Higgs width at LHC

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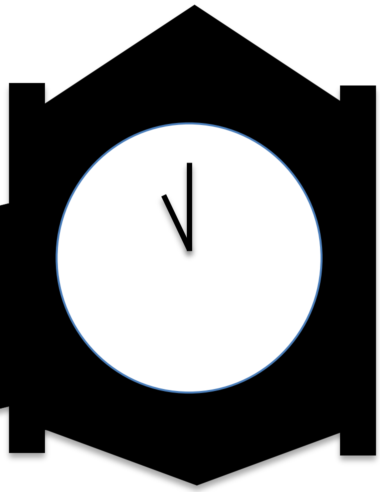
LPC Physics Forum
FERMILAB
28 March 2019



Introduction to Higgs Physics

Run-2 News

Higgs boson width

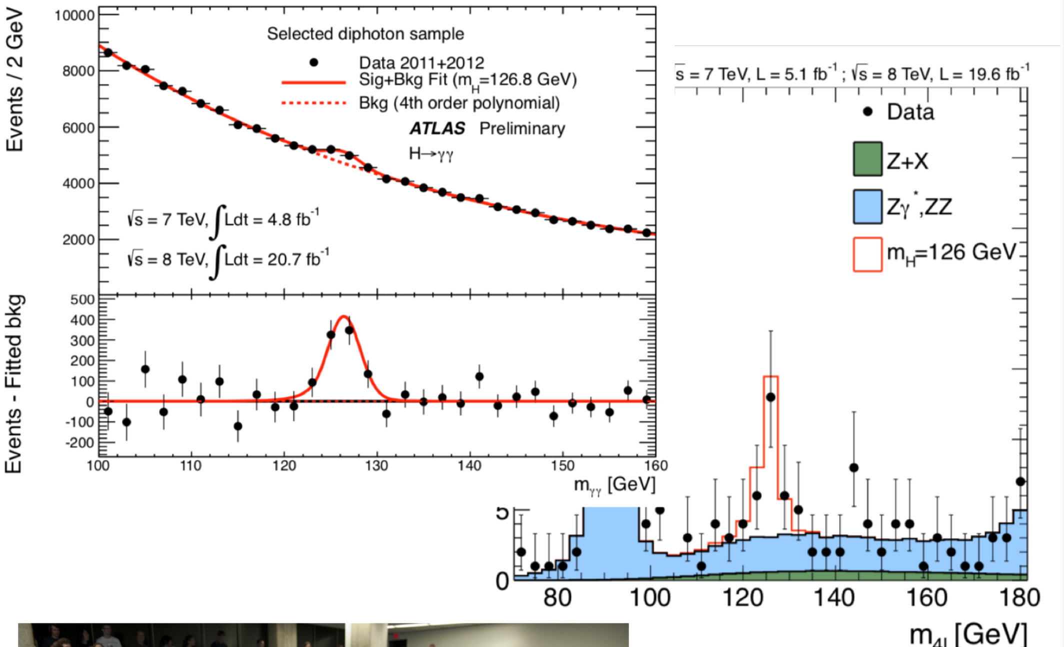
Higgs boson width: experimental results

Conclusions

Disclaimer: Inspired by chats/talks with/by F. Caola, C. Vernieri and C. Williams

Introduction to Higgs Physics

4th July 2012: a Nobel birthday!



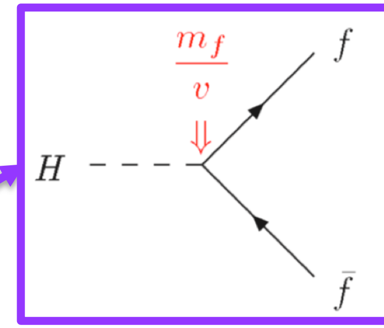
- We have just recently celebrated the 6th Higgs birthday
- Peter W. Higgs and Francois Englert: the 2013 Nobel Prize in physics

The Higgs boson in the SM

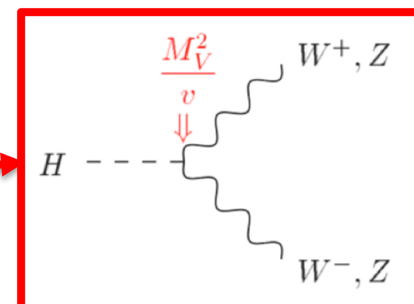
- By interacting with all the SM particles, the Higgs field gives them mass
  - Two different types of tree-level couplings

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi + h.c.$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

Fermions

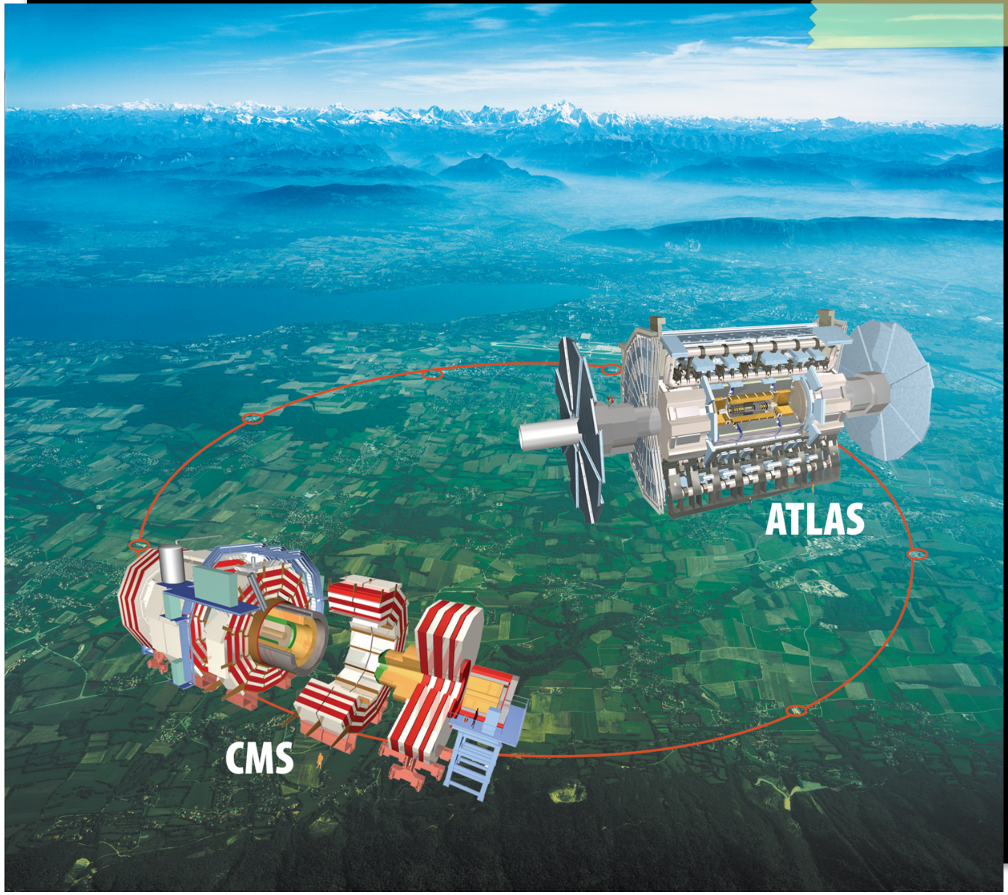


Bosons



The Large Hadron Collider, LHC

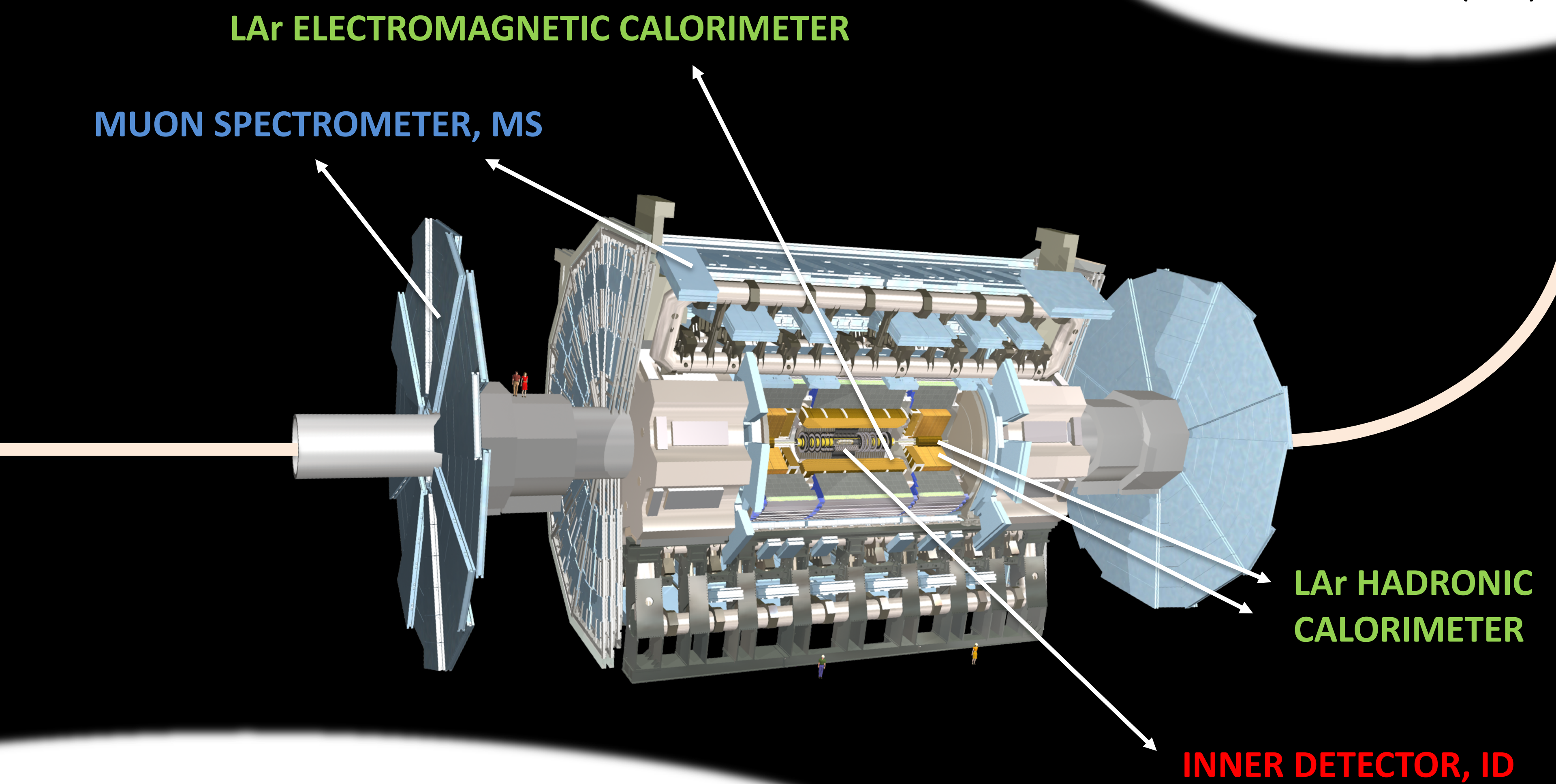
- Proton-proton collider with four interaction points: ATLAS, CMS, LHCb and ALICE



- Peak Luminosity: $2 \cdot 10^{34}$ cm^{-2}s^{-1}
  - Design Lumi. exceeded by a factor of two!
- 27-km ring of superconducting magnets
- Two phases at $\sqrt{s}$:
  - 7,8 TeV Run 1
  - 13 TeV Run 2

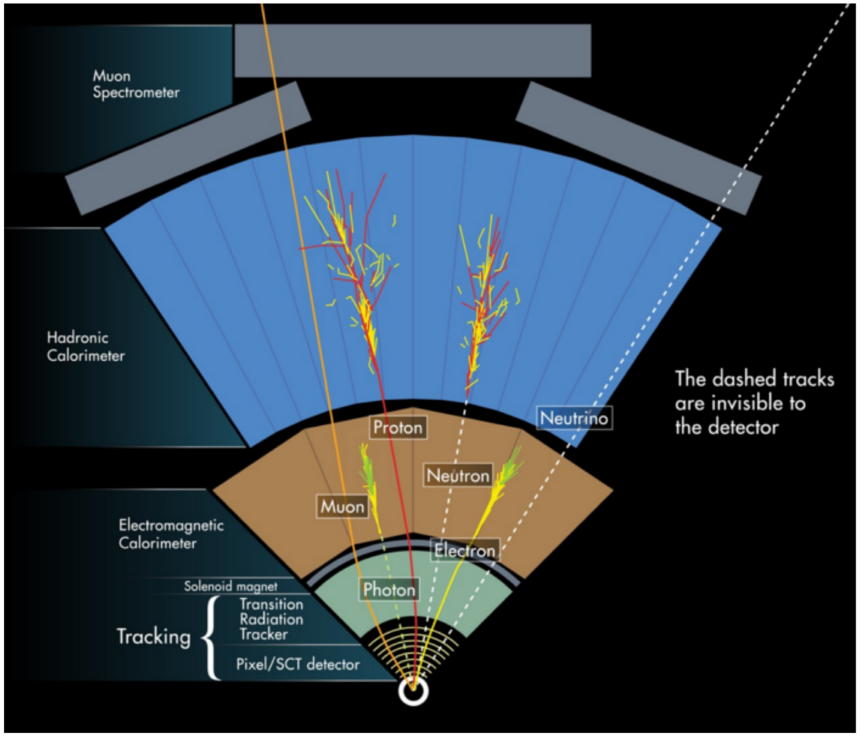
The ATLAS detector

- Two-magnet detector:
  - Solenoid 2 T (tracker)
  - Toroid 0.5 T (MS)



- **Multi-purpose detector with onion shape**
- During the shutdown before Run 2, initial design completed

From the detector to the paper



➢ The typical HEP detector layout:

- **Tracking detectors** to reconstruct charged particles and the production and decay vertices
- **Electromagnetic and hadronic calorimeters** to measure energy of e, γ and jets
- **Muon spectrometer** to detect muons trough the detector

CHALLENGING PHYSICS OBJECTS:

➢ Jets, Missing Transverse Energy (ν_s) :

- Low resolution and recon. efficiency
- Partial vertex matching

IDEAL PHYSICS OBJECTS:

➢ Electrons, photons and muons:

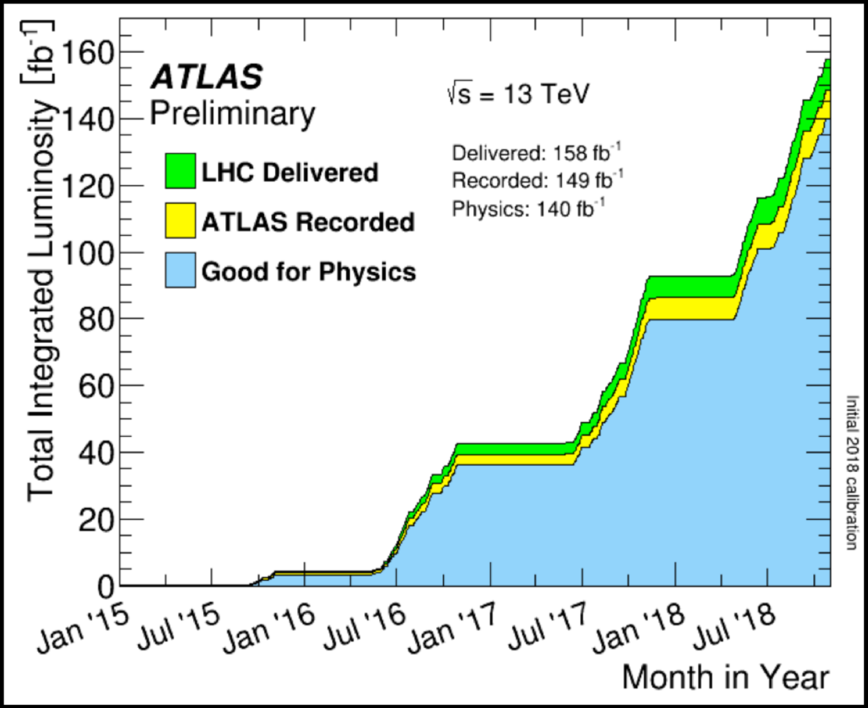
- good resolution and reconstruction efficiency
- Good vertex matching

Higgs physics at LHC

- At the Large Hadron collider the delivered luminosity was:
  - **28 fb^{-1}** at 7/8 TeV
    Higgs discovery!
  - **158 fb^{-1}** at 13 TeV

- **1 Higgs boson produced every 10^{10} proton-proton collisions**

Exceptional performance in Run 2!



- **ATLAS recorded 149 fb^{-1}**
  - **140 fb^{-1} are GOOD for physics**
  - **36.1 fb^{-1} in 2015-2016**
- **We successfully reached the Run-2 goal of 150 fb^{-1} !**

Higgs physics at LHC

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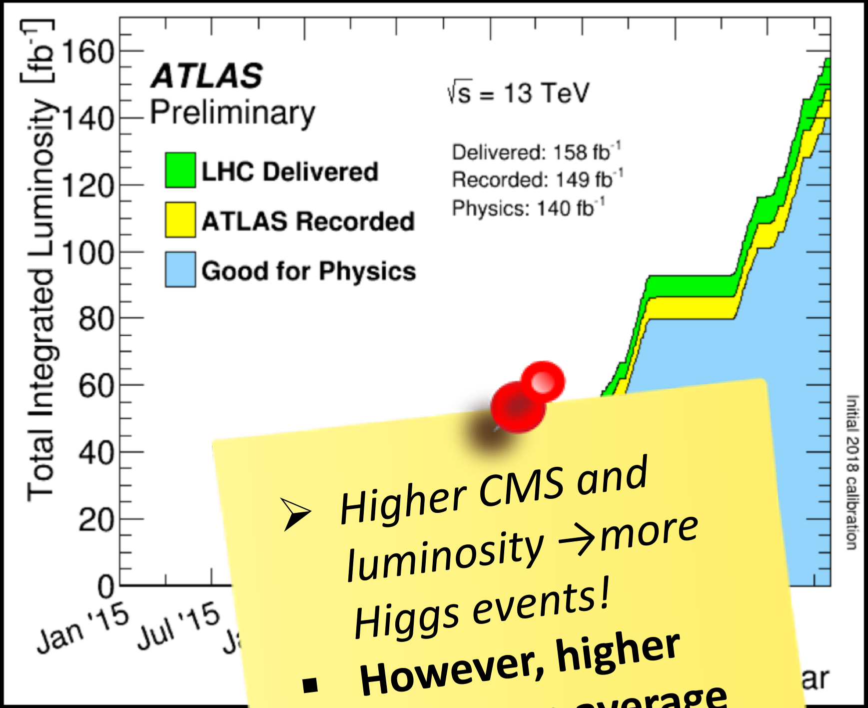
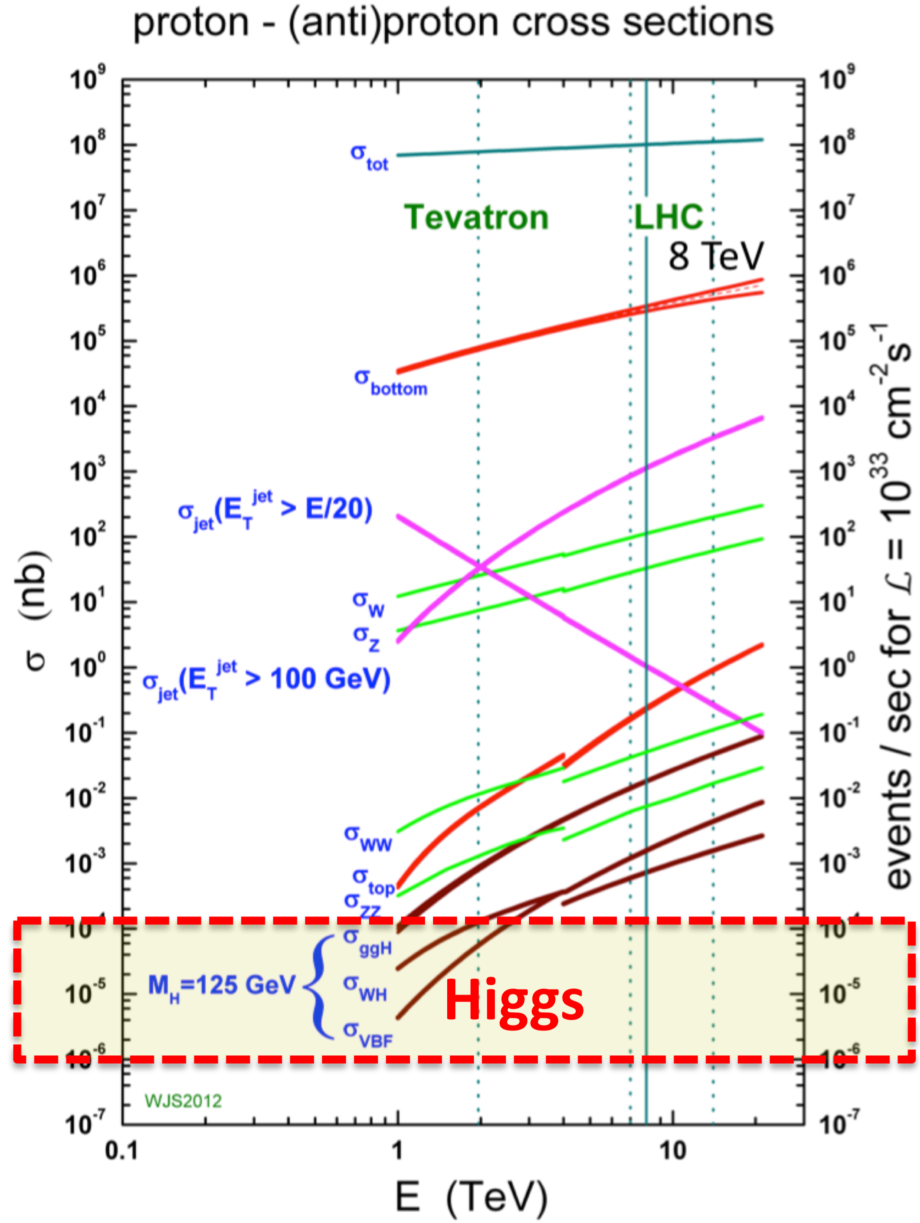


- *Higher CMS and luminosity → more Higgs events!*
  - **However, higher pileup, on average <μ>=58**
  - **No pain, no gain!**

- **ATLAS re**
  - **140 f**
  - **36.1 f ... 2016**
- **We successfully reached the Run-2 goal of 150 fb^{-1} !**

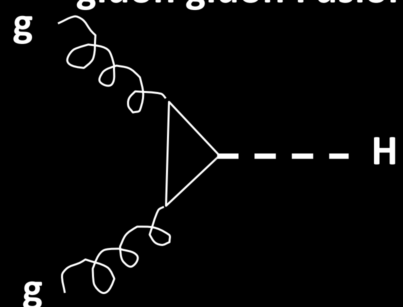
LHC pp collisions

- QCD background dominant
  - 5 orders of magnitude higher compared to single boson production
  - Higgs boson decays involving leptons or photons in the final state are our smoking gun against abundant background



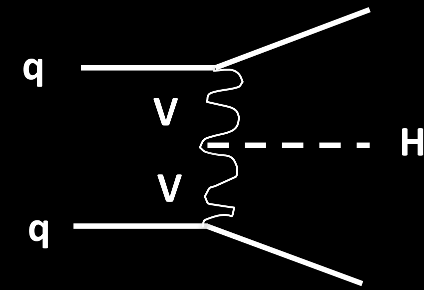
Higgs boson production at LHC

ggF: 88%
gluon gluon Fusion

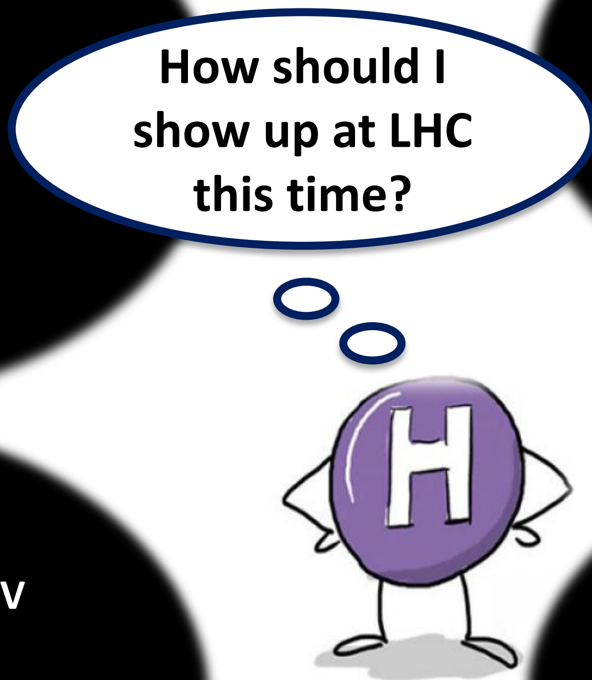


~ 6.8M Higgs*

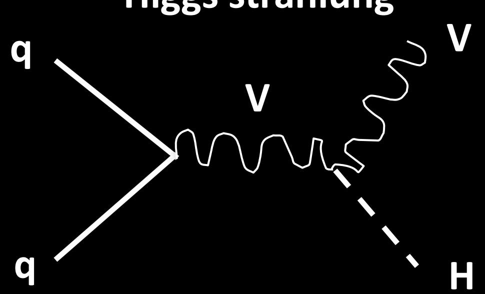
VBF: 7%
Vector Boson Fusion



~ 530k Higgs

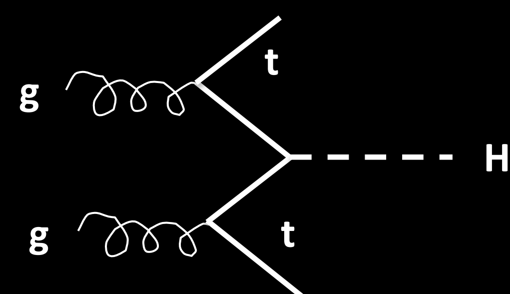


VH: 4%
Higgs strahlung



~ 320k Higgs

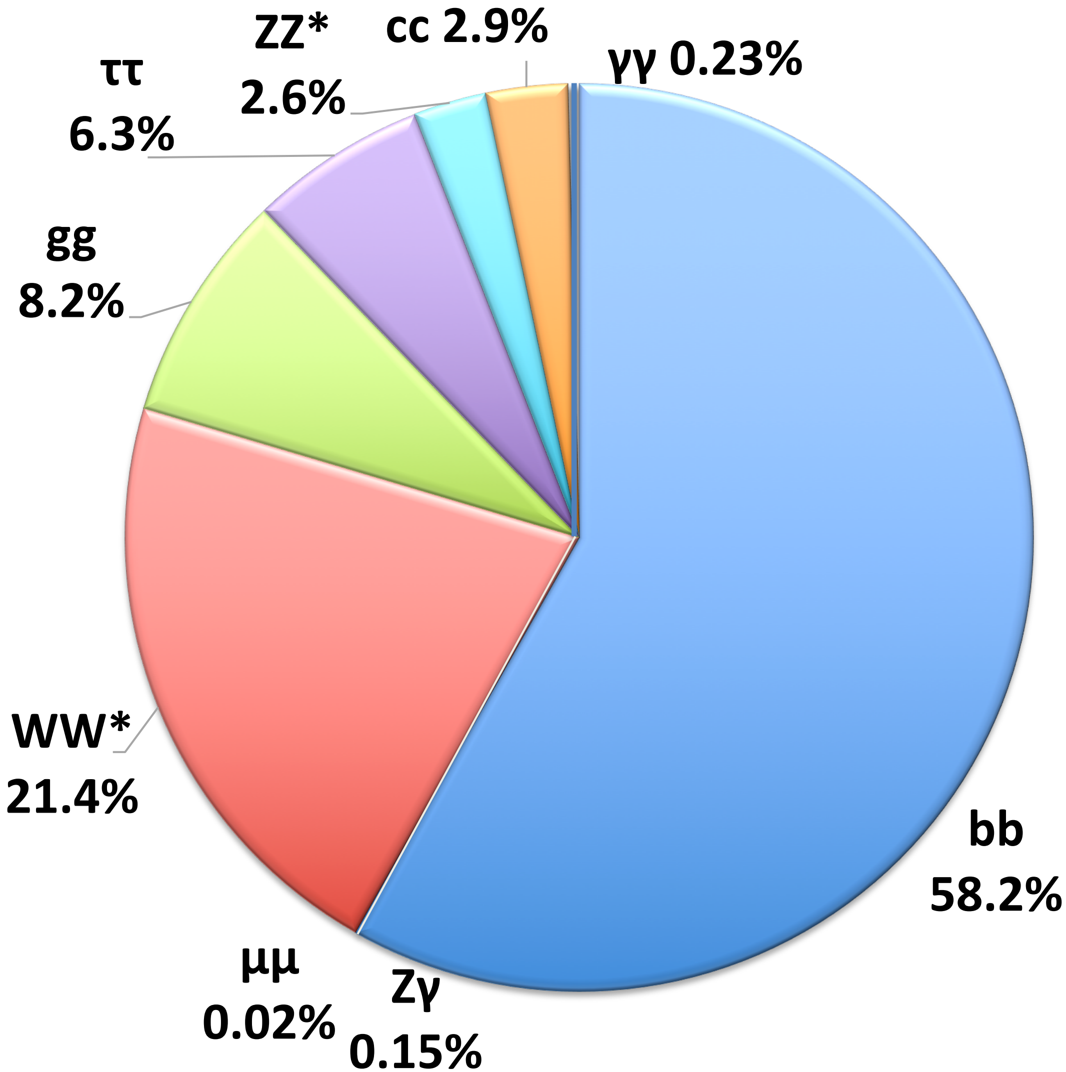
ttH: 1%
Top Fusion



~ 70k Higgs

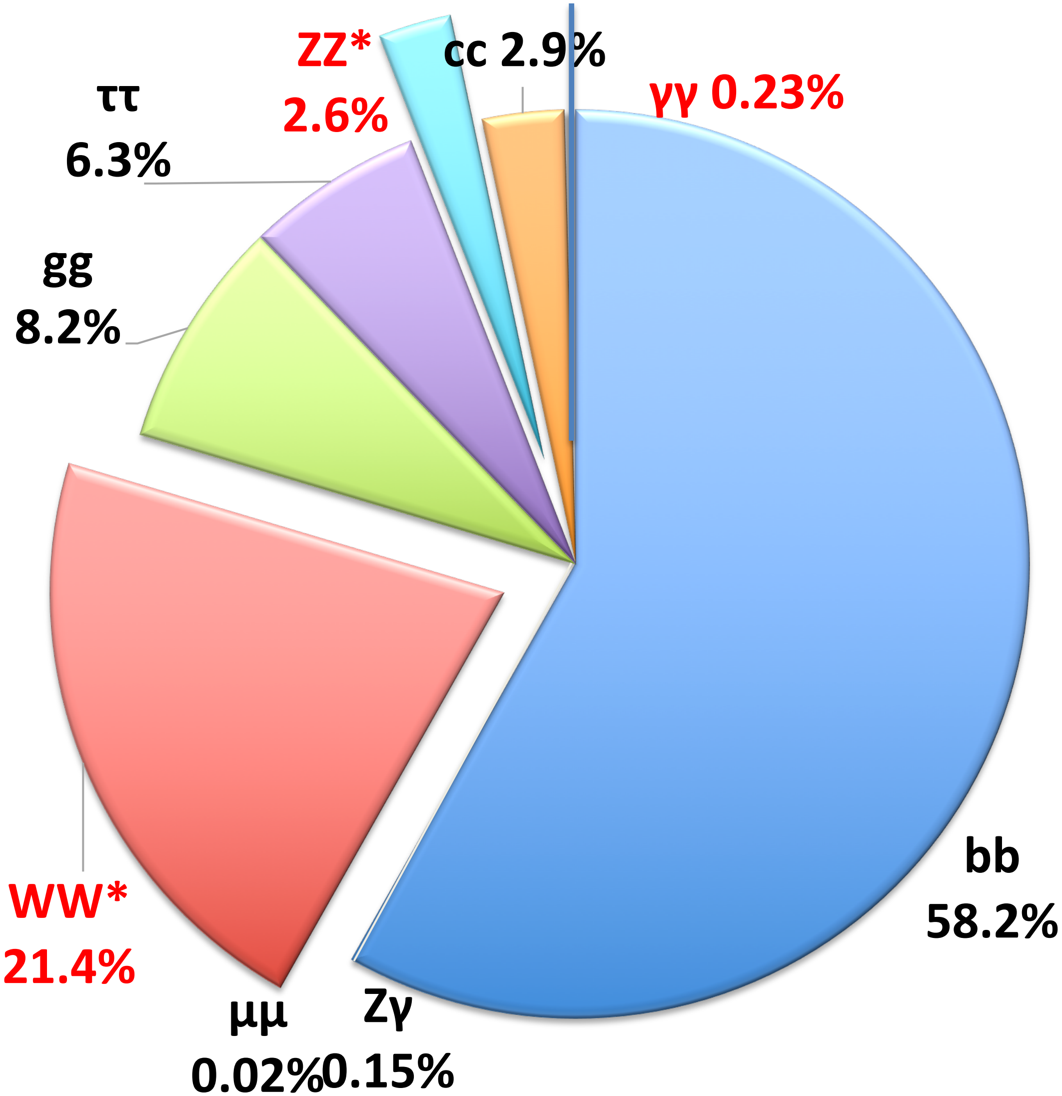
*Higgs candidates in Run 2

Higgs boson decays



- Various decay channels
  - Analyses ongoing in all the main channels, directly or indirectly
- Combination of all the channels is crucial
  - to increase sensitivity
- No couplings measurements without theory assumptions

Higgs to Bosons



ZZ*, γγ

Good mass resolution

- Ideal for precision measurements since well modelled background and clear signatures

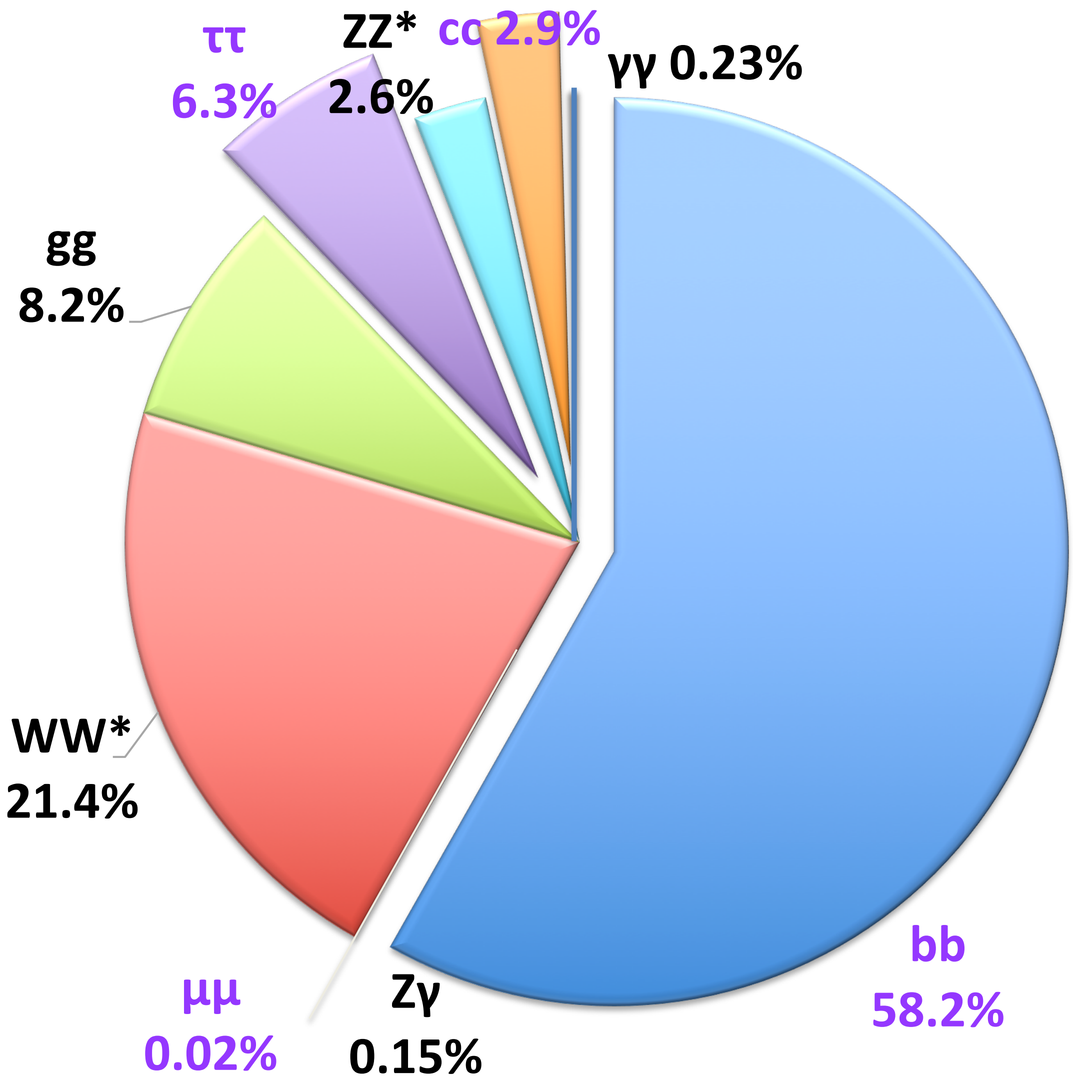
Low BR, especially ZZ*, 0.012% in 4l

WW*

High BR, but reduced in the di-lepton mode, 1.1%

Low mass resolution because of ν_s in final states

Higgs to Fermions



bb, ττ, cc

Significant BR

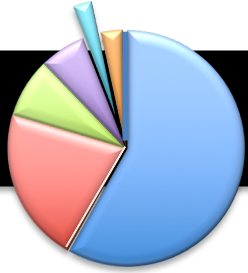
- Allow direct probe to fermions

Low S/B, challenging measurement

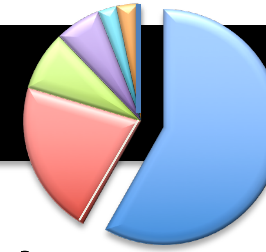
μμ

It allows couplings measurements to 2nd generation

Very small BR



H→ZZ* Golden channel

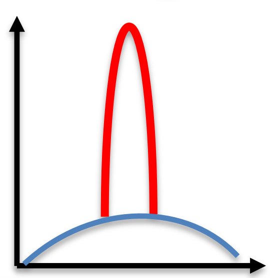


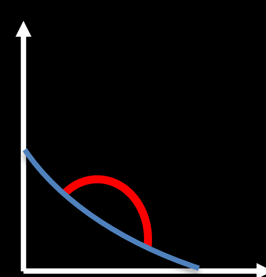
Because of the extremely good mass resolution, H→ZZ*→4l:

- **was one of the golden channels for the Higgs discovery**
- **is now used for precision measurements (Higgs boson mass …)**

Let's compare it with the so popular Hbb …

	H → ZZ* → 4l	H → bb
Branching Ratio	0.012%	58%
Mass resolution	1%	10%
S/B	2	0.02

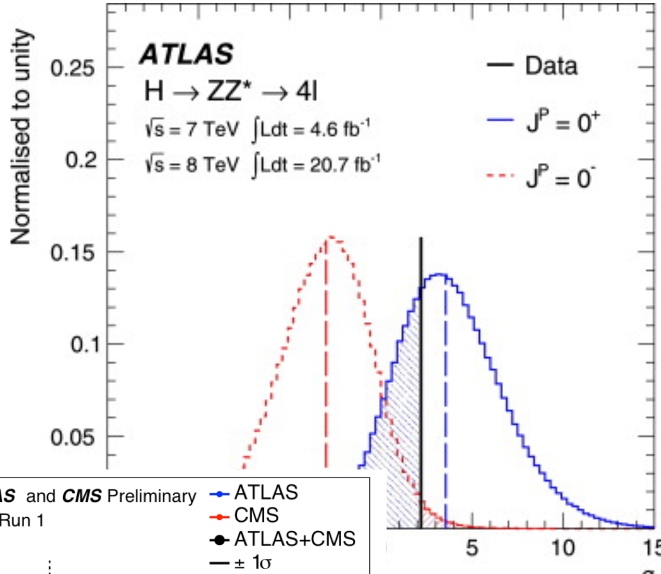


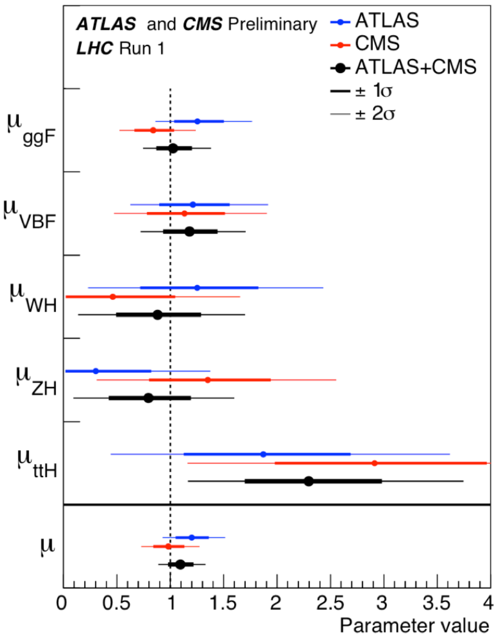


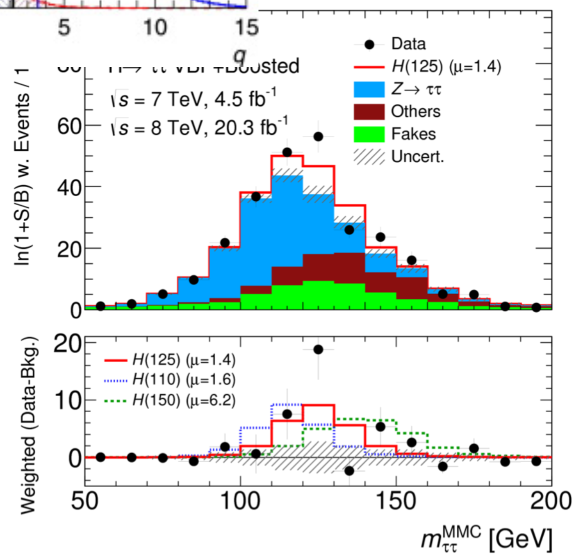
More is not always better!

The Run-1 lesson

What did we learn in Run 1?

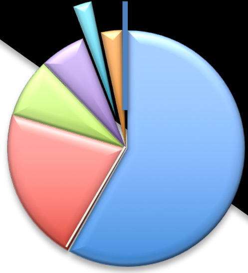




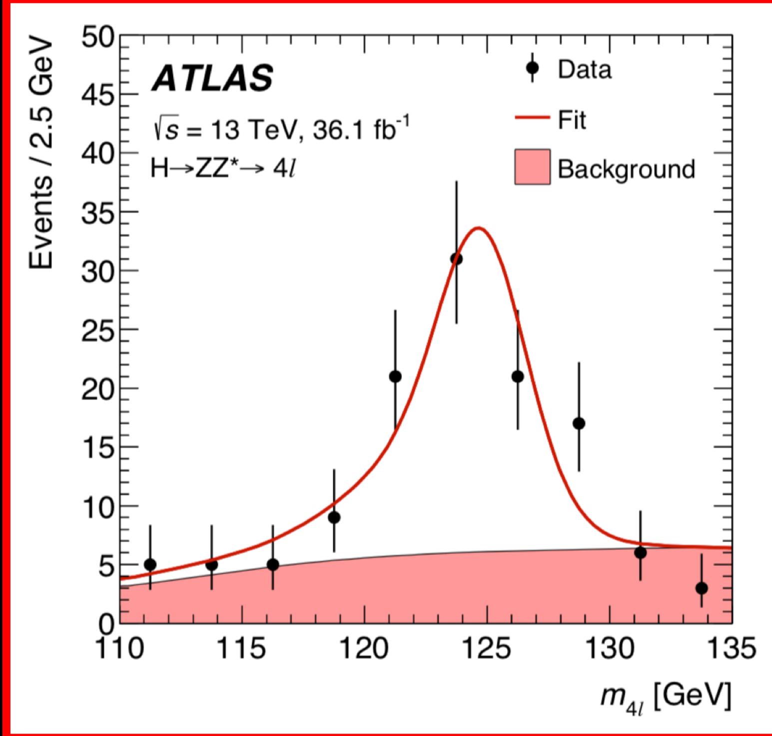


- Narrow resonance with a mass of 125 GeV (ATLAS with CMS 1.9 permille) and Spin/Parity 0^+
- Two production modes observed: VBF and ggF
- Decays observed: vector bosons and τ_s (ATLAS+CMS)
- Couplings agree within 10% with SM

Run-2 News



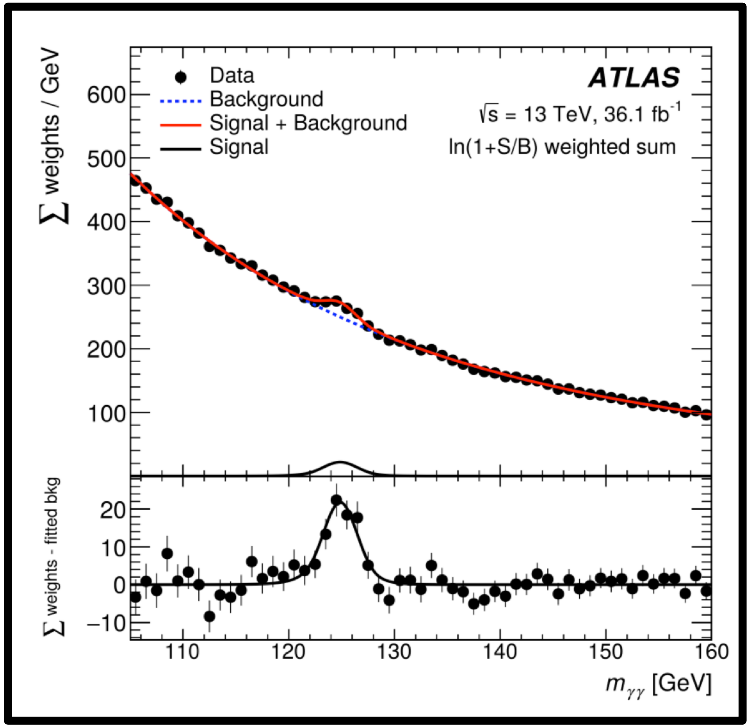
Higgs boson mass



Extraction from a fit to the di-photon inv.mass

+

Extraction from a fit to the 4l inv.mass



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Run-2 result based on the 2015-16 dataset

ATLAS Combination with Run 1:

m_H = (124.97±0.24) GeV

In Run 1 the 1.9 permille precision was achievable only when combining with CMS results!

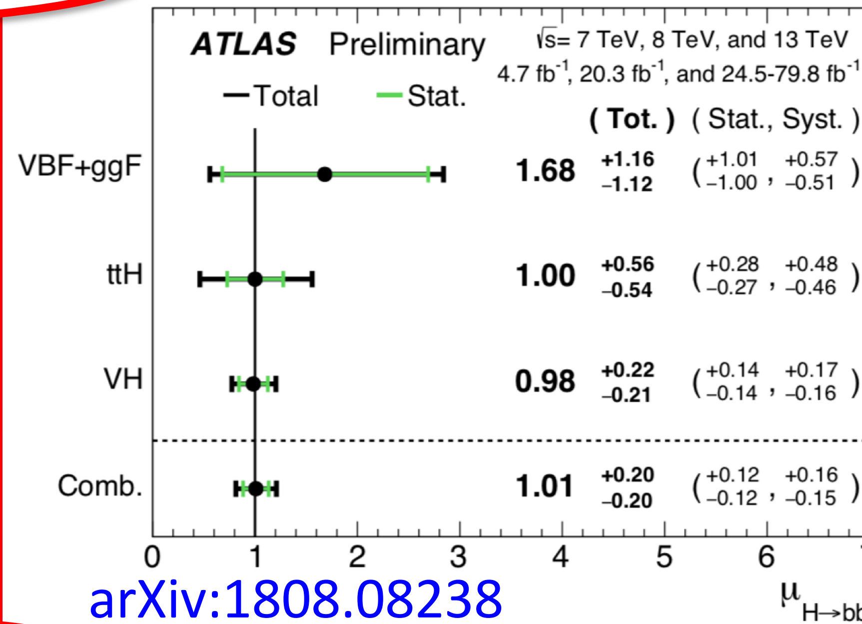
VH and Hbb Observation

H →bb combination

Run-1 and Run-2 analyses:

- ***VH, H →bb***
- ***VBF(+ggF), H →bb***
- ***ttH, H →bb***

Significance :
5.4σ obs. (5.5σ exp.)
Observation of H →bb !



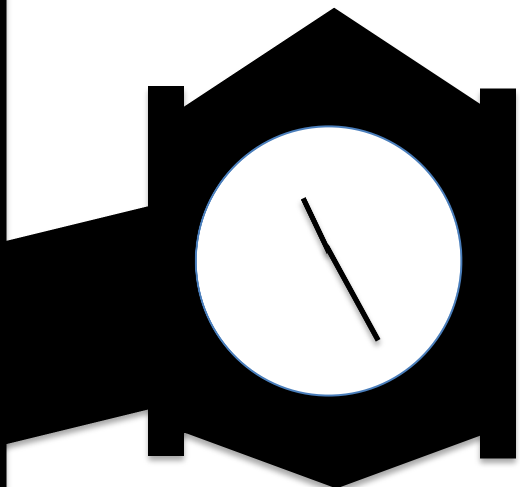
arXiv:1808.08238

VH combination

Run-2 analyses:

- *VH, H →bb*
- *VH, H →γγ*
- *VH, H →ZZ**

Significance : arXiv:1808.08238
5.3σ obs. (4.8σ exp.)
Observation of VH production !

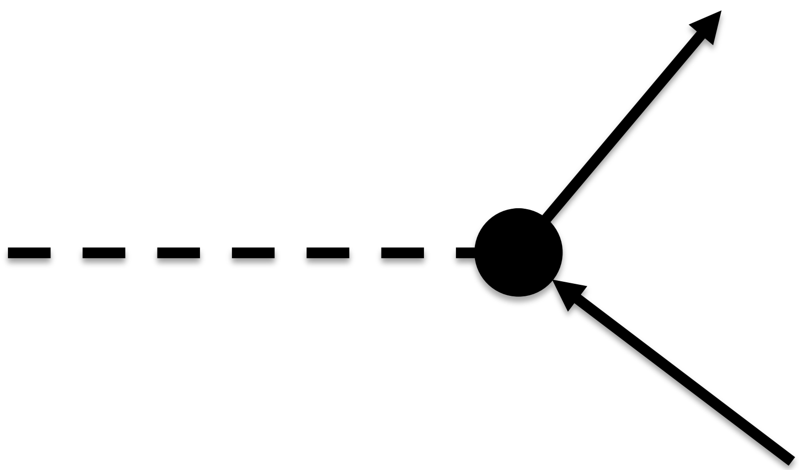


Higgs boson width

From partial widths …

- The Higgs boson is unstable
  - We just observe its decay products in the LHC detectors

- The rate for each open decay is defined by partial widths:



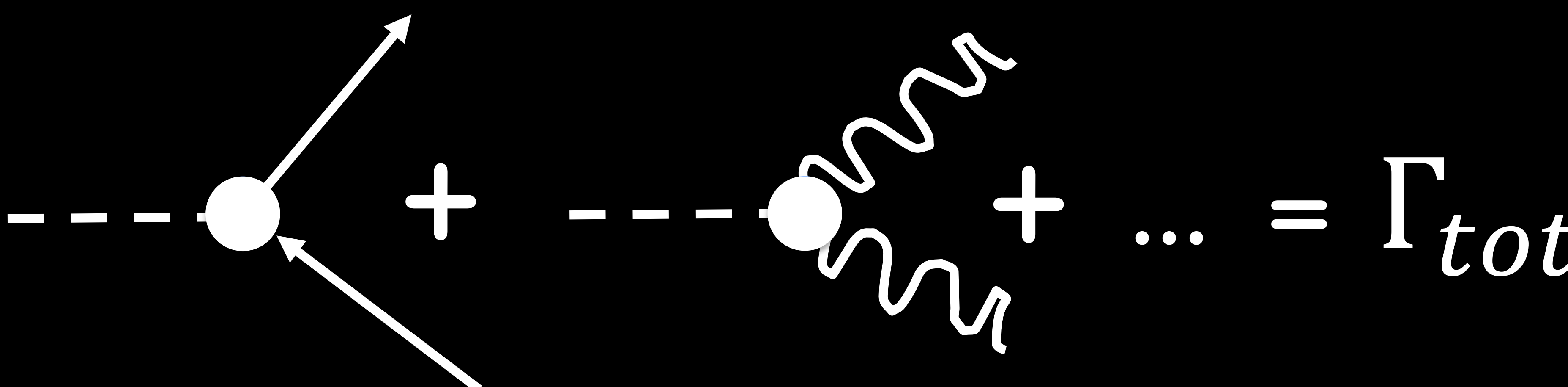
$\sim\Gamma_{b\bar{b}}$

with $BR(H \to b\bar{b}) = \frac{\Gamma_{b\bar{b}}}{\Gamma_{tot}}$

From partial widths … to total width

- The Higgs boson is unstable
  - We just observe its decay products in the LHC detectors

- The total width is the sum of all the partial widths:



What can we measure at LHC?

- Assuming a narrow width for the Higgs boson, we can write:

$$\sigma_{i\to H\to f} = \sigma_{i\to H} \times BR_{H\to f} = \frac{\sigma_{i\to H}\Gamma_{H\to f}}{\Gamma_H} \propto \frac{g_i^2 g_f^2}{\Gamma_H}$$

- At LHC:
  - we only have access to couplings ratio
  - measurements of individual channels require the total width measurement ➡ global information

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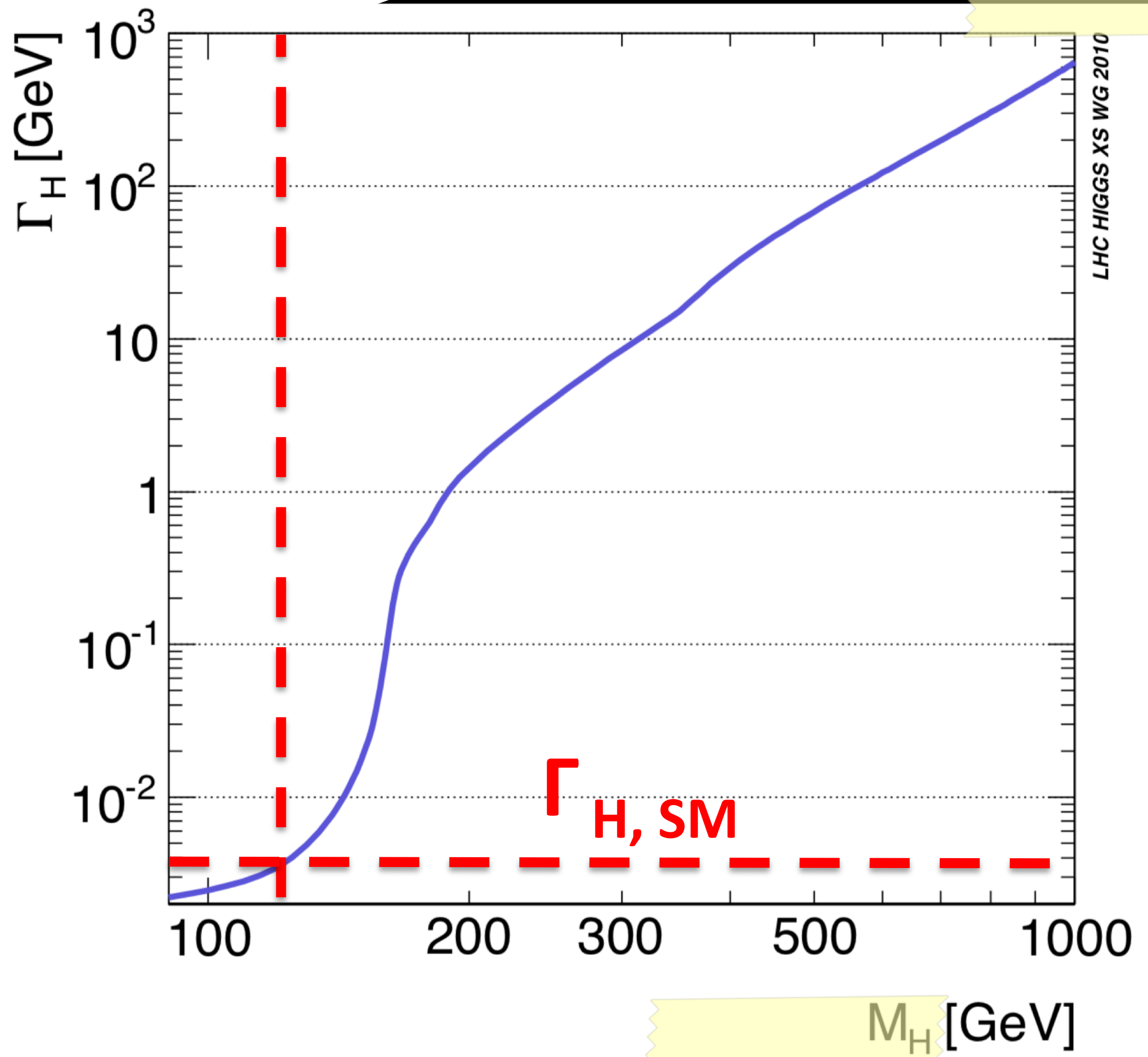
- At LHC:
  - we only have access to couplings ratio
  - measurements of individual channels require the total width measurement ➡ Theory dependence
  - How can we measure the Higgs boson width?

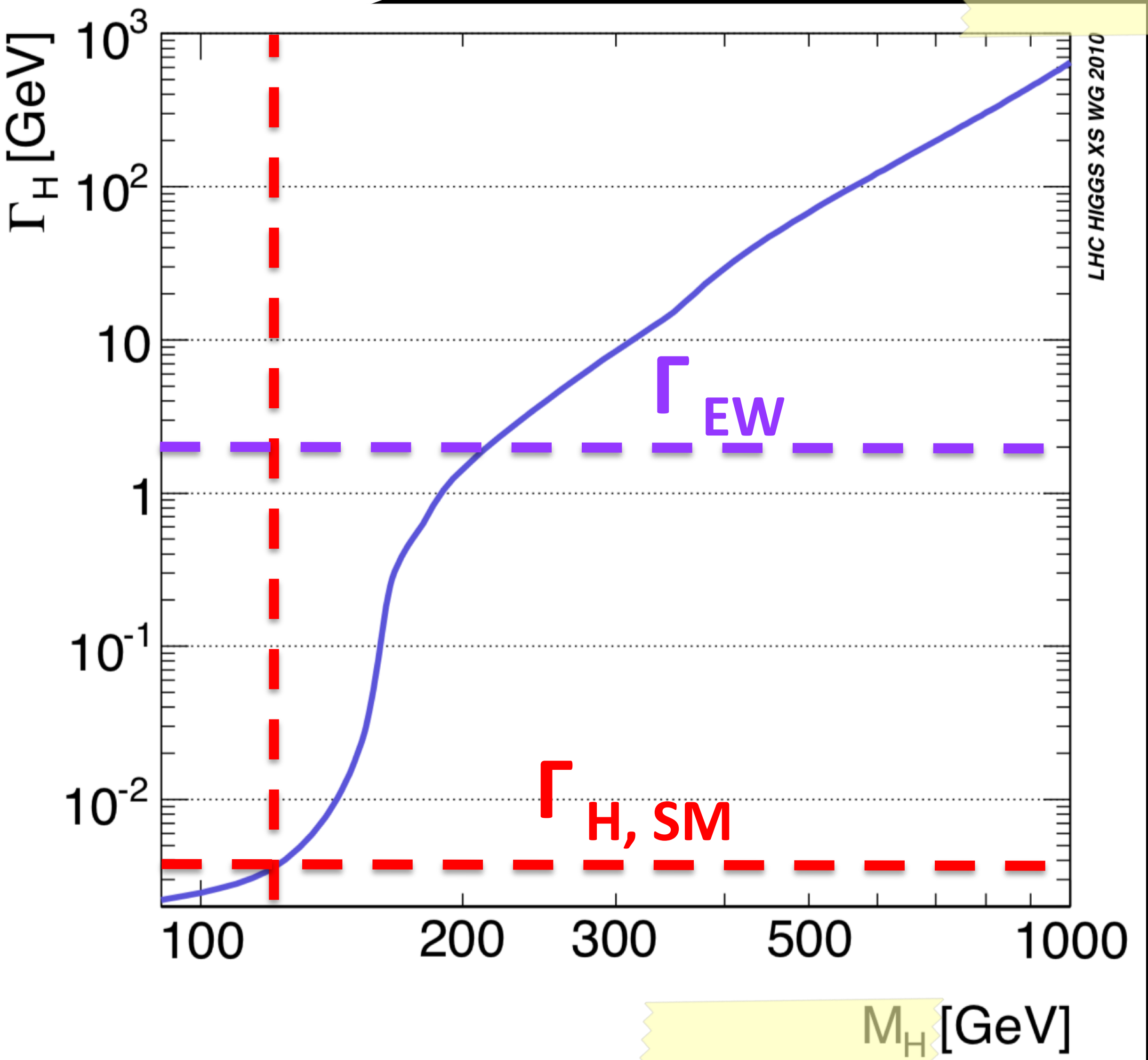
The Higgs boson width



The SM expectation for Γ_H for $m_H \sim 125$ GeV is **~ 4 MeV** …

… extremally small!

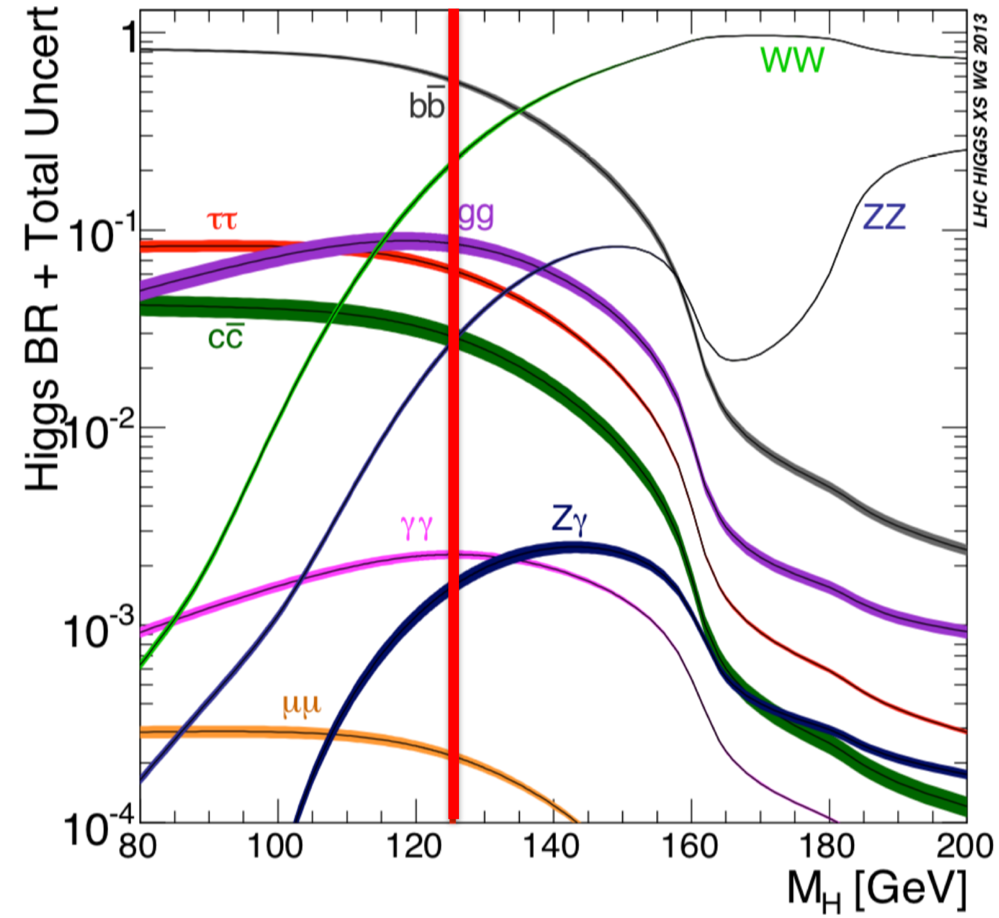
And the other EW bosons?



We have long experience with heavy EW bosons (W and Z). However, their width is **~ 2 GeV** …

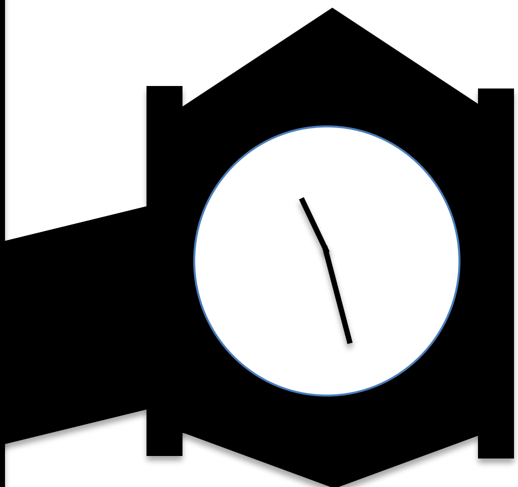
A narrow peak

- As said, the total width is the sum of all the partial widths



- The Higgs bosons prefers decays to *b* quarks
- You do the math …

$$\Gamma_H \sim \frac{m_b^2}{m_{EW}^2}\,\Gamma_{EW}$$



Higgs boson width: experimental results

How can we measure Γ_H at LHC?

- 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

How can we measure Γ_H at LHC?

- On the contrary of LEP or ILC, at LHC only $\sigma \cdot BR$ can be measured
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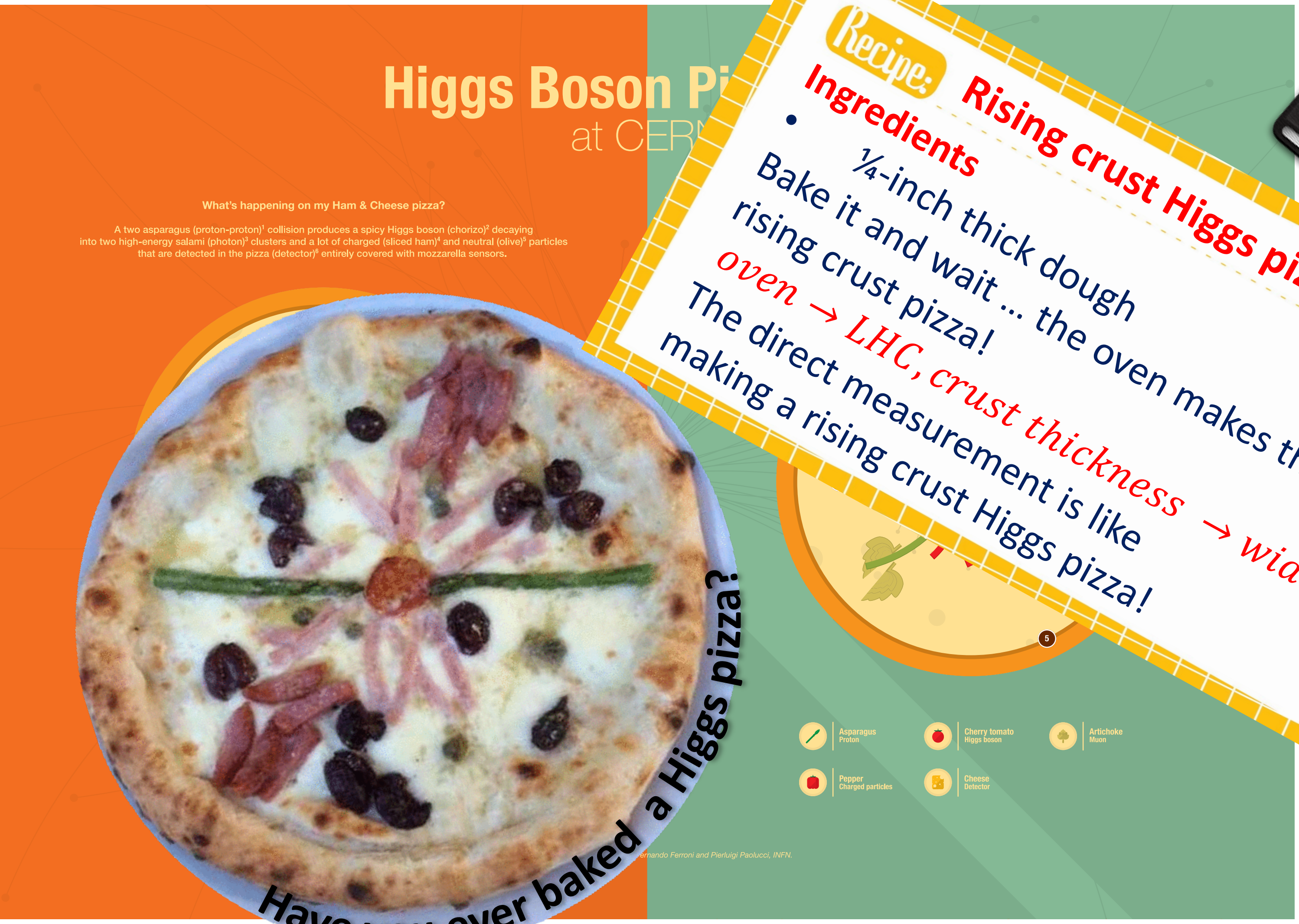
- **Direct** and indirect **strategies** have been considered
  - From the on-shell mass peak
  - From the lifetime

How about a Higgs pizza?



Have you ever baked a Higgs pizza?

Recipe: **Rising crust Higgs pizza**

Ingredients

- ¼-inch thick dough

Bake it and wait … the oven makes the miracle: a rising crust pizza!

oven → LHC, crust thickness → width

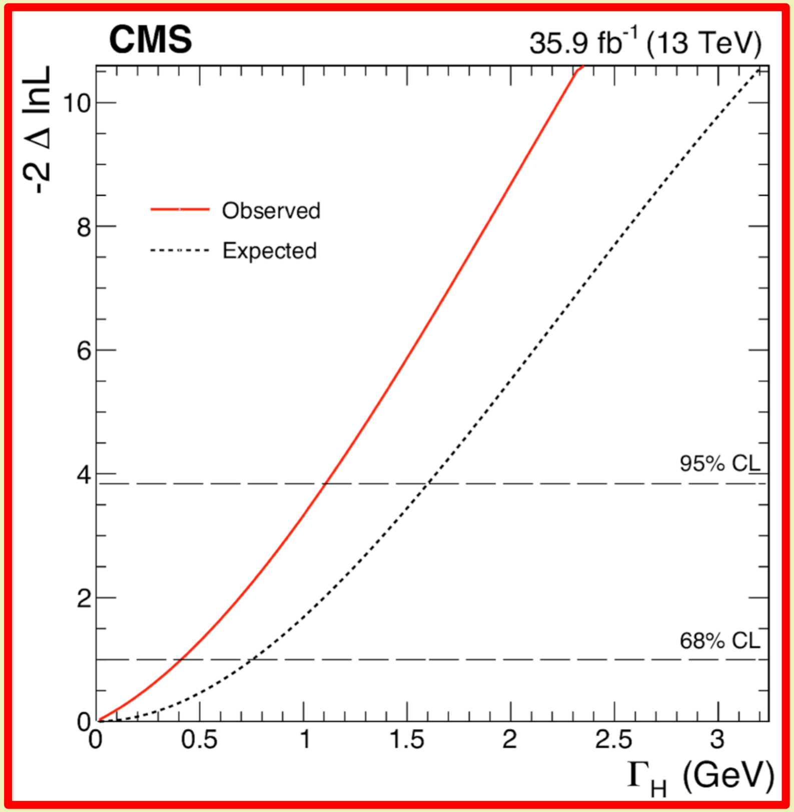
The direct measurement is like making a rising crust Higgs pizza!

Direct strategies

From the on-shell mass peak

- Convolution of natural width ($4.1\ MeV$) and experimental mass resolution ($\sim 1.3\ GeV$)
- 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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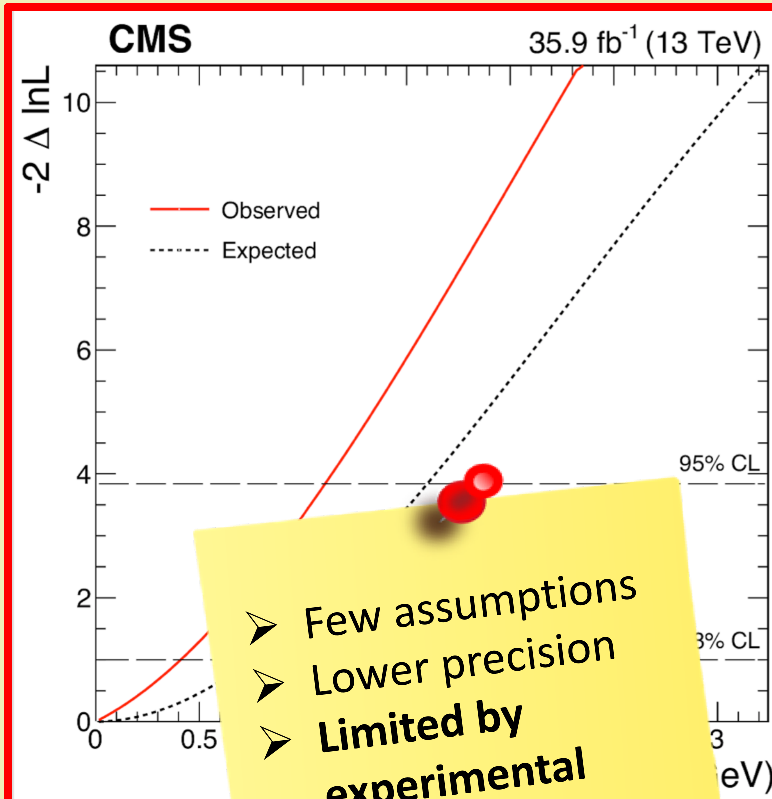
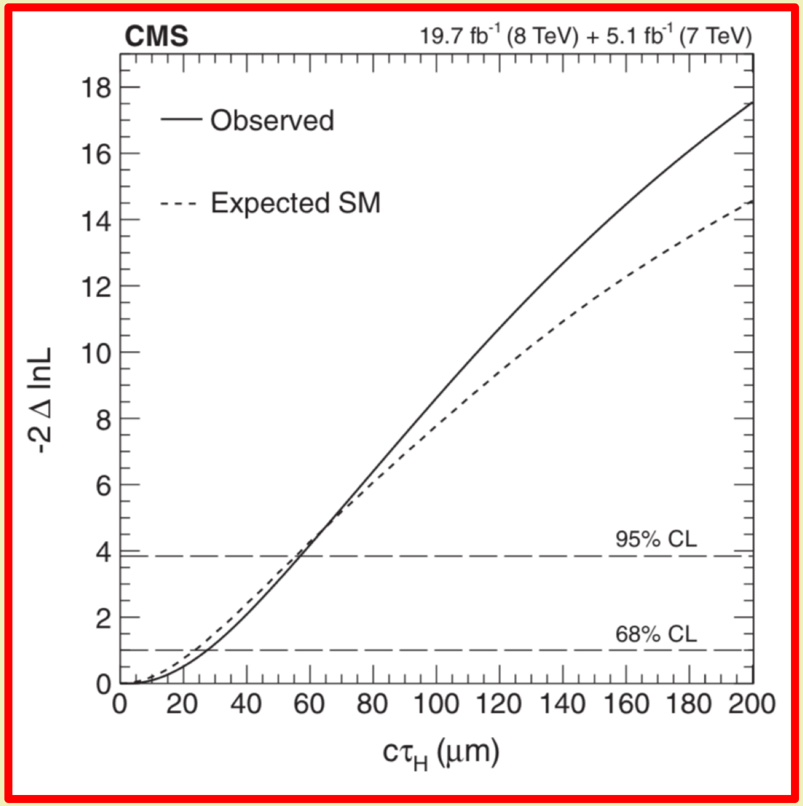


- Few assumptions
- Lower precision
- **Limited by experimental resolution**

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

Direct strategies

From the lifetime



- Using the Higgs lifetime we can set a direct lower bound
- $\Gamma_H = \hbar\ /\tau_H\ with\ c\tau_H = 48\ \text{fm}$
  - 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:] $c\tau_H < 57\ \mu\text{m}\ \rightarrow \boldsymbol{\Gamma_H > 3.5\ \cdot 10^{-3} eV\ at\ 95\%\ CL}$

How can we measure Γ_H at LHC?

- 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

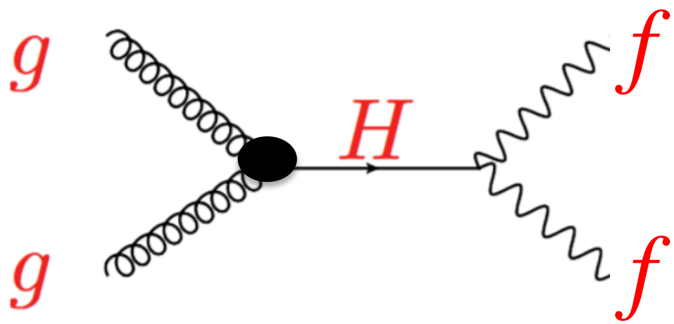
- Direct and **indirect strategies** have been considered
  - From the on-shell mass peak
  - From the lifetime
  - From couplings
  - From off-shell to on-shell production …**Best proxy to-date!**

Sometimes it's just a matter of bon-ton!

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:



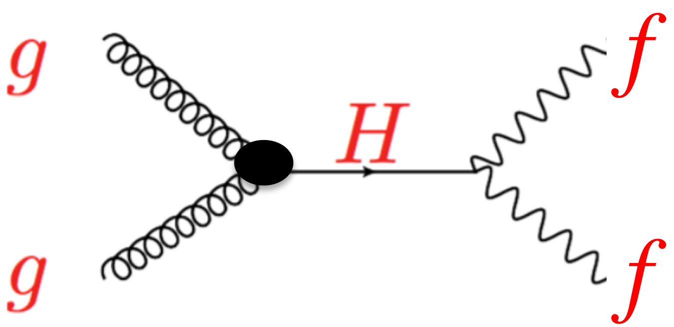
Production cross section

$$\boxed{\frac{d\sigma_{gg\to H\to ff}}{dm^2} \sim \frac{g_i^2 g_f^2}{(m^2-m_H^2)^2+m_H^2\Gamma_H^2}}$$

- On-shell production $\sigma^{on-shell}_{gg\to H\to ff} \sim \frac{g_i^2 g_f^2}{m_H \Gamma_H}$
- **No way to measure the Higgs couplings and width separately**

Off-shell Higgs production

- Why off-shell production?

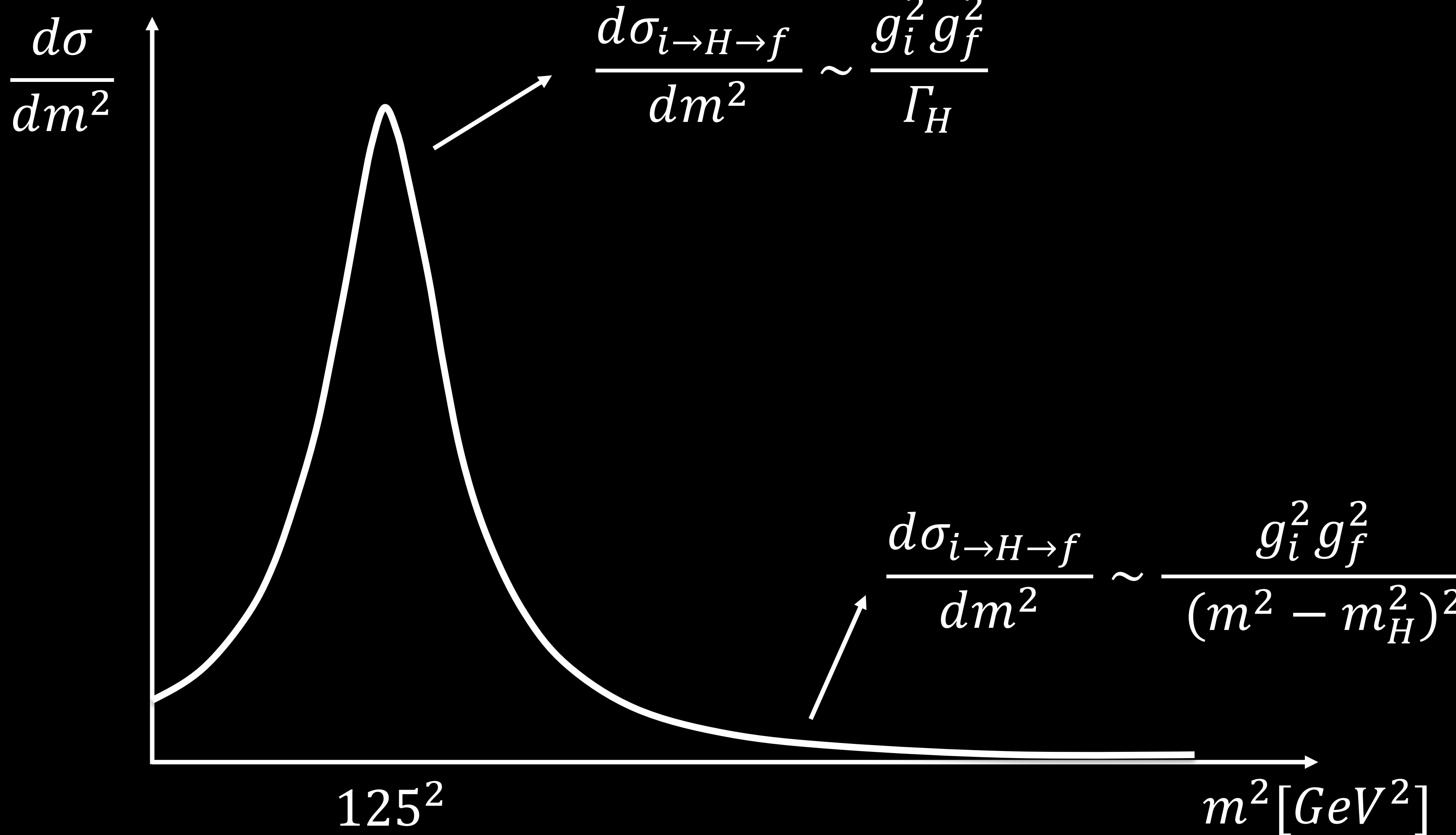


Production cross section

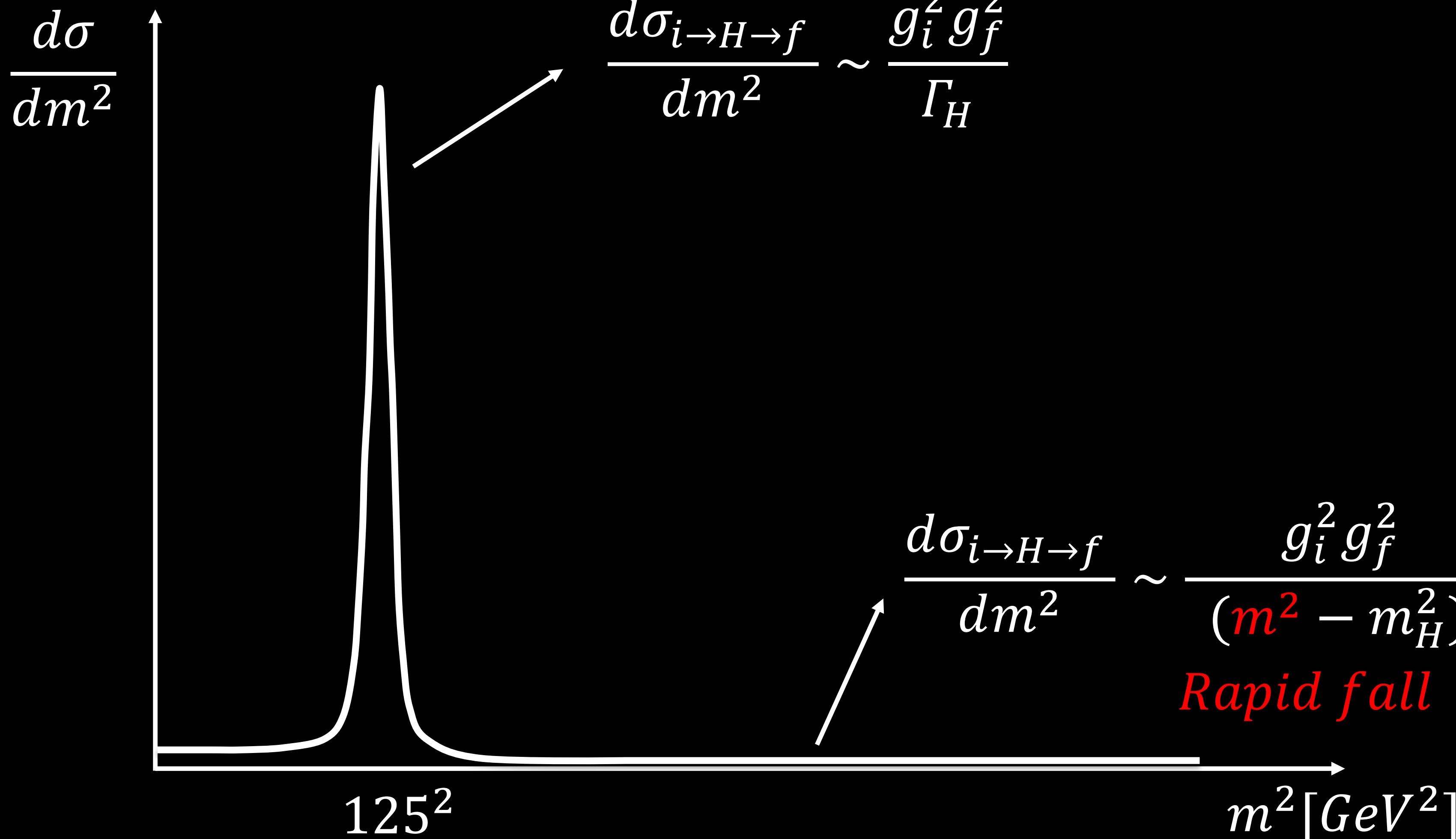
$$\boxed{\frac{d\sigma_{gg\to H\to ZZ}}{dm^2} \sim \frac{g_i^2 g_f^2}{(m^2-m_H^2)^2+m_H^2\Gamma_H^2}}$$

- Off-shell production (for $m > 2m_Z$) $\sigma_{gg\to H^*\to ff}^{off-shell} \sim \frac{g_i^2 g_f^2}{(m^2-m_H^2)^2}$
  - ***Width-independent: width-couplings ambiguity resolved***
  - Unfortunately, the off-shell contribution is expected to be extremely small …

On-shell vs Off-shell Higgs production



On-shell vs Off-shell Higgs production

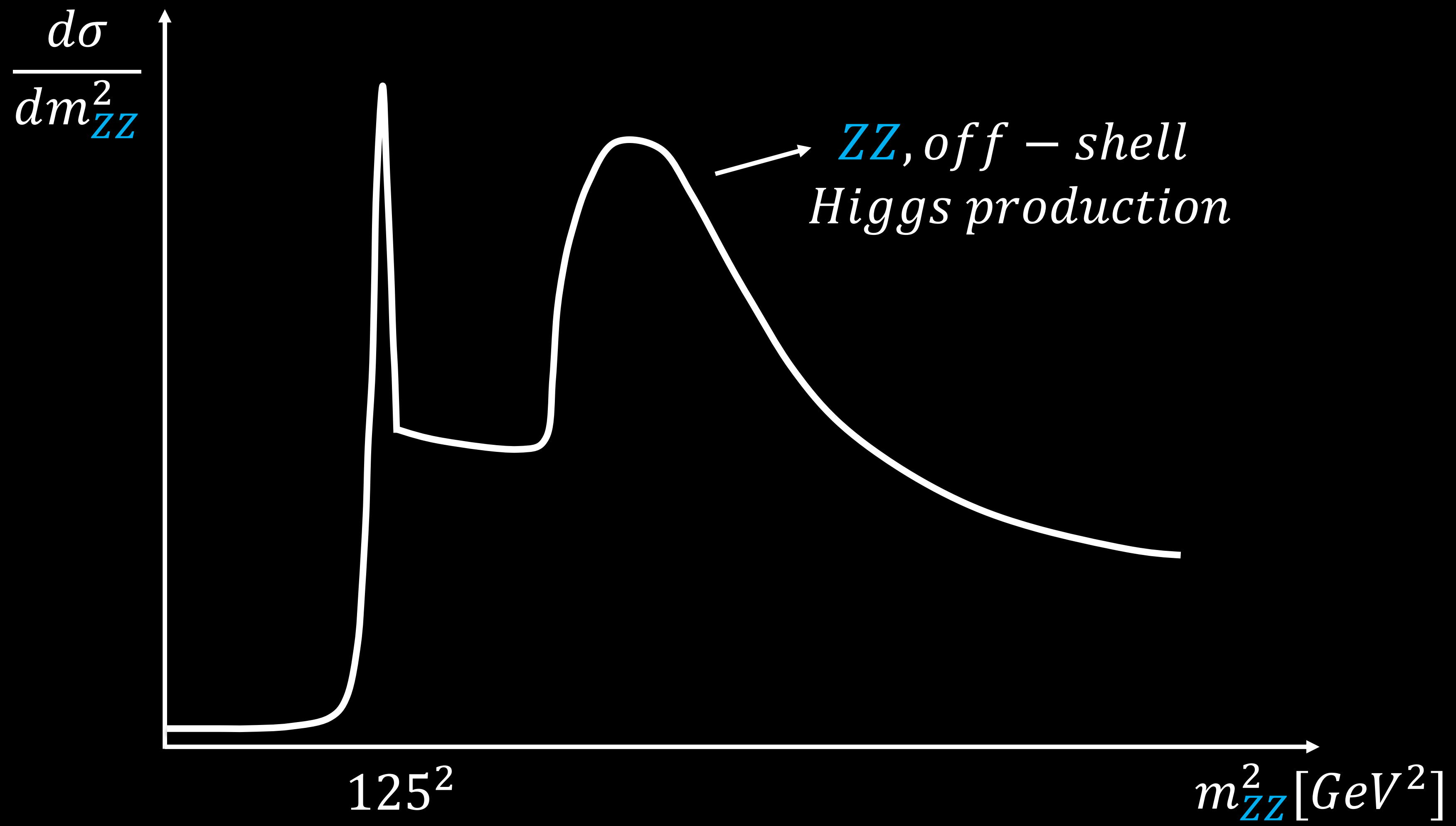


$$\frac{d\sigma_{i\to H\to f}}{dm^2} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

$$\frac{d\sigma_{i\to H\to f}}{dm^2} \sim \frac{g_i^2 g_f^2}{(m^2 - m_H^2)^2}$$

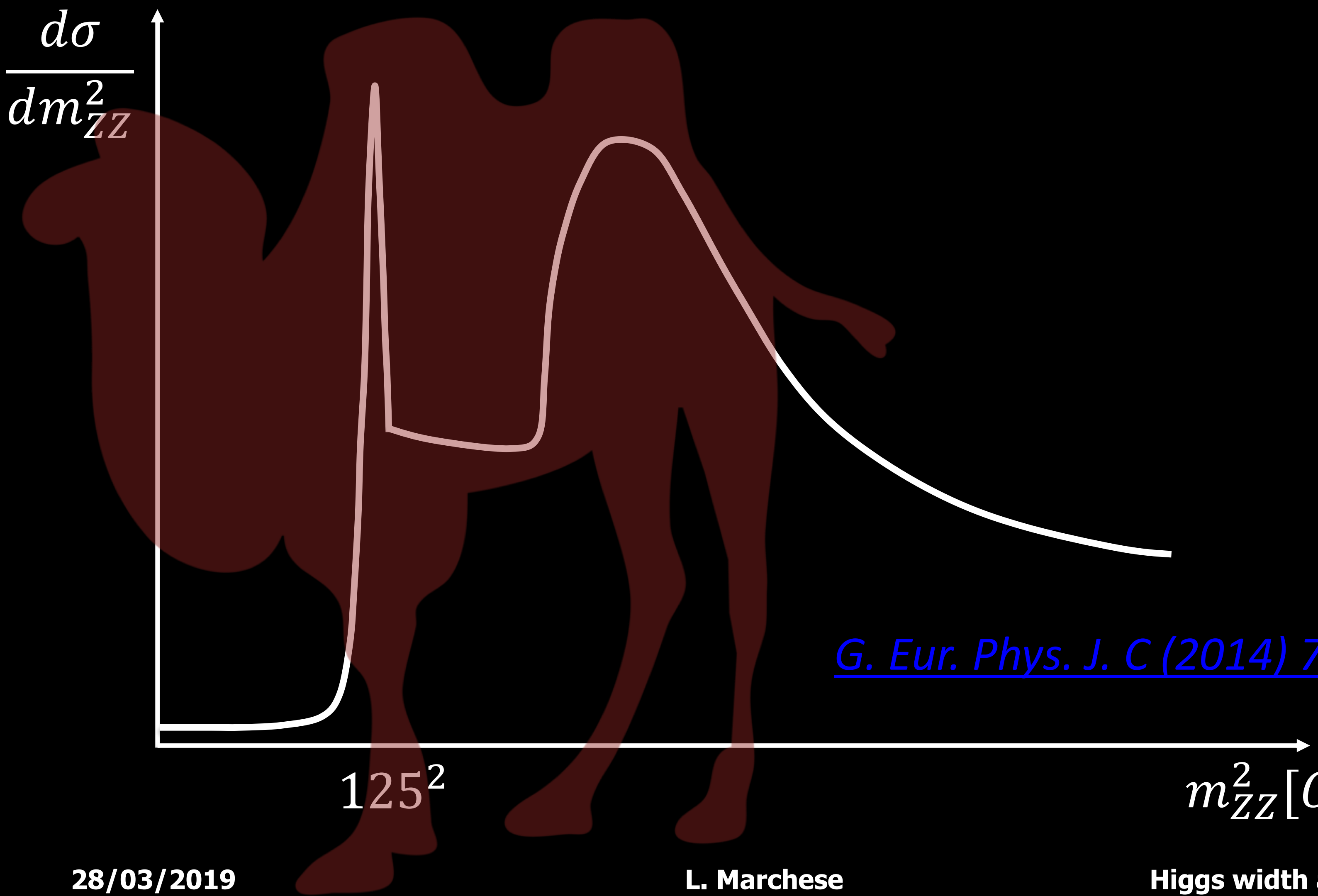
Rapid fall

On-shell vs Off-shell Higgs production



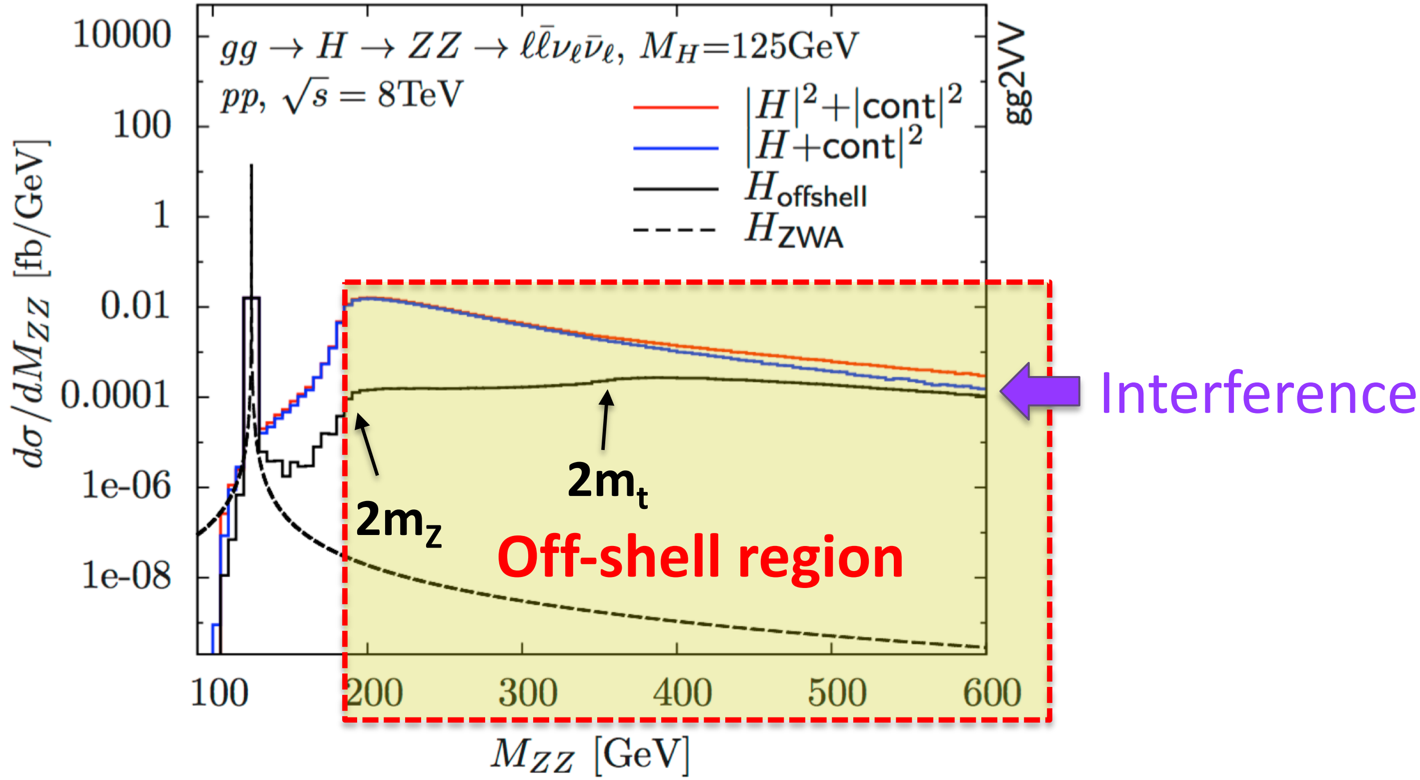
A camel-shaped mass-line

There is so much physics in a camel hump!



[G. Eur. Phys. J. C (2014) 74: 2866]

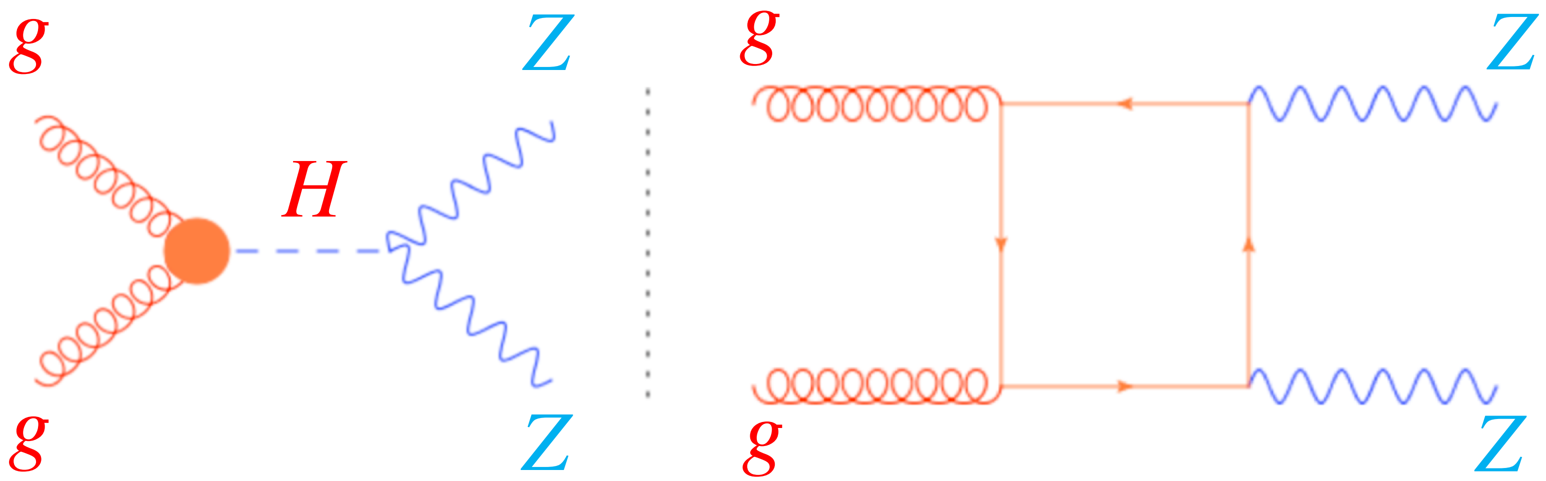
Once upon a paper …



- 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



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

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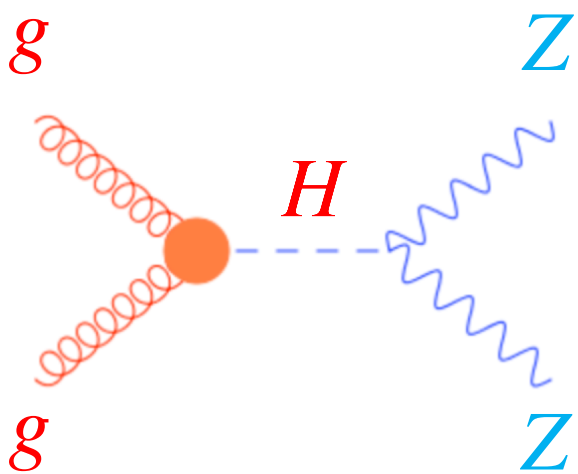
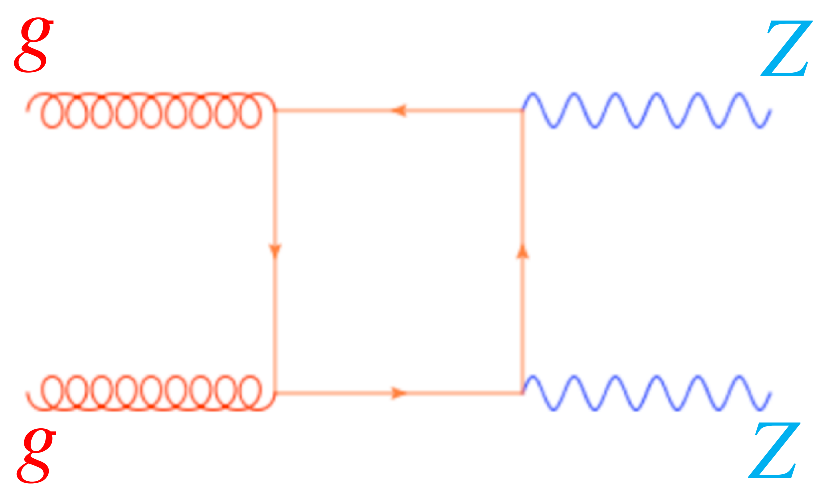




$$\mu_{off-shell} - independent$$

$$|\mathcal{M}_{ZZ}|^2 = \left|\mathcal{M}_H + \mathcal{M}_{Bkg}\right|^2 = \underbrace{|\mathcal{M}_H|^2}_{\sim\mu_{off-shell}} + \left|\mathcal{M}_{Bkg}\right|^2 + \underbrace{2Re(\mathcal{M}_H\mathcal{M}_{Bkg}^*)}_{\sim\sqrt{\mu_{off-shell}}}$$

Analysis idea

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

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

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

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

From an independent analysis

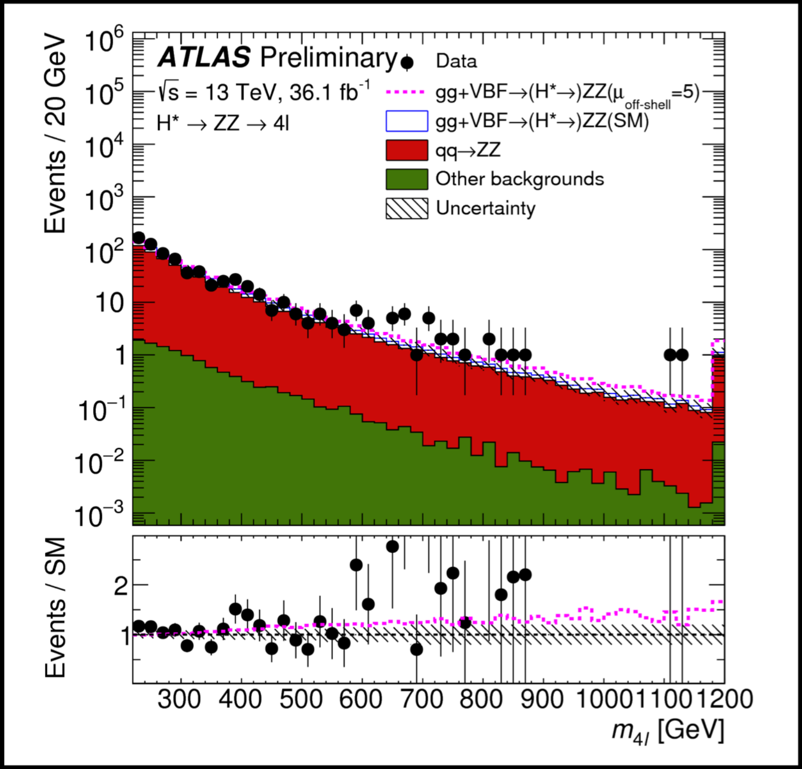
- **This strategy is assuming identical on-shell and off-shell couplings**
  - **No new physics alters the Higgs couplings in the off-shell regime**

Analysis strategy

- Two decay channels, $H^* \to ZZ \to 4l$ and $H^* \to ZZ \to 2l2v$
- Analysis performed inclusively, ggF+VBF

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

ATLAS 4l invariant mass



Theory Corr.

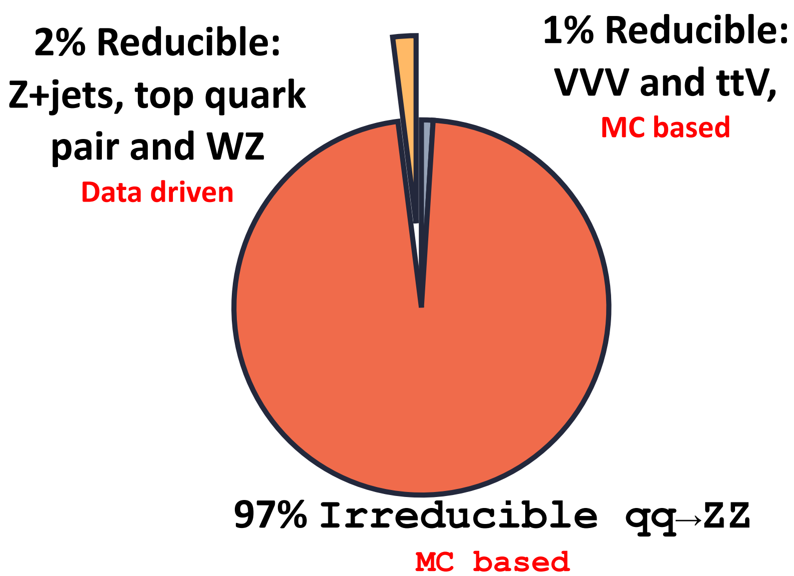
- [NLO corrections]() finally available for Interference and background for $gg \to (H^*) \to ZZ$ as a function of m(ZZ)

- Significant improvement w.r.t. the Run-1 results, still **leading systematics at 20%**

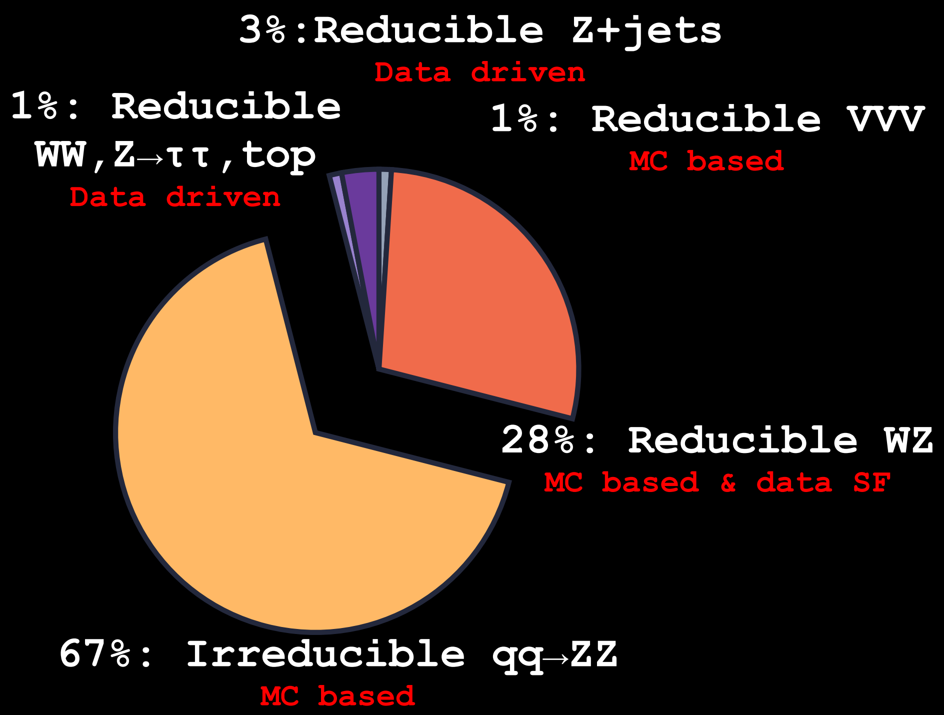
Background contributions

➢ In both the channels, the leading background is qq→ZZ

Background composition in 4l



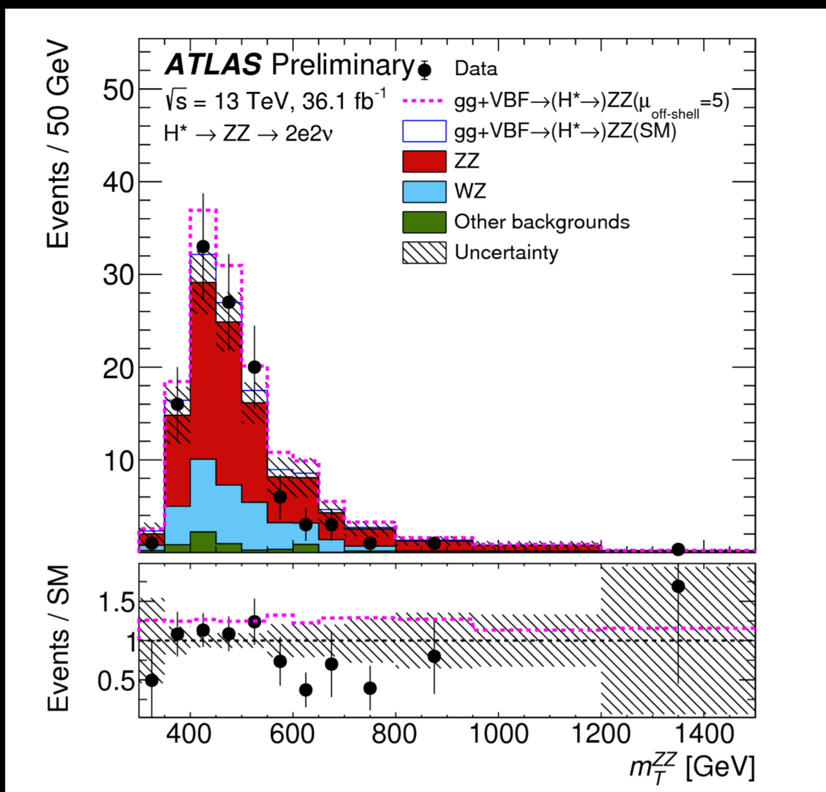
Background composition in 2l2v



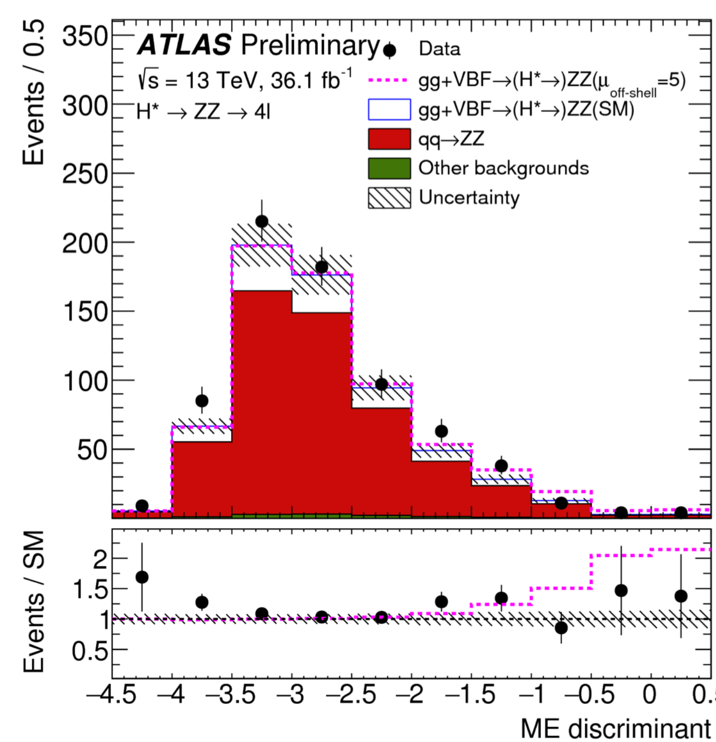
Discriminants

- 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



Analysis combination

- Two-step strategy:

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

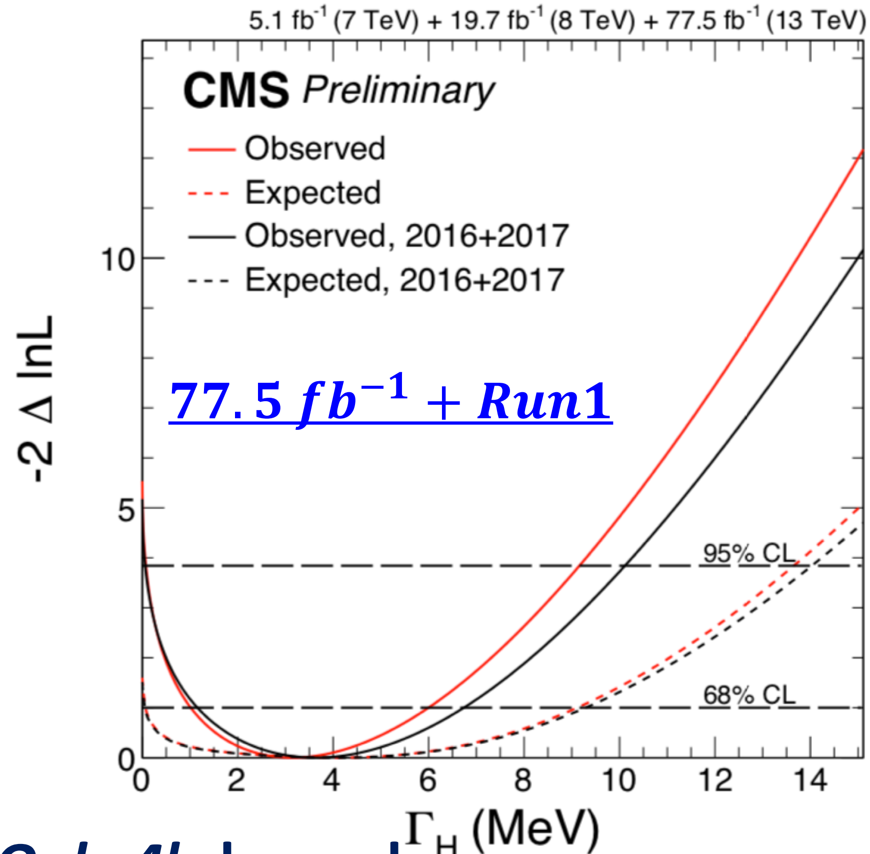
Higgs boson total width constraints

- 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

Run-2 results

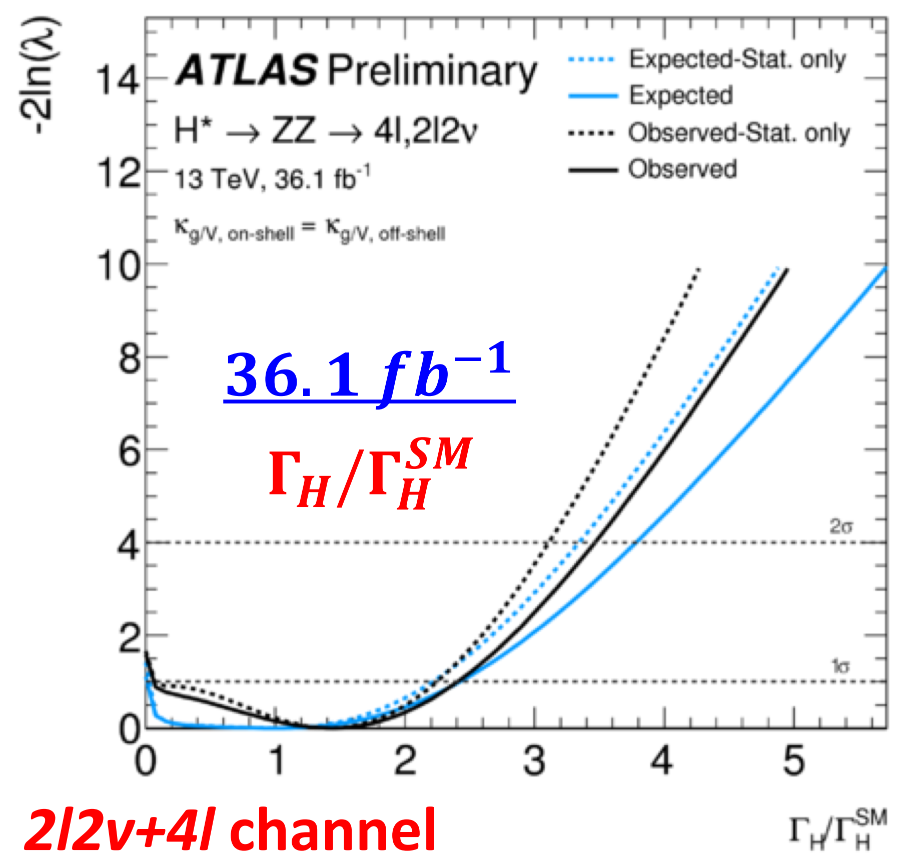
- Hypothesis testing for a parameter of interest
- Confidence intervals based on the profile likelihood ratio

$\Gamma_H < 9.16$ MeV obs. (13.7 MeV exp.)



***Only 4l* channel**

$\Gamma_H < 14.4$ MeV obs. (15.2 MeV exp.)



***2l2v+4l* channel**

Run-2 results

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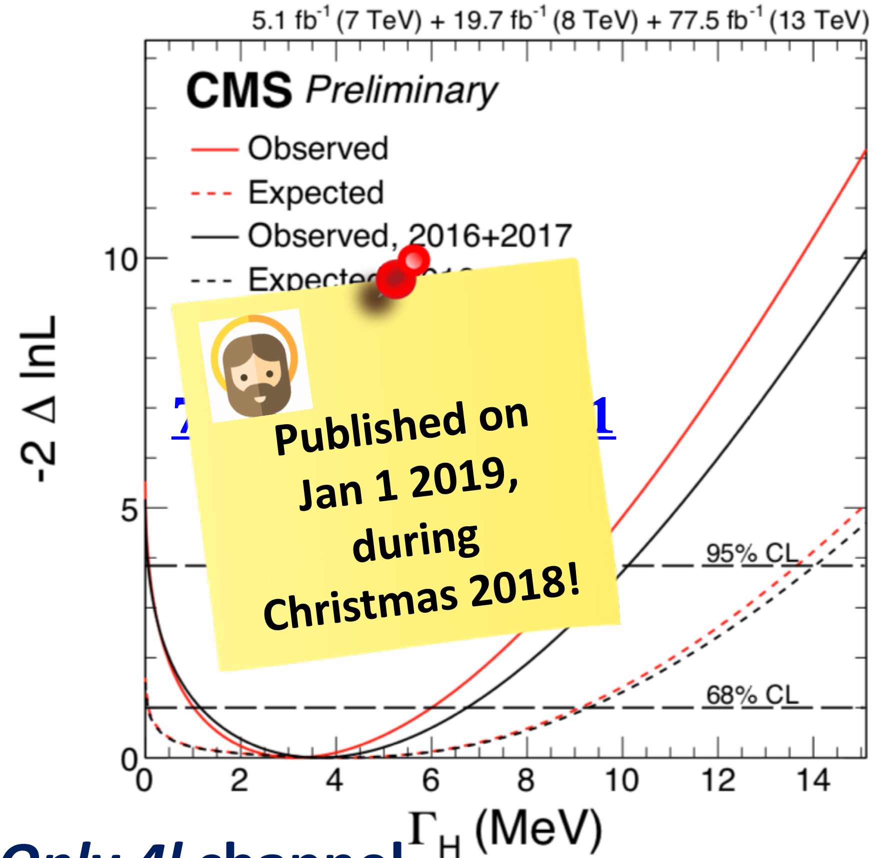

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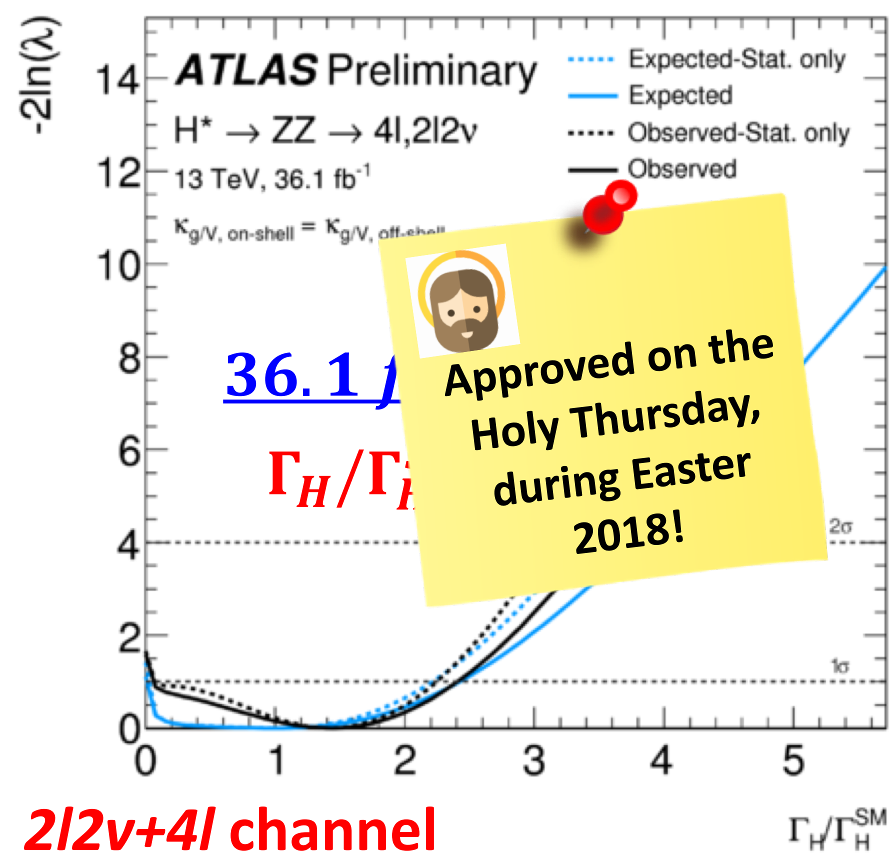


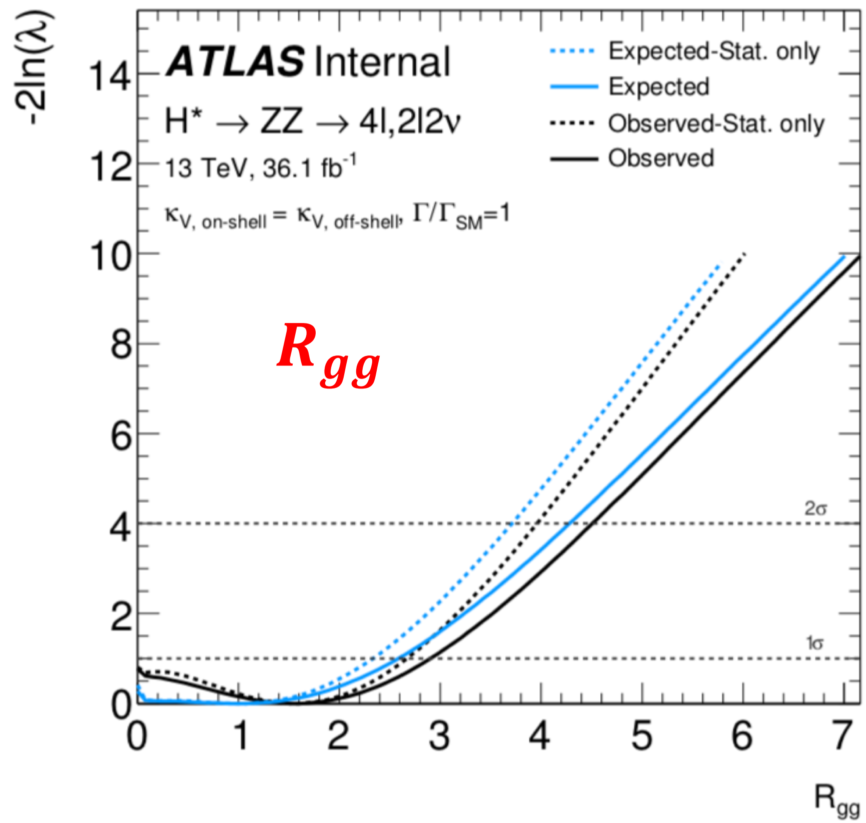
***2l2v+4l* channel**

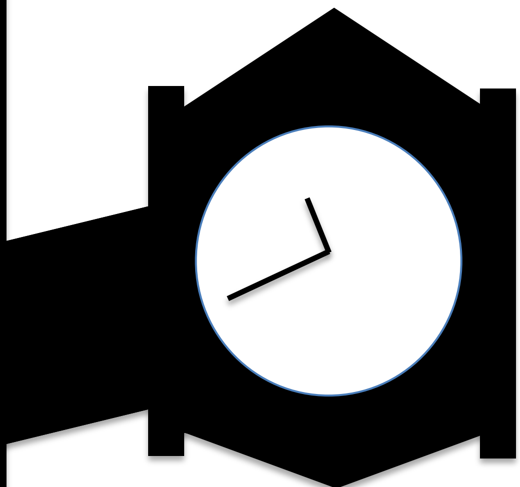
R_{gg} interpretation

- In a second combination, ATLAS considers 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





Conclusions

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- 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):

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

$$CMS\ 77.5\ fb^{-1} + Run\ 1\text{: } \Gamma_H < 9.16\ obs.\,(13.7\ exp.\,)MeV$$

  - 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 a factor 2 !

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

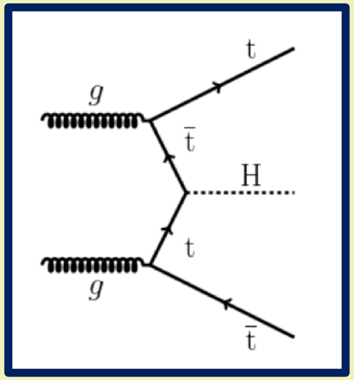
- At ILC the accuracy achievable is 1.7%

Back-up

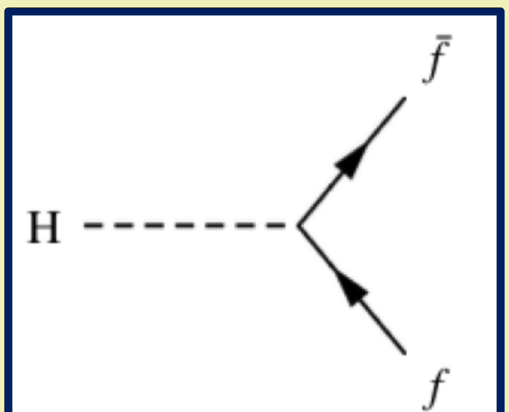
Higgs couplings

DIRECT PROBES

at tree level



ttH

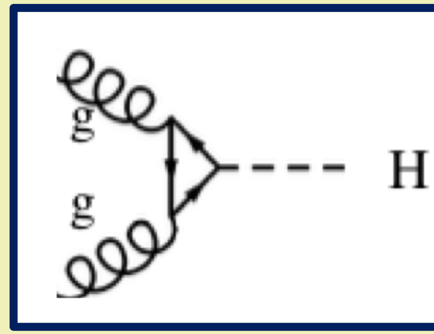


Different generations:

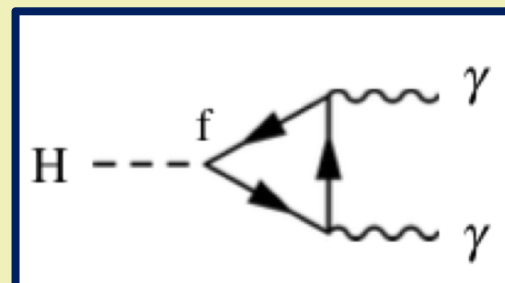
- Leptons
- Up-type quarks
- Down-type quarks

INDIRECT PROBES

via loop diagrams



gluons



photons

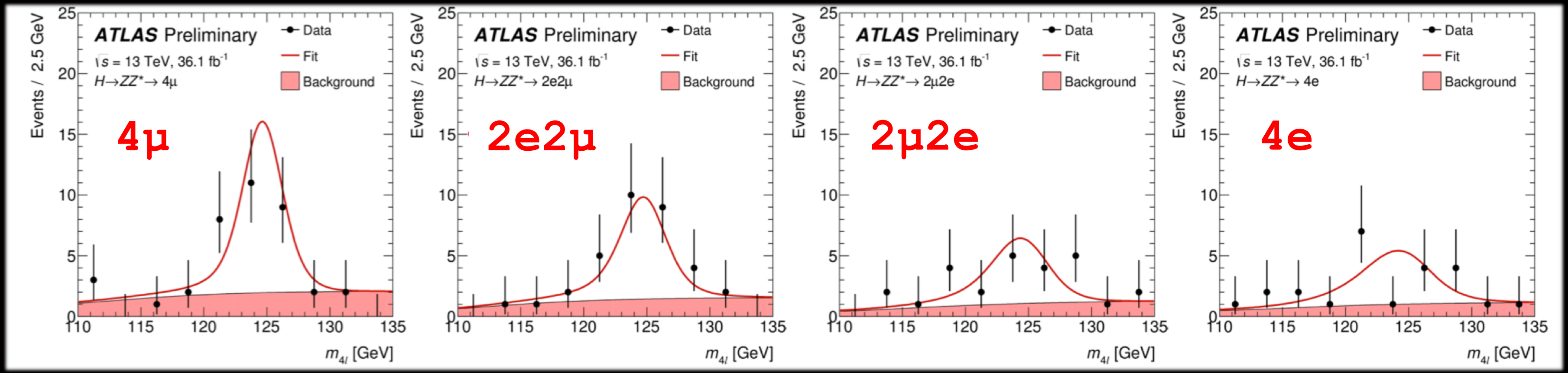
Higgs boson mass in the 4l channel

- **Event selection and categorization as in other HZZ* analyses: 2 same-flavour opposite-sign leptons organized in 4 categories 4μ,2e2μ,2μ2e and 4e**

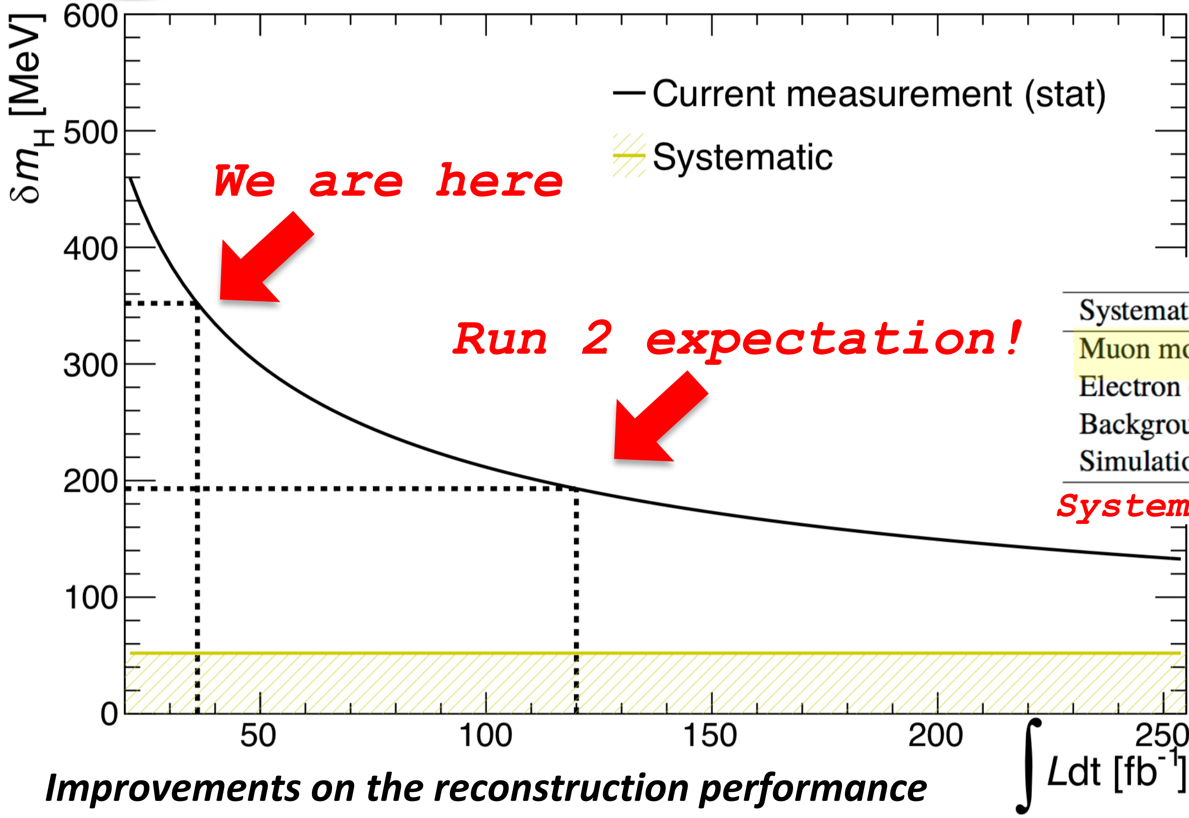
Strategy: $BDT(p_T^{4l}, \eta^{4l}, \mathcal{D}_{ZZ*})$ to distinguish H→ZZ*→4l from ZZ*→4l, (dominant background) with $\mathcal{D}_{ZZ*} = log|m_{H\to ZZ*}|/|m_{ZZ*}|)$

➢ **Higgs boson mass determined from a simultaneous profile likelihood fit to 16 data categories:**

4 final states × 4 BDT bins



Higgs boson mass: Run-2 prospects



Systematic effect	Uncertainty on $m_H^{ZZ^*}$ [MeV]
Muon momentum scale	40
Electron energy scale	20
Background modelling	10
Simulation statistics	8

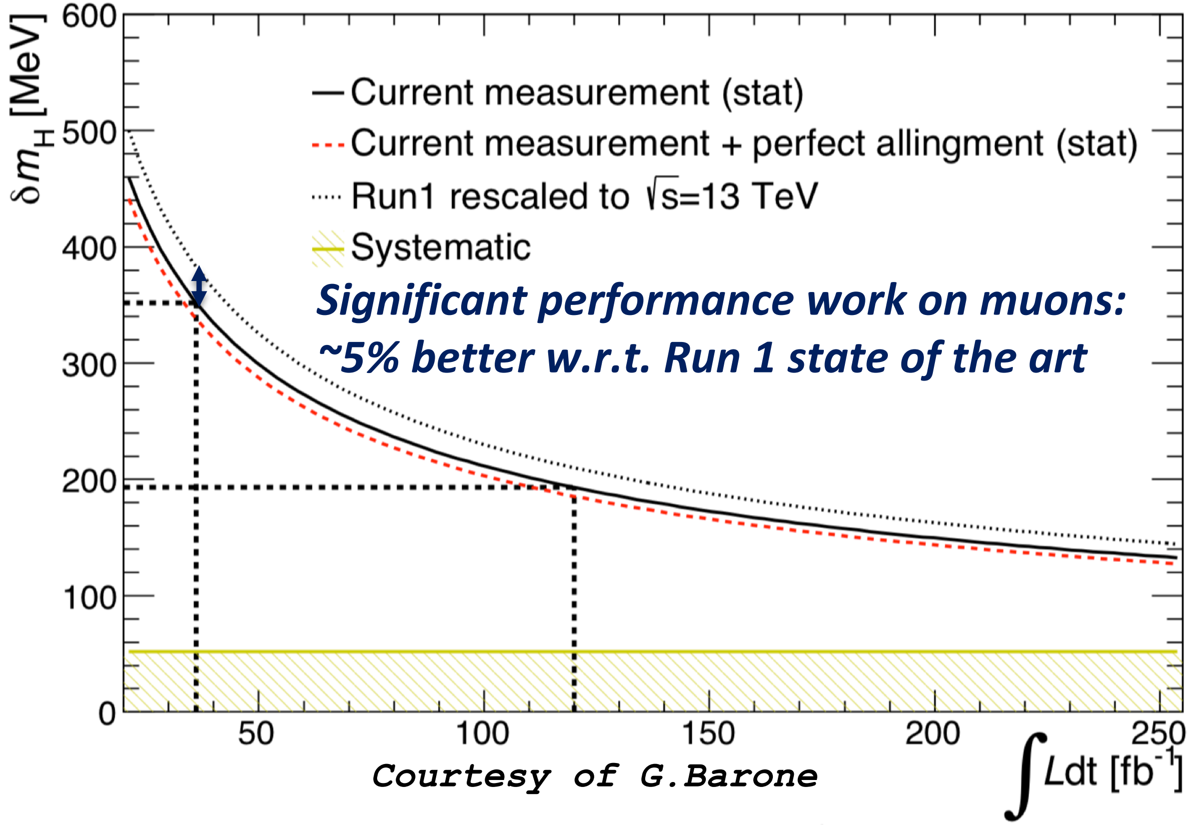
Systematics breakdown (2015-2016)

Improvements on the reconstruction performance of muons/electrons

$$\delta m_H = \frac{\sigma}{\sqrt{N_{Sig\ events}}}$$

- Statistically limited
- δm_H scales linearly with resolution improvements

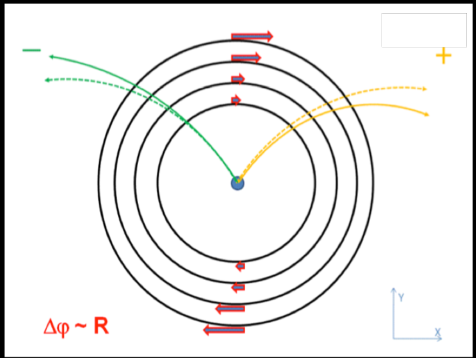
Higgs boson mass: performances

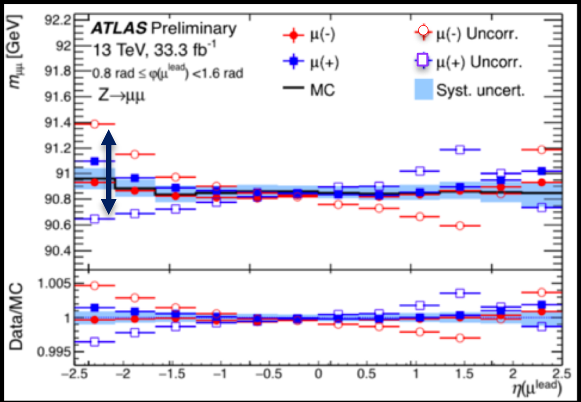


Courtesy of G.Barone

ID DISTORTIONS

ID Deformations induce local scale biases and degrade resolution in a charge asymmetric way

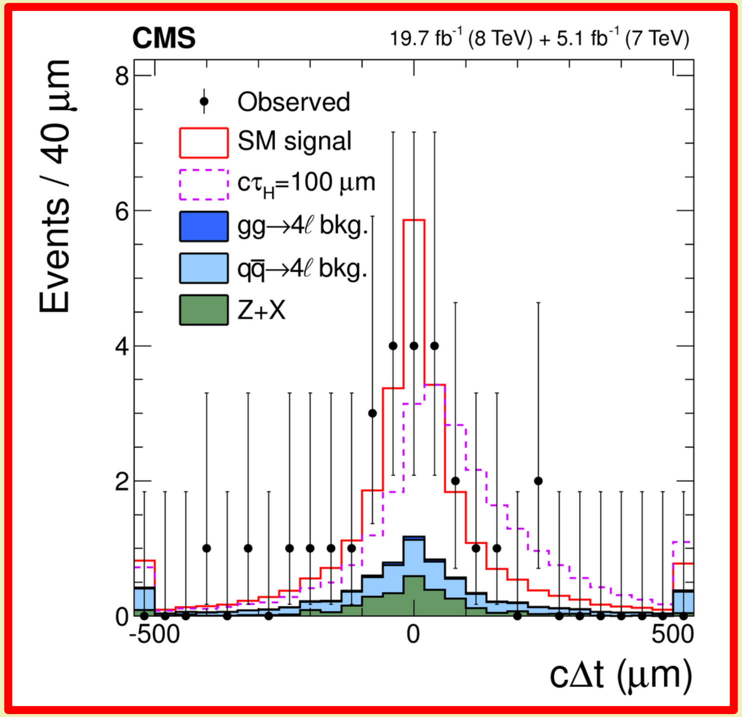




Key to precise Higgs boson mass measurement is the calibration of the ATLAS detector

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:

  $\Delta t\ and\ D_{bkg}(m_{4l}$ and $D^{kin})$

Indirect strategies: from couplings

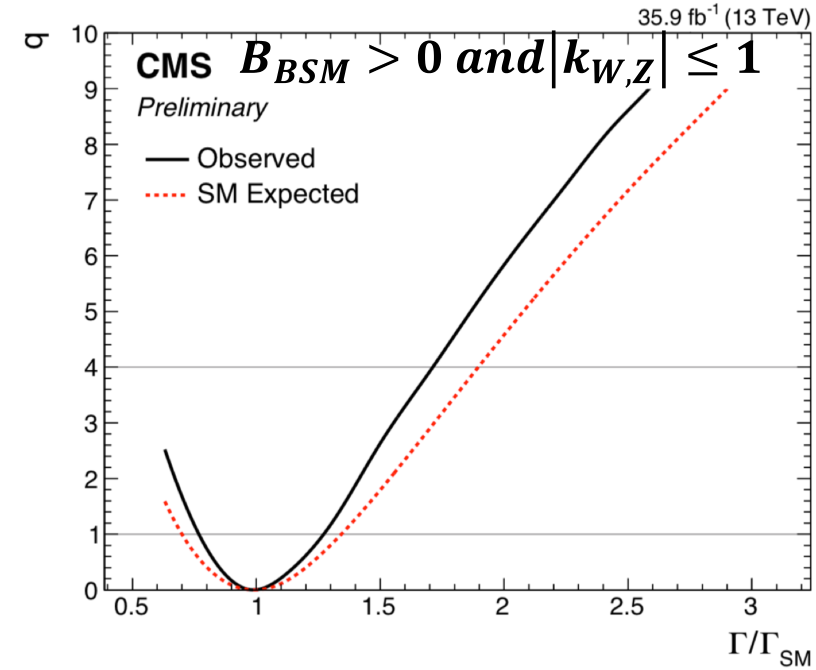
- Using the [coupling analysis framework]() we can constrain Γ_H:

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

Two possible interpretations:

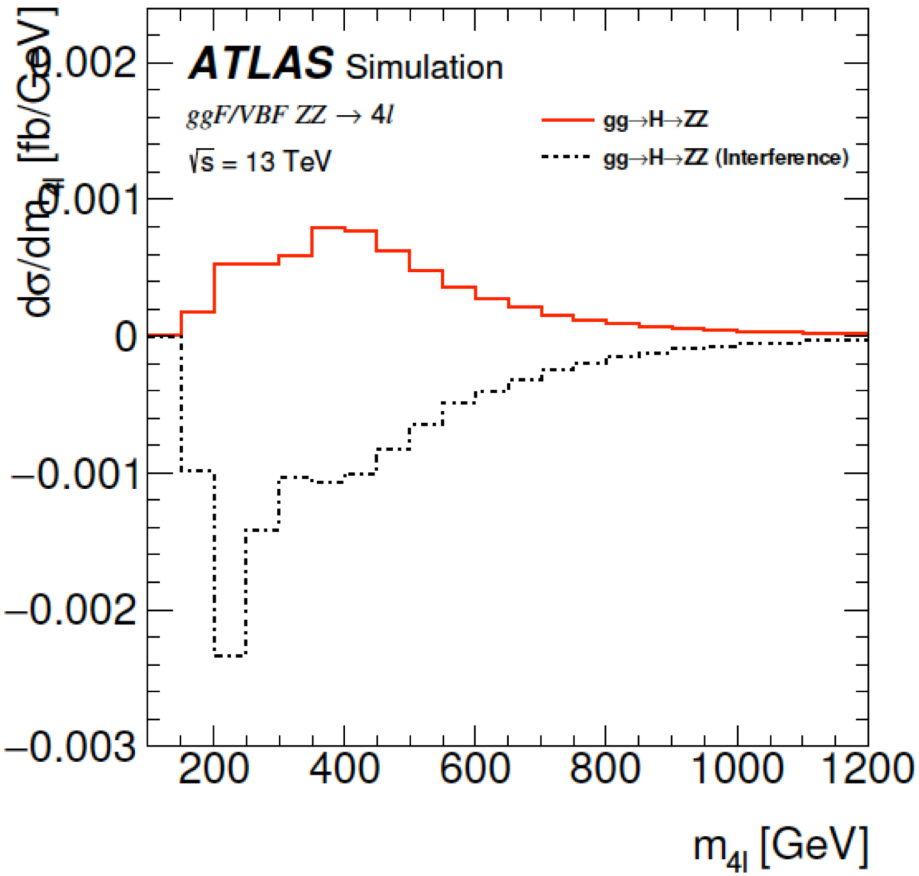
- $B_{BSM} = 0$
- $B_{BSM} > 0 \; and \; |k_{W,Z}| \leq 1$

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



Interference

- Negative contribution of the interference term



Off-shell: 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.

2l2v 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

Off-shell: analysis strategy in 4l

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

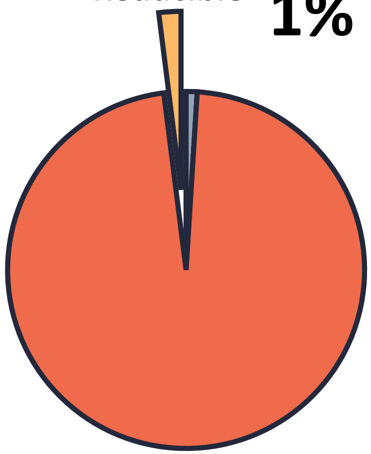
- Shape fit to ME(Matrix Element)-based kinematic discriminant:

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

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

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

Irreducible background in 4l



➢ $qq \rightarrow ZZ\ background$

1. Simulated with Sherpa 2.2.2(0, 1 jets at NLO, 2, 3 jet at LO)
2. NNPDF3.0 NNLO PDF set, Sherpa PS with MePs at NLO prescription
3. NLO EW corrections applied as a function of m_{ZZ}

Systematic uncertainties

1. *Theoretical:* QCD scale variation (10% in high mass), PDF variation (2%), additional syst. on EW correction (<2%)
2. *Experimental:* mainly from lepton reconstruction efficiency (few percent)

➢ $gg \rightarrow ZZ\ background$

1. Simulated with Sherpa 2.2.2, merging with Sherpa PS using MePs at NLO prescription
2. Normalisation from MCFM with NLO or NNLO QCD corrections applied

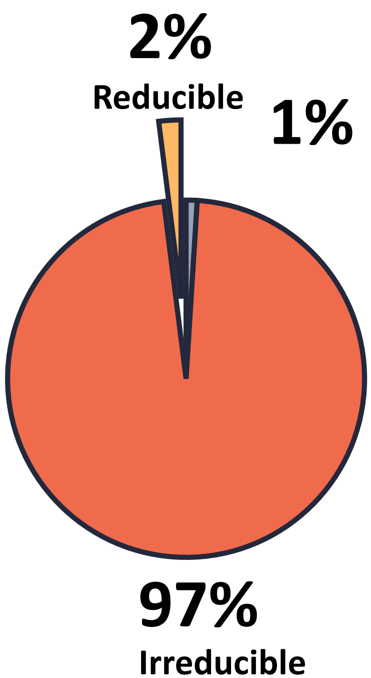
Systematic uncertainties

1. *Theoretical:* From QCD HO corrections (20%), PDF variation (2%)
2. *Experimental:* negligible

➢ **Predictions are checked using two data Control Regions:**
$RegionA: 160\ GeV < m_{4l} < 220\ GeV$ and $RegionB: 220\ GeV < m_{4l} < 1200\ GeV\ and\ ME < -1.5$

➢ **Overall good agreement** with data 1.1σ above expectations

Reducible background in 4l



- Data-driven estimation
  - except for tribosons and ttV contributions

- Contributions from ***Z+jets* (light and heavy flavour jets), $t\bar{t}$ and WZ** processes, entering the SR due to fake and non-isolated leptons

- **$Z + ee$: misidentified electrons from light jets, photon conversion or heavy quark**
  - Background yields from data and shape from MC

- **$Z + \mu\mu$: non prompt muons from $t\bar{t}$ and *Z* decays**
  - Normalised in data and shape from MC

Analysis channel	Estimated reducible background events
4e	1.14 ± 0.18
$2e2\mu$	1.49 ± 0.19
4μ	0.42 ± 0.04

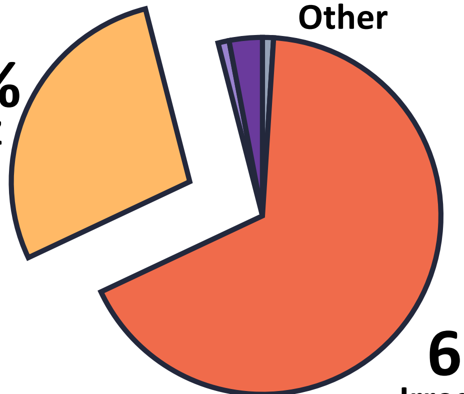
Off-shell: analysis strategy in 2l2ν

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

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

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

Irreducible background in 2l2v



- $qq \rightarrow ZZ$ ***background***
  1. Simulated with Sherpa 2.2.2(0, 1 jets at NLO, 2, 3 jet at LO)
  2. NNPDF3.0 NNLO PDF set, Sherpa PS with MePs at NLO prescription
  3. NLO EW corrections applied as a function of m_{ZZ}

  Systematic uncertainties
  1. *Theoretical:* QCD scale variation (10% in high mass), PDF variation (2%), additional syst. on EW correction (<2%)
  2. *Experimental:* mainly from lepton reconstruction efficiency (3,4%) and JER(3%)
- **gg**$\rightarrow$ ***ZZ background***
  1. Simulated with Sherpa 2.2.2, merging with Sherpa PS using MePs at NLO prescription
  2. Normalisation from MCFM with NLO or NNLO QCD corrections applied

  Systematic uncertainties
  1. *Theoretical:* From QCD HO corrections(20%), PDF variation (2%)
  2. *Experimental:* negligible

Reducible background in 2l2v: WZ

- $WZ, W \to l\nu, Z \to ll$ is the second leading background
- Third lepton not reconstructed or outside the acceptance, hadronic τ decays contribution
- Normalised to data from a *3l* Control Region
  - MC prediction corrected with a normalisation factor
- MET shape from simulation

NF — CR→SR transfer factor

$$N^{2\ell SR}_{WZ,data} = N^{2\ell CR}_{WZ,MC} \cdot \boxed{\frac{N^{3\ell CR}_{WZ,data}}{N^{3\ell CR}_{WZ,MC}}} = N^{3\ell CR}_{WZ,data} \cdot \boxed{\frac{N^{2\ell SR}_{WZ,MC}}{N^{3\ell CR}_{WZ,MC}}}$$

= **1.29 ± 0.03 (stat.)**

systematics on TF assessed from
1) QCD/PDF variations (negligible)
2) exp. uncertainties (~4%)

$3l$ Control Region

- $ee, \mu\mu + additonal\ e, \mu\ with\ p_T > 7\ GeV$
- $m_{ll} \sim m_Z\ as\ in\ SR$
- $m_T(W) > 60\ GeV$
- $non - WZ\ background\ subtracted\ from\ data$

ee	32.76±1.30±1.62
$\mu\mu$	34.94±1.36±1.73

Reducible background in 2l2v: eμ

- Contribution of $t\bar{t}, WW, Z\tau\tau$ *and* Wt events
  - estimated from eμ events by exploiting the flavour symmetry ee : μμ : eμ = 1 : 1 : 2
- Data driven estimate with MC shape
- Due to lack of statistics, we release MET cut down to 120 GeV, Loose Control Region

$$N_{ee}^{SR} = \frac{1}{2} \times \boxed{\varepsilon} \times N_{e\mu}^{data,sub} \qquad N_{\mu\mu}^{SR} = \frac{1}{2} \times \frac{1}{\boxed{\varepsilon}} \times N_{e\mu}^{data,sub}$$

where

$$N_{e\mu}^{data,sub} = N_{e\mu}^{data} - \sum_{i}^{non-e\mu} N_i^{MC}$$

$$\varepsilon^2 = \frac{N_{ee}}{N_{\mu\mu}}$$

ε accounts for e/μ difference in trigger/reconstruction/ ID efficiency

- Since it was introduce a Loose CR, the $m_T(ZZ)$ shape was extrapolated to the SR through a m_T-Transfer Function

Data Estimate	Binned (p_T, η)
N_{ee}	1.3 ± 0.5± 0.5
$N_{\mu\mu}$	1.3 ± 0.5 ± 0.5

Systematics breakdown

	MC closure	shape	Transfer Function	Total
ee	12%	10%	38%	41%
$\mu\mu$	12%	10%	38%	41%

Reducible background in 2l2v: Z+jets

- $Z + jets$ background has no real MET
  1. Events passing the ll+MET selection due to jets mismeasurements
  2. Data driven estimate (expected at 2-3%)
- Normalisation taken from data CR, built inverting MET/HT cut
- Extrapolation to SR through MC-based transfer factor
- Due to low statistics, shape is taken from MC, but DD shape extracted and used to assess shape systematic

$$N_{SR}^{est} = N_{CR}^{data} \times \underbrace{\boxed{\frac{N_{SR}^{MC}}{N_{CR}^{MC}}}}_{\text{Transfer Factor}} = N_{CR}^{data} \times \frac{\overbrace{\boxed{(N_{SR}^{MC} / N_{SR-\Delta\phi(jet,MET)-bveto}^{MC})}}^{\text{Acceptance Factor}}}{N_{CR}^{MC}}$$

Channel	Sideband estimate	MC expected
ee	4.3±1.9(stat.)±0.8(sys.)	3.0±1.2(stat.)±0.4(sys.)
$\mu\mu$	1.7±0.8(stat.)±1.1(sys.)	1.8±0.7(stat.)±0.6(sys.)

On- Off- shell: combination

- Determination of $\mu_{off-shell}$ when fixing the ratio of the signal strength in ggF and VBF to the SM prediction: $\boldsymbol{\frac{\mu^{ggF}_{off-shell}}{\mu^{VBF}_{off-shell}} = 1}$

- We can define the coupling ratios

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

- The relationships between the *on*- and *off-shell* signal strength are:

$$\mu^{ggF}_{off-shell} = R_{gg} \cdot R_{VV} \cdot \mu^{ggF}_{on-shell} \frac{\boldsymbol{\Gamma_H}}{\boldsymbol{\Gamma^{SM}_H}} \quad \mu^{VBF}_{off-shell} = R^2_{VV} \cdot \mu^{VBF}_{on-shell} \frac{\boldsymbol{\Gamma_H}}{\boldsymbol{\Gamma^{SM}_H}}$$

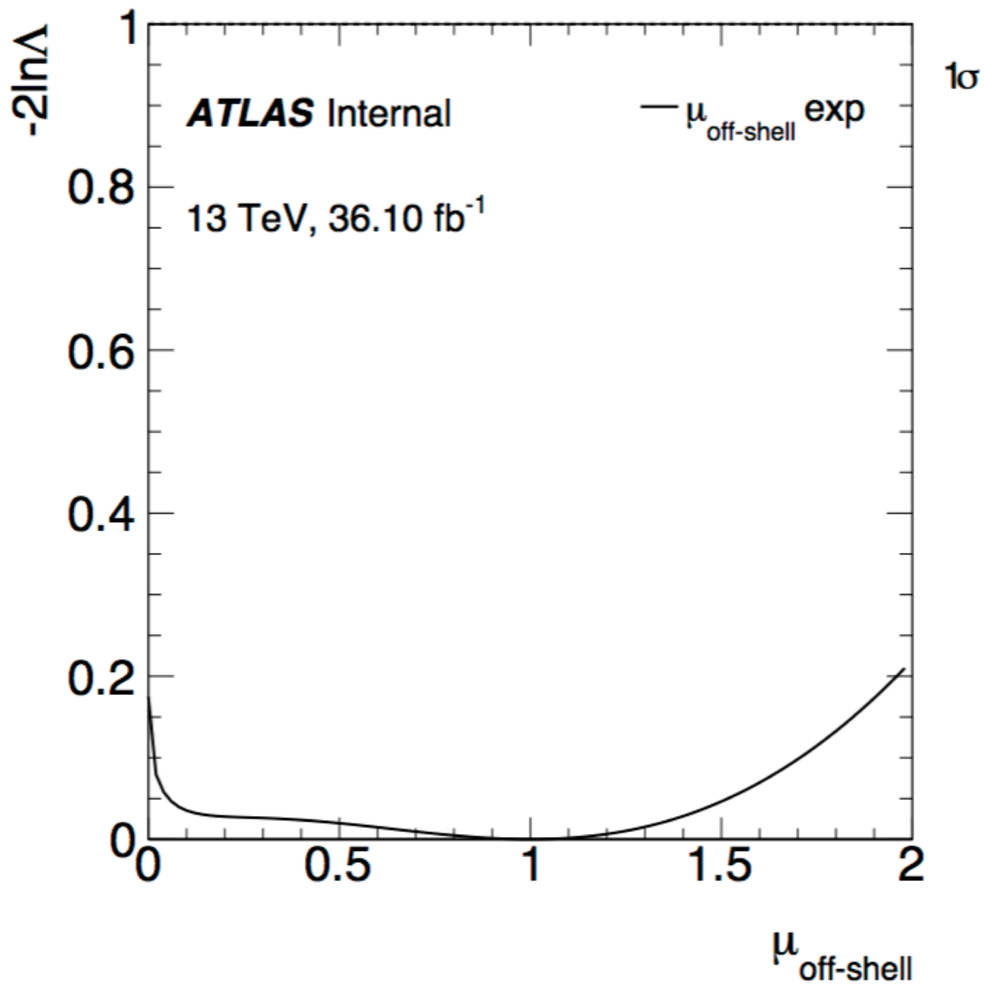
On- Off- shell: combination

$$\mu^{ggF}_{off-shell} = R_{gg} \cdot R_{VV} \cdot \mu^{ggF}_{on-shell} \frac{\boldsymbol{\Gamma_H}}{\boldsymbol{\Gamma_H^{SM}}}$$

$$\mu^{VBF}_{off-shell} = R^2_{VV} \cdot \mu^{VBF}_{on-shell} \frac{\boldsymbol{\Gamma_H}}{\boldsymbol{\Gamma_H^{SM}}}$$

- We can assume $R_{gg} = 1 = R_{VV}\ and\ \mu^{ggF}_{on-shell} = \mu^{VBF}_{on-shell} = \mu_{on-shell}$
- We scan $\frac{\boldsymbol{\Gamma_H}}{\boldsymbol{\Gamma_H^{SM}}}$, our Parameter of Interest, POI
- We profile the common $\mu_{on-shell}$

Llikelihood around 0



Run 2 – Run 1 results

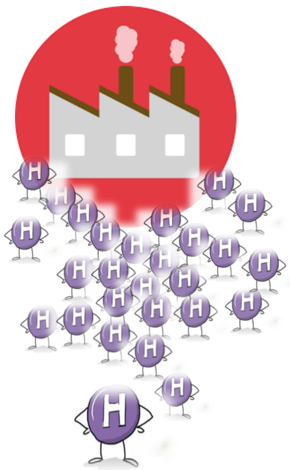
- Using the CLs method, we derive the Observed (Expected) limits at 95% C.L.

Run-2 results:
(ZZ only, 4l only for CMS)
- $ATLAS$: $\Gamma_H < 14.4(15.2) MeV$
- CMS: $\Gamma_H < 9.16\ (13.7) MeV$

Run-1 results:
(ZZ+WW)
- $ATLAS$: $\Gamma_H < 22.7(33)\ MeV$
- CMS: $\Gamma_H < 22\ (33) MeV$

- 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

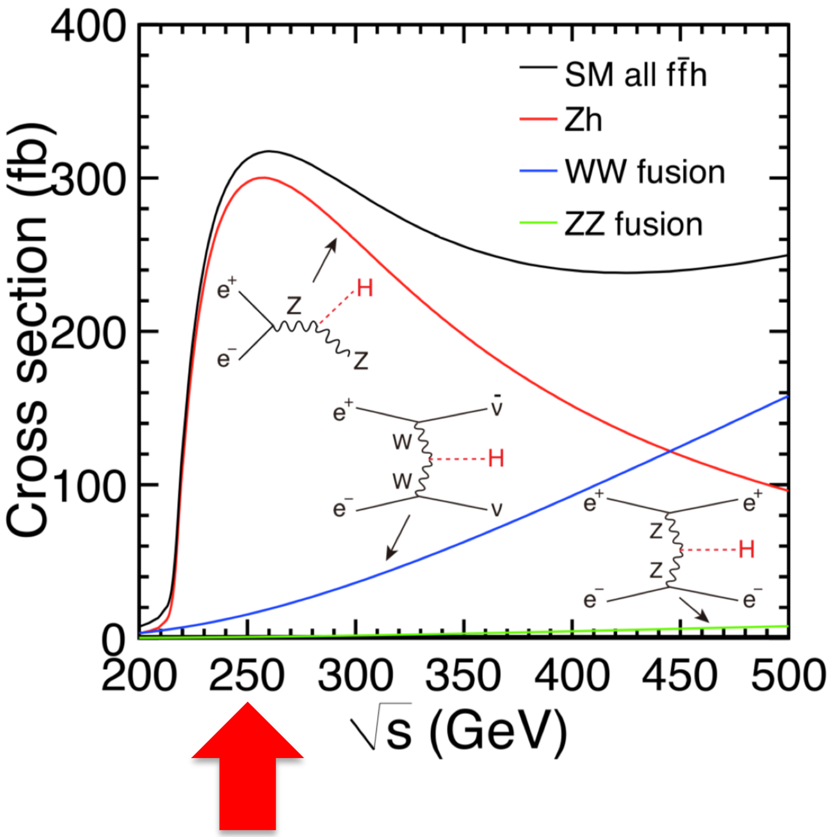
Improvement on Run-1 expected limits by almost a factor 2 !



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

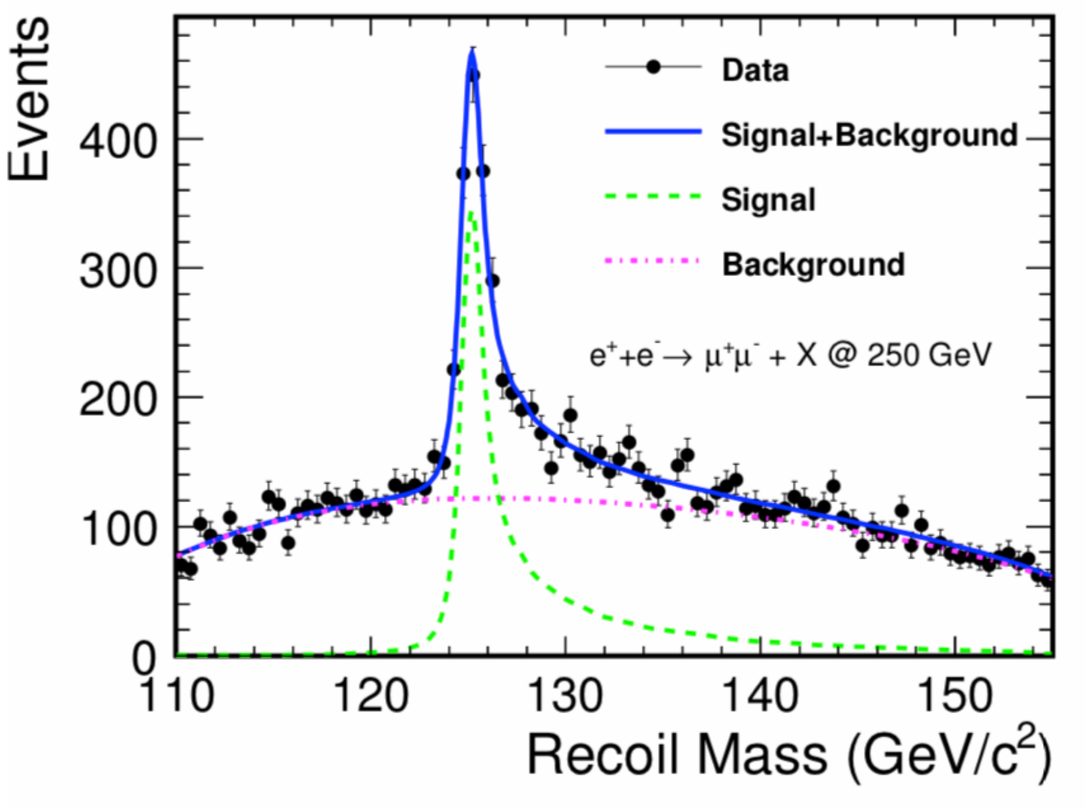


- The Higgs-strahlung production is maximum at 250 GeV
- 2000 fb^{-1} in 20 years of data acquisition (H20 program):
  - ZH ➡ $\sim 500\ K$ Higgs
  - WW-fusion ➡ $\sim 15\ K$ Higgs

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

Measuring the HZ coupling at ILC

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



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

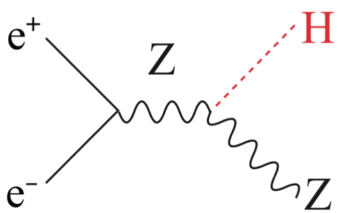
- Higgs events are tagged with the Z boson decays, independently of the Higgs decay mode

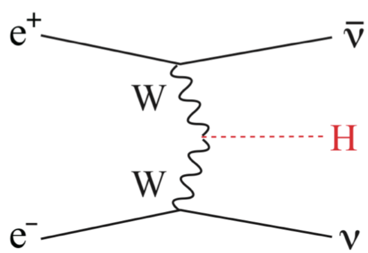
- From the HZ sample, measurement of g_{HZZ}:

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

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 $H \to X\bar{X}$:





$$\frac{\text{(Higgs-strahlung)}}{\text{(WW-fusion)}} = \frac{\dfrac{g^2_{HZZ} \cdot g^2_{HXX}}{\Gamma_H}}{\dfrac{g^2_{HWW} \cdot g^2_{HXX}}{\Gamma_H}} \Rightarrow g^2_{HWW}$$

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

$\boldsymbol{\Gamma_H}$ [Accuracy achievable 1.7%(ILC250+ILC500)]