

Collider Particle Physics - Chapter 12 -

Higgs properties measurements at LHC

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Chapter Summary

- ❑ A brief introduction on the Higgs at the Large Hadron Collider (LHC)
- ❑ An experimental overview of the discovery of the Higgs boson
 - Covering in some detail the two main discovery channels
- ❑ The first properties measurements
 - Mass and width
 - Spin and parity
- ❑ Status of the most recent measurements
 - Couplings and combination of all channels
 - Di-Higgs production
- ❑ Simplified template cross sections and coupling measurements
- ❑ BSM couplings in the Effective Field Theory
- ❑ Plans for the coming runs of LHC

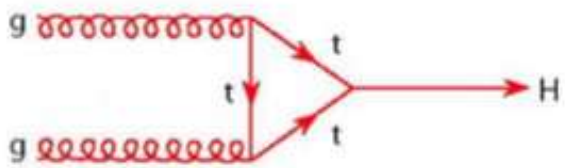
DISCLAIMER: I am including a few more results from ATLAS just because I am more familiar with them, but of course CMS has a pretty similar set of results

The search for the Higgs boson

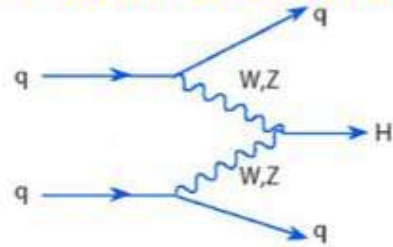
□ In the Standard Model (SM), p-p collisions can lead to the production of an Higgs boson via the following diagrams

- A loop is needed to couple the Higgs to massless gluons: dominated by top-quark loop because the Higgs coupling is proportional to the mass

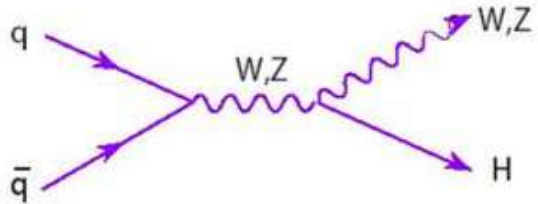
~88% Gluon fusion (ggF)



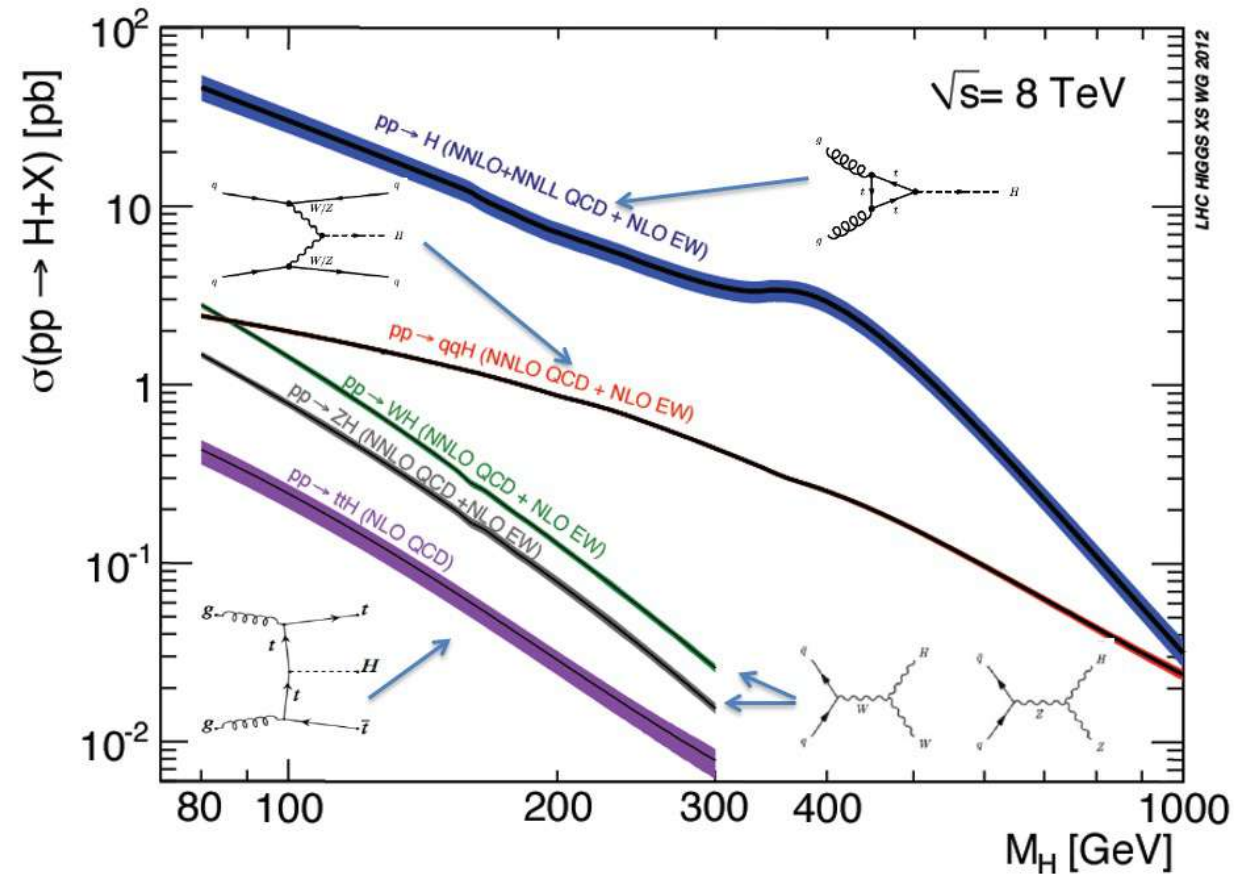
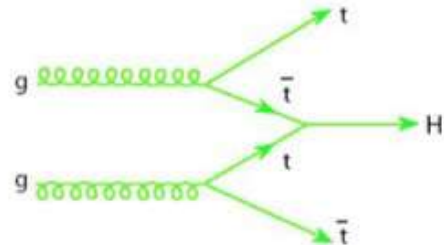
~7% Vector-boson-fusion (VBF)



~4% Higgs-Strahlung (VH)



~1% Association with $t\bar{t}$ (ttH)



Higgs decays

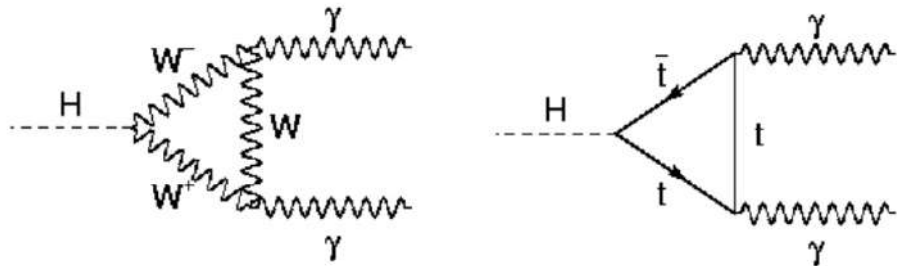
- What we "see" in a detector are the Higgs decay products
- Higgs coupling to fermions (bosons) is proportional to the mass (mass squared)

$$g_F = \sqrt{2} \frac{m_f}{v}$$

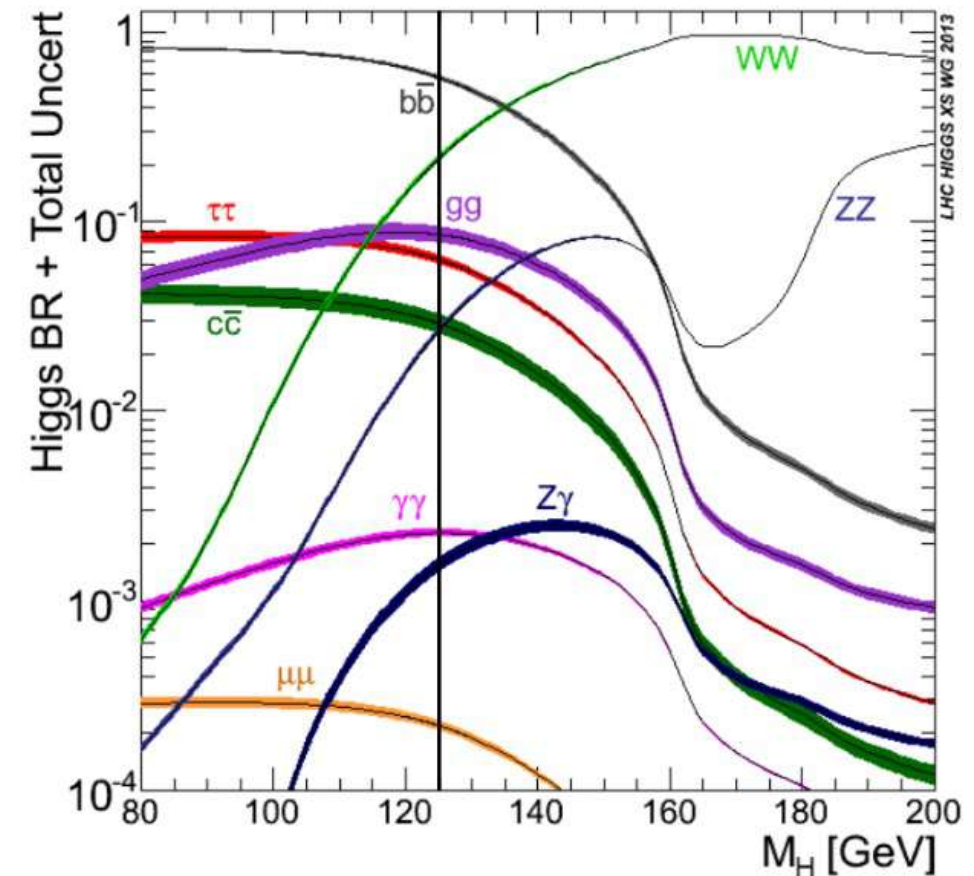
$$g_V = 2 \frac{m_V^2}{v}$$

➤ NB, the two Z's are identical particles → reduced BR with respect to $H \rightarrow W+W-$ because of phase space

- The photon is massless, but still the Higgs decays to $\gamma\gamma$ via loop diagrams with W and top

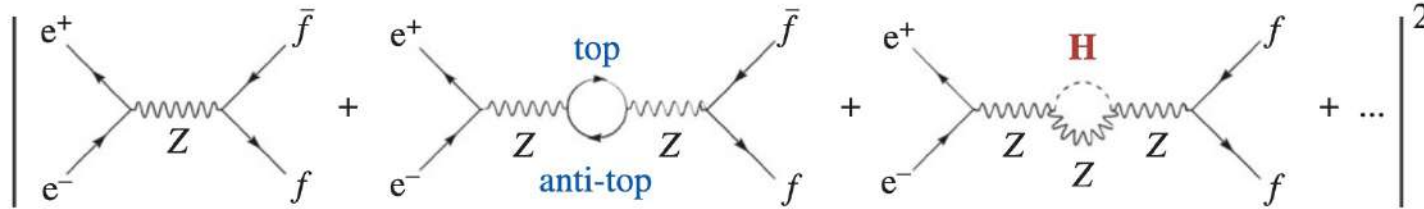


- In the case of the decays to W and Z bosons, one has also to consider the decay BR of the weak bosons into each possible final state



The situation after LEP

Every electroweak observable can be expressed in terms of the Higgs and top mass



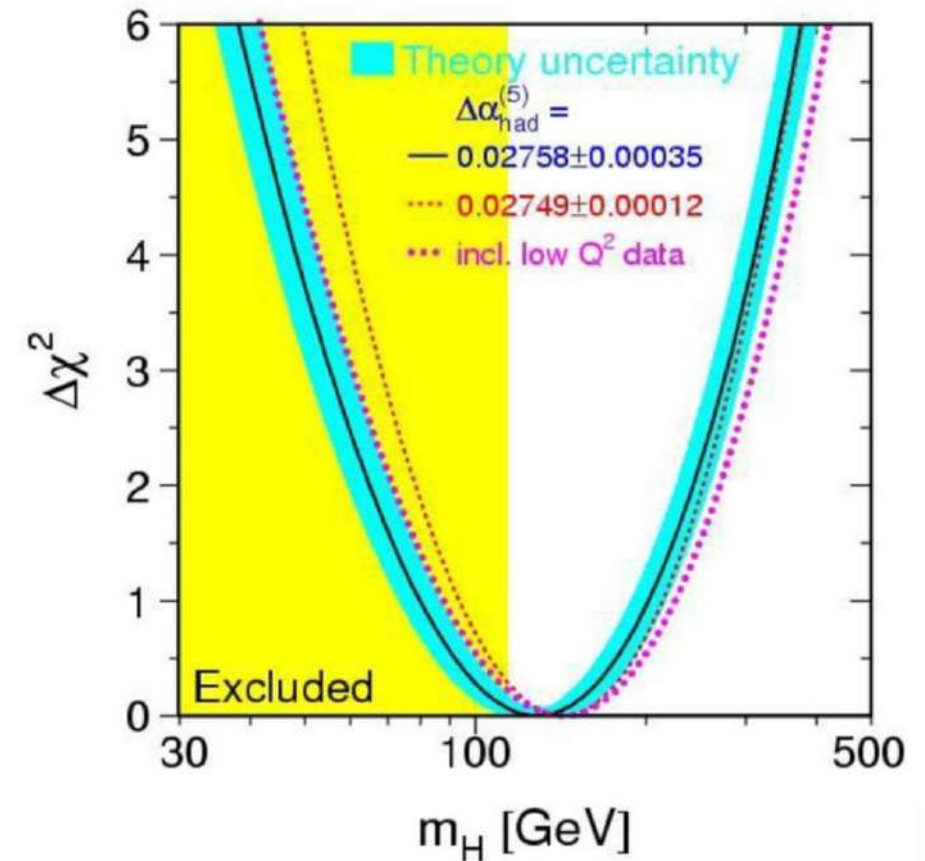
$$m_W^2 \sin^2 \theta_W = m_Z^2 \cos^2 \theta_W \sin^2 \theta_W = \frac{\pi \alpha}{\sqrt{2} G_F} (1 + \Delta r)$$

$$\Delta r \propto \frac{3 G_F}{8 \pi^2 \sqrt{2}} m_t^2, \frac{\sqrt{2} G_F}{16 \pi^2} \left(\frac{11}{3} \ln \frac{m_H^2}{m_Z^2} + \dots \right)$$

Precision measurements of the Z (LEP), W (LEP and Tevatron), and top (Tevatron) allowed a fit of the Higgs mass

Only valid in the SM hypothesis → the experiments were designed for a search over a broader mass range

Best fit for the Higgs mass was 129_{-49}^{+74} GeV. and upper limit at 95% CL was at 285 GeV



LHC

❑ LHC is a proton-proton collider that can operate at proton-proton center of mass energies of up to 14 TeV

➤ Reminder: that is not the center of mass energy of the interaction between the partons

❑ The LHC experiments, ATLAS and CMS have taken data up to now in three periods:

❑ Run-1: 2010-2012

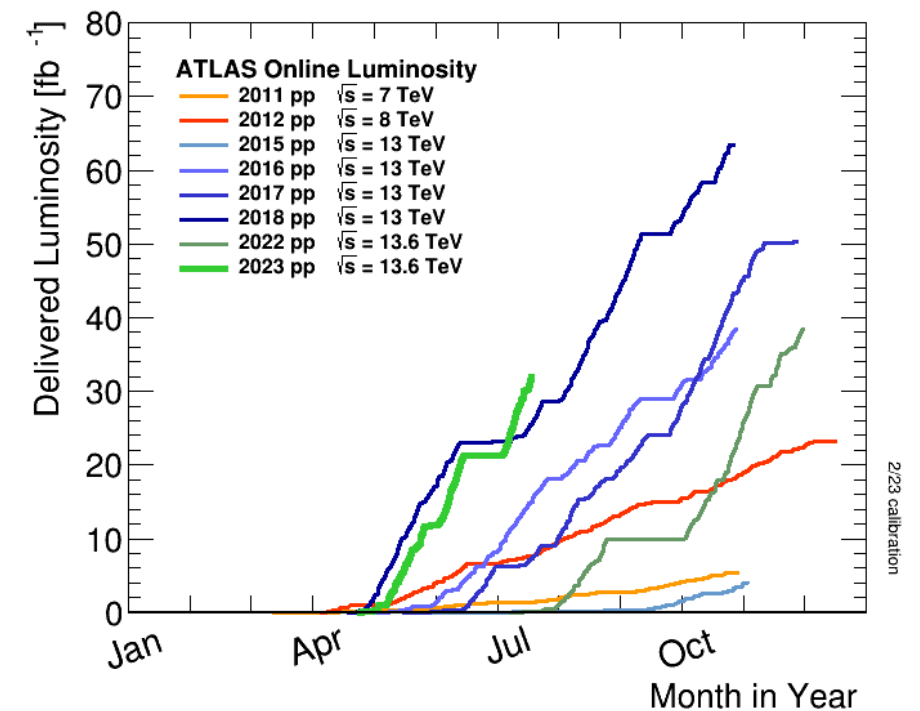
➤ center of mass energies of 7 and 8 TeV, fb^{-1}

❑ Run-2: 2015-2018

➤ center of mass energy of 13 TeV, 139 fb^{-1}

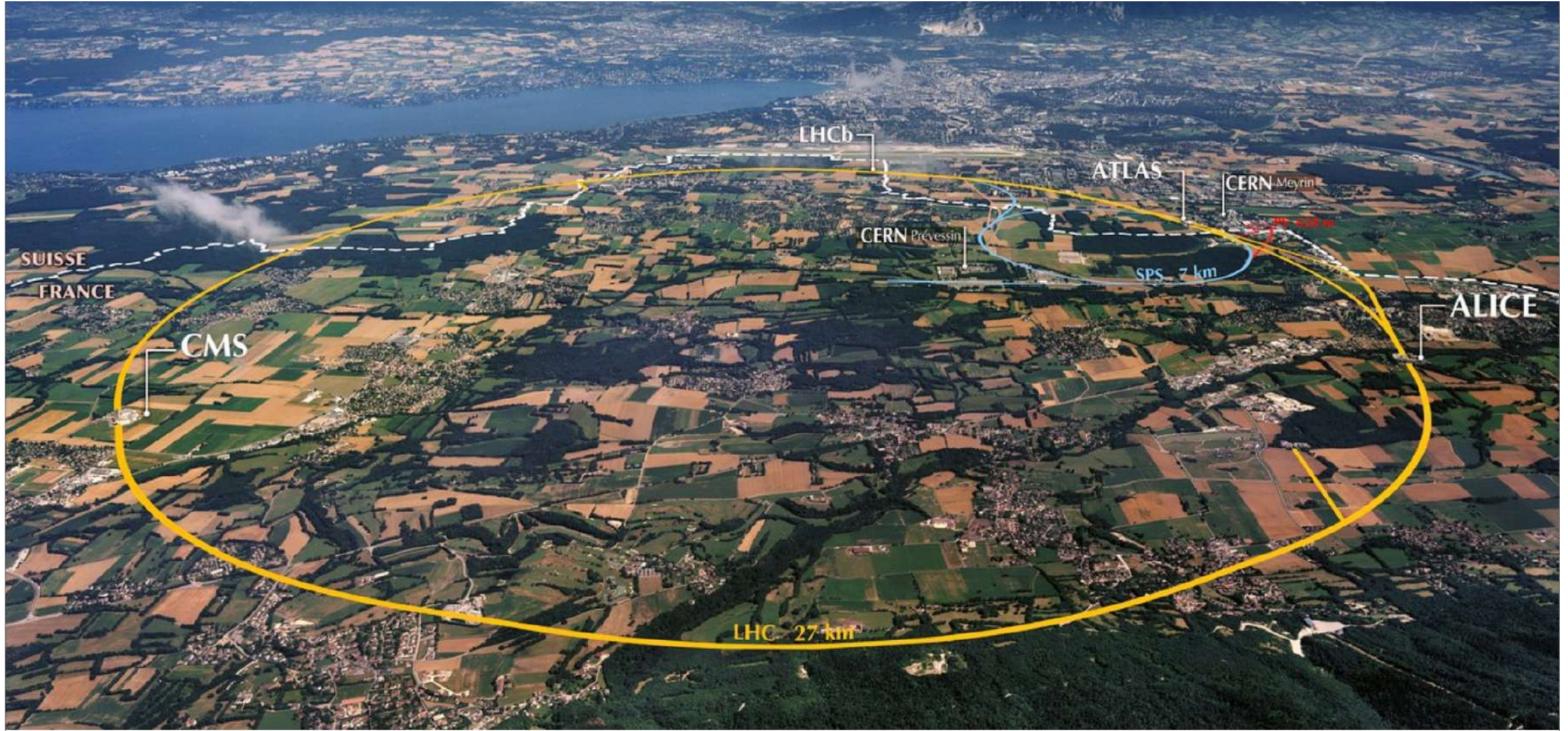
❑ Run-3: 2022-ongoing

➤ center of mass energy of 13.6 TeV, at the moment $\sim 70 \text{fb}^{-1}$



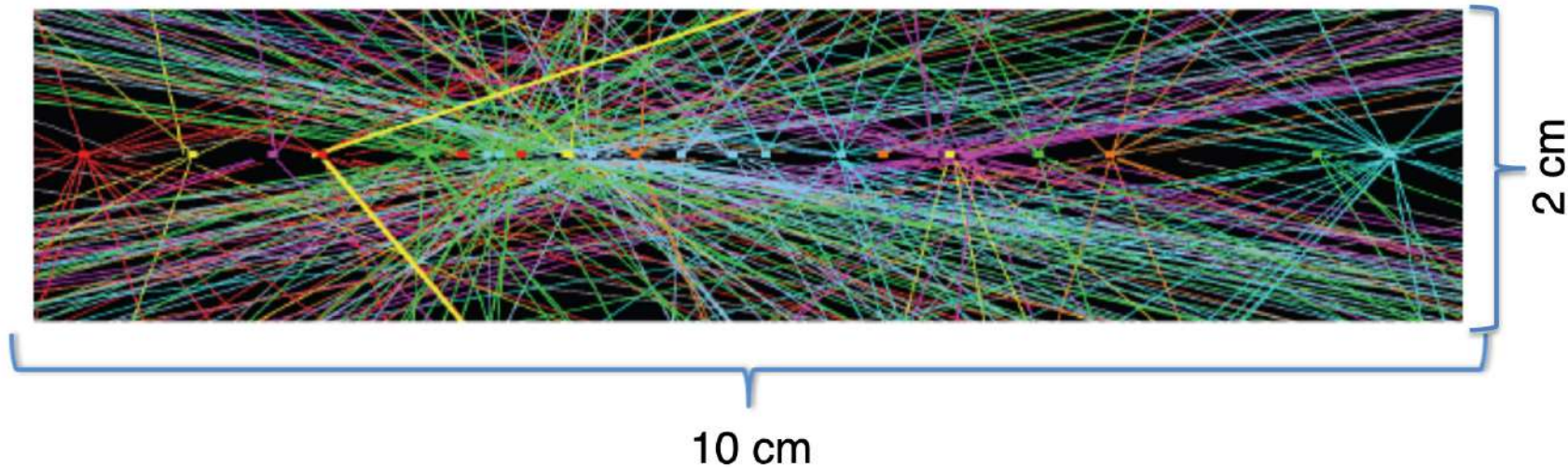
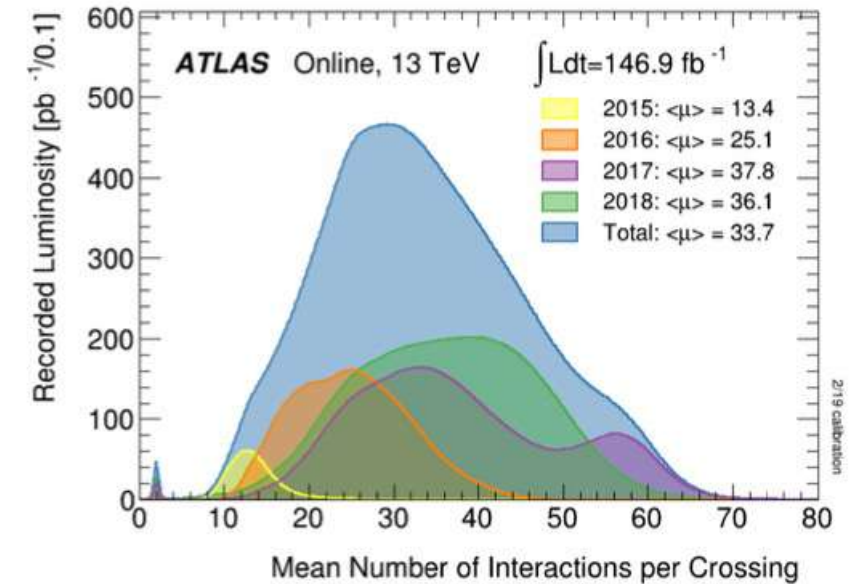
❑ When talking about the discovery I will show Run-1 results, while all the results on properties measurements will include the most recent Run-2 results

LHC

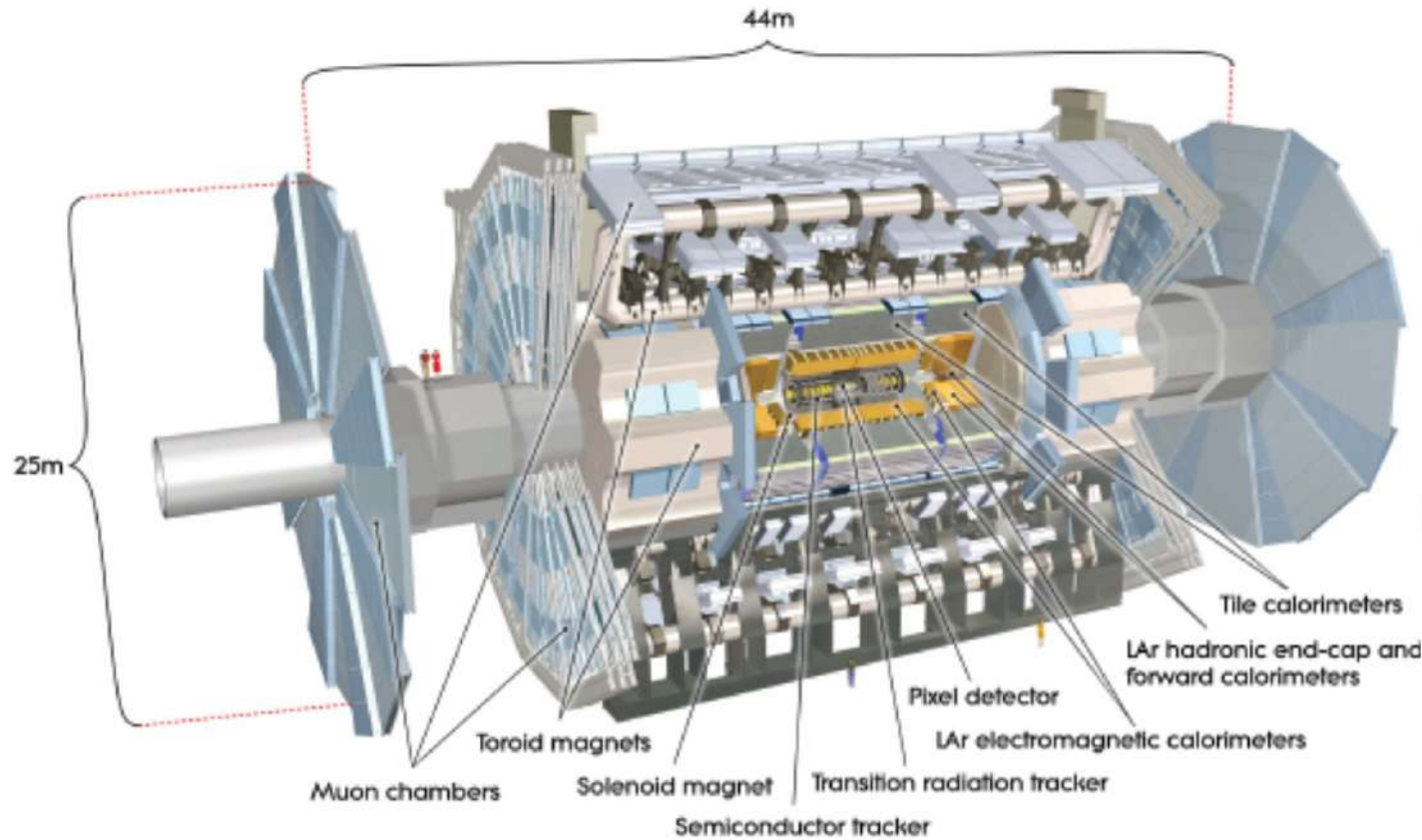


Luminosity and pileup

- ❑ In each bunch-crossing there are multiple proton-proton interactions occurring
- ❑ The interaction points are distributed along the z axis with a σ of ~ 5 cm
- ❑ Each primary vertex is reconstructed fitting a common position to groups of track
- ❑ The resulting resolution on the z of each primary vertex is ~ 90 microns thus making it possible to separate the vertices using the z
- ❑ We now reached 60 mean interactions, and will reach 200 in run-4



The LHC detectors: ATLAS



Magnets

1 Central Solenoid (2 T)
+ 3 air-core toroids

Tracking

Silicon+Transition radiation
tracker

EM calo

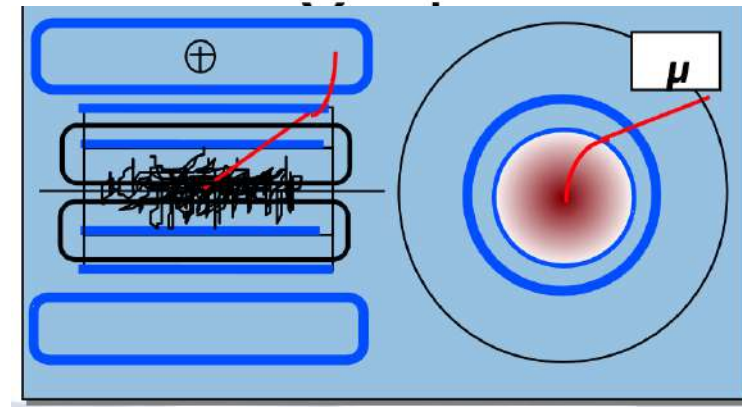
Sampling LAr calo

HAD calo

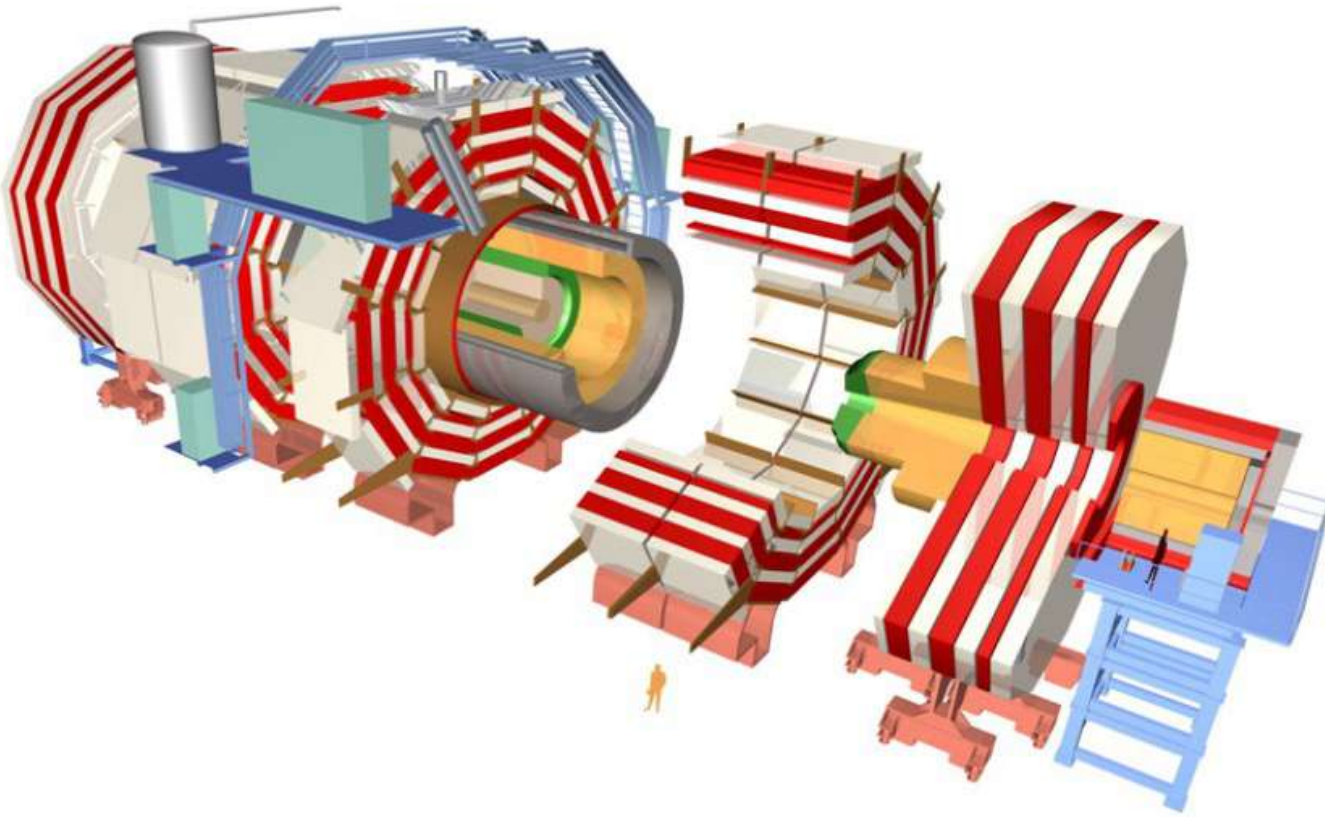
Plastic scintillator (barrel)
LAr technology (endcap)

Muon

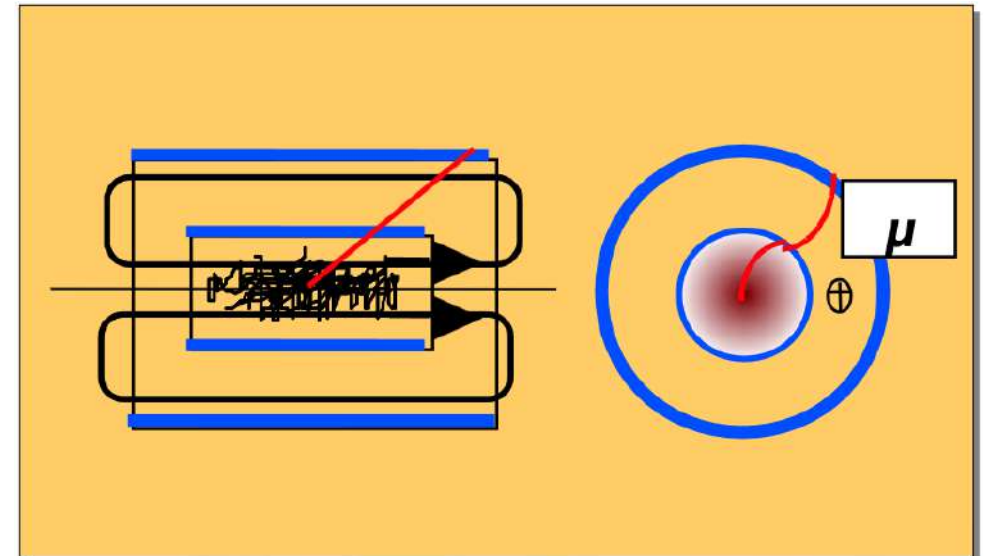
Reco and trigger
Standalone reco capabilities



The LHC detectors: CMS



- 1 central solenoid with 4T field
- Muon chambers magnetic field in the solenoid return yoke
- Silicon trackers in the inner detector
- Crystal electromagnetic calorimeter
- Hadronic calo in brass + plastic scintillator



Searching the Higgs events

Some of the most sensitive channels

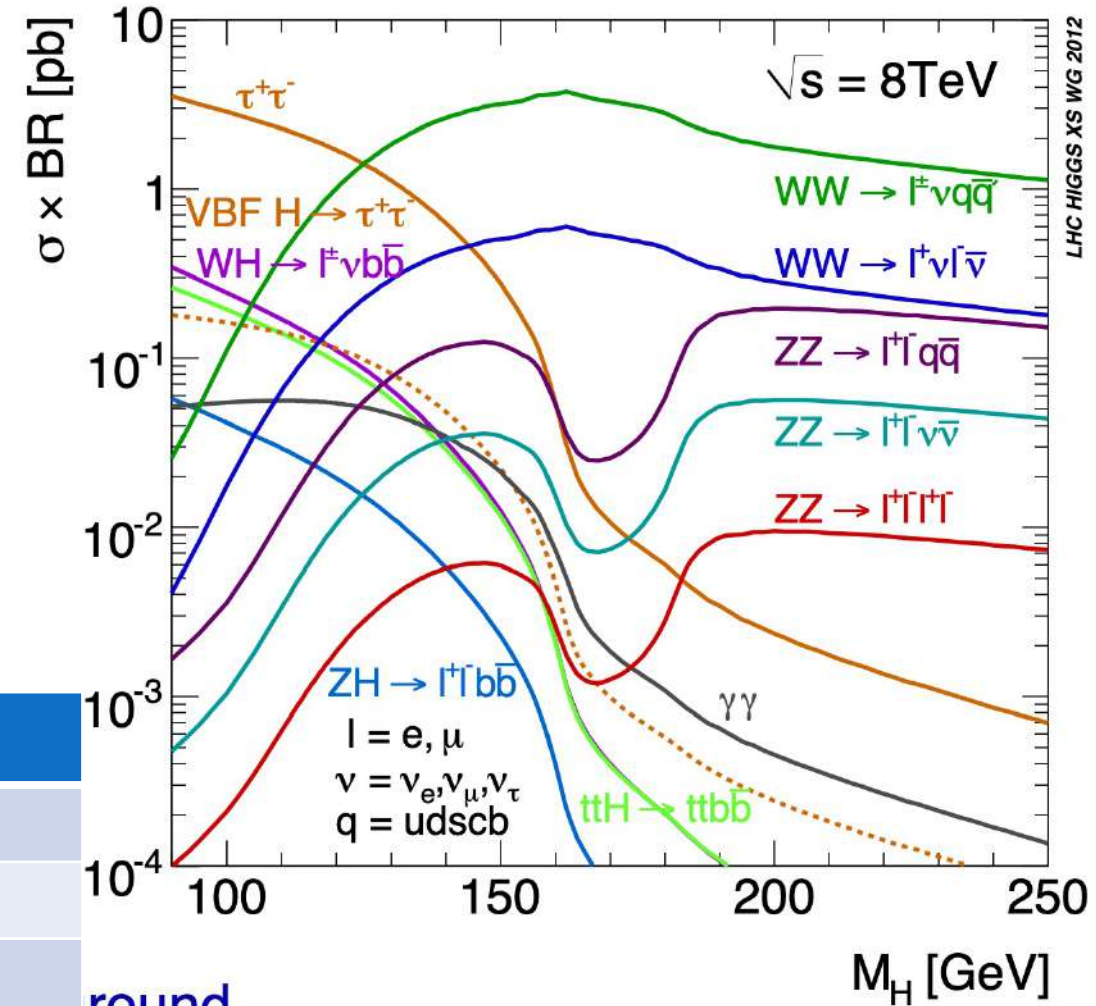
- ❑ The most sensitive channels depend on the Higgs mass
- ❑ In the low mass ($m_H < 150$ GeV), in spite of the low branching ratios, the $ZZ(*) \rightarrow 4l$ channel
- ❑ Channels including jets are in general difficult
 - Large backgrounds
 - Worse resolution in jet reconstruction
- ❑ Exception are the b-jets (and c-), that can be indentified thanks to their longer lifetime
- ❑ Leptons and photons provide a cleaner signature

Events expected in 20 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$, for $m_H = 125 \text{ GeV}$

These are the events before any selection!

At 13 TeV the rates increase by a factor ~ 2

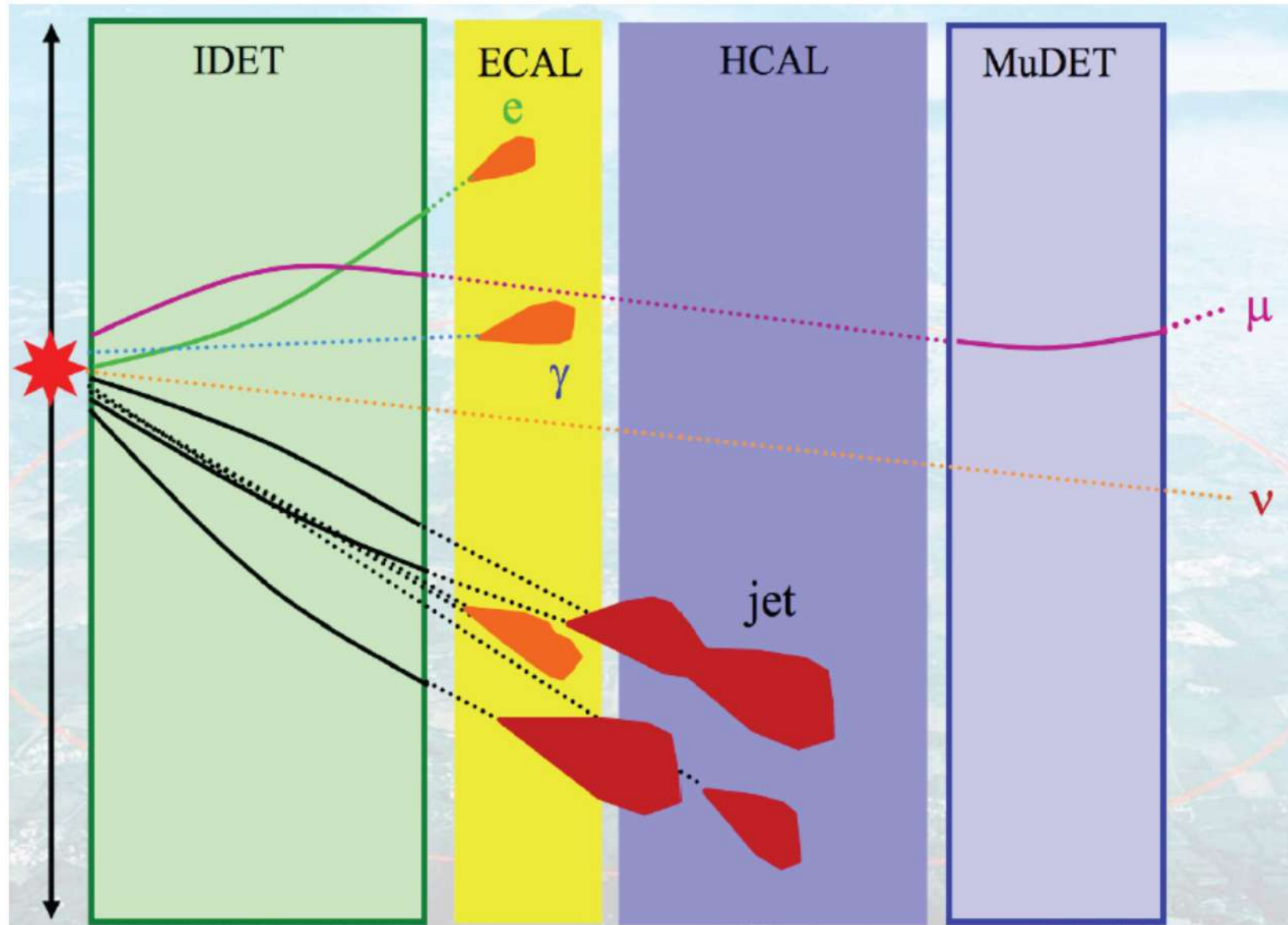
Decay Channel	Signal Events
$H \rightarrow \gamma\gamma$	~ 1000
$H \rightarrow ZZ^* \rightarrow 4l$	~ 60
$H \rightarrow WW \rightarrow l\nu l\nu$	~ 4000
$H \rightarrow \tau\tau$	~ 20000



Steps for building a selection

- ❑ In particular for searches, it is very important to develop the signal selection **without looking at the data** (blind analysis) in the signal region
- ❑ This avoids biases in the selection: looking at the data can cause even involuntarily to pick excess regions and artificially increase the significance
- ❑ The analysis can be developed using MonteCarlo, and looking at the so-called control regions
 - Regions selected with cuts that remove completely the signal and only keep the backgrounds under study
- ❑ And, when looking for a signal, the most important thing is... the background:
 - Processes that give the same signature as the signal you are looking for
 - Can be either identical (same final state): irreducible background or a different final state that can be mis-identified as the signal
- ❑ For each signal a selection must be developed, aiming at maximizing the efficiency for the signal, and the rejection for the background

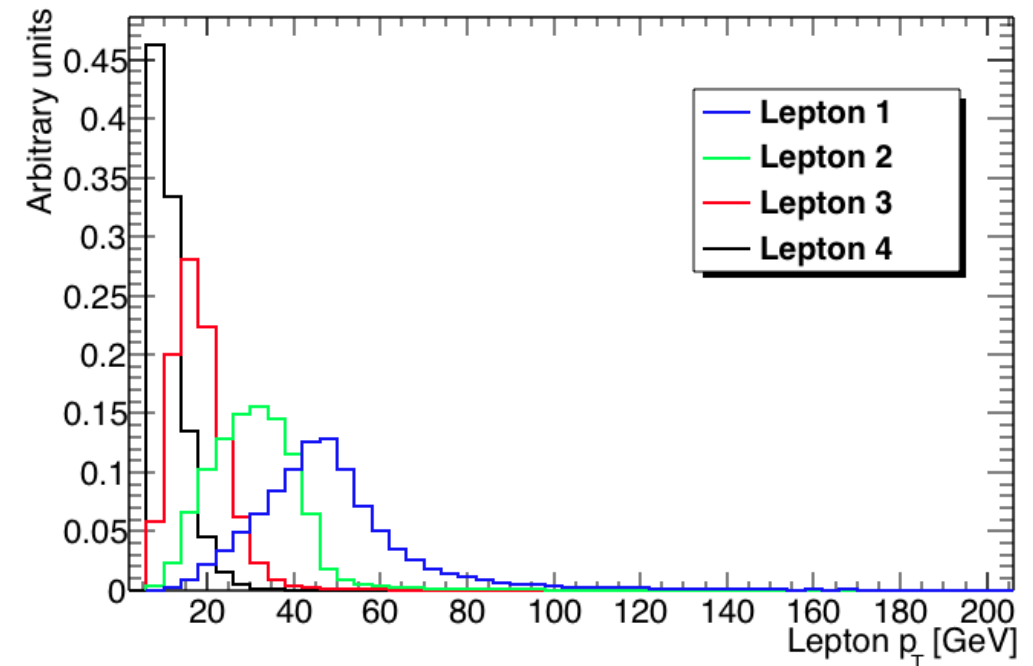
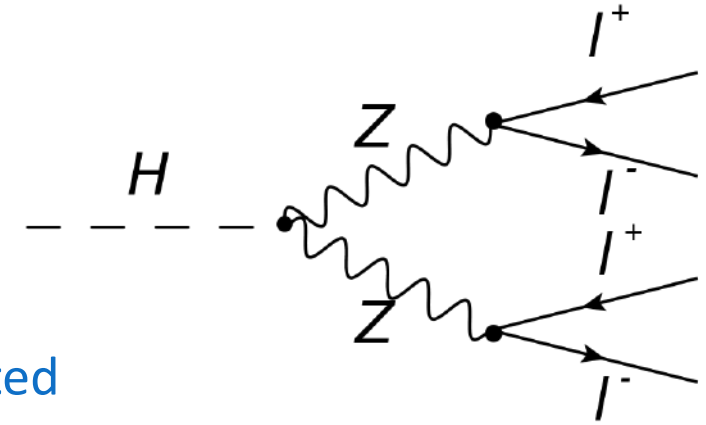
Identification and reconstruction



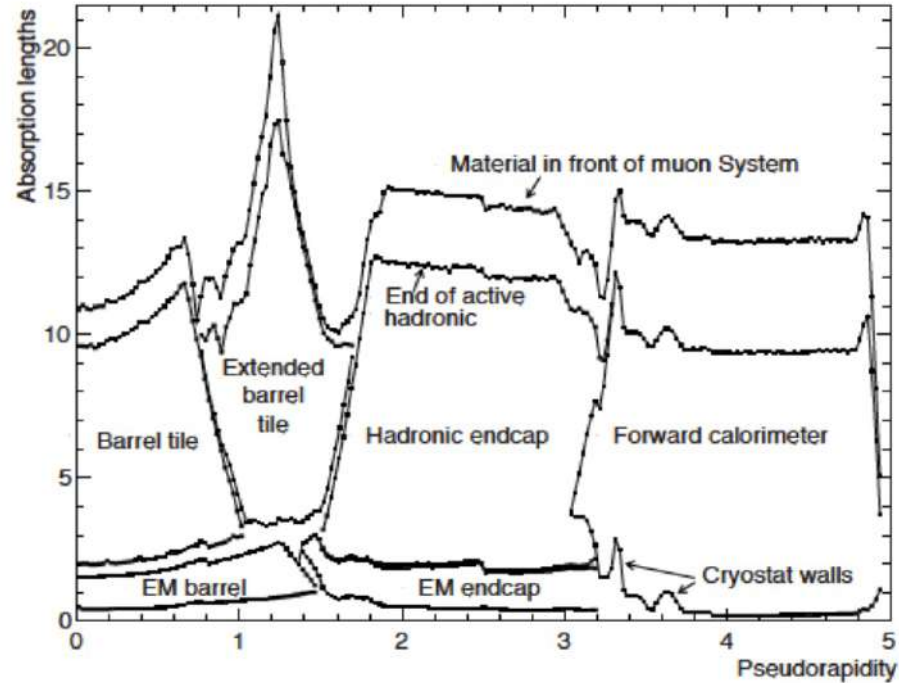
Schematic view of a generic detector parts and their usage for particle identification

The $H \rightarrow ZZ^* \rightarrow 4\text{-lepton}$ channel

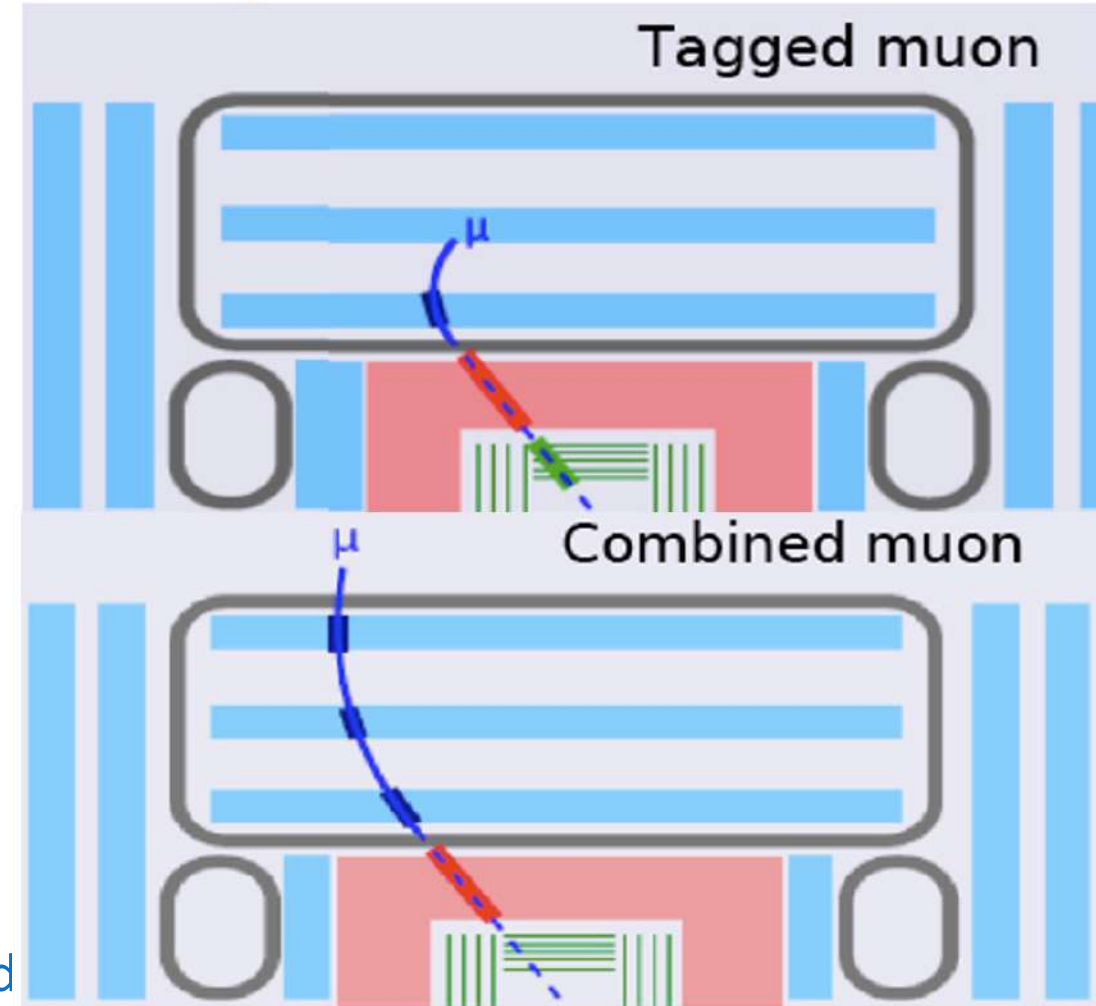
- ❑ Consider only electrons and muons because:
 - taus decay with neutrino(s) in the final state
 - channels with jets ($llqq$, $qqqq$) have larger BR but much larger backgrounds, and worse mass resolution
 - channels with neutrinos in the final state can't be fully reconstructed
- ❑ Electrons and muons are the final state particles that can be reconstructed with the best resolution
- ❑ The Higgs mass defines whether the two Z's are both on shell or not
 - For masses above 114 GeV, at least one Z must be on-shell
- ❑ For the Higgs at 125 GeV, only one Z is on-shell, the other is a virtual Z^* with mass above ~ 12 GeV



Identifying the muons



- ❑ If a particle reaches the muon spectrometer, it is already identified as a muon
 - Small fraction of punch-through
- ❑ Then the muons can be reconstructed in different ways, mostly as “combined” muons
 - This depends also on the experiment layout, i.e. CMS and ATLAS are a bit different in this aspect



Muon momentum measurement

- In case of a spectrometer with a uniform magnetic field:

$$p_T = qB\rho = 0.3B(\text{T})\rho(\text{m})$$

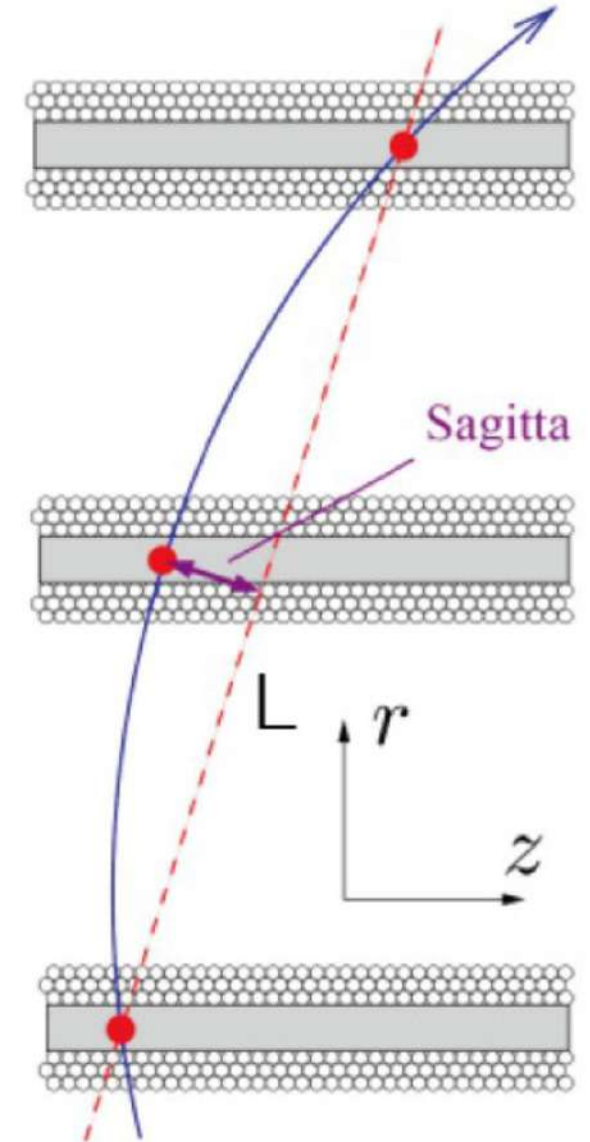
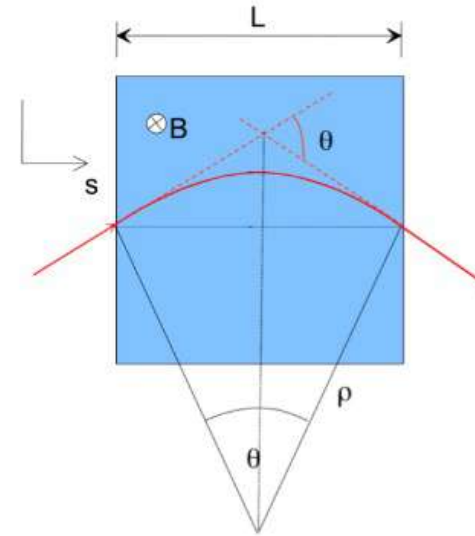
- What is usually measured is the “sagitta” s

$$s = \frac{0.3BL^2}{8p_T}$$

- For example, measuring s via 3 equidistant points, $s = (x_1 + x_3)/2 - x_2$

$$\frac{\sigma(p_T)}{p_T} = \sqrt{\frac{3}{2}} \sigma_x \frac{8p_T}{0.3BL^2}$$

- The impact of the detector resolution on the momentum resolution increases vs p_T



Muon momentum measurement

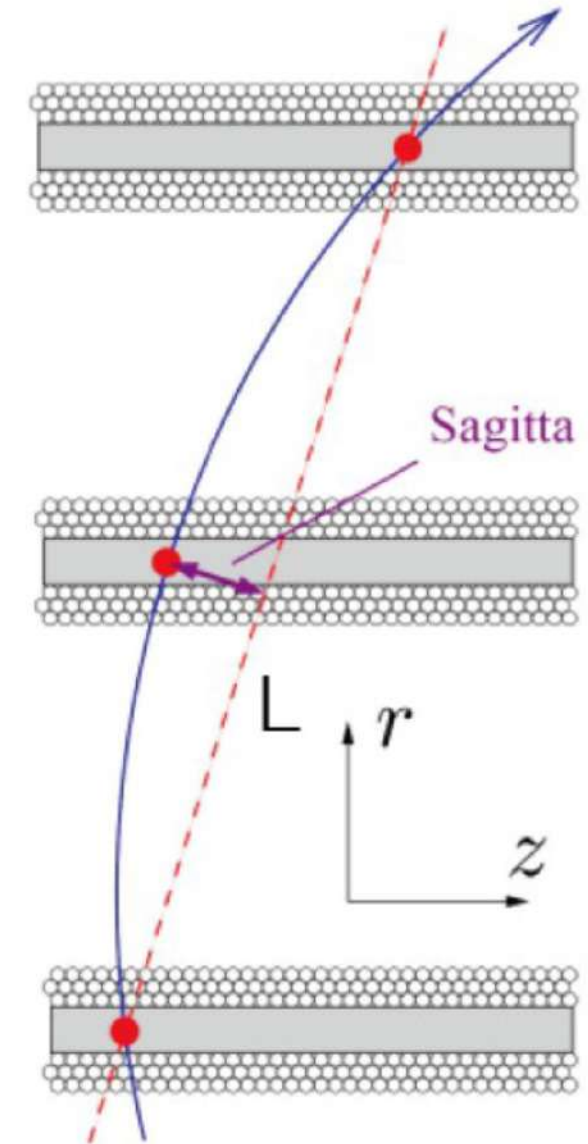
- ❑ In addition there is the contribution from the multiple scattering
 - stochastic scattering in the materials crossed by the muon

- ❑ The impact on the track direction decreases with the momentum

$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{x/X_0} \left[1 + 0.038 \ln(x/X_0) \right]$$

- ❑ So the final impact on the relative momentum resolution
 - σ_{p_T}/p_T is \sim constant

- ❑ In general the resolution is a combination of the detector resolution and the multiple scattering, whose balance depends on the detector structure

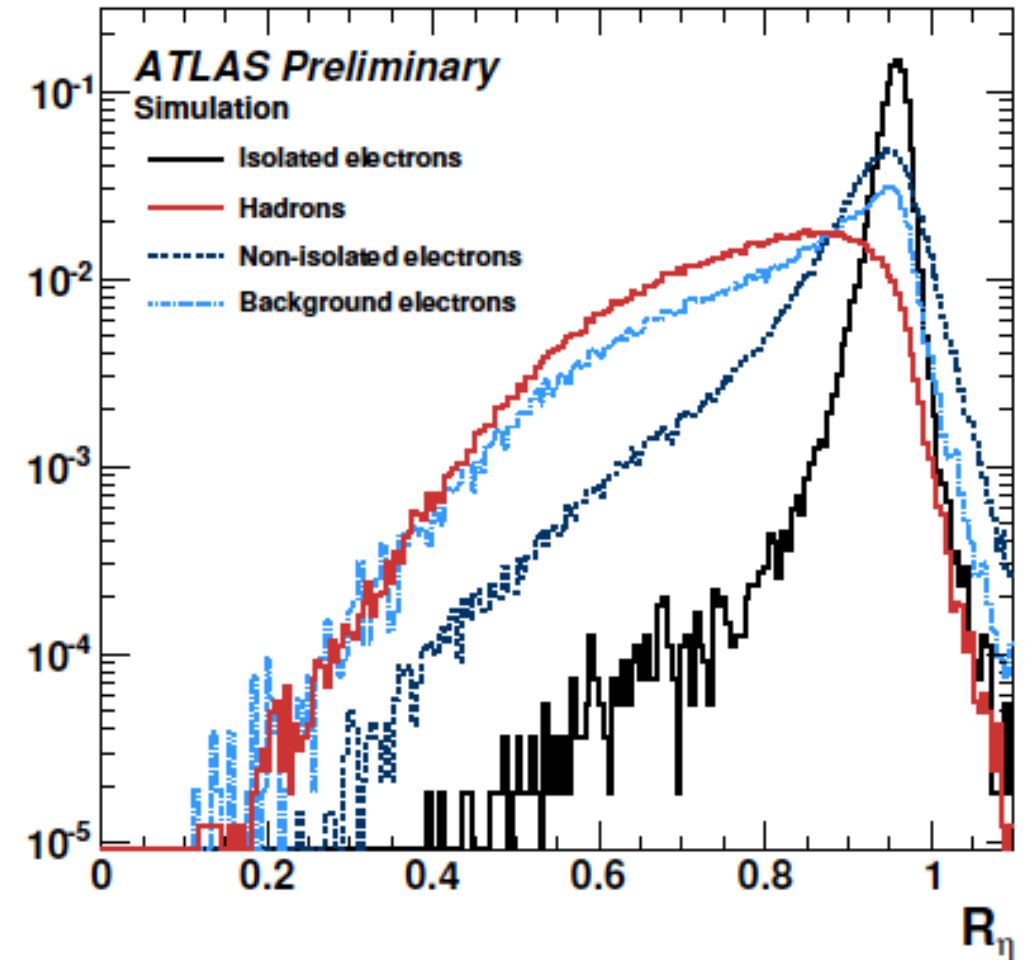
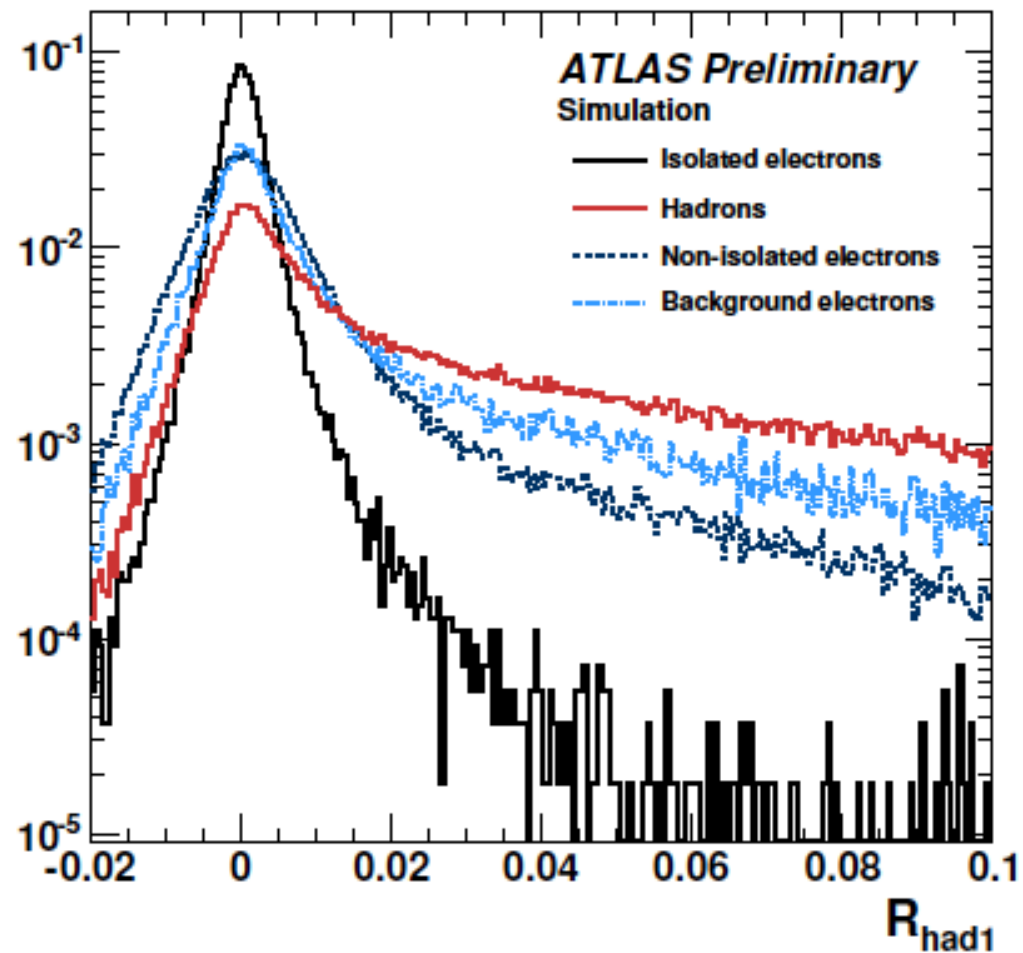


Identifying electrons and photons

- ❑ An electron is identified by a track in the inner detector, spatially matched to a cluster of energy cells in the EM calorimeter
- ❑ The criterium is in principle simple, but there are other objects that can create a fake electron
 - jets and hadrons from quarks hadronization have tracks and energy deposits → main background to electron identification
 - photons have clusters exactly like of the electrons but no track in the ID → but another track in the event can be mis-associated to the EM cluster
- ❑ Some criteria to identify the electrons are:
 - Low activity in the hadronic calorimeter in correspondence of the EM cluster
 - Shape of the EM cluster
 - Compatibility between the track and the cluster
- ❑ After the identification, the direction of the electron is given by the track, the energy by the EM cluster energy
- ❑ For the photons, the criteria are ~ the same as for the electrons on the EM clusters, but of course no requirement of a track and all the related variables

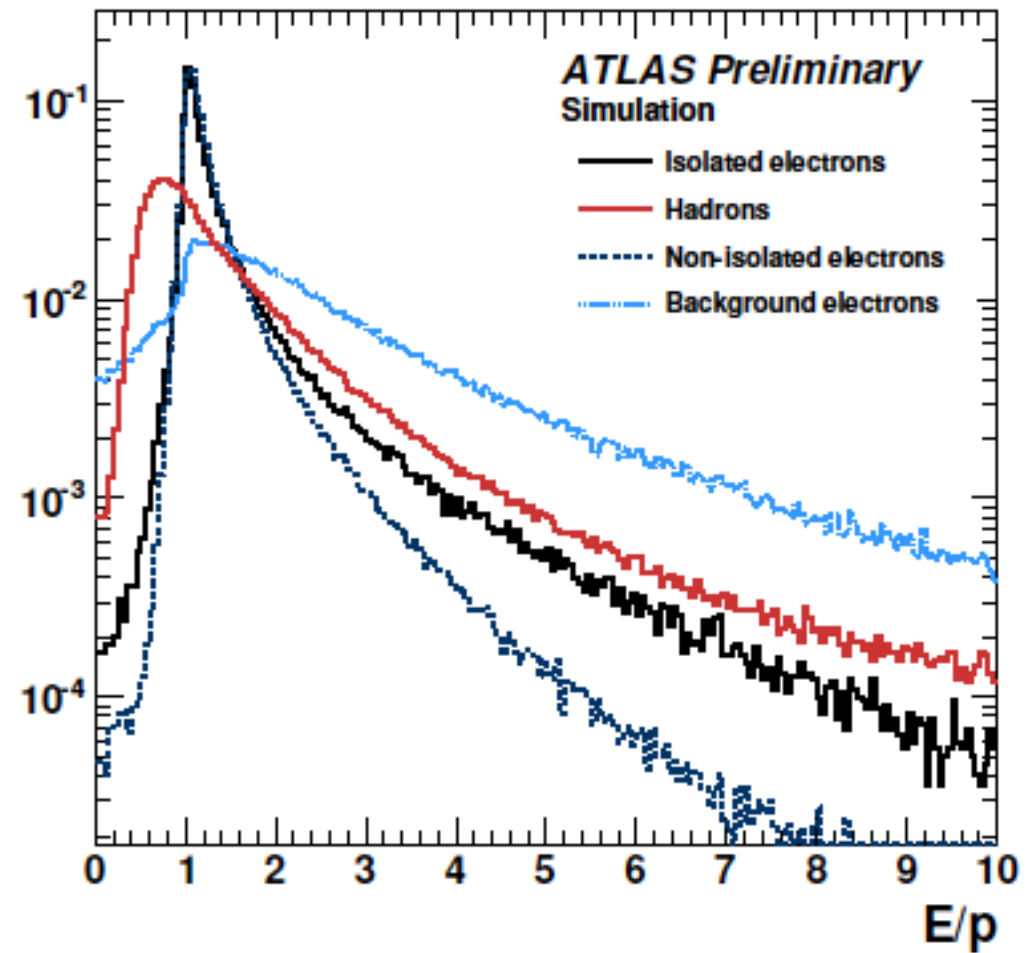
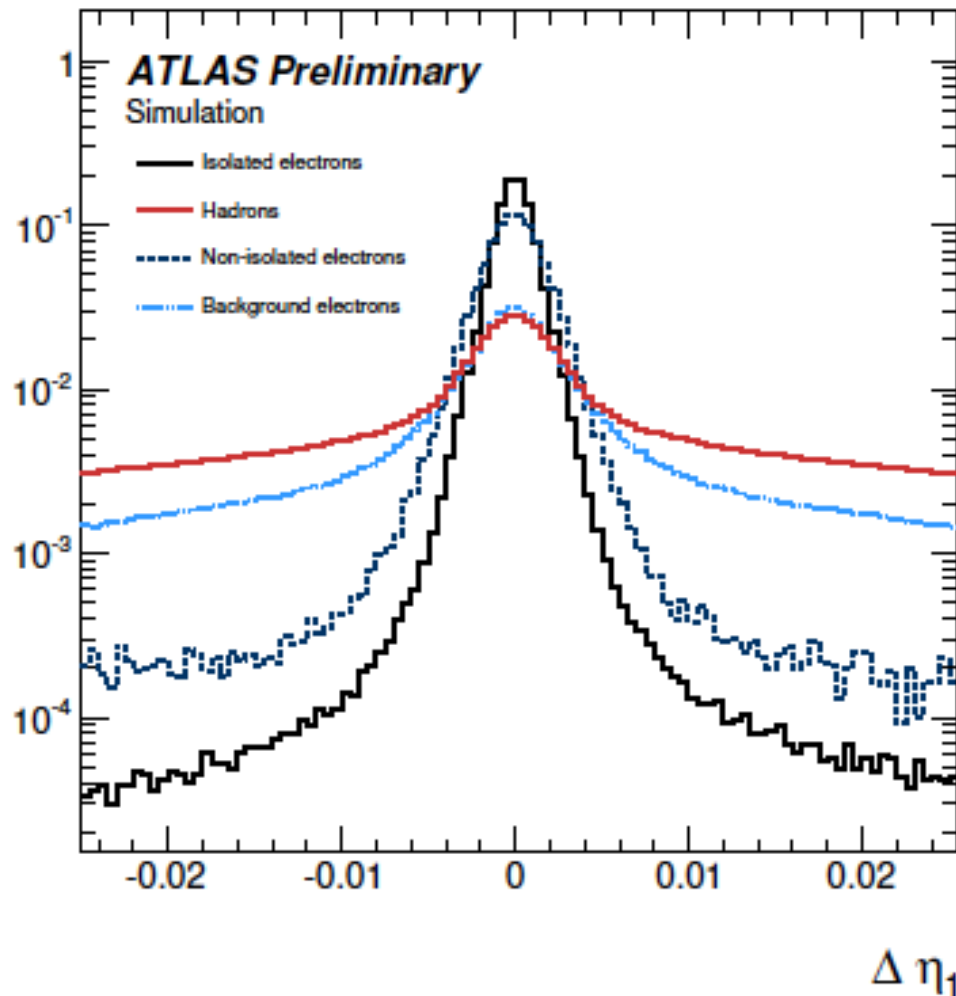
Some electron discriminating variables

- Hadronic leakage and inner cells/total cluster energy



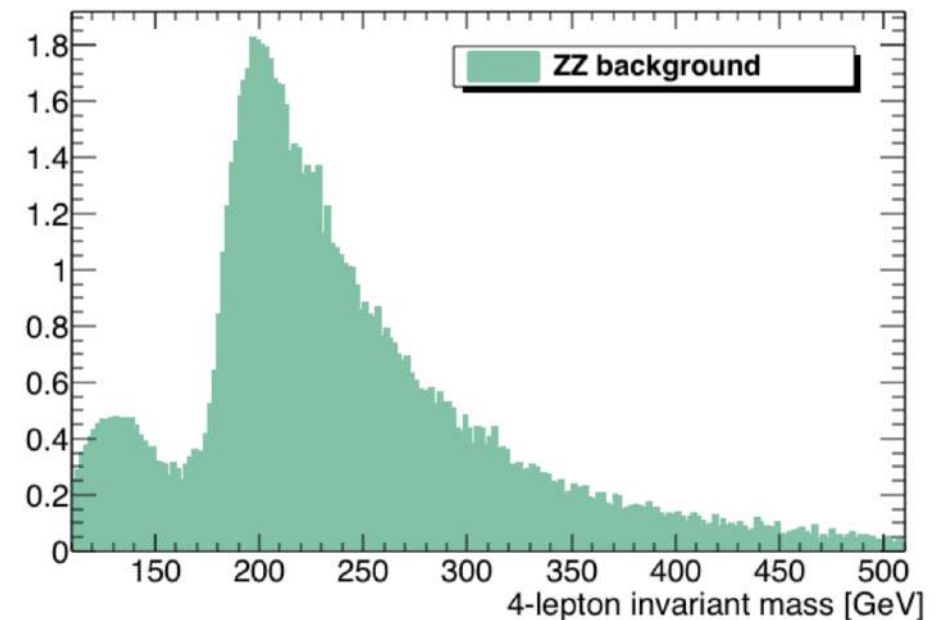
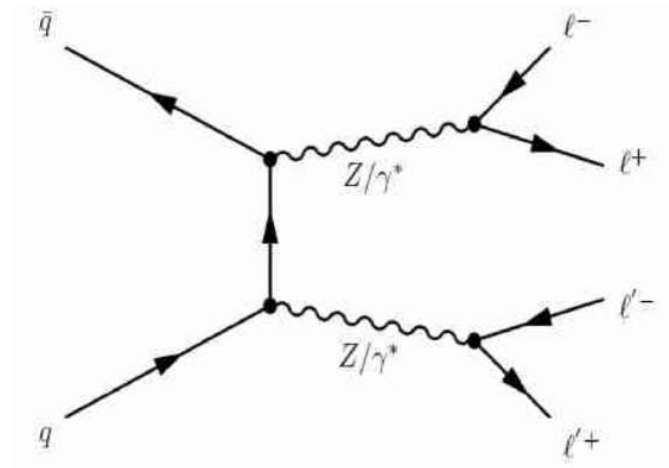
Some electron discriminating variables

- $\Delta\eta$ between track and cluster, and cluster energy / track momentum



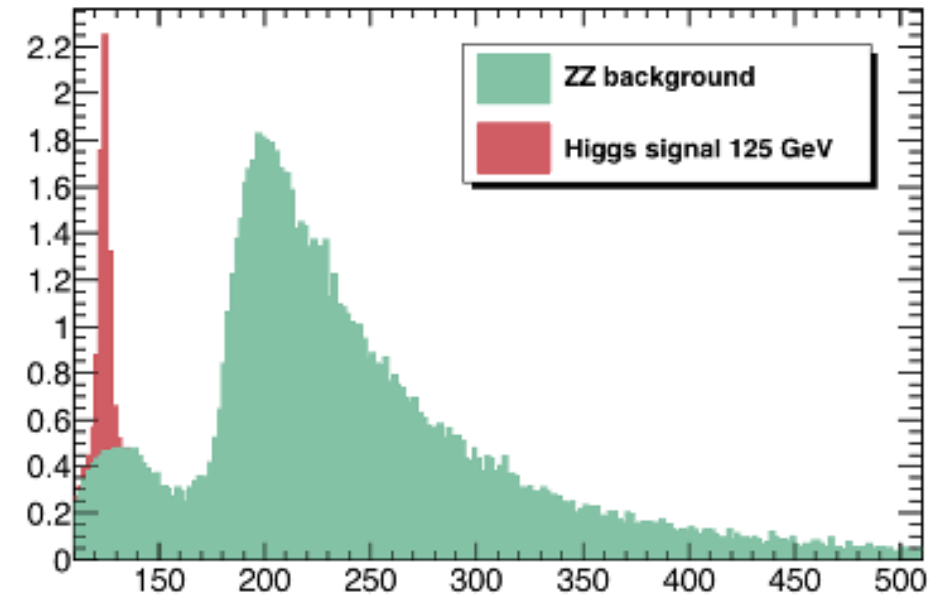
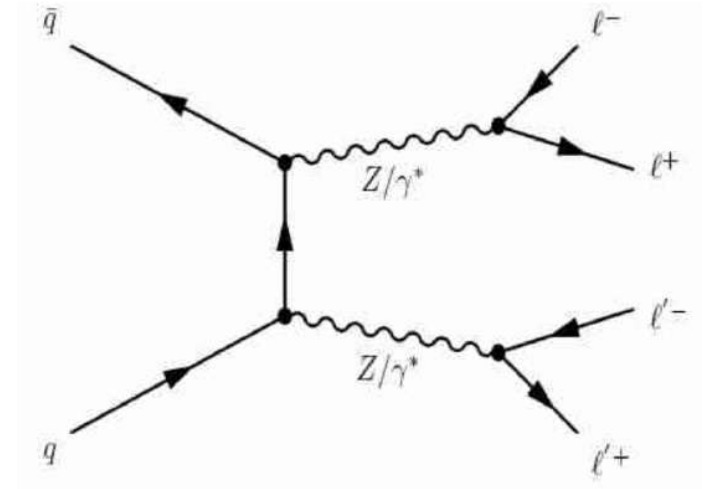
4-lepton irreducible background

- ❑ $qq \rightarrow ZZ(*) \rightarrow 4l$ has the same final state as the signal, but with a continuous mass distribution
- ❑ The shape comes from the onset of the two on-shell Z 's production at $\sim 2 \times M_Z$
- ❑ The variable that can be used to discriminate the signal from the background is in this case only the mass of the 4-leptons
 - Doing an assumption on the SM scalar Higgs hypothesis, also the decay products angular distributions are discriminating
- ❑ Here the plots are normalized to 20 fb^{-1} at 8 TeV
 - Expected SM distributions



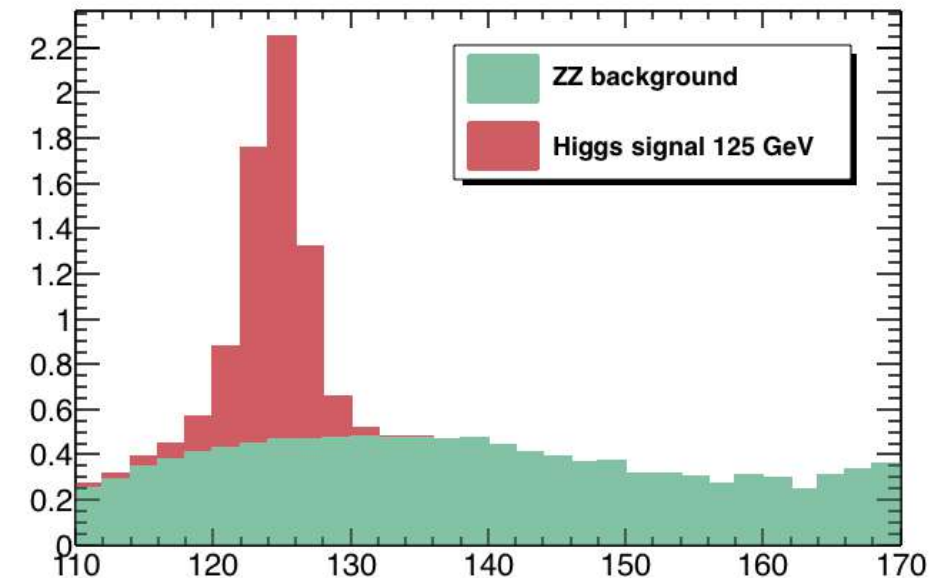
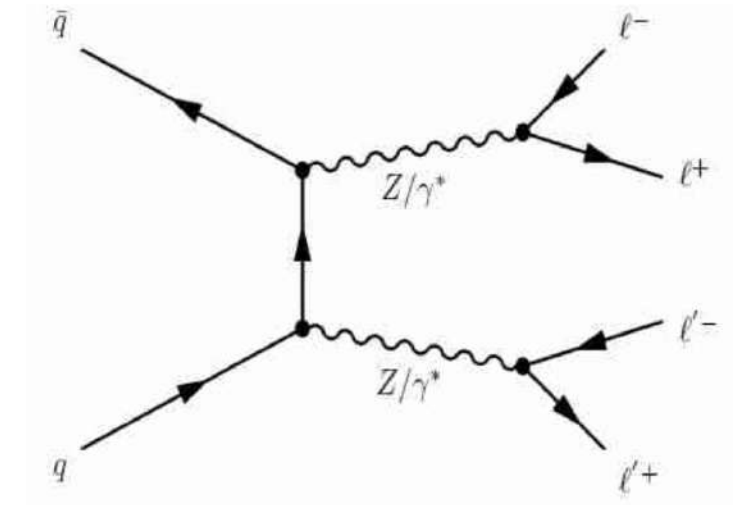
Irreducible background

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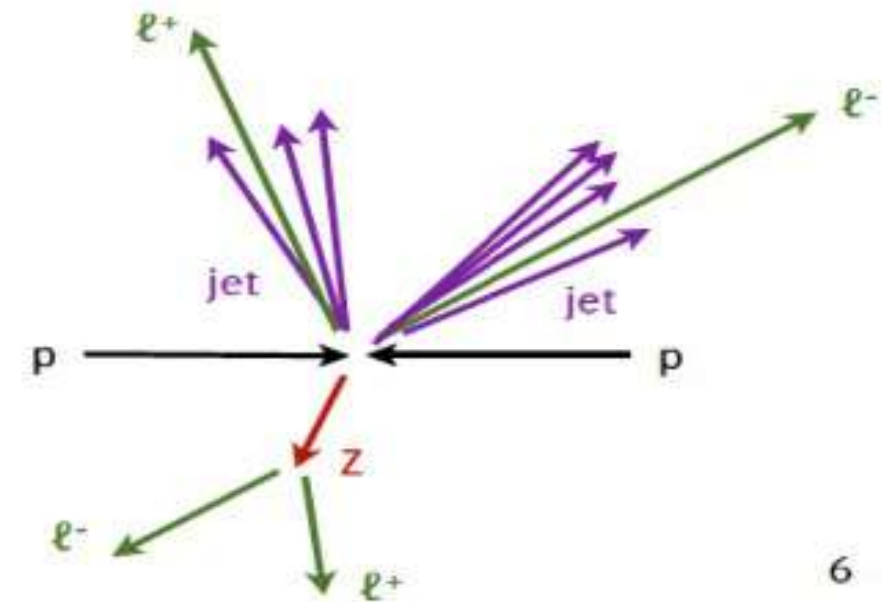
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 - Doing an assumption on the SM scalar Higgs hypothesis, also the decay products angular distributions are discriminating
- ❑ Here the plots are normalized to 20 fb⁻¹ at 8 TeV
 - Expected SM distributions



Reducible backgrounds

- ❑ In this case the final state is not exactly the same as for the signal, but there are objects that can “fake” the signal signature
- ❑ For $H \rightarrow 4l$ the main reducible background is a single Z produced in association with two jets
- ❑ In case of jets from light-quarks (not b or c):
 - possible misidentification of the
 - decay in-flight of pions and kaons within the jet ($\pi \rightarrow \mu\nu$ $K \rightarrow \mu\nu$) that can produce a muon track
- ❑ Or, they can contain leptons produced via decays like:
 - $\pi \rightarrow \mu\nu$ $K \rightarrow \mu\nu$, easier to discriminate
 - decays of hadrons with heavy quarks
- ❑ All these occurrences are very rare, and in general can be discriminated via cuts on the track impact parameter and on the isolation, but, the Z+jets cross section is ~ 5 orders of magnitude larger than the signal one



July 2012: the discovery

- Number of events in a mass window around the signal peak 120-130 GeV

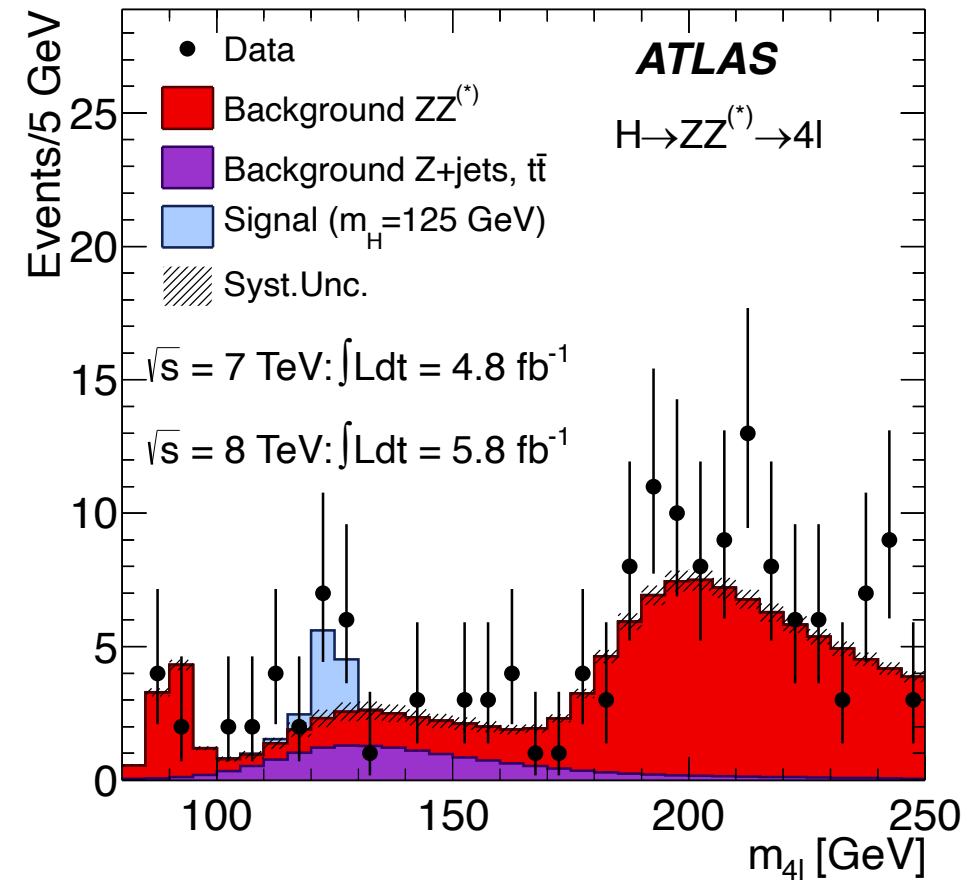
	Signal	$ZZ^{(*)}$	$Z + \text{jets}, t\bar{t}$	Observed
4μ	2.09 ± 0.30	1.12 ± 0.05	0.13 ± 0.04	6
$2e2\mu/2\mu2e$	2.29 ± 0.33	0.80 ± 0.05	1.27 ± 0.19	5
$4e$	0.90 ± 0.14	0.44 ± 0.04	1.09 ± 0.20	2

Total expected signal: 5.3 events

Total expected background: 4.9 events

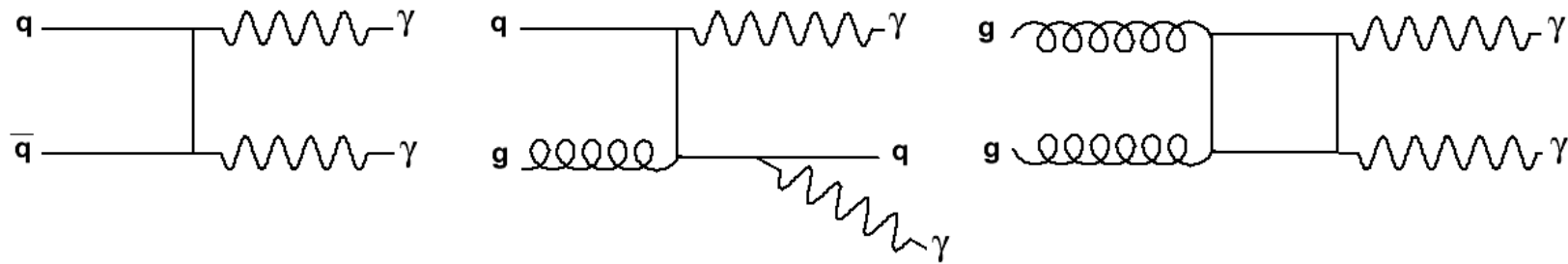
Total observed events in data: 13 !

Already a simple calculation shows you something: probability to observe 13 events when you expect 4.9 is **0.17 %** (of course no errors no syst here)

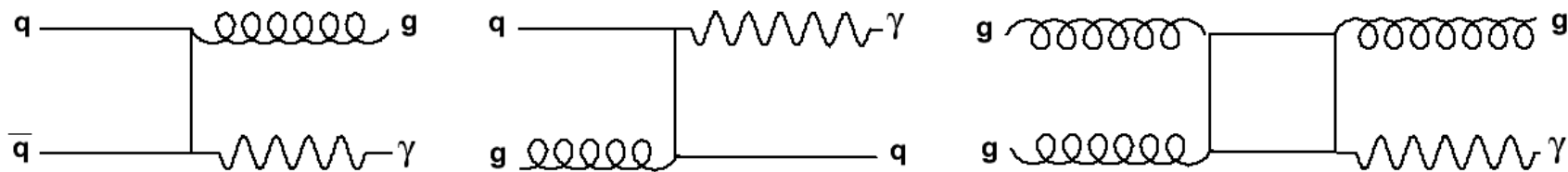


$H \rightarrow \gamma\gamma$ selection

- ❑ In spite of the low BR ($\sim 0.2\%$) this channel has the clear signature of two energetic and isolated photons, with a narrow mass peak
- ❑ The main backgrounds are the irreducible 2-photon continuum:



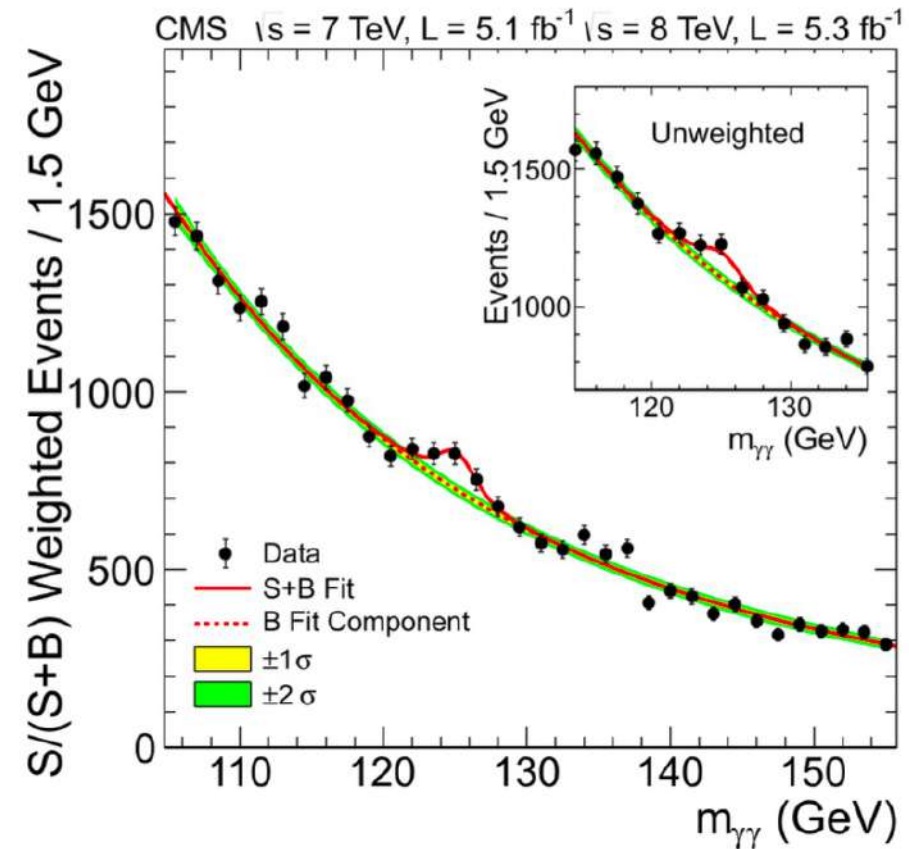
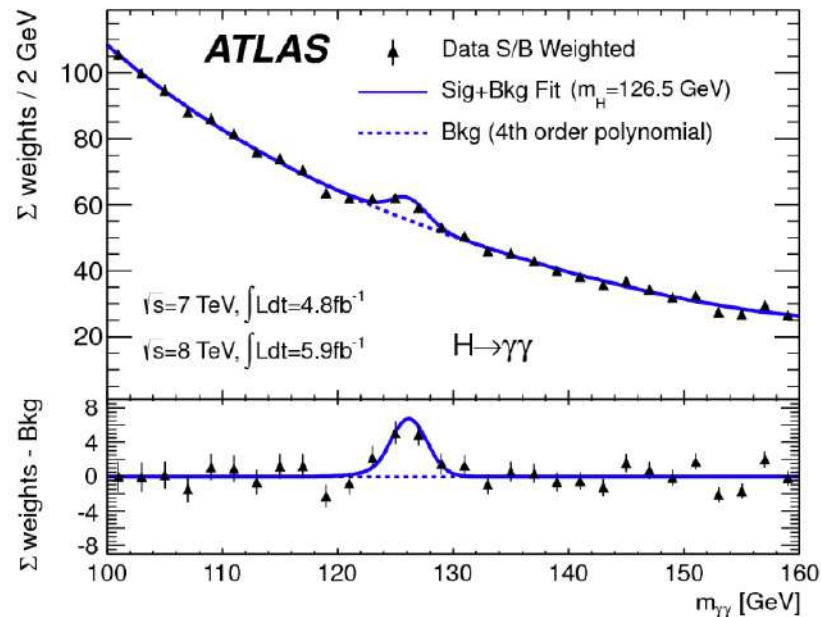
- ❑ And the +jet, or 2-jets, or 2-electrons, in which jets or electrons are misidentified as photons



- ❑ The continuum background can be fitted with empirical functions (close to an exponential)

H $\rightarrow\gamma\gamma$ results in July 2012

- ❑ In this case the background has to be fully extracted from a fit to the data distribution
 - The functions to be used in the fit can be studied on the MC, on a sample that contains a mix of the expected backgrounds
 - It's very important to avoid introducing fake signals with the fit
- ❑ Events are divided in categories based on number of jets, region of the photons
 - Purpose is to select the categories with the best S/B ratio, as this enhances the sensitivity
 - categories optimized on MC+data



Exclusion or discovery ?

- ❑ Let's consider the simple case of a counting experiment
 - One can always go back to this case selecting a narrow mass window around the signal peak
- ❑ First of all we need to consider the “expected” number of Signal (S) and Background (B)
 - These can be derived either from simulation (signal , and in some cases also the backgrounds), or from data (backgrounds)

- ❑ Then, we need to consider the number of events that pass the selection in data: N
- ❑ There are two possible cases:
 - N is close to B or smaller
 - N is close to $S+B$ or larger
- ❑ Plus, all the cases in which N is somewhere in between B and $S+B$
- ❑ If we consider a mass window around the signal, and count the events in that window, our search becomes a counting experiment
- ❑ Let's see how to deal with these cases in the frequentistic approach

Exclusion

- ❑ If N is close to B , or smaller than that, we can probably exclude the presence of a signal, but how can we quantify the probability that a signal is excluded ?
- ❑ We must consider the hypothesis of $S+B$ expected events, i.e. that a signal exists, and calculate the probability to observe $n \leq N$ events.

➤ $P(n \leq N | S+B)$

- ❑ In other words, we calculate the probability that $S+B$ can fluctuate down to N or lower: if this probability is low enough, we can exclude the presence of a signal (CL_s)
- ❑ To set a limit at α confidence level, the probability must be:

$$P(n \leq N | S+B) < 1 - \alpha$$

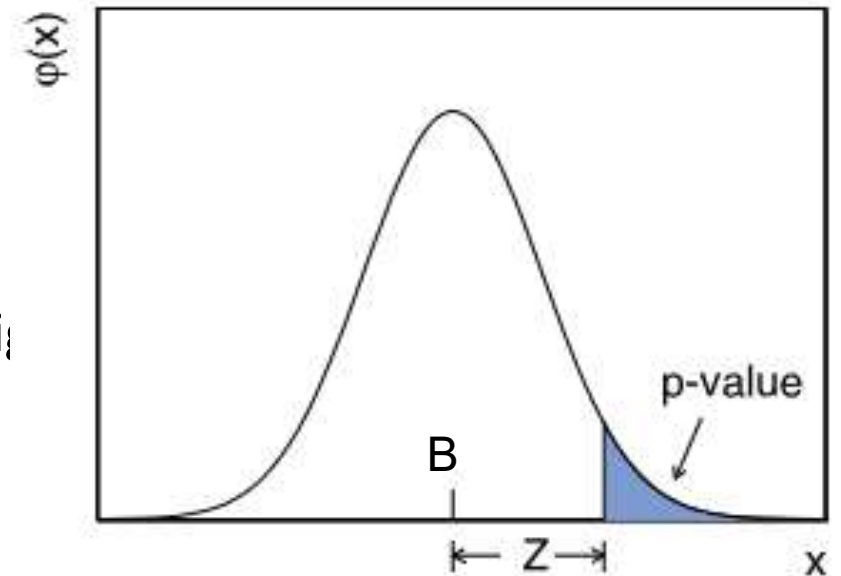
- ❑ So for example if $\alpha = 95\%$ (the value normally used), the probability must be $< 5\%$
- ❑ The probability distribution to be considered for n depends on how large $S+B$ is

Discovery

- ❑ When the number of observed events is instead close to $S+B$, it's possible that we are observing a signal... But how to quantify the observation ?
- ❑ In this case we must consider the hypothesis of only background B , and calculate the probability that the number of events can fluctuate to N or a number larger than that:

$$p = P(n \geq N | B)$$

- ❑ The significance Z is defined as $Z = \Phi^{-1}(1-p)$ where Φ is the cumulative of the standard gaussian
- ❑ In other words when p is equal to the 1-sided probability content of a gaussian, corresponding to the integral from $B+Z$ sig



- It becomes S/\sqrt{B} for a gaussian distribution: the probability that B fluctuates to $S+B$
- ❑ A discovery is normally claimed at 5 sigmas, but there are intermediate situations, i.e. in which one can neither exclude nor claim the discovery of a signal
 - Exactly the situation in which we were in December 2011 !

1-sided 5-sigmas corresponds to a p value of 3×10^{-7}

Likelihood ratio

- ❑ The actual significance calculation is actually more complex, but based on the same principle of testing the (in)compatibility of the data with an hypothesis
 - Only background hypothesis for discovery
 - Signal+background hypothesis for exclusion
- ❑ Use distributions instead of pure counting experiment (binned or unbinned)
- ❑ Introduce systematic uncertainties
 - For example, one might have an uncertainty on the normalization of a given background, or on its shape and composition
 - Or, the uncertainties could come from detector performance, for example, how well do I know the efficiency of electron/muon/photon reconstruction?
- ❑ In this cases one introduces a set of “nuisance parameters” Θ (a vector) each component corresponding to a given systematic effect

Likelihood ratio

□ So as a function of μ and $\boldsymbol{\theta}$ one can write a likelihood:

$$L(\mu, \boldsymbol{\theta}) = \prod_{j=1}^N \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)}$$

i.e. the product of the poisson probabilities over all bins of the distribution. μ is a scale factor for the signal, i.e. $\mu=1$ means a SM signal

□ To test a value of μ , letting the syst vary one can write the profile likelihood ratio

$$\lambda(\mu) = \frac{L(\mu, \hat{\boldsymbol{\theta}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

where $\hat{\boldsymbol{\theta}}$ is the set of nuisance parameters that maximizes the likelihood function for a given value of μ (so the conditional set of nuisance parameters), that can be scanned

While the denominator is the maximum likelihood, obtained for the values $(\hat{\mu}, \hat{\boldsymbol{\theta}})$ fixed i.e. in this case the maximum is a normalization

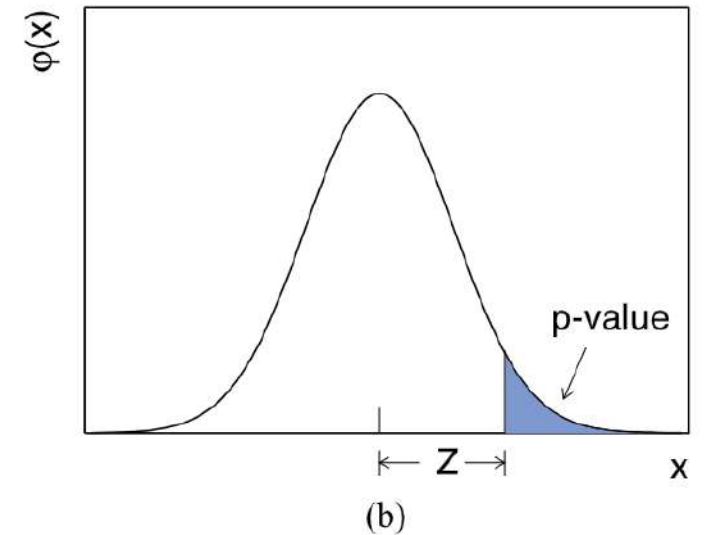
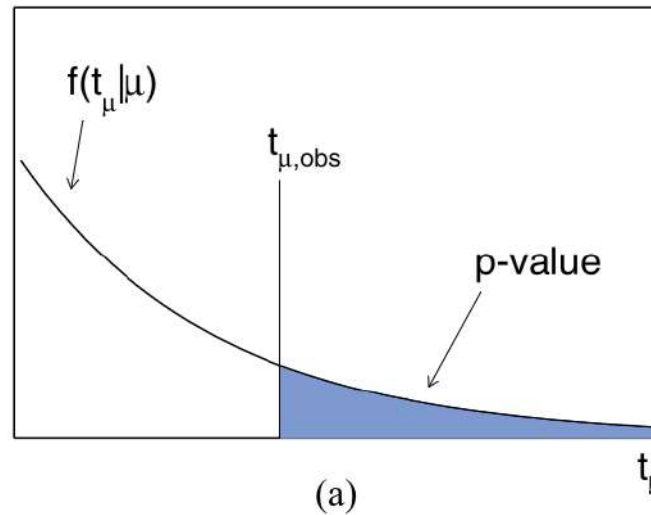
Likelihood ratio and significance

- So to calculate the discovery significance using the likelihood ratio one should refer to the case of background-only (as in the counting experiment) and use the “test-statistics”:
 $q_0 = -2 \ln \lambda(0)$, or better:

$$q_0 = \begin{cases} -2 \ln \lambda(0), & \hat{\mu} \geq 0, \\ 0, & \hat{\mu} < 0, \end{cases}$$

- Then the p-value to quantify the disagreement with the background-only hypothesis is:

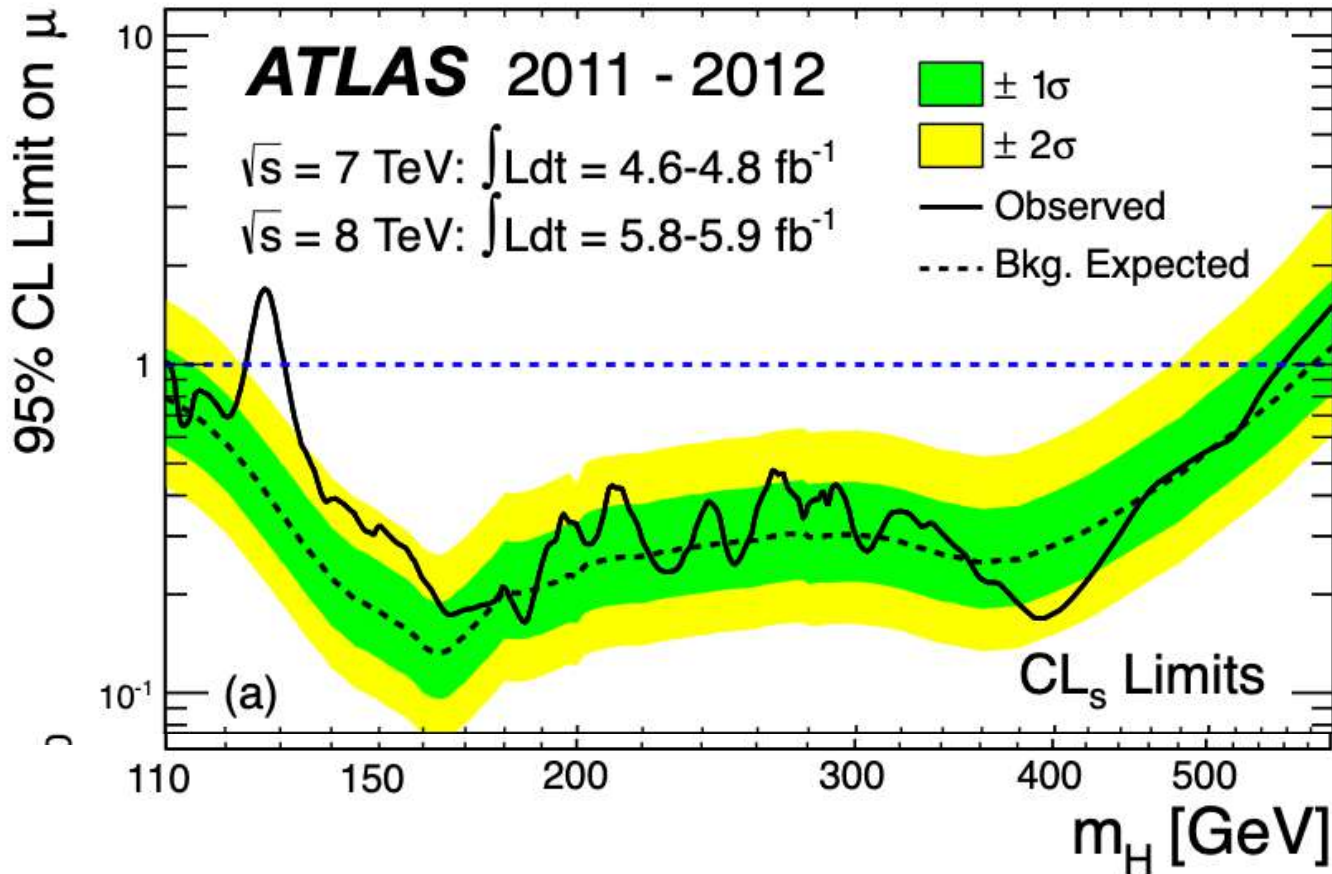
$$p_0 = \int_{q_{0,obs}}^{\infty} f(q_0|0) dq_0$$



- The $f(q_0|0)$ can be analytically calculated using some approximations, or, derived from the simulation
- You can find more on that in: Eur. Phys. J. C (2011) 71: 1554

Exclusion plots

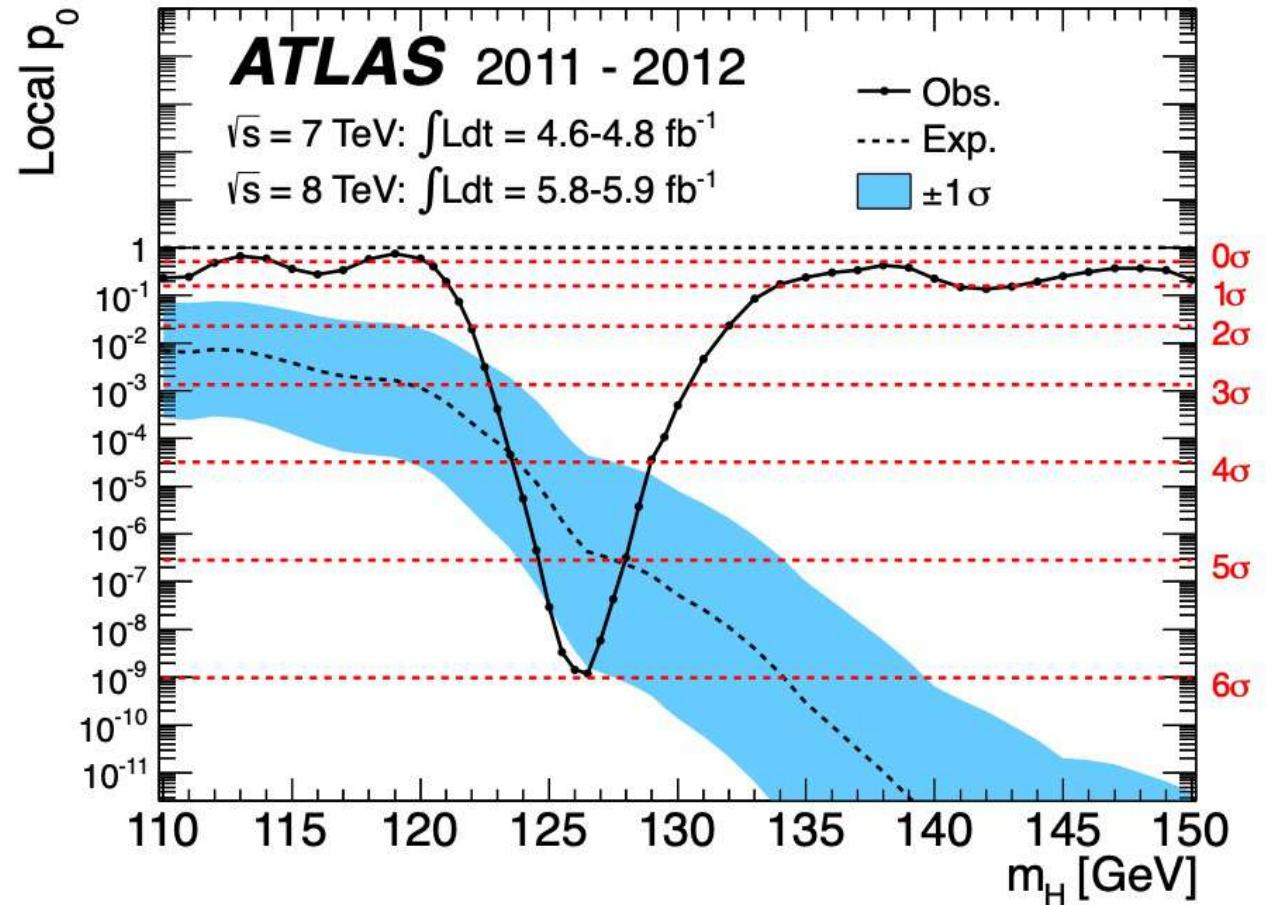
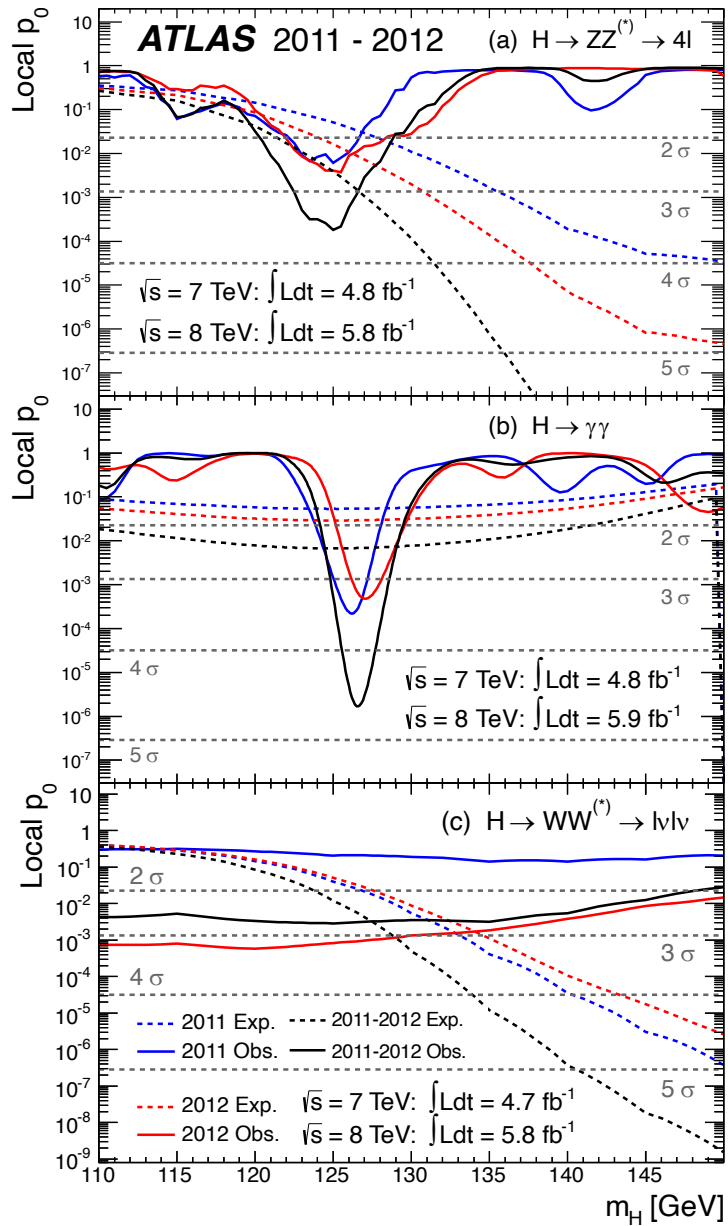
- The exclusion can be applied on the value of μ , i.e. say a value of μ about a given value is excluded at 95%



In fact, a clear region appears, where $\mu = 1$ can't be excluded

The actual discovery plots

p-values as a function of the tested Higgs mass
 → Discovery at $m_H \sim 125$ GeV



Mass and Width

Mass measurements

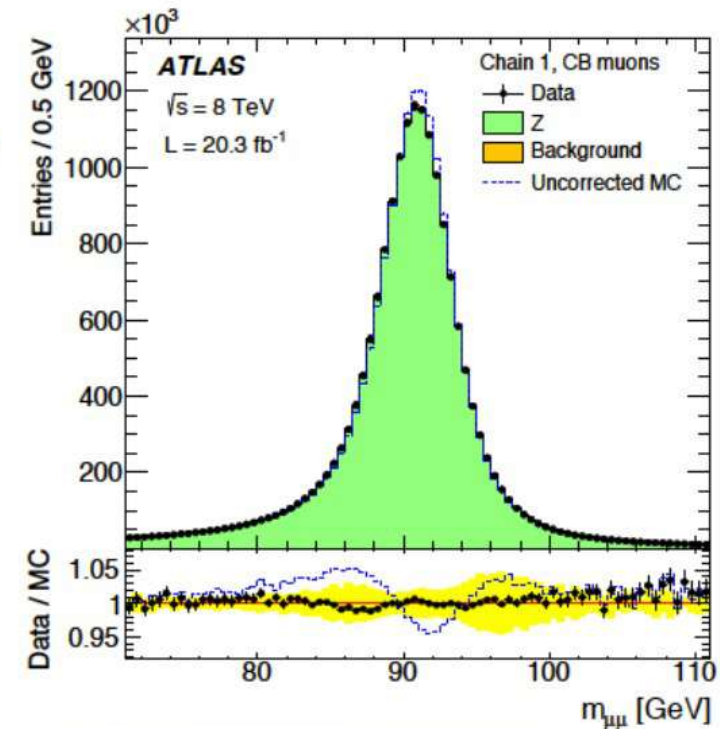
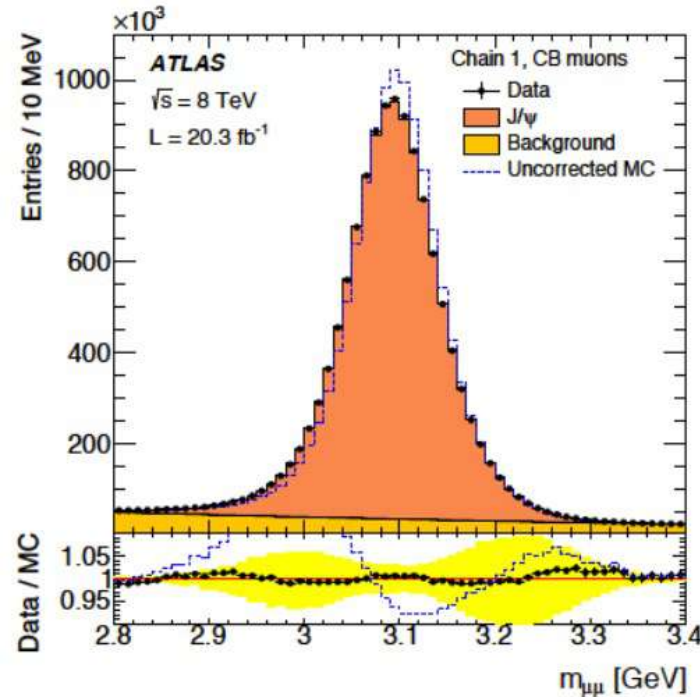
- ❑ You have seen the Z and W mass measurement techniques:
 - Z: measure the cross section at different e+e- center of mass energies
 - W mass: use direct reconstruction of the mass peak, or the W+W- cross section vs the center of mass energy

- ❑ In the case of the Higgs at LHC, the mass can be measured directly reconstructing the resonance invariant mass, in the channels where that's possible, in spite of their low BR
 - In the $H \rightarrow ZZ^* \rightarrow 4\text{-leptons}$ and $H \rightarrow \gamma\gamma$ is visible as a peak on top of the background

- ❑ Crucial point is the calibration of the muons, electrons and photons energy scales
- ❑ In fact the detector response is affected by many experimental effects, that is usually difficult to model in the simulation
 - Detectors alignment, knowledge of the magnetic fields, active and passive materials

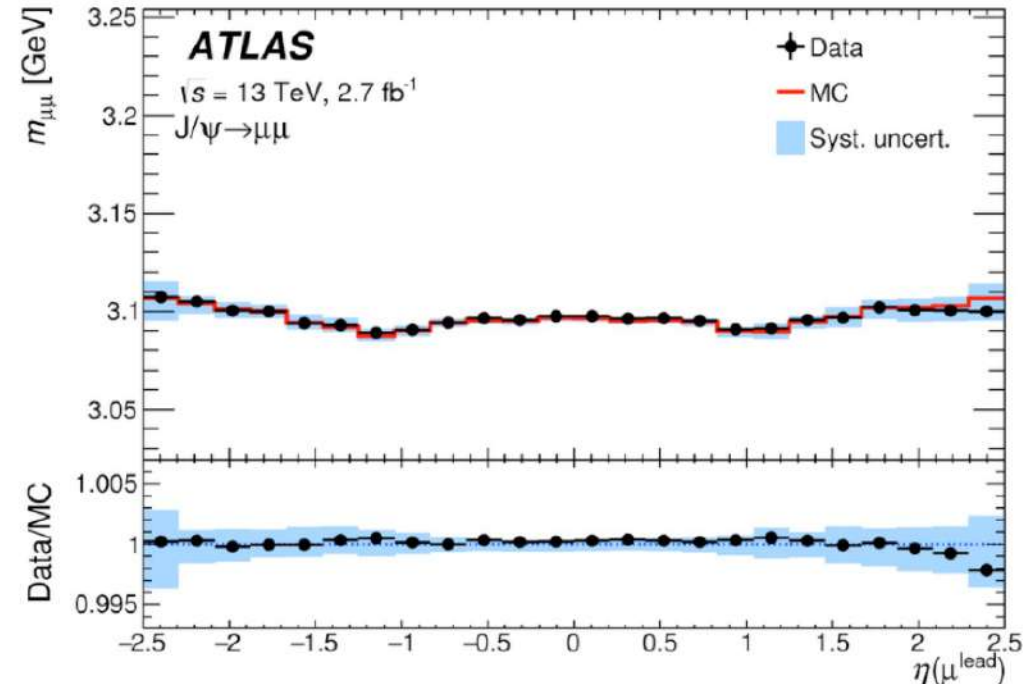
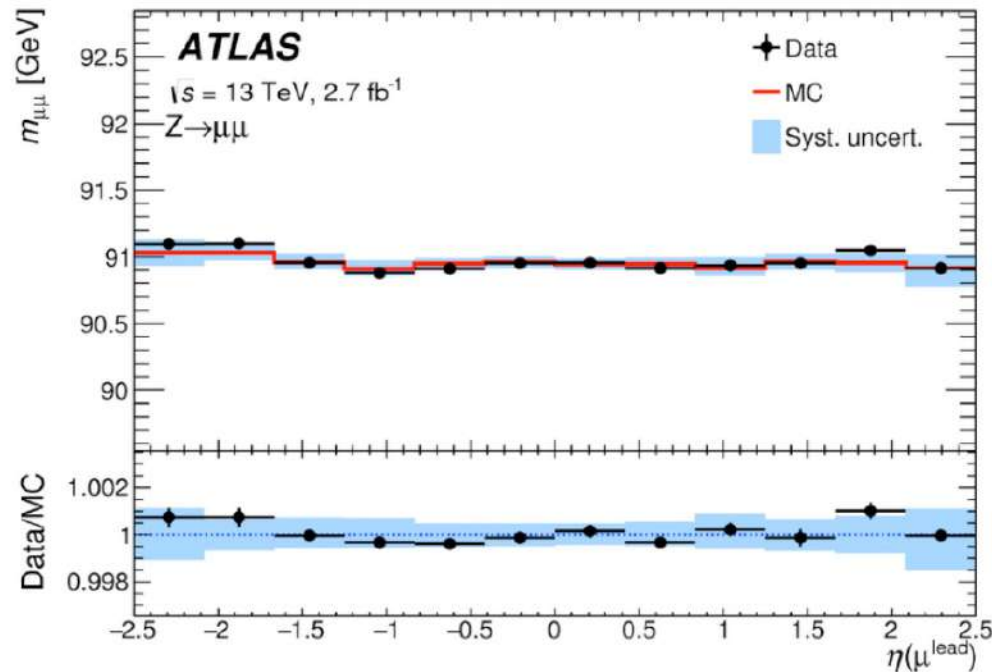
Calibrations for the 4-lepton channel

- ❑ Leptons energy scale and resolution need to be calibrated, to make sure that the simulation reproduces exactly the data
 - The peak of known resonances (Z , J/ψ) can be used on this purpose
- ❑ Get MC corrections in bins of η (one can also correct data)
 - scale: $p_T = s_0 + p_T(1 + s_1)$
 - resolution: add a smearing with sigmas Δr_0 , $\Delta r_1 \times p_T$
- ❑ The procedure is similar for muons and electrons



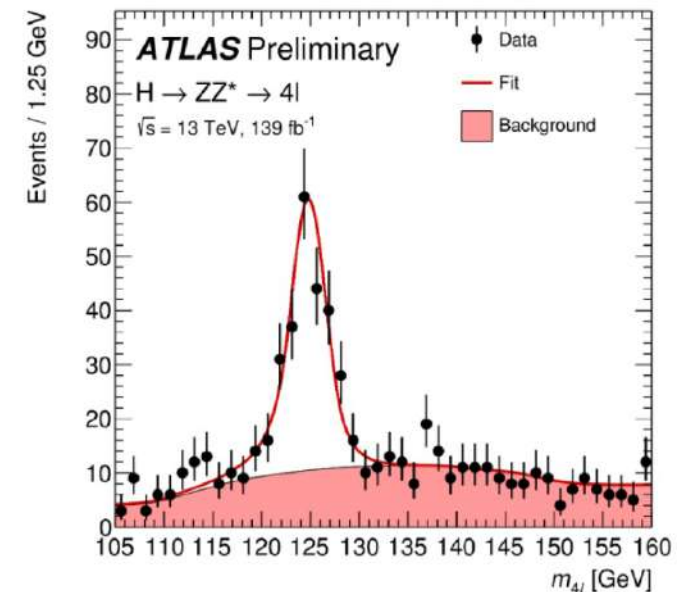
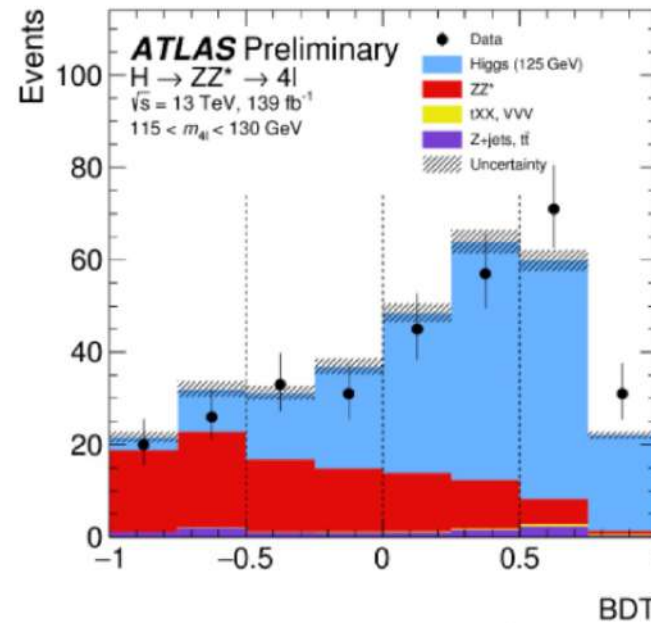
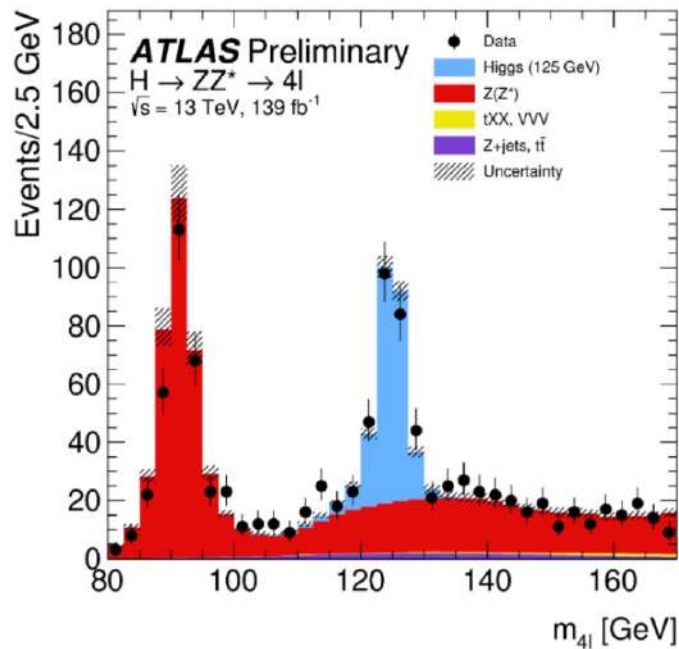
Systematics

- ❑ Like every calibration, the momentum scale and resolution is affected by systematic uncertainties
- ❑ In the case of the 4-lepton channel, whose error is at the moment still dominated by the statistical component, systematics are not



4-lepton mass fit

- One lepton pair comes from an on-shell Z, so constraining their invariant mass to M_Z leads to an improvement on the resolution
 - Likelihood fit constraining the di-lepton mass to the Z lineshape
 - Up to $\sim 17\%$ improvement in the resolution
- Recovering photons from final state radiations leads to a $\sim 1\%$ improvement
- Besides the 4l mass, more variables enter in the fit mass
 - Events categorized based on a BDT designed to separate the signal from the irreducible background
 - Event-by-event uncertainty on the 4l mass



Mass in $H \rightarrow \gamma\gamma$

- The resolution on the invariant mass depends on

$$m_{\gamma\gamma} = \sqrt{2 E_1 E_2 (1 - \cos \Delta\theta)} = 2\sqrt{E_1 E_2} \sin \frac{\Delta\theta}{2}$$

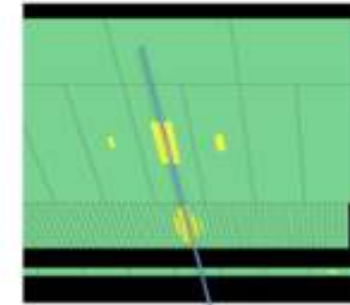
$$\frac{\delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \left(\frac{1}{2} \frac{\delta E_1}{E_1} \right) \oplus \left(\frac{1}{2} \frac{\delta E_2}{E_2} \right) \oplus \left(\frac{\delta \sin(\frac{\Delta\theta}{2})}{\sin(\frac{\Delta\theta}{2})} \right)$$

For the typical values of photons energy resolution ($\sim 3\%/\sqrt{E}$) and angular resolution (~ 5 mrad) one can see that the angular term is larger than the energy one \rightarrow right vertex association is very relevant

- Photon energy calibration more difficult than for the leptons, as no calibration resonance can be used

➤ Still events like Z (or J/ψ) $\rightarrow ee+\gamma$, can be used, after having calibrated the electrons

- in general however the systematics on photon calibration are larger than those for electrons and muons

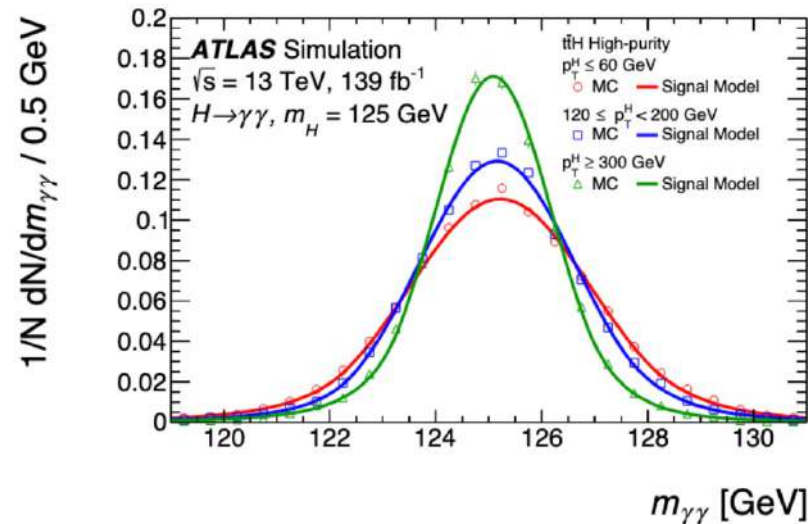
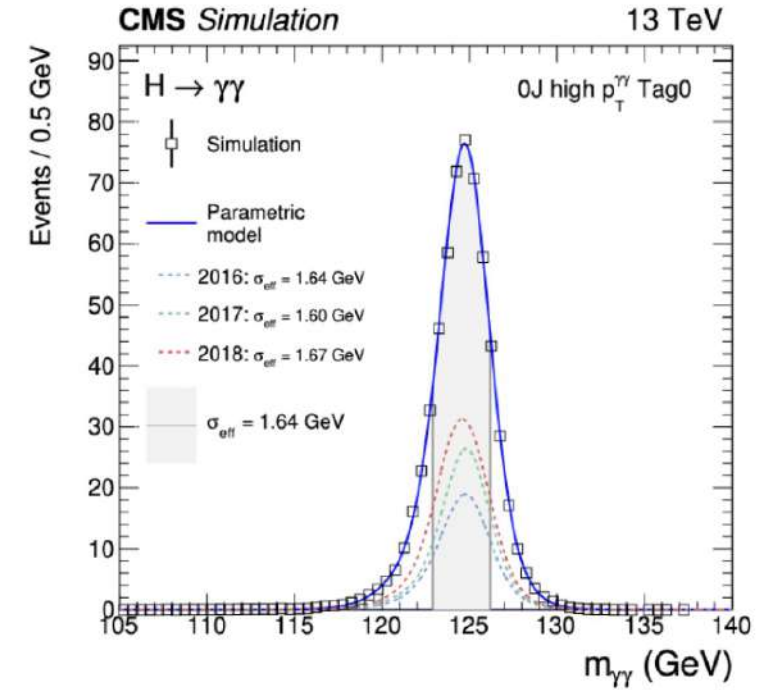
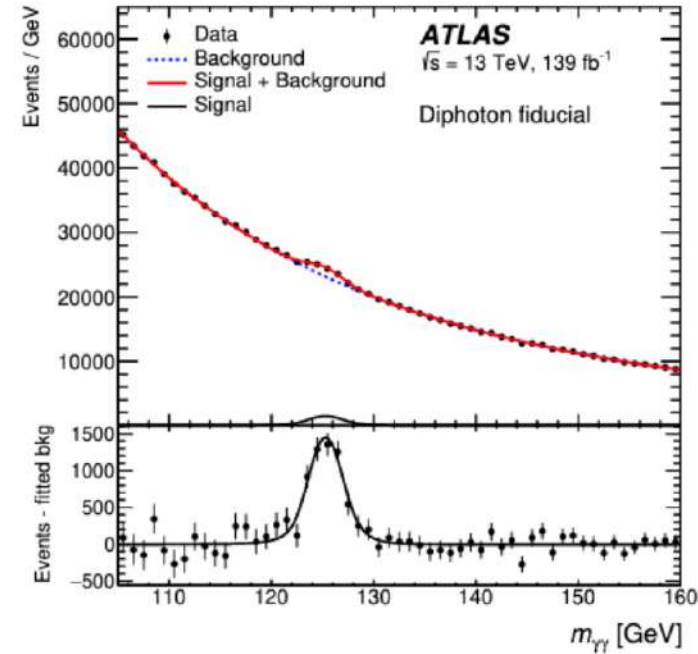


1.- Measure photon direction

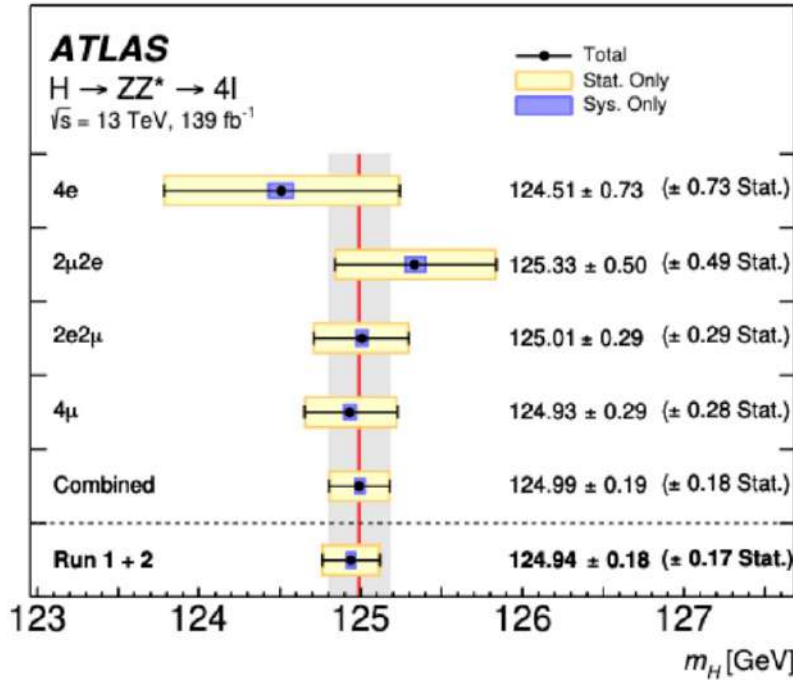
2.- Deduce z of PV

H → $\gamma\gamma$ mass fit

- Split selected events in categories (31) with different mass resolutions and S/B
- Background modeling (mainly $\Upsilon\Upsilon$, γj , jj) with empirical functions
- Signal distribution models, either fit with double-sided Crystal Ball or with sums of gaussians
- Systematics mostly from E calibration

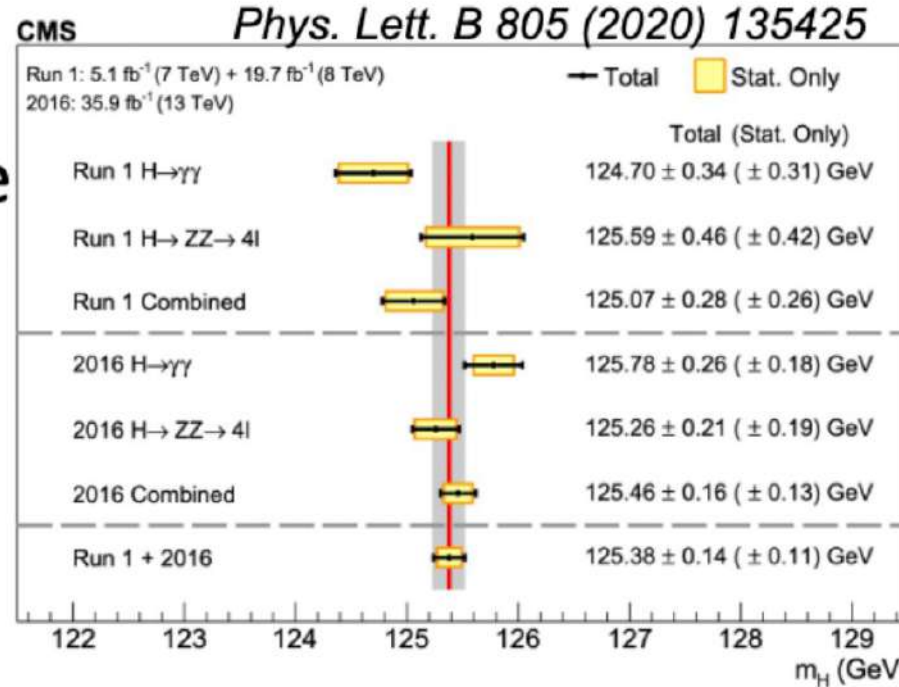


Summary of the current results on the mass

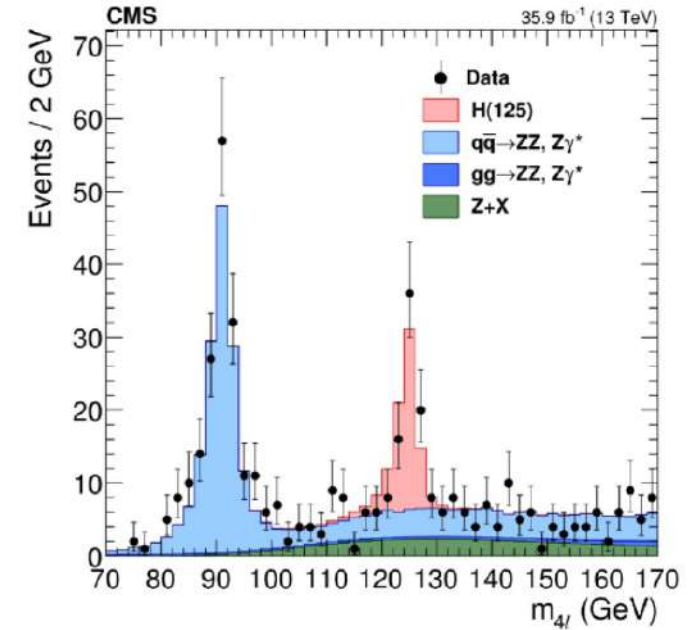


ATLAS 4l with 139 fb⁻¹ at 13 TeV
 $m_H = 124.94 \pm 0.17 (\text{stat}) \pm 0.03 (\text{syst})$

ATLAS $\gamma\gamma$ with 36 fb⁻¹ at 13 TeV
 $m_H = 125.32 \pm 0.19 (\text{stat}) \pm 0.29 (\text{syst})$

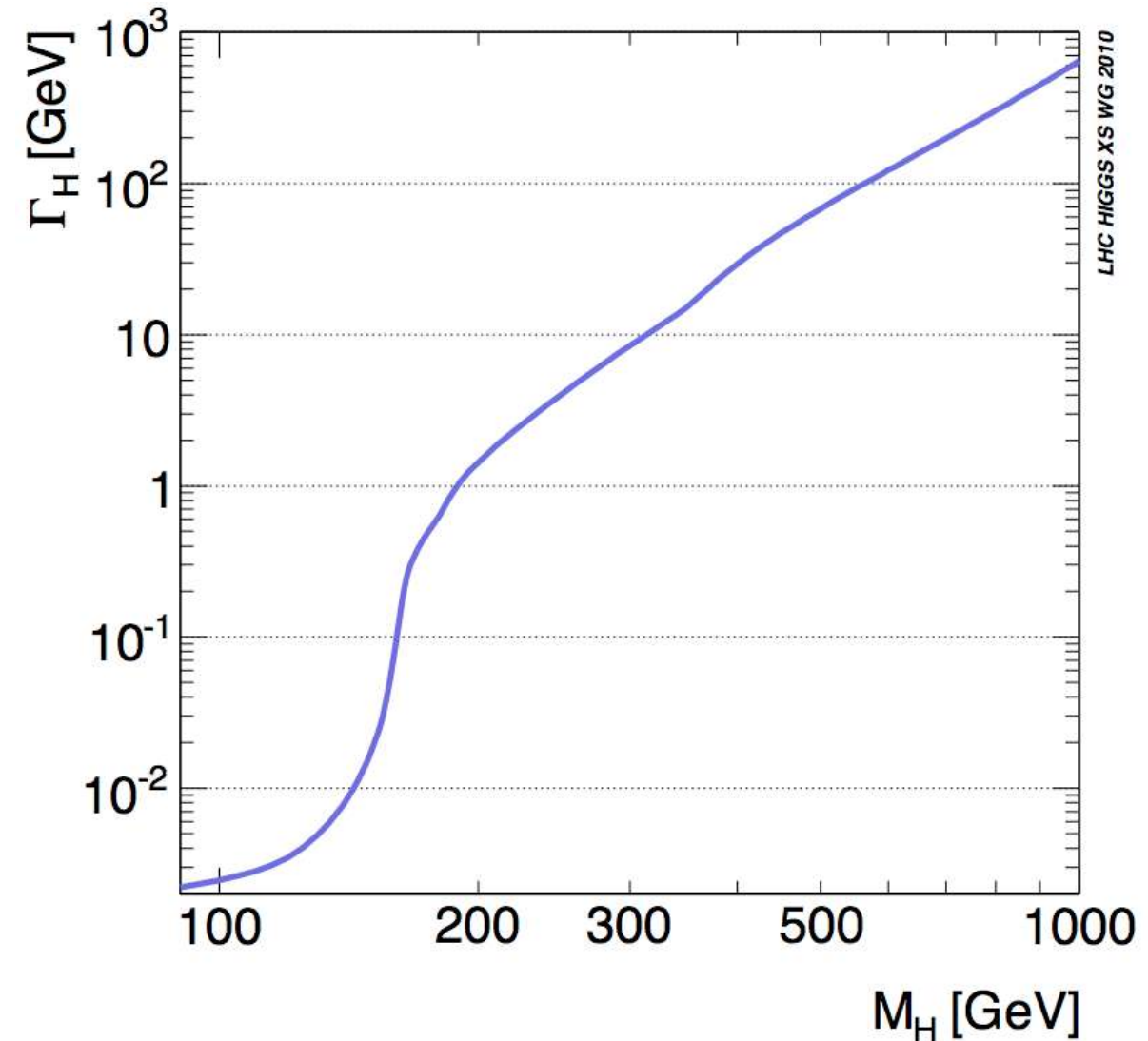


CMS combined 4l and $\gamma\gamma$
 $m_H = 125.38 \pm 0.11 (\text{stat.}) \pm 0.08 (\text{syst.}) \text{ GeV}$



Width measurement

- ❑ In the SM, the width of the Higgs at 125 GeV is only 4 MeV
- ❑ We have seen that the experimental resolutions on the Higgs mass are of the order of the GeV, so three order of magnitudes
 - No way to directly measure the width
 - only limits very far from the SM value can be set
- ❑ But, there is a way to indirectly measure the width, looking at the off-shell signal strength



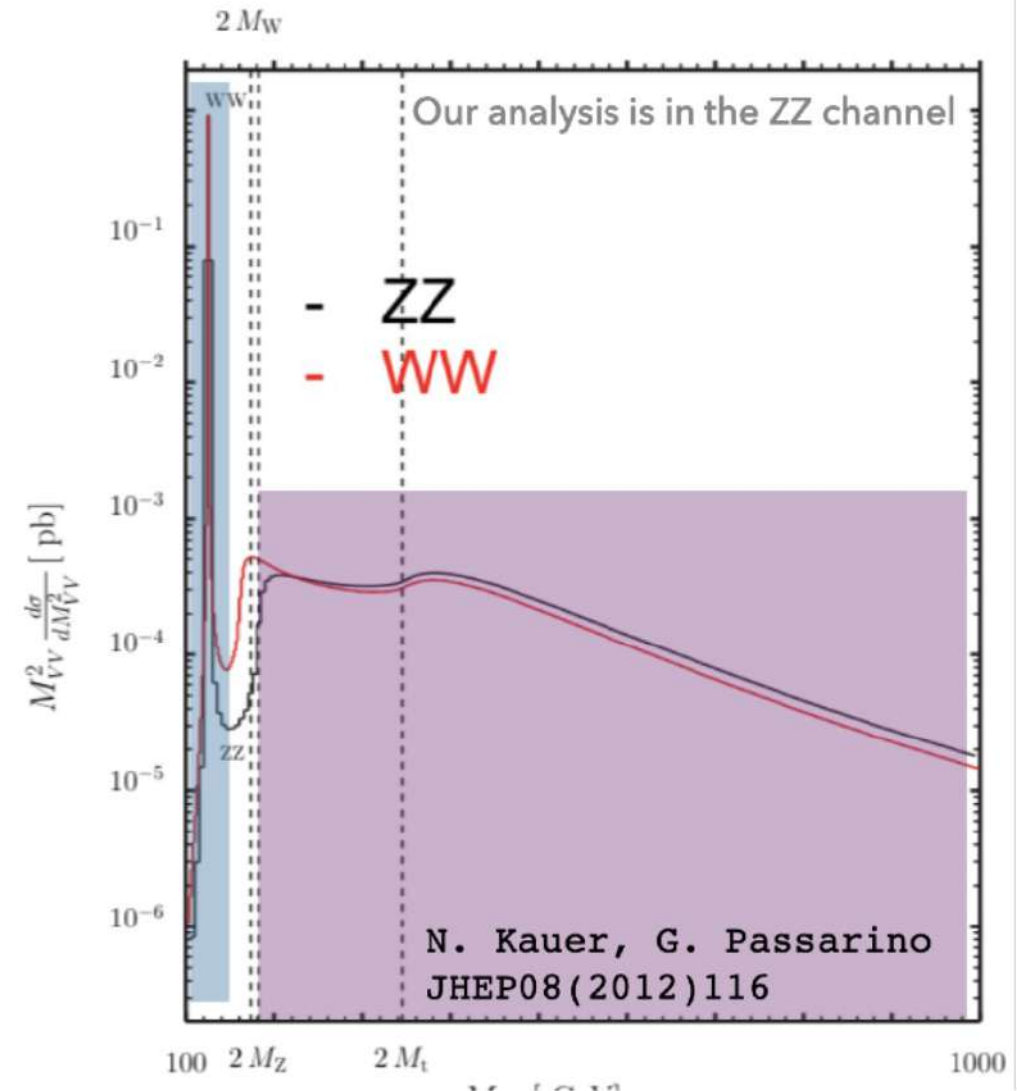
Width measurement

- ❑ Better limits on the width can be set using the off-shell Higgs signal strength
- ❑ The two most sensitive channels are $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow WW \rightarrow l\nu l\nu$
- ❑ Some assumptions need to be done:
 - Same couplings for the on-shell and off-shell Higgs
 - No new resonance exists in the region below ~ 2 TeV (as confirmed by direct searches)

$$\sigma_{pp \rightarrow H \rightarrow ZZ}^{\text{onshell}} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{m_H \Gamma_H}$$

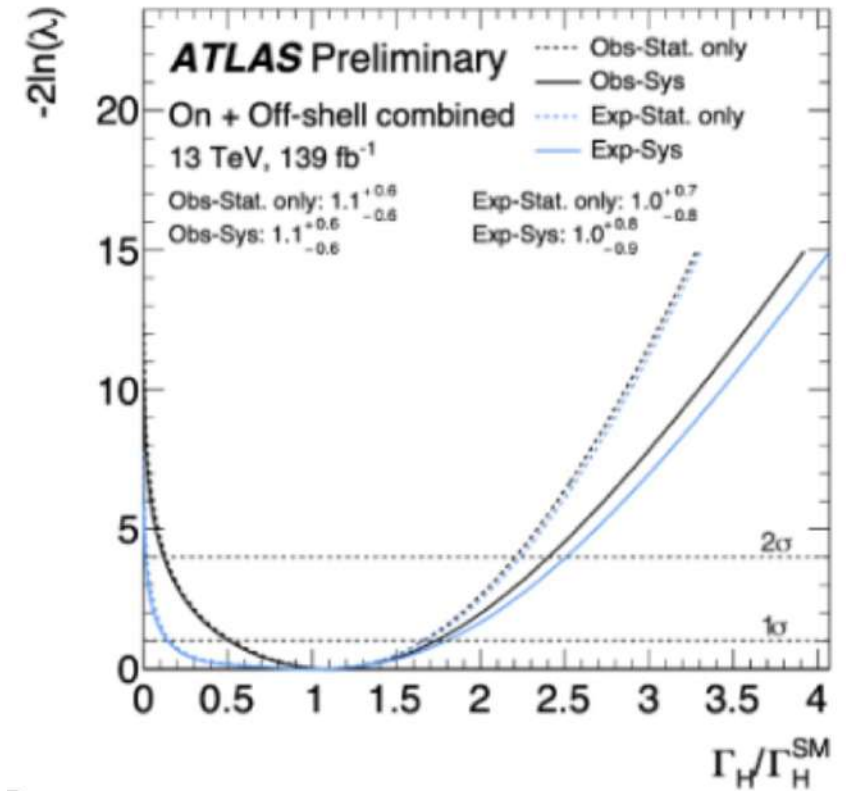
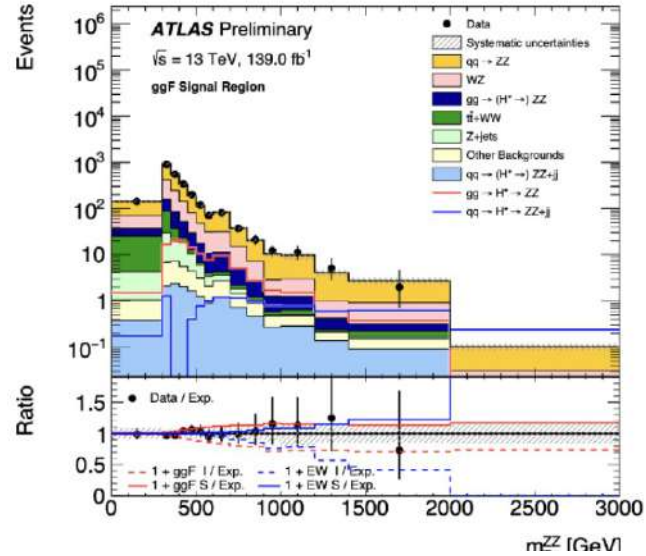
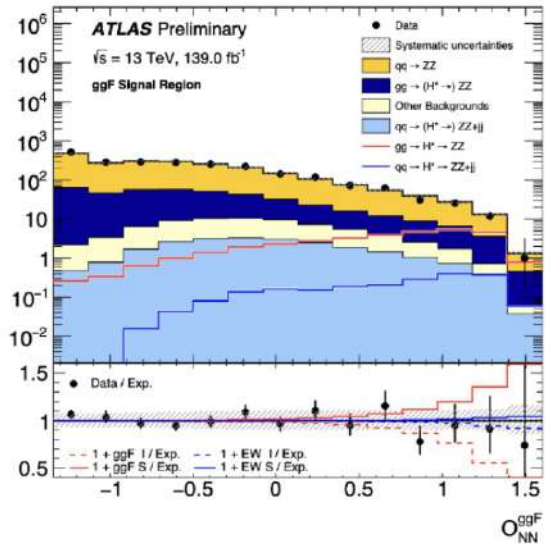
$$\sigma_{pp \rightarrow H \rightarrow ZZ}^{\text{offshell}} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{M_{ZZ} - m_H}$$

$$\frac{\sigma_{\text{offshell}}}{\sigma_{\text{onshell}}} \propto \Gamma_H$$



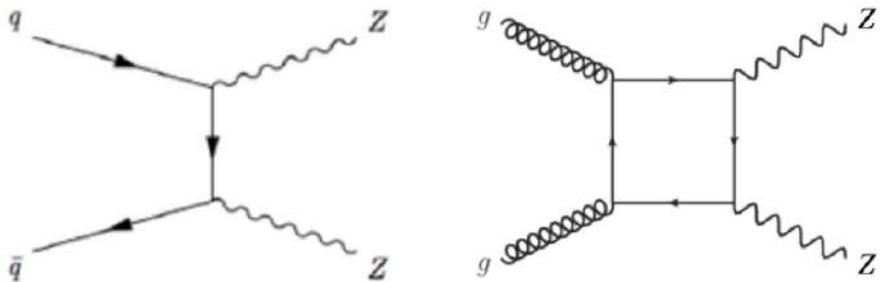
Example of width results

- Combining the 4l and the llvv channels from ZZ decays
- DNN discriminant and transverse mass to discriminate the signal from the backgrounds



$$\Gamma_H = 4.6_{-2.5}^{+2.6} \text{ MeV}$$

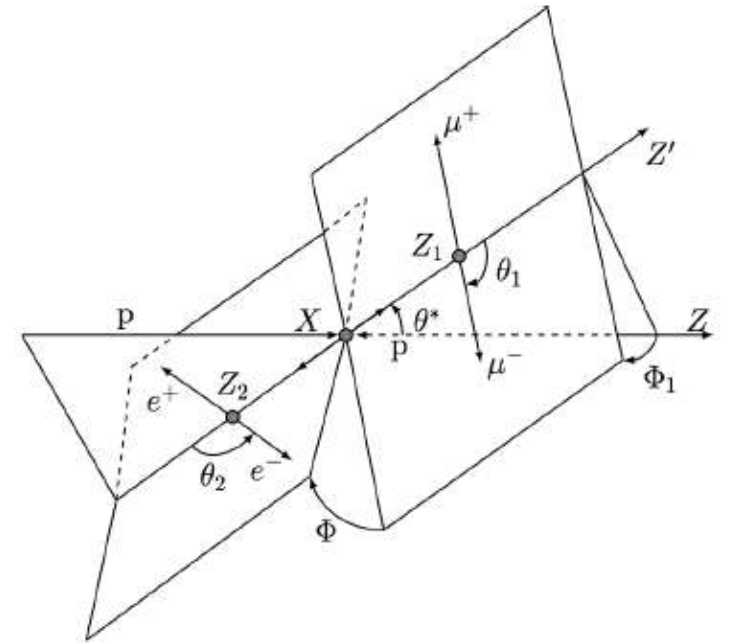
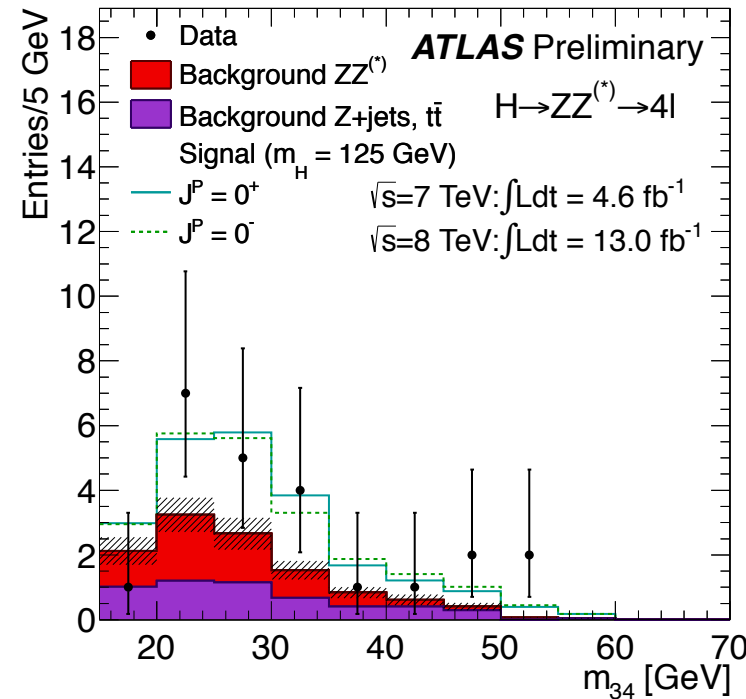
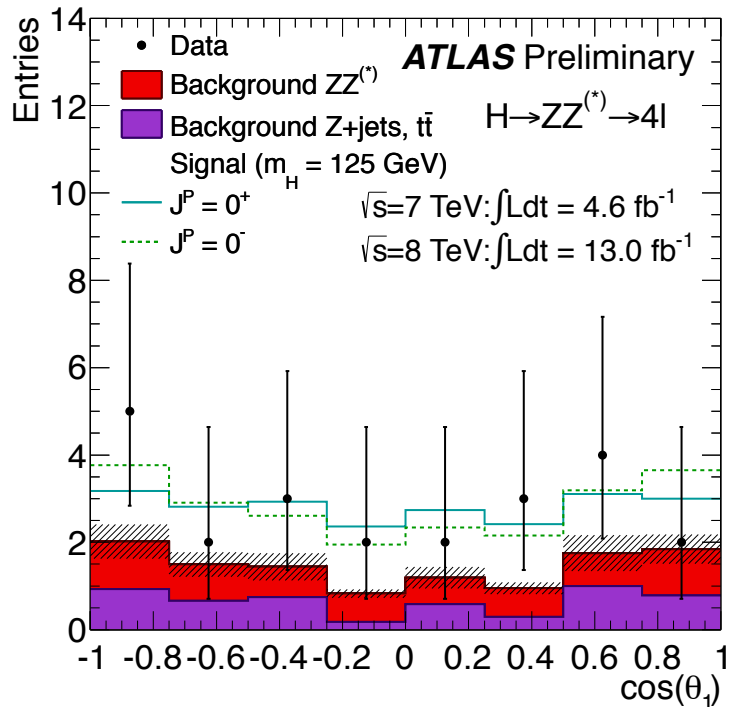
Main backgrounds



$$m_T^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_T^{\text{miss}})^2} \right]^2 - \left| \vec{p}_T^{\ell\ell} + \vec{E}_T^{\text{miss}} \right|^2}$$

Spin and parity

- Just after the discovery, the spin and parity quantum numbers had to be measured to verify the scalar hypothesis (0^+)
- For this, the angular distributions of the decay products in $H \rightarrow ZZ$, $H \rightarrow WW$ and $H \rightarrow \gamma\gamma$ have been used

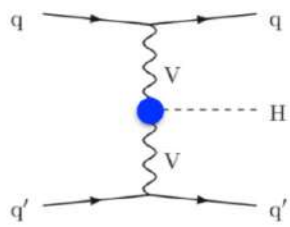


Higgs Couplings

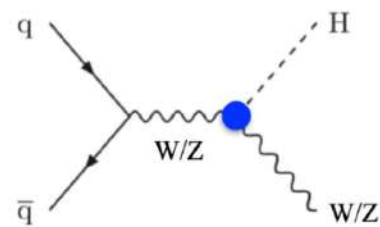
Higgs couplings

- Gauge couplings to the vector bosons

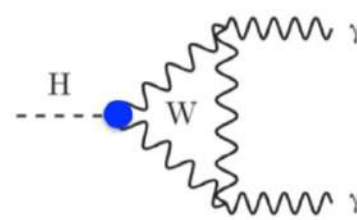
VBF Production



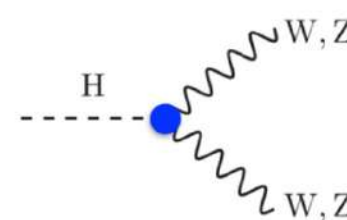
Associated Production



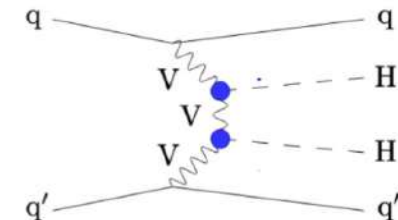
$\gamma\gamma$ decay



VV decay

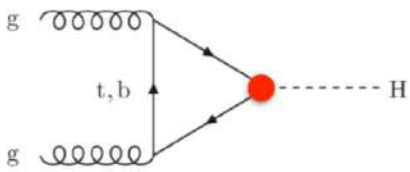


VBF pair production

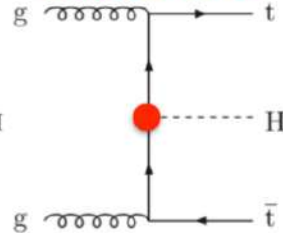


- Yukawa couplings to fermions

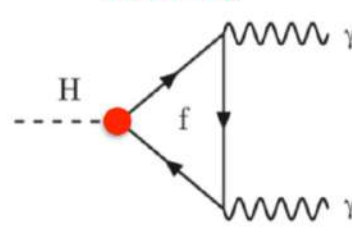
ggF production



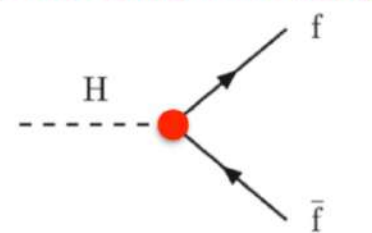
ttH production



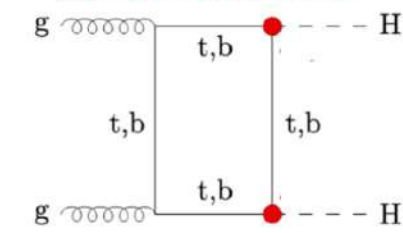
$\gamma\gamma$ decay



fermion-antifermion decay

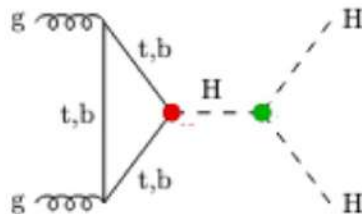


ggF pair production

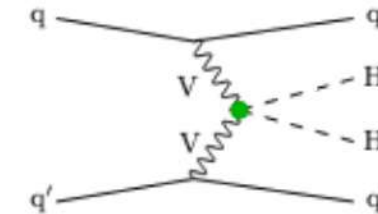
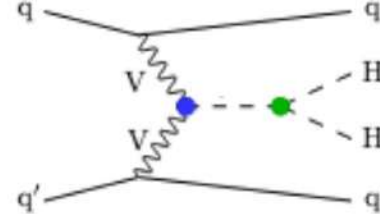


- Higgs self coupling and VVHH coupling

Higgs-pair production via self-coupling

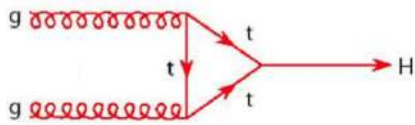


Higgs-pair production via VVHH coupling

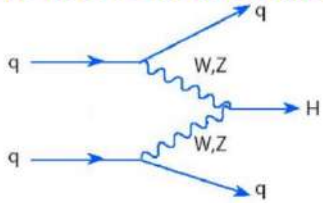


Identifying the production modes

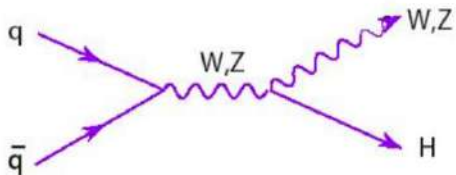
~88% Gluon fusion (ggF)



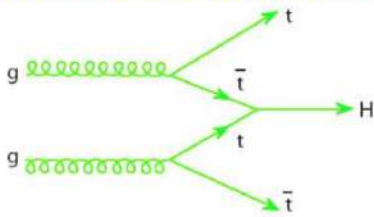
~7% Vector-boson-fusion (VBF)



~4% Higgs-Strahlung (VH)



~1% Association with $t\bar{t}$ (ttH)



- ggF is the dominant production mechanism
 - use characteristics of the other production modes can be used to disentangle them
- VBF
 - Select events with two jets in the forward regions, and with large eta separation
- VH Associated production (or Higgs-Strahlung)
 - look for the decay products of the W,Z boson
 - typically leptons (e,mu) to avoid large background contaminations
- ttH is a complex final state
 - can be characterized by the presence of b-jets from top decays
 - also, high multiplicity events
- None of these selections is perfect → always some level of contamination

Signal strength

- An observable that is very important for the couplings measurements is the signal strength
 - Defined as the ratio between the measured and the SM cross section times BR

$$\mu_i^f = \frac{\sigma_i \times \text{BR}_f}{(\sigma_i \times \text{BR}_f)_{\text{SM}}} \equiv \mu_i \times \mu_f, \quad \text{with } \mu_i = \frac{\sigma_i}{(\sigma_i)_{\text{SM}}} \quad \text{and} \quad \mu_f = \frac{\text{BR}_f}{(\text{BR}_f)_{\text{SM}}}$$

- Thus the number of events per channel can be defined as:

$$n_s^c = \sum_i \sum_f \mu_i (\sigma_i)_{\text{SM}} \times \mu_f (\text{BR}_f)_{\text{SM}} \times A_{if}^c \times \varepsilon_{if}^c \times \mathcal{L}^c$$

- Measuring the event yields per production mode and decay channel allows to look for possible deviations from the SM (μ 's different from 1)

Signal strength and κ -framework

Signal strength

- The first characterisation of the Higgs couplings properties happens via the measurement of the signal strength

- Can fit a global μ or fit μ_i assuming SM for the decay, or fit μ_f assuming SM for the production cross section

$$\mu_i^f = \frac{\sigma_i \times \text{BR}_f}{(\sigma_i \times \text{BR}_f)_{\text{SM}}}$$

- Global μ fit results:

- ATLAS $\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03(\text{stat}) \pm 0.03(\text{exp}) \pm 0.02(\text{bkg th}) \pm 0.04(\text{sig th})$
- CMS $\mu = 1.002 \pm 0.057 = 1.002 \pm 0.029(\text{stat}) \pm 0.033(\text{syst}) \pm 0.036(\text{sig th})$

κ -framework

- In this framework a set of coupling modifiers κ alter the signal strength, without affecting the kinematic distributions
- Each $\sigma \times \text{BR}$ can be parametrized in terms of these couplings strength modifiers
- Can also accomodate any non-SM invisible or undetected component

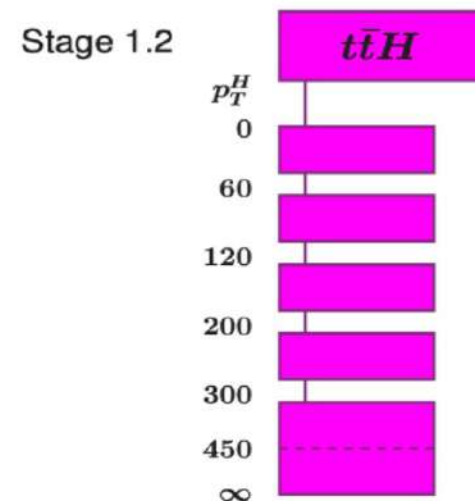
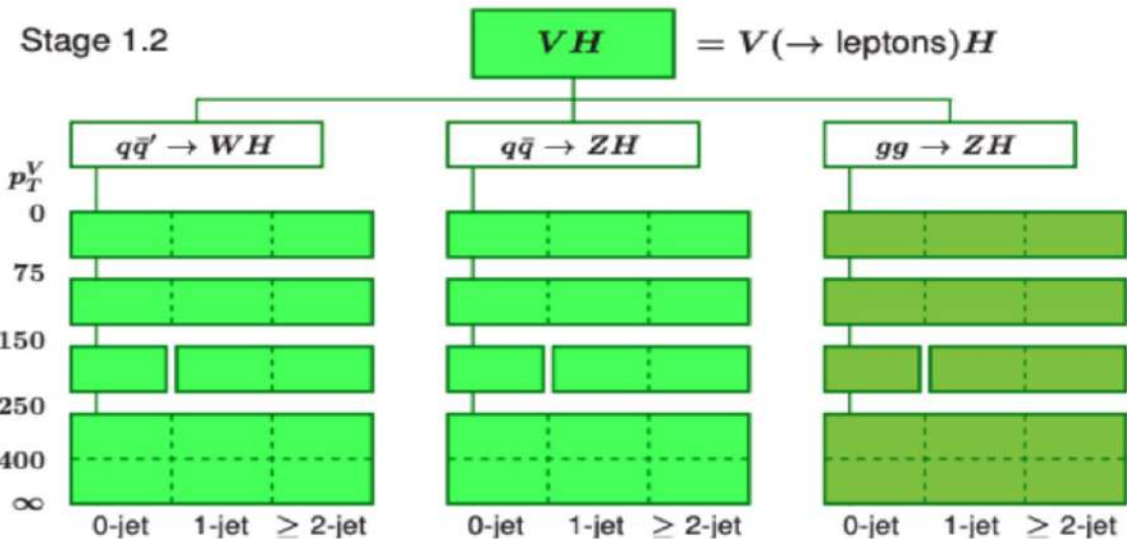
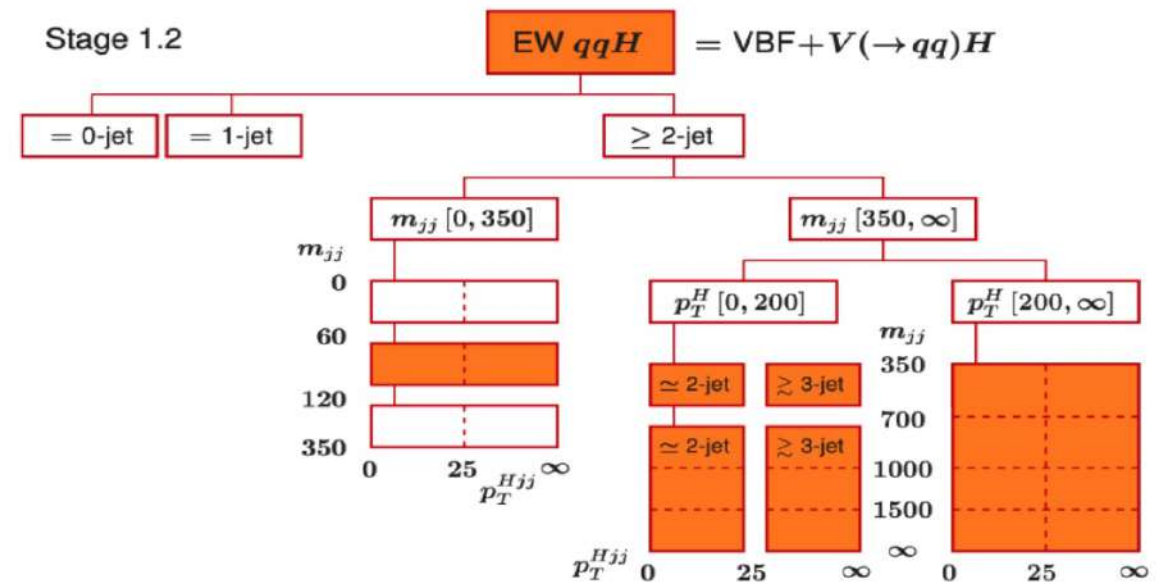
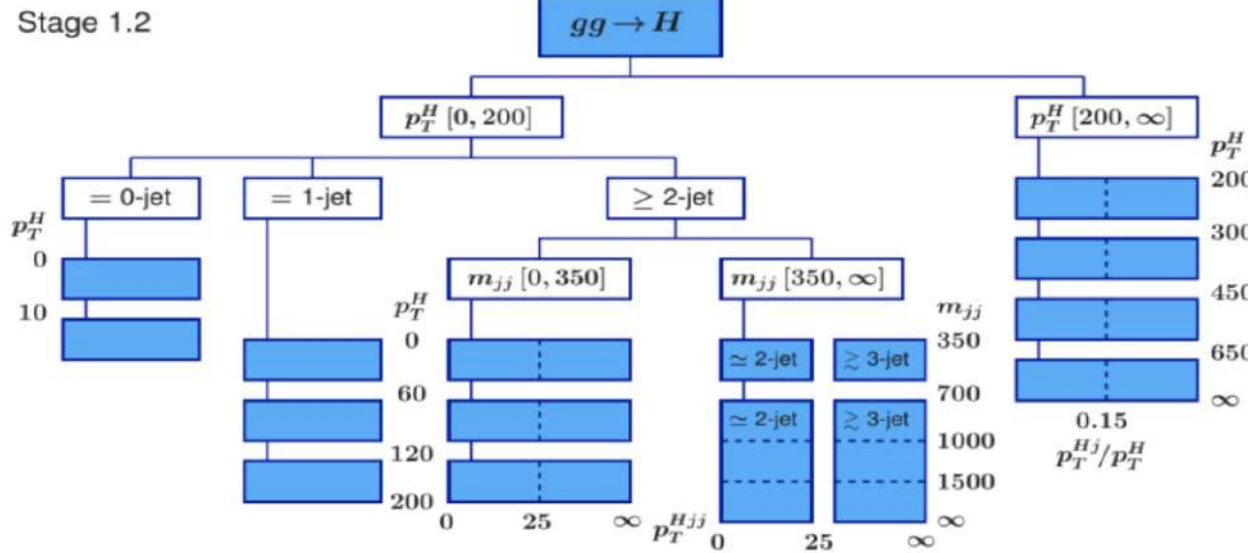
$$(\sigma_i \times B_f) = k_i^2 \sigma_i^{\text{SM}} \frac{k_f^2 \Gamma_f^{\text{SM}}}{k_H^2 \Gamma_H^{\text{SM}}}$$

Simplified template cross sections (STXS)

- ❑ Including this topic for completeness (but no need to go into the details...)

- ❑ The κ -framework introduces modification factors that do not alter the kinematic distribution with respect to the Standard Model
 - Only an overall normalization of each coupling contribution is left free to vary
- ❑ To allow looking for deviations of the differential distributions, the so-called STXS framework is used
- ❑ Measure signal strengths in bin of the truth quantities
 - Within each bin the SM behavior is assumed
- ❑ Use the same binning definition for all channels simplifies a lot the final combination

STXS bins

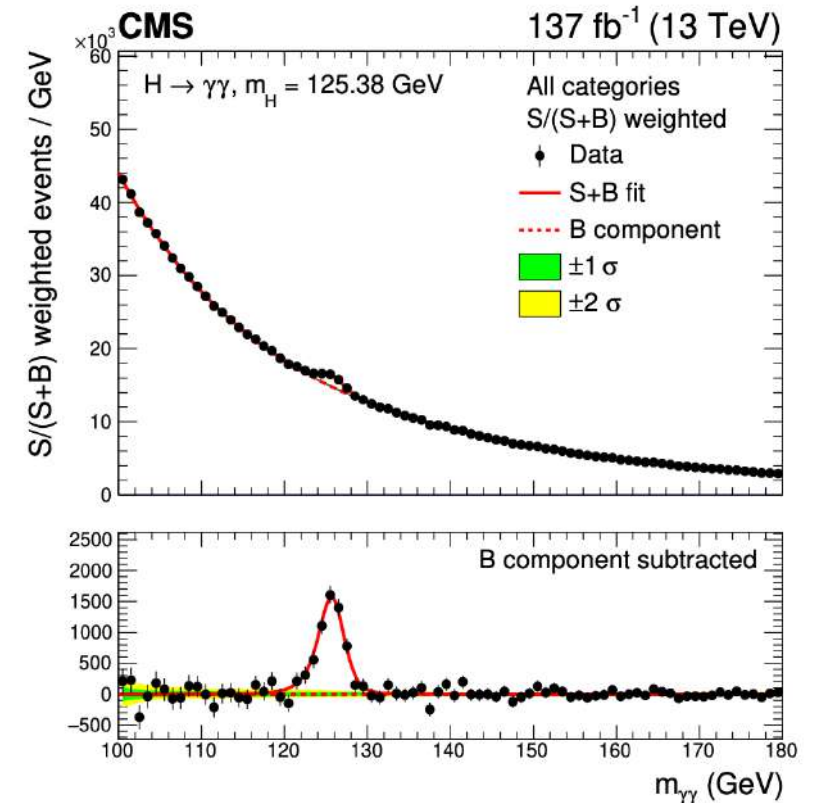
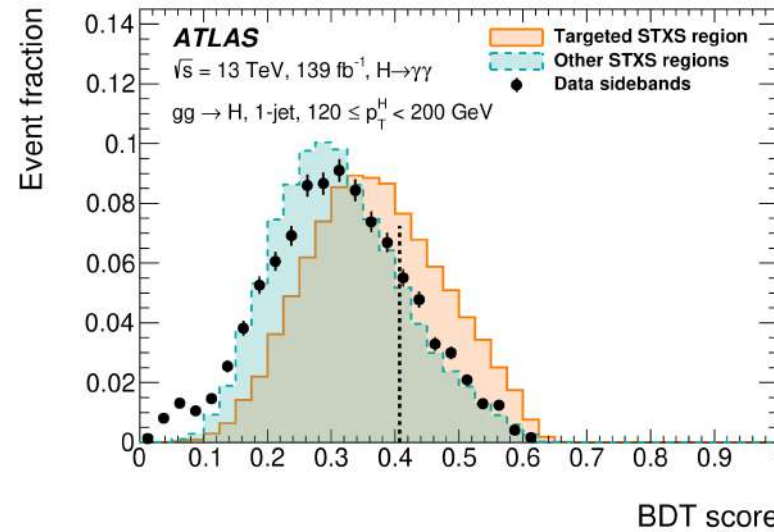
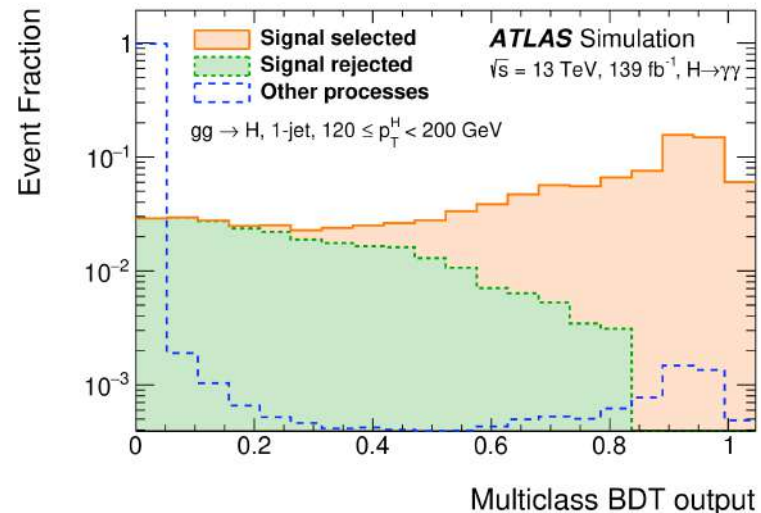


The analyses are designed trying to match the bins of truth quantities

Different granularity --> can be chosen depending on the channel's statistics

Main results with run-2 data

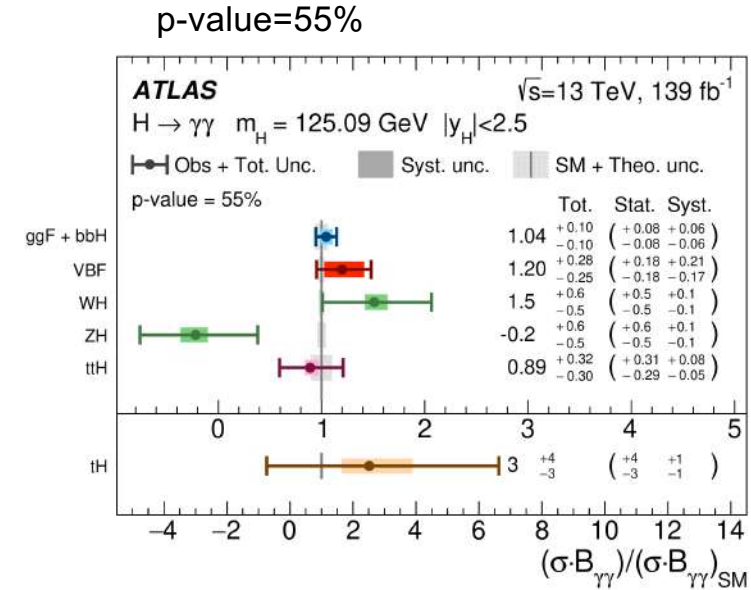
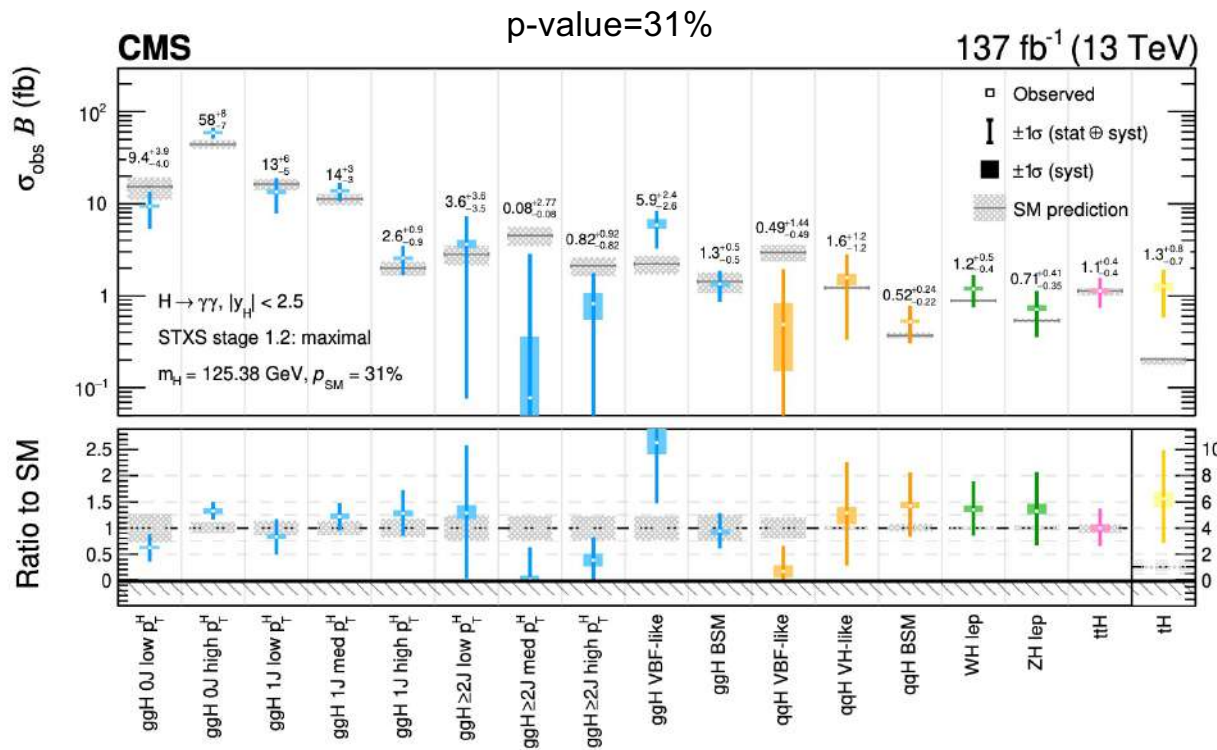
- Analysis requiring two high momentum photons, background fit from data
- Machine Learning -based algorithms for event categorization
- Multi-class discriminant to categorize the events aiming at STXS bins
 - Better performance than just using $P_T(\gamma\gamma)$ and N_{jets}
- Dedicated discriminants to separate signal from background in each STXS bin
 - Training on signal MC and background sidebands
 - Choosing variables in such a way that no bias on the $m_{\gamma\gamma}$ distribution can be caused
 - e.g. use $p_T(\gamma)/m_{\gamma\gamma}$ instead of just $p_T(\gamma)$



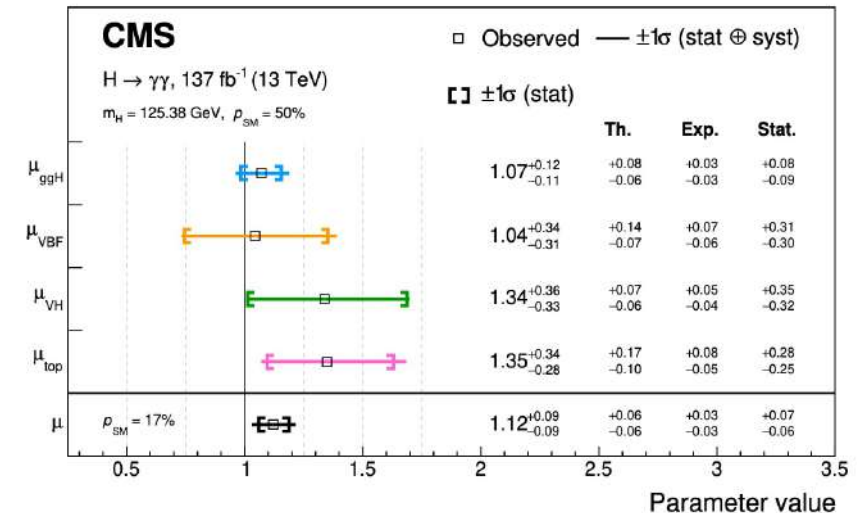
H → γγ signal strengths and STXS

CERN-EP-2022-094
JHEP07 (2021) 027

- STXS number of parameters of interest can change depending on the merging scheme adopted,
 - Min merging scheme 28 bins, results from both ATLAS and CMS

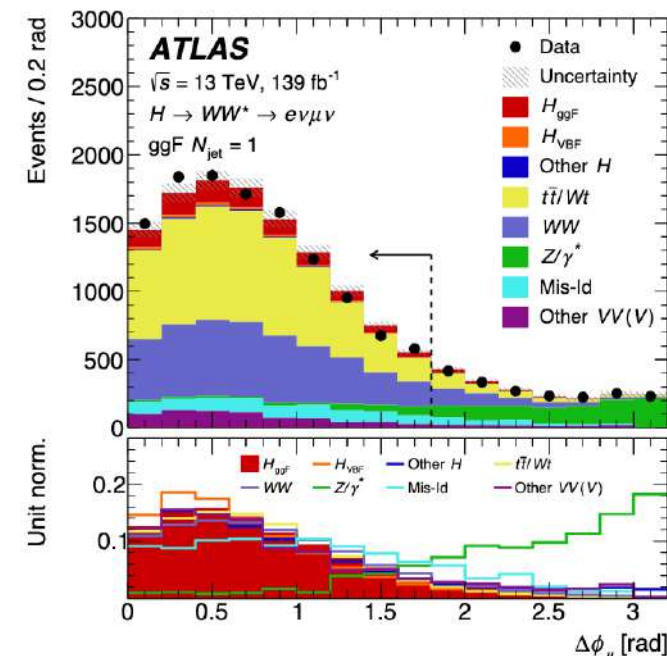
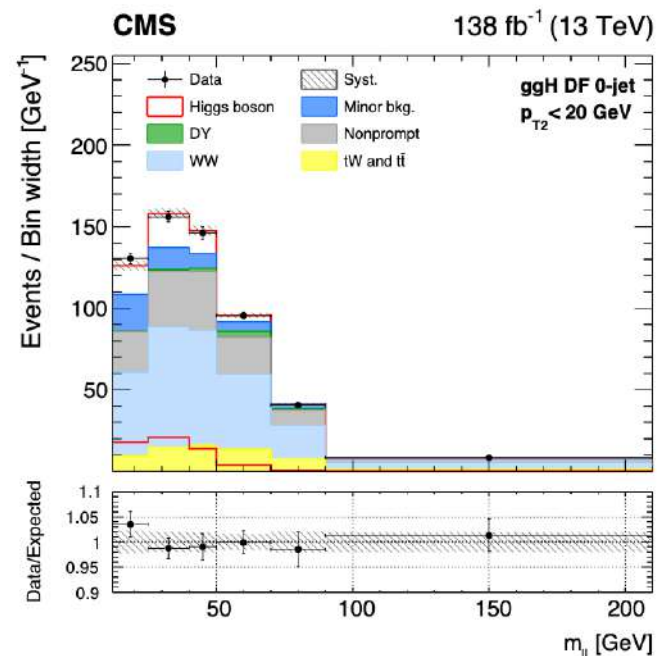
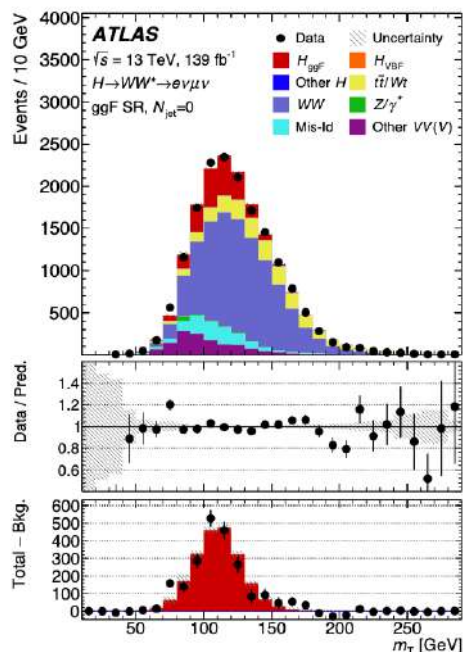


$p\text{-value}=50\%$



- Given the large BR, this channel is one of the most relevant in the couplings measurement
 - Analyses either Different-Flavor only (ATLAS) or Different+Same-Flavor (CMS)
 - Further categorization based on kinematic properties
 - Backgrounds mainly from control regions normalizations
- Signal strength extraction from the transverse mass, m_{Tl} , or from the fit to ML-based discriminants (in particular for VBF and associated production channels)
 - Dedicated discriminant against DY in SF channels

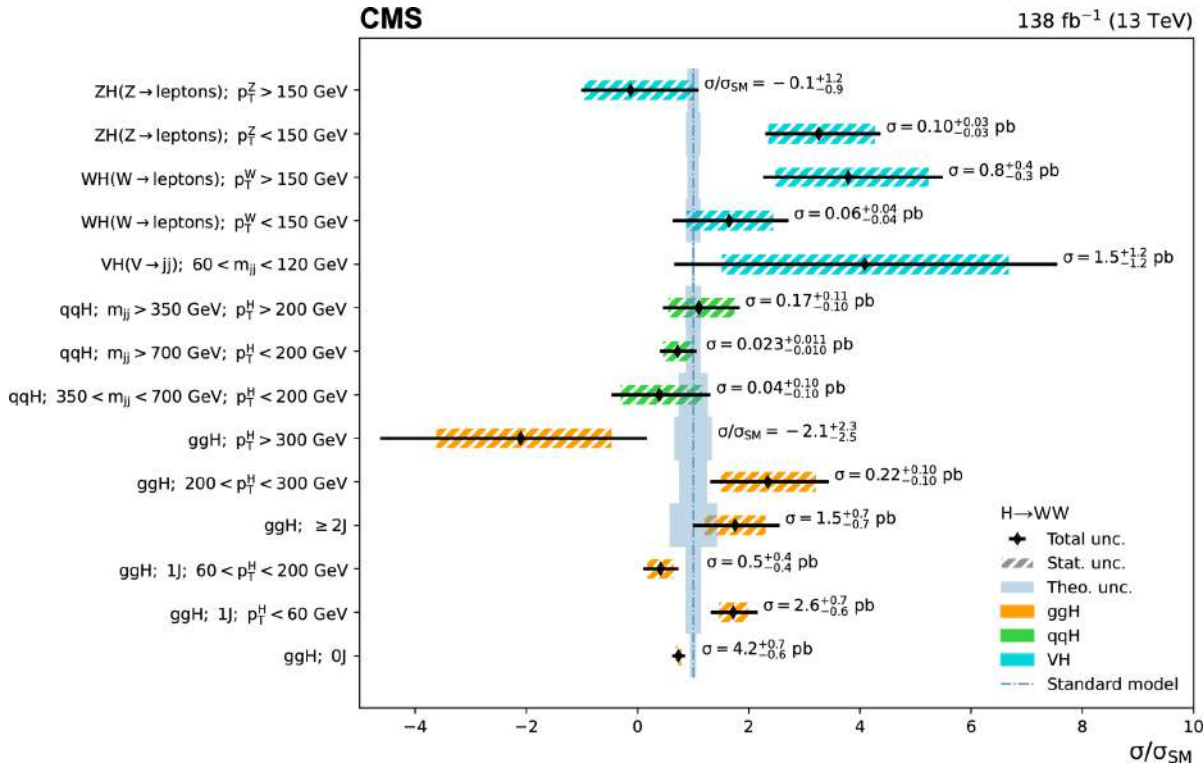
$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 + |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{\text{miss}}|^2}$$



H → WW → lνlν STXS results

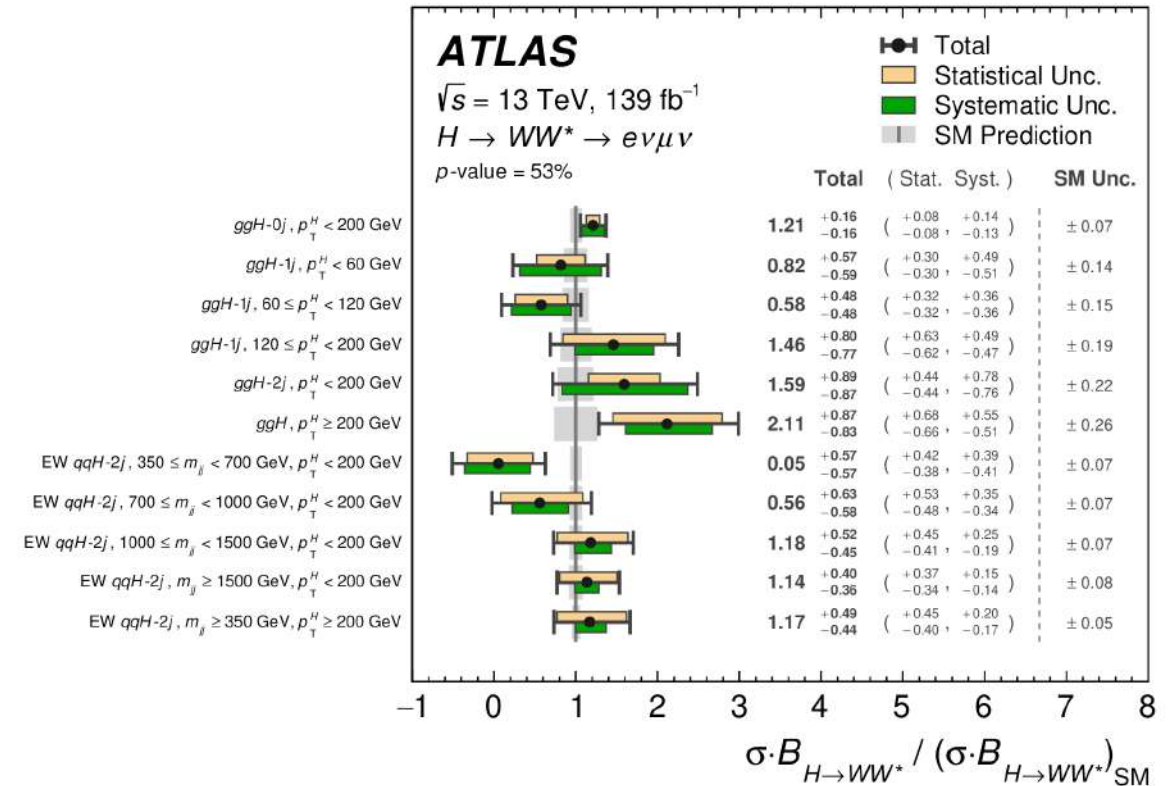
CERN-EP-2022-078

CERN-EP-2022-120



- STXS measurement via analysis categories targeting STXS bins

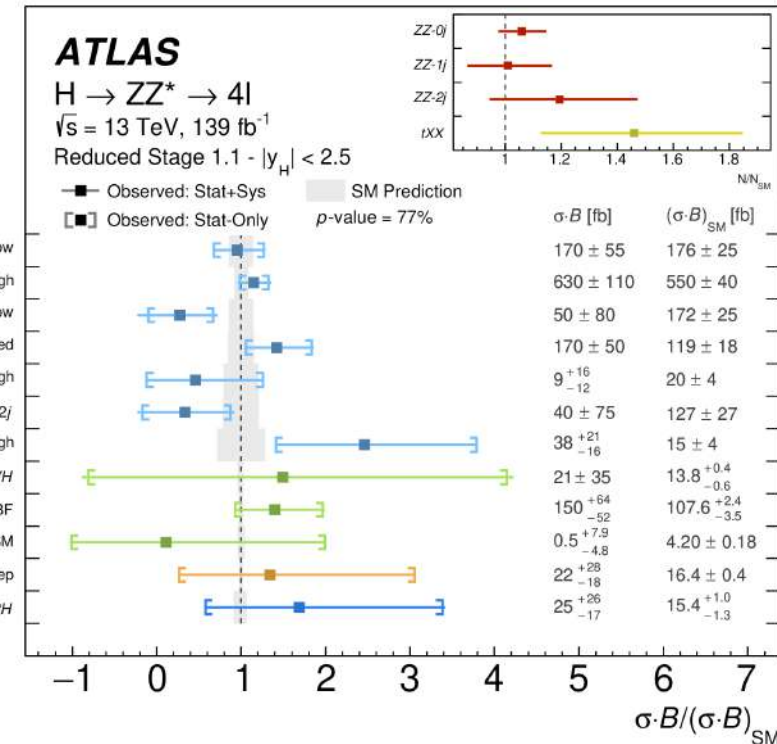
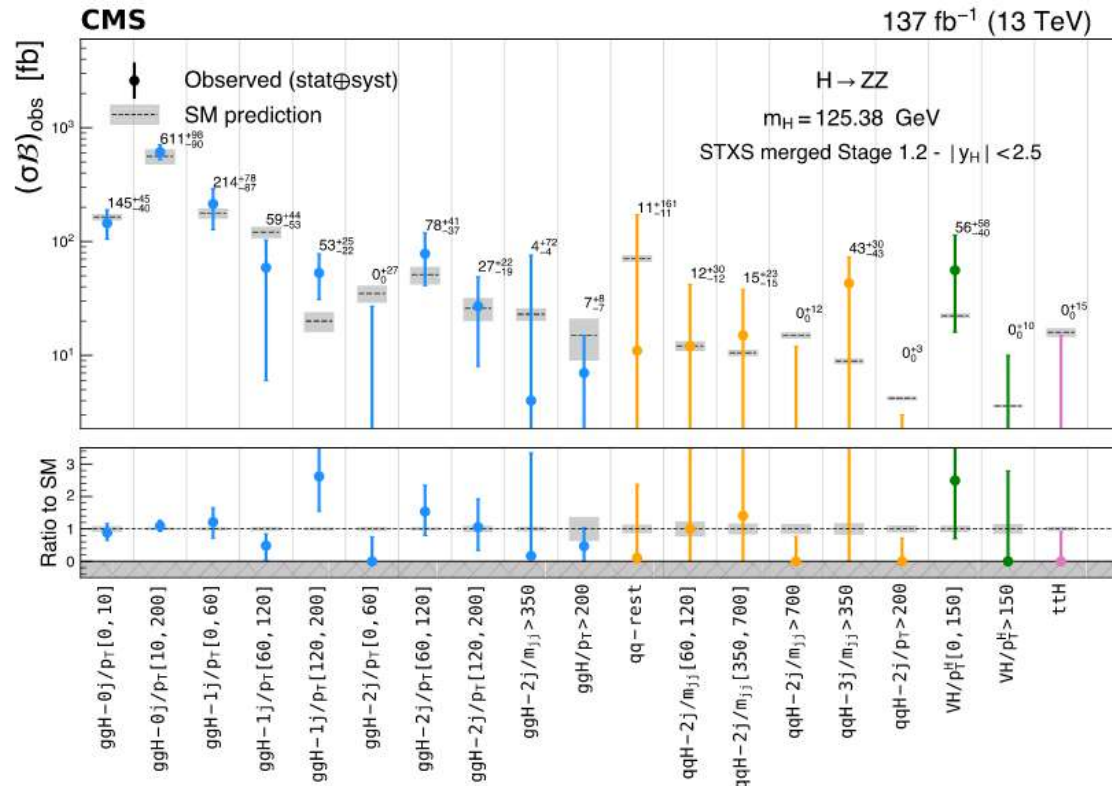
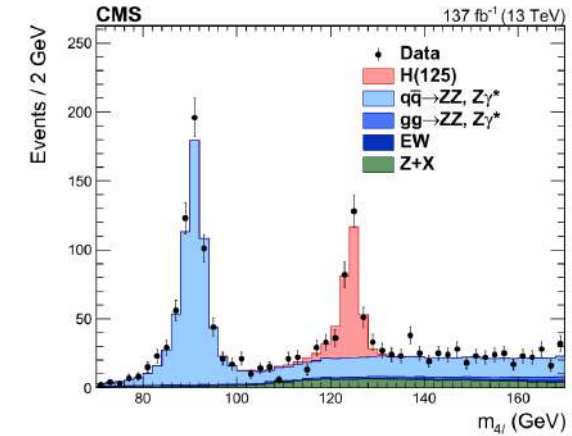
The p-value of the compatibility with the SM is 53% (ATLAS) and 1% (CMS)



H → ZZ* → 4l

Eur. Phys. J. C 80 (2020) 957
 Eur. Phys. J. C 81 (2021) 488

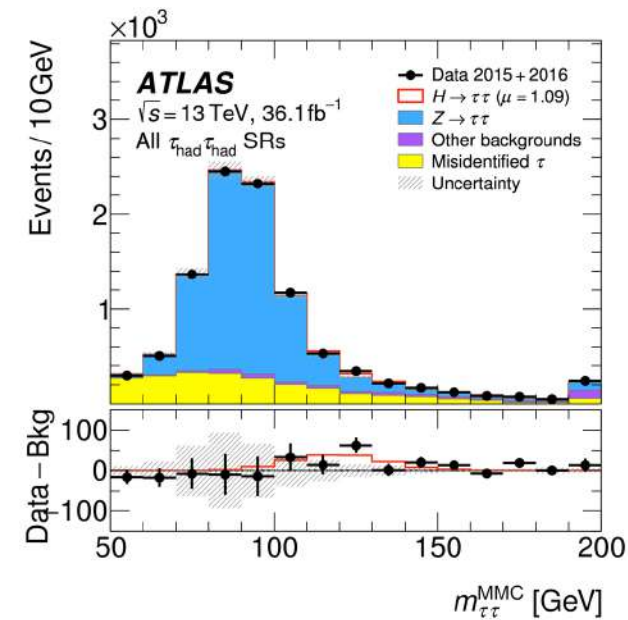
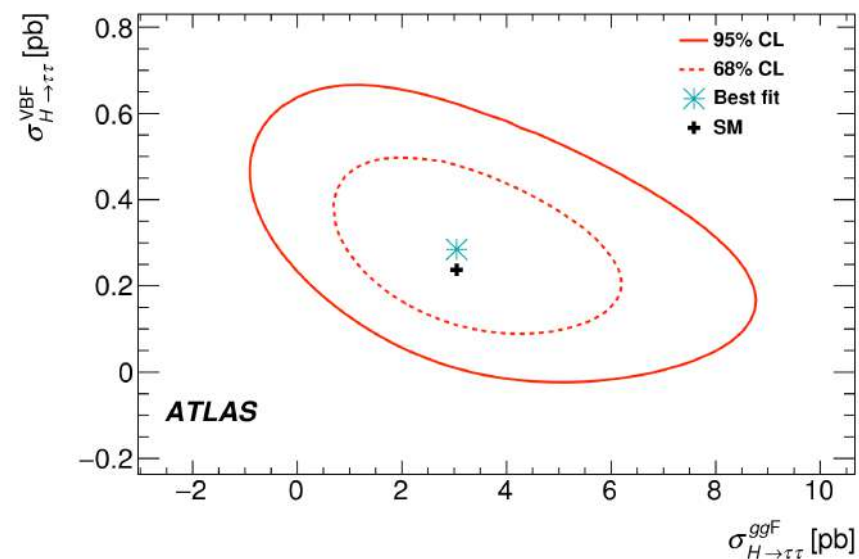
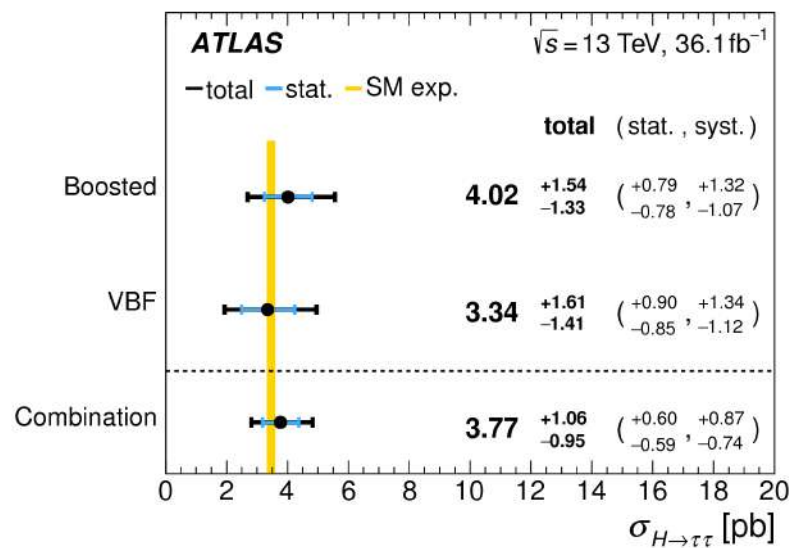
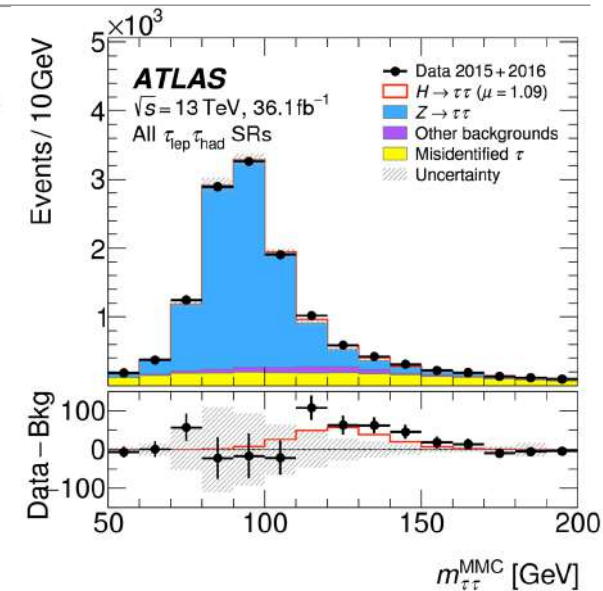
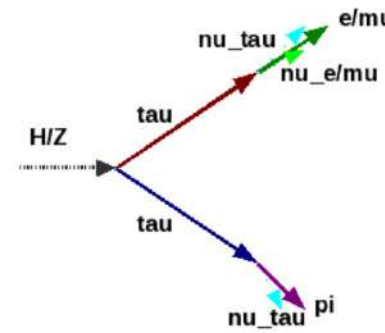
- Very clean signature, limited by the small BR
- Mass peak clearly reconstructed on top of the background, ideal channel for many precision measurement of Higgs properties



H → ττ

Phys. Rev. D 99 (2019) 072001

- First direct decay to fermions observed
 - Combining 13, 8 and 7 TeV results
- Select the three combination of decay channels
 - lep-lep, lep-had, had-had
- Reconstruct the invariant mass in the collinear approximation
- Main background is Z → ττ, mostly determined from data
- Events categorized in VBF-like and "boosted", i.e. with large H p_T, due to either ggF+jets or VH production
 - Mainly to remove Z background

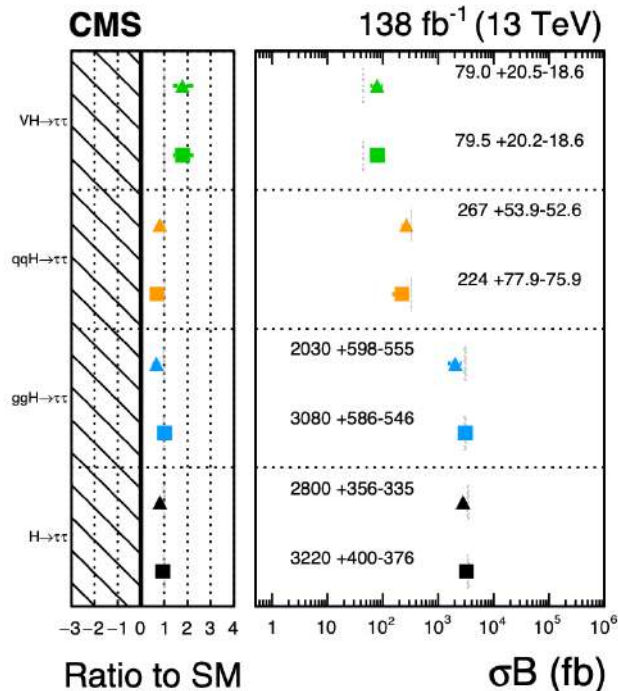
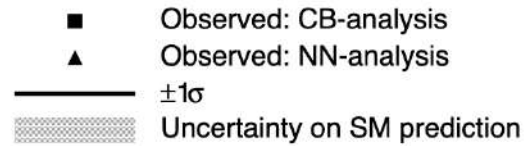


H → ττ updated results

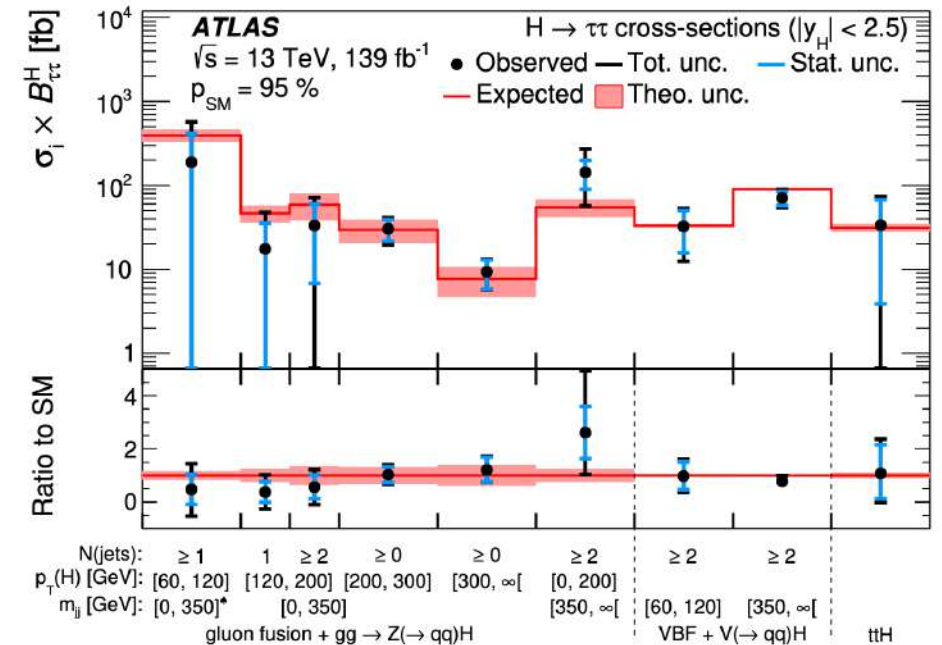
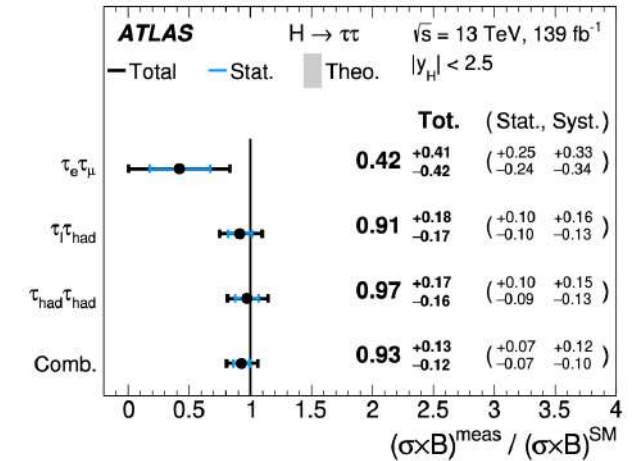
CERN-EP-2022-027

JHEP 08 2022 175

- Channel with the highest BR to leptons (first observation of lepton coupling), but with up to 4 neutrinos in the final state. Large background from Z → ττ.
- All three decay channels ll hh entering in the analysis
- Dedicated categories for each production mode (ggF, VBF, VH, ttH)



Error on the inclusive signal strength at ~13% for each experiment



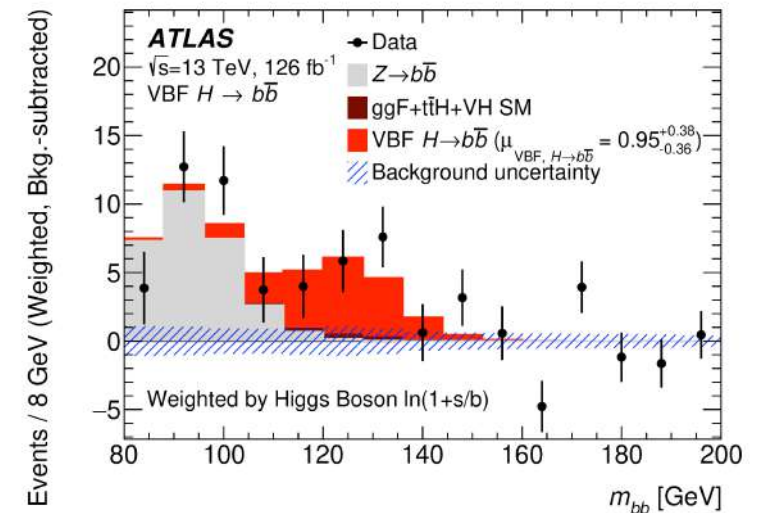
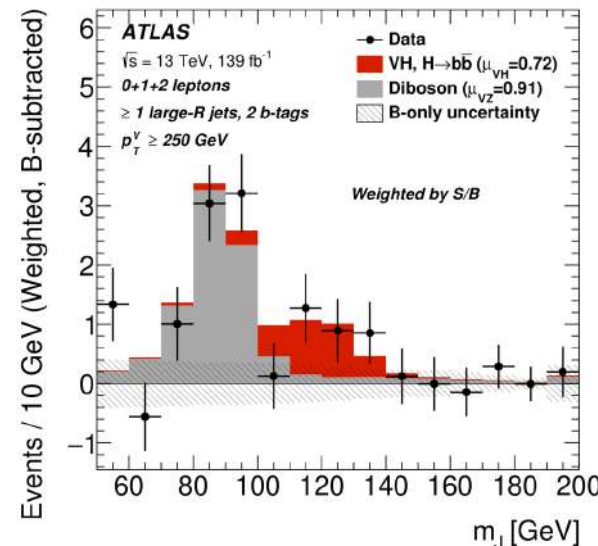
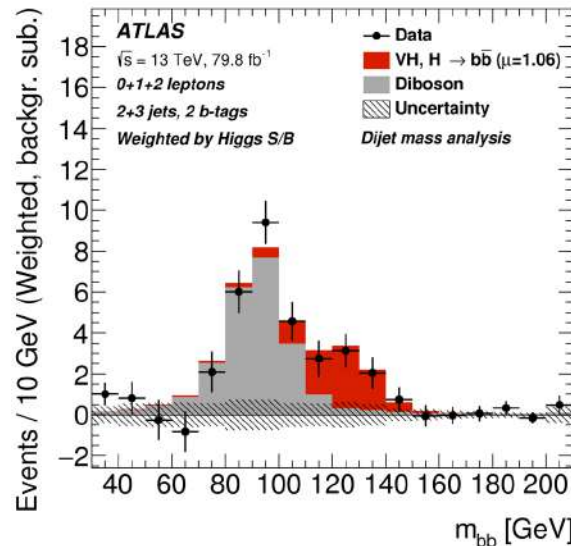
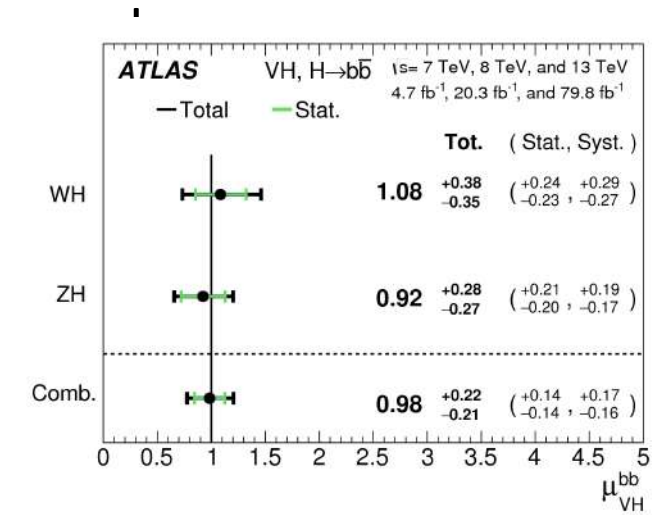
H → bb

[Eur. Phys. J. C. 81 \(2021\) 537](#)

[Phys. Lett. B 816 \(2021\) 136204](#)

[Eur. Phys. J. C 81 \(2021\) 178](#)

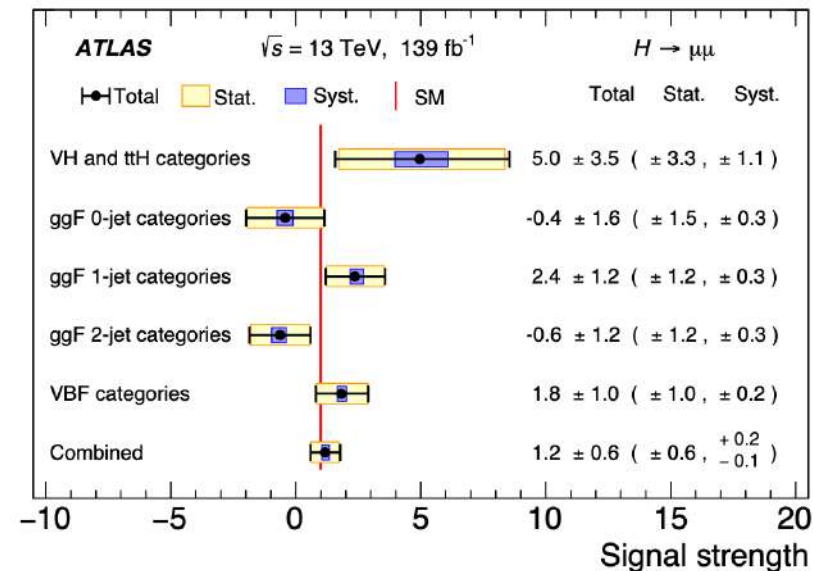
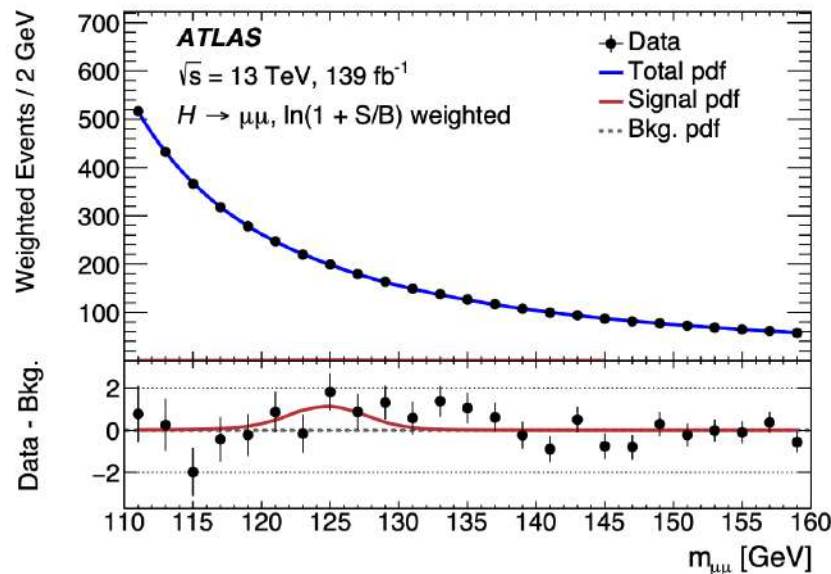
- Channel with the largest BR, but complicated due to the large background at hadron colliders
- Observed exploiting the associated production signature
- Many exclusive channels added later
 - VBF, VH and VH boosted
- Boosted topologies looking for "fat" jets with sub-jet structures (2 b tagged subjets)



Search for the $H \rightarrow \mu\mu$ decay

[Phys. Lett. B 812 \(2021\) 135980](#)

- The $H \rightarrow \mu\mu$ decay offers the best opportunity to measure the Higgs interactions with a second-generation fermion
- Events are categorized in 20 mutually exclusive categories
 - Di-lepton mass fit in the 110-160 GeV region, correct for muon QED FSR
 - Background modeling from core function (LO DY mass shape) convolved with di-lepton mass dependent resolution x empirical functions, category dependent
- Result improve by a factor ~ 2.5 previous ATLAS result, with a factor ~ 2 coming from the increased int. luminosity an additional $\sim 25\%$ from analysis improvements
 - Signal strength $\mu = 1.2 \pm 0.6$ corresponding to an observed(expected) significance of 2.0σ (1.7σ)

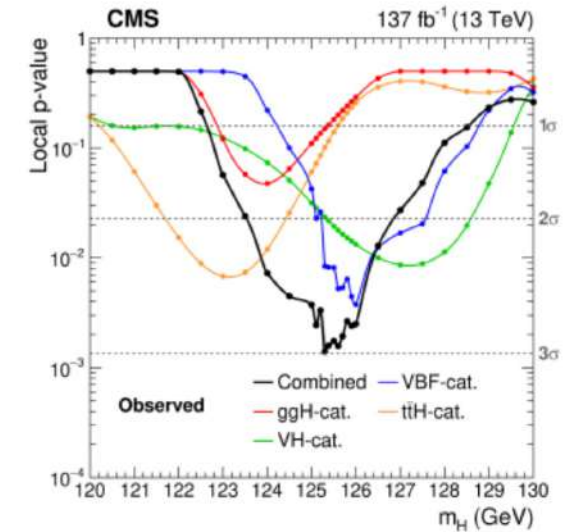
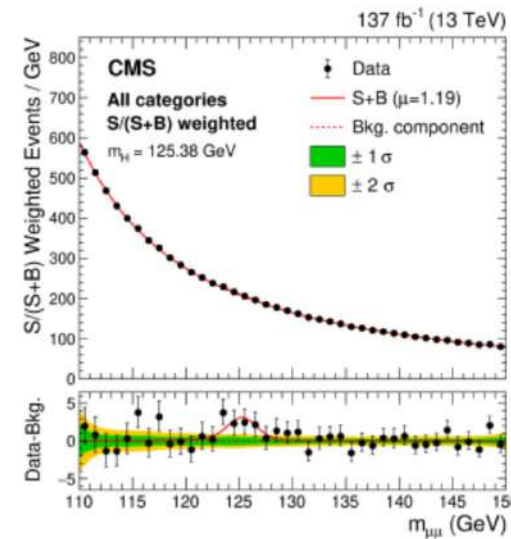


$H \rightarrow \mu\mu$ decay

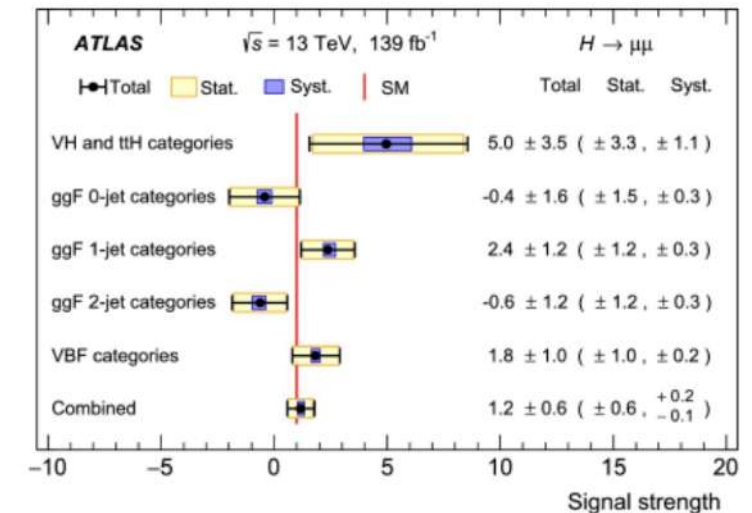
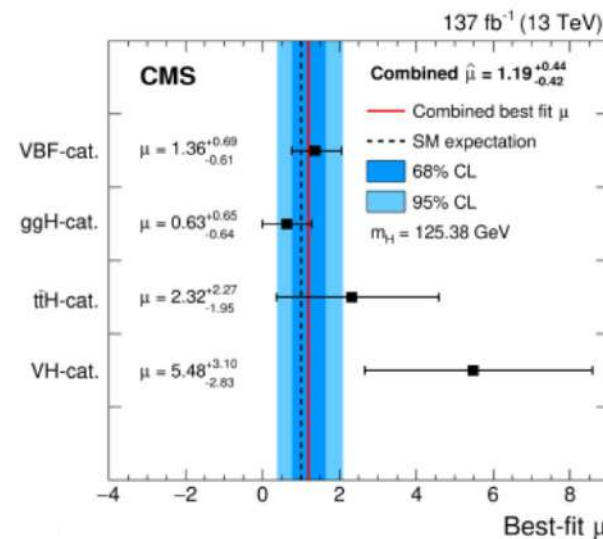
JHEP 01 (2021) 148

Phys. Lett. B812 (2021) 135980

- Rare decay channel (BR=0.02%) that offers the possibility of observing the direct coupling to second generation fermions
- Check of the non-universality of the Higgs-leptons coupling
- Selection optimized exploiting signature of the different production modes and categorization, plus multi-variate discriminants
- Drell-Yan Background fit from data in each category



- CMS obs (exp) significance
 - **3.0 σ (2.5 σ)**
 - Evidence of $\mu\mu$ decay
- ATLAS obs (exp) significance
 - **2.0 σ (1.7 σ)**

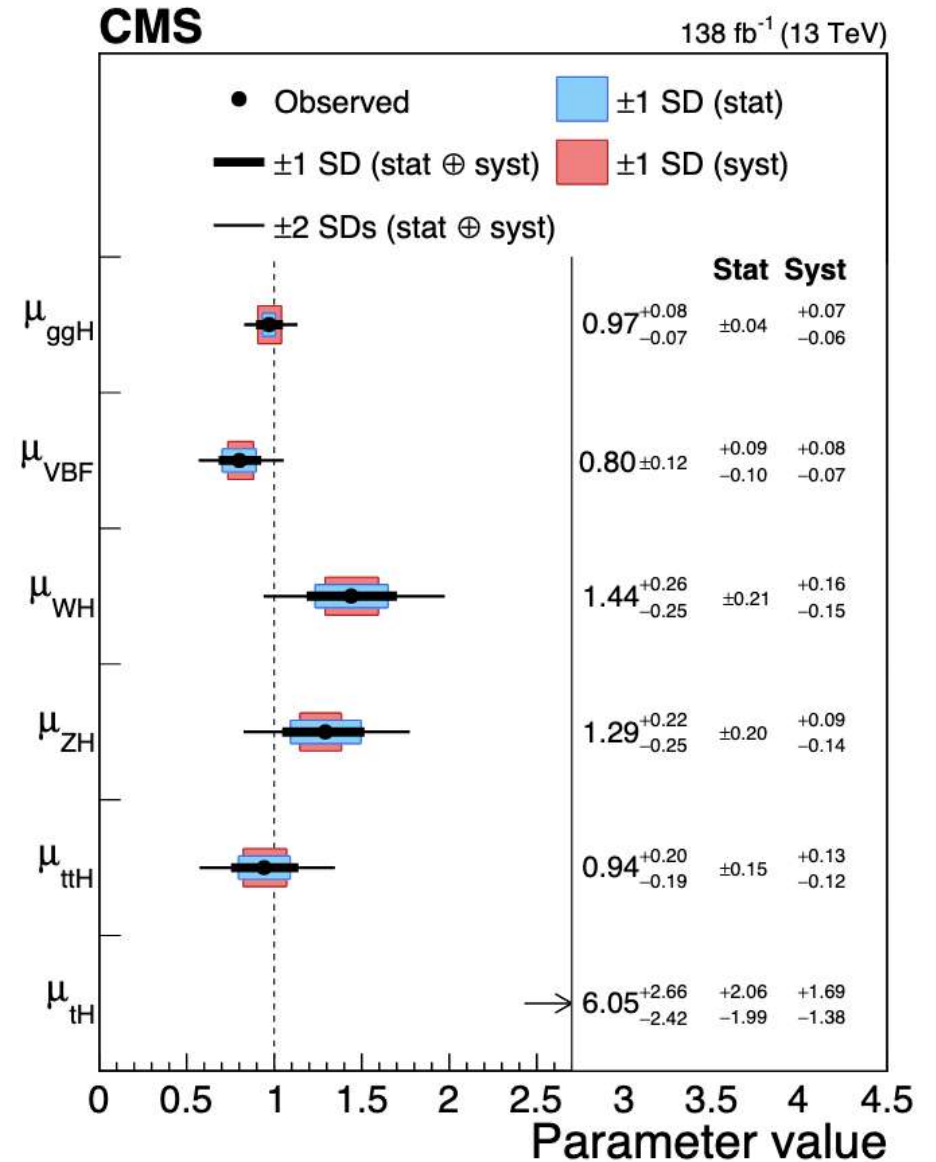
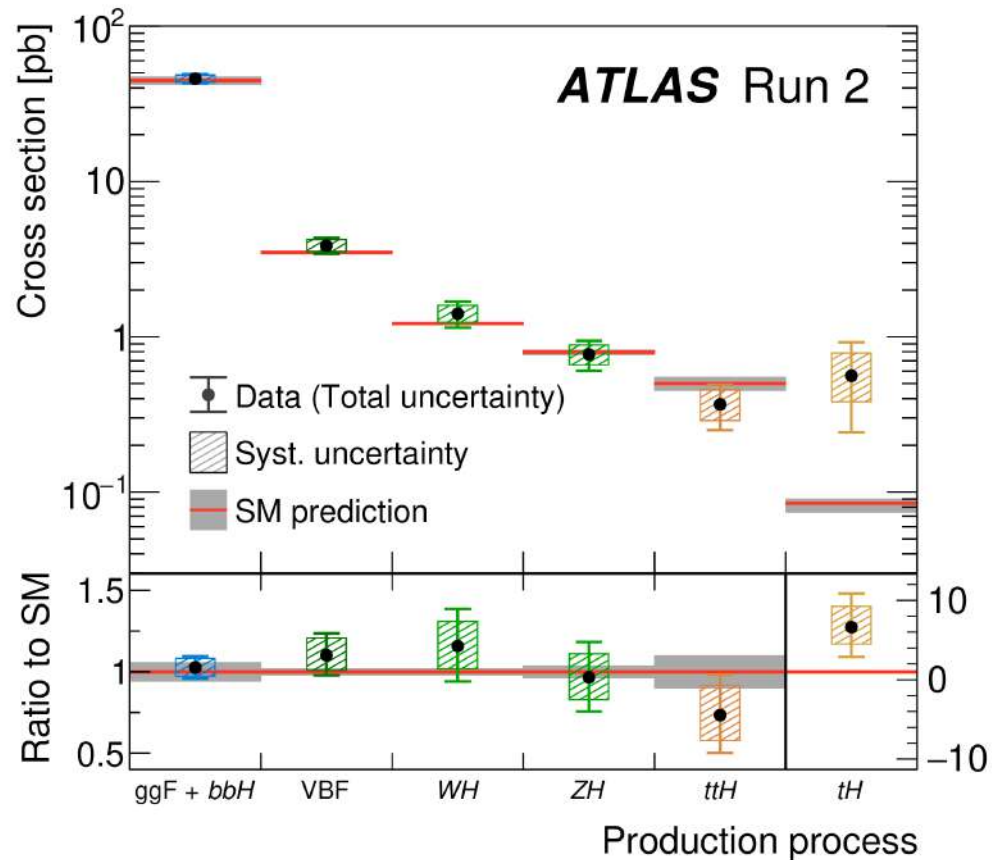


Combined couplings fits

Signal strength: production modes

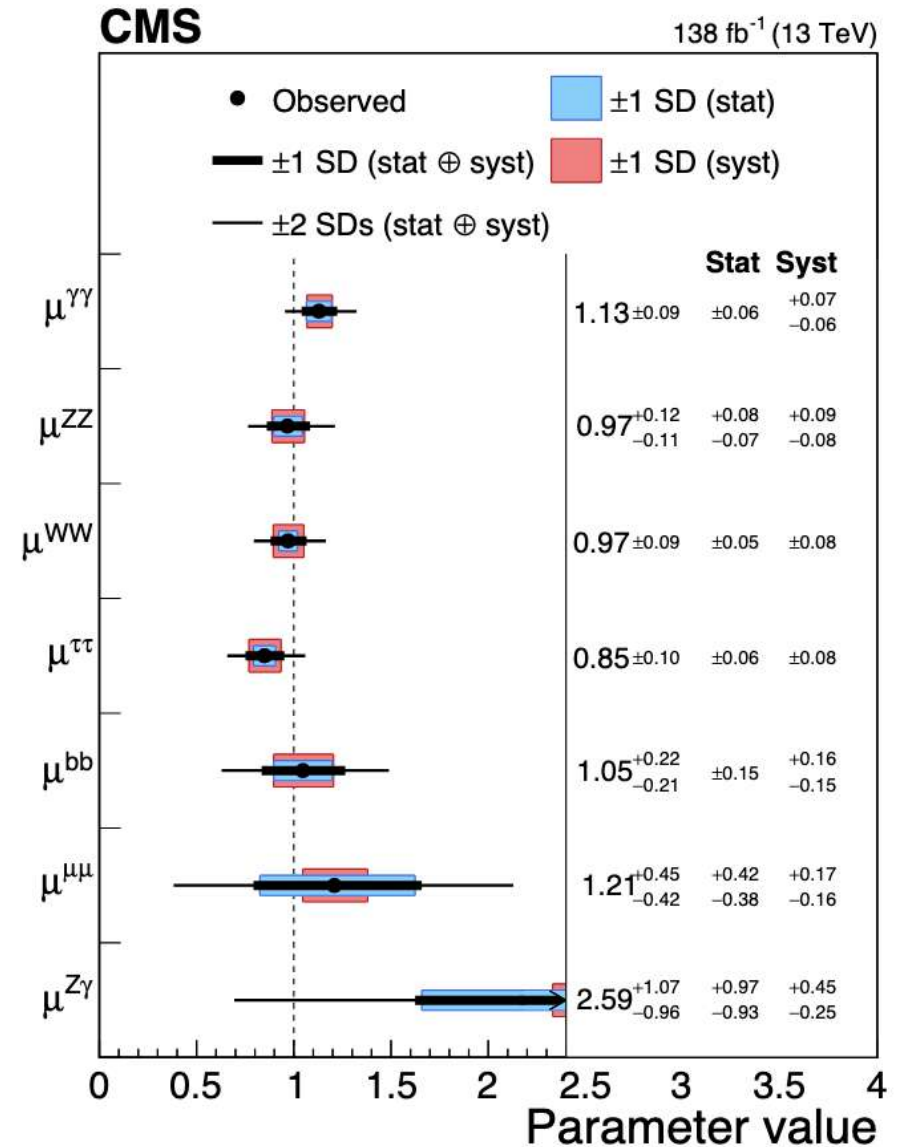
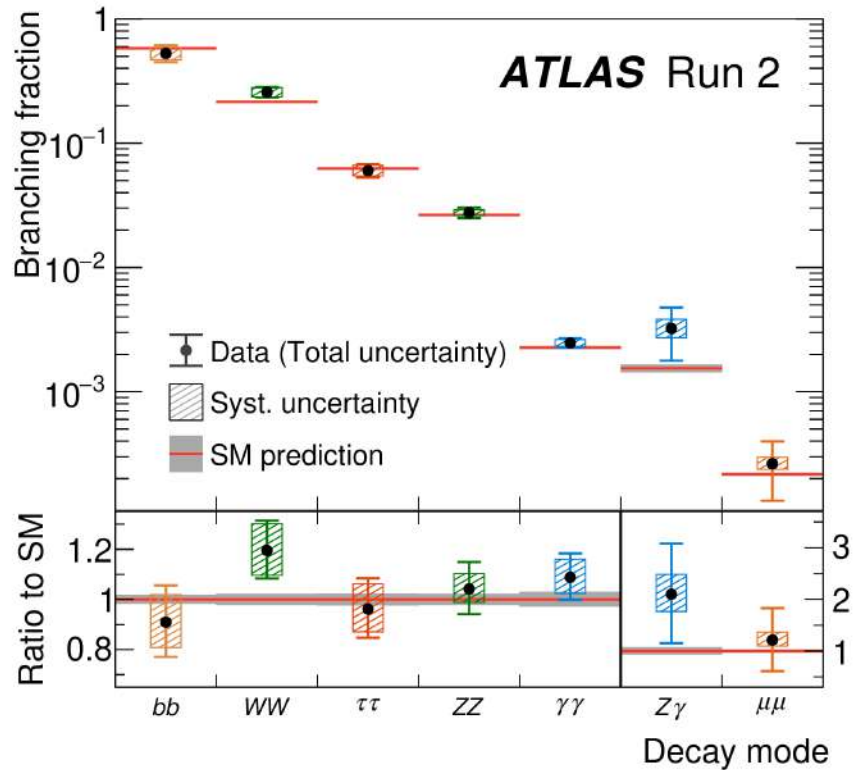
- By production mode, assuming SM decay BR
- All the main production modes have been observed with a significance of 5σ or more

➤ Uncertainties from $\sim 7\%$ to $\sim 25\%$



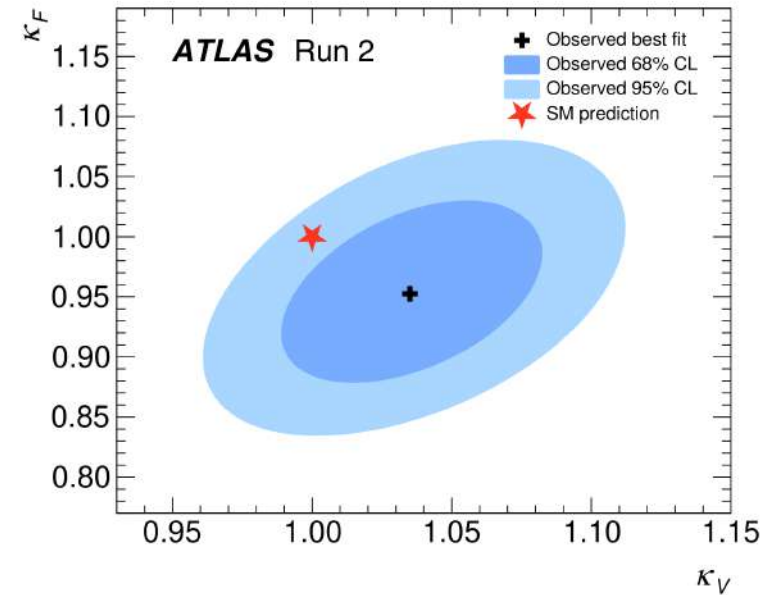
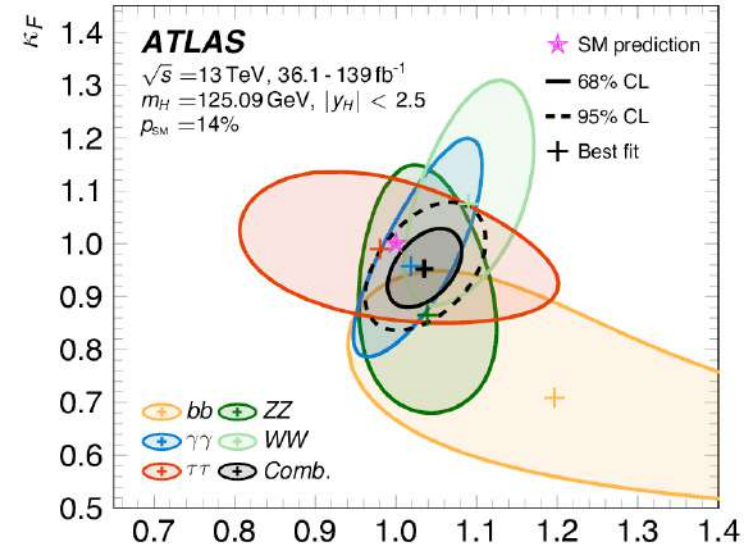
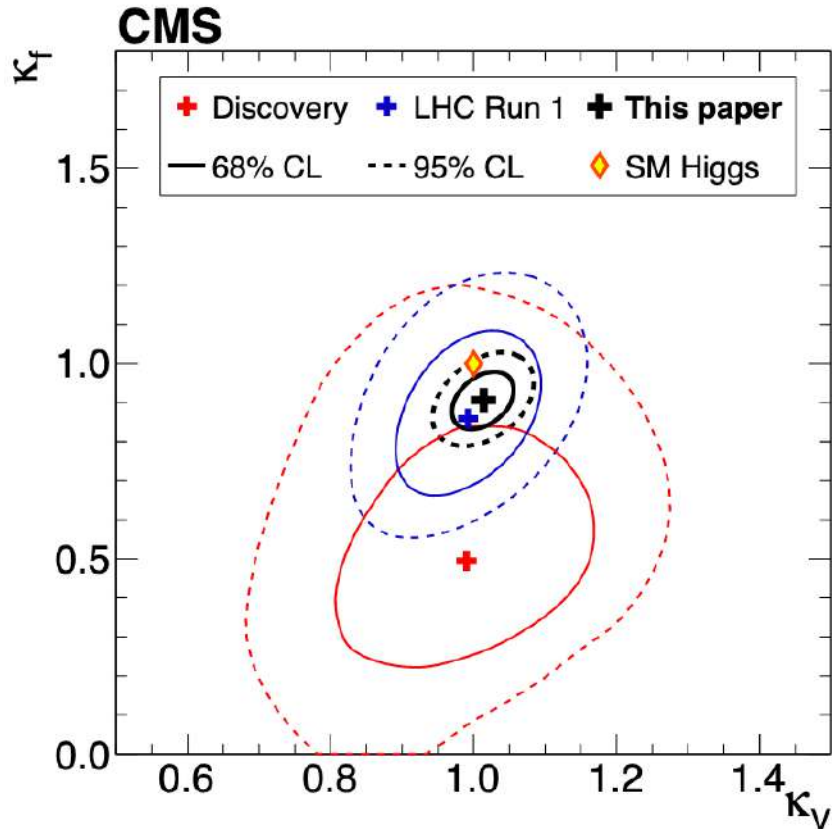
Signal strength: decay channels

- ❑ Signal strengths per decay channel, assuming SM values for production cross sections
- ❑ Rare decay channels $Z\gamma$ and $\mu\mu$ not observed yet, all other decay modes observed with more than 5σ significance



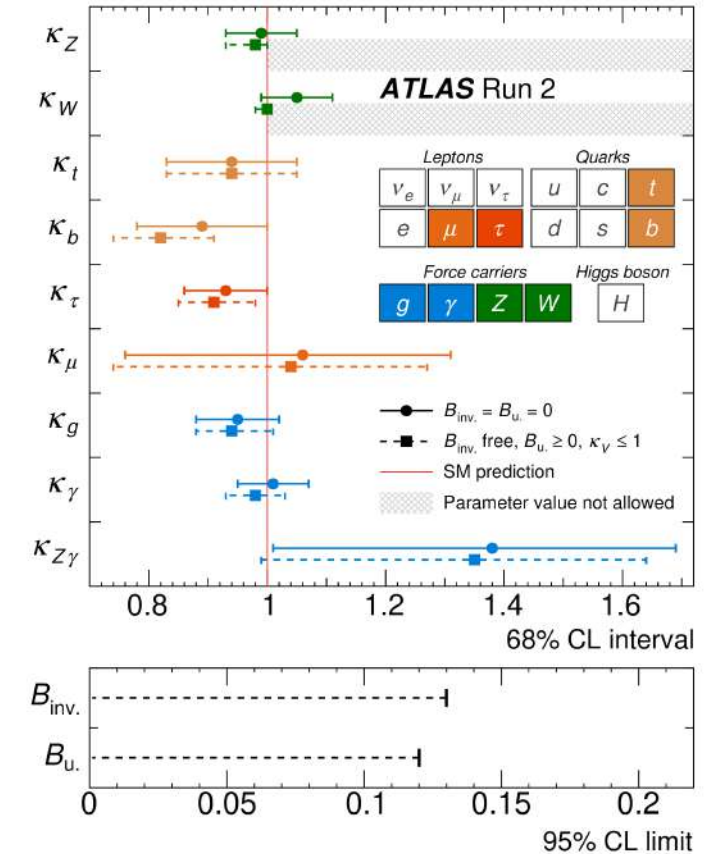
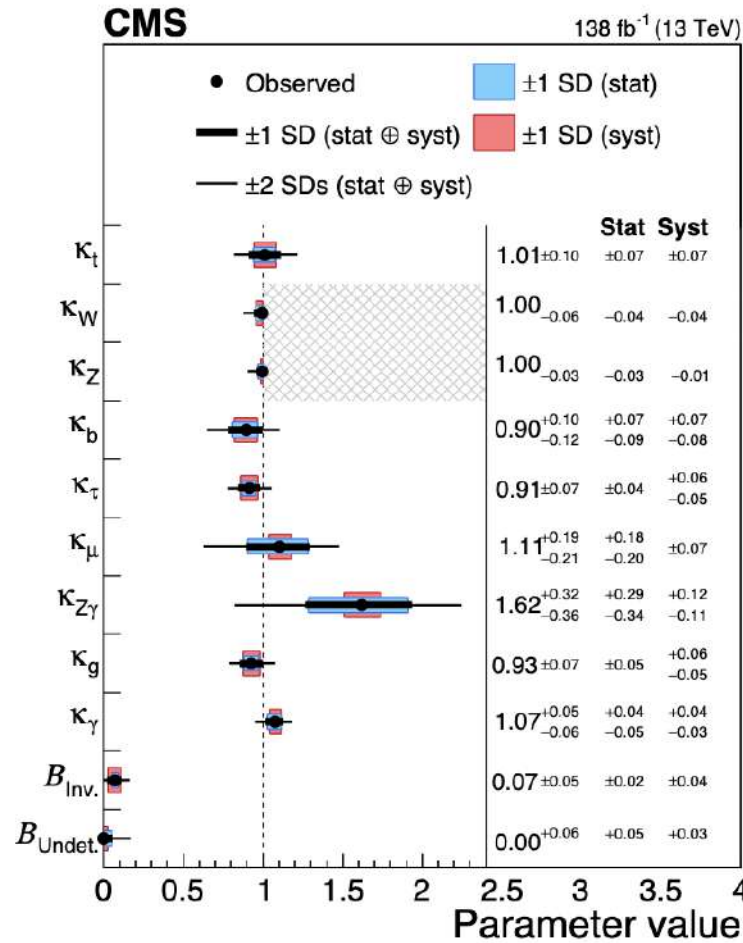
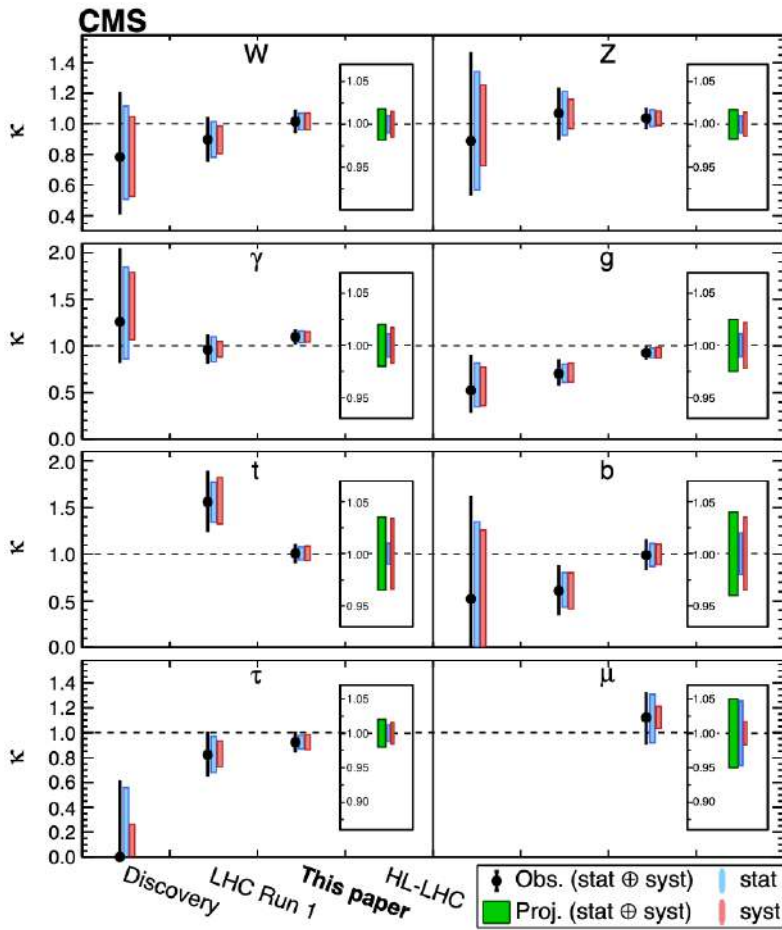
κ -framework fits

- ❑ Fitting only two coupling modifiers, one for all vector bosons and one for all fermions
- ❑ Assuming no BSM invisible or undetected decays



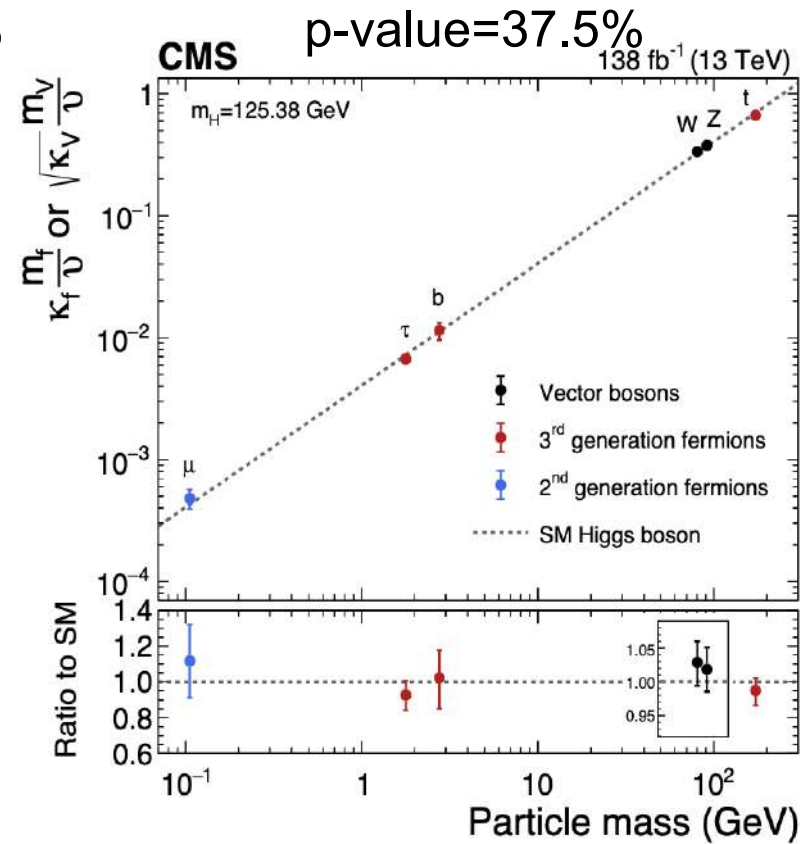
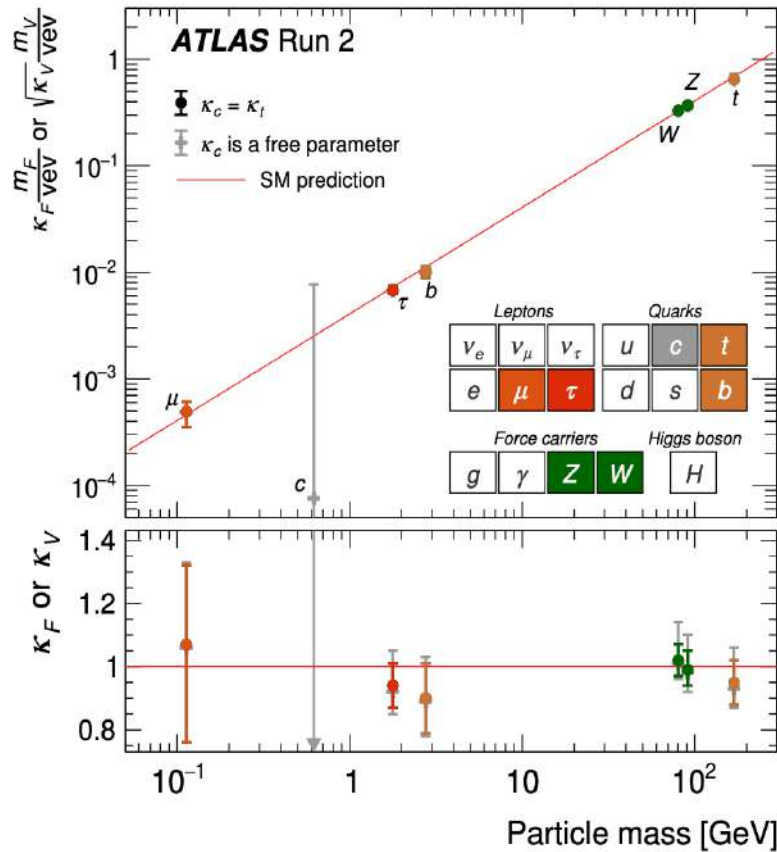
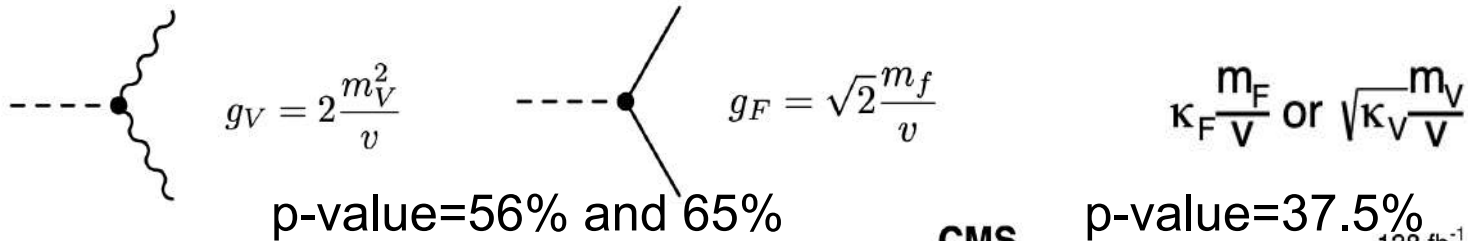
κ -framework fits

- ❑ Couplings modifiers per interaction vertex, left free in the combination of all production and decay modes
 - Including effective couplings for loop-mediated processes
- ❑ Also fit in a scenario in which invisible (SM+BSM) and undetected decays can contribute to the total width



Couplings vs mass

□ Cross check of the linear behaviour of the vector bosons and Yukawa couplings



Fiducial and differential cross sections

Cross sections

- ❑ Use the events selected, in a window around the mass peak, to measure the production cross sections
 - Another important check of consistency with SM predictions
- ❑ To be completely model independent, the “fiducial” cross section can be measured
 - Define the acceptance A as the fraction of signal events falling in the detector volume
 - This can be a model-dependent quantity
 - Efficiency C as the fraction of signal events within the acceptance, that are reconstructed and selected

$$A = \frac{N(\text{Fiducial})}{N(\text{Generated})} \quad C = \frac{N(\text{Reco})}{N(\text{Fiducial})} \quad \sigma_{\text{Tot}} \cdot BR = \frac{N_{\text{sig}}}{A \cdot C \cdot \mathcal{L}_{\text{int}}}$$

The fiducial cross section is simply given by:

$$\sigma_{\text{Fid}} \cdot BR = \frac{N_{\text{sig}}}{C \cdot \mathcal{L}_{\text{int}}}$$

Differential cross sections

$$\frac{d\sigma_{\text{fid},i}}{dx_i} = \frac{n_i^{\text{sig}}}{c_i \cdot \mathcal{L}_{\text{int}} \cdot \Delta x_i}$$

N_{sig} is calculated as the number of events in data, minus the number of expected events

$$c_i = \frac{N_i^{\text{reco}}}{N_i^{\text{fid}}}$$

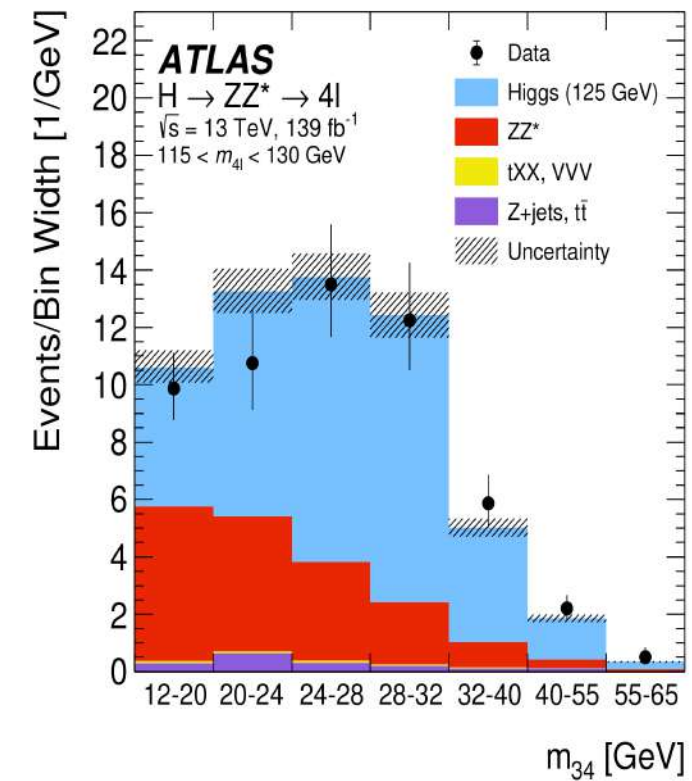
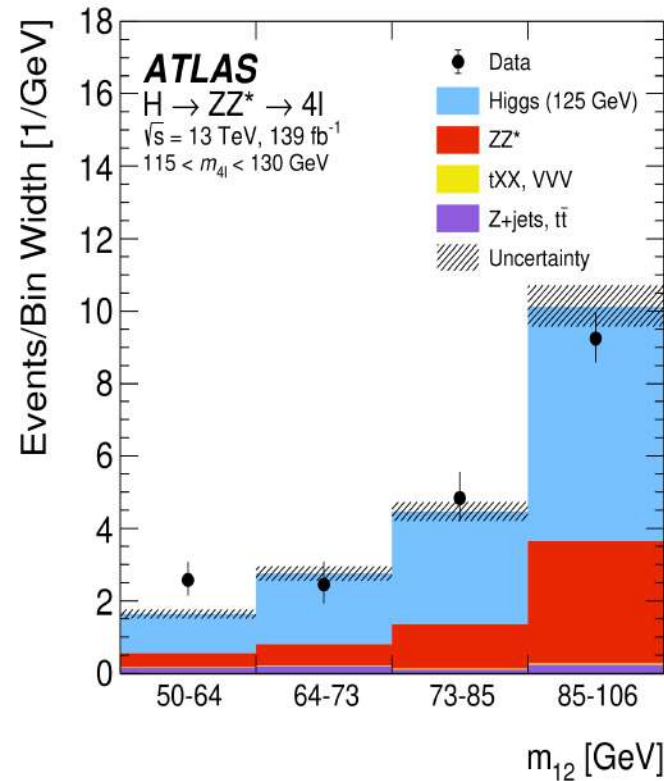
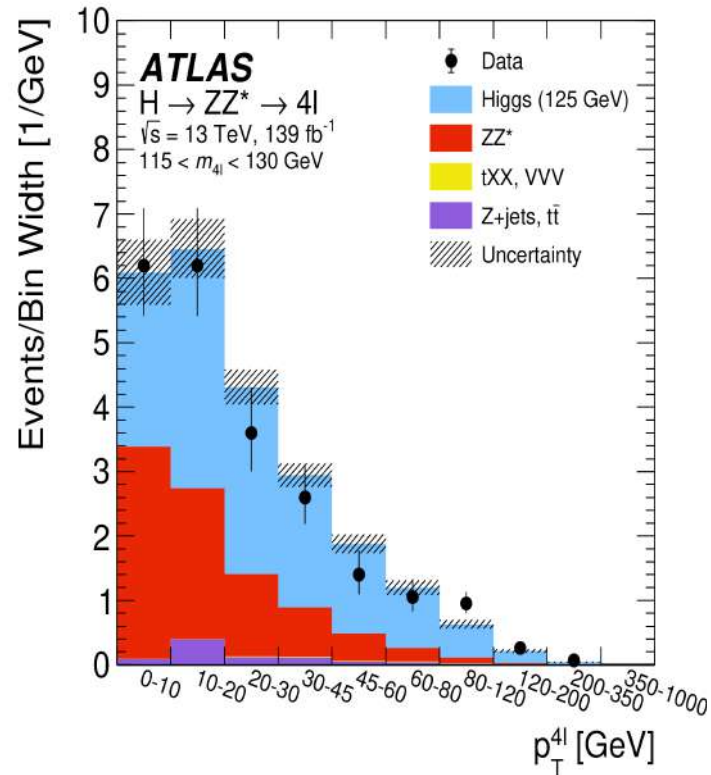
Correction factors calculated for each distribution bin

- ❑ In fact, the correction factors need to take into account the detector effects
- ❑ Typical variables for which the differential cross sections are calculated are those most sensitive to possible New Physics
 - p_T and rapidity of the Higgs
 - number of jets, and their transverse energy
 - for channels like $H \rightarrow ZZ^* \rightarrow 4l$, the invariant masses of the 2 lepton pairs

Differential cross sections in $H \rightarrow ZZ^* \rightarrow 4l$

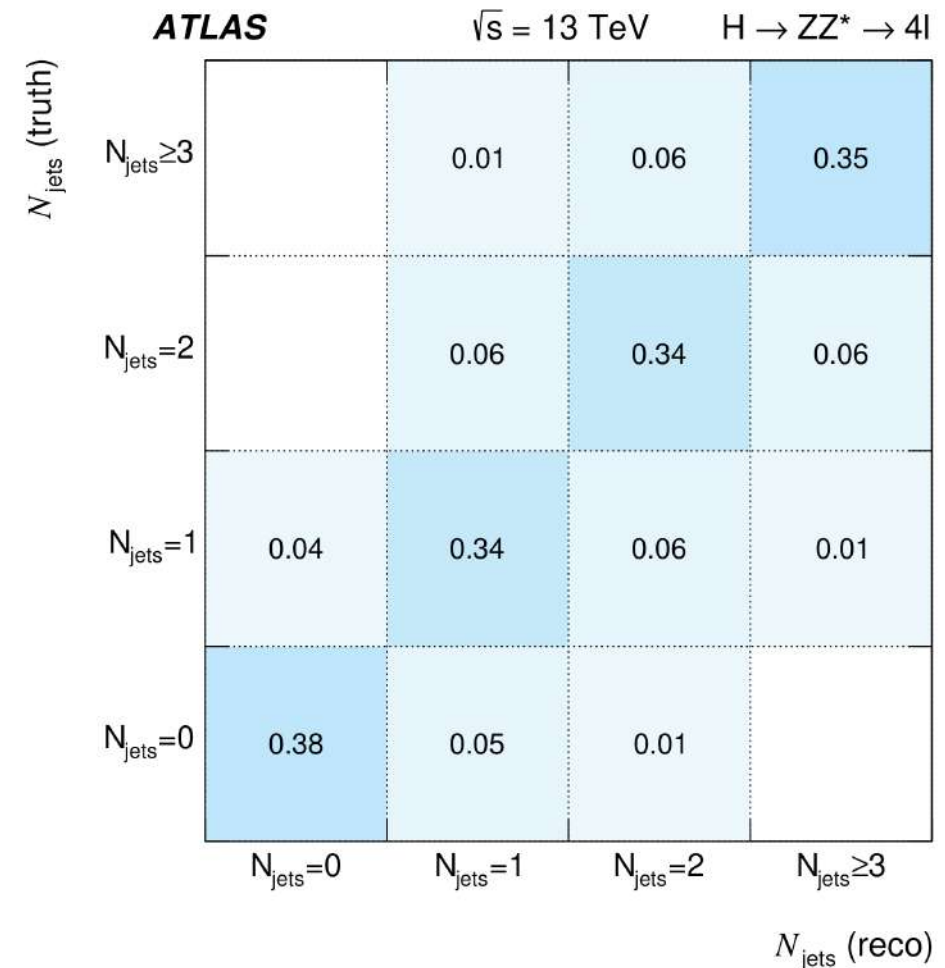
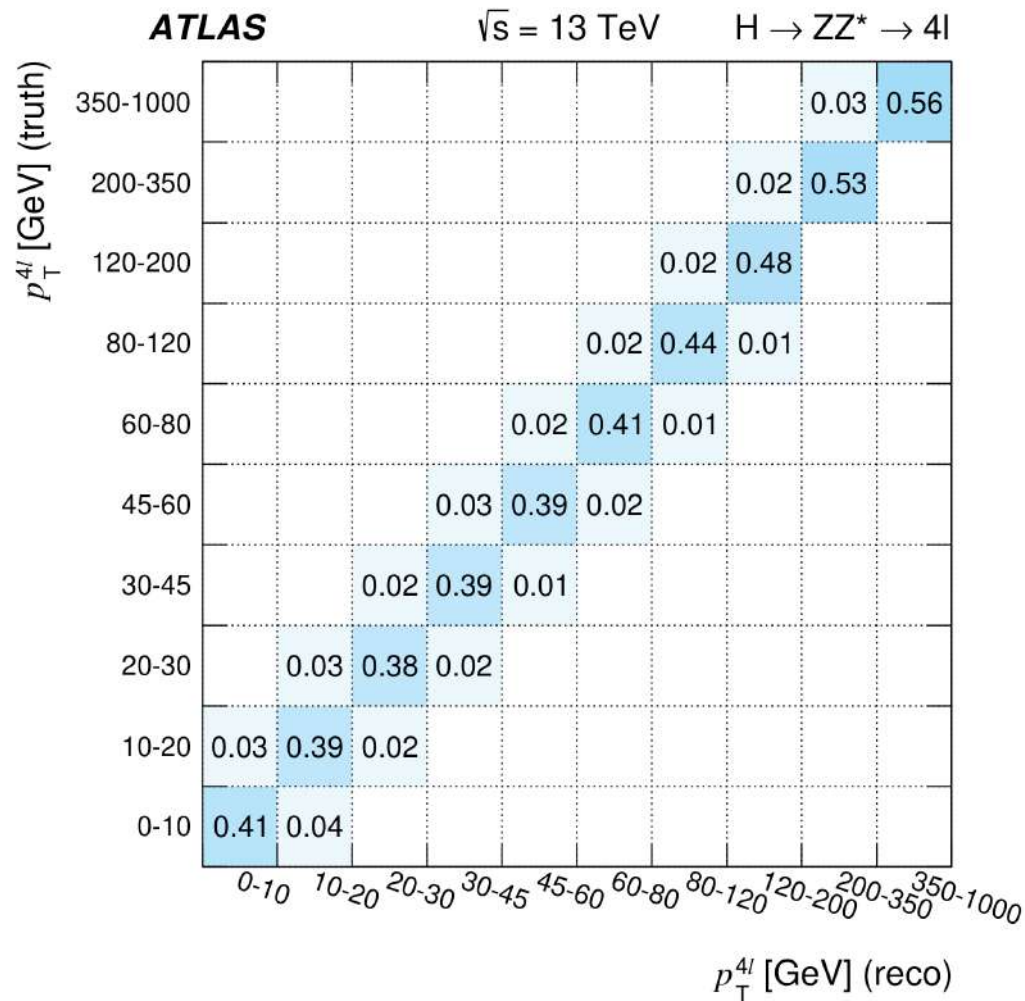
□ General method to extract the cross section:

- Consider the signal region (via e.g. a $4l$ mass window)
- Subtract the background, unfold to truth level quantities with bin-by-bin correction factors



Unfolding matrices

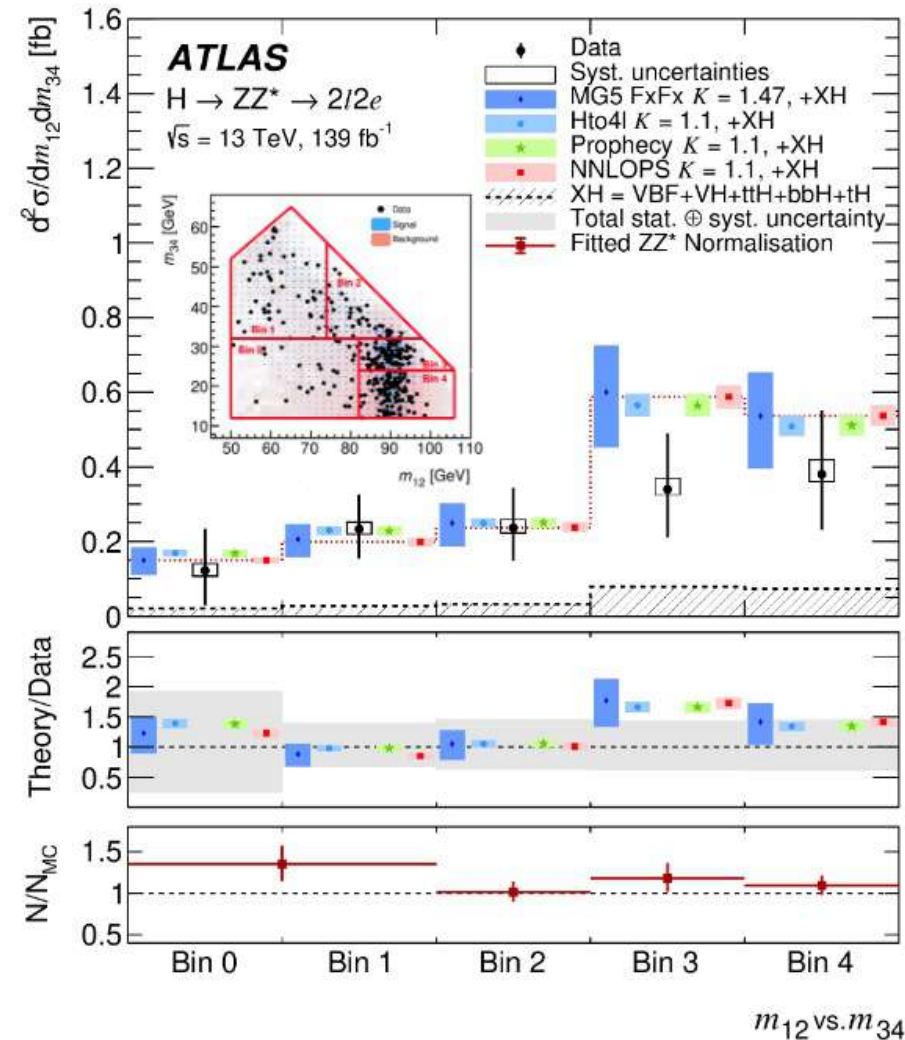
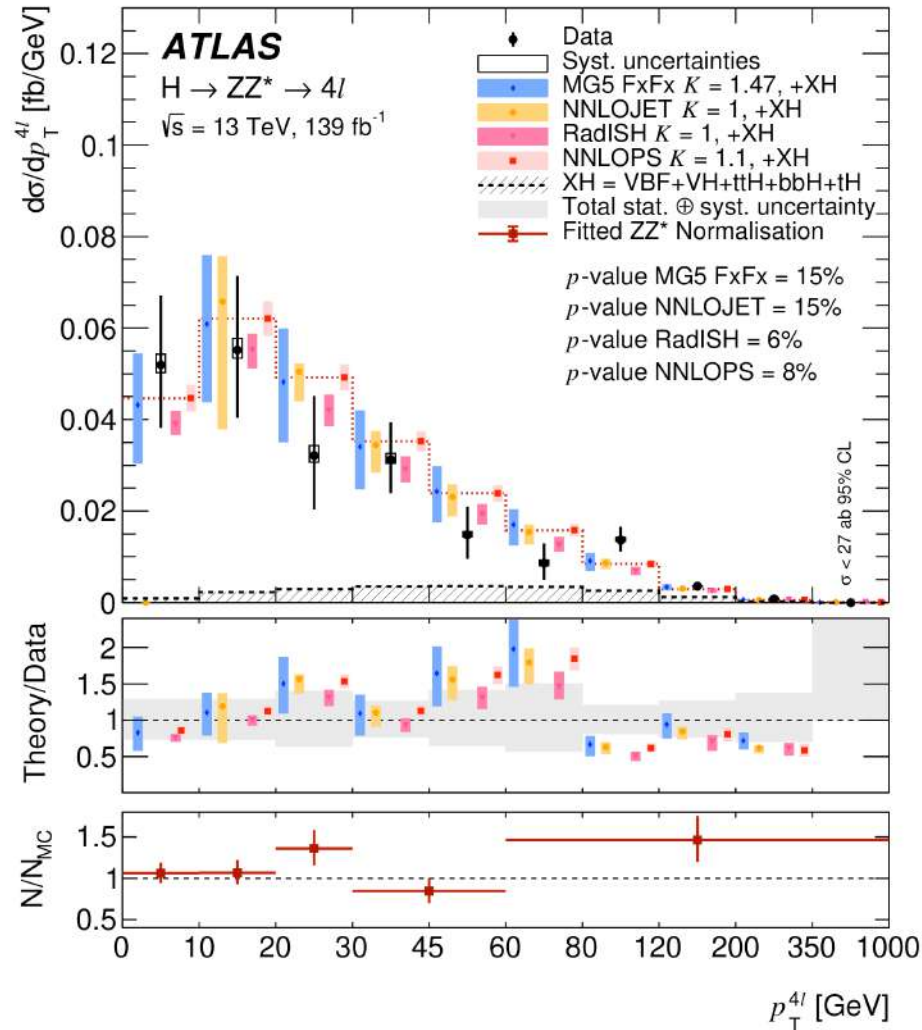
- Get (from simulation) the probability $P(\text{truth bin} | \text{reco bin})$ with the binning required for the differential measurement



Differential fiducial cross sections in 4l

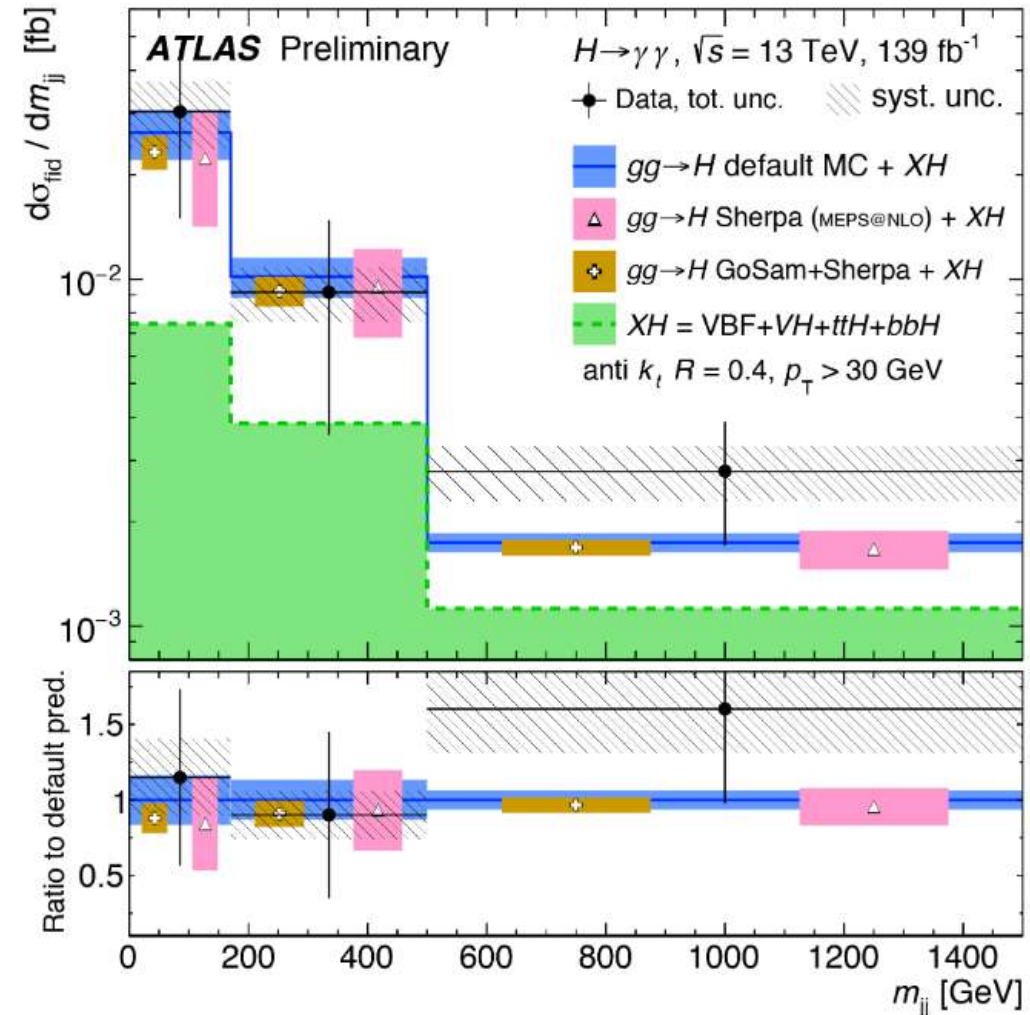
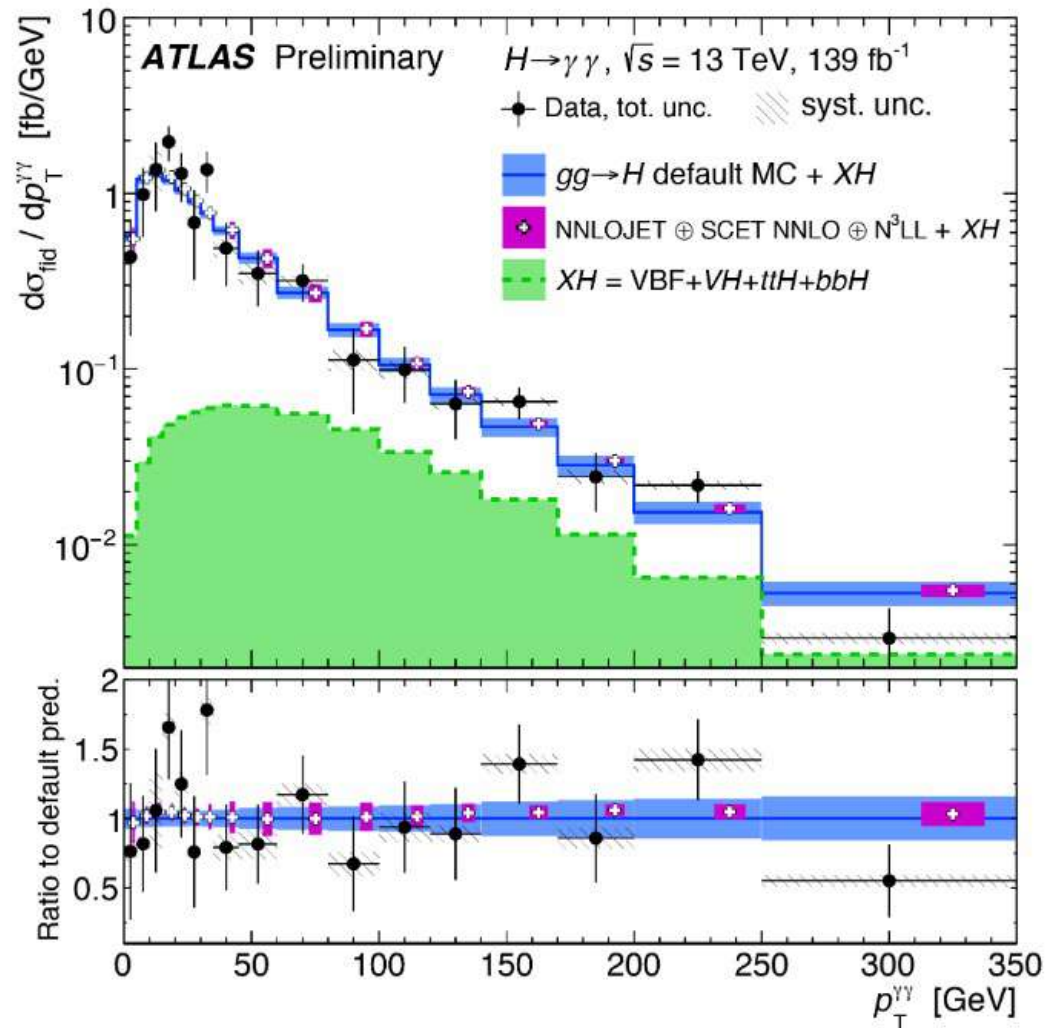
Eur. Phys. J. C 80 (2020) 942

- Some results and comparison to models / generators



Differential fiducial cross sections in $\gamma\gamma$

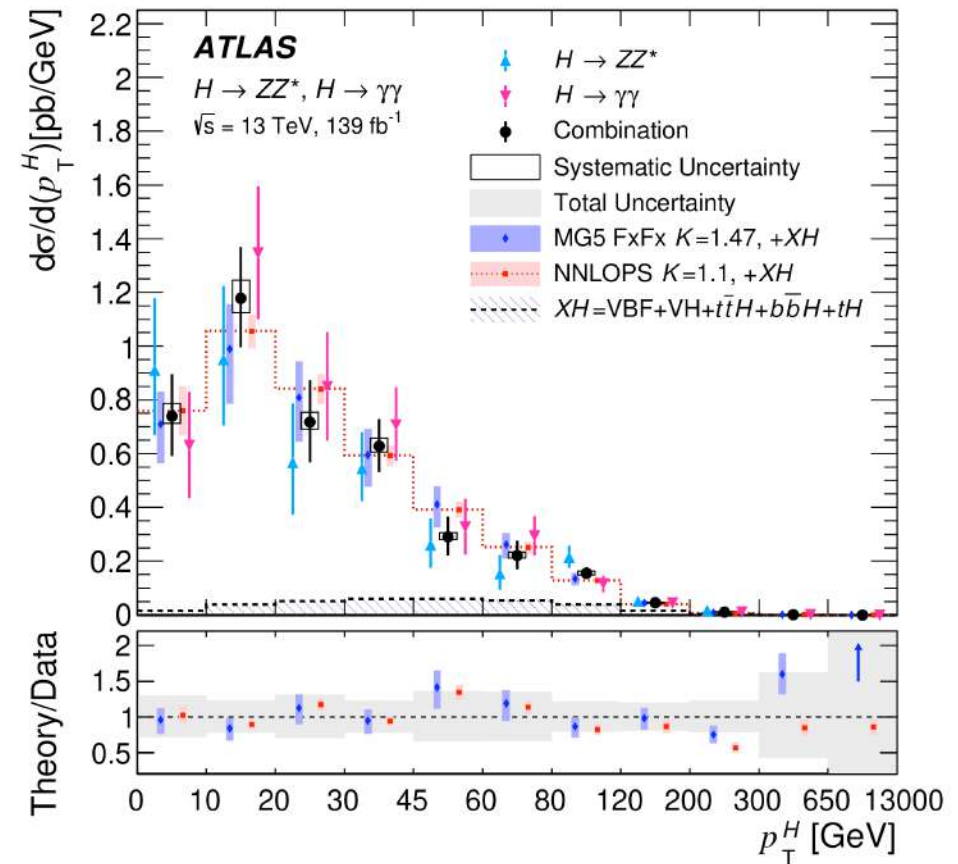
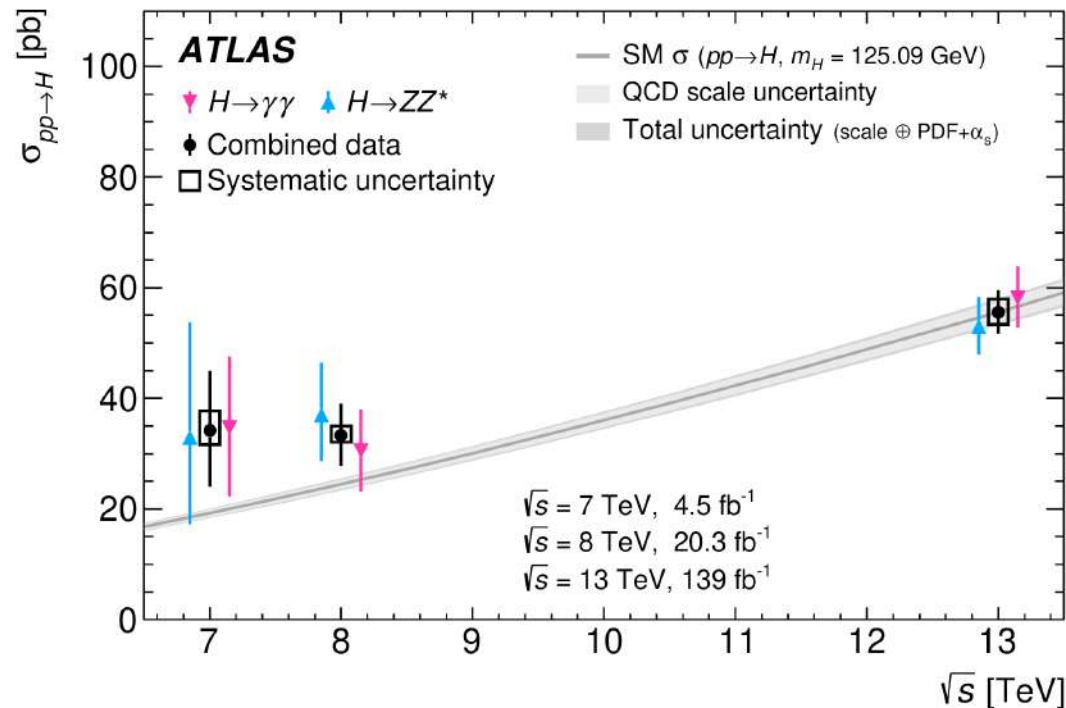
JHEP 08 (2022) 027



Combination of 4l and $\gamma\gamma$

arXiv:2207.08615

- Total and differential cross sections
- Typical variables that can be combined are the Higgs p_T and rapidity
 - Sensitive to possible new physics contributions



Effective field theory

- Effective Field Theory (EFT) is a tool to study possible effects beyond the SM, whose direct observation, for example via a new resonance, would be possible only at scales higher than those actually reachable

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \dots$$

- Limiting to O(6) operators, a given matrix element can be expressed as:

$$\mathcal{M}_{\text{SMEFT}} = \left| \mathcal{M}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{M}_i \right|^2$$

$$\begin{aligned} \sigma \propto |\mathcal{M}_{\text{SMEFT}}|^2 &= \left| \mathcal{M}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{M}_i \right|^2 \\ &= |\mathcal{M}_{\text{SM}}|^2 + \sum_i 2\text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_i) \frac{c_i}{\Lambda^2} \\ &\quad + \sum_{ij} 2\text{Re}(\mathcal{M}_i^* \mathcal{M}_j) \frac{c_i c_j}{\Lambda^4}, \end{aligned}$$



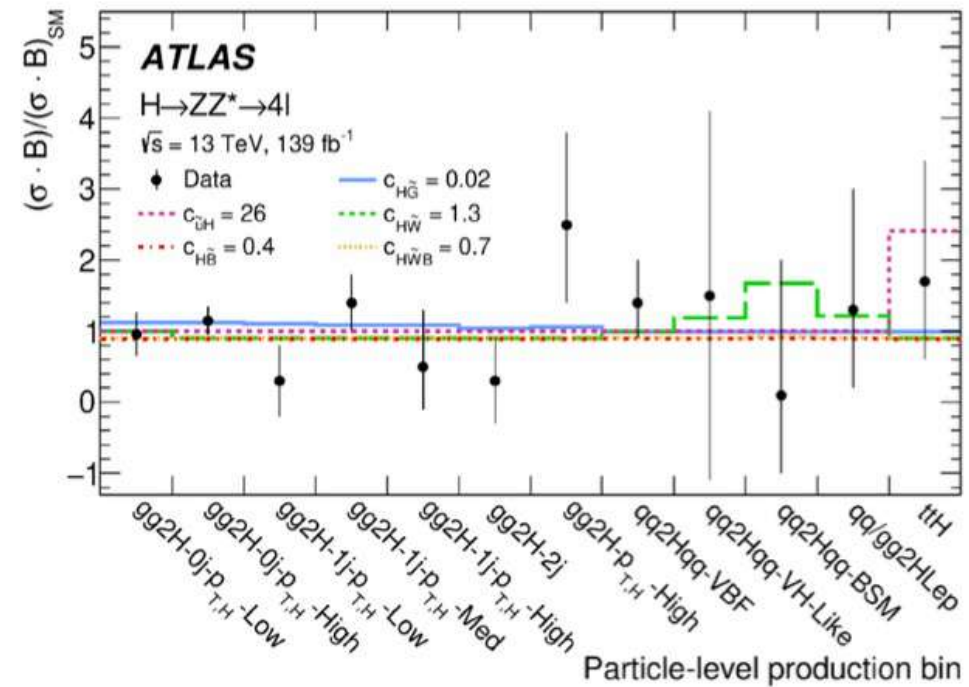
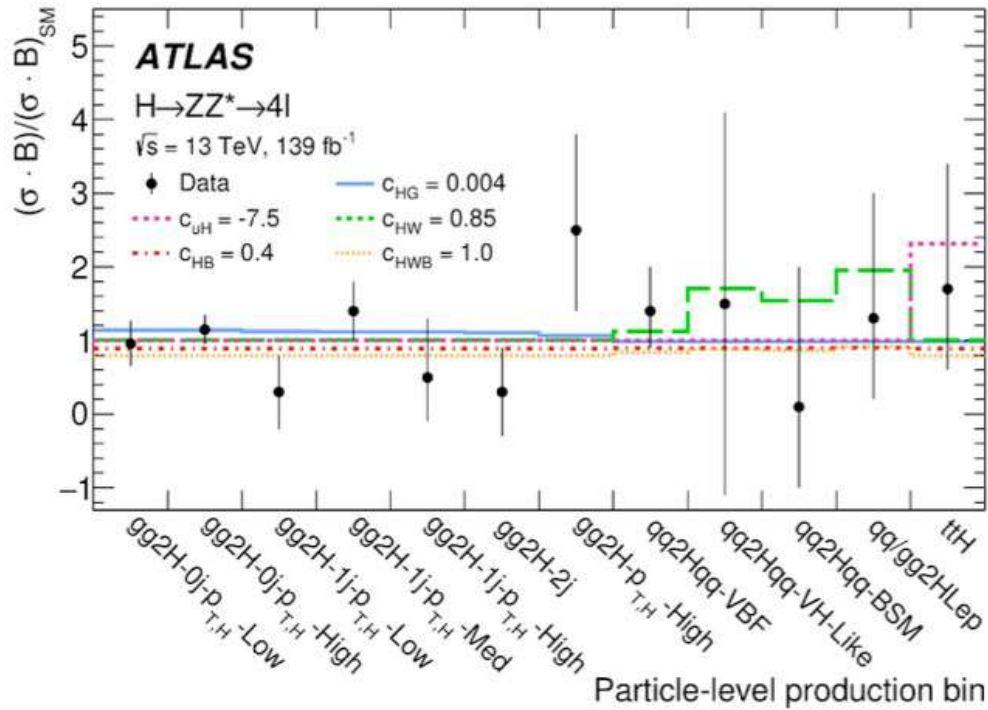
$$\frac{\sigma^P(\vec{c})}{\sigma_{\text{SM}}^P} = 1 + \sum_i A_i^P c_i + \sum_{ij} B_{ij}^P c_i c_j,$$

Interference terms can contain CP-even Beyond Standard Model contributions, while CP-odd can only be BSM

EFT couplings fit in $H \rightarrow ZZ^* \rightarrow 4l$

Each production mode is more sensitive to a different set of couplings

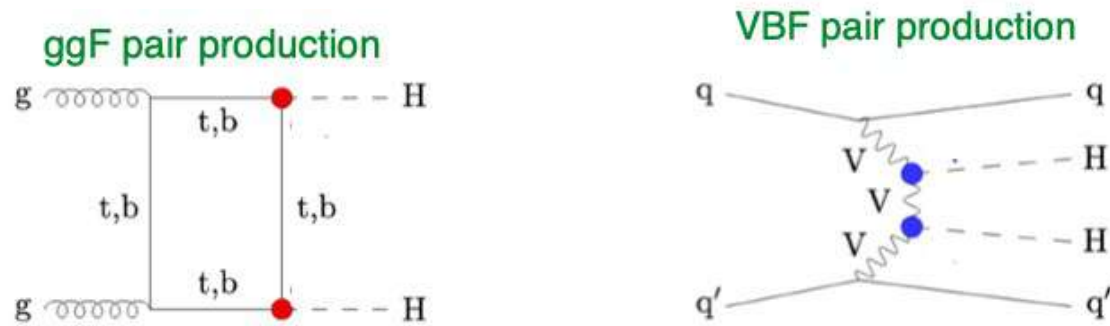
CP-even			CP-odd			Impact on	
Operator	Structure	Coeff.	Operator	Structure	Coeff.	production	decay
O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	c_{uH}	$O_{\bar{u}H}$	$HH^\dagger \bar{q}_p u_r \tilde{H}$	$c_{\bar{u}H}$	$t\bar{t}H$	-
O_{HG}	$HH^\dagger G_{\mu\nu}^A G^{\mu\nu A}$	c_{HG}	$O_{H\bar{G}}$	$HH^\dagger \tilde{G}_{\mu\nu}^A G^{\mu\nu A}$	$c_{H\bar{G}}$	ggF	Yes
O_{HW}	$HH^\dagger W_{\mu\nu}^I W^{\mu\nu I}$	c_{HW}	$O_{H\bar{W}}$	$HH^\dagger \tilde{W}_{\mu\nu}^I W^{\mu\nu I}$	$c_{H\bar{W}}$	VBF, VH	Yes
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\bar{B}}$	$HH^\dagger \tilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\bar{B}}$	VBF, VH	Yes
O_{HWB}	$HH^\dagger \tau^I W_{\mu\nu}^I B^{\mu\nu}$	c_{HWB}	$O_{H\bar{W}B}$	$HH^\dagger \tau^I \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$c_{H\bar{W}B}$	VBF, VH	Yes



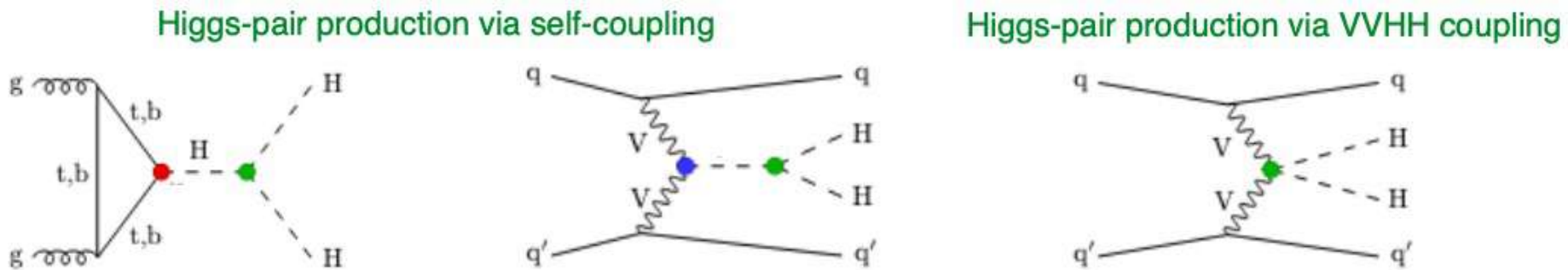
Double Higgs production

Double Higgs production

□ Double Higgs production can happen via ggF and VBF, with fermion and vector boson couplings:



□ Or, via Higgs self-coupling and VVHH quartic coupling:



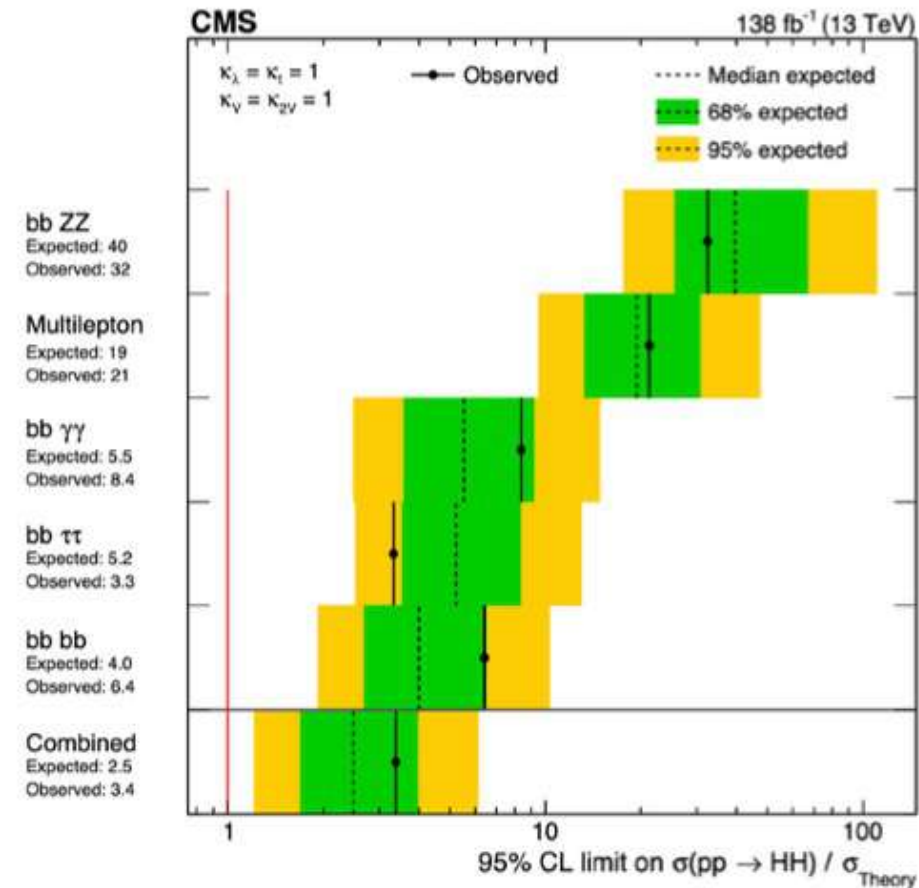
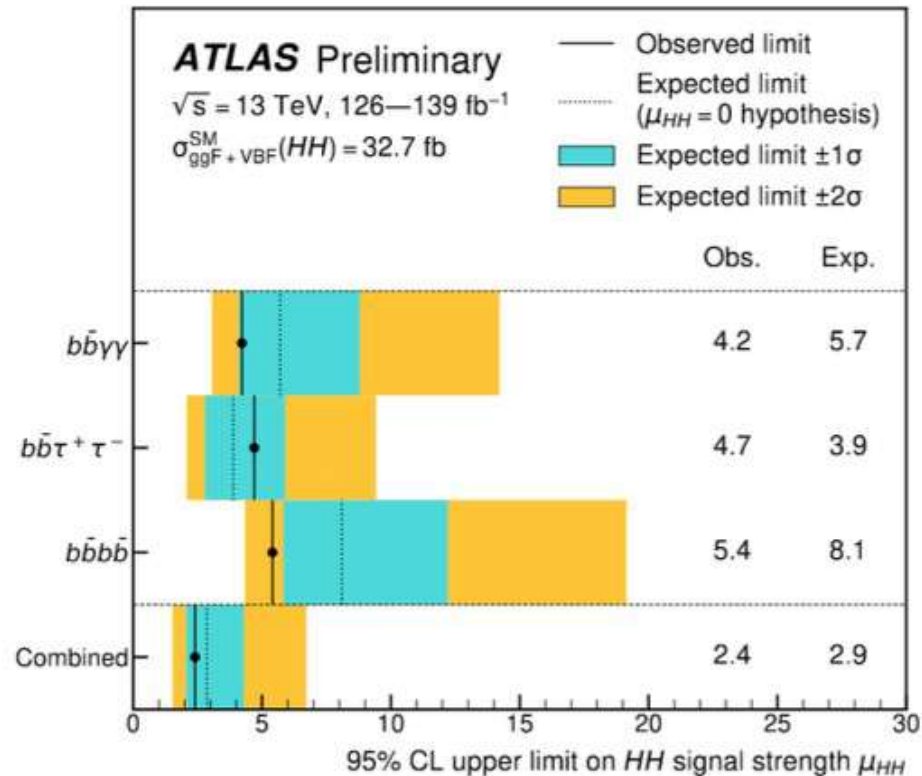
□ But, the total cross section is three orders of magnitude smaller than the one for the single Higgs

Di-Higgs analyses

- Given the very small cross section, in this case one has to rely on the highest-BR channels
- Main analyses are $bb+(bb, \tau\tau, \gamma\gamma)$, although also multi-lepton and ZZ are considered
- Current observed (expected) limits on the HH signal strength are:

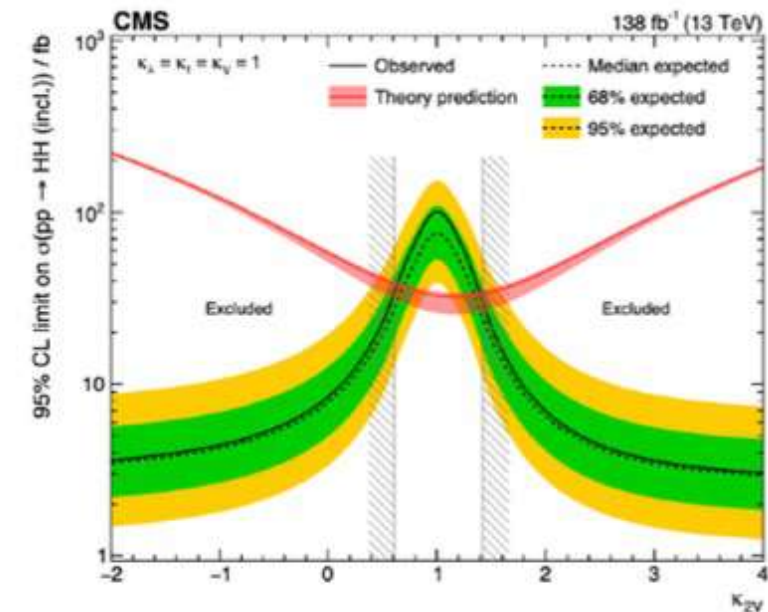
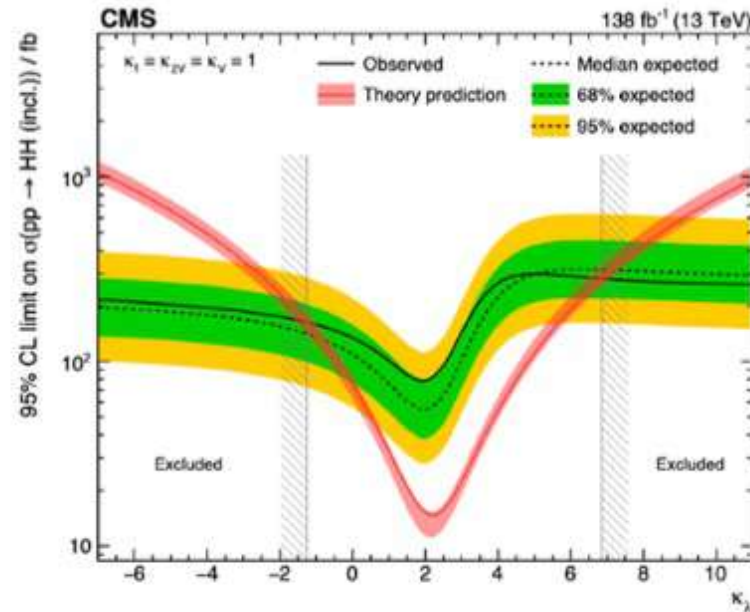
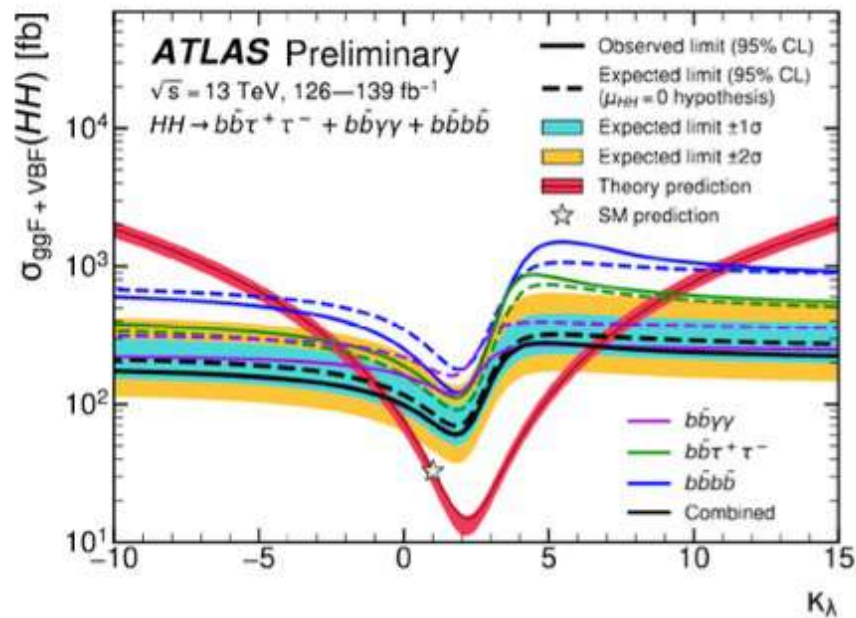
ATLAS-CONF-2022-050
Nature 607 (2022) 60-68

- CMS: $\mu_{HH} < 3.4$ (2.5)
- ATLAS: $\mu_{HH} < 2.4$ (2.9)

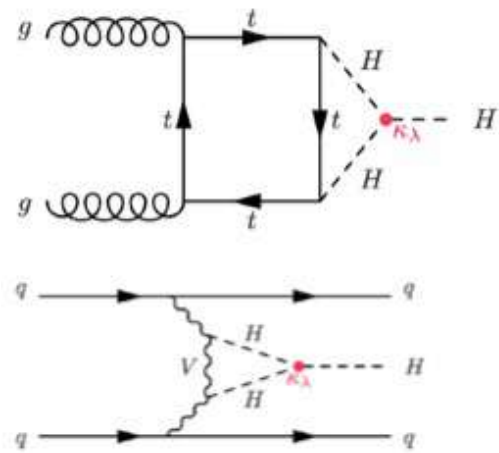


Self and quartic couplings modifiers

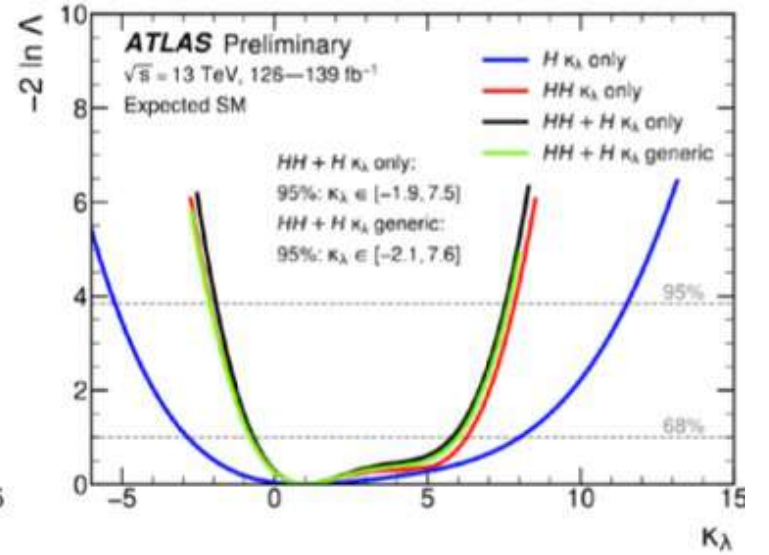
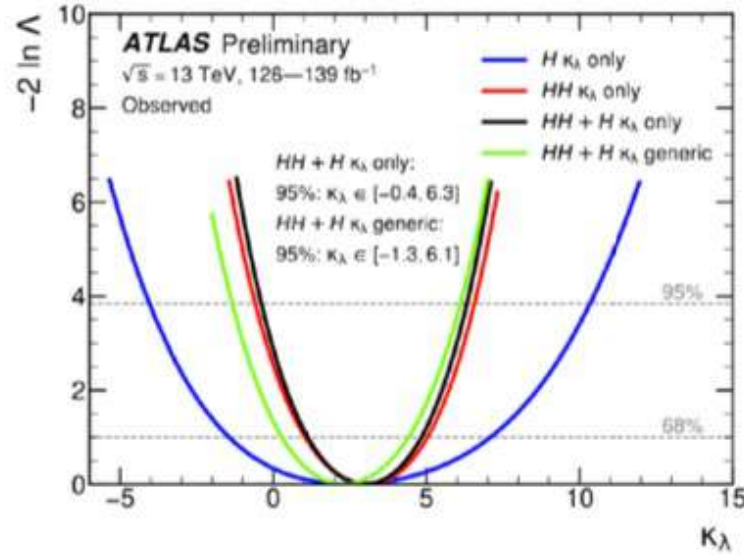
- ❑ Limits on the signal strengths can be used to derive limits on coupling modifiers κ_λ κ_{2V} , applied to the HHH and VVHH vertices respectively
- ❑ The cross-section dependency on the modifiers comes from interference
- ❑ $\kappa_{2V}=0$ excluded by CMS with 6.6σ significance



Self and quartic couplings modifiers

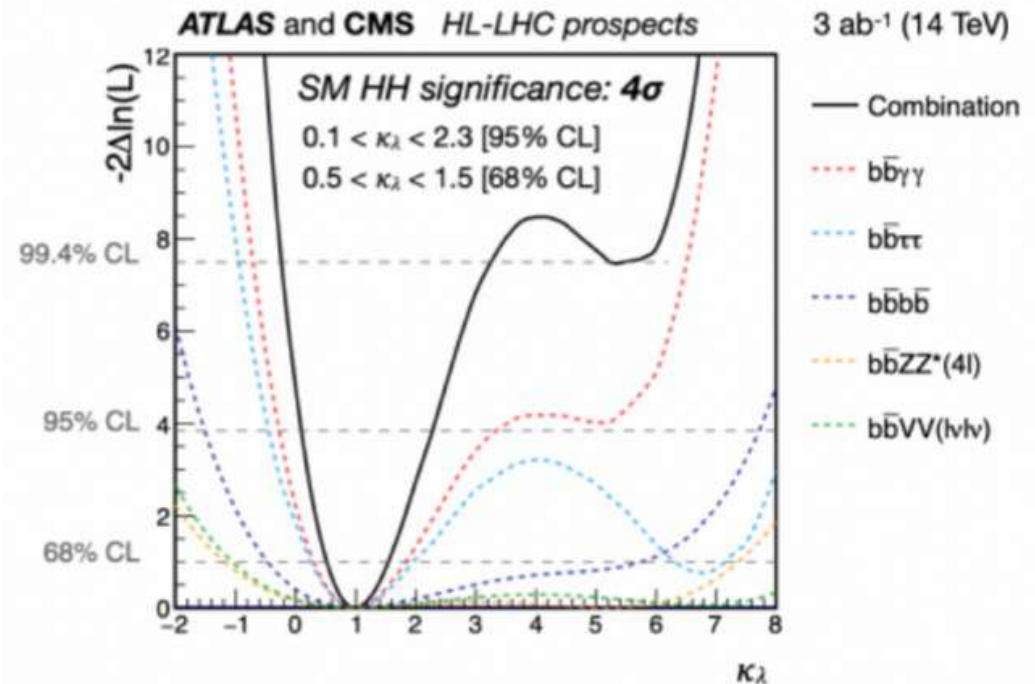
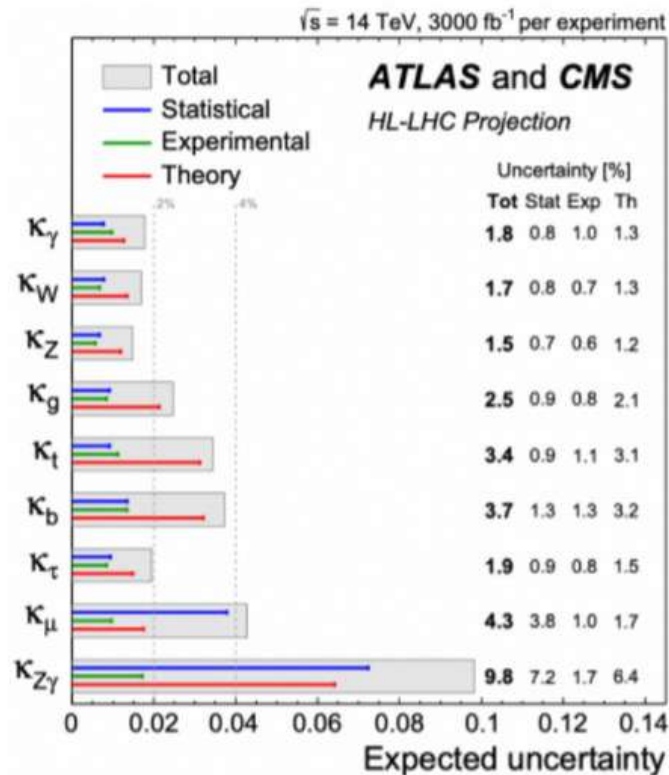


One-loop single Higgs production depending on κ_λ , included in the ATLAS combination



Conclusions

- ❑ Run-3 has just started, providing new data at 13.6 TeV with upgraded detectors
 - Plan is reach $\sim 300 \text{ fb}^{-1}$
- ❑ A lot of new results on Higgs properties measurements will be based on these new data
- ❑ Hi-Lumi LHC with phase-2 upgraded detectors and further improved theoretical calculations will bring even more the Higgs measurements in the era of the precision measurements



What you can mostly focus on

- Higgs production mechanisms and their main characteristics
- Higgs decays and their main characteristics and signatures
- Main discovery channels
 - Experimental signatures and main backgrounds
- Exclusion and discovery significance (only in the case of a simple counting experiment)
- Higgs mass and width
- Methods to extract information on the Higgs couplings and look for possible deviations from the Standard Model (you don't have to know the results in detail, just understand the methods)
 - Signal strengths
 - κ -factor method
 - Fiducial and differential cross sections
- Double Higgs production

- In case of questions just pass by the office 229



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End of chapter 12