



Higgs width at LHC



UNIVERSITY OF
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**SLAC
Experimental Seminar
May 2, 2019**

Introduction to Higgs Physics

Run-2 News

Higgs boson width

Higgs boson width: experimental results

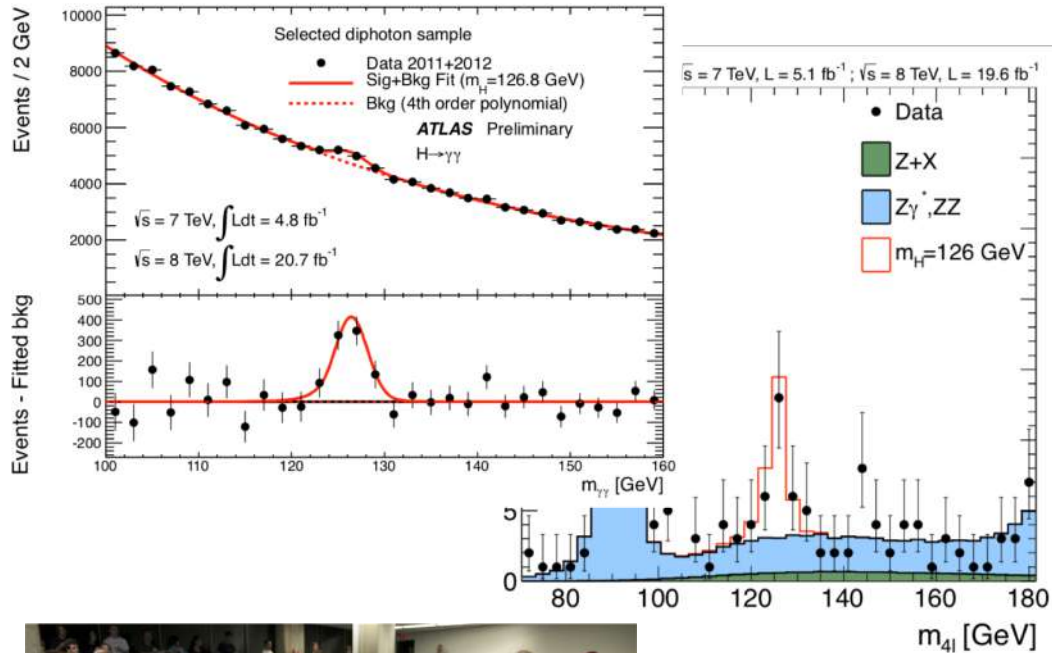
Conclusions

Disclaimer: Inspired by chats/talks with/by F. Caola, 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

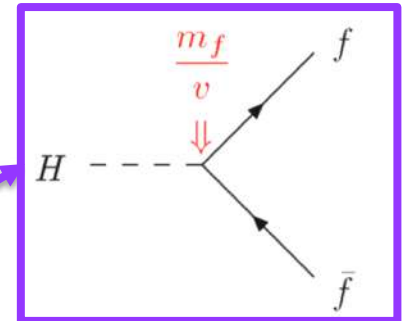


The Higgs boson in the SM

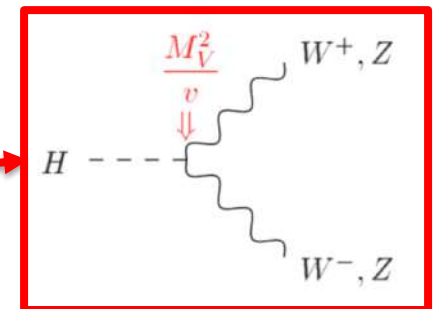
- By interacting with all the SM particles, the Higgs field gives them mass
 - Two different types of tree-level couplings

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\Psi} \not{D} \Psi + h.c. \\ & + \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c. \\ & + \left[\frac{1}{2} D_\mu \phi | \phi \right]^2 - V(\phi)\end{aligned}$$

Fermions

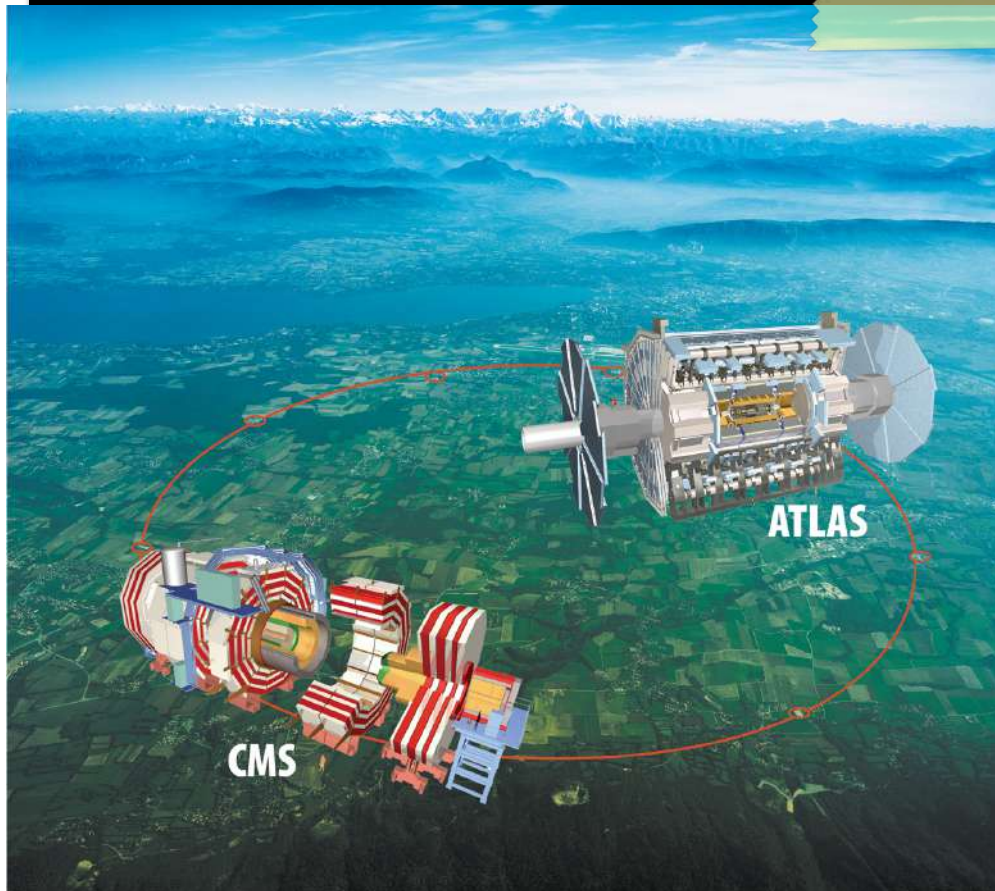


BOSONS



The Large Hadron Collider, LHC

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



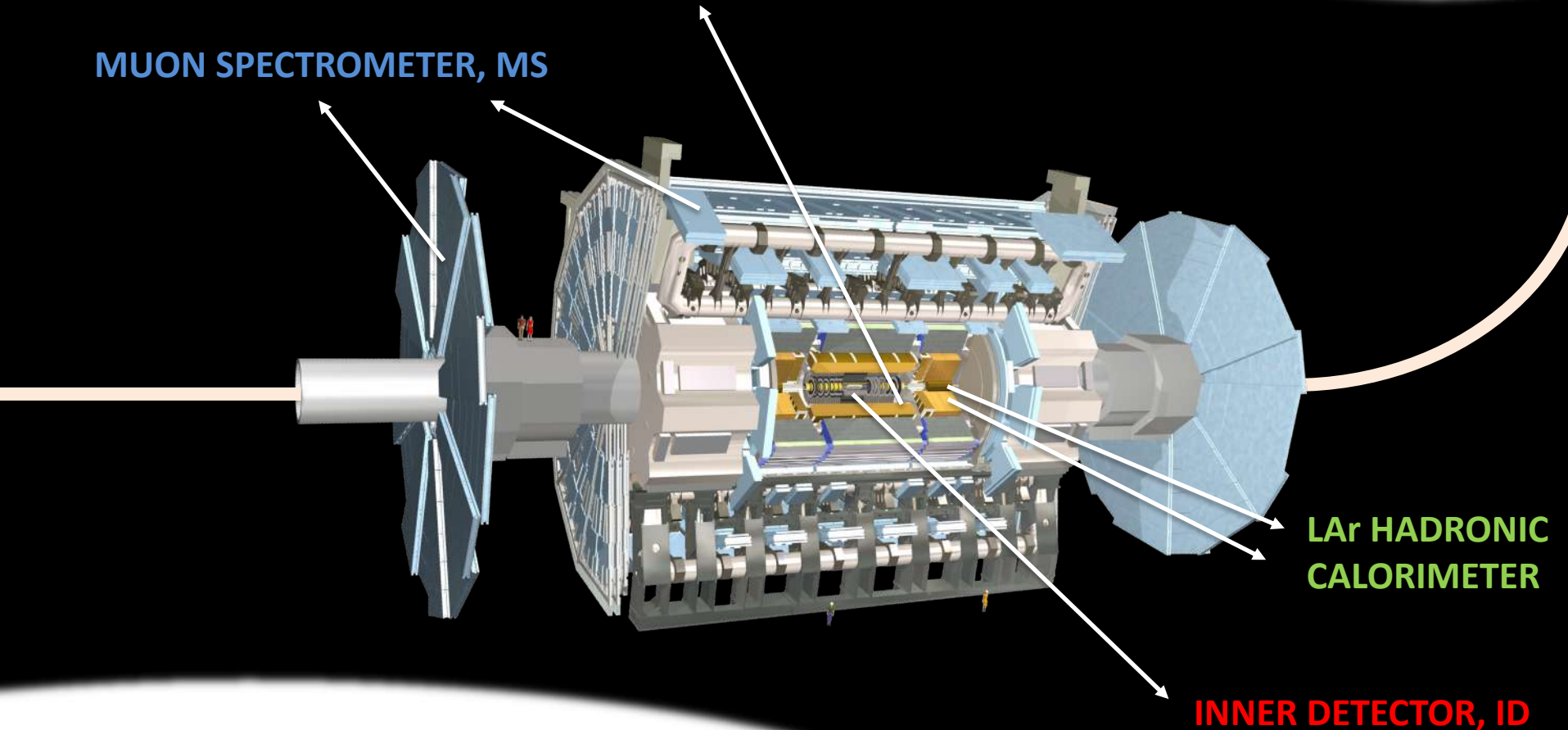
- Peak Luminosity: $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
 - Design Lumi. exceeded by a factor of two!
- 27-km ring of superconducting magnets
- Two phases at \sqrt{s} :
 - 7,8 TeV Run 1
 - 13 TeV Run 2

The ATLAS detector

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

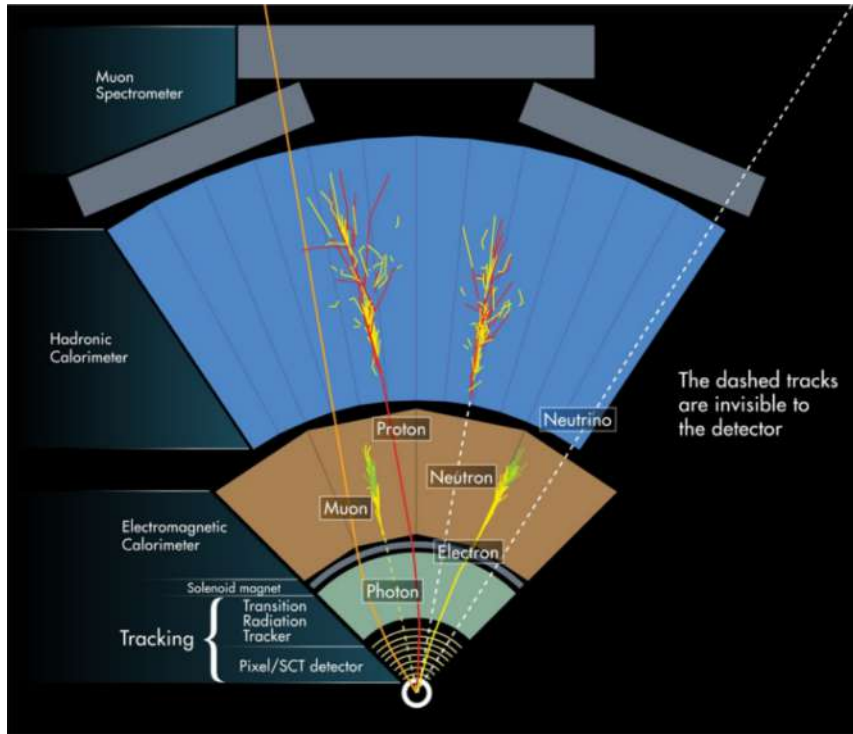
LAr ELECTROMAGNETIC CALORIMETER

MUON SPECTROMETER, 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 through the detector

IDEAL PHYSICS OBJECTS:

- Electrons, photons and muons:
 - good resolution and reconstruction efficiency
 - Good vertex matching

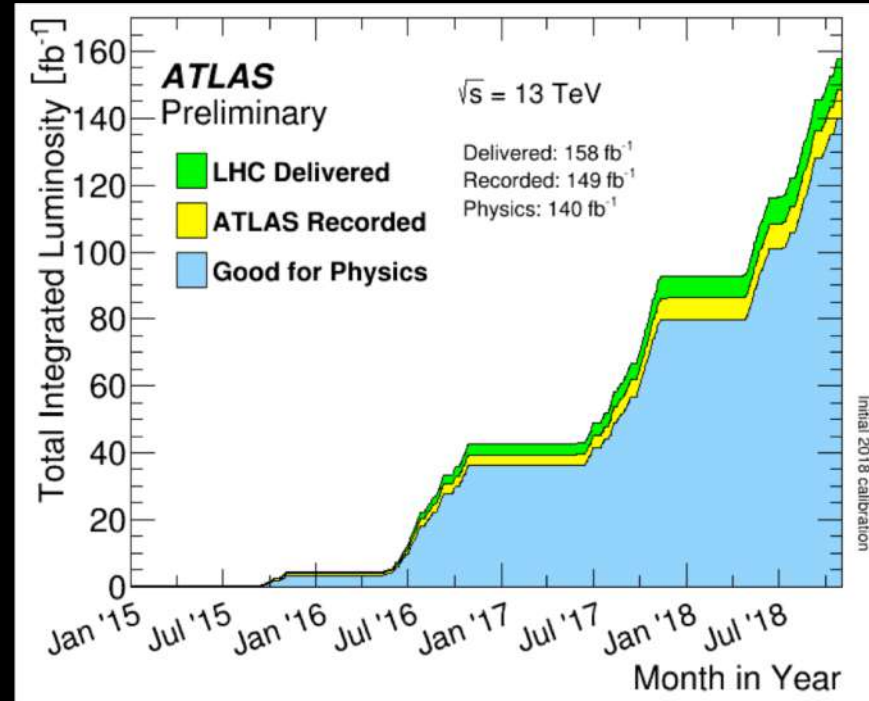
CHALLENGING PHYSICS OBJECTS:

- Jets, Missing Transverse Energy (ν_s):
 - Low resolution and recon. efficiency
 - Partial 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 10¹⁰ proton-proton collisions**

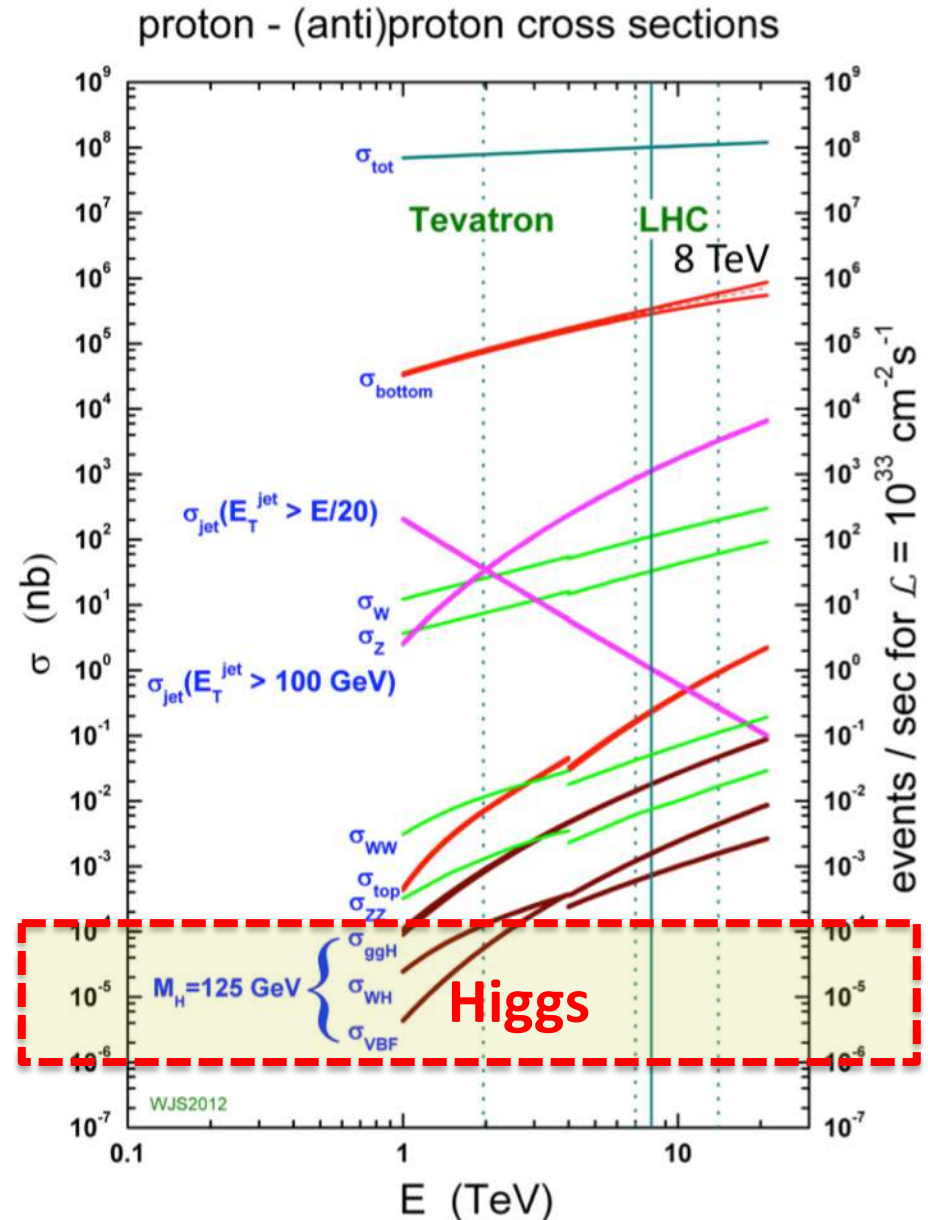
Exceptional performance in Run 2!



- 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!

LHC pp collisions

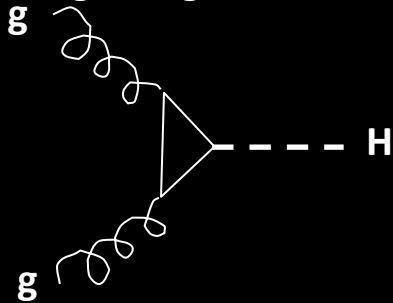
- QCD background dominant
 - 5 orders of magnitude higher compared to single boson production
 - Higgs boson decays involving leptons or photons in the final state are our smoking gun against abundant background



Higgs boson production at LHC

ggF: 88%

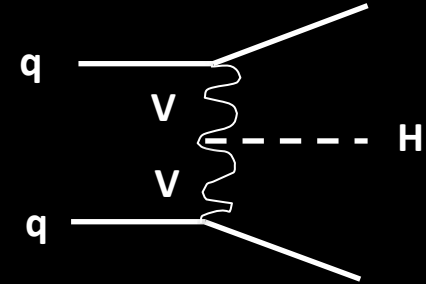
gluon gluon Fusion



~ 6.8M Higgs*

VBF: 7%

Vector Boson Fusion



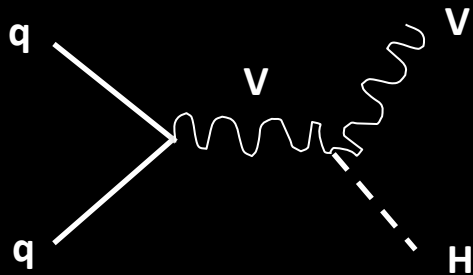
~ 530k Higgs

How should I
show up at LHC
this time?



VH: 4%

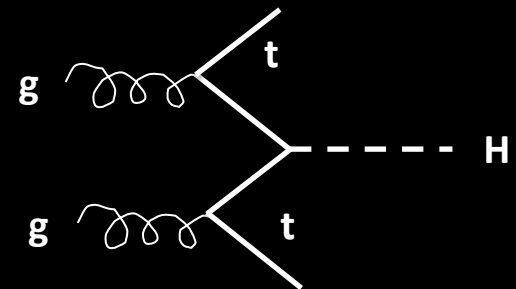
Higgs strahlung



~ 320k Higgs

ttH: 1%

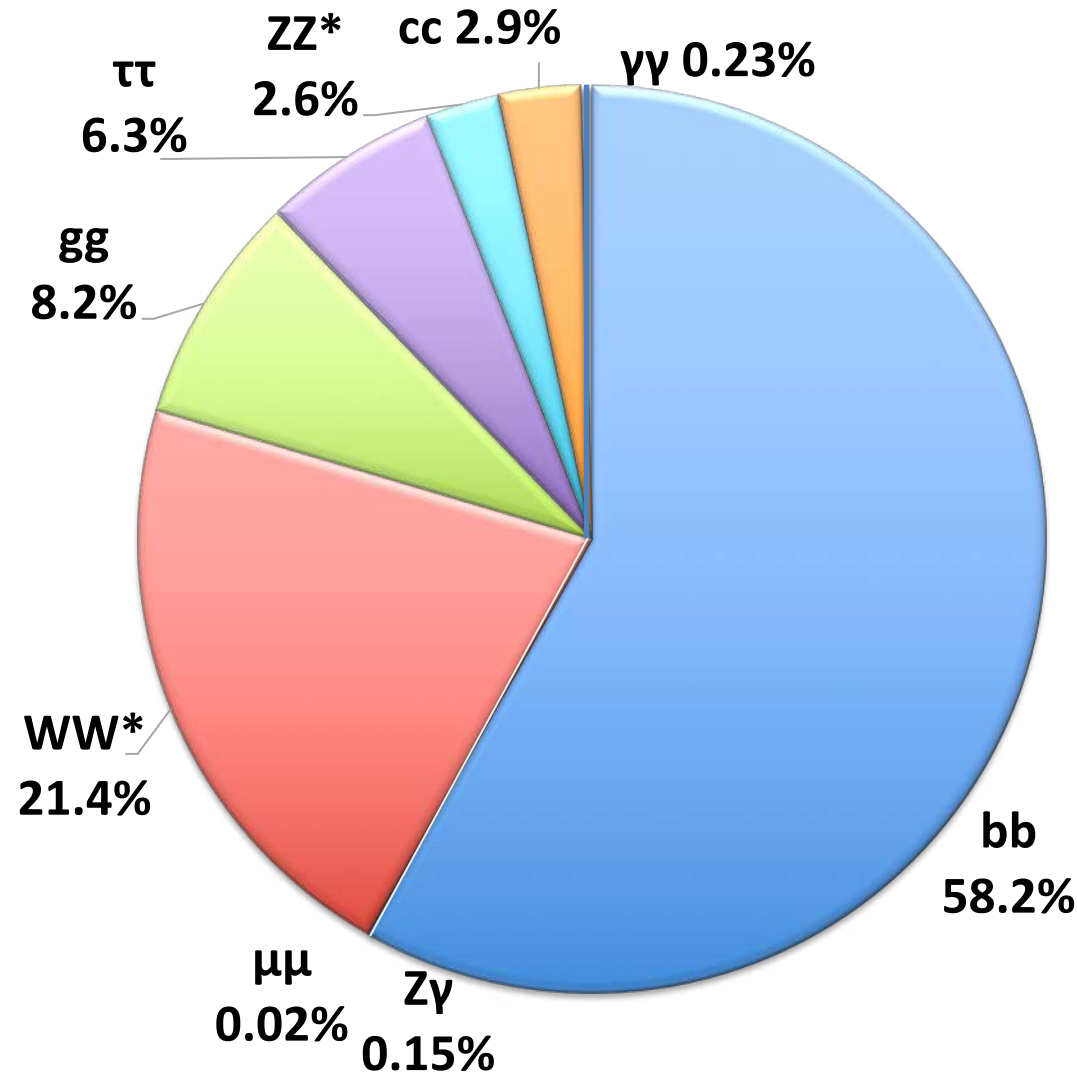
Top Fusion



~ 70k Higgs

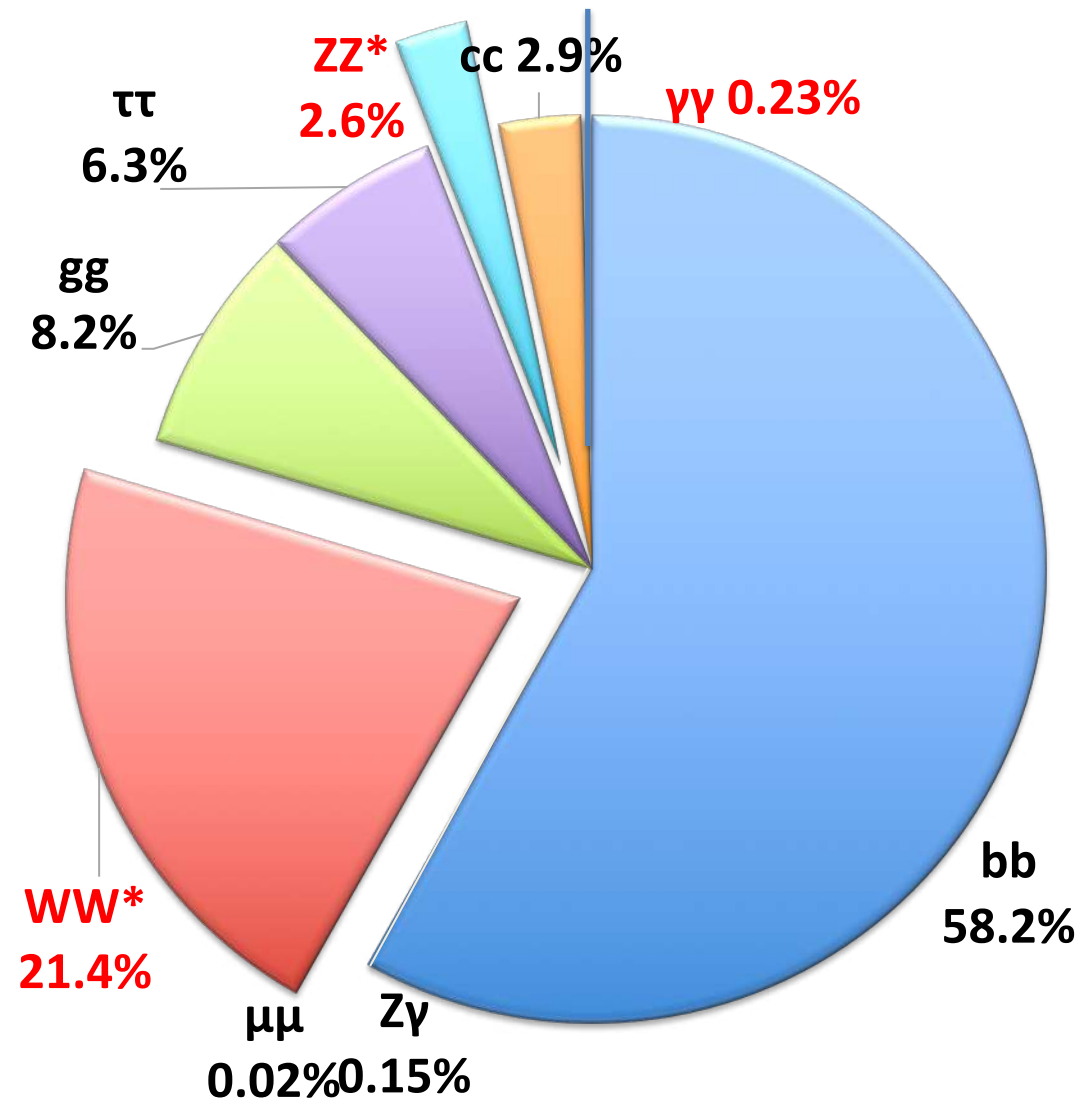
*Higgs candidates in Run 2

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



$ZZ^*, \gamma\gamma$



Good mass resolution

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



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

WW^*

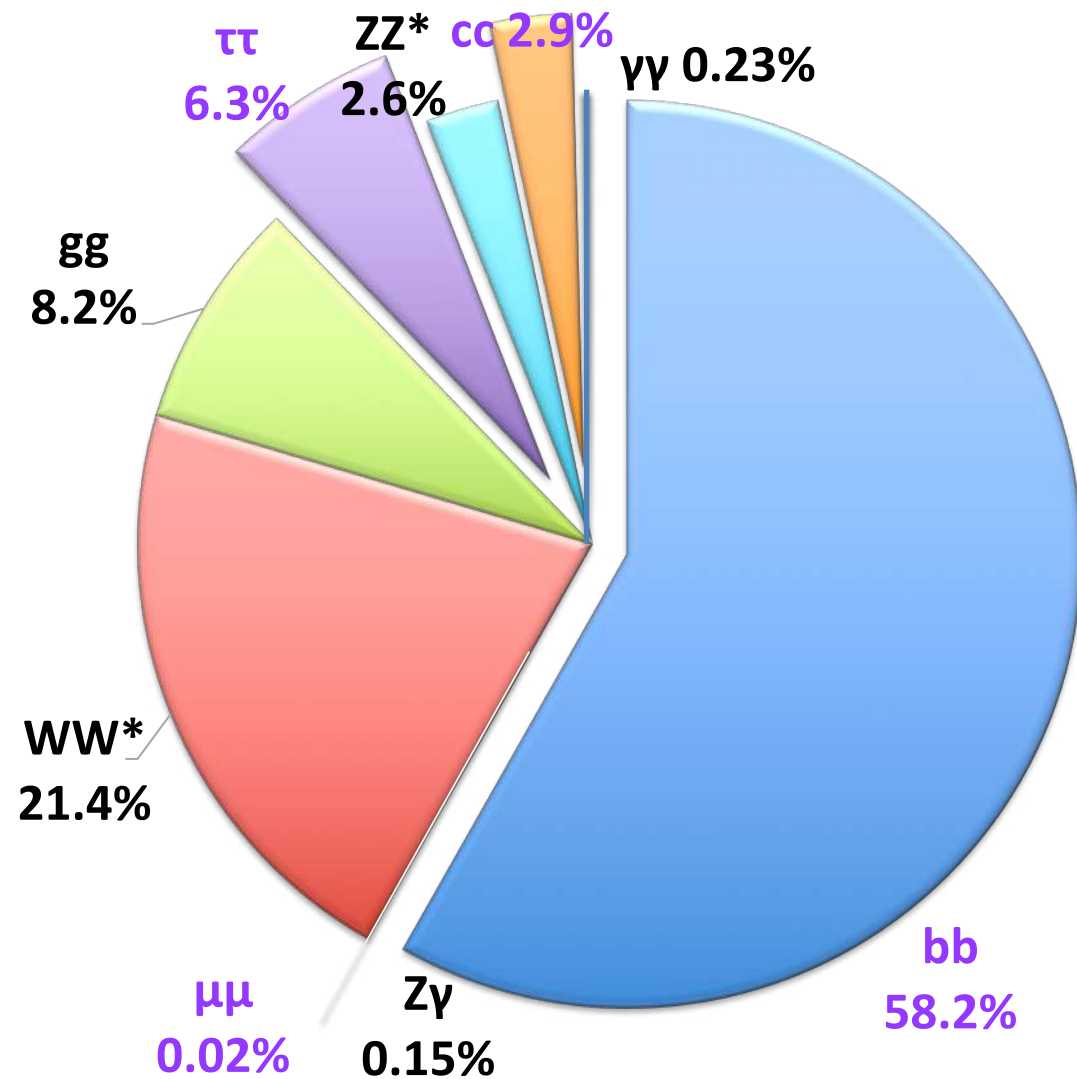


High BR, but reduced in the dilepton mode, 1.1%



Low mass resolution because of ν_s in final states

Higgs to Fermions



$bb, \tau\tau, cc$



Significant BR

- Allow direct probe to fermions



Low S/B, challenging measurement

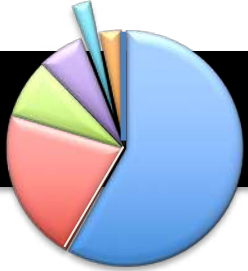
$\mu\mu$



It allows couplings measurements to 2nd generation



Very small BR



H → ZZ* Golden channel



Because of the extremely good mass resolution, $H \rightarrow ZZ^* \rightarrow 4l$:

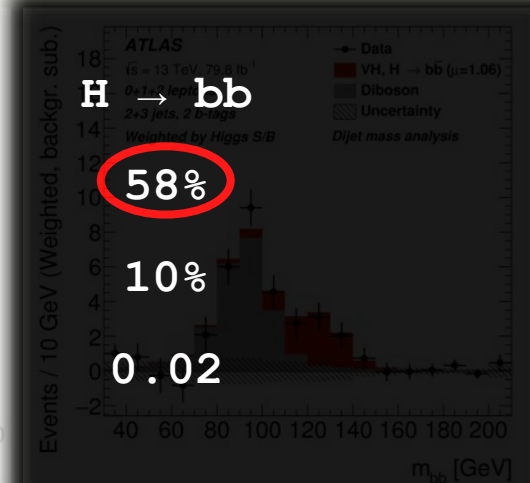
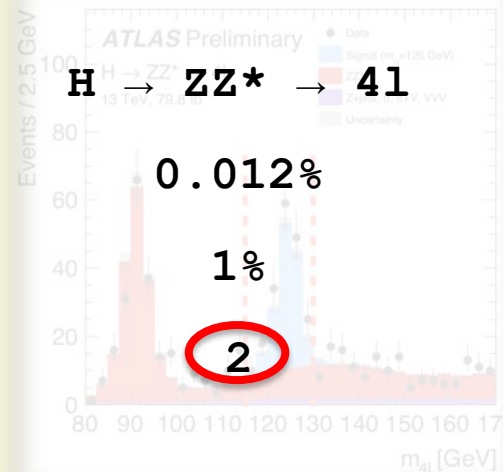
- was one of the golden channels for the Higgs discovery
- is now used for precision measurements (Higgs boson mass ...)

Let's compare it with the so popular Hbb ...

Branching Ratio

Mass resolution

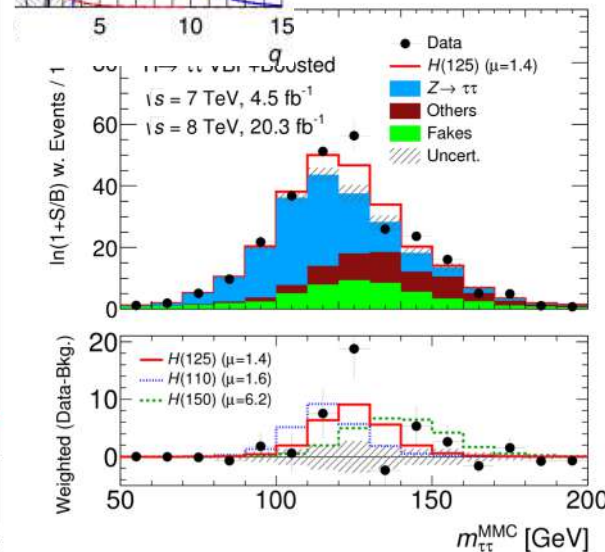
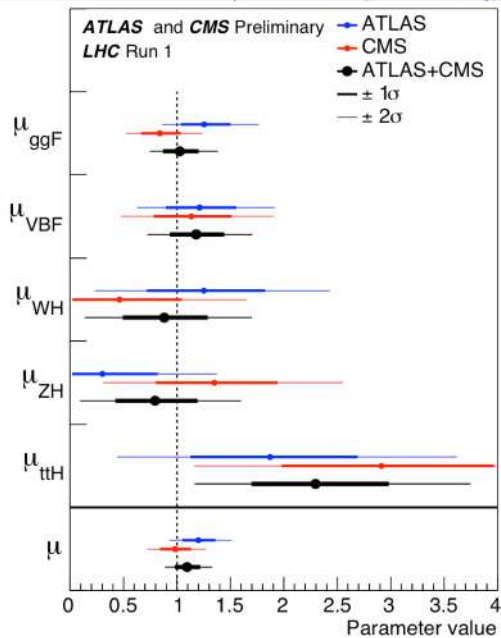
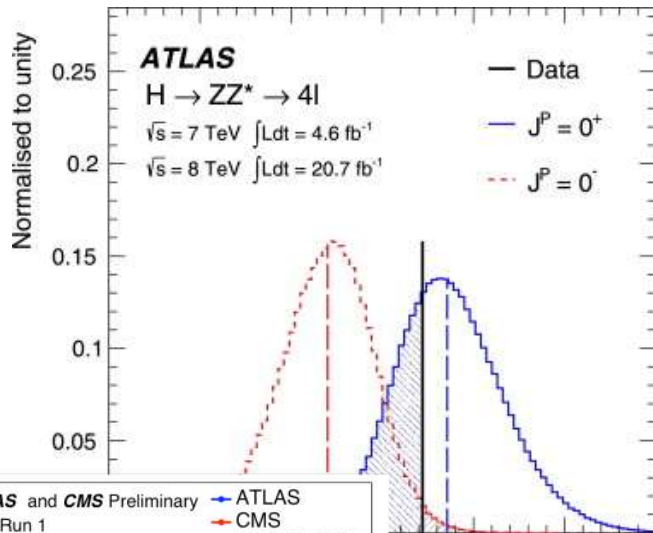
S/B



More is not always better!

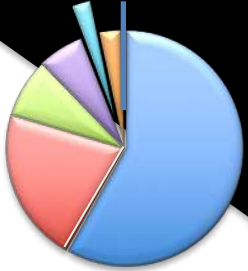
The Run-1 lesson

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

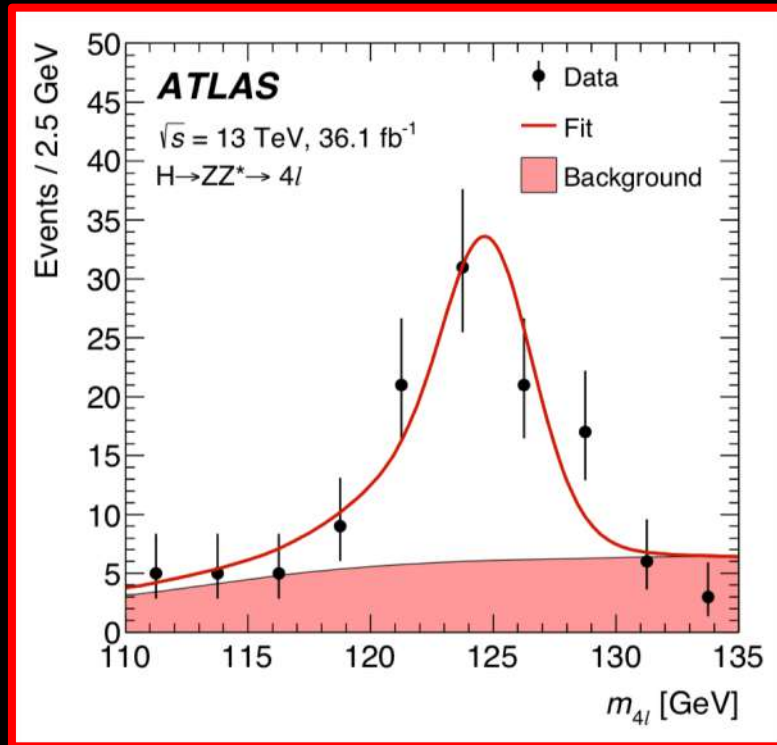
Run-2 News



Higgs boson mass

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

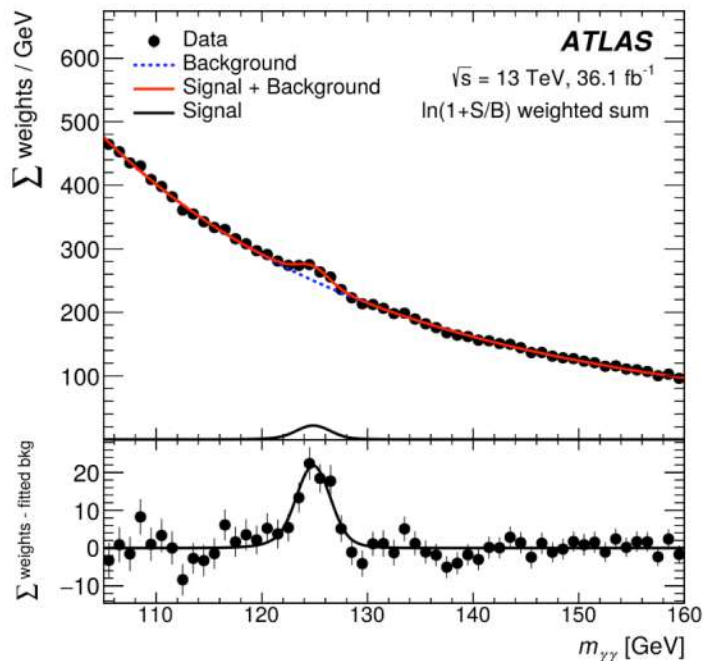
Extraction from a fit
to the
4l inv.mass



[Phys. Lett. B 784 \(2018\) 345](#)

Run-2 result based
on the 2015-16
dataset

**ATLAS
Combination
with Run 1:
 $m_H = (124.97 \pm 0.24) \text{ GeV}$
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:

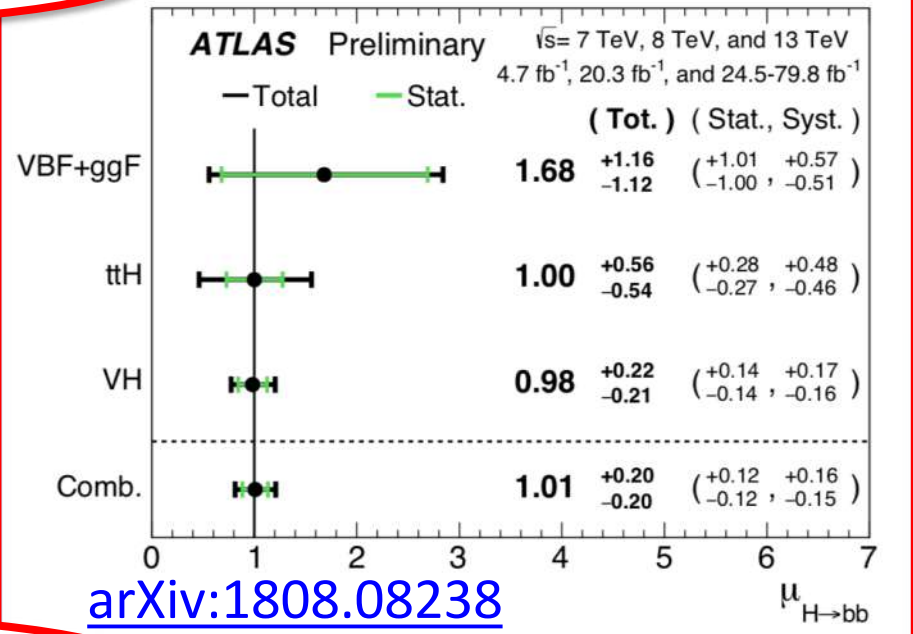
- VH, H → bb
- VBF(+ggF), H → bb
- ttH, H → bb



Significance :

5.4σ obs. (5.5σ exp.)

Observation of H → bb !



VH combination

Run-2 analyses:

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



Significance : [arXiv:1808.08238](https://arxiv.org/abs/1808.08238)

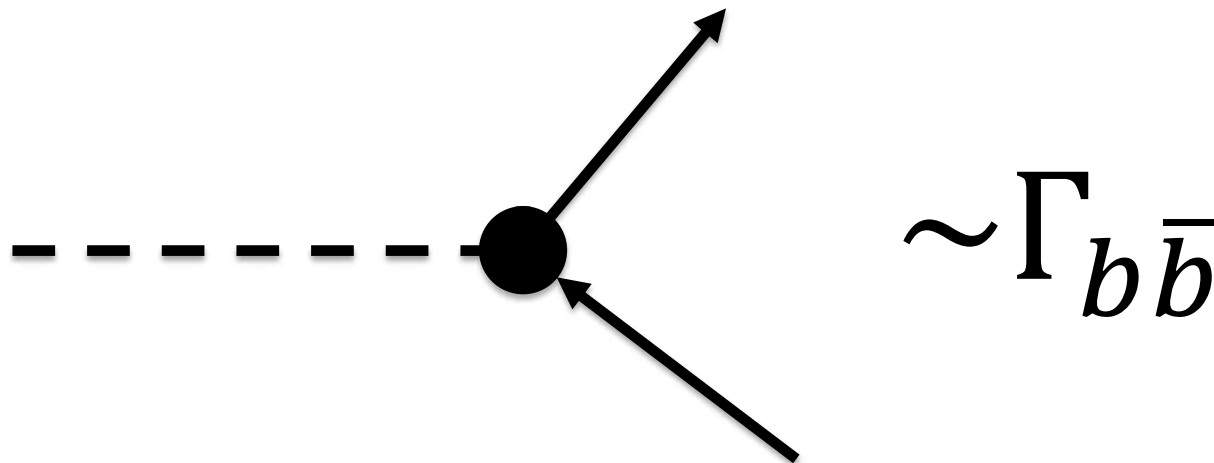
5.3σ obs. (4.8σ exp.)

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:

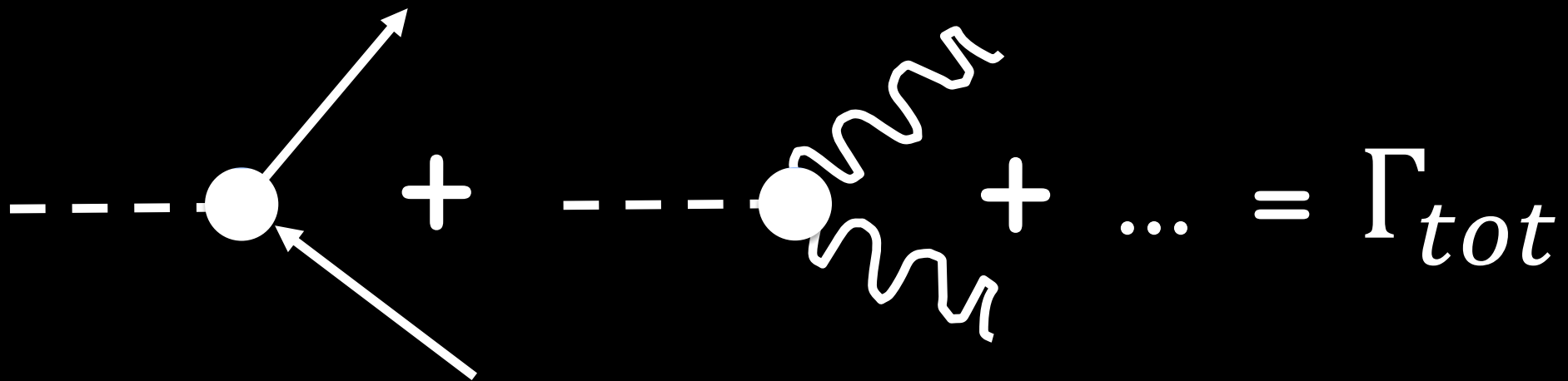


$$\sim \Gamma_{b\bar{b}}$$

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

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:

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

➤ At LHC:

- we only have access to couplings ratio
- measurements of individual channels require the total width measurement \longrightarrow global information

What can we measure at LHC?

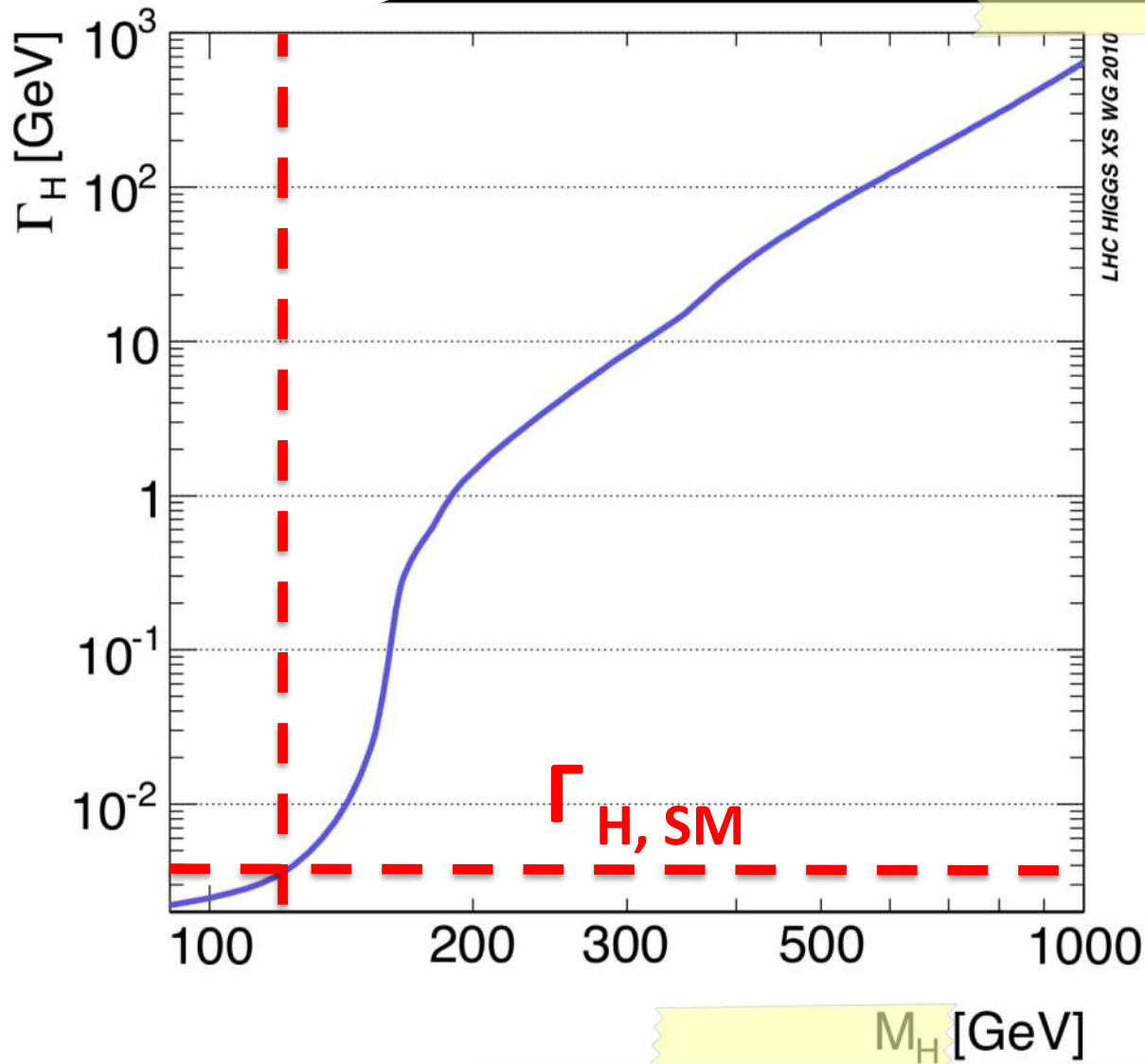
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➤ At LHC:

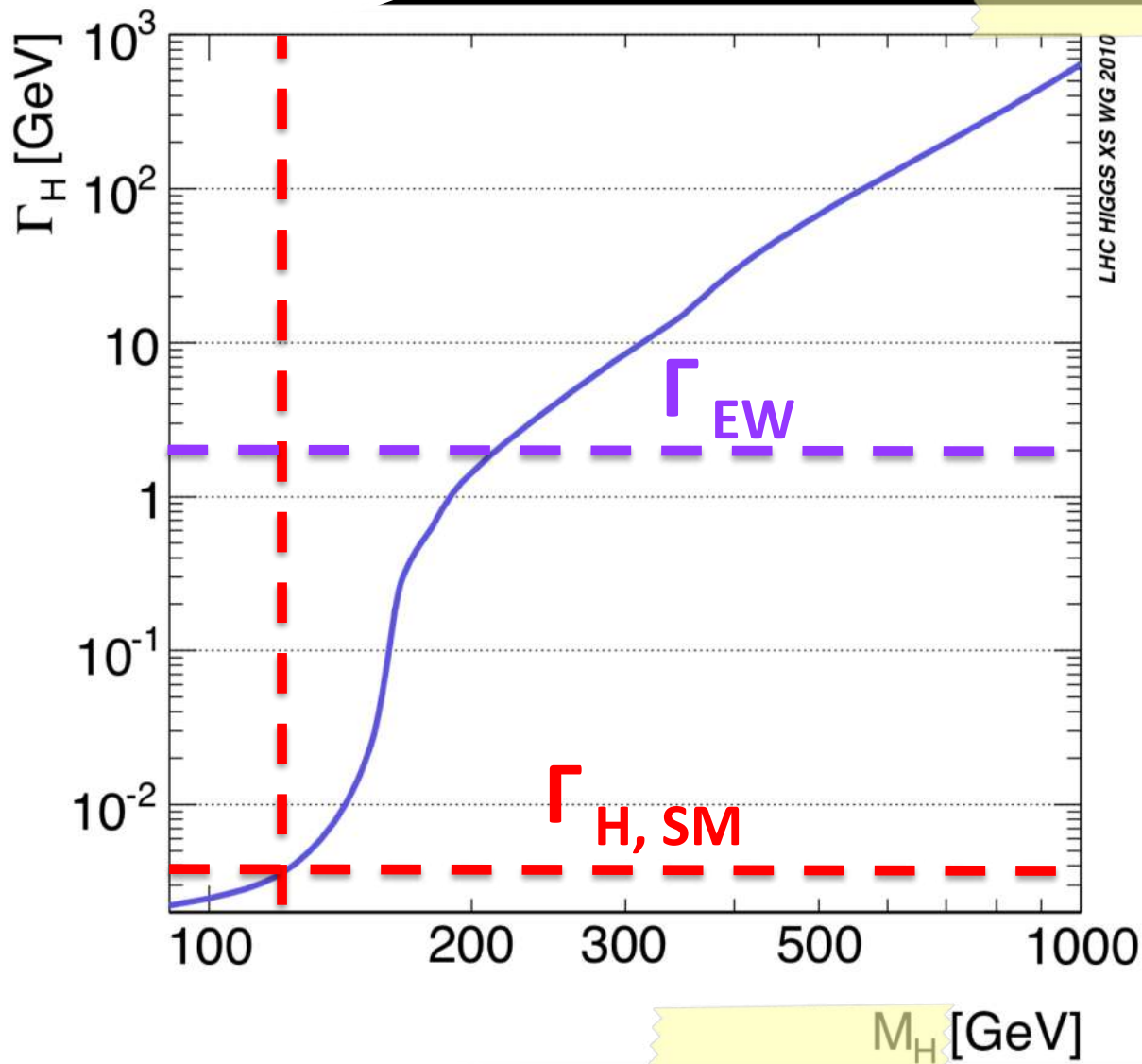
- we only have access to couplings ratio
- measurements of individual channels require the total width measurement **➡ Theory dependence**
- How can we measure the Higgs boson width?

The Higgs boson width



The SM expectation for Γ_H for $m_H \sim 125$ GeV is **~ 4 MeV** ...
... extremely small!

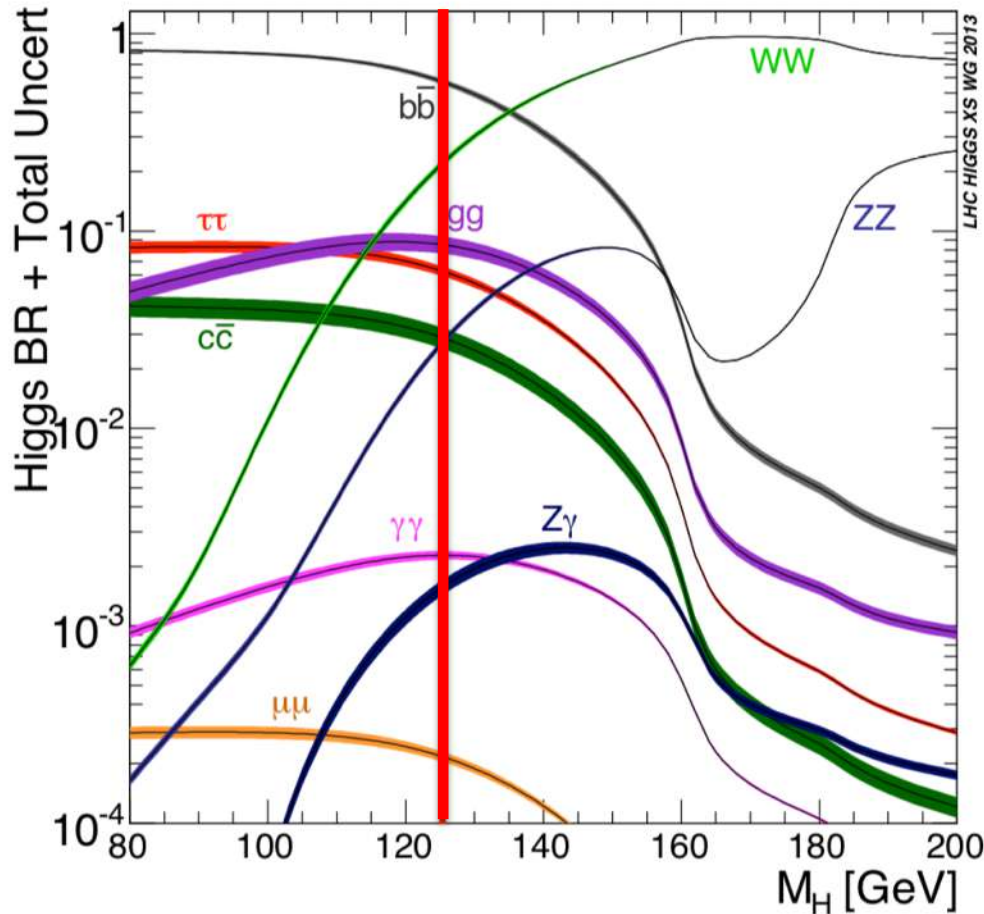
And the other EW bosons?



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 ...

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

The background of the slide features a black silhouette of a city skyline against a white background. On the left, the Golden Gate Bridge is prominent. In the center, a tall skyscraper, likely the Empire State Building, stands out. To the right, another suspension bridge is visible. The right half of the slide is a solid black rectangle.

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
 - 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



How can we measure Γ_H at LHC?

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 - 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



How about a Higgs pizza?

Higgs Boson Pizza at CERN

What's happening on my Ham & Cheese pizza?

A two asparagus (proton-proton) collision produces a spicy Higgs boson (chorizo) decaying into two high-energy salami (photon) clusters and a lot of charged (sliced ham) and neutral (olive) particles that are detected in the pizza (detector) entirely covered with mozzarella sensors.



Renzo Fermi and Pierluigi Paducci, INFN

Recipe: Rising crust Higgs pizza

Ingredients

- 1/4-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!

- Asparagus Proton
- Cherry tomato Higgs boson
- Artichoke Neutrino
- Pepper Charged particles
- Cheese Detector



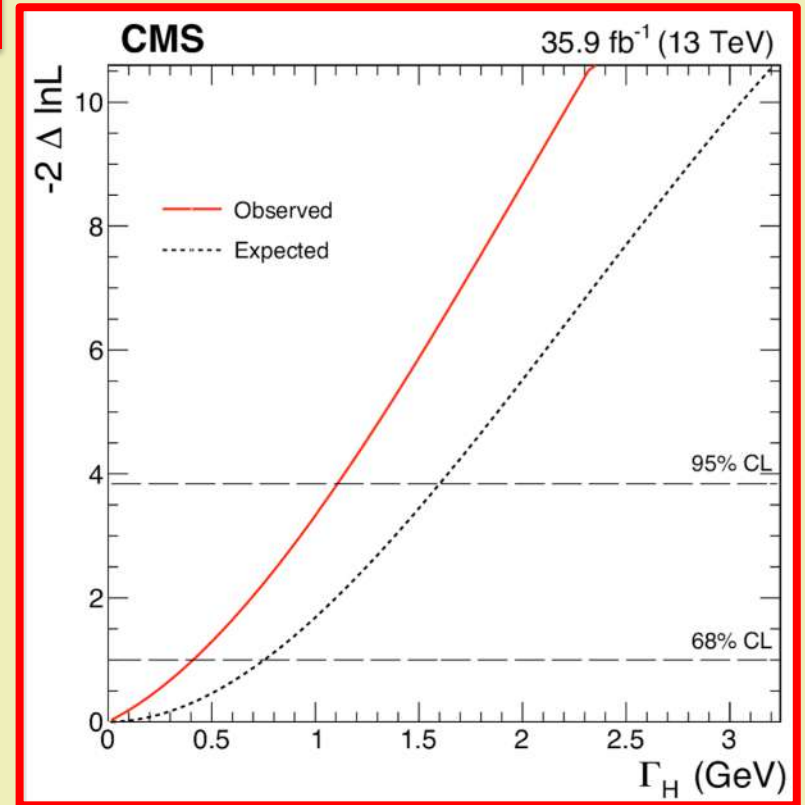
Direct strategies

From the on-shell mass peak

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

- ~ 270 (CMS) ~ 630 (ATLAS) times larger than the SM value





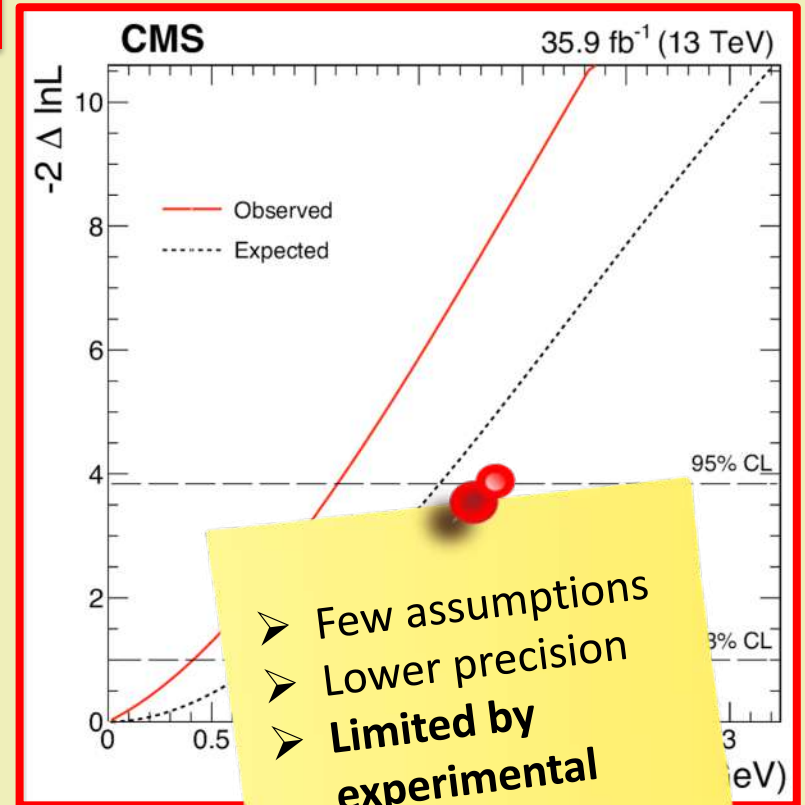
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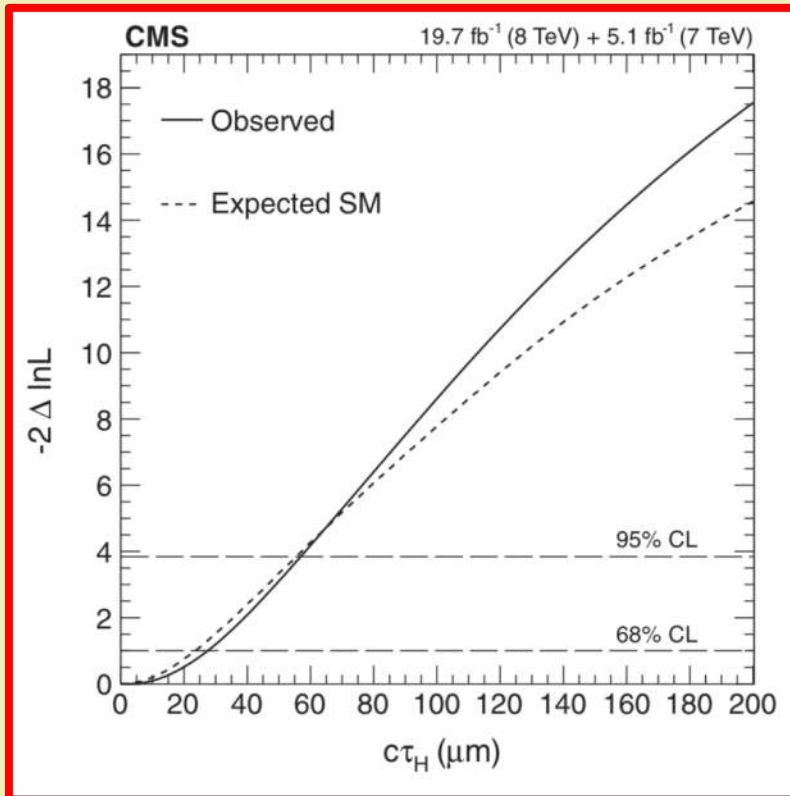
- ~ 270 (CMS) ~ 630 (ATLAS) times larger than the SM value





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 $\sim 10 \mu\text{m}$
- $H \rightarrow 4l$ ideal channel to extract the lifetime using the **flight distance**
 - Displacement between the production and decay vertices

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



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!

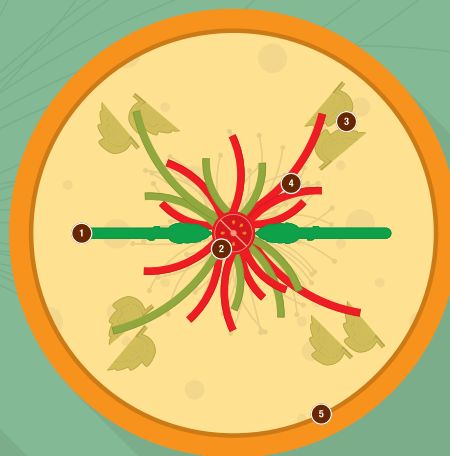
Higgs Boson Pizza Day at CERN

What's happening on my Ham & Cheese pizza?

A two asparagus (proton-proton) collision produces a spicy Higgs boson (chorizo) decaying into two high-energy salami (photon) clusters and a lot of charged (sliced ham) and neutral (olive) particles that are detected in the pizza (detector) entirely covered with mozzarella sensors.

What's happening on my Vegetarian pizza?

A two asparagus (proton-proton) collision produces a juicy Higgs boson (cherry tomato) decaying into four high-energy peppers producing a tasty signal in the artichoke (muon) chambers and a lot of charged (red and green peppers) particles that are detected in the pizza (detector) entirely covered with mozzarella sensors.



-  Asparagus
Proton
-  Cherry tomato
Higgs boson
-  Artichoke
Muon
-  Pepper
Charged particles
-  Cheese
Detector

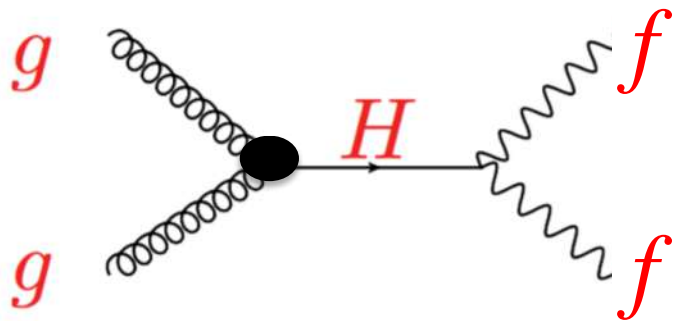
Renzo Fermi and Pierluigi Paducci, INFN

$g g \rightarrow H \rightarrow ZZ \rightarrow 4\mu$
 $g g \rightarrow H \rightarrow ZZ \rightarrow 4e$
 $g g \rightarrow H \rightarrow ZZ \rightarrow 2e2\mu$
 $g g \rightarrow H \rightarrow ZZ \rightarrow 2e2e$



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

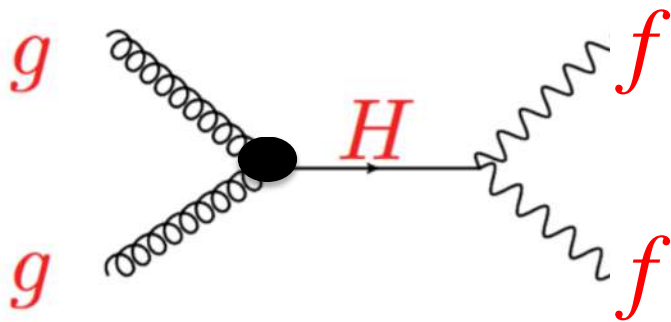
$$\frac{d\sigma_{gg \rightarrow H \rightarrow ff}}{dm^2} \sim \frac{g_i^2 g_f^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

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



Off-shell Higgs production

- Why off-shell production?



Production cross section

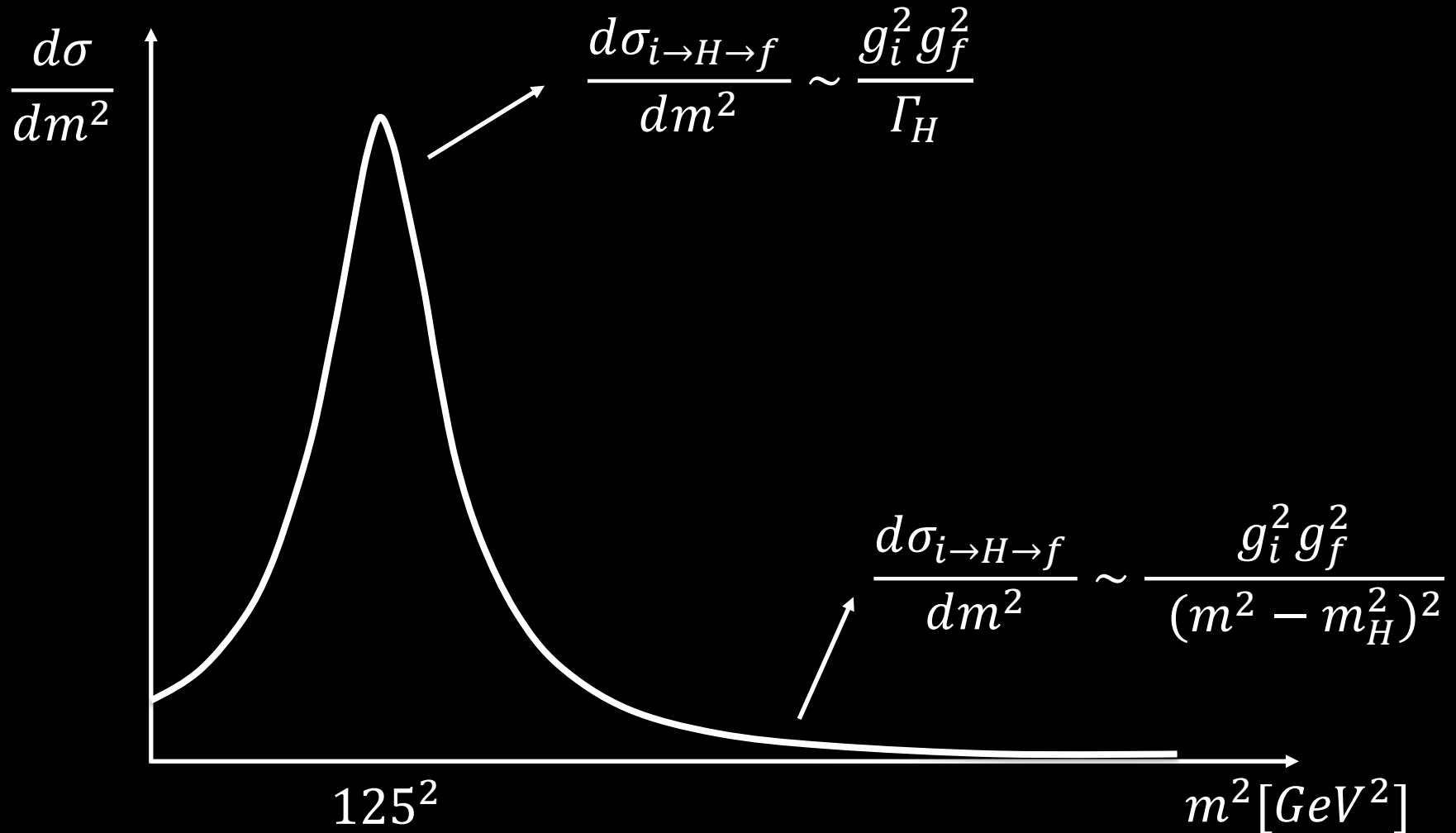
$$\frac{d\sigma_{gg \rightarrow H \rightarrow ZZ}}{dm^2} \sim \frac{g_i^2 g_f^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

- Off-shell production (for $m > 2m_Z$) $\sigma_{gg \rightarrow H^* \rightarrow ff}^{off-shell} \sim \frac{g_i^2 g_f^2}{(m^2 - m_H^2)^2}$

- **Width-independent: width-couplings ambiguity resolved**
- Unfortunately, the off-shell contribution is expected to be extremely small ...

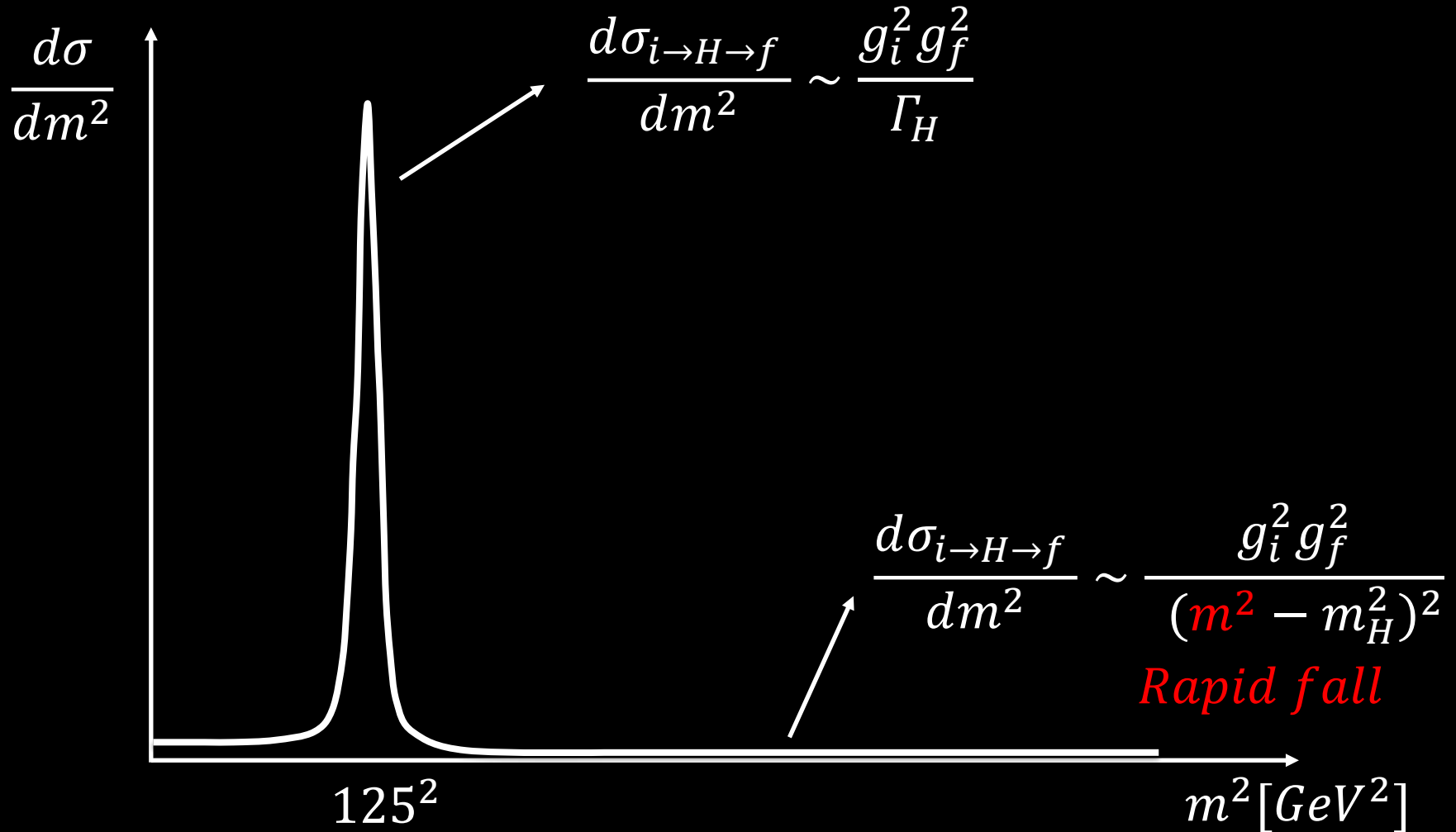


On-shell vs Off-shell Higgs production



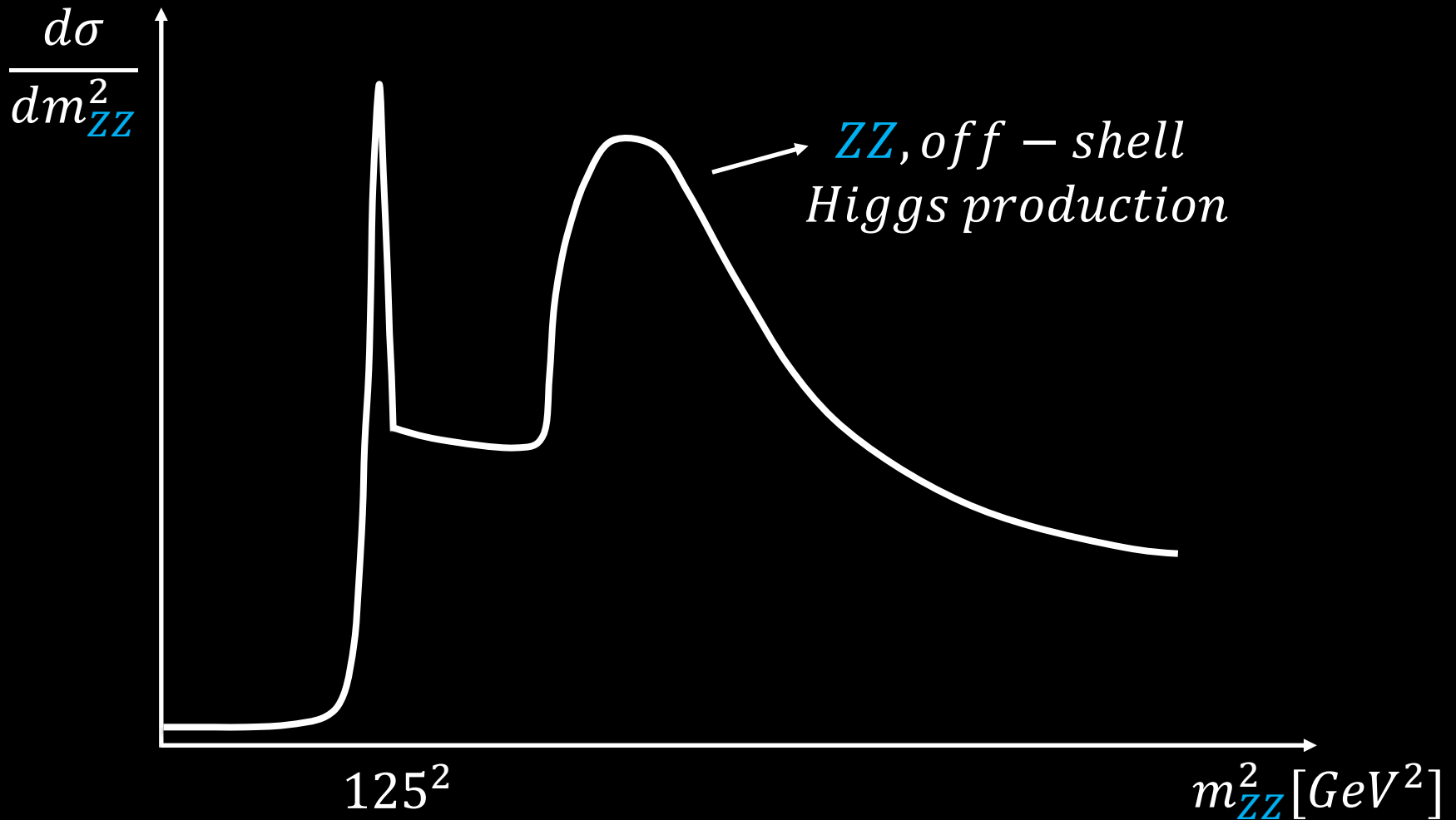


On-shell vs Off-shell Higgs production





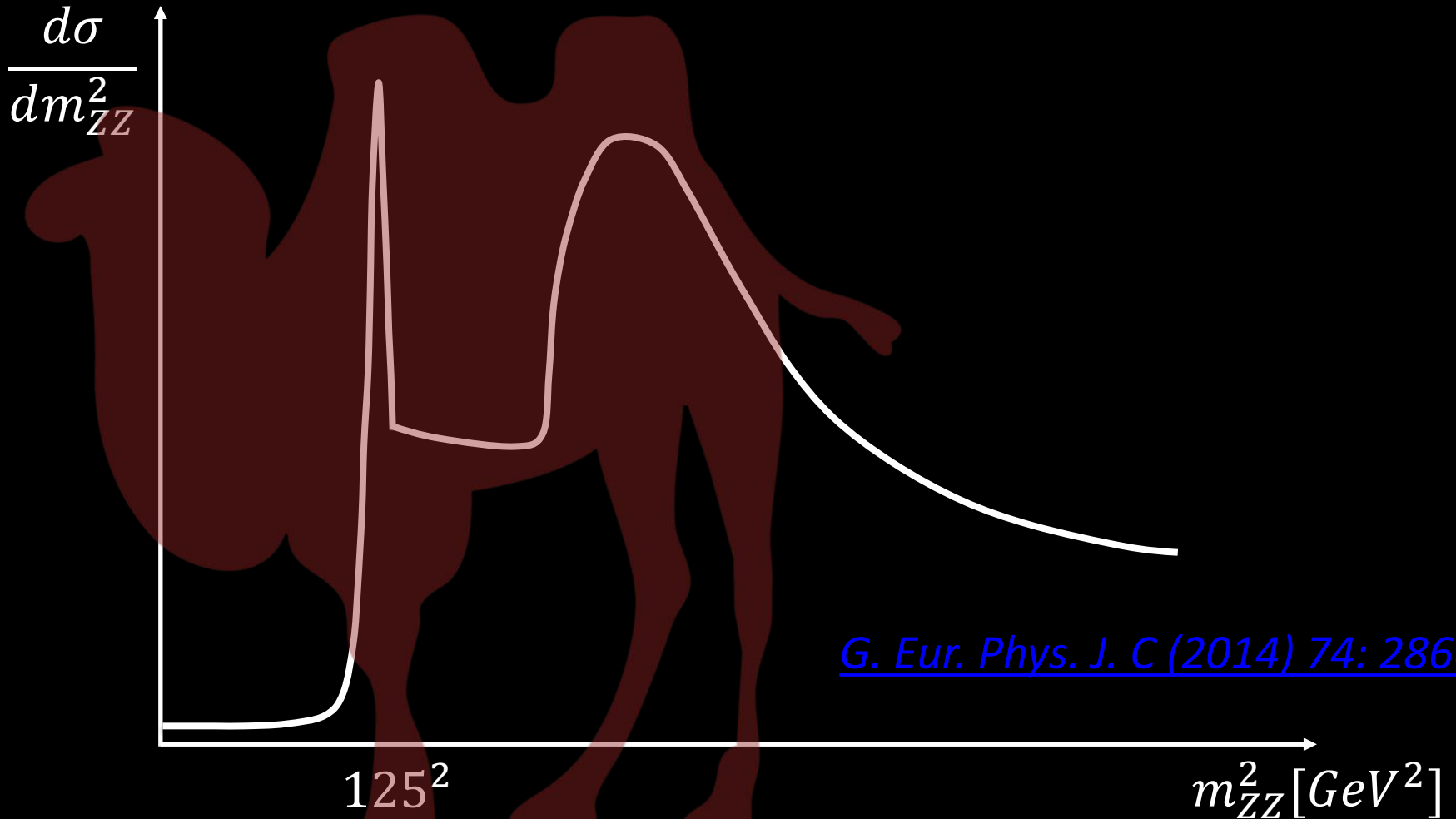
On-shell vs Off-shell Higgs production





A camel-shaped mass-line

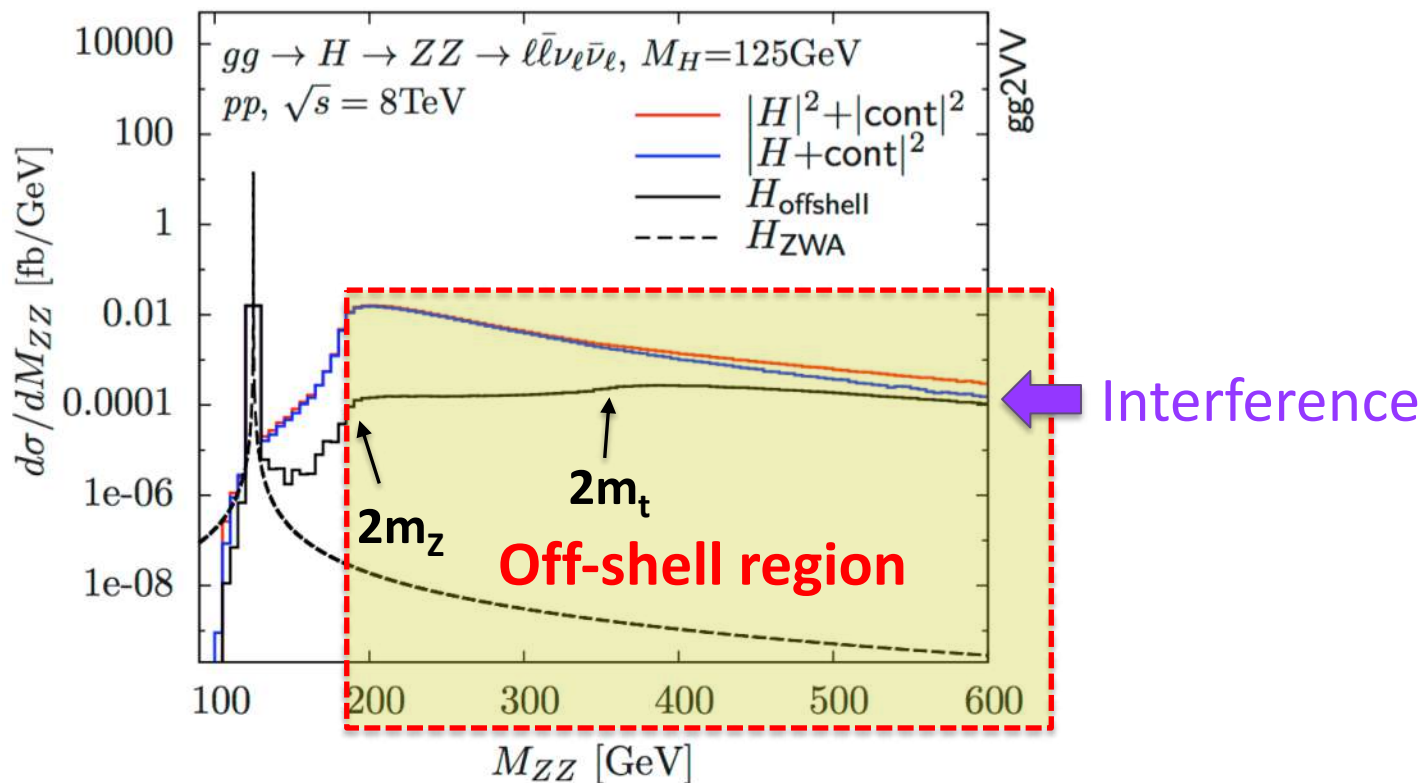
There is so much physics in a camel hump!



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



Once upon a paper ...

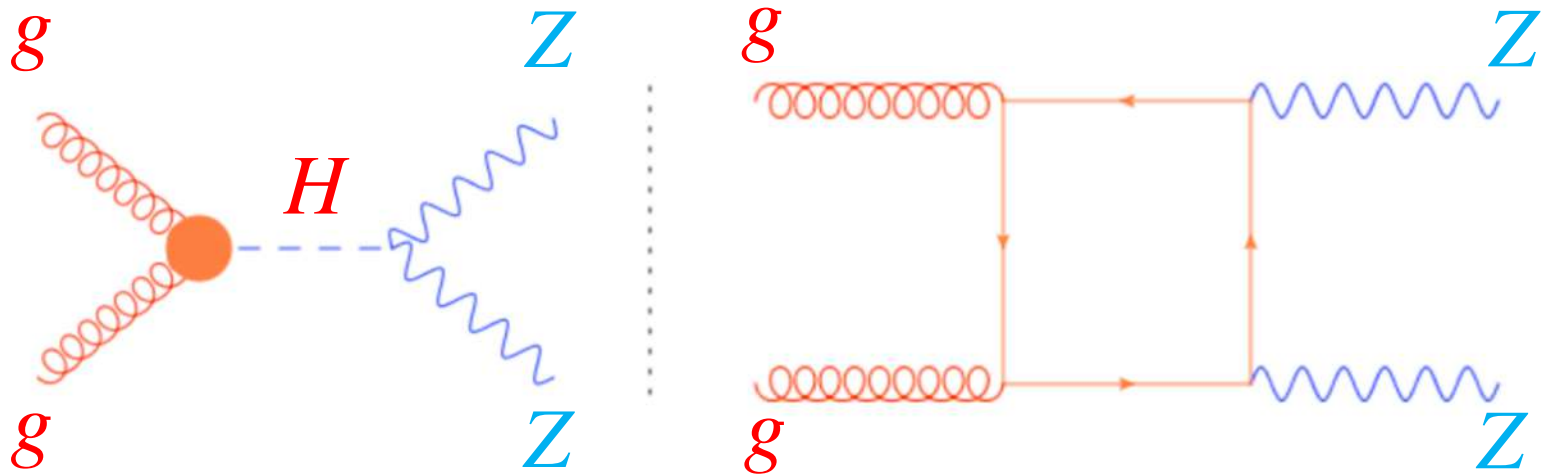


- In 2013 [Kauer](#) and Passarino pointed out that a significant enhancement in the off-shell production exists with two jumps
 - at the ZZ – *threshold*
 - at the $\bar{t}t$ – *threshold*



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

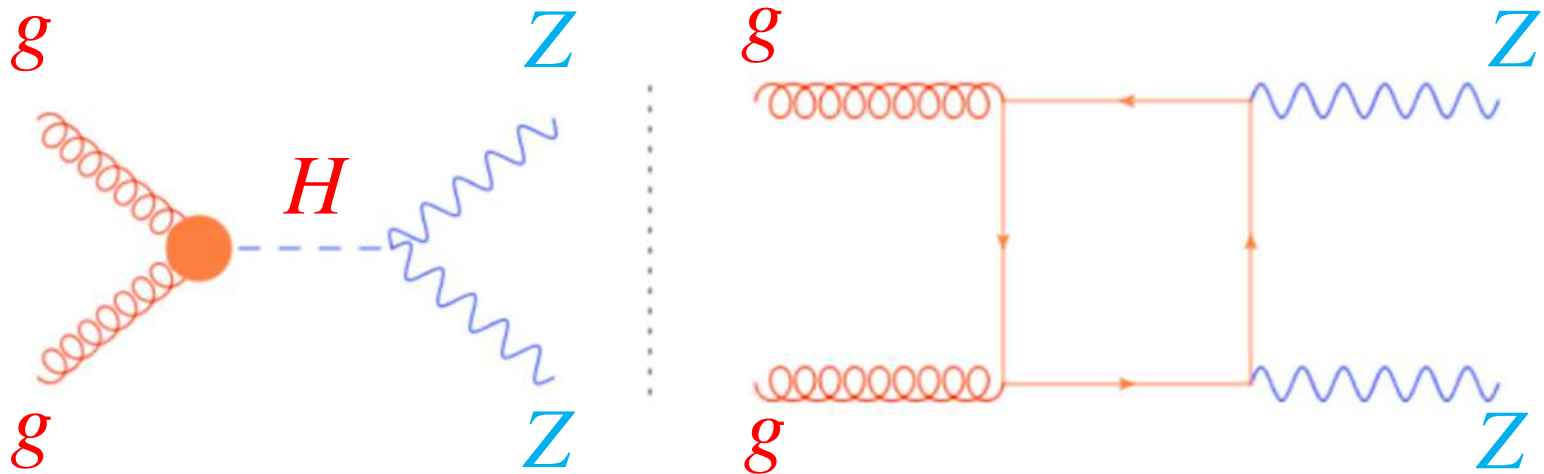


$$|\mathcal{M}_{ZZ}|^2 = |\mathcal{M}_H + \mathcal{M}_{Bkg}|^2 = |\mathcal{M}_H|^2 + |\mathcal{M}_{Bkg}|^2 + 2\text{Re}(\mathcal{M}_H \mathcal{M}_{Bkg}^*)$$



Interference

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$\mu_{off-shell}$ - independent

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

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



Analysis idea

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

$$\mu_{off-shell}^{ggF} = \frac{\sigma_{off-shell}^{ggF}}{\sigma_{off-shell, SM}^{ggF}} = k_{g,off-shell}^2 \cdot k_{V,off-shell}^2$$

$$\mu_{on-shell}^{ggF} = \frac{\sigma_{on-shell}^{ggF}}{\sigma_{on-shell, SM}^{ggF}} = \frac{k_{g,on-shell}^2 \cdot k_{V,on-shell}^2}{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

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

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

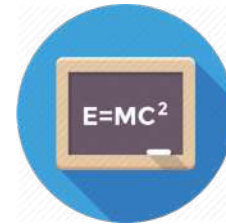
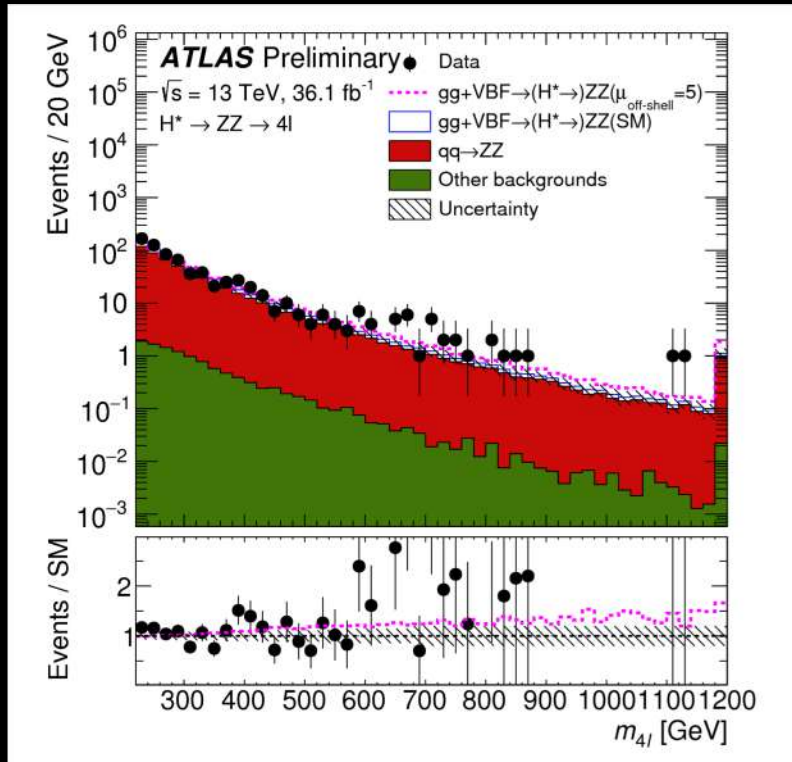


Analysis strategy

- Two decay channels⁺⁺, $H^* \rightarrow ZZ \rightarrow 4l$ and $H^* \rightarrow ZZ \rightarrow 2l2\nu$
- Analysis performed inclusively, ggF+VBF

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

ATLAS 4l invariant mass



Theory Corr.

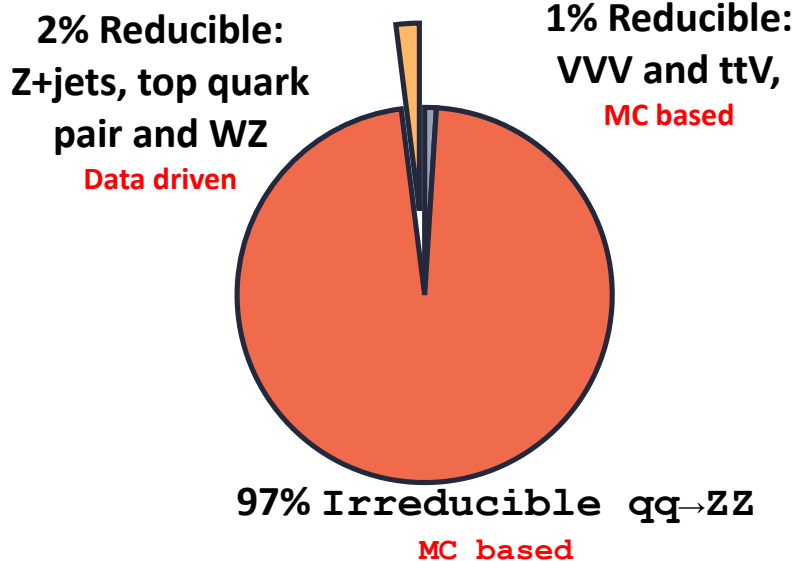
- NLO corrections finally available for Interference and background for $gg \rightarrow (H^*) \rightarrow ZZ$ as a function of $m(ZZ)$
- Significant improvement w.r.t. the Run-1 results, still leading systematics at **20%**



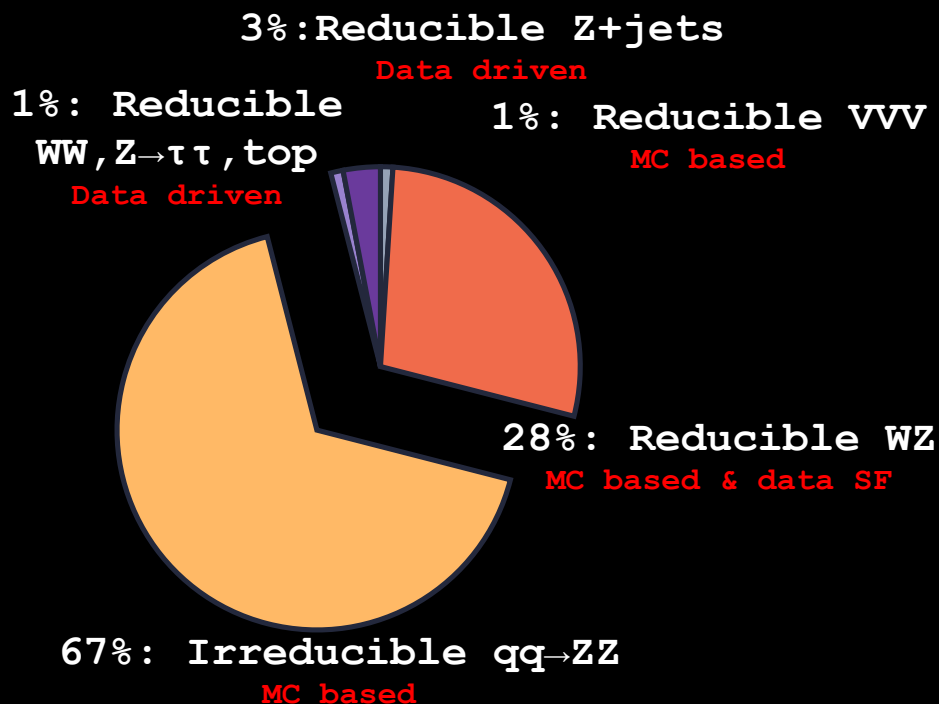
Background contributions

- In both the channels, the leading background is $qq \rightarrow ZZ$

Background composition in $4l$



Background composition in $2l2\nu$

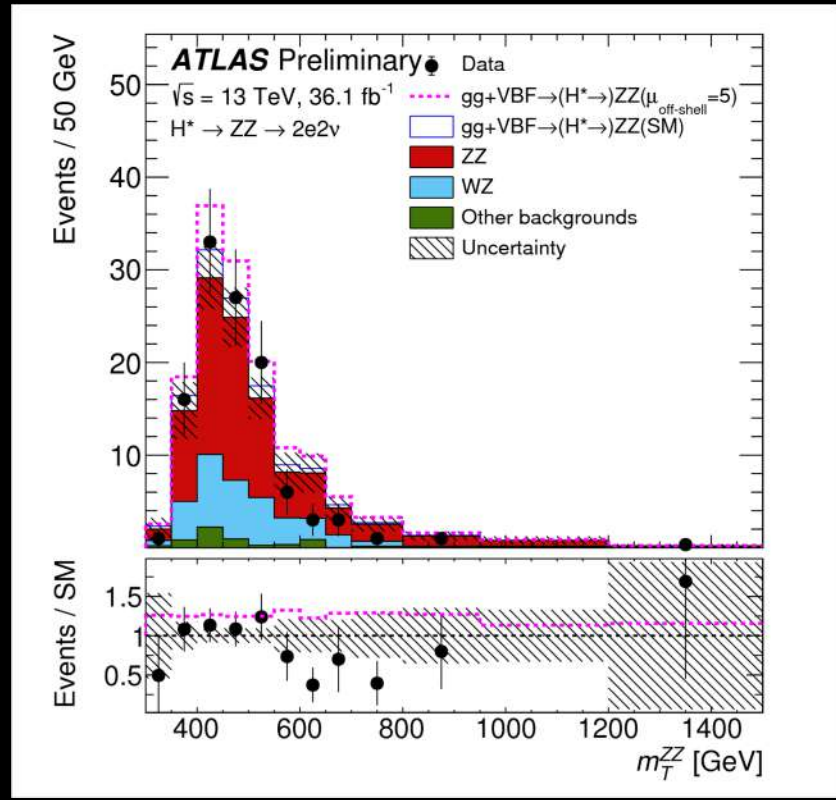




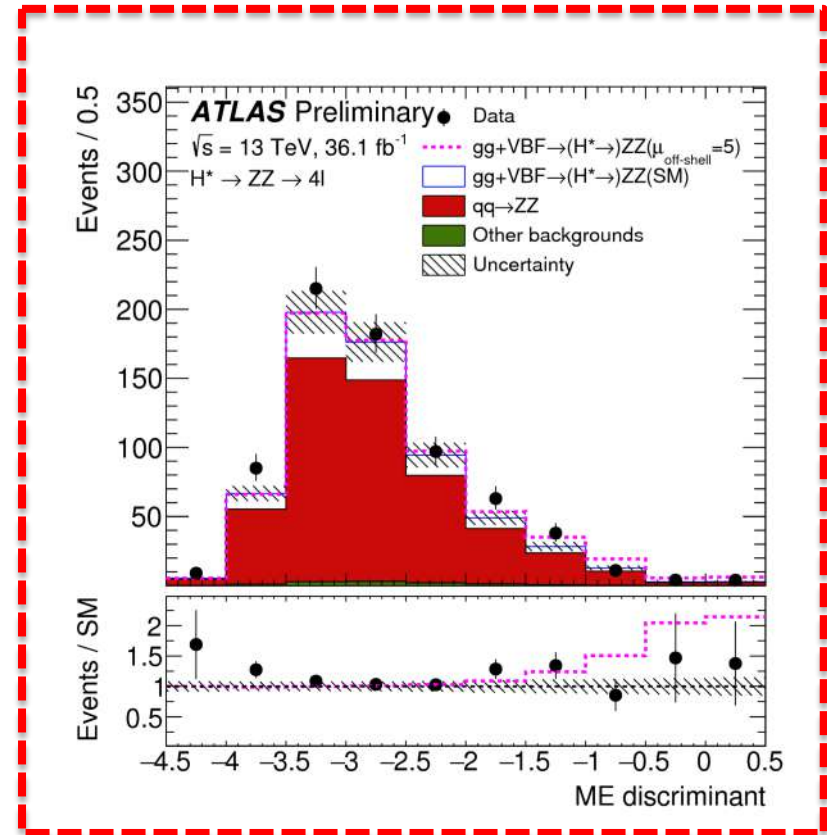
Discriminants

- 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

$$\text{prediction: } \frac{\mu_{off-shell}^{ggF}}{\mu_{off-shell}^{VBF}} = 1$$

2

Higgs boson total width constraints

➤ Combination with the on-shell result assuming the same

- on-shell signal strength in VBF and ggF: $\frac{\mu_{on-shell}^{ggF}}{\mu_{on-shell}^{VBF}} = 1$
- on-shell and off-shell couplings

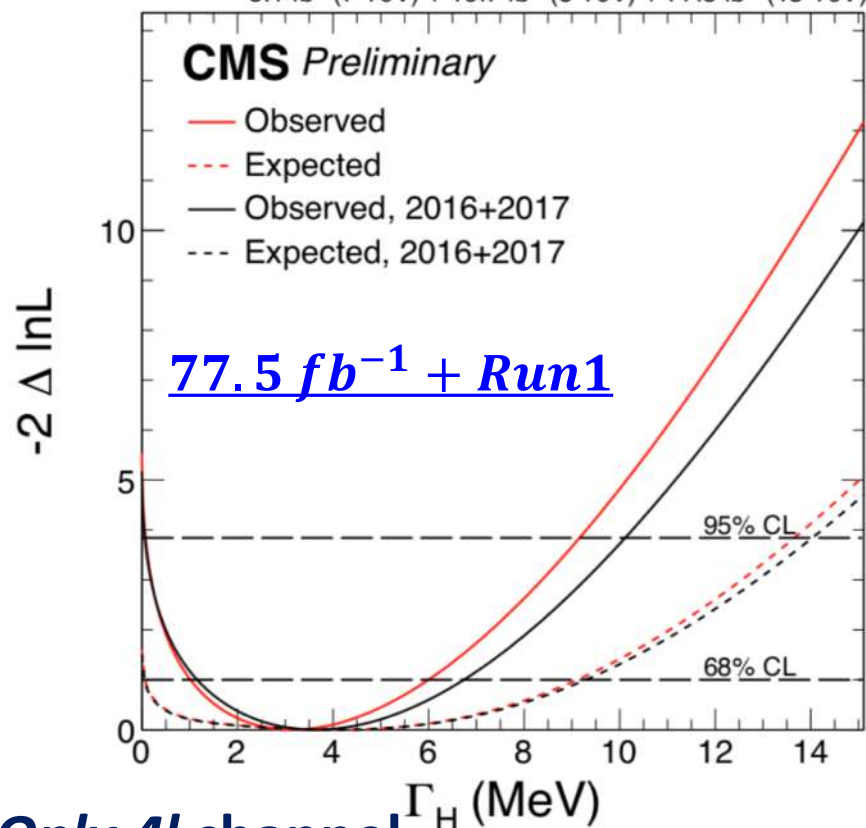


Run-2 results

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

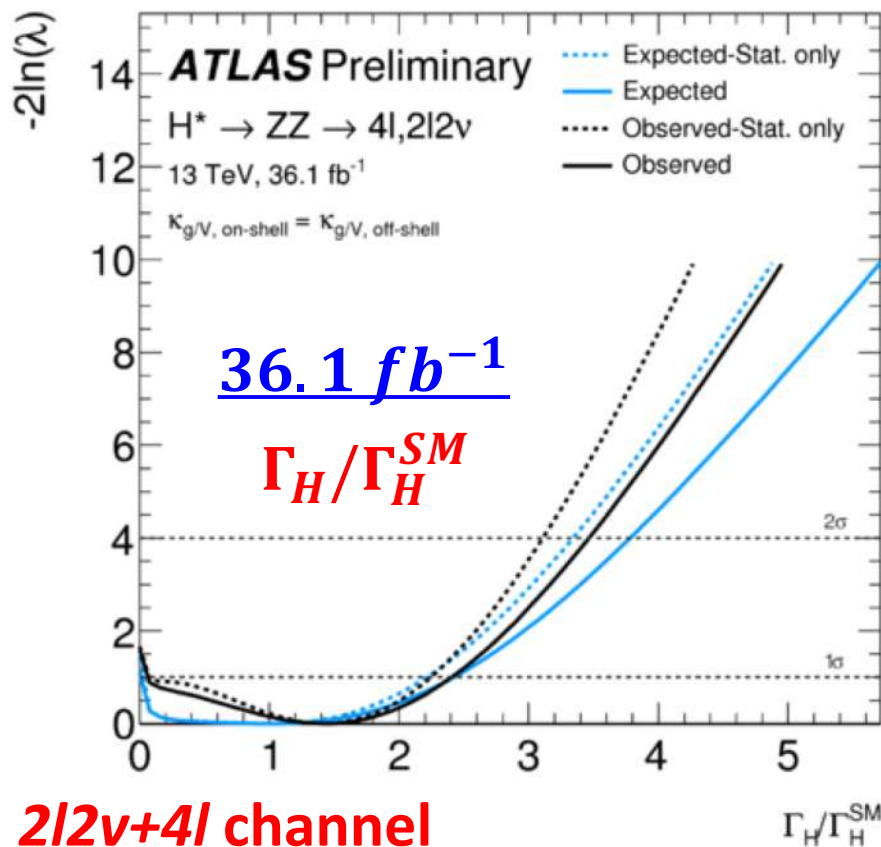
$\Gamma_H < 9.16 \text{ MeV}$ obs. (13.7 MeV exp.)

5.1 fb⁻¹ (7 TeV) + 19.7 fb⁻¹ (8 TeV) + 77.5 fb⁻¹ (13 TeV)



Only 4l channel

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



2l2v+4l channel

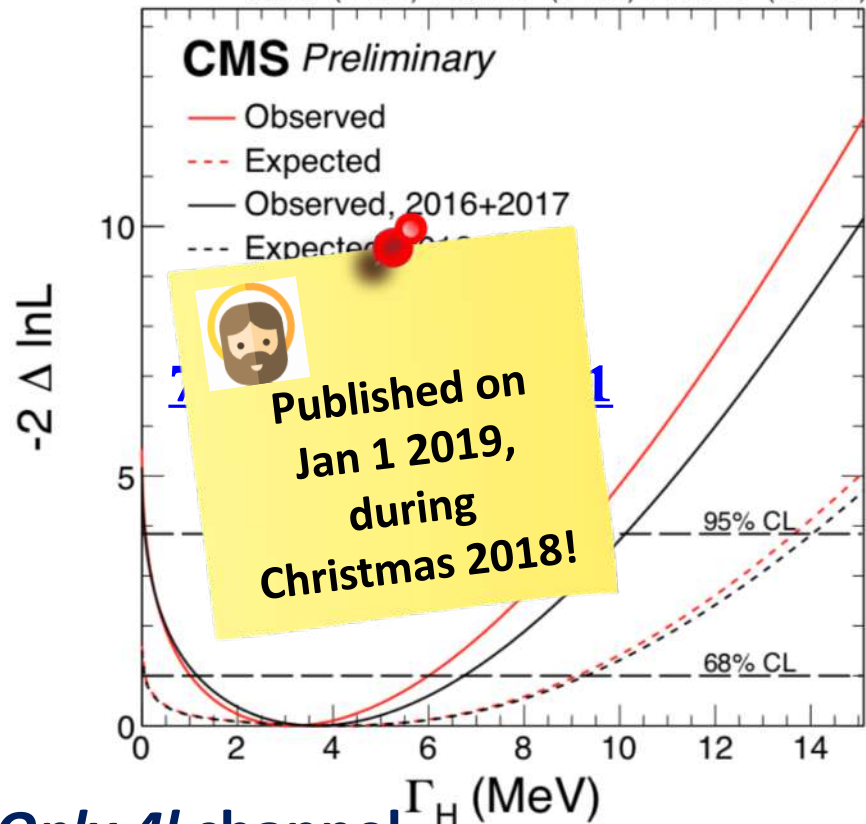


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- Hypothesis testing for a parameter of interest
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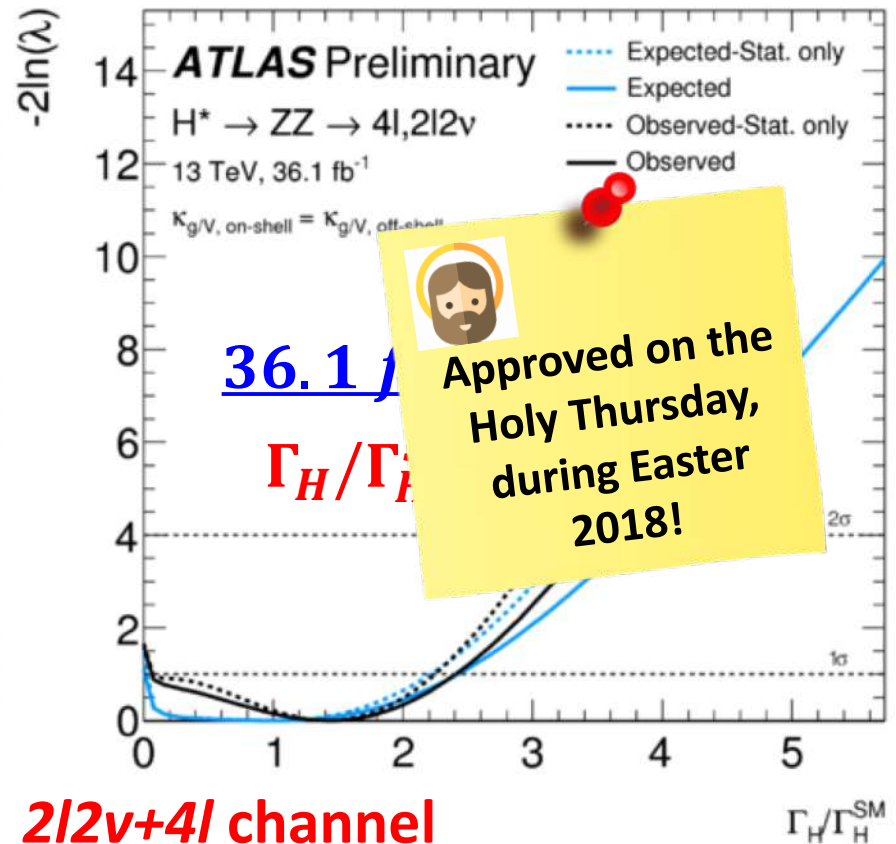
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2l2v+4l channel



R_{gg} interpretation

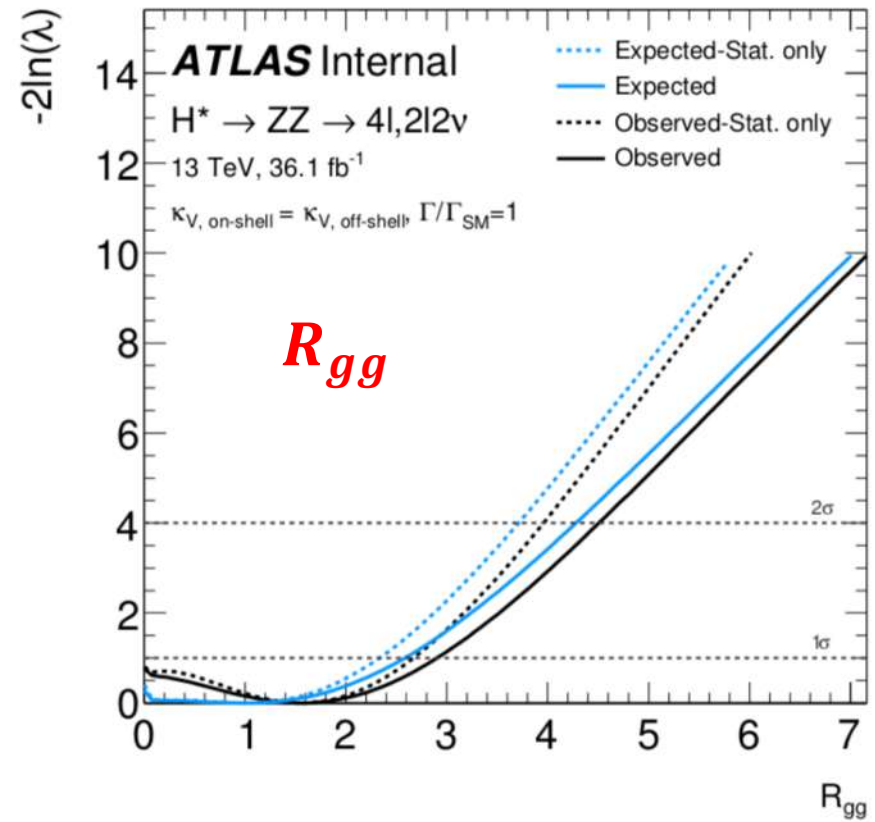
➤ In a second combination, ATLAS considers a gg -interpretation of the results

➤ The parameter of interest is

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

➤ 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



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: $\Gamma_H < 14.4$ obs. (15.2 exp.) MeV*
 - CMS 77.5 fb⁻¹ + Run 1: $\Gamma_H < 9.16$ obs. (13.7 exp.) MeV*
 - [ATLAS HL-LHC prospects](#) for the off-shell strategy with 3 ab⁻¹:
$$\Gamma_H = 4.2_{-2.1}^{+1.5} \text{ MeV}$$



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



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Conclusions

- The current results for the Higgs total width measurements have been presented
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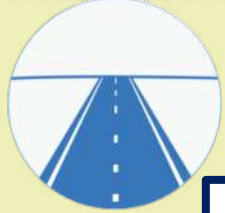


Improvement on Run-1 expected limits by a factor 2 !

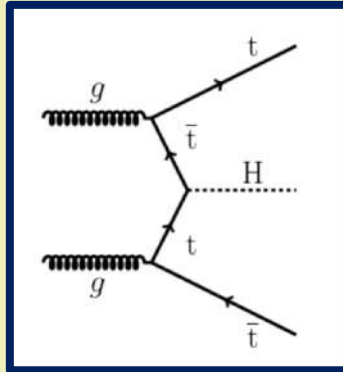
- At ILC the result would be at 1.7%

Back-up

Higgs couplings



DIRECT PROBES *at tree level*

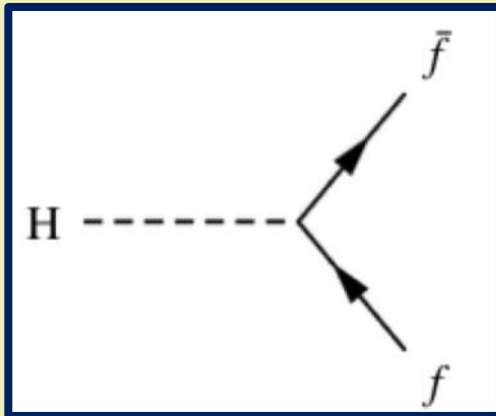


ttH

Different

generations:

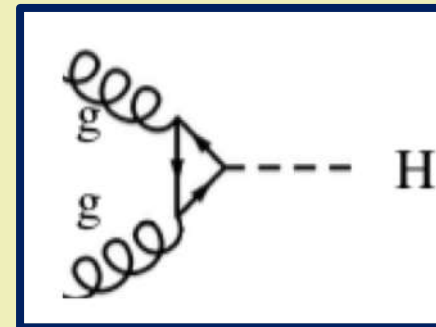
- Leptons
- Up-type quarks
- Down-type quarks



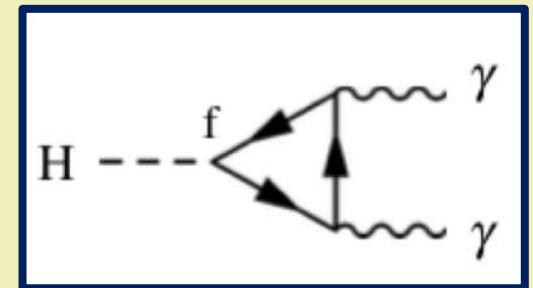
INDIRECT PROBES



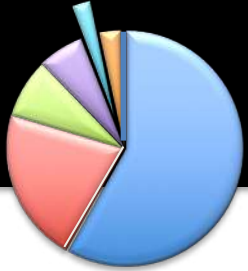
via loop diagrams



gluons



photons



Higgs boson mass in the 4l channel

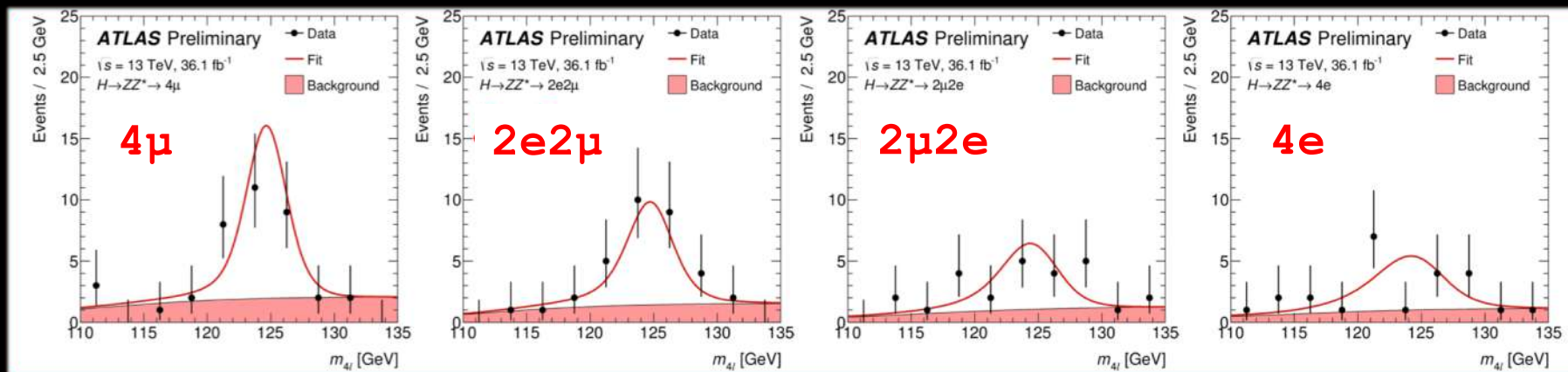
- Event selection and categorization as in other HZZ^* analyses:
2 same-flavour opposite-sign leptons organized in 4 categories
 $4\mu, 2e2\mu, 2\mu 2e$ and $4e$

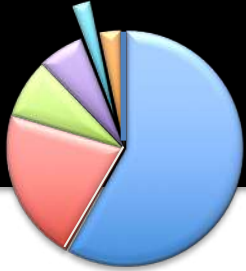


Strategy: $BDT(p_T^{4l}, \eta^{4l}, \mathcal{D}_{ZZ^*})$ to distinguish $H \rightarrow ZZ^* \rightarrow 4l$ from $ZZ^* \rightarrow 4l$, (dominant background) with $\mathcal{D}_{ZZ^*} = \log |m_{H \rightarrow ZZ^*}| / |m_{ZZ^*}|$

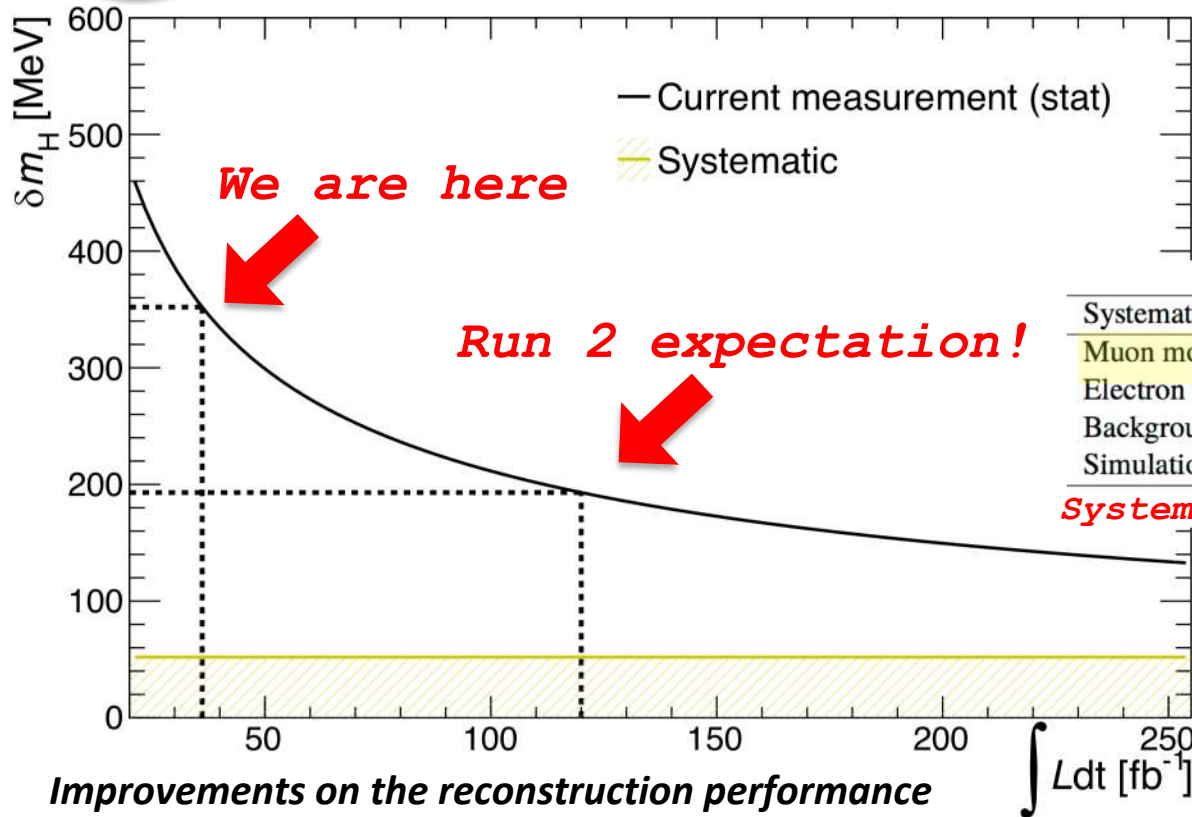
- Higgs boson mass determined from a simultaneous profile likelihood fit to 16 data categories:

4 final states \times 4 BDT bins





Higgs boson mass: Run-2 prospects



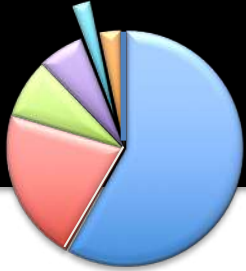
Systematic effect	Uncertainty on $m_H^{ZZ^*}$ [MeV]
Muon momentum scale	40
Electron energy scale	20
Background modelling	10
Simulation statistics	8

Systematics breakdown (2015-2016)

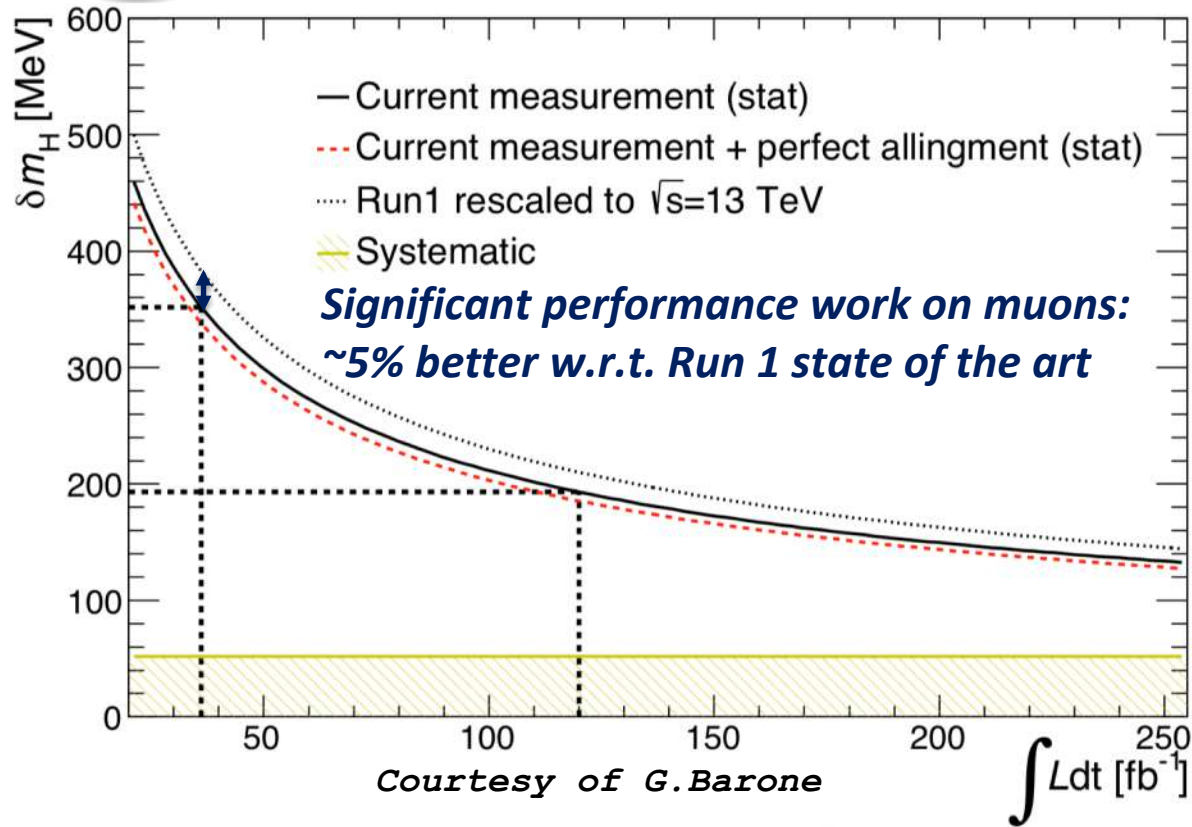
Improvements on the reconstruction performance of muons/electrons

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

- Statistically limited
- δm_H scales linearly with resolution improvements



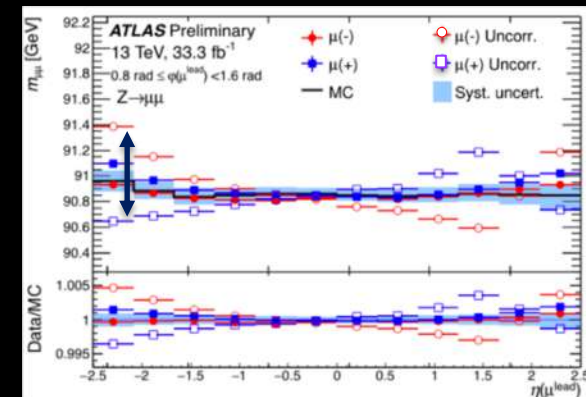
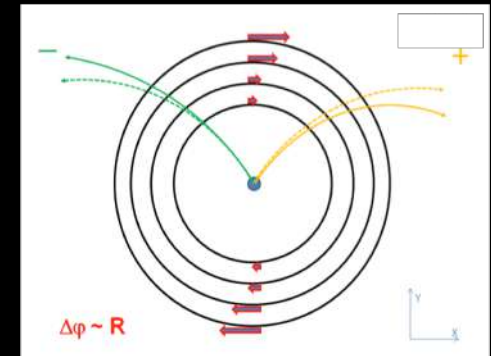
Higgs boson mass: performances



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

ID DISTORTIONS

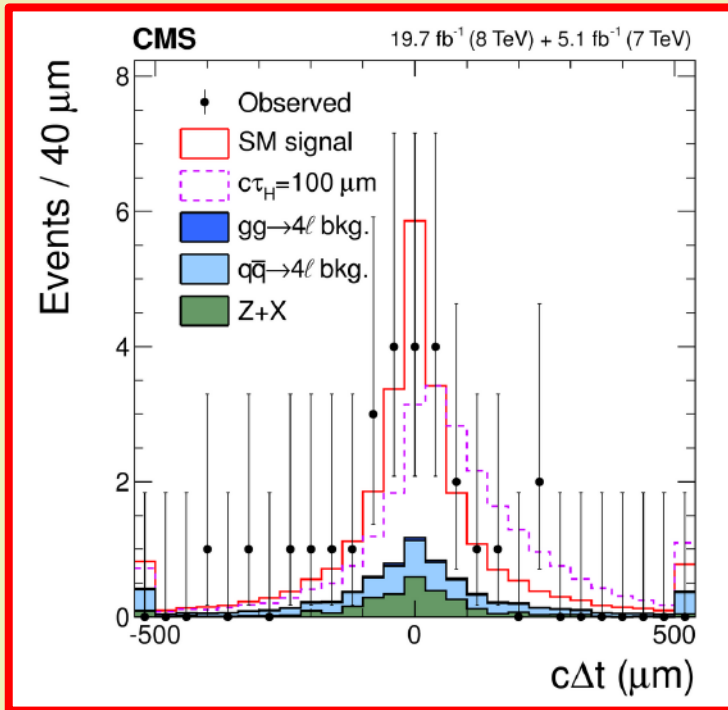
ID Deformations induce local scale biases and degrade resolution in a charge asymmetric way





Direct strategies

From the lifetime



- Using the Higgs lifetime we can set a direct lower bound
- $\Delta t = \frac{m_{4l}}{p_T} (\Delta \vec{r}_t \cdot \widehat{p}_T) \rightarrow$
 - $\langle \Delta t \rangle = \tau_H = \hbar / \Gamma_H$
- 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 $D^{kin})$



Indirect strategies: from couplings

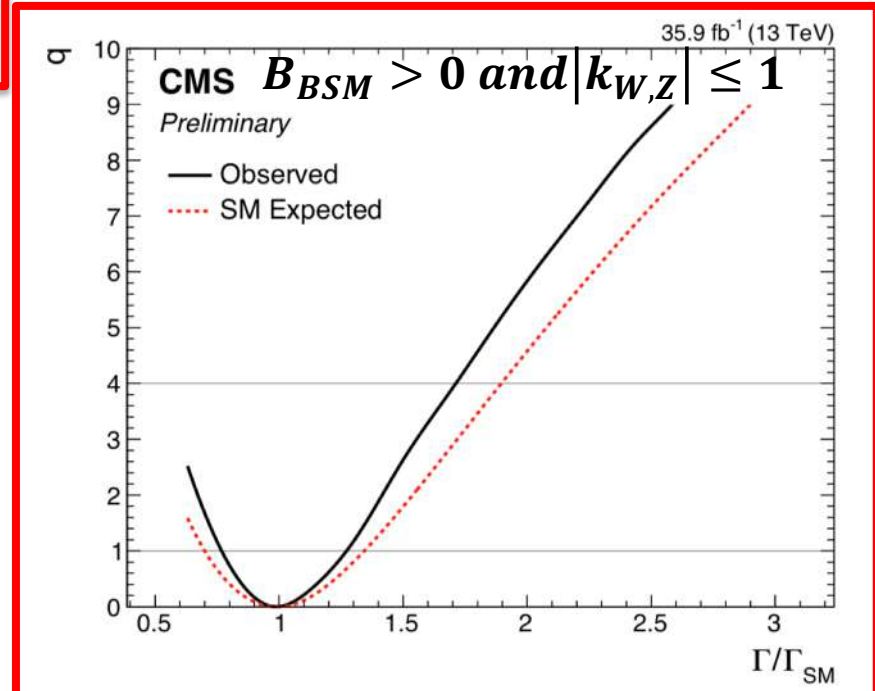
➤ Using the [coupling analysis framework](#) we can constrain Γ_H :

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

Two possible interpretations:

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

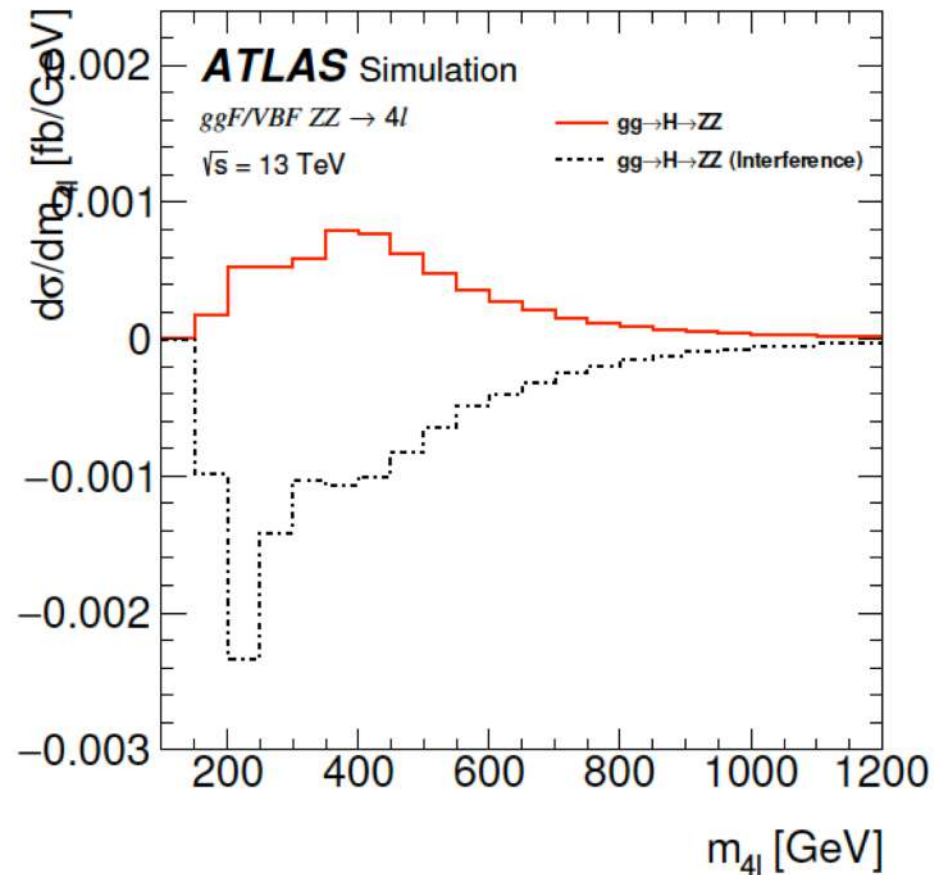
Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(\text{ggH})$	✓	b-t	κ_g^2	$1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	-	-	-	$0.73 \cdot \kappa_W^2 + 0.27 \cdot \kappa_Z^2$
$\sigma(\text{WH})$	-	-	-	κ_W^2
$\sigma(\text{qq/qg}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





Interference

- Negative contribution of the interference term





Off-shell: analysis selection

4l channel

Event Selection	
QUADRUPLET SELECTION	<ul style="list-style-type: none"> - Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-charge leptons fulfilling the following requirements: <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - Contribution from the other leptons of the quadruplet is subtracted - Muon track isolation ($\Delta R \leq 0.30$): $\Sigma p_T/p_T < 0.15$ - Muon calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T/p_T < 0.30$ - Electron track isolation ($\Delta R \leq 0.20$): $\Sigma E_T/E_T < 0.15$ - Electron calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T/E_T < 0.20$
IMPACT PARAMETER SIGNIFICANCE	<ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - Require a common vertex for the leptons: <ul style="list-style-type: none"> - $\chi^2/\text{ndof} < 6$ 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
$E_T^{\text{miss}} > 175$ GeV
$\Delta R_{\ell\ell} < 1.8$
$\Delta\phi(Z, E_T^{\text{miss}}) > 2.7$
Fractional p_T difference < 0.2
$\Delta\phi(\text{jet}(p_T > 100 \text{ GeV}), E_T^{\text{miss}}) > 0.4$
$E_T^{\text{miss}}/H_T > 0.33$
b-jet veto



Off-shell: analysis strategy in 4l

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

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

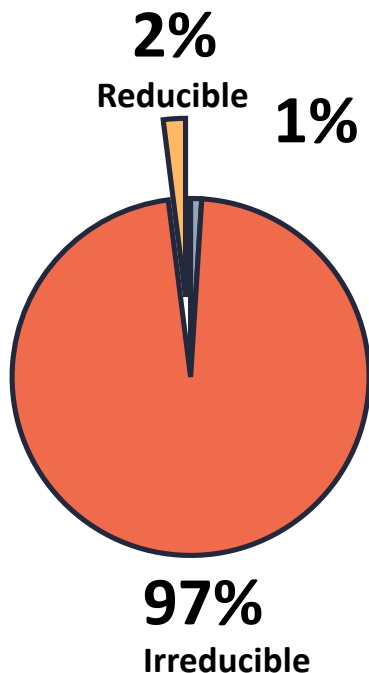
$$ME = \log_{10} \left(\frac{P_H}{P_{gg} + c \cdot P_{q\bar{q}}} \right)$$

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

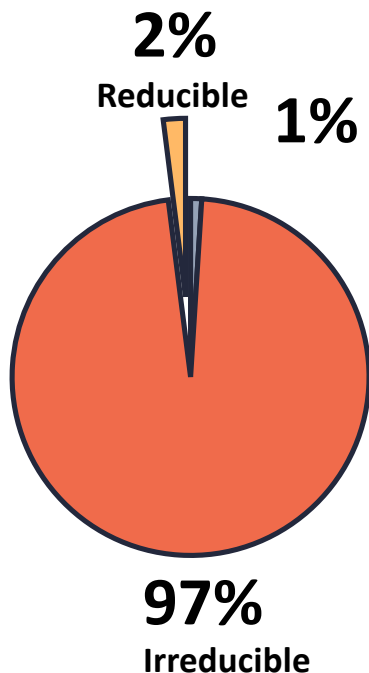
➤ Predictions are checked using two data Control Regions:

RegionA: $160 \text{ GeV} < m_{4l} < 220 \text{ GeV}$ and *RegionB*: $220 \text{ GeV} < m_{4l} < 1200 \text{ GeV}$ and $ME < -1.5$

➤ Overall good agreement with data 1.1σ above expectations



Reducible background in 4l



- Data-driven estimation
 - except for tribosons and $t\bar{t}$ 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 μ	1.49 ± 0.19
4 μ	0.42 ± 0.04



Off-shell: analysis strategy in 2l2v

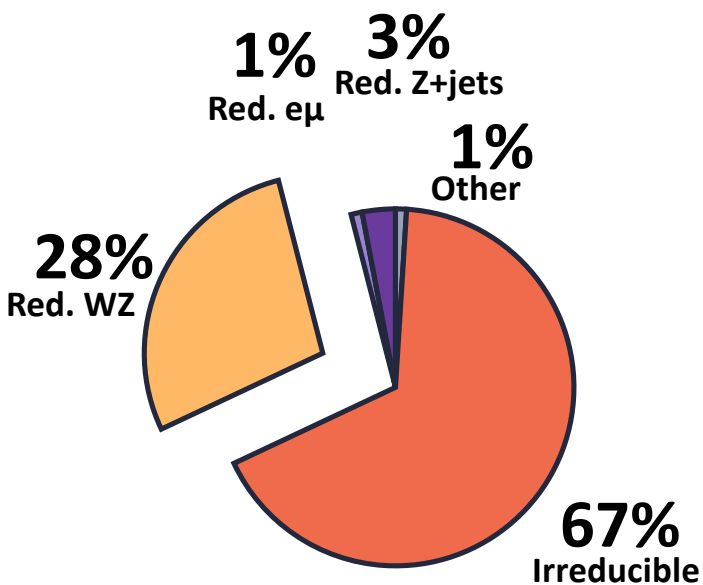
- High-Mass- $H \rightarrow ZZ \rightarrow ll\nu\nu$ -analysis event selection used as baseline in the off-peak region with further re-optimisation :
 - MET cut $120 \text{ GeV} \rightarrow 175 \text{ GeV}$
 - MET/ H_T cut $0.4 \rightarrow 0.33$ with H_T scalar sum of lepton and jet p_T

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

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



Irreducible background in 2l2v



➤ $qq \rightarrow ZZ$ background

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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

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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

- $WZ, W \rightarrow l\nu, Z \rightarrow ll$ 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

3l Control Region

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

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

NF CR→SR transfer factor
1.29 ± 0.03 (stat.)

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

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



Reducible background in 2l2v: $e\mu$

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

$$N_{ee}^{SR} = \frac{1}{2} \times \epsilon \times N_{e\mu}^{data,sub} \quad N_{\mu\mu}^{SR} = \frac{1}{2} \times \frac{1}{\epsilon} \times N_{e\mu}^{data,sub} \quad \text{where} \quad N_{e\mu}^{data,sub} = N_{e\mu}^{data} - \sum_i^{non-e\mu} N_i^{MC}$$

$$\epsilon^2 = \frac{N_{ee}}{N_{\mu\mu}} \quad \left| \begin{array}{l} \epsilon \text{ accounts for } e/\mu \\ \text{difference in} \\ \text{trigger/reconstruction/} \\ \text{ID efficiency} \end{array} \right.$$

- Since it was introduced 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}	$1.3 \pm 0.5 \pm 0.5$
$N_{\mu\mu}$	$1.3 \pm 0.5 \pm 0.5$

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

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

➔

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



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: $\frac{\mu_{off-shell}^{ggF}}{\mu_{off-shell}^{VBF}} = 1$

- We can define the coupling ratios

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

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

$$\mu_{off-shell}^{ggF} = R_{gg} \cdot R_{VV} \cdot \mu_{on-shell}^{ggF} \frac{\Gamma_H}{\Gamma_H^{SM}} \quad \mu_{off-shell}^{VBF} = R_{VV}^2 \cdot \mu_{on-shell}^{VBF} \frac{\Gamma_H}{\Gamma_H^{SM}}$$



On- Off- shell: combination

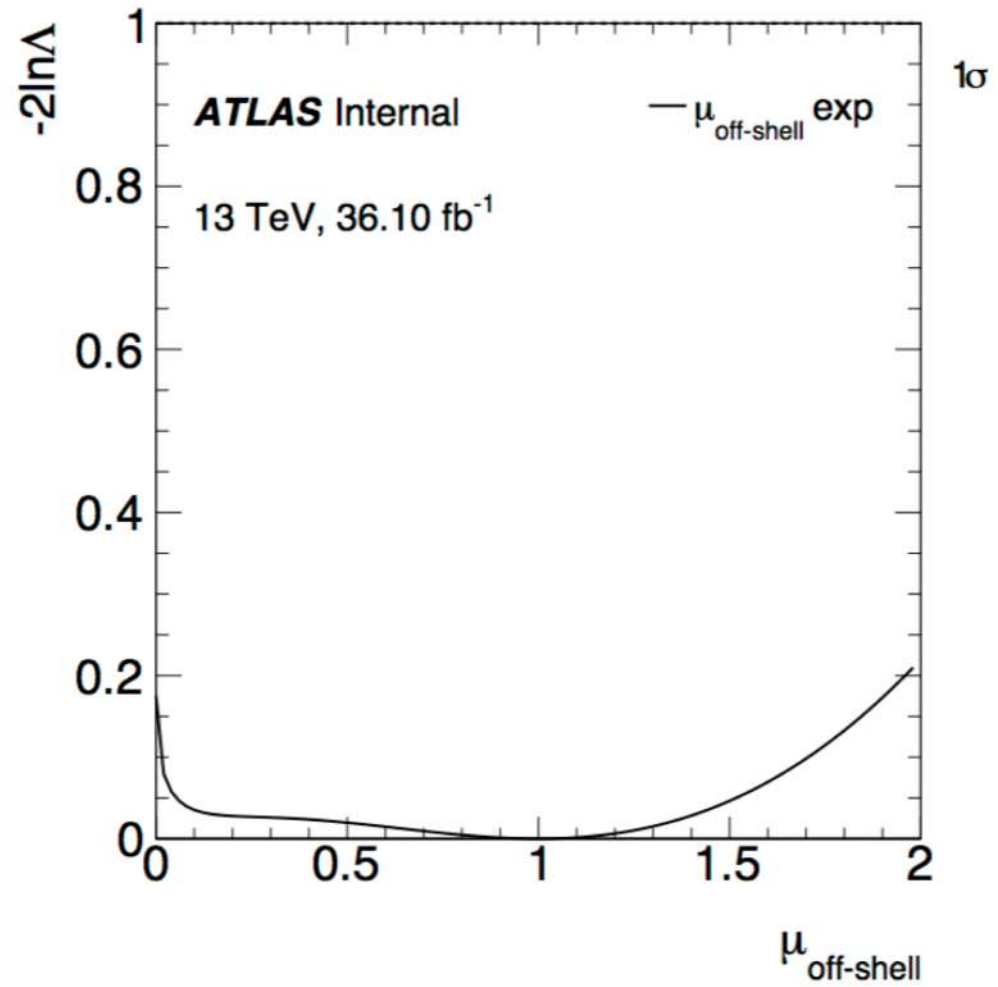
$$\mu_{off-shell}^{ggF} = R_{gg} \cdot R_{VV} \cdot \mu_{on-shell}^{ggF} \frac{\Gamma_H}{\Gamma_H^{SM}}$$

$$\mu_{off-shell}^{VBF} = R_{VV}^2 \cdot \mu_{on-shell}^{VBF} \frac{\Gamma_H}{\Gamma_H^{SM}}$$

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



Likelihood 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)

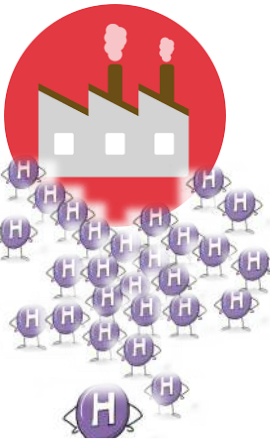
- *ATLAS*: $\Gamma_H < 22.7(33) MeV$
- *CMS*: $\Gamma_H < 22(33)MeV$



- 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

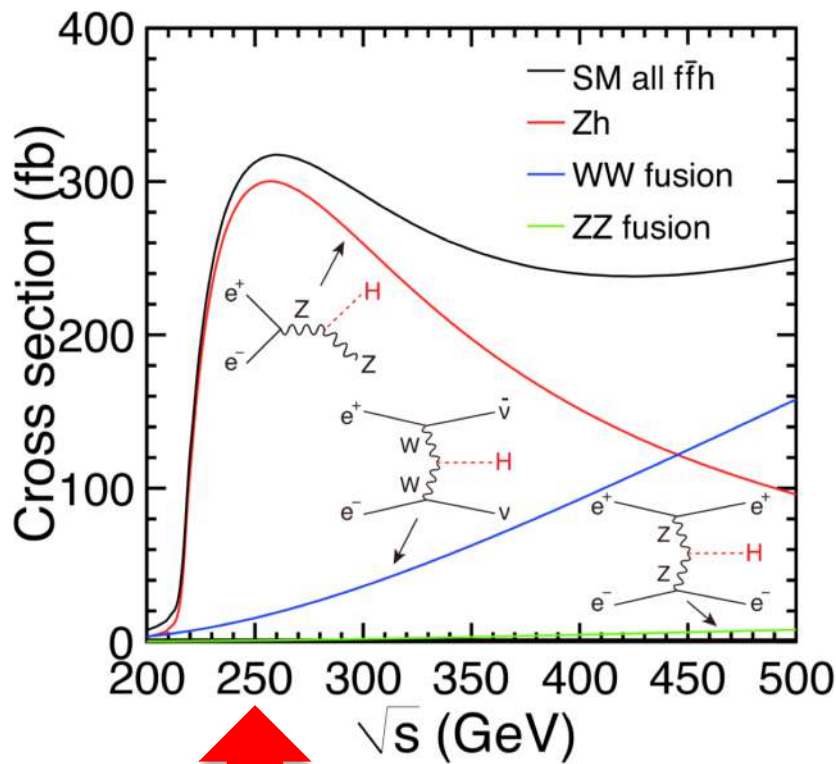


Improvement on Run-1 expected limits by almost a factor 2 !



ILC: the future Higgs factory?

- 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 ➡ ~500 K Higgs
 - WW-fusion ➡ ~15 K Higgs

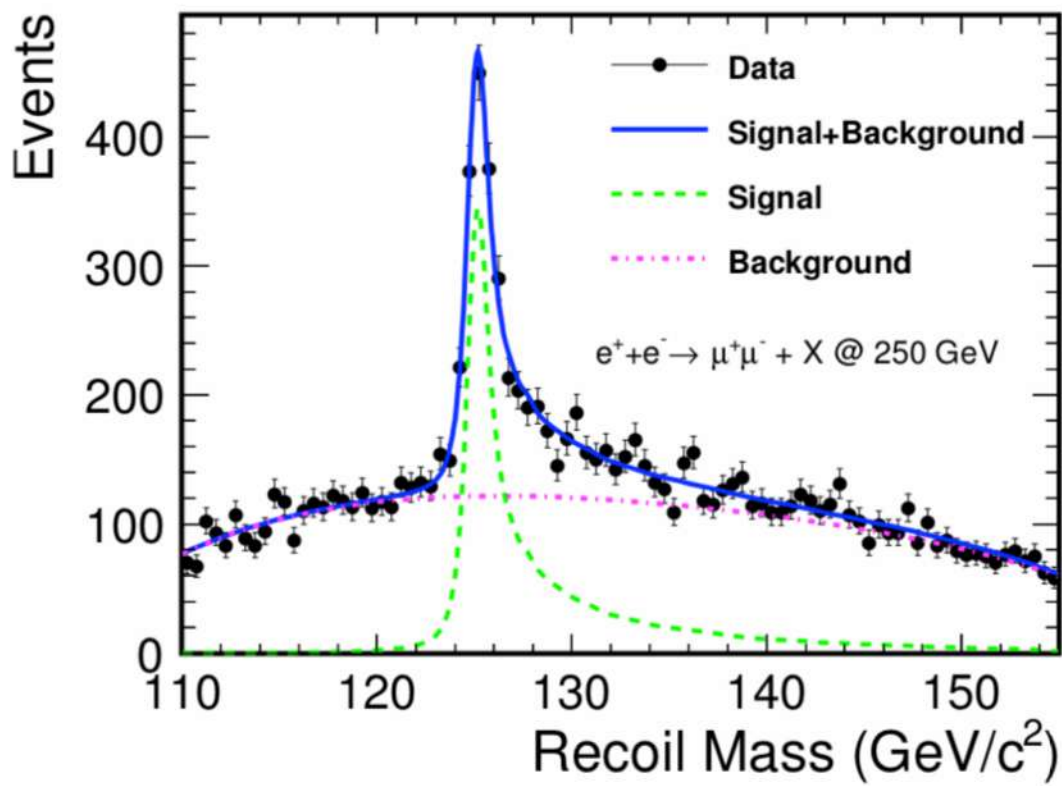
➤ ZH cross section measurable at 1.0%

➤ From the HZ sample, measurement of g_{HZZ} : $\sigma(e^+e^- \rightarrow ZH) \propto g_{HZZ}^2$



Measuring the HZ coupling at ILC

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



$$M_{rec}^2 = (\sqrt{s} - E_{ll})^2 - |\vec{p}_{ll}|^2$$

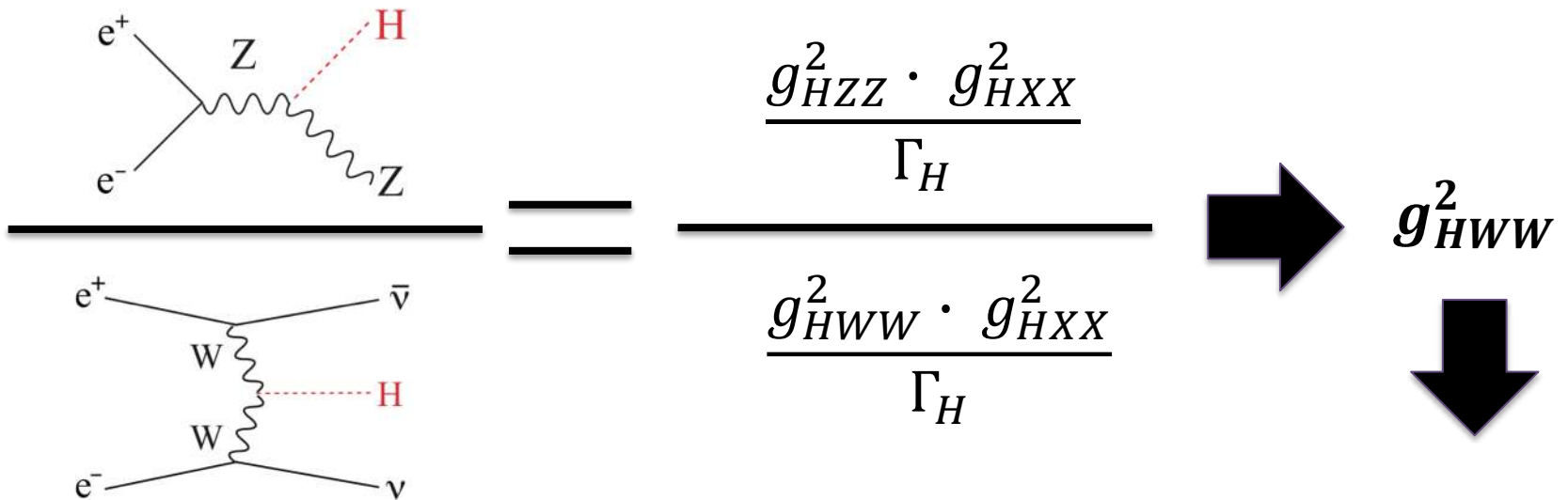
- Higgs events are tagged with the Z boson decays, independently of the Higgs decay mode
- From the HZ sample, measurement of g_{HZZ} :

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



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



Measuring $\sigma(e^+e^- \rightarrow ZH) \times BR(H \rightarrow WW^*) \propto \frac{g_{HZZ}^2 \cdot g_{HWW}^2}{\Gamma_H}$

Γ_H [Result at 1.7%\(ILC250+ILC500\)](#)