Pelourinho, Salvador – colourful painting of the old colonial houses by street artist from yesterday tour

Measurement of cross sections and properties of the Higgs boson using the ATLAS detector

Luigi MARCHESE, Oxford university

on behalf of the ATLAS collaboration

LISHEP2018, 9-14 September, Salvador de Bahía

OUTLINE

- Introduction to Higgs physics
- Higgs properties and cross sections
  - couplings
  - Higgs width
  - Higgs mass
- Conclusions

NEW Several new ATLAS results released in the past months

INTRODUCTION

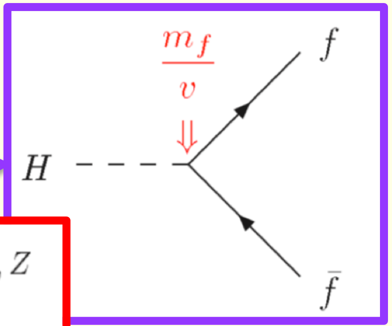
- We have just recently celebrated the 6th Higgs birthday
- The Higgs boson discovery opened a new window into the sector of the SM Lagrangian responsible for EW symmetry breaking!
- Precision measurements are vital to test theoretical models
  - Initial results in Run 1
  - Many results in Run 2

THE HIGGS BOSON IN THE STANDARD MODEL

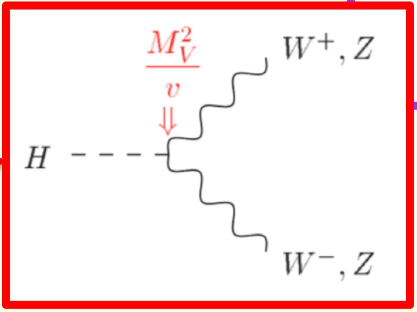
- By interacting with all the SM particles, the Higgs field gives them mass
  - Two different types of tree-level couplings

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

Fermions

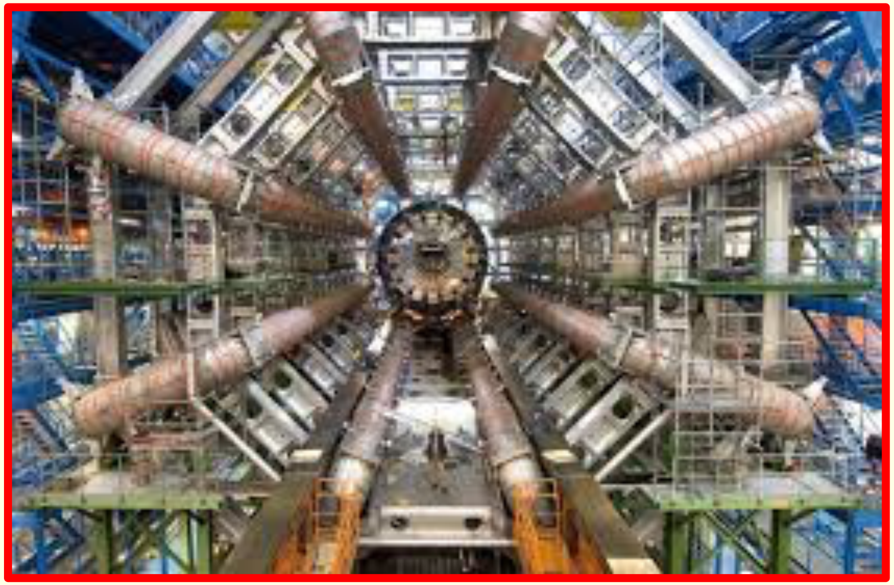


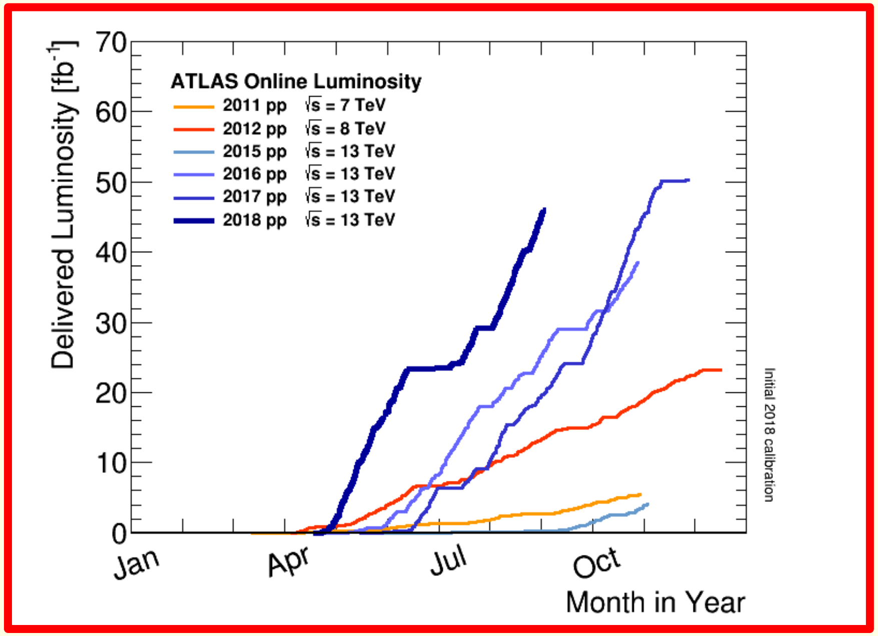
Bosons



HIGGS PHYSICS AT LHC

- At the Large Hadron collider the delivered luminosity was:
  - 25 fb^{-1} at 7/8 TeV – Run 1 Higgs discovery!
  - 36 fb^{-1} (2015+2016), 44 fb^{-1} (2017) at 13 TeV – Run 2





- 1 Higgs boson produced every 10^9 proton-proton collisions

HIGGS PHYSICS AT LHC

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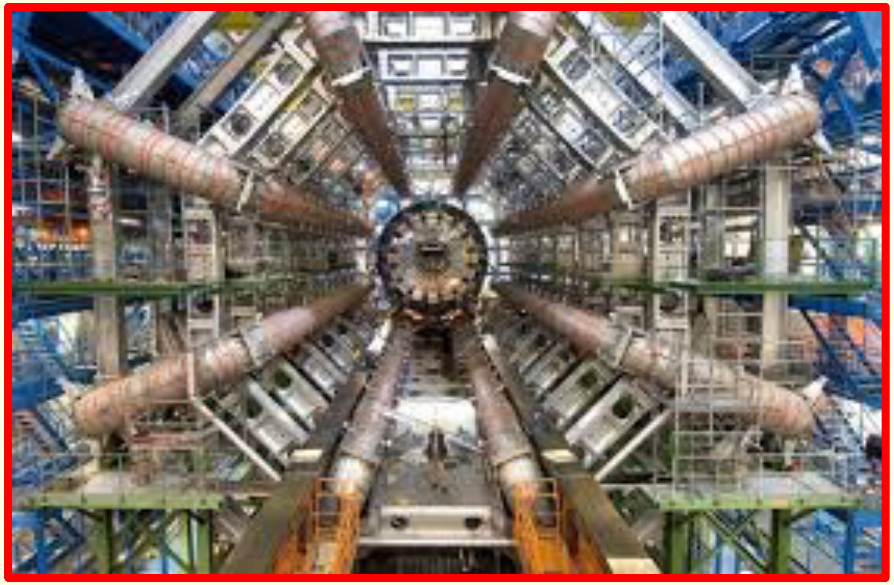
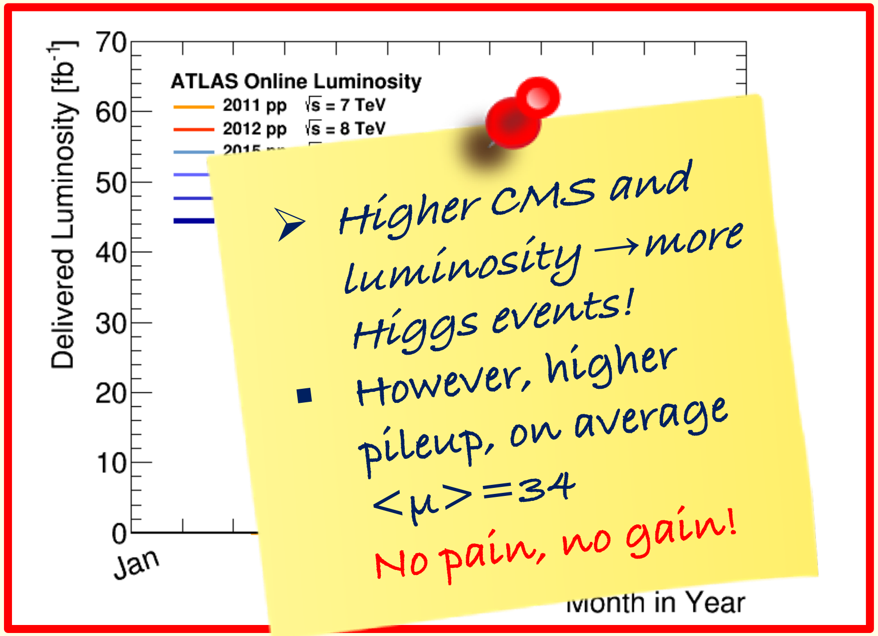
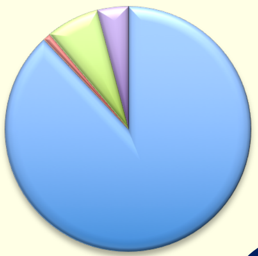




- Higher CMS and luminosity → more Higgs events!
- However, higher pileup, on average $<\mu>=34$

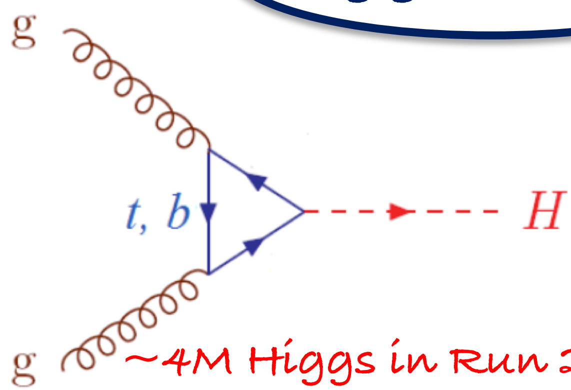
No pain, no gain!

- 1 Higgs boson produced every 10^9 proton-proton collisions



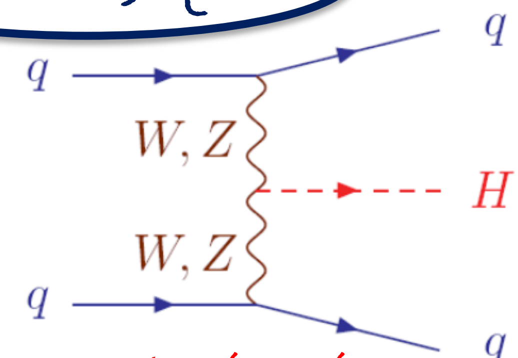
HIGGS PRODUCTION AT LHC

ggF: 88%



~4M Higgs in Run 2*

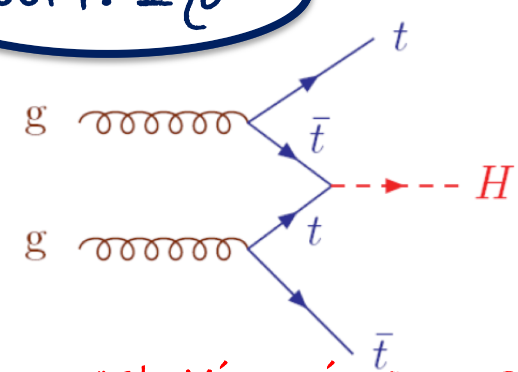
VBF: 7%



~300k Higgs in Run 2

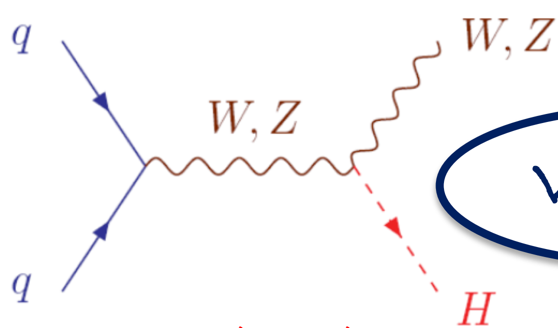
How should I be produced this time?

ttH: 1%



~40k Higgs in Run 2

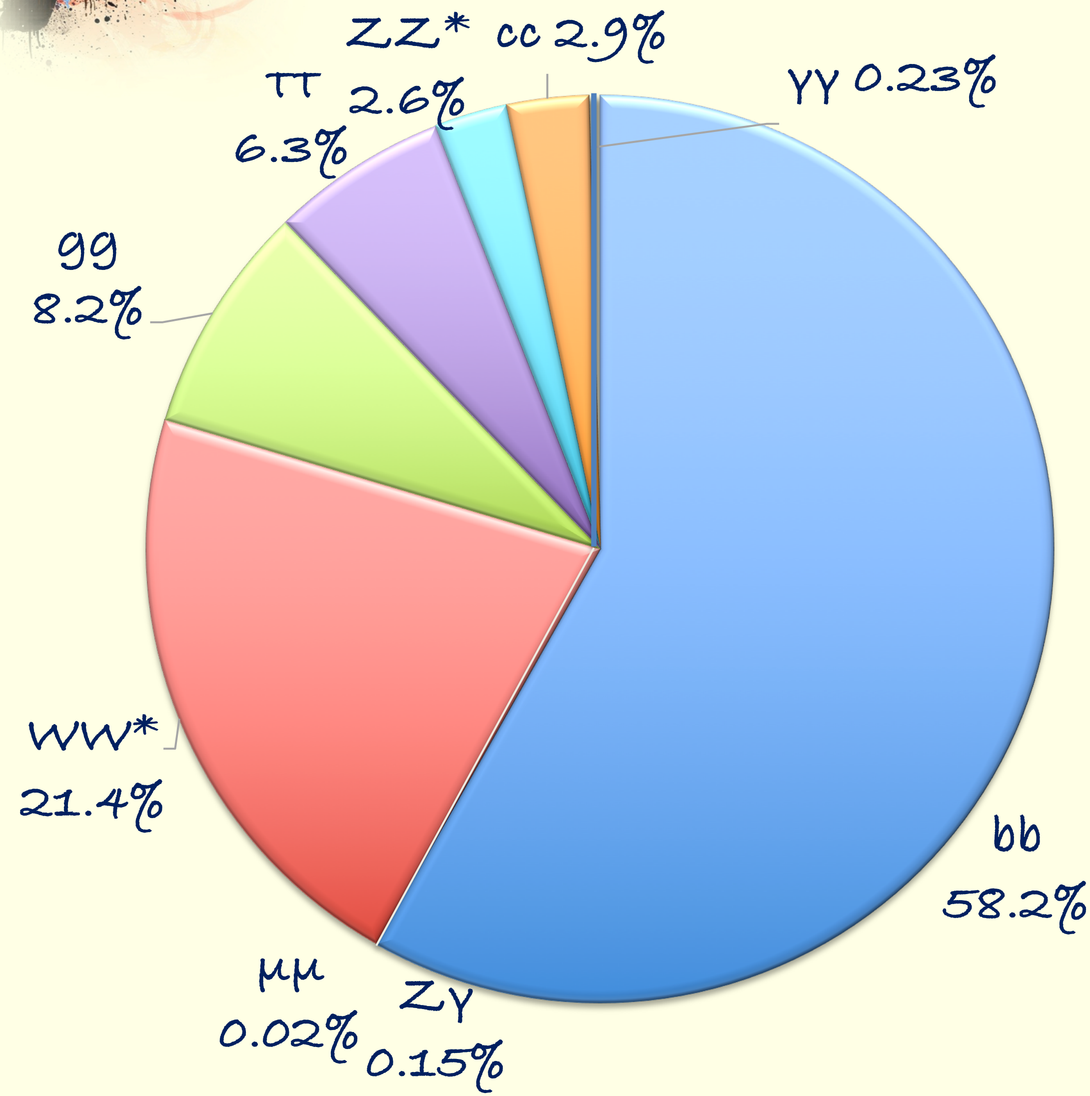
VH: 4%



~200k Higgs in Run 2

*Run 2 refers to 2015-2017 at 13 TeV

HIGGS BOSON DECAY MODES

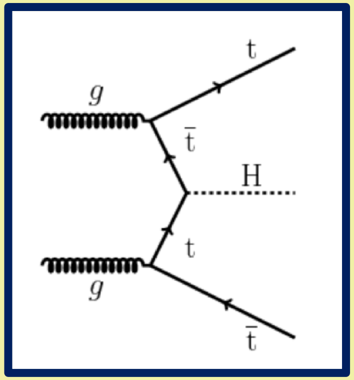


- Analyses ongoing in all the main channels, directly or indirectly
  → No couplings measurements without theory assumptions
- Combination of all the channels is crucial:
  - to increase sensitivity
  - to resolve ambiguity

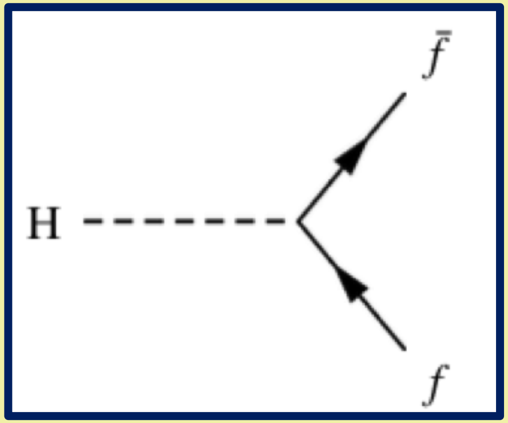
HIGGS COUPLINGS

DIRECT PROBES

at tree level



ttH

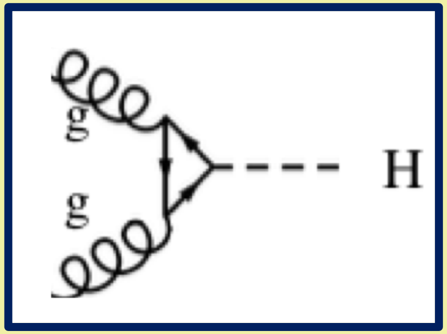


Different generations:

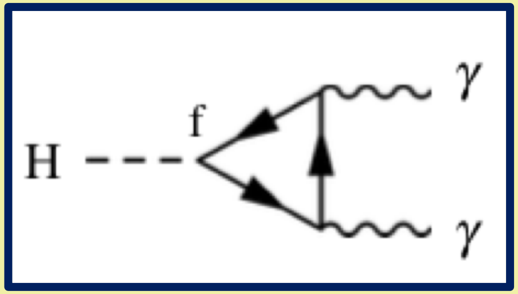
- Leptons
- Up-type quarks
- Down-type quarks

INDIRECT PROBES

via loop diagrams

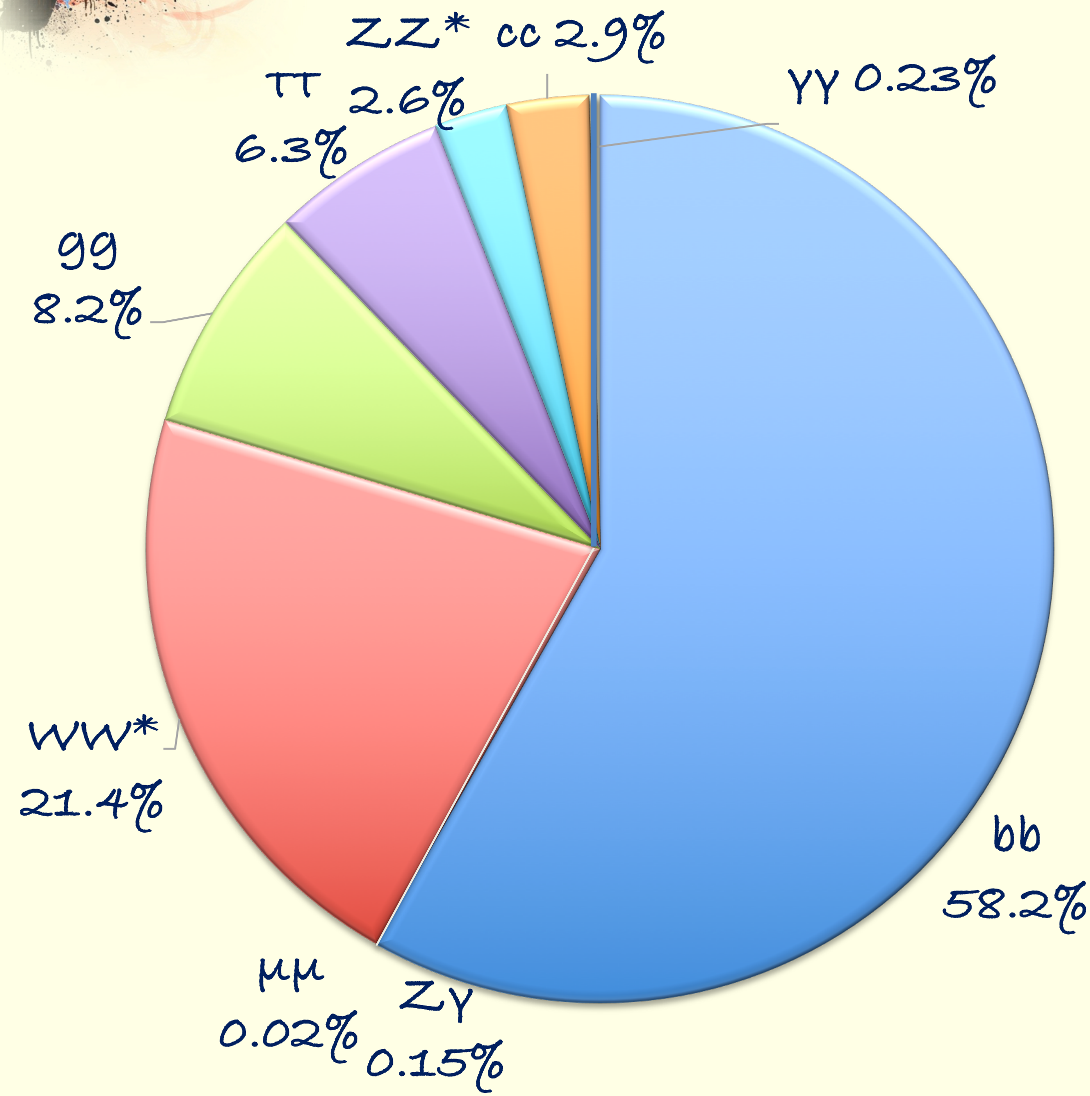


gluons



photons

HIGGS TO BOSONS

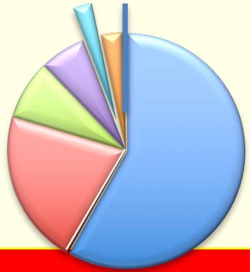


ZZ*, γγ

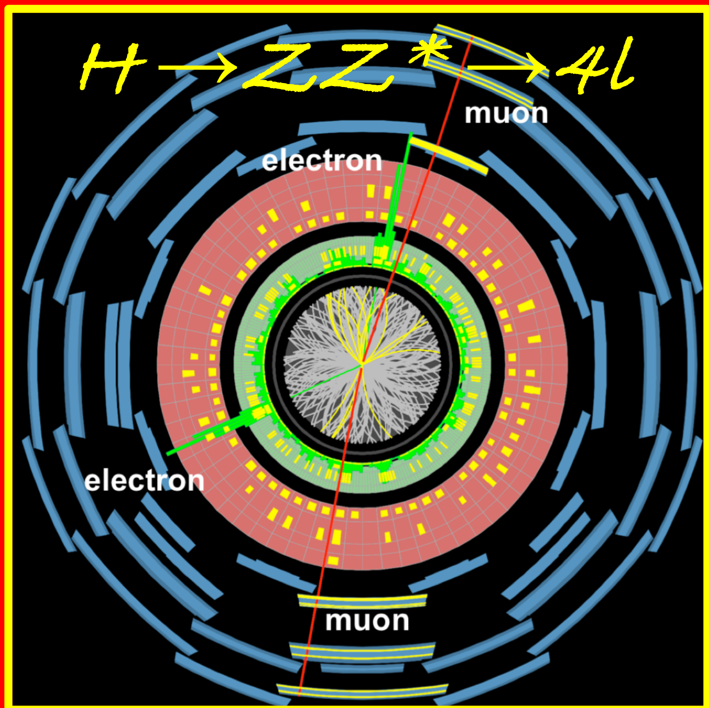
- Good mass resolution
  - Ideal for precision measurements since well modelled background and clear signatures
- Low BR, especially ZZ*, 0.012% in 4l

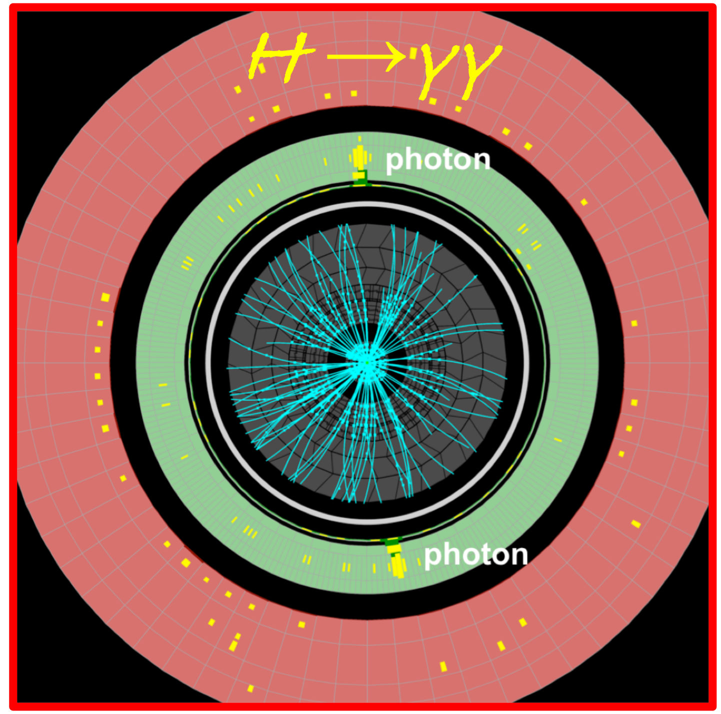
WW*

- High BR, but reduced in the di-lepton mode, 1.1%
- Low mass resolution because of ν_s in final states



$H \to ZZ^*$ and $H \to \gamma\gamma$: DISCOVERY CHANNELS





Run-2 results (79.8 fb^{-1}):

ATLAS-CONF-2018-018

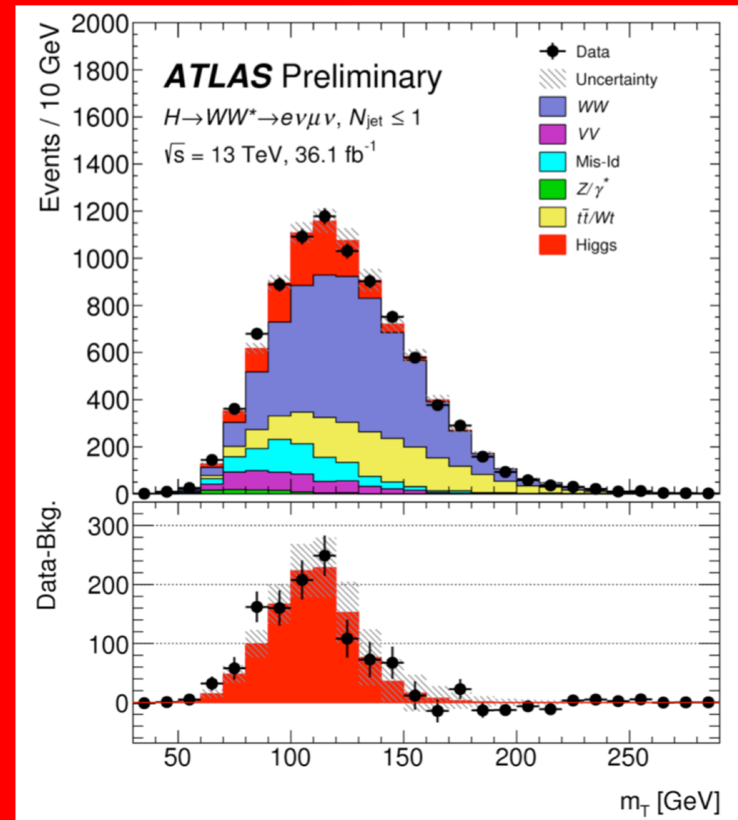
$\sigma_{ggF} B_{HZZ^*} = 1.22 \pm 0.18$ pb

$\sigma_{VBF} B_{HZZ^*} = 0.25 \pm 0.09$

ATLAS-CONF-2018-028

$\sigma_{inclusive} = 60.4 \pm 6.1$ (stat.) ± 0.3 (theo.) fb

$H \to WW^*$



- Most precise cross-section measurements in Run 1
- Focus on leptonic decays $H \to WW^* \to l\nu l\nu$
  - *Hard signature because of MET (i.e. Missing Transverse Energy)*
  - *MET gets harder as pileup rises*

Run-2 cross section measurements:

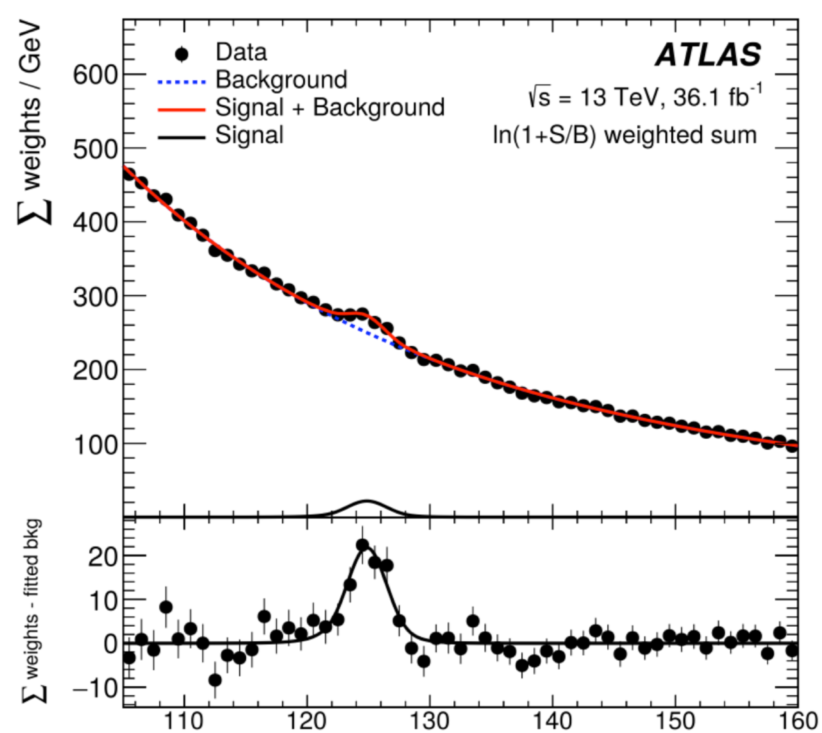
$\sigma_{ggF} B_{HWW^*} = 12.6^{+1.3}_{-1.2}(stat.)^{+1.9}_{-1.8}$ (syst.) pb and $\mu_{ggF} = 1.21^{+0.22}_{-0.21}$

$\sigma_{VBF} B_{HWW^*} = 0.50^{+0.24}_{-0.23}(stat.) + 0.18(syst.)$ pb and $\mu_{VBF} = 0.62^{+0.37}_{-0.36}$

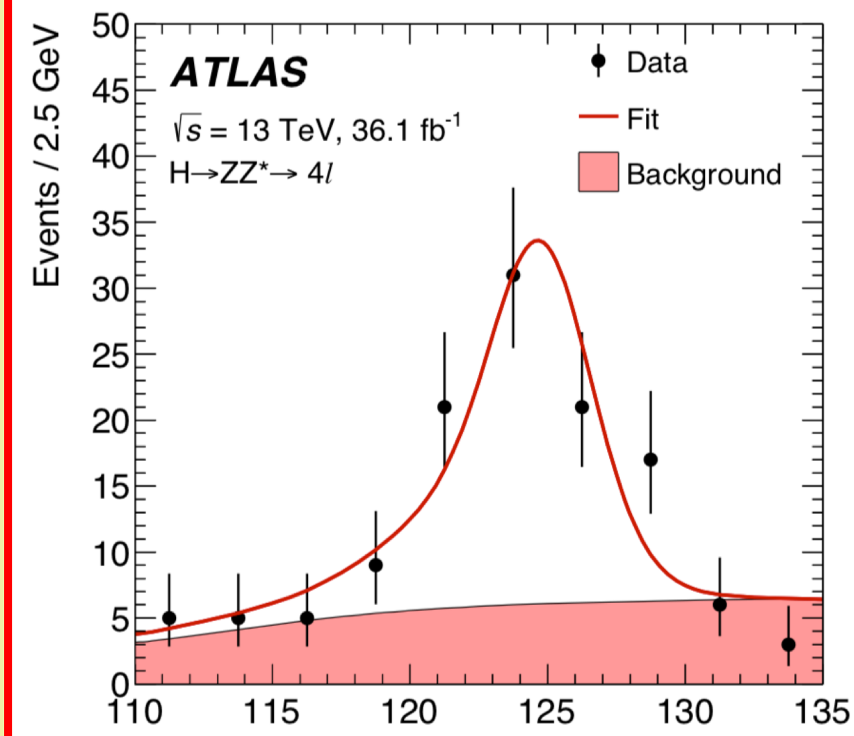
ATLAS-CONF-2018-004

HIGGS BOSON MASS

- Extraction based on di—photon and 4l invariant mass



m_H=124.93±0.40 GeV



m_H=124.79±0.37 GeV

Combination with Run 1 : arXiv:1806.00242

m_H = (124.97±0.24) GeV – 1.9 permille

HIGGS BOSON WIDTH

- In contrast 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. The SM expectation is 4 MeV.
- Direct and indirect strategies have been considered:
  - From the on-shell mass peak – limited by mass resolution, ~1 GeV arXiv:1806.00242
  - From the lifetime

HIGGS BOSON WIDTH

- In contrast 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. The SM expectation is 4 MeV.
- Direct and indirect strategies have been considered:
  - From couplings
  - From off-shell to on-shell production
    → Best proxy to-date (under some assumptions)!

CONSTRAINING THE HIGGS BOSON WIDTH

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

$$\mu_{\text{off-shell}} = \frac{\sigma_{\text{off-shell}}}{\sigma_{\text{off-shell,SM}}} = k^2_{g,\text{off-shell}}\, k^2_{V,\text{off-shell}}$$

$$\mu_{\text{on-shell}} = \frac{\sigma_{\text{on-shell}}}{\sigma_{\text{on-shell,SM}}} = \frac{k^2_{g,\text{off-shell}}\, k^2_{V,\text{off-shell}}}{\Gamma_H / \Gamma_{H,\,SM}}$$

$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma_H}{\Gamma_{H,\,SM}}$$

From an independent analysis

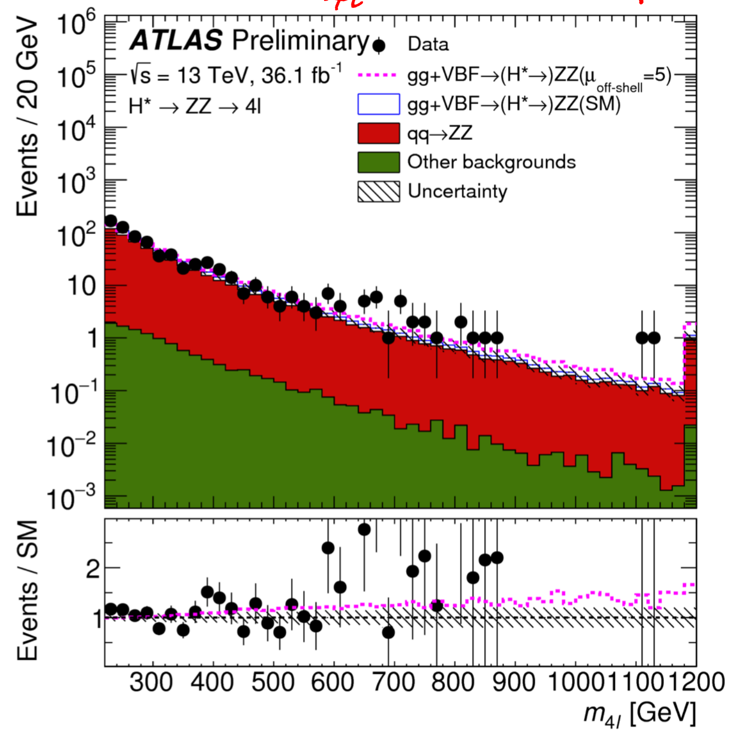
- This strategy is assuming identical on-shell and off-shell couplings
  - No new physics alters the Higgs couplings in the off-shell regime

STRATEGY AND RESULTS

- Two decay channels, $H^* \to ZZ \to 4l$ and $H^* \to ZZ \to 2l2\nu$
- Discriminants: transverse mass ($2l2\nu$) and Matrix-Element ($4l$)

$4l$ invariant mass

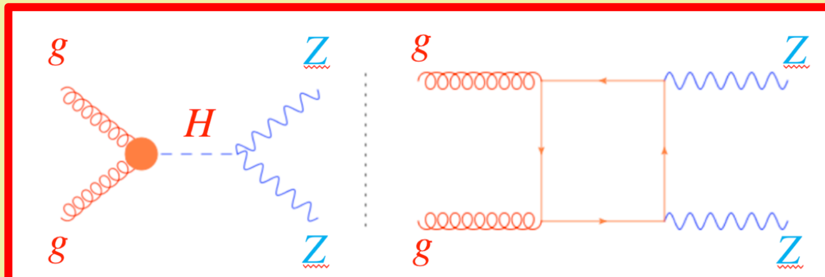
$220 < m_{4l} < 2000$ GeV



NEW

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

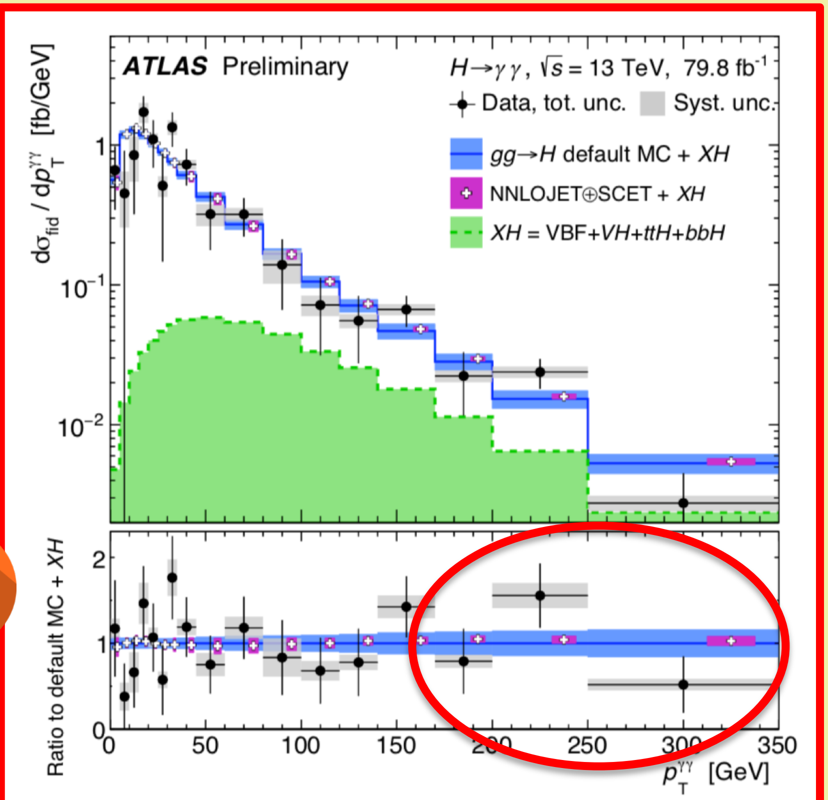


Run 2 result: $\Gamma_H < 14.4$ MeV obs. (15.2 MeV exp.) arXiv:1808.0119

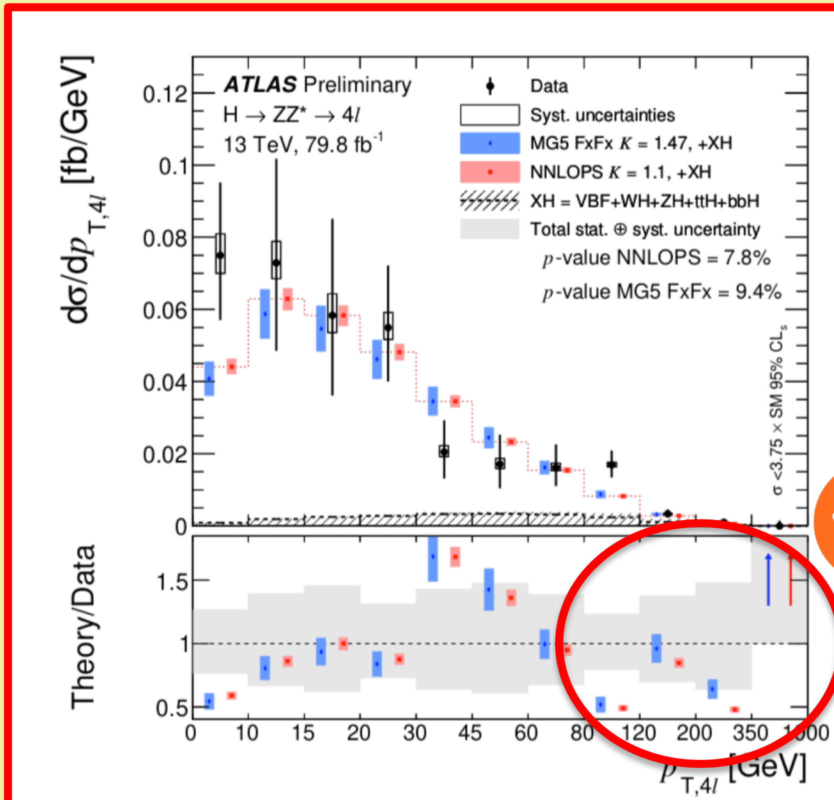
DIFFERENTIAL MEASUREMENTS

- New precision on the Higgs-p_T spectrum
- Distribution tails sensitive to new physics

NEW



ATLAS-CONF-2018-004

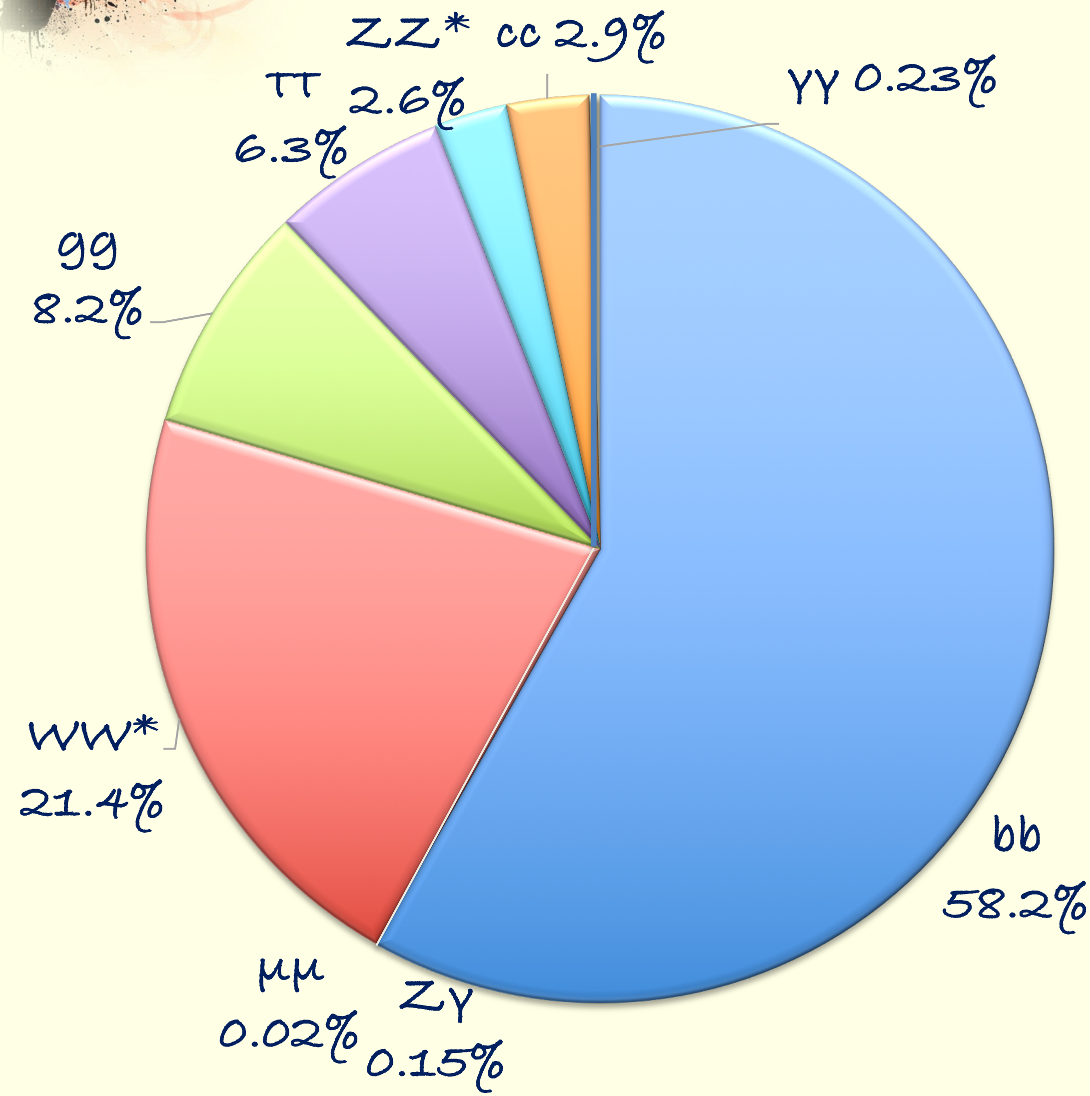


NEW

ATLAS-CONF-2018-018

No signs of new physics!

HIGGS TO FERMIONS



bb, ττ

👍 Significant BR
- Allow direct probe to fermions

👎 Low S/B, challenging measurement

μμ

👍 It allows couplings measurements to 2^{nd} generation

👎 Very small BR

$H \rightarrow bb$

- Direct probe to coupling to b-type quarks
- Because of the large BR, the uncertainty on the total decay width (→measurement of the absolute couplings) relies on this channel

First Evidence
from TEVATRON in 2012
2.8σ Obs. (1.5σ Exp.)
3.1σ Global
Phys. Rev. Lett. 109 (2012) 071804

LHC
Evidence in 2017
3.6σ Obs. (4.0σ Exp.) ATLAS
3.8σ Obs. (3.8σ Exp.) CMS

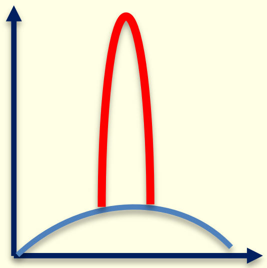
JHEP 12 (2017) 024, Phys. Lett. B 780 (2018) 501

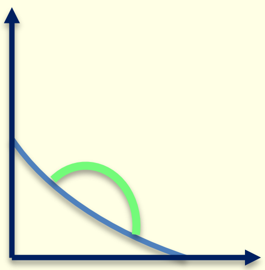
- VH production is the most sensitive mode to search for $H \rightarrow bb$ at LHC

CHALLENGES OF $H \to bb$

- Let's compare it with one of the discovery channels
  - values in the table before the analyses strategies (discriminants, BDT ...)

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





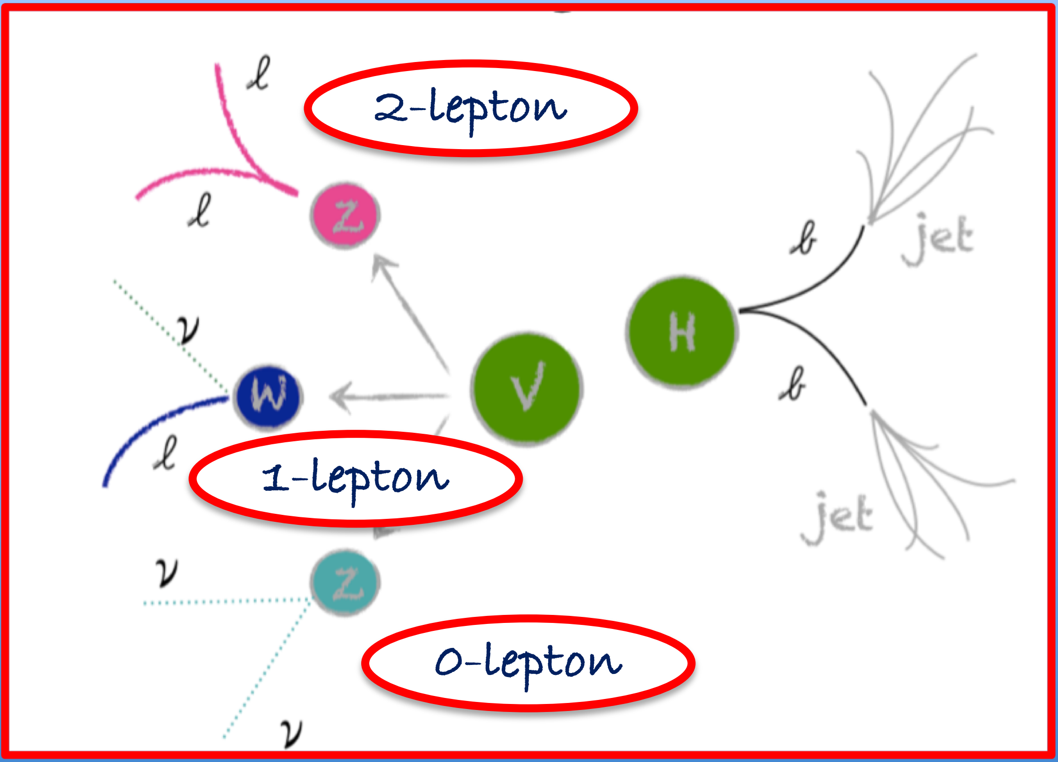
RECIPE FOR THE PERFECT SEARCH

1. Great b-jet identification performance
2. Best possible m(bb) resolution
3. Leverage on all the event information

→ More is not always better!

$VH(H \rightarrow bb)$ TOPOLOGY

SIGNAL

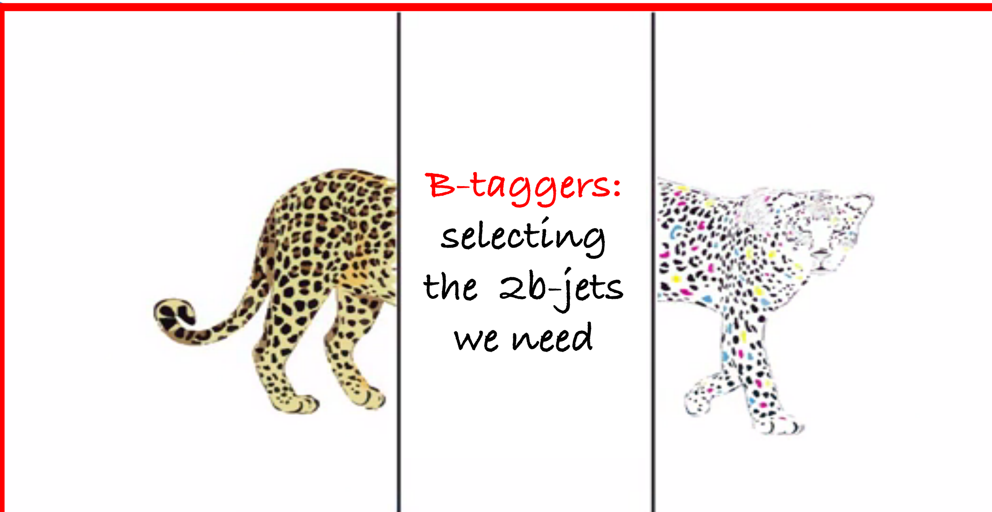


CATEGORIZATION

- 3 decay channels
  - Classification based on the number of leptons from V=W/Z bosons

VH(H→bb) TOPOLOGY

SIGNAL



b-jet efficiency 70%

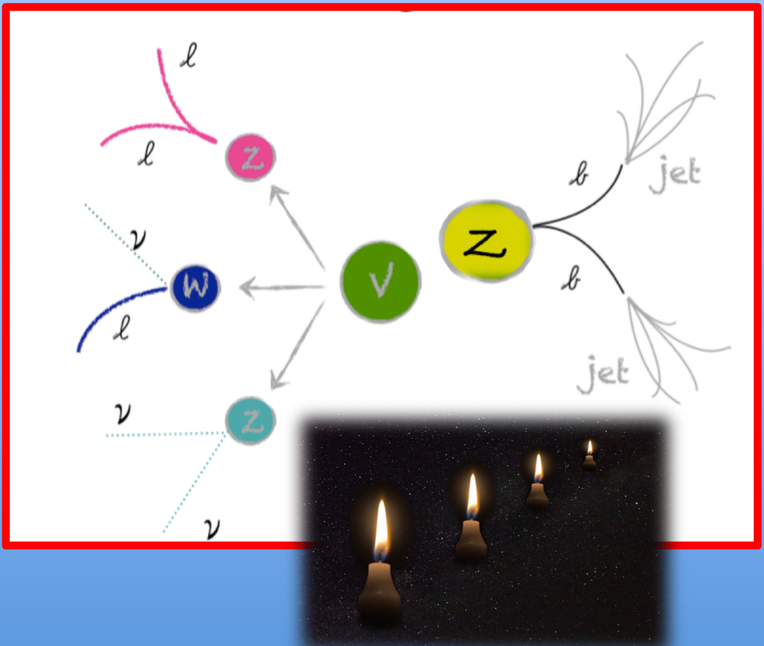
SELECTION

- 2 b-jets from Higgs + leptons from V decay
  - $p_T(V) > 75$ or 150 GeV
  - b-jets identification based on multivariate techniques exploiting the long b-hadron lifetime

VH(H→bb) TOPOLOGY

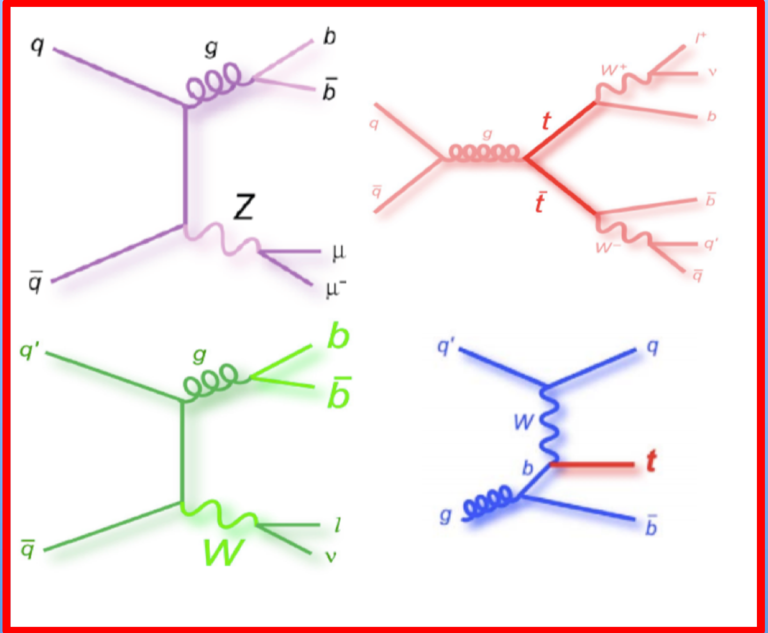
BACKGROUND

DIBOSON



VZ, a perfect standard candle to validate the analysis strategy

OTHERS IRREDUCIBLE



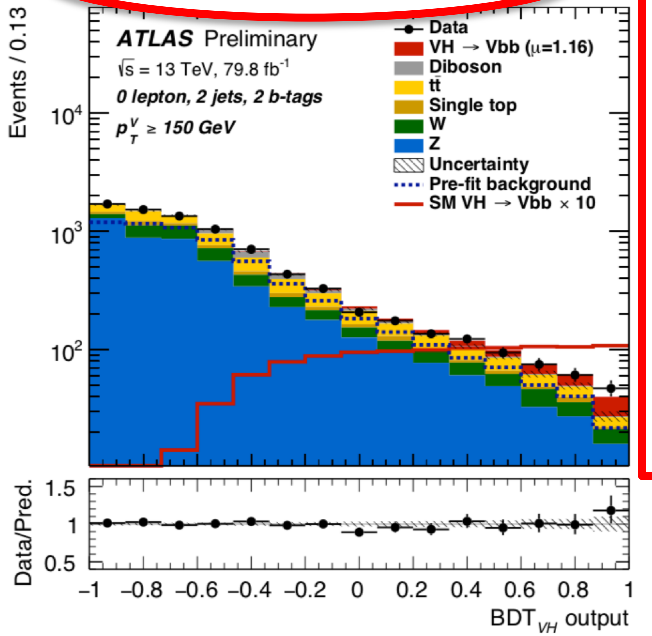
Normalization from data (CR), shapes from MC

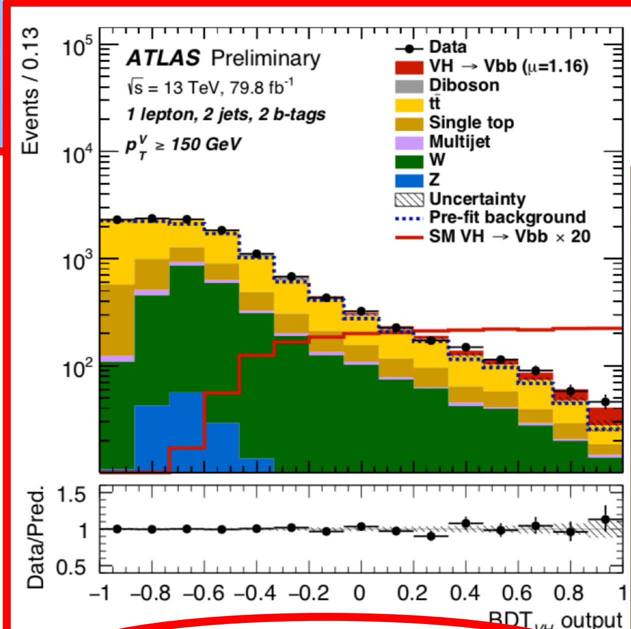
VH(H→bb) STRATEGY AND RUN-2 RESULTS

- Main discriminants m_{bb}, $p_T(V)$ and ΔR_{bb} combined into a Boosted Decision Tree (BDT)

NEW

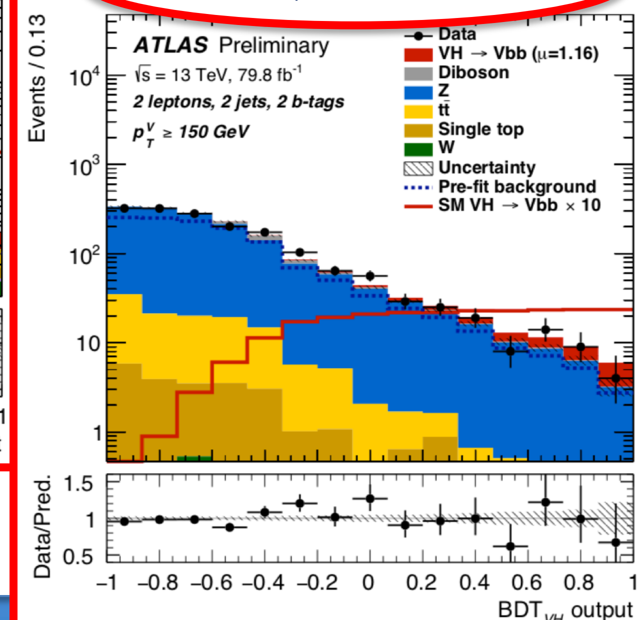
ZH → ννbb





WH → lνbb

ZH → llbb



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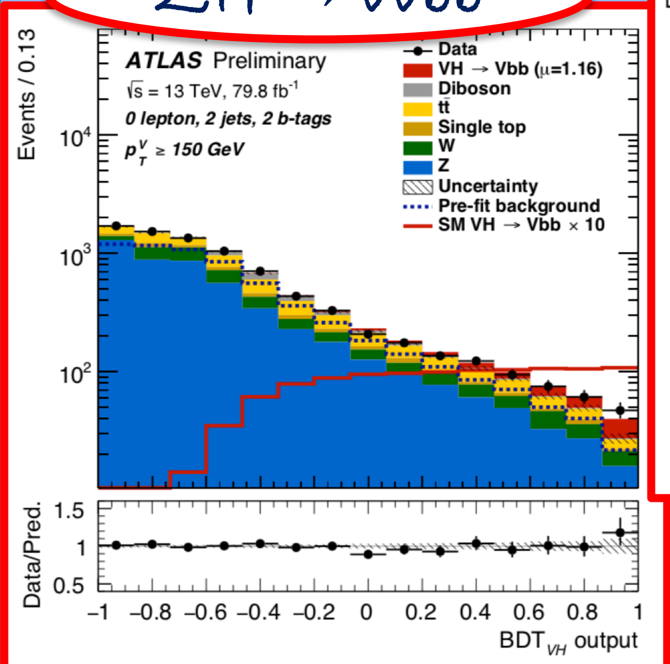
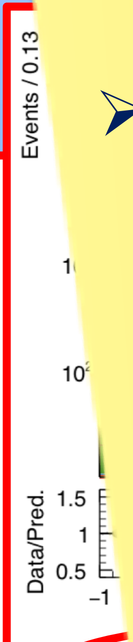
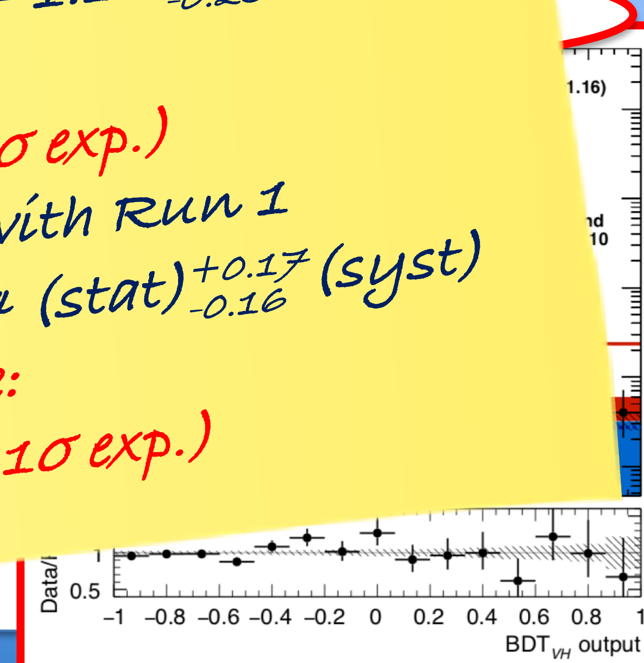






RESULTS

- Fit result with 79.8 fb^{-1} (Run 2)
  $\mu=\sigma_{meas}/\sigma_{SM}=1.16^{+0.27}_{-0.25}$
  Significance:
  4.9σ obs. (4.3σ exp.)
- Combination with Run 1
  $\mu=0.98\pm0.14\ (stat)^{+0.17}_{-0.16}\ (syst)$
  Significance:
  4.9σ obs. (5.1σ exp.)

VH and H→bb RESULTS

H→bb combination

Run-1 and Run-2 analyses:

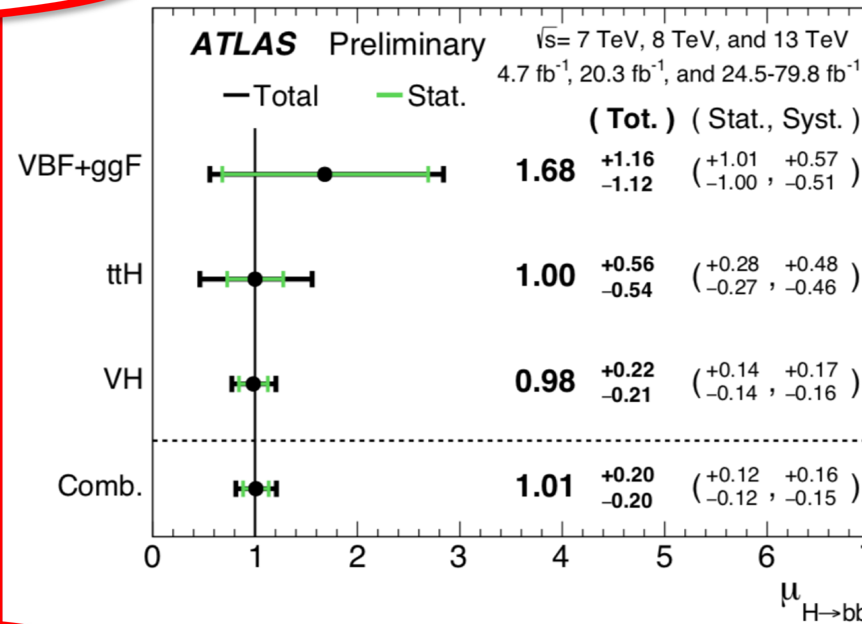
- VH, H→bb
- VBF(+ggF), H→bb
- ttH, H→bb

NEW

Significance : arXiv:1808.08238

5.4σ obs. (5.5σ exp.)

Observation of H→bb !



VH combination

Run-2 analyses:

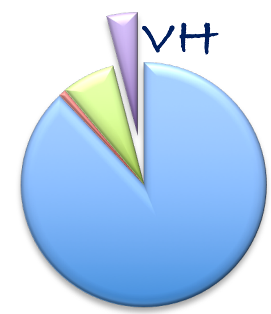
- VH, H→bb
- VH, H→γγ
- VH, H→ZZ*

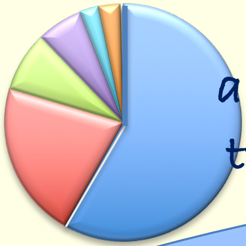
NEW

Significance : arXiv:1808.08238

5.3σ obs. (4.8σ exp.)

Observation of VH production !

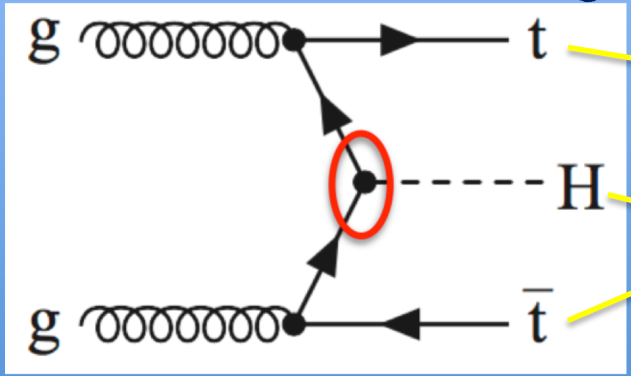




and tt ?

COUPLING TO TOP-QUARK

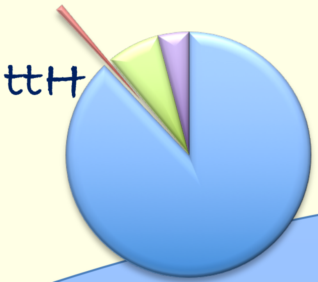
- The largest coupling to top quark
  - can only be studied directly in ttH production mode
  - can be studied indirectly using ggF, being dominated by the top quark in the SM
- tth: high multiplicity of final state objects → complex analysis



2 b-jets + { lνlν / lν+2jets / 4jets }

Jets, leptons, MET, γ

- Several categories analysed with multivariate algorithms



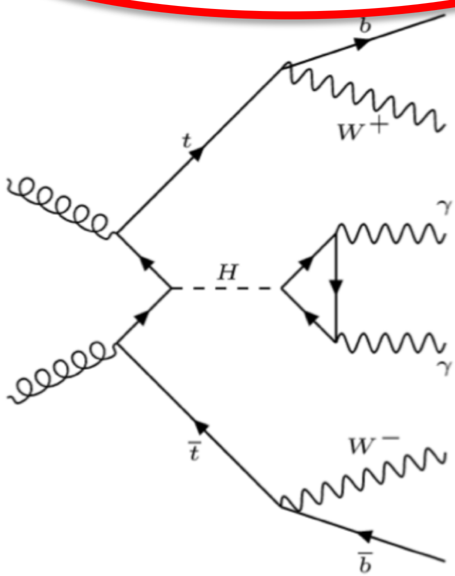
ttH CATEGORIES

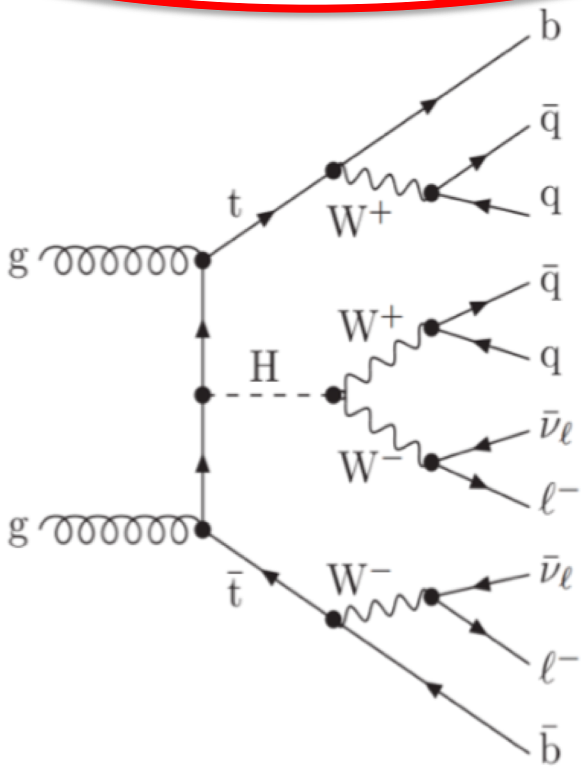
- H → WW* → lνlν
- H → ττ and
- H → ZZ* without ZZ* →4l

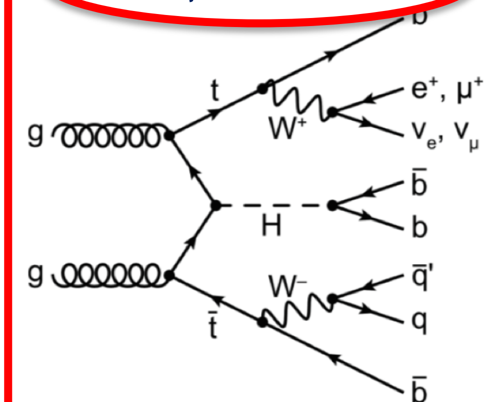
Multi-leptons

- H → ZZ* → 4l
- H → γγ

H →bb







ttH

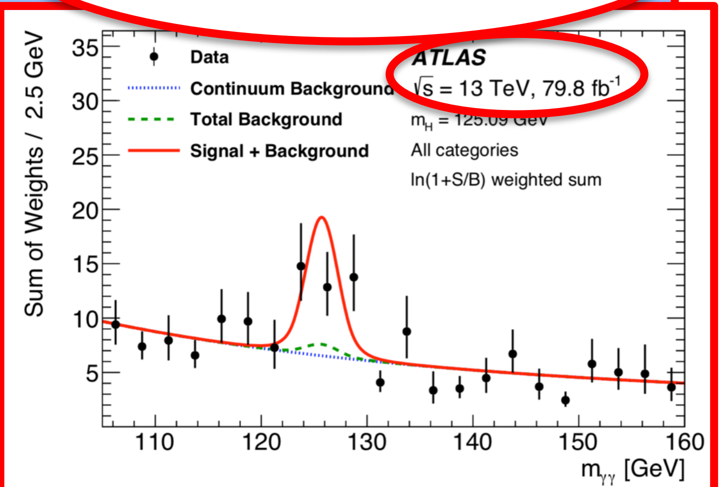
ttH CATEGORIES

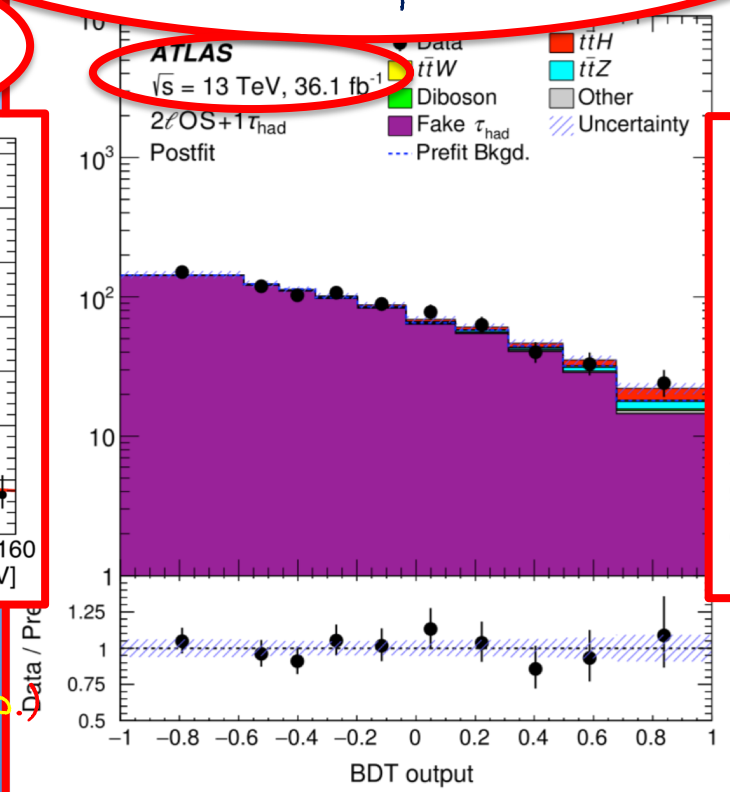
- H → WW* → lνlν
- H → ττ and
- H → ZZ* without ZZ* →4l

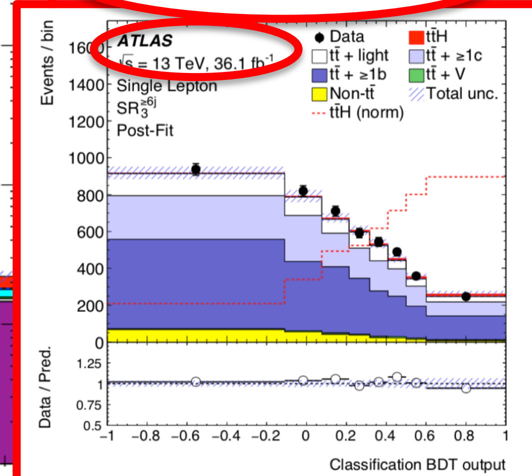
Multi-leptons

- H → ZZ* → 4l
- H → γγ

H → bb



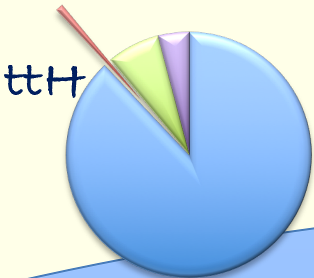




tt(H → γγ) 4.1σ obs. (3.7σ exp.)
tt(H → ZZ*) 0.0σ obs. (1.2σ exp.)

tt(H → bb) 1.4σ obs. (1.6σ exp.)

tt(H → multi-lepton) 4.1σ obs. (2.8σ exp.)



ttH RESULTS

ttH combination

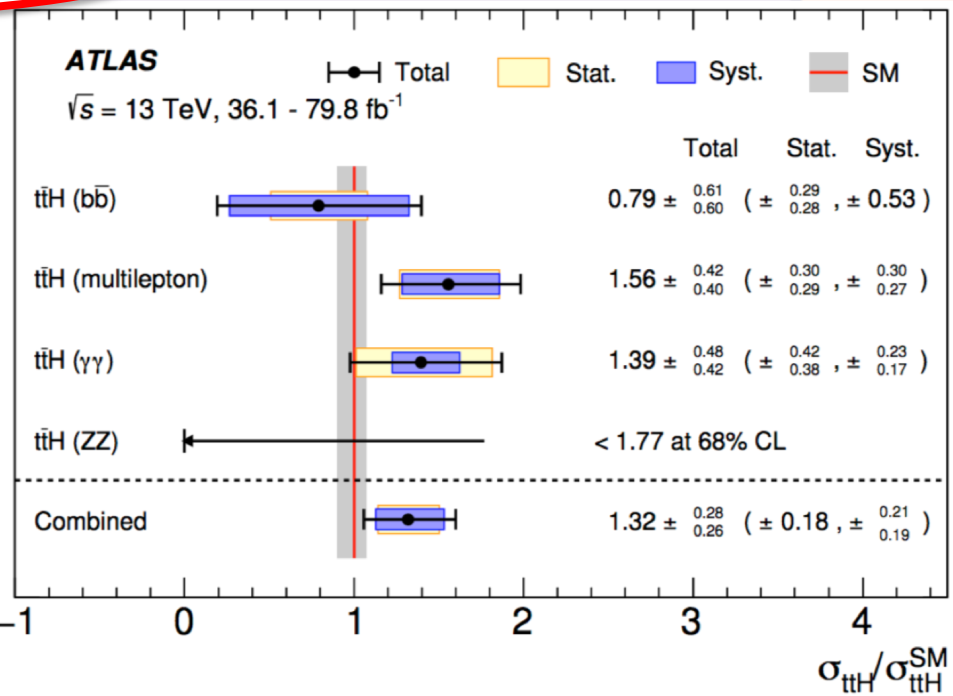
Run-2 analyses:

- ttH, $H \to bb$
- ttH, multilepton
- ttH, $H \to \gamma\gamma$
- ttH, $H \to ZZ^*$

Significance : arXiv:1806.00425

5.8σ obs. (4.9σ exp.)

Observation of ttH production!



Run-2+Run-1 analyses: Significance 6.3σ obs. (5.1σ exp.)

Cross section: $\sigma_{ttH} = 670 \pm 90\ (\text{stat.})^{+110}_{-100}\ (\text{syst.})$ fb

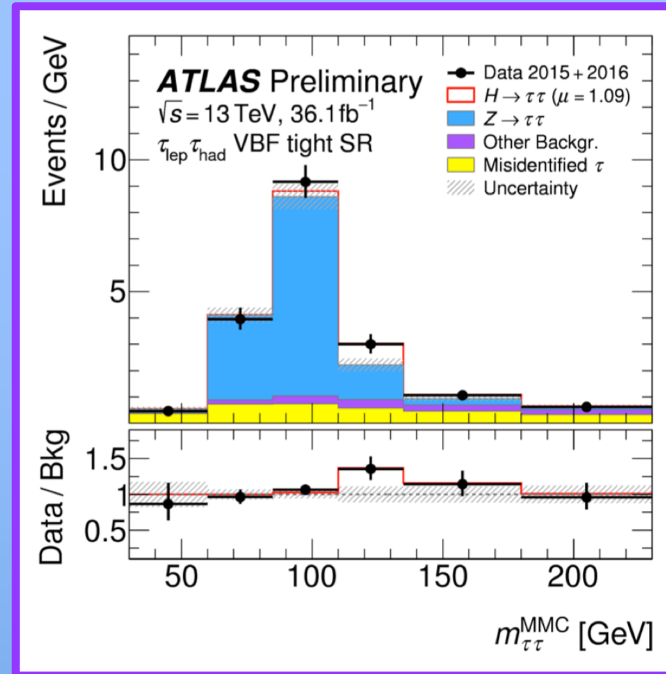
with $\sigma_{ttH,\,SM} = 507^{+35}_{-50}$ fb arXiv:1806.00425

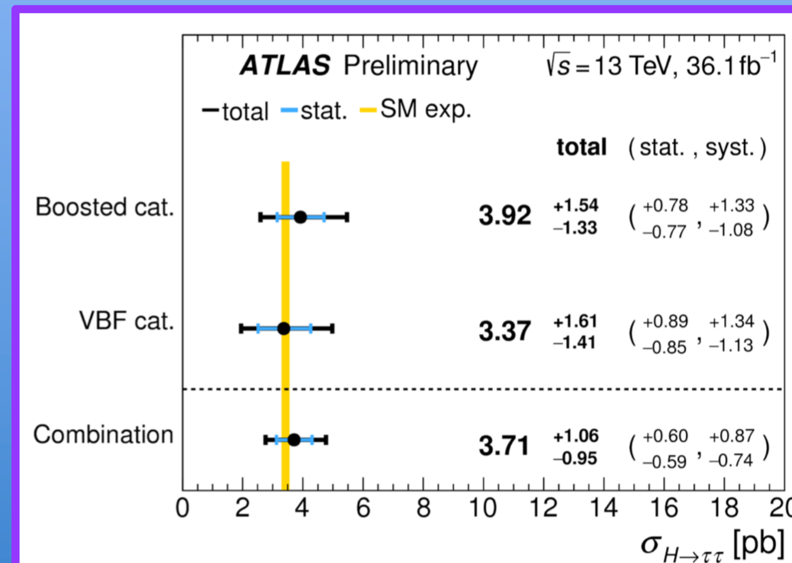
$H \rightarrow \tau\tau$

- Analyses use all the τ leptonic and hadronic decay modes: $\tau \rightarrow hadrons + \nu$ and $\tau \rightarrow l\nu\nu$
- Categories considered: VBF and ggF in the "boosted regime"
- Main background $Z \rightarrow \tau\tau$
  - Normalization from data and shapes from MC
- Main discriminant $m_{\tau\tau}$

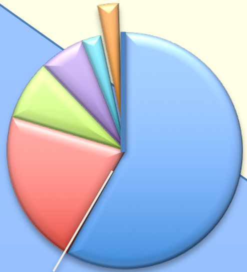
Significance Run 1+Run 2: 6.4σ obs. (5.4σ exp.)

ATLAS-CONF-2018-021



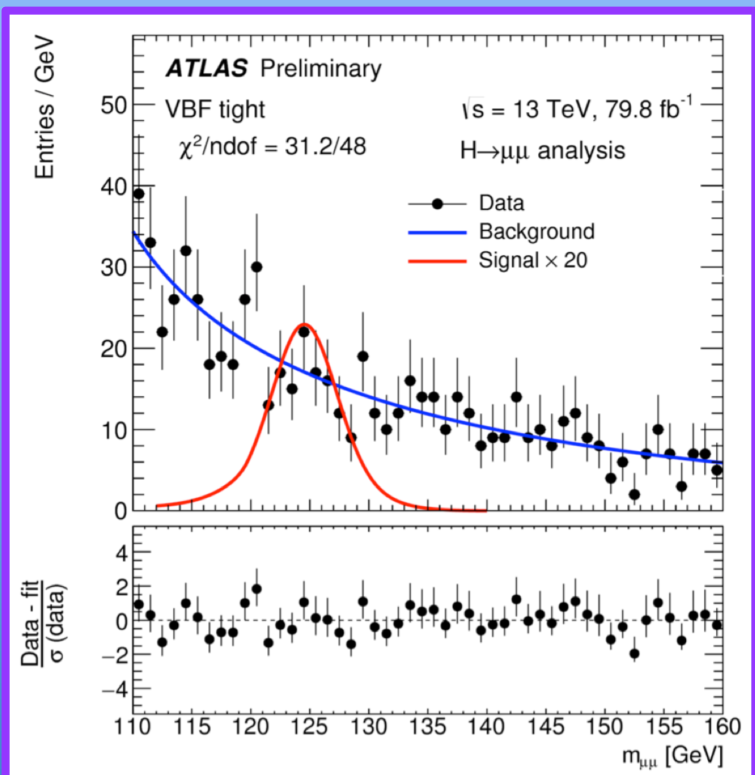


2^{nd} GENERATION: $H\rightarrow cc$ and $H\rightarrow\mu\mu$



$H\rightarrow\mu\mu$

Selection: events with 2 isolated and opposite-sign muons



ATLAS-CONF-2018-026

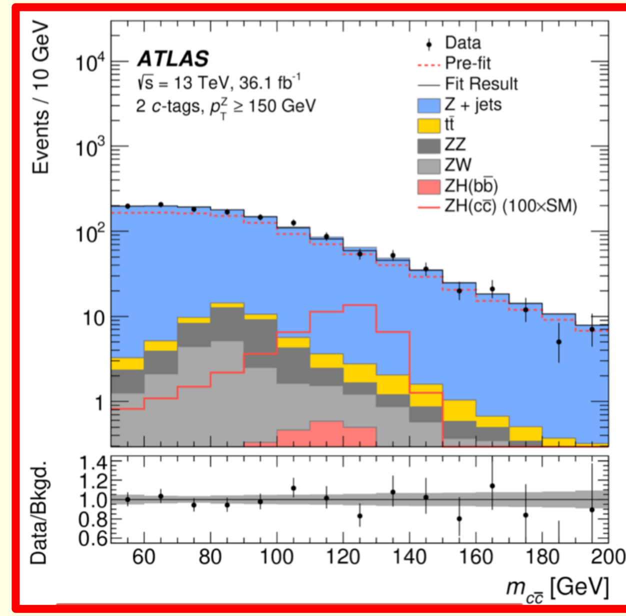
Run 2 (80 fb^{-1}) getting close to SM sensitivity

$\mu_{\mu\mu} = 0.1^{+1.0}_{-1.1}$

$\mu_{\mu\mu} < 2.1$ obs. (2.0 exp.)

$H\rightarrow cc$

Selection: similar to $H\rightarrow bb$, but based on specific c-tagging techniques



arXiv:1802.04329

Run 2 (36.1 fb^{-1})

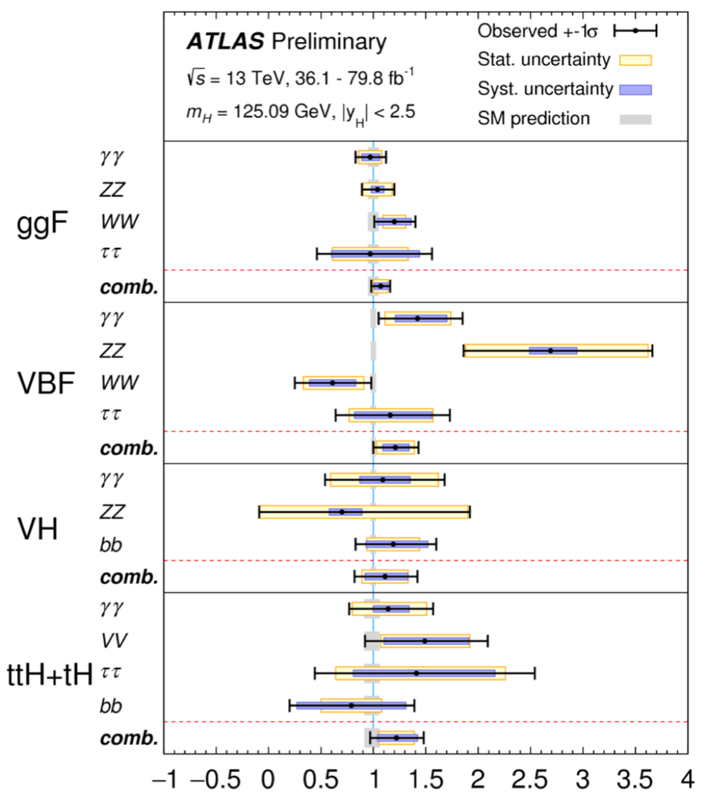
$\mu_{cc} < 110$ w.r.t. SM exp.

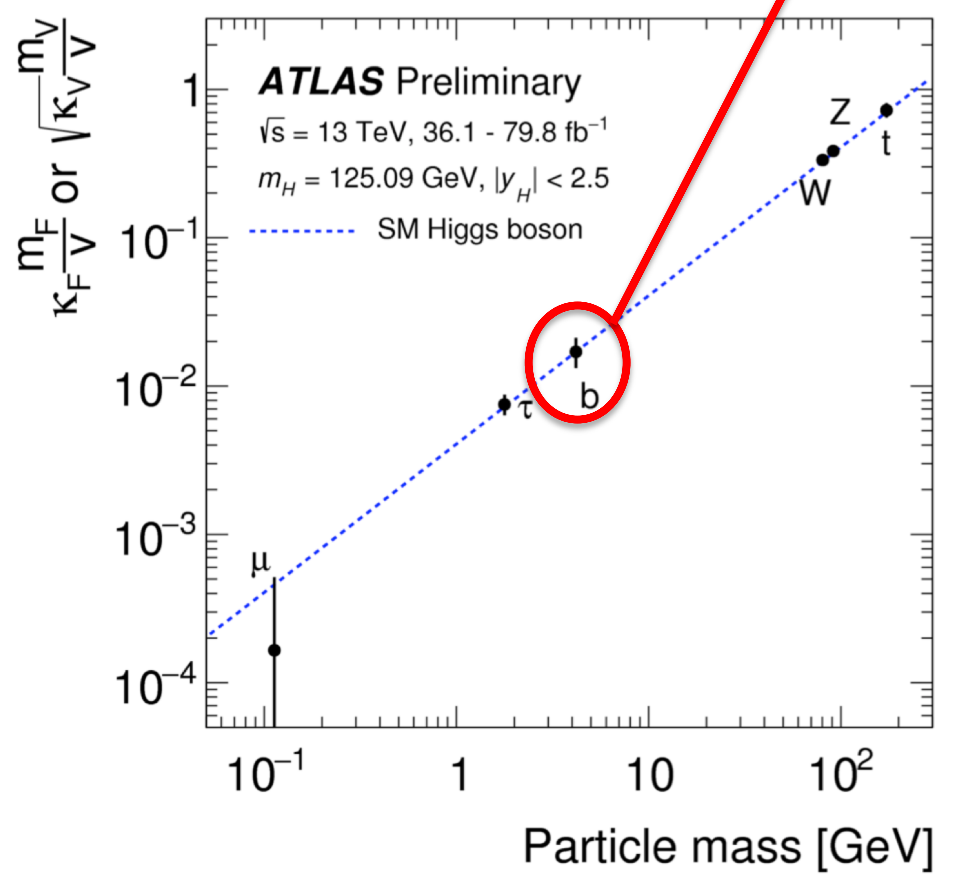
COMBINING ALL THE MEASUREMENTS

To be updated with the Hbb observation

COUPLINGS

PRODUCTION





Global signal strength: $\mu_H = 1.13^{+0.09}_{-0.08}$ ATLAS-CONF-2018-031

CONCLUSIONS

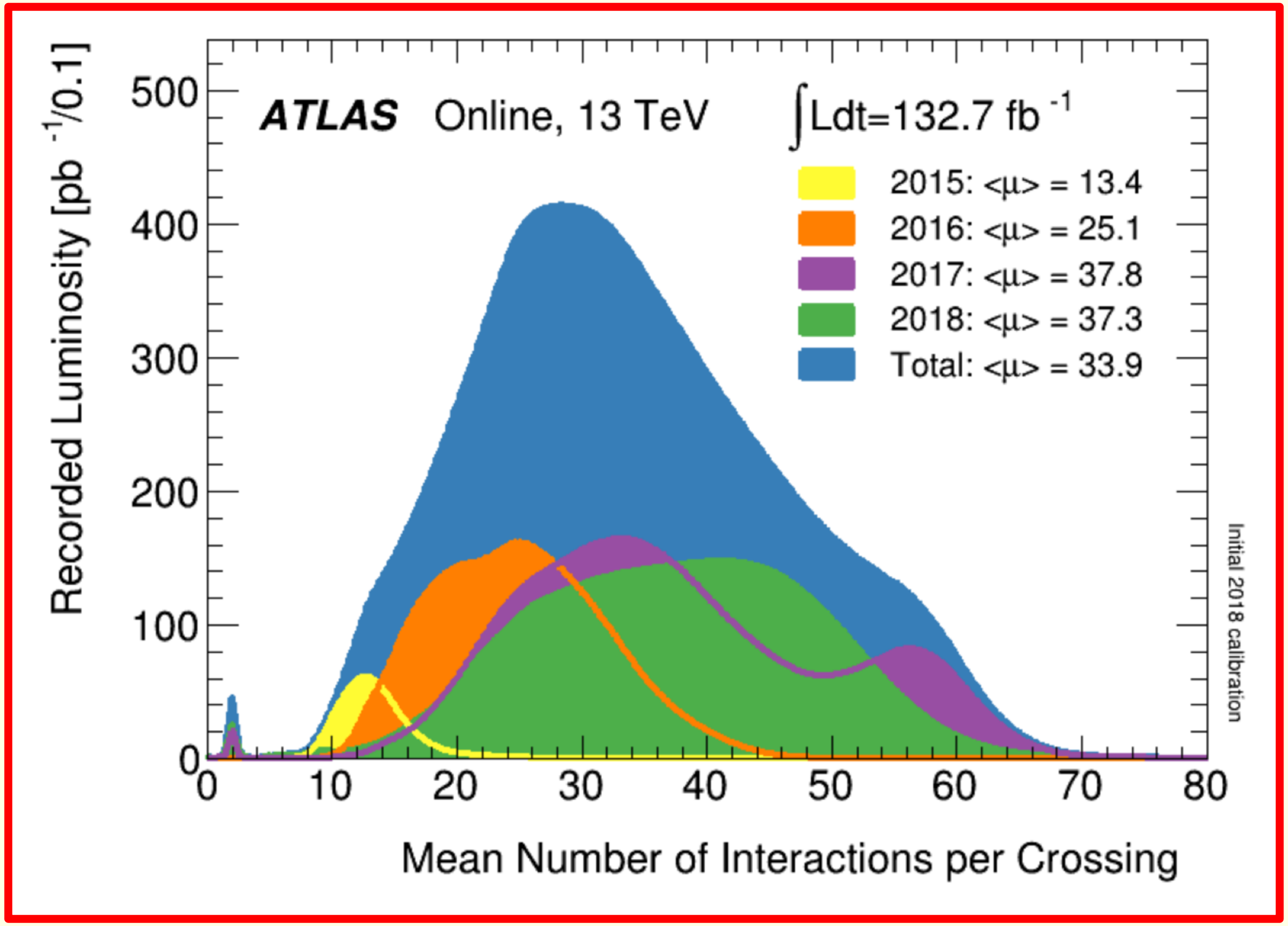
- The LHC Run 2 has improved the precision of Higgs physics and allowed new couplings measurements
  - Direct observation for all the main production modes: ggF, VBF, VH and ttH
  - All five decay modes foreseen for light Higgs (WW*, ZZ*, $\gamma\gamma$, bb and $\tau\tau$) observed
  - New precision for the mass *and better (indirect) constraints for the width:*

    m_H = (124.97±0.24) GeV and Γ_H<14.4 MeV
  - *Couplings to muons look promising*
  - *SM consistency reduces BSM possibilities*

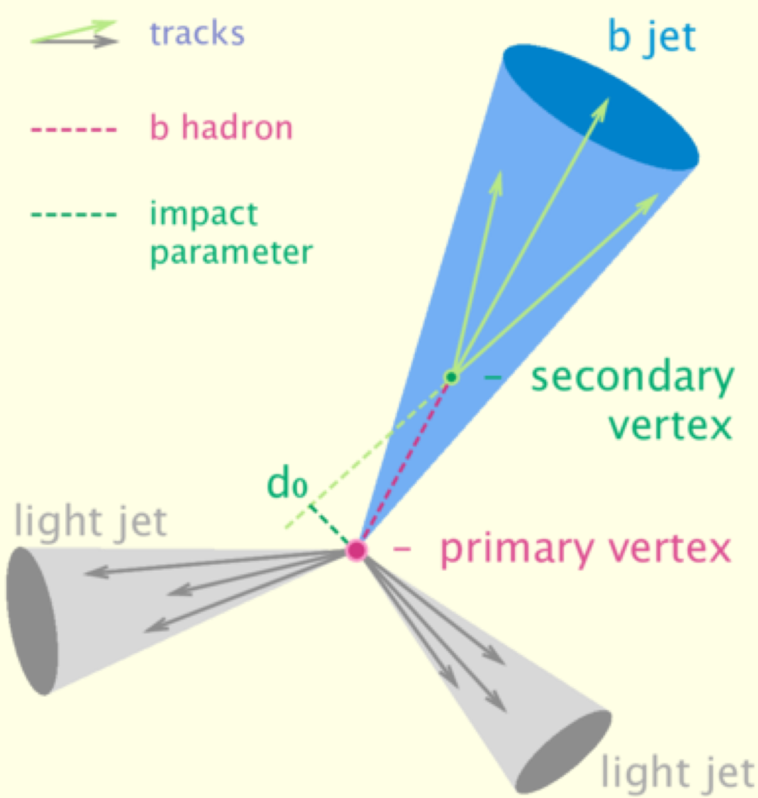

We have shed light on 5 orixas-couplings ...
more to come!
H_t
H_μ
H_W
H_c
H_Z
H_b
H_τ
H_γ
Lagoa dos Orixas, Dique do Tororo, Salvador
MUITO OBRIGADO!

BACK-UP

PILEUP


ATLAS Online, 13 TeV
∫Ldt=132.7 fb⁻¹
2015: <μ> = 13.4
2016: <μ> = 25.1
2017: <μ> = 37.8
2018: <μ> = 37.3
Total: <μ> = 33.9
Recorded Luminosity [pb⁻¹/0.1]
Mean Number of Interactions per Crossing
Initial 2018 calibration
0
100
200
300
400
500
0
10
20
30
40
50
60
70
80

b-TAGGING

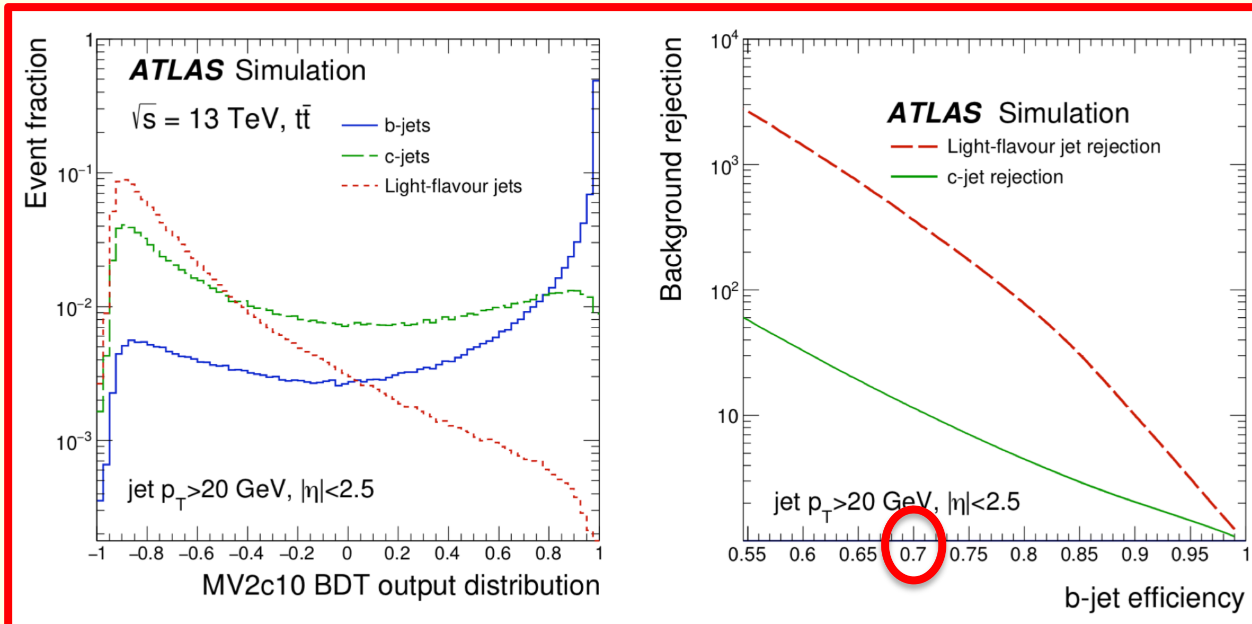


- Specific algorithms developed to identify (tag) jets produced by b-quarks
- Separation of b-jets from light (u, d, s, g) jets using specific b-hadrons properties:
  - Long b-hadron lifetime $\tau \sim 1.5$ ps $\rightarrow$ 20 GeV b-hadrons decays after $\sim$ 2mm
  - Search for tracks or vertexes displaced w.r.t. primary vertex and large impact parameters for displaced tracks
  - Search leptons from semileptonic b decays, with large transverse momentum w.r.t. jet axis

b-TAGGING PERFORMANCES

- A new multivariate b-tagging algorithm, MV2c10, was developed for Run2 and it's based on a BDT: arXiv:1805.01845
  - BDT trained on a events from a tt sample
  - Selection tuned to produce an average efficiency of 70% for b-jets
  - Jets are tagged as containing b-hadrons by requiring a large MV2c10 BDT output value

- b-jet purity is:
  eμ SAMPLE
  72% - 2j sample
  53% - 3j sample
  ee/μμ SAMPLE
  62% - 2j sample
  48% - 3j sample



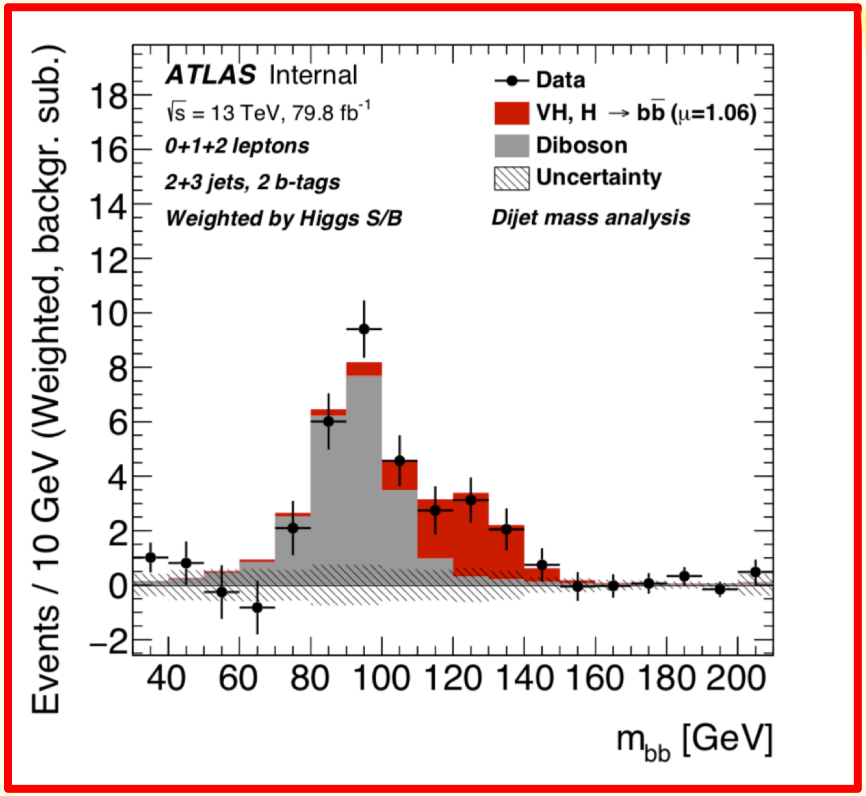
VH(Hbb) SYSTEMATIC UNCERATAINTIES

- Breakdown of the contributions to the uncertainty in $\mu_{VH(Hbb)}$
  - Leading contributions:
    - Modelling of the signal
    - Limited size of simulated samples
    - Modelling of background
    - b-tagging efficiency

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	b-jets	0.061
	c-jets	0.042
	light jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multijet		0.005
MC statistical		0.070

VH(Hbb): VALIDATION

- A validation of the multivariate analysis is performed using the m_{bb} variable as a discriminant



RESULTS

- Fit result with 79.8 fb^{-1} (Run 2)

  $\mu = 1.06^{+0.36}_{-0.33}$

Good agreement with the multivariate analysis!

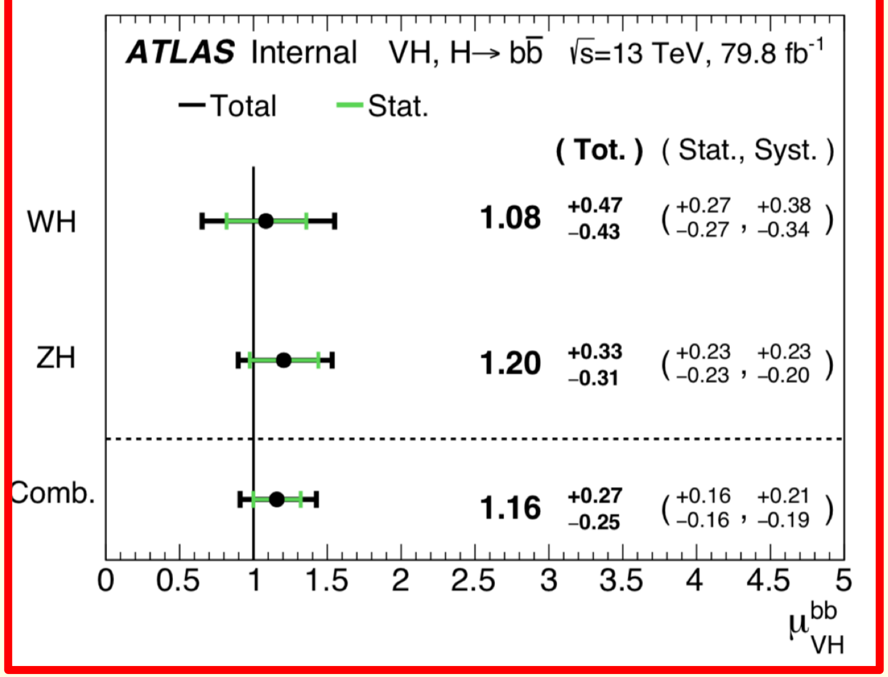
Significance:
3.6σ obs. (3.5σ exp.)

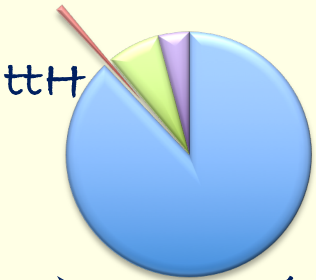
VH(Hbb) INDIVIDUAL RESULTS

- Individual-category results: 80% compatibility

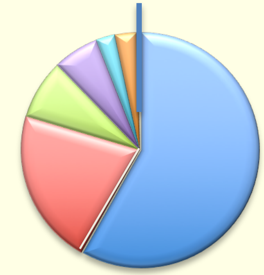
Signal strength parameter	Signal strength
0-lepton	$1.04^{+0.34}_{-0.32}$
1-lepton	$1.09^{+0.46}_{-0.42}$
2-lepton	$1.38^{+0.46}_{-0.42}$
$VH, H \rightarrow b\bar{b}$ combination	$1.16^{+0.27}_{-0.25}$

- WH and ZH results: 84% compatibility

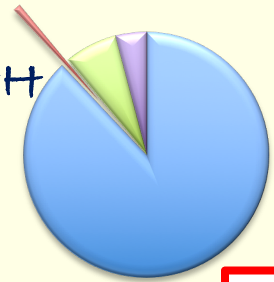




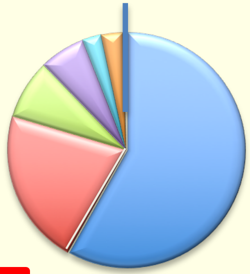
ttH $H \rightarrow \gamma\gamma$

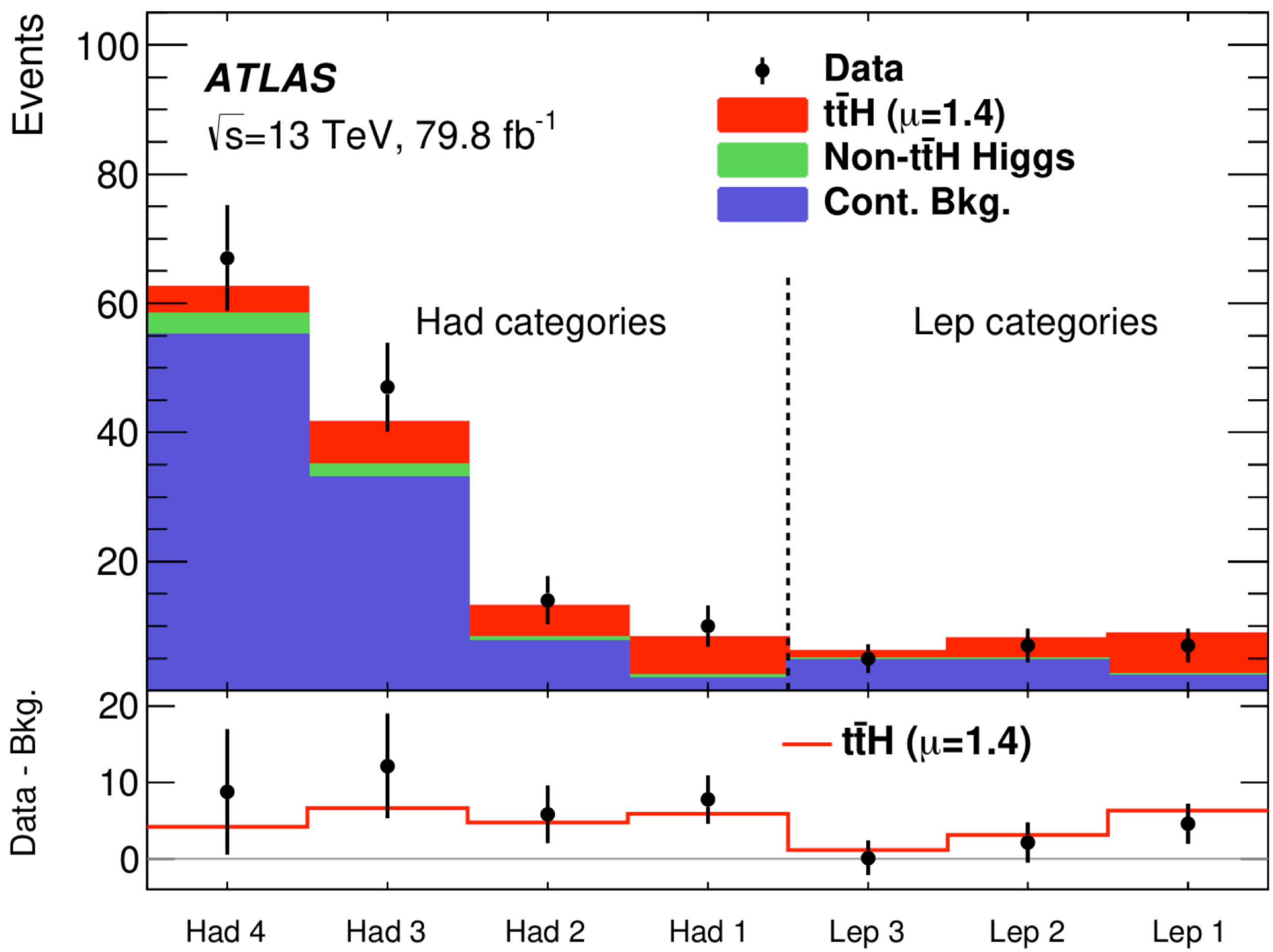


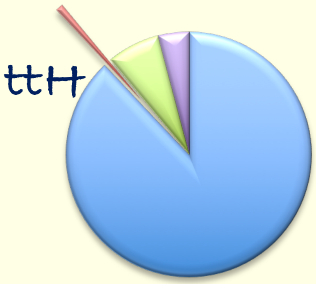
- Clear signature: 2 isolated photons + at least one b-tagged jet
- 2 SRs
  - Had: at least 2 additional jets and no isolated leptons
    Enriched in hadronic top-decays
  - Lep: at least one isolated leptons
    Enriched in semi-leptonic top-decays
- Background: non-resonant diphoton processes, including tt+2γ. *Also* non-ttH processes, i.e. tH and ggF in 'Had' and tH and VH in 'Lep'
- Strategy: 2 dedicated BDTs whose input variables are: [p_T, η, ϕ and E of the jets (leptons)] + ($p_T/m_{\gamma\gamma}$,*MET info,* η and ϕ of the photons)
  - BDT bins chosen to optimize the expected ttH sensitivity
  - In each BDT bin the ttH signal yield is extracted by performing an unbinned likelihood fit to the diphoton invariant mass


ttH

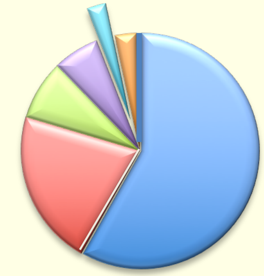
ttH H→γγ



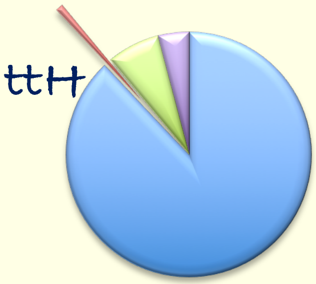

ATLAS
√s=13 TeV, 79.8 fb-1
Data
tt̄H (μ=1.4)
Non-tt̄H Higgs
Cont. Bkg.
Had categories
Lep categories
Events
Data - Bkg.
tt̄H (μ=1.4)
100
80
60
40
20
20
10
0
Had 4
Had 3
Had 2
Had 1
Lep 3
Lep 2
Lep 1



ttH $H \rightarrow ZZ^* \rightarrow 4l$



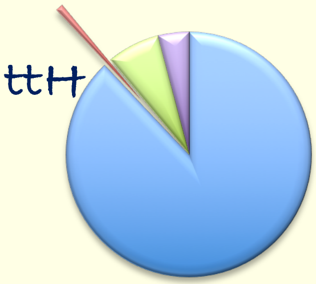
- Clear signature: at least 4 isolated leptons (sfos) + at least one b-tagged jet
- 2 SRs: 'Had' (at least 3 additional jets and no isolated leptons) and 'Lep' (at least one additional isolated lepton and one jet) similarly to ttH $H \rightarrow \gamma\gamma$
- Background: ttW, ttZ and non-ttH processes (ggF and tH for 'Had' and tH for 'Lep')
- Strategy: BDT in 'Had' whose input variables are kinematic variables of jets and leptons and a single region for 'Lep'
  - 2 BDT bins chosen to optimize the expected ttH sensitivity in the 'Had'
  - The ttH observed signal and expected background yields extracted in the 'Had' BDT bins and in the 'Lep' regions are used as input for a likelihood fit to the diphoton invariant mass to extract the ttH yield.



ttH COMBINATION

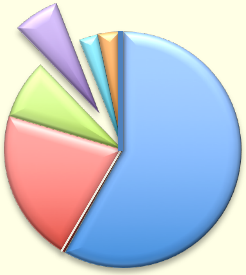
- The final combination is performed using the profile likelihood method based on simultaneous fits to the signal regions and CRs of the individual analyses
- Syst. uncertainties effects taken into account through nuisance parameters
- Non-ttH processes fixed to SM predictions in the final fit

Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H \to \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	4.1σ	3.7σ
$H \to$ multilepton	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	4.1σ	2.8σ
$H \to b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	1.4σ	1.6σ
$H \to ZZ^* \to 4\ell$	79.8	<900 (68% CL)	0σ	1.2σ
Combined (13 TeV)	36.1–79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8σ	4.9σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3σ	5.1σ



ttH SYSTEMATIC UNCERATANTIES

Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-leptons	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4



$H \to \tau\tau$

- Three analyses channels: $\tau_{lep}\tau_{lep\tau}$, $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$

- Background: $Z \to \tau\tau$ dominant in all the channels, contributions from top and vector bosons decays , as well as from misidentified leptonic or hadronic τ decays depend on the channel considered

- Two categories: 'boosted' ggF (additional recoiling jet) and VBF

- Higgs is reconstructed from the visible decay products of τ_s and from MET

- Di-tau invariant mass derived using the Missing Mass Calculator, MMC

- Strategy: maximum likelihood fit performed on data using distributions of the di-tau mass in SRs simultaneously with event yields from CRs (included to constrain normalization of major backgrounds estimated from simulation)

NEW PHYSICS: THE EFT APPROACH

- The SM can be be supplemented by possible new physics effects

  3 dim6 operators modifying the t- and b- quark couplings + point-like Hg coupling

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \cdots$$

New physics at the the scale Λ

arXiv:1612.00283

With c_i dimensionless coefficients and O_i operators of dim6 from the SM

- Multi-TeV scale can be:
  - tested with sub-percent level measurements

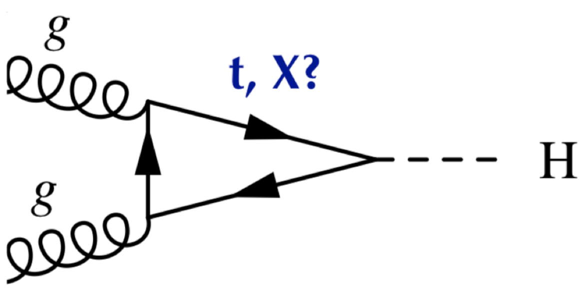
$$\delta\mathcal{O} \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{TeV}{\Lambda}\right)^2$$ – 1% effect on coupling for $\Lambda \sim 2.5$ TeV

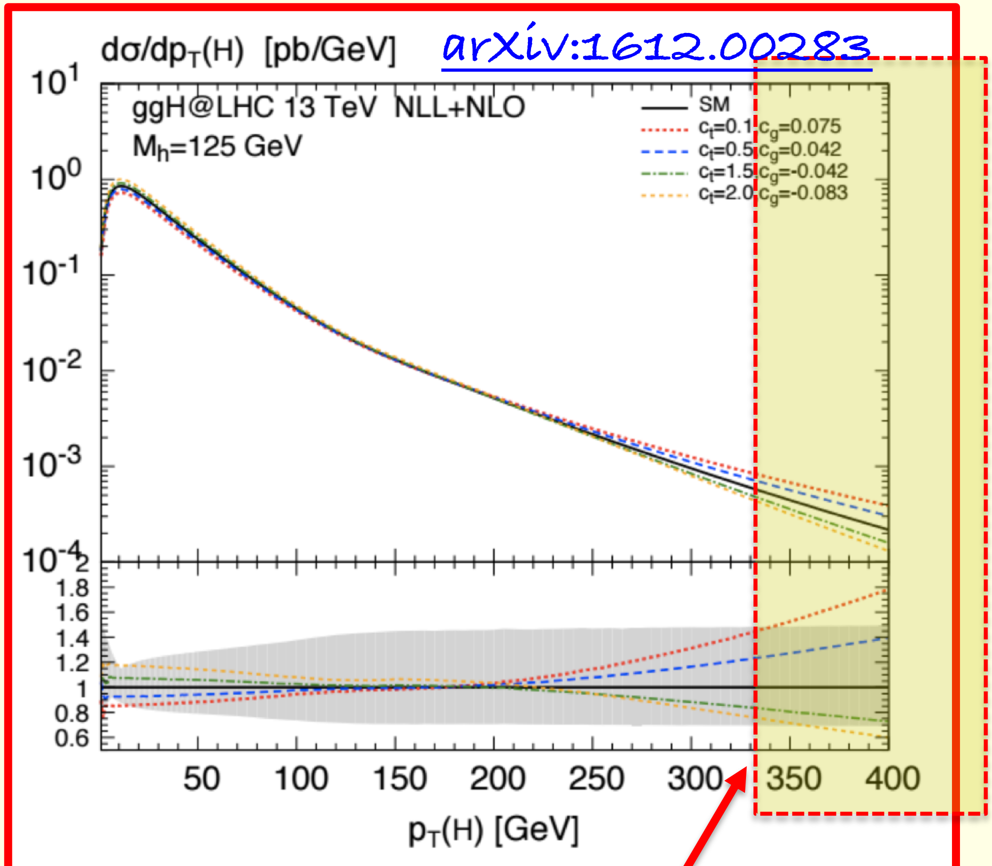
  - tested with high-p_T measurements even if at low precision

$$\delta\mathcal{O} \sim \left(\frac{Q}{\Lambda}\right)^2$$ – 16% effect on coupling for $\Lambda \sim 2.5$ TeV

HIGH-p_T HIGGS

- At high-p_T Higgs we can probe modifications in top couplings

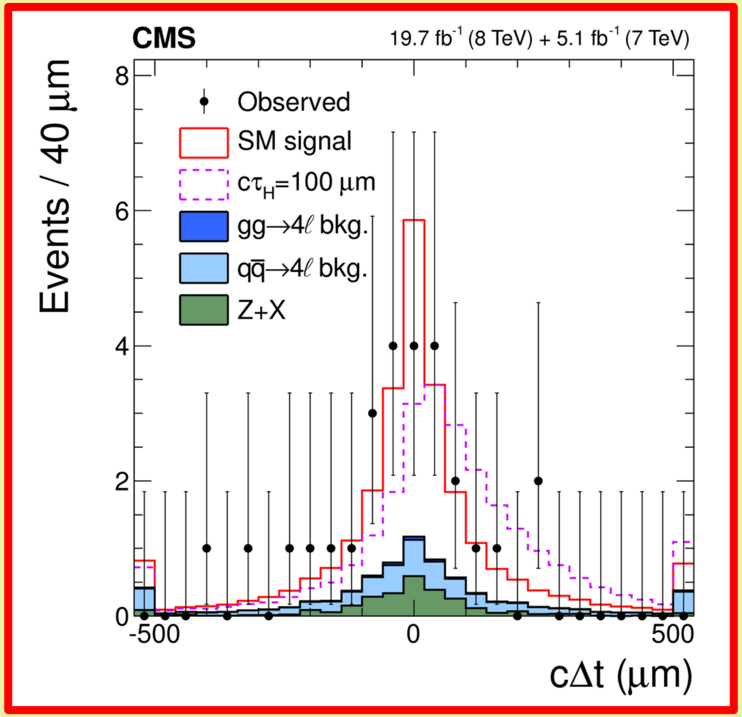




ggF Hbb: powerful test

HIGGS WIDTH: DIRECT STRATEGIES

From the lifetime



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

Lifetime of each H candidate

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

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

HIGGS WIDTH: FROM COUPLINGS

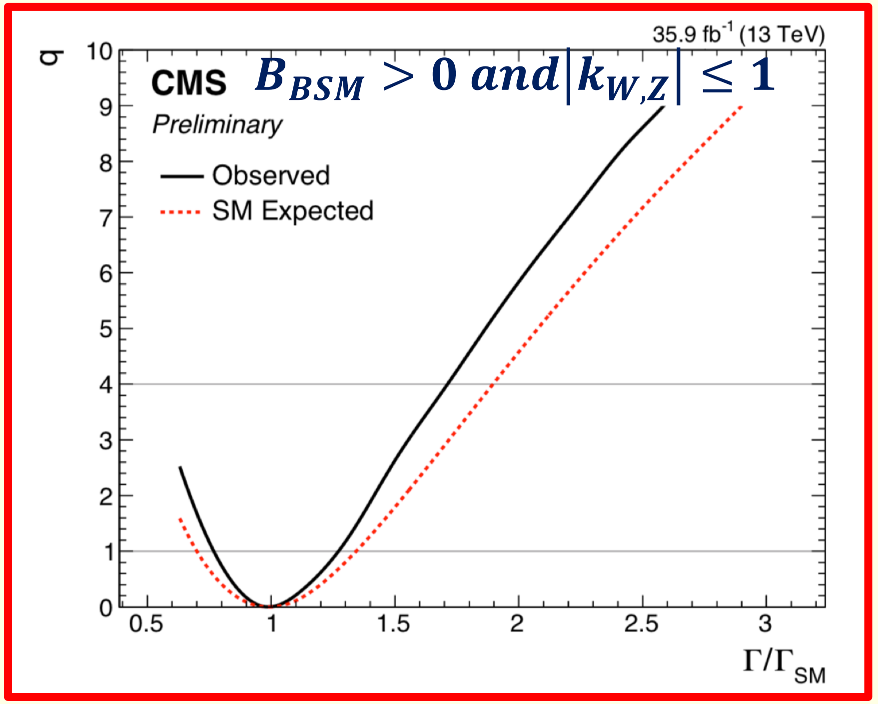
➤ Using the coupling analysis framework we can constraint Γ_H:

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

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 $\mathrm{BR}_{\mathrm{BSM}} = 0$				
Γ_H	✓	–	κ_H^2	$0.58 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.08 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa_\tau^2 + 0.026 \cdot \kappa_Z^2 + 0.029 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa_\gamma^2 + 0.0015 \cdot \kappa_{Z\gamma}^2 +$ $+ 0.00025 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$



HIGGS WIDTH: OFF-SHELL STRATEGY

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

1

Off-shell signal strength constraints

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

2

Higgs boson total width constraints

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

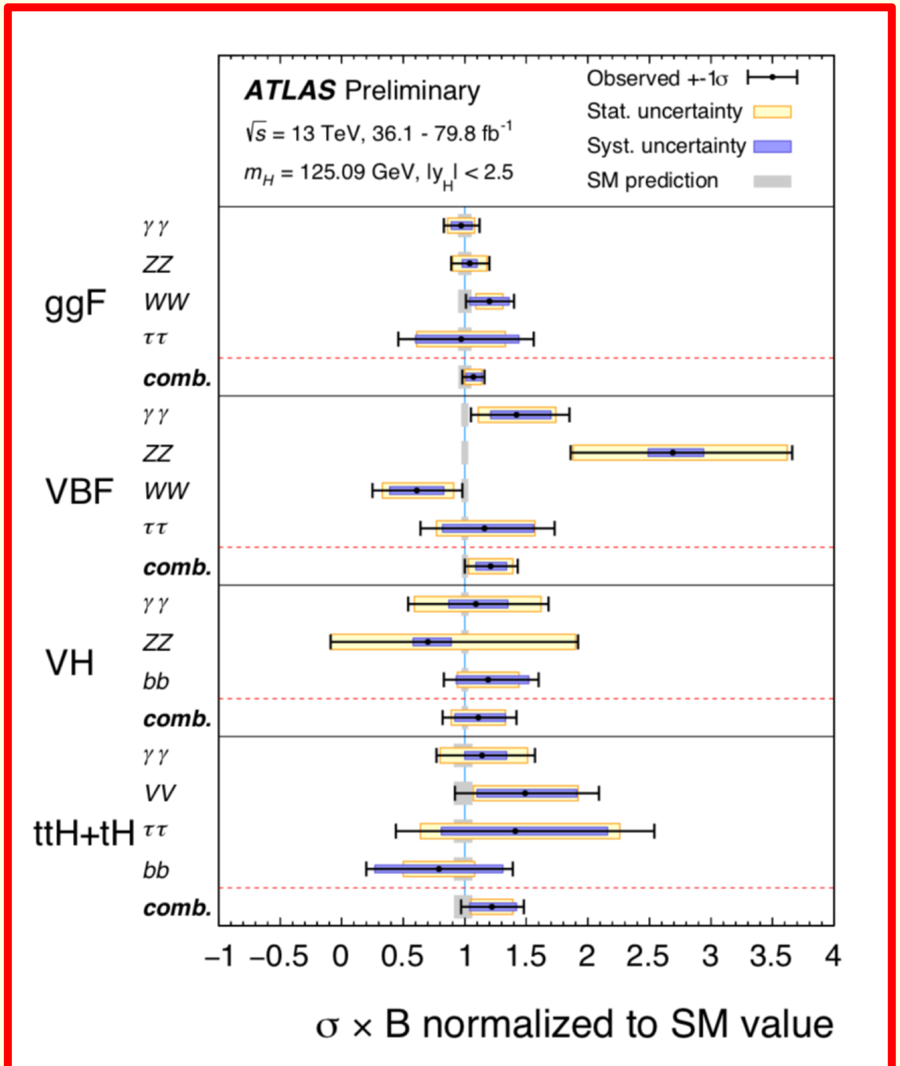
CROSS-SECTIONS IN RUN 2

- No absolute couplings measurements at LHC

- For the observable $\sigma(AA \to H) BR(H \to BB)$ the quantity measurable is proportional to:

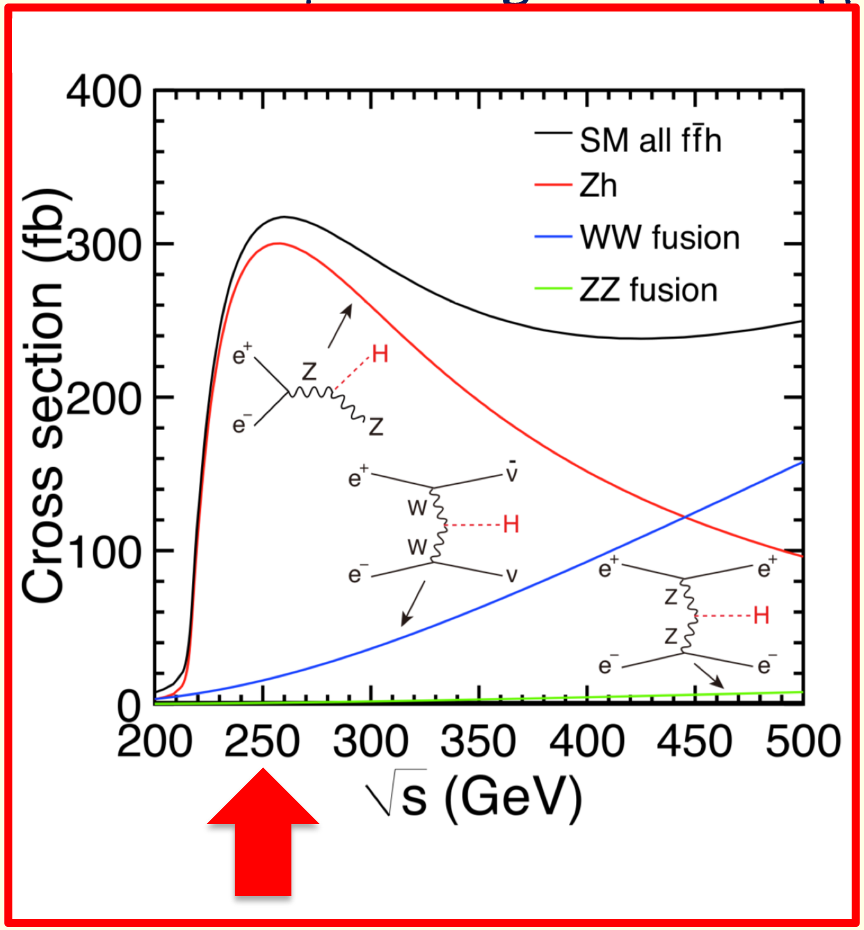
$$g^2(HAA)\, g^2(HBB) / \Gamma_H$$

The Higgs boson total width must be known to have absolute magnitudes of the couplings!



HIGGS PHYSICS AT ILC

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



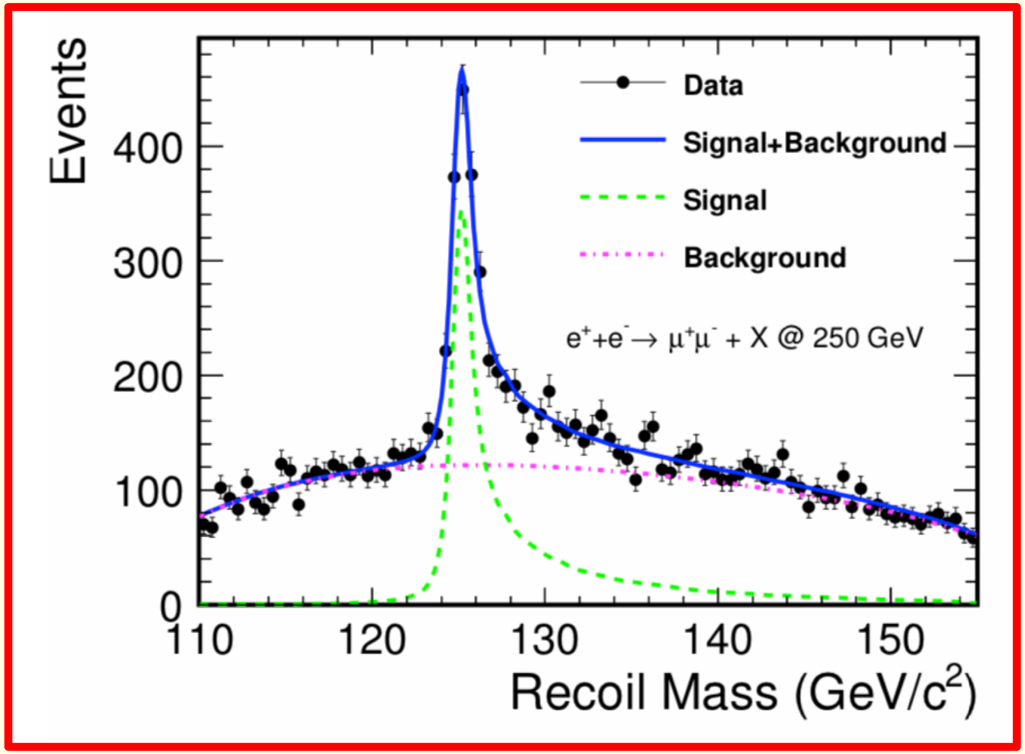
- The Higgs-strahlung production is maximum at 250 GeV
- 2000 fb^{-1} in 20 years of data acquisition (H20 program):
  - ZH ➡ ~500 K Higgs
  - WW-fusion ➡ ~15 K Higgs

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

HZ COUPLING AT ILC

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

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



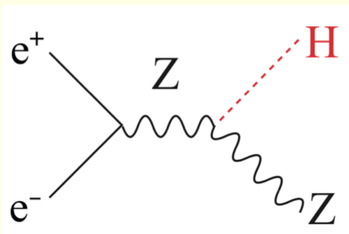
- Higgs events are tagged with the Z boson decays, independently of the Higgs decay mode

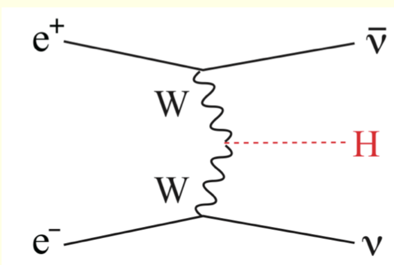
- From the HZ sample, measurement of g_{HZZ}:

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

g_{HZZ}: KEY TO THE ILC PROGRAM

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





$$\frac{\sigma(e^+e^- \to ZH)}{\sigma(e^+e^- \to \nu\bar{\nu}H)} = \frac{\dfrac{g^2_{HZZ} \cdot g^2_{HXX}}{\Gamma_H}}{\dfrac{g^2_{HWW} \cdot g^2_{HXX}}{\Gamma_H}} \Rightarrow g^2_{HWW}$$

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

Γ_H Accuracy achievable 1.7% (ILC250+ILC500)

COUPLINGS PRECISION IN FUTURE