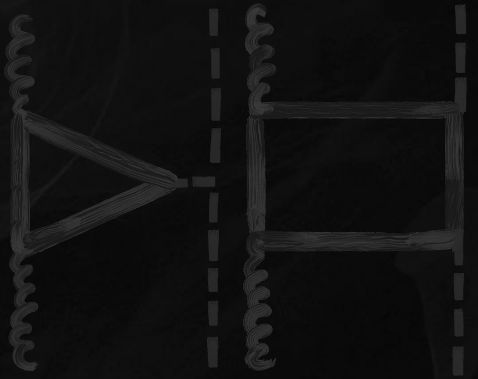
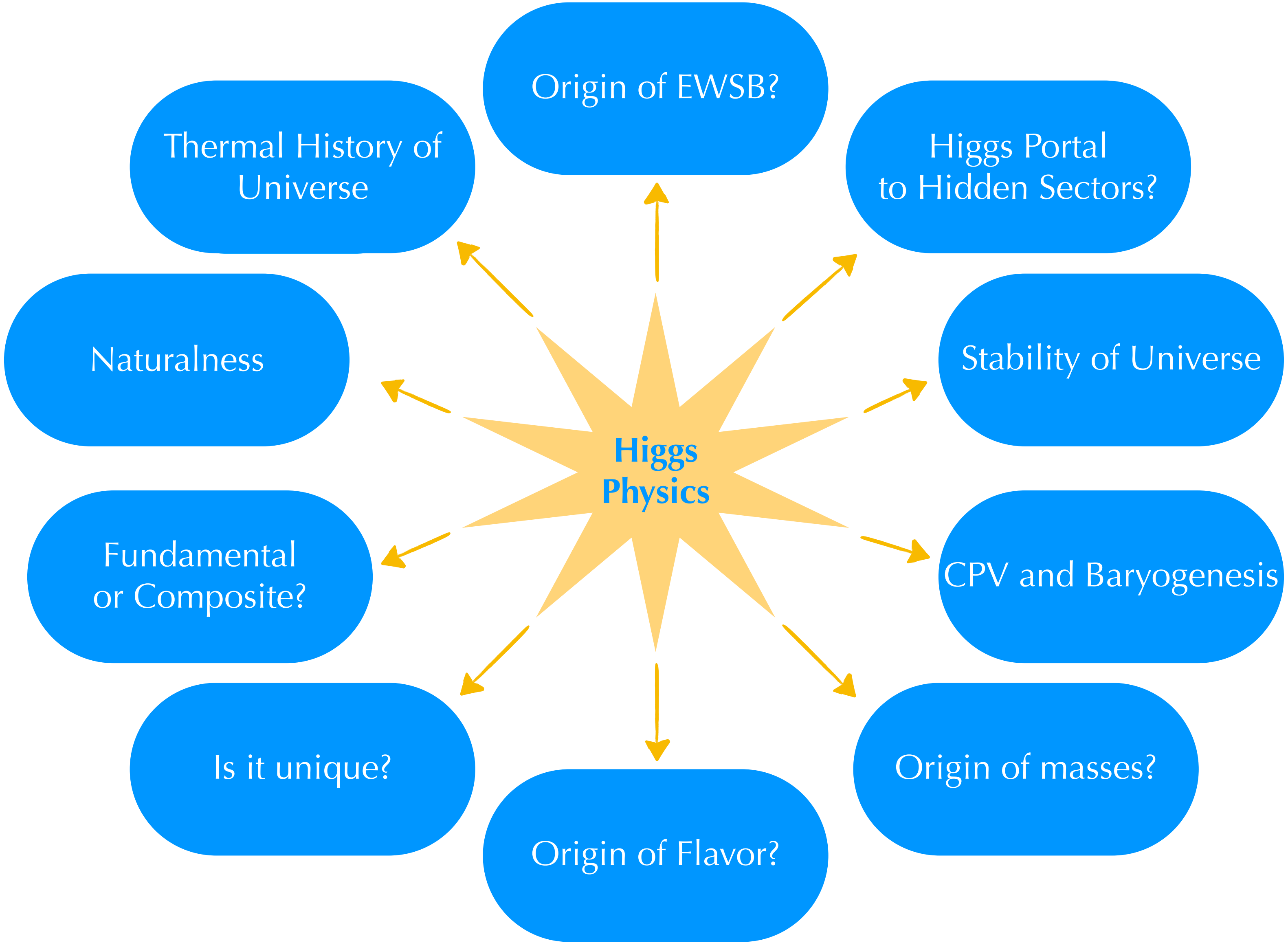
Di-Higgs at the LHC

Caterina Vernieri



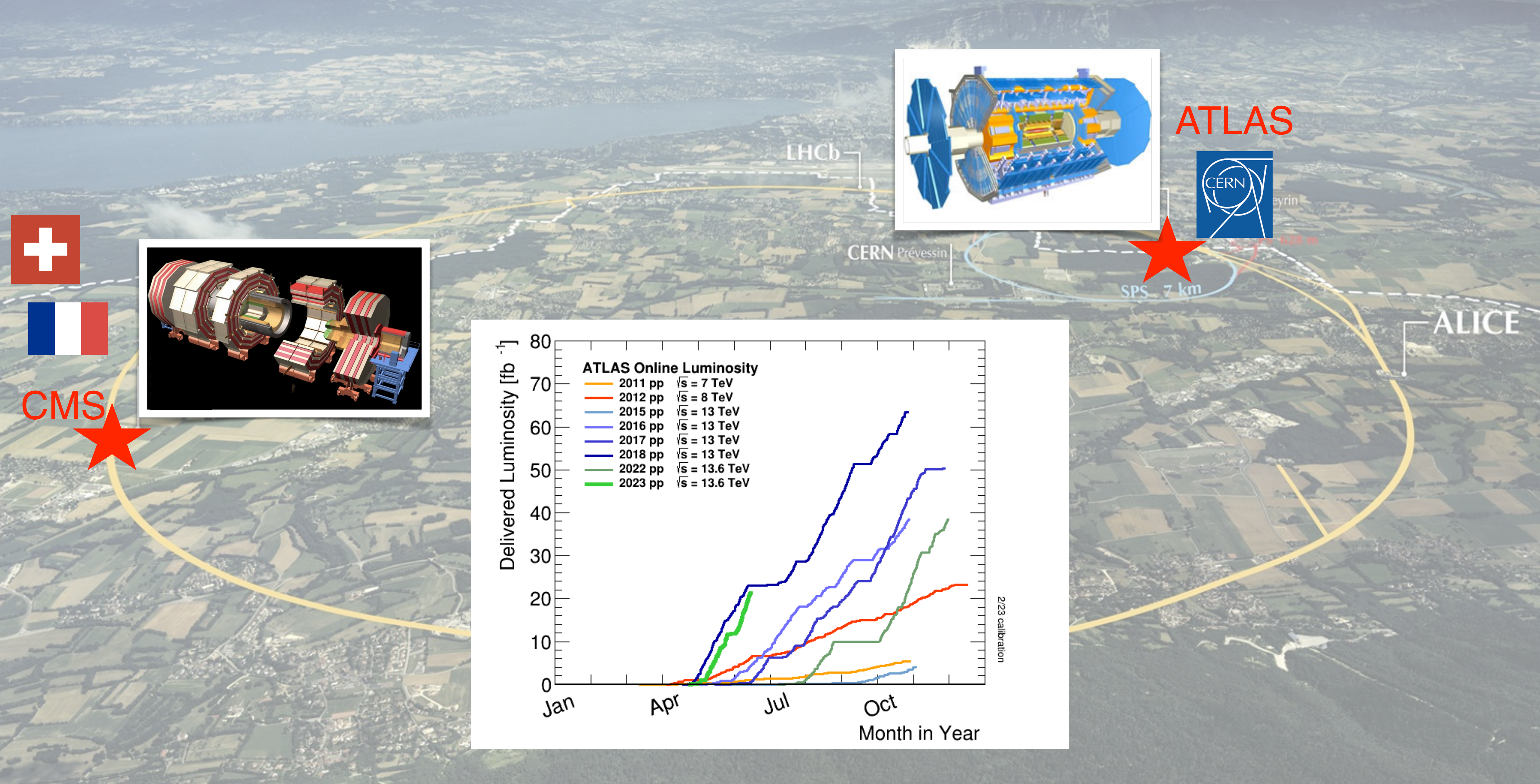
SLAC June, 26 2023

LOOPFEST XXI



Caterina Vernieri (SLAC)

The Large Hadron Collider (LHC)



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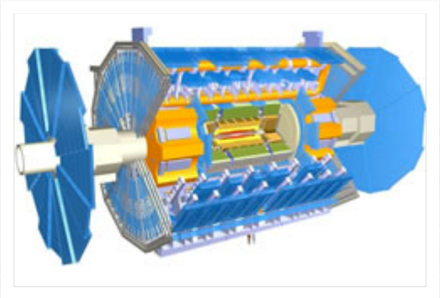


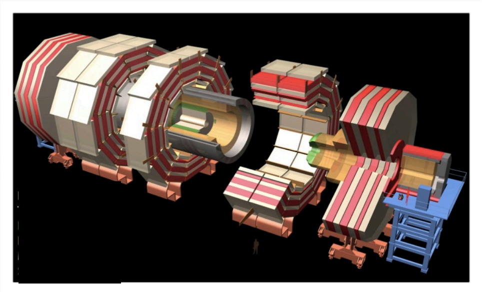
ATLAS

LHCb

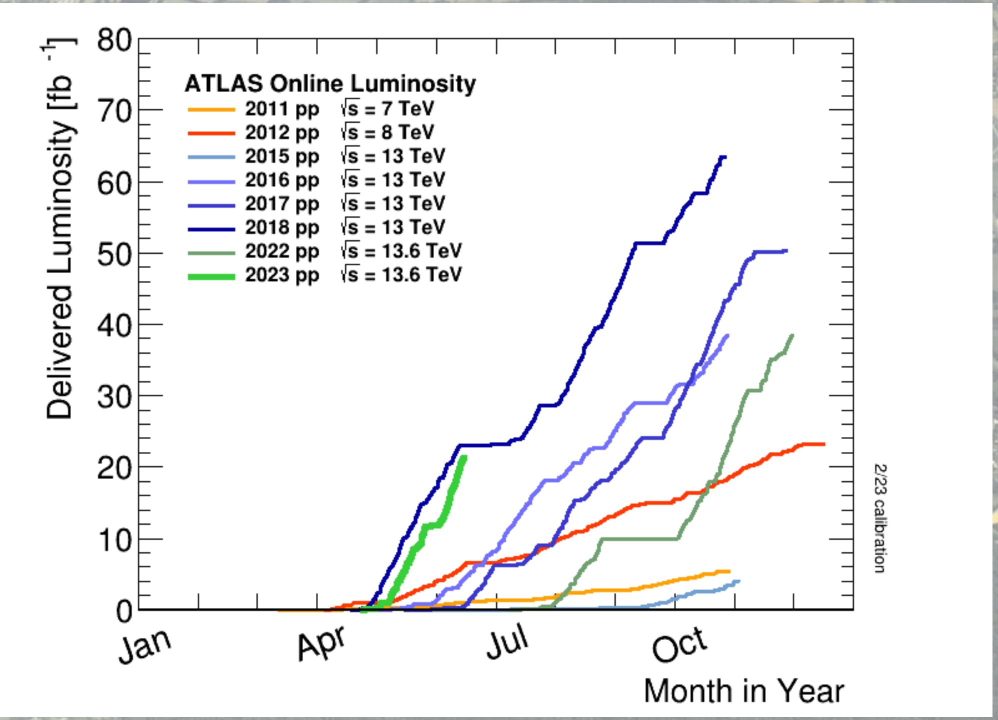
CERN Prévessin

SPS 7 km

ALICE

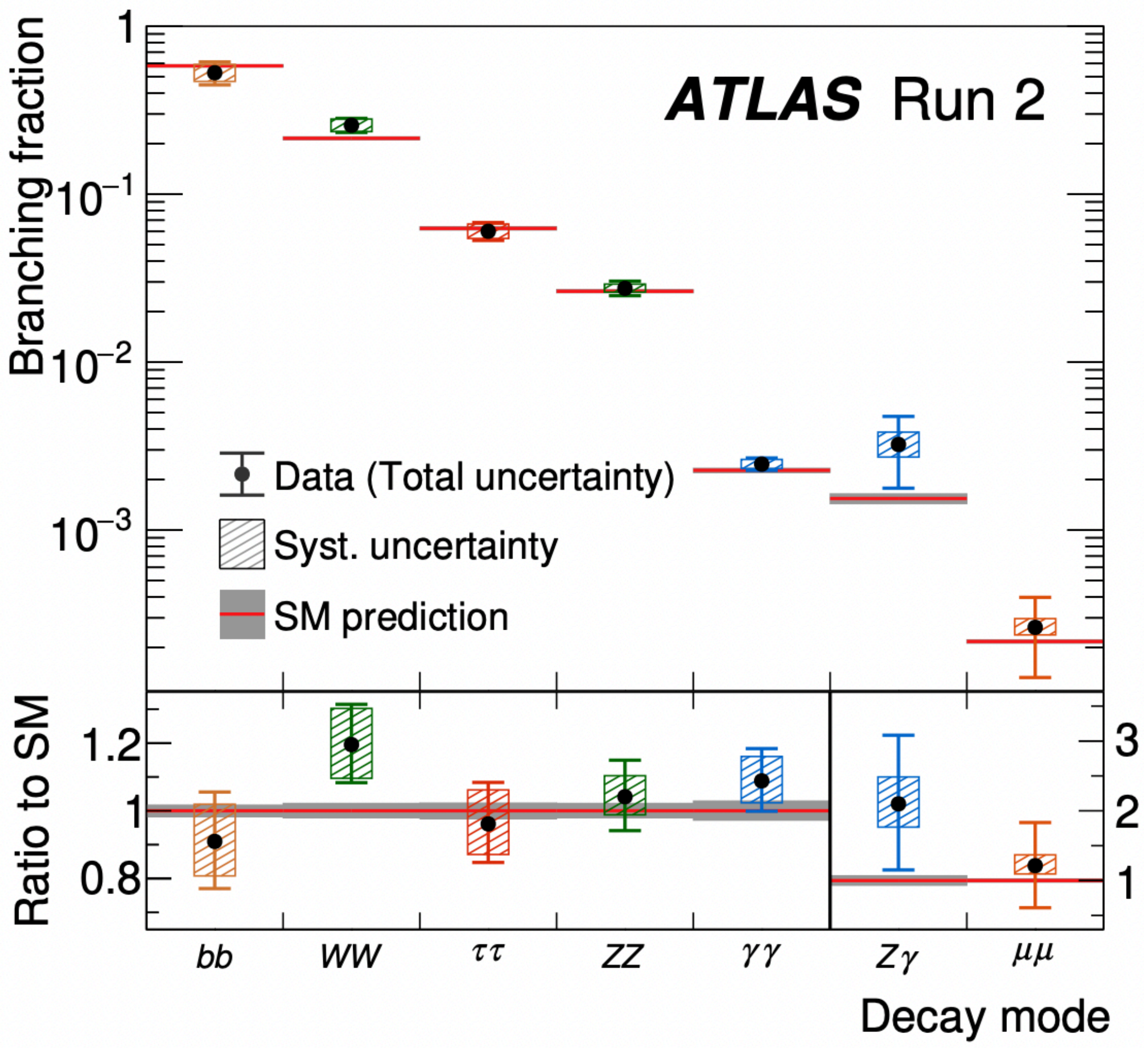


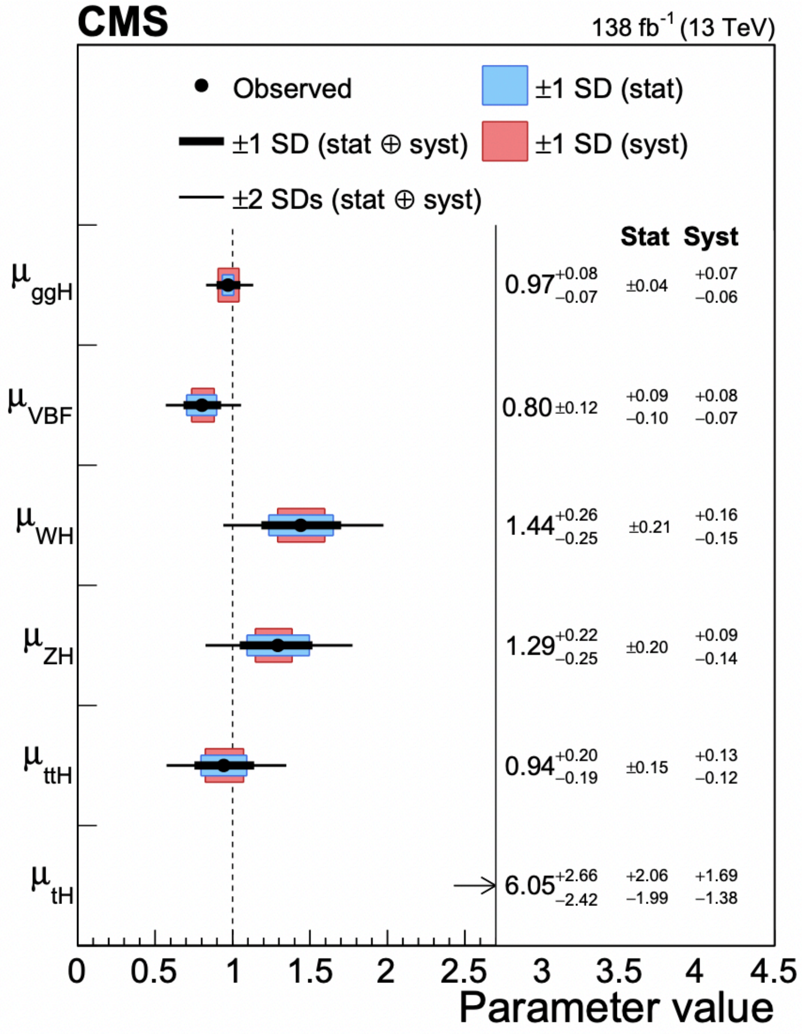
CMS



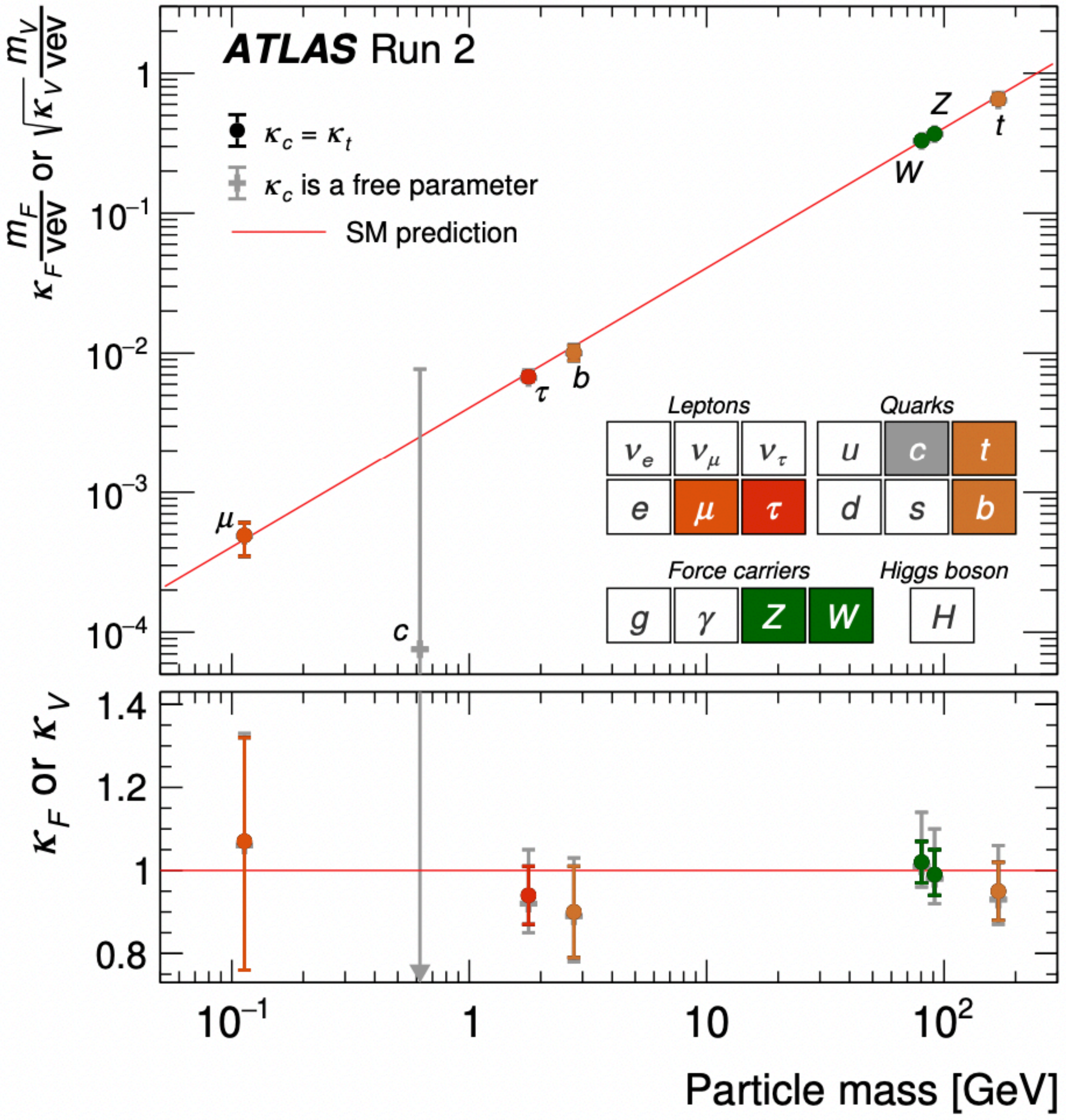
A factor 20x more data than at the time of the Higgs discovery

Higgs in 2022





CMS-Nature 607, 60–68 (2022)
ATLAS-Nature 607, 52–59 (2022)



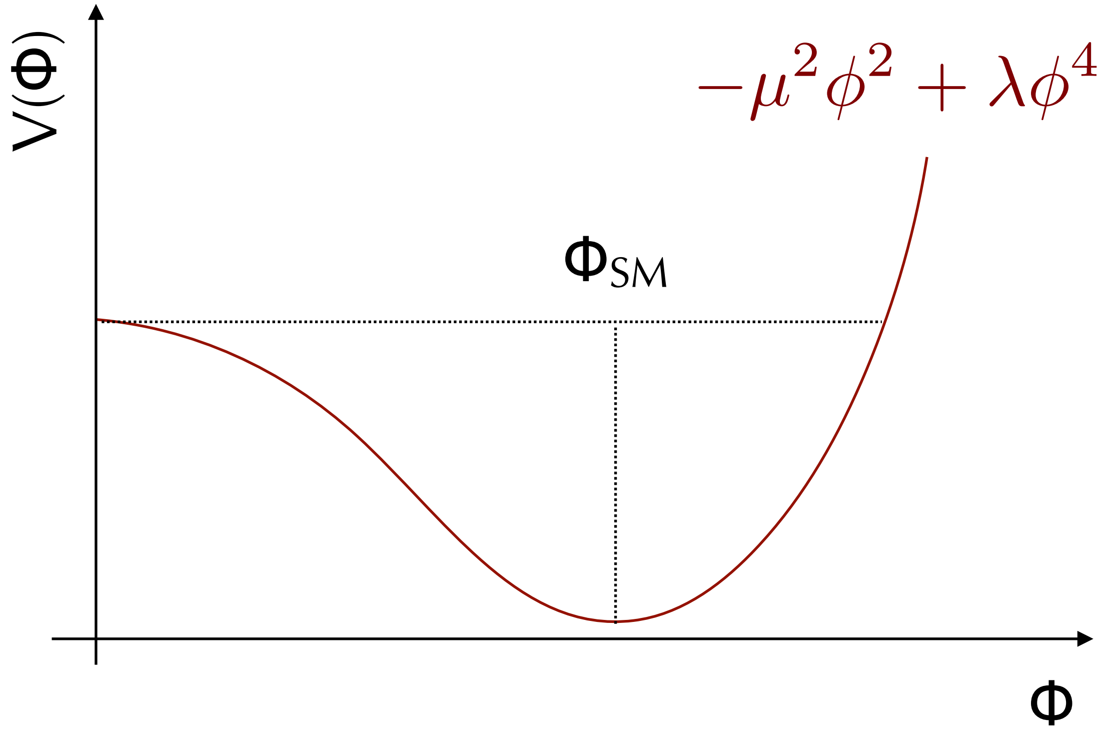
BR(inv.) < 0.17 (0.11)

CMS-PAS-HIG-20-003

Iκcl<3.4

CMS-PAS-HIG-21-008

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

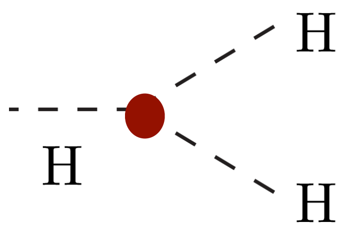


Probing this Higgs Boson potential

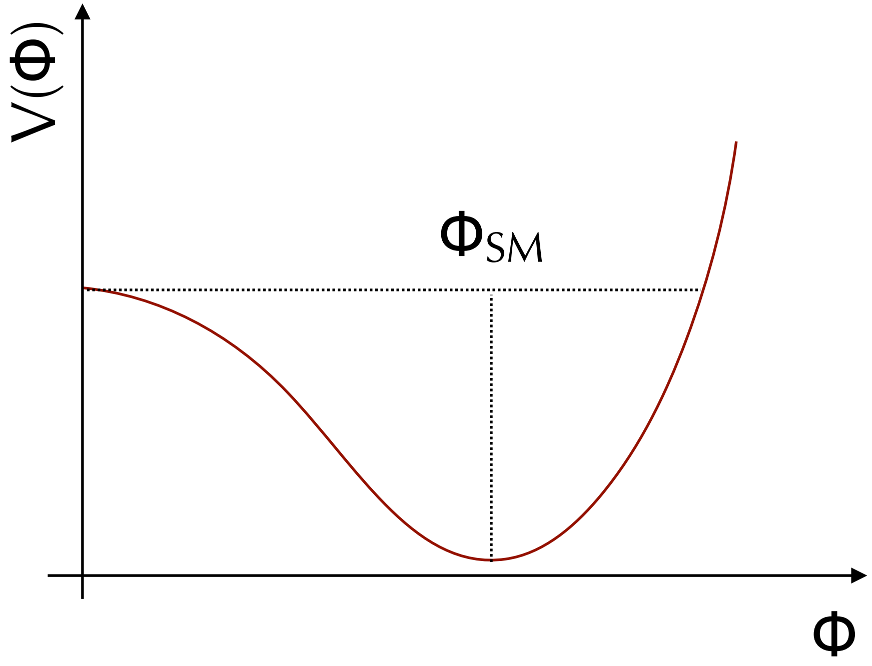
Testing the shape

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

$$V(v+h) = V_0 + \frac{1}{2}m_h^2h^2 + \frac{m_h^2}{2v^2}vh^3 + \frac{1}{4}\frac{m_h^2}{2v^2}h^4$$



$$\lambda = \frac{m_h^2}{2v^2} = 0.13$$



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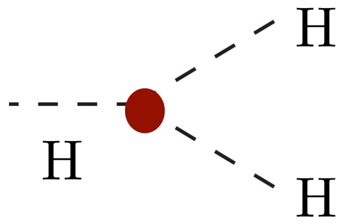

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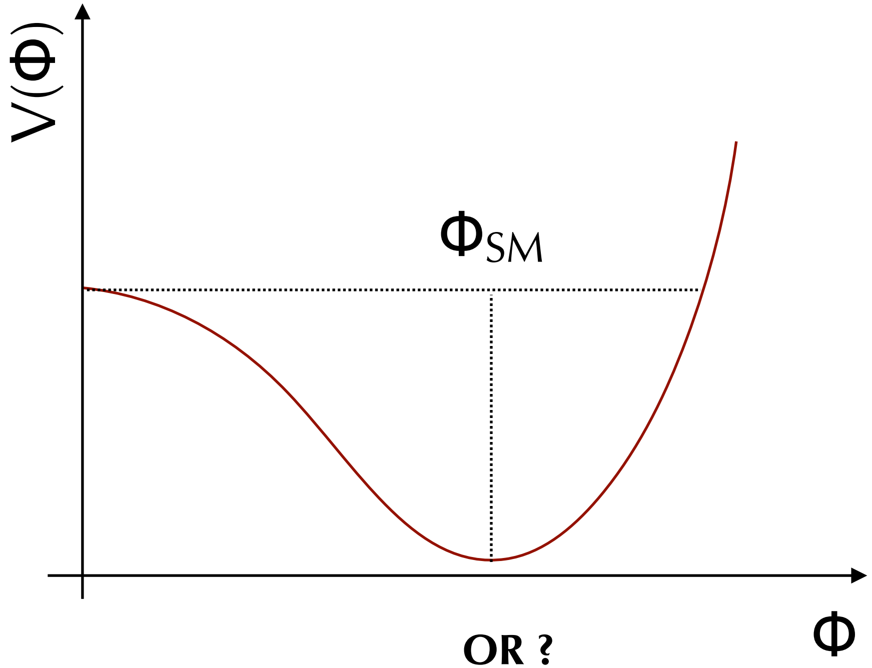
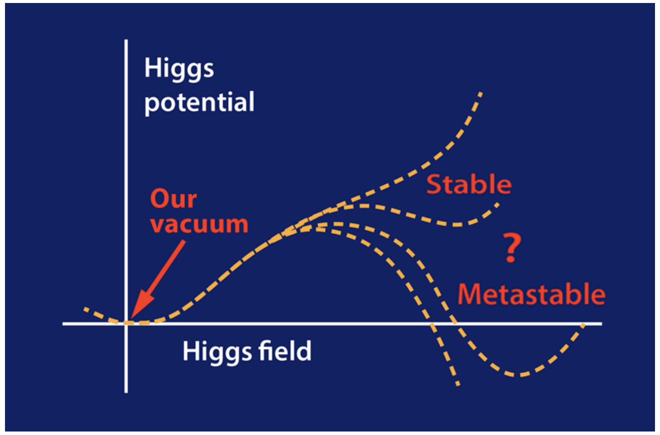
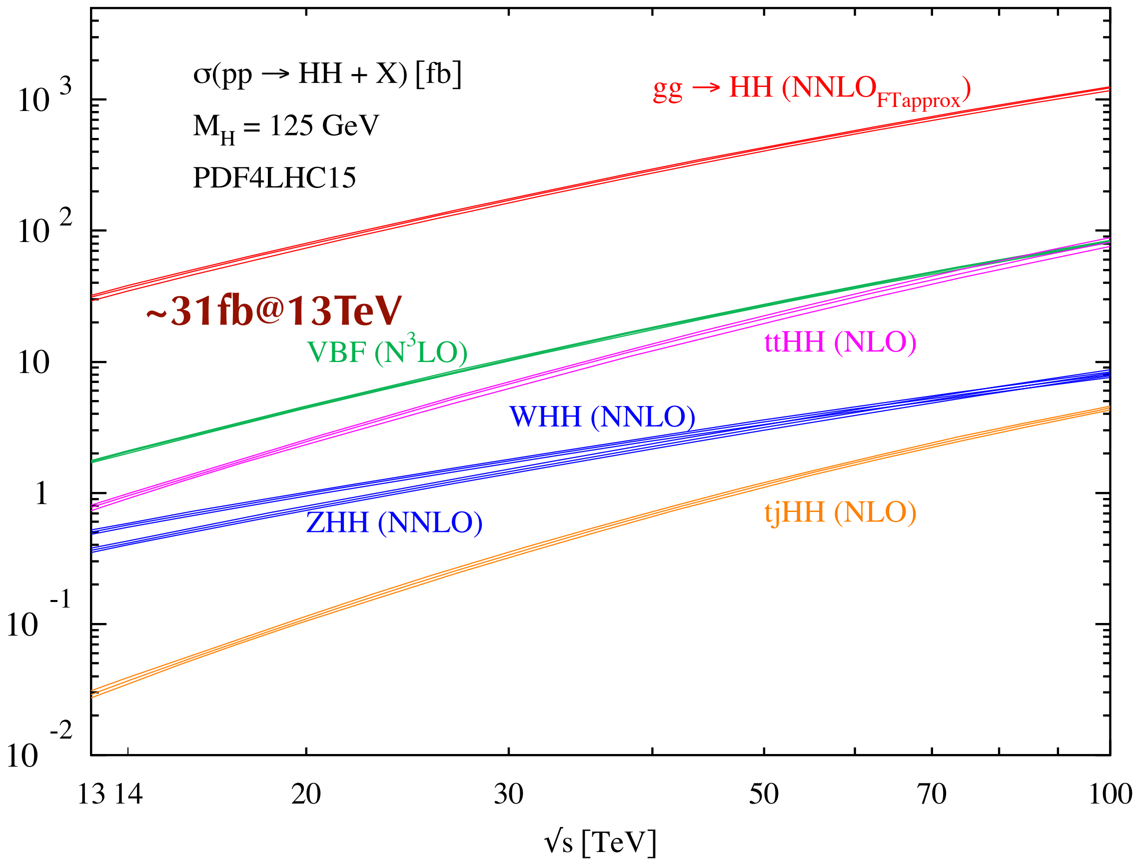


OR ?



Higgs boson self-coupling



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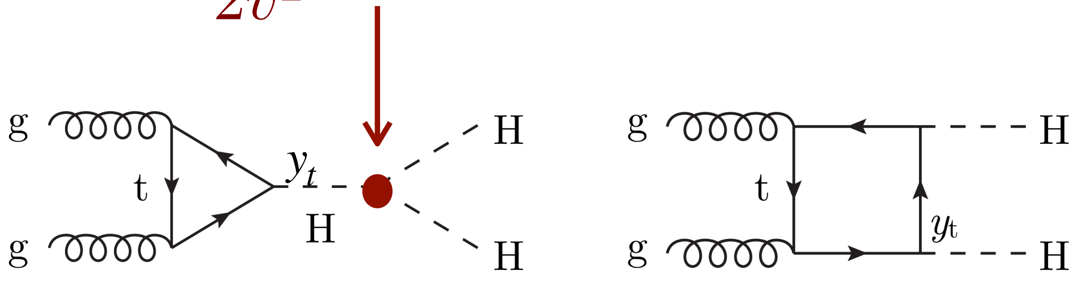
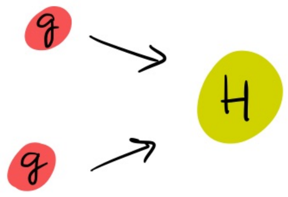
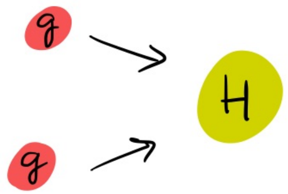


HH production allows to probe the self-coupling: $\Delta\sigma/\sigma \sim \Delta\lambda/\lambda$ **if** $\lambda \sim \lambda_{SM}$

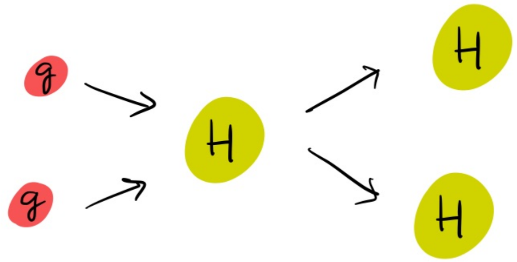
Extremely challenging measurement at the LHC, but **it can be sensitive to large deviations from BSM**: $\kappa_\lambda = \lambda/\lambda_{SM}$



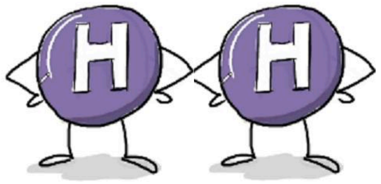
H **1 in a billion**



H **1 in a billion**



HH **1 in a trillion**

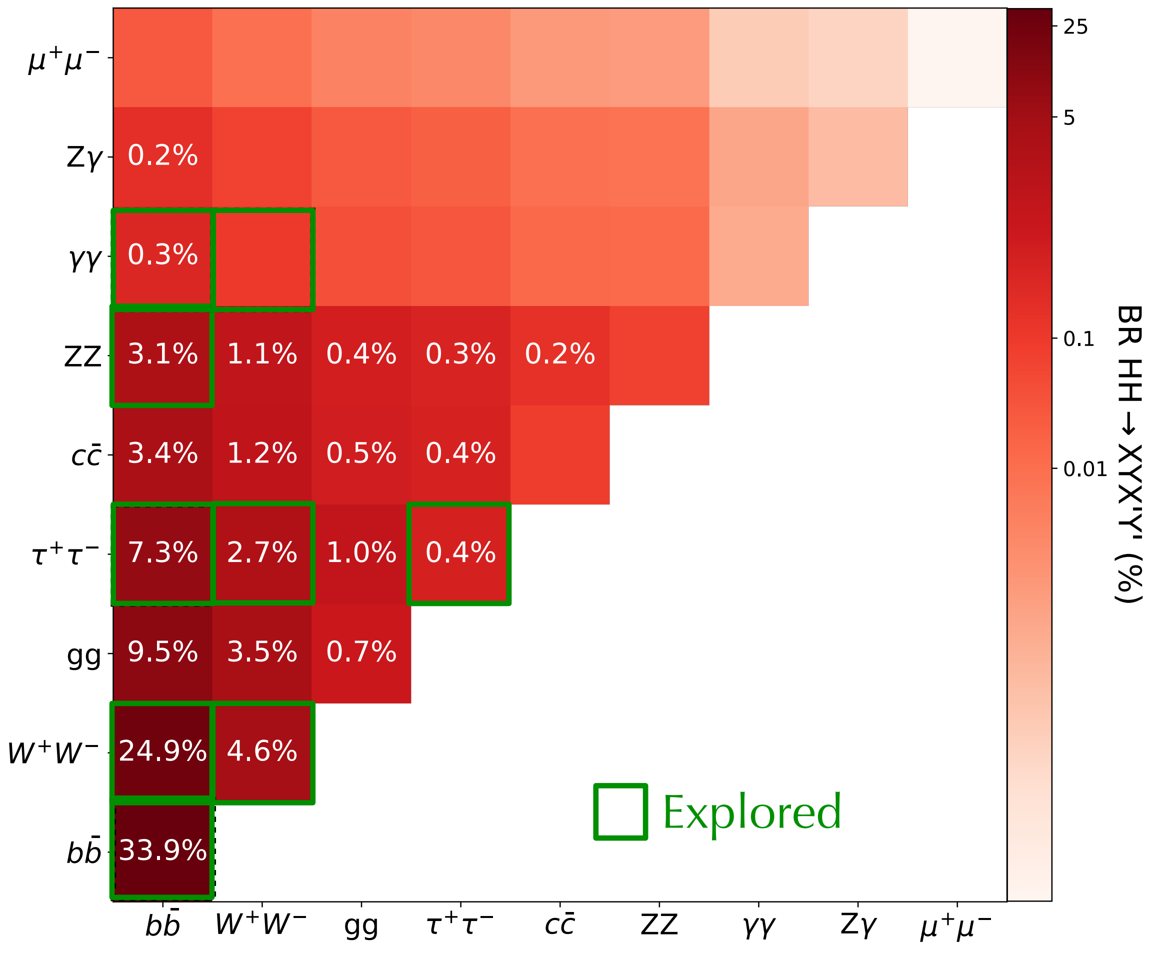



H

The Higgs Boson potential

- At the present time, we have no experimental evidence that the Higgs boson results from the scalar potential of the SM
    - Observing double Higgs Boson production is crucial.
- **Precision measurements of double Higgs** boson production can then be combined **with single Higgs** measurements for a better understanding of the structure of the Higgs potential.
- Models of **new physics that contain multiple Higgs bosons** can lead to the production of Higgs bosons with different masses, leading to new experimental signatures.

HH, a variety of final states



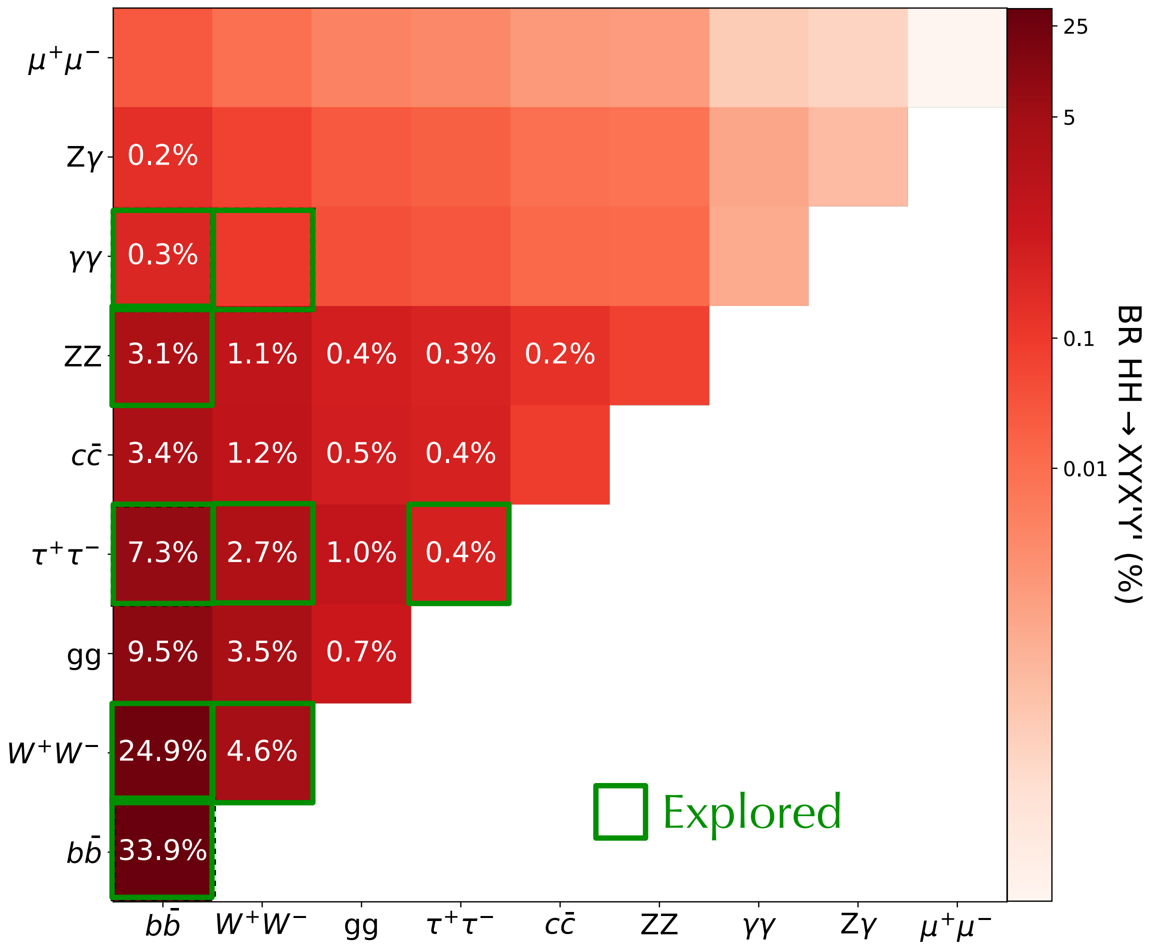
H($b\bar{b}$) is a key element in the exploration of HH at the LHC

- **highest BR**
- good b-jets identification performance: 70% efficiency at 0.3-1% q/g mistag probability

H(γγ)

- clean final state
- **excellent mass resolution**, ~1%

HH, a variety of final states



H(bb̄) is a key element in the exploration of HH at the LHC

- **highest BR**
- good b-jets identification performance: 70% efficiency at 0.3-1% q/g mistag probability

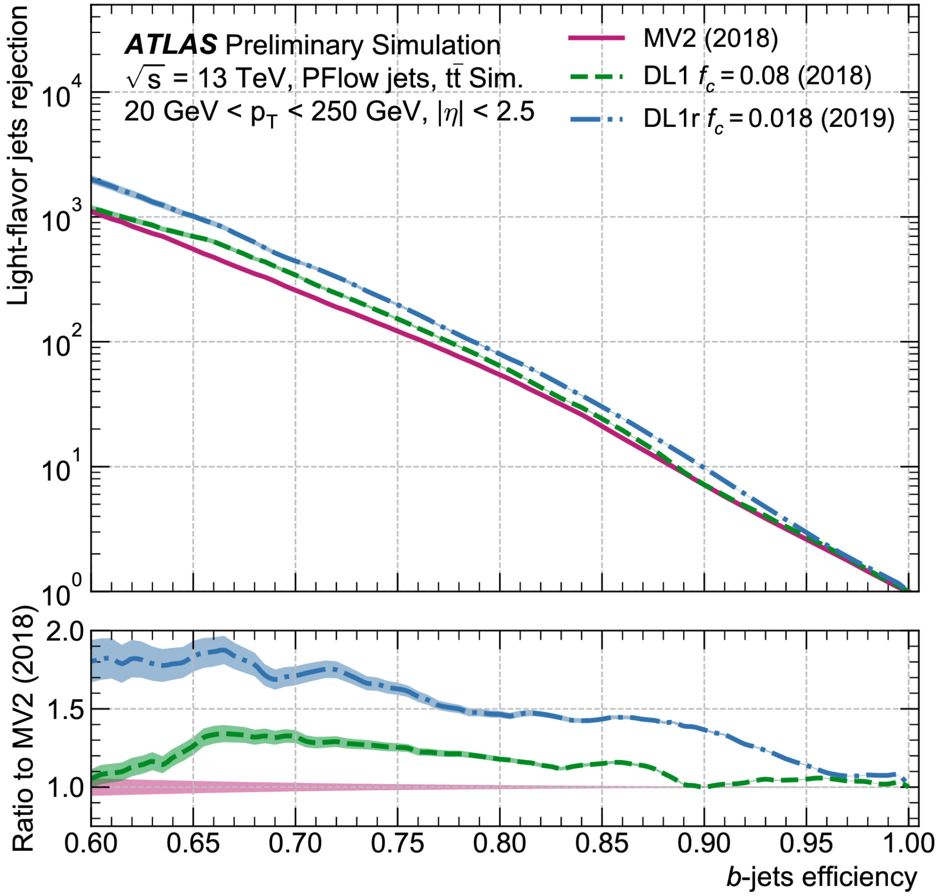
H(γγ)

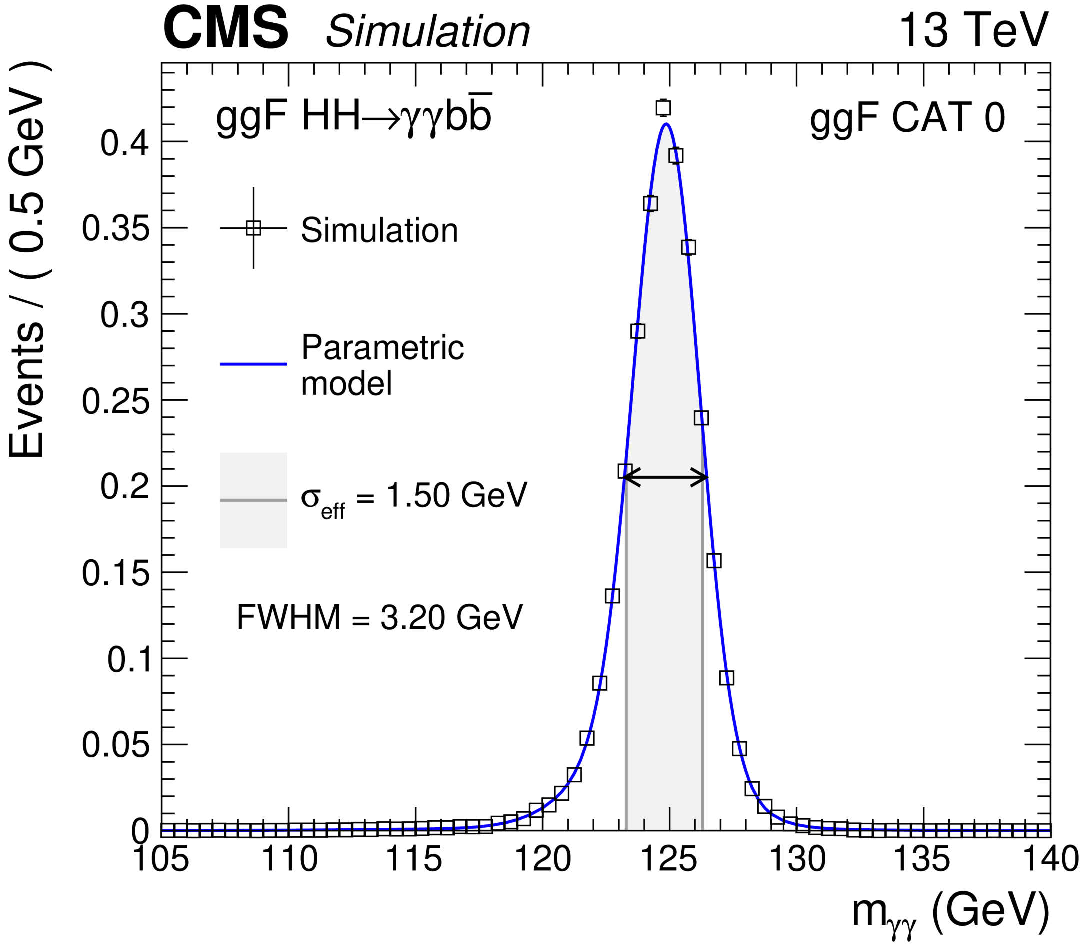
- clean final state
- **excellent mass resolution**, ~1%

Several channels have been investigated:

- Similar sensitivity to SM HH
- Different coverage on m_{HH}

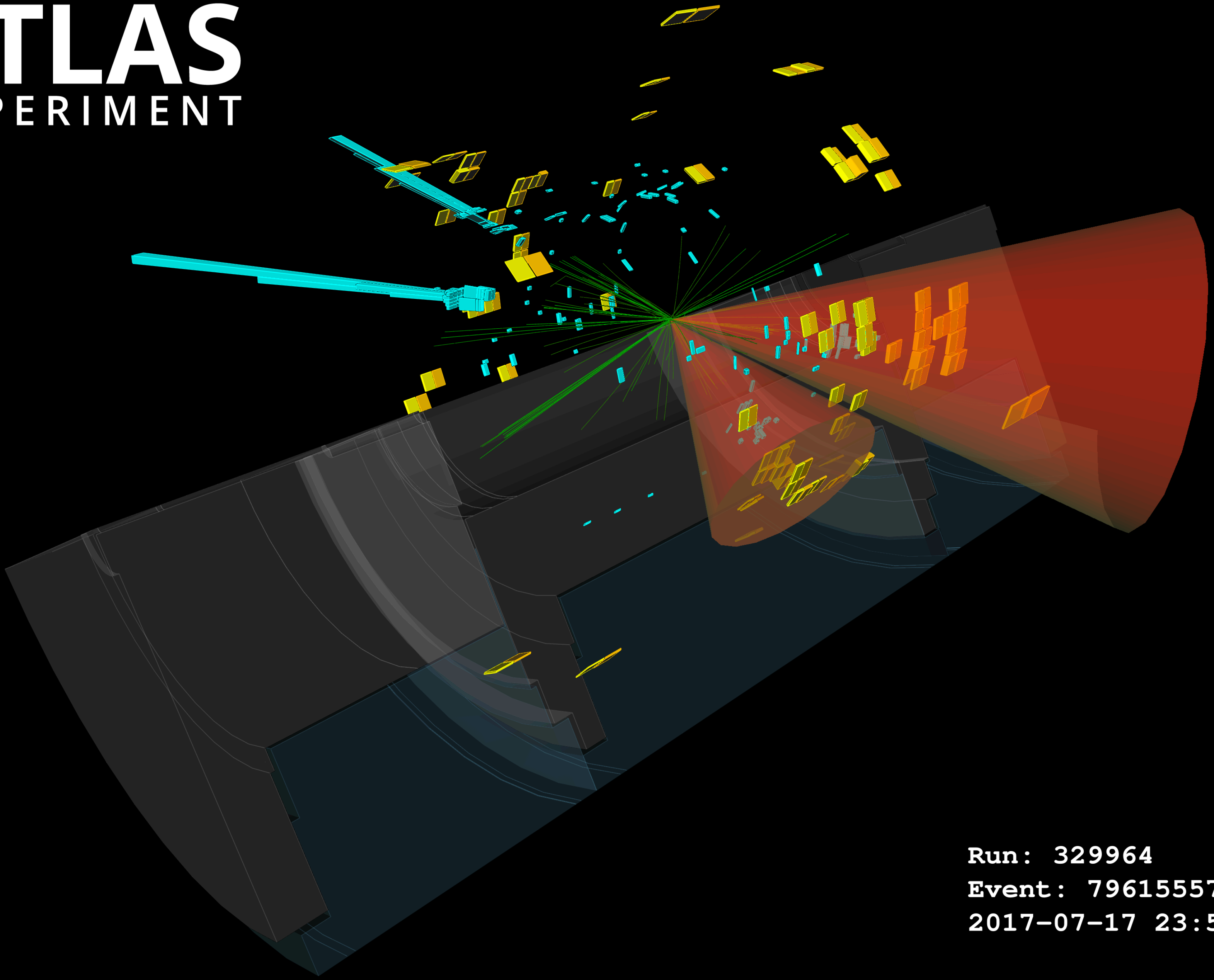
H($b\bar{b}$) and H(γγ)

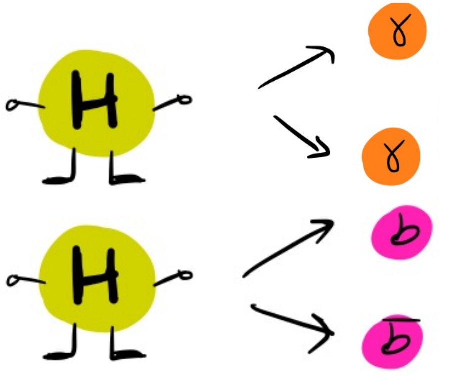




- good b-jets identification performance: 70% efficiency at 0.7-1% q/g (10-20% c) mistag probability
- excellent diphoton (γγ) mass resolution, ~1%

ATLAS
EXPERIMENT

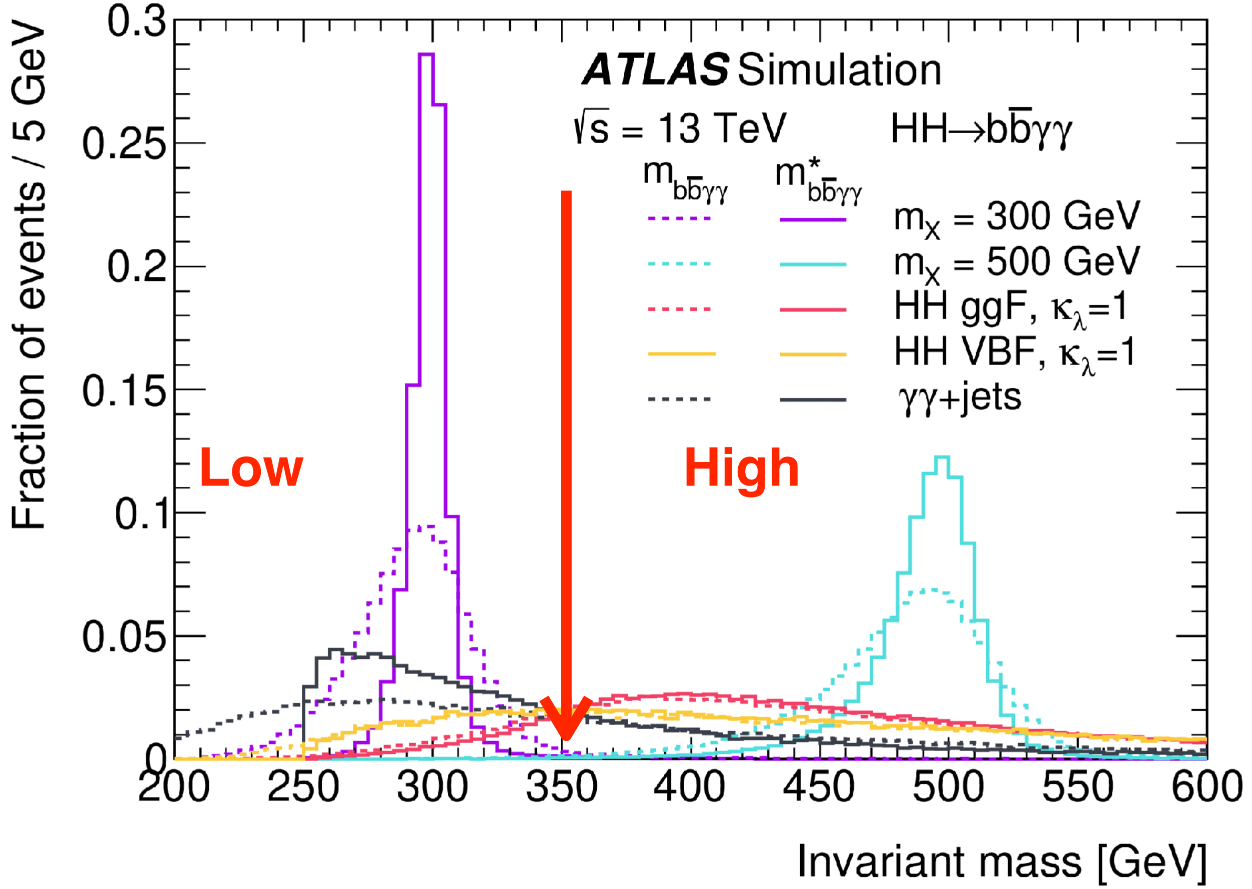




Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST

ATLAS-Phys. Rev. D 106, 052001
CMS-JHEP 03 (2021) 257

HH to $b\bar{b}\gamma\gamma$

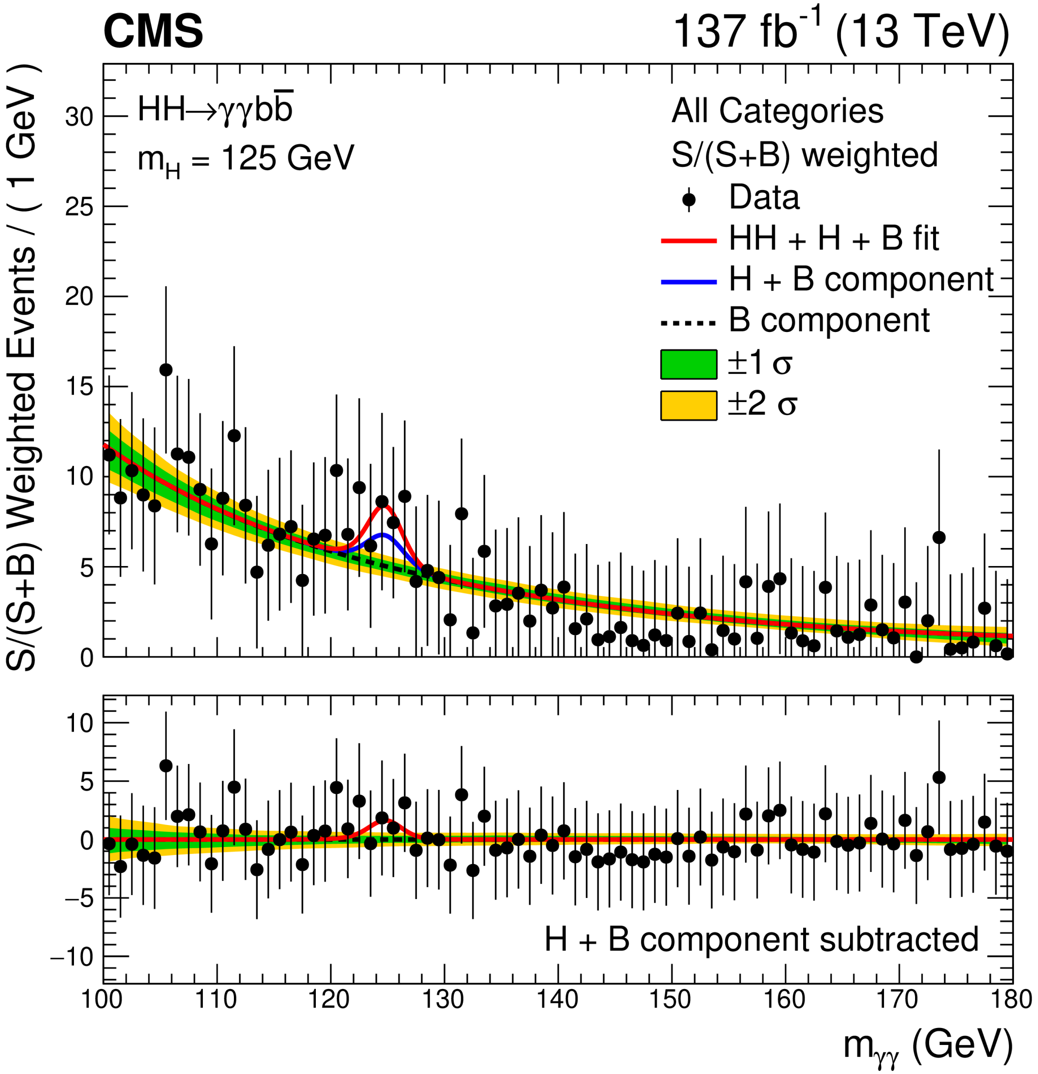


$$m^*_{\gamma\gamma b\bar{b}} = m_{\gamma\gamma b\bar{b}} - (m_{b\bar{b}} - m_H) - (m_{\gamma\gamma} - m_H)$$

- Photon selection similar to $H(\gamma\gamma)$ measurements
  - $m_{\gamma\gamma}$ and $m(b\bar{b})$ compatible with the Higgs boson mass
- **Mx** and **BDT (includes angular correlations)** used to categorize events
- Main **backgrounds** are:
  - $\gamma\gamma$+jets (prompt or jets misidentified as γ)
  - **SM single Higgs**
- **Sensitivity to Low/High** $m_{\gamma\gamma b\bar{b}}$

ATLAS-Phys. Rev. D 106, 052001
CMS-JHEP 03 (2021) 257

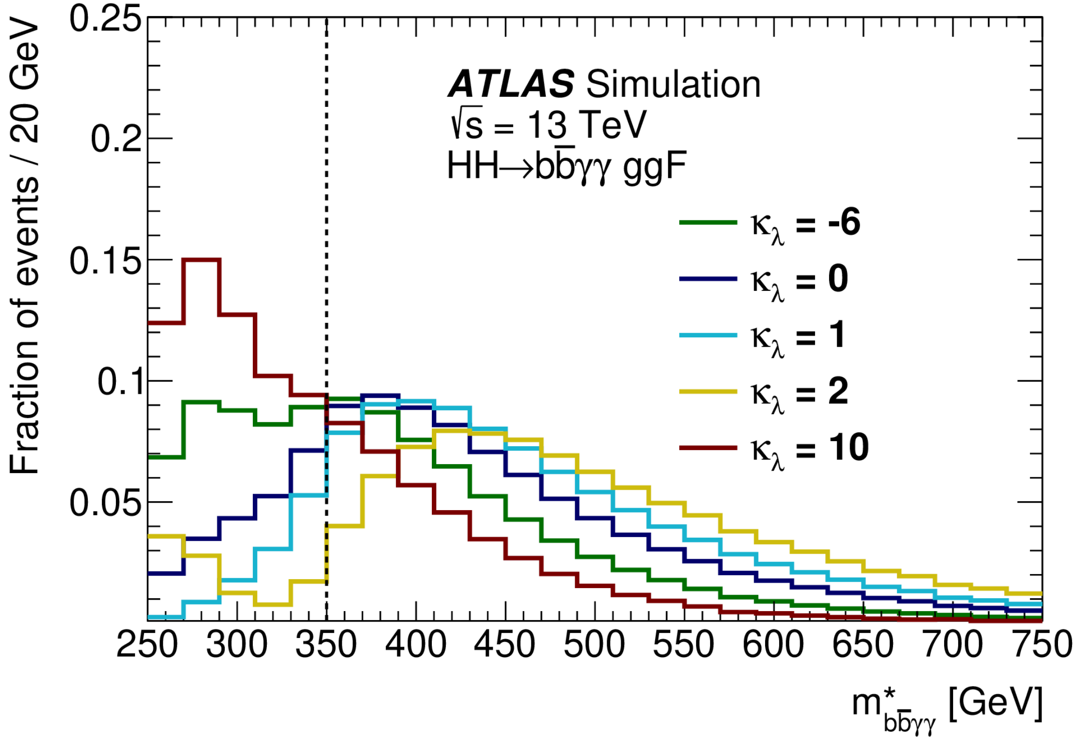
HH to $b\bar{b}\gamma\gamma$

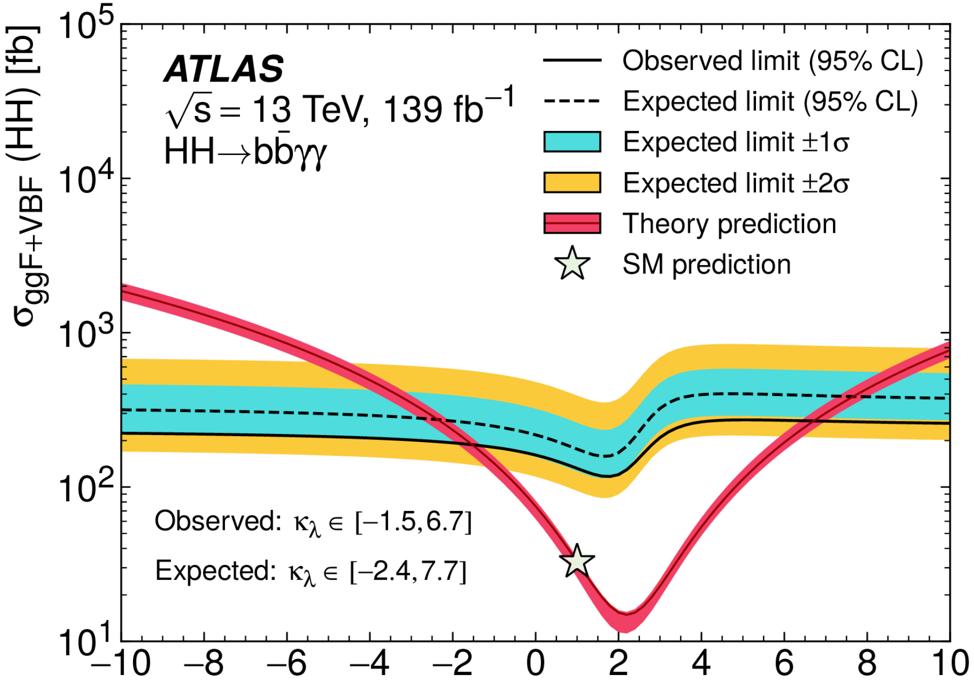


- CMS performs a likelihood fits simultaneous to $m(b\bar{b})$ and $m(\gamma\gamma)$ while ATLAS only uses the $m(\gamma\gamma)$ distribution
- ATLAS 95% CL limits on HH production observed (expected) at 4.1 (5.5) times the SM prediction
  - 5× improvement over previous result and current best available limits
- CMS observes 7.7 times SM predictions (expected 5.2x)

SLAC

Constraints on κ_λ from $b\bar{b}\gamma\gamma$





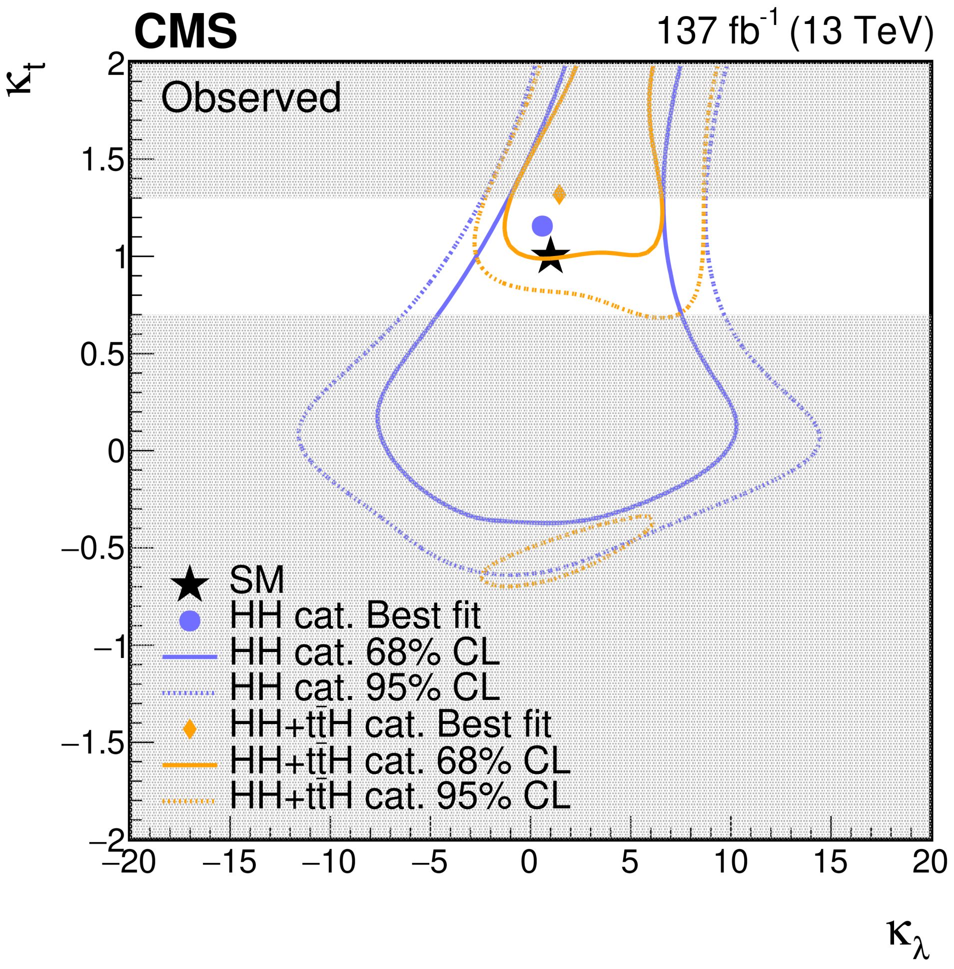
$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$

$\kappa_\lambda \in$ [-1.5, 6.7] ATLAS / [-3.3, 8.5] CMS assuming SM top-H coupling

More on the constrains from HH on κ_λ

CMS-JHEP 03 (2021) 257

It is impossible to extract κ_λ constraints from HH production without assumptions on κ_t



- A simultaneous likelihood scan for κ_λ and κ_t is performed to account for the modifications to
  - production HH and single Higgs cross sections
  - $B(H \to b\bar{b})$ and $B(H \to \gamma\gamma)$
- Combination with ttH (lep. & had.) categories improves the constraints on κ_t

A combination of single H and HH measurements would provide a more model independent determination of κ_λ

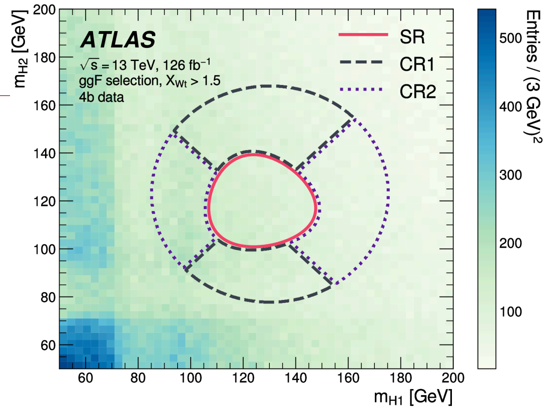
HH to $b\bar{b}b\bar{b}$

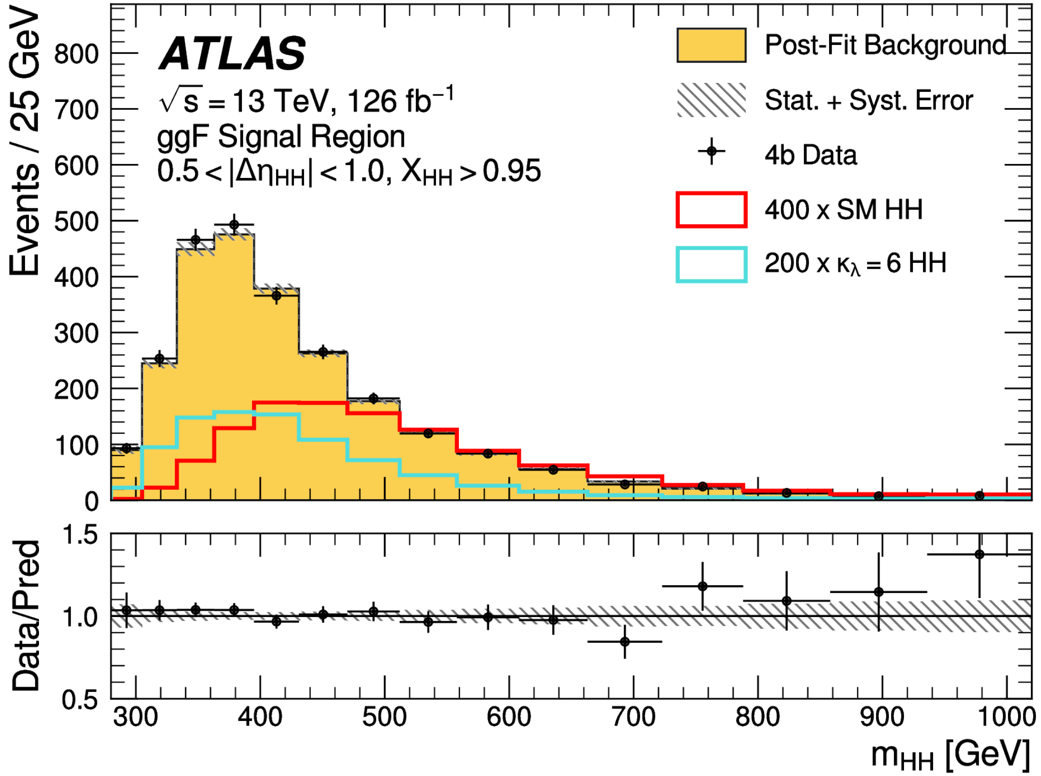
Large background from QCD multi-jet processes

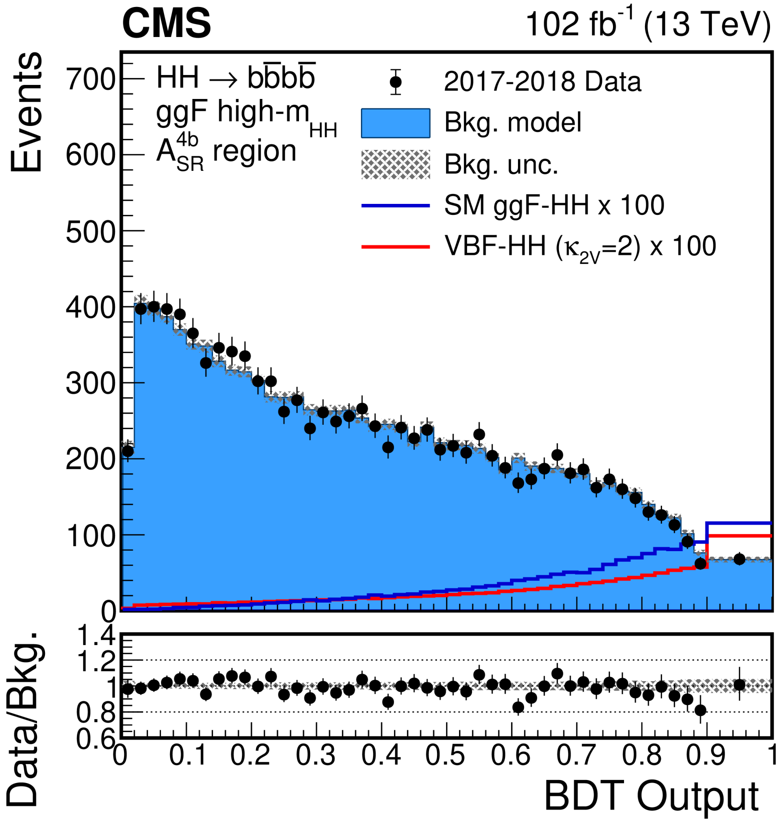
Online b-tagging requirements to suppress multi-jet background

Dedicated b-jet momentum corrections, to improve mass resolution (10–13%)

Data driven background modeling with multi-variate kinematic reweighing from control regions



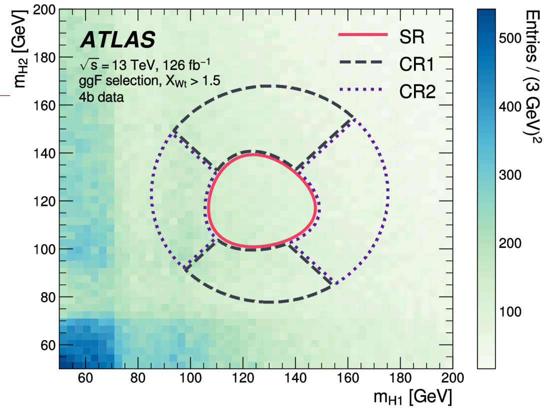




CMS-Phys. Rev. Lett. 129 (2022) 081802

ATLAS-arXiv:2301.03212

HH to $b\bar{b}b\bar{b}$



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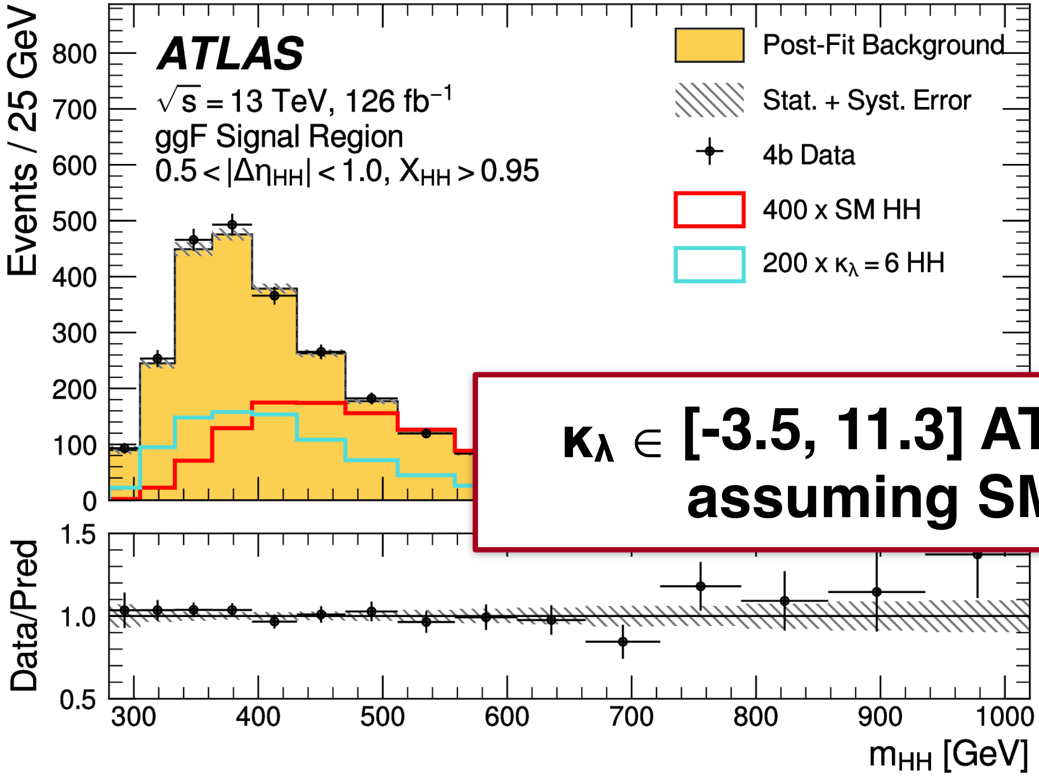
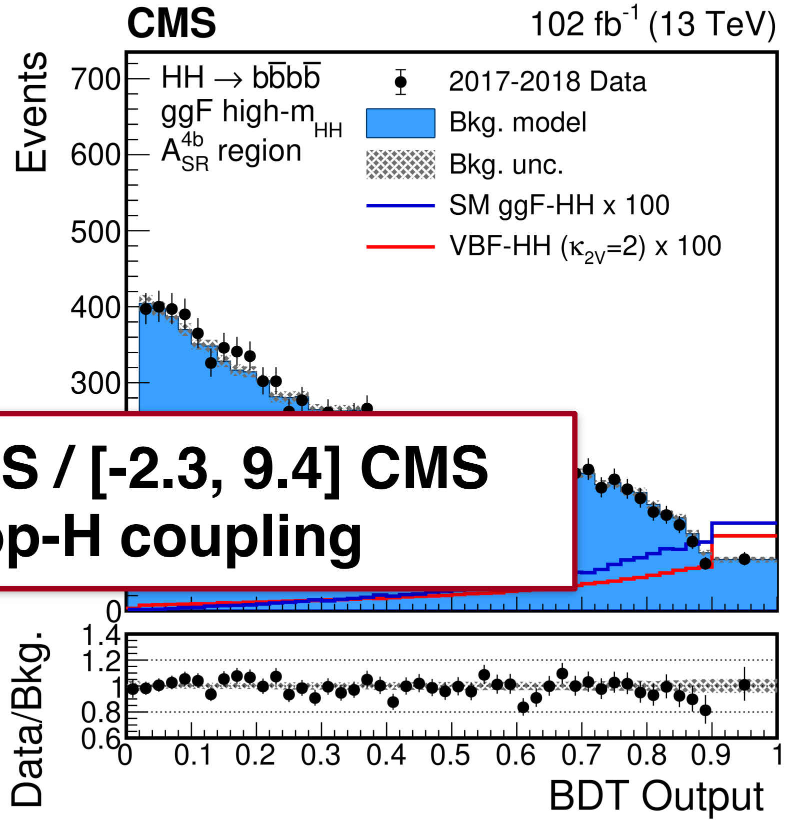




$\kappa_\lambda \in$ [-3.5, 11.3] ATLAS / [-2.3, 9.4] CMS assuming SM top-H coupling

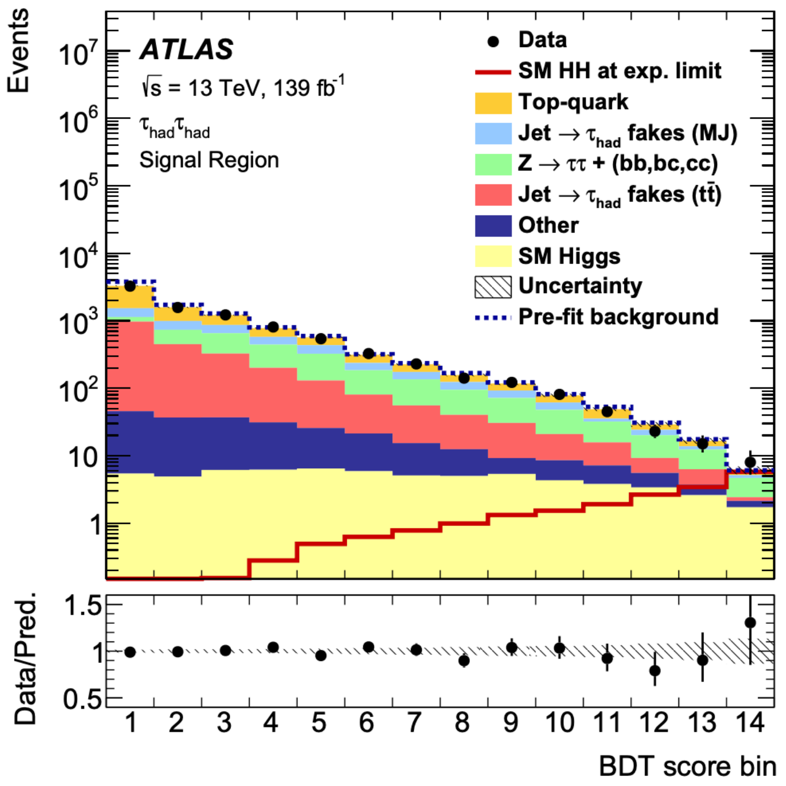
CMS-Phys. Rev. Lett. 129 (2022) 081802

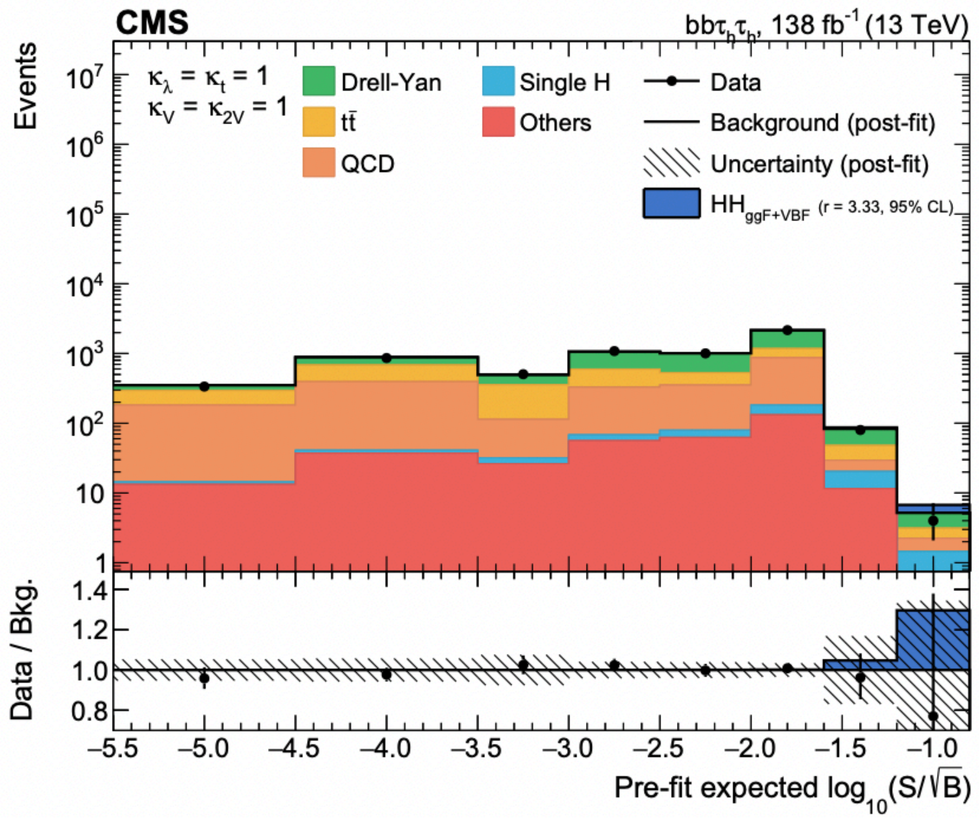
ATLAS-arXiv:2301.03212

HH to $b\bar{b}\tau\tau$

$\tau_h\tau_\mu+\tau_h\tau_e+\tau_h\tau_h$, 88% of H(ττ)

- 2 jets (resolved) or 1 large-R jet (boosted) [CMS]
- Events are then categorized by number of b-tags (1 b-tag category adds 10% to sensitivity in CMS)
- NNs to separate signal from background based on angular separation of leptons and reconstructed invariant mass





ATLAS-arXiv:2209.10910
CMS-arXiv:2206.09401

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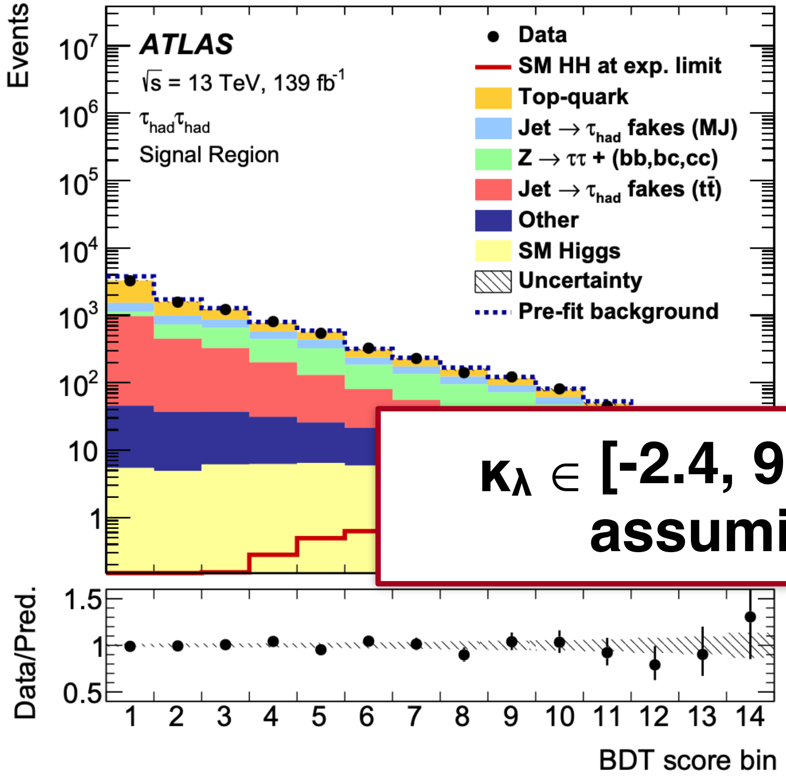
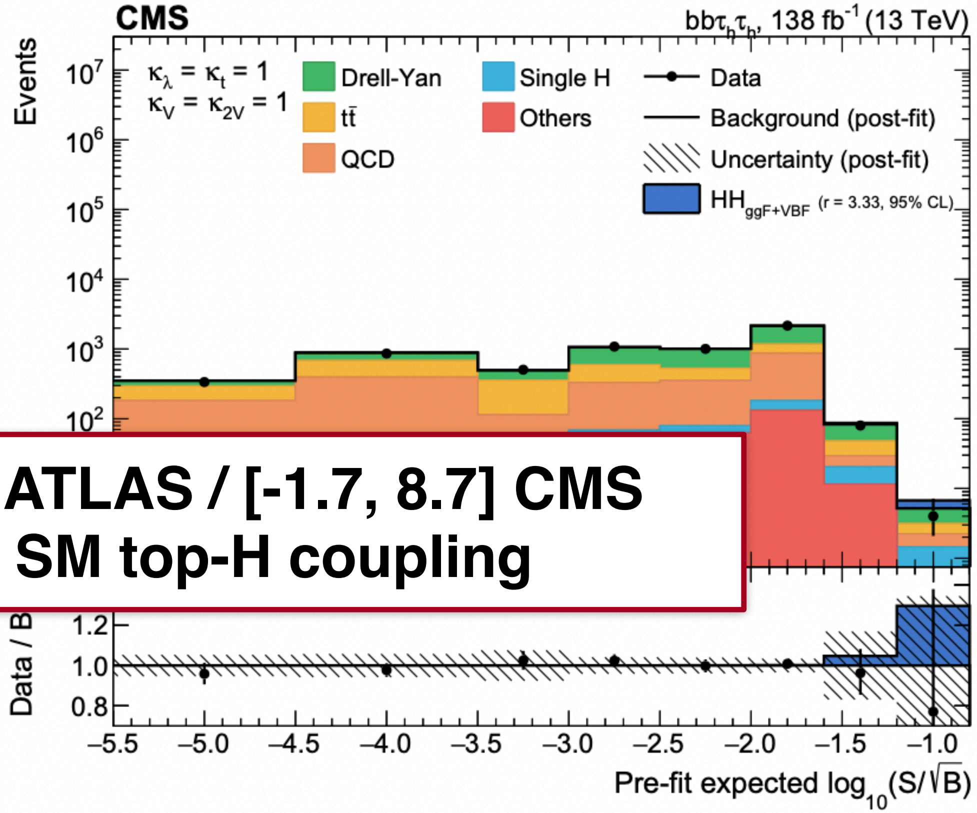
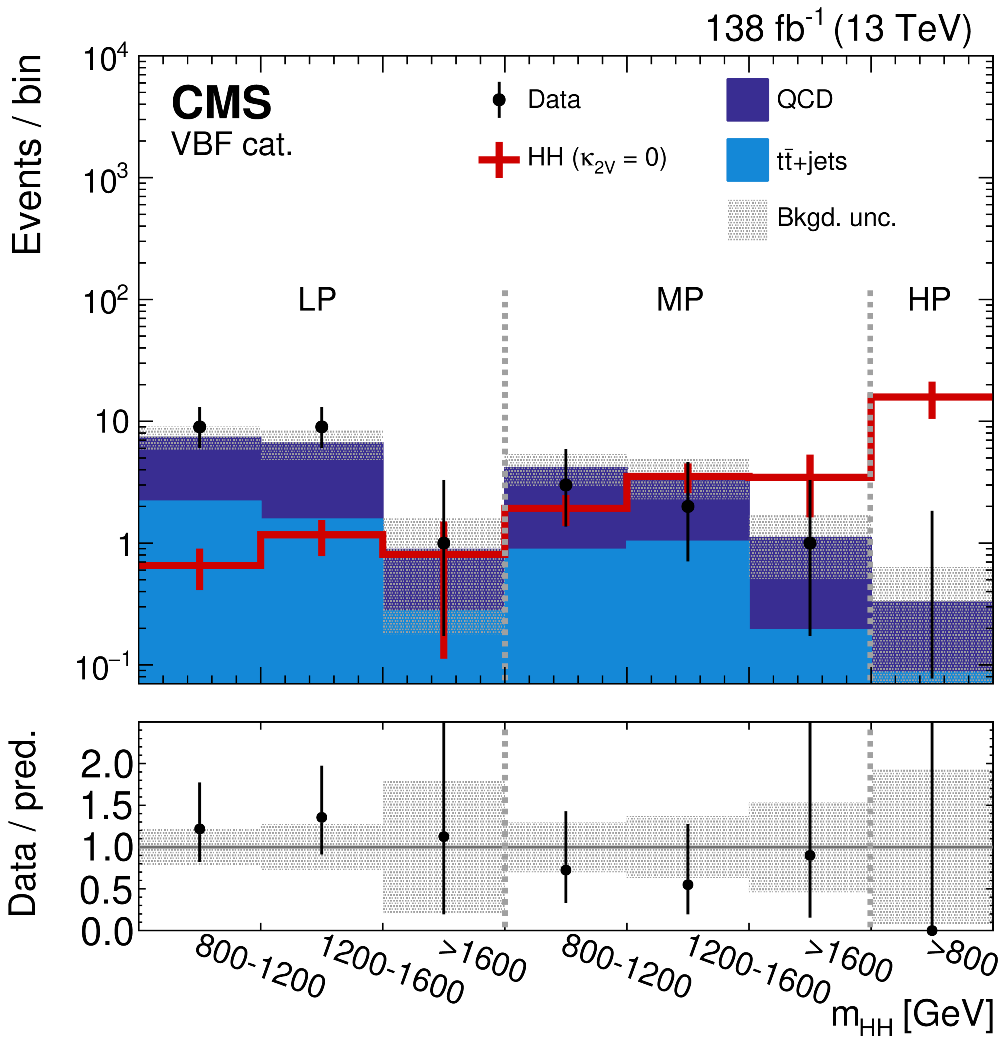




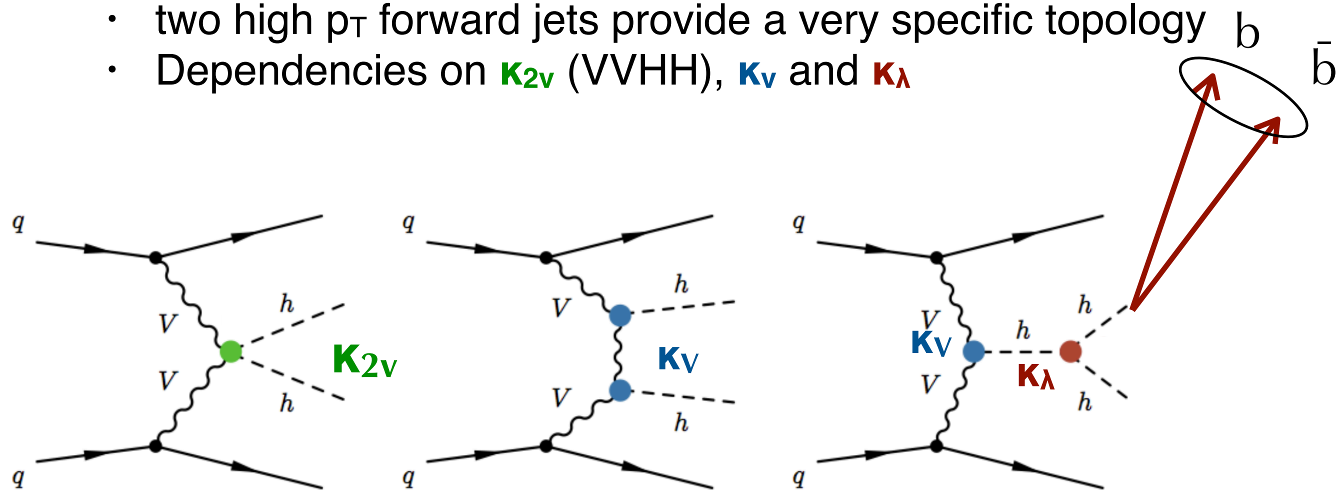
$\kappa_\lambda \in$ [-2.4, 9.2] ATLAS / [-1.7, 8.7] CMS assuming SM top-H coupling

VBF production



VBF production has a small cross-cross-section (1.73 fb @ N³LO)

- two high p_T forward jets provide a very specific topology
- Dependencies on κ_{2V} (VVHH), κ_V and κ_λ

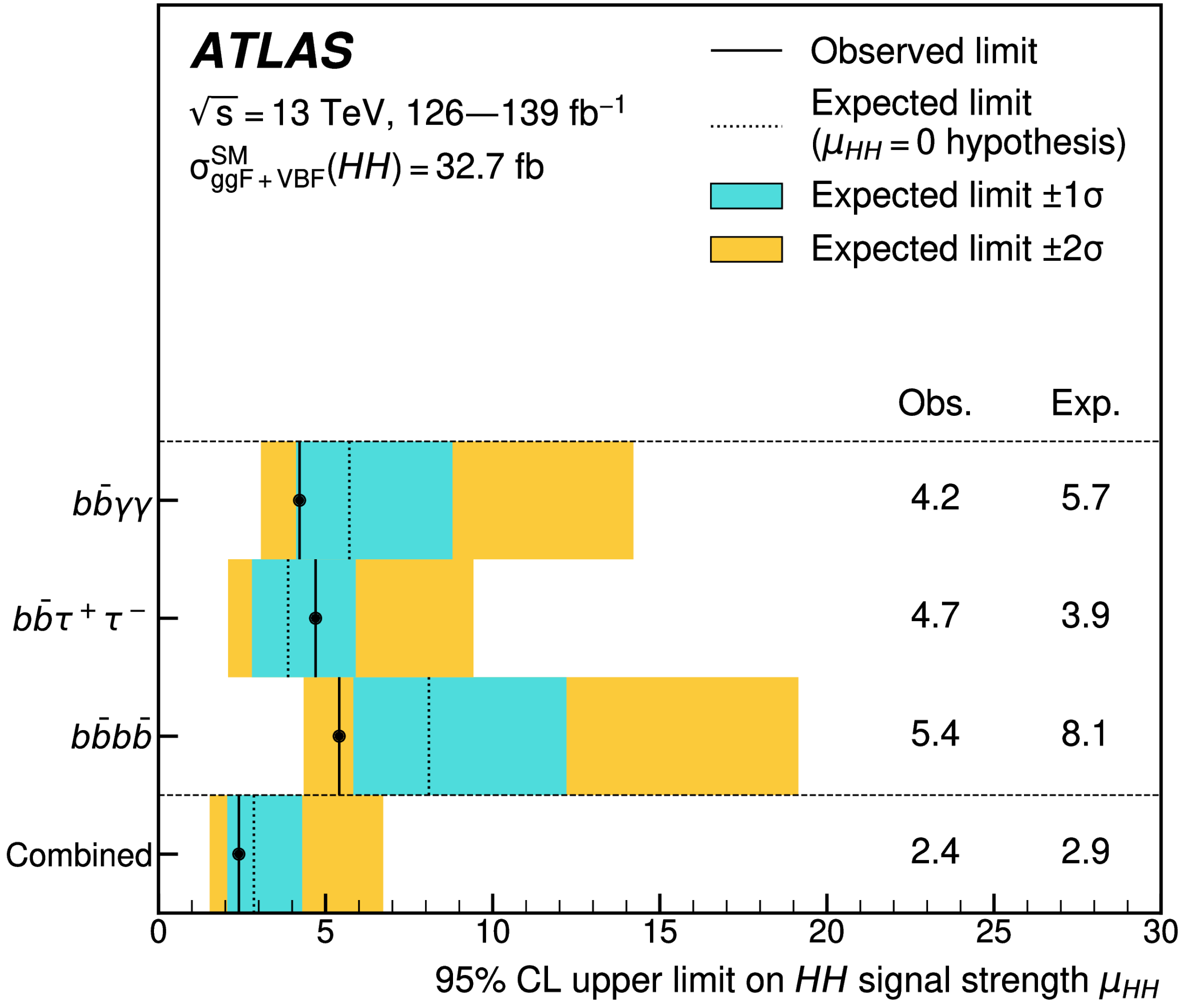


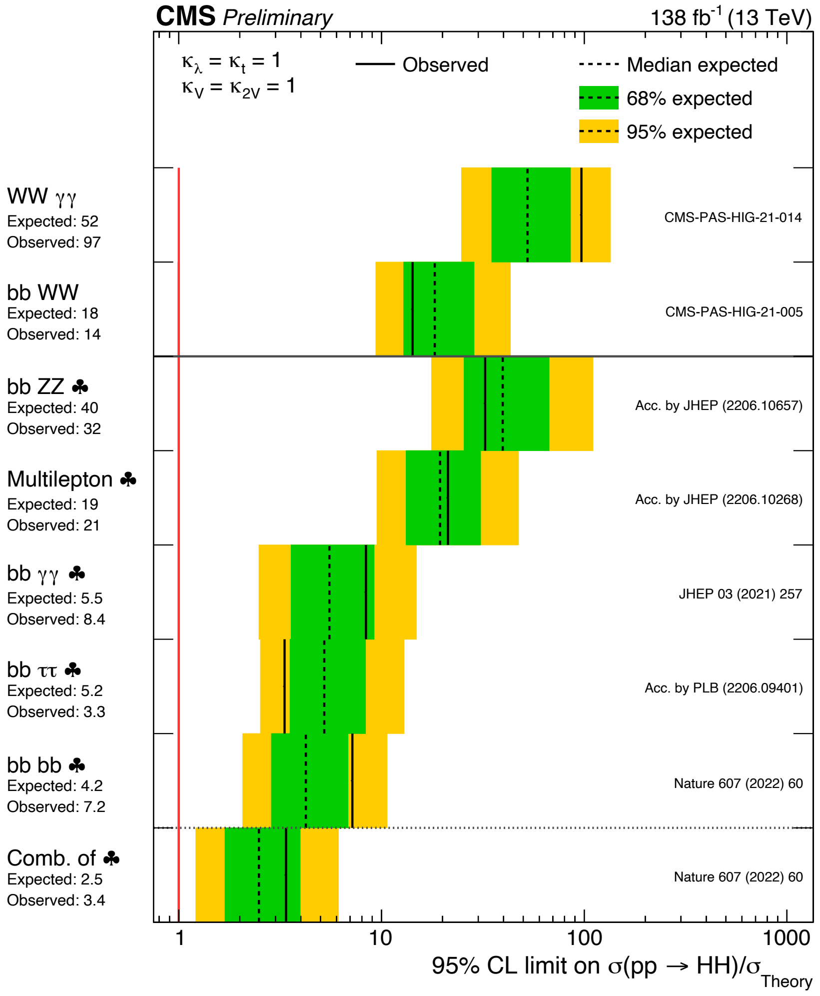
- New results from CMS for $b\bar{b}b\bar{b}$ which targets Higgs bosons with high Lorentz boost
  - It probes large deviations of κ_V and κ_{2V} from their SM predictions, which result in a harder m_{HH} spectrum and higher momentum for the b-jet from the Higgs boson decay.
  - Each $H \to b\bar{b}$ decay is reconstructed as a large-radius jet with characteristic substructure
  - The observed (expected) limits constraint κ_{2V} within $0.6 < \kappa_{2V} < 1.4$ at 95% CL - ***strongest limit on*** κ_{2V}
    - ***x30 improvement wrt early Run 2 results***

ATLAS-Phys. Lett. B 843 (2023) 137745
Nature 607 (2022) 60-68

Double Higgs Results

Similar sensitivity from $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$ to SM HH production





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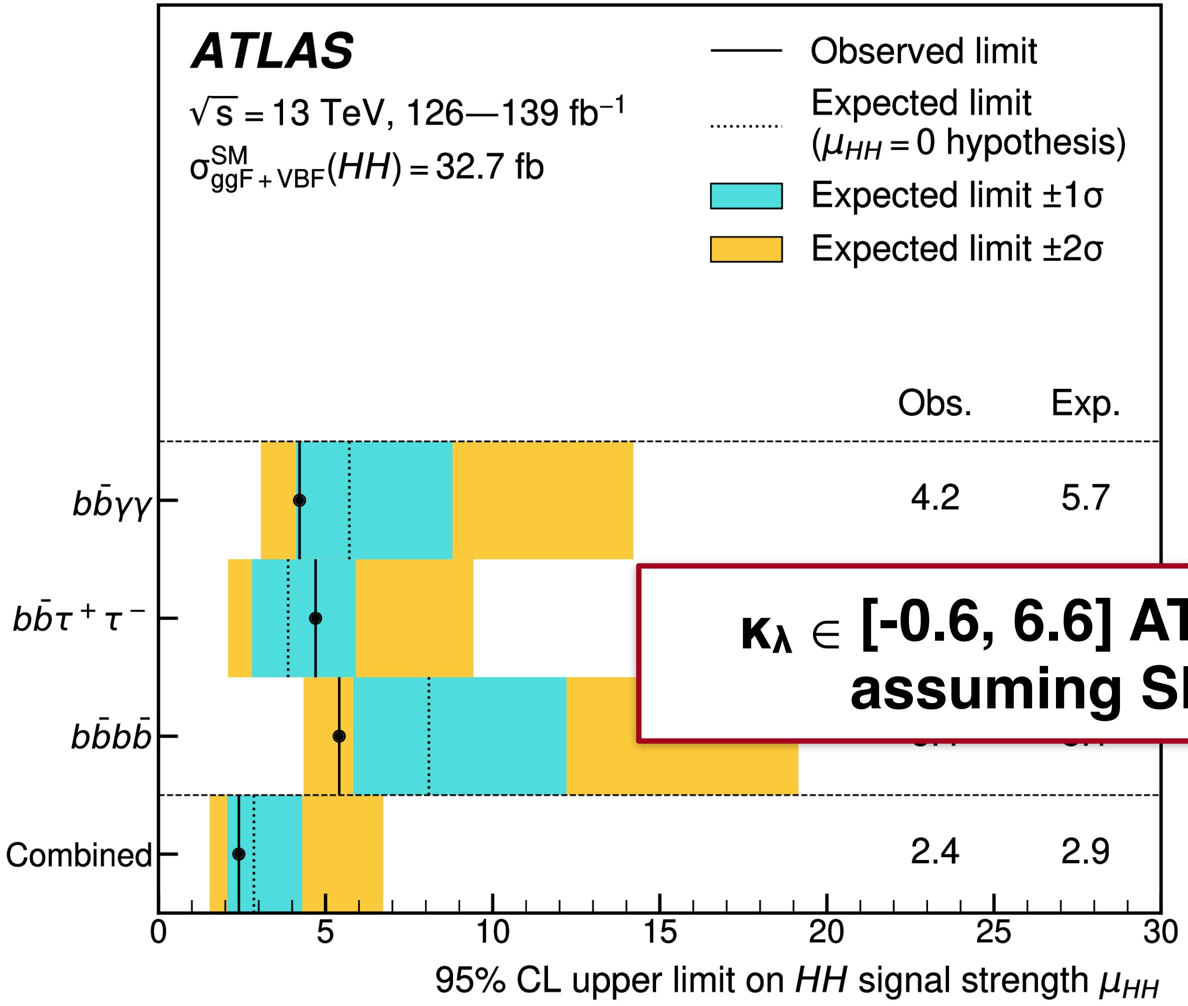
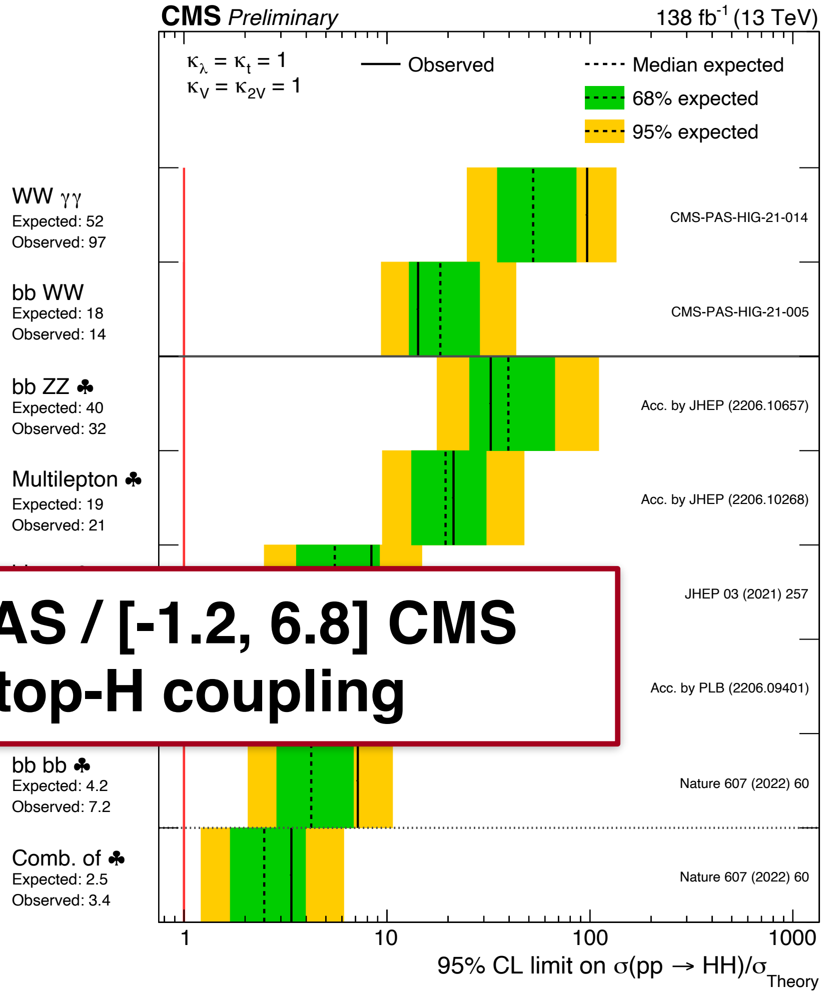
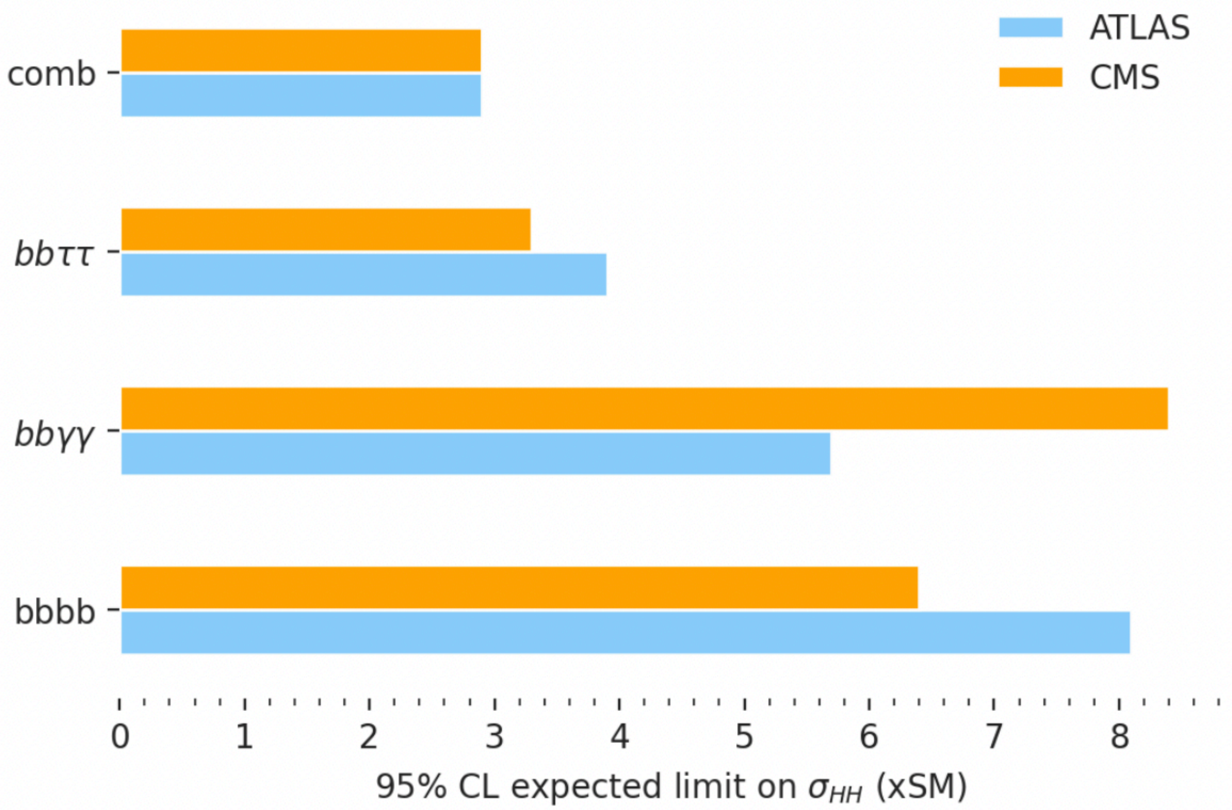


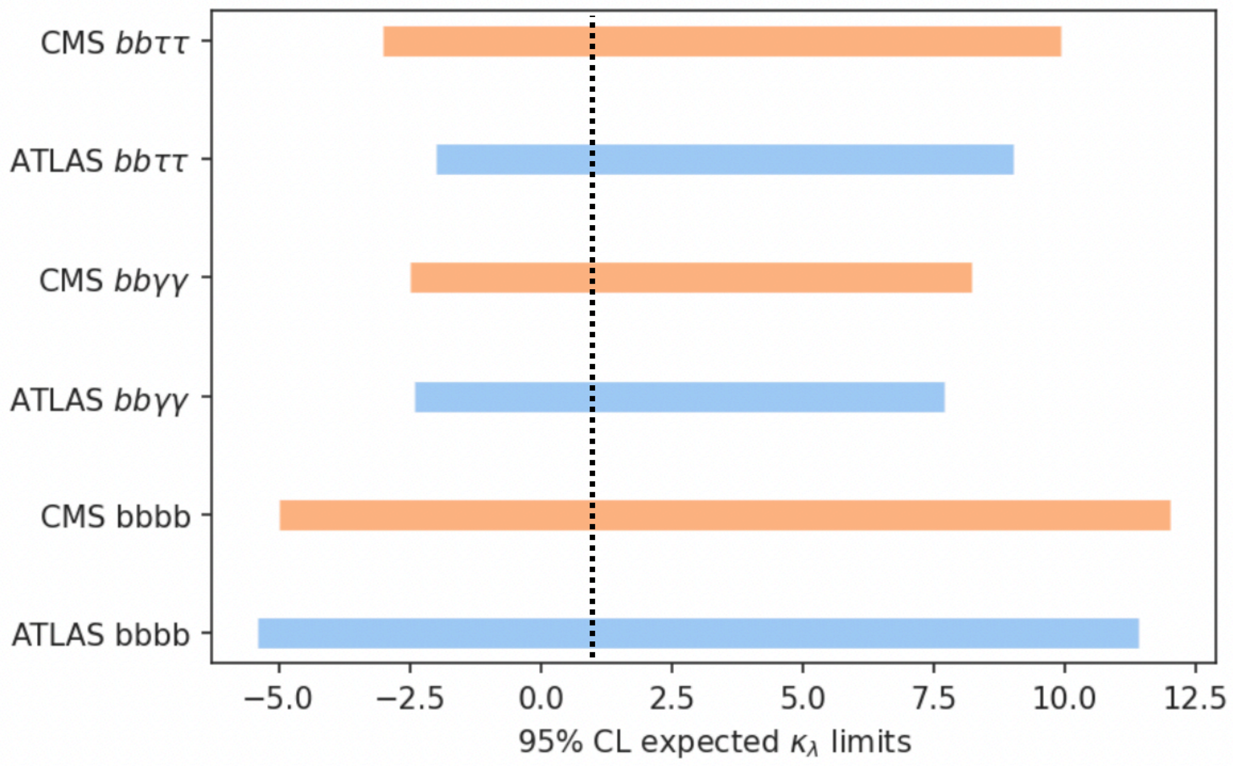


$\kappa_\lambda \in$ [-0.6, 6.6] ATLAS / [-1.2, 6.8] CMS assuming SM top-H coupling

Self-coupling : HH searches at the LHC



Snowmass Higgs report

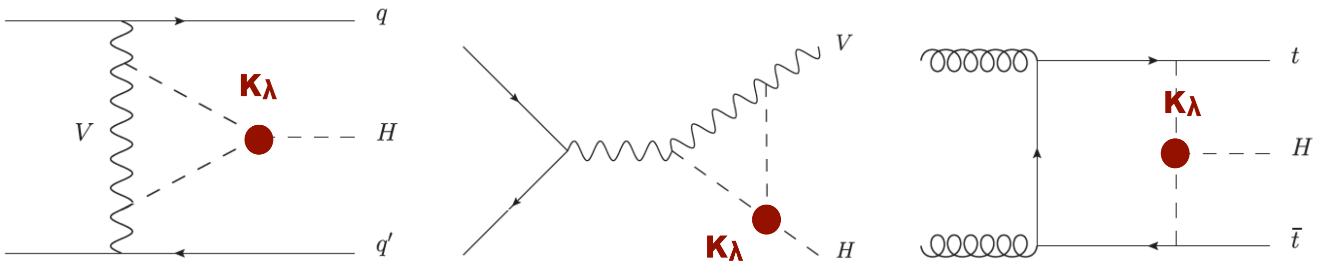


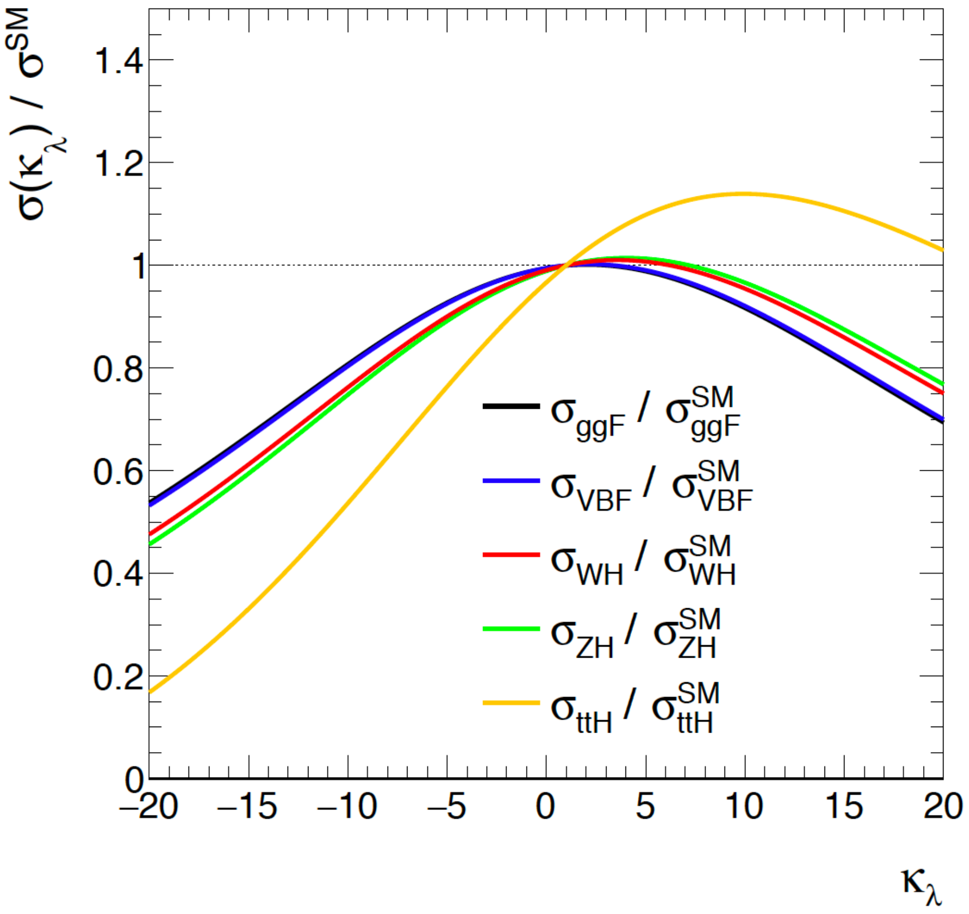
Main channels only based on full Run 2 (126-139/fb) analyses

Single Higgs to probe κ_λ

Single Higgs processes are sensitive to λ via NLO EW κ_λ-dependent corrections to

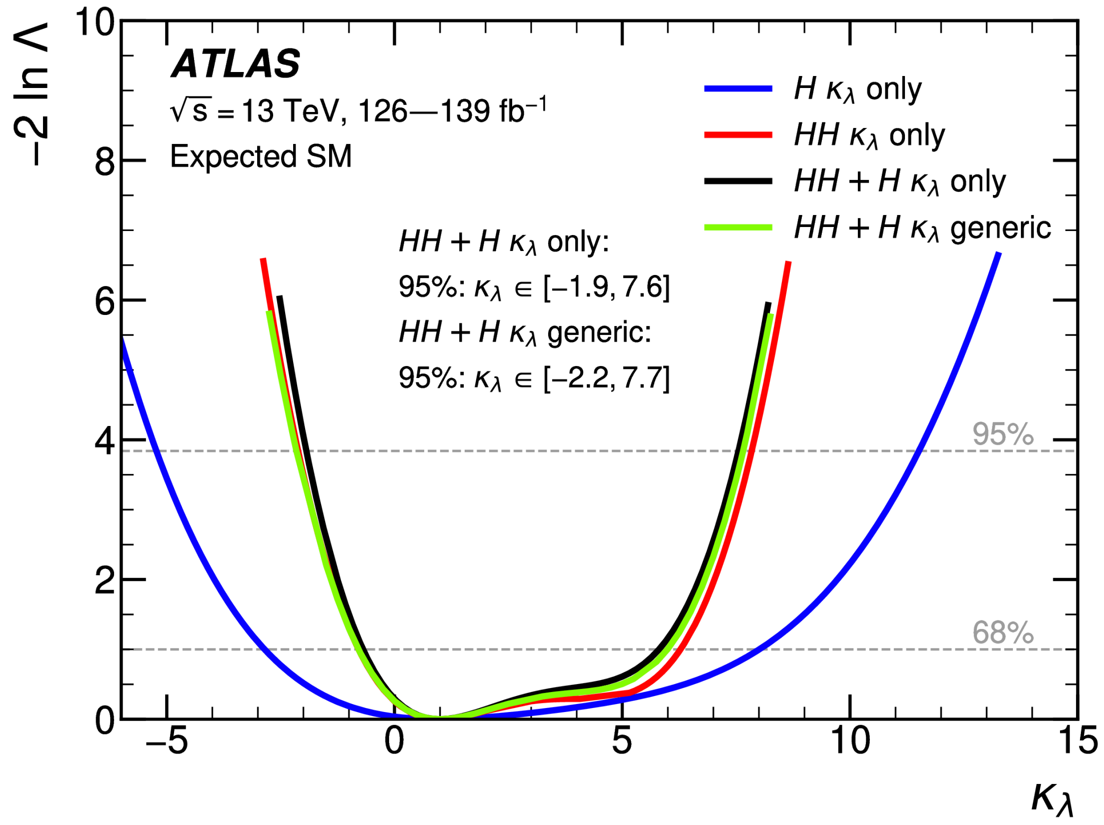
- cross-sections (**ttH, ggF, VH, VBF**)
- Higgs boson decay rates
- kinematics properties of the event (differential distributions)





JHEP 12 (2016) 080,
Eur. Phys. J. C77 (2017) 887

First double and single Higgs combination

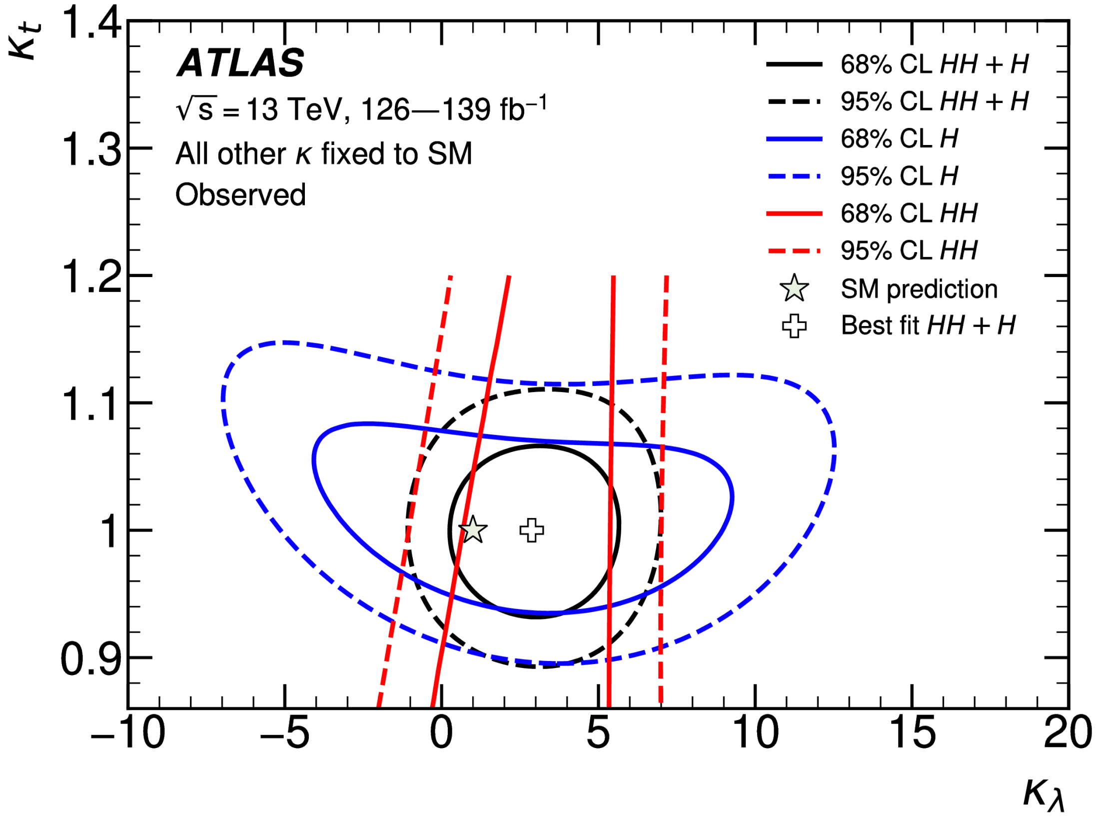


<u>First constraints</u> derived from 13 TeV single H + double H measurements with 126-139/fb

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	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

ATLAS-Phys. Lett. B 843 (2023) 137745

First double and single Higgs combination



First constraints derived from 13 TeV single H + double H measurements with 126-139/fb

They are compatible to those derived from HH direct searches but an EFT global analysis is needed to proper account of BSM contributions

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Towards an (SM)EFT analysis for the self-coupling

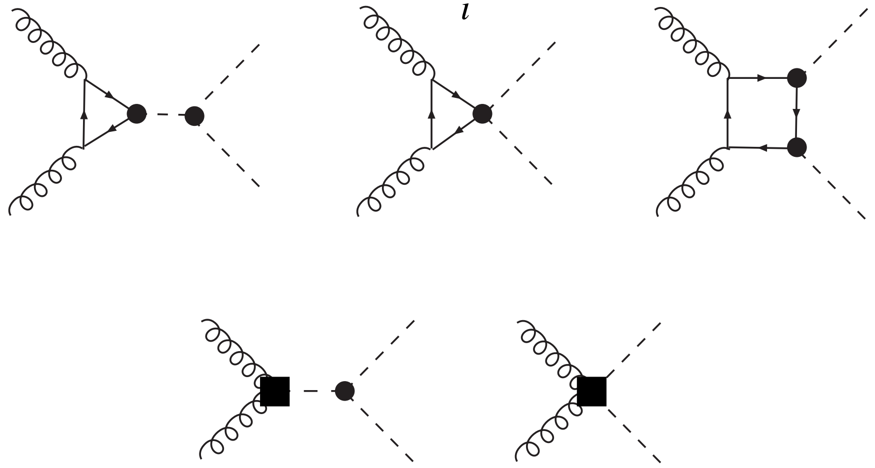
The EFT formalism summarizes deviations that might appear in a very wide class of models beyond the SM

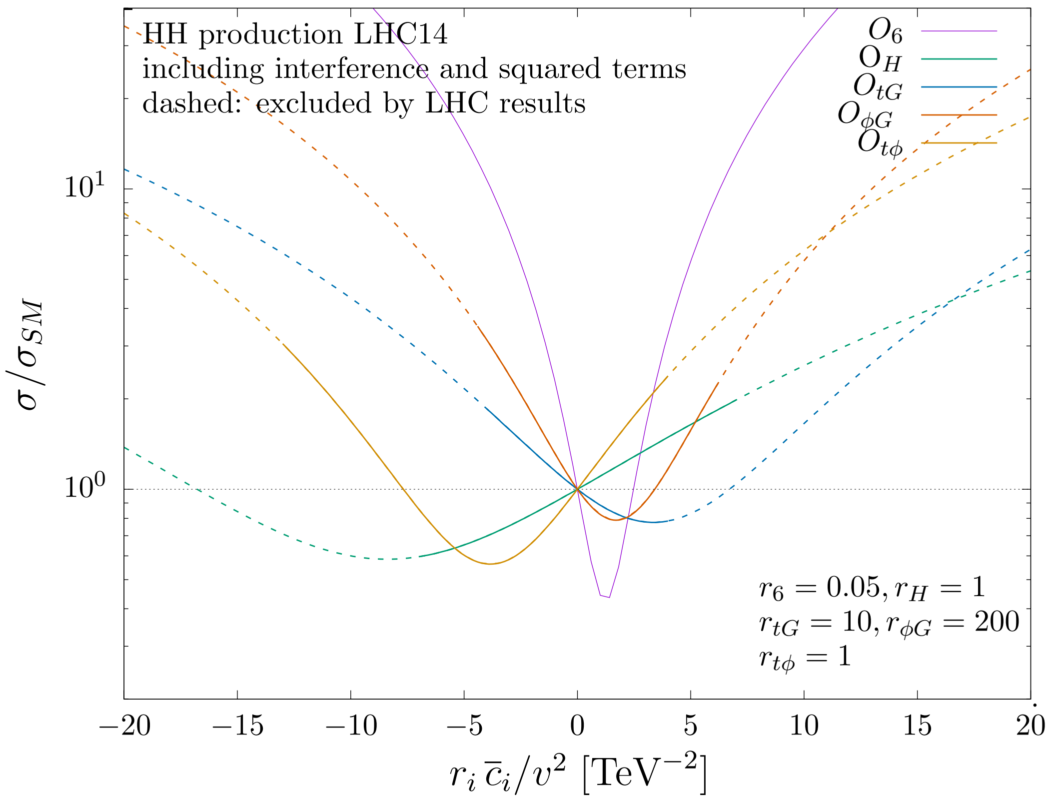
The most general set of BSM perturbations will modify other interactions and not just the self-coupling

Within the EFT formalism, data from several different processes can be combined to constrain the new physics parameters

BSM contributions to HH production cross sections are at most of size E^2/M^2, if E~m_H and M~ O(TeV):

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \sum_i \frac{\hat{c}_i}{M^2}\mathcal{O}_i + \cdots$$



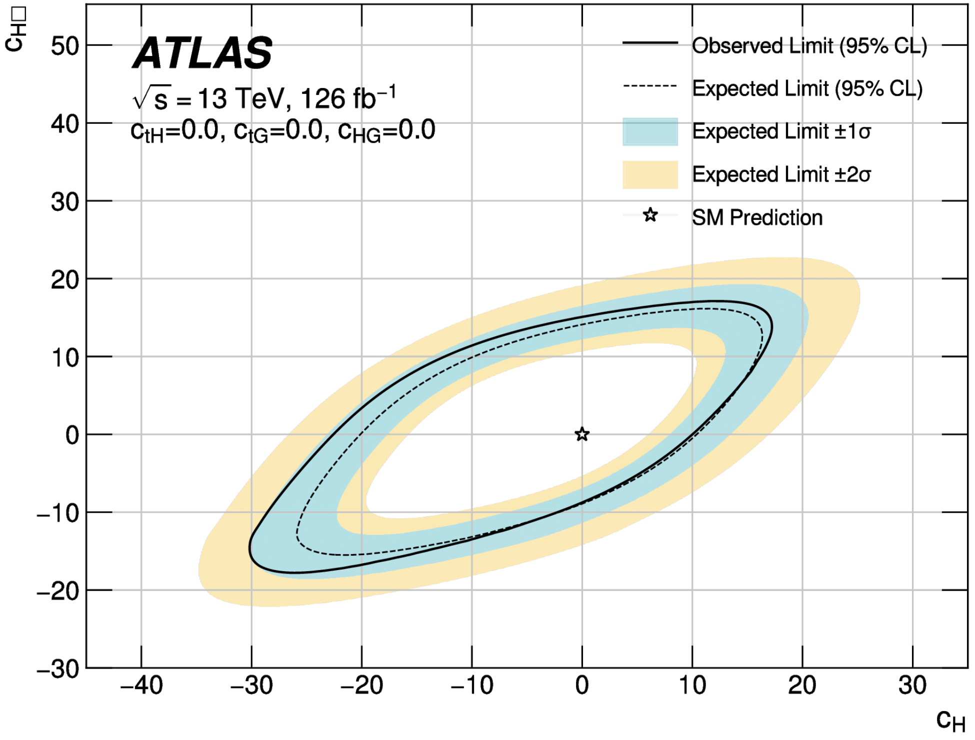


To determine the self-coupling at O(10%) we could consider only a subset of operators contributing **at LO to** $gg \to HH$

- **5 operators contribute** to the process - if CP conserved

An example, HH to $b\bar{b}b\bar{b}$

1D & 2D constraints on Wilson Coefficients



Wilson Coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$
c_{HG}	$H^\dagger H G^A_{\mu\nu} G^{\mu\nu}_A$
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}G^A_{\mu\nu}$

Parameter	Expected Constraint		Observed Constraint	
	Lower	Upper	Lower	Upper
c_H	−20	11	−22	11
c_{HG}	−0.056	0.049	−0.067	0.060
$c_{H\Box}$	−9.3	13.9	−8.9	14.5
c_{tH}	−10.0	6.4	−10.7	6.2
c_{tG}	−0.97	0.94	−1.12	1.15

LHC → High Luminosity LHC

LHC | HL-LHC

Run 2
8M H

Upgrade of accelerator and experiments

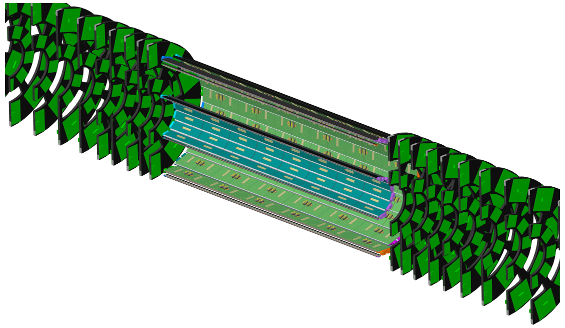
Run 3
16M H

HL-LHC installation
ATLAS/CMS Upgrades

Run 4/5
170M H
120k HH

2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	...	2039

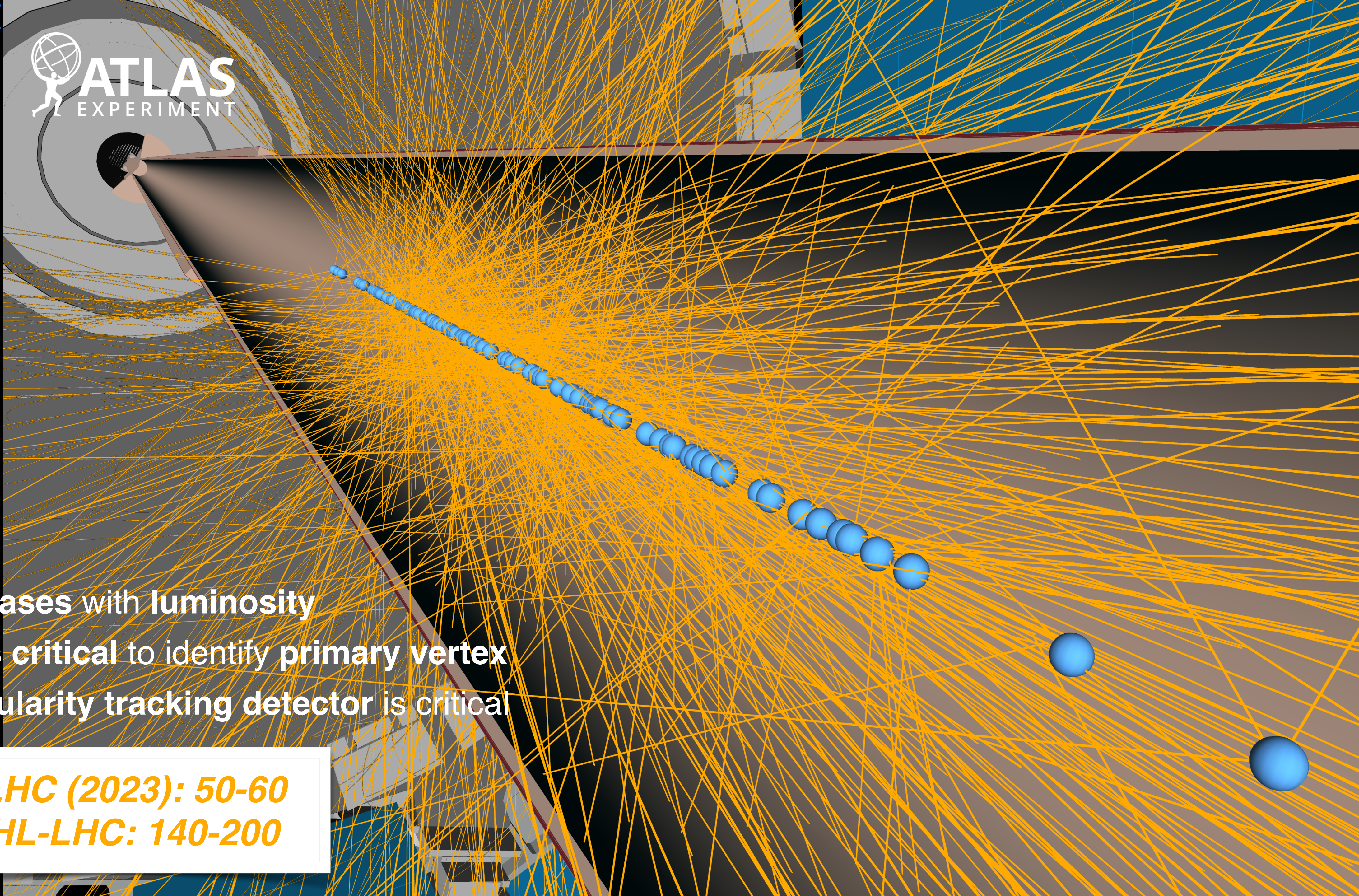
link!



Today

Phase-2 HL-LHC detector upgrades are being built

ref

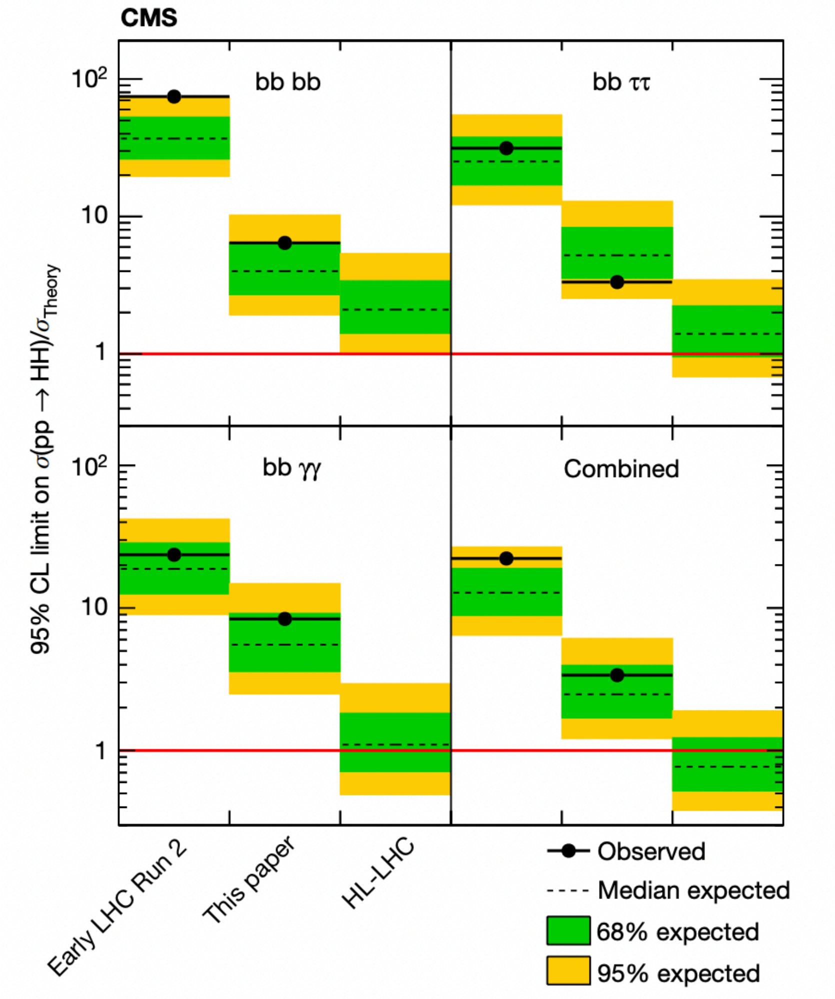


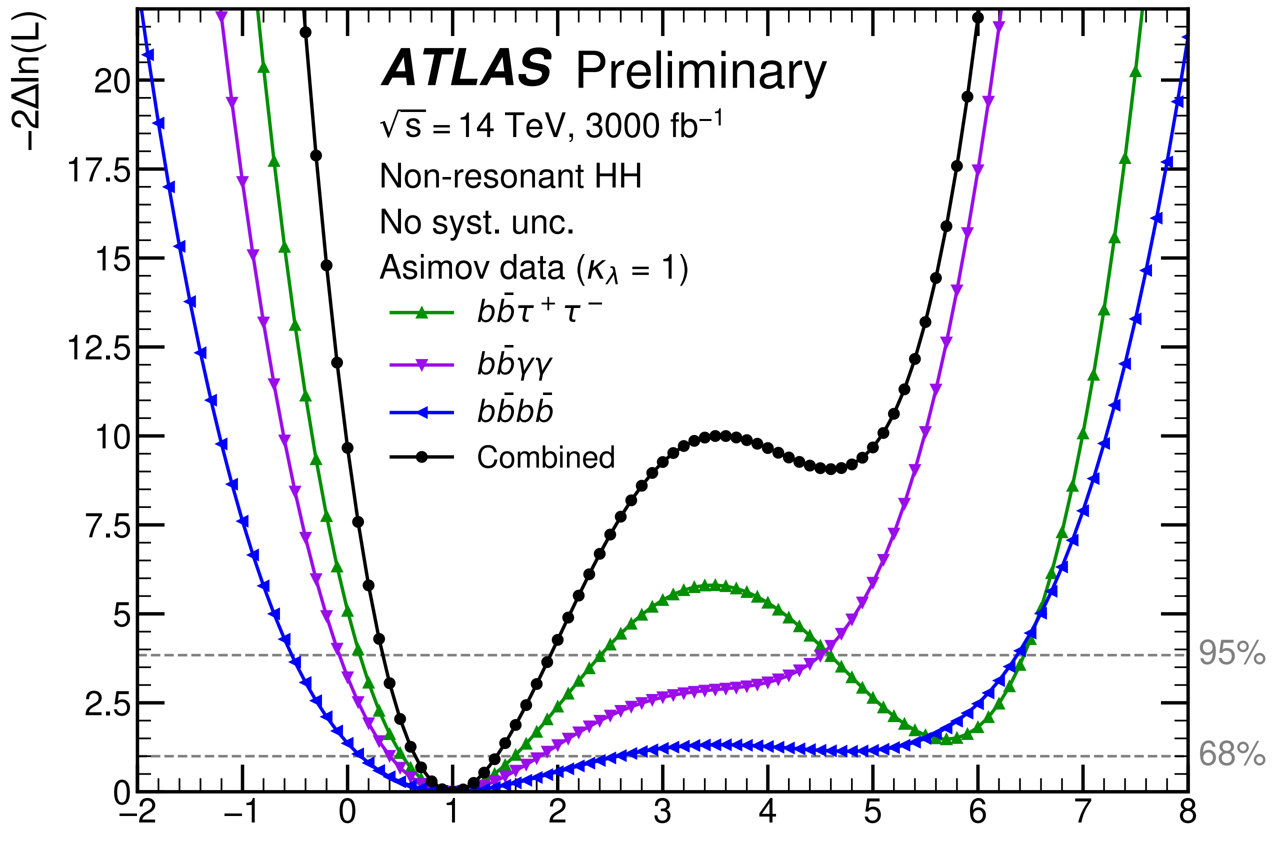
- **Pileup increases** with **luminosity**
- **z position is critical** to identify **primary vertex**
  - **High granularity tracking detector** is critical

LHC (2023): 50-60
HL-LHC: 140-200

Higgs physics at the HL-LHC

Extrapolations from Run 2 analyses





From 3.3σ to 4.9σ on the expected SM σ_{HH}

Conclusions and perspectives

Experiments at LHC are approaching SM sensitivity to non-resonant HH production

- Several final states investigated, more to exploit with more data
    - new improved analysis techniques
    - ML approaches being used in most final states
- More to be learned on the self-coupling from differential m_{HH}, VBF topology and single H measurements
- First H+HH and EFT combined analyses for a more general interpretation
- At HL-LHC more data will be available to test the self-coupling and probe rare (new?) processes
    - Challenging experimental environment for online selections and b-tagging
    - Improved tracker detectors should allow us to maintain or even yield to increased acceptance

Conclusions and perspectives

Experiments at LHC are approaching SM sensitivity to non-resonant HH production

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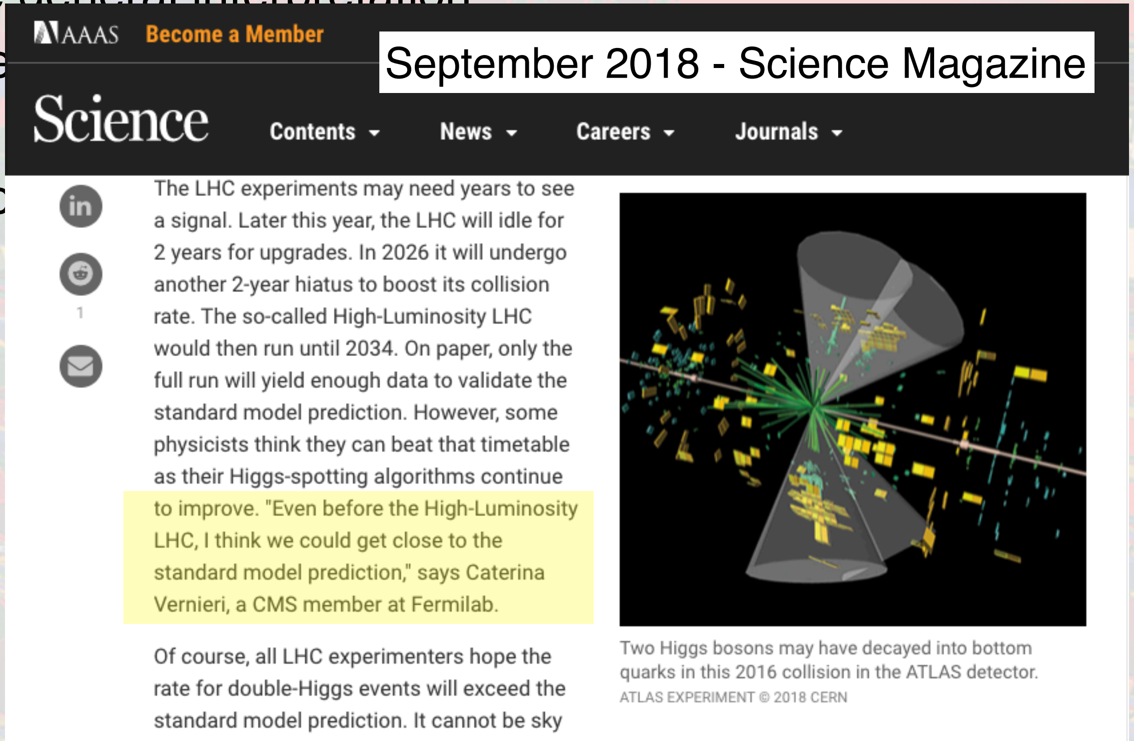

September 2018 - Science Magazine

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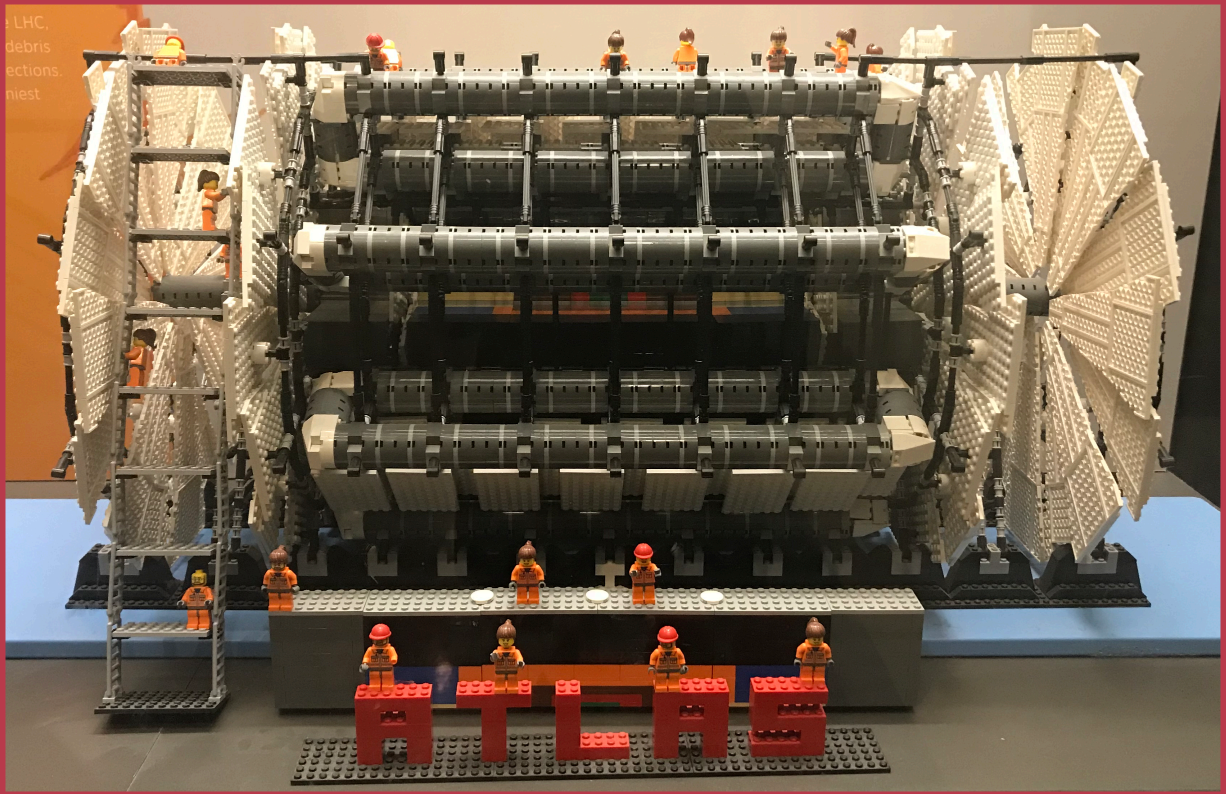
Science Contents News Careers Journals

The LHC experiments may need years to see a signal. Later this year, the LHC will idle for 2 years for upgrades. In 2026 it will undergo another 2-year hiatus to boost its collision rate. The so-called High-Luminosity LHC would then run until 2034. On paper, only the full run will yield enough data to validate the standard model prediction. However, some physicists think they can beat that timetable as their Higgs-spotting algorithms continue to improve. "Even before the High-Luminosity LHC, I think we could get close to the standard model prediction," says Caterina Vernieri, a CMS member at Fermilab.

Of course, all LHC experimenters hope the rate for double-Higgs events will exceed the standard model prediction. It cannot be sky

Two Higgs bosons may have decayed into bottom quarks in this 2016 collision in the ATLAS detector.
ATLAS EXPERIMENT © 2018 CERN



thank you!

arXiv:1910.00012

Which precision on the self-coupling is needed?

Bronze 100%

Silver 25–50%

Gold 5–10%

Platinum 1%

Sensitivity to:

models where we expect new particles of few hundred GeV mass

mixing of the Higgs boson with a heavy scalar with a mass of order 1 TeV

loop diagram effects created by any new particle with strong coupling to the H

typical quantum corrections to the Higgs self-coupling generated by loop diagrams

Which precision on the self-coupling is needed?

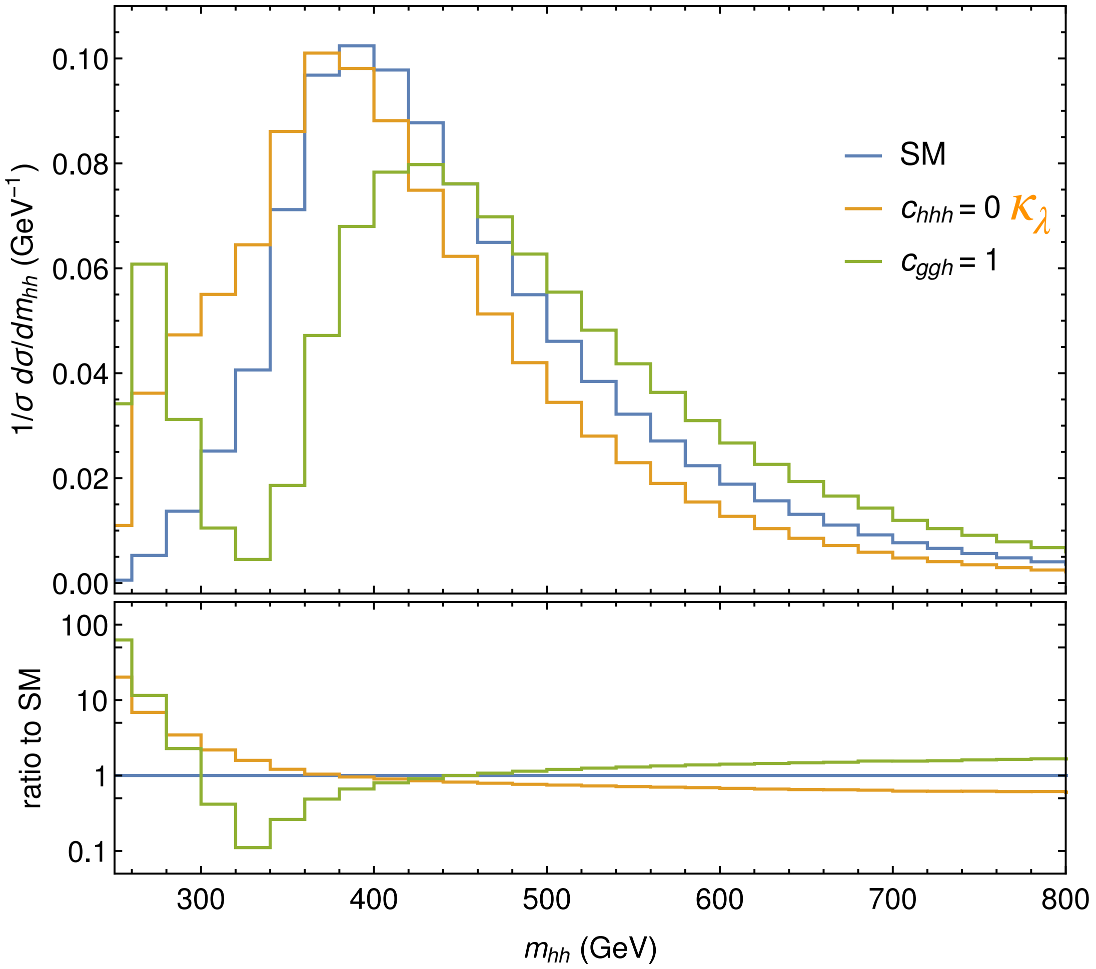
Bronze 100% | **Silver 25–50%** | **Gold 5–10%** | **Platinum 1%**

Sensitivity to:

models where we expect new particles of few hundred GeV mass

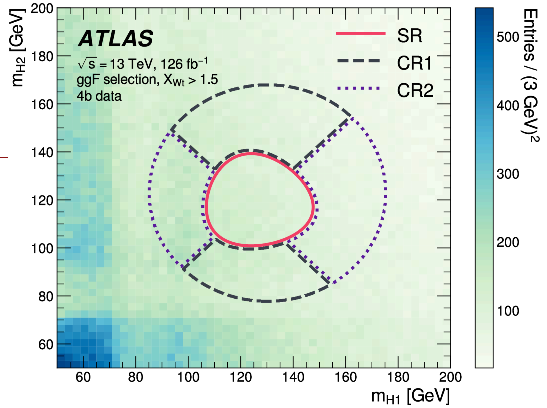
Interplay between precisions inference and direct searches for new particles.

Impact on m_{HH}



- A global SMEFT interpretation could constrain the $\mathcal{O}_6$ coefficient at levels of order 1 with HL-LHC dataset
- All these effective operators induce different distortions in the **m_{HH} distribution**
  - A shape analysis can thus help in disentangling the various operators in a **global fit**

HH to $b\bar{b}b\bar{b}$

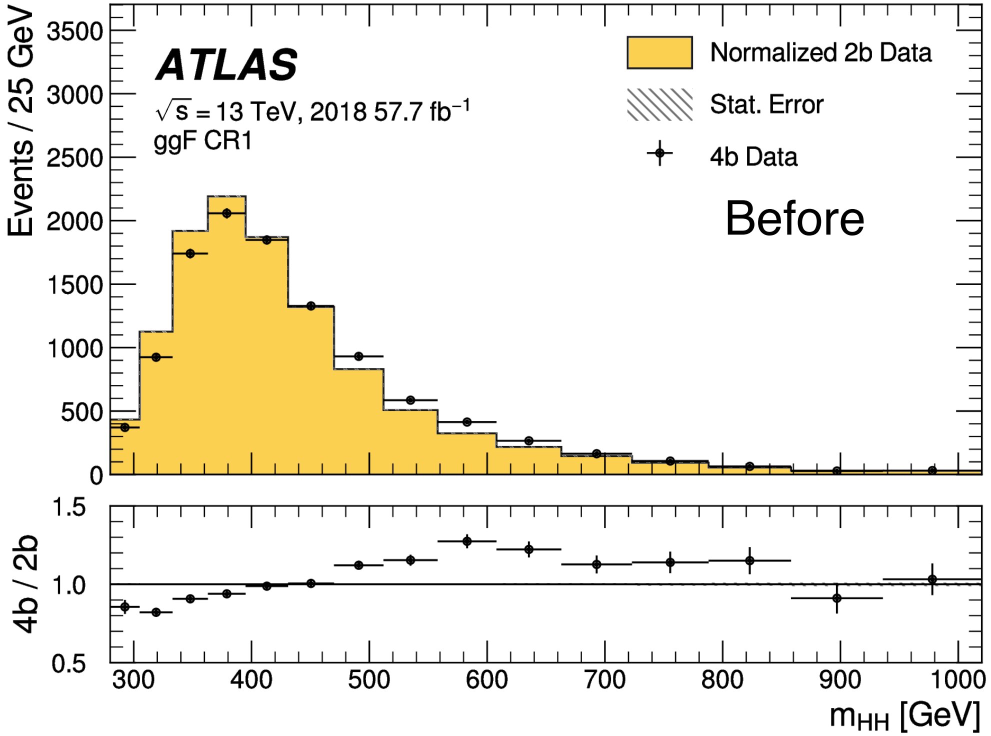


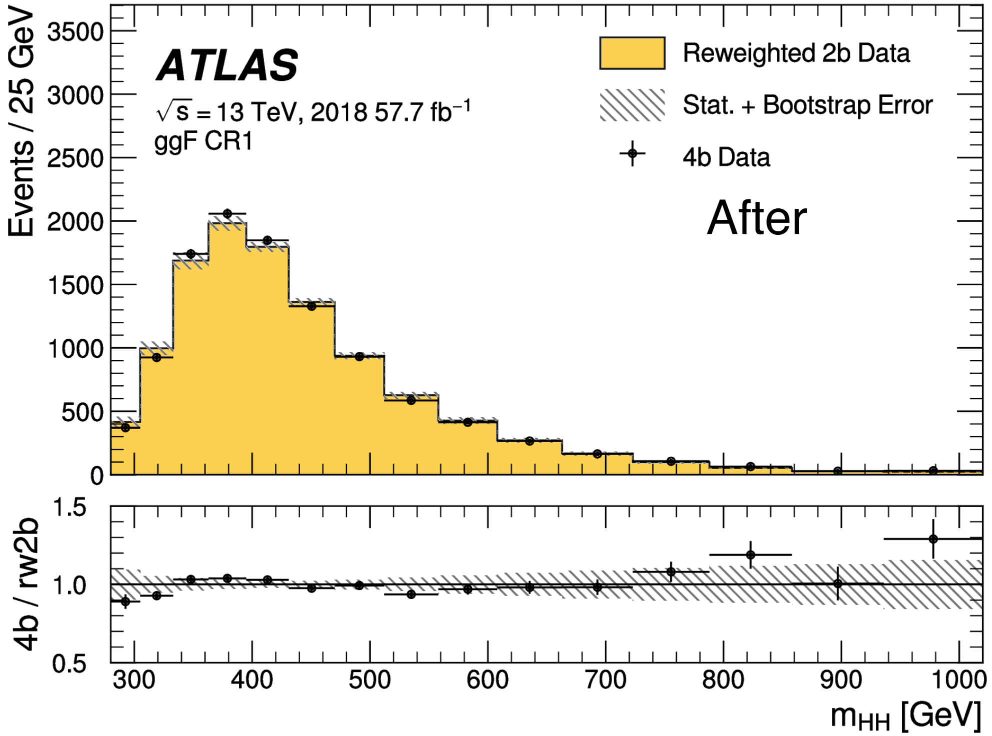
Large background from QCD multi-jet processes

Online b-tagging requirements to suppress multi-jet background

Dedicated b-jet momentum corrections, to improve mass resolution (10–13%)

Data driven background modeling with multi-variate kinematic reweighing from control regions

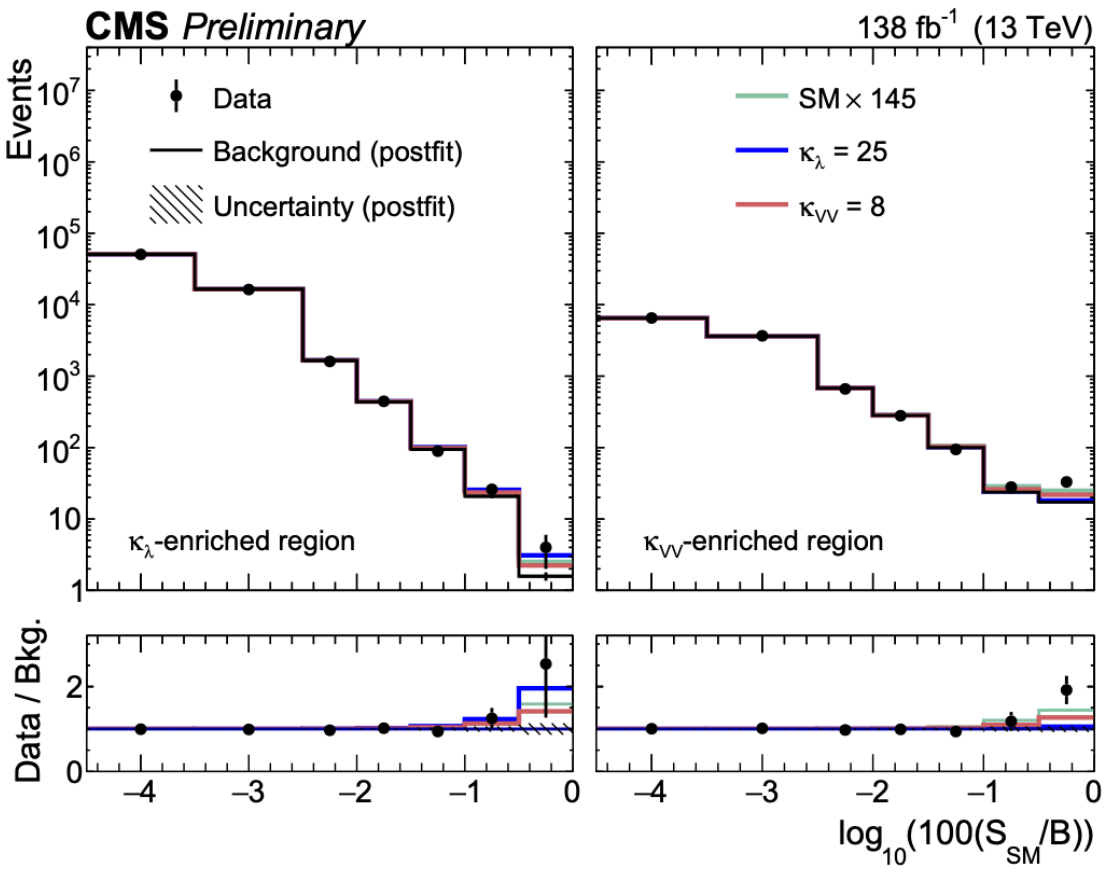




ATLAS-arXiv:2301.03212

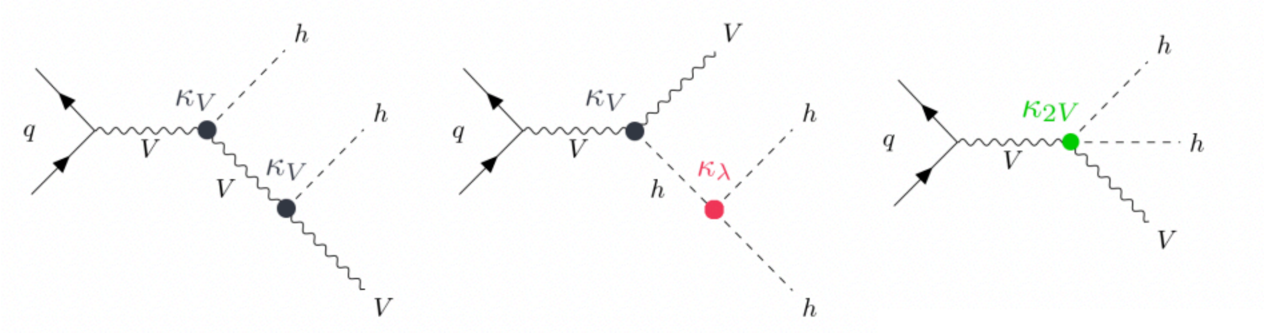
CMS-Phys. Rev. Lett. 129 (2022) 081802

VHH production



VHH production has a small cross-cross-section (0.86 fb @ NNLO)

- Dependencies on κ_{2V} (VVHH), κ_V and κ_λ

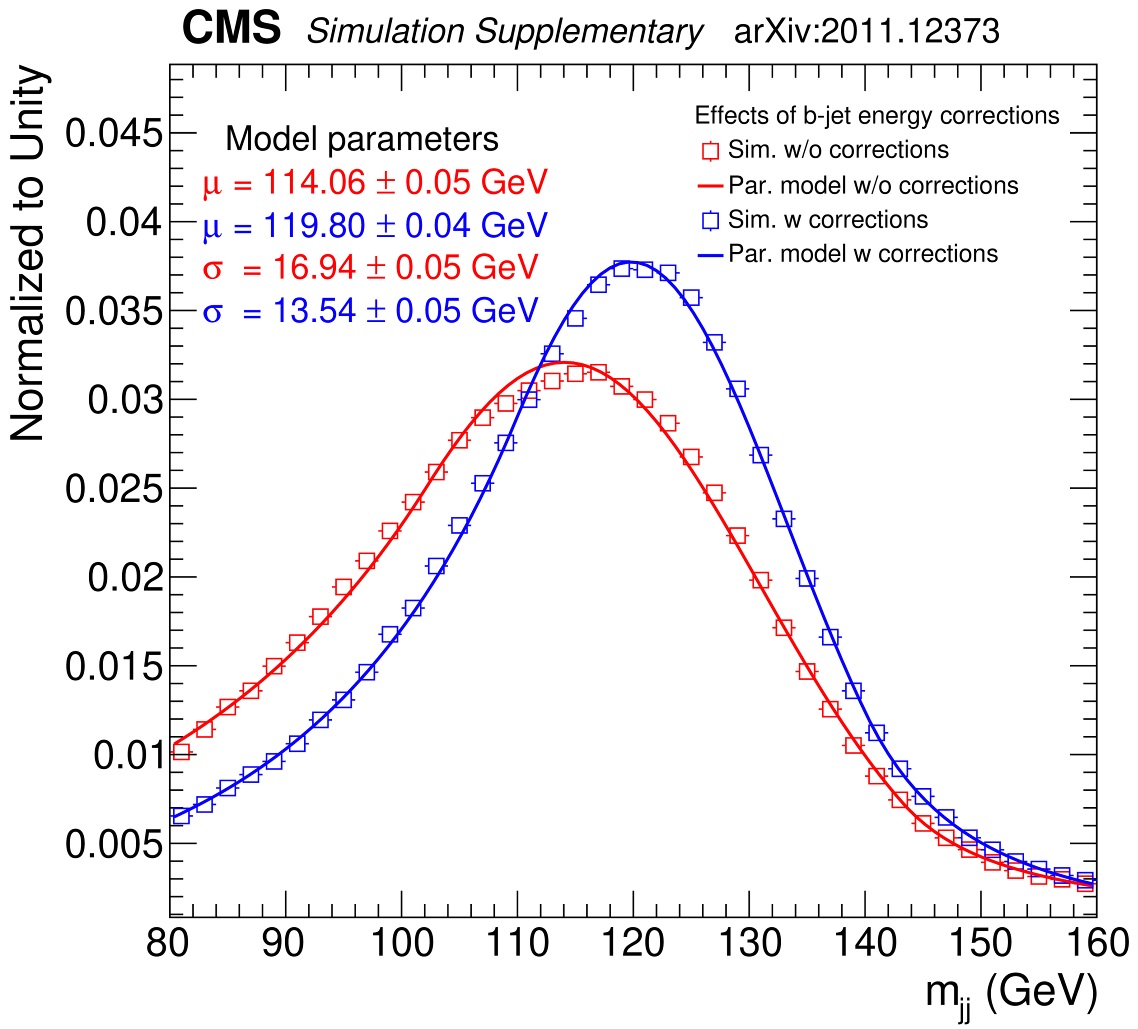


VHH production allows separation of WHH and ZHH

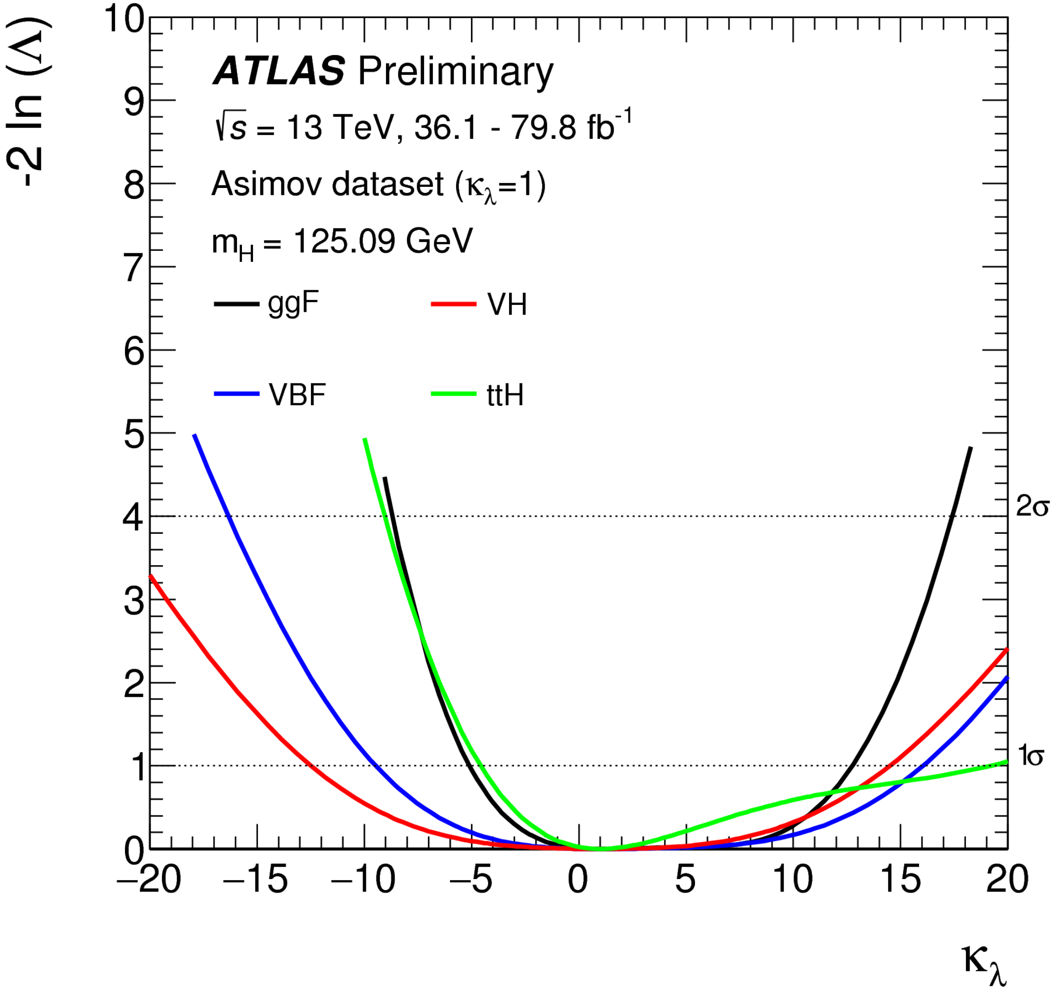
- Three leptonic channels (0L, 1L, 2L), one for each leptonic decay mode of the W and Z bosons
- HH in the $b\bar{b}b\bar{b}$ final state

- The observed (expected) limits constraint κ_{2V} within -8.6 < κ_{2V} < 10 at 95% CL (ATLAS) and -12.2 < κ_{2V} < 13.5 at 95% CL (CMS)

Impact of the regression for b-jets



Single Higgs constraints



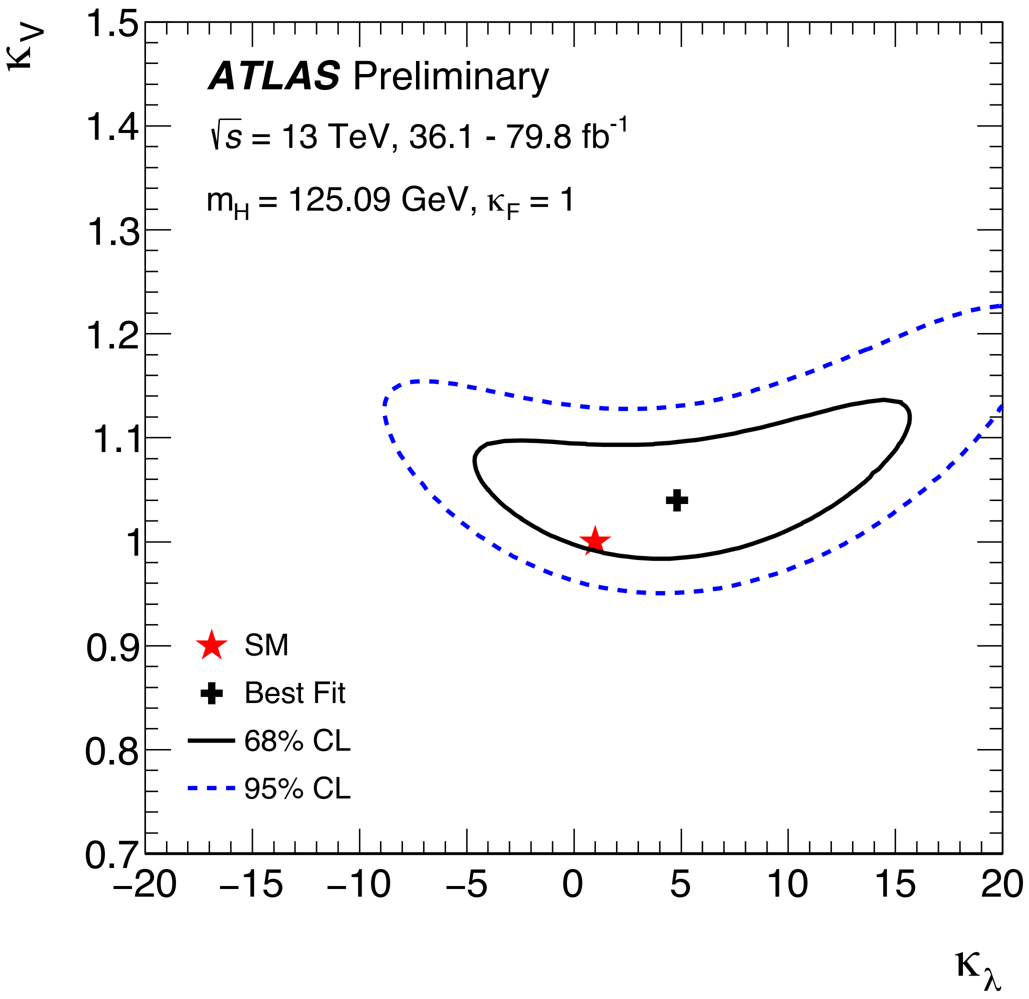
<u>First constraints</u> derived from 13 TeV single H measurements with 36-80/fb

$\kappa_\lambda = 4.0^{+4.3}_{-4.1}$

$\kappa_\lambda \in$ **[-3.2,11.9] @95%CL ($\kappa_F = \kappa_V$ =1)** [-6.2,14.4] exp.

ATLAS-Phys. Lett. B 843 (2023) 137745

Single Higgs constraints



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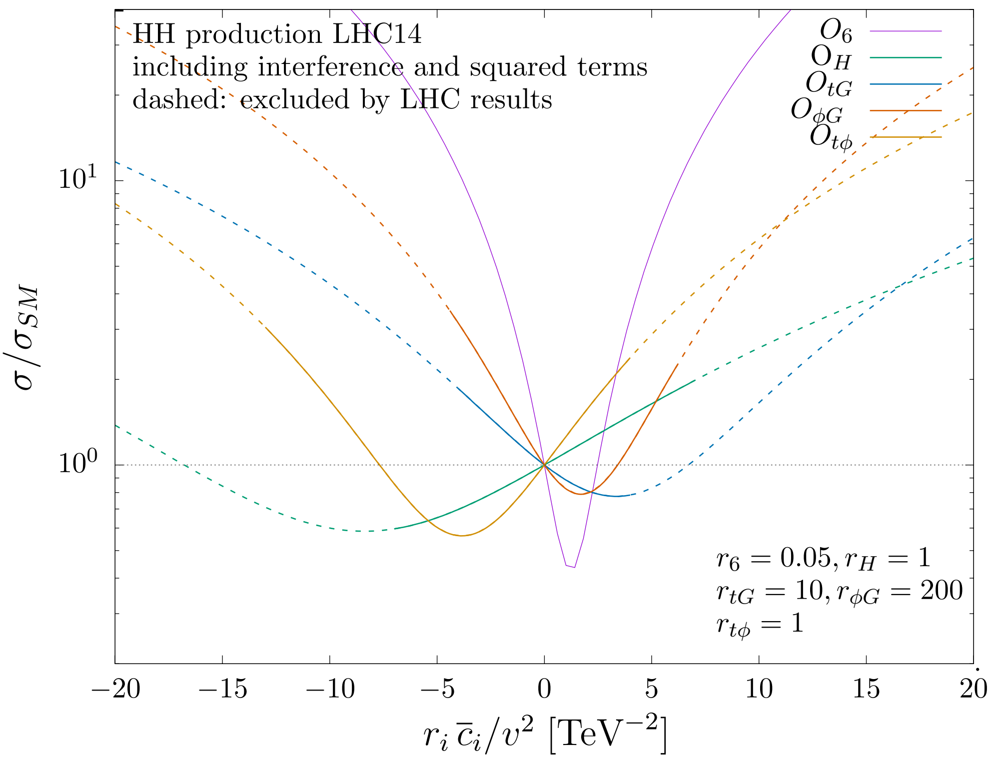
$gg \to HH$ in SMEFT



The LO $gg \to HH$ cross section depends rather strongly on **five coefficients**

- **Top quark** measurements would constrain the dipole operator $\mathcal{O}_{tG}$
- The top Yukawa operator $\mathcal{O}_u$ can be constrained by **ttH**
- $\mathcal{O}_{\phi G}$ can be determined by **ggF**
- $\mathcal{O}_H$ can be extracted as a uniform rescaling of all Higgs couplings
- $\mathcal{O}_6$ can lead to deviations of order 10 in the HH cross section

- A global SMEFT interpretation could constrain the $\mathcal{O}_6$ coefficient at levels of order 1 with HL-LHC dataset

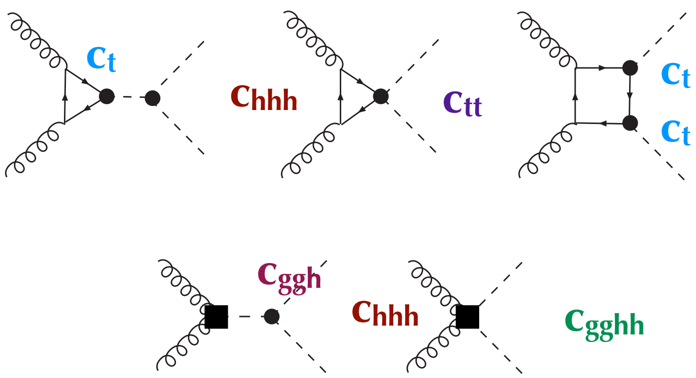
$$\kappa_\lambda = 1 + c_6 - \frac{3}{2} c_H + \cdots$$

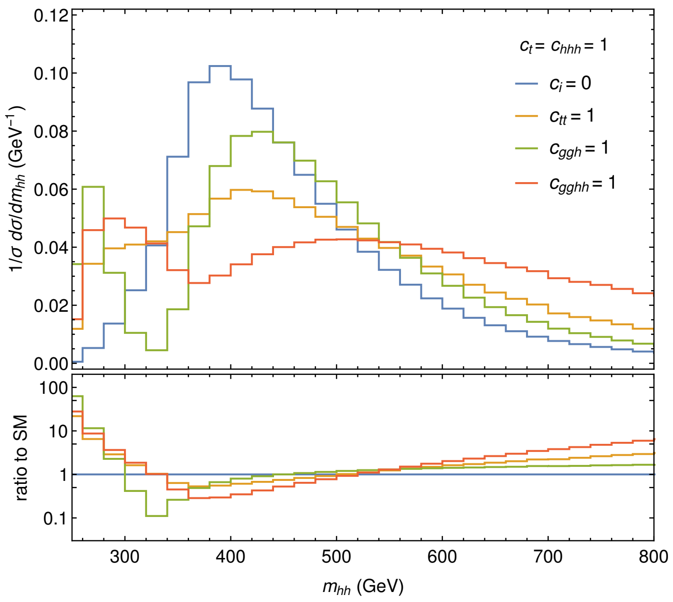
$gg \to HH$ in the HEFT

- HEFT singles out the anomalous Higgs couplings as the leading effects of new physics in the EW sector
  - At LO it provides a field-theory basis for the empirical κ-framework
- For $gg \to HH$ the relevant terms in the HEFT Lagrangian are

$$\Delta\mathscr{L}_\chi = -m_t\left(c_t\frac{h}{v}+c_{tt}\frac{h^2}{v^2}\right)\bar{t}\,t - c_{hhh}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v}+c_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}$$

- The SMEFT relations between c_t and c_{tt} , c_{gghh} and c_{ggh} are not present here
- c_{hhh} can be extracted only through a global analysis
  - c_{tt} and c_{gghh}, appear only in processes involving HH and we cannot use single Higgs data to fix them as in SMEFT
  - $t\bar{t}HH$ production can allow a determination of c_{tt} independently from c_{hhh}





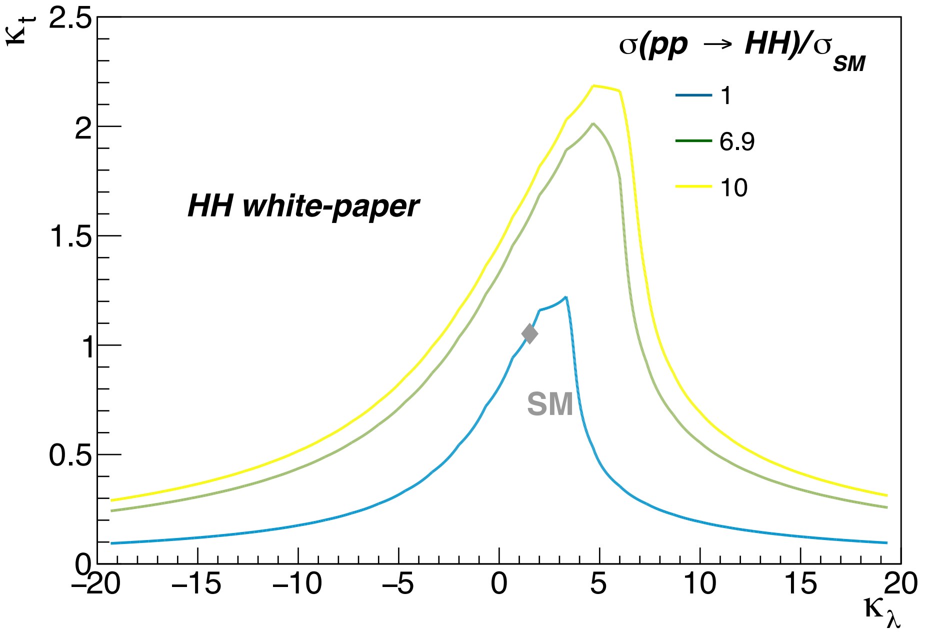
H vs HH in the HEFT

If $c_{tt} = c_{gghh} = c_{ggh} = 0$, $gg \to HH$ depends only from c_t and c_{hh}

$$\mathscr{A} = c_t^2 \mathscr{A}_1 + c_t\, c_{hhh} \mathscr{A}_2$$

$$\sigma_{gg\to HH}(c_t, c_{hhh}) \propto \left(c_t^4 \overline{|\mathscr{A}_1|^2} + 2c_t\, c_{hhh} \overline{\Re \mathscr{A}_1 \mathscr{A}_2^*} + c_{hhh}^2 \overline{|\mathscr{A}_2|^2} \right)$$

$$\propto c_t^4 \left[\overline{|\mathscr{A}_1|^2} + 2 \left(\frac{c_{hhh}}{c_t} \right) \overline{\Re \mathscr{A}_1 \mathscr{A}_2^*} + \left(\frac{c_{hhh}}{c_t} \right)^2 \overline{|\mathscr{A}_2|^2} \right]$$



It is impossible to extract c_{hhh} constraints from HH production withou

- c_t and c_{hhh} can be constrained also using single Higgs measurements.
- A combination of single H and HH measurements would provide a more model independent determination of c_{hhh}

Perspectives for HH at HL-LHC

Estimates of the sensitivity to HH at HL-LHC are based on:
- extrapolations from Run-2 analyses
- dedicated studies with smeared/parametric detector response, corresponding to pile-up of 200

A combined significance to the **SM HH process of 4σ** can be achieved with all systematic uncertainties

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0