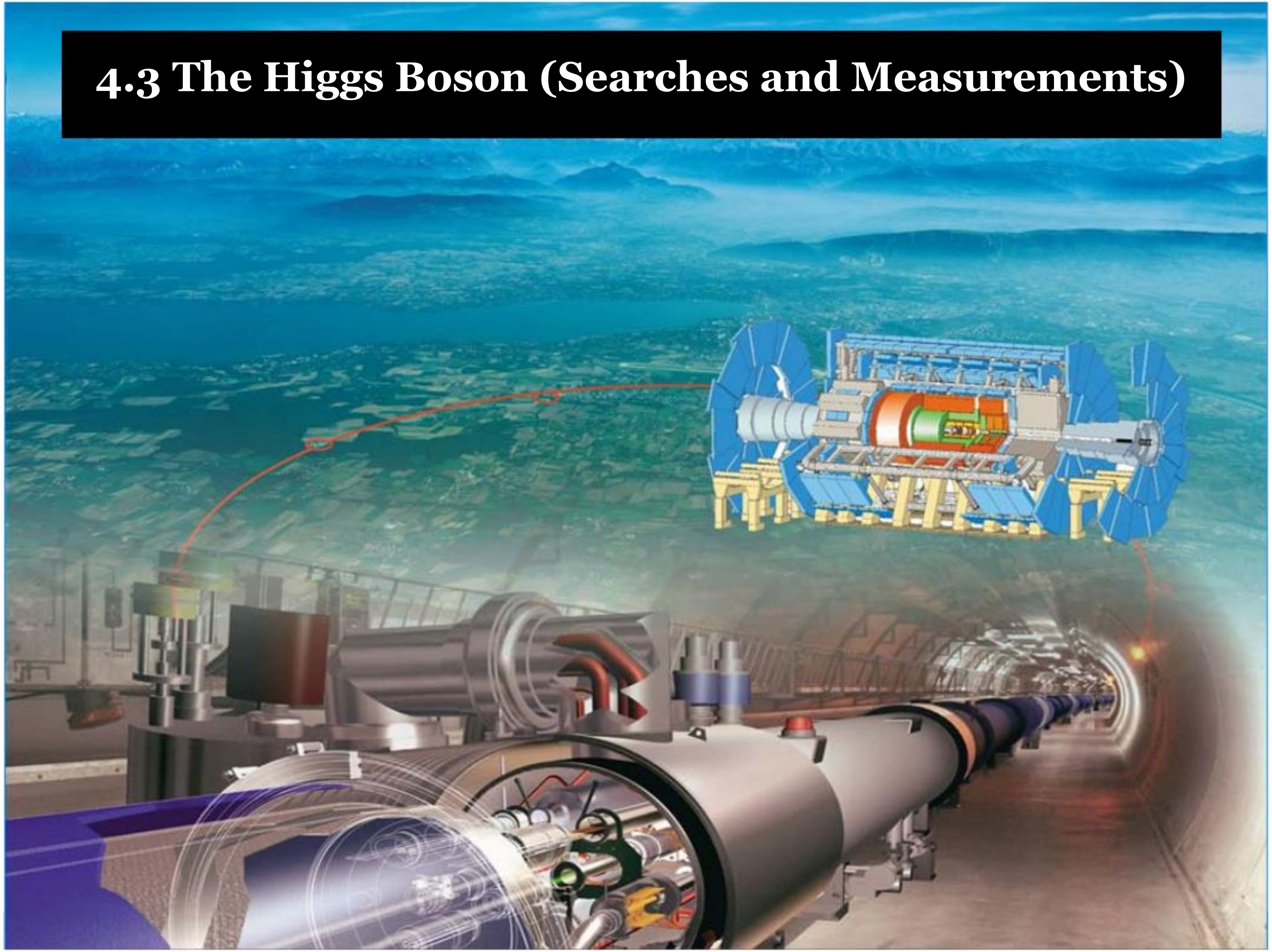
Testing the Standard Model of Elementary Particle Physics II

4th lecture

Dr. Dominik Duda

20th May 2021

4.3 The Higgs Boson (Searches and Measurements)



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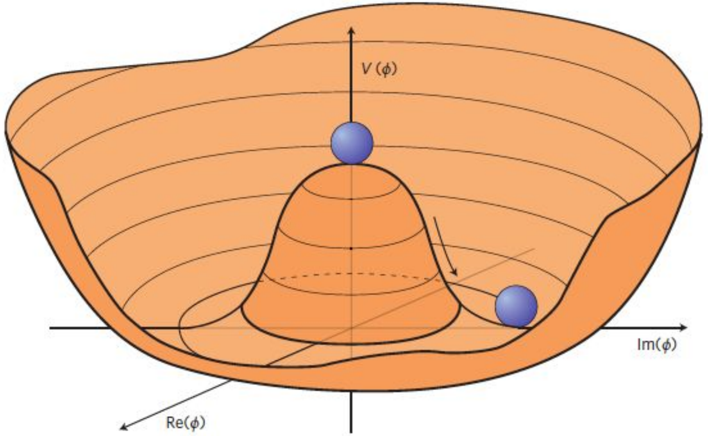
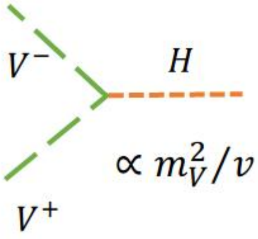
The Higgs boson: Last puzzle piece of the SM

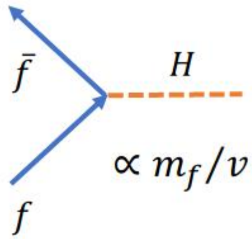
- Particles acquire mass via coupling to Higgs field (spontaneous symmetry breaking)
  - Postulated in 1964
  - Higgs boson (excitation of the Higgs field) was finally discovered in 2012



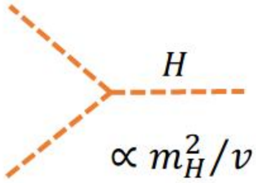
Gauge coupling:



Yukawa coupling:



Self coupling:



- **Higgs-potential**:

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

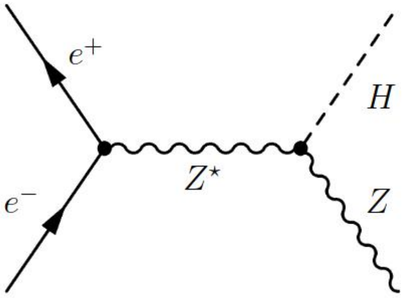
- **Vacuum expectation value**

$$v = \frac{\mu}{\sqrt{\lambda}}$$

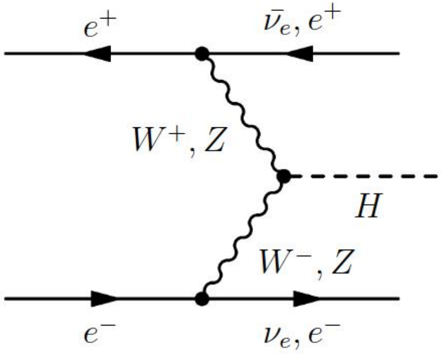
Higgs boson production at LEP

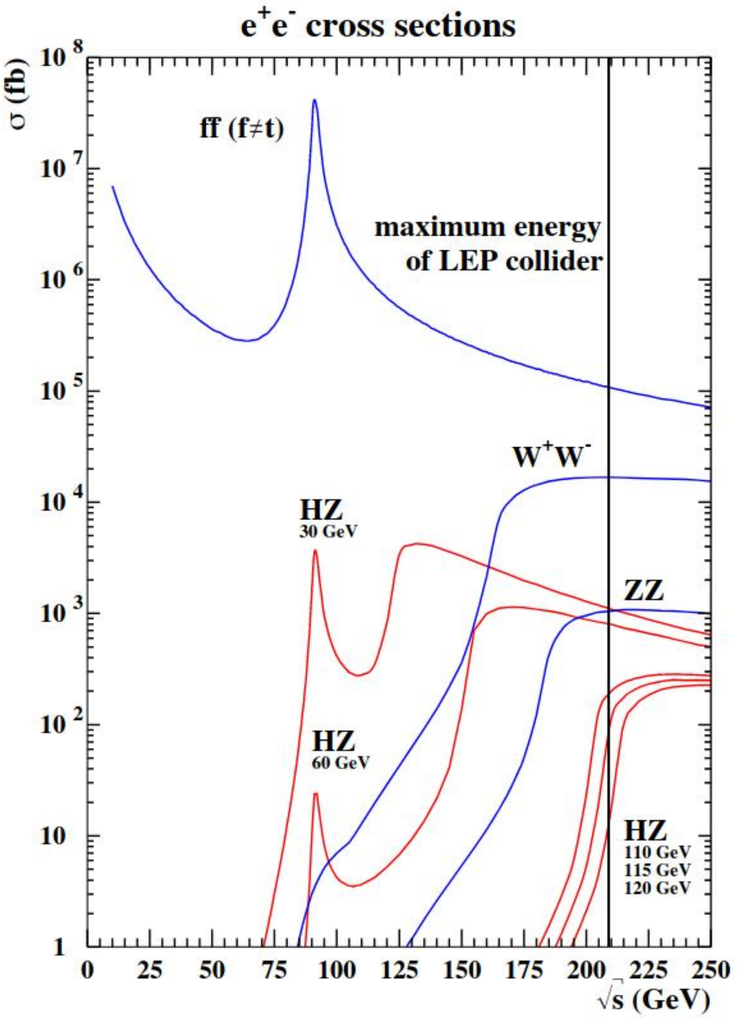
- Higgs Strahlung was dominant production mode at LEP
  - Since CoM was smaller than $m_H + m_Z$ HZ production was only possible with off-shell Z boson

Higgs Strahlung

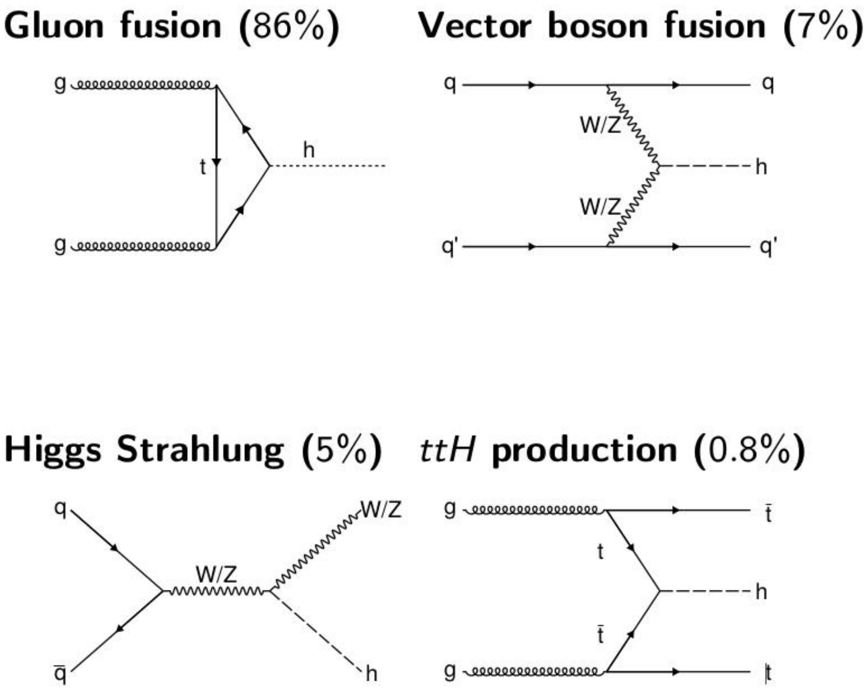


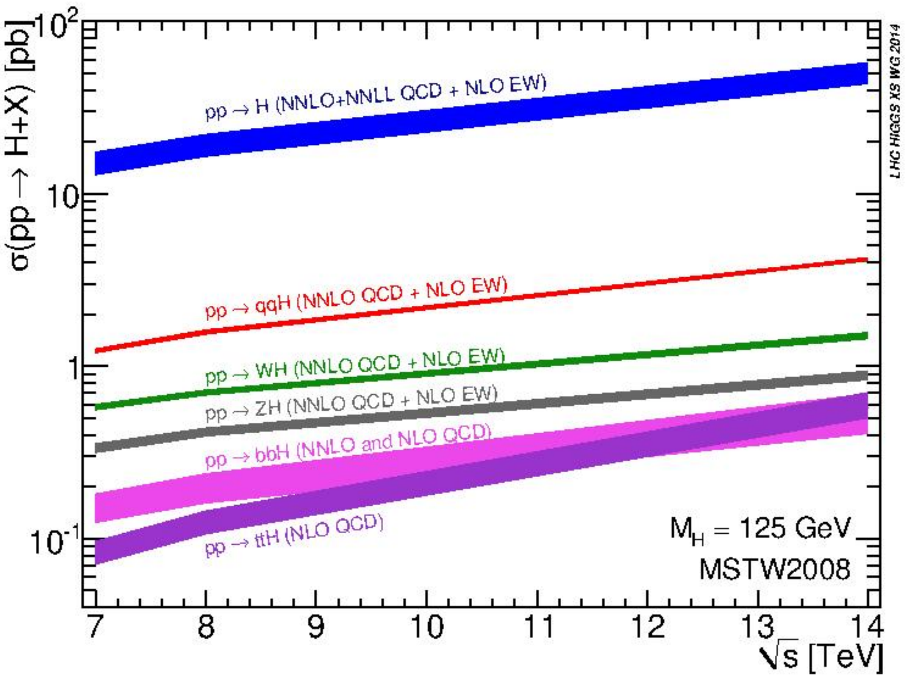
Vector boson fusion





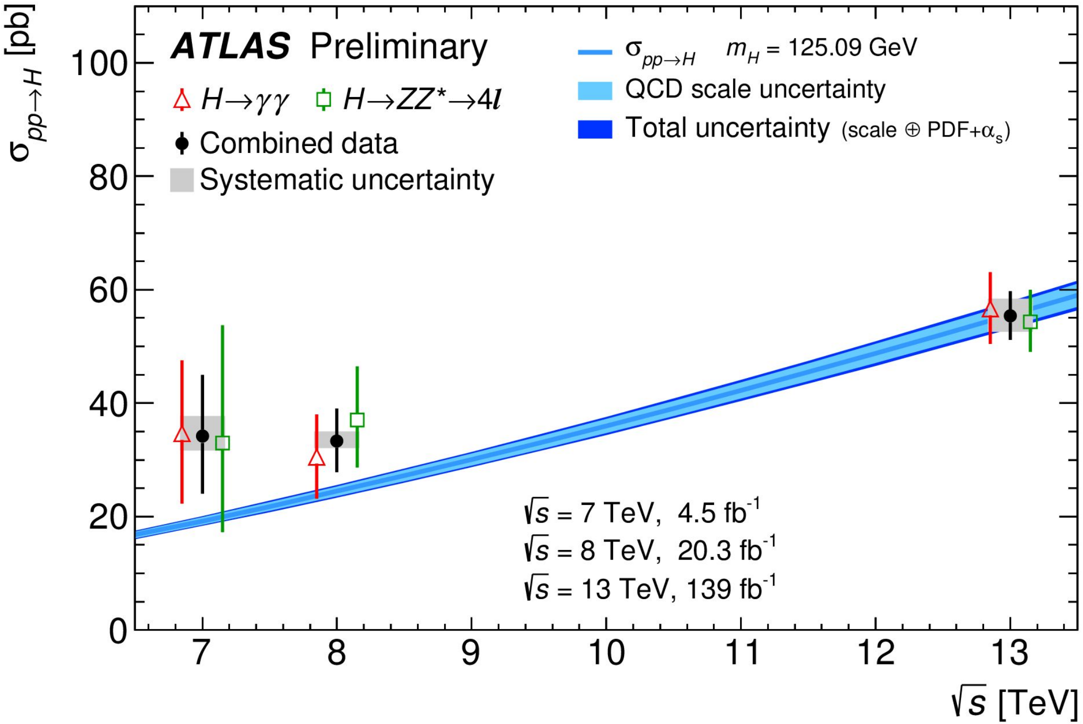
Higgs boson production at the LHC

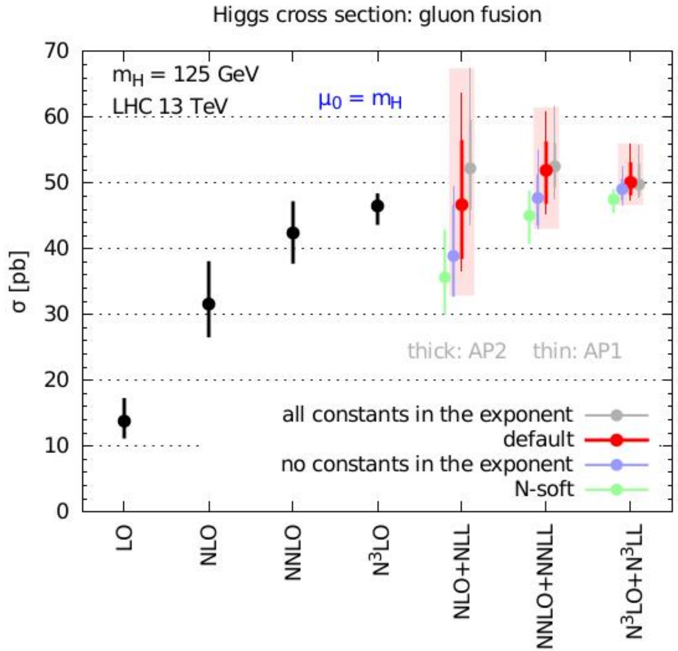




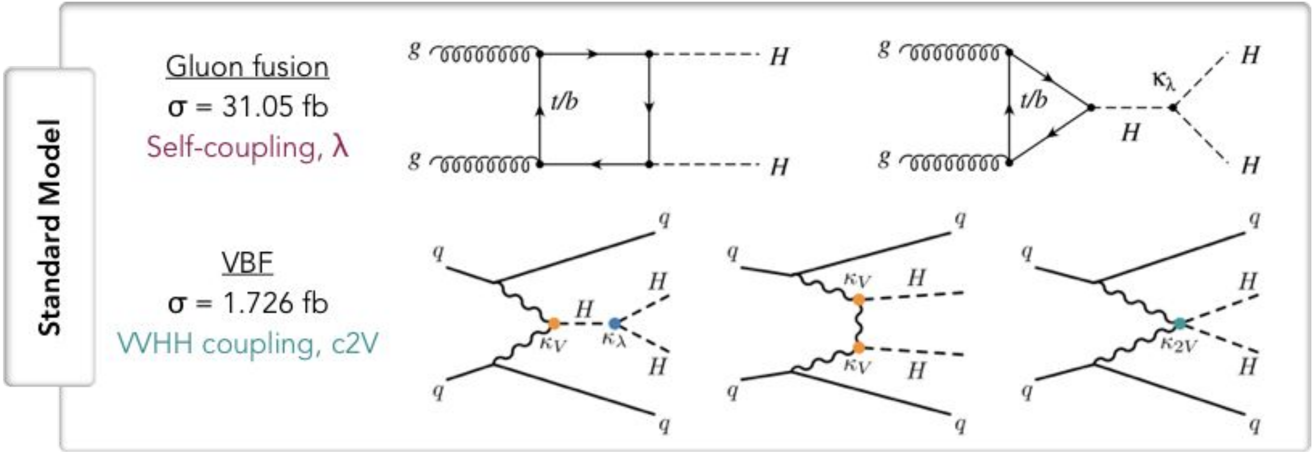
- All main production modes are probed at the LHC

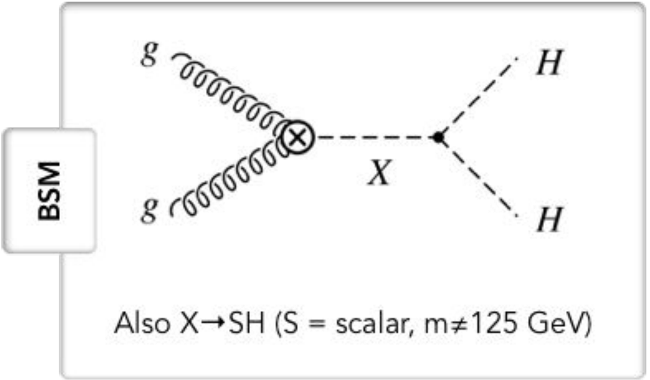
Higgs boson production cross section





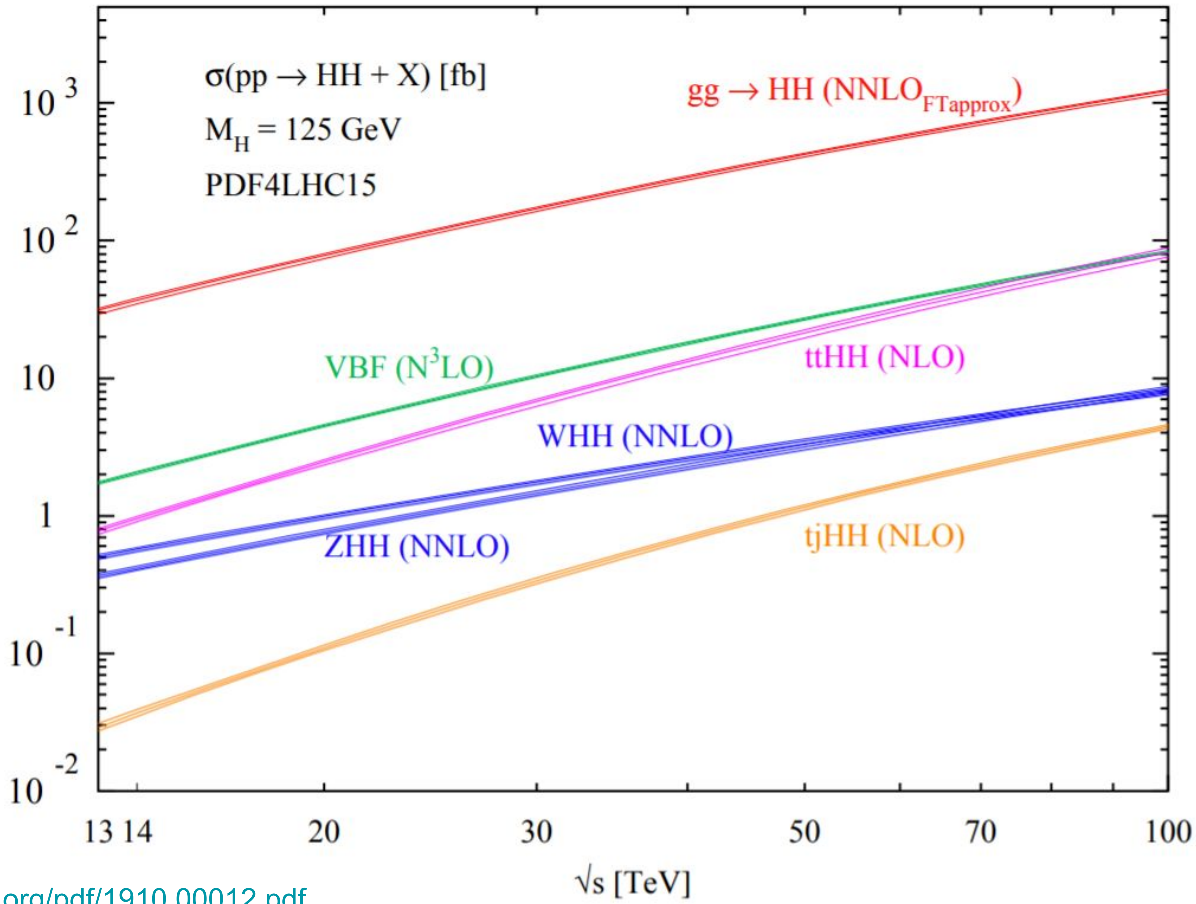
Di-Higgs boson production at the LHC





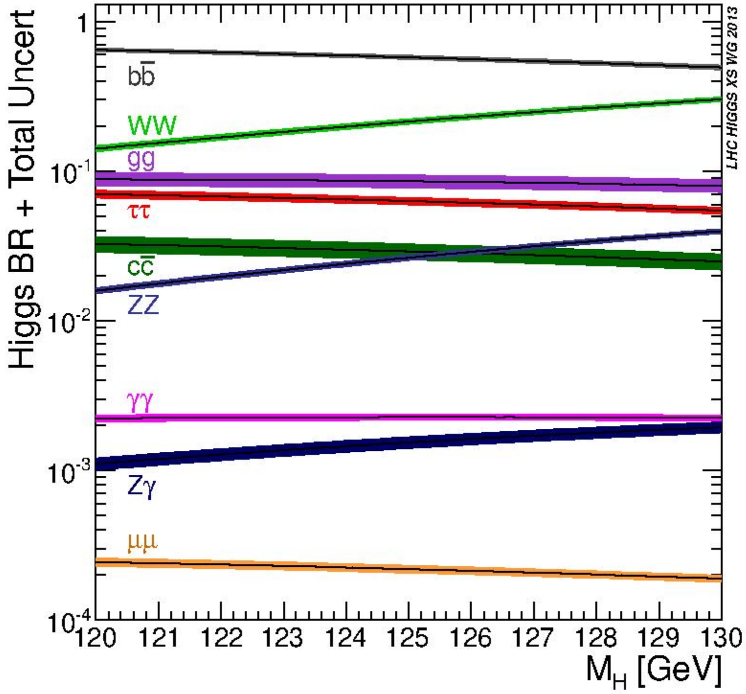
- Probing the Di-Higgs production modes will further our understanding of the SM
  - Parameter of interests:
    - **Self-coupling κ_λ**
    - **Quartic VVHH coupling κ_{2V}**
  - Probing the self-coupling of the Higgs boson allows us to verify the form of the Higgs potential
  - **Sensitive to contribution from BSM physics**

Di-Higgs boson production cross section



Taken from: https://arxiv.org/pdf/1910.00012.pdf

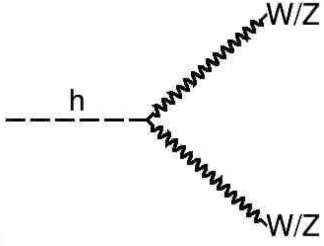
Higgs boson decay



Decay mode	Branching fraction [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW^*$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ^*$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

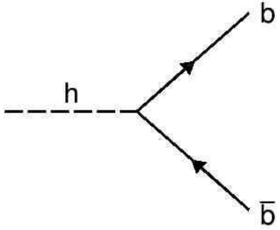
- **Some channels with low BR have a clean signature in the detector**
  - e.g. H → ZZ and H → yy

Higgs boson decays

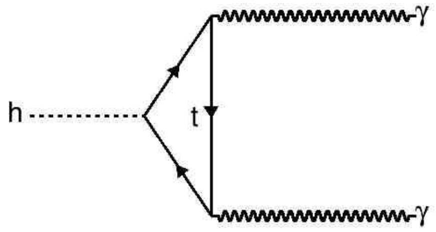


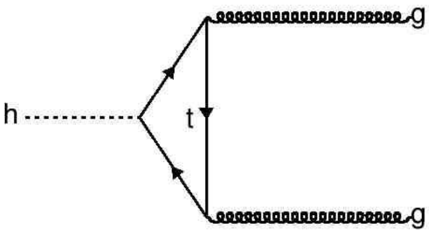
- Strength of the coupling between the Higgs boson and other particles is proportional to the particle mass:

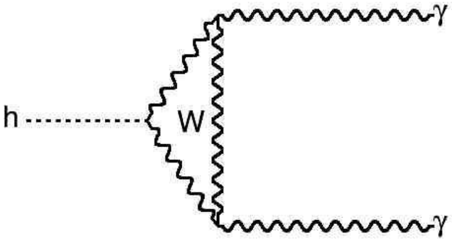
$$\mathcal{L}_{Hff} = -\frac{m_f}{v} h f \bar{f} \qquad \text{and} \qquad \mathcal{L}_{HVV} = \frac{1}{v}\left(2m_W^2 W_\mu^+ W^{-\mu} + 2m_Z^2 Z_\mu Z^\mu\right) h$$

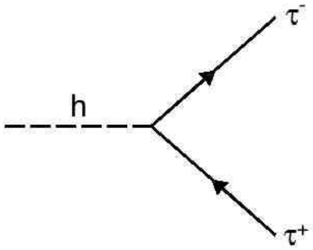


- Thus decays to massless particles such as photon or gluons is only possible via top quark (or W boson) loops
- The masses of the particles running in these loops are large and thus such decay modes can compete with decays to fermions or W and Z bosons

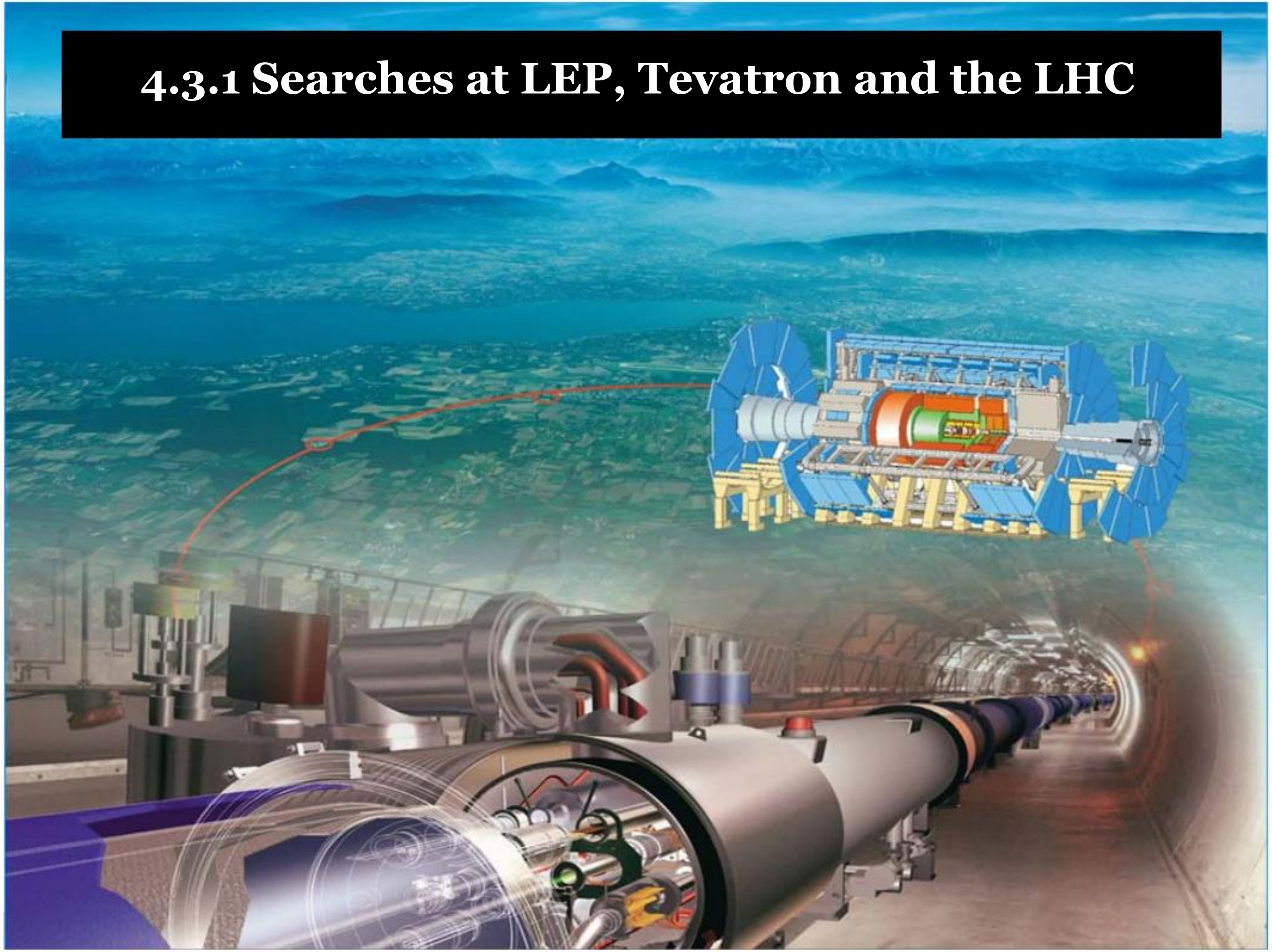




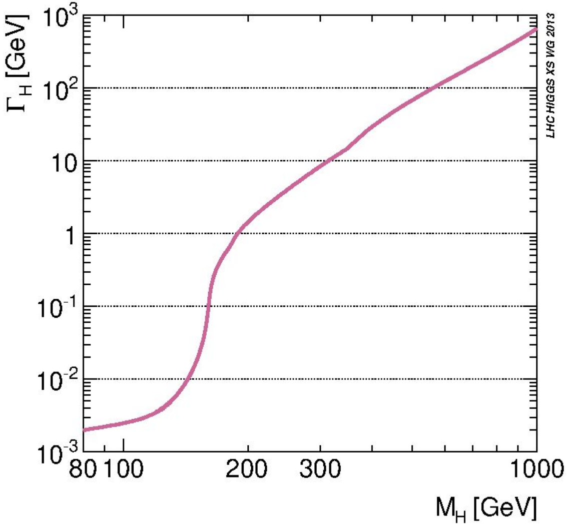


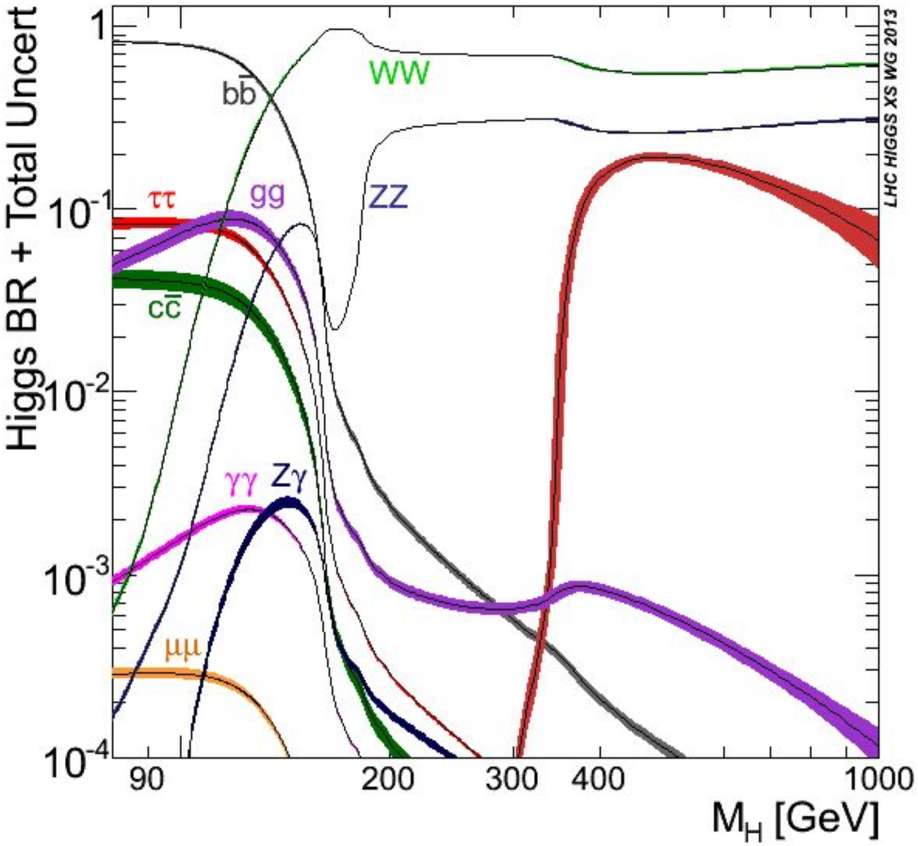


4.3.1 Searches at LEP, Tevatron and the LHC



Higgs boson searches at the LEP and Tevatron

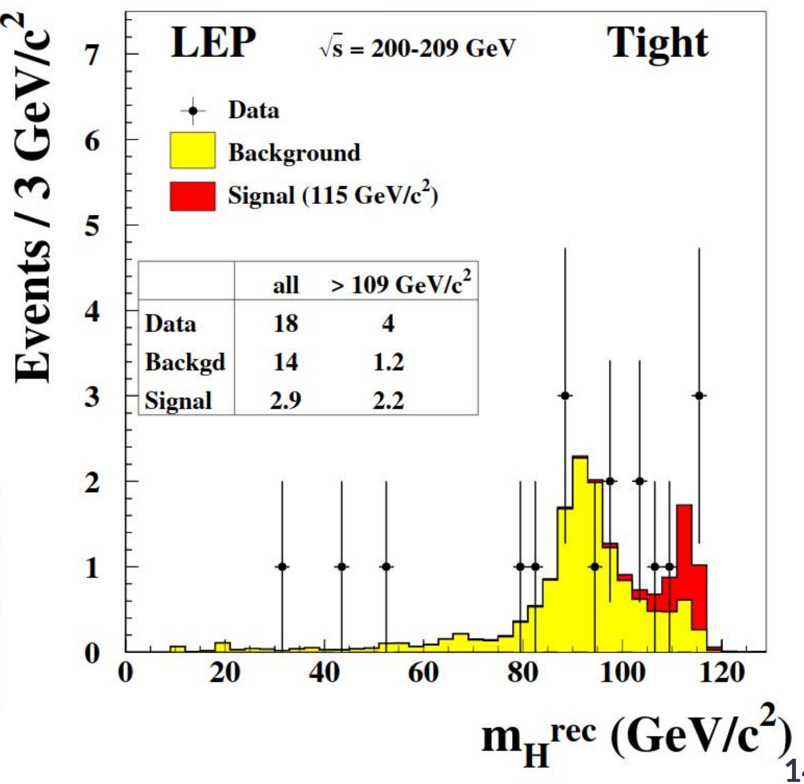




- Search for SM Higgs boson had to cover large range of masses
  - Properties of Higgs boson change significantly as a function of the mass

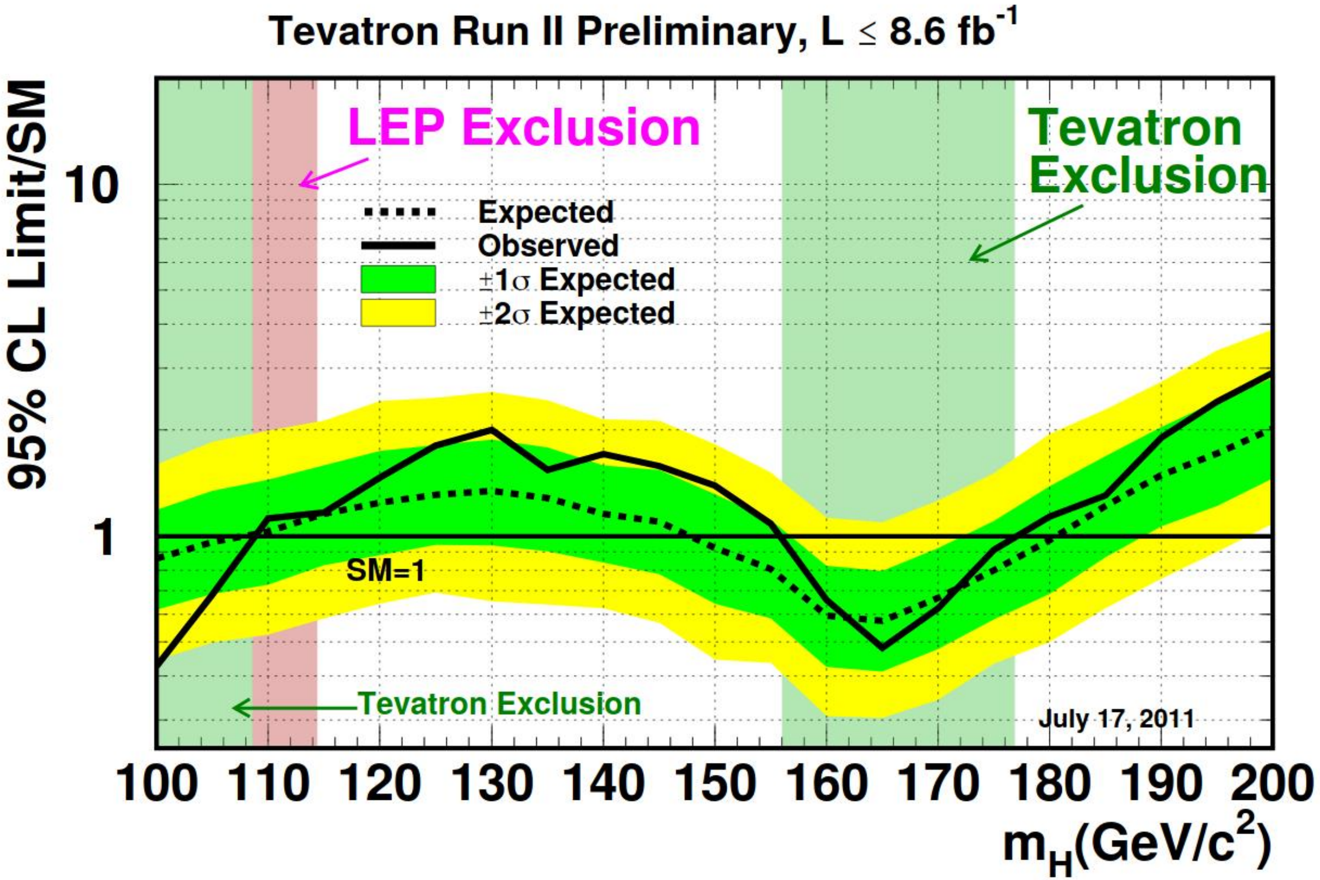
Higgs boson searches at the LEP and Tevatron

- Extensive searches for the Higgs boson have been performed at LEP
  - Found small **excess of h → bb candidate events**
  - Significance of signal events over background expectations reached two standard deviations
  - Integrated luminosity and CoM energy were not large enough for an observation



Integrated luminosities in pb^{-1}					
	ALEPH	DELPHI	L3	OPAL	LEP
$\sqrt{s} \geq 189$ GeV	629	608	627	596	2461
$\sqrt{s} \geq 206$ GeV	130	138	139	129	536

Higgs boson searches at the LEP and Tevatron

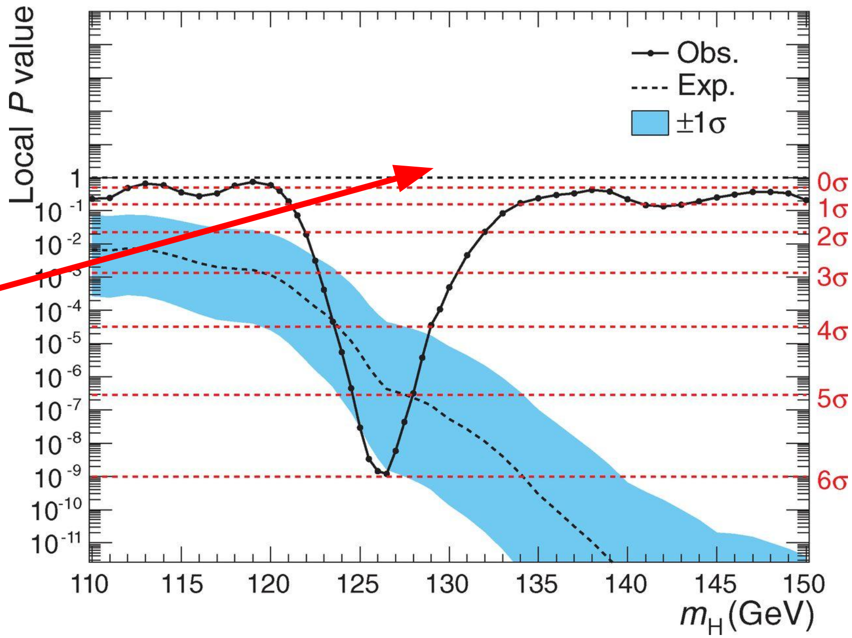


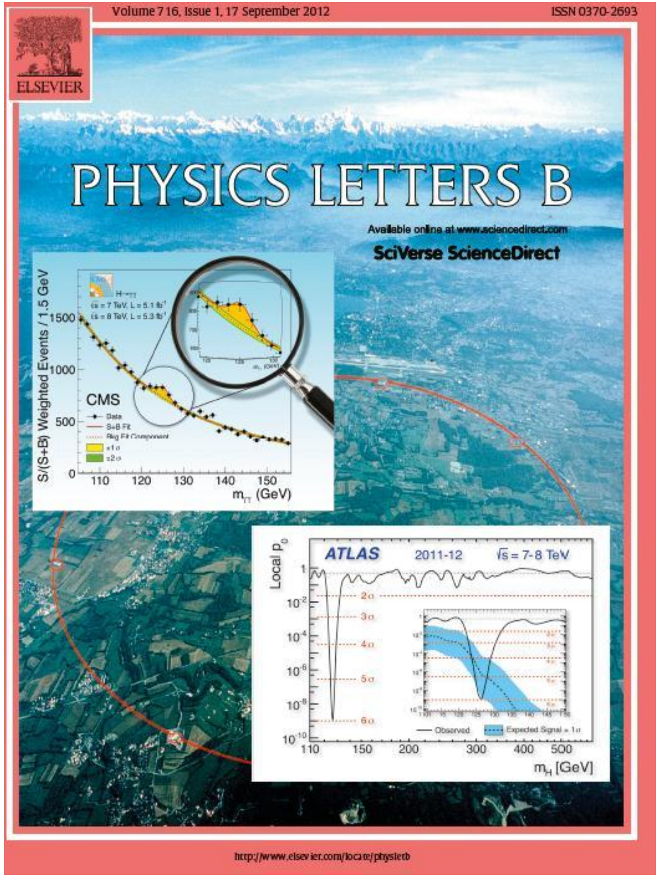
Discovery of the Higgs boson

- Discovery of a new particle compatible with the SM Higgs boson was published by the ATLAS and CMS collaborations in the Summer of 2012
  - Based on data from the 7 and 8 TeV runs of the LHC in the years 2010-2012

Combination of:

- **H → γγ**
- **H → ZZ***
- **H → WW***





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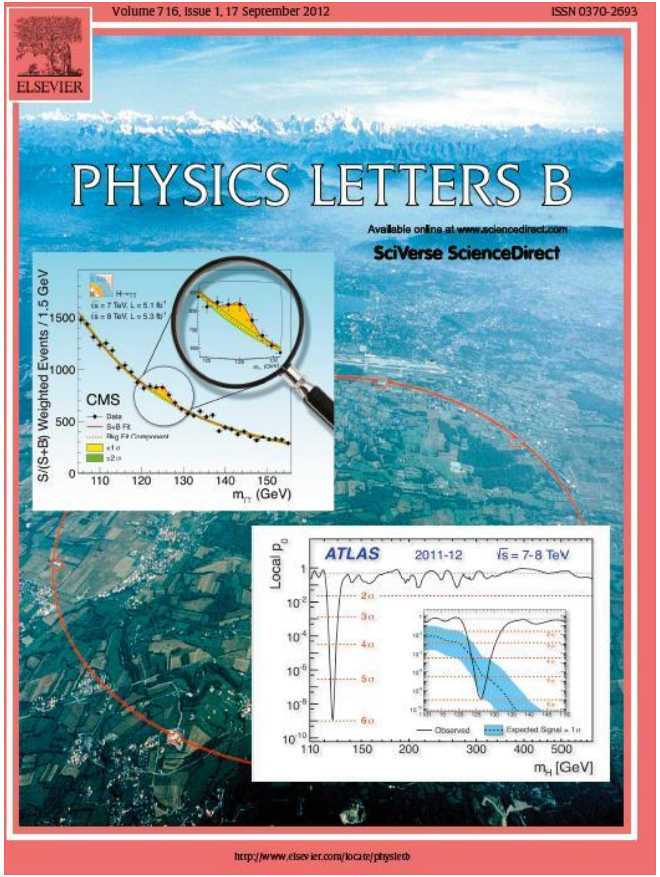
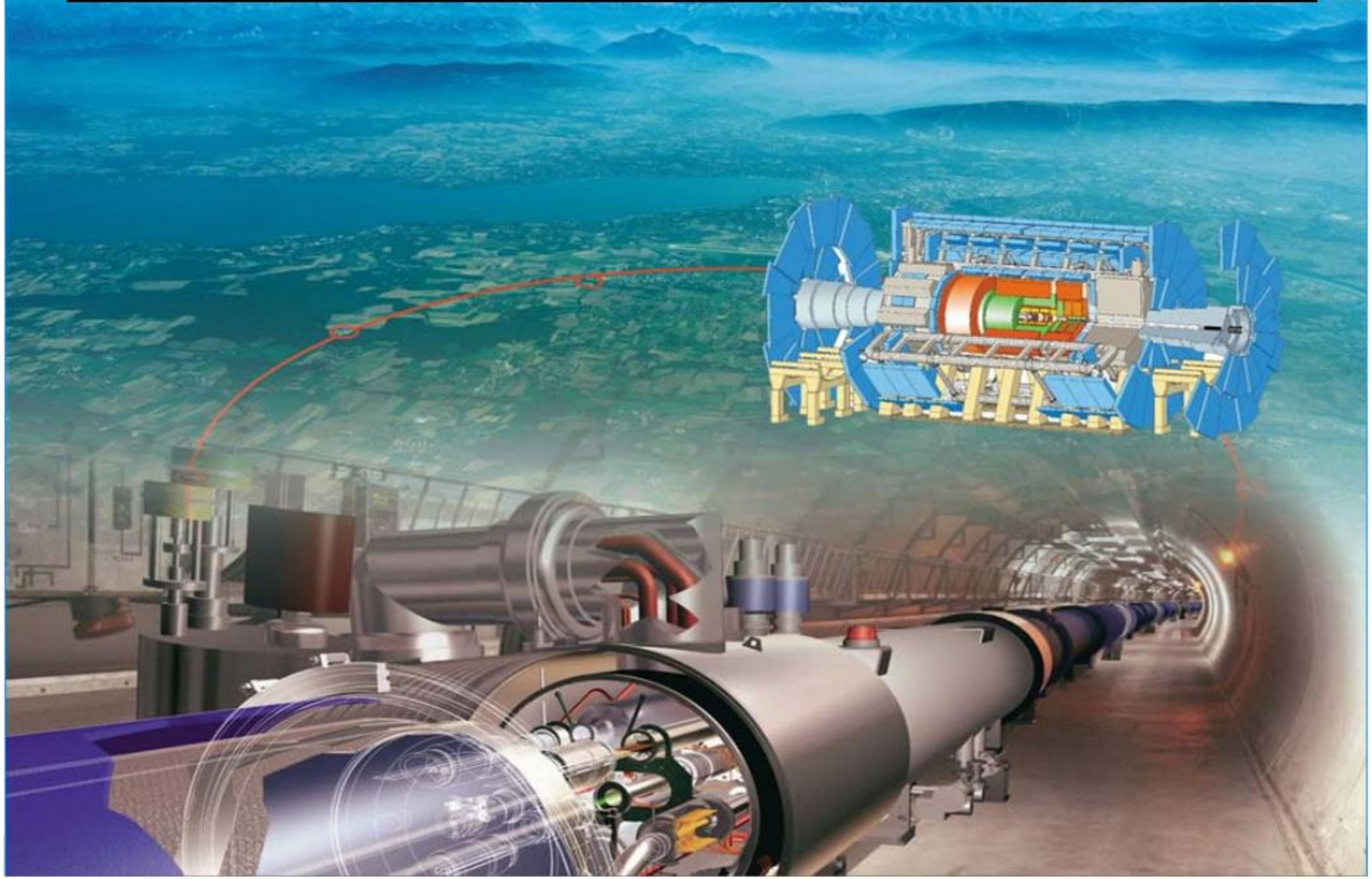
Channel	July 2012
$H \to \gamma\gamma$	4.5σ
$H \to ZZ^{(*)} \to 4\ell$	3.6σ
$H \to WW^{(*)} \to \ell\nu\ell\nu$	2.8σ
$H \to \tau\tau$	no excess
$H \to bb$	no excess

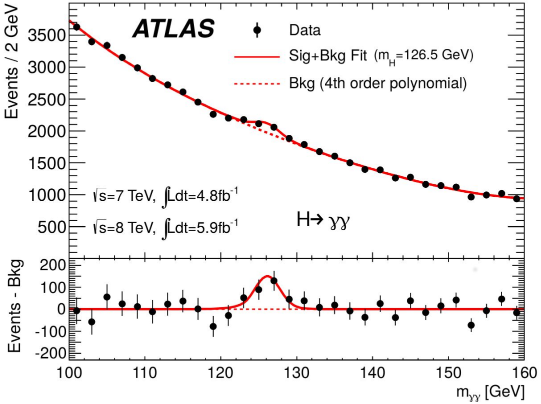


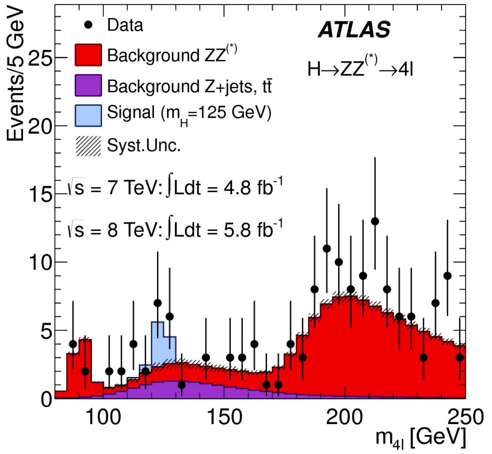
4.3.2 Measurements of Higgs boson properties



Higgs boson properties

- So far all measurements of the Higgs boson properties are consistent with the SM
  - Spin and CP state of the Higgs-boson are determined probing angular distribution of decay products
    - ATLAS data hints very strongly to a Spin^{CP} state of 0^+
    - Alternative models are rejected with a CL of more than 99.9%
- Higgs-boson mass measured by ATLAS and CMS:
  $m_H = 125.09 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{syst})$ GeV





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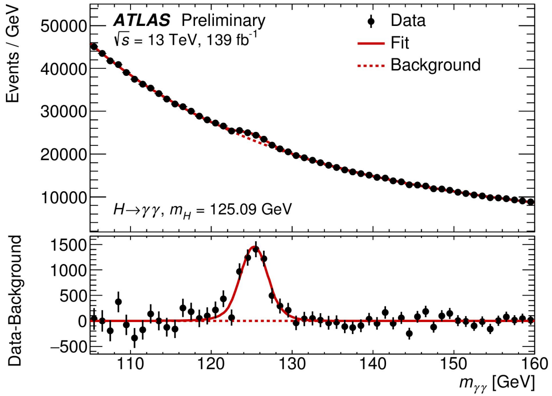
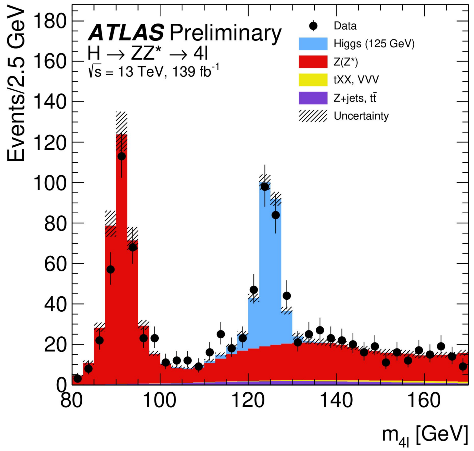
    - ATLAS data hints very strongly to a Spin^{CP} state of 0^+
    - Alternative models are rejected with a CL of more than 99.9%
- Higgs-boson mass measured by ATLAS and CMS: $m_H = 125.09 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{syst})$ GeV
- **With the large statistics of the full Run-II data set, we can probe differential distributions with high precision**
  - Makes the Higgs boson to a tool to search for new physics





Higgs boson property measurements

- **Analysis channels:**
  - $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ (ggF, VBF, VH, ttH)
  - $H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$ (ggF, VBF, VH, ttH)
  - $H \rightarrow \gamma\gamma$ (ggF, VBF, VH, ttH)
  - $H \rightarrow Z\gamma$ (ggF + VBF + VH + ttH)

Higgs boson coupling to bosons

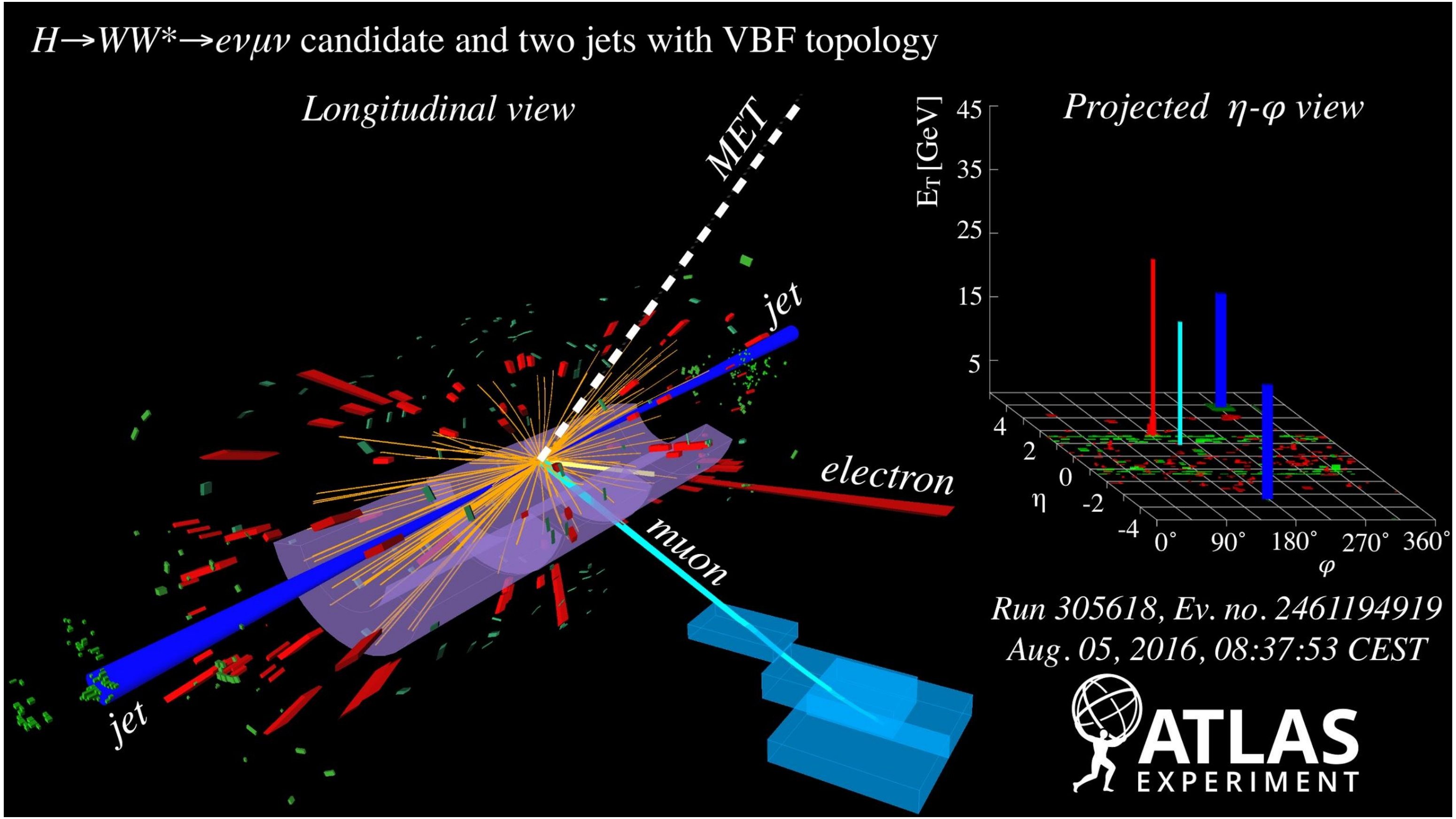
  - $H \rightarrow bb$ (VH, VBF)
  - $H \rightarrow cc$ (VH)

Higgs boson coupling to quarks

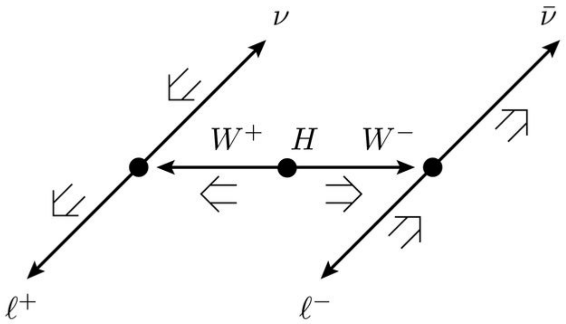
  - $H \rightarrow \tau\tau$ (ggF, VBF)
  - $H \rightarrow \mu\mu$ (ggF, VBF)

Higgs boson coupling to leptons

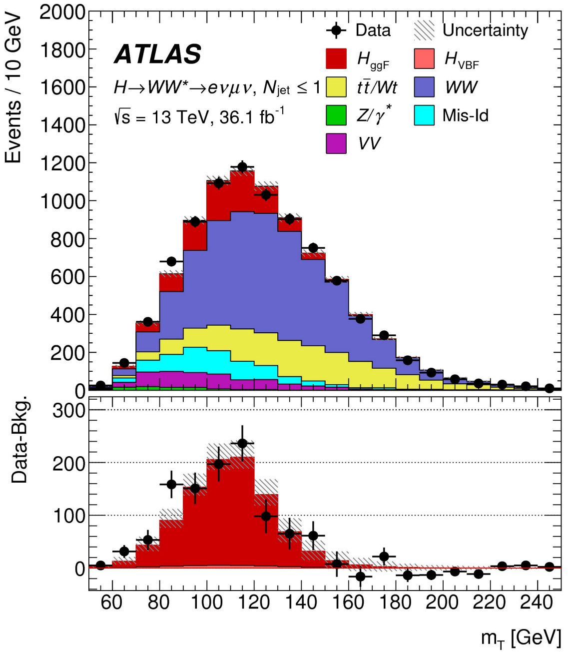
VBF H (→ WW* → eνμν) jj



$H \to WW^* \to e\nu\mu\nu$



- $H \to WW^* \to e\nu\mu\nu$ is one of the most frequent decay modes of the Higgs boson
  - Cleaner signature wrt $H \to b\bar{b}$
  - Higher statistics than $H \to ZZ^*$ or $H \to \gamma\gamma$
- Characteristics of $H \to WW^* \to e\nu\mu\nu$ decay:
  - Two oppositely charged leptons with small opening angle and invariant mass m_{ll}
  - Presence of neutrinos prevents direct measurement of invariant mass m_H instead use transverse mass m_T

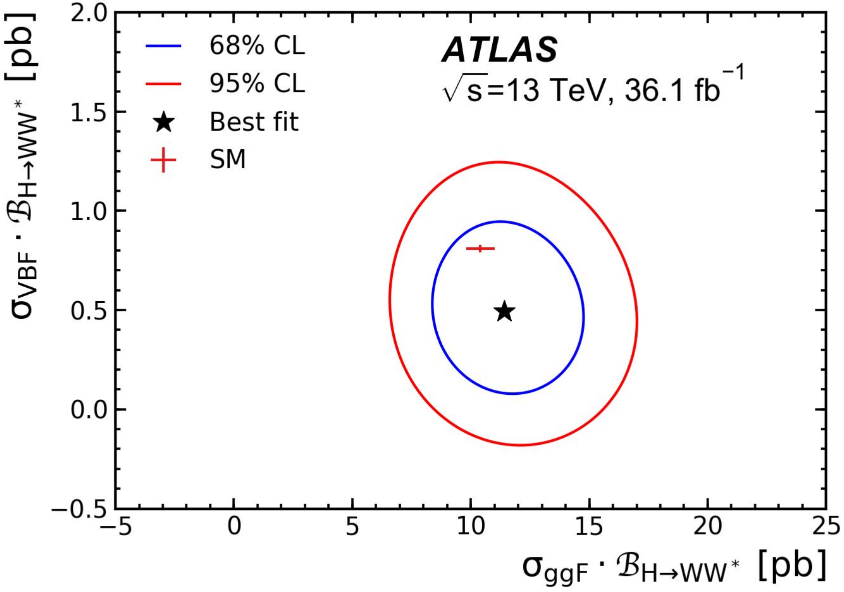


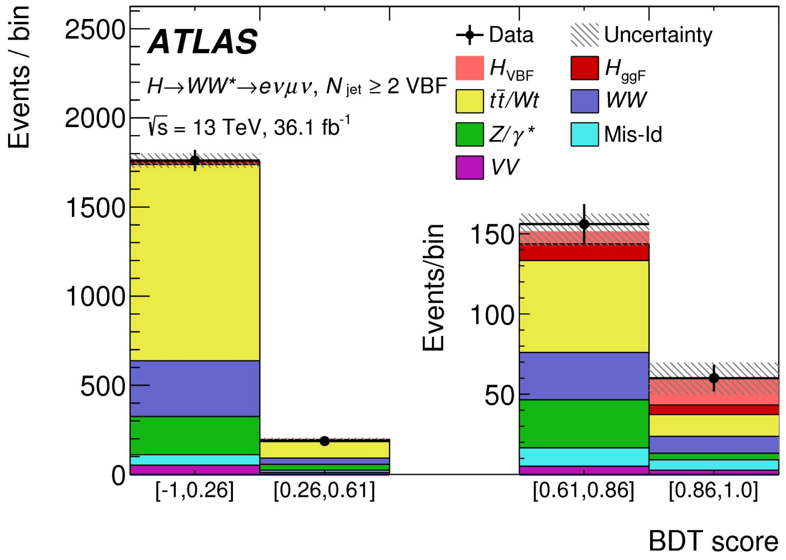
$$m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + p_{\mathrm{T}}^{\nu\nu}\right)^2 - \left|\boldsymbol{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{p}_{\mathrm{T}}^{\nu\nu}\right|^2}$$

with $$E_{\mathrm{T}}^{\ell\ell} = \sqrt{(p_{\mathrm{T}}^{\ell\ell})^2 + (m_{\ell\ell})^2}$$

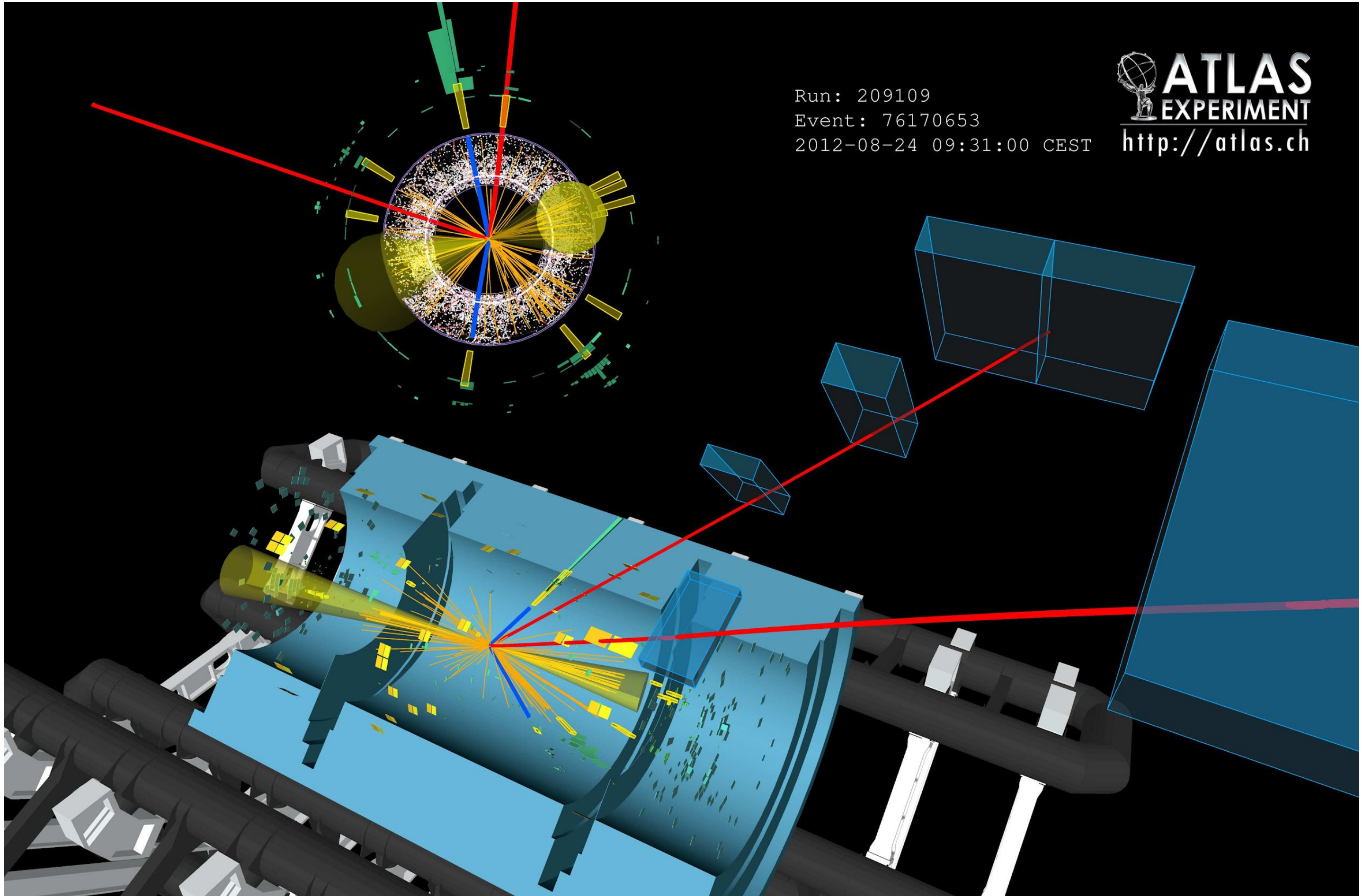
$H \to WW^* \to e\nu\mu\nu$

- ggF and VBF cross sections are obtained by maximum likelihood fit
  - **ggF: transverse mass m_T**
  - **VBF: score of a boosted decision tree**
  - **Profile ggF production when fitting VBF cross section, and vice-versa**
- **Measured cross sections are consistent to SM predictions**



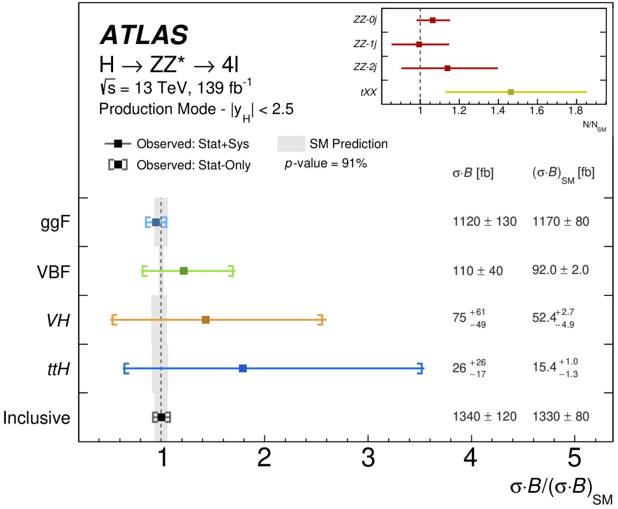


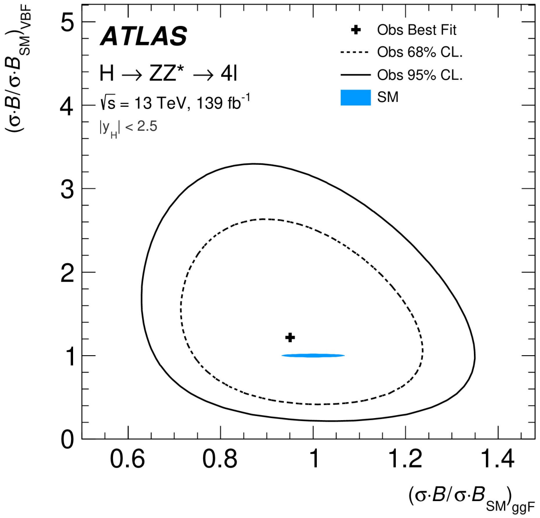
$H \to ZZ^* \to \ell\ell\ell\ell$

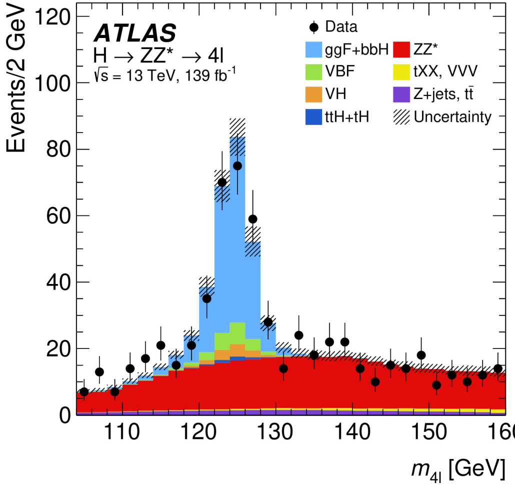


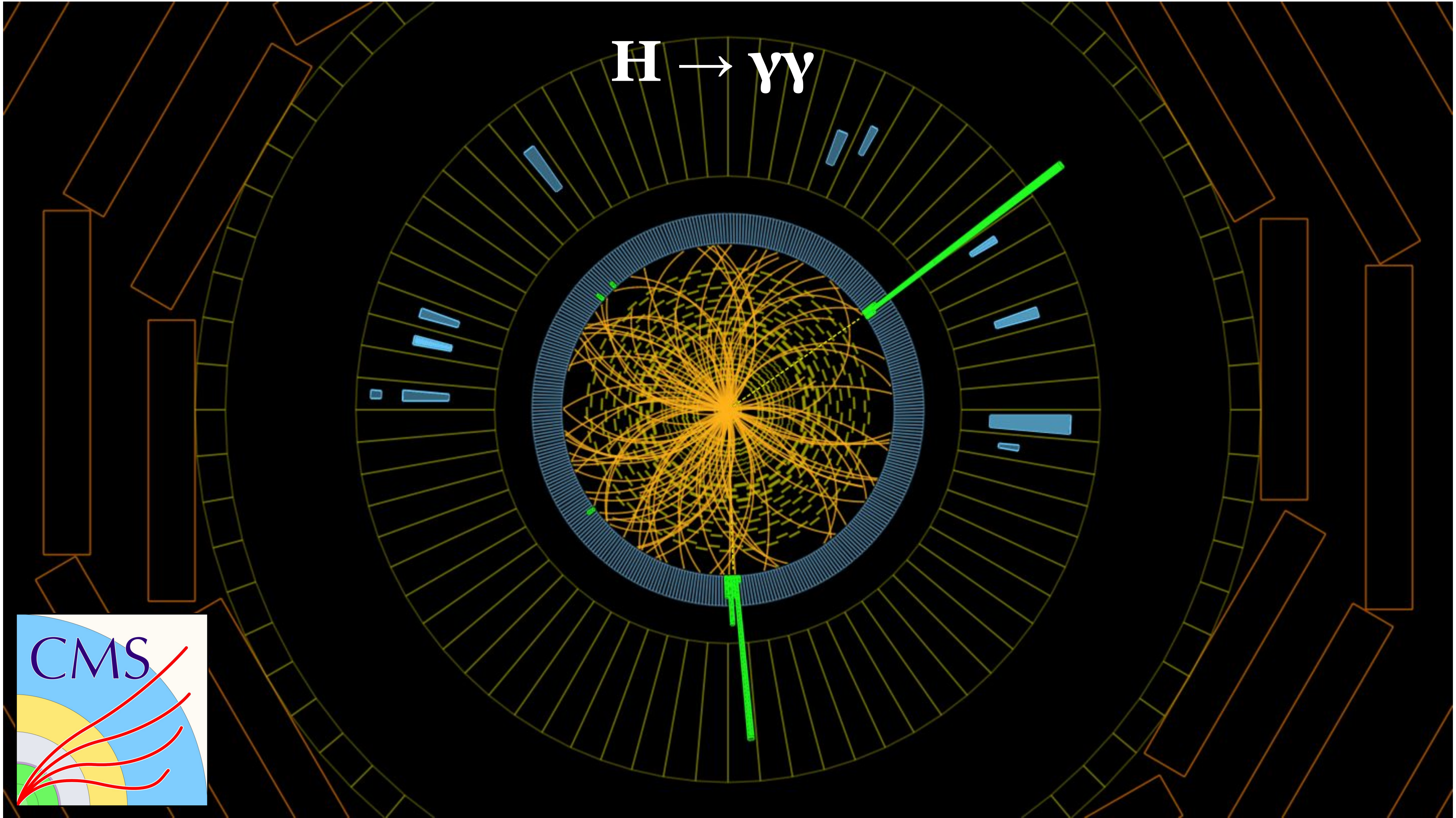
H → ZZ* → ℓℓℓℓ

- H→ ZZ* → ℓℓℓℓ events provide a clean signature in the detector and thus have relative low background contributions
  - **Good channel to measure properties of the Higgs boson precisely**
  - Analyses are based on finding two pairs of isolated leptons with same flavor and opposite electric charges



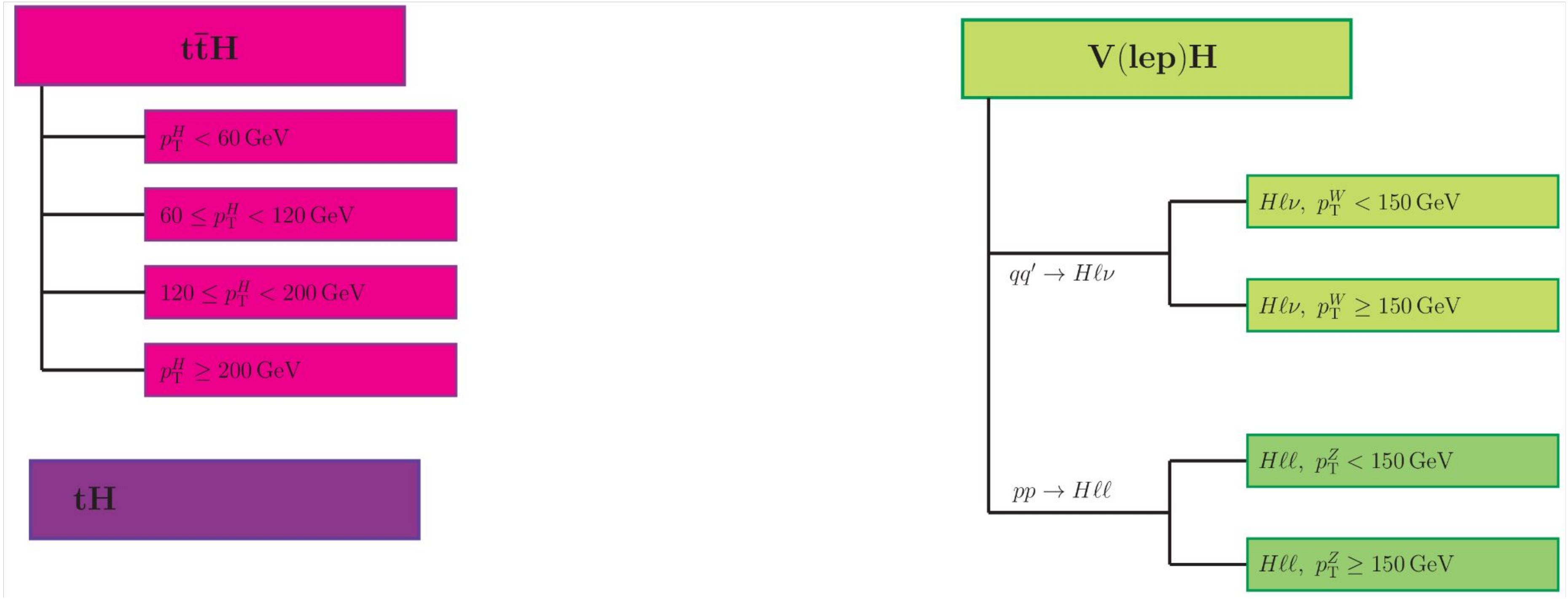




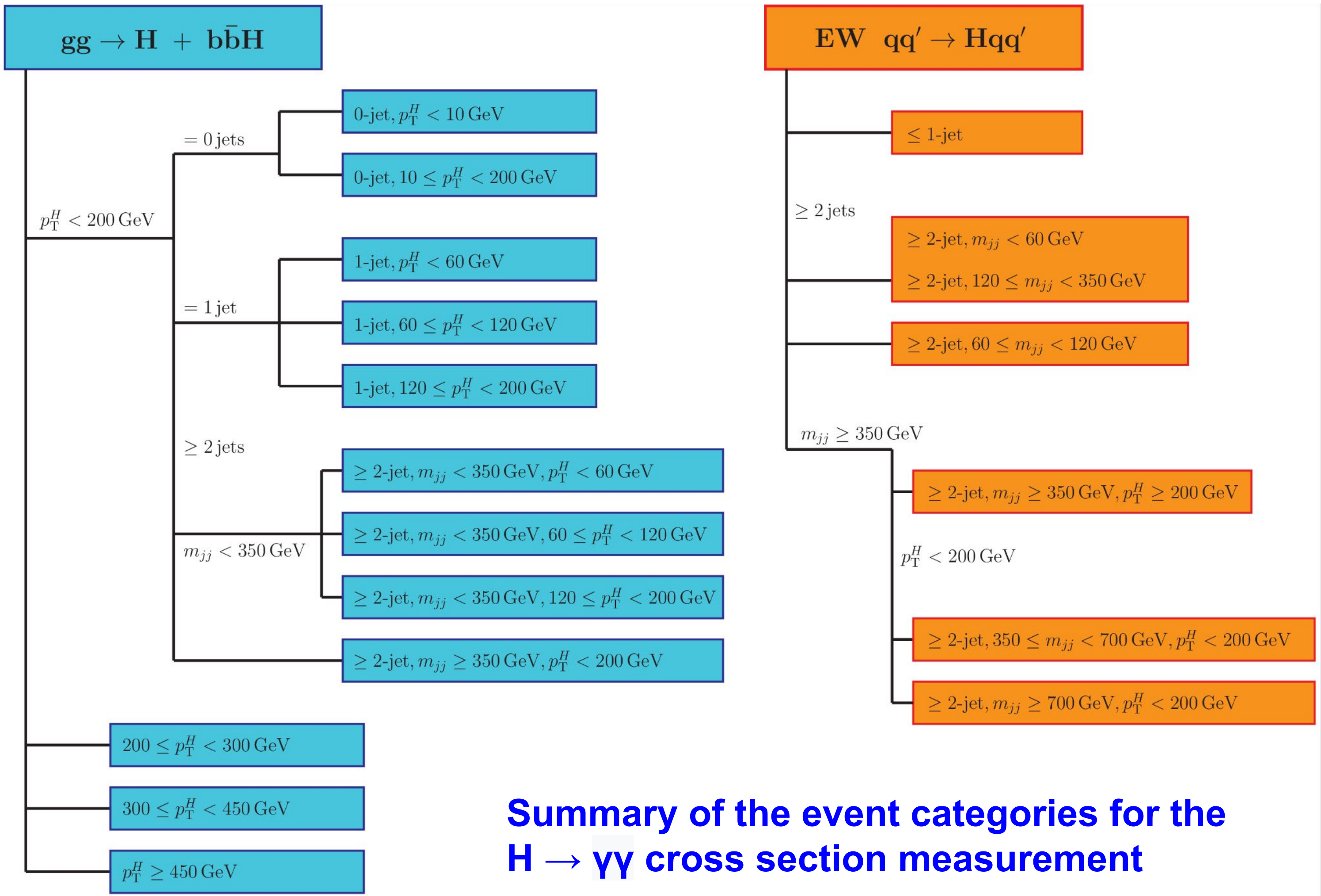


H → γγ
CMS

$H \rightarrow \gamma\gamma$



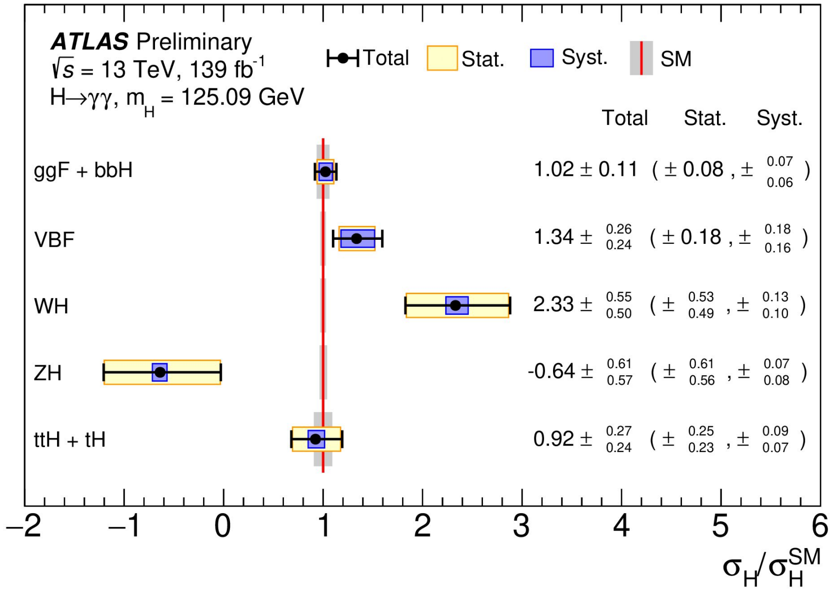
Summary of the event categories for cross section measurement

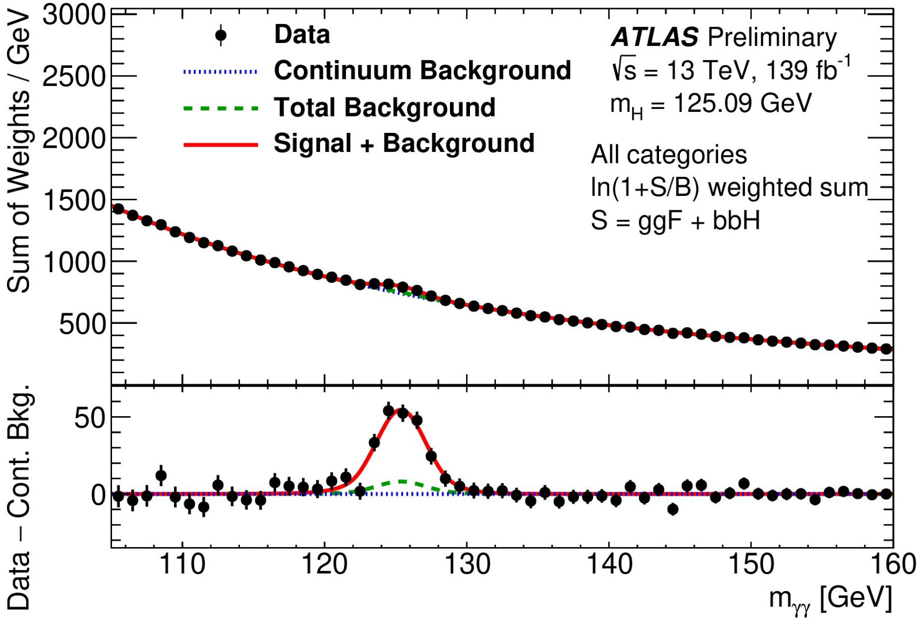


Summary of the event categories for the $H \to \gamma\gamma$ cross section measurement

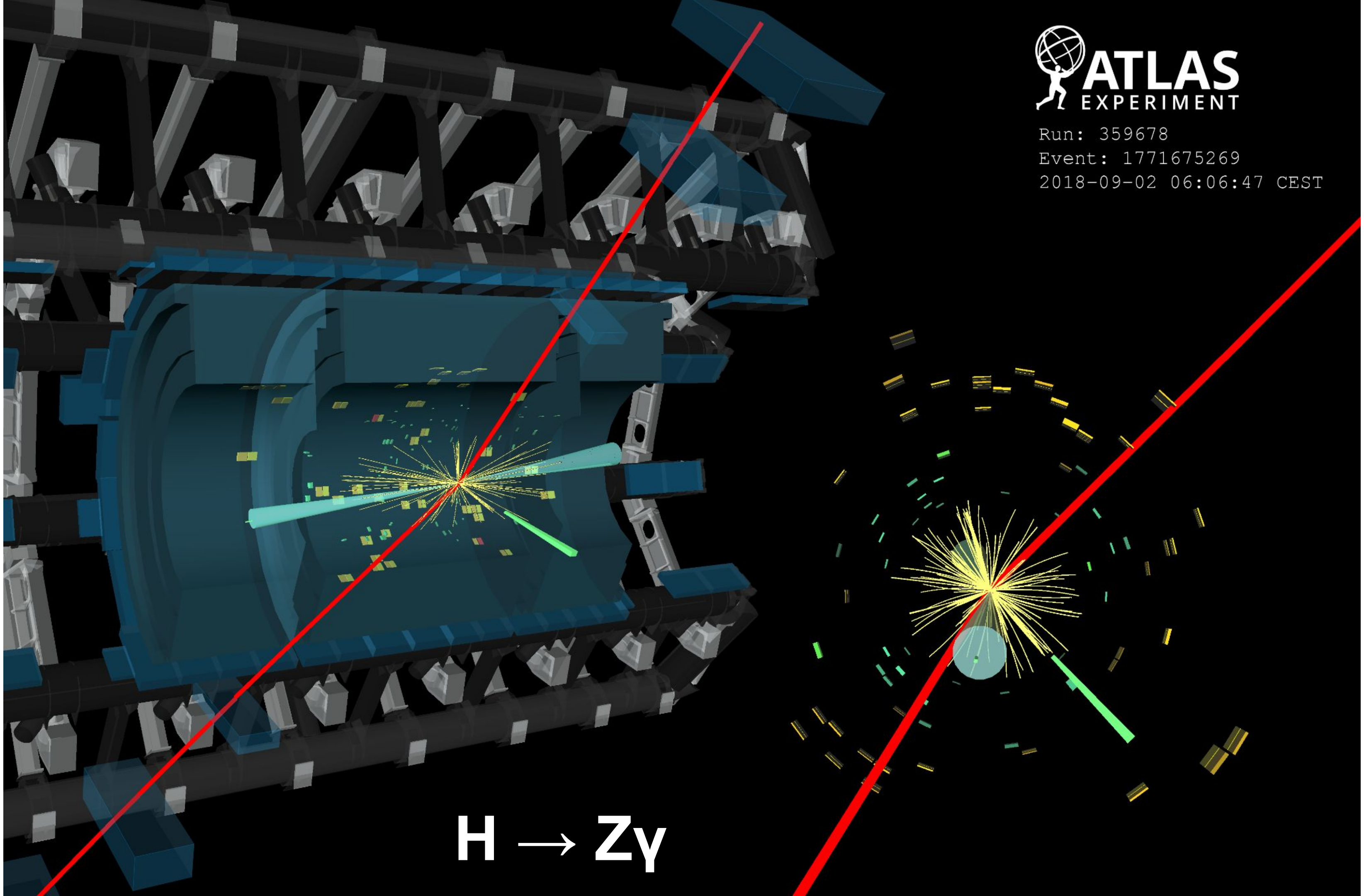
$H \rightarrow \gamma\gamma$

- Analysis is sensitive to the cross sections of (almost all) Higgs boson production modes
- Final results are obtained by fit to all categories





Taken from: http://cdsweb.cern.ch/record/2725727/files/ATLAS-CONF-2020-026.pdf

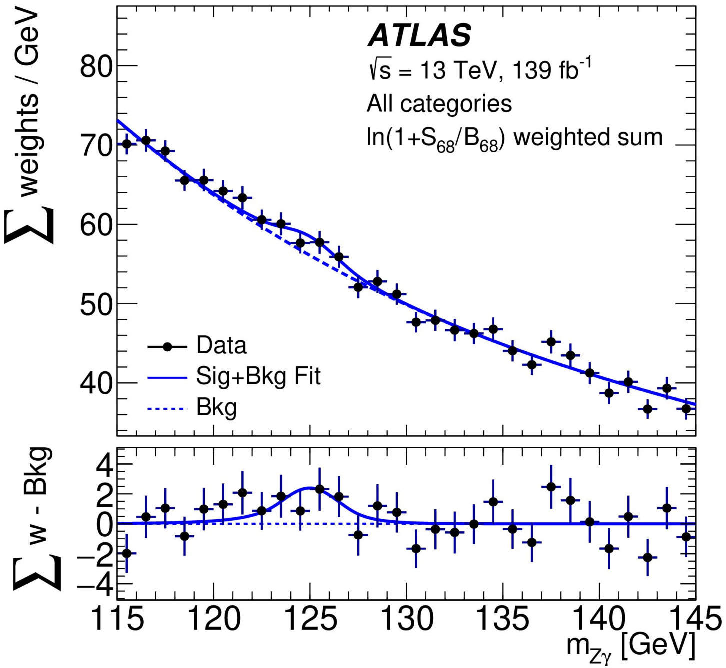


$H \rightarrow Z\gamma$

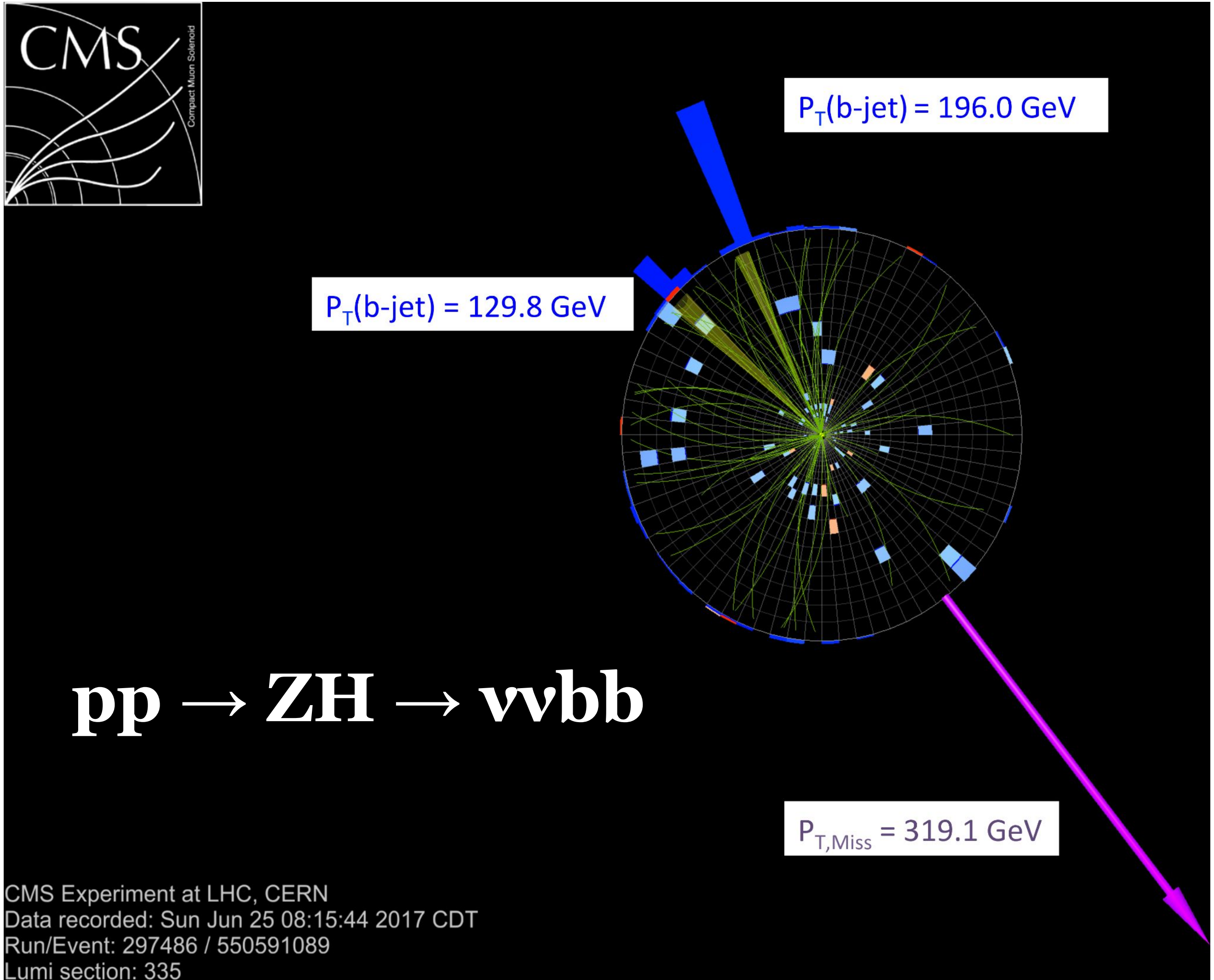
H → Zγ

- Low predicted branching ratio $B(H \to Z\gamma)$ = (1.54 ± 0.09) × 10^{-3}
  - Can differ from the SM value if Higgs boson is:
    - a composite state
    - part of an extended scalar sector
- Categorize events:
  - VBF-like
  - High p_T

Category	μ	Significance
VBF-enriched	$0.5^{+1.9}_{-1.7}\ (1.0^{+2.0}_{-1.6})$	0.3 (0.6)
High relative p_T	$1.6^{+1.7}_{-1.6}\ (1.0^{+1.7}_{-1.6})$	1.0 (0.6)
High p_{Tt} ee	$4.7^{+3.0}_{-2.7}\ (1.0^{+2.7}_{-2.6})$	1.7 (0.4)
Low p_{Tt} ee	$3.9^{+2.8}_{-2.7}\ (1.0^{+2.7}_{-2.6})$	1.5 (0.4)
High p_{Tt} $\mu\mu$	$2.9^{+3.0}_{-2.8}\ (1.0^{+2.8}_{-2.7})$	1.0 (0.4)
Low p_{Tt} $\mu\mu$	$0.8^{+2.6}_{-2.6}\ (1.0^{+2.6}_{-2.5})$	0.3 (0.4)
Combined	$2.0^{+1.0}_{-0.9}\ (1.0^{+0.9}_{-0.9})$	2.2 (1.2)

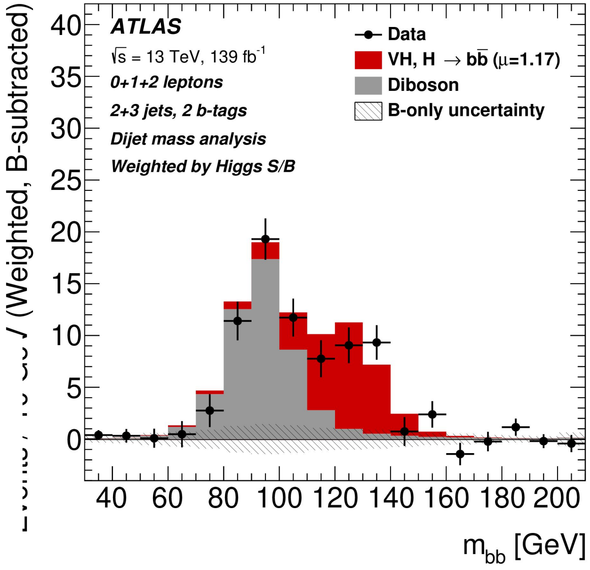


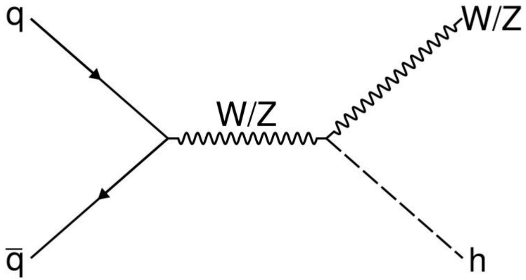
Taken from: https://arxiv.org/pdf/2005.05382.pdf

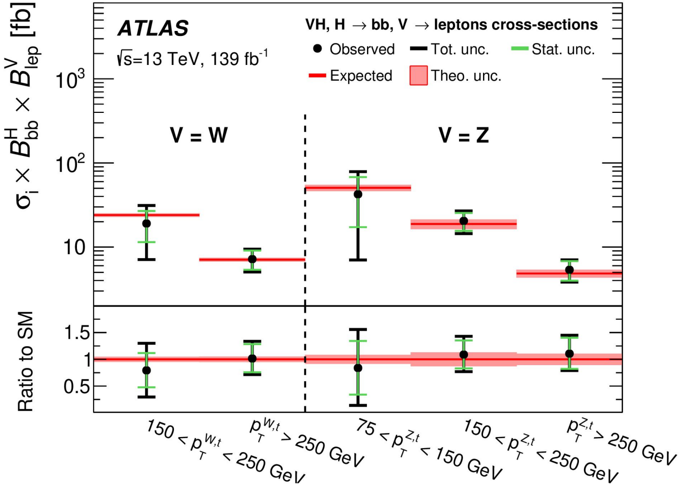

CMS
Compact Muon Solenoid
P_T(b-jet) = 196.0 GeV
P_T(b-jet) = 129.8 GeV
pp → ZH → vvbb
$P_{T,Miss}$ = 319.1 GeV
CMS Experiment at LHC, CERN
Data recorded: Sun Jun 25 08:15:44 2017 CDT
Run/Event: 297486 / 550591089
Lumi section: 335

VH H → bb

- ggF H → bb has a large σ × BR, but can not be separated from huge dijet backgrounds and is difficult to trigger
  - **Instead, probe H→ bb in Higgs-Strahlungs events (bb-pair is produced in addition to charged leptons)**
- **Observation of H → bb decays and VH production mode in 2018**

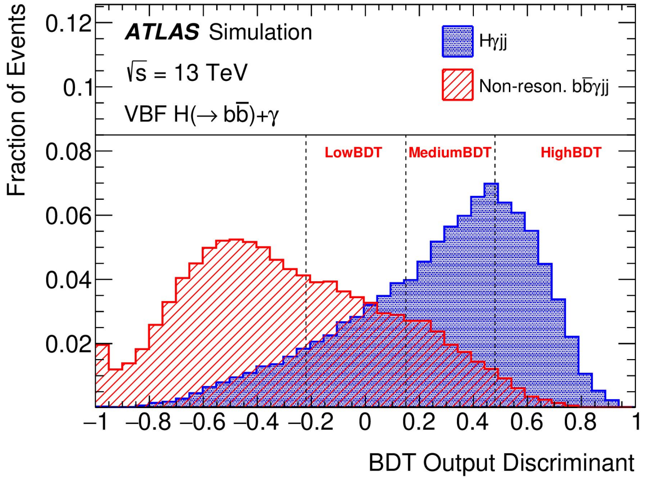


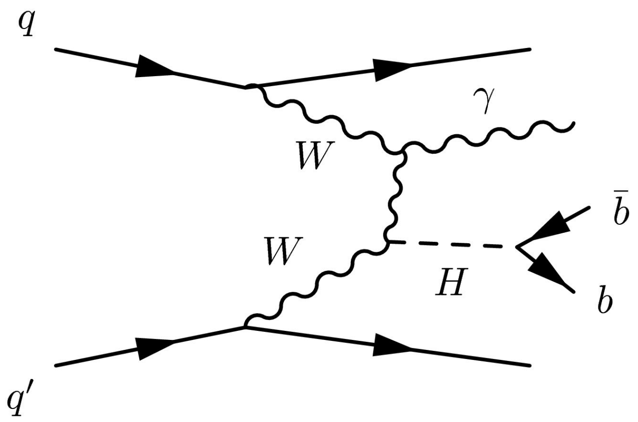


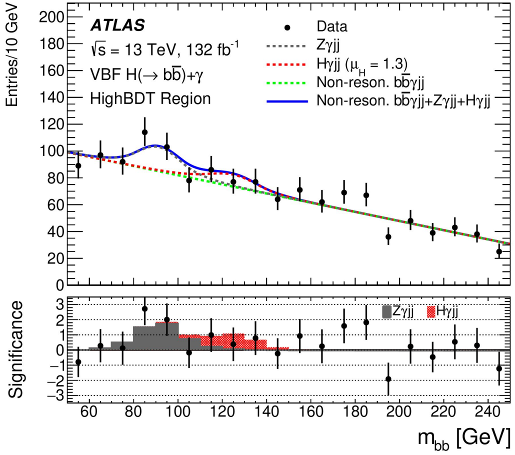


VBF H (→ bb) jj

- Study VBF + photon
  - Relative low backgrounds
  - Use photon trigger
- Kinematic event properties are used in a boosted decision tree to classify signal and background events
- The measured Higgs boson signal strength is 1.3 ± 1.0
- The observed (expected) significance of the signal above the background-only hypothesis is 1.3σ (1.0σ)



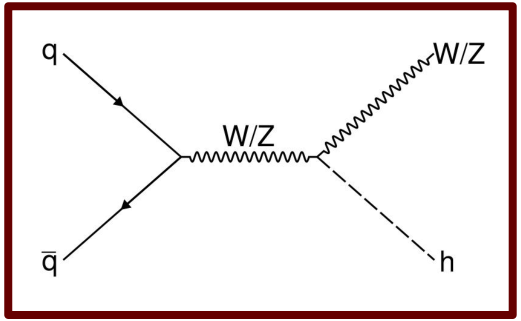


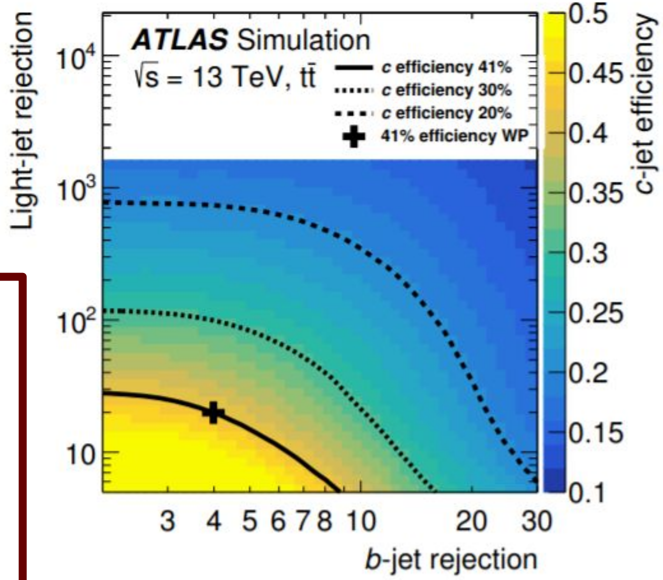


VH H → cc

- Study of Yukawa coupling of the Higgs boson to 2nd generation quarks is challenging at hadron colliders, due to small branching fractions and large backgrounds
- **Charm tagging is crucial for eventual H → cc observation**
- Upper limit on σ(pp → ZH)×B(H → cc) at the 95% CL:
  - **Observed:** 2.7 pb (104 times the SM predictions)
  - **Expected:** 3.9 +2.1/−1.1 pb

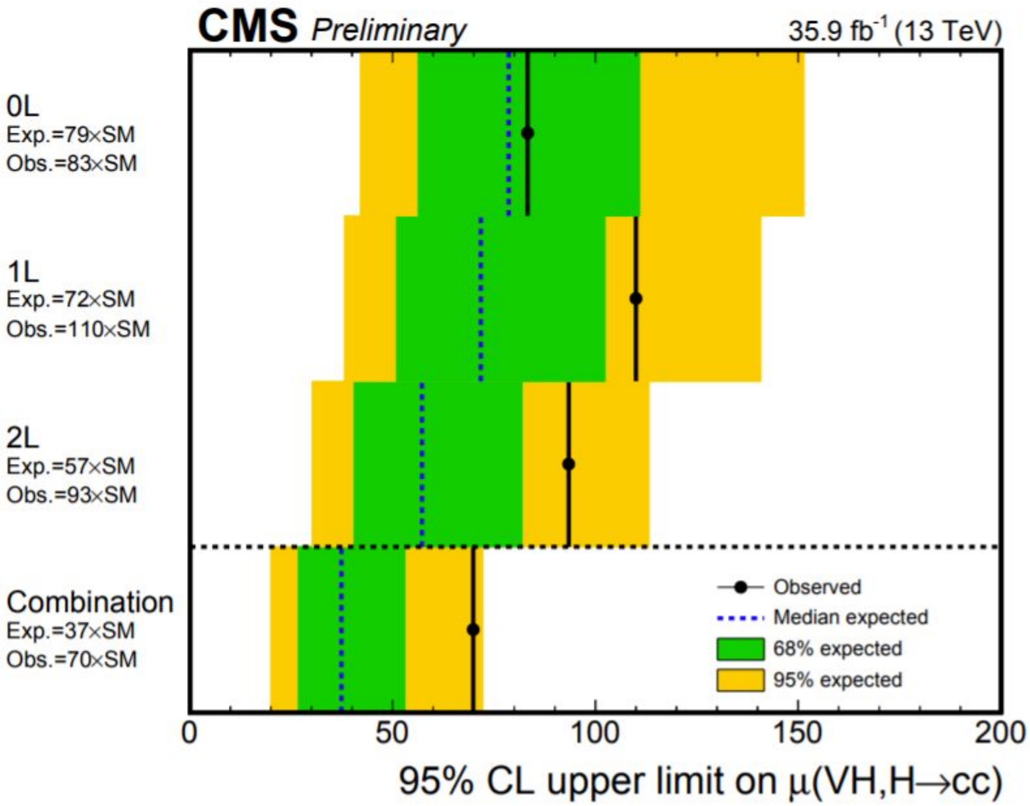
Source	$\sigma/\sigma_{\text{tot}}$
Statistical	**49%**
Floating Z + jets normalization	31%
Systematic	**87%**
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%

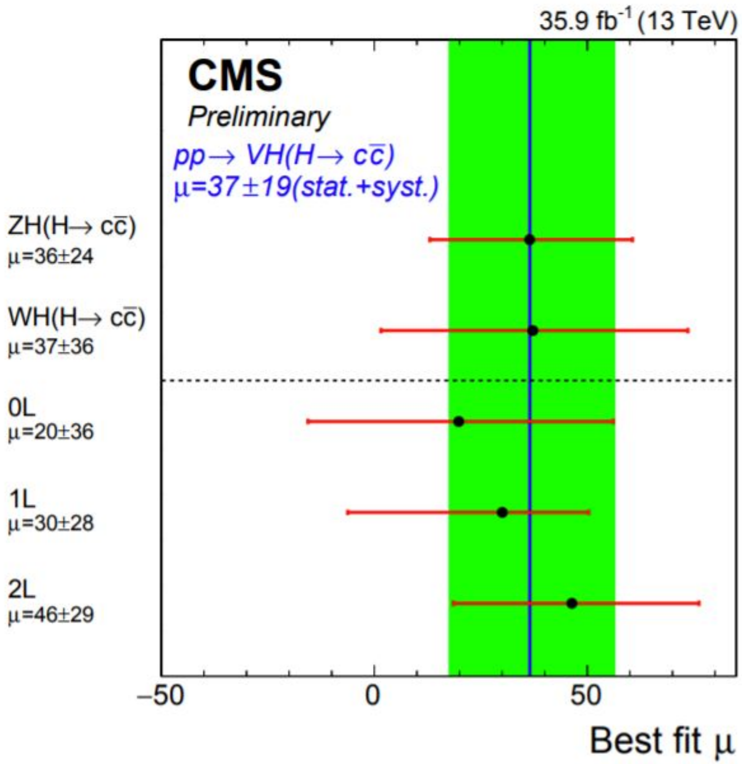




Taken from https://arxiv.org/pdf/1802.04329.pdf

VH $H \to cc$



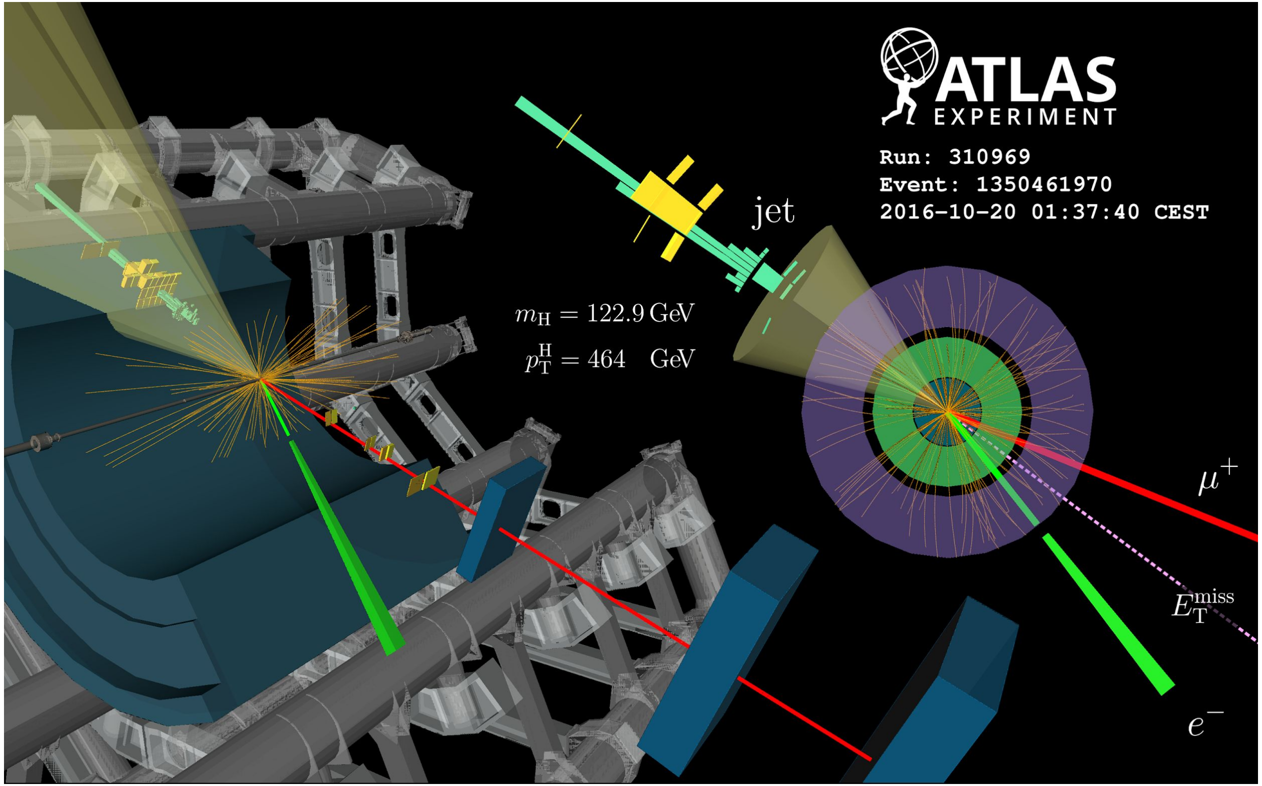


Taken from https://inspirehep.net/files/8f40463278676edecdd49e0d89fb861e

$H \to \tau\tau$

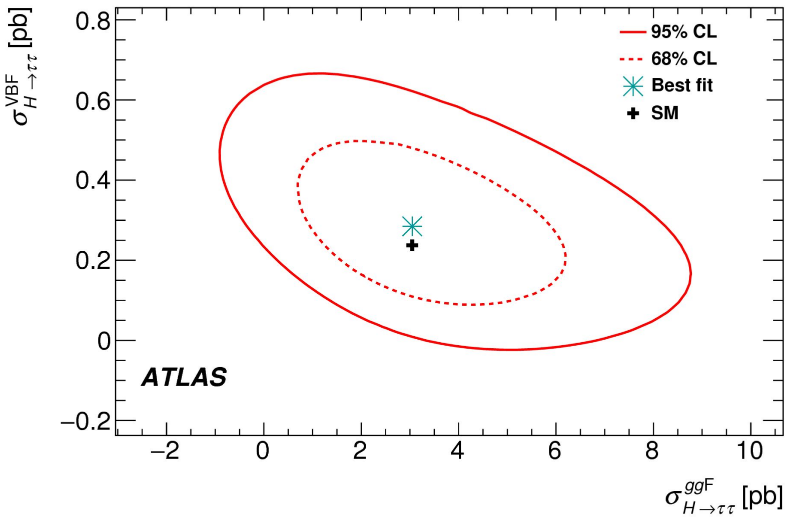
- Here: H + 1 jet event
  - Di-tau decay
    - $\tau \to e$
    - $\tau \to \mu$
    - $\tau \to$ hadrons

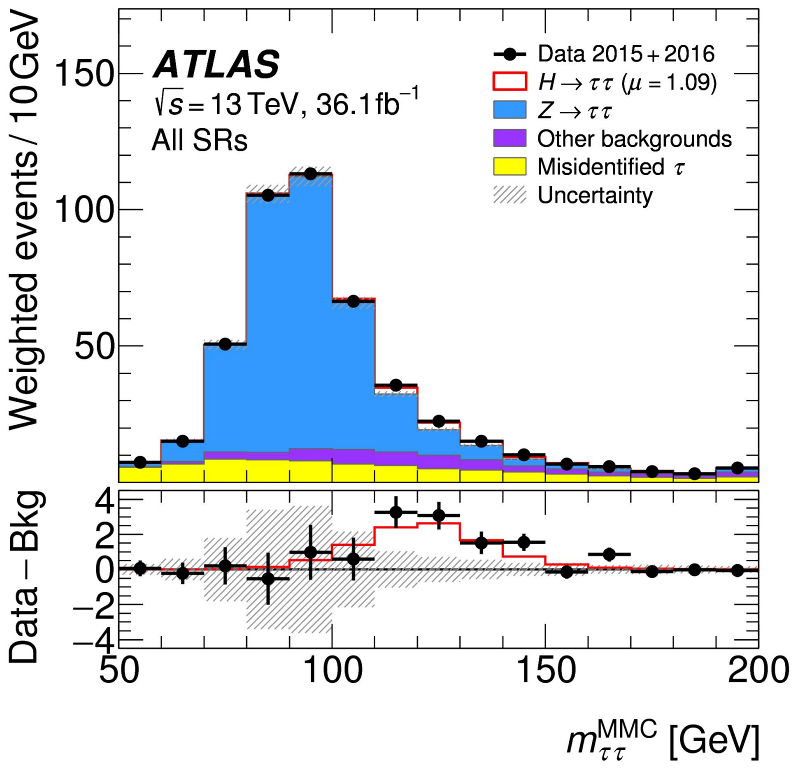
Decay Mode	BR
$\tau^- \to e^- \nu_e \nu_\tau$	$(17.83 \pm 0.04)\%$
$\tau^- \to \mu^- \nu_\mu \nu_\tau$	$(17.41 \pm 0.04)\%$
$\tau^- \to \pi^- \pi^0 \nu_\tau$	$(25.52 \pm 0.09)\%$
$\tau^- \to \pi^- \nu_\tau$	$(10.83 \pm 0.06)\%$
$\tau^- \to \pi^- \pi^0 \pi^0 \nu_\tau$	$(9.30 \pm 0.11)\%$
$\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$	$(8.99 \pm 0.05)\%$
$\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$	$(2.74 \pm 0.07)\%$
$\tau^- \to \pi^- \pi^0 \pi^0 \pi^0 \nu_\tau$	$(1.04 \pm 0.07)\%$



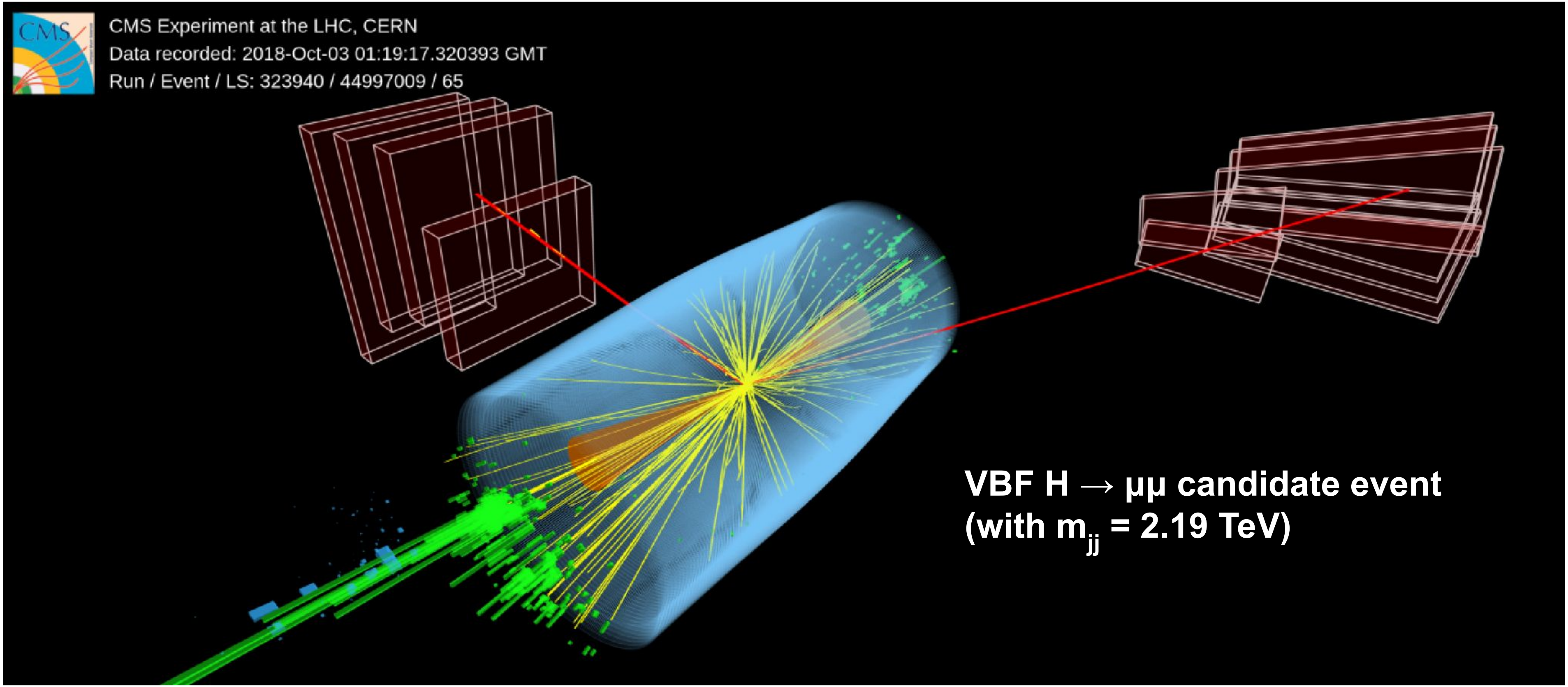
H → ττ

- H → ττ decay is the best channel to study coupling between the Higgs boson and fermions
  - Relies on efficient τ reconstruction and identification



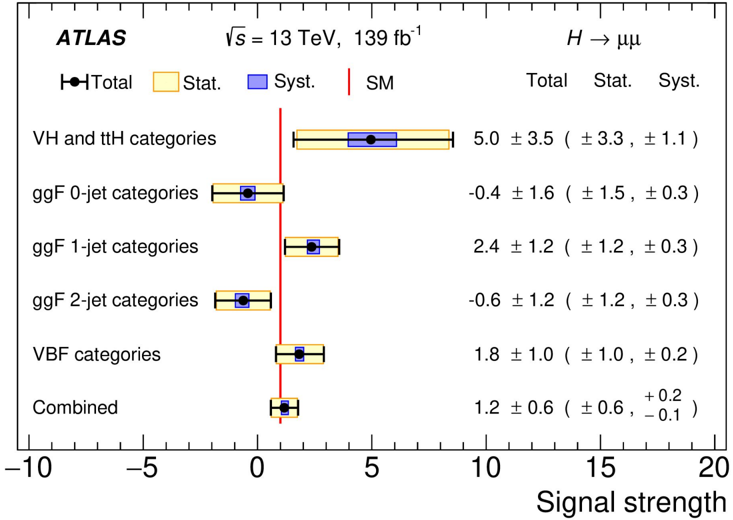


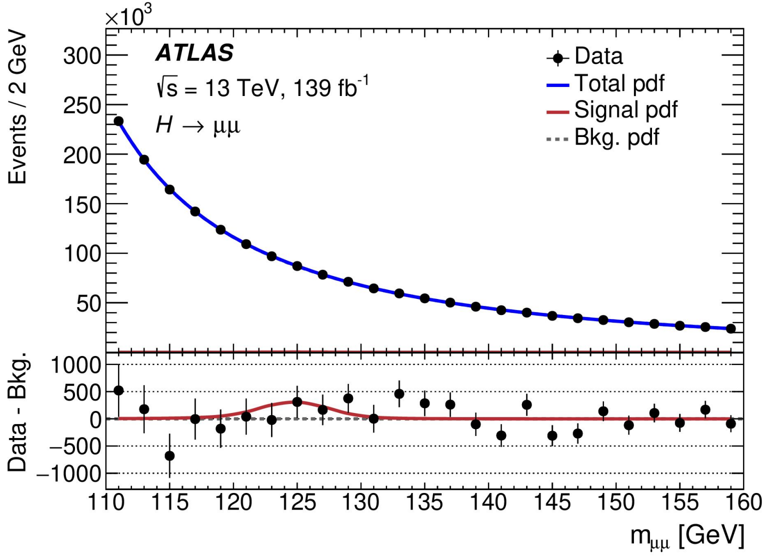
$H \to \mu\mu$


CMS Experiment at the LHC, CERN
Data recorded: 2018-Oct-03 01:19:17.320393 GMT
Run / Event / LS: 323940 / 44997009 / 65
VBF H → μμ candidate event
(with m_jj = 2.19 TeV)

H → μμ

- The $H \to \mu\mu$ decay offers the best opportunity to measure the Higgs interactions with a 2nd generation fermion
- Events are divided into 20 mutually-exclusive categories (to increase the sensitivity)
  - Use properties of additional jets or leptons



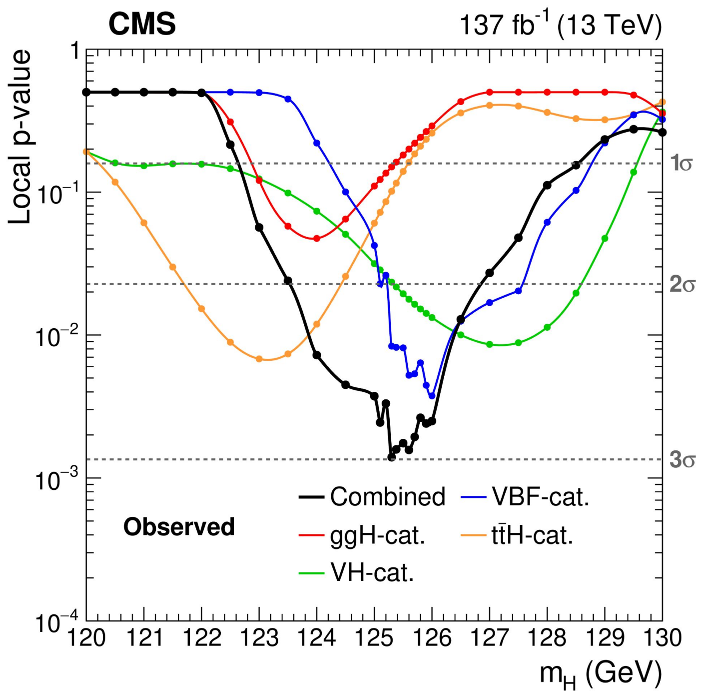


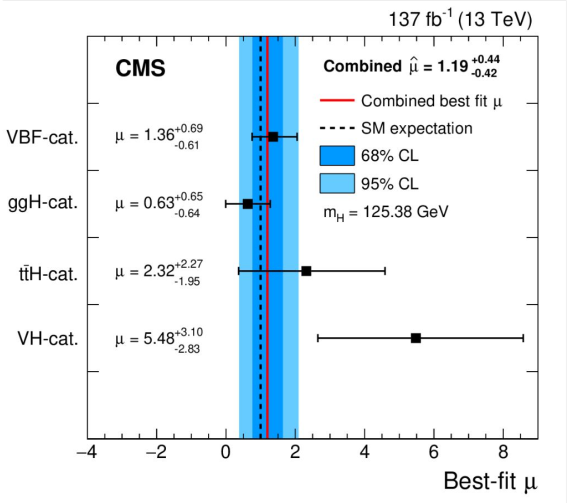
- A first hint of the Higgs boson decaying to a muon pair
  - Observed significance over the background-only hypothesis is 2.0σ

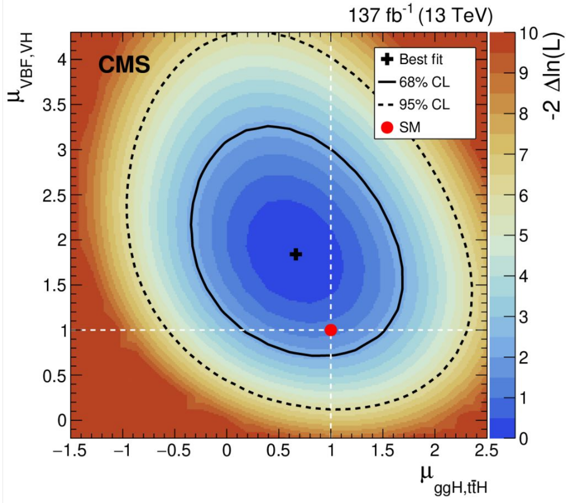
Taken from: https://arxiv.org/pdf/2007.07830.pdf

H → μμ

First evidence for a Higgs boson decay to a pair of muons

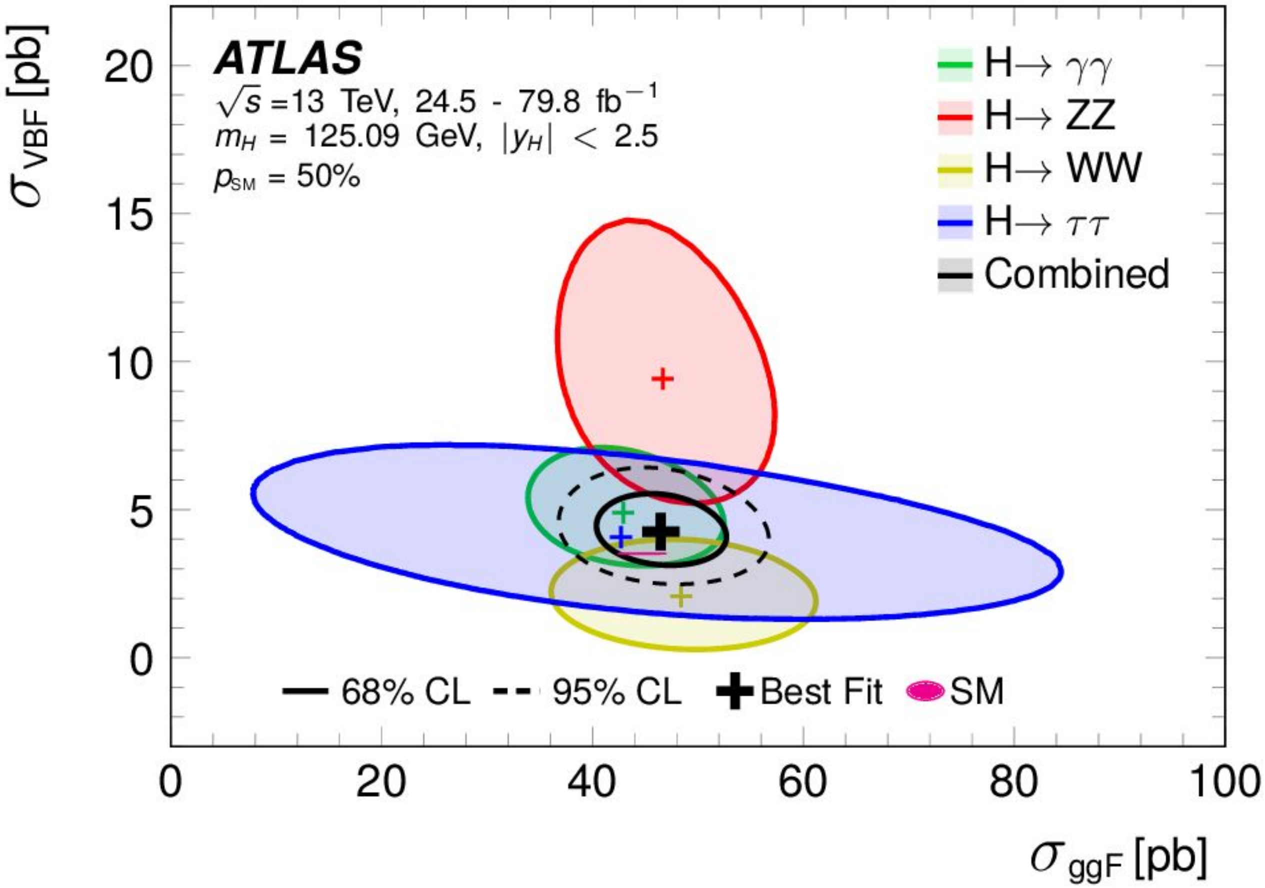






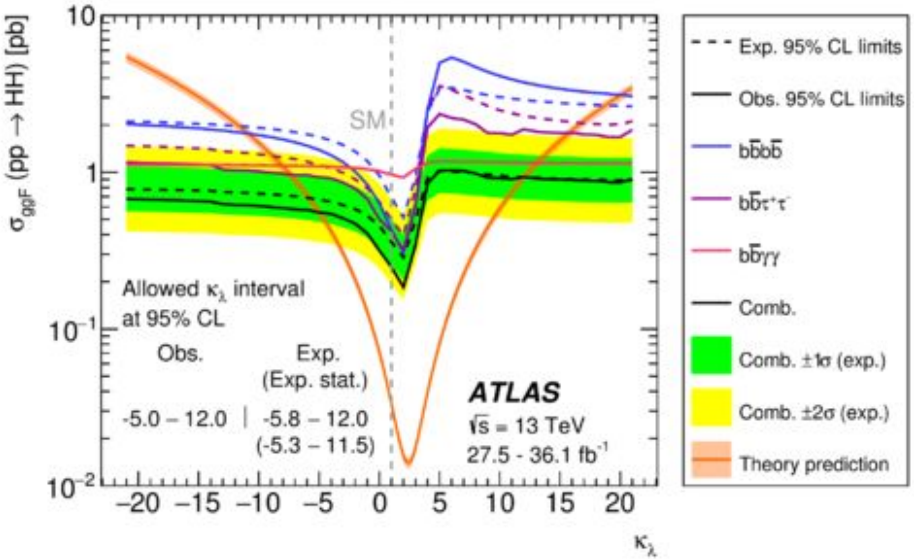
- **Dominant uncertainties on $\Delta\mu$:**
  - Total uncertainties: +0.44/-0.42
  - Statistical uncertainties: +0.41/-0.40
  - Experimental uncertainties: +0.12/-0.11
  - Theoretical uncertainties: +0.10/-0.11

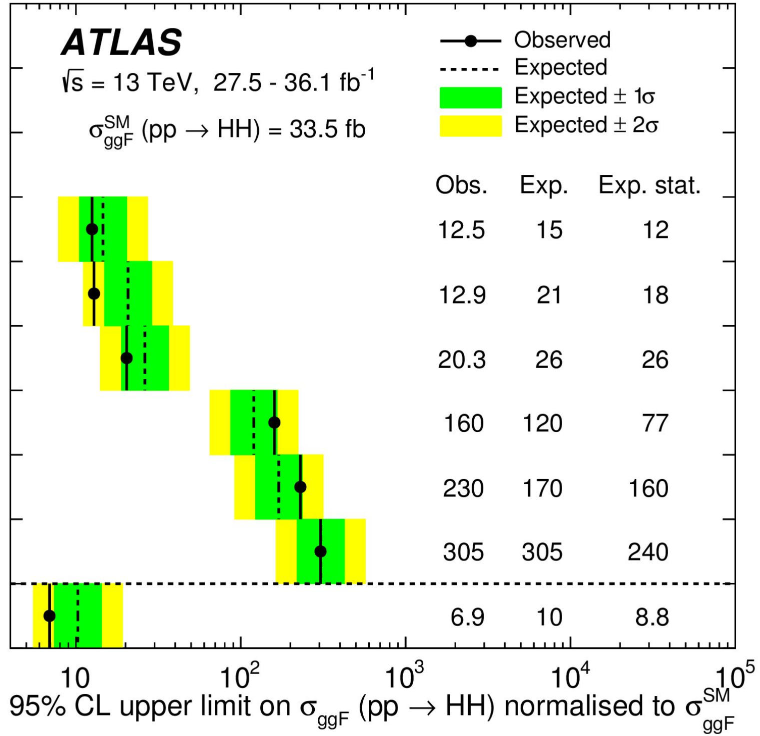
Combinations



Di-Higgs and Higgs self-coupling

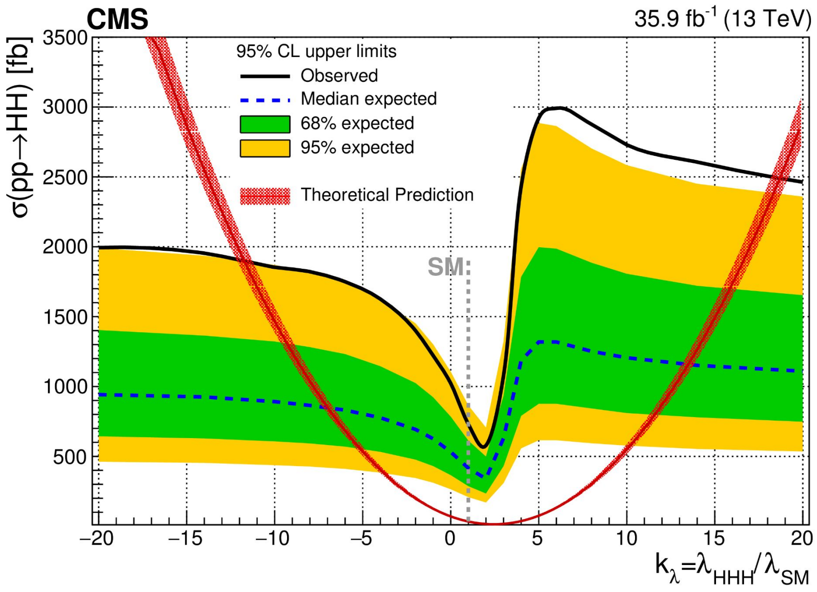
- So far, we can only set limits on the self-coupling strength and the Di-Higgs production cross section
- **Will need the full dataset from HL-LHC phase until we can measure these observables**

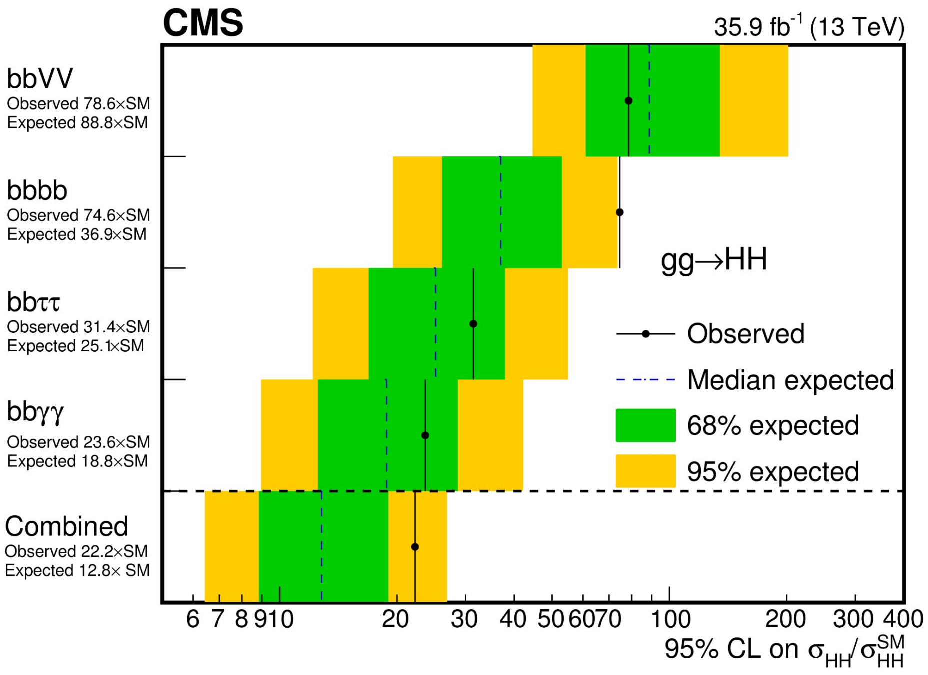




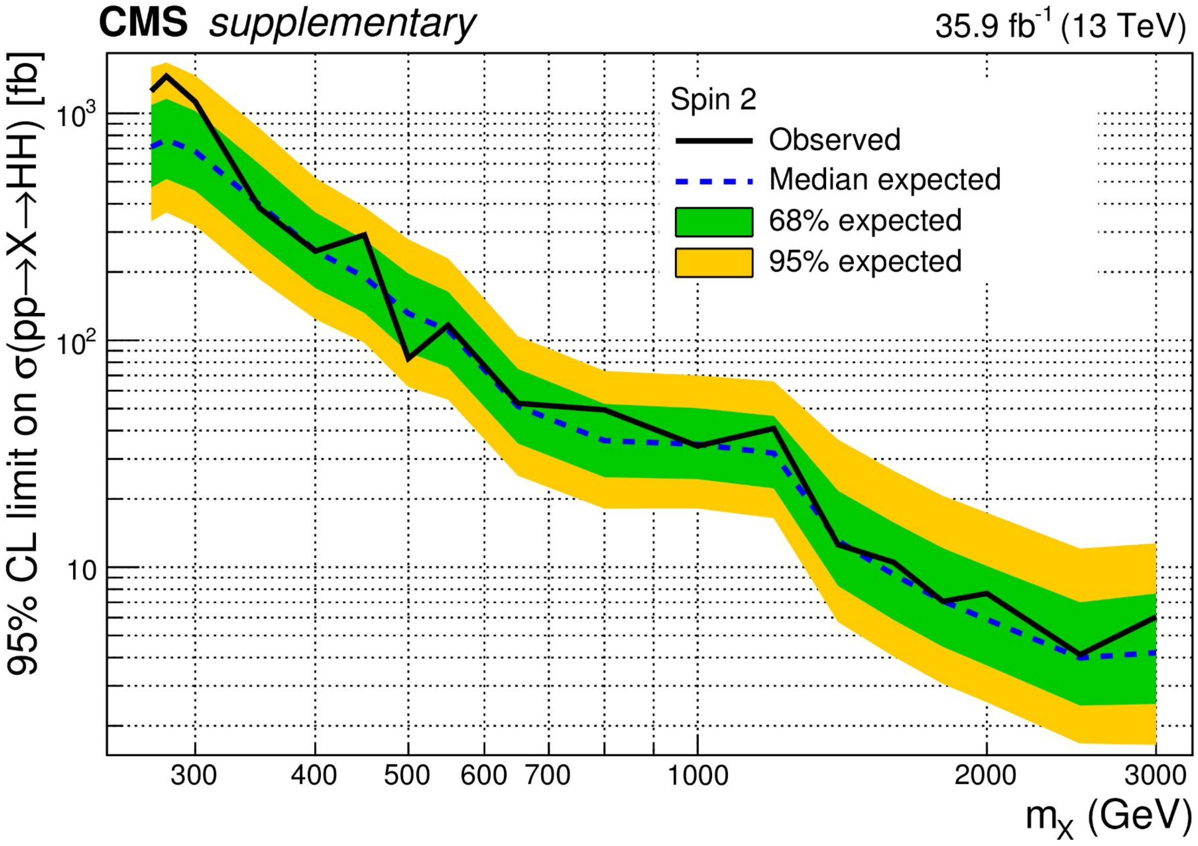
	Obs.	Exp.	Exp. stat.
HH→ $b\bar{b}\tau^+\tau^-$	12.5	15	12
HH→ $b\bar{b}b\bar{b}$	12.9	21	18
HH→ $b\bar{b}\gamma\gamma$	20.3	26	26
HH→ $W^+W^-W^+W^-$	160	120	77
HH→ $W^+W^-\gamma\gamma$	230	170	160
HH→ $b\bar{b}W^+W^-$	305	305	240
Combined	6.9	10	8.8

Di-Higgs and Higgs self-coupling



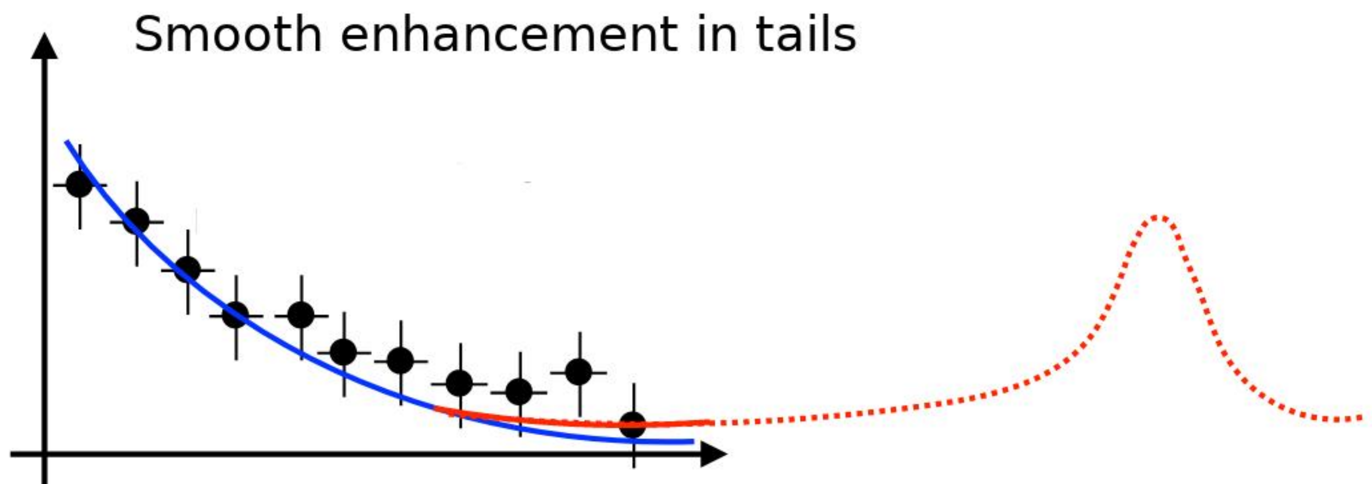


Search for resonant di-Higgs production



Effective field theories

- So far no hints for new physics in direct searches
- What if scale of new physics is outside the reach of the LHC?
  - **Search for smooth enhancements in the tails of our observables**
    - E.g. from resonances with masses beyond our reach
  - **Probing for shape modifications of our observables**
    - E.g. from anomalous couplings
- **Effective field theories (EFT) allow for model independent approaches to search for such new physics effects**

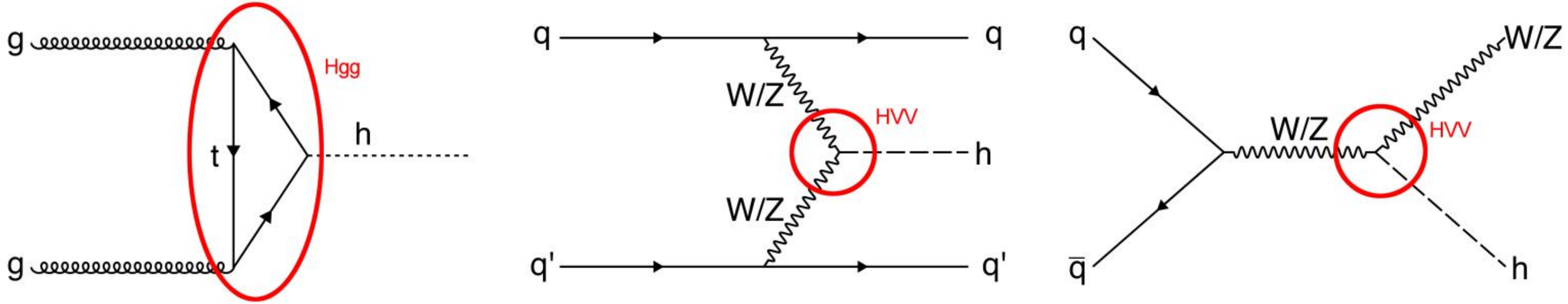


Effective field theory (EFT)

- **In EFTs, Lagrangian of the Standard Model of particle physics is supplemented with additional BSM terms:**

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda} \mathcal{O}_i$$

- $\mathcal{O}_i$ are higher dimension operators
- c_i are the so-called Wilson coefficients
  - Specify the strength of a new CP-even (or CP-odd) interaction (i.e. they describe deviation from SM)
- Λ is mass scale for new particle



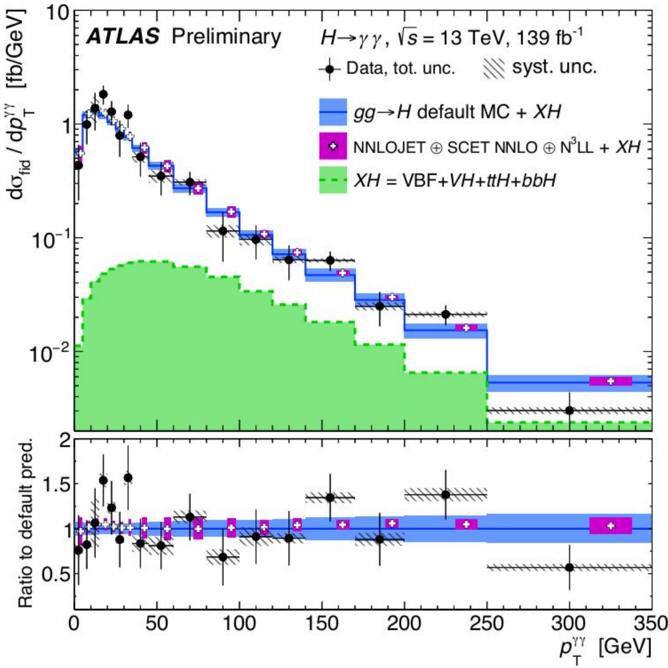
Differential measurements

- **Re-interpretation of differential cross section measurements are used to constrain EFT parameters**
- Measurement of **differential** cross sections
  1. Measure number of Higgs signal events N^{signal} in i-th p_T^H bin (or of any other observable)
  2. Background subtraction
  3. **Unfolding:** Derive correction factor from MC information:

$$c_i = \frac{N^{\text{reco}}}{N^{\text{part}}}$$

  4. Calculate differential cross section:

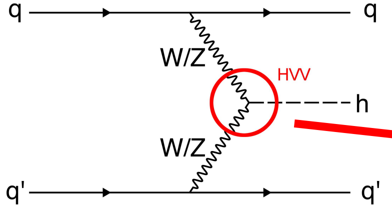
$$\left(\frac{d\sigma}{dx}\right)_i = \frac{N^{\text{signal}}}{c_i \Delta p_{i,\mathrm{T}}^H \mathcal{L}_{\text{int}}}$$

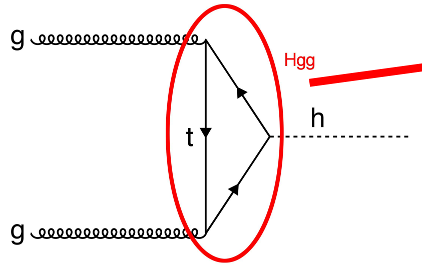


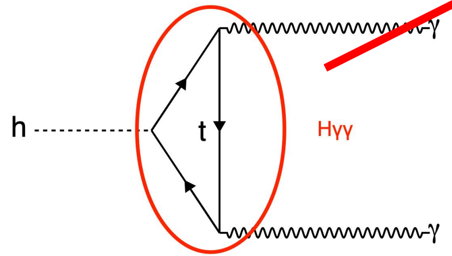
Effective field theory (EFT)

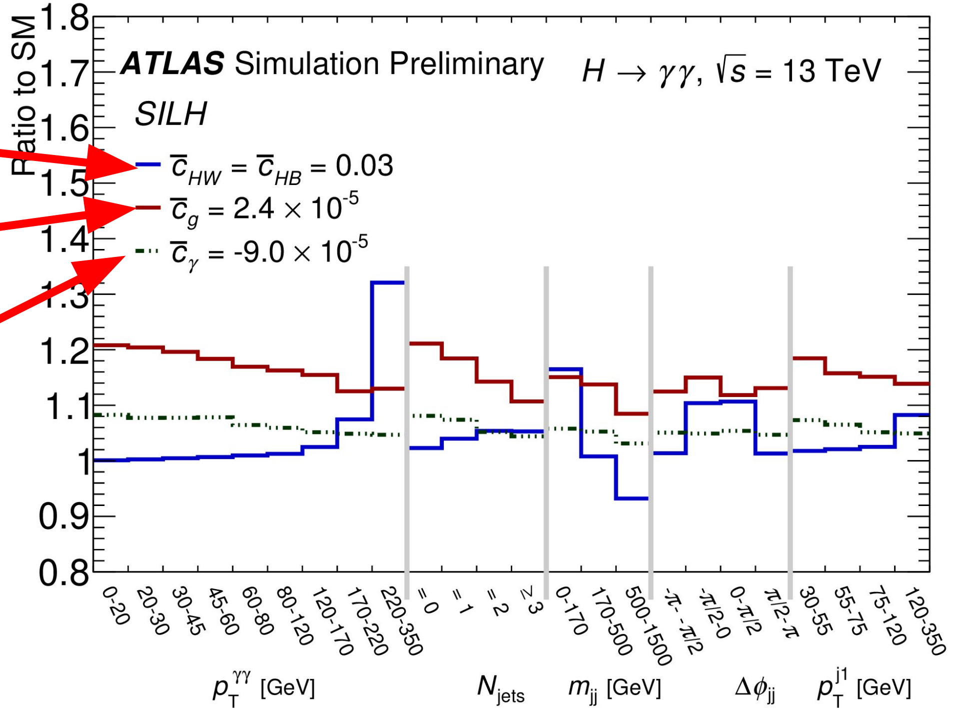
H→ yy is sensitive to:

$\bar{c}_g \mathcal{O}_g \leftarrow$ CP even $\rightarrow \bar{c}_{HW} \mathcal{O}_{HW} \quad \bar{c}_{HB} \mathcal{O}_{HB}$





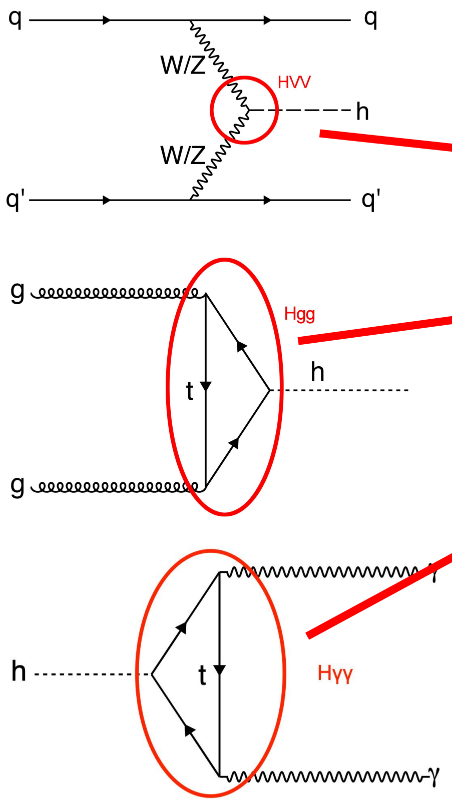


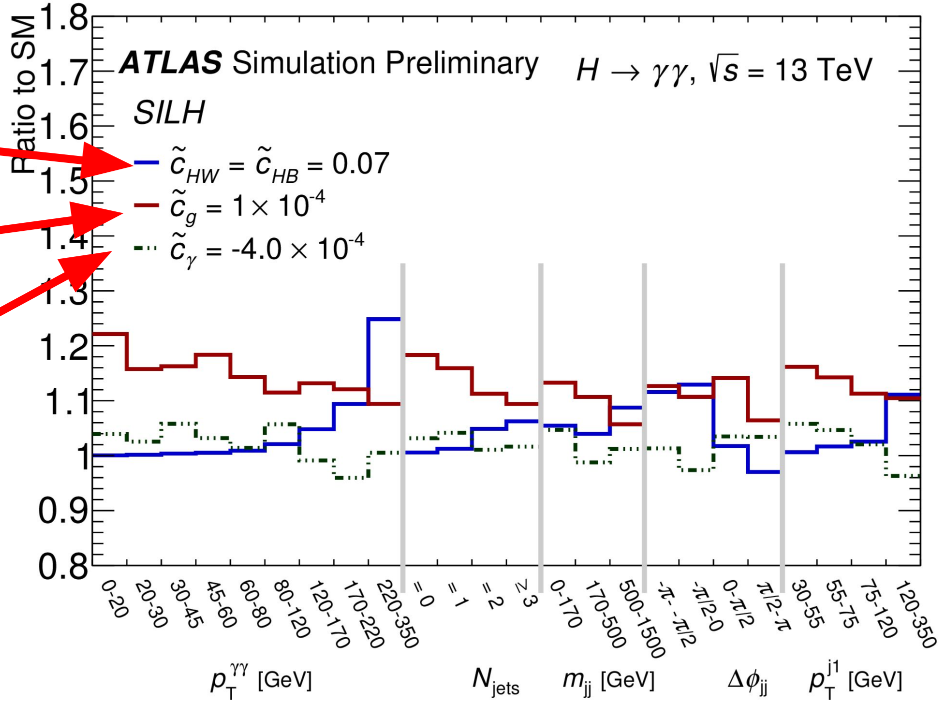


Effective field theory (EFT)

H→ γγ is sensitive to:

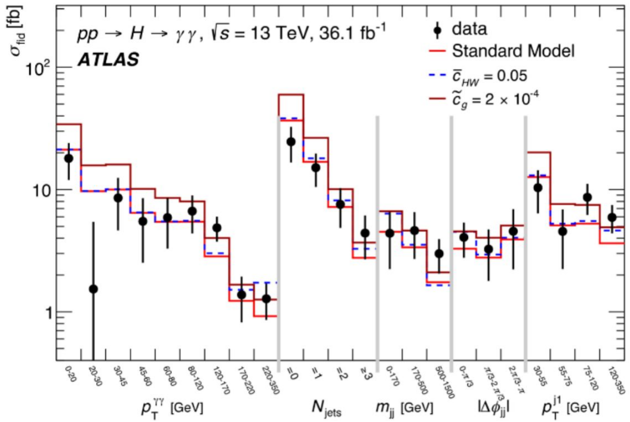
$$\tilde{c}_g \tilde{O}_g \leftarrow \text{CP odd} \rightarrow \tilde{c}_{HW} \tilde{O}_{HW} \qquad \tilde{c}_{HB} \tilde{O}_{HB}$$



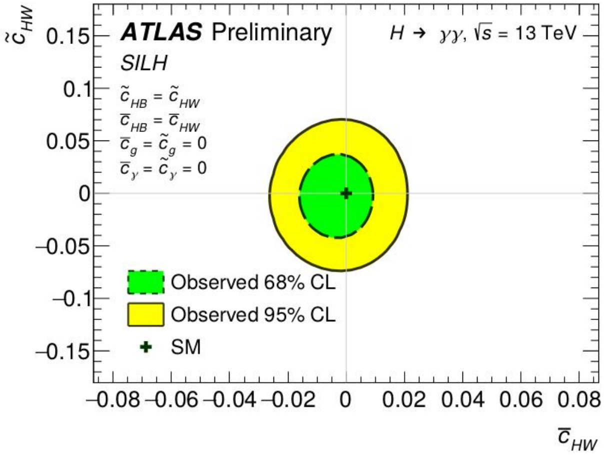


Effective field theory (EFT)

- **Analysis strategy:**
  1) Measure differential cross sections
  2) Perform likelihood fit to measured distributions
  - Constrain Wilson coefficients
- Exclude large range of EFT parameter space
- **So far: No significant deviations from the SM expectations found**
  - However, not yet sensitive to range really relevant for EFTs

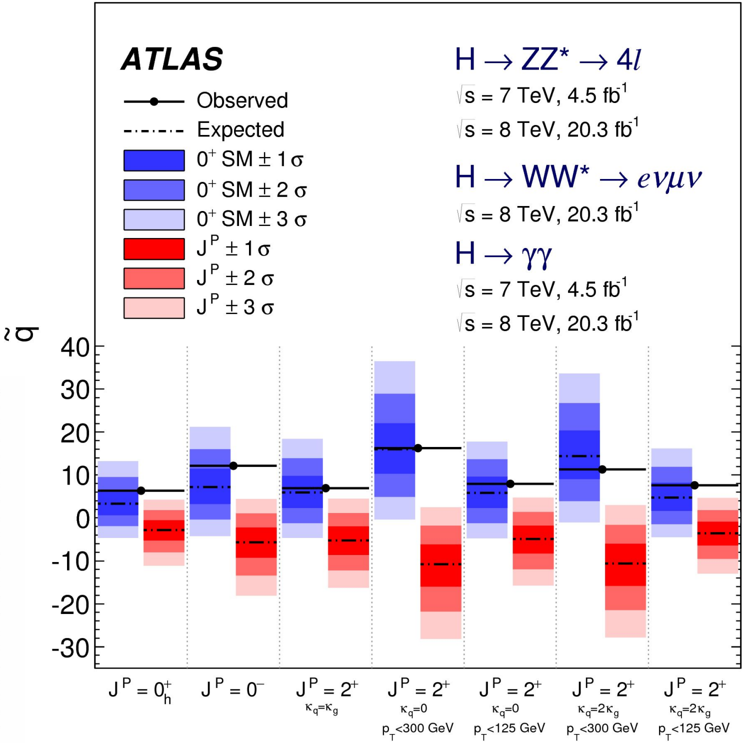


Coefficient	Observed 95% CL limit	Expected 95% CL limit
$\bar{c}_g$	$[-0.26, 0.26] \times 10^{-4}$	$[-0.25, 0.25] \cup [-4.7, -4.3] \times 10^{-4}$
$\tilde{c}_g$	$[-1.3, 1.1] \times 10^{-4}$	$[-1.1, 1.1] \times 10^{-4}$
$\bar{c}_{HW}$	$[-2.5, 2.2] \times 10^{-2}$	$[-3.0, 3.0] \times 10^{-2}$
$\tilde{c}_{HW}$	$[-6.5, 6.3] \times 10^{-2}$	$[-7.0, 7.0] \times 10^{-2}$
$\bar{c}_\gamma$	$[-1.1, 1.1] \times 10^{-4}$	$[-1.0, 1.2] \times 10^{-4}$
$\tilde{c}_\gamma$	$[-2.8, 4.3] \times 10^{-4}$	$[-2.9, 3.8] \times 10^{-4}$



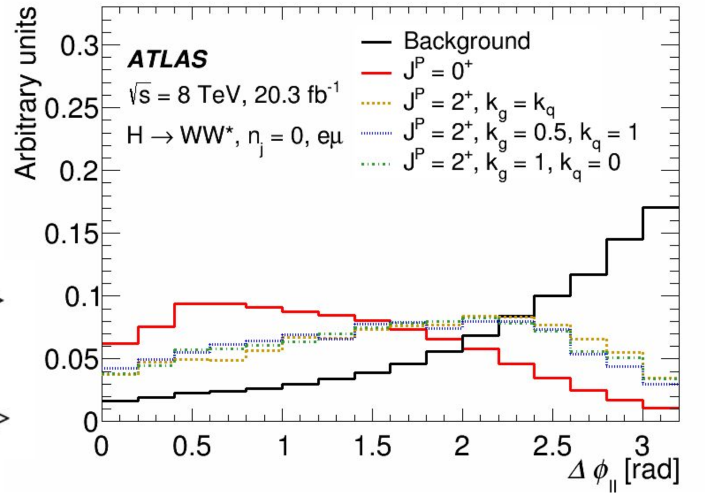
Higgs CP/Spin

- Spin and CP state of Higgs-boson are determined probing angular distribution of decay products
  - Data hints very strongly to a Spin CP state of 0+
  - Alternative models are rejected with a CL of more than 99 .9 %
- Spin-1 hypothesis was theoretically excluded by observation of H->yy decay mode (**Yang's theorem**):
  - *A massive spin-1 particle cannot decay into a pair of identical massless spin-1 particles.*



$$\text{CP} - \text{even}: \quad CP|\Phi>=|\Phi>$$

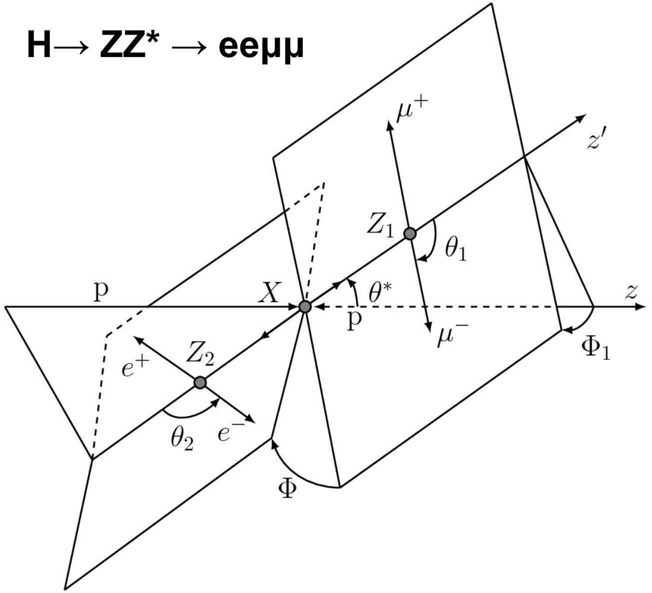
$$\text{CP} - \text{odd}: \quad CP|\Phi>=-|\Phi>$$

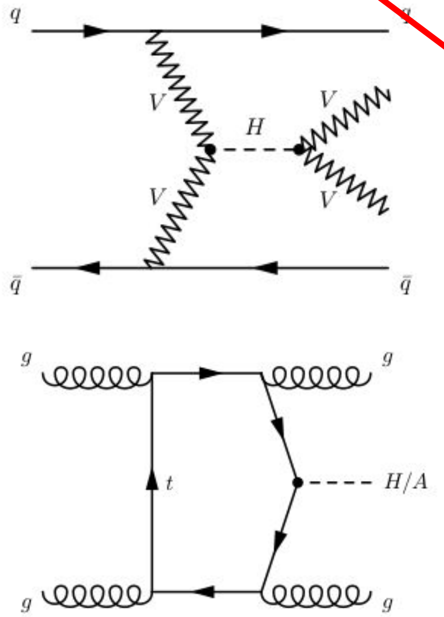


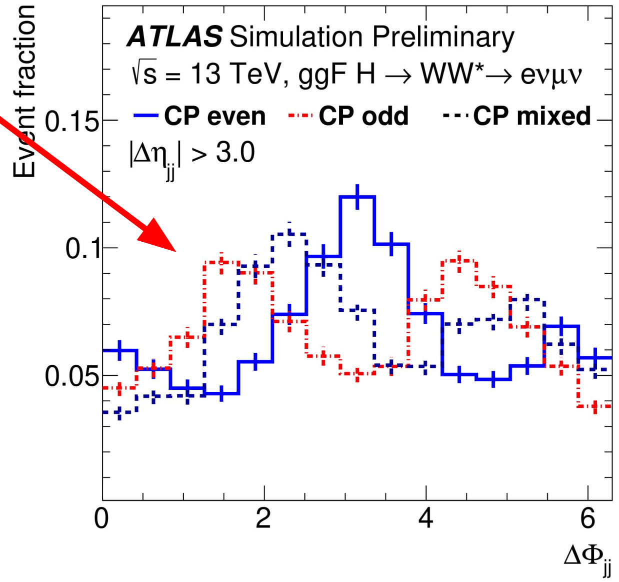
Constraints on CP properties

- **The effective field theory approach is also used to directly constrain the CP properties of the Higgs boson**
  - Probe either angles between decay products or **angles between jets produced in association with the Higgs boson**

H→ ZZ* → eeμμ





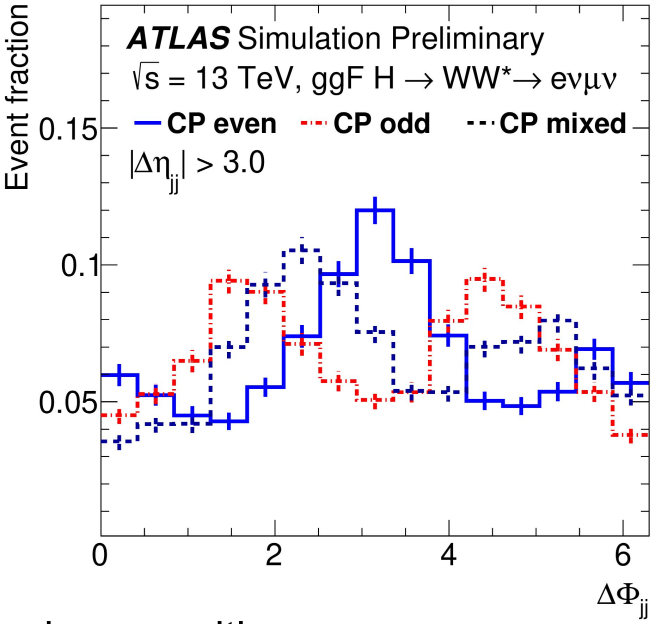


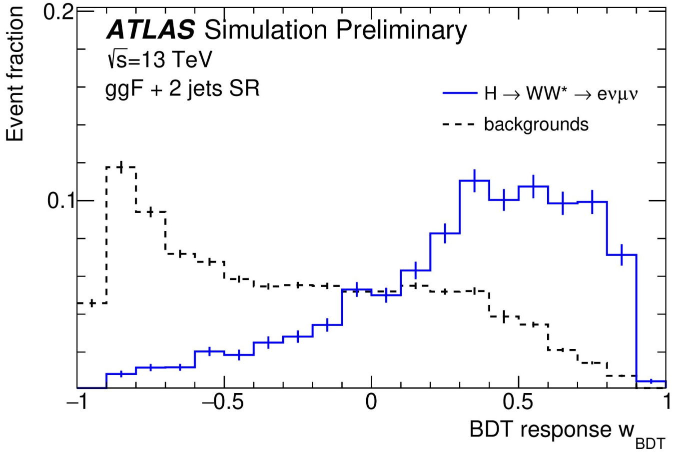
Constraints on CP properties

- The effective Lagrangian that describes the Higgs-gluon interaction is expressed as:

$$\mathcal{L}_0^{\text{loop}} = -\frac{1}{4}\left(\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \kappa_{Agg} g_{Hgg} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}\right) H$$

Scale factors for the CP-even and CP-odd interactions

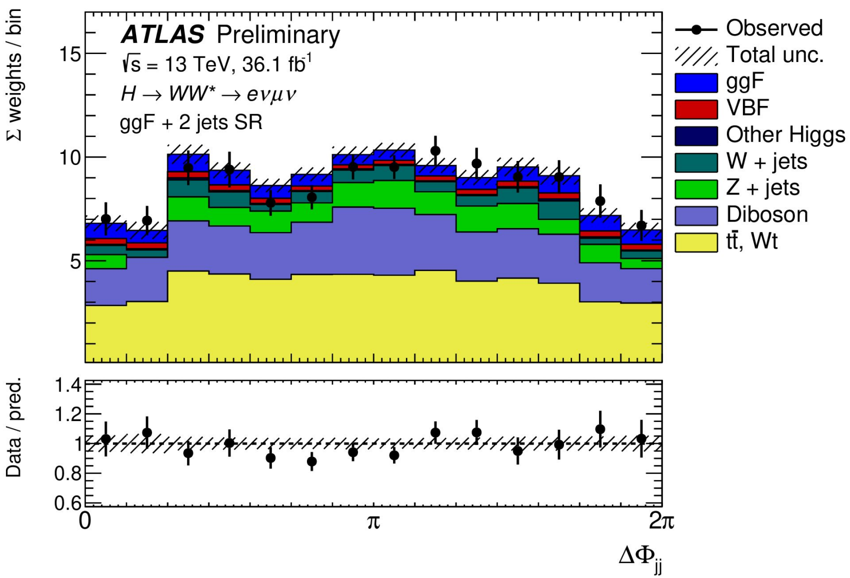


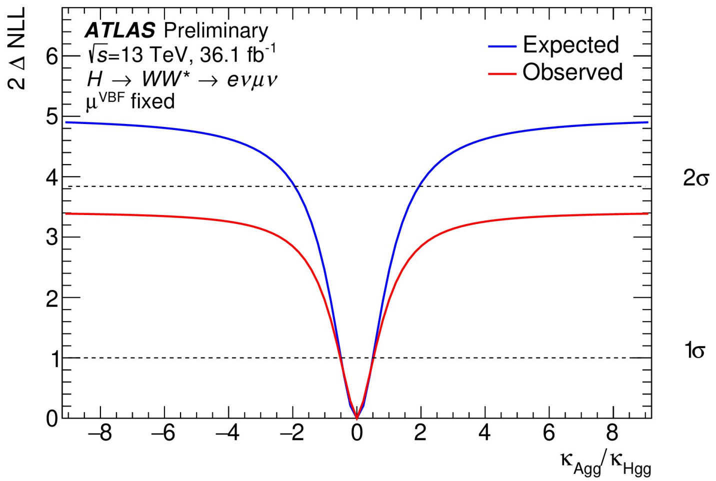


- Complex background composition:
  - Largest contribution from top-quark pairs and diboson WW processes
- Use boosted decision trees to reduce background contributions

Constraints on CP properties

- Apply a maximum likelihood procedure individually to each coupling parameter hypothesis
  - Background prediction is only affected by changes to nuisance parameters





- A negative log-likelihood (NLL) curve is constructed as a function of the coupling parameters.
- The best estimate for the parameter of interest is obtained at the point where the NLL curve reaches its minimum

Taken from: http://cdsweb.cern.ch/record/2743624/files/ATLAS-CONF-2020-055.pdf

Constraints on CP properties

- **Probe HVV vertex present in VBF Higgs events to constrain CP odd contributions**
  - From:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \tilde{g}_{HAA} H\tilde{A}_{\mu\nu}A^{\mu\nu} + \tilde{g}_{HAZ} H\tilde{A}_{\mu\nu}Z^{\mu\nu} + \tilde{g}_{HZZ} H\tilde{Z}_{\mu\nu}Z^{\mu\nu} + \tilde{g}_{HWW} H\tilde{W}^{+}_{\mu\nu}W^{-\,\mu\nu}$$

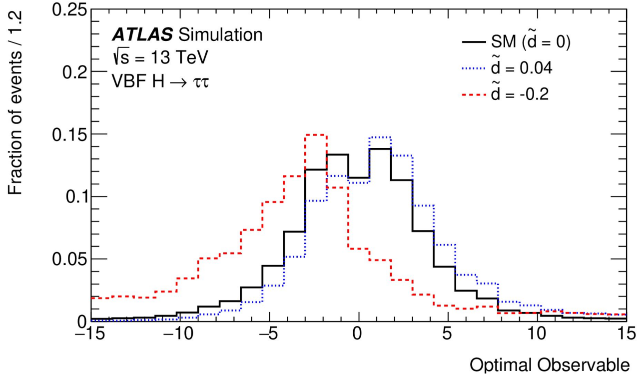
width

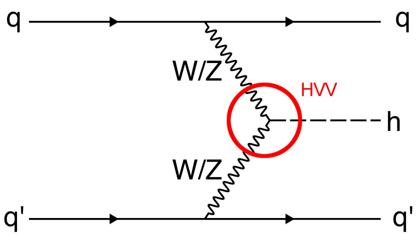
$$\tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}$$

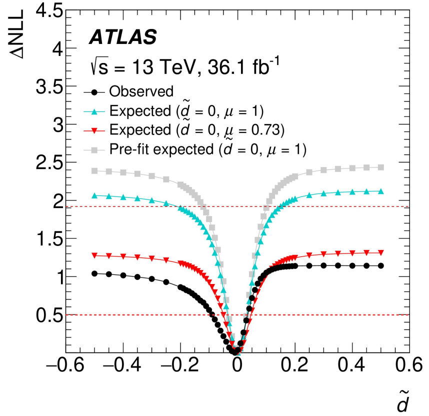
where d˜ governs the strength of CP violation.

  - **Exploit optimal observable which is constructed from the 2 VBF jets:**

$$\mathcal{OO} = \frac{2 \cdot Re\left(\mathcal{M}^{*}_{SM}\mathcal{M}_{CP-\text{odd}}\right)}{|\mathcal{M}_{SM}|^2}$$

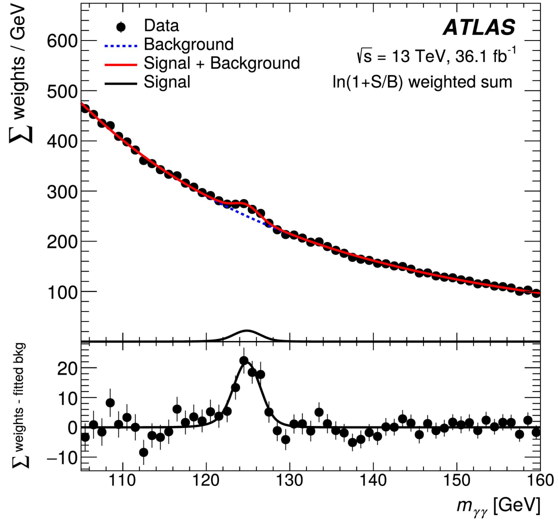


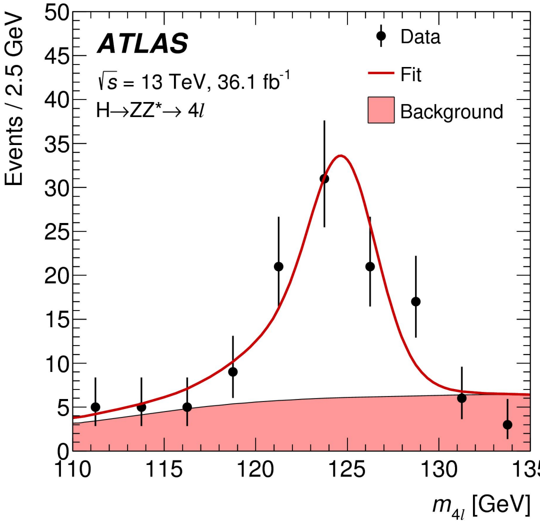


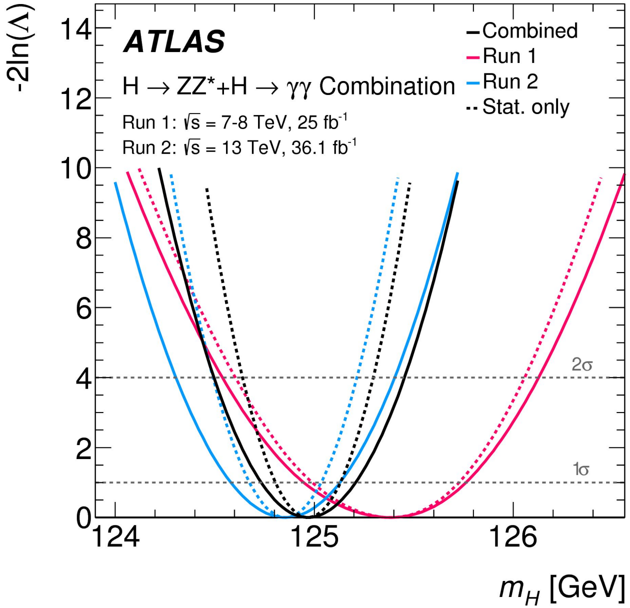


Higgs boson mass measurement

- Higgs boson mass is measured in H → ℓℓℓℓ and H → γγ events
  - Apply a maximum likelihood method simultaneously to both analyses channels
- Run 1 + 2 combination yields: m_H = 124.97 ± 0.24 GeV





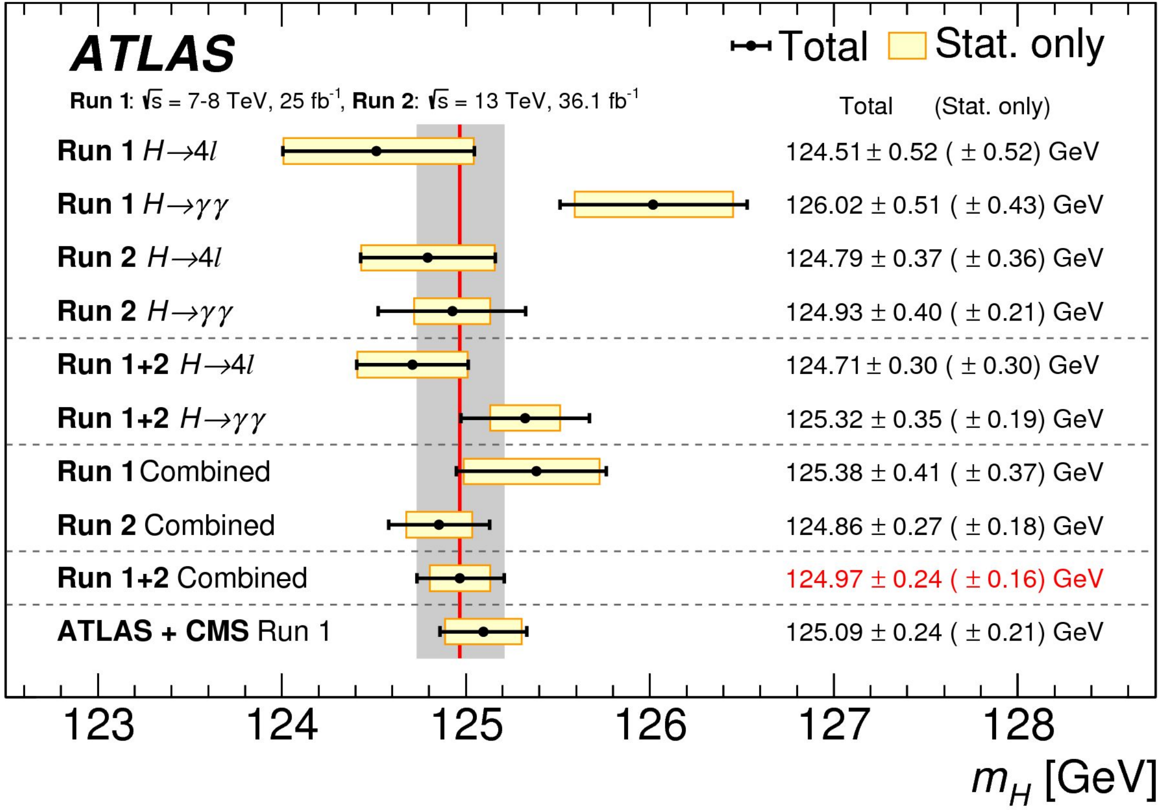


Taken from: https://arxiv.org/pdf/1806.00242.pdf

Uncertainties on Higgs boson mass measurement

Source	Systematic uncertainty in m_H [MeV]
EM calorimeter response linearity	60
Non-ID material	55
EM calorimeter layer intercalibration	55
$Z \to ee$ calibration	45
ID material	45
Lateral shower shape	40
Muon momentum scale	20
Conversion reconstruction	20
$H \to \gamma\gamma$ background modelling	20
$H \to \gamma\gamma$ vertex reconstruction	15
e/γ energy resolution	15
All other systematic uncertainties	10

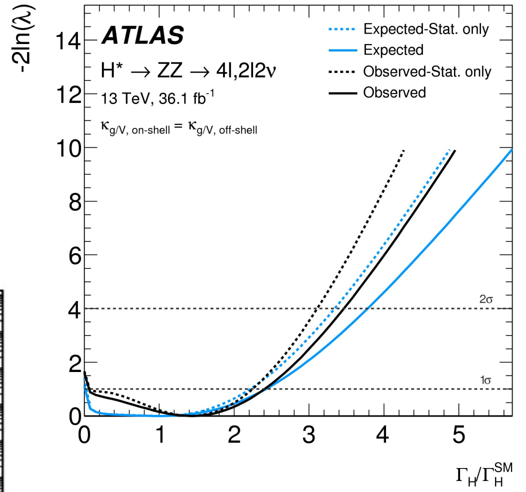
Higgs boson mass measurement



Measurement of Higgs boson width

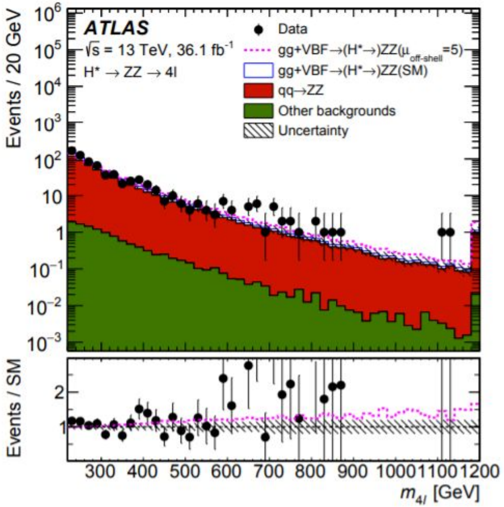
- A measurement of the relative off-shell and on-shell event yields provides direct information about Γ_H:

$$\boxed{\frac{\mu_{\mathrm{off-shell}}}{\mu_{\mathrm{on-shell}}} = \frac{\Gamma_H}{\Gamma_H^{SM}}}$$



- Off-shell contribution is heavily impacted by interference between H→ZZ* and ZZ continuum

- Results:
  - The observed (expected) limit on Γ_H / Γ^{SM}_H is 3.5 (3.7) at the 95% CL
  - The observed (expected) 95% CL limit on the Higgs boson total width of 14.4 (15.2) MeV



Taken from: https://arxiv.org/pdf/1808.01191.pdf