Higgs width at LHC and ILC

Luigi Marchese, Oxford university
on behalf of the ATLAS and CMS collaborations

Higgs Hunting 2018
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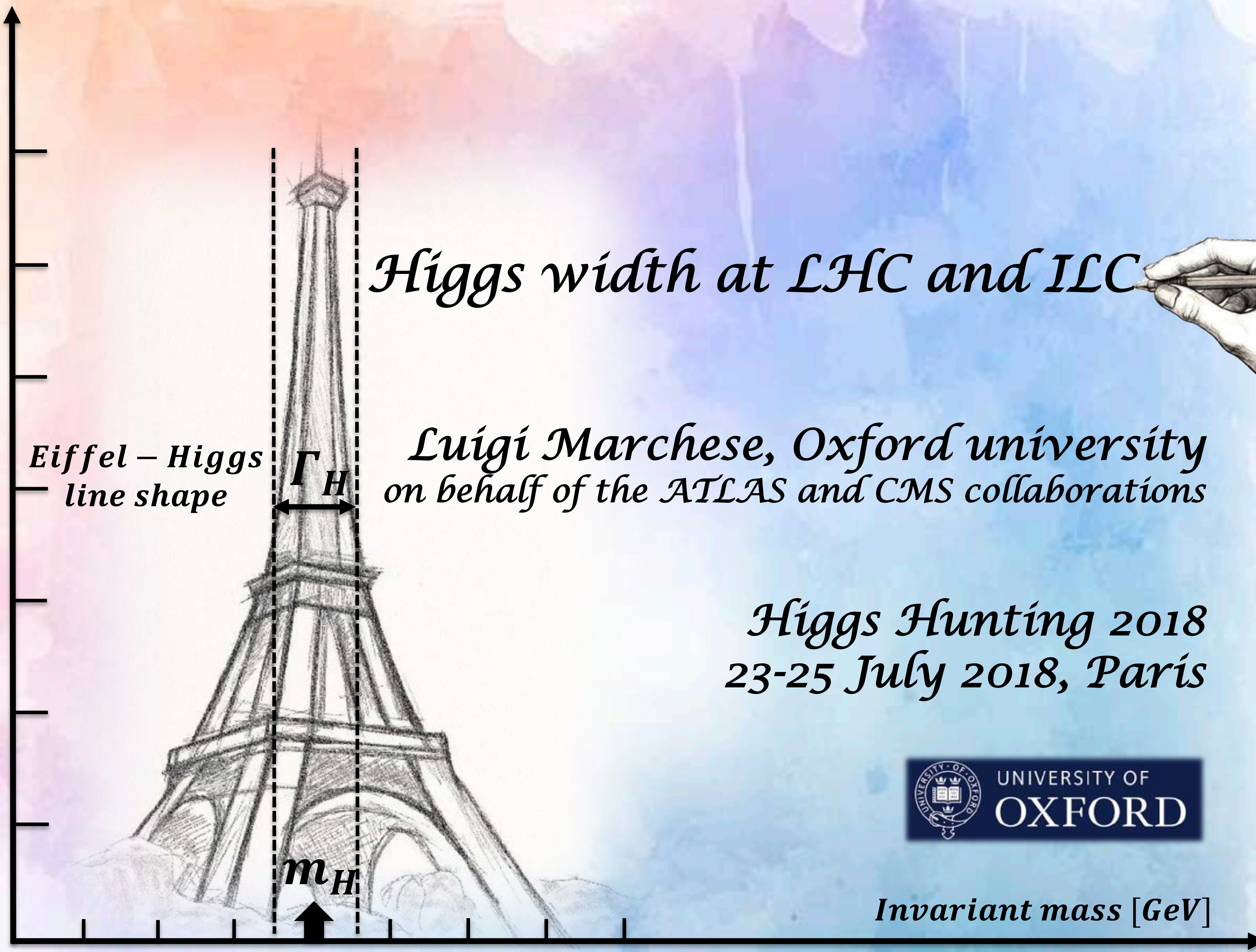

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Introduction

- Motivation
- Higgs width at LHC
  - Overview of strategies
  - Off-shell strategy
  - Results in Run 2
- Higgs width at ILC
- Conclusions

Motivation

- We have just recently celebrated the 6th Higgs birthday
- Since 2012, many Higgs properties have been measured (couplings, cross section …)
- The Higgs width is still a challenging measurement
- Several strategies have been proposed in the past years

"La nuit étoilée" by Van Gogh ,
idealized view of
Saint Remy de Provence
(southern France) – *MOMA museum*

Higgs width at LHC

Overview of strategies

- On the contrary of LEP or ILC, at LHC only $\sigma \cdot BR$ can be measured
  - $\boxed{\text{The measurement of } \Gamma_H \text{ is extremely hard at LHC}}$
  - Γ_H cannot be inferred from measurements of Higgs boson rates

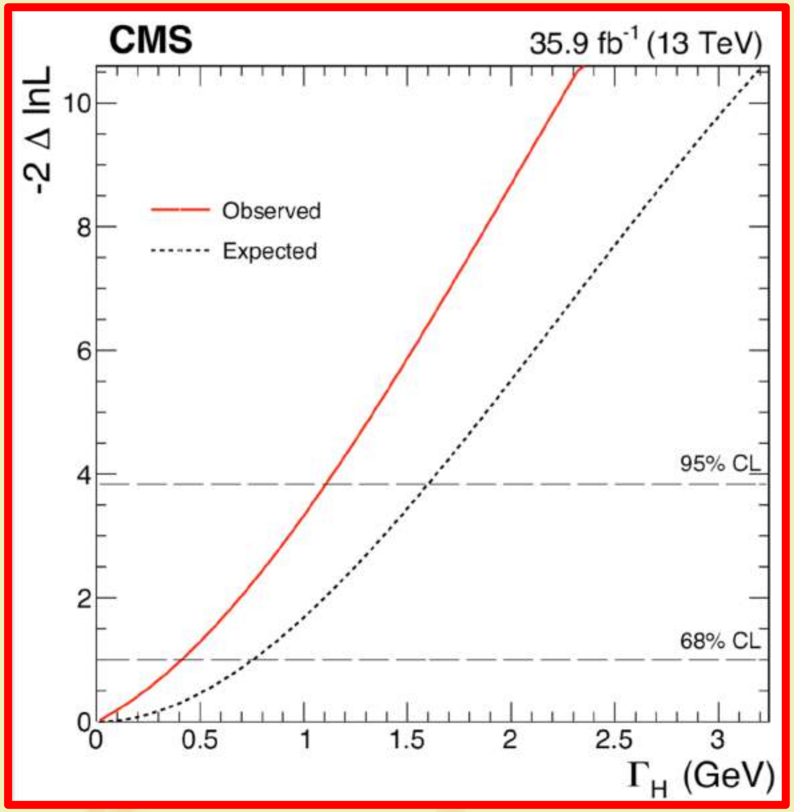
- **Direct** and indirect **strategies** have been considered
  - From the on-shell mass peak
  - From the lifetime

Direct strategies

From the on-shell mass peak

- Convolution of natural width ($4.1\ MeV$) and experimental mass resolution ($\sim 1.5\ GeV$)
- Excellent mass resolution is required: $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$

Channel	Obs (Exp) [GeV] at 95% CL
ATLAS $\gamma\gamma$	5.0(6.2)
ATLAS 4l	2.6(6.2)
CMS 4l	1.1(1.6)



- $\sim 270\ (CMS) \sim 630\ (ATLAS)$ **times larger than the SM value**

Direct strategies

From the on-shell mass peak

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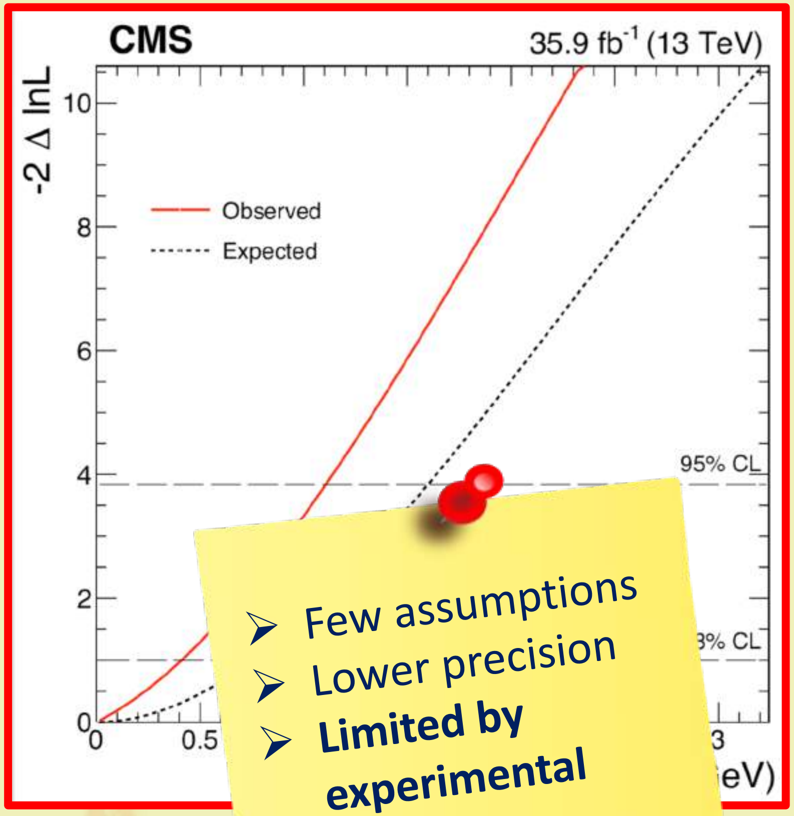
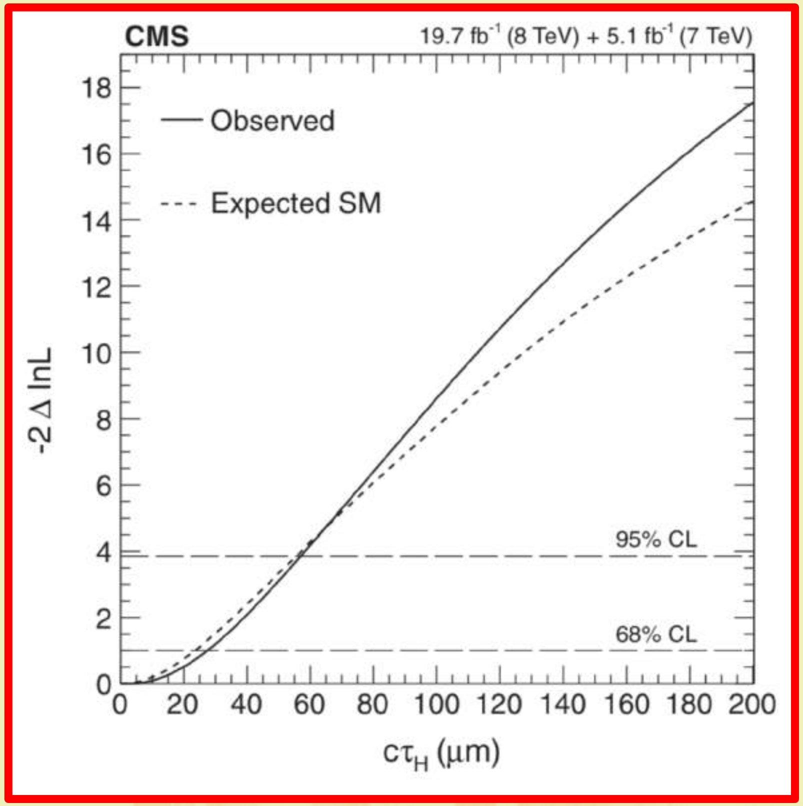


- Few assumptions
- Lower precision
- **Limited by experimental resolution**

- **$\sim 270\ (CMS) \sim 630\ (ATLAS)$ times larger than the SM value**

Direct strategies

From the lifetime



- Using the Higgs lifetime we can set a direct lower bound
- $\Gamma_H = \hbar \cdot \tau_H \; with \; c\tau_H = 48 \text{ fm}$
  - Far away from the exper. sensitivity of $\sim 10 \; \mu m$
- $H \rightarrow 4l$ ideal channel to extract the lifetime using the **flight distance**
  - **Displacement between the production and decay vertices**

$CMS\ Run1:\ c\tau_H < 57 \text{ μm} \rightarrow \boldsymbol{\Gamma_H > 3.5 \cdot 10^{-3} eV \; at \; 95\% \; CL}$

Indirect strategies

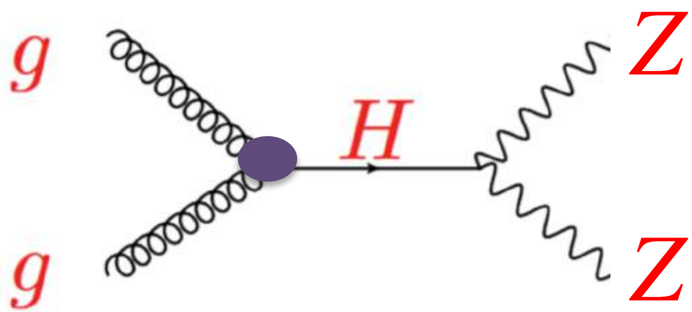
- On the contrary of LEP or ILC, at LHC only $\sigma \cdot BR$ can be measured
  - The measurement of Γ_H is extremely hard at LHC
  - Γ_H cannot be inferred from measurements of Higgs boson rates
- Direct and **indirect strategies** have been considered
  - From the on-shell mass peak
  - From the lifetime
  - From couplings – recent CMS contribution, see back-up
  - From off-shell to on-shell production
    Best proxy to-date!

ATLAS: D. Rebuzzi's talk
CMS: Thomas Klijnsma's talk

On-shell Higgs production

- Constraints on the total Higgs boson width, Γ_H, can be determined using the relative on-shell and off-shell production

- Let's consider the ggF production mode with $H \rightarrow ZZ$



Production cross section

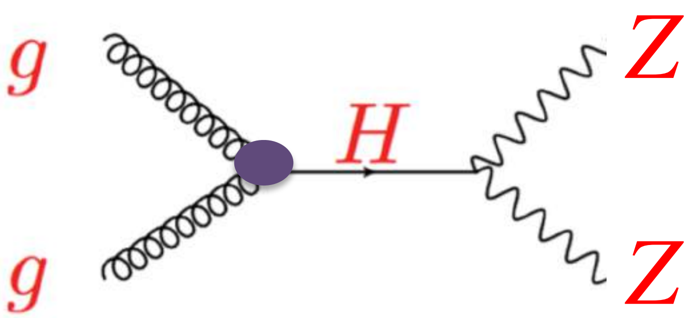
$$\boxed{\frac{d\sigma_{gg\rightarrow H\rightarrow ZZ}}{dm_{ZZ}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}}$$

- On-shell production $\frac{d\sigma_{gg\rightarrow H\rightarrow ZZ^*}^{on-shell}}{dm_{ZZ}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{m_H \Gamma_H}$

- **No way to measure the Higgs couplings and width separately**

Off-shell Higgs production

- Why off-shell production?



Production cross section

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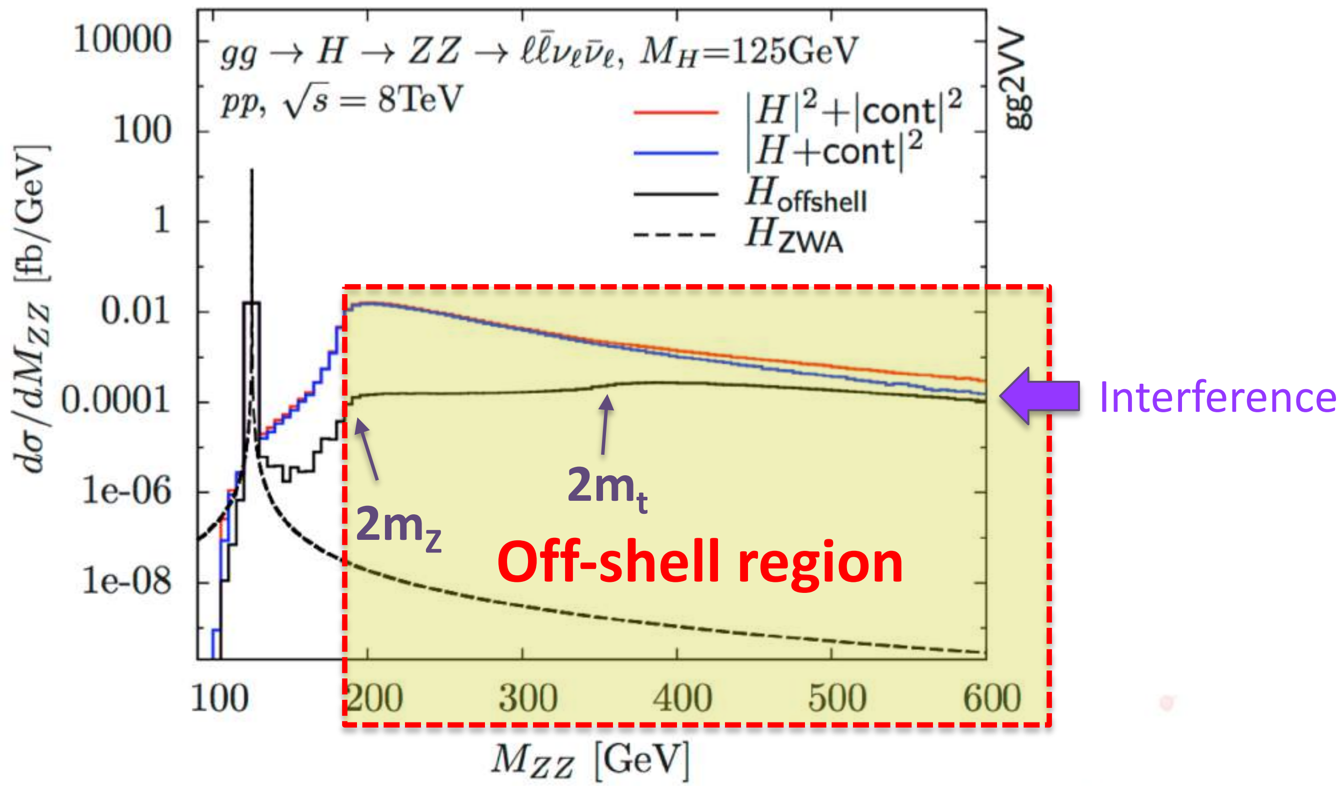
- Off-shell production (for $m_{ZZ} > 2m_Z$) $\frac{d\sigma_{gg\to H^*\to ZZ}^{off-shell}}{dm_{ZZ}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(2m_Z)^2}$

- ***Width-independent: width-couplings ambiguity resolved***

- Unfortunately, the off-shell contribution is expected to be extremely small …

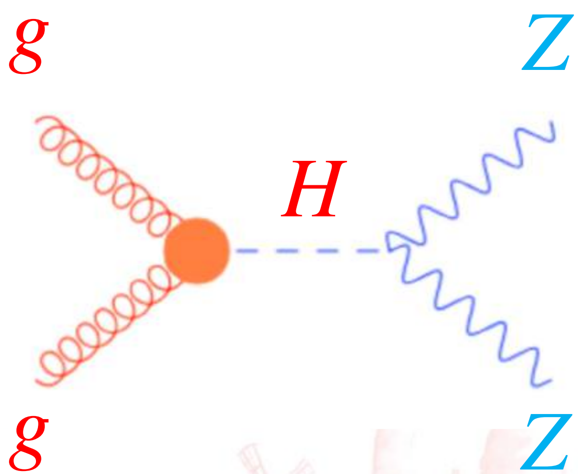
Once upon a paper …

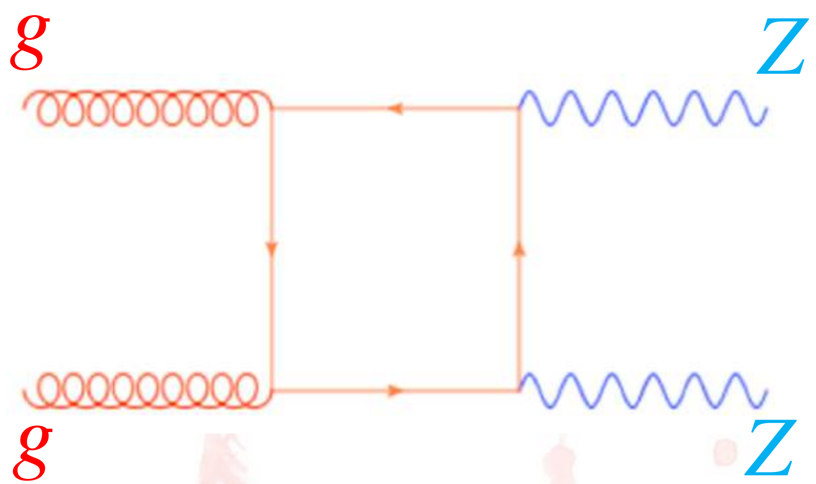


- In 2013 Kauer and Passarino pointed out that a significant enhancement in the off-shell production exists with two jumps
  - at the $ZZ - threshold$
  - at the $\bar{t}t - threshold$

Interference

- Production of two Z bosons in fusion of two gluons can occur either directly or through the Higgs bosons
- The two amplitudes interfere destructively in the SM
- The same considerations apply to the WW final state





$$|\mathcal{M}_{ZZ}|^2 = \left|\mathcal{M}_H + \mathcal{M}_{Bkg}\right|^2 = |\mathcal{M}_H|^2 + \left|\mathcal{M}_{Bkg}\right|^2 + 2Re(\mathcal{M}_H\mathcal{M}_{Bkg}^*)$$

Analysis idea

- Using the relative on-shell and off-shell production, we can indirectly constrain the Higgs boson total width

$$\mu^{ggF}_{off-shell} = \frac{\sigma^{ggF}_{off-shell}}{\sigma^{ggF}_{off-shell,SM}} = k^2_{g,off-shell} \cdot k^2_{V,off-shell}$$

$$\mu^{ggF}_{on-shell} = \frac{\sigma^{ggF}_{on-shell}}{\sigma^{ggF}_{on-shell,SM}} = \frac{k^2_{g,on-shell} \cdot k^2_{V,on-shell}}{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

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

From an independent analysis

- **This strategy is assuming identical on-shell and off-shell couplings**
  - **No new physics alters the Higgs couplings in the off-shell regime**

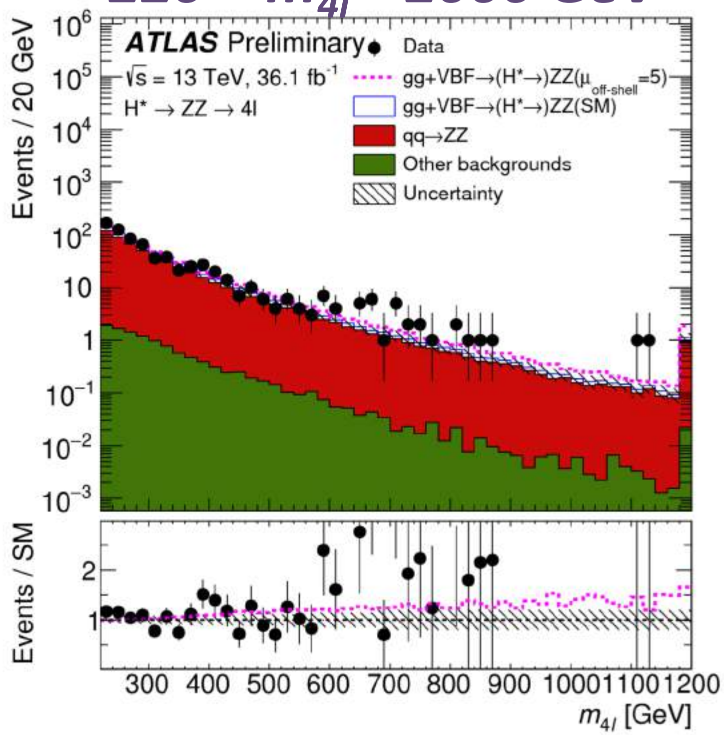
Analysis strategy

- Two decay channels[++], $H^* \to ZZ \to 4l$ and $H^* \to ZZ \to 2l2v$
- CMS: dedicated gluon-gluon fusion (ggF) and Vector-boson fusion (VBF) categories, ATLAS: analysis performed inclusively, ggF+VBF

NEW

ATLAS 4l invariant mass

$220 < m_{4l} < 2000$ GeV



Theoretical correction

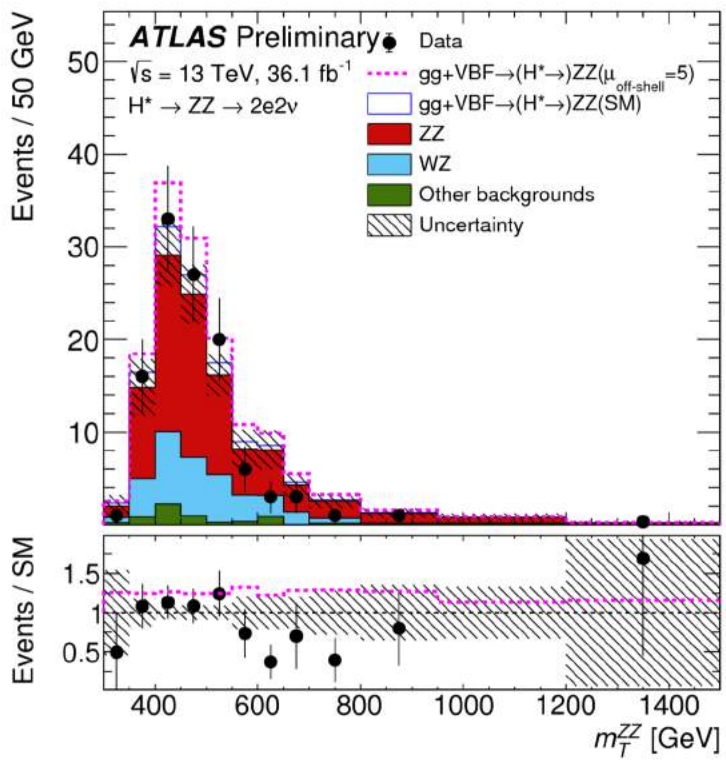
- [NLO corrections](#) finally available for Interference and background for $gg \to (H^*) \to ZZ$ as a function of m(ZZ)
- Significant improvement compared to Run 1 results

[++] Run 1 results included $H^* \to WW \to lvlv$

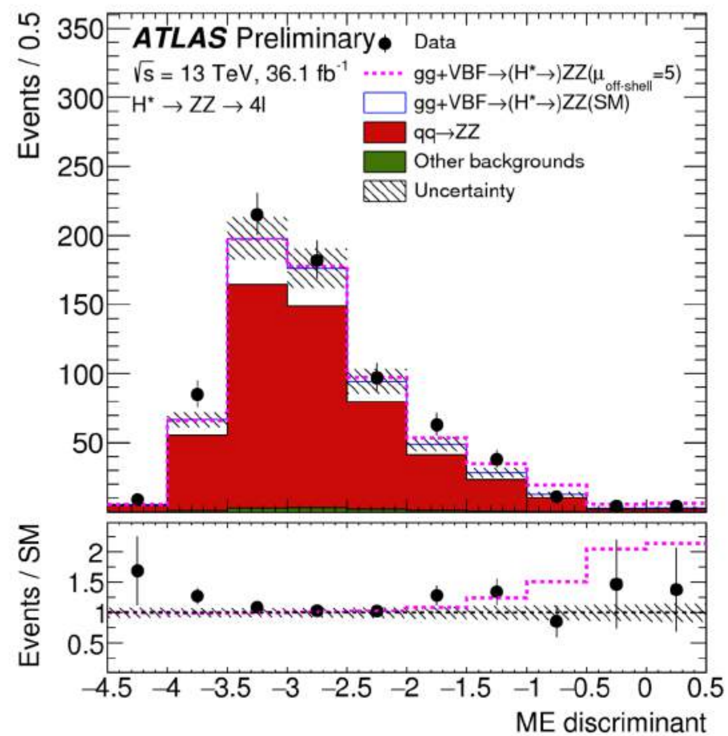
Discriminants

- Maximum likelihood fit to the Matrix-Element (ME) based discriminant distribution (4l) and the transverse-mass, $m_T(ZZ)$, distribution (2l2v)

2e2v discriminant

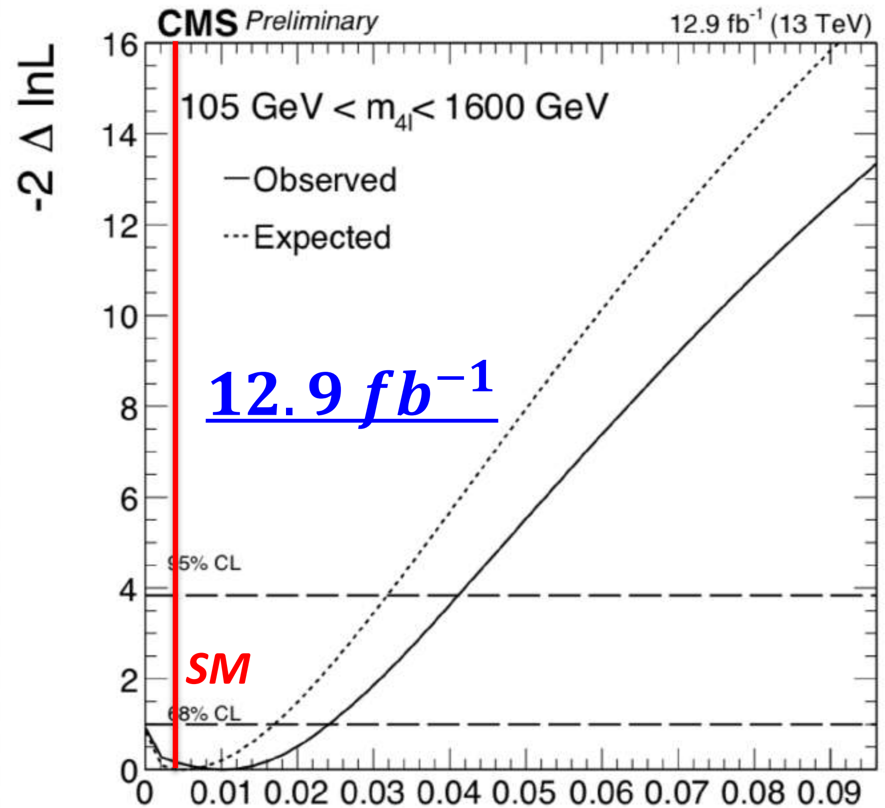


4l discriminant



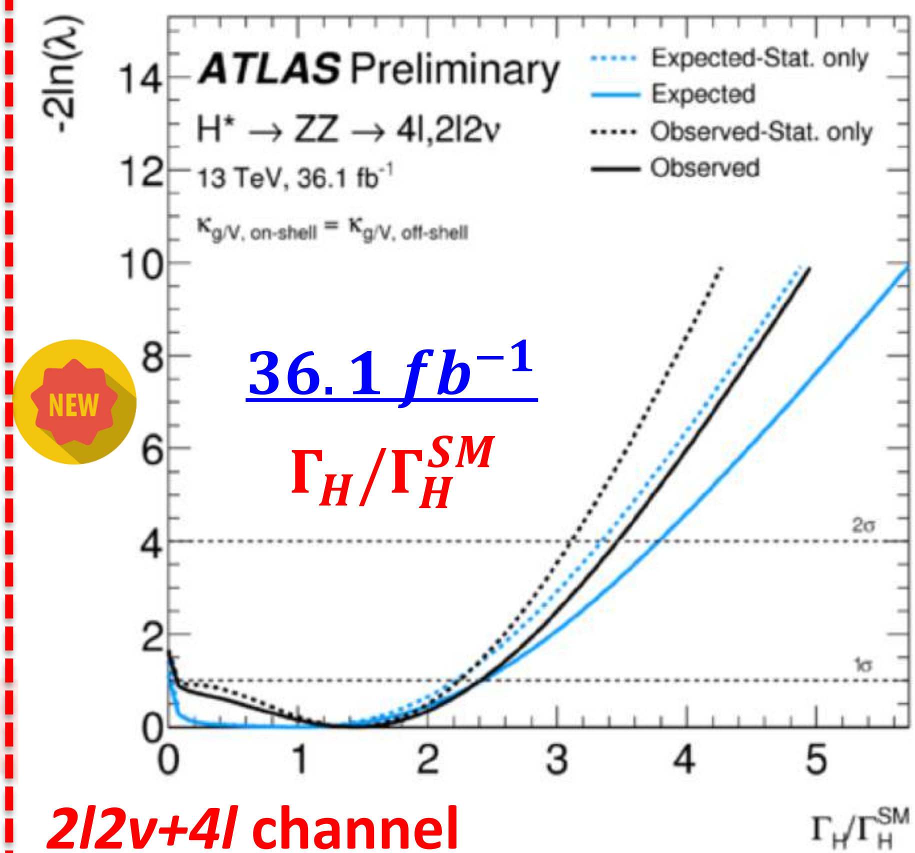
Run 2 results

- Hypothesis testing for a parameter of interest (Γ_H/Γ_H^{SM} ATLAS and Γ_H CMS)
- Confidence intervals based on the profile likelihood ratio



$\underline{12.9\ fb^{-1}}$

Only 4l channel



$\underline{36.1\ fb^{-1}}$

Γ_H/Γ_H^{SM}

2l2ν+4l channel

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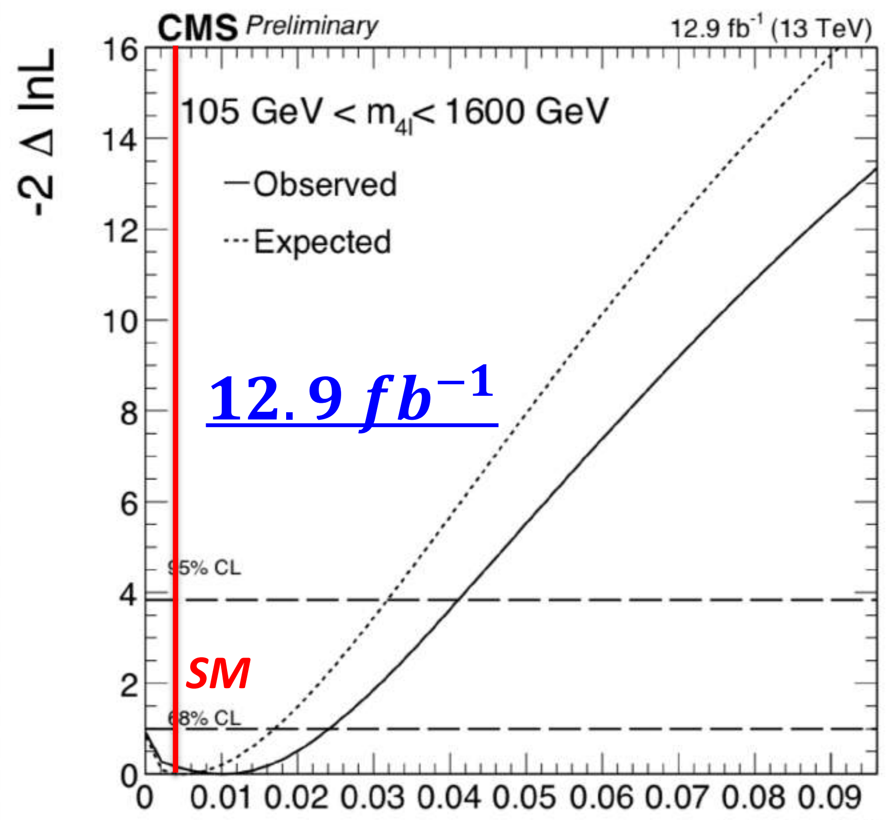

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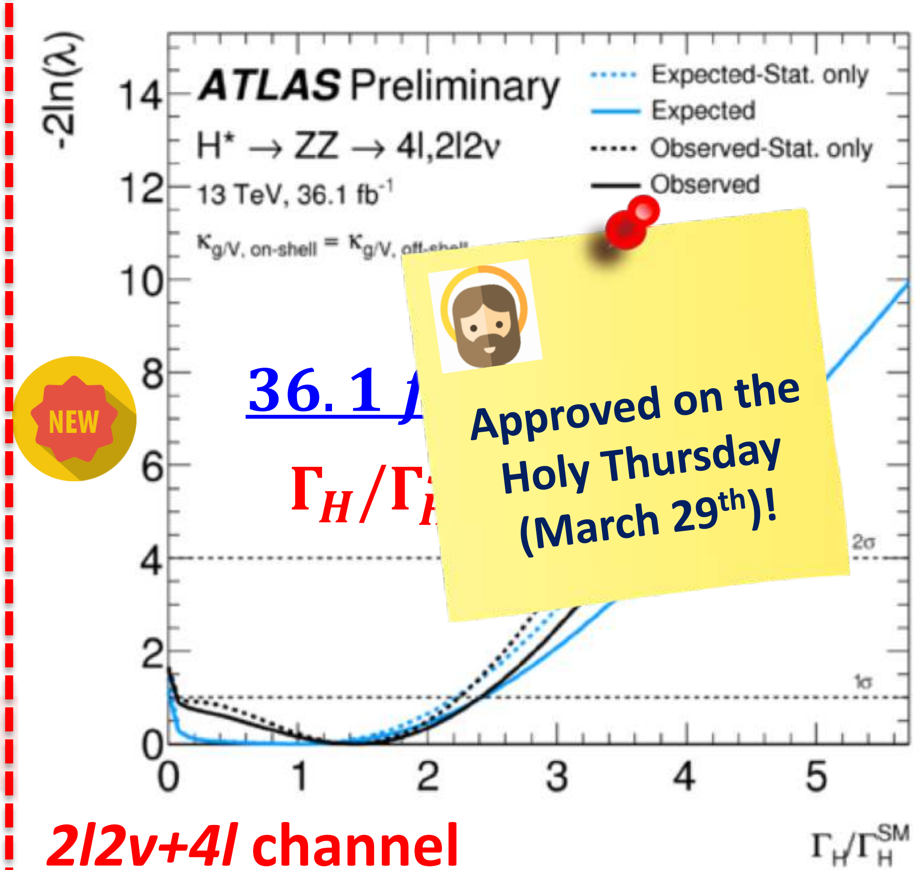


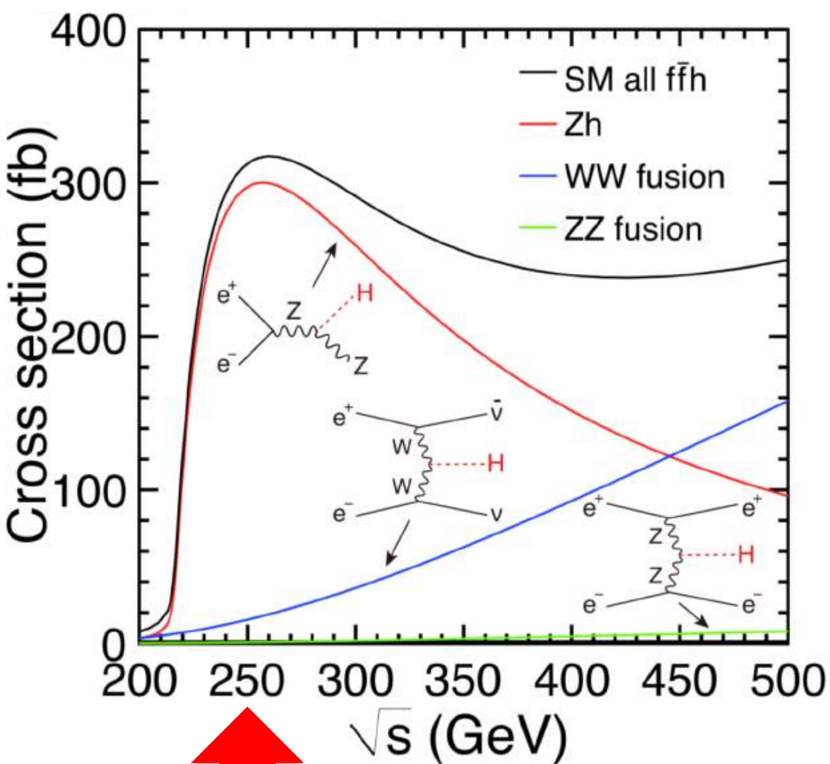
2l2ν+4l channel

Higgs width at ILC

ILC: the future Higgs factory?

[Physics case for the ILC arXiv:1710.07621]

- At ILC the total Higgs production cross section could be measured ➡ measurement of Γ_H
- Depending on $\sqrt{s}$ different production modes



- The Higgs-strahlung production is maximum at 250 GeV
- 2000 fb^{-1} in 20 years of data acquisition (H20 program):
  - ZH ➡ $\sim 500\ K$ Higgs
  - WW-fusion ➡ $\sim 15\ K$ Higgs

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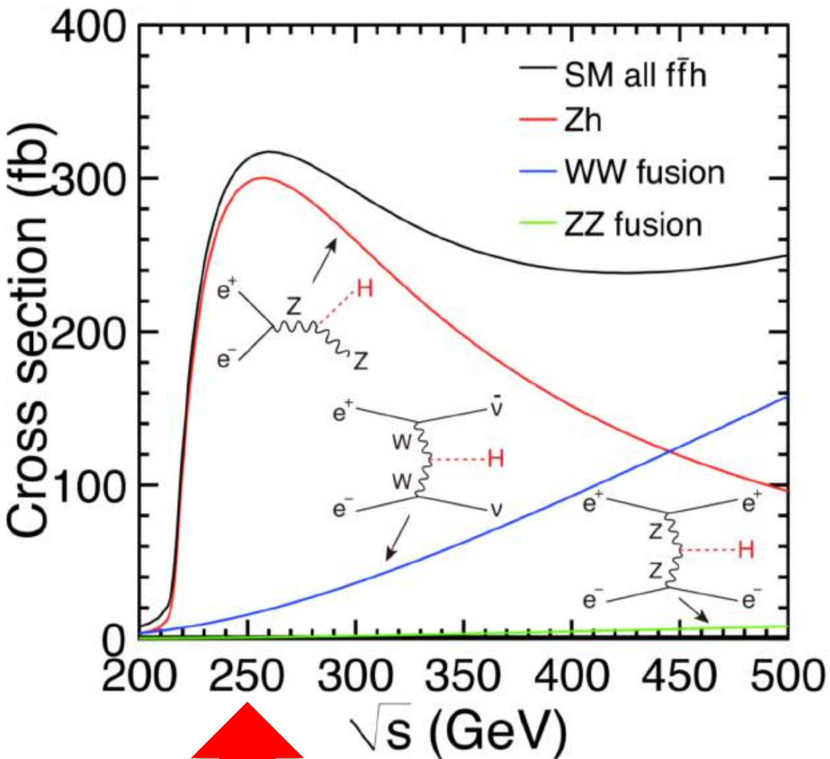

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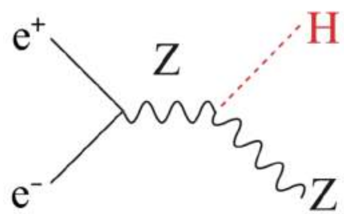
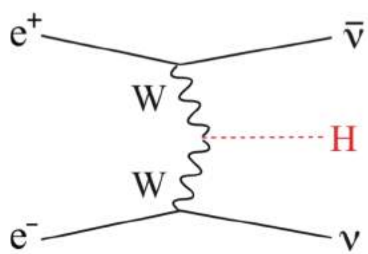
- ZH cross section measurable at 1.0%
- From the HZ sample, measurement of g_{HZZ}: $\boxed{\sigma(e^+e^- \rightarrow ZH) \propto g^2_{HZZ}}$

g_{HZZ} : key to the ILC scientific program

- From the ratio of the Higgs-strahlung and WW-fusion cross sections for the same exclusive Higgs boson final-state $H \to X\bar{X}$:





$$= \frac{\dfrac{g^2_{HZZ} \cdot g^2_{HXX}}{\Gamma_H}}{\dfrac{g^2_{HWW} \cdot g^2_{HXX}}{\Gamma_H}} \Rightarrow g^2_{HWW}$$

Measuring $\sigma(e^+e^- \to ZH)\times BR(H \to WW^*) \propto \dfrac{g^2_{HZZ} \cdot g^2_{HWW}}{\Gamma_H}$

Γ_H	Accuracy achievable 1.7%(ILC250+ILC500)

Conclusions

- The current results for the Higgs total width measurements have been presented
  - Because of experimental resolution, direct measurements will be challenging even at HL-LHC
  - The current best results based on the off-shell strategy, under well-defined assumptions, are (*CLs* method):

$$ATLAS\ \ 36.1\ fb^{-1}\text{:}\ \Gamma_H < 14.4\ obs.\ (15.2\ exp.)MeV$$

$$CMS\ 12.9\ fb^{-1}\text{:}\ \Gamma_H < 41\ obs.\ (32\ exp.)MeV$$

  - ATLAS HL-LHC prospects for the off-shell strategy with 3 ab^{-1}:

$$\Gamma_H = \ 4.2^{+1.5}_{-2.1} MeV$$

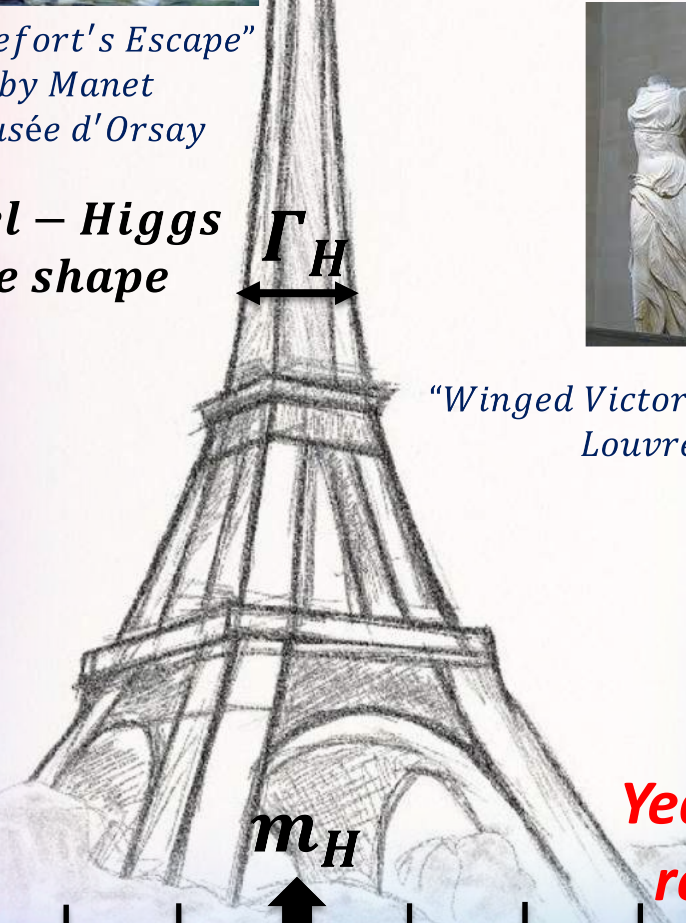
Improvement on Run-1 expected limits by almost a factor 2 !

- At ILC the accuracy achievable is 1.7%

Before 2012: hunting the Higgs boson ...

Higgs artistic time-line

"Rochefort's Escape"
by Manet
Musée d'Orsay



Eiffel – Higgs line shape

2012-2013: when we observed the Higgs boson

"Winged Victory of Samothrace"
Louvre Museum

After 2013: many properties still to be measured

"Mona Lisa" by Leonardo Da Vinci
Louvre Museum

Year after year, we are measuring them ...
reading the enigmatic Higgs Lisa's smile!

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$\boldsymbol{Eiffel - Higgs}$
$\boldsymbol{line\ shape}$

$\boldsymbol{\Gamma_H}$

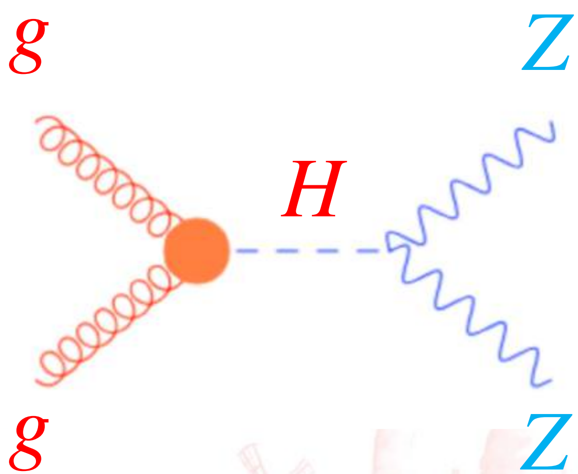
$\boldsymbol{m_H}$

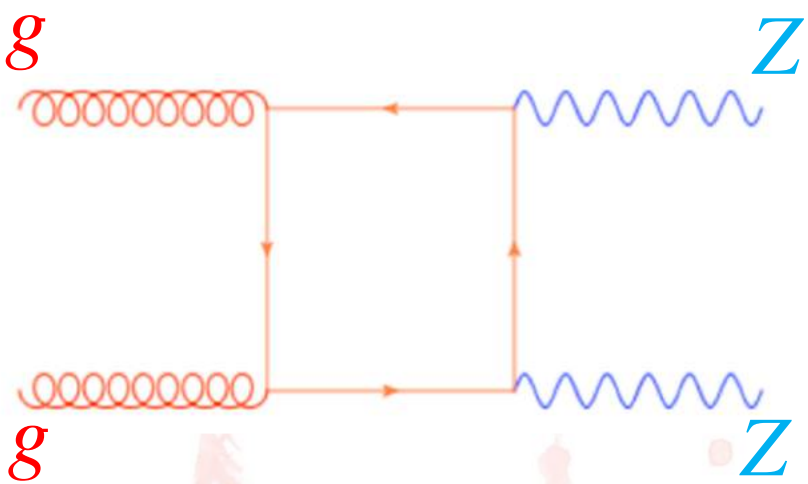
Merci beaucoup!

Back-up

Interference

- Production of two Z bosons in fusion of two gluons can occur either directly or through the Higgs bosons
- The two amplitudes interfere destructively in the SM
- The same considerations apply to the WW final state





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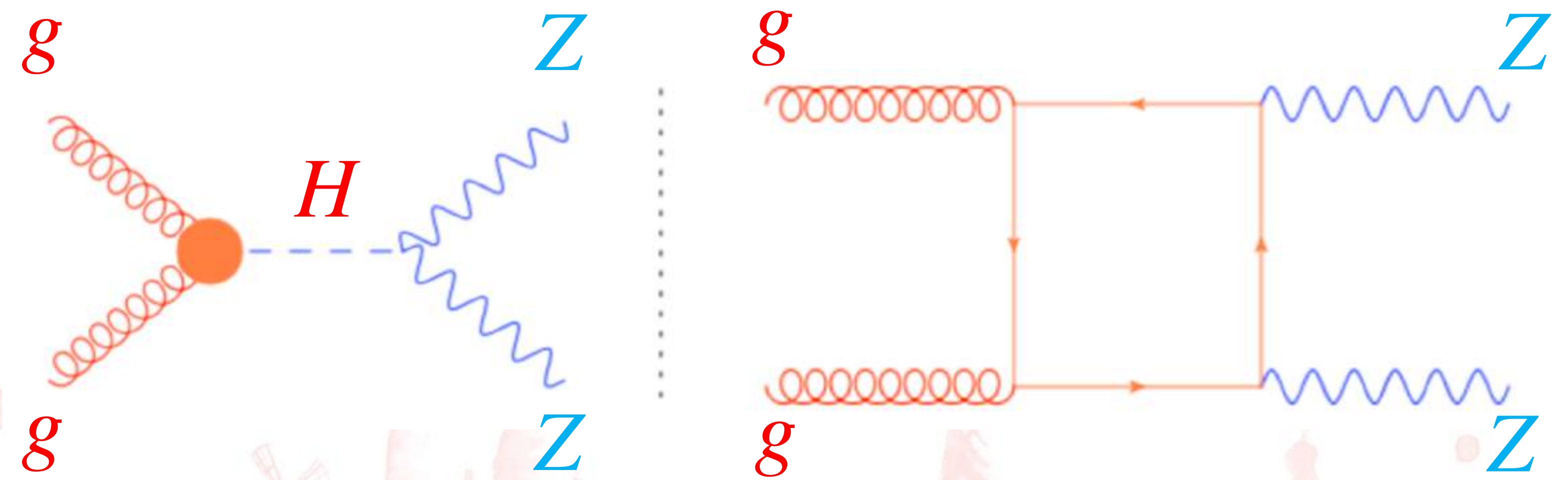


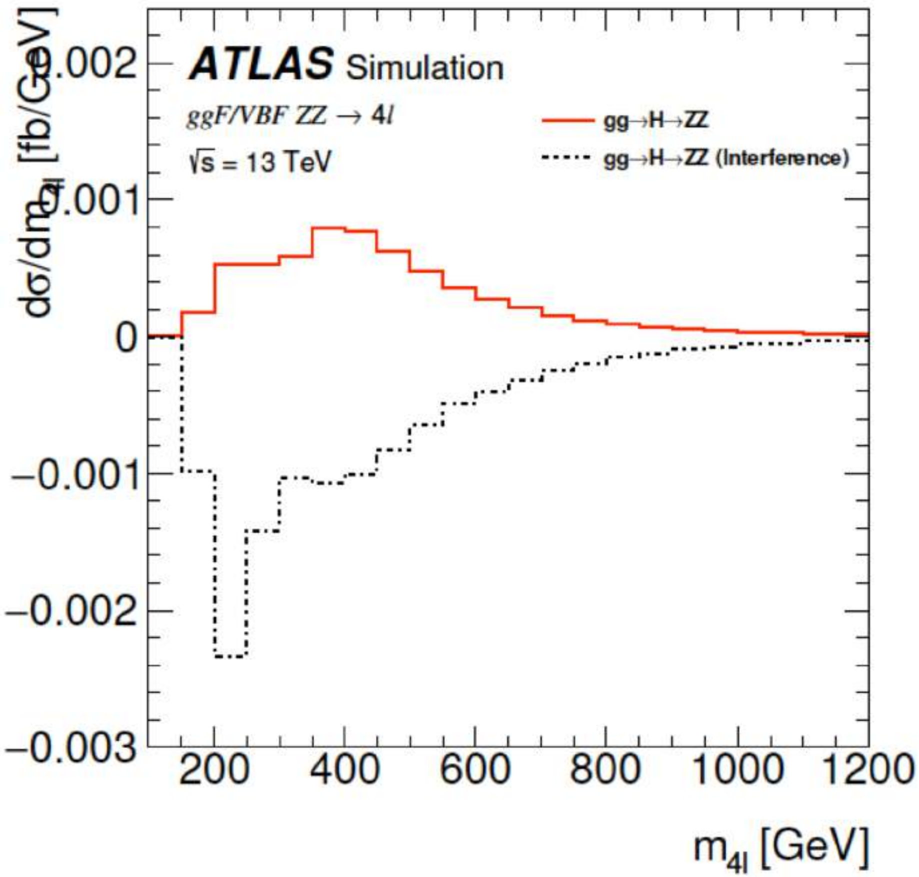
$\mu_{off-shell} - independent$

$$|\mathcal{M}_{ZZ}|^2 = \left|\mathcal{M}_H + \mathcal{M}_{Bkg}\right|^2 = |\mathcal{M}_H|^2 + \left|\mathcal{M}_{Bkg}\right|^2 + 2Re(\mathcal{M}_H\mathcal{M}^*_{Bkg})$$

$\sim\mu_{off-shell}$ $\sim\sqrt{\mu_{off-shell}}$

Interference

- Negative contribution of the interference term



ATLAS analysis selection

4l channel

	Event Selection
Quadruplet Selection	- Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-charge leptons fulfilling the following requirements: - p_T thresholds for three leading leptons in the quadruplet: 20, 15 and 10 GeV - Maximum one calo-tagged or stand-alone muon or silicon-associated forward per quadruplet - Select best quadruplet (per channel) to be the one with the (sub)leading dilepton mass (second) closest the Z mass - Leading di-lepton mass requirement: $50 < m_{12} < 106$ GeV - Sub-leading di-lepton mass requirement: $12 < m_{34} < 115$ GeV - $\Delta R(\ell, \ell') > 0.10$ (0.20) for all same (different) flavour leptons in the quadruplet - Remove quadruplet if alternative same-flavour opposite-charge di-lepton gives $m_{\ell\ell} < 5$ GeV
Isolation	- Contribution from the other leptons of the quadruplet is subtracted - Muon track isolation ($\Delta R <= 0.30$): $\Sigma p_T / p_T < 0.15$ - Muon calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T / p_T < 0.30$ - Electron track isolation ($\Delta R <= 0.20$) : $\Sigma E_T / E_T < 0.15$ - Electron calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T / E_T < 0.20$
Impact Parameter Significance	- Apply impact parameter significance cut to all leptons of the quadruplet - For electrons: $d_0 / \sigma_{d_0} < 5$ - For muons: $d_0 / \sigma_{d_0} < 3$
Vertex Selection	- Require a common vertex for the leptons: - χ^2/ndof < 6 for 4μ and < 9 for others.

2l2ν channel

Event Selection
Two same flavour opposite-sign leptons (e^+e^- OR $\mu^+\mu^-$)
Veto of any additional lepton with Loose ID and $p_T > 7$ GeV
$76 < M_{\ell\ell} < 106$ GeV
$E_T^{miss} > 175$ GeV
$\Delta R_{\ell\ell} < 1.8$
$\Delta\phi(Z, E_T^{miss}) > 2.7$
Fractional p_T difference < 0.2
$\Delta\phi(\text{jet}(p_T > 100\,\text{GeV}), E_T^{miss}) > 0.4$
$E_T^{miss} / H_T > 0.33$
b-jet veto

ATLAS analysis in 4l: strategy

➢ On-shell event selection used as a baseline in the off-peak region: $220\ GeV < m_{4l} < 2000\ GeV$

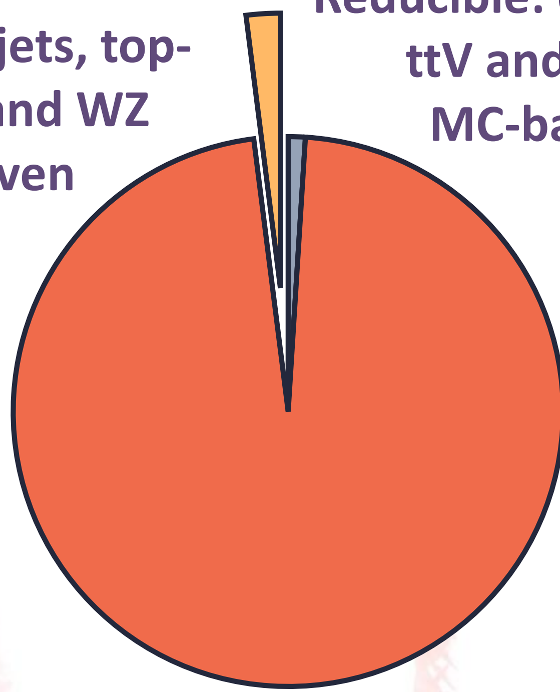
➢ Shape fit to ME(Matrix Element)-based kinematic discriminant:

$$ME = log_{10}\left(\frac{P_H}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$$

ME is based on 8 variables which defines the event kinematics in the centre-of-mass frame of the *4l-system*

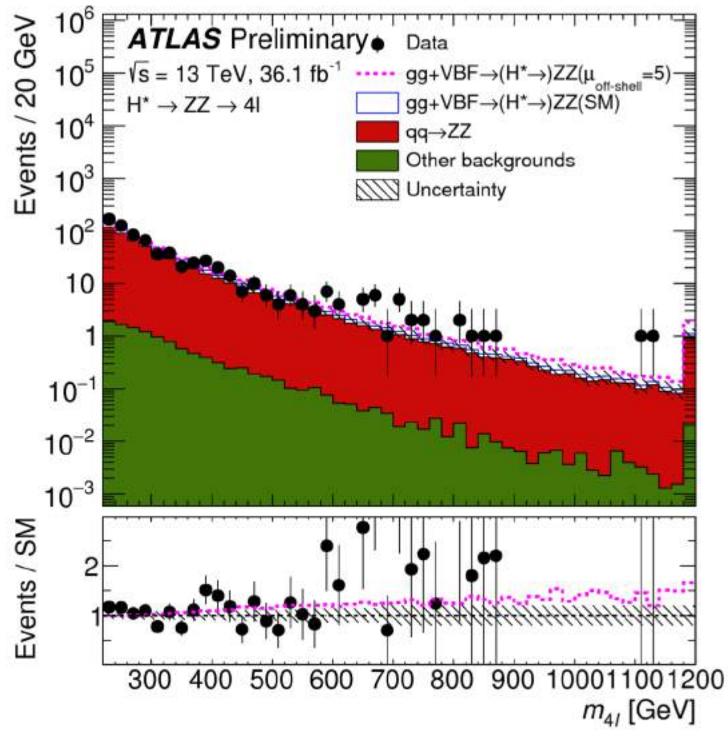
- $P_H = matrix\ element\ for\ on-shell\ gg \to H \to ZZ^* \to 4l$
- $P_{qq} = matrix\ element\ for\ qq \to ZZ \to 4l$
- $P_{gg} = matrix\ element\ for\ gg \to H^* \to ZZ \to 4l$
- $c = 0.1$, empirical constant

ATLAS analysis in 4l: background

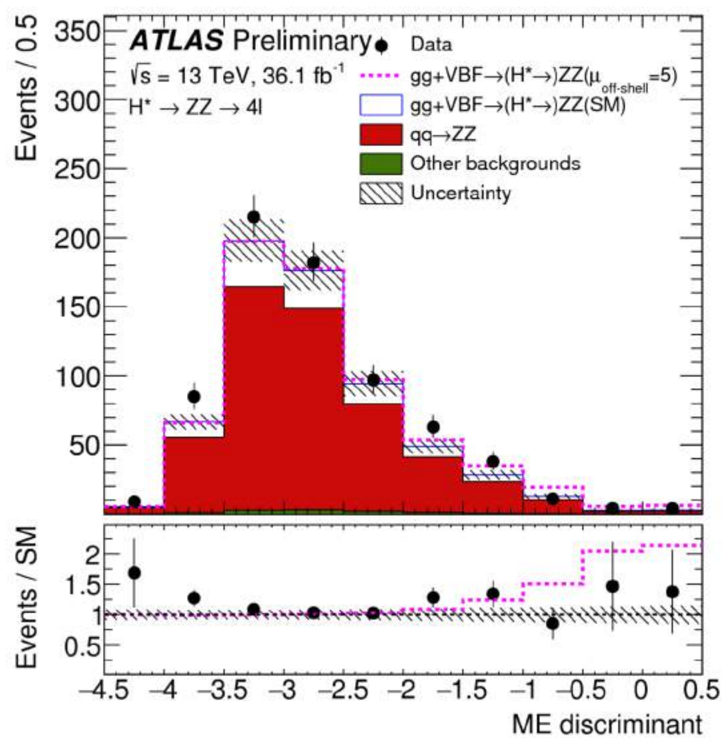


ATLAS analysis in 4l: discriminant

4l invariant mass



4l discriminant



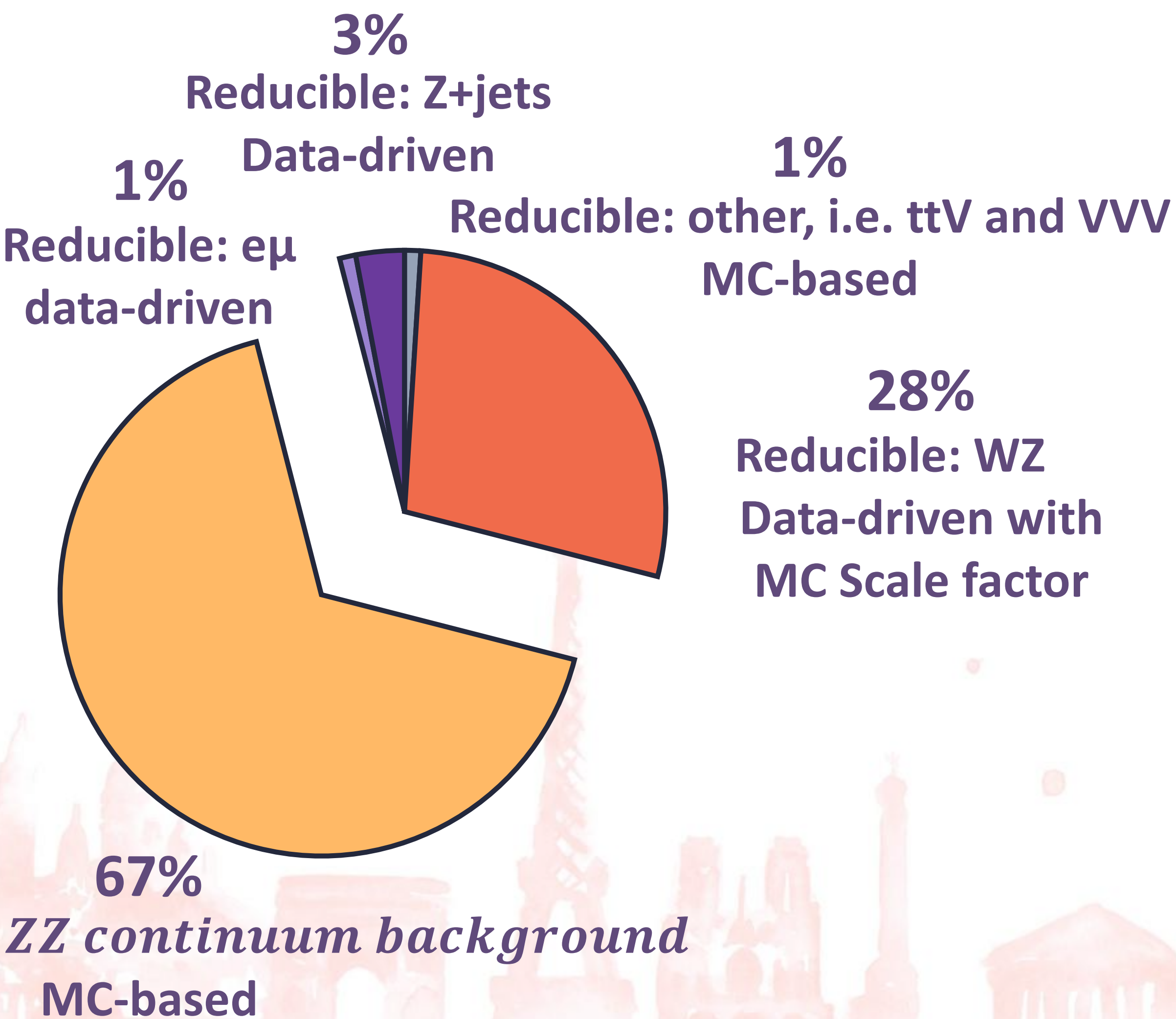
ATLAS analysis in 2l2v: strategy

- High-Mass-$H \rightarrow ZZ \rightarrow ll\nu\nu$-analysis event selection used as baseline in the off-peak region with further re-optimisation :
  - MET cut 120 $GeV \rightarrow$ 175 GeV
  - MET/H_T cut 0.4 $\rightarrow$ 0.33 with H_T scalar sum of lepton and jet p_T

- Shape fit to the transverse mass $m_T(ZZ)$ distribution

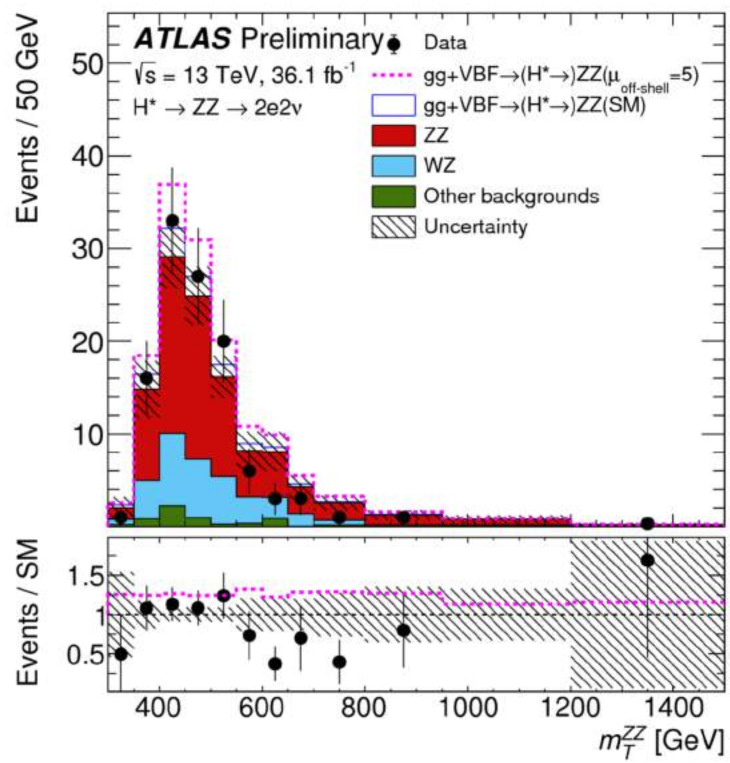
$$(m_T^{ZZ})^2 = \left(\sqrt{m_Z^2 + \left|p_T^{ll}\right|^2} + \sqrt{m_Z^2 + \left|E_T^{miss}\right|^2} - \left|\overrightarrow{p_T}^{ll} + \overrightarrow{E_T}^{miss}\right|^2 \right)$$

ATLAS analysis in 2l2v: background

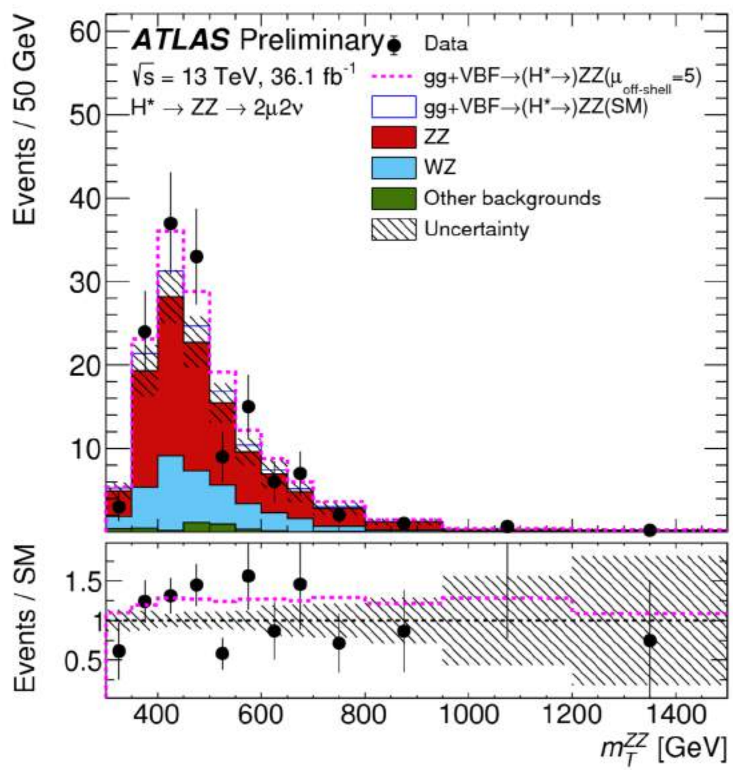


ATLAS analysis in 2l2v: discriminant

2e2ν channel



2μ2ν channel



Two-step strategy

- Maximum likelihood fit to the Matrix-Element (ME) based discriminant distribution (4l) and the transverse-mass, $m_T(ZZ)$, distribution (2l2v)

1

Off-shell signal strength constraints

- Combination of the 2l2v and 4l channel fixing the ratio of the signal strength in ggF and VBF to the SM prediction: $\frac{\mu^{ggF}_{off-shell}}{\mu^{VBF}_{off-shell}} = 1$

2

Higgs boson total width constraints

- Combination with the on-shell result assuming the same
  - on-shell signal strength in VBF and ggF: $\frac{\mu^{ggF}_{on-shell}}{\mu^{VBF}_{on-shell}} = 1$
  - on-shell and off-shell couplings

Systematic uncertainties

- Experimental systematic uncertainties small, a few percent
  - Mostly due to leptons reconstruction efficiencies, Jet energy scale and resolution

- Largest contribution from theoretical uncertainties on $gg \rightarrow H^* \rightarrow ZZ$ process, $gg/qq \rightarrow ZZ$ background process and the interference between signal and background
  - $qqZZ: 5 - 10\%\ QCD\ scale\ variation, 3\%\ from\ PDF$
  - $ggZZ: 10 - 20\%\ QCD\ scale\ variation, 3\%\ from\ PDF$

R_{gg} interpretation

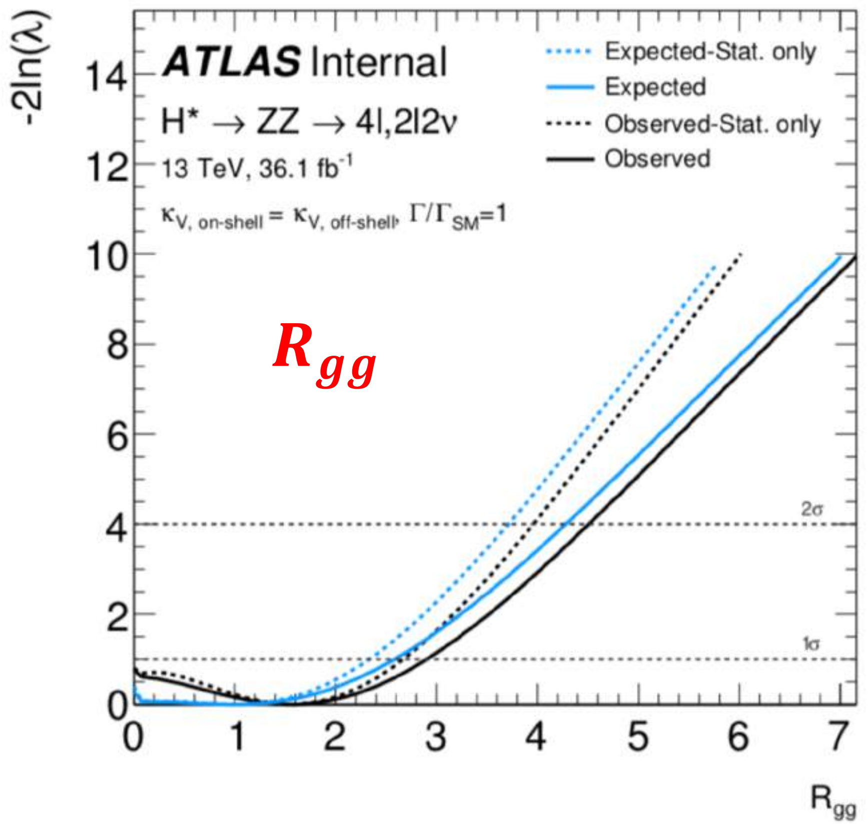
- In a second combination, we consider a gg-interpretation of the results

- The parameter of interest is

$$R_{gg} = \frac{k^2_{g,off-shell}}{k^2_{g,on-shell}}$$

- The total width is assumed to be the SM prediction

- We are assuming the same on-shell and off-shell coupling scale factors k_V



Run 2 - Run 1 results

- Using the CLs method, we derive the Observed (Expected) limits at 95% C.L.

Run-2 results:
(ZZ only, 4l only for CMS)

- $ATLAS$: $\Gamma_H < 14.4(15.2) MeV$
- CMS: $\Gamma_H < 41\ (32) MeV$

Run-1 results:
(ZZ+WW)

- $ATLAS$: $\Gamma_H < 22.7(33)\ MeV$
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- Similar strategies
- More data for ATLAS:
  - $20.3\ fb^{-1}\ \sqrt{s} = 8\ TeV$ vs $36.1\ fb^{-1}\ \sqrt{s} = 13\ TeV$
- Less assumptions on HO QCD corrections for ggZZ
  - NLO k-factors for $gg \rightarrow (H^* \rightarrow) ZZ$ available for Signal, Background and Interference

Improvement on Run-1 expected limits by almost a factor 2 !

Indirect strategies

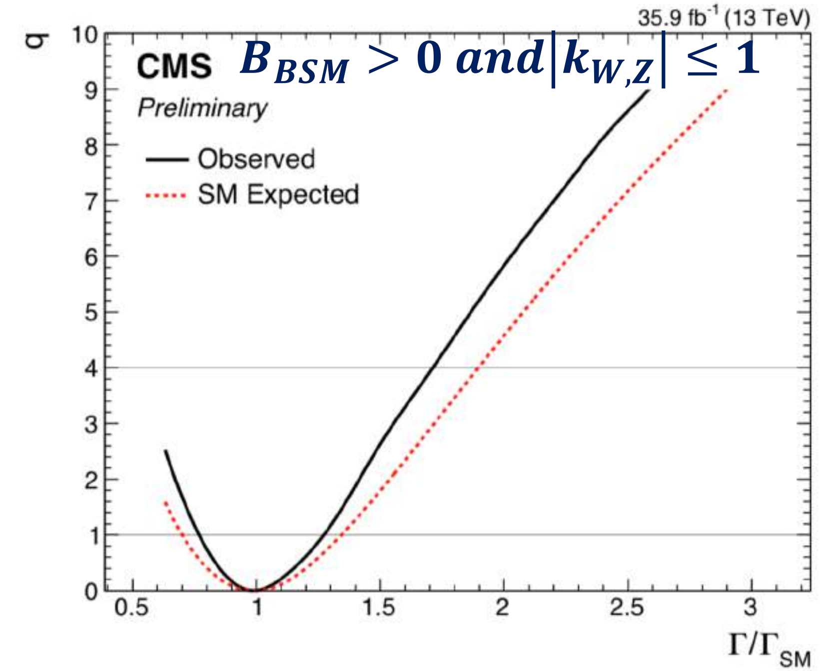
- Using the coupling analysis framework we can constraint Γ_H:

$$\Gamma_i = \Gamma_i^{SM} \cdot k_i^2 \text{ and so } \boxed{\Gamma_H = \frac{k_H^2 \cdot \Gamma_H^{SM}}{1 - B_{BSM}}}$$

Two possible interpretations:

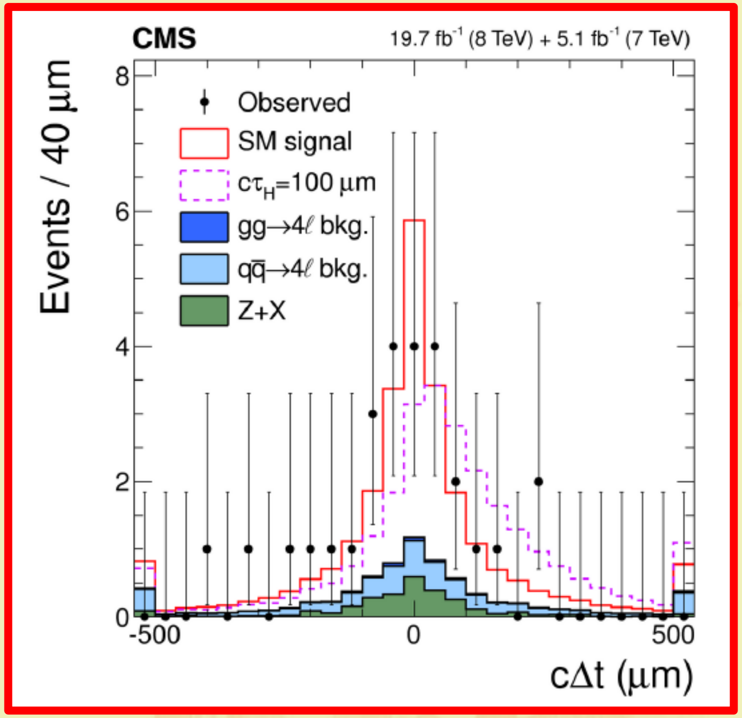
- $B_{BSM} = 0$
- $B_{BSM} > 0 \; and \; |k_{W,Z}| \leq 1$

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggH)$	✓	$b-t$	κ_g^2	$1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–		$0.73 \cdot \kappa_W^2 + 0.27 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	$Z-t$		$2.46 \cdot \kappa_Z^2 + 0.47 \cdot \kappa_t^2 - 1.94 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to WtH)$	–	$W-t$		$2.91 \cdot \kappa_t^2 + 2.40 \cdot \kappa_W^2 - 4.22 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$		$2.63 \cdot \kappa_t^2 + 3.58 \cdot \kappa_W^2 - 5.21 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	$W-t$	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.67 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width for $BR_{BSM} = 0$				
Γ_H	✓	–	κ_H^2	$0.58 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.08 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.026 \cdot \kappa_Z^2 + 0.029 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0015 \cdot \kappa_{Z\gamma}^2 + 0.00025 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$



Direct strategies

From the lifetime



- Using the Higgs lifetime we can set a direct lower bound
- $\Delta t = \frac{m_{4l}}{p_T}(\Delta\vec{r_t} \cdot \widehat{p_T}) \rightarrow$
  - $< \Delta t >= \tau_H = \hbar/\Gamma_H$

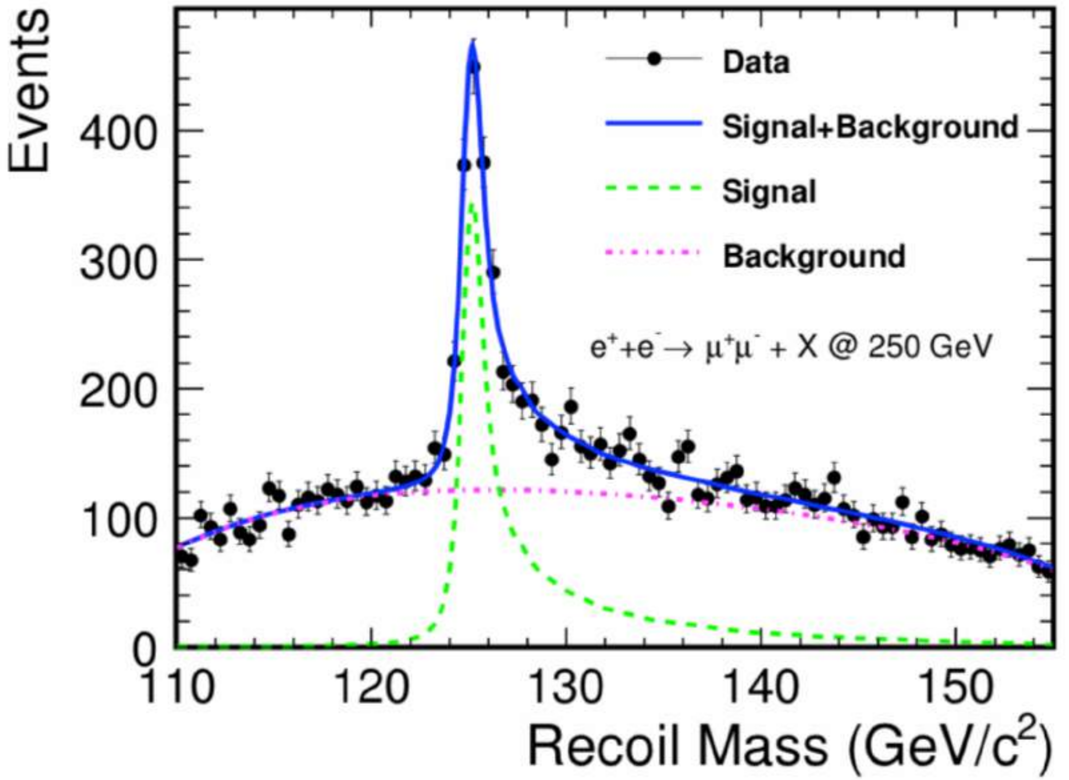
  Lifetime of each H candidate

  - $\Delta\vec{r_t}$ **Displacement between the production and decay vertices in the transverse plane**
- Observables:

  Δt *and* $D_{bkg}(m_{4l}$ and $D^{kin})$

Measuring the HZ coupling at ILC

- Unique opportunity for a model-independent measurement of the HZ coupling from the recoil mass distribution in $e^+e^- \to ZH$



$$M_{rec}^2 = (\sqrt{s} - E_{ll})^2 - |\overrightarrow{p_{ll}}|^2$$

- Higgs events are tagged with the Z boson decays, independently of the Higgs decay mode

- From the HZ sample, measurement of g_{HZZ}:

$$\boxed{\sigma(e^+e^- \to ZH) \propto g_{HZZ}^2}$$