The Higgs boson: a glimpse under the peak

Virtuelle DPG-Frühjahrstagung 2021 (Dortmund)

Matthias Schröder

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Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

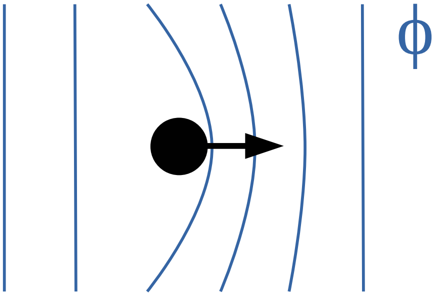
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

How do particles get mass?

Fundamental question:

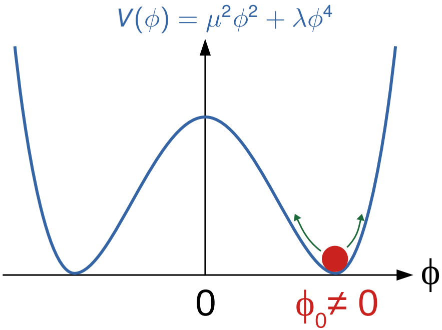
If the electron was massless, there would be no stable atoms!

How do particles get mass?



Interaction with Higgs field $\phi \rightarrow$ particle mass

The Higgs potential



Universe at minimum of $V(\phi)$

Excitation of ϕ around minimum $\rightarrow$ Higgs boson H (necessary consequence!)

The Standard Model Higgs sector

Gauge interaction
W/Z boson masses

$$\mathcal{L} = |D_\mu \phi|^2 - V(\phi) + y_f \overline{\psi} \phi \psi$$

Higgs potential
symmetry breaking

Yukawa interaction
fermion masses

Special, unlike anything probed before

The Higgs boson: a special particle

J. Cham

Scalar particle (spin 0, CP even)

Couples in a unique way to other SM particles:

to bosons $\propto m_V^2$

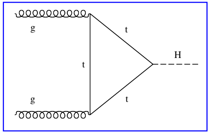
to fermions $\propto m_f$

Once Higgs-boson mass is known:
all other properties and interactions precisely predicted

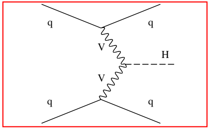
Excellent probe of the Higgs sector and window to new physics

(Complementary approach: direct search for additional Higgs bosons or forbidden decays)

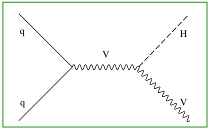
Higgs-boson production at the LHC



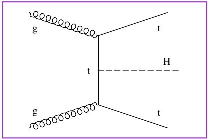
ggF: 43.9 pb (87 %)



VBF: 3.8 pb (7 %)

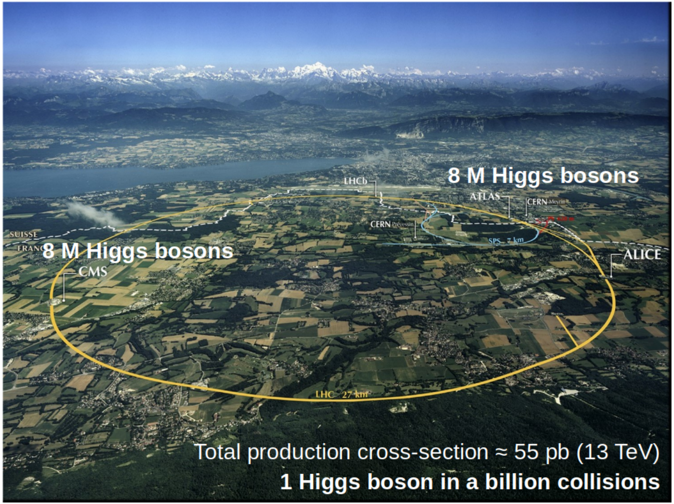


VH: 2.3 pb (4 %)



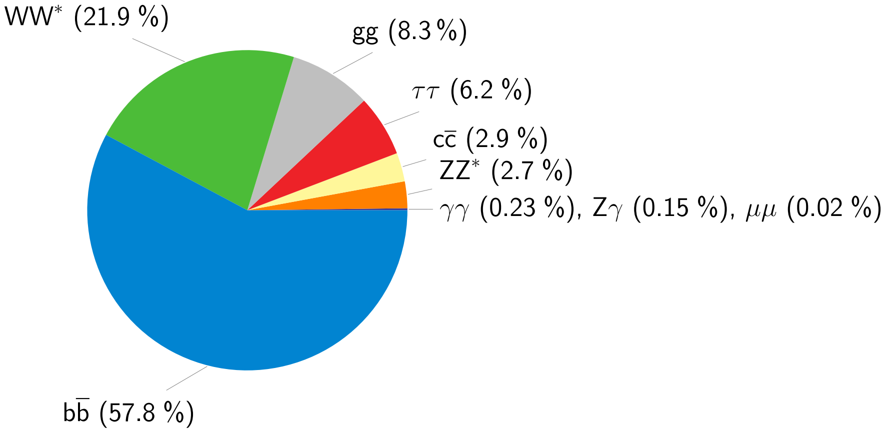
$t\bar{t}H$: 0.5 pb (1 %)

(for $m_H = 125$ GeV, 13 TeV)



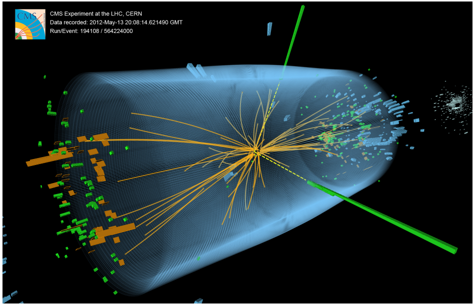
Higgs-boson decay channels

Branching ratios ($m_{\mathrm{H}} = 125\,\mathrm{GeV}$)



Higgs-boson decay channels

$H \to \gamma\gamma$ candidate event



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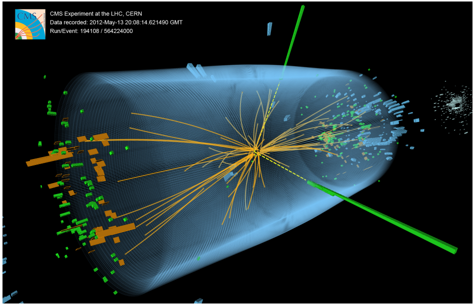
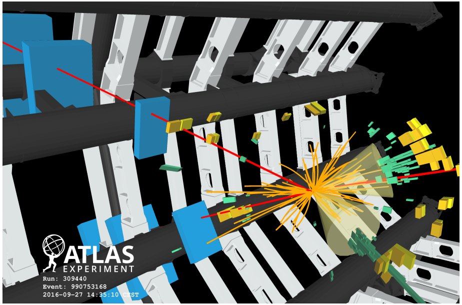


$\mathrm{H} \rightarrow \mathrm{b\bar{b}}$ candidate event



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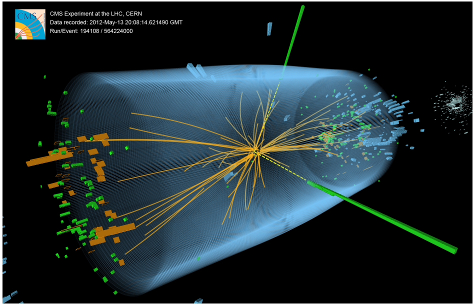

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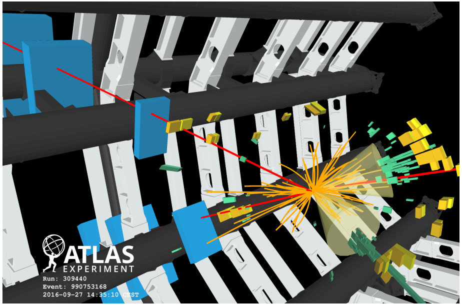

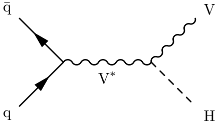

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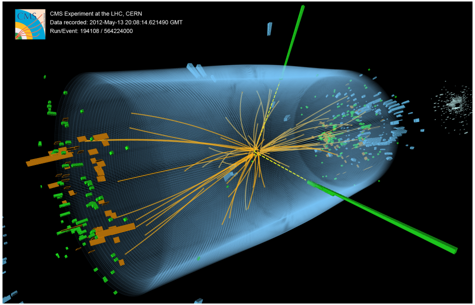

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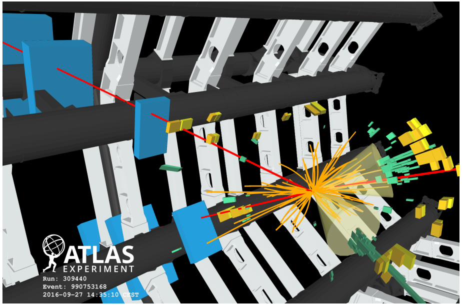
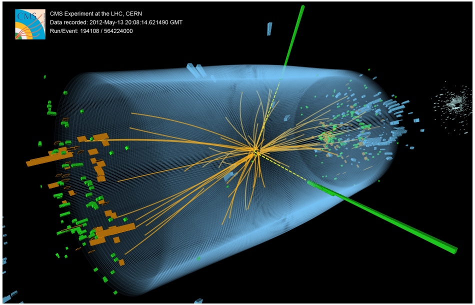


All detector components needed in Higgs-boson analysis

Higgs-boson decay channels

H $\longrightarrow \gamma\gamma$ candidate event



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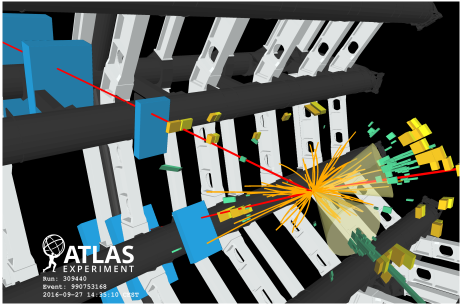
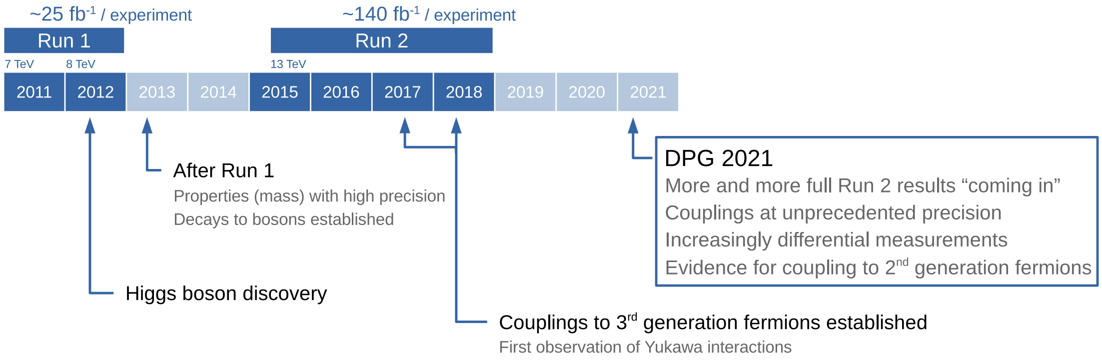


All detector components needed in Higgs-boson analysis

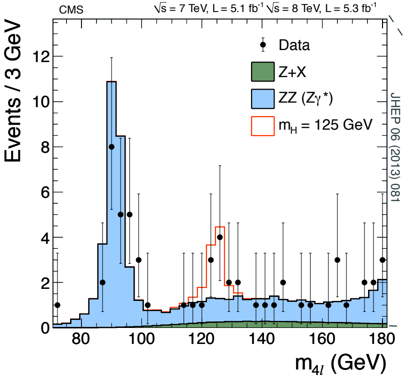
Continuous progress in analysis methods, machine-learning techniques have become a key tool

Where do we stand?

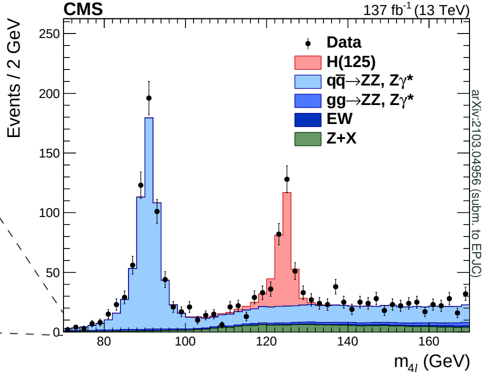


Where do we stand?

Higgs-boson discovery



Full Run 2 dataset



Outline

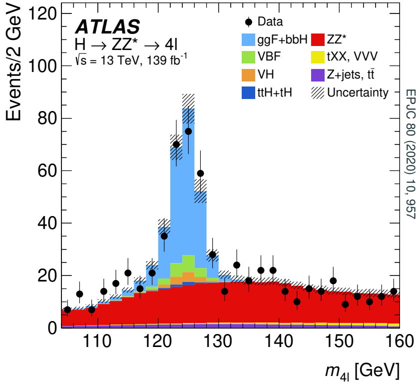
1. Measuring properties and couplings of the Higgs boson
2. Direct measurement of Yukawa interactions
3. Probing the Higgs potential
4. What is next?

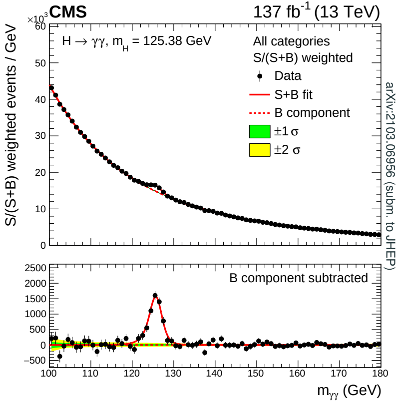
ATLAS & CMS results selected without particular preference,
typically similar results by respective other experiment

High-resolution channels $H \to ZZ^* \to 4\ell$ & $H \to \gamma\gamma$

Electrons, muons, photons measured with excellent resolution ($\mathcal{O}(1\,\%)$ p_T resolution)

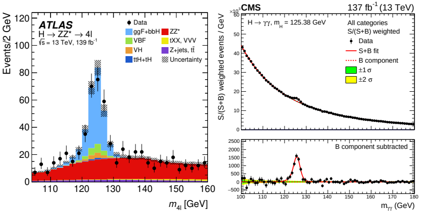
Higgs-boson candidates can be reconstructed with high precision





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

Higgs-boson properties



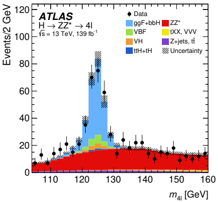
Higgs-boson properties

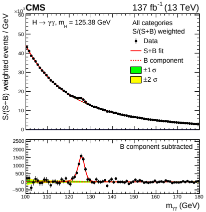
Mass

Precision reaching 0.1 %

(125.38 ± 0.14) GeV

[PLB 805 (2020) 135425] (Run 1 + partial Run 2)





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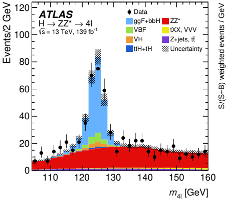
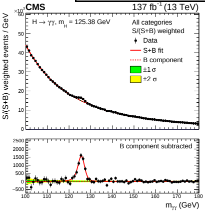
Width (SM $\approx 4\,\mathrm{MeV}$)

Indirect measurements e. g. from ratio on-shell/off-shell production: $< 9.16\,\mathrm{MeV}$

[PRD 99 (2019) 11, 112003] (Run 1 + partial Run 2)





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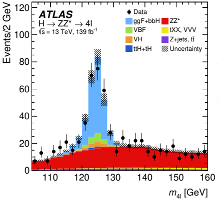
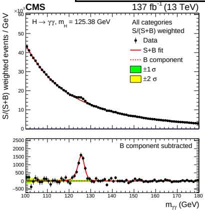




Spin and CP (SM: spin 0 / CP even)

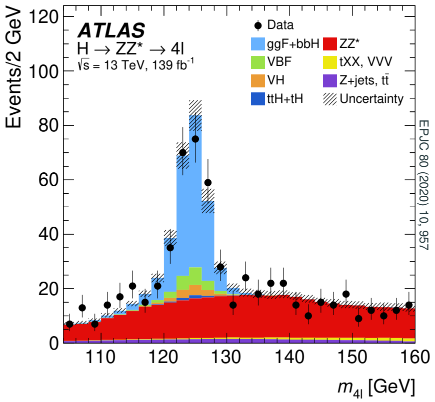
Spin 0 firmly established with Run 1 data

Pure CP odd state strongly excluded

[PLB 726 (2013) 120] [PRD 92, 012004 (2015)]

How can we study the Higgs-boson couplings?

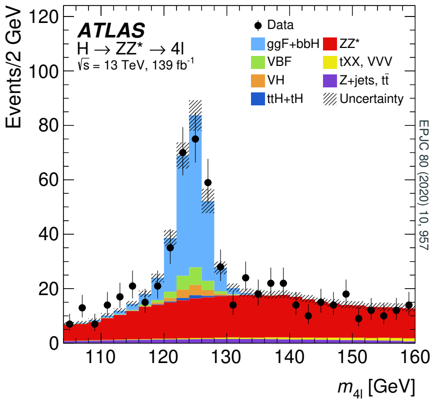
What we measure



How can we study the Higgs-boson couplings?

What we measure

number of events



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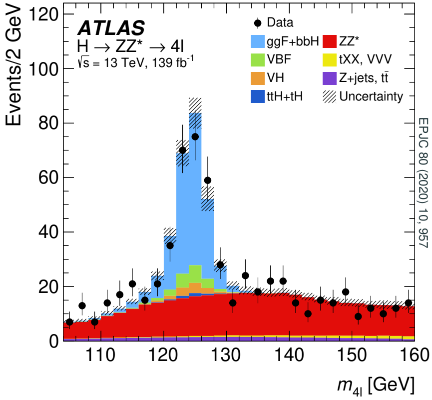
What we measure

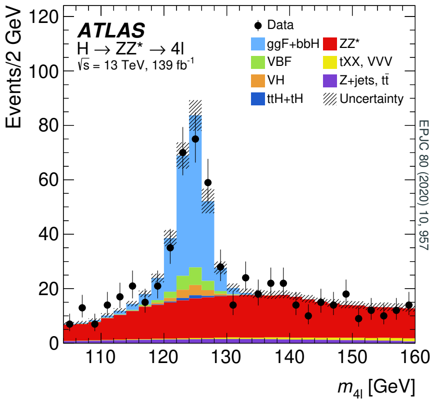
$$\sigma \times \mathcal{B}$$



How can we study the Higgs-boson couplings?

What we measure (actually)

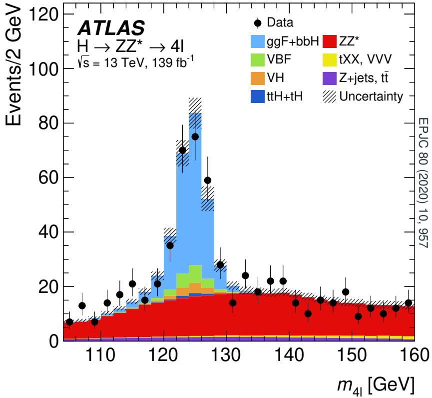
$$\sigma \times \mathcal{B} \times \alpha \times \epsilon$$



How can we study the Higgs-boson couplings?

What we measure

$$\frac{\sigma \times \mathcal{B} \times \alpha \times \epsilon}{\sigma_{\text{SM}} \times \mathcal{B}_{\text{SM}} \times (\alpha \times \epsilon)_{\text{SM}}}$$



How can we study the Higgs-boson couplings?

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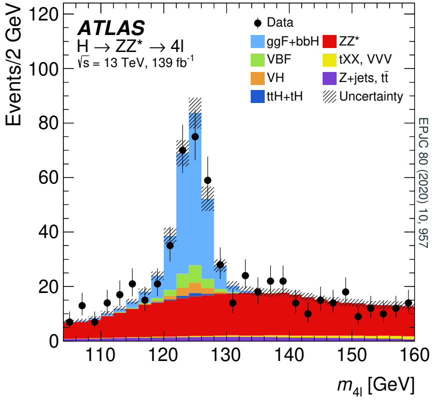
$$\text{signal strength } \mu = \frac{\sigma \times \mathcal{B}}{\sigma_{\mathrm{SM}} \times \mathcal{B}_{\mathrm{SM}}}$$



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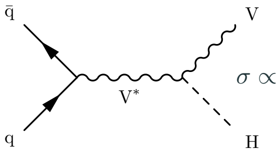
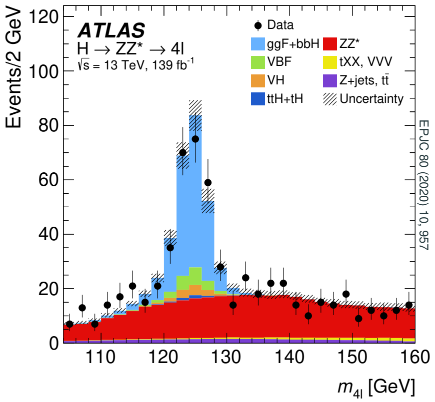
μ depends on the coupling strength



$$\sigma \propto |\text{coupling}|^2$$



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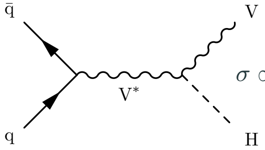

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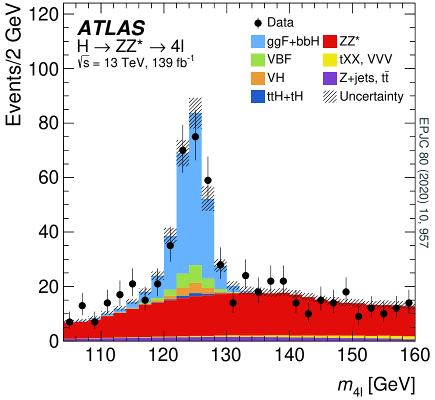
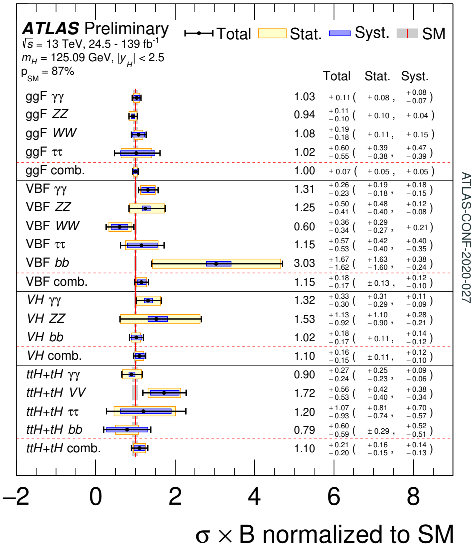


Always measure production $\times$ decay:
$\rightarrow$ cannot unambiguously infer coupling from one measurement

How can we study the Higgs-boson couplings?

Signal strength measured in various different channels
$\rightarrow$ **combine to infer information on couplings**



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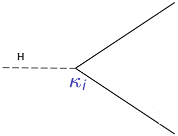
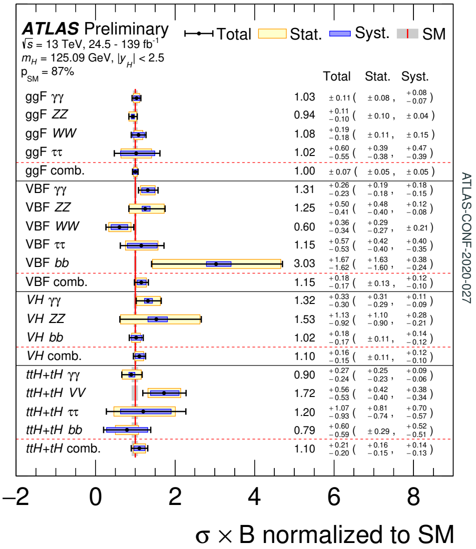
Modify SM Higgs tree-level couplings





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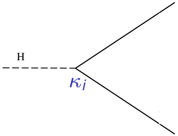

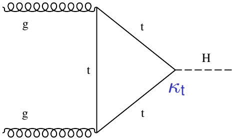

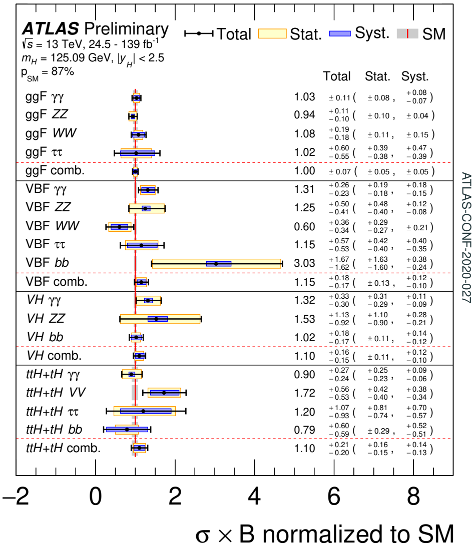

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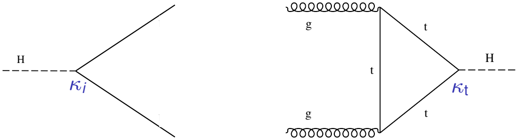
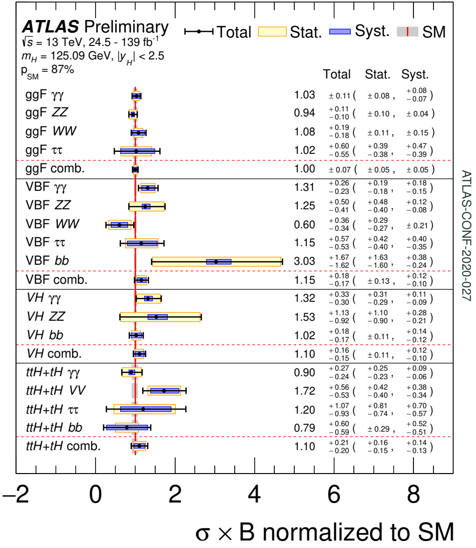
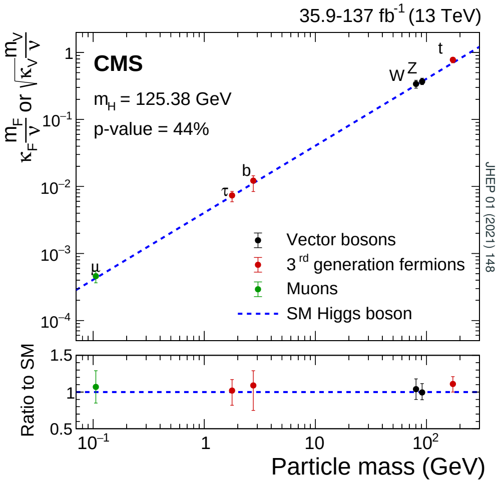


Indirect: need to make model assumptions
Which particles in the loops? Unmeasured decays?

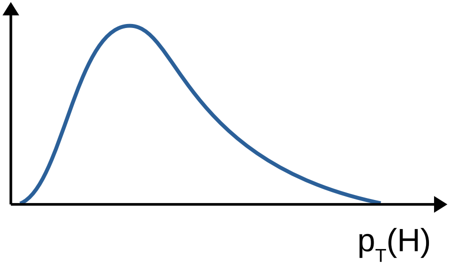


Scaling of coupling strength with particle mass



Excellent agreement with SM expectation over 3 orders of magnitude

Beyond inclusive measurements



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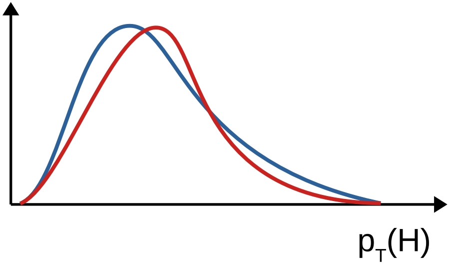
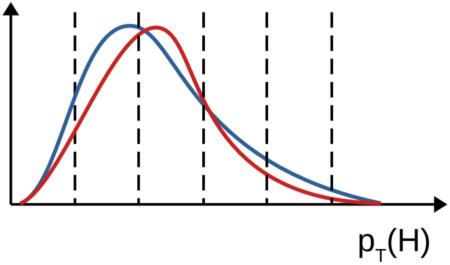


New physics might modify kinematics

Beyond inclusive measurements



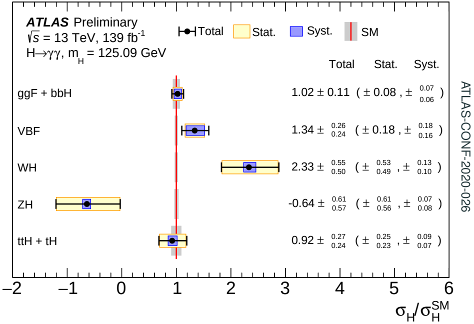
New physics might modify kinematics

Measure differentially!

Simplified Template Cross Sections (STXS)

Target different **production modes**

In each category: measure cross section



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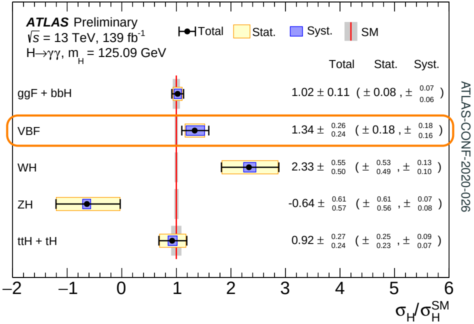
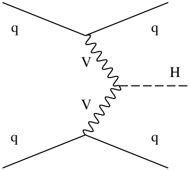
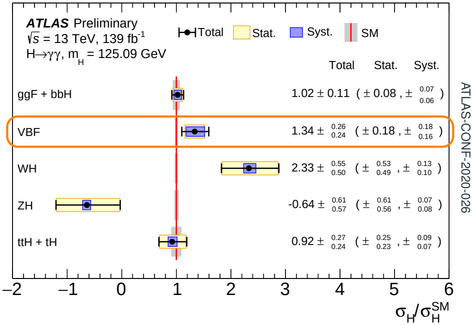


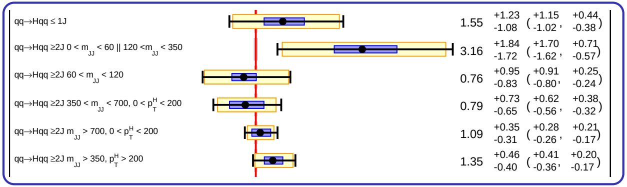


Simplified Template Cross Sections (STXS)

Target different **production modes** and **kinematic regions**

In each category: measure cross section





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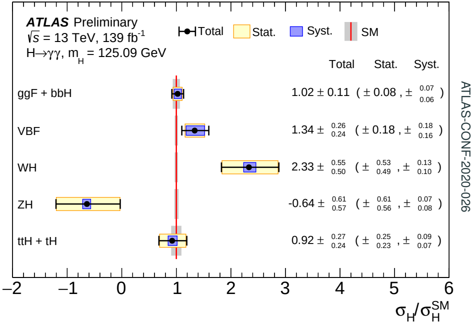
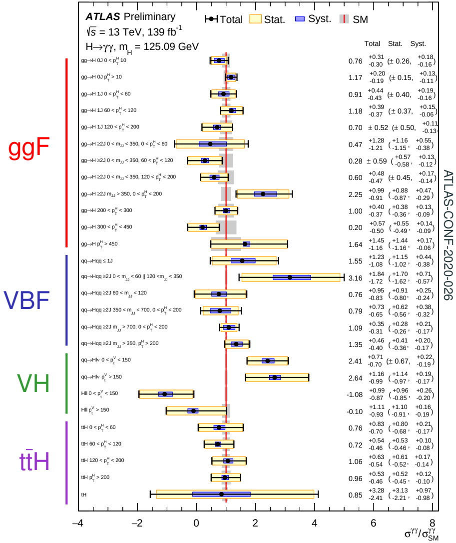
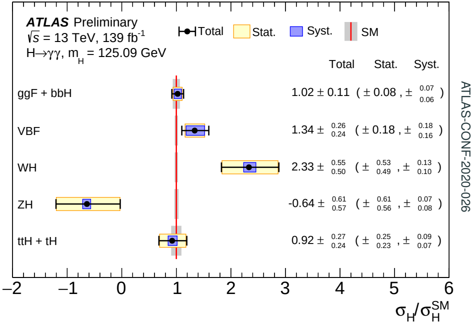


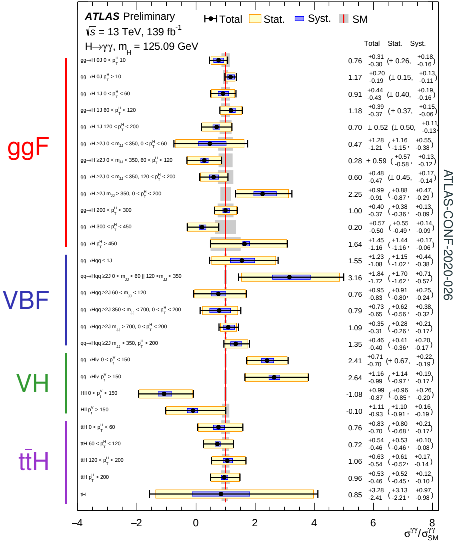


Simplified Template Cross Sections (STXS)

Target different **production modes** and **kinematic regions**

In each category: measure cross section





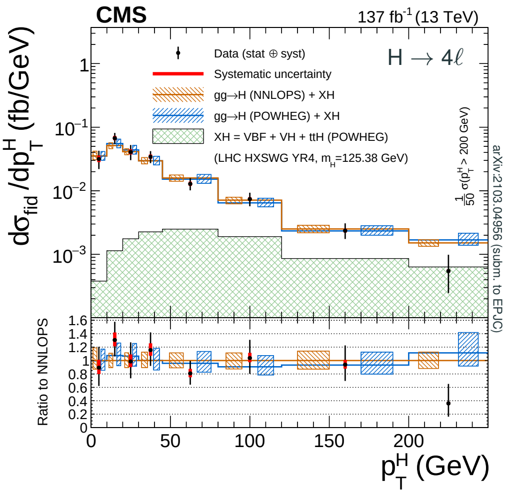
Important step to **reduce model dependence**
in Higgs-boson measurements

Designed for combination across channels and experiments

Differential cross sections

Measurement of specific observables, e. g. $p_T(H)$

Corrected to particle level via **unfolding**



Model-independent measurement
in specific Higgs-boson decay channel

Can be directly compared to theory predictions without detector modelling

Evolution of Higgs-boson measurements

Inclusive signal strength to establish signal

Simplified Template Cross Section

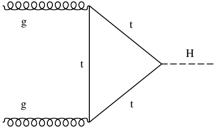
By now in many channels
(with varying granularity)

Differential cross section

Mainly in 4ℓ, $\gamma\gamma$ channels
First results in WW, $b\bar{b}$

Coupling constraints from differential cross section

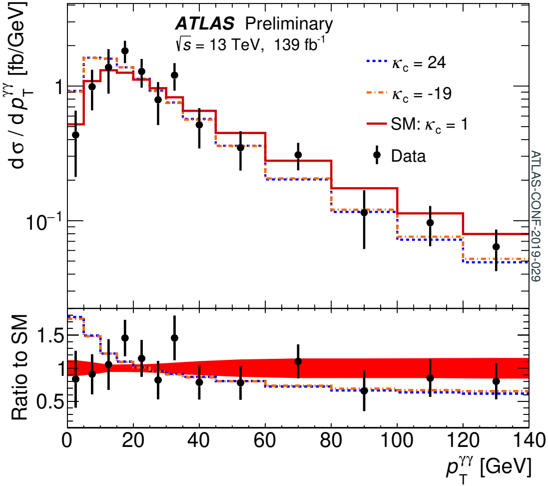
p_T(H) in H $\to \gamma\gamma$



Sensitive to

- new heavy particles in the loop
- other Higgs-boson couplings

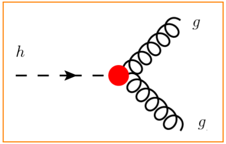
Constraints on couplings not-yet directly accessible



indirect sensitivity to charm-Higgs coupling complementary to direct searches

Interpretation in Effective Field Theories (EFT)

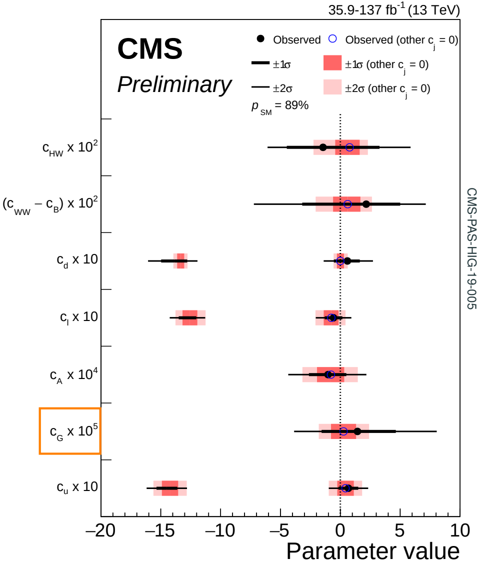
Parameterise all low-energy effects of new physics at higher scales
New couplings of Higgs boson to SM particles



Effect on rate + shape of measured distributions
Differential measurements important!

Constraints e. g. from H $\rightarrow 4\ell/\gamma\gamma$ channels
and combination of STXS measurements
[EPJC 80 (2020) 10, 957] [CMS-PAS-HIG-19-009] [ATLAS-CONF-2020-053] [CMS-PAS-HIG-19-005]

Hot topic: techniques evolve as more data is analysed



1. Measuring properties and couplings of the Higgs boson
2. **Direct measurement of Yukawa interactions**
3. Probing the Higgs potential
4. What is next?

Direct measurement of Yukawa interactions

LHC Run 2: **Observation** of couplings to 3rd-generation fermions by ATLAS and CMS

u	c	t ✓	[Phys. Lett. B784 (2018) 173] [PRL 120 (2018) 231801]
d	s	b ✓	[PLB 786 (2018) 59] [PRL 121 (2018) 121801]
e	μ	τ ✓	[PRD 99 (2019) 072001] [PLB 779 (2018) 283]

First direct measurement of Yukawa interactions

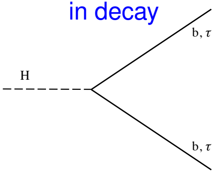
Milestone in probing the Higgs sector and understanding how fermions acquire mass

Direct measurement of Yukawa interactions

LHC Run 2: **Observation** of couplings to 3rd-generation fermions by ATLAS and CMS

u	c	t
d	s	b
e	μ	τ

in decay



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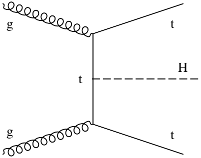
Direct measurement of Yukawa interactions

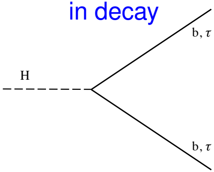
LHC Run 2: **Observation** of couplings to 3rd-generation fermions by ATLAS and CMS

u	c	t
d	s	b
e	μ	τ

in $t\bar{t}$H production



in decay

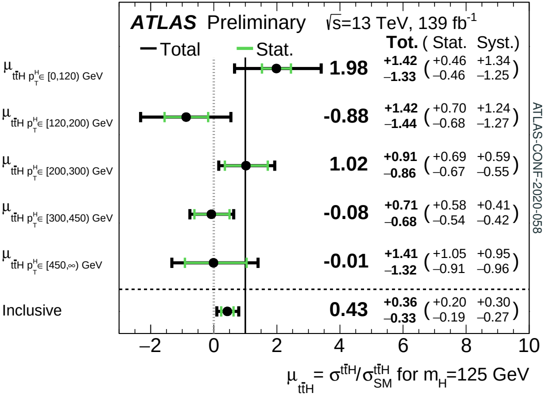


First direct measurement of Yukawa interactions

Milestone in probing the Higgs sector and understanding how fermions acquire mass

Coupling to top quarks: $t\bar{t}H$ production

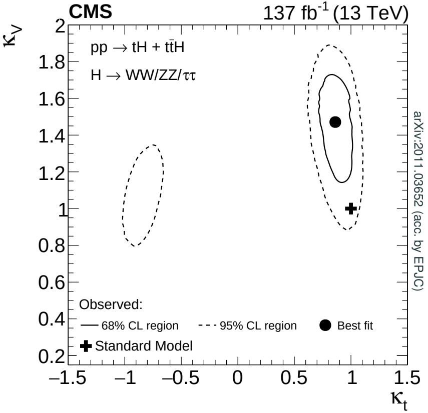
$H \rightarrow b\bar{b}$ channel $1.3\,\sigma$ (3.0 exp.)



First $t\bar{t}H(b\bar{b})$ measurement differential in $p_T(H)$

multi-lepton channel $4.7\,\sigma$ (5.2 exp.)

targets $H \rightarrow WW^*, \tau\tau, ZZ^*$ decays (w/o 4ℓ)



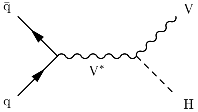
Combined measurement of $t\bar{t}H$ + tH production

$\rightarrow$ sensitivity to sign of top-Higgs coupling

Coupling to bottom quarks: $H \rightarrow b\bar{b}$

Dominant decay channel but **huge QCD-multijet background**

Best sensitivity: VH channel, has driven observation



Coupling to bottom quarks: $H \to b\bar{b}$

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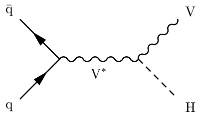
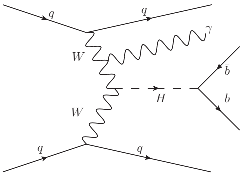
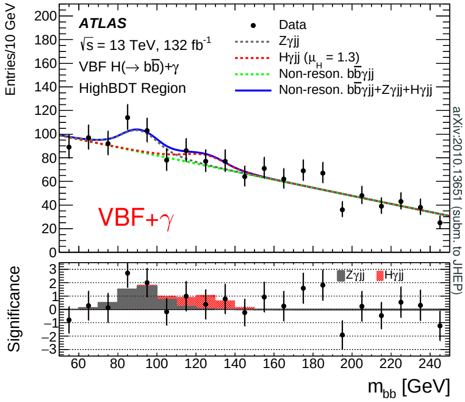


Other channels also accessible, e. g. boosted ggF or VBF

New approaches: VBF+γ (Hγ forbidden in ggF)





Significance 1.3 σ (1.0 exp.)

CP structure of Yukawa couplings

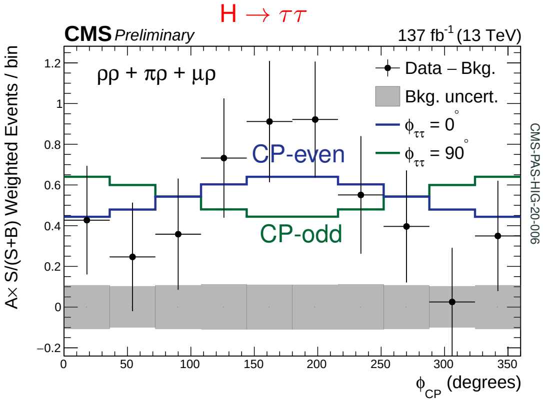
Yukawa interaction: CP-odd component at tree-level in principle allowed

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

CP-even/CP-odd Yukawa coupling

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

$\rightarrow$ **can modify kinematics of decay products and associated particles**

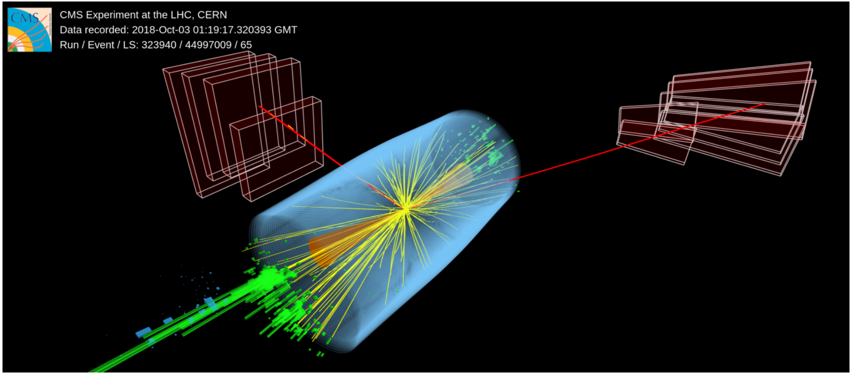


$\mathrm{H} \rightarrow \tau\tau$ and $\mathrm{t\bar{t}H}$ ($\mathrm{H} \rightarrow \gamma\gamma/4\ell$): **first test of CP structure of Higgs-fermion couplings**

Pure CP-odd hypothesis excluded at $3\,\sigma$ level

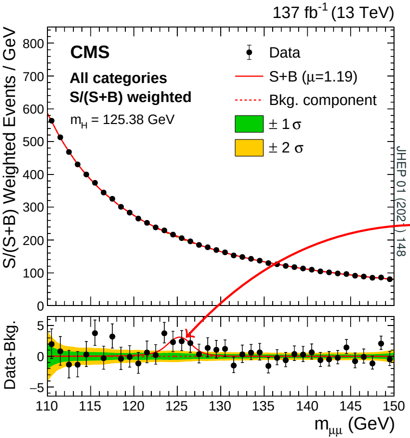
[CMS-PAS-HIG-20-006] [PRL 125 (2020) 6, 061802] [PRL 125 (2020) 6, 061801] [CMS-PAS-HIG-19-009]

The next generation: H $\rightarrow \mu\mu$



Rare decay with $\mathcal{B} \approx 2 \cdot 10^{-4}$ + large irreducible background from Drell-Yan production

The next generation: H $\rightarrow \mu\mu$



3.0 σ significance

(2.5 expected)

Another milestone in probing the Yukawa sector

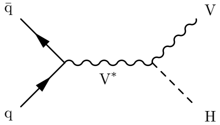
First evidence that the Higgs boson couples to 2nd generation fermions

Search for $H \to c\bar{c}$

Large **background from QCD**

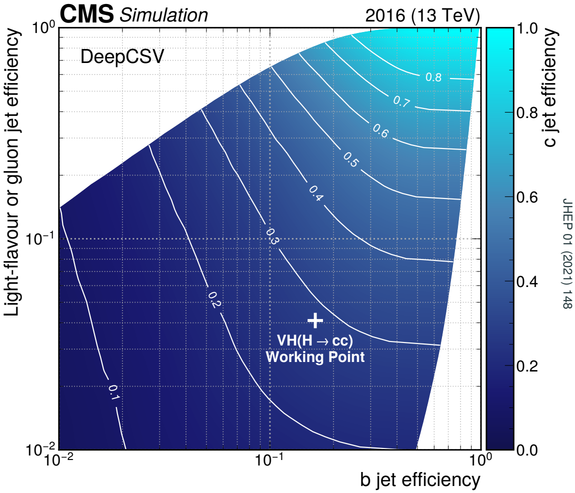
Identification of c-quark jets critical

Direct searches in VH channel



Limit $\sigma(\mathrm{VH})\mathcal{B}(\mathrm{H} \to c\bar{c}) < 70$ (37 exp.) $\times$ SM

(with partial Run 2 dataset)



Direct measurement of Yukawa interactions: status

u	c	t ✓
d	s	b ✓
e	μ	τ ✓

✓ observation

Direct measurement of Yukawa interactions: status

u	c	t ✓
d	s	b ✓
e	μ	τ ✓

✓ observation

3rd generation: increasing precision

STXS measurements in all channels

CP measurements in $H \rightarrow \tau\tau$ and $t\bar{t}H$

Direct measurement of Yukawa interactions: status

u	c ✓	t ✓
d	s	b ✓
e	μ ✓	τ ✓

✓ observation
✓ evidence

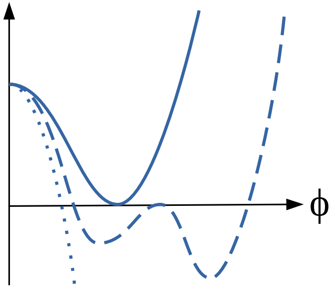
3rd generation: increasing precision
STXS measurements in all channels
CP measurements in $H \to \tau\tau$ and $t\bar{t}H$

Entering the 2nd generation
Evidence for $H \to \mu\mu$ decays
Searches for $H \to c\bar{c}$ ($< 70 \times$ SM)

Higgs-boson self-coupling

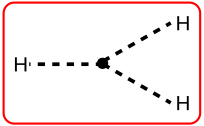
Self-coupling λ related to the shape of the Higgs potential:

- responsible for electroweak symmetry breaking
- implications for the stability of the vacuum



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

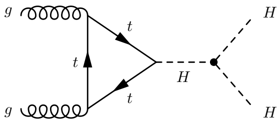
$$V(\mathrm{H}) = -\tfrac{1}{2} m_{\mathrm{H}} \mathrm{H}^2 + \boxed{\lambda v \mathrm{H}^3} + \tfrac{1}{4}\lambda \mathrm{H}^4$$



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

Higgs-boson pair production at the LHC

Rare process in the SM: $\sigma_{\mathrm{HH}} \approx 33.5\,\mathrm{fb}$ at $13\,\mathrm{TeV} < \mathbf{10^{-3}}$ **of single-H production**



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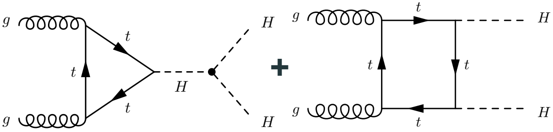
Negative interference suppresses cross section



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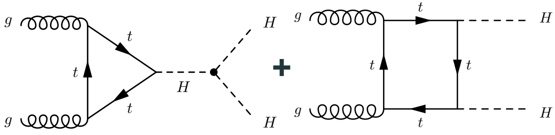
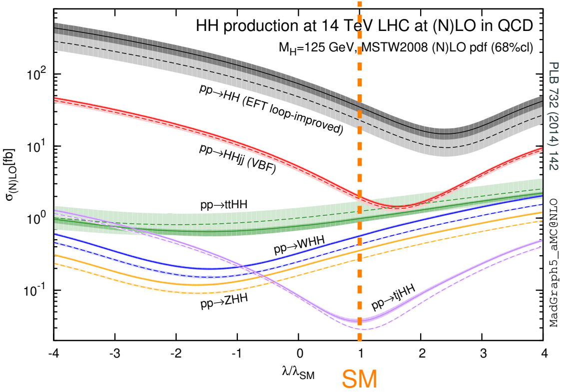


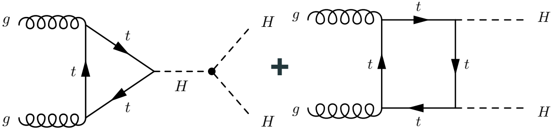
But **highly sensitive** to variations of self-coupling



Higgs-boson pair production at the LHC

Rare process in the SM: $\sigma_{\mathrm{HH}} \approx 33.5\,\mathrm{fb}$ at 13 TeV $<$ **10^{-3} of single-H production**

Negative interference suppresses cross section



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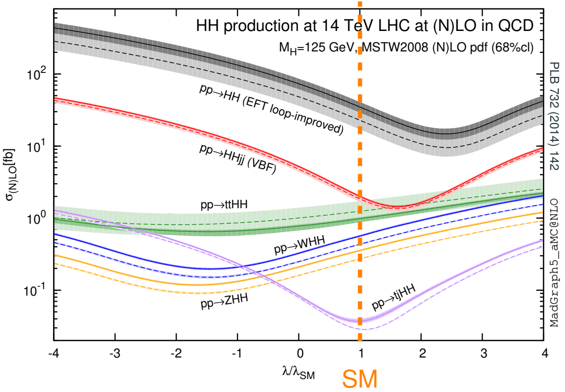
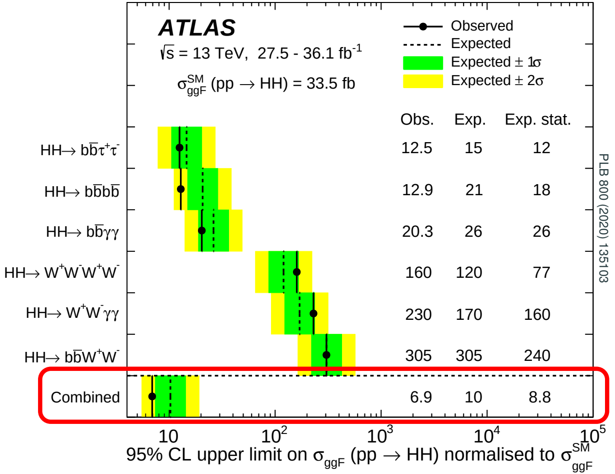


Observing HH production now → new physics!

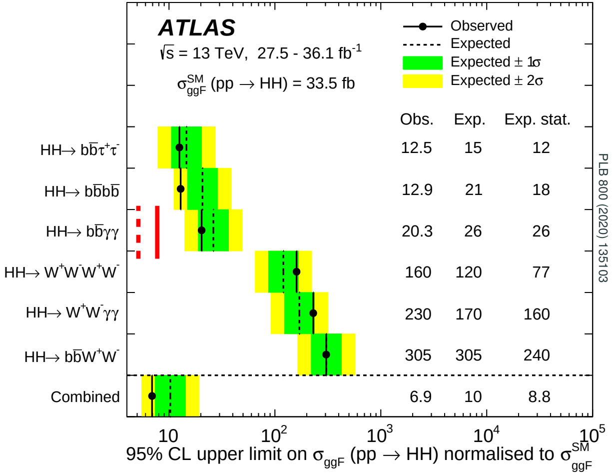
Where do we look for HH production?



Searches in different HH final states, typically at least one $H \to b\bar{b}$ decay

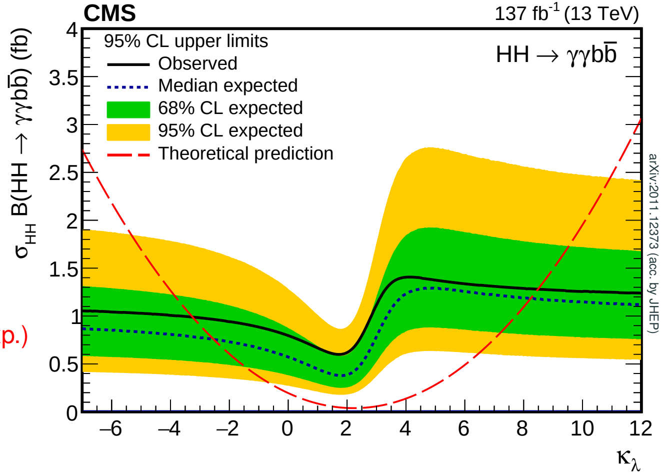
Where do we look for HH production?

Full Run 2 dataset
7.7 (5.2 expected)
arXiv:2011.12373 (acc. by JHEP)



Searches in different HH final states, typically at least one H $\to b\bar{b}$ decay

Constraints on Higgs-boson self-coupling

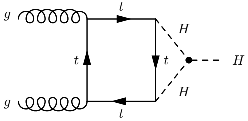


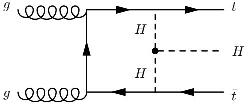
$-3.3 < \kappa_\lambda < 8.5$
$-2.5 < \kappa_\lambda < 8.2$ (exp.)

Limits on HH cross-section $\rightarrow$ **limits on self-coupling** (assuming $\kappa_t = 1$)

Self-coupling from single-Higgs production

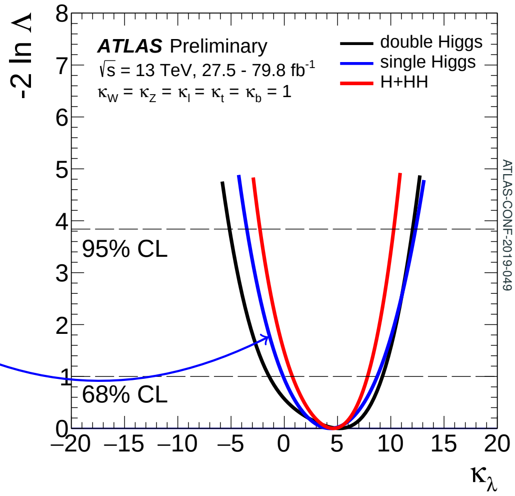
Single-H production indirectly sensitive to λ via higher-order corrections





Constraints on λ from combination of single-H coupling measurements

Similar sensitivity to direct HH searches



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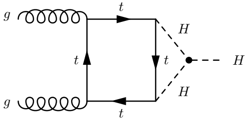
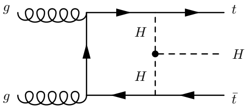
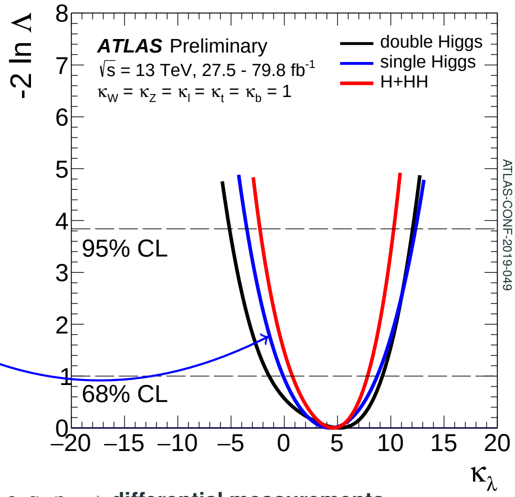






Constraints on λ from combination of single-H coupling measurements

Similar sensitivity to direct HH searches

Enhanced sensitivity from kinematic observables, e. g. $p_T \rightarrow$ **differential measurements**

1. Measuring properties and couplings of the Higgs boson
2. Direct measurement of Yukawa interactions
3. Probing the Higgs potential
4. **What is next?**

What is next?

95 % of the data still to come
We are just at the beginning!

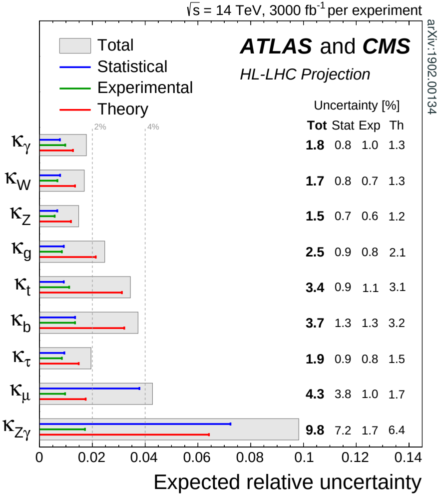
A bright future for Higgs-boson measurements!

Expected performance at the High Luminosity LHC:

- Precision of coupling measurements at few-% level
- Not-yet discovered decays:
  Observation of H $\rightarrow \mu\mu$ and H $\rightarrow Z\gamma$
- Testing the shape of the Higgs potential:
  HH production at 4 σ significance

Projections based on the current state-of-the-art

We will work hard to do even better!



Conclusions

The Higgs boson is special!
Has properties and interactions never seen before

J. Cham

Unprecedented precision with large LHC Run 2 datasets
challenging the SM

- Differential measurements
- Direct measurements of Yukawa interactions
- Starting to probe the Higgs potential

Important contributions by German institutes

Much more data to come: **truly exciting Higgs-physics times ahead of us!**

The Higgs boson: a special particle!