HIGGS PHYSICS: QUO VADIS

Greg Landsberg

Madrid, Spain, 10.06.24

SUSY 2024: Theory Meets Experiment

BROWN

Outline

- ✦Higgs Experimental Highlights
- ✦Higgs Theory Highlights
- ✦Additional Higgs Bosons
- ✦Rare Higgs Boson Decays
- ✦Toward Triple Higgs
- ✦Conclusions: Quo Vadis?

✦ Disclaimer: this talk is a rapporteur talk reflecting my own thoughts on the most interesting aspects of Higgs physics today and a quick preview of detailed results to be shown in the rest of this parallel session track. (All links are clickable.)

Dedication: I'd like to dedicate this talk to the memory of Peter Ware Higgs (29.05.29-08.04.24), whose transformative and groundbreaking ideas laid the foundation for the physics of the standard model and the very particle named after him

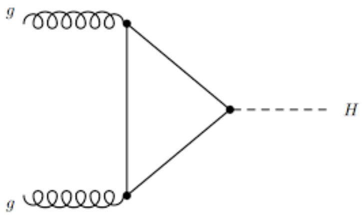
Higgs Experimental Highlights

BROWN

ATLAS+CMS Physics Reports

- ATLAS and CMS just submitted several Phys. Rept. articles on various aspects of their physics program
  - These are legacy Run 2 papers and a valuable resource on experimental techniques and results
  - There are several that concern Higgs physics
- ATLAS:
  - arXiv:2404.05498, Characterising the Higgs boson with ATLAS data from Run 2 of the LHC
  - arXiv:2405.04914, ATLAS searches for additional scalars and exotic Higgs boson decays with the LHC Run 2 dataset
- CMS:
  - arXiv:2403.16926, Searches for Higgs boson production through decays of heavy resonances
  - arXiv:2405.18661, Stairway to discovery: a report on the CMS programme of cross section measurements from millibarns to femtobarns

Higgs Factory



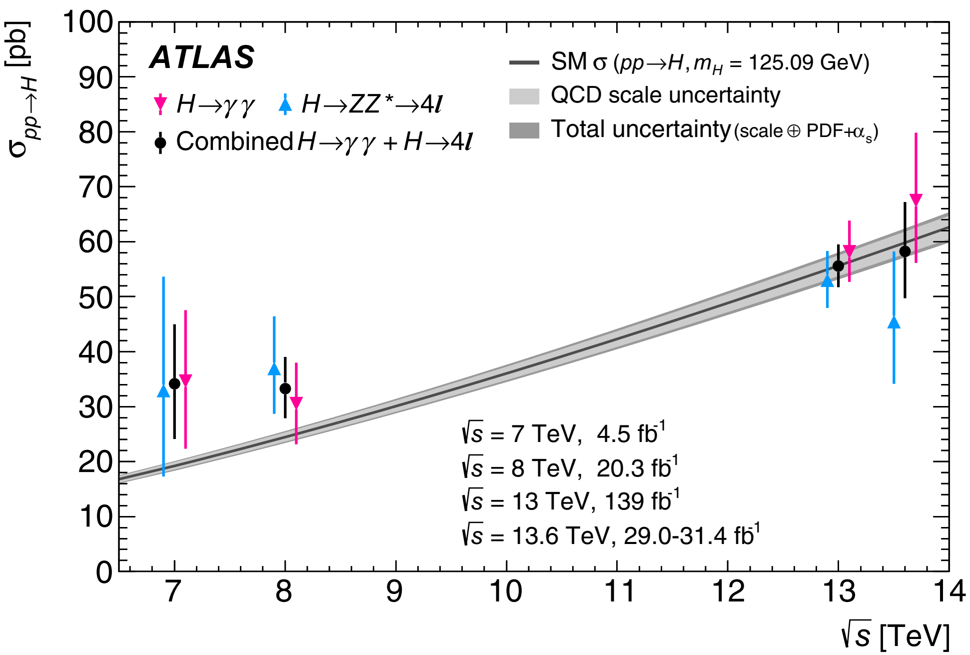
- LHC is the Higgs factory and the only place to study Higgs physics directly today
- At 13 TeV, the production cross section for the Higgs boson, dominated by gluon-gluon fusion, is ~50 pb
  - 15M Higgs bosons delivered by the LHC in Run 2!
  - By now ATLAS and CMS *could* have accumulated as many Higgs bosons as four LEP experiments accumulated Z bosons
  - With the cross section @13.6 TeV of ~60 pb another 12M have been already delivered in Run 3!
- But: triggering is a big challenge:
  - Most of gg → H(bb) events were never put on tape, which is how half of Higgs bosons at the LHC are produced and decay
- Need to pursue aggressive triggering strategies and go for lower cross section production mechanisms to observe all possible Higgs boson decays and couplings

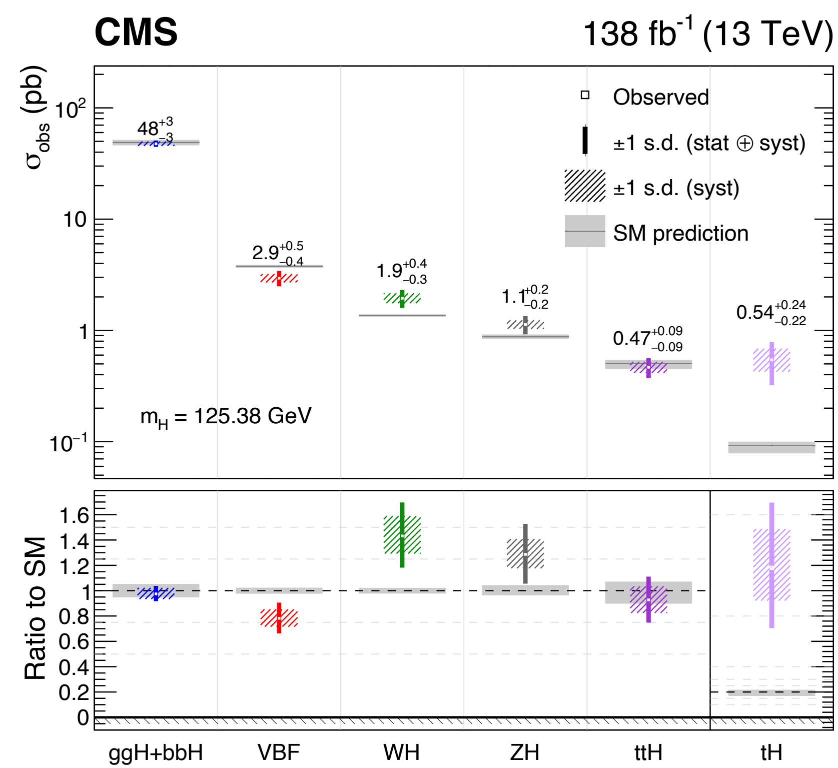
Higgs Boson Cross Sections

- Inclusive and fiducial cross section in multiple production modes have been measured and broadly agree with the SM predictions
- All four major production mechanisms: ggH, qqH, VH, and ttH have been firmly established

CMS arXiv:2405.18661

ATLAS EPJC 84 (2024) 78

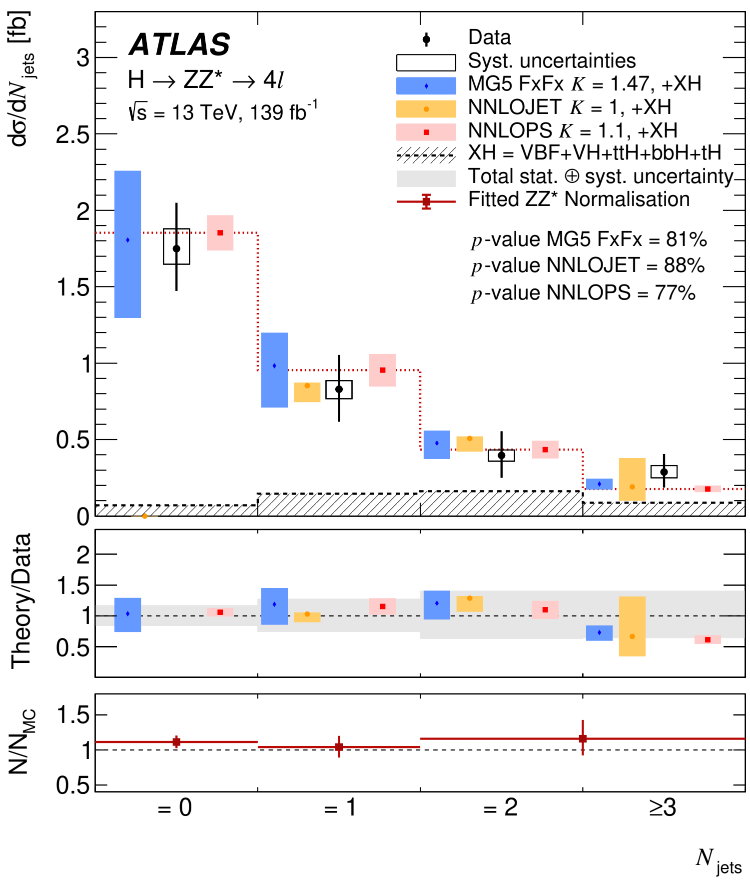


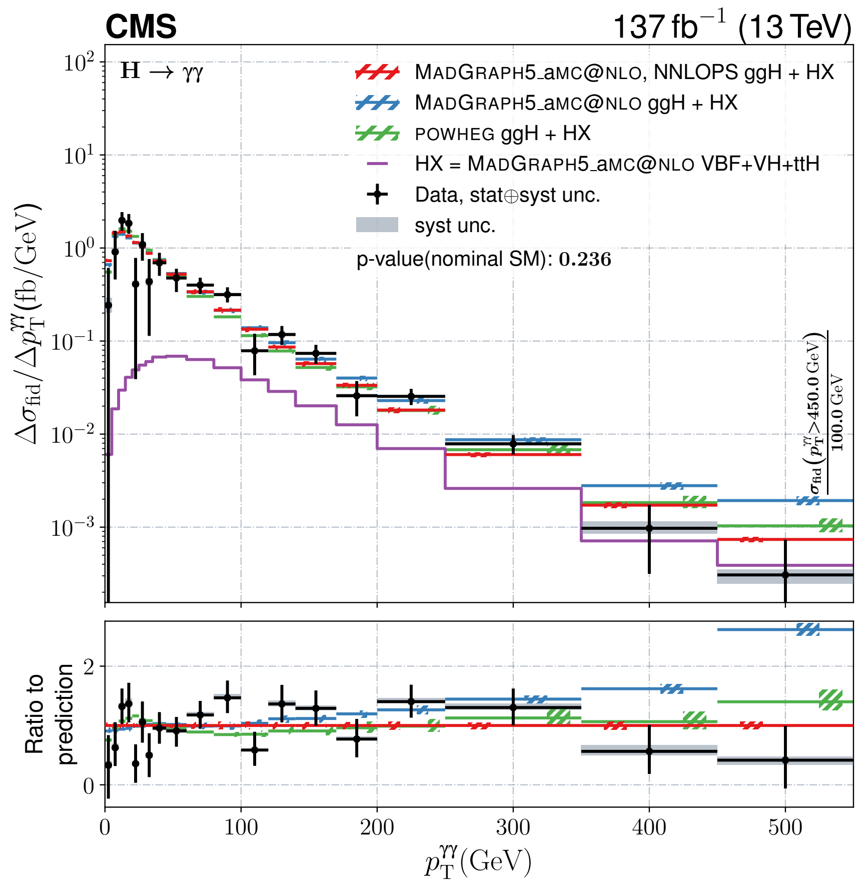


Going Differential

- By now the number of recorded Higgs bosons is large enough to start measuring differential cross sections
- Stress tests of higher-order theoretical calculations and parton shower generators

ATLAS EPJC 80 (2020) 941



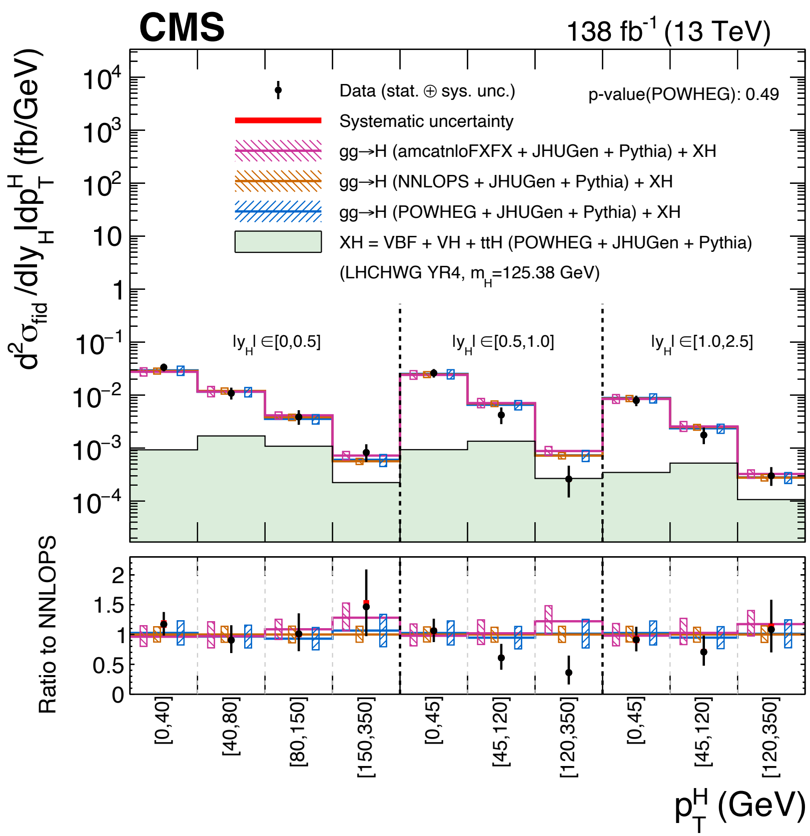


CMS JHEP 07 (2023) 091

Going Doubly Differential

- Already started probing double-differential cross sections with reasonable precision
- Important for testing theory prediction at high $p_T(H)$, high associated jet multiplicity, high rapidity, etc.

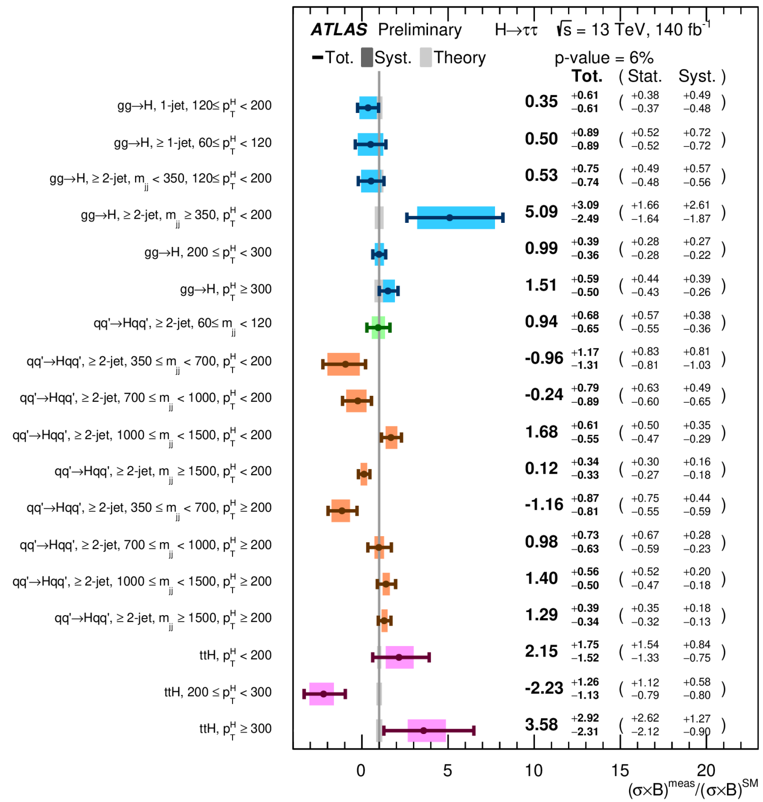
CMS JHEP 08 (2023) 040



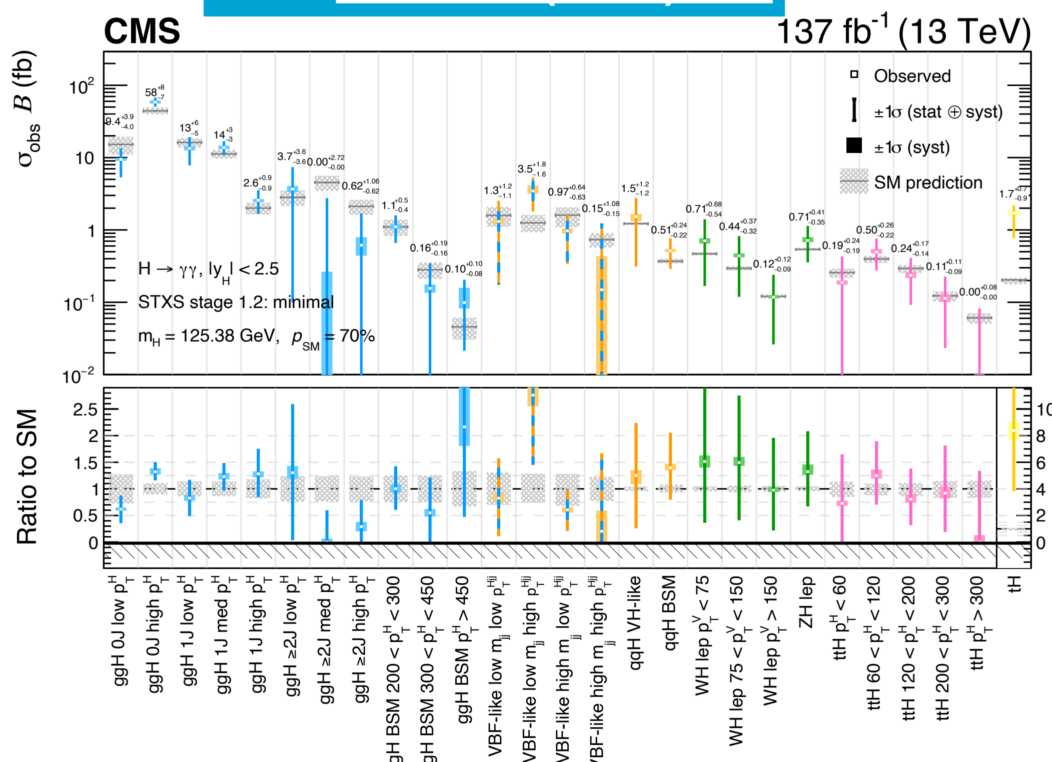
Going STXS

- More and more results are being interpreted in the Simplified Template Cross Section (STXS) framework, which is somewhat in between fully inclusive and fully differential measurements
- Allows for a straightforward SMEFT reinterpretation and setting constraints on various Wilson coefficients, thus providing sensitivity to BSM physics

ATLAS CONF-2024-007



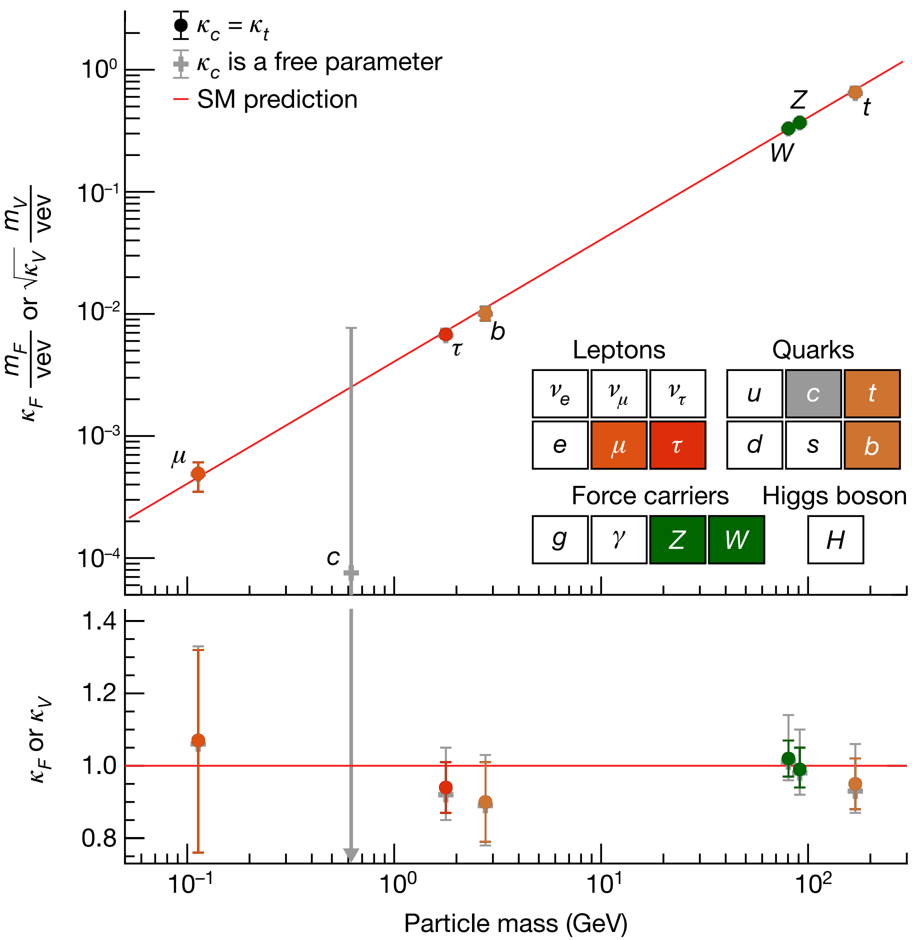
CMS JHEP 07 (2021) 027



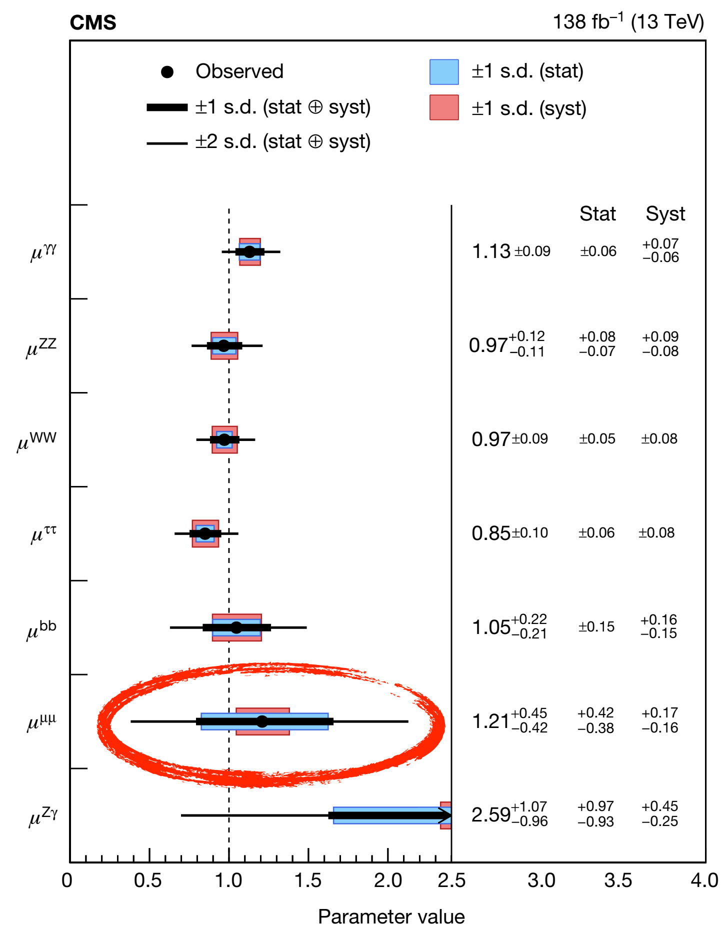
Higgs Boson Couplings

- Couplings to third-generation fermions and EW bosons have been measured; first evidence for coupling to muons

ATLAS Nature 607 (2022) 52



CMS Nature 607 (2022) 60

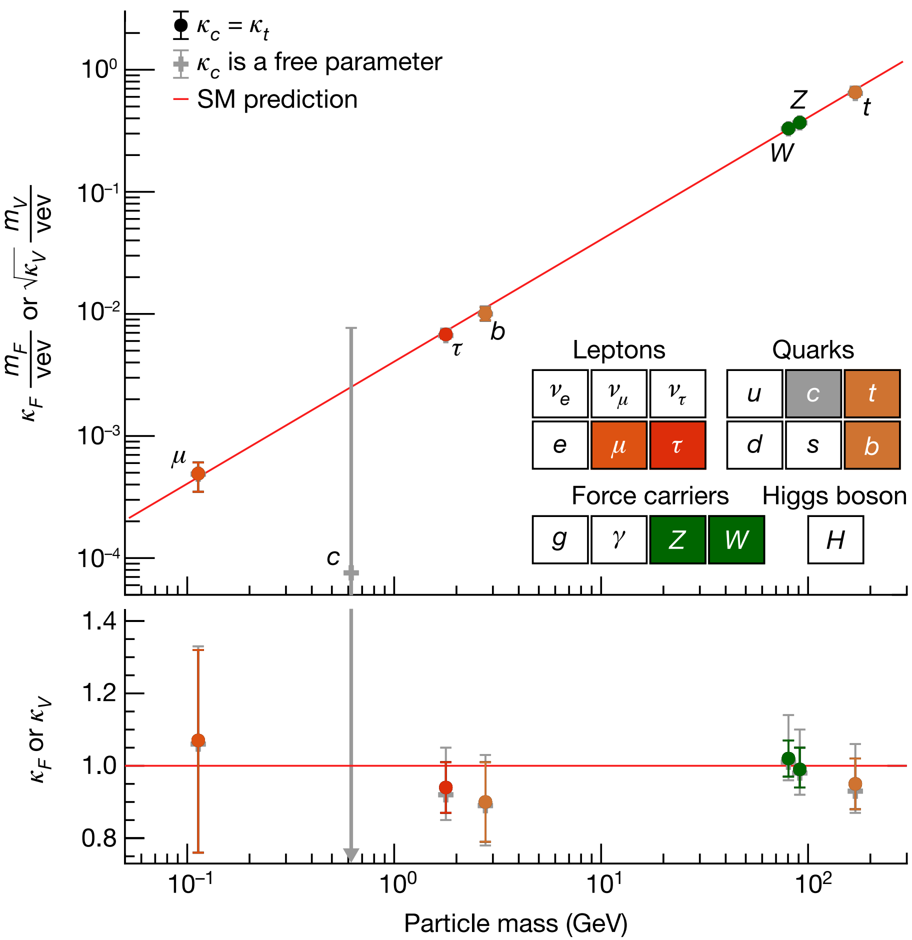


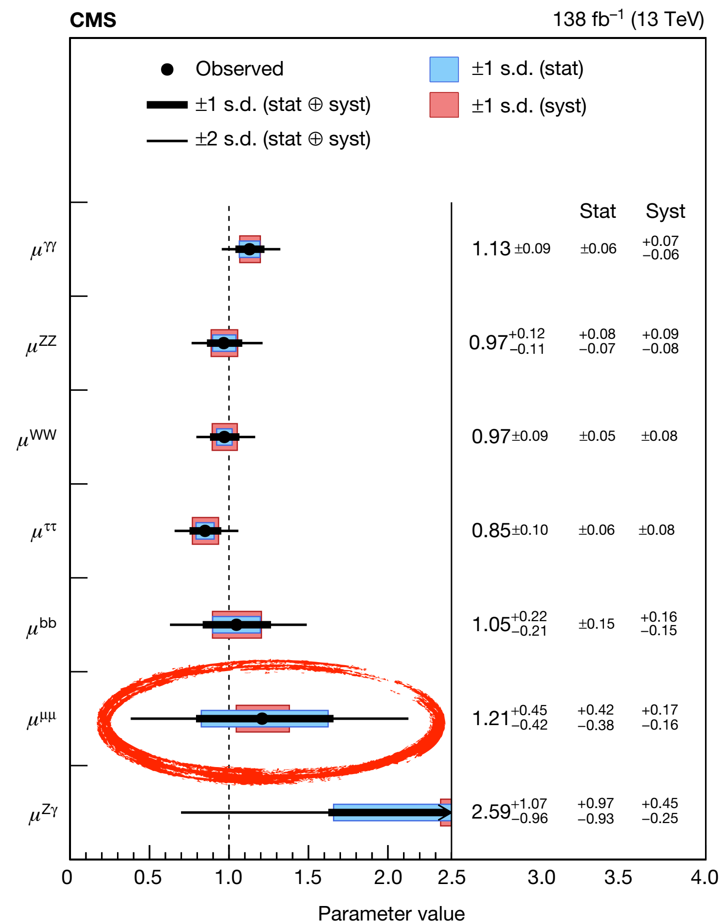
Higgs Boson Couplings

- Couplings to t ... V bosons have been me ... ng to muons

ATLAS Nat ... 07 (2022) 60

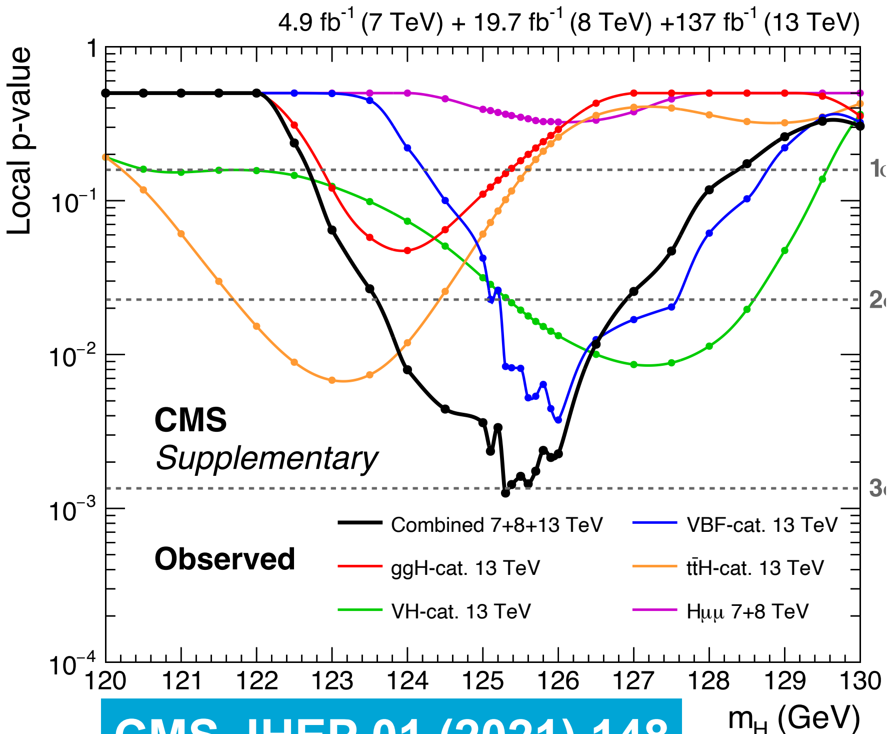
More on Higgs boson production and properties in the following talks: R.Barrué, D. Mungo (Tue), R. Zhang (Fri)





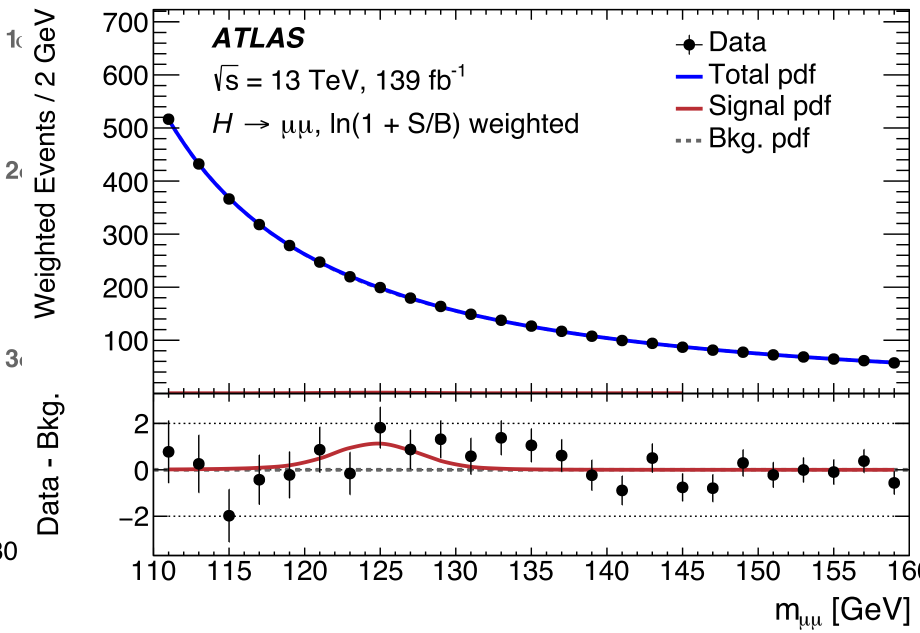
Couplings to 2nd Generation

- ✦ First evidence for Higgs coupling to muons has been established at 3σ by CMS and 2σ by ATLAS
- ✦ One of the highest priorities is to reach the observation level w/ Run 1-3 data, which should be possible in the ATLAS+CMS combination



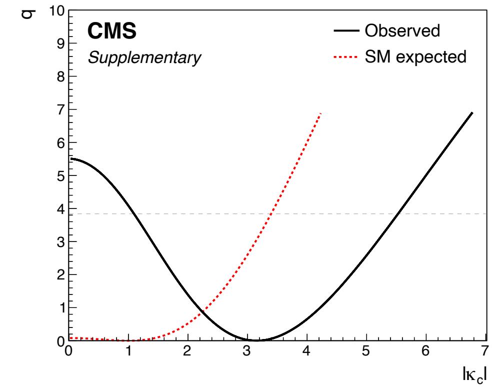
CMS JHEP 01 (2021) 148

ATLAS PLB 812 (2021) 135980

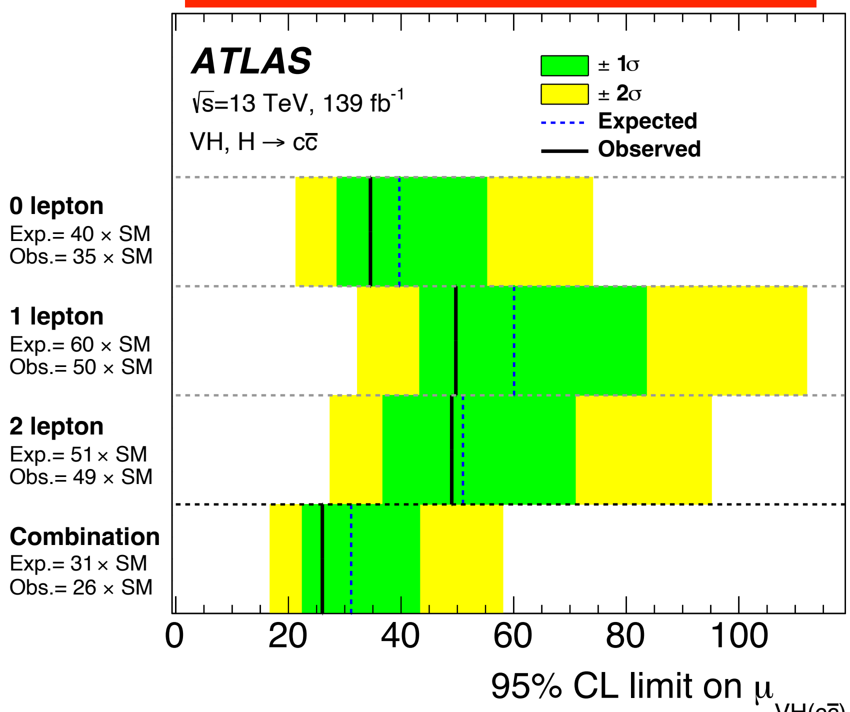


Coupling to Charm

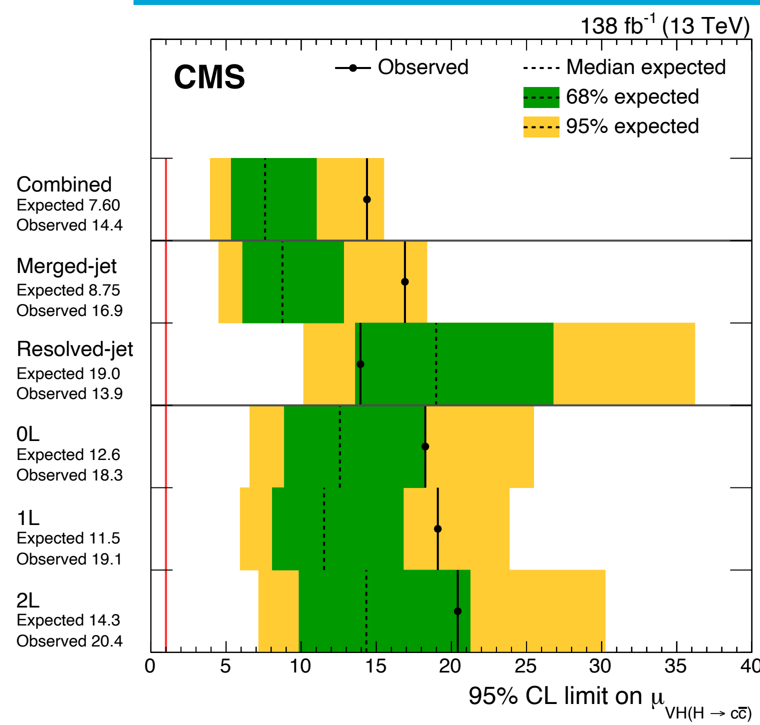
- Couplings to charm quark are much harder to establish (and still long way to go!)
  - Significant breakthrough with the dedicated ML charm taggers in the past couple of years
  - Much better sensitivity than originally expected
    - CMS reached 1.1 < $|\kappa_c|$ < 5.5 ($|\kappa_c|$ < 3.4 exp.) @ 95% CL



ATLAS EPJC 82 (2022) 717



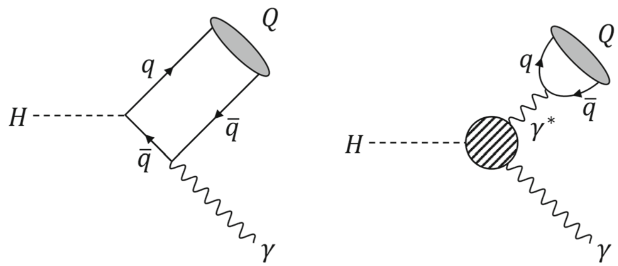
CMS PRL 131 (2022) 061801



BROWN

Other Ways to Probe Hqq?

- One could probe charm Yukawa coupling through Higgs decays via charmonium, e.g., $H \to J/\psi\gamma$, $\psi(2S)\gamma$
  - SM predicted branching fraction is $\sim 10^{-6}$
  - Unfortunately, it is largely dominated by the Dalitz decay, not the direct Hcc coupling diagram



(a) Direct amplitude (b) Indirect amplitude

ATLAS EPJC 83 (2023) 781

CMS PAS SMP-22-012

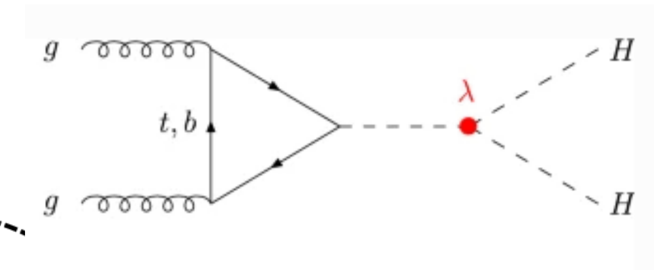
- Current limits on the branching fraction $\lesssim 2 \times 10^{-4}$, which corresponds to $|\kappa_c/\kappa_\gamma| \lesssim 150$
- Significantly worse than the VH(cc) limits, but it may be the only way to probe coupling to the s quark (via $H \to \phi(1020)\gamma$) or the first-generation quarks (via $H \to \rho(780)\gamma$)
- First limits are already available

ATLAS JHEP 07 (2018) 127

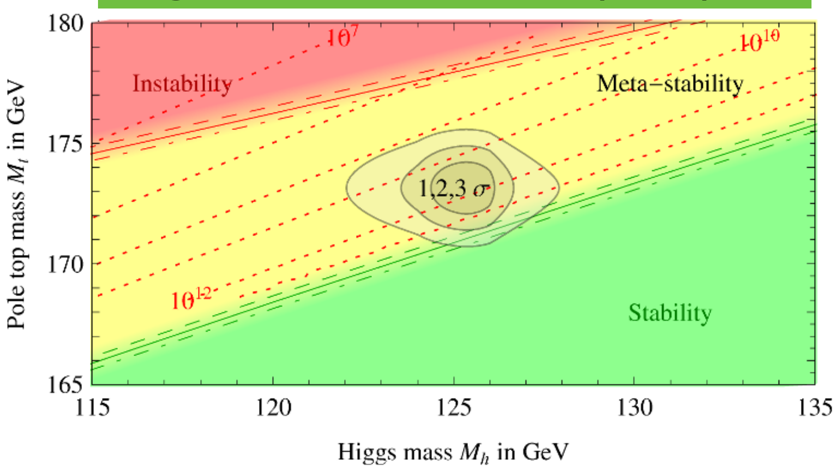
CMS PAS HIG-23-005

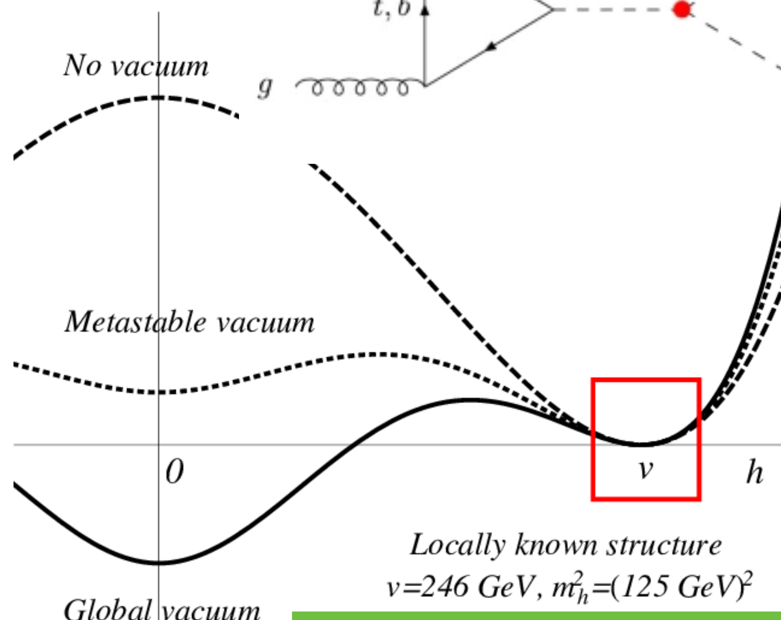
Exploring Higgs Potential

- One of the most important couplings is a Higgs boson self-coupling, λ
- Directly affects the shape of the Higgs potential, with implications for both early and late universe (e.g., EW vacuum stability)
- Depends on λ (or, in the SM, $m_H = \sqrt{2\lambda}v$), m_t, and α_s
- Important to precisely measure all these parameters, including λ, to test the predictions of the Higgs mechanism



Degrassi et al. JHEP 08 (2012) 098



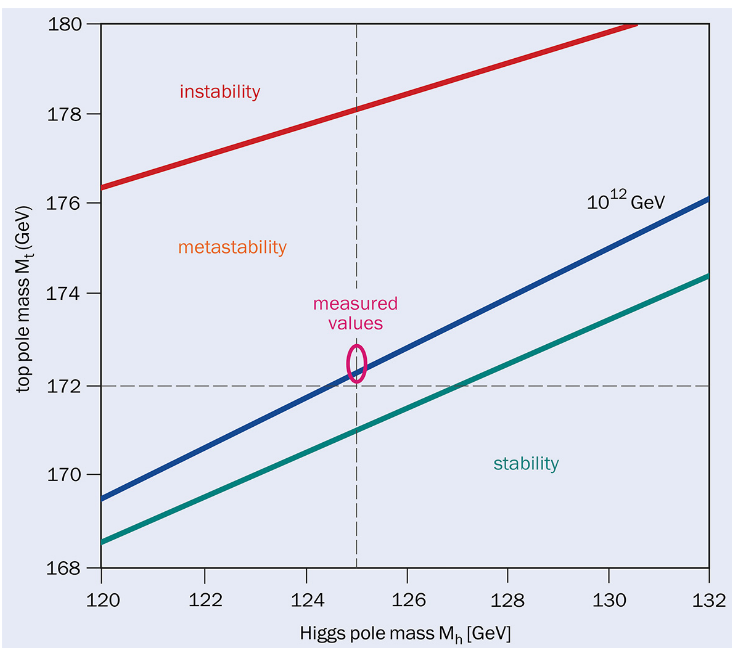


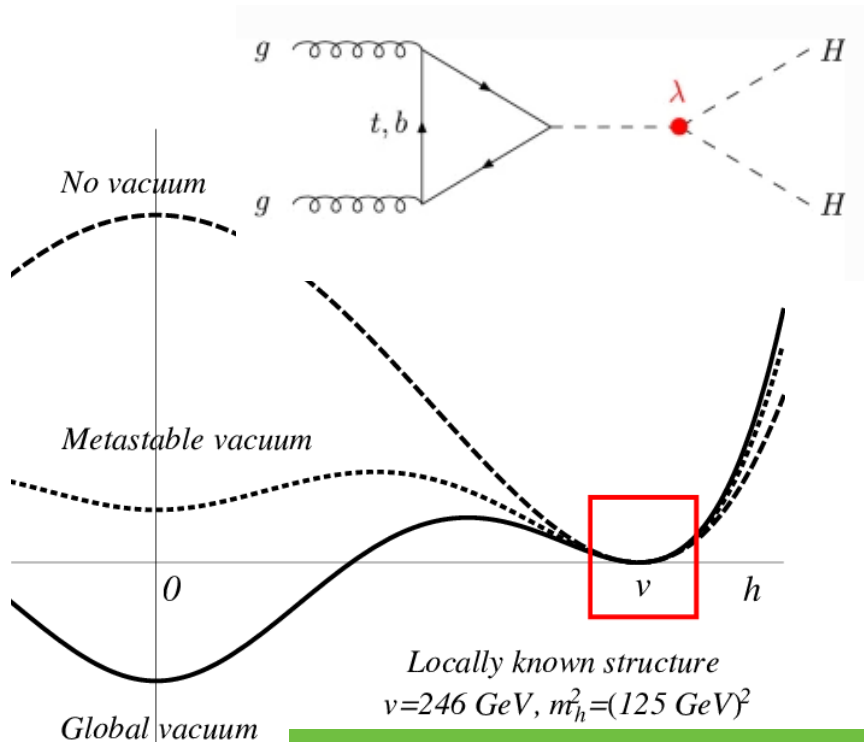
Bai et al. JHEP 07 (2021) 225

Exploring Higgs Potential

- One of the most important couplings is a Higgs boson self-coupling, λ
- Directly affects the shape of the Higgs potential, with implications for both early and late universe (e.g., EW vacuum stability)
- Depends on λ (or, in the SM, $m_H = \sqrt{2\lambda}v$), m_t, and α_s
- Important to precisely measure all these parameters, including λ, to test the predictions of the Higgs mechanism

J. Ellis, CERN Courier 62 (2022) 59





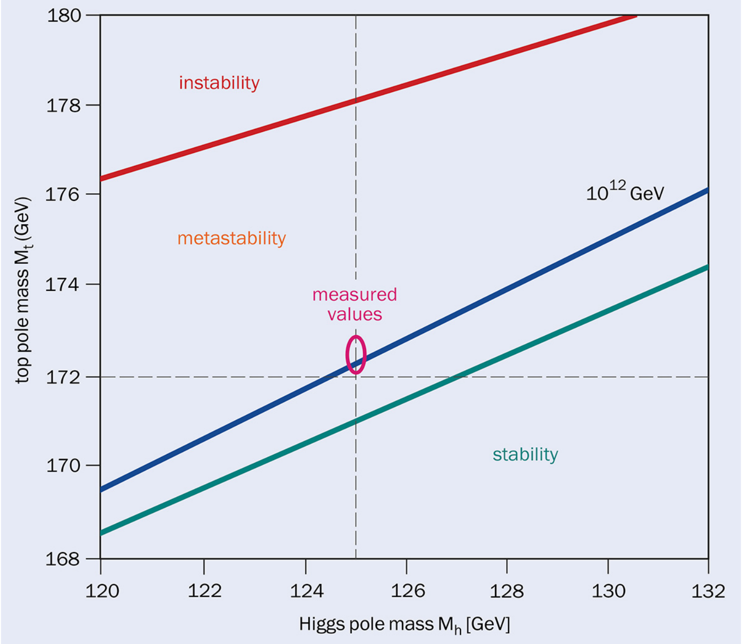
Bai et al. JHEP 07 (2021) 225

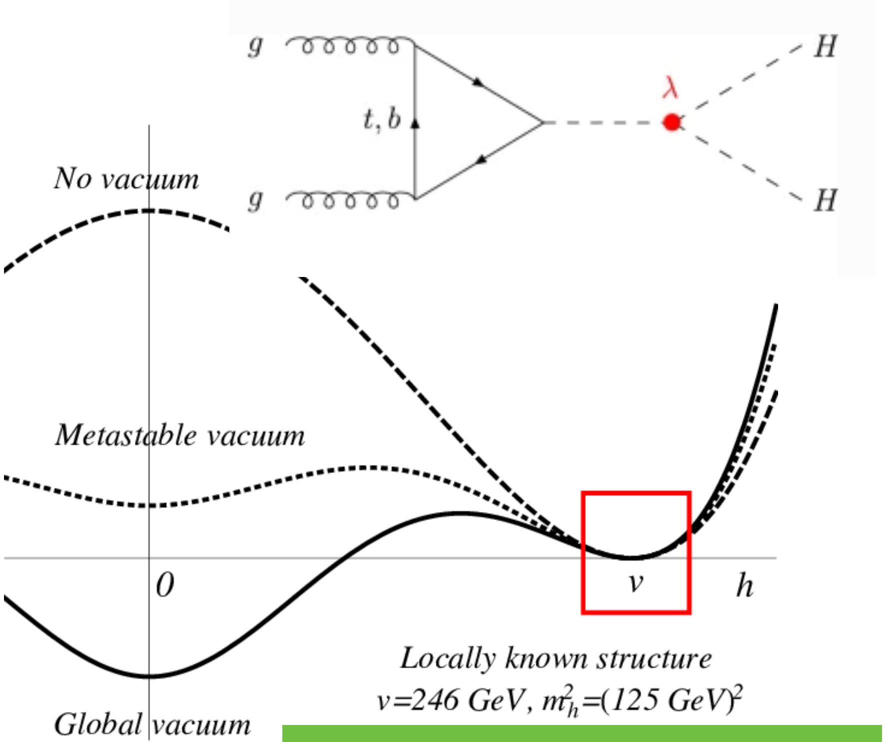
Exploring Higgs Potential

- One of the most i… …oupling, λ
- Directly affects th… …tions for both early and late univ…
- Depends on λ (or,…
- Important to preci… …ng λ, to test the predictions of the Higgs mechanism

More on connection of the Higgs boson and cosmology in the following talks:
K. Radchenko Serdula (Mon),
M. Mlinarevic (Thu), M. Sassi, A. Dashko,
T. Biekötter (Fri)

J. Ellis, CERN Courier 62 (2022) 59





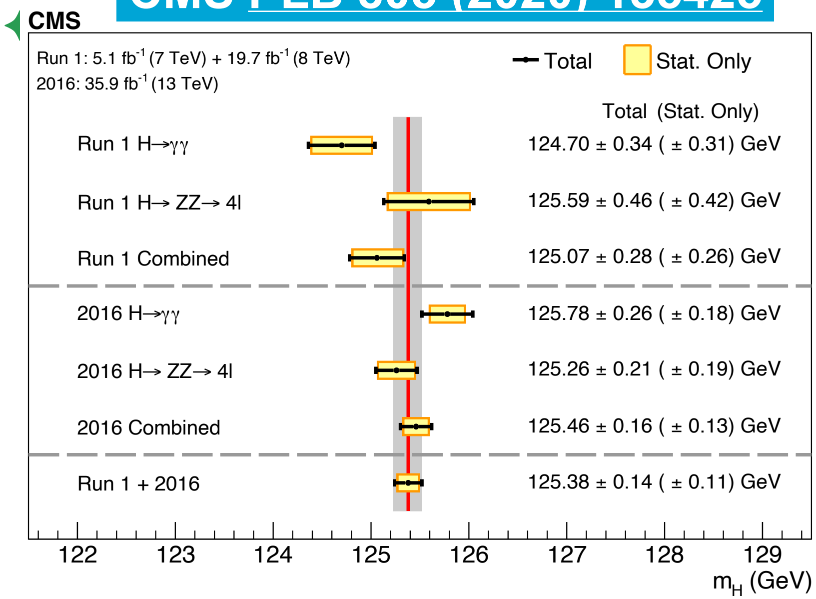
Bai et al. JHEP 07 (2021) 225

BROWN

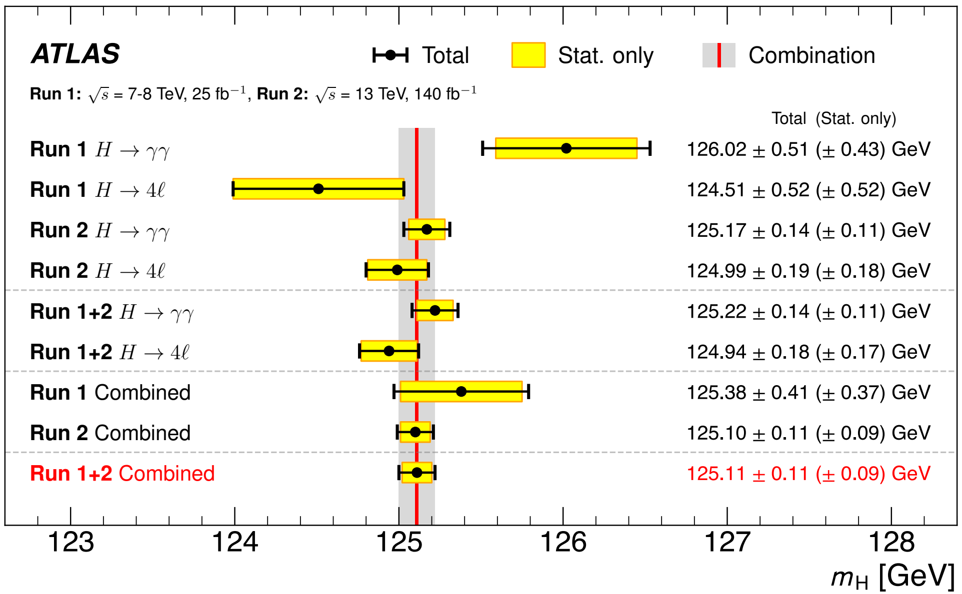
Higgs Boson Mass (and Width)

- New, more precise measurements of the Higgs boson mass by ATLAS and CMS, with sub-permille precision per experiment achieved!
- The two experiments also measured the Higgs boson width by combining on-shell and off-shell production of H(ZZ) with
  - $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV **CMS Nature Phys. 18 (2022) 1329**
  - $\Gamma_H = 4.5^{+3.3}_{-2.4}$ MeV **ATLAS PLB 846 (2023) 138223**
  - Measurements are in agreement with the SM prediction of Γ_H = 4.1 MeV

CMS PLB 805 (2020) 135425



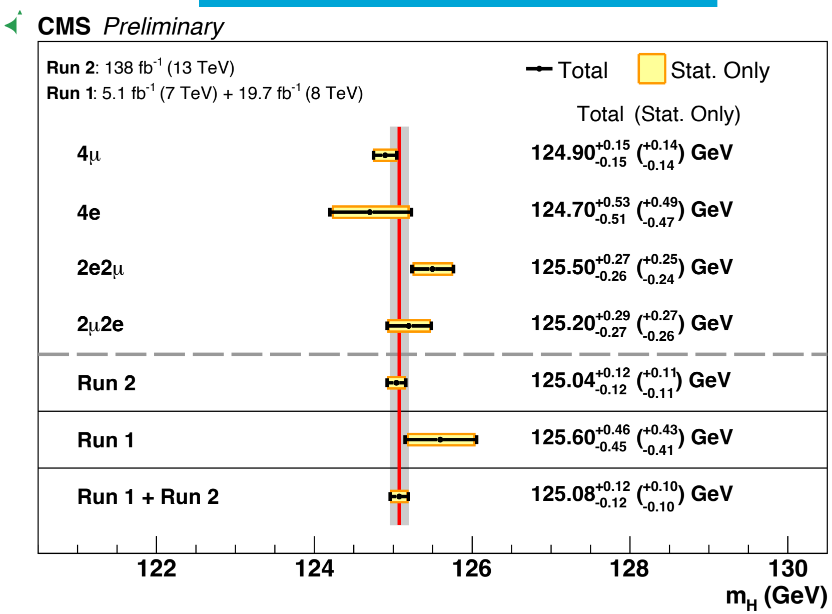
ATLAS PRL 131 (2023) 251802



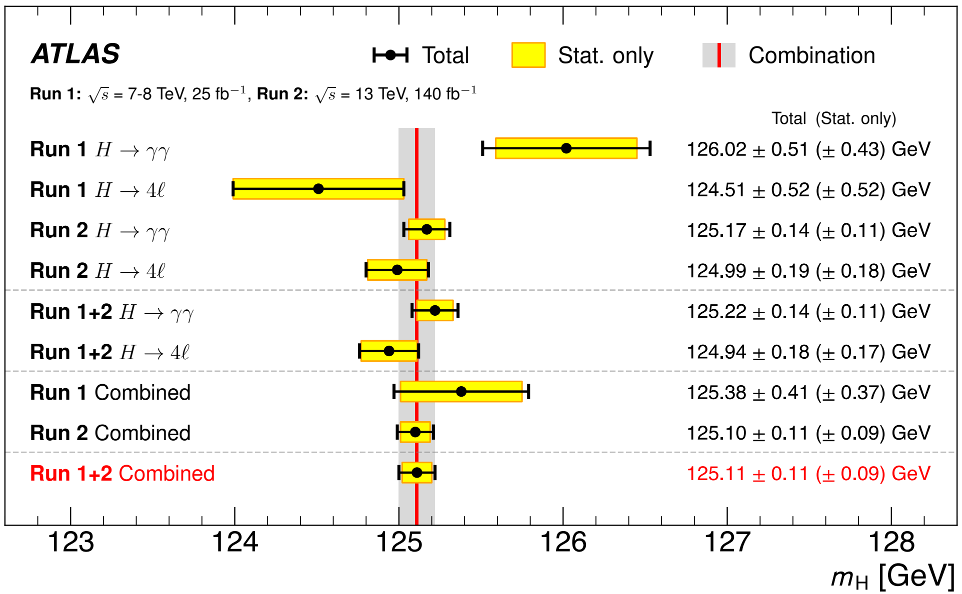
Higgs Boson Mass (and Width)

- New, more precise measurements of the Higgs boson mass by ATLAS and CMS, with sub-permille precision per experiment achieved!
- The two experiments also measured the Higgs boson width by combining on-shell and off-shell production of H(ZZ) with
  - $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV — CMS Nature Phys. 18 (2022) 1329
  - $\Gamma_H = 4.5^{+3.3}_{-2.4}$ MeV — ATLAS PLB 846 (2023) 138223
  - Measurements are in agreement with the SM prediction of Γ_H = 4.1 MeV

CMS PAS HIG-21-019

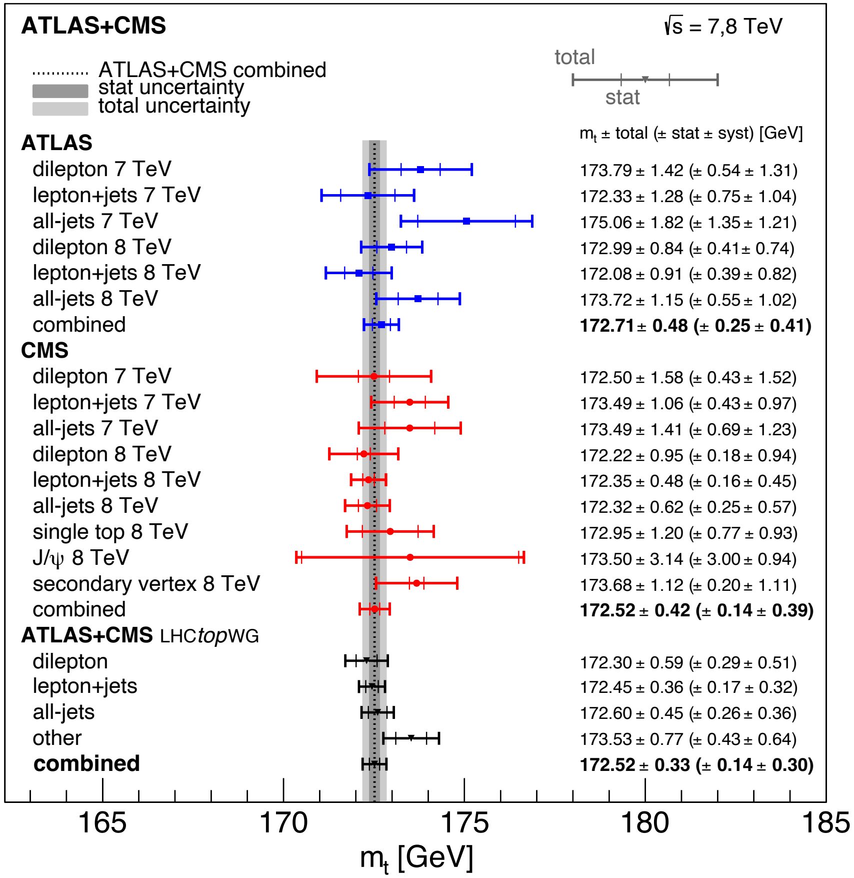


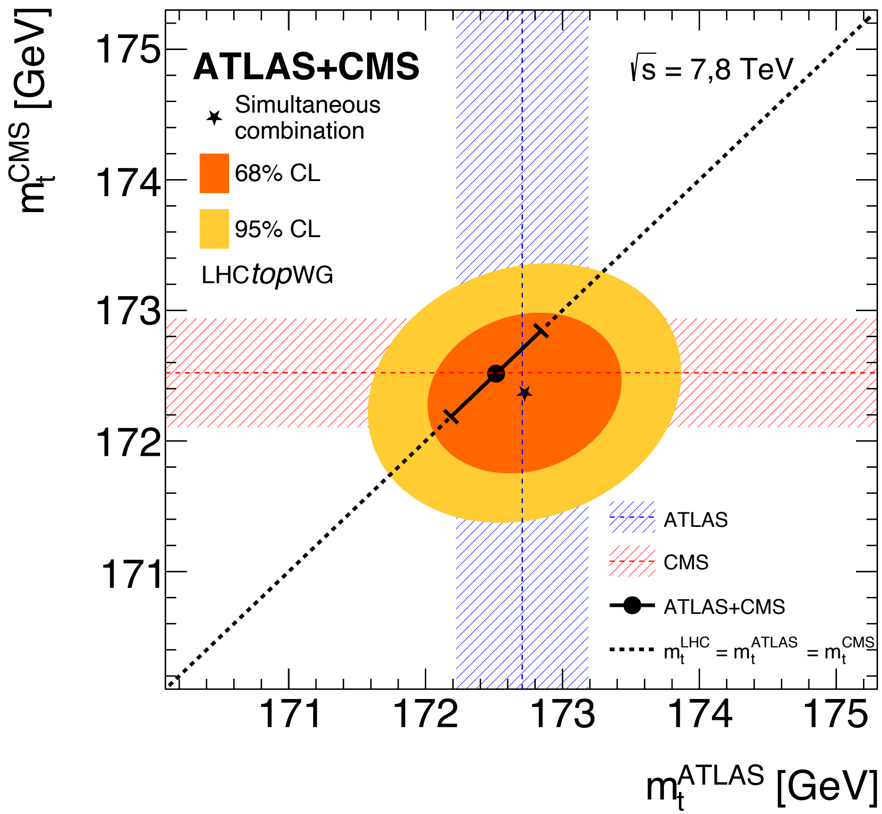
ATLAS PRL 131 (2023) 251802



Top Quark Mass Measurement

- The most precise measurement of the top quark mass is currently from a recent Run 1 combination of ATLAS and CMS measurements: $m_t = 172.52 \pm 0.33$ GeV, with <2‰ precision
  - The most precisely measured quark mass!



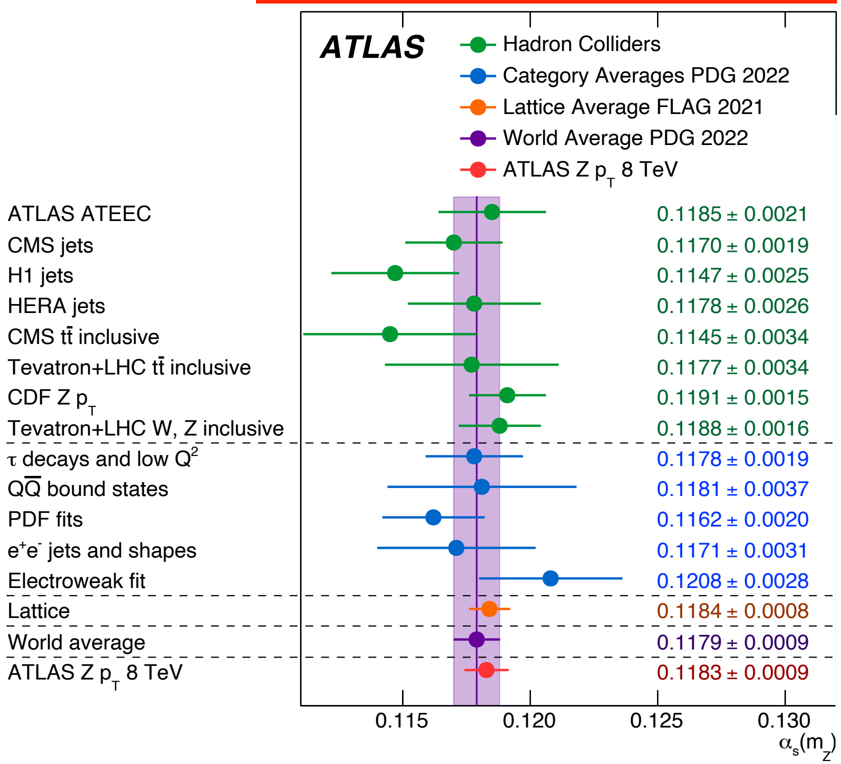


ATLAS & CMS arXiv:2402.08713

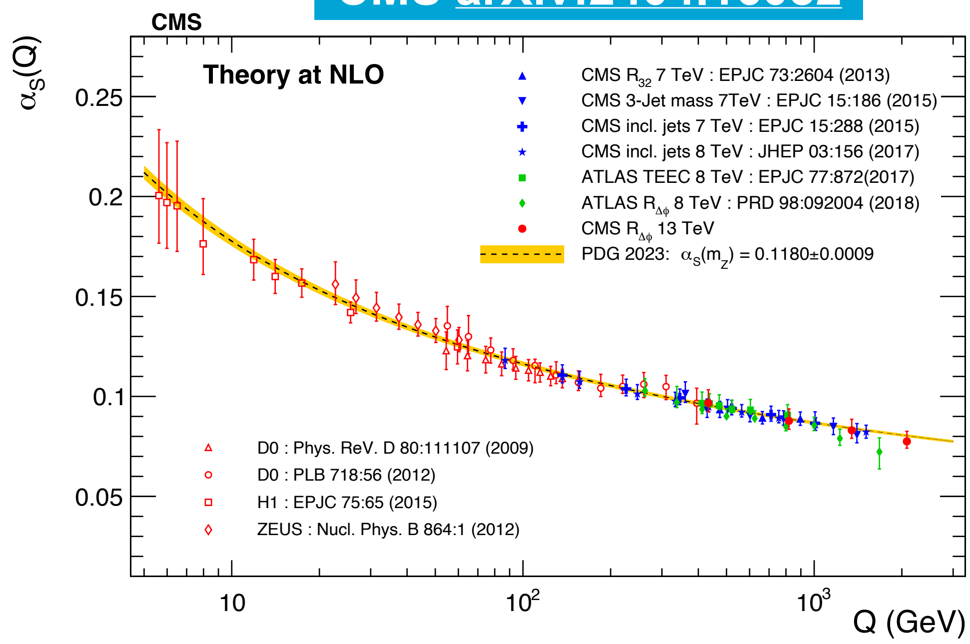
Strong Coupling Measurement

- ✦ Several new results from ATLAS and CMS, including ATLAS's novel N^3LO extraction based on Z boson p_T spectrum, which is as precise as the 2022 world average! [Submitted to Nature Physics.]
- ✦ The running of $\alpha_S(Q)$ has been probed at the LHC over nearly 3 orders of magnitude in Q and agrees very well with the QCD NLO RGE evolution

ATLAS arXiv:2309.12986



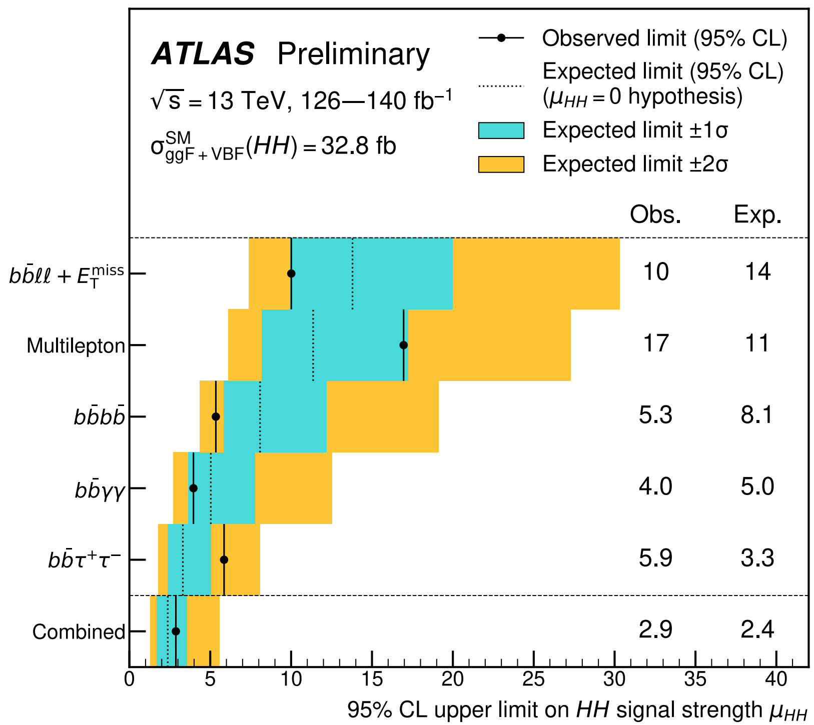
CMS arXiv:2404.16082

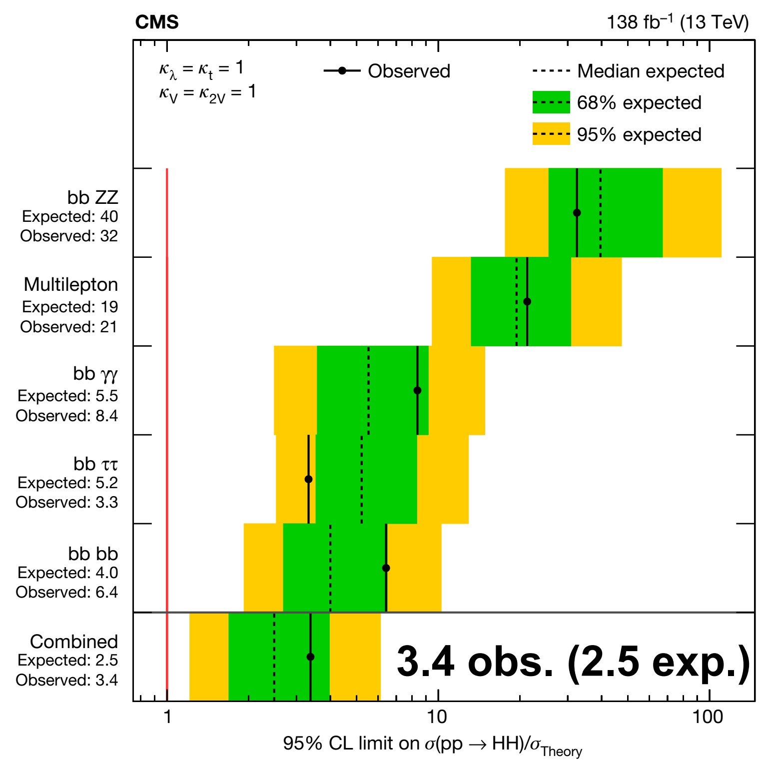


Probing Self-Coupling

- Measurement of Higgs boson self-coupling λ is an ultimate goal of HL LHC
- The cross section is very low, due to large negative interference between the diagrams contributing to Higgs boson pair production
- Enormous progress has been achieved using ML b-tagging techniques and multivariate methods
- Current 95% CL limits on $\mu = \sigma/\sigma_{SM}$ for HH production are <2.9 (2.4) in ATLAS and <3.4 (2.5) in CMS [already exceeded early 300 fb^{-1} projections!]

ATLAS PLB 843 (2024) 137745

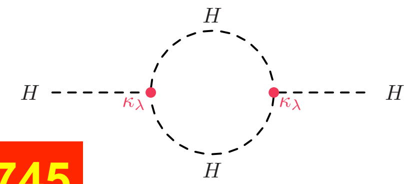




CMS Nature 607 (2022) 60

Sensitivity to λ

- Because of the negative interference, sensitivity to λ is non-trivial
  - Combination of single and double Higgs production helps to constrain the self-coupling in a more model-independent way: **ATLAS PLB 843 (2024) 137745** and **CMS PAS HIG-23-006**



  - Here focus on just the HH analyses:

$-1.2 < \kappa_\lambda < 7.2$ @ 95% CL

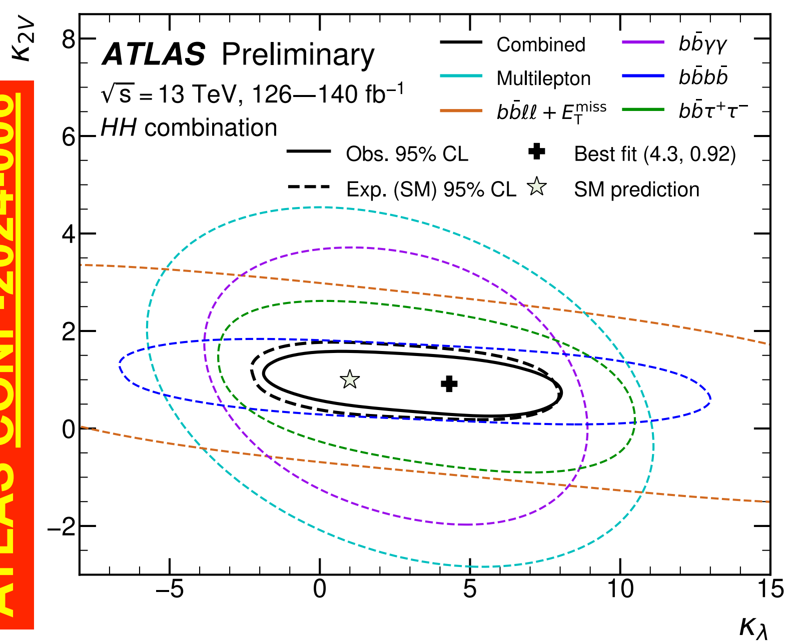
$0.57 < \kappa_{2V} < 1.48$ @ 95% CL

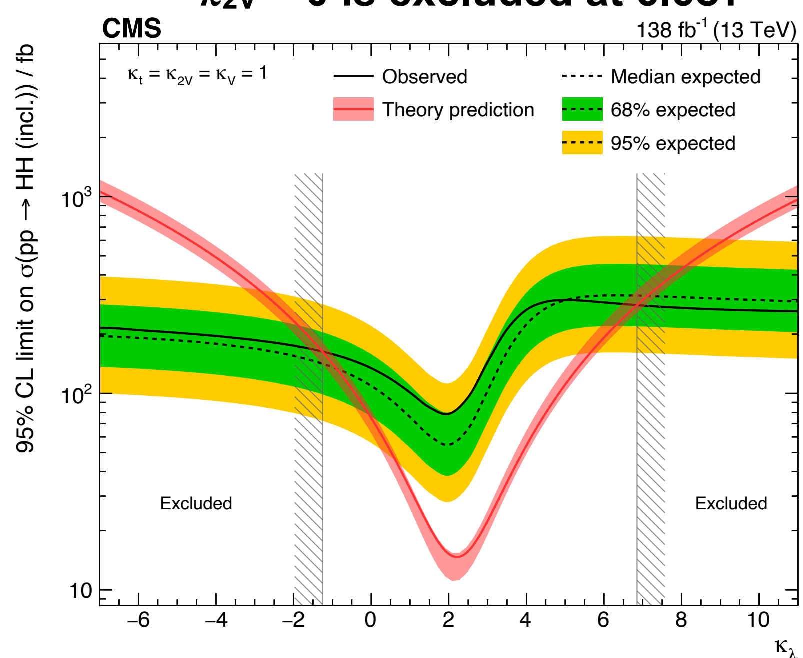
$-1.24 < \kappa_\lambda < 6.9$ @ 95% CL

$0.67 < \kappa_{2V} < 1.38$ @ 95% CL

$\kappa_{2V} = 0$ is excluded at 6.6σ!

ATLAS CONF-2024-006





CMS Nature 607 (2022) 60

Interplay of Different Channels

- The sensitivity to HH production is dominated by bbbb, $bb\tau\tau$, and $bb\gamma\gamma$ channels
  - Somewhat different relative sensitivities in ATLAS and CMS, mostly due to different triggering strategies and background estimation methods
- Analyses, particularly in the bbbb channel, are done separately in resolved and merged topologies
  - Important to add a semi-merged topology, currently missing
  - The resolved topology dominates sensitivity to κ_λ
  - The merged topology dominates sensitivity to κ_{2V}
  - Both contribute similarly to μ_{HH} determination

Interplay of Different Channels

✦ The sensitiv… …ated by bbbb, bbττ, …

- Somewha… …ATLAS and CMS, mostly due to different triggering strategies and background estimation methods

More on Higgs boson pair production in the following talks:
A. Verduras, E. Martin Viscasillas,
M. Mlinarevic (Thu), J. Dávila Illán (Fri)

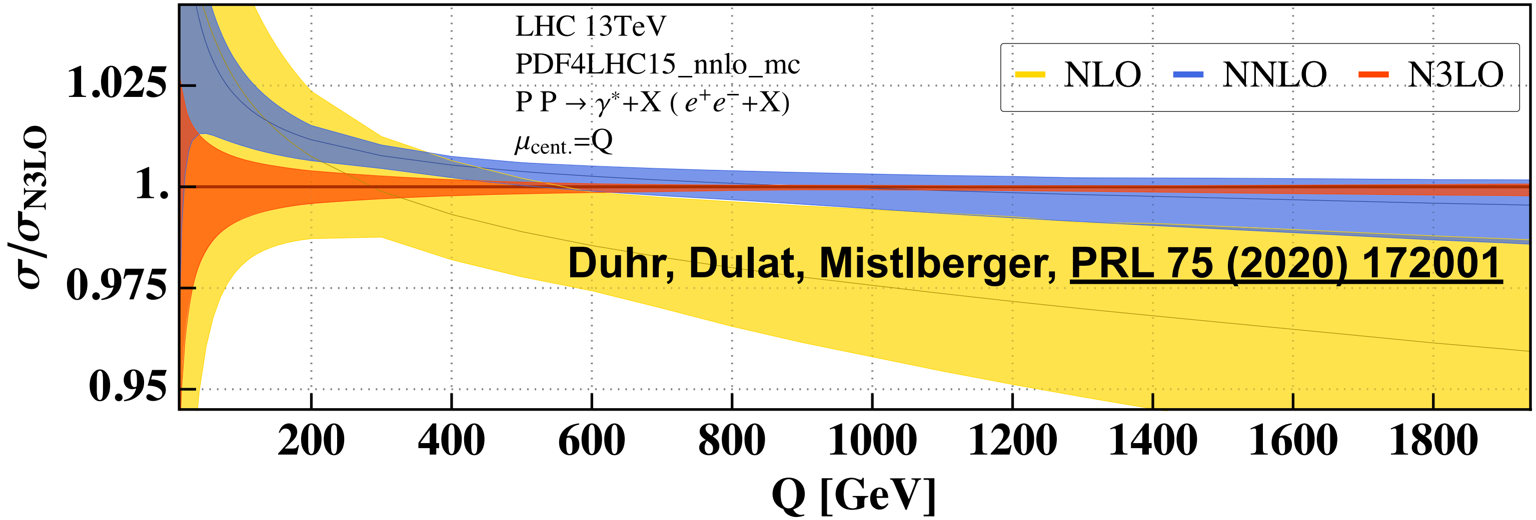
✦ Analyses, particularly in the bbbb channel, are done separately in resolved and merged topologies

- Important to add a semi-merged topology, currently missing
- The resolved topology dominates sensitivity to κ_λ
- The merged topology dominates sensitivity to κ_{2V}
- Both contribute similarly to μ_{HH} determination

Higgs Theory Highlights

NLO → NNLO → N^3LO

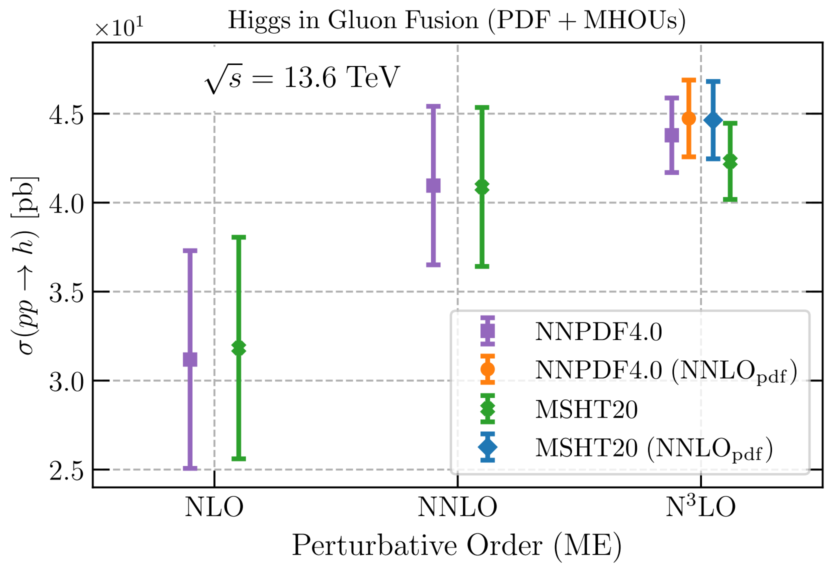
- Amazing theoretical progress in both precision Higgs boson calculations and related matters (backgrounds, PDFs, α_S)
- NNLO revolution of the past decade: by now all the 2 → 2 and a few 2 → 3 processed are calculated at NNLO (QCD) + NLO (EW)
  - This quickly became a de facto standard
- Now moving to N^3LO: now available for a number of 2 → 1 processes; the challenge is to have N^3LO 2 → 2 calculations
  - Recent success with DY, HH, VH, partial dijet production @ N^3LO



Higher-Order PDFs and α_S

- Huge progress in higher-order matrix element calculations requires matching precision in PDF and α_S extraction, as well as better parton shower accuracy
- Significant progress in all these areas:
  - NNLOPS with NLO logarithmic matching; towards NNLL accuracy very recently
  - First N^{3}LO PDFs - large impact on inclusive ggH cross section O(5%) - beyond theory uncertainty
  - N3LO α_S extraction from Drell-Yan p_T spectrum

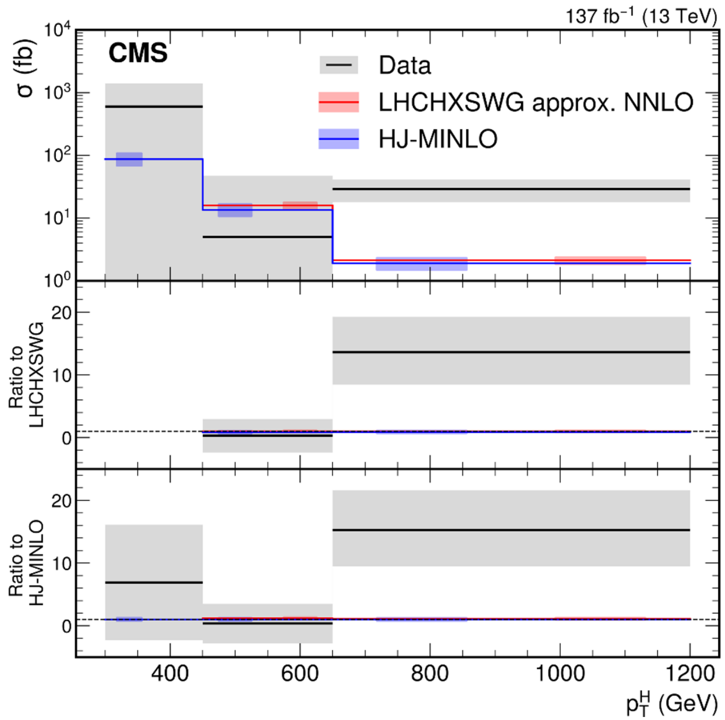
Ball et al., arXiv:2402.18635



Still Several Open Issues

- With the data accuracy achieving differential and double-differential cross section extraction, need best possible theoretical calculations
- Example: very high p_T Higgs boson ggH spectrum
  - CMS data in H(bb) + ISR jet are significantly above the theoretical predictions at very high p_T - a hint for new physics or insufficiently accurate $p_T(H)$ spectrum modeling?

CMS JHEP 12 (2020) 085



Still Several Open Issues

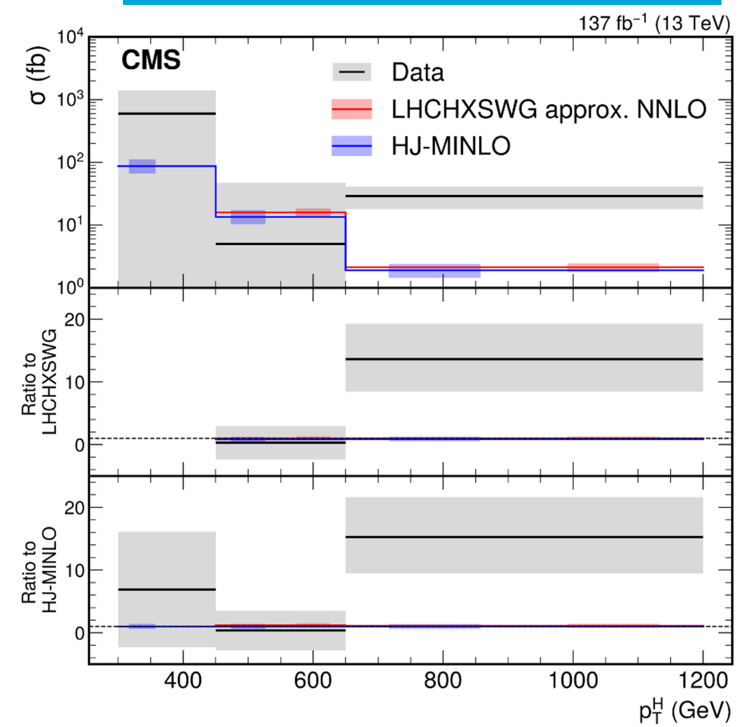
✦ With the da[…]tial and double-diffe[…]n, need best possib[…]

✦ Example: ve[…]spectrum

More on theoretical aspects of Higgs physics in the following talks:
P. Bandyopadhyay (Mon),
D. Kotlarski, C. Borschensky (Tue), F. Arco,
J. Braathen, K. Radchenko Serdula (Thu),
C. Borschensky, R .Kumar (Fri)

- CMS data in H(bb) + ISR jet are significantly above the theoretical predictions at very high p_T - a hint for new physics or insufficiently accurate $p_T(H)$ spectrum modeling?

CMS JHEP 12 (2020) 085

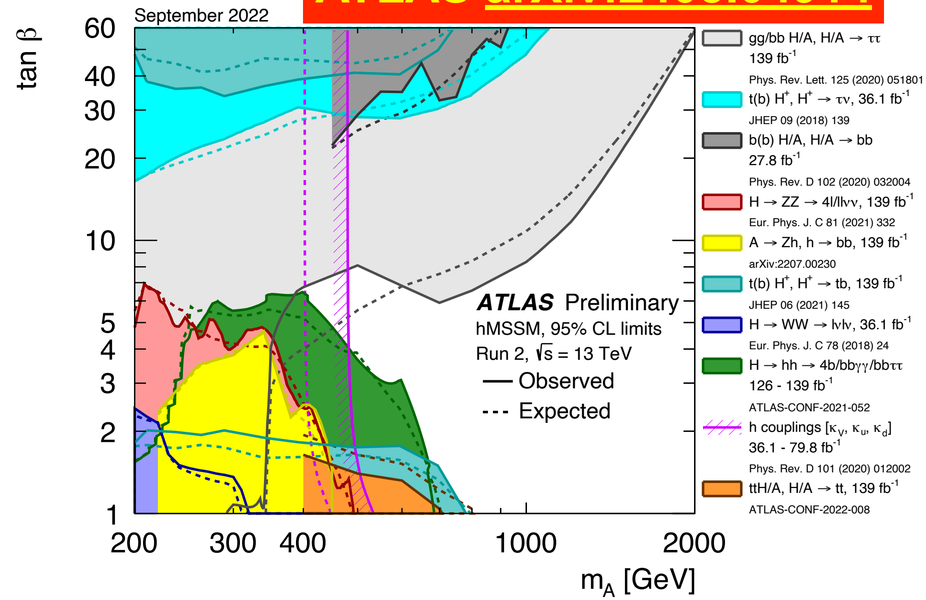


Additional Higgs Bosons

Additional Higgs Bosons

- Many searches have been done for light and heavy additional Higgs bosons, typically in the context of (h)MSSM or generic 2HDM, 2HDM+S, and 2HDM+a models
- While some hints have been seen at various high masses, by now none of them really survived

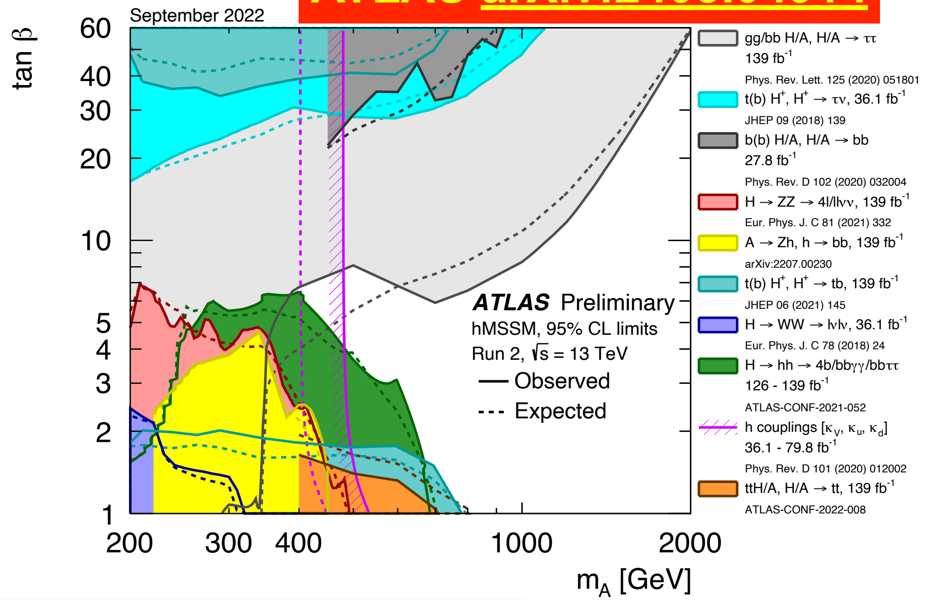
ATLAS arXiv:2405.04914



- Still searches continue, with larger data sets and in more sophisticated models and via different production mechanisms
- Of particular interest are generic X → YH searches, where X, Y are two new resonances (do not have to be spin-0 though), which are being aggressively pursued by ATLAS and CMS in multitude of channels
- Perhaps the only excess that has survived so far is the infamous 95 GeV one

Additional Higgs Bosons

ATLAS arXiv:2405.04914

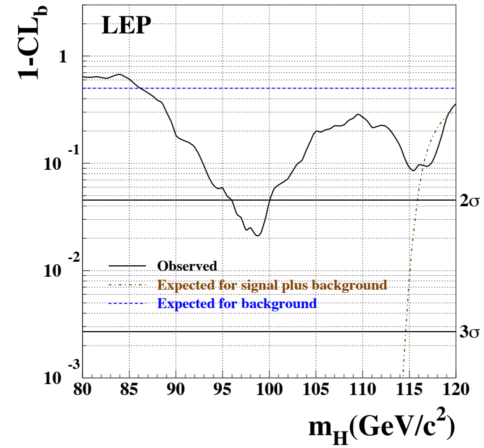


- Many searches have been done for light and heavy additional Higgs bosons, typically in the context of (h)MSSM or generic 2HDM, 2HDM+S, and 2HDM+a models
- While some hints have been seen at various high masses, by now none of them really survived
- Still searches c ... re sophisticated models and via ...
- Of particular in ... here X, Y are two new resonances (do not have to be spin-0 though), which are being aggressively pursued by ATLAS and CMS in multitude of channels
- Perhaps the only excess that has survived so far is the infamous 95 GeV one

More on additional Higgs bosons in the following talks:
T. Qiu, G. Weiglein (Mon)

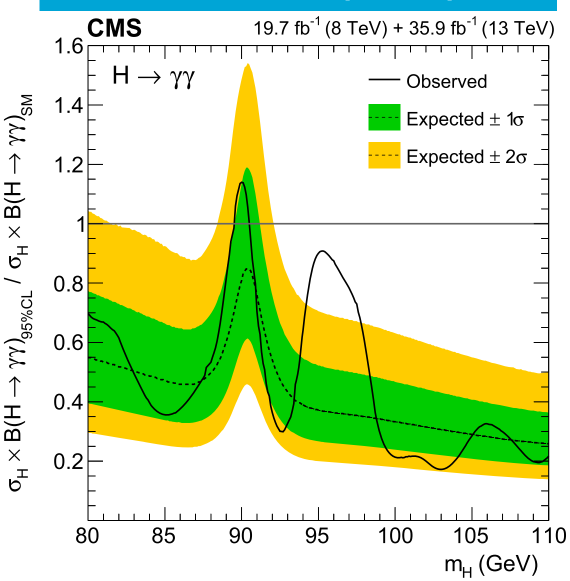
The 95 GeV Puzzle

- The long-standing puzzle with a ~2σ hint seen since LEP era
- A 2.8σ hint seen in CMS in H(γγ) analysis with 20 fb^{-1} of 8 TeV + 36 fb^{-1} of 13 TeV data
- Recent CMS analysis of full Run 2 data sees a similar excess (albeit with much smaller cross section)
- New ATLAS result neither confirms nor kills this excess

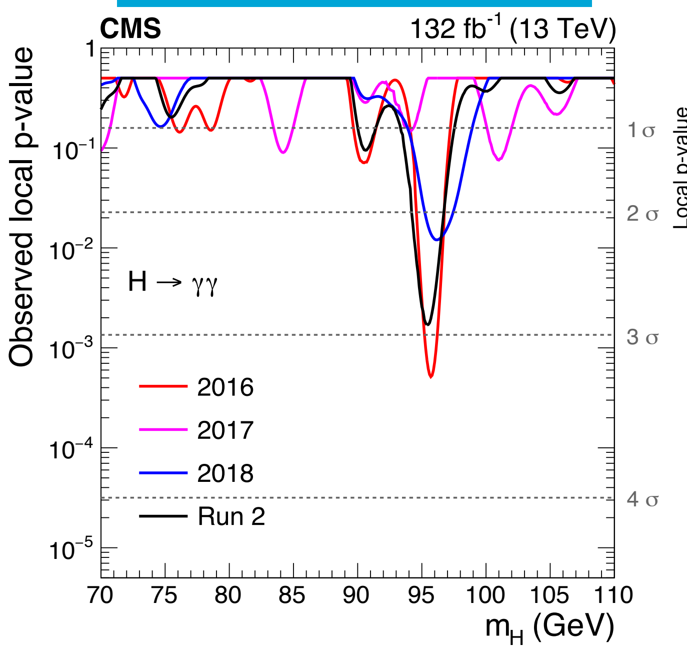


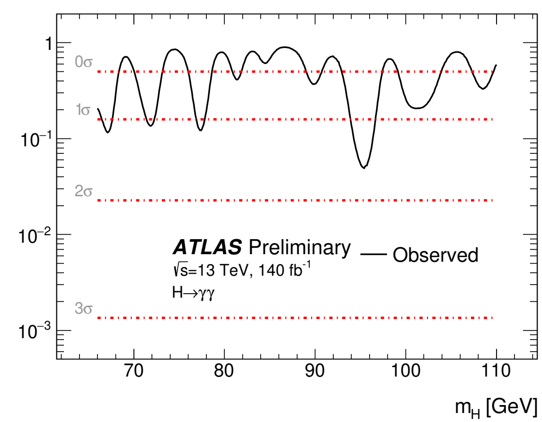
ADLO hep-ex/0306033

CMS PLB 793 (2019) 320



CMS arXiv:2405.18149



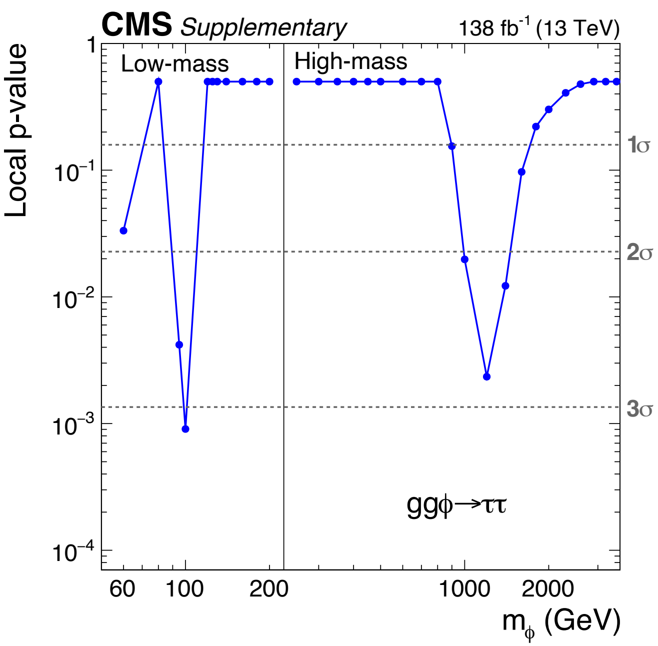


ATLAS CONF-2023-035

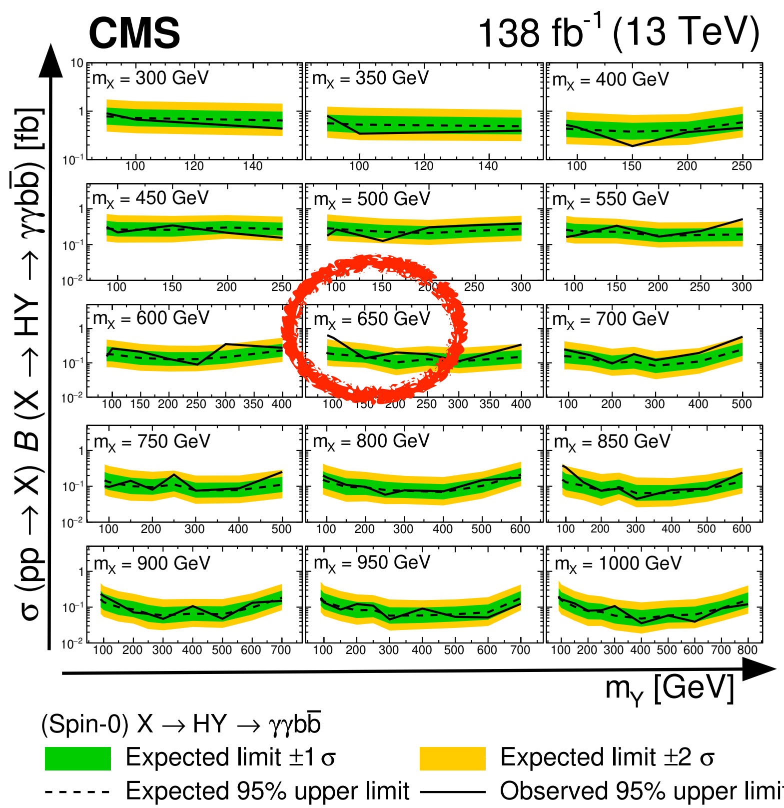
Wait, there is More!

- Two more CMS results seems to suggest some excess in the same 95 GeV region
  - MSSM H(ττ) search with an excess at m(ττ) ≈ 100 GeV
  - X → H(γγ)Y(bb) search with M_X ≈ 650 GeV and M_Y ≈ 100 GeV

CMS JHEP 07 (2023) 073



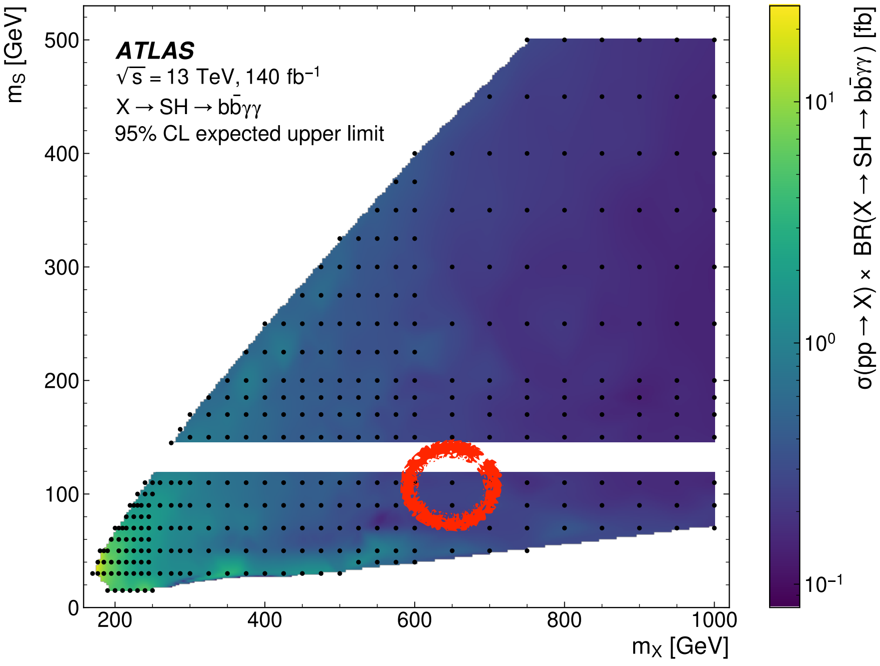
CMS JHEP 05 (2024) 316

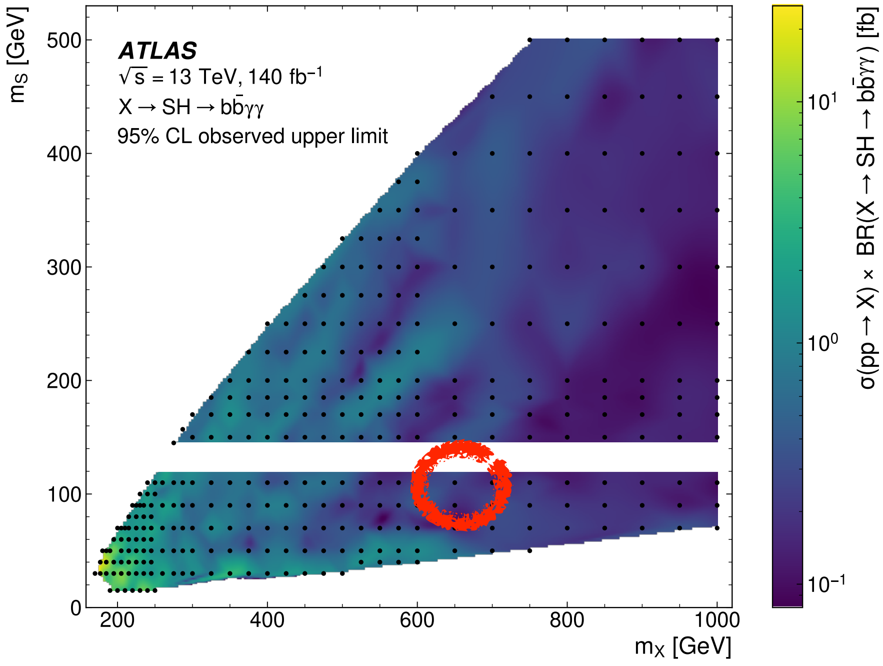


But…

- Recent ATLAS result in the same X → H(γγ)Y(bb) channel sees no excess at the (650,100) GeV point and sets an upper limit on the cross section of 0.2 fb
- The jury is still out

ATLAS arXiv:2404.12915



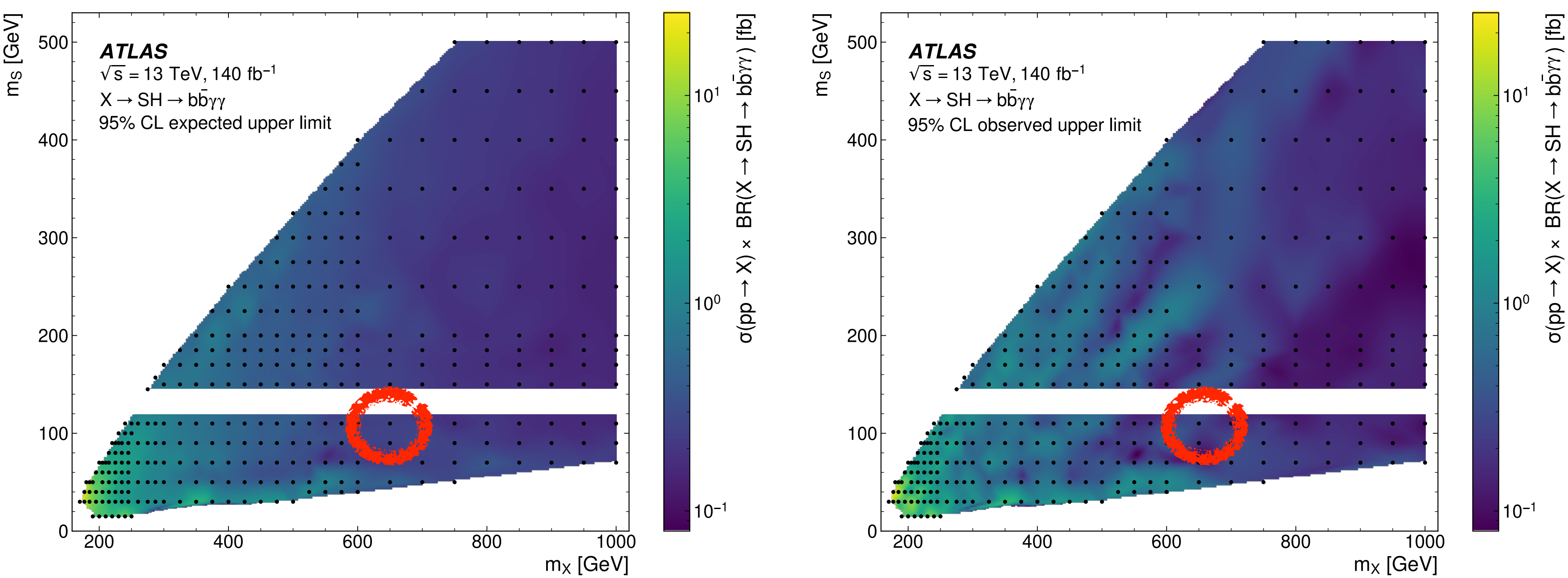


But…

- Recent AT … (γγ)Y(bb) channel se … GeV point and sets an upper limit on the cross section of 0.2 fb
- The jury is still out

More on the 95 GeV excess in the following talk:
S. Heinemeyer (Mon)

ATLAS arXiv:2404.12915

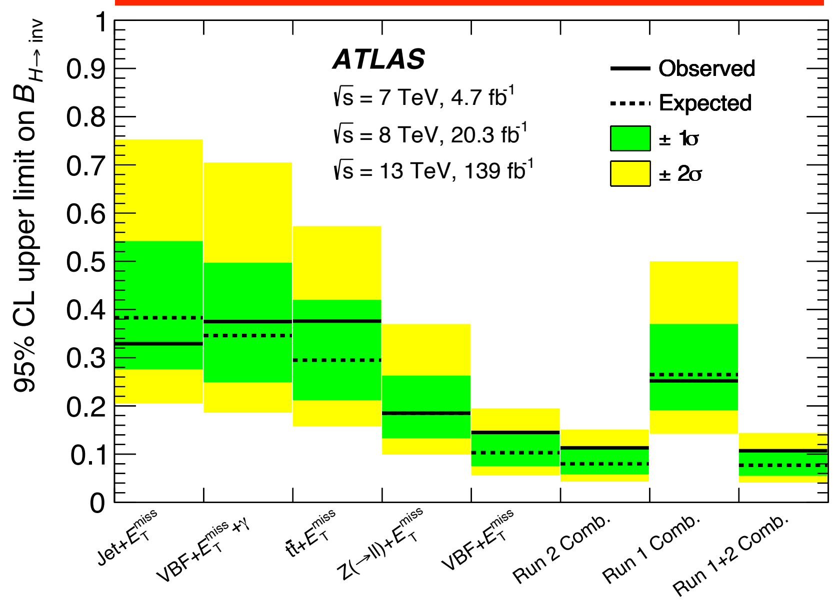


Rare Higgs Boson Decays

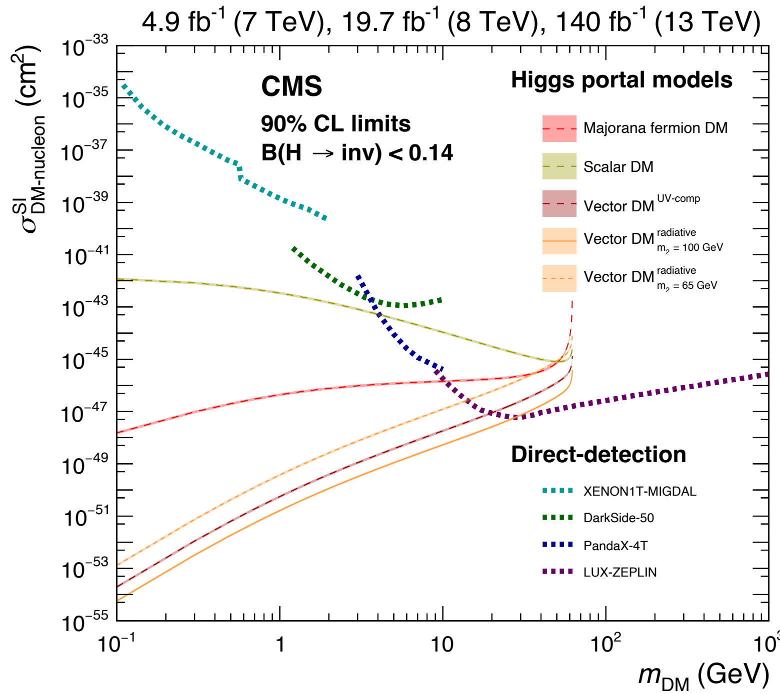
Rare Higgs Boson Decays

- ✦ This is another promising avenue of searches for new physics in the Higgs sector
- ✦ Typically, branching fractions of the Higgs boson are currently known to ≈10% precision, leaving some space for rare Higgs boson decays
- ✦ The most prominent one is H → inv., which also serves as a sensitive probe for relatively light dark matter via an on-shell Higgs mediator
    - ◉ Current best combined observed (expected) limits are:
        - ✤ B(H→ inv.) < 0.107 (0.077) @95% CL (ATLAS)
        - ✤ B(H→ inv.) < 0.15 (0.10) @95% CL (CMS)

ATLAS PLB 842 (2023) 137963



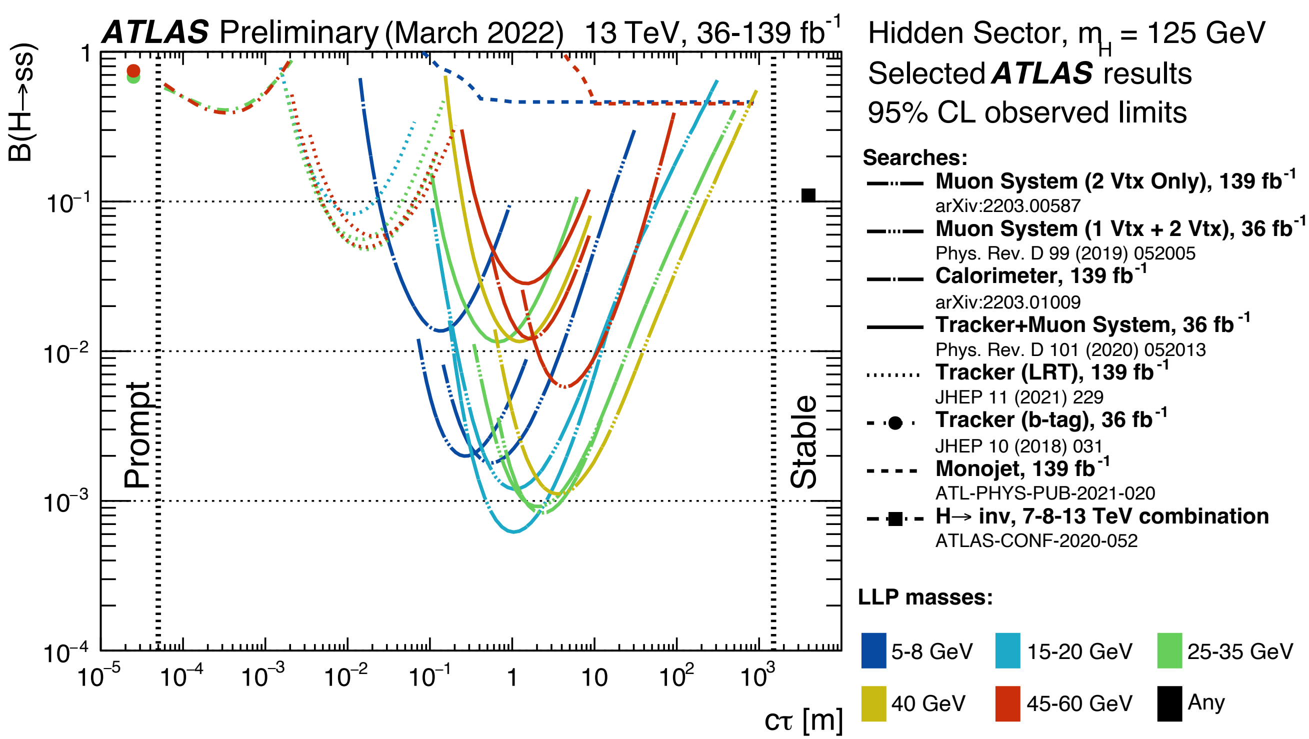
CMS EPJC 83 (2023) 933



Other Rare Decays

- Many other rare decays are being sought:
  - $H \to aa$, SS (including long-lived decay products)
  - LFV $H \to e\mu$, $e\tau$, $\mu\tau$
  - $H \to Za$

ATLAS arXiv:2405.04914

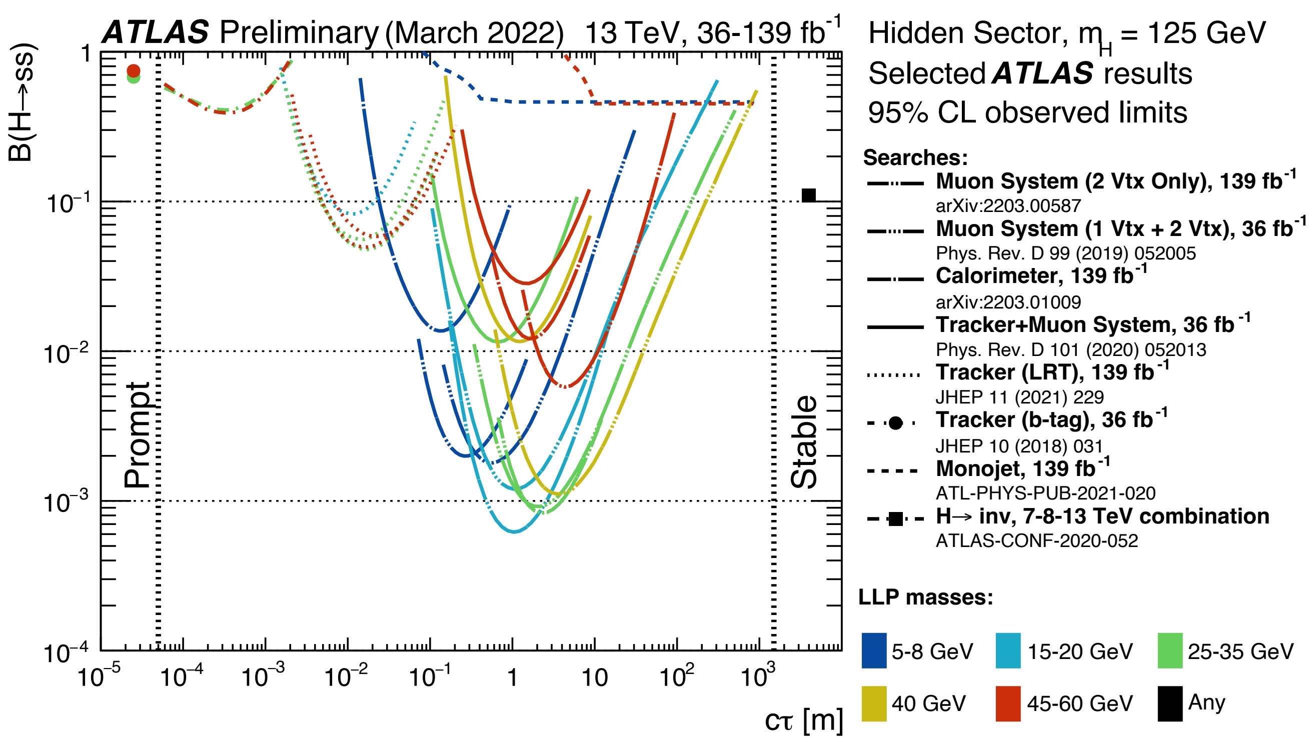


Other Rare Decays

- Many othe… t:
  - H → aa, … oducts)
  - LFV H → eμ, eτ, μτ
  - H → Za

More on rare Higgs boson decays in the following talk:
M. Cepeda (Mon)

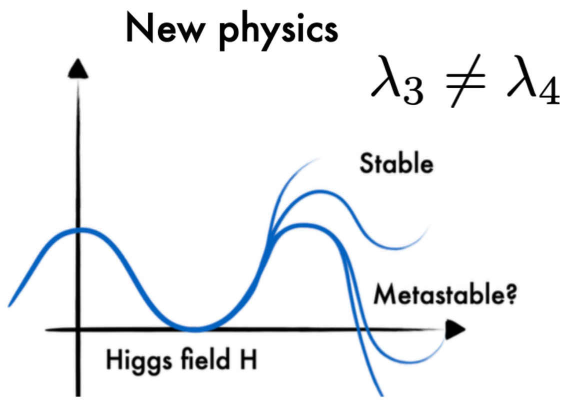
ATLAS arXiv:2405.04914



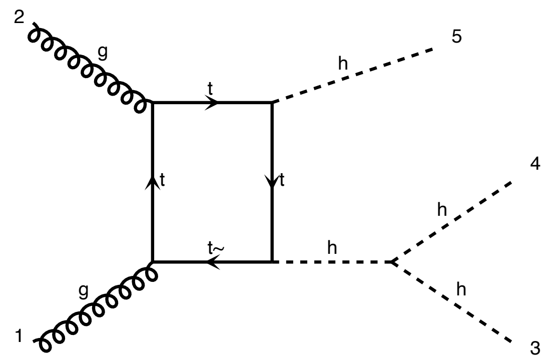
Toward Triple Higgs

HHH Production

- Study of quartic Higgs coupling remain outside the realm of the HL-LHC, since HHH production cross section is very small: σ^{HHH}(14 TeV, NNLO) = 0.1 fb

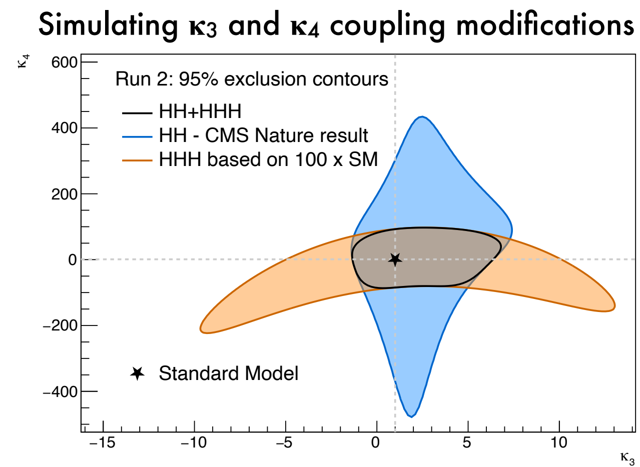


- In the SM, $\lambda_3 = \lambda_4 = 0.13$, but it is possible that they are not the same
- Out of 50 LO diagrams contributing to HHH production, only 2 contain λ_4, while there are 18 $\sim y_t^2\lambda_3$ and another 6 $\sim y_t\lambda_3^2$



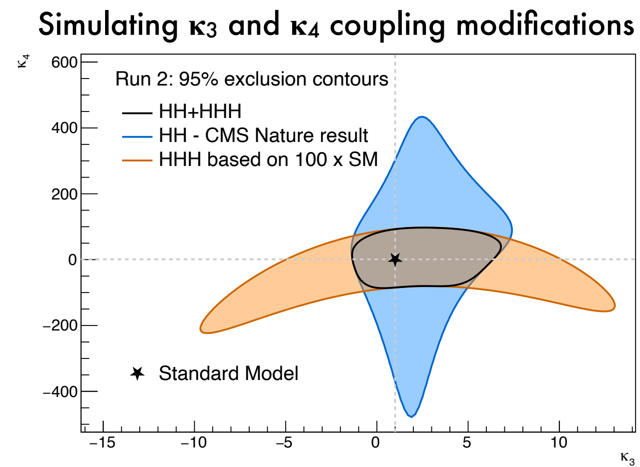
- Thus study of HHH production will help to constrain λ_3
- Moreover, there a many models in which HHH can be enhanced via resonance decays, e.g., Y → XH, X → HH
- All of these makes HHH studies quite exciting already now

Dubrovnik Workshop 2023



- A kick-off HHH Workshop took place in Dubrovnik last July and was very interesting
- About to post the White Paper on the arXiv
- Many interesting ideas
  - Best channels, triggers, merged vs. resolved
  - Resonance decay benchmarks
  - Tools against combinatorics
- Plan a follow-up workshop in September 2025 when we expect first experimental results already be available

Dubrovnik Workshop 2023



- A kick-off HHH Workshop took place in Dubrovnik last July and was very interesting
- About to po
- Many intere
  - Best channels, triggers, merged vs. resolved
  - Resonance decay benchmarks
  - Tools against combinatorics
- Plan a follow-up workshop in September 2025 when we expect first experimental results already be available

More on the HHH production in the following talk:
P. Stylianou (Thu)

Conclusions: Quo Vadis?

- Discovery of the Higgs boson in 2012 has completed the particle content of the standard model of particle physics and paved an avenue for decades of exploration
  - Cf. the richness of top quark physics now, nearly 30 years after the discovery!
- Unlike the top quark, the Higgs boson is a unique particle, never seen before; its deep understanding, both theoretically and experimentally, is of crucial importance to answer big questions, including those about the origin and fate of our universe
- While several Higgs boson parameters have been precisely measured and agree with the SM predictions, there is still space for new physics in the Higgs sector
- Key avenues to pursue in the (near) future are:
  - Couplings to the 2^{nd} generation fermions
  - Higgs self-coupling
  - Rare Higgs boson decays
  - Searches for resonances decaying into H + anything, including triple-object resonances, such as HHH, VHH, VVH
- All of these require continuous theoretical support and state-of-the-art calculational techniques
- Higgs will remain an exploratory machine for the next two or more decades, and it will shine the way toward the next steps in particle physics

ChatGPT Conclusions

In the realm of particles so grand,
Where mysteries lie in each strand,
The Higgs boson takes its place,
With secrets held in its embrace.

Its self-coupling, a subtle dance,
A tryst of particles in cosmic expanse.
Yet direct measurements remain unseen,
As scientists strive to grasp its serene.

Indirect constraints like whispers told,
Unveiling truths in the particles' fold.
With bounds and limits, we seek to find,
The Higgs self-coupling, an enigma entwined.