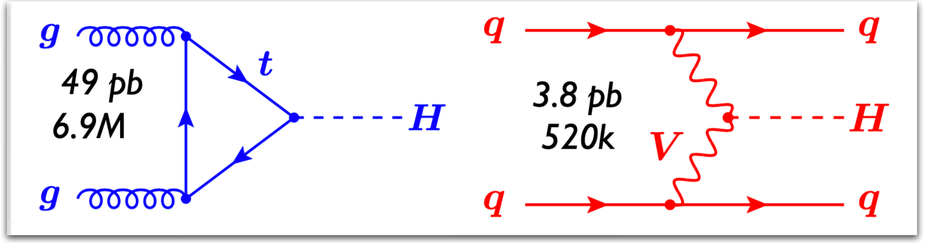


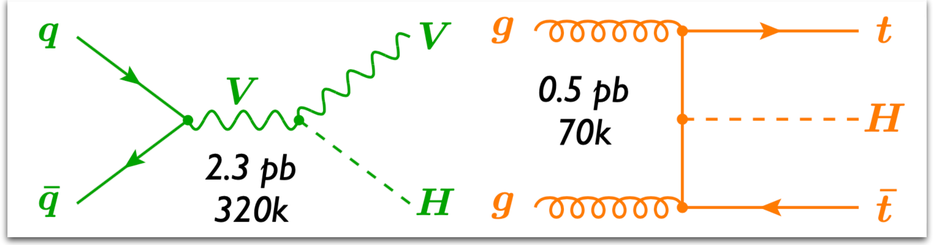
3 Rich decay modes @ 125 GeV



bb	WW	ττ	cc	ZZ	γγ	Zγ	μμ	gg, qq, ee
58%	21%	6.3%	2.9%	2.6%	0.23%	0.15%	0.022%	9%

2 Multiple production modes



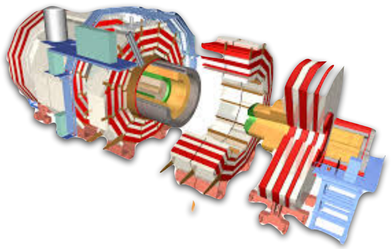


gg	VBF	WH	ZH	ttH	tH	bbH
87.2%	6.8%	2.5%	1.6%	0.9%	0.2%	0.9%

O(10M events produced / experiment)

Multi-purpose detectors + Novel analysis techniques

4



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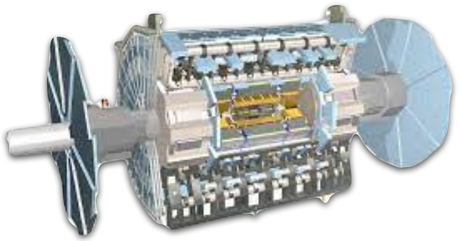
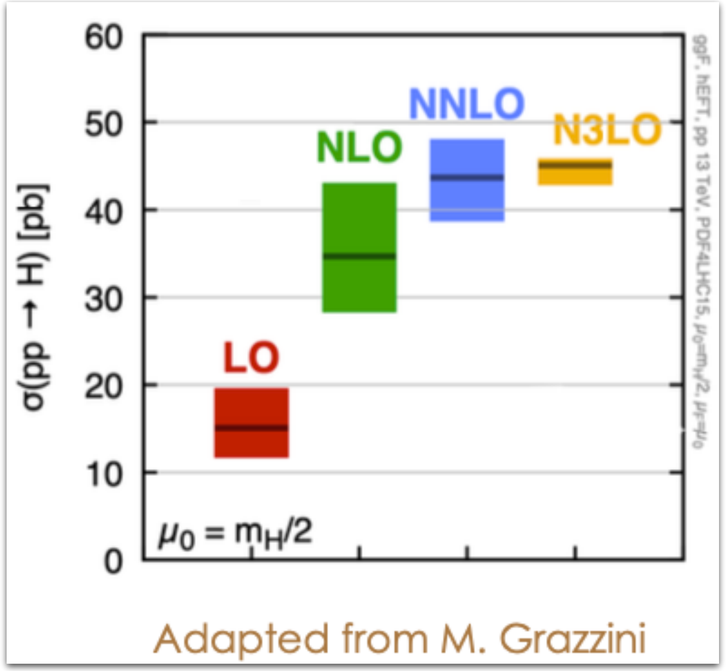


- Trigger on and measure with precision all final state objects:
  jets, μ, e, tau, b, Et_miss
- ML at every stage of analysis
- Reduction of syst. w/ more data
- More sophisticated triggers
- Mega likelihood combination fits
- Computing

6

Continuously improving theoretical understanding



H xsec to QCD N3LO
More precise backgrounds
tt+bb, di-V, etc.
HH cross sections
PDF's
Etc

Why can we do so much?

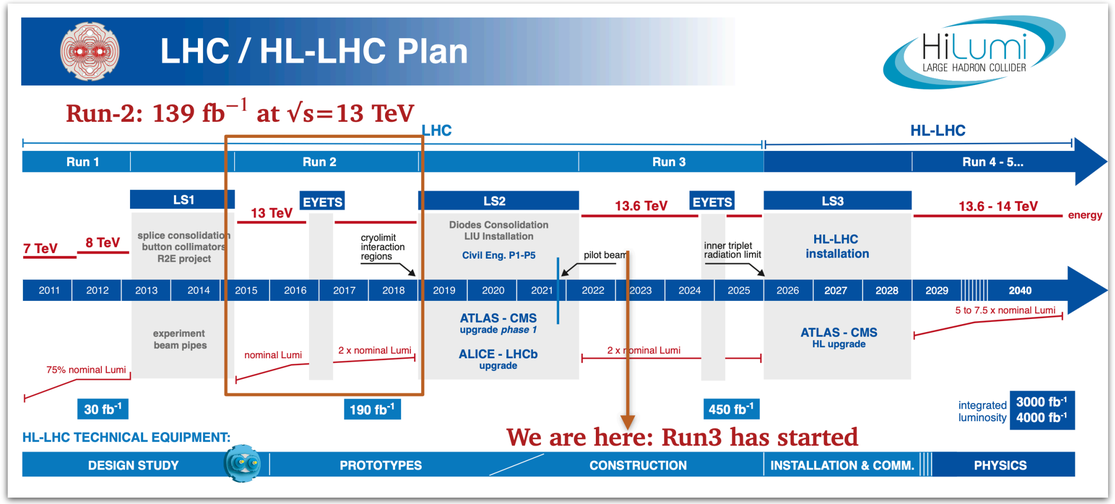
7

Team Work

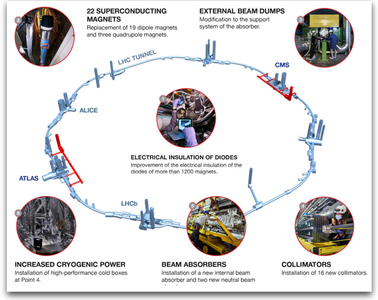
The LHC Higgs landscape

- LHC data
  - Run 1 [2011-12]: 5/20 fb-1 @ 7/8 TeV
  - Run 2 [2015-2018]: ~ 140 fb-1 @ 13 TeV ★
  - Run 3 [2022-2025]: started, ~ 300 fb-1 @ 13.6 TeV
  - HL-LHC [2029:40+]: x20 more data than most results here !

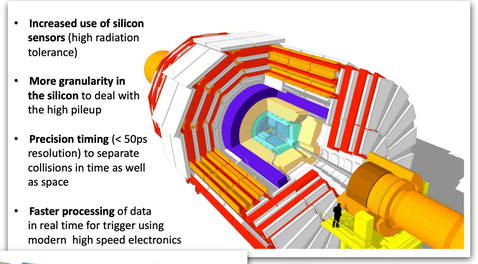
    => Higgs investigation still in its infancy

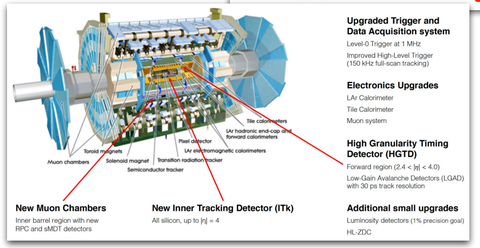


- Two broad directions of exploration
  - **More precise measurements**
    - Test SM consolidation and/or possible BSM deviations
    - By probing its couplings via production & decays
      - reach few % level… beyond that, new machines needed
    - By measuring its properties: mass, width, CP, spin
  - **Detection of new interactions**
    - Move from third (heavy) generation to second (first)
    - Higgs self-interaction
    - Higgs as probe of BSM physics

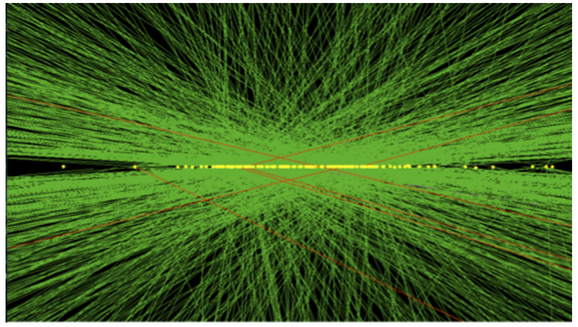


Accelerator Complex Upgrades





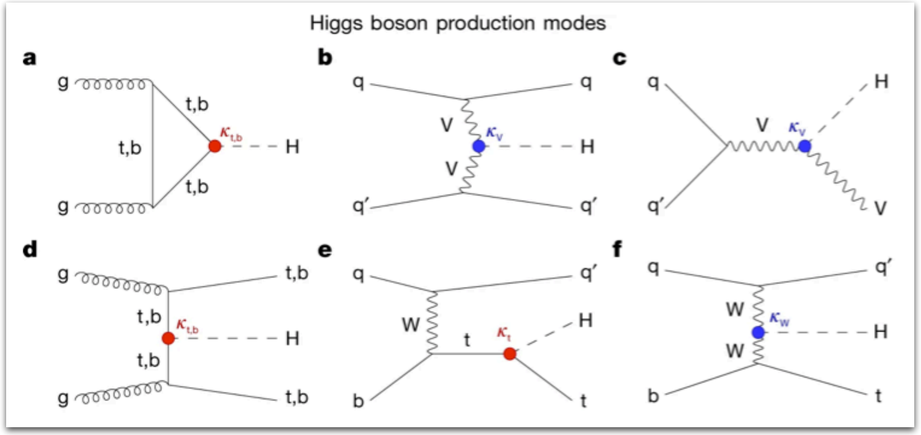
Detector Upgrades

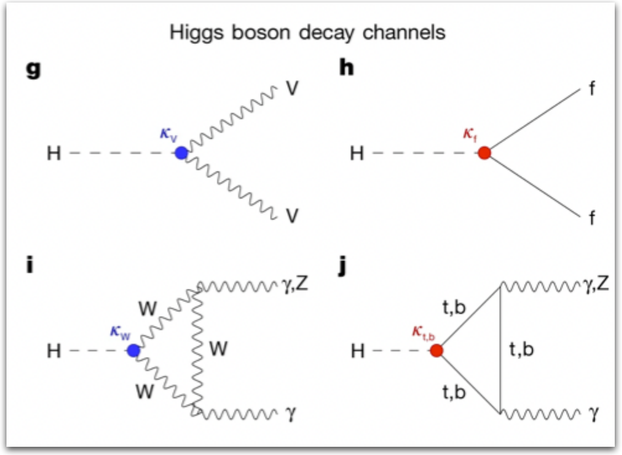


HL-LHC "pileup" challenge

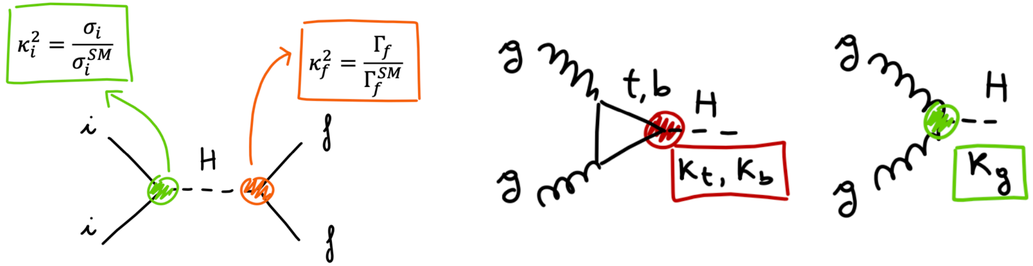
Precision: Couplings

- Using the many SM production modes and decay channels
  - Allows probing couplings to specific bosons and fermions
  - Allows measurements of production and decay mode rates, with good precision, relative to the Standard Model predictions — and look for deviations





- Method
  - Analyze as many processes as possible
    - ggF, VBH, VH, ttH, tH
  - With all observable decays
    - ZZ, γγ, WW, $\tau\tau$, bb,
  - Measure event rates: estimate acceptance, background, and uncertainties
  - Use a combined fit to estimate the parameters of interest
  - Work of many teams: detector, MC, analysis, reviewers etc.



$$\sigma_i \times \mathcal{B}_f = \sigma_i^{SM} \times \mathcal{B}_f^{SM} \times \kappa_i^2 \times \kappa_f^2$$

κ- framework: effective Higgs couplings modifiers

Precision: Couplings

- Using the many SM production modes and decay channels
  - Allows probing couplings to specific bosons and fermions
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- Method
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    - ggF, VBH, VH, ttH, tH
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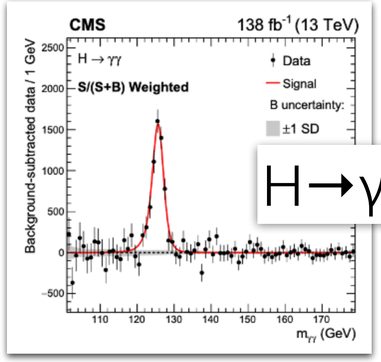
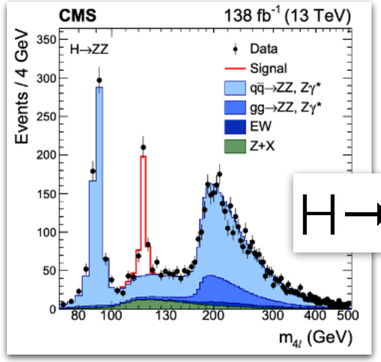
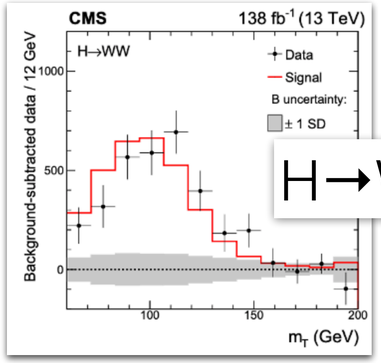
Higgs => bosons



H→γγ

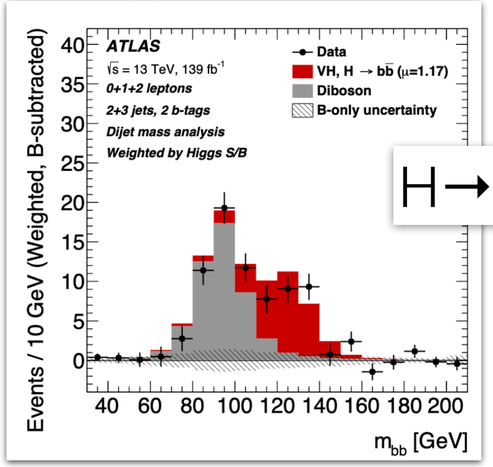


H→ZZ

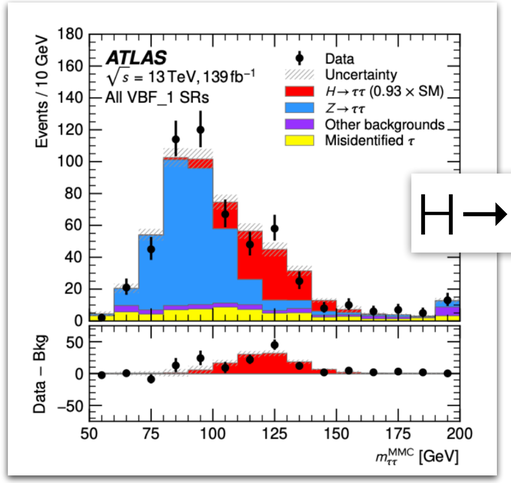


H→WW

Higgs => fermions



H→bb



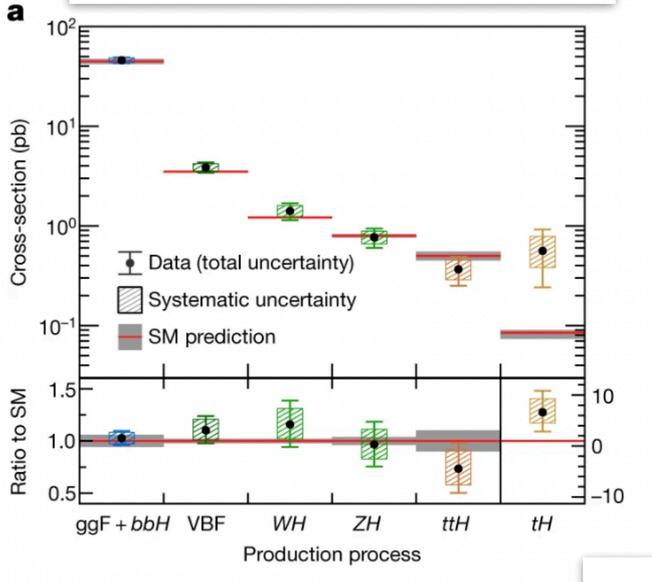
H→ττ

Decays from many production modes combined

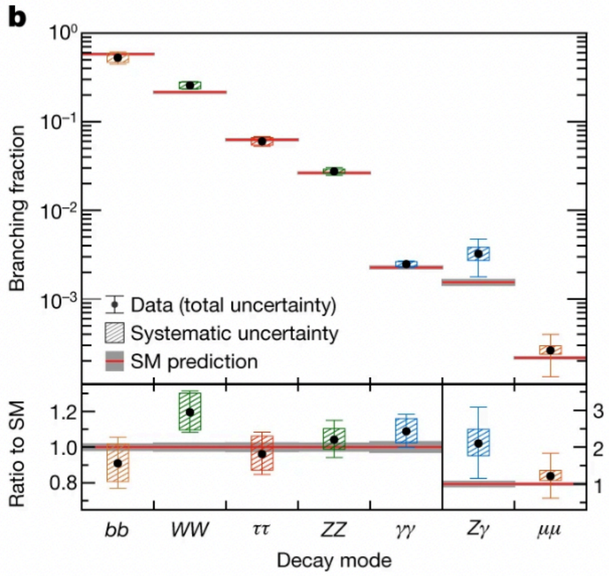
Couplings: Highlights

Many ways to interpret/slice the data

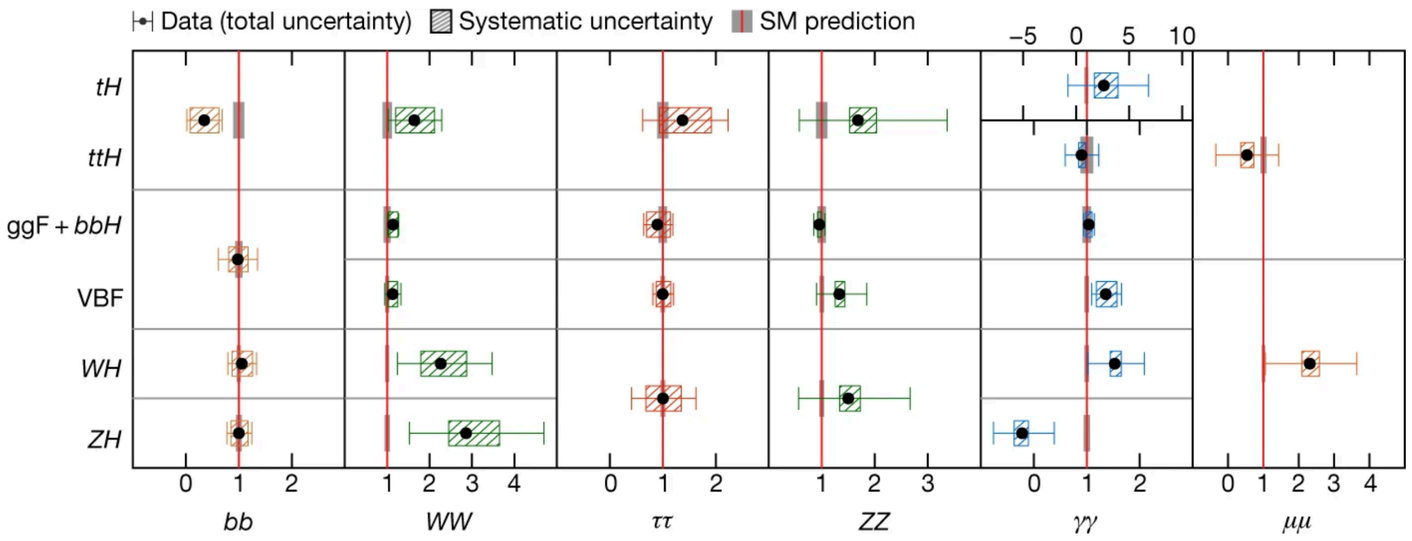
ATLAS: cross sections w/ SM BR



ATLAS: BR w/ SM xsec



ATLAS: production and decay mode combined



Uncertainties <10% for main production and decay modes

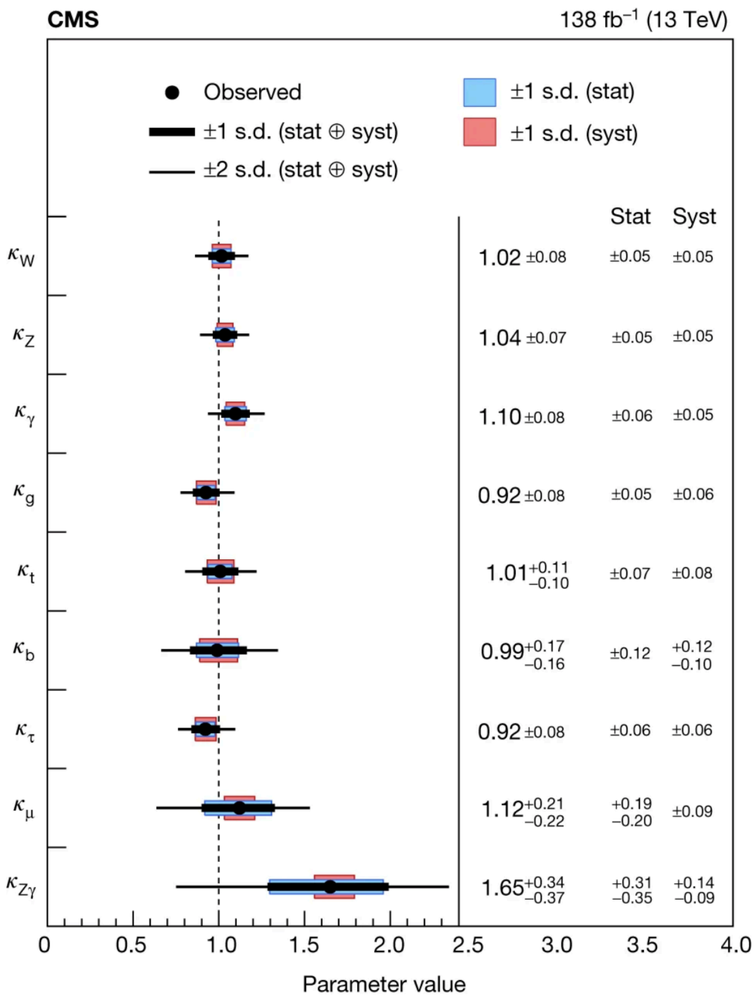
No significant deviation from SM expectations

Nature 607, 52-59 (2022)

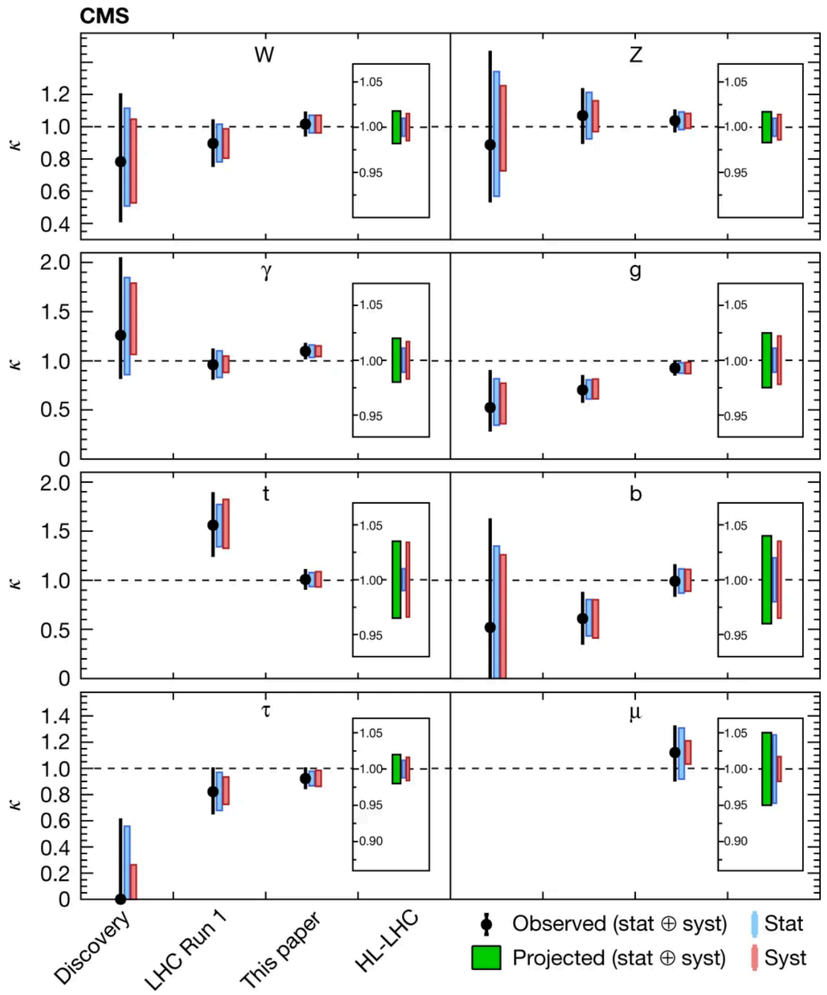
Many ways to interpret/slice the data

Couplings: Highlights

CMS: κ coupling modifiers



CMS: κ uncertainty evolution



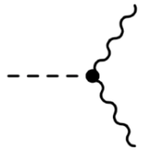
Both statistical and systematic uncertainties decrease with more data
So keep probing with more and more precision/luminosity…!

Uncertainties ~ 1-5 % expected @ HL-LHC for all modes…

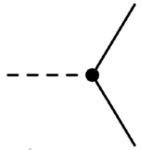
Nature 607, 60-68 (2022

Couplings: Highlights

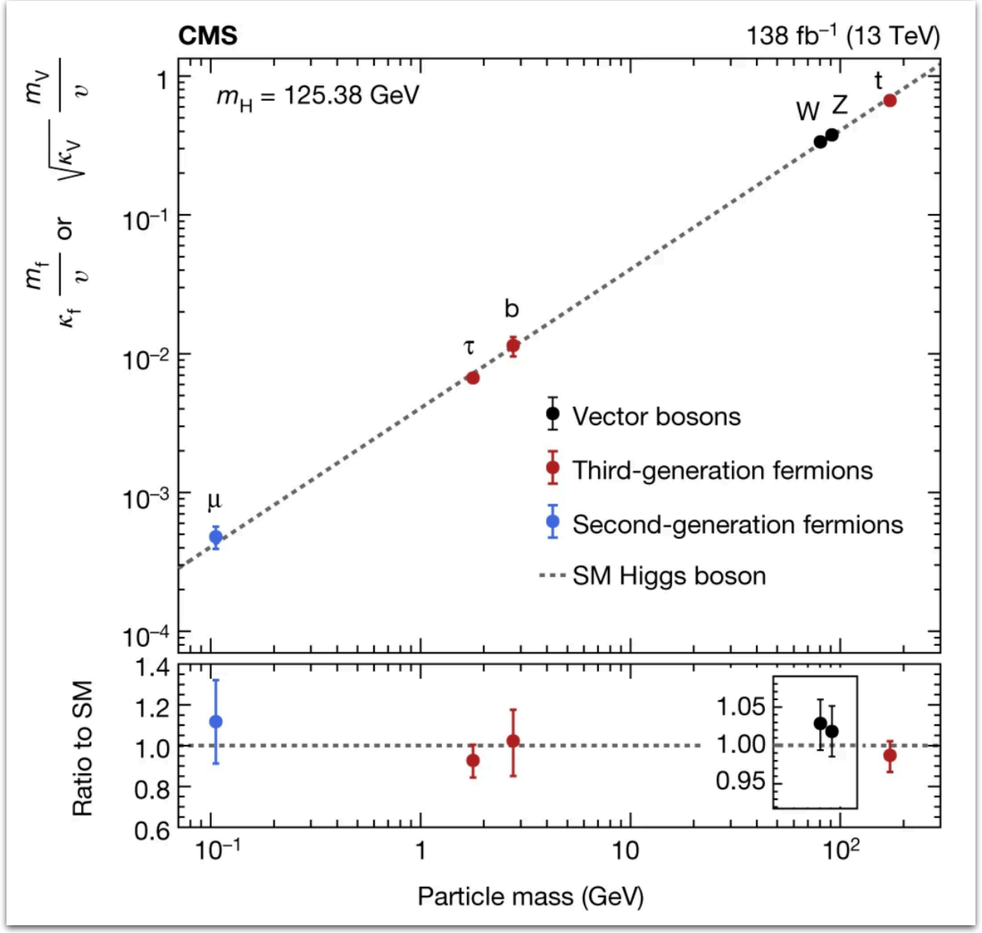
- Key confirmation: Higgs couples to mass as predicted !



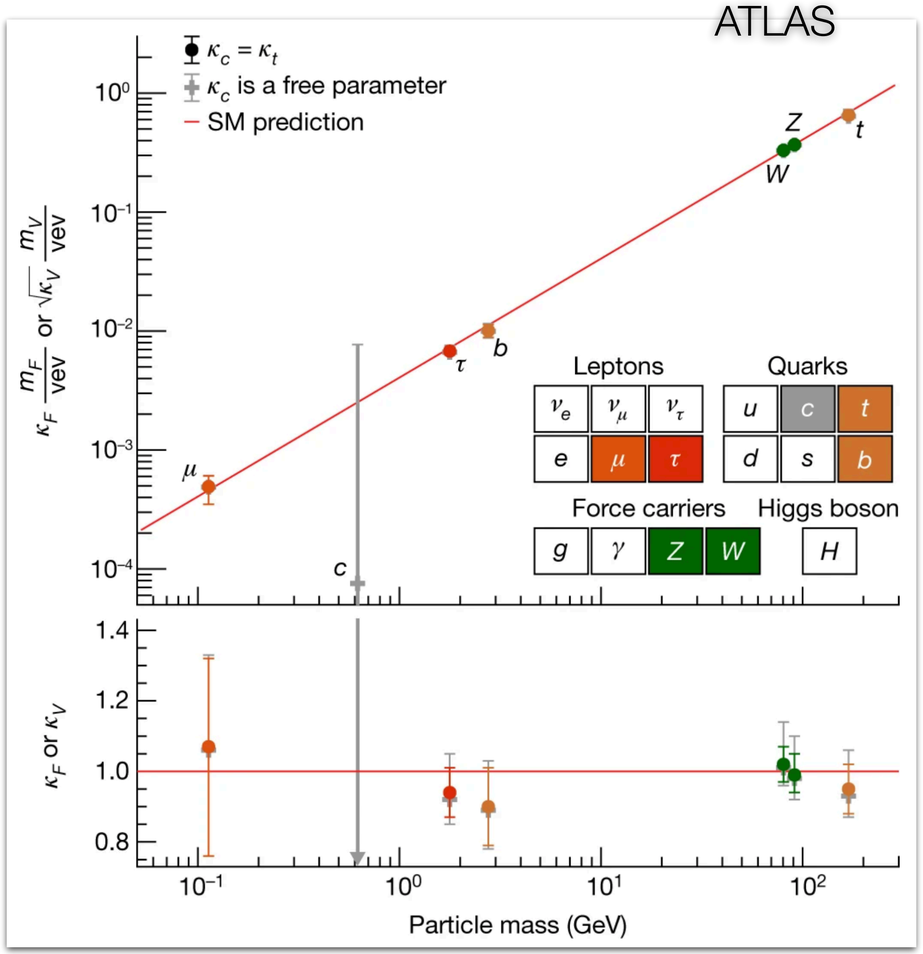
$$g_V = 2\frac{m_V^2}{v}$$



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



Nature 607, 60-68 (2022



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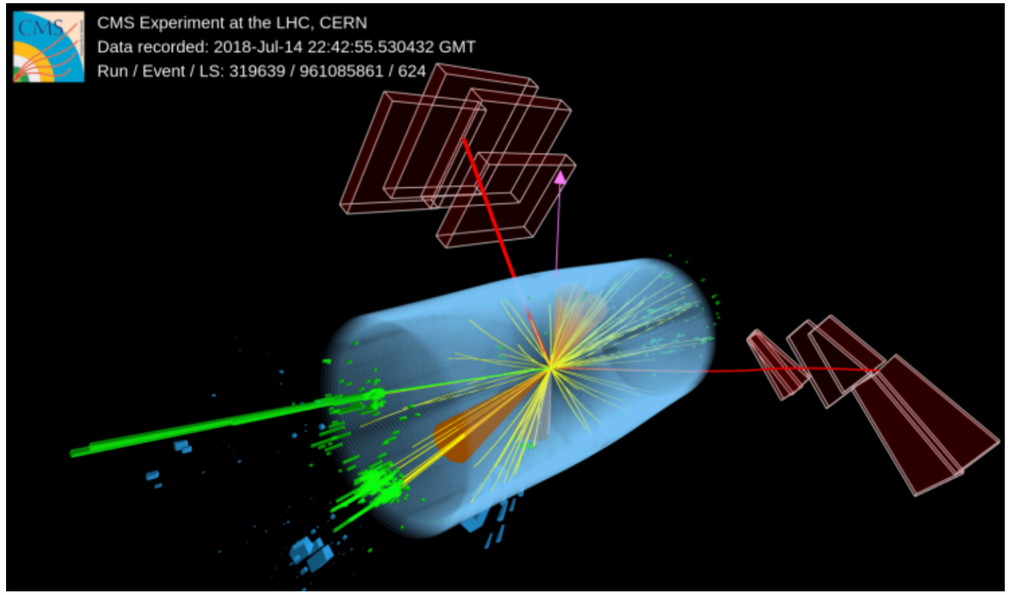
How amazing is this ?

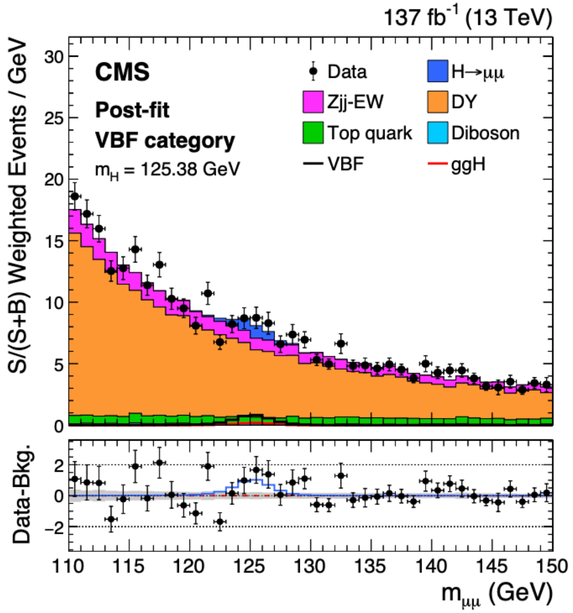
Looking at rarer SM decays

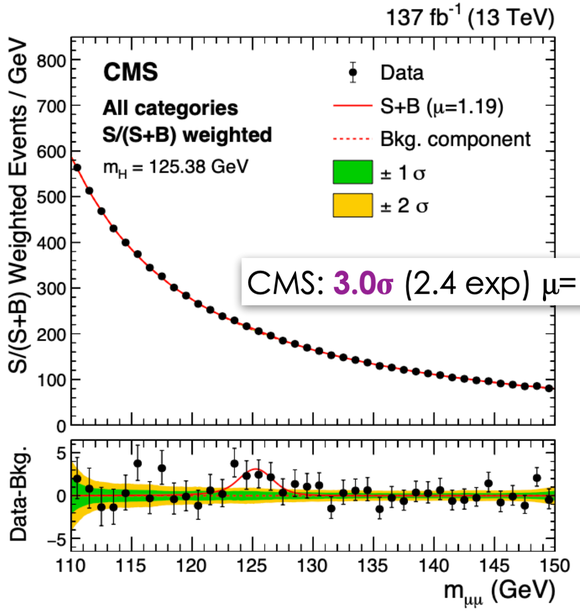
- More challenging, so throw everything at them:
  - Use all production modes
  - Characterize events by jet multiplicity, regions in the detector, etc
  - Use ML to individualize resolutions event by event

BR(H→μμ)=.022%. !!

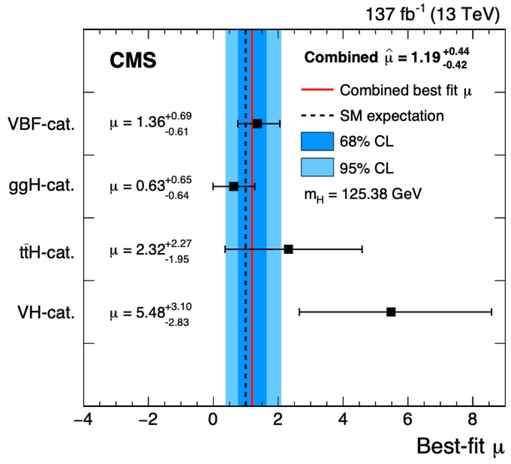
H→μμ: 2nd gen coupling evidence

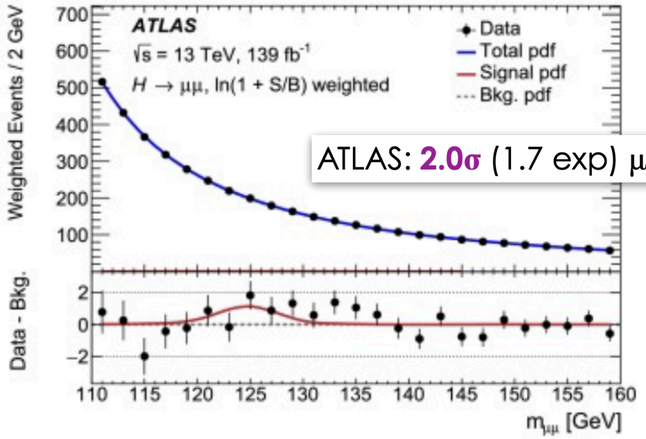






CMS: **3.0σ** (2.4 exp) μ=1.19 ± 0.43



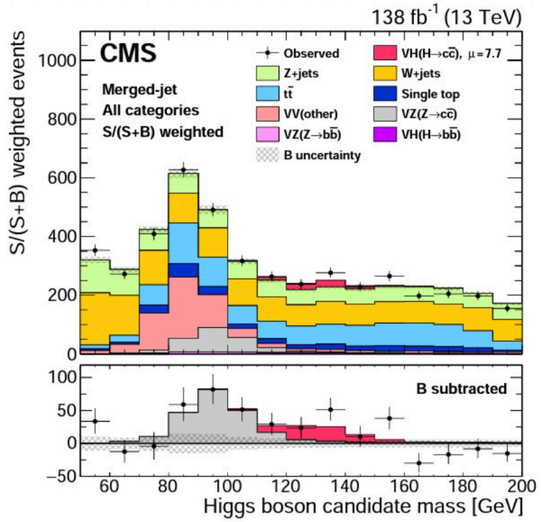


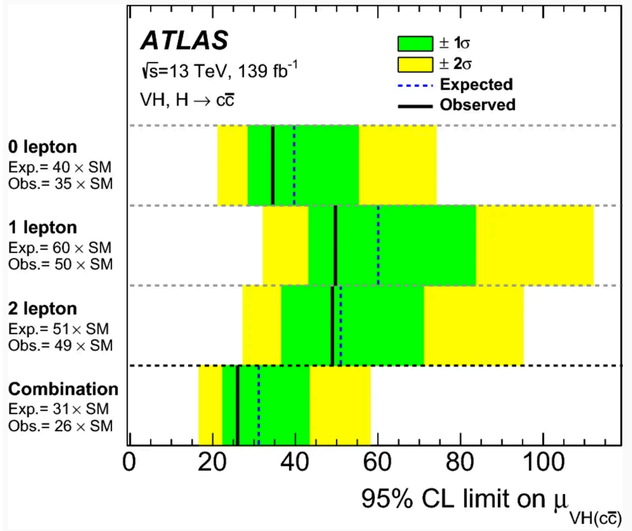
ATLAS: PLB 812 (2021) 135980
CMS: JHEP 01 (2021) 148

H→cc

BR(H→cc)=2.9 %. …

- Separate from light flavor jets and b-jets: ML c-tagging
- Hard to trigger: search using VH, with V => leptons: 0,1,2
- Validate with e.g. VZ with Z→cc & ZW with W→cq
- ATLAS: WZ(cc) @ 2.6 (2.2) & ZW(cq) @ 3.8 (4.6) obs. (exp.) times SM σxBR
- CMS: VZ(cc) observed @ 5.7 σ significance !





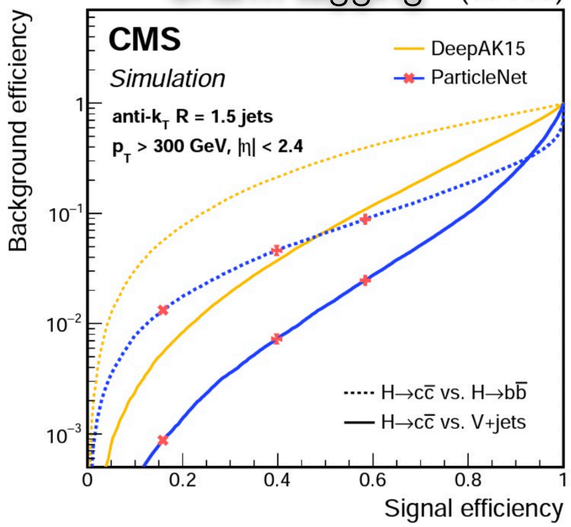
CMS limit:
VH(cc) @ 14 (31) times SM σxBR

1.1 < |κc| < 5.5 @ 95% CL

ATLAS limit:
VH(cc) @ 26 (31) times SM σxBR

|κc| < 8.5 (7.6) @ 95% CL

Charm tagging (13 TeV)

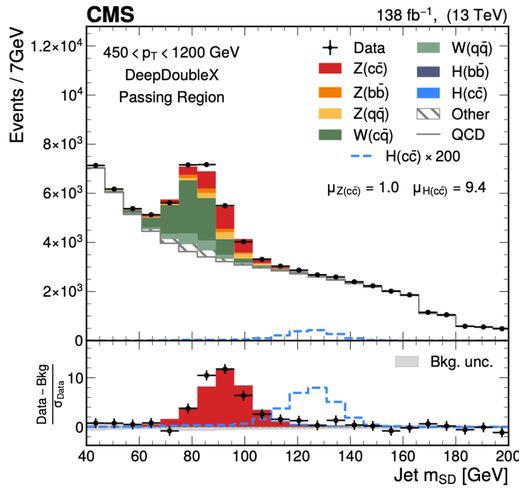


ATLAS: Eur. Phys. J. C 82 (2022) 717
CMS: arXiv:2205.05550

- NEW (CMS) new
- Boosted ggH(H→cc) p_T(H)> 450 GeV
- w/ special ML double-c-tagger

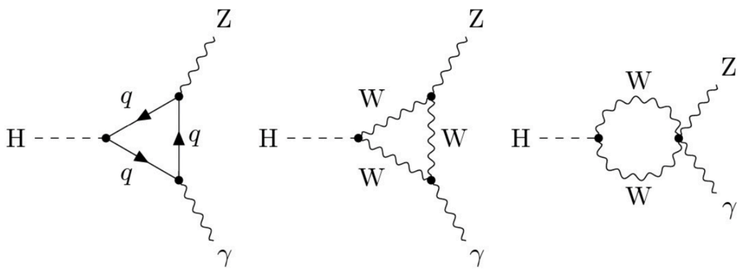
Z →cc observed with μ=1.00 (+0.19/-0.17) SM σxBR - well over 5-σ !

σ(H)xBR(H→cc) limit 47 (39) times SM expectation



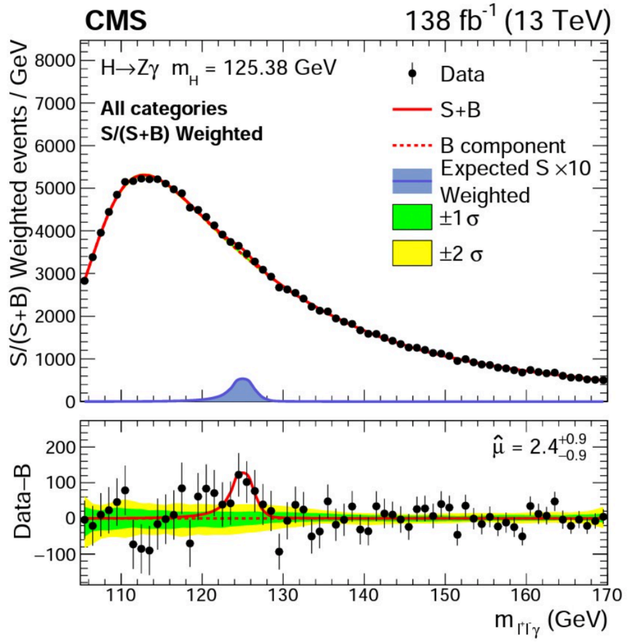
Couplings: Even rarer decays

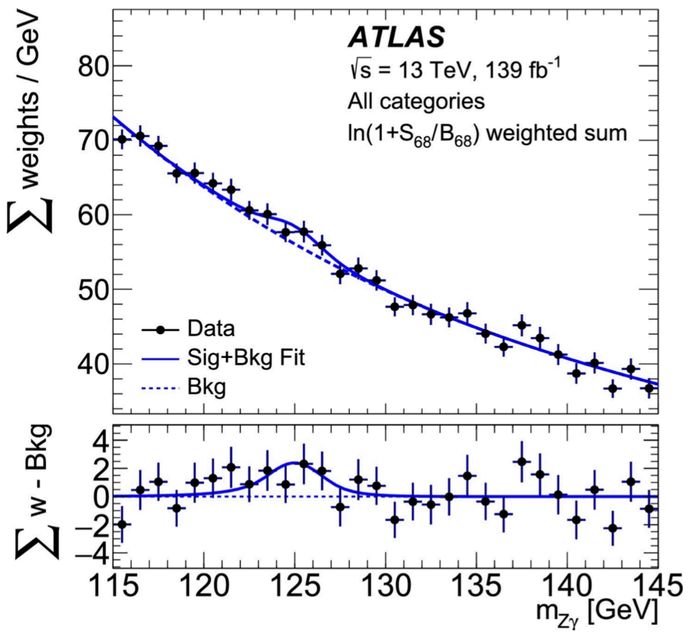
- Decays through loops test for new physics:



BR(H→Zγ) ~ 1.6 x 10^{-3}

The ratio of BR(H→Zγ)/H→γγ) can be affected by BSM effects





- Use several production processes with eeγ & μμγ final states
  - ML discriminators for S/B improvements

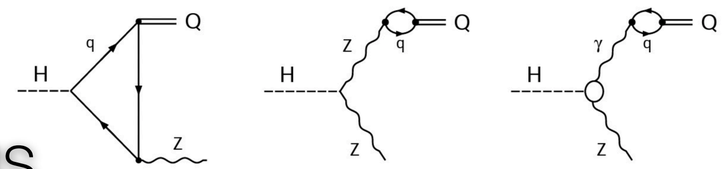
Observed 2.7σ (1.2σ exp.)
Strenght = 2.4+-0.9 SM
BR(H→Zγ)/H→γγ) = 1.54 (+065,-0.58)
consistent @ 1.5σ w/ SM

Observed 2.2σ (1.2σ exp.)
Strength = 2.0 (+1.0,-0.9) SM
BR(H→Zγ)/H→γγ) = 1.54 (+065,-0.58)

Run 3 data will consolidate further the study of this process

Couplings: Even rarer decays

Higgs and Quarkonia



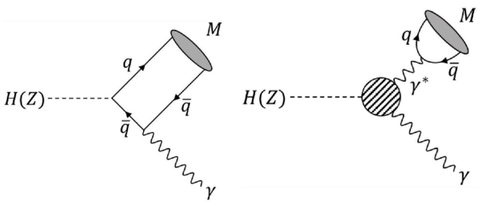
CMS

- $Br(H \to Z\, J/\Psi) \sim 2\times10^{-6}$,
- $Br(H \to J/\Psi\, J/\Psi) \sim 2\times10^{-10}$

final state search with Z → ee/μμ and additional μμ

sensitivities @ level of 3-4 orders of magnitude larger than SM

ArXiv: 2206.03525 = > no excess found…

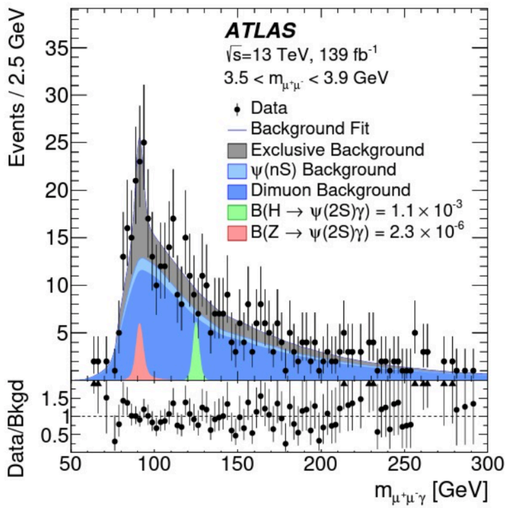


ATLAS

$Br(H \to J/\Psi\, \gamma) \sim 3\times10^{-6}$

$Br(H \to \Upsilon\, \gamma) \sim 10^{-9}$

final state search with μμγ



sensitivities @ level of 2 orders of magnitude larger than SM

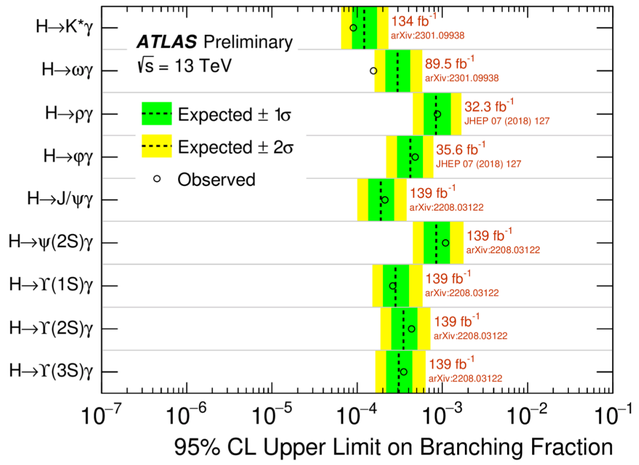
ArXiv: 2208.03122 = > no excess found…

- $H(Z) \to \omega\gamma \to \pi^+\pi^-\pi^0\gamma$
- $H \to K^* \to K^+\, \pi^-\gamma$

new

Channel	95% CL upper limit Expected	Observed
$H \to \omega\gamma\ [10^{-4}]$	$3.0^{+1.2}_{-0.8}$	1.5
$Z \to \omega\gamma\ [10^{-7}]$	$5.7^{+2.3}_{-1.6}$	3.8
$H \to K^*\gamma\ [10^{-5}]$	$12.2^{+4.9}_{-3.4}$	8.9

ATLAS

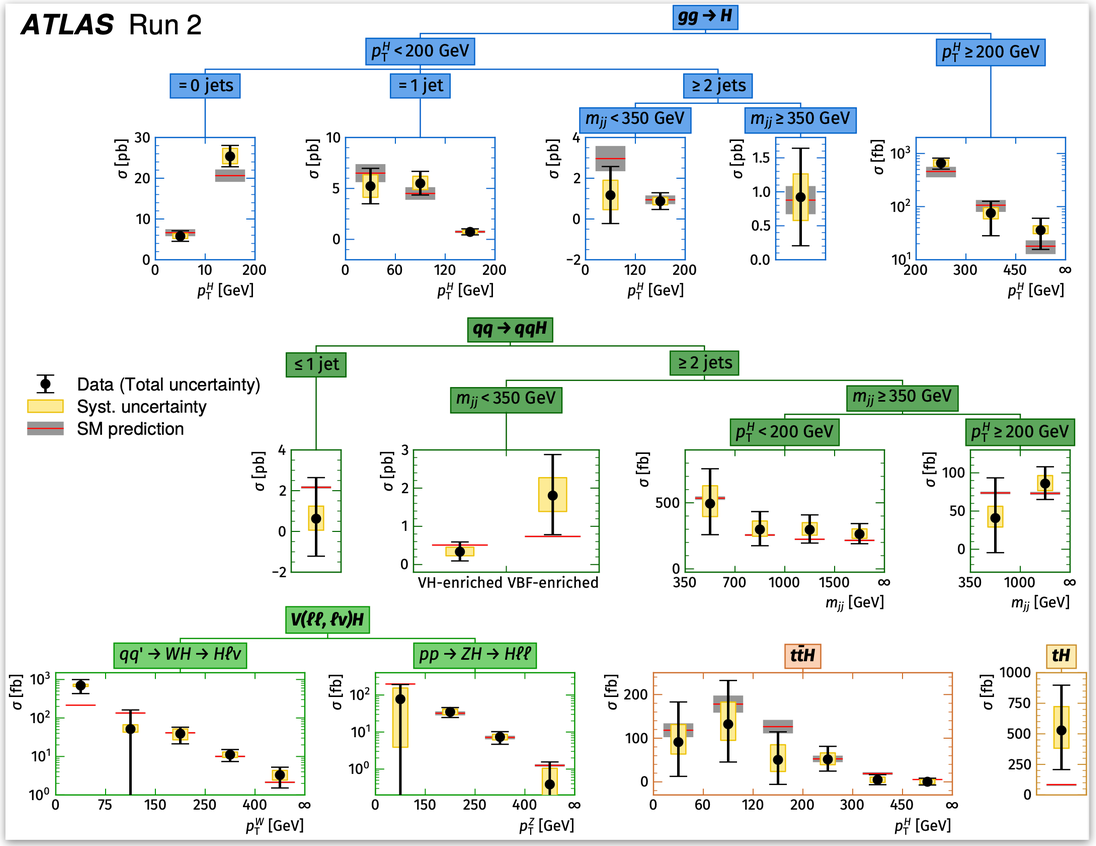


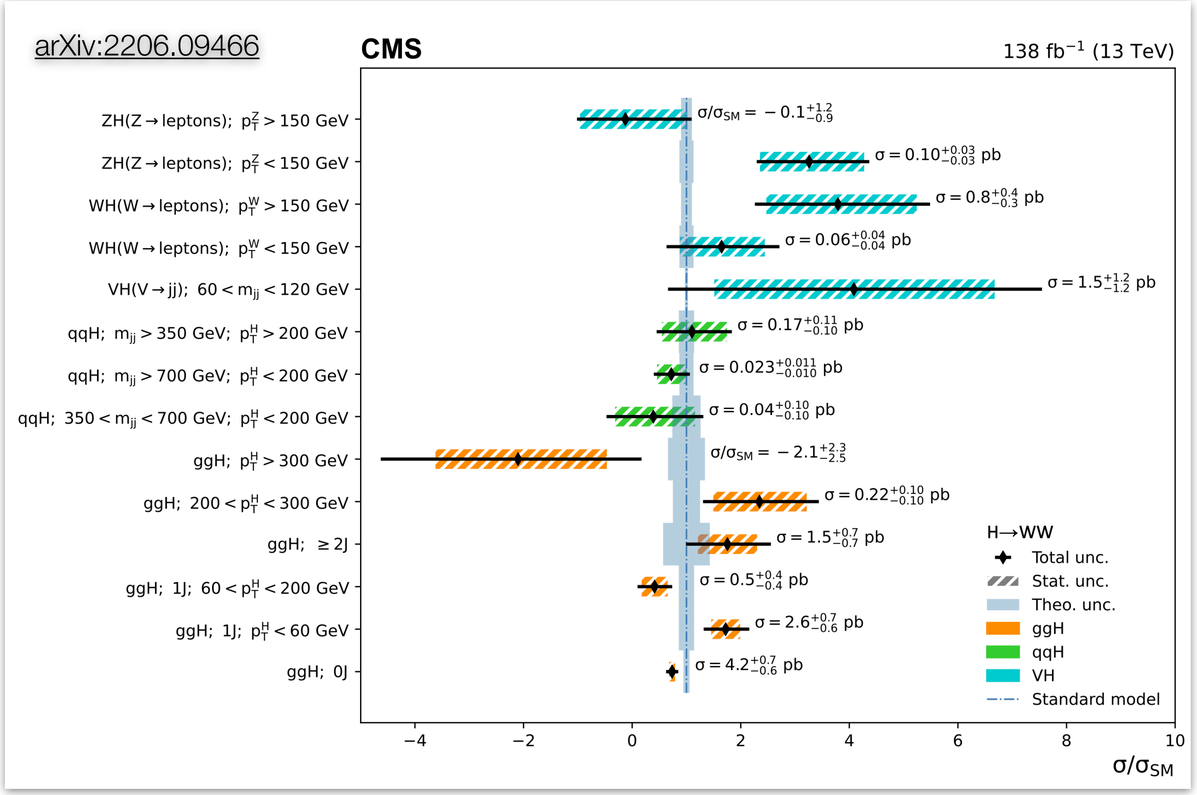
sensitivities @ level of 2 orders of magnitude larger than SM

ArXiv:2301.09938 = > no excess found…

More detailed examination

- Look in more detail
  - More than event counting examine kinematical distributions
    - STXS framework Stage 1.2
      - Measure different production modes in exclusive kinematic regions
        - Split in pT(H), pT(V), #jets, mjj…
      - Sensitivity to BSM (e.g. @ high pT)
        - combine many decay channels for better statistics



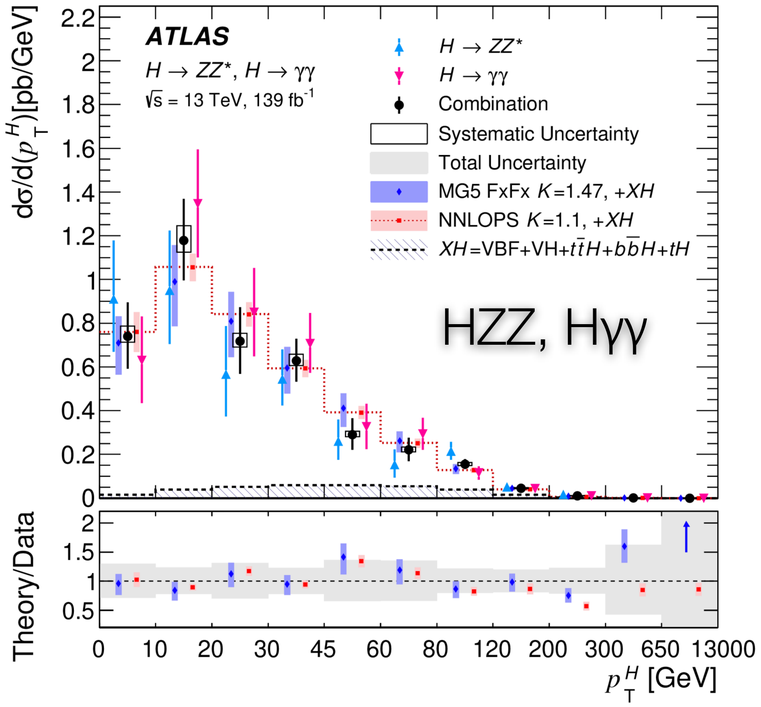


e.g. H→WW: observed cross sections in each STXS bin

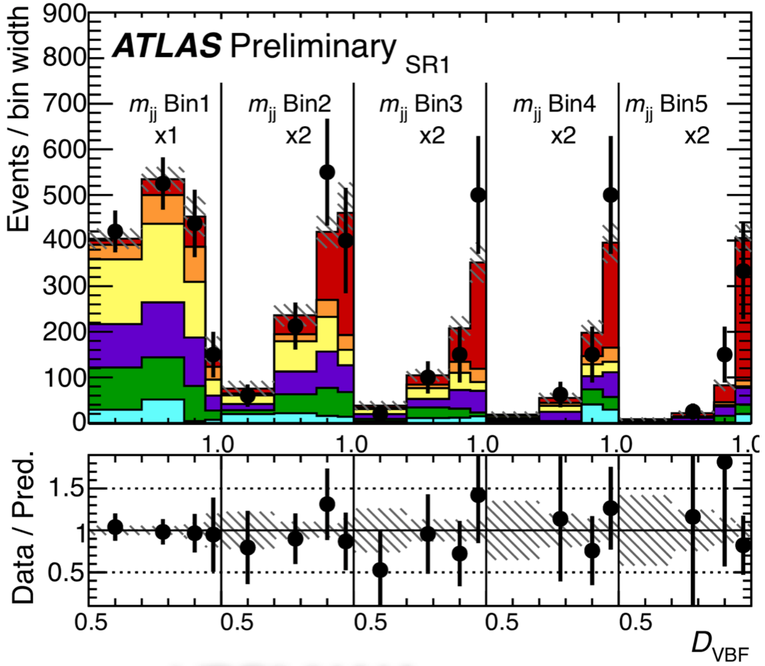
Consistency w/ SM so far but a very rich environment to keep steadily testing

More detailed examination

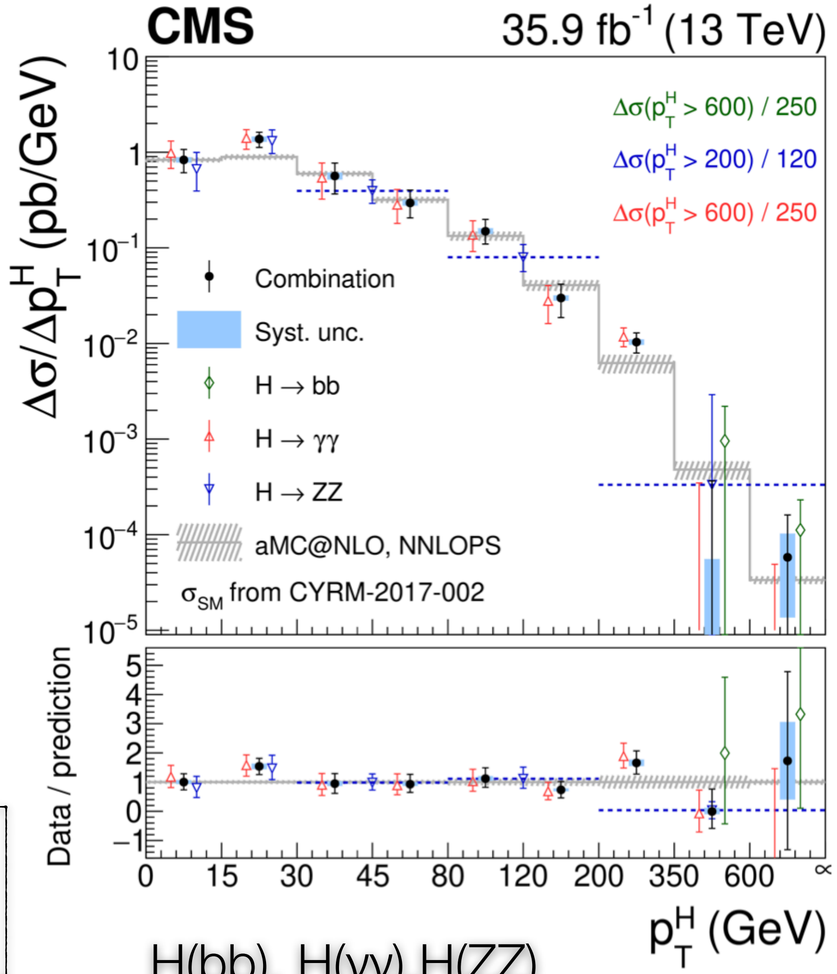
- Study differential cross sections
  - Also measured in many different channels



VBF(WW) paper link



VBF(HWW)



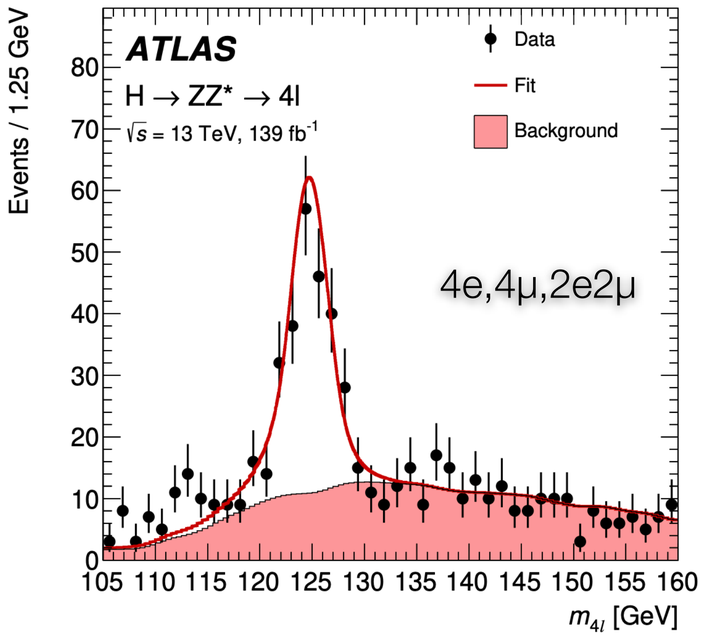
H(bb), H(γγ),H(ZZ)

Consistency w/ SM so far but a very rich environment to keep continuously testing … keep and eye at high pT

Properties: mass

- Channels with full final state reconstruction + great resolution
  - Measure mass with: H→ZZ*→4 leptons & H→γγ
  - Combine all channels and Run 1 and [part of] Run 2

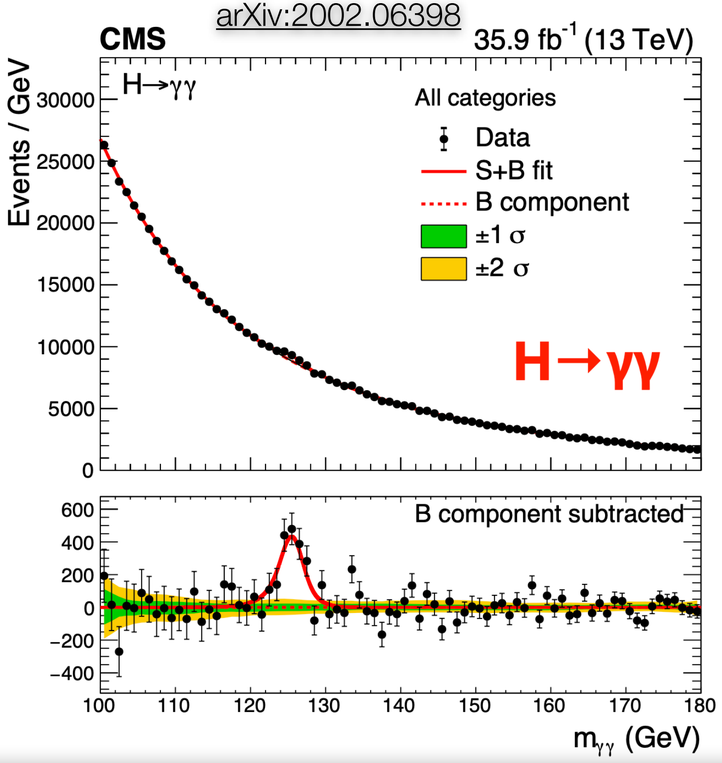
arXiv:2207.00320



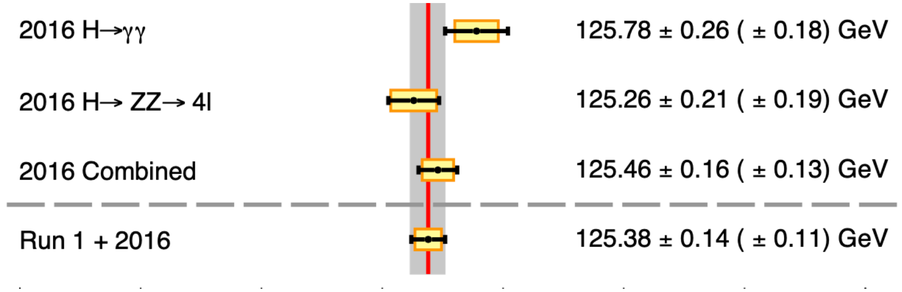
$$m_H = 124.94 \pm 0.18\ [\pm 0.17(stat) \pm 0.03(syst)]\ GeV$$

Systematic Uncertainty	Contribution [MeV]
Muon momentum scale	±28
Electron energy scale	±19
Signal-process theory	±14

arXiv:2002.06398



$$m_H = 125.38 \pm 0.14\ [\pm 0.11(stat) \pm 0.08(syst)]\ GeV$$



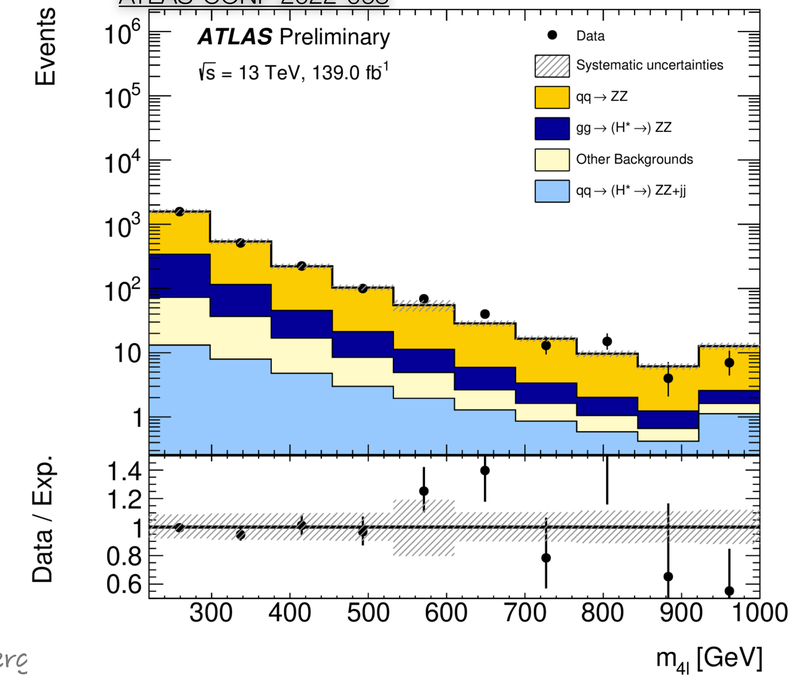
0.1% uncertainty (stat dominated) will improve with more data (also syst)

Properties: width

- Direct width measurement is difficult due to detector resolutions
  - Γ(H) is 4.07 MeV(PDG) but…
  - Using off-shell H→ZZ (4l and 2l2v) production makes it possible
  - About 10% of H→ZZ is off shell (m_{ZZ}> 200 GeV)

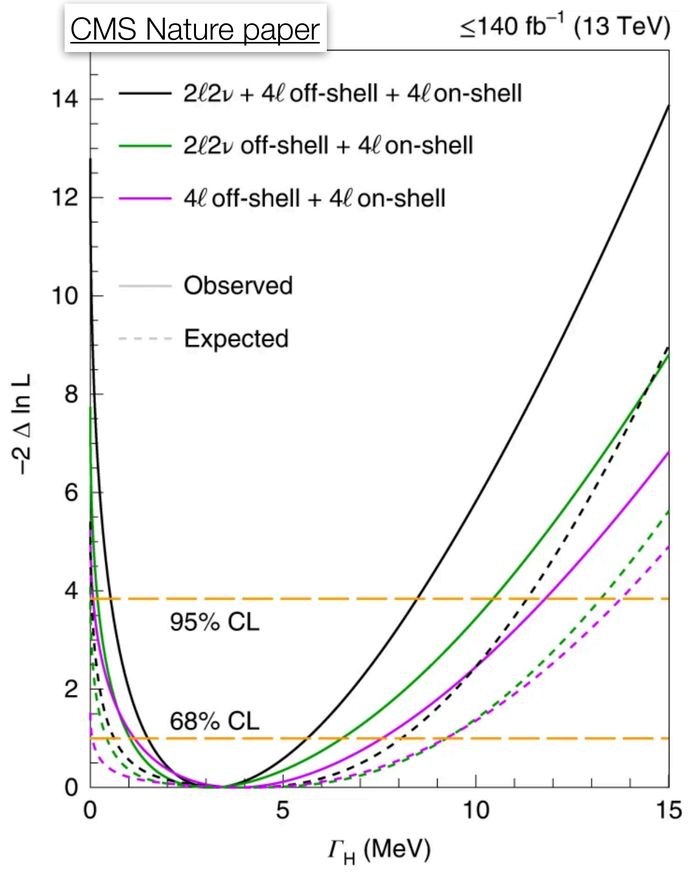
$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \dfrac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \dfrac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$

ATLAS-CONF-2022-068



m4l

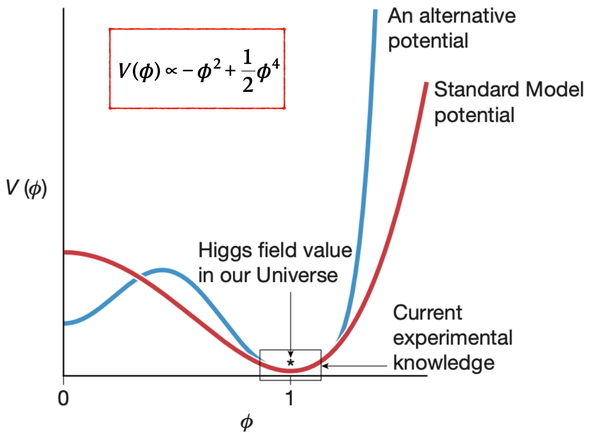
CMS Nature paper



CMS	$\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV	excludes no off-shell at 3.6 sigma
ATLAS	$\Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV	excludes no off-shell at 3.2 sigma

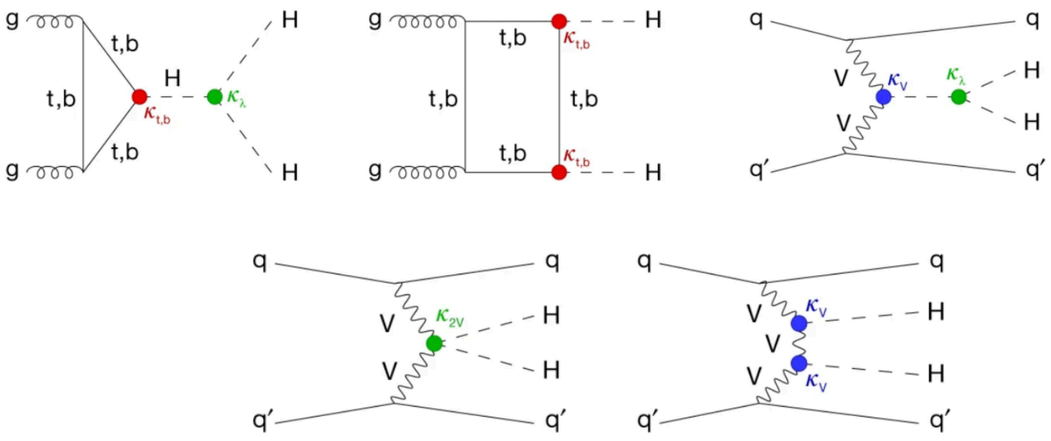
Uncertainties will improve with more data (also syst)

Higgs self-coupling



test this experimentally

- Di-Higgs production probes the tri-Higgs (quartic) coupling κ_λ (κ_{2V})



$$\mathcal{L} \supset -V(\phi), \quad V(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

EW symmetry breaking

$$\mu^2 = \lambda v^2$$
$$m_H^2 = 2\lambda v^2$$

$$V(H) = \frac{1}{2}m_H^2 H^2 + \boxed{\lambda v H^3} + \frac{\lambda}{4}H^4,$$

ggHH dominates w/ xsec ~31 fb

BR (HH → XXYY) [%]

	γγ	ZZ	τ⁺τ⁻	W⁺W⁻	bb̄
bb̄					33.872
W⁺W⁻				4.580	12.455
τ⁺τ⁻			0.393	1.342	3.649
ZZ		0.069	0.164	0.561	1.525
γγ	0.001	0.006	0.014	0.049	0.132

As "usual" include as many process as possible:

- bb,bb / bb,γγ / bb,$\tau\tau$ <= highest sensitivity
- bb,WW / bb,ZZ, WWγγ
- WW,WW / WW,$\tau\tau$ /$\tau\tau$,$\tau\tau$

So 3 orders of magnitude smaller than single Higgs production !

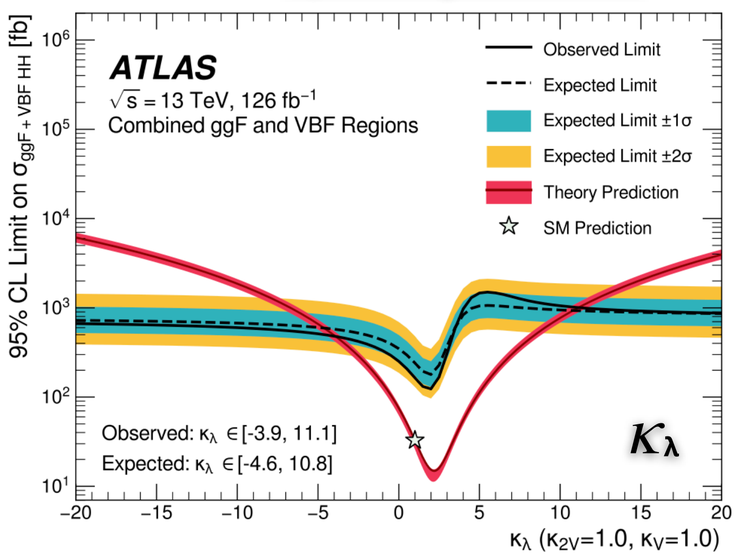
Higgs self-coupling

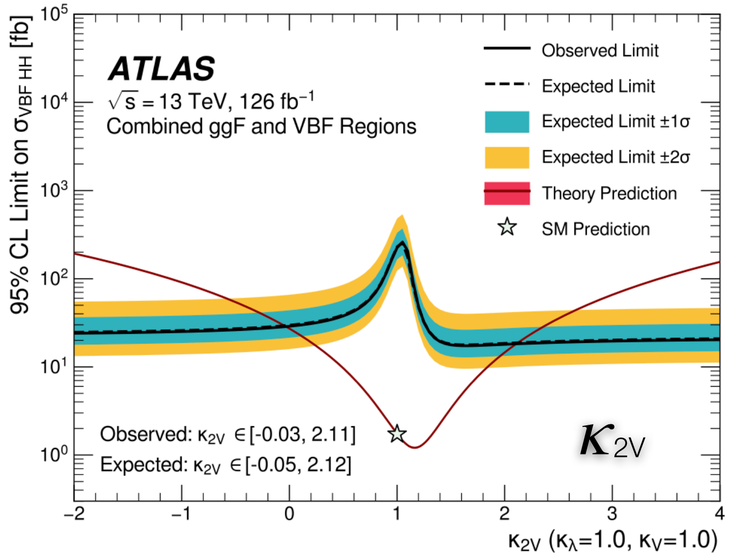
One case: HH=>4b (resolved and boosted)

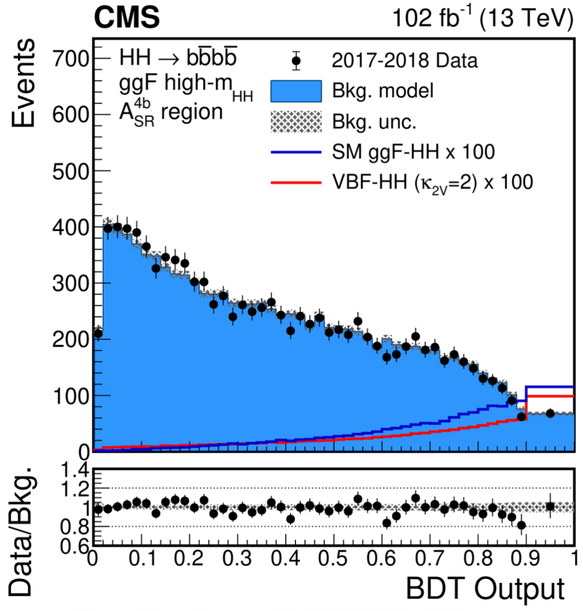
- Trigger and b-tagging are critical
- Background shape (QCD) as well => data driven
- Fit m_{HH} (ATLAS) or BDT (CMS)
- Boosted CMS uses GNN for tagging

- Perform scans for κ_λ (κ_{2V}) - set interval limits
- Set cross section limits for HH production

https://arxiv.org/abs/2301.03212







Phys. Rev. Lett. 129 (2022) 081802

Resolved (no merging of b's)

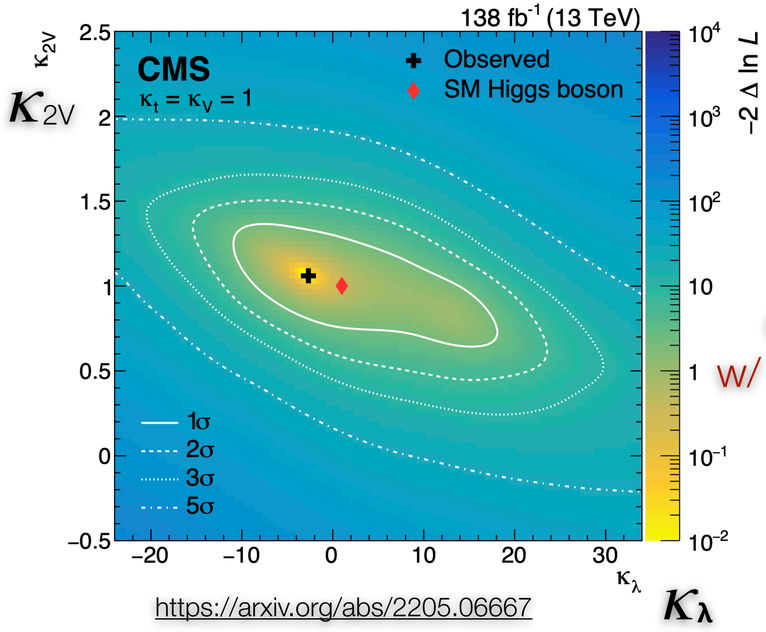
Cross section upper limits: obs (exp)

CMS: 3.9 (7.8) times the SM
ATLAS: 5.4 (8.1) times the SM

Boosted: two "fat" [bb] jets w/ ML tagging)

CMS: 9.9 (5.1) times the SM. !

Phys. Rev. D 101 (2020) 056019



https://arxiv.org/abs/2205.06667

boosted

κ2V = 0 excluded w/ significance of 6.3 σ

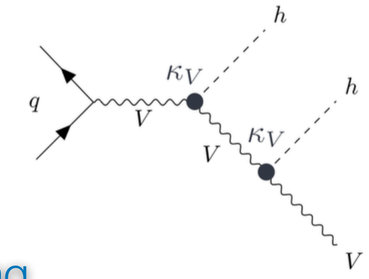
Higgs self-coupling

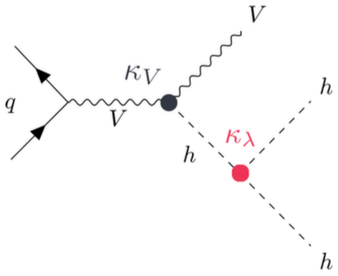
Another case: HH=>4b (VHH)

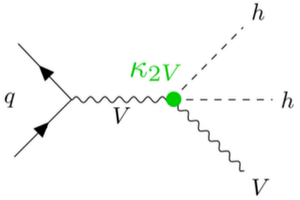
new

"Associated pair production"

HH=> 4b and V to leptons {0,1,2}







Not very sensitive… but worth checking

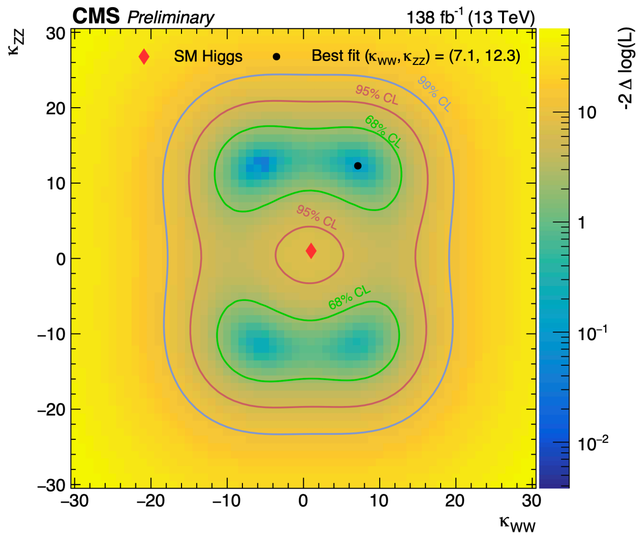
CMS: 95% CL Observed (exp.) upper limit on σ/σ(SM) is 294 (124)

$-14.0 < \kappa_{2W} < 15.4$
$(-10.2 < \kappa_{2W} < 11.6)$

$-17.4 < \kappa_{2Z} < 18.5$
$(-10.5 < \kappa_{2Z} < 11.6)$

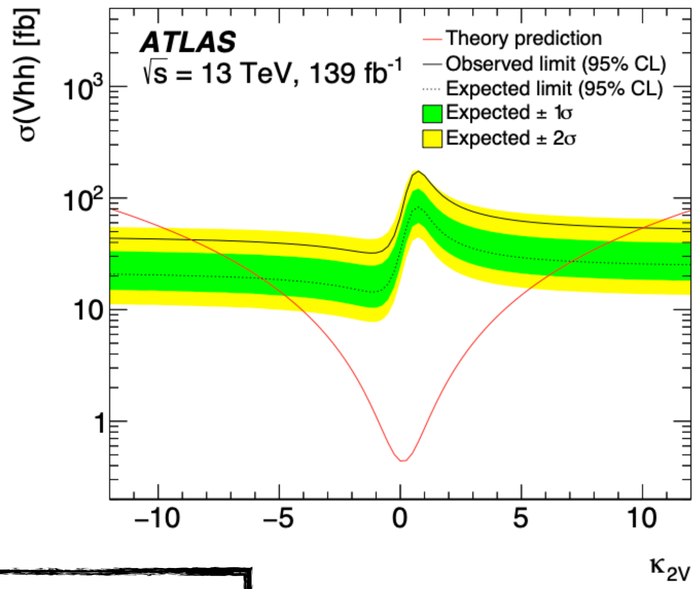
CMS

https://cds.cern.ch/record/2853338



ATLAS

https://arxiv.org/abs/2210.05415



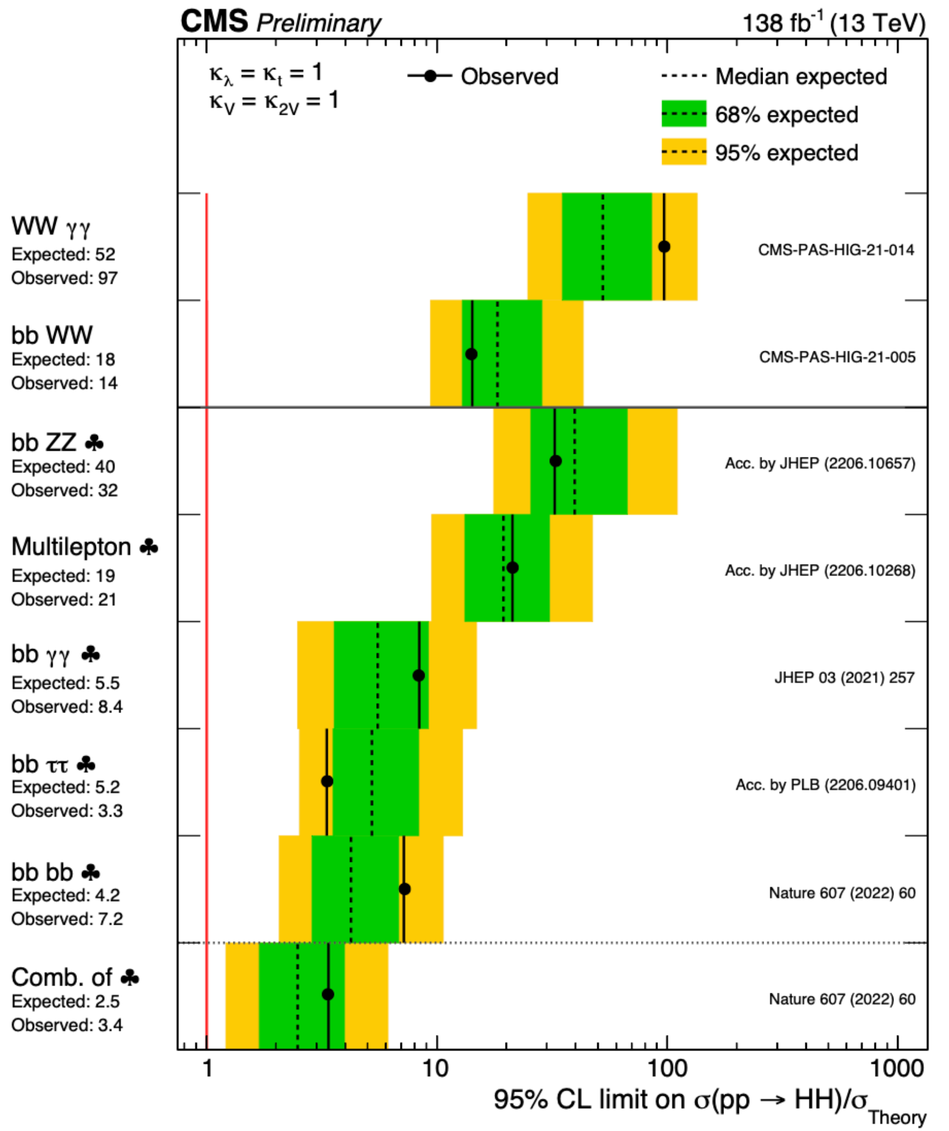
SM *Vhh*: 183 (87^{+41}_{-24}) x σ_{SM}

$-34.3 < \kappa_\lambda < 33.3$ $(-24.1 < \kappa_\lambda < 22.9)$

$-8.6 < \kappa_{2V} < 10.0$ $(-5.7 < \kappa_{2V} < 7.1)$

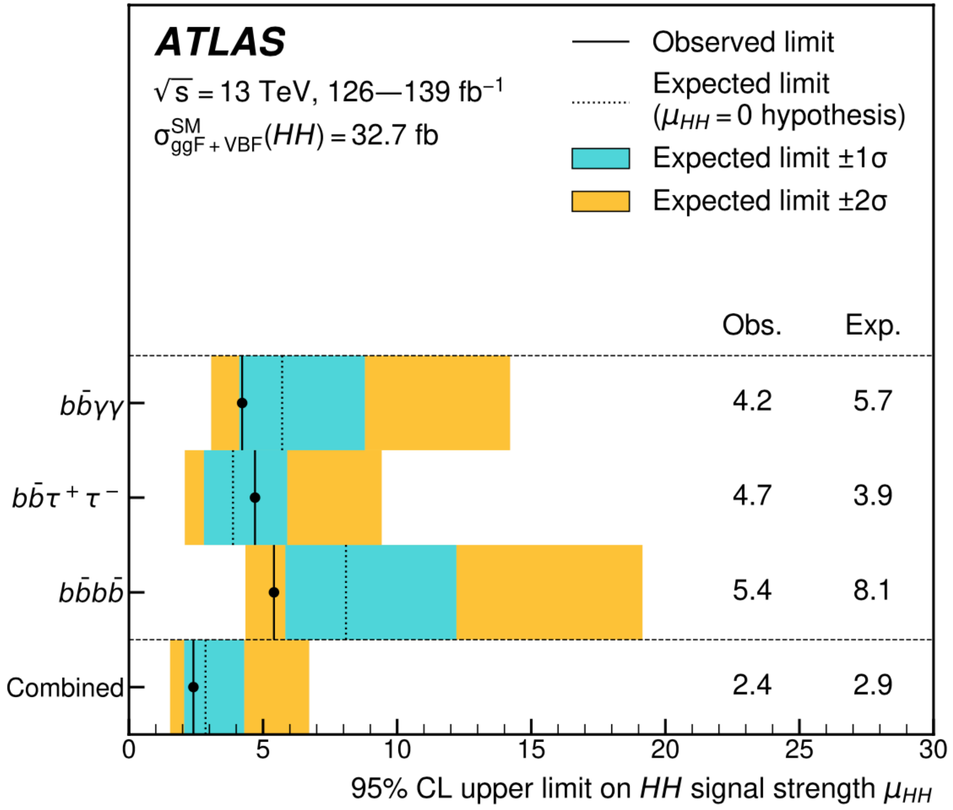
Di-Higgs combinations

Just updated: CMS public



95% CL limit on $\sigma(HH)/\sigma(HH)_{SM}$

Di-Higgs cross section limits



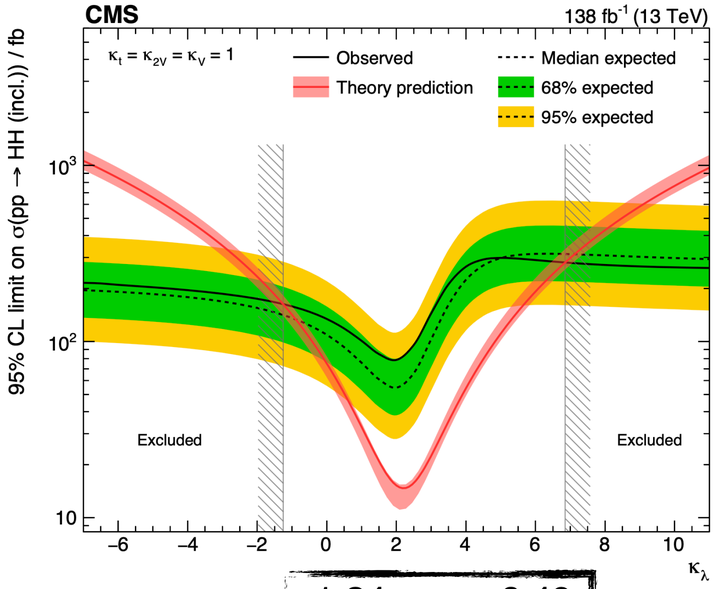
Another remarkable unexpected achievement for the LHC experiments…

How far can we go?

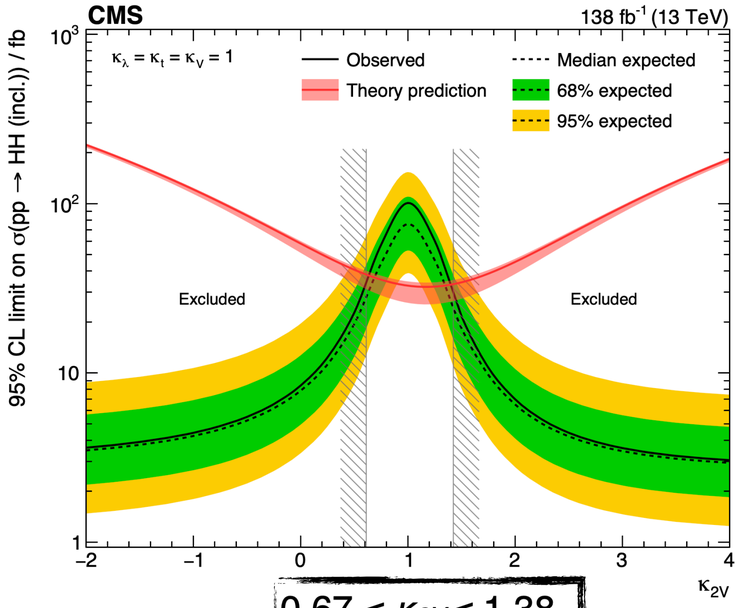
CMS: 3.4 observed (2.5 expected)
ATLAS: 2.4 observed (2.9 expected)

Di-Higgs combinations

Setting interval limits on κ_λ / κ_{2V}

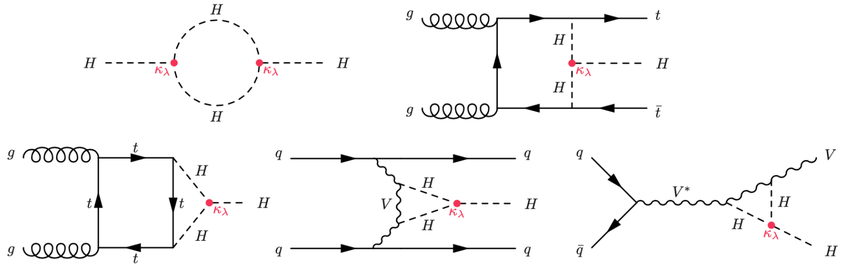


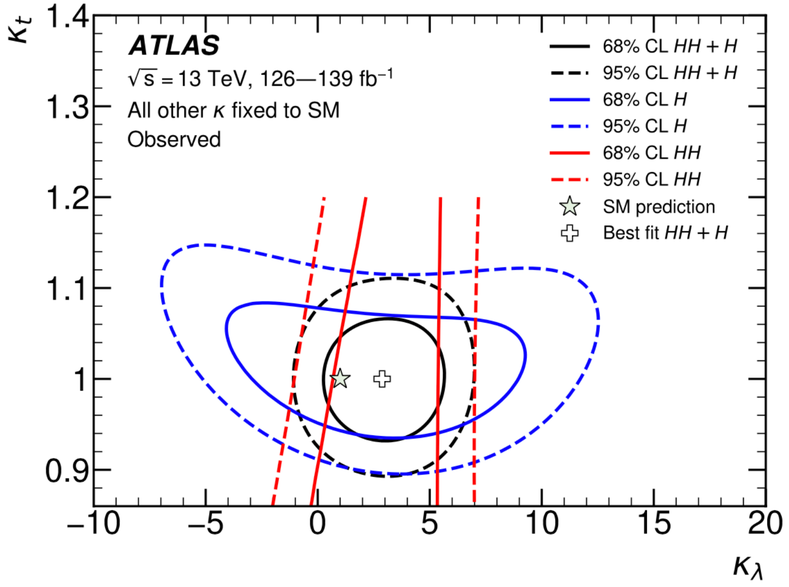
$-1.24 \leq \kappa_\lambda \leq 6.49$



$0.67 \leq \kappa_{2V} \leq 1.38$

ATLAS: HH + H combination





Another remarkable unexpected achievement for the LHC experiments…

How far can we go?

$-1.4 < \kappa_\lambda < 6.1$

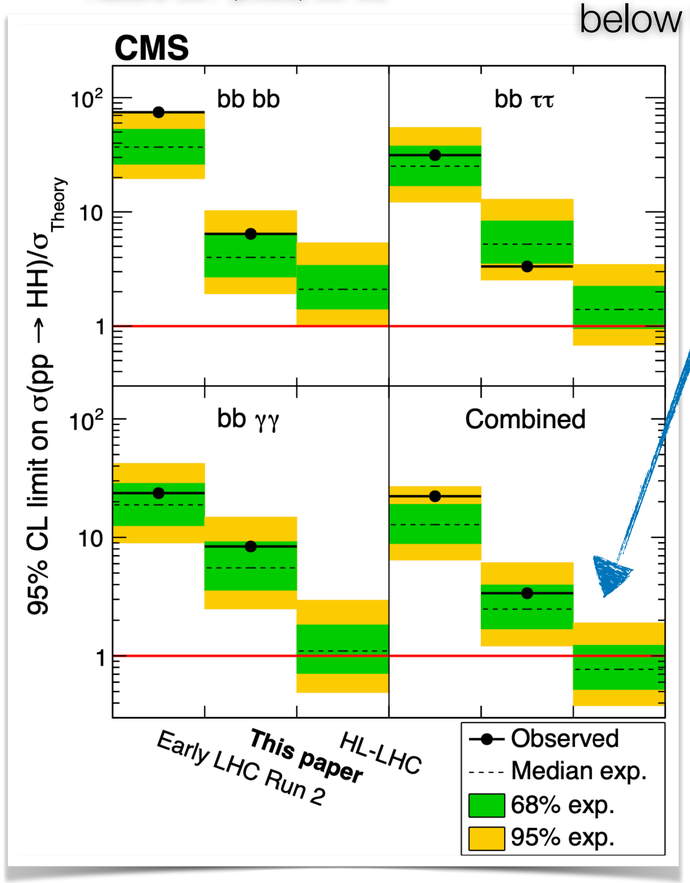
Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

Single-H helps just a bit

Di-Higgs reach

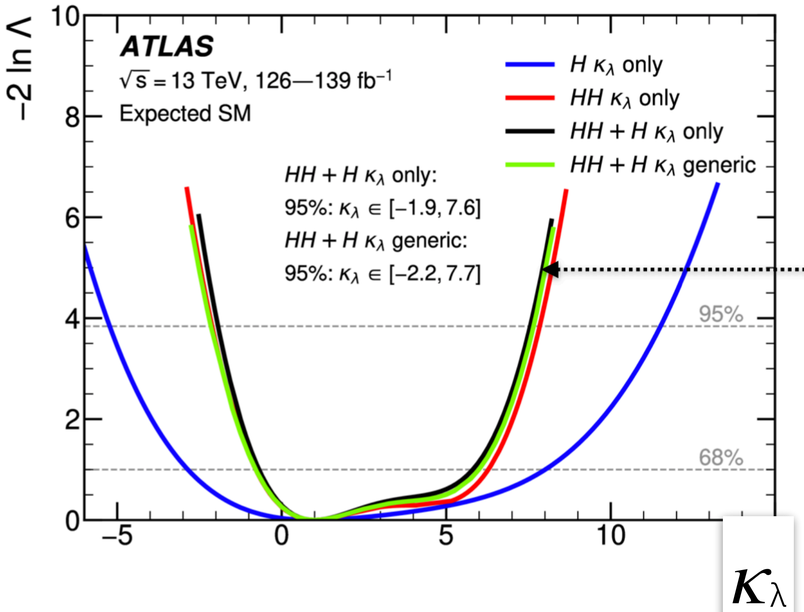
Nature 607 (2022) 60-68

Single experiment sensitivity below the SM @ HL-LHC

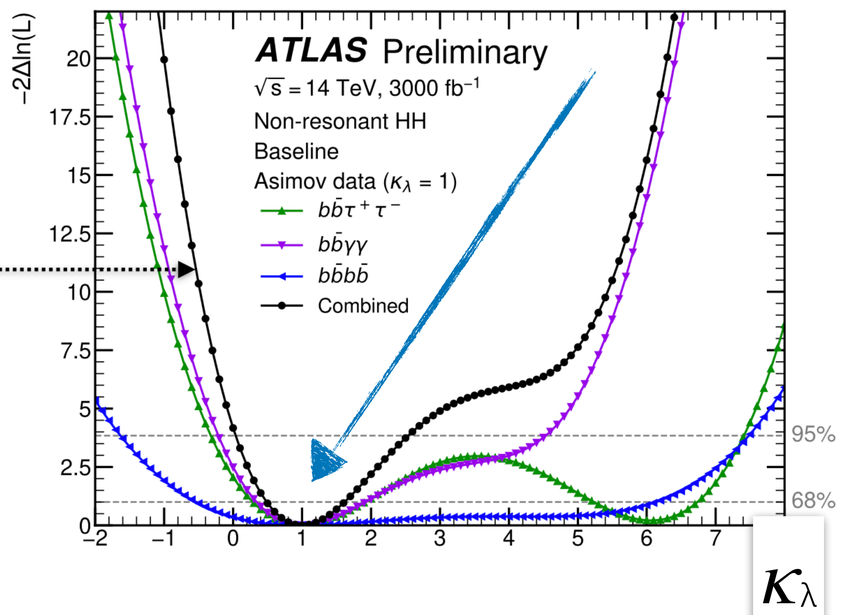


How far can we go?

- Expected self-coupling modifier 95% C.L. constraint:
  - Single- and di-Higgs current combination: [-1.9, 7.6] vs HL-LHC projection: [0.0, 2.5]



Run2: [arXiv:2211.01216]



HL-LHC projection [ATL-PHYS-PUB-2022-053]

We'll combine ATLAS and CMS + (improvements)^n…

5-sigma evidence for di-Higgs production at the HL-LHC quite possible […3-sigma after Run 3 - why not]

BSM new interactions

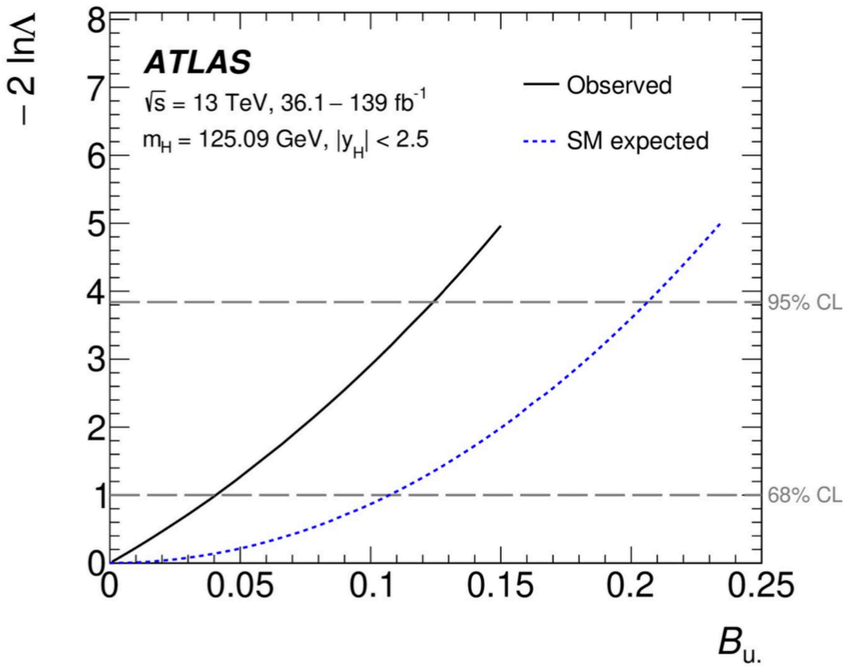
- Is there room for decays to undetected/invisible particles?
  - given all that has been observed/measured…

One way to do that would be to consider the Higgs coupling measurements and then see how much space is left for “left-out” decays (“undetected”)

95% CL limits on Higgs to undetected:

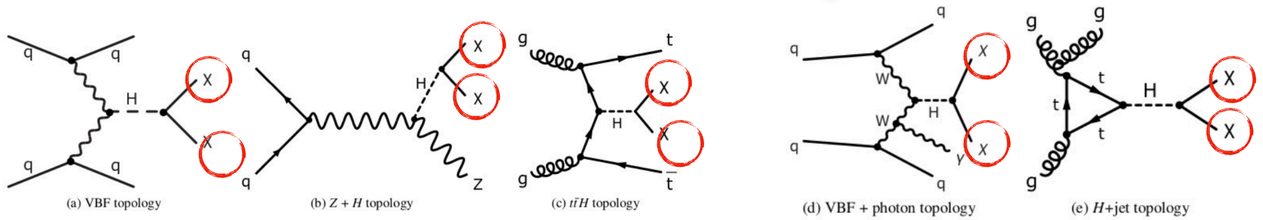
ATLAS: < 12% arXiv:2207.00092

CMS: < 16% arXiv:2207.00043

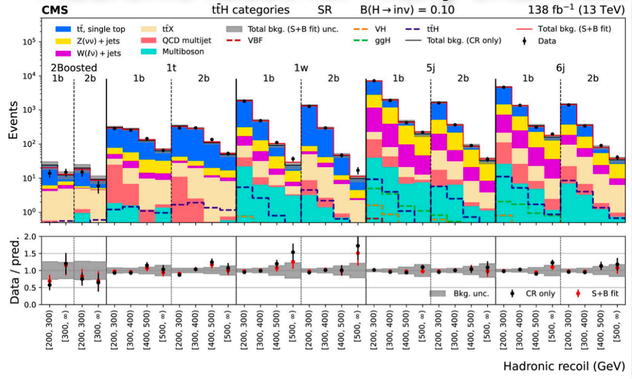


So quite a bit of room still…

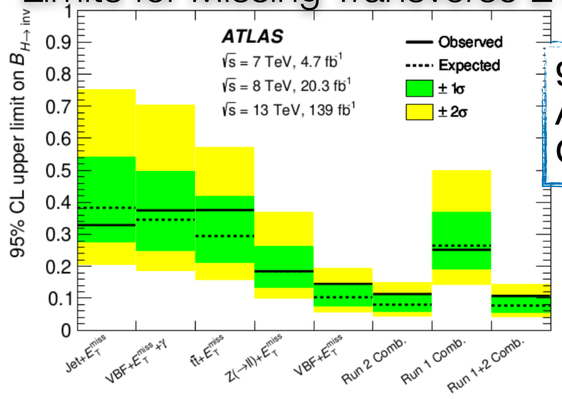
Can also search directly:



Hadronic recoil for many channels

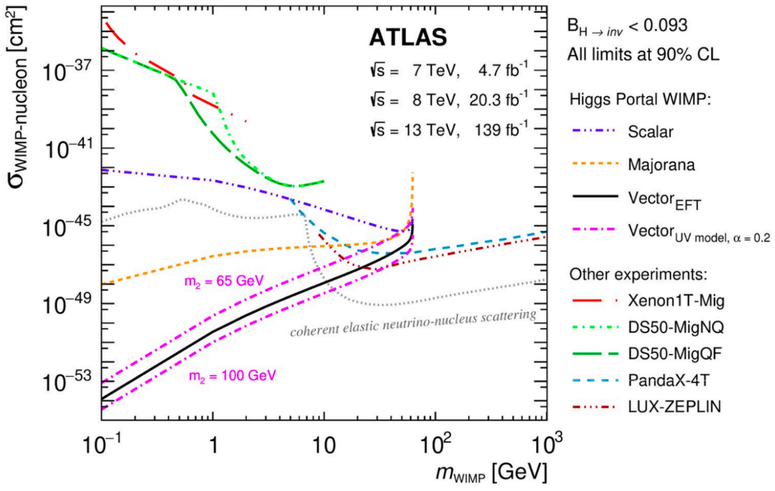


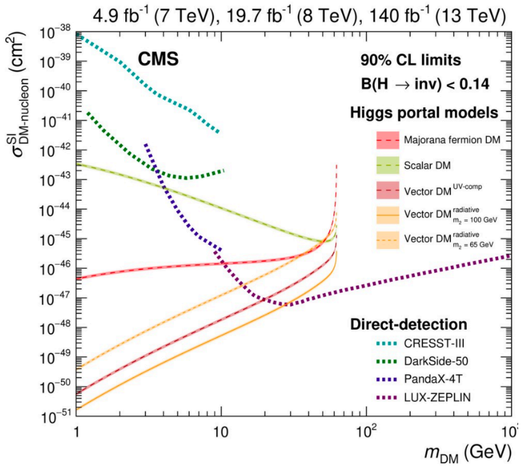
Limits for Missing Transverse E channels



95% CL limit for H→ inv:
ATLAS: 10.7% (7.7% exp.)
CMS: 15% (8% exp.)

ATLAS:arXiv:2301.10731
CMS: arXiv:2303.01214





Interpretation in DM models

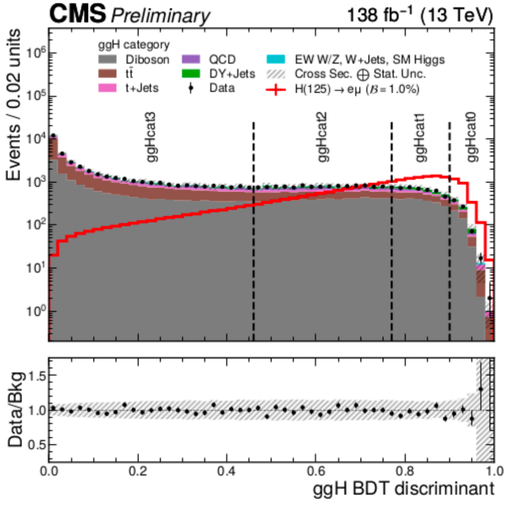
Does the Higgs violate lepton flavor?

- needs to be tested

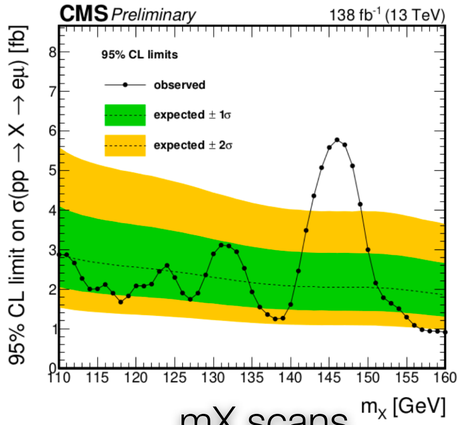
BSM new interactions

CMS search for H → eμ for m_H: 110–160 GeV

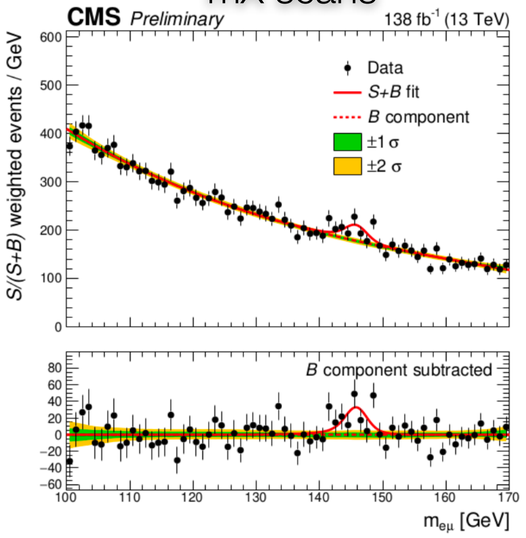
HIG-22-002



BDT score



mX scans



BR(H[125]→eμ)
< 4.4 (4.7) x 10^{-5} at 95%CL

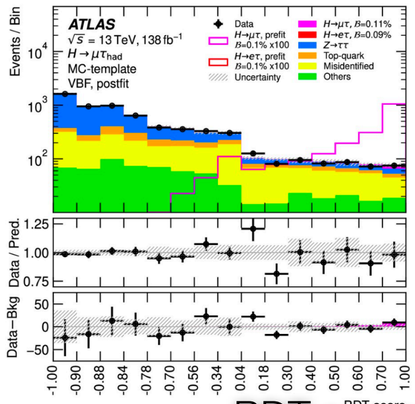
2.6 sigma excess at Meμ ~ 146 GeV

ATLAS search for H → eτ and H → μτ

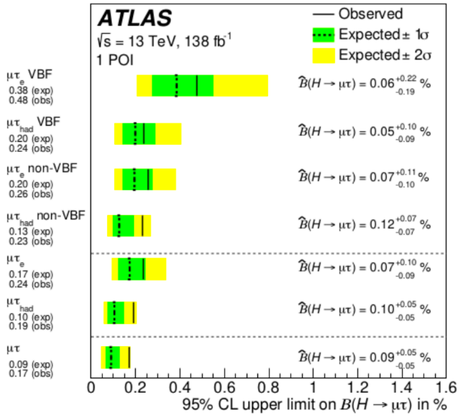
arXiv:2302.05225

H→eτ assuming BR(H→μτ) = 0
or for
H→μτ assuming BR(H→eτ) = 0

BR(H→eτ) < 0.23% (0.12% exp)
BR(H→μτ) < 0.17% (0.09% exp)

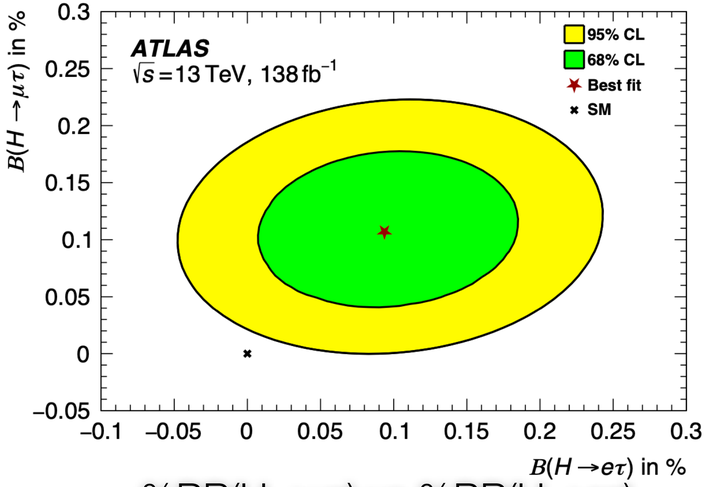


BDT score



Simultaneous search for H→eτ and H→μτ

BR(H→eτ) < 0.20% (0.12% exp)
BR(H→μτ) < 0.18% (0.09% exp)



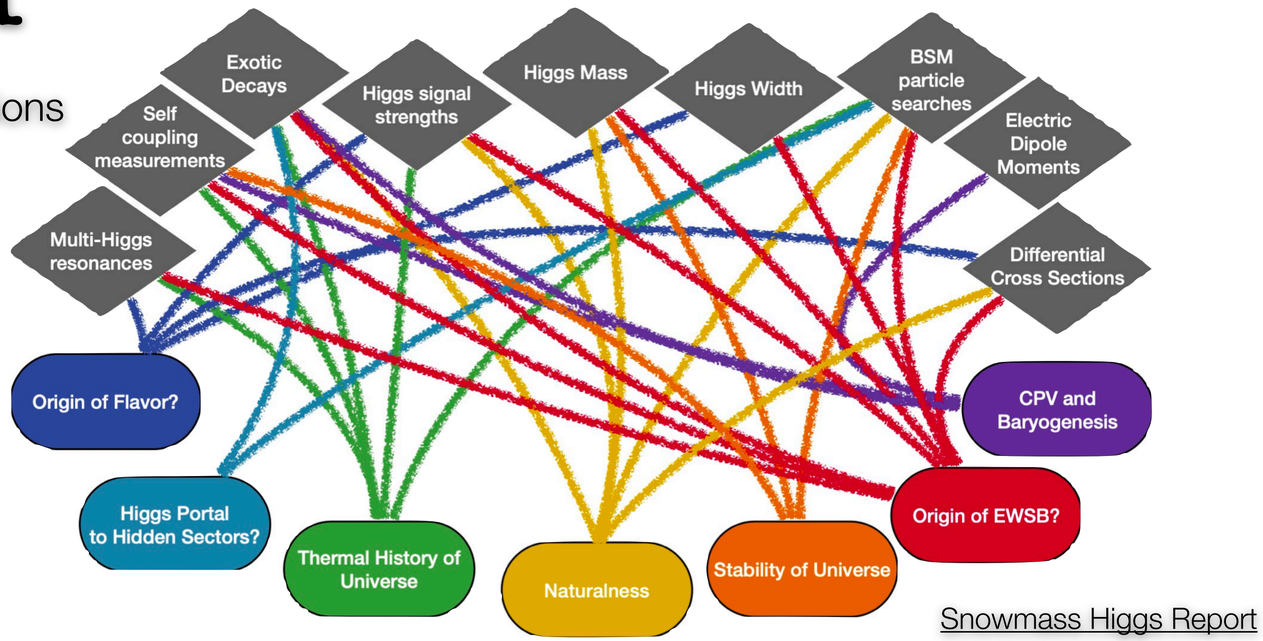
%BR(H→μτ) vs %BR(H→eτ)

2.1 sigma compatibility with SM

=> Keep testing…

The end

But not the end to the questions



Snowmass Higgs Report

Stay tuned for more and more innovative results / techniques from Run 2 and Run 3

As we prepare for the surprises that the HL-LHC will yield

"So "new physics" [beyond bump plots] is much more deeply about new phenomena and new principles. The discovery of the Higgs particle - especially with nothing else accompanying it so far - is unlike anything we have seen in any state of nature, and it is profoundly "new physics" in this sense…"

"…It is the first example we've seen of the simplest possible type of elementary particle. It has no spin, no charge, only mass, and this extreme simplicity makes it theoretically perplexing".

"…measure the hell out of these crazy phenomena!

— N. Arkani-Hamed April 2019 CERN Courier

Acknowledgements

Some References

- Higgs Turns Ten:
  - Perspective: Nature 607, 41-47 (2022)
  - ATLAS: Nature 607, 52-59 (2022)
  - CMS: Nature (607), 60-68 (2022)
- Sampled material from:
  - LISHEP, LaThuille, Moriond EWK/QCD
    - Chen, Maravin, Meridiani, Wang, Errico, Roy
    - Palacino, Rompotis
    - and many more…
  - Other presentations:
    - Korytov, Jessop, Newman
- Thanks
  - ATLAS and CMS Higgs Group convenors etc
    - Padley, DeWit, Brost, Berger,

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HDBSPublicResults