Experimental Review of Electroweak and Higgs Physics

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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

content of today and tomorrow

Lecture 1: Electroweak physics

- electroweak precision tests:
  - precisions measurement with single Z and W bosons
    - LEP legacy, new LHC results: $\sin^2\theta^l_{\text{eff}}$, $\Gamma(Z \rightarrow \text{inv})$, M_W , Γ_W, $\mathcal{B}(W \rightarrow \tau\nu_\tau)$
  - global checks of internal consistency, aka 'global EW fits'
- multiboson production at high energies: TGC and QGC
  - diboson production, triboson production
    - vector-boson scattering (VBS), towards polarized VBS

Lecture 2: Higgs physics

- Higgs boson properties (mass, spin and parity, width)
- Higgs boson couplings
  - signal strength, differental cross sections, Simplified Template Cross Sections (STXS), CP violation in the Higgs sector
- Probing the Higgs potential

content of today and tomorrow

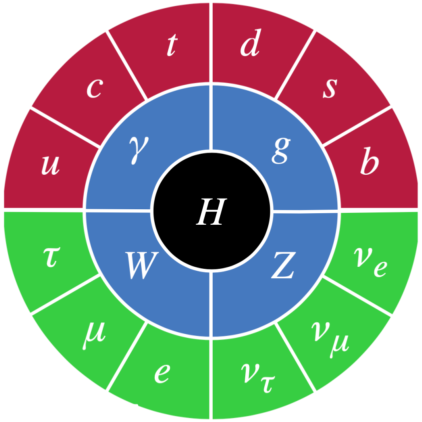
Personal selection from huge wealth of ATLAS and CMS Higgs physics results
Usually very similar results by both experiments, and much more than I can cover

You can find all Higgs physics results at the ATLAS and CMS public pages

The Higgs boson: a special particle

Higgs boson plays a special role in SM: emerges from mechanism that generates the masses of the fundamental particles

- Only scalar particle (spin 0, CP even)
- Couples in unique way to other particles:
  - to bosons ∝ m_V^2
  - to fermions ∝ m_f

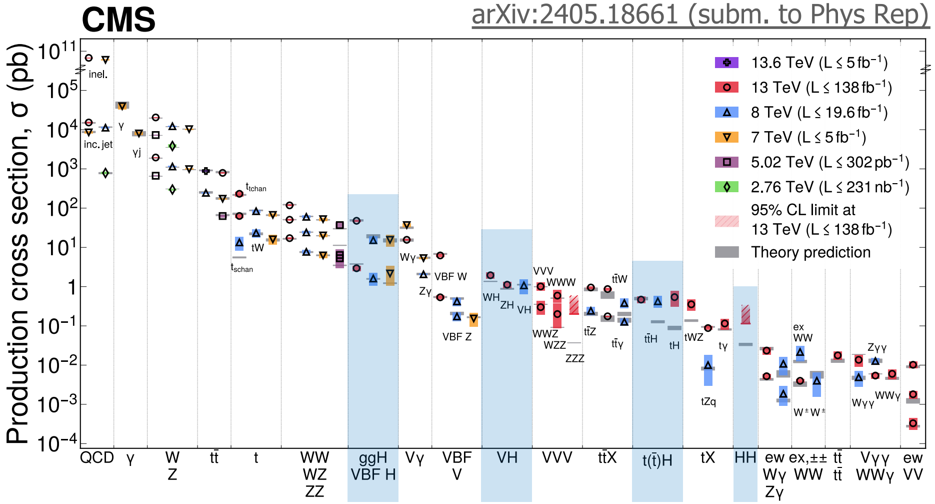


Precise prediction of all Higgs boson properties and interactions
Only free parameter is Higgs boson mass

Higgs boson excellent probe of Higgs mechanism + window to new physics

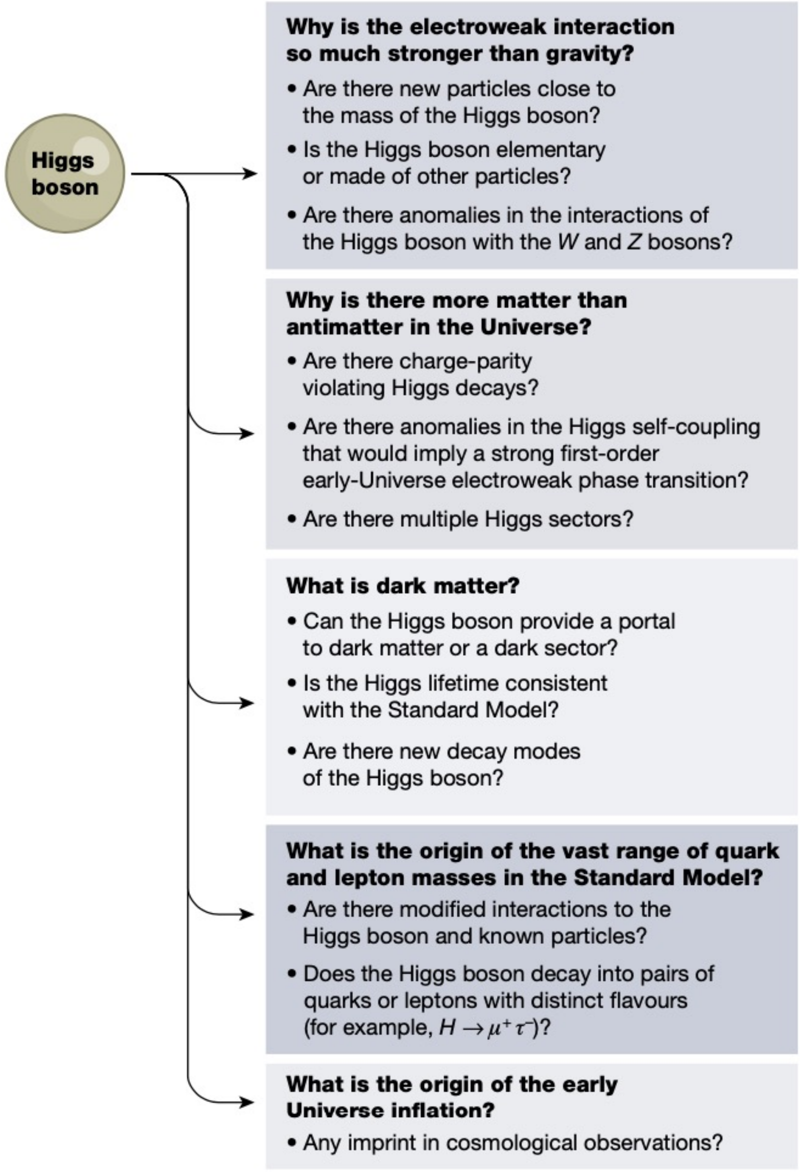
„Experimental history“:

- Indirect constraints on m_H from EWK fits
- Direct searches at LEP and Tevatron
- Discovery at the LHC in 2012
- Since then: measure everything we can!



arXiv:2405.18661 (subm. to Phys Rep)

The Higgs boson: a special particle



Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs boson with the *W* and *Z* bosons?

Why is there more matter than antimatter in the Universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-Universe electroweak phase transition?
- Are there multiple Higgs sectors?

What is dark matter?

- Can the Higgs boson provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs boson?

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs boson decay into pairs of quarks or leptons with distinct flavours (for example, $H \to \mu^+\tau^-$)?

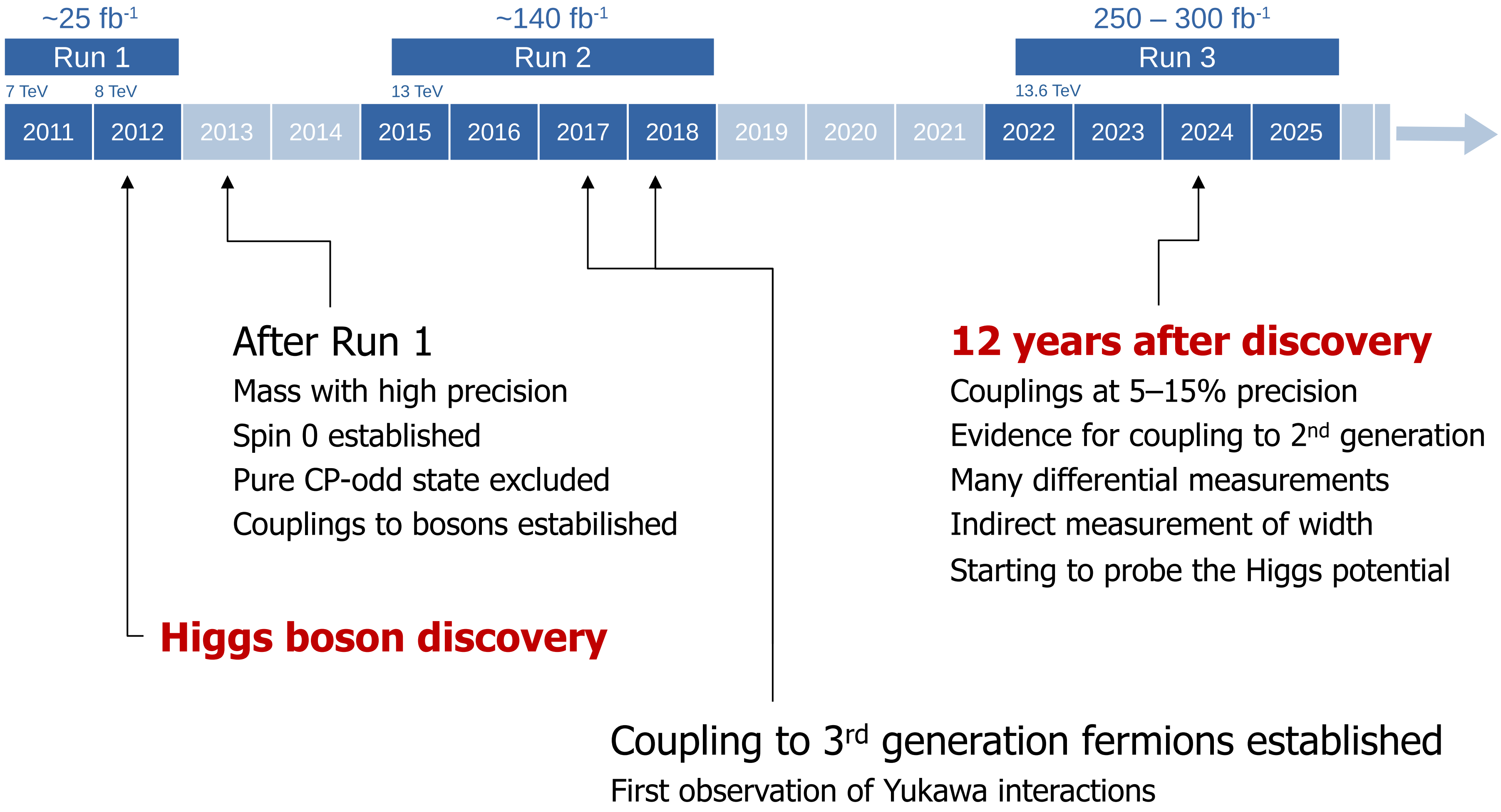
What is the origin of the early Universe inflation?

- Any imprint in cosmological observations?

Higgs boson is connected to major open questions in particle physics and cosmology

Nature 607 (2022) 41

The Higgs boson at the LHC



~25 fb^{-1}

Run 1

7 TeV

8 TeV

~140 fb^{-1}

Run 2

13 TeV

250 – 300 fb^{-1}

Run 3

13.6 TeV

2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025

Higgs boson discovery

After Run 1

Mass with high precision

Spin 0 established

Pure CP-odd state excluded

Couplings to bosons estabilished

Coupling to 3rd generation fermions established

First observation of Yukawa interactions

12 years after discovery

Couplings at 5–15% precision

Evidence for coupling to 2nd generation

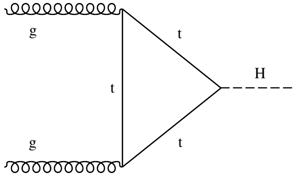
Many differential measurements

Indirect measurement of width

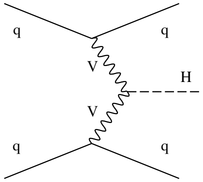
Starting to probe the Higgs potential

Higgs boson production at the LHC

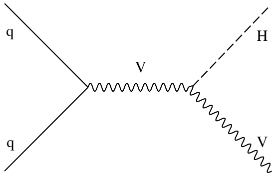
Gluon-gluon fusion (ggF): 48.6 pb (87%)



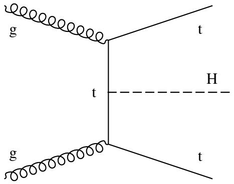
Vector boson fusion (VBF): 3.8 pb (7%)

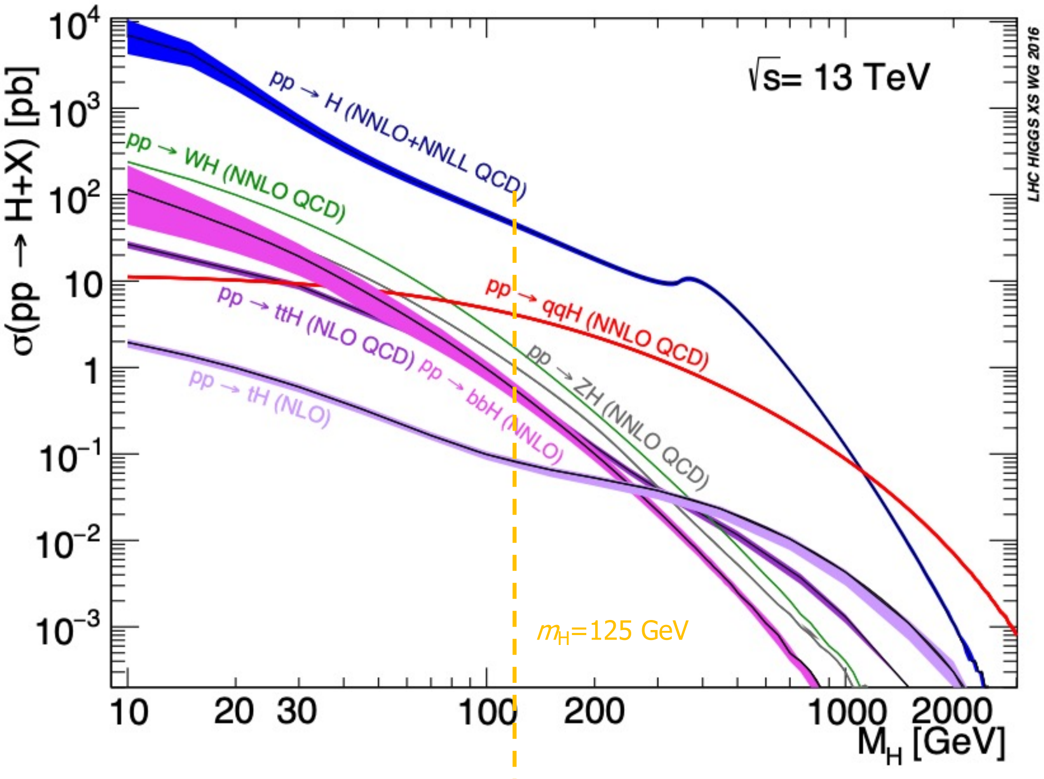


W/Z associated production (VH): 2.3 pb (4%)



t/b associated production (ttH/bbH): 0.5 pb (1%)





LHC Run 2 conditions:

- ~1 Higgs boson per 10^9 pp collisions
- ~1 Higgs boson per second

Cross sections for m_H=125 GeV at 13 TeV LHC Higgs Working Group

Higgs boson production at the LHC

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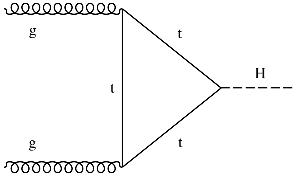

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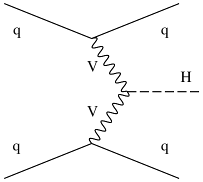

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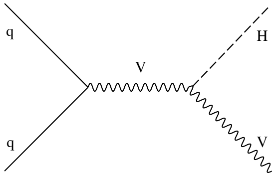

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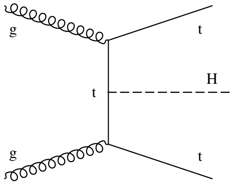
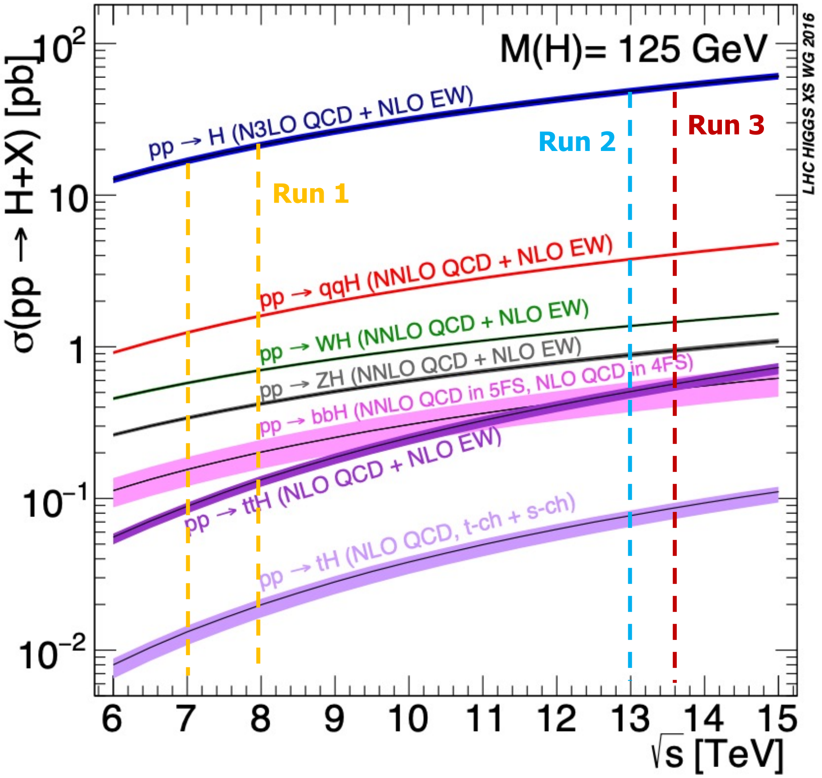




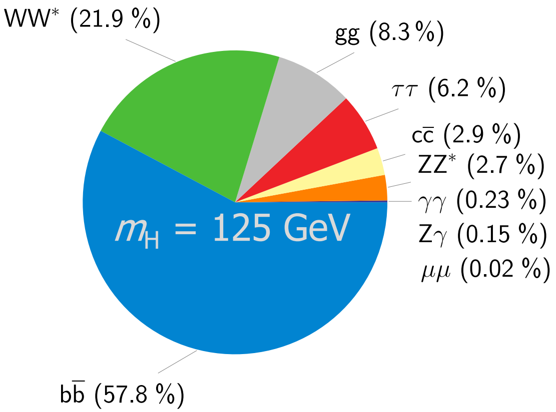
Higgs bosons produced per experiment:

- discovery (part of Run 1): ~200k
- Aug 2024 (Run 1+2+partly 3): ~14M

Cross sections for m_H=125 GeV at 13 TeV LHC Higgs Working Group

Experimental access to the Higgs boson

At 125 GeV: many open channels — experimentally very lucky!

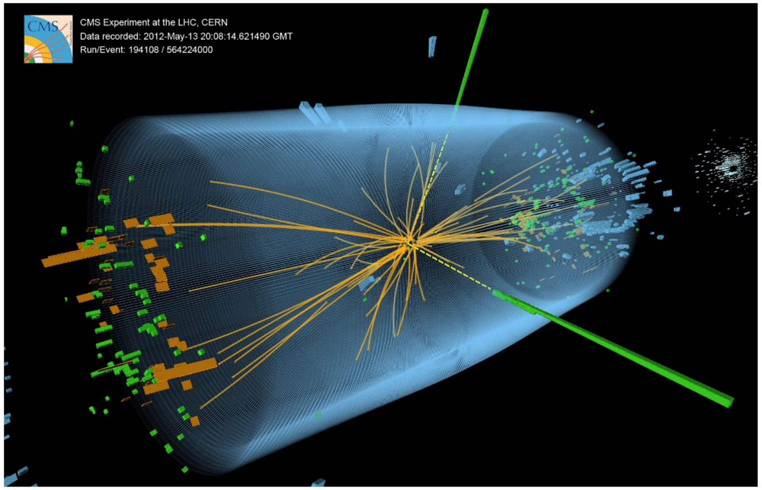


Different experimental challenges, not all channels accessible

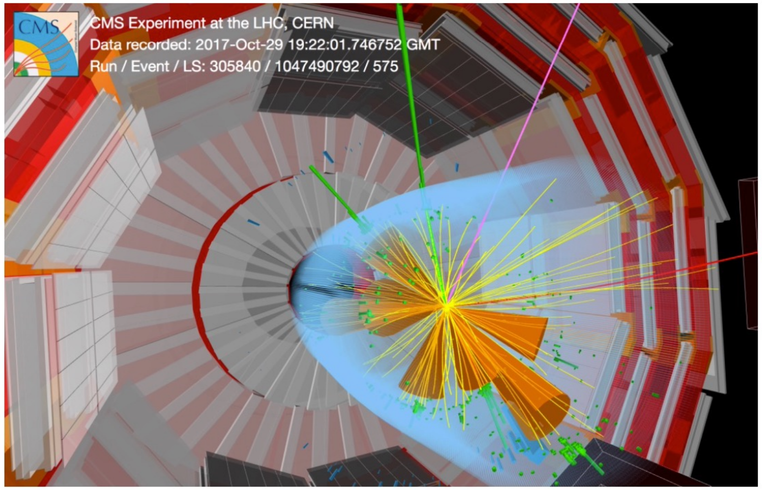
- Sensitivity depends on branching ratio, selection efficiency and resolution of final-state objects, background composition
- All detector components needed in Higgs boson analysis

Continuous progress in analysis methods, machine-learning (ML) techniques have become a key tool

$H \rightarrow \gamma\gamma$ candidate



ttH with $H \rightarrow bb$ candidate



What we want to know about the Higgs boson

Mass

In the SM: if mass known, all interactions predicted

Other properties

Spin/parity, width

J. Cham

Couplings to bosons and fermions

Probe Higgs mechanism (boson/fermion masses)

Self coupling

Probe shape of Higgs potential

High-resolution channels $H \rightarrow ZZ^{(*)} \rightarrow 4l$ / $H \rightarrow \gamma\gamma$

ATLAS: Eur. Phys. J. C 80 (2020) 957 JHEP 07 (2023) 088
CMS: Eur. Phys. J. C 81 (2021) 488 JHEP 07 (2021) 027

4l/$\gamma\gamma$ channels have driven discovery and subsequent measurements of the Higgs boson

Tiny rates but very clean experimental signatures

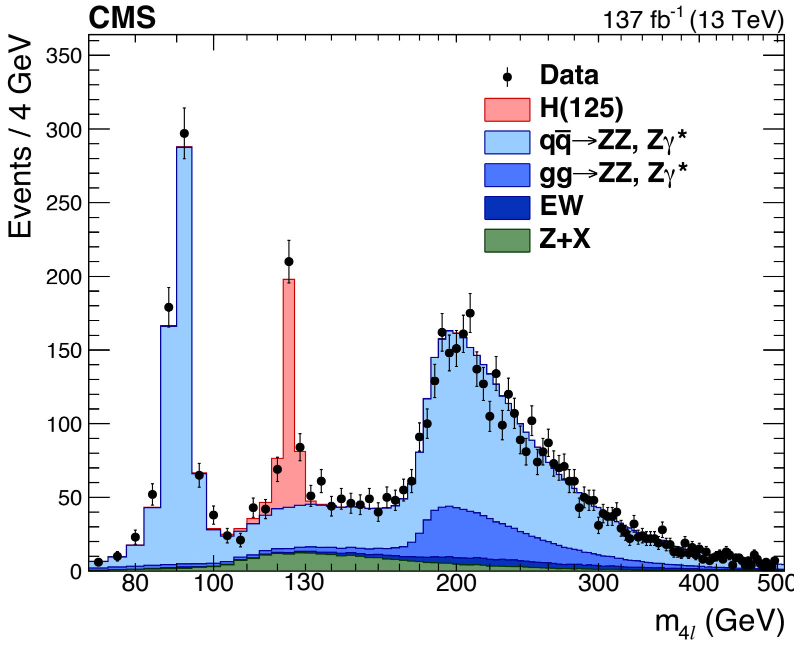
- 4 leptons (4μ/4e/2μ2e) / 2 photons, isolated + high p_T
- e, μ, γ measured with excellent resolution O(1%)

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (tiny signal rate)
- BR = 0.01%, small background

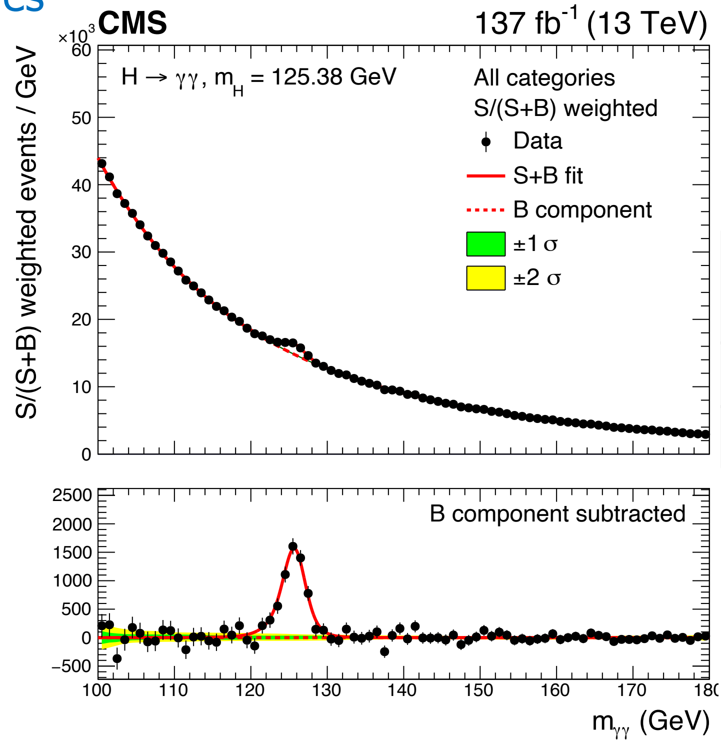
$H \rightarrow \gamma\gamma$ (low signal purity)
- BR = 0.23%, large background

H boson can be fully reconstructed from final-state particles

Signal extracted as peak in invariant 4l/$\gamma\gamma$ mass spectrum



Eur. Phys. J. C 81 (2021) 488



JHEP 07 (2021) 027

High-resolution channels $H \rightarrow ZZ^{(*)} \rightarrow 4l$ / $H \rightarrow \gamma\gamma$

ATLAS: Eur. Phys. J. C 80 (2020) 957 JHEP 07 (2023) 088
CMS: Eur. Phys. J. C 81 (2021) 488 JHEP 07 (2021) 027

In practice, all analyses very complex

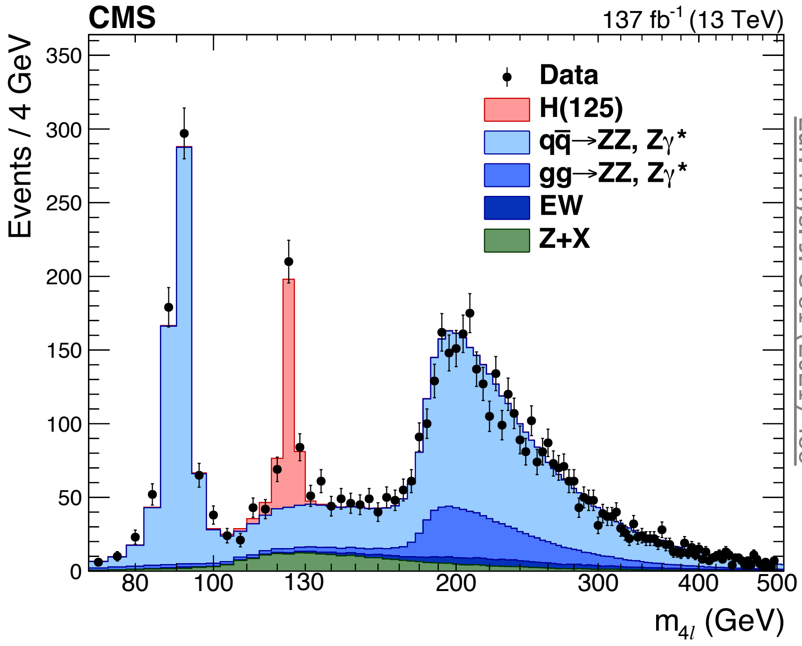
- Sophisticated object identification and calibration
- Many categories targeting signal and background components to enhance signal significance and provide background estimates
- 4l: kinematic discriminants *D* based on event probability from matrix element calculations, separating different signal or background processes, 2D fits in (D, m_{4l}) space
- $\gamma\gamma$: BDT-based photon ID and event selection, fit to $m_{\gamma\gamma}$ distribution to extract signal and determine background

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (tiny signal rate)

- BR = 0.01%, small background

$H \rightarrow \gamma\gamma$ (low signal purity)

- BR = 0.23%, large background



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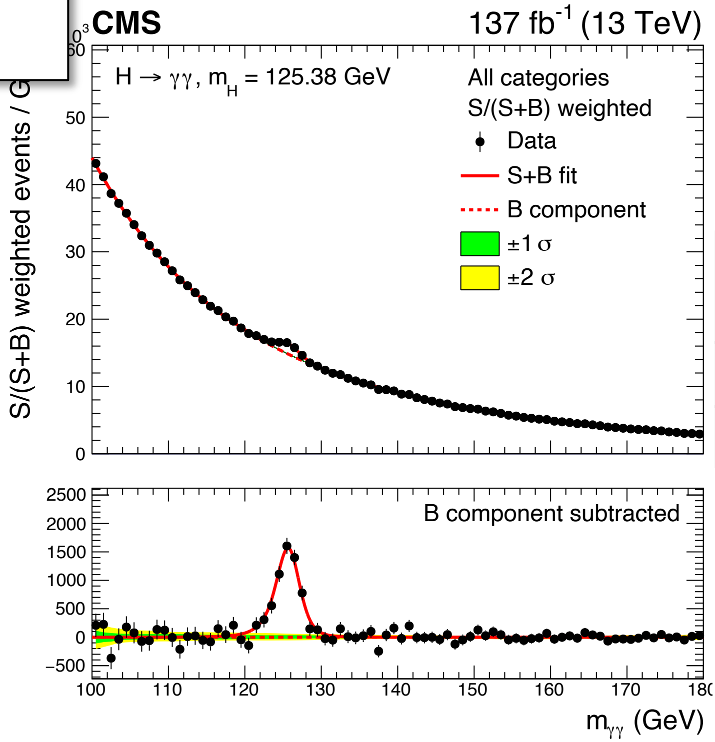


JHEP 07 (2021) 027

Properties

Higgs boson mass

ATLAS: Phys. Rev. Lett. 131 (2023) 251802
CMS: CMS-PAS-HIG-21-019

Reminder: m_H only free parameter of SM Higgs sector

(Weak) indirect constraints from combined EWK fits (100+/-25 GeV) arXiv:2211.07665

Direct measurements in high-resolution channels $H \rightarrow ZZ^{(*)} \rightarrow 4l$, $H \rightarrow \gamma\gamma$

Measurement precision at 0.1% level

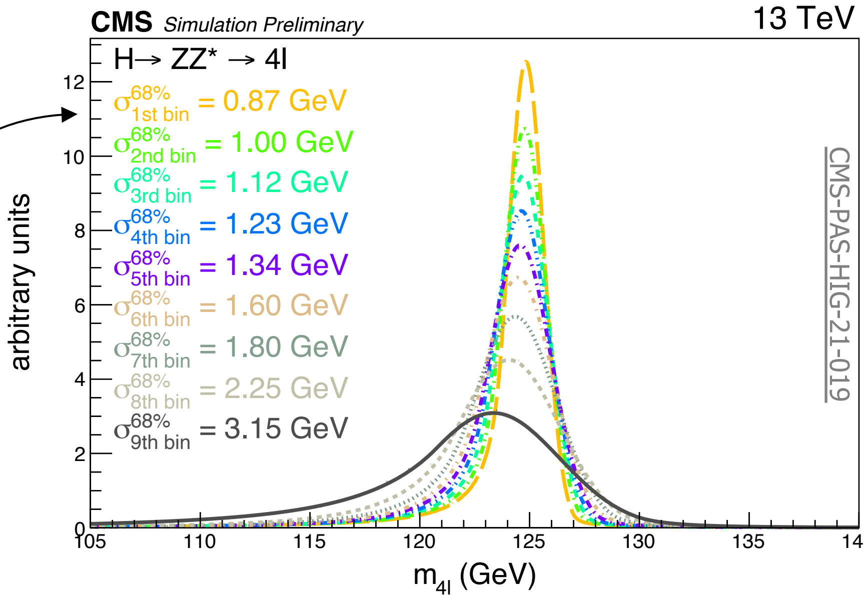
- One of the most precisely known SM parameters
- Already high precision with early Run 1 results (discovery)

Challenge: control of lepton/photon momentum scale with very high precision

- Particular effort in detector+object calibration

Analysis strategy e.g. $H \rightarrow 4l$

- Events categorised by mass resolution
  - Event-by-event estimate from uncertainties of lepton reconstruction (track fit + ECAL meas.)
- 2D fit of m_{4l} and kinematic discriminants from matrix element calculations



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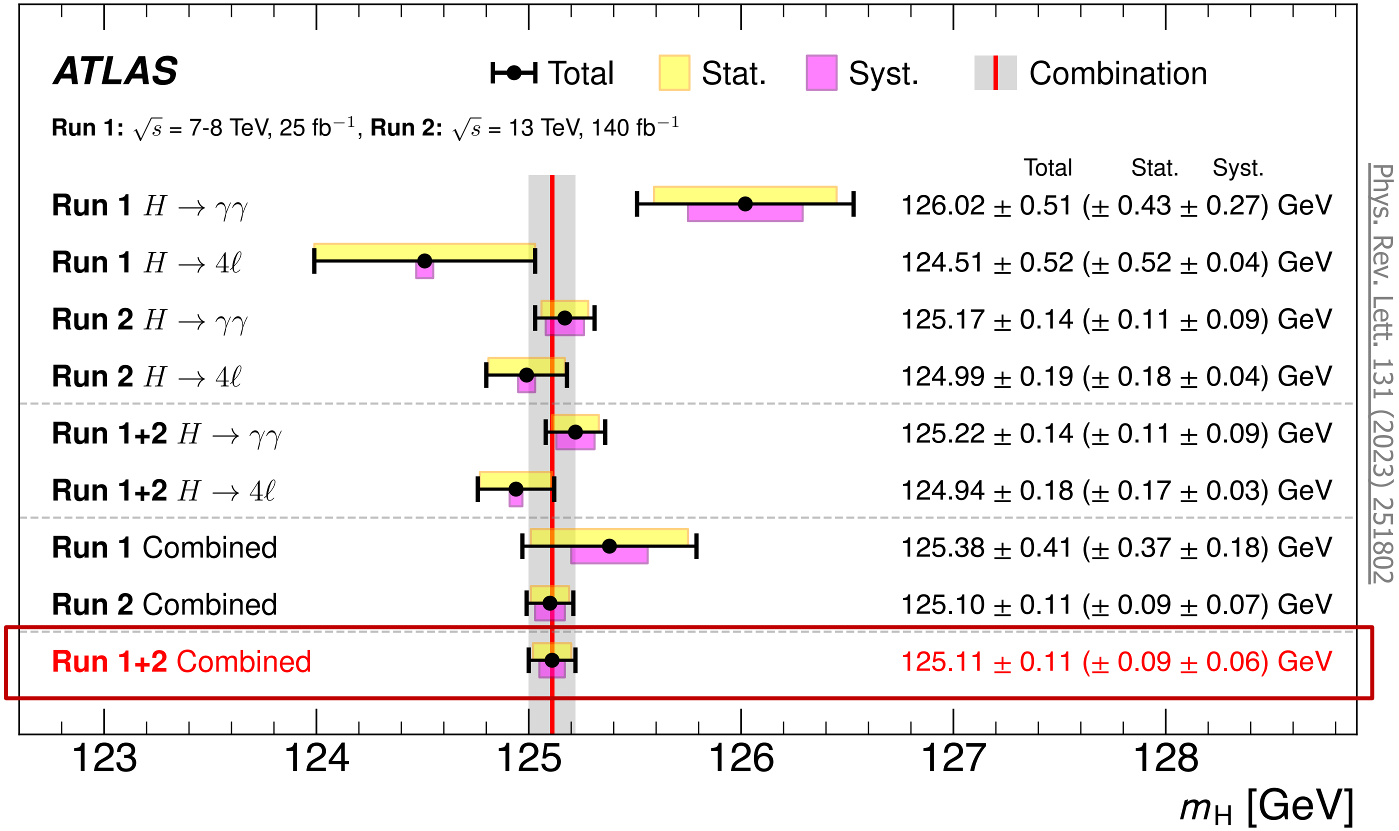


Phys. Rev. Lett. 131 (2023) 251802

Combination of H → 4l and H → γγ from Run 1+2: 0.09% relative precision

Statistical uncertainties still larger than systematic (dominated by γ/l energy scale uncertainty)

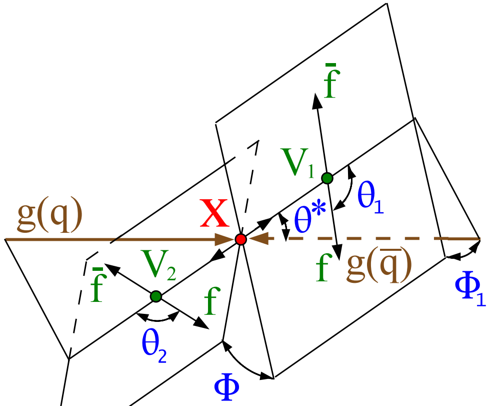
Phys. Rev. D 86 (2012) 095031

Higgs boson spin and parity

Determination of spin and parity one of the first ”completed” tasks, already with Run 1 data

Experimental access:

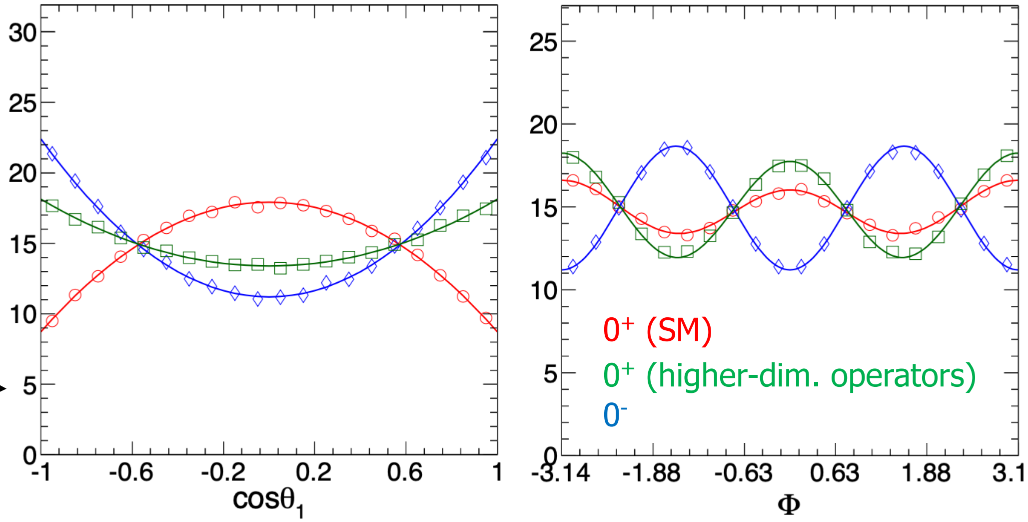
- **Spin** can be determined from angular distributions of Higgs boson decay products
  - Done in $H \rightarrow ZZ^{(*)} \rightarrow 4l$, $H \rightarrow \gamma\gamma$, $H \rightarrow WW$
  - NB: spin 1 is excluded since $H \rightarrow \gamma\gamma$ exists (Landau—Yang theorem)
- Different **parity** creates different spin correlations in Higgs boson decay products: look at angular distributions of their decay products
  - Done in $H \rightarrow ZZ^{(*)} \rightarrow 4l$, $H \rightarrow WW \rightarrow 2l2\nu$
  - e.g. $H \rightarrow 4l$: decay kinematics determined by m_{Z1}, m_{Z2}, 5 angles



Parametrisation of $H \rightarrow 4l$ decay angles (in the decaying particle’s rest frame)

θ_1 and Φ for different J^P hypotheses of H

Phys. Rev. D 86 (2012) 095031



Higgs boson spin and parity

ATLAS: Eur. Phys. J. C 75 (2015) 476
CMS: Phys. Rev. D 92 (2015) 012004

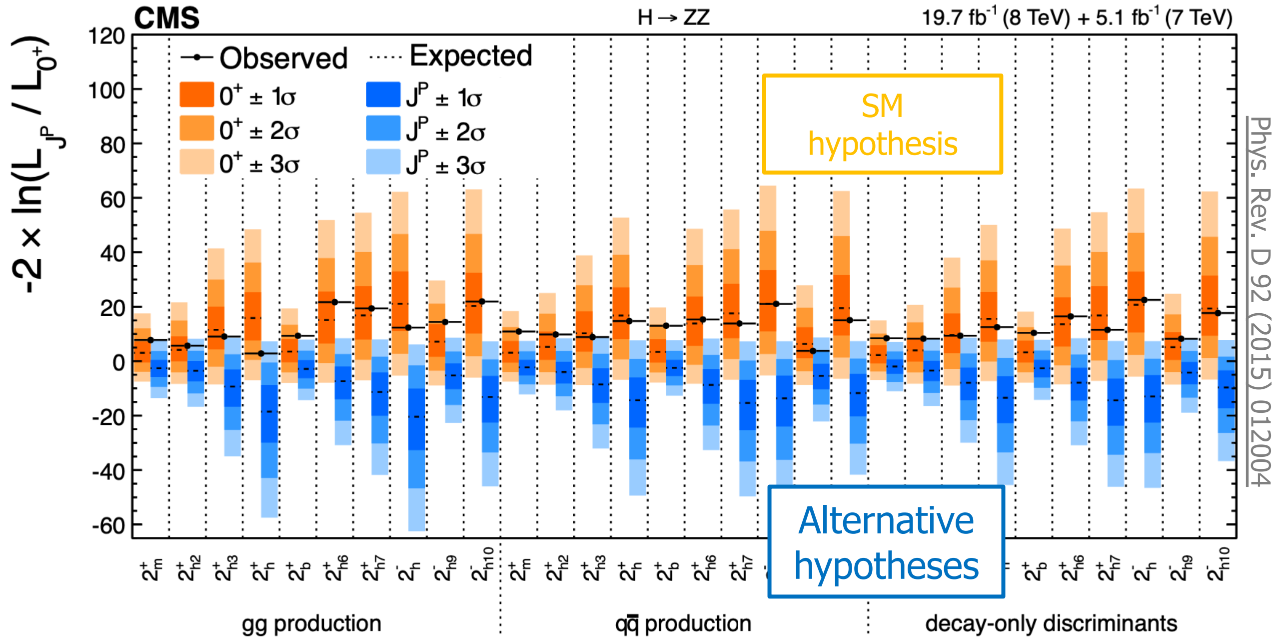
Approach: test alternative hypotheses against SM prediction $J^P = 0^+$

Kinematic discriminants defined from ratios of event probabilities $P(m_{Z1}, m_{Z2}, \Omega \mid m_{4l}, J^P)$ computed from matrix elements, for different J^P and process hypotheses ("Matrix element likelihood approach")

$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\mathrm{SM}}}{\mathcal{P}_{\mathrm{SM}} + \mathcal{P}_{J^P}}$$

- Can be approx. from reconstruction-level objects due to good resolution of final-state particles
- Multi-dimensional fit: add. discriminants of signal vs. background

Expected median of test statistic for SM and alternative J^P hypotheses

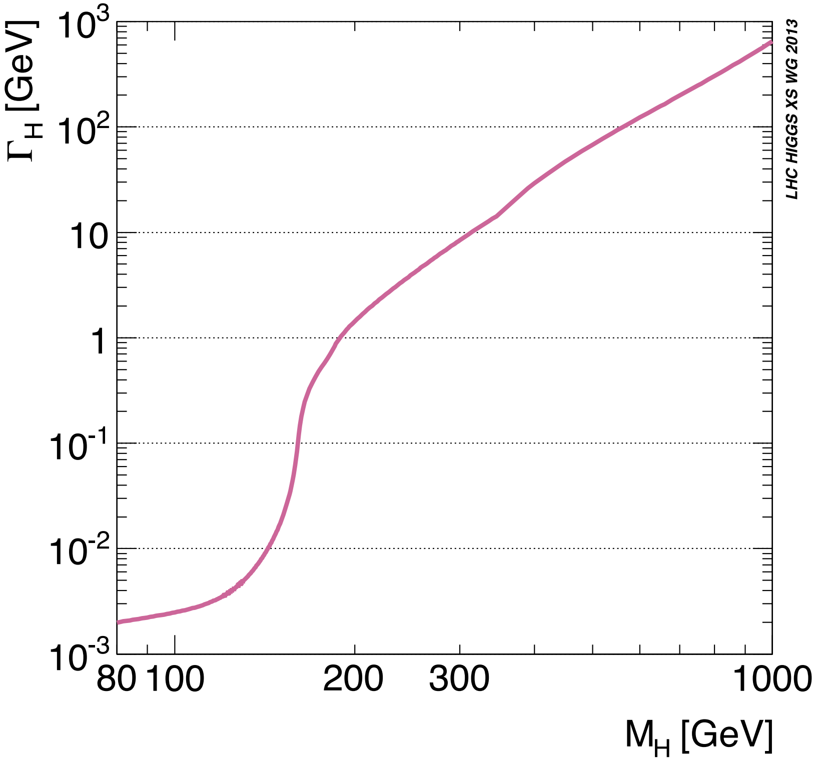


Data strongly favours $J^P = 0^+$ (SM hypothesis)
Pure states with different spin/parity values excluded

Higgs boson width

SM: small width $\Gamma_H = 4.1$ MeV
(NB: Z boson width 2.5 GeV)

- Decay to off-shell vector bosons (W/Z) or loop suppressed ($\gamma\gamma$)
- Small Yukawa couplings (small fermion masses)



Experimental resolution $m_{4l/\gamma\gamma}$~1–2 GeV:
Direct measurements by far not sensitive enough to reach SM value CMS-PAS-HIG-21-019 PRD 92 (2015) 072010

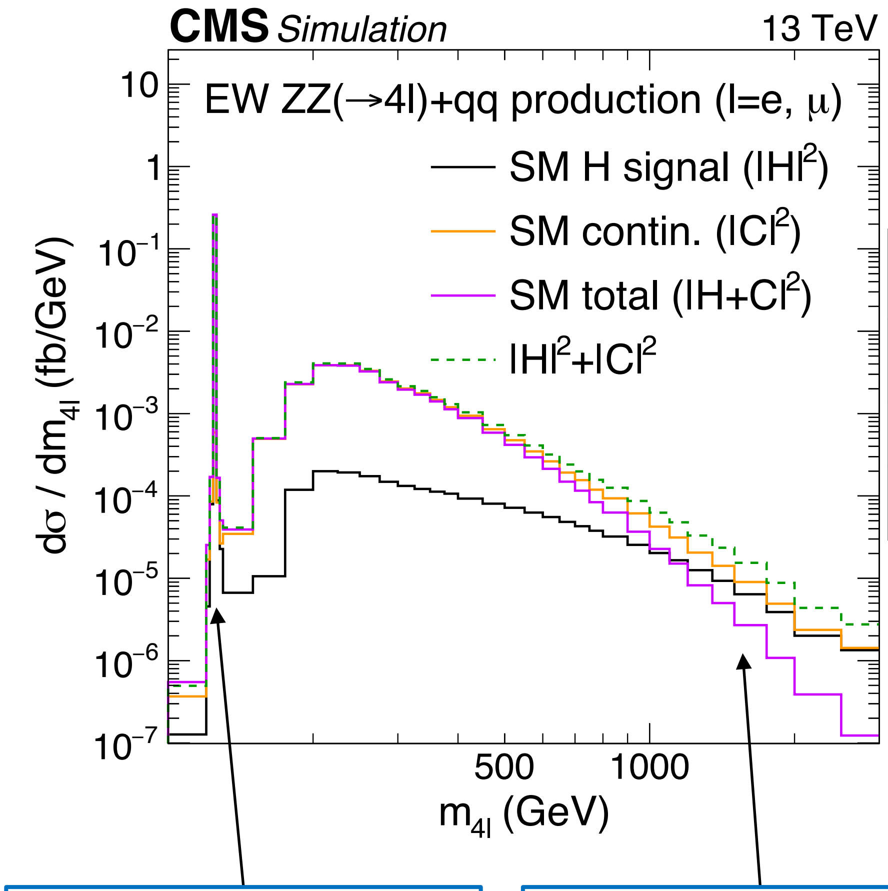
- Lineshape (4l): Γ_H <330 MeV at 95% CL
- Lifetime (4l): Γ_H >3.5x10^{-9} MeV at 95% CL

Indirect methods (model assumptions)

- Main measurements: ratio off-shell/on-shell Higgs boson production in 4l
  - Top processes with on-shell (ttH) and off-shell (4t) Higgs boson (Γ_H < 450 MeV) arXiv:2407.10631 (subm. to PLB)
- Shift of H → $\gamma\gamma$ due peak due to interference with background (~100 MeV) arXiv:1305.3854

Indirect measurement of Higgs boson width

ATLAS: Phys. Lett. B 846 (2023) 138223
CMS: CMS-PAS-HIG-21-019



Nat. Phys. 18 (2022) 1329

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggF}} g^2_{\text{HZZ}}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggF}} g^2_{\text{HZZ}}}{m^2_{ZZ}}$$

$$\boxed{\Gamma_H = \sigma\text{ (off-shell) / }\sigma\text{(on-shell)}}$$

Best sensitivity H → 4l channel:

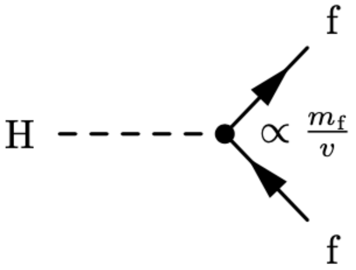
$$\Gamma_H = 2.9\,^{+1.9}_{-1.4}\text{ MeV}$$

- Assuming same couplings *g* on shell and off shell (model dependence!)
- Experimental complication: interference with continuum ZZ* production

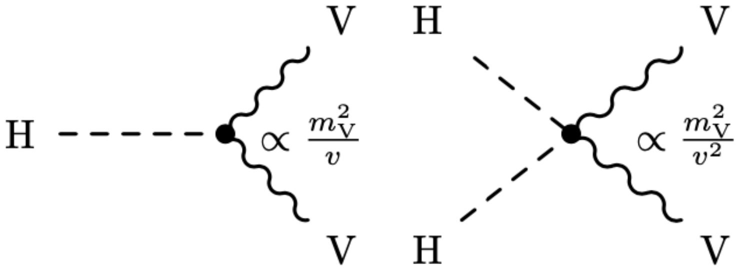
Couplings

Reminder: Higgs boson couplings in the SM

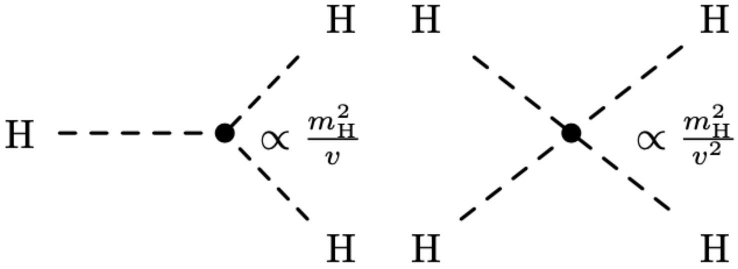
to fermions:



to massive gauge bosons $V = W^\pm, Z$:



self coupling:



Signal strength

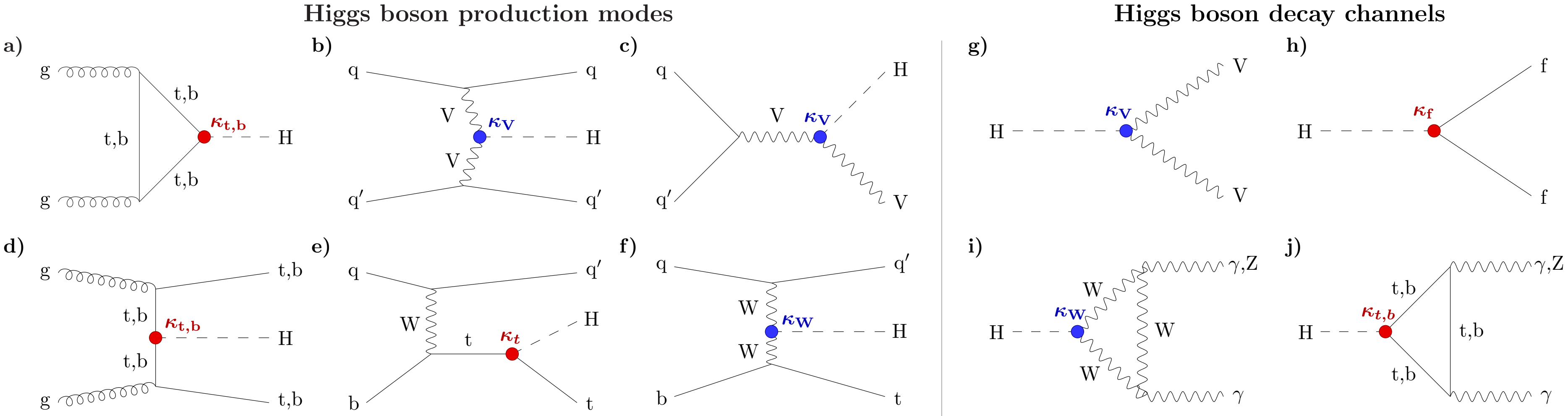
ATLAS: Nature 607 (2022) 52
CMS: Nature 607 (2022) 60

Basic input to coupling measurements: **signal strength σ · BR**

- Simplest check of SM compatibility
- Typically quantified by **signal-strength modifier μ**

$$\boxed{\mu(i \to \mathrm{H} \to f) = \frac{\sigma(i \to \mathrm{H})}{\sigma_{\mathrm{SM}}(i \to \mathrm{H})} \cdot \frac{\mathcal{B}(\mathrm{H} \to f)}{\mathcal{B}_{\mathrm{SM}}(\mathrm{H} \to f)} \equiv \mu_i \cdot \mu^f}$$

Narrow-width approx. (SM: Γ_H = 4.1 MeV)
→ production and decay factorise



Nature 607 (2022) 60

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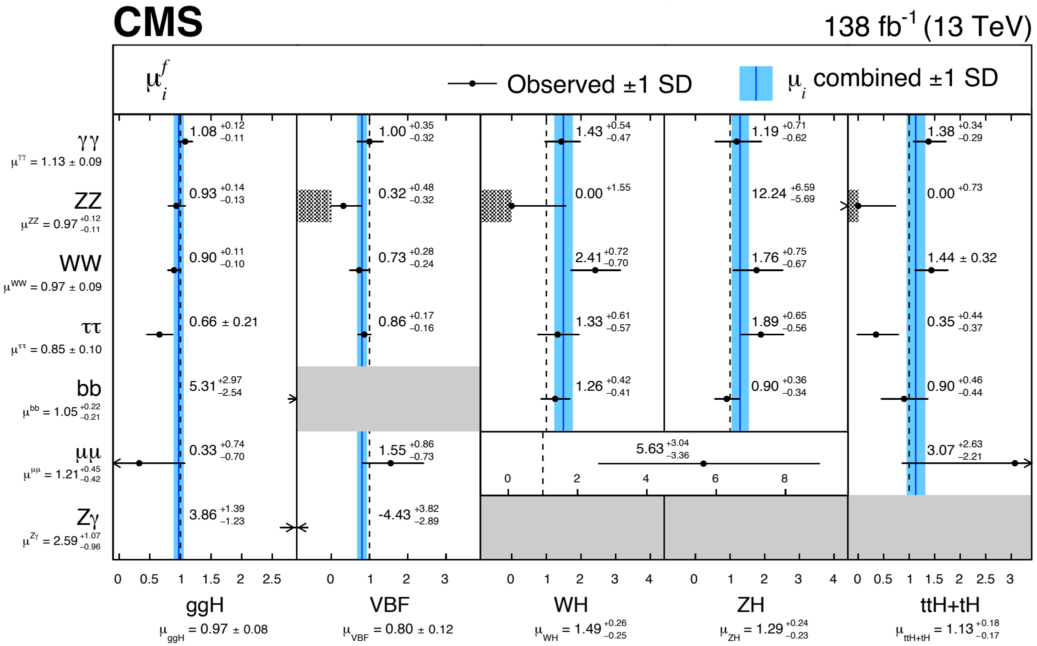
→ production and decay factorise

μ measured in various combinations of production and decay channels



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Narrow-width approx. (SM: Γ_{H} = 4.1 MeV)
→ production and decay factorise

μ measured in various combinations of production and decay channels

- Close to what we actually measure:

$$\textbf{N(events)} = \boxed{\sigma \cdot \mathrm{BR}} \cdot \boxed{\underset{\substack{\uparrow \\ \text{measurement}}}{\text{luminosity}} \cdot \underset{\substack{\uparrow \\ \text{simulation}}}{\text{acceptance}} \cdot \underset{\substack{\uparrow \\ \text{simulation or measurement}}}{\text{efficiency}}}$$

- In practice, analyses very complex
  - Many categories targeting different signal and background components to enhance signal significance and improve background modelling
  - Machine learning used at many levels, e.g. for categorisation and observables, regression

Example: H → ττ decays

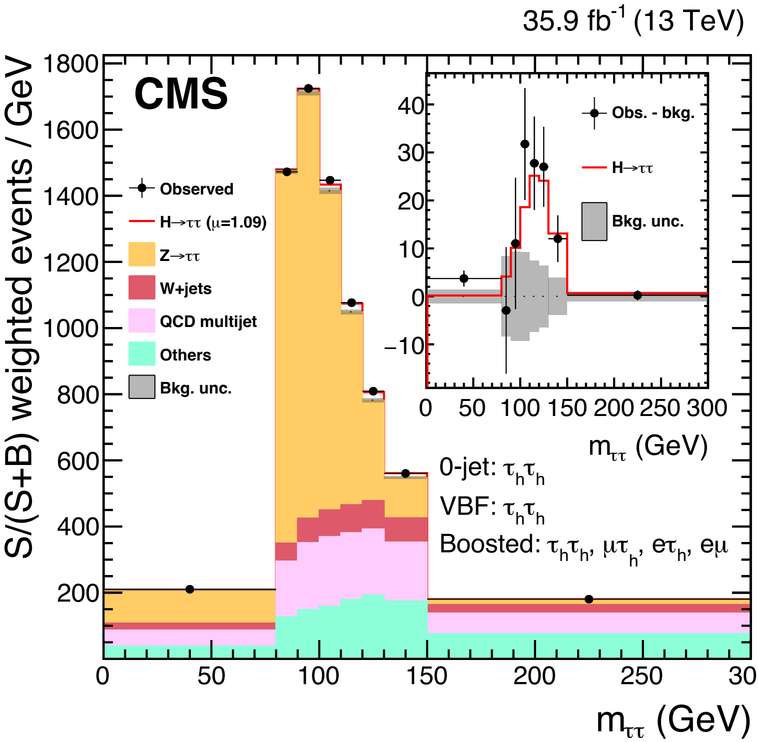
First observed (5σ sign.) Higgs-fermion decay (2017), independently by ATLAS and CMS

Observation (CMS): $\mu = 1.09 \pm 0.26$ (2016 data) Phys. Lett. B 779 (2018) 283

Status today (CMS): $\mu = 0.82 \pm 0.11$ (full Run 2) Eur. Phys. J. C 83 (2023) 562

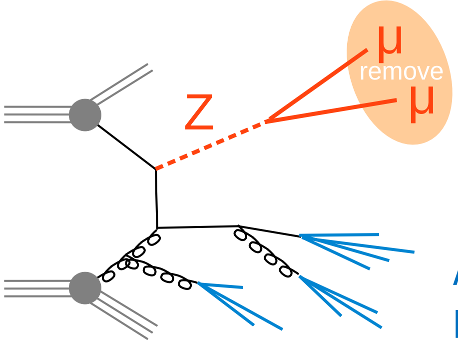
BR(H → ττ) = 6% but relatively clear to tag over QCD multijets background

- Various categories targeting H production modes, τ decay channels, and kinematic regions
- Dedicated τ reconstruction techniques:
  → **search in $m_{\tau\tau}$ or m_{vis} invariant mass**



Phys. Lett. B 779 (2018) 283

Major background Z → ττ estimated from data using τ **embedding technique**



Replace μ by simulated τ decay products

Advantage: difficult to model hadronic part of the event taken from data

Example: H → bb/cc decays

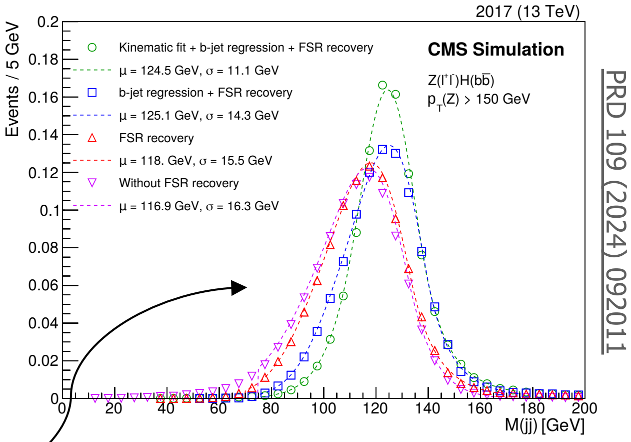
H → bb dominant decay channel but **huge QCD multijets background**

Approach: look at events with Higgs boson recoiling against other objects that can be tagged above the background

Most sensitive: VH with V → ll/lν/νν μ = 1.15±0.21 (CMS Run 2)
PRD 109 (2024) 092011

But also:

- ttH: additional tt system
- VBF: two forward jets
- ggF + hard ISR jet: dijet with boosted H

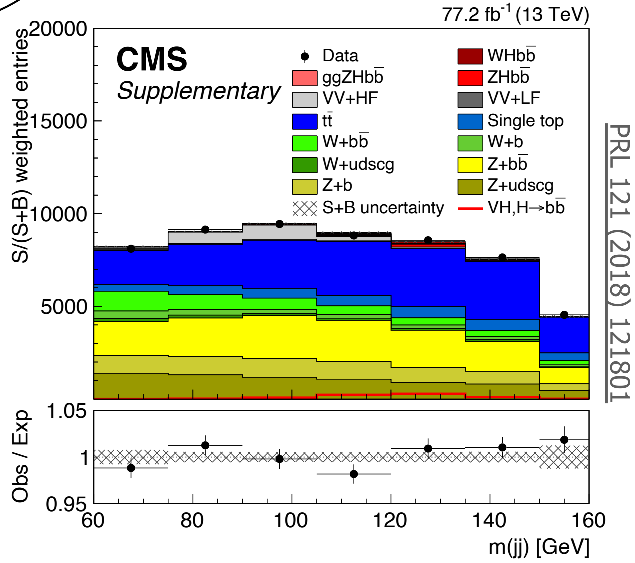


PRD 109 (2024) 092011

Dedicated calibration of b jet energy scale using constraint of decay topology H → bb, e.g. b jet regression

Ultimate sensitivity only by using **ML techniques**

- B tagging (rapid progress in techniques: BDTs → feed-forward NNs → Graph NNs, transformer NNs, …)
- Final observable: NN output



PRL 121 (2018) 121801

Similar approaches for H → cc

- A lot of development also in c tagging
- Exclusion of about μ > 10 at 95% CL PRL 131 (2023) 061801

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PRD 109 (2024) 092011

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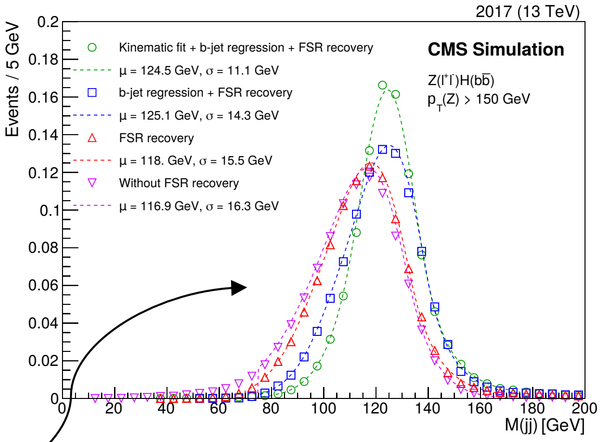

PRD 109 (2024) 092011

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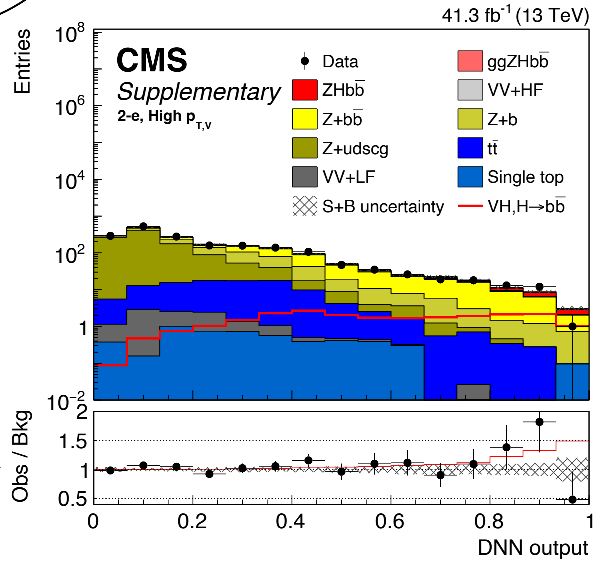


PRL 121 (2018) 121801

Similar approaches for H → cc

- A lot of development also in c tagging
- Exclusion of about $\mu > 10$ at 95% CL PRL 131 (2023) 061801

Example: top-Higgs coupling

Measurement in decay H → tt kinematically not possible

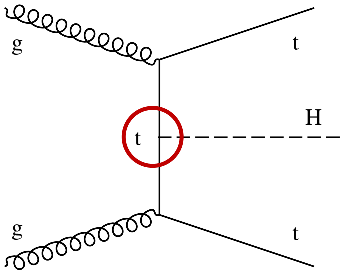
Indirect constraints from ggF production and H → $\gamma\gamma$ decays

*indirect constraints also from 4t and tt cross section

Eur. Phys. J. C 84 (2024) 156

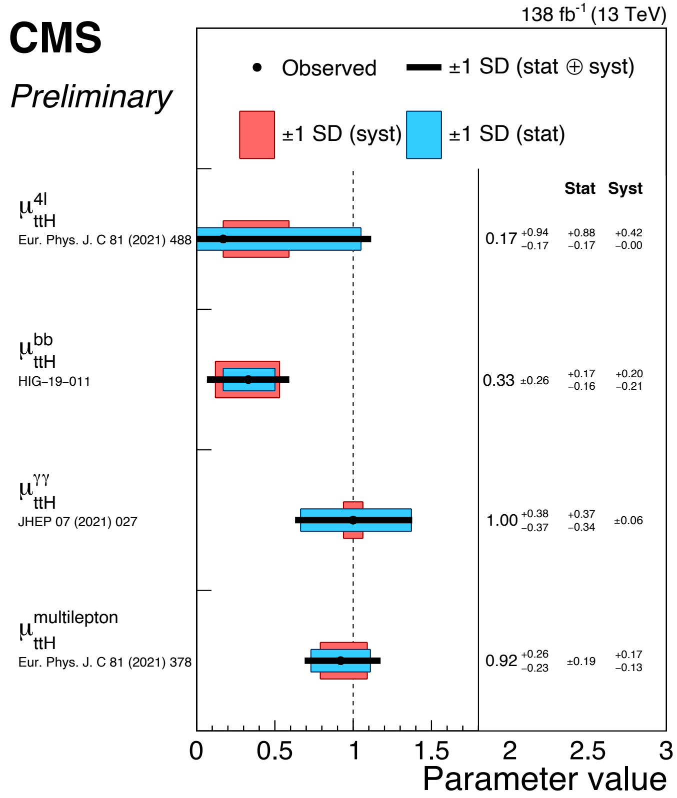
Phys. Lett. B 844 (2023) 138076

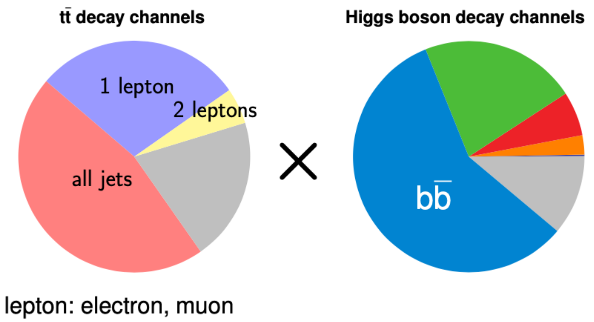
Phys. Rev. D 102 (2020) 092013



Direct measurement: **ttH production**

- Small cross section of 0.5 pb at 13 TeV (1% of total Higgs boson production rate)
- Multitude of possible final states with many objects
  - Different backgrounds and experimental challenges
    - E.g. ttbb and ttW backgrounds difficult to model, systematically limit bb and multilepton channels
  - Dedicated analysis techniques per channel
    - By now also constraints on CP structure of top-Higgs coupling





lepton: electron, muon

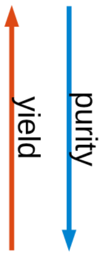
H → b$\bar{b}$

H → WW*/$\tau\tau$/ZZ*

“multi-lepton analysis”

H → $\gamma\gamma$

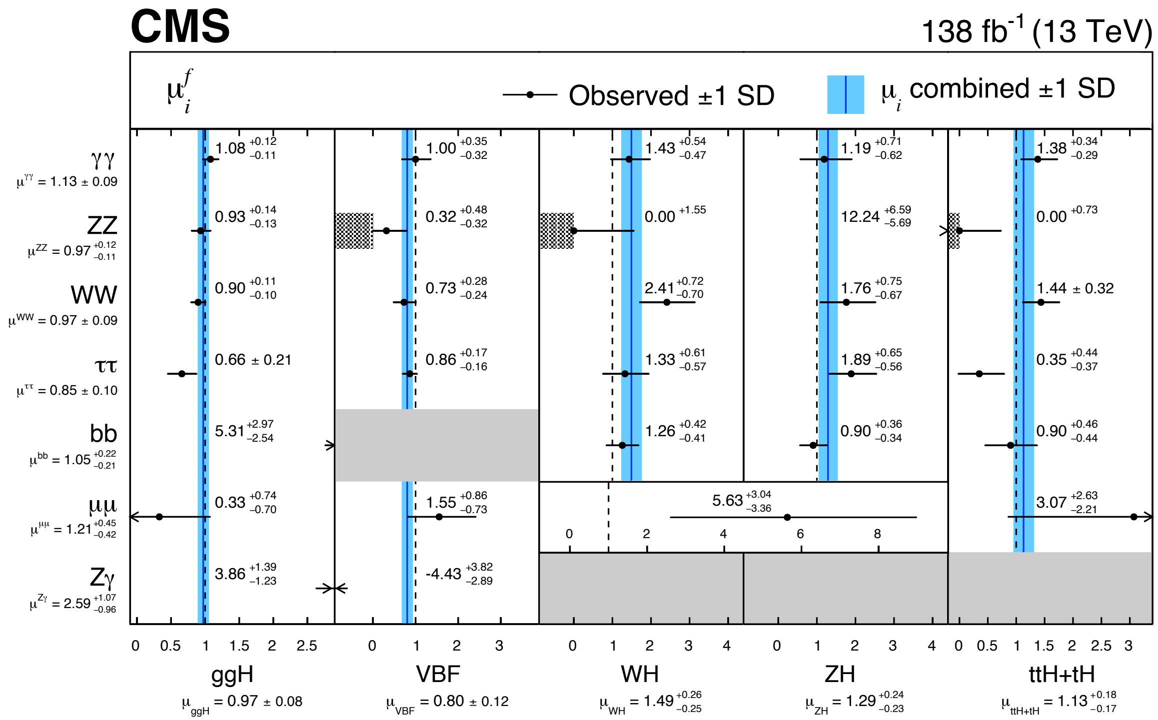
H → ZZ* → 4l



Signal strength measurements

ATLAS: Nature 607 (2022) 52
CMS: Nature 607 (2022) 60

Signal strength measured **in many different channels:** consistent with SM prediction



Nature 607 (2022) 60

Combined fit of μs, e.g. uncertainties are correlated

Problem: always measure production x decay, i.e. typically more than one coupling
→ **cannot unambigiously infer coupling from one measurement**

Solution: combine information from measurements in many channels to infer couplings

κ framework

Combine information from measurements in many channels to infer couplings

Idea: same coupling can be present in different production and decay channels

Coupling modifiers κ for each Higgs boson coupling vertex

⟶ allow coupling strength to vary relative to SM

$$\boxed{\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \qquad \kappa_f^2 = \frac{\Gamma^f}{\Gamma^f_{\mathrm{SM}}}}$$

JHEP 08 (2016) 045

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(gg\mathrm{F})$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{\mathrm{BSM}} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

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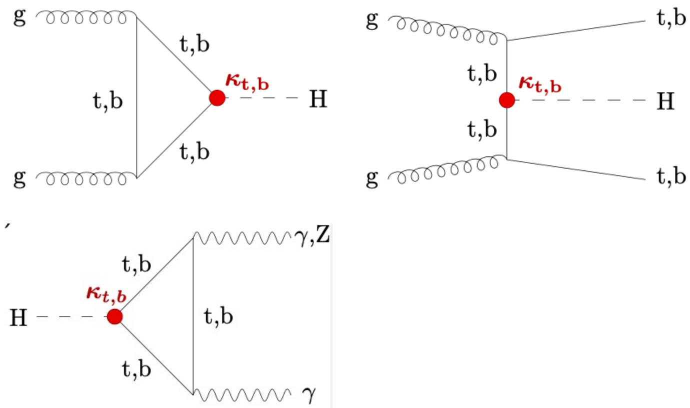
E.g. top-Higgs coupling:



JHEP 08 (2016) 045

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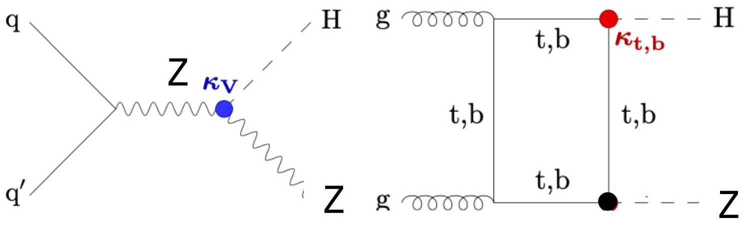
Interference: cross section depends on κ (not κ^2) → information on sign of coupling!



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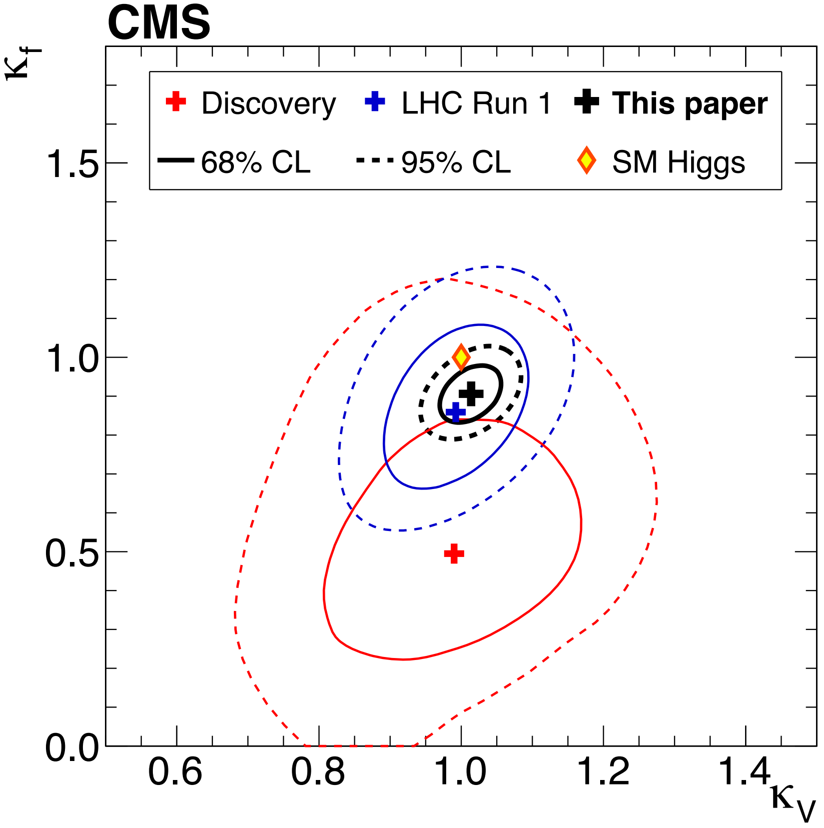
Testing different coupling hypotheses

ATLAS: Nature 607 (2022) 52
CMS: Nature 607 (2022) 60

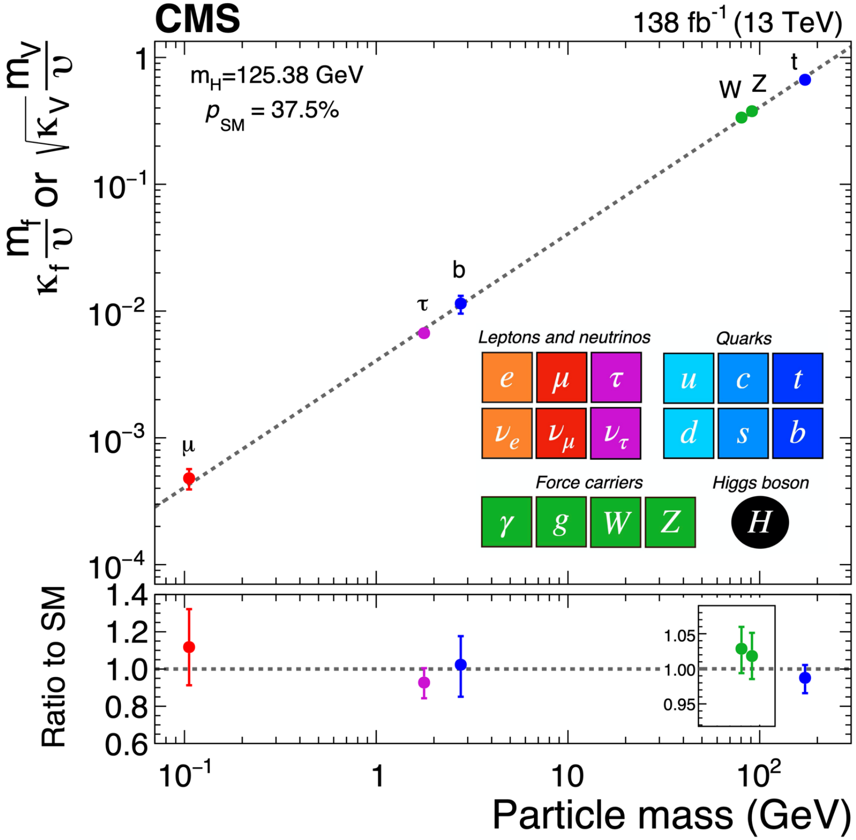
κ framework allows testing different hypotheses of Higgs boson coupling structure, e.g.

- ➢ assume same coupling modifier for fermions and bosons
- ➢ assume SM coupling structure, i.e. resolve loops

We find exactly the unique coupling behaviour of the SM Higgs boson!



Nature 607 (2022) 60



Nature 607 (2022) 60

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ATLAS: Nature 607 (2022) 52
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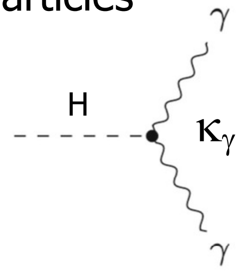
Allow contributions of BSM particles:

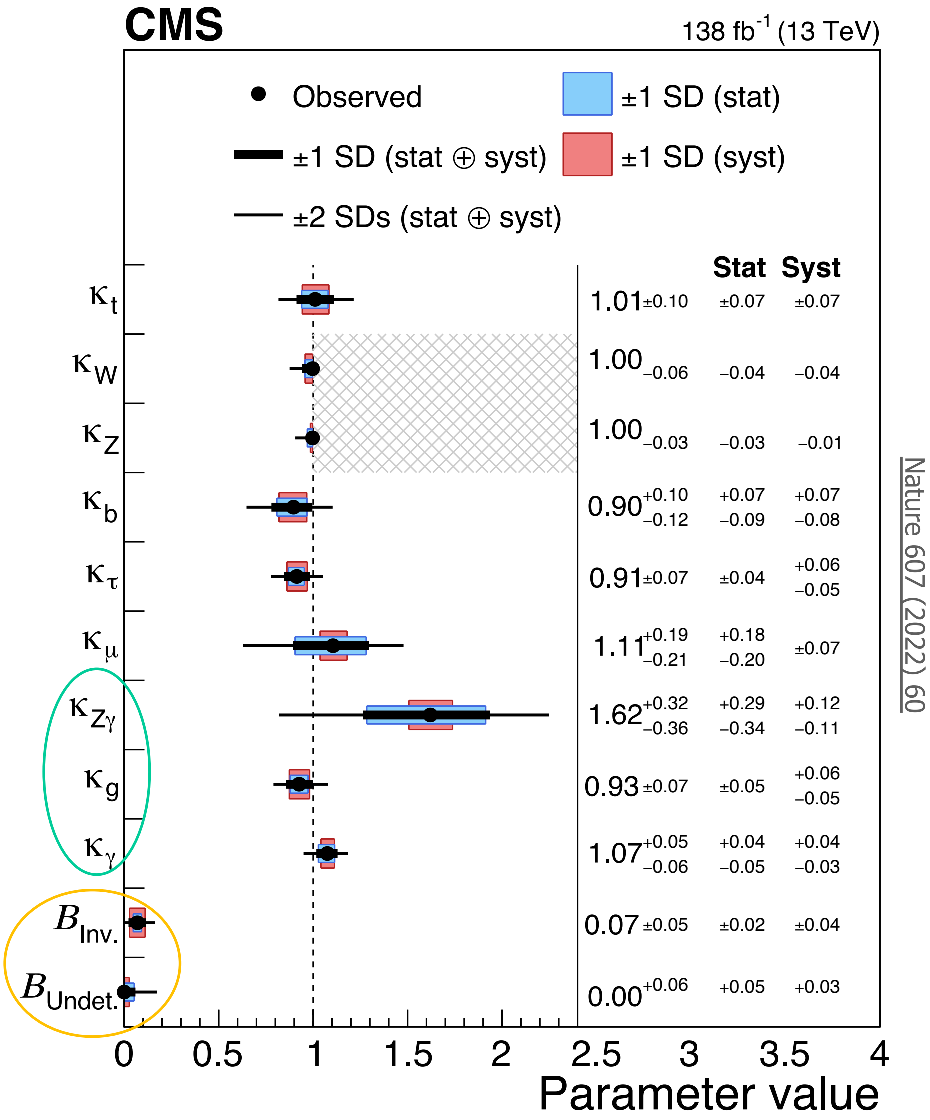
- In the loops: do not resolve loops but introduce effective coupling modifiers κ_g, κ_γ, $\kappa_{Z\gamma}$ to capture virtual contributions from new particles



- Additional decays to new particles $m < m_H$ (invisible/undetected in considered analyses)
  - Additional decays alter Higgs total width:

$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - B_{BSM}}$$

  - Degeneracy between altering B_{BSM} and κ_H: resolved by constraint κ_V <1



Nature 607 (2022) 60

Differential cross sections

ATLAS: EPJC 80 (2020) 942
CMS: CMS-PAS-HIG-24-013

Differential cross section measurements

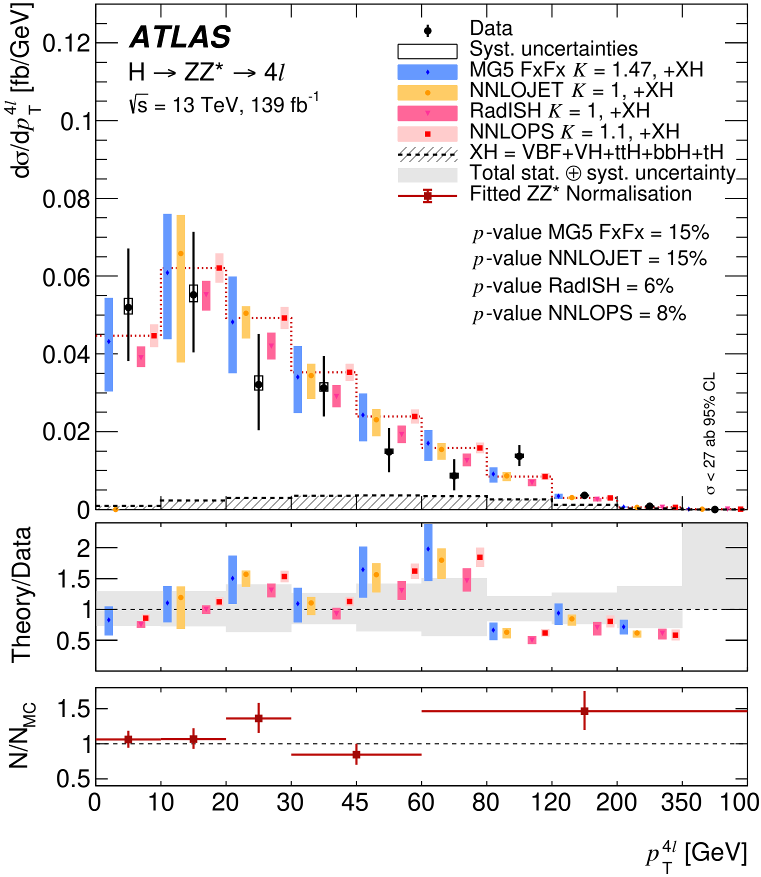
So far: reconstructed distributions of observables compared to expected distributions from theory prediction (+detector simulation): results are model-dependent

- E.g. signal strength does not parametrise shape changes and results depend on SM prediction

Differential cross sections provide
model-independent test of Higgs physics

- Cross sections as a function of one or more specific observable, e.g. $p_T(H)$, N_{jets}, in fiducial phase-space region
  - Usually inclusive in production modes
- Detector effects corrected via unfolding → particle-level distribution
  - In high-resolution channels, unfolding by simple matrix inversion often sufficient
  - Nowadays likelihood unfolding: uncertainties included via nuisance parameters
- Can be directly compared with theory prediction

Main channels: $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$,
but also $H \rightarrow WW$, bb, $\tau\tau$



Eur. Phys. J. C 80 (2020) 942

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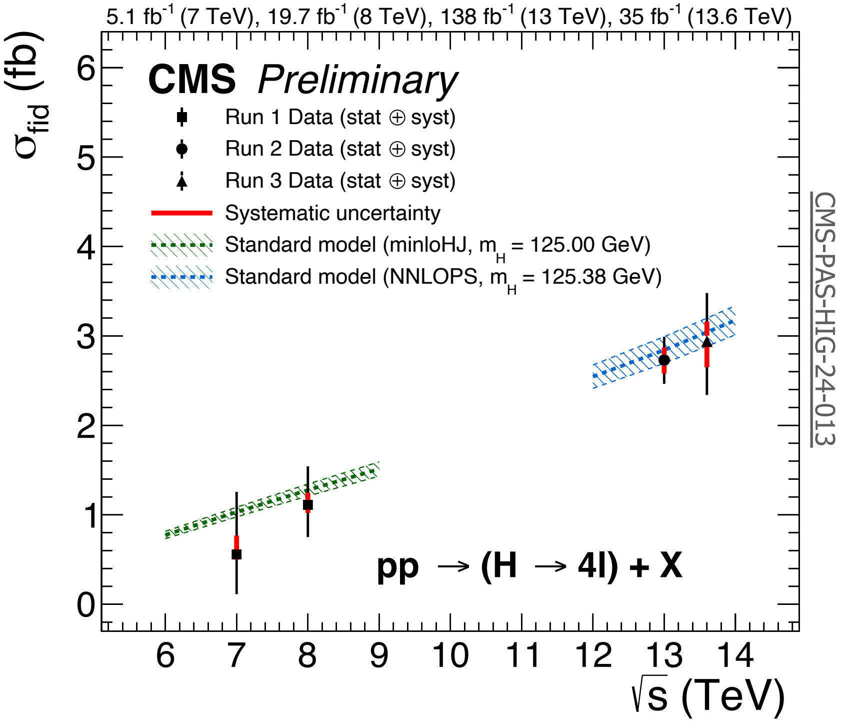
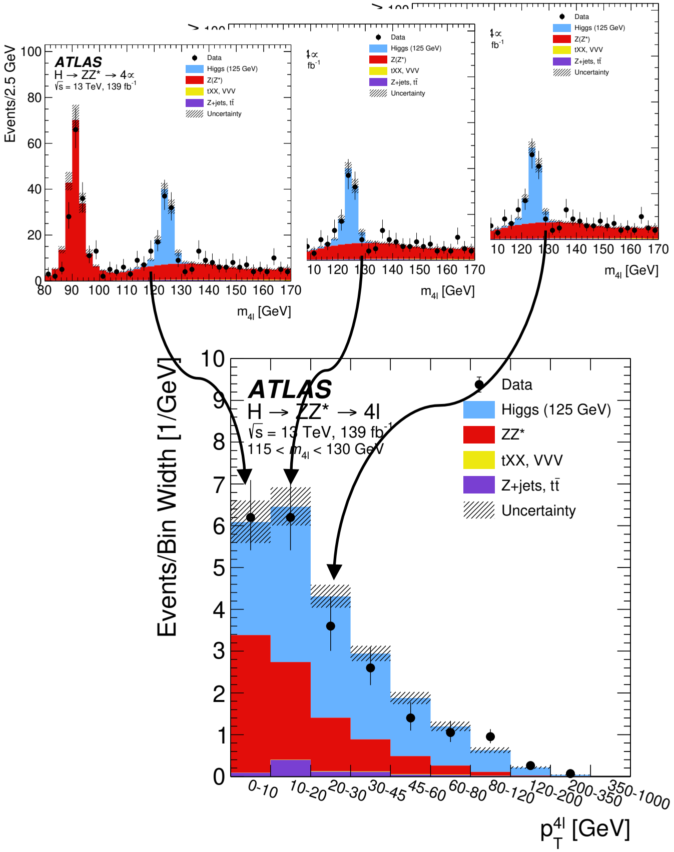
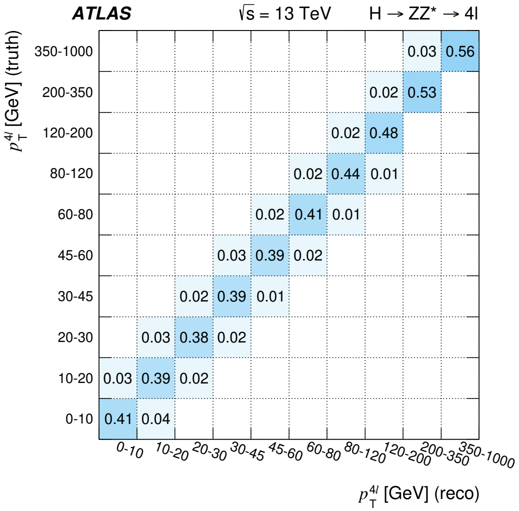


Already first Run 3 measurements!

Differential cross section measurements

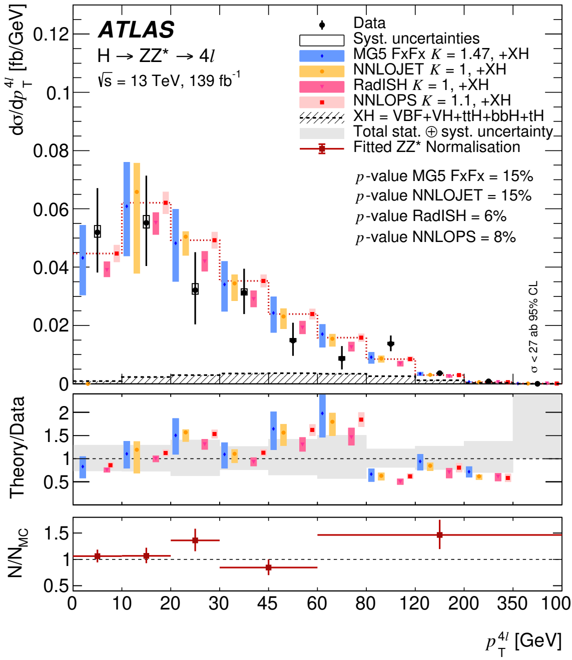


Signal extraction in each bin *i* of observable



	0-10	10-20	20-30	30-45	45-60	60-80	80-120	120-200	200-350	350-1000
350-1000									0.03	0.56
200-350								0.02	0.53	
120-200							0.02	0.48		
80-120						0.02	0.44	0.01		
60-80					0.02	0.41	0.01			
45-60				0.03	0.39	0.02				
30-45			0.02	0.39	0.01					
20-30		0.03	0.38	0.02						
10-20	0.03	0.39	0.02							
0-10	0.41	0.04								

Detector response (migration *ij*)



Eur. Phys. J. C 80 (2020) 942

Cross section in each bin *j*

$$\boxed{N_i(m_{4\ell})} = \sum_j \boxed{r_{ij}} \cdot (1 + f_i^{\mathrm{nonfid}}) \cdot \boxed{\sigma_j^{\mathrm{fid}}} \cdot \mathcal{P}_i(m_{4\ell}) \cdot \mathcal{L} + N_i^{\mathrm{bkg}}(m_{4\ell})$$

$$\boxed{\sigma_j^{\mathrm{fid}} = \sigma_j \cdot A_j \cdot \mathcal{B}}$$

Likelihood unfolding: σ determined in simultaneous likelihood fit, uncertainties included via nuisance parameters

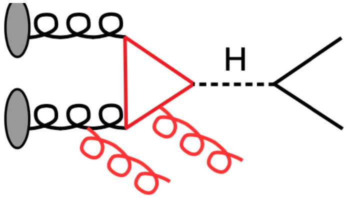
"Fiducial" cross section: σ in restricted phase space close to experimental acceptance, including branching ratio, to avoid extrapolation

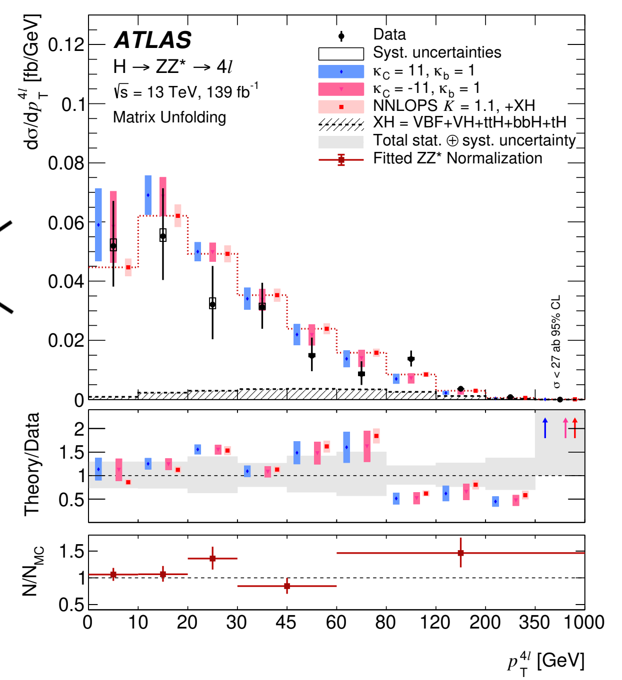
Example: Higgs boson p_T

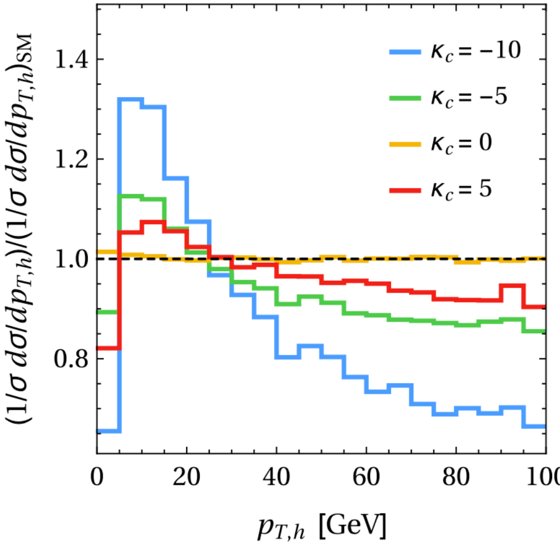
ATLAS: EPJC 80 (2020) 942
CMS: CMS-PAS-HIG-24-013

Differential measurements provide strong probe of Higgs sector, e.g. Higgs boson p_T sensitive to

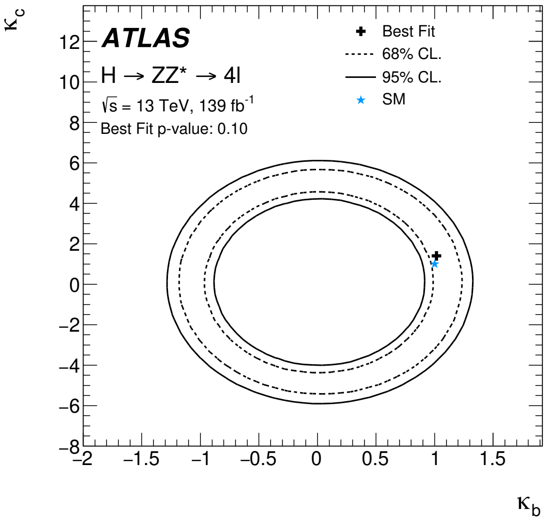
- Modelling of QCD radiation
- Higgs boson couplings: constraints on couplings not yet accessible direcly, e.g.
  - Higgs-charm coupling
  - Higgs self-coupling
- New heavy particles in the ggF loop



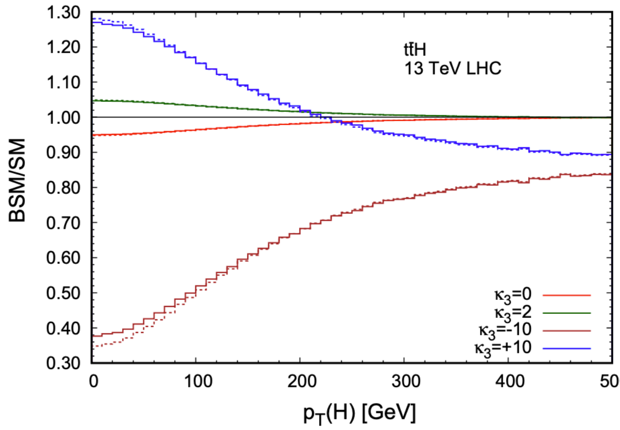




Phys. Rev. Lett. 118 (2017) 121801



Eur. Phys. J. C 80 (2020) 942



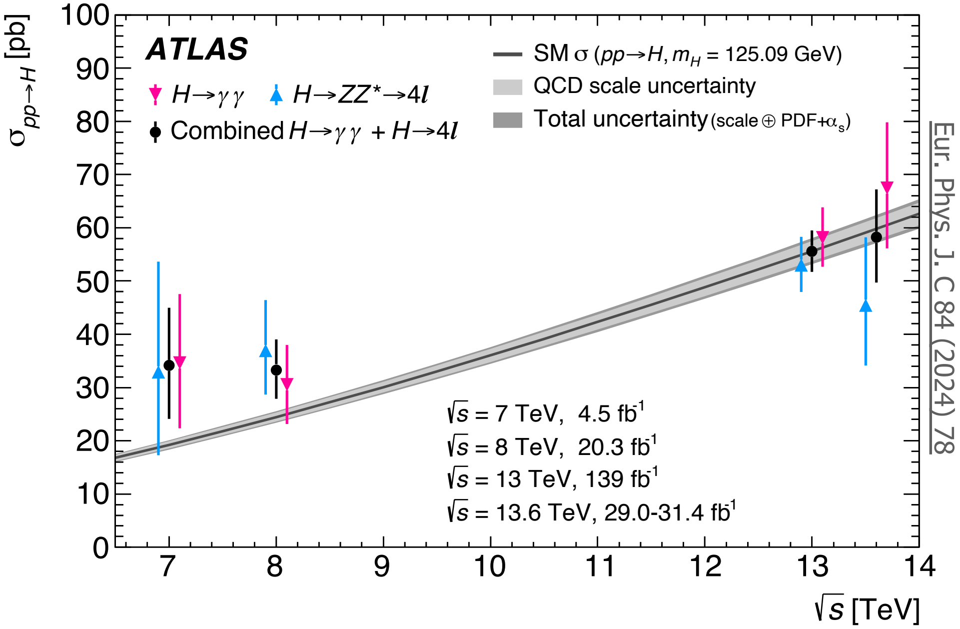
Eur. Phys. J. C 77 (2017) 887

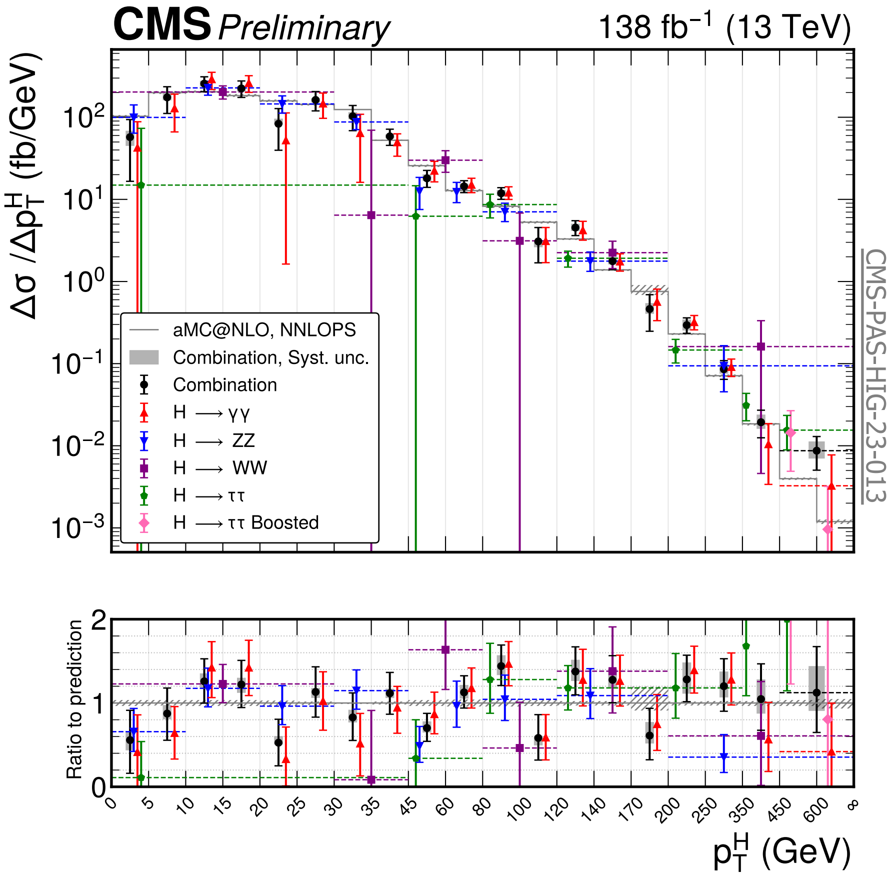
Combination of cross section measurements

ATLAS: Eur. Phys. J. C 84 (2024) 78
CMS: CMS-PAS-HIG-23-013

Combination of (differential) cross sections across channels requires some model assumptions, i.e. definition of fiducial volume is channel dependent

- Branching ratios
- Possibly also kinematic regions





Simplified Template Cross Sections (STXS)

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Specific measurements (signal strength, κ-framework, spin, …)

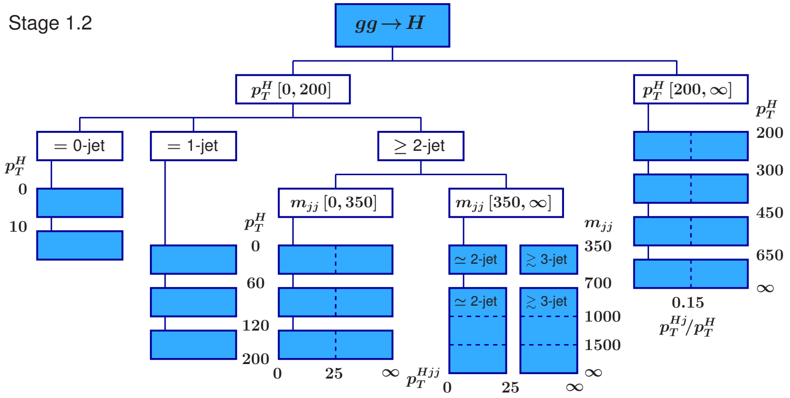
- Maximum sensitivity by highly specific observables, e.g. machine-learning based
- Theory predictions are direct part of the measurement, e.g. to build signal templates
- Probe specific variation, e.g. only overall rate changes in signal strength measurements

Differential cross section measurements

- Best model and theory independence
- Smaller sensitivity: measurements use simpler cuts and observables
- Combination across channels only by introducing model dependence

Simplified Template Cross Section (STXS) "in between"

- Signal strength for each Higgs boson production mode
- Separated further in different phase-space regions ("bins")
    - Consistently defined across experiments and theory: useful for combinations and interpretations
- Likelihood unfolding from reconstruction-level categories that aim to match the particle-level bins
- Allows using arbitrary observables, e.g. machine-learning based, and including background control regions to maximise sensitivity



Example: STXS bins for ggH LHC Higgs Working Group

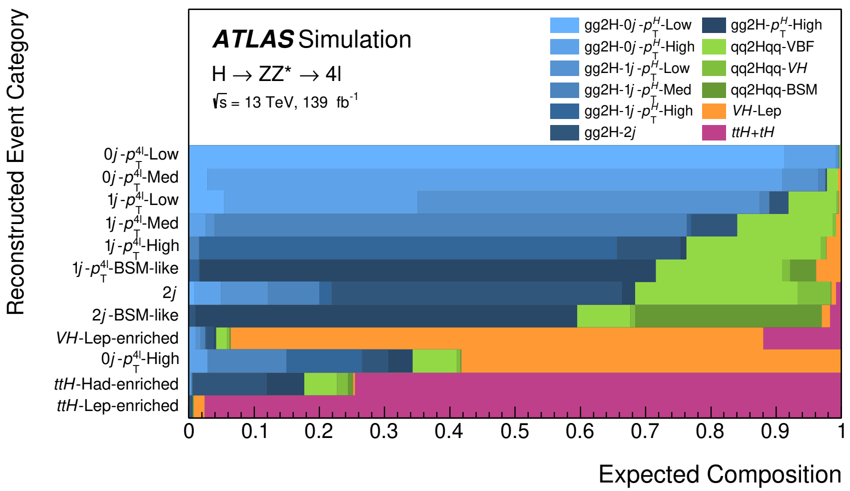
STXS example: H → 4l

Different observables per category

- ➢ ggF: m_T (ggF), VBF: NN

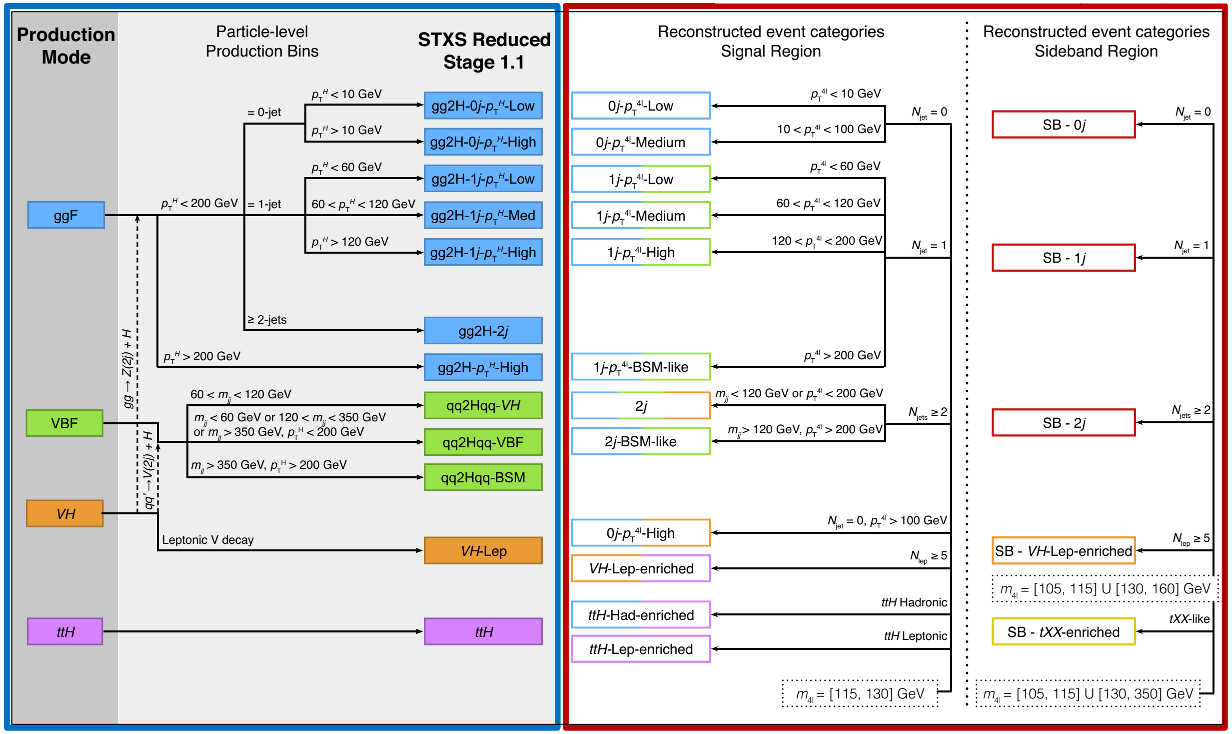
Simultaneous fit to signal and control regions

- ➢ POIs: cross section in each STXS bin



Eur. Phys. J. C 80 (2020) 957

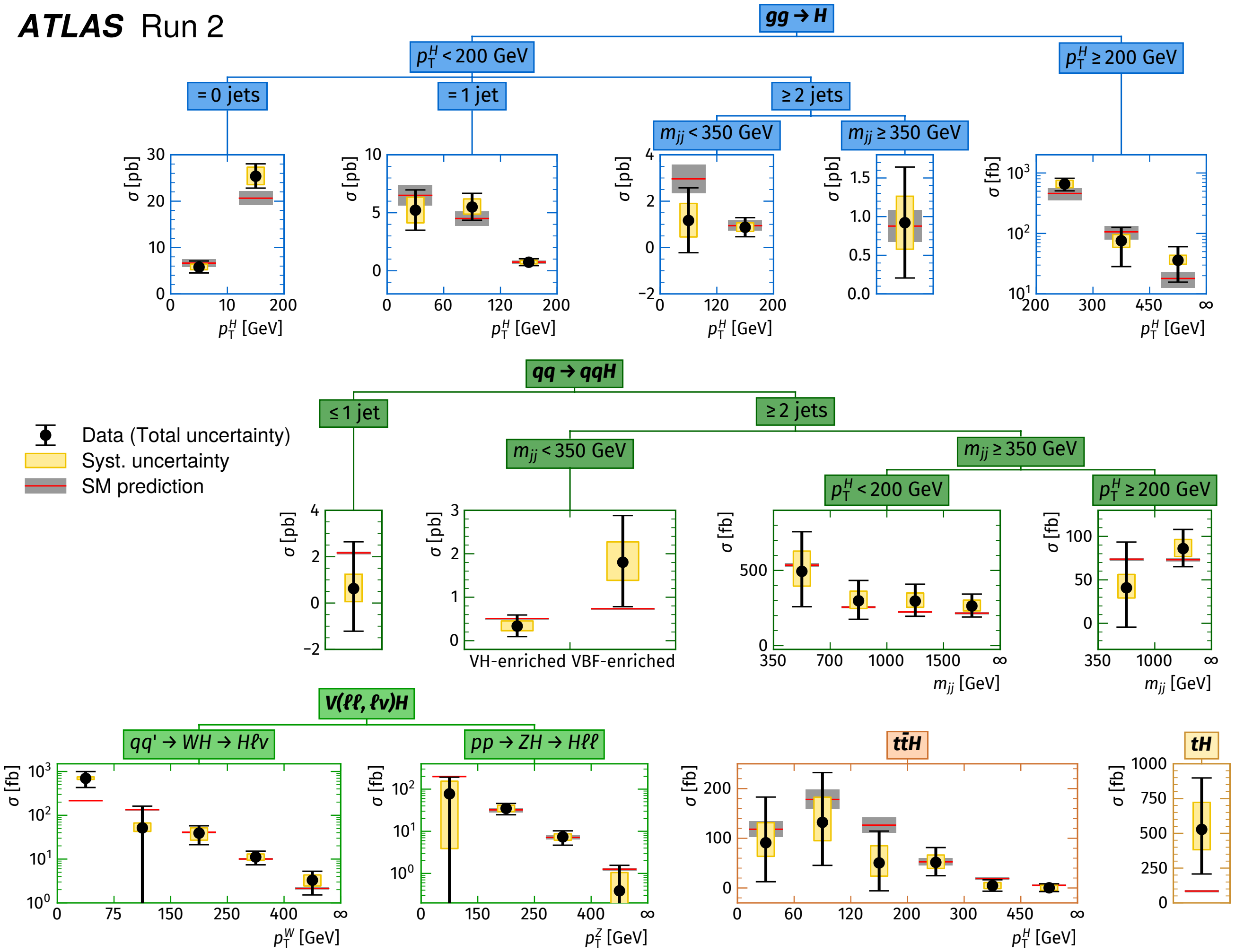
Theory: particle-level **STXS bins**



Experiment: reco-level **analysis categories**

STXS status: combination of decay channels

By now, STXS measurements in many channels: detailed probe of Higgs boson interactions



Combined fit of STXS across many channels

- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ^* \rightarrow 4l$
- $H \rightarrow WW^* \rightarrow e\nu\mu\nu$
- $H \rightarrow \tau\tau$
- $H \rightarrow bb$

Uncertainties correlated (common nuisance param.)

Nature 607 52 (2022)

CP violation in Higgs sector

CP violation in Higgs sector?

Pure Higgs states with non-SM spin/parity values excluded by Run 1 measurements

But mixture of CP-even and CP-odd Higgs interactions conceivable → **CP violation**

- Additional sources of CP violation needed to explain baryon asymmetry in early Universe

Very different structure of Higgs coupling to vector bosons and to fermions: implications for possible of size CP-odd couplings Phys. Rev. D 88 (2013) 076009

- **Vector boson couplings**: CP violation requires dimension-6 operators → strongly suppressed by high mass scale
  - Similar strategy as spin/parity measurements
  - Pure CP-odd HVV coupling disfavoured

- **Fermion couplings**: SM tree level (dimension-4 operators) possible → potentially large effects

$$\mathcal{L}(Hff) = -\frac{\mathrm{m_f}}{\mathrm{v}}\bar{\psi}\left(\kappa_\mathrm{f} + i\tilde{\kappa}_\mathrm{f}\gamma_5\right)\psi\mathrm{H}$$

CP-even/CP-odd Yukawa coupling

SM: $\kappa_\mathrm{f} = 1,\ \tilde{\kappa}_\mathrm{f} = 0$

CP violation in Yukawa interactions?

Hot topic, first results only recently:

- ttH with H → $\gamma\gamma$/multilepton/bb
- H → $\tau\tau$

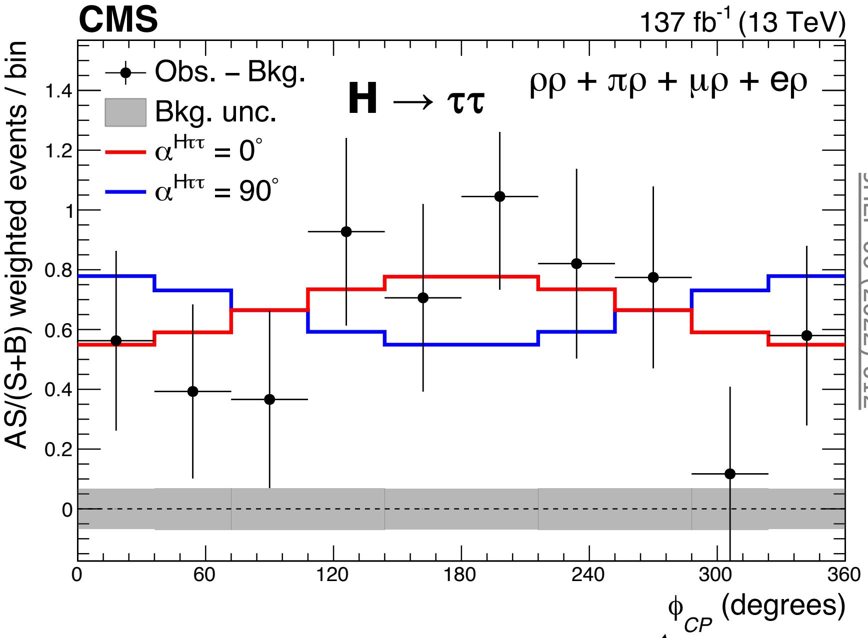
Dedicated observables (angular, NN/BDT) or relative rate changes of ttH and tH production

Pure CP-odd structure excluded at 3.7σ level

$$\mathcal{L}(Hff) = -\frac{m_f}{v}\bar{\psi}\left(\kappa_f + i\tilde{\kappa}_f\gamma_5\right)\psi H$$

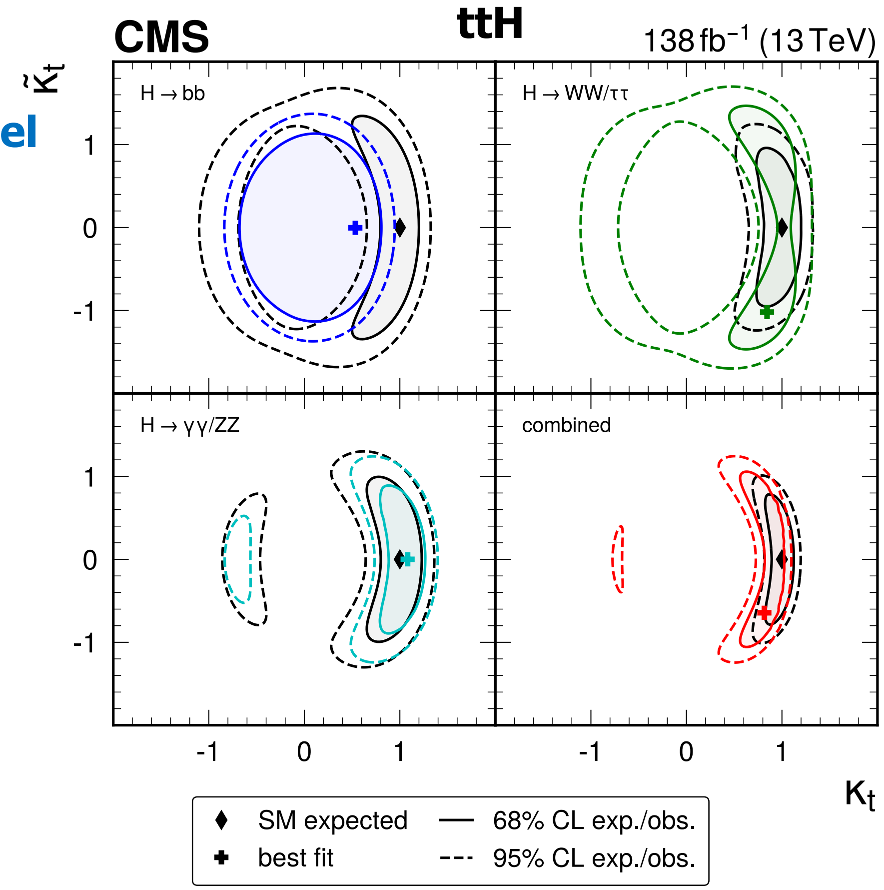
CP-even/CP-odd Yukawa coupling

SM: $\kappa_f = 1,\ \tilde{\kappa}_f = 0$



JHEP 06 (2022) 012

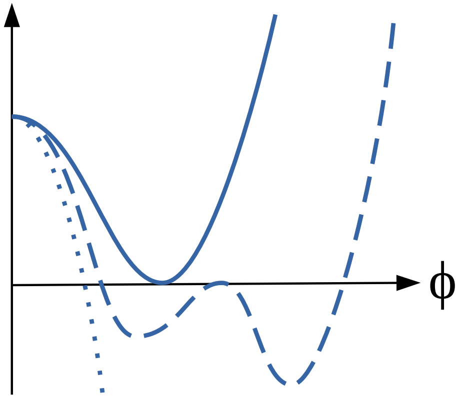
Angle between τ decay planes



arXiv:2407.10896 (subm. to JHEP)

Probing the Higgs potential

Higgs boson self-coupling



Self-coupling strength λ related to **shape of the Higgs potential**

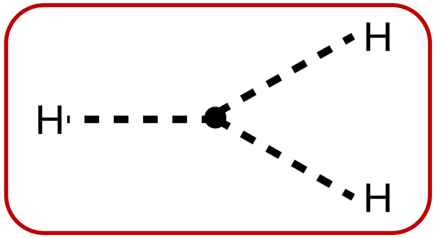
- Responsible for electroweak symmetry breaking
- Implications for (meta-)stability of the vacuum

Measuring λ is a key objective of the remaining LHC Higgs programme

$$V(H) = \frac{1}{2} m_H^2 H^2 + \boxed{\lambda_3 v\, H^3} + \frac{1}{4}\lambda_4\, H^4$$

$$\frac{1}{2} m_H^2 H^2 + \frac{1}{2}\frac{m_H^2}{v} H^3 + \frac{1}{8}\frac{m_H^2}{v^2} H^4$$

SM: $\lambda_3 = \lambda_4 = \lambda = \frac{m_H^2}{2v^2}$



Assuming SM: λ is fixed by m_H measurement! – but is true?

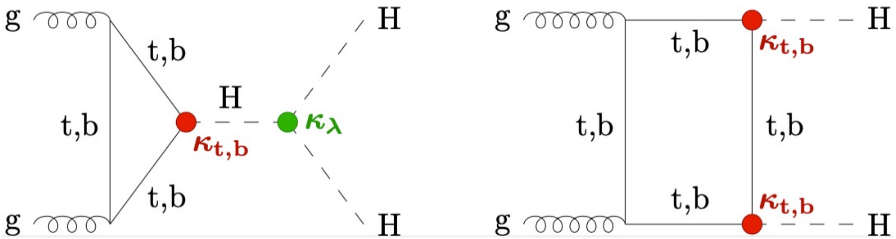
Higgs boson pair (HH) production best direct probe of self-coupling

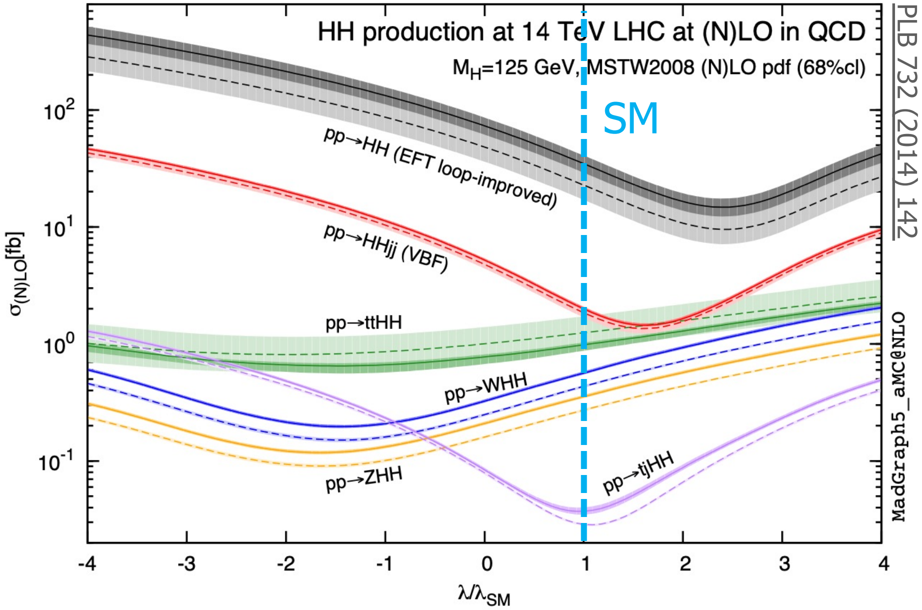
“HH white book” arXiv:1910.00012

HH production at the LHC

Rare process in the SM: σ_{HH} ~33.5 fb (13 TeV), i.e. 1000 x smaller than single-H production

- ggF dominant production channel
- Large destructive interference



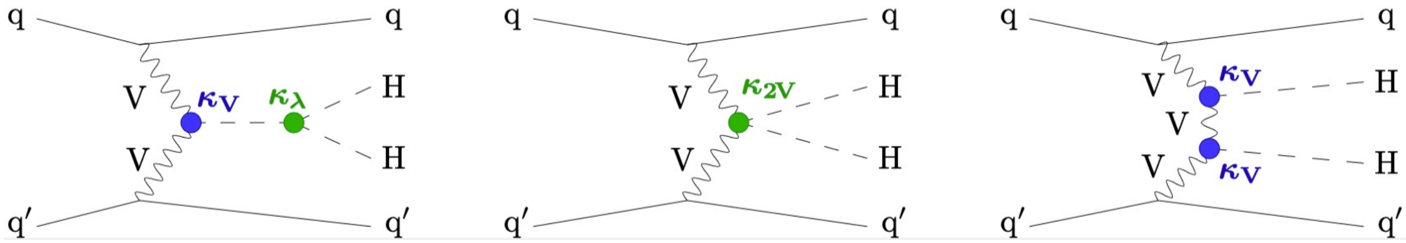


PLB 732 (2014) 142

But highly sensitive to variations of λ

- Observing HH production now: new physics!
- Hot topic in Higgs physics

VBF channel unique probe of quartic VVHH coupling, $\sigma_{HH\text{-}VBF}$ ~1.7 fb (13 TeV)



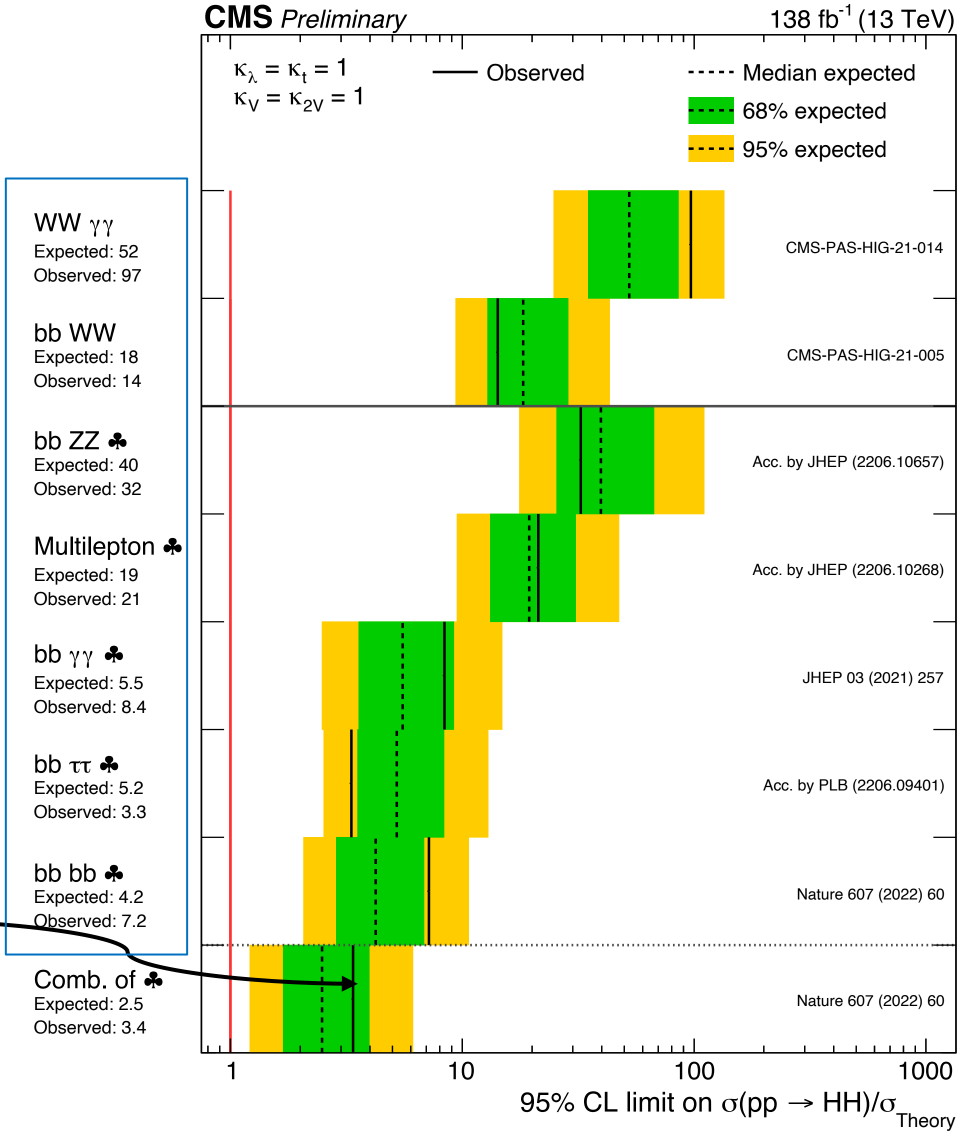
ATLAS: arXiv:2406.09971 (subm. to PRL)
CMS: Nature 607 (2022) 60

Search for HH production

HH searches target various combinations of Higgs boson decay channels

- Typically include H → bb decay to exploit large BR and compensate for low σ_{HH}
- Best sensitivity from 4b, bb$\tau\tau$, bb$\gamma\gamma$

Excluding σ_{HH} >3.4 x SM at 95% CL



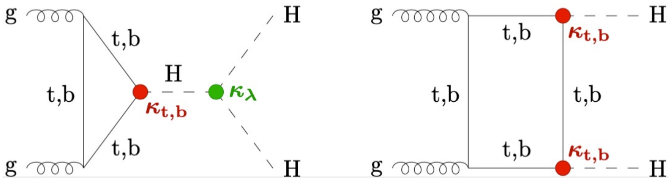
ATLAS: arXiv:2406.09971 (subm. to PRL)
CMS: Nature 607 (2022) 60

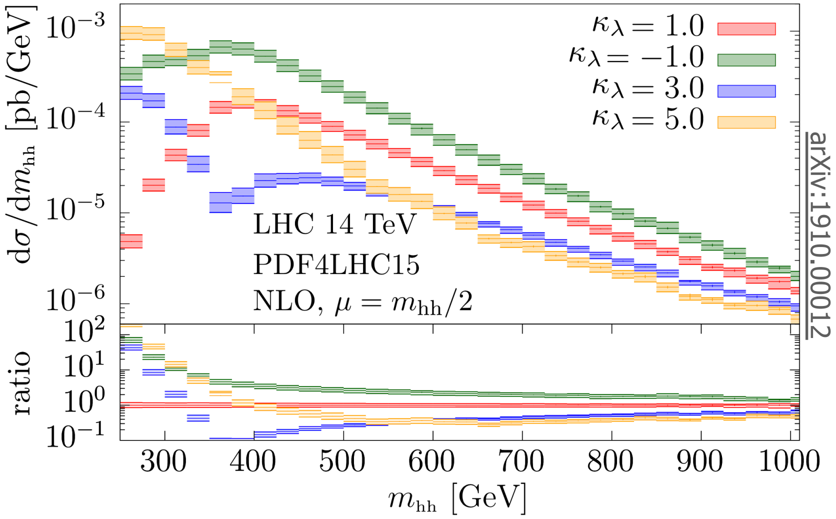
Higgs boson self-coupling

Limits on HH cross section → **limits on the Higgs boson self-coupling λ**

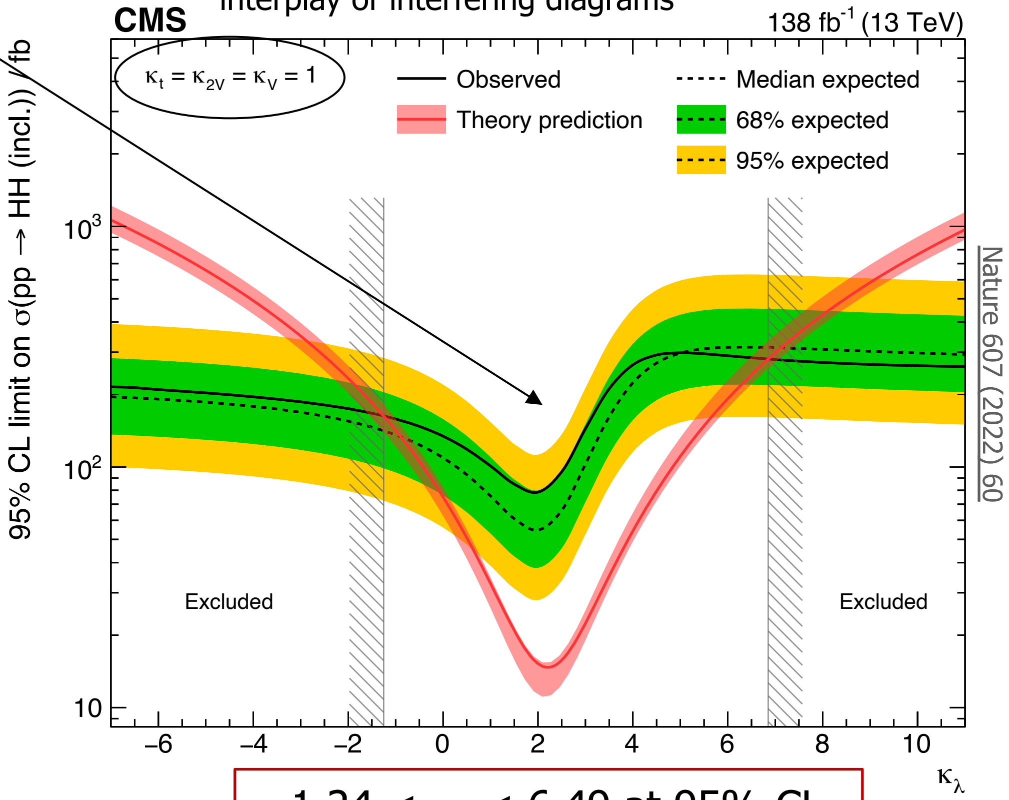
Kinematics of HH system depend on κ_λ

- Different κ_λ → different relative contributions of diagrams
- Affects experimental sensitivity





Assuming κ_t = 1 to resolve interplay of interfering diagrams



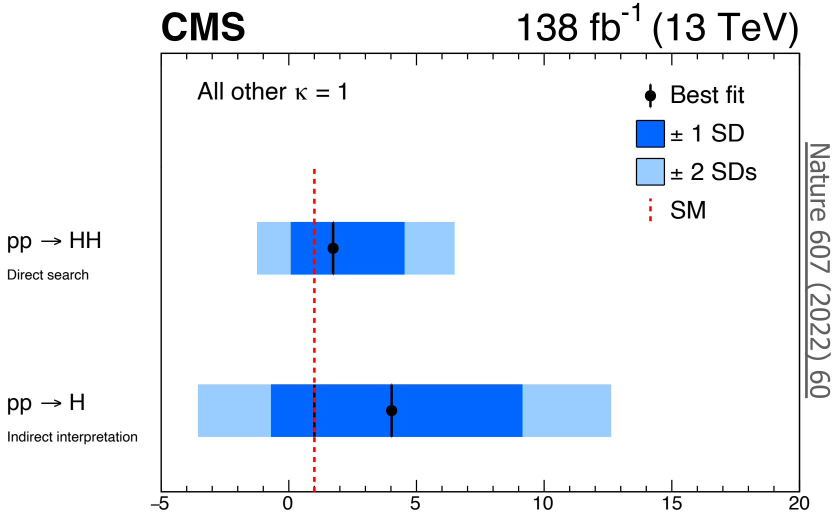
-1.24 < κ_λ < 6.49 at 95% CL

Analogous procedure for VBF: 0.67 < κ_λ < 1.38 at 95% CL

Higgs boson self-coupling

Benefits from combination of HH and single-H measurements

- Single-H production indirectly sensitive to λ via higher-order corrections
  - Similar sensitivity to direct HH searches, but model dependence
  - Both rate and shape effects, e.g. p_T(H) (differential measurements!)
- Single-H production provides strong constraints on κ_t: allows measurement of κ_λ without assumptions on κ_t



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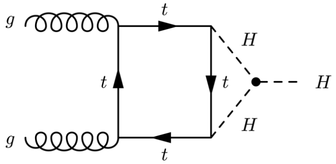
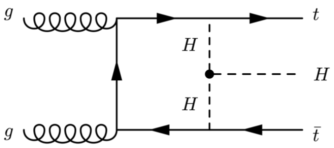
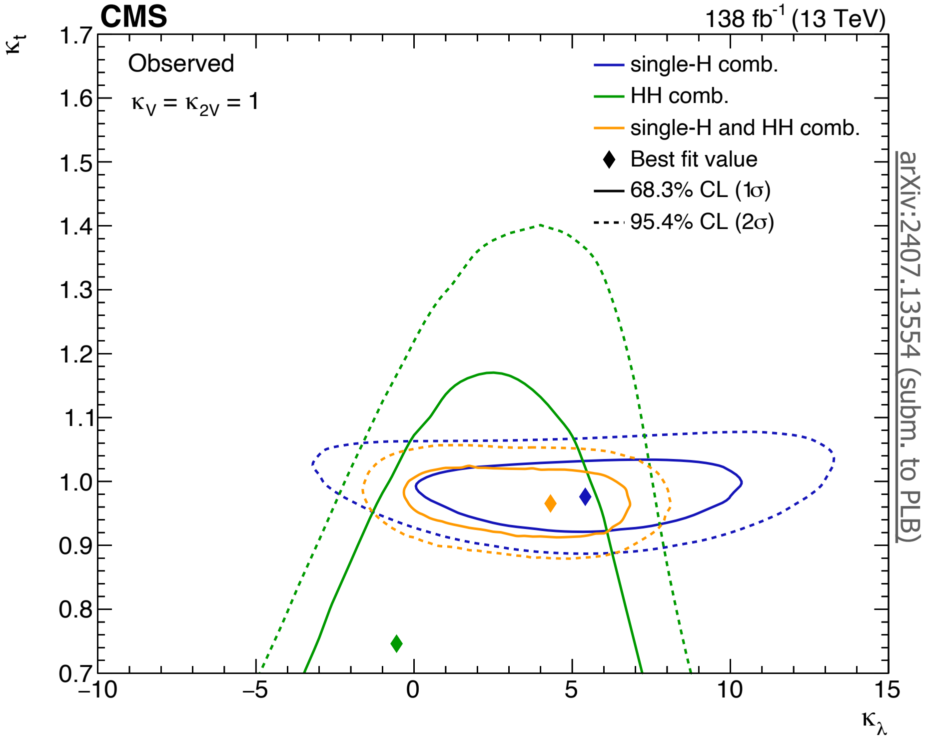






arXiv:2407.13554 (subm. to PLB)

What we know about the Higgs boson

12 years after the discovery

Mass

125.11 +/- 0.11 GeV
(0.1% precision!)

Other properties

Spin/parity 0^+ (pure state)

$\Gamma_H = 2.9\,^{+1.9}_{-1.4}\,\mathrm{MeV}$ (indirect)

J. Cham

Couplings to bosons and fernions

Couplings at ~5–20% precision

$\gamma\gamma$/WW/ZZ directly observed

$\tau\tau$/bb/tt directly observed

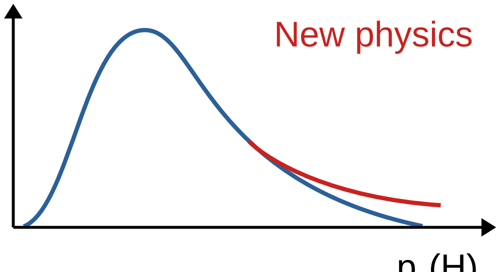
Evidence for $H \rightarrow \mu\mu$

Self coupling

$-1.24 < \kappa_\lambda < 6.49$ at 95% CL

Additional remarks

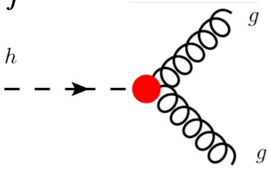
Interpretation in Effective Field Theories (EFT)



Parameterise all low-energy effects of new physics at a higher scale

Can modify SM couplings or appear like new (effective) couplings

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d=6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d=8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \dots$$

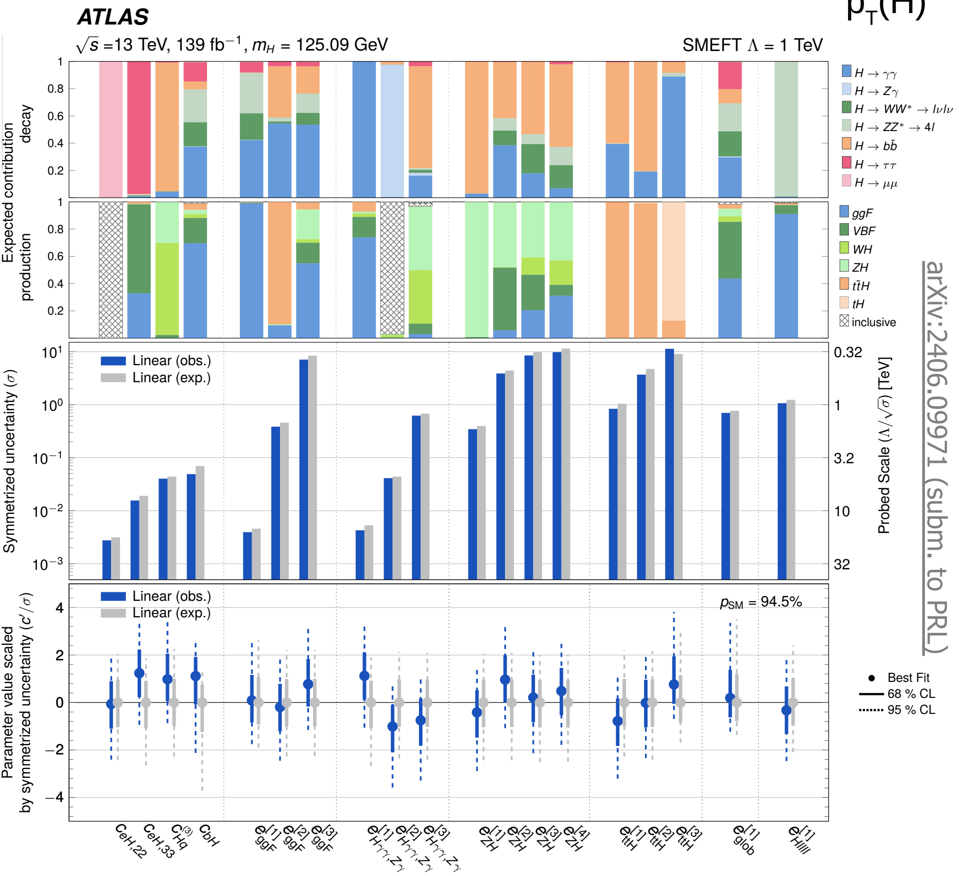


Effect on rate+shape of distributions

Experimentally: fit of coupling modifiers

- ➢ Differential measurements beneficial
- ➢ Also STXS results used as input

e.g. constraints on EFT parameters (linear comb. of Wilson coefficients c_i) obtained from STXS combination



arXiv:2406.09971 (subm. to PRL)

Rapidly developing topic: techniques evolve as more an more data is analysed

BSM Higgs

SM Higgs sector simplest form to provide particle masses, but could be more complicated, e.g.

- Extended Higgs sector, e.g. two doublets → additional Higgs bosons
- Higgs boson could couple to non-SM sector, e.g. Dark Matter particles

1. Higgs boson precision measurements crucial to probe SM nature of Higgs sector: any deviation from the SM prediction is a clear signal of new physics

- E.g. couplings SM-like within measurement precision (~5—20%): room BSM effects

2. Vast amount of direct searches for BSM Higgs signatures

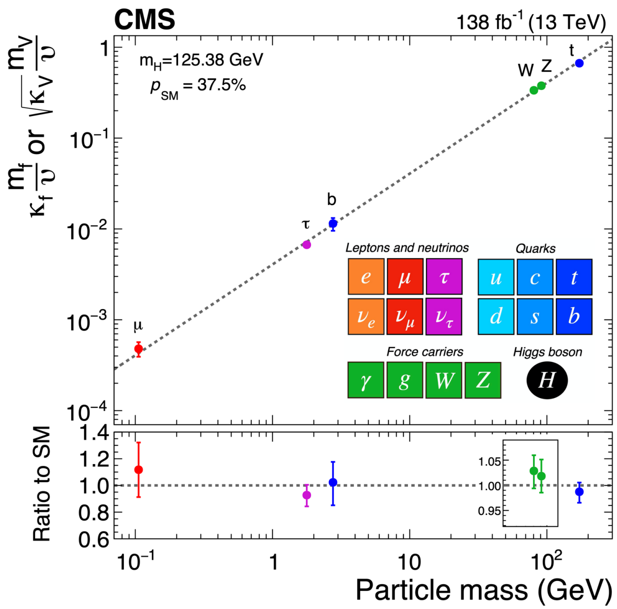
- Direct **searches for additional Higgs bosons**
  - Typically heavier than 125 GeV
  - But also light (<125 GeV) Higgs bosons conceivable, e.g. with large scalar admixture such that reduced coupling to vector bosons (LEP limits not valid)
- Direct **searches for non-SM couplings** of the Higgs boson
  - Lepton-flavour violating decays H → eμ
  - „H → invisible“ decays, e.g. decays to Dark Matter particles
- 125 GeV **Higgs boson tool in searches** for other heavy particles
  - Decays of new heavy particles to HH → searches for resonant HH production

Summary of second part (Higgs)

J. Cham

Higgs boson discovery has started new era in particle physics: **we are probing the mechanism that generates masses** at the fundamental level!

Higgs boson offers a unique window to test the SM and search for the physics beyond



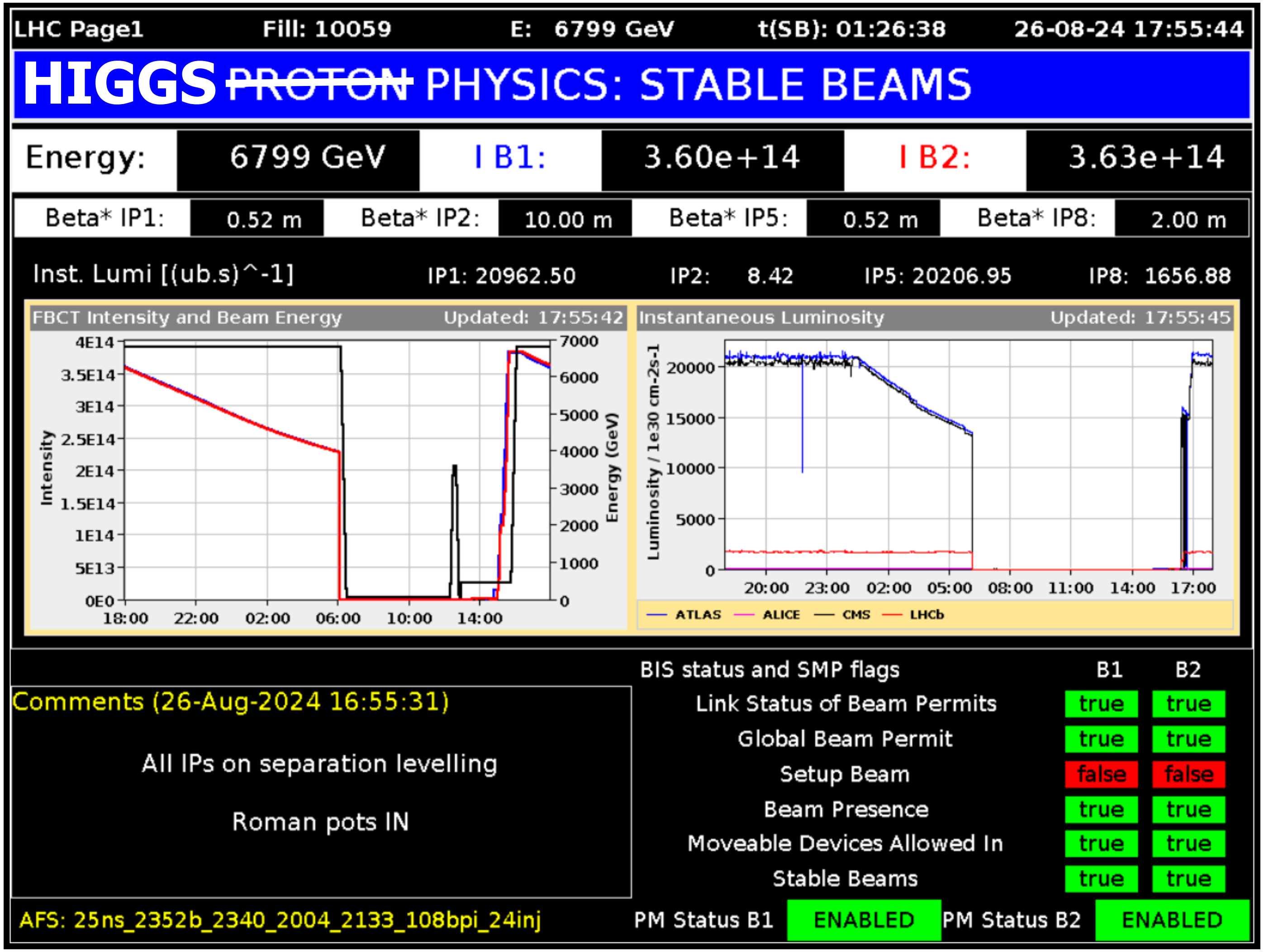
Nature 607 (2022) 60

Rhich Higgs physics programme at the LHC

- Large datasets and vast progress in experimental methods
- Measuring Higgs-boson properties and couplings to vector bosons and heavy fermions with ever increasing precision, differential measurements in many cases
- Evolving suite of interpretations matching experimental precision

Run 3 at full swing + HL-LHC at the horizon: **A bright Higgs future ahead!**

More Higgs bosons being produced as we speak!



LHC Page1 Fill: 10059 E: 6799 GeV t(SB): 01:26:38 26-08-24 17:55:44

HIGGS ~~PROTON~~ PHYSICS: STABLE BEAMS

Energy:	6799 GeV	I B1:	3.60e+14	I B2:	3.63e+14

Beta* IP1:	0.52 m	Beta* IP2:	10.00 m	Beta* IP5:	0.52 m	Beta* IP8:	2.00 m

Inst. Lumi [(ub.s)^-1] IP1: 20962.50 IP2: 8.42 IP5: 20206.95 IP8: 1656.88

Comments (26-Aug-2024 16:55:31)

All IPs on separation levelling

Roman pots IN

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 25ns_2352b_2340_2004_2133_108bpi_24inj

PM Status B1 ENABLED PM Status B2 ENABLED