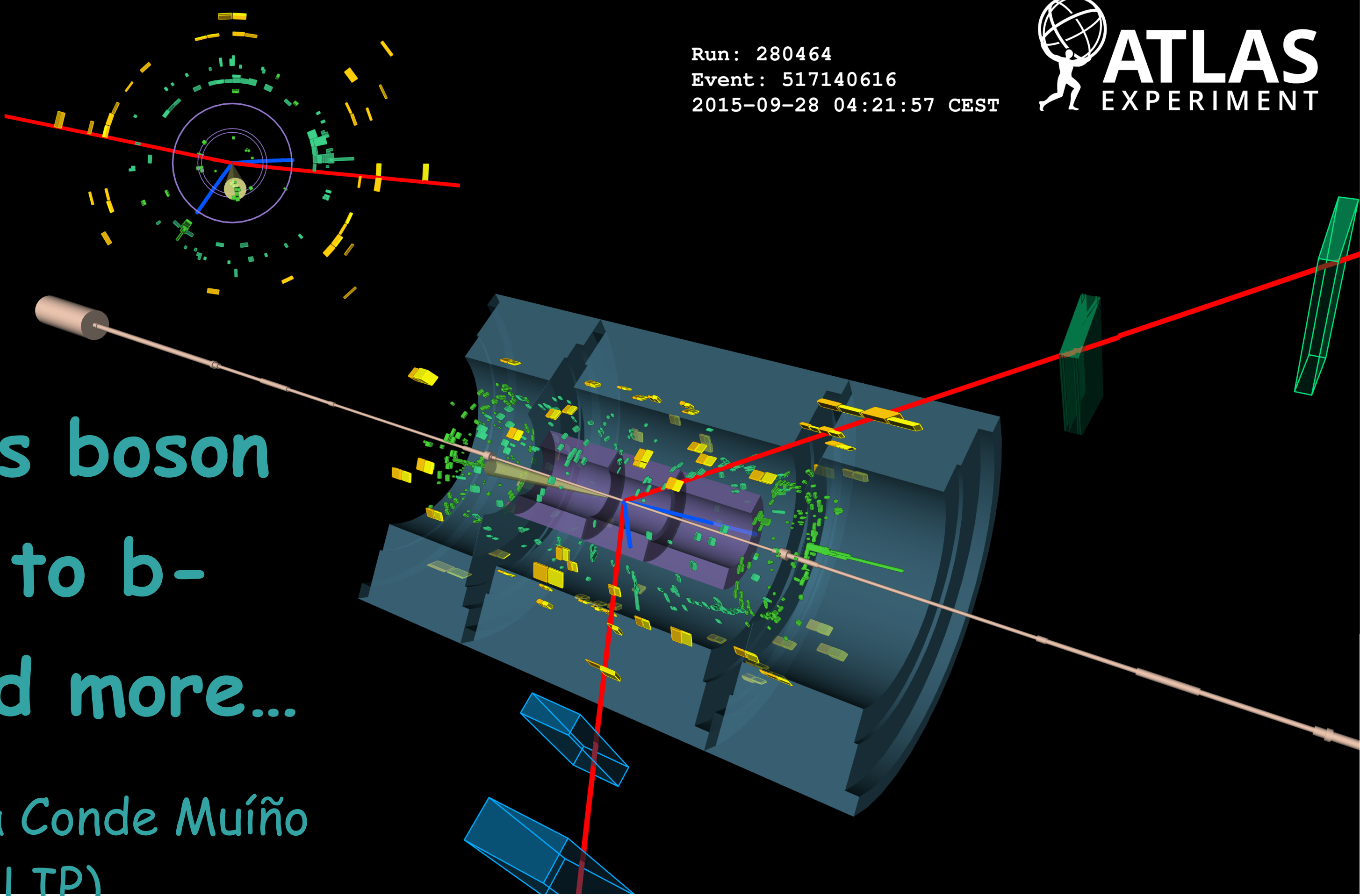


The Higgs boson Decays to b-quarks and more…

Patricia Conde Muíño
(IST & LIP)

Higgs lectures so far…

Course on Physics at the LHC

from **Monday, 2 March 2020 (07:00)** to **Friday, 26 June 2020 (18:40)**
LIP (Conference Room)

: Sessions / : Talks : Bre

	2 Mar 2020	6 Mar 2020	9 Mar 2020	10 Mar 2020	16 Mar 2020	
AM						
PM	17:00 Experimental program at the LHC - Joao Varela (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part) (Conference Room) Lecture1-Exp at LHC.pdf	17:00 Standard Model at the LHC - Joao Varela (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part) (Conference Room) Lecture2-SM at LHC.pdf	17:00 Detectors 1 - Pedro Vieira De Castro Ferreira Da Silva (CERN) Michele Gallinaro (LIP Lisbon) (Conference Room) detectors_March2019.pdf	17:00 Detectors 2 - Pedro Vieira De Castro Ferreira Da Silva (CERN) (Conference Room)	17:00 Statistics 1 - Pietro Vischia (Universite' Catholique de Louvain (UCL)) (Conference Room) 2020-03-16to18_Statistics_LIP-LHC-Course_vischia_part1.pdf	17:00 Sta (Co

23 Mar 2020	24 Mar 2020	30 Mar 2020	1 Apr 2020	6 Apr 2020
17:00 Top Physics 1 - Michele Gallinaro (LIP Lisbon) (Conference Room) 2020_course_Top_Lecture1.pdf	17:00 Top Physics 2 - Michele Gallinaro (LIP Lisbon) (Conference Room) 2020_course_Top_Lecture2.pdf	17:00 Top Physics 3 - Antonio Onofre (Universidade de Coimbra (PT)) (Conference Room) ToptopCouplings_AO.pdf	17:00 Higgs Physics 1 - Ricardo Jose Morais Silva Goncalo (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part) (Conference Room) HiggsLecture1.pdf	17:00 Higgs Physics 2 - Pedro Vieira De Castro Ferreira Da Silva (CERN) (Conference Room) higgsproperties_6Apr2020.pd

Higgs lectures so far...

Wednesday, 1 April

17:00 → 18:30 **Higgs Physics 1**

Introduction
Reminder of some shortcomings of the SM: masses, WW scattering.
The Higgs mechanism. Production and decay of the Higgs boson at colliders: LEP, Tevatron and LHC.
Previous searches at LEP and the Tevatron.

Speaker: Ricardo Jose Morais Silva Goncalo (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)

HiggsLecture1.pdf

Monday, 6 April

17:00 → 18:30 **Higgs Physics 2**

Models, properties, and interpretation.
Case-study of the coupling strengths.
Case-study of the hypothesis test for different spin-parity assignments.

Speaker: Pedro Vieira De Castro Ferreira Da Silva (CERN)

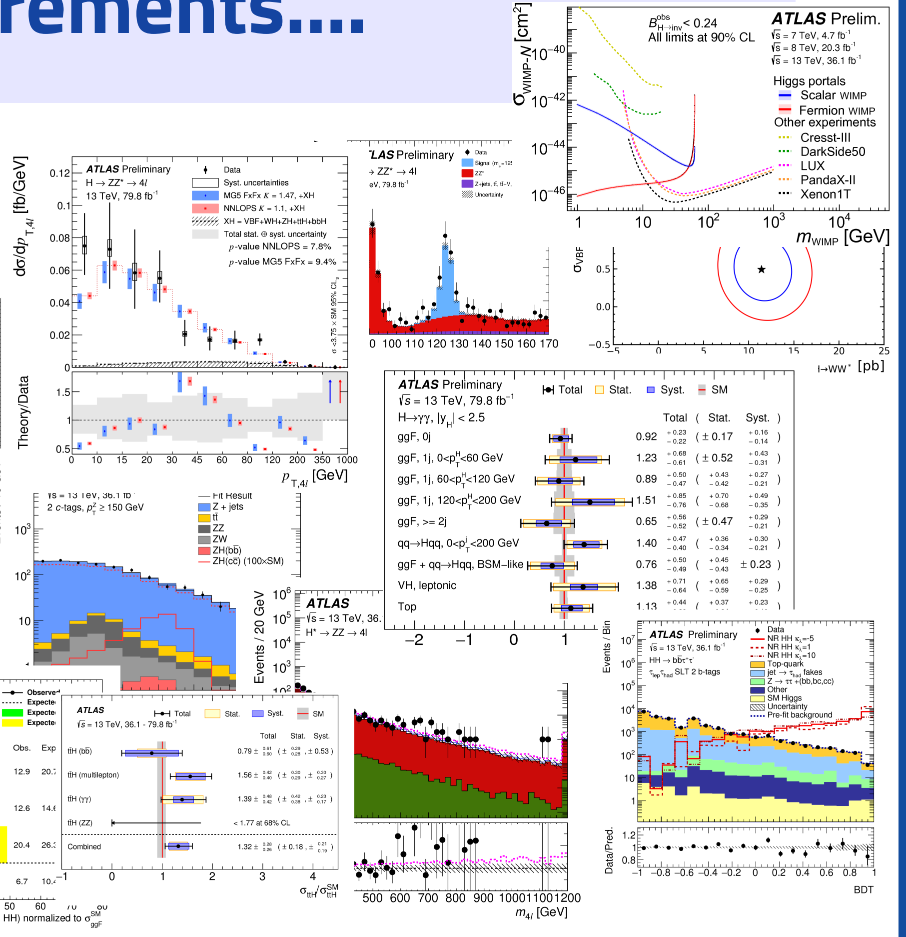
higgsproperties_6A...

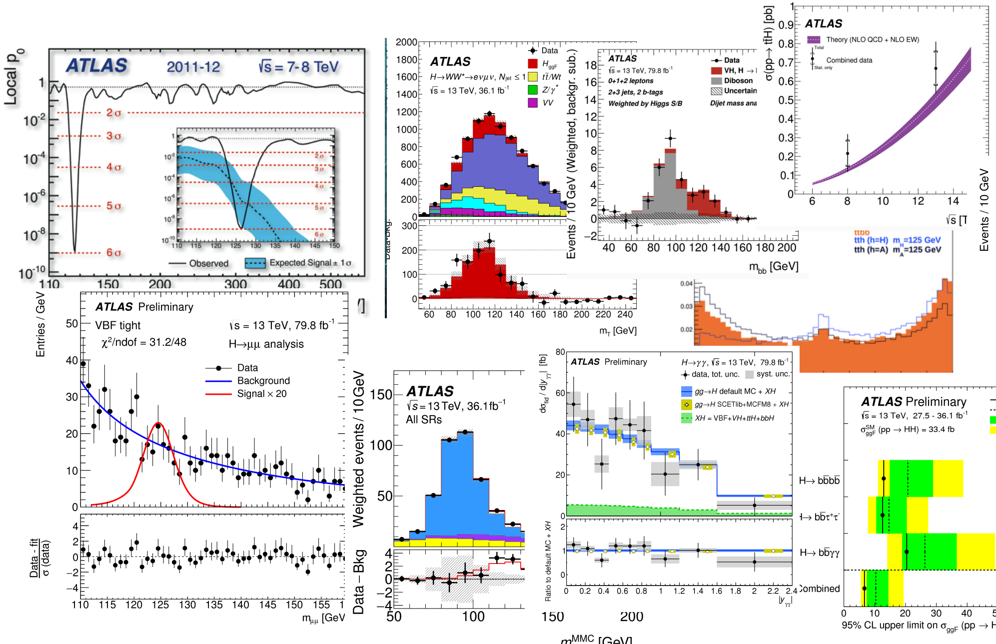
In this lecture

- ✳Reminder
  - The Higgs Lagrangian in the SM and how to probe it
- ✳Challenges and difficulties of the Higgs boson study at the LHC
- ✳Photon reconstruction and the searches in the $H\to\gamma\gamma$ channel
- ✳The H→bb search
  - Event selection
  - Background measurement
  - Fits
  - Combinations
- ✳Other channels to look at the Higgs couplings to quarks
  - Is it possible to improve/complement the measurements done?

Lots of different measurements….

- How to make sense of them?



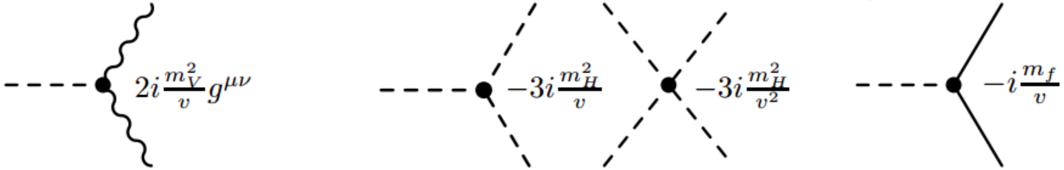


SM Higgs Lagrangian after symmetry breaking

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

Couplings to EW gauge bosons | Higgs self-couplings | Couplings to fermions

$$\left[m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \frac{h}{v}\right)^2 \qquad -\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4 \qquad -\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$



$$m_H = \sqrt{2}\mu = \sqrt{\lambda} v \ (v = \text{vacuum expectation value})$$

★ Very predictive theory:

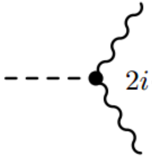
- ★ Can calculate everything but the Higgs boson mass...
- ★ Once the Higgs boson is found... we can also probe everything!

The SM Higgs Lagrangian after symmetry breaking

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \tfrac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

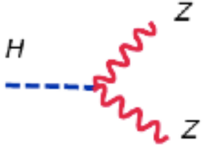
Couplings to
EW gauge bosons

$$\left[m_W^2 W^{\mu +} W_\mu^- + \tfrac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \tfrac{h}{v}\right)^2$$

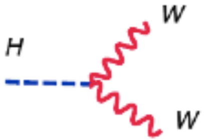


$$2i\frac{m_V^2}{v} g^{\mu\nu}$$

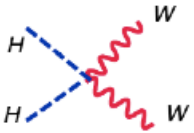
$$m_H = \sqrt{2}\mu = \sqrt{\lambda} v \; (v =$$



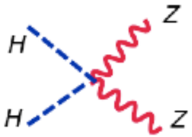
$$2i\frac{M_Z^2}{2v} g_{\mu\nu}$$



$$2i\frac{M_W^2}{v} g_{\mu\nu}$$

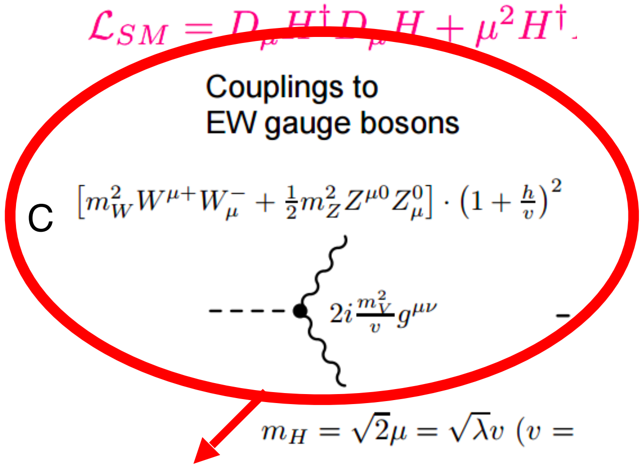


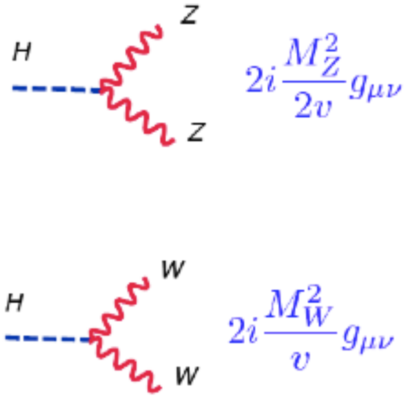
$$2i\frac{M_W^2}{2v} g_{\mu\nu}$$



$$2i\frac{M_Z^2}{4v} g_{\mu\nu}$$

Higgs decays to vector bosons





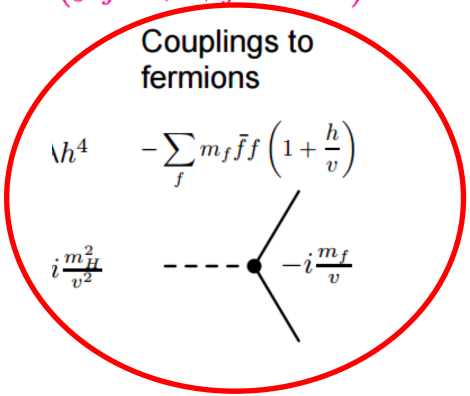
- ✳ H → WW
- ✳ H → ZZ

- ✳ First observation
- ✳ Cross sections at 7, 8 and 13 TeV

Differential distributions

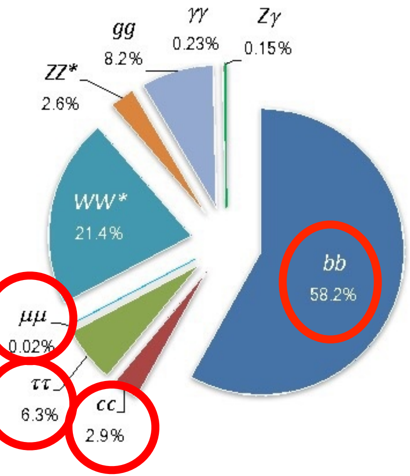
Higgs couplings to fermions

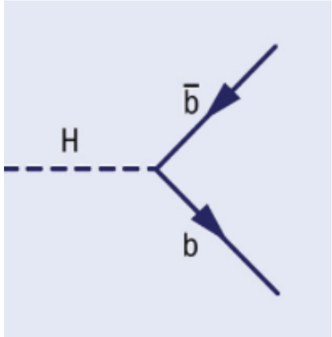
$(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.})$



- Couplings to fermions
- Experimental measurements:

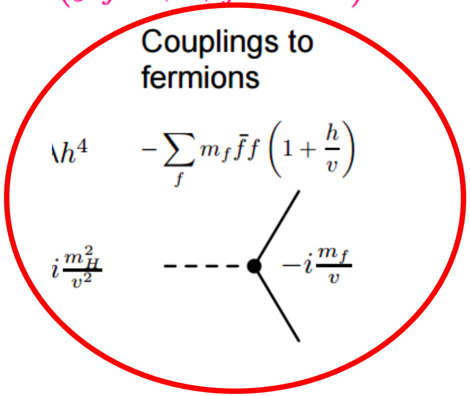
Decay rates to quarks & leptons





Higgs couplings to fermions

$$(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.})$$



- Couplings to fermions
- Experimental measurements:

  Decay rates to quarks & leptons

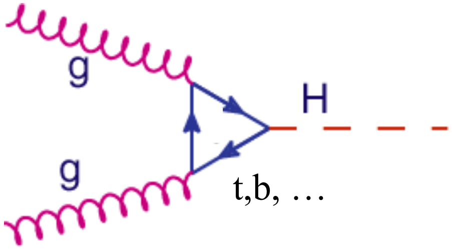
  Top quark coupling:

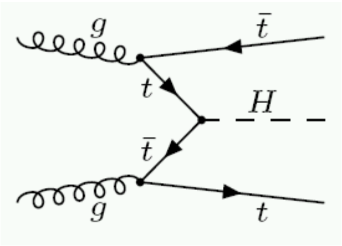
    Indirect: gg fusion production mode

      But model dependent —> need direct probes!

    ttH associated production

  Rare decays





Higgs couplings to fermions

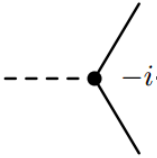
$$\left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

- Couplings to fermions
- Experimental measurements:
  - Decay rates to quarks & leptons
  - Top quark coupling:
    - Indirect: gg fusion production mode
      - But model dependent —> need direct probes!
    - ttH associated production
  - Rare decays

Couplings to fermions

λh^4 $\quad -\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$

$i\frac{m_H^2}{v^2}$



$-i\frac{m_f}{v}$

Phys. Lett. B 786 (2018) 134

ATLAS-CONF-2018-053

Phys. Rev. Lett. 120 (2018) 211802

arXiv:1811.08856

Phys. Lett. B 786 (2018) 59

ATLAS-CONF-2018-026

Phys. Rev. D 98 (2018) 052003

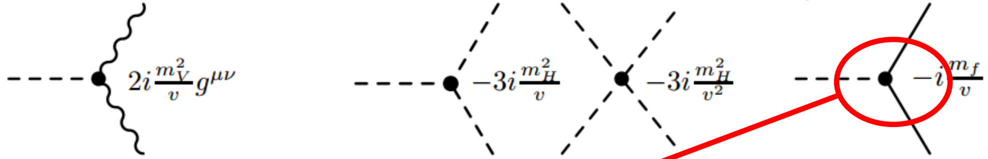
Phys. Lett. B 784 (2018) 173

New particles? What about dark matter?

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

Couplings to EW gauge bosons | Higgs self-couplings | Couplings to fermions

$$\left[m_W^2 W^{\mu+} W_\mu^- + \tfrac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \tfrac{h}{v}\right)^2 \qquad -\mu^2 h^2 - \tfrac{\lambda}{2} v h^3 - \tfrac{1}{8}\lambda h^4 \qquad -\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$



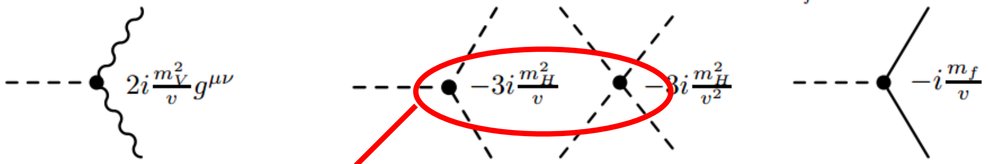
$$m_H = \sqrt{2}\mu = \sqrt{\lambda} v \ (v = \text{vacuum expectation value})$$

- ✳ Couplings to new particles?
- ✳ Experimental measurements:
  - Search for invisible decays
  - Total decay width:
    - Constraint from visible decays
    - Interference effects in ZZ production

Higgs self interactions

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

Couplings to EW gauge bosons	Higgs self-couplings	Couplings to fermions
$[m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0] \cdot (1+\frac{h}{v})^2$	$-\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4$	$-\sum_f m_f \bar{f} f \left(1+\frac{h}{v}\right)$



$m_H = \sqrt{2}\mu = \sqrt{\lambda} v$ (v = vacuum expectation value)

- ✳ Higgs potential
- ✳ Experimental measurements:
  - Higgs mass
  - HH production

Phys. Lett. B 784 (2018) 345

Phys. Lett. B 786 (2018) 223

Phys. Rev. Lett. 121 (2018) 191801

Eur. Phys. J. C 78 (2018) 1007

arXiv:1811.11028

JHEP 11 (2018) 040

arXiv:1811.04671

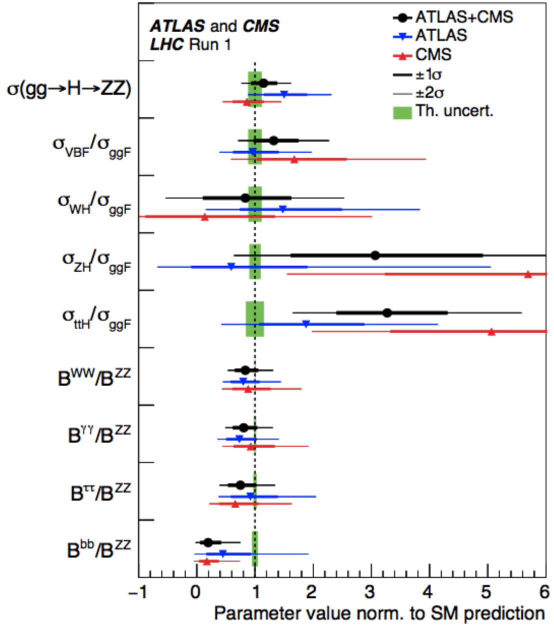
arXiv:1804.06174

ATLAS-CONF-2018-043

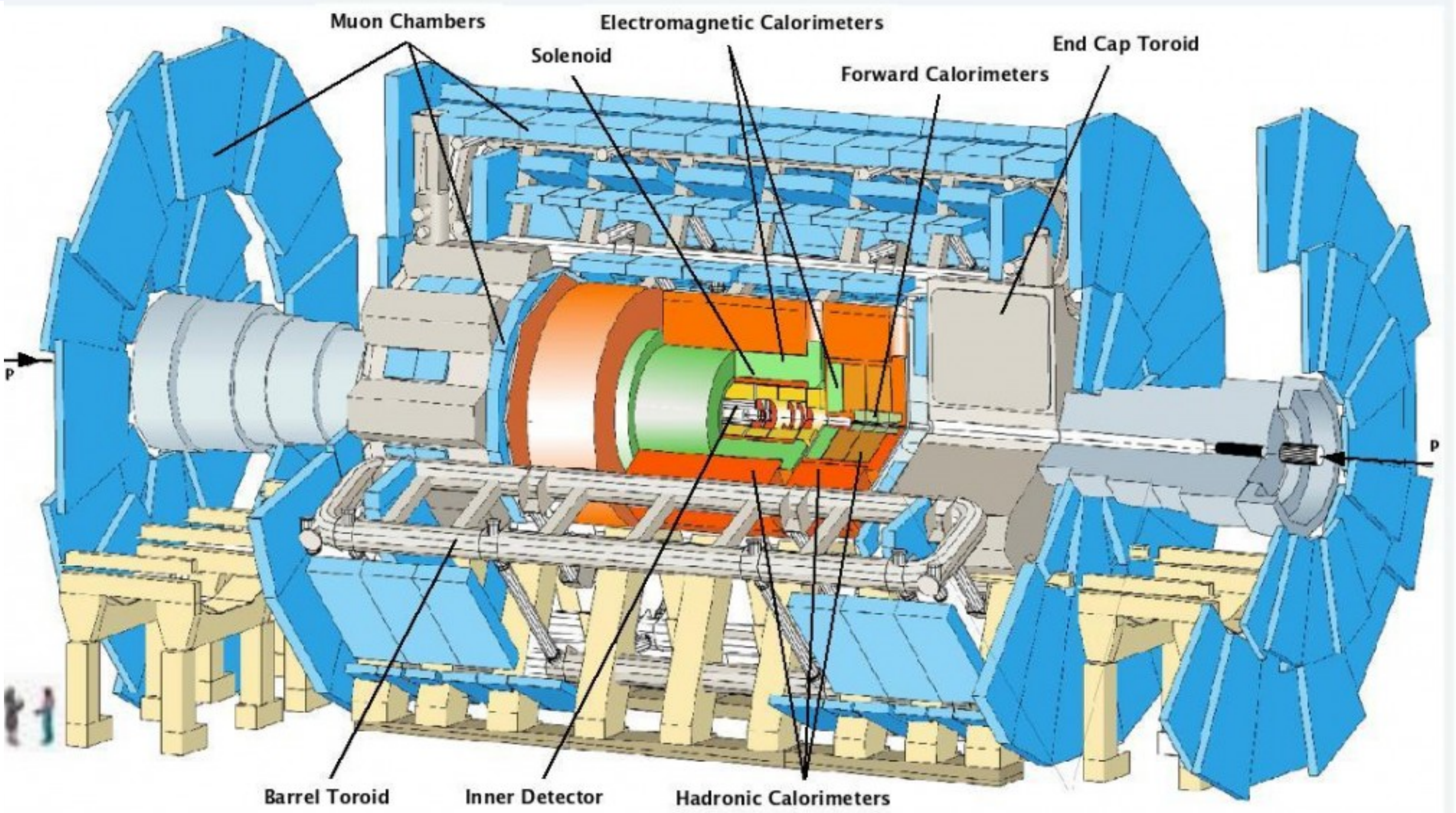
The search for H→bb decays

- Higgs boson observed & measured mainly in bosonic channels ($\gamma\gamma$, WW, ZZ)
  - All results compatible with SM
- H→bb: largest BR in the SM (~58%)
  - Constrain total width and measure absolute couplings
  - Probe the Higgs couplings to up-type quarks
- Evidence of fermionic decays in Run 1:
  - H→: 5.5**σ** (expected 5**σ**)
  - H→bb: 2.6**σ** (expected 3.7**σ**)
- Run 1 signal strength for H→bb: $\mu_{bb}^{CMS+ATLAS} = 0.70^{+0.29}_{-0.27}$

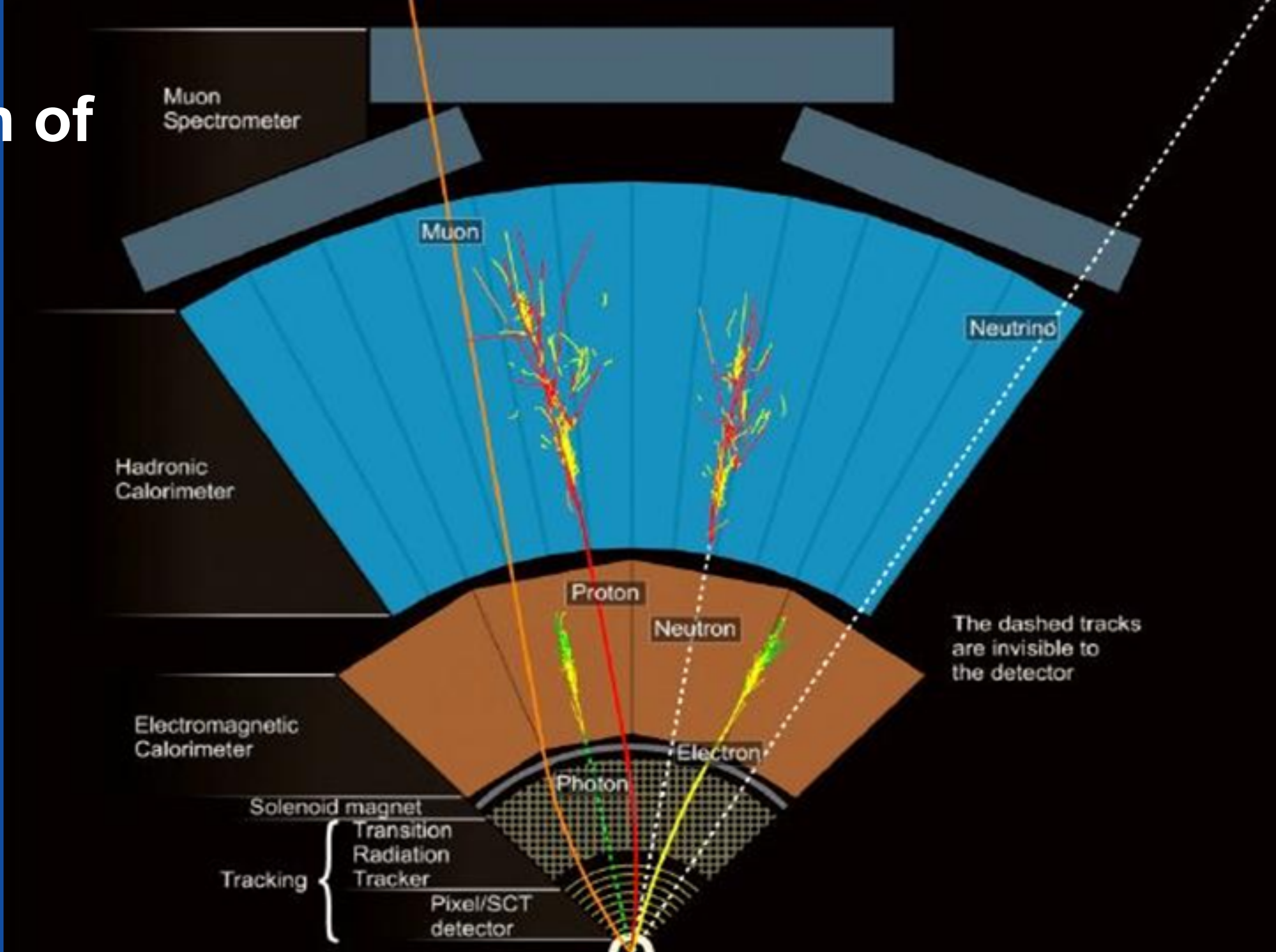
ATLAS+CMS Run 1
Coupling combination



The ATLAS detector

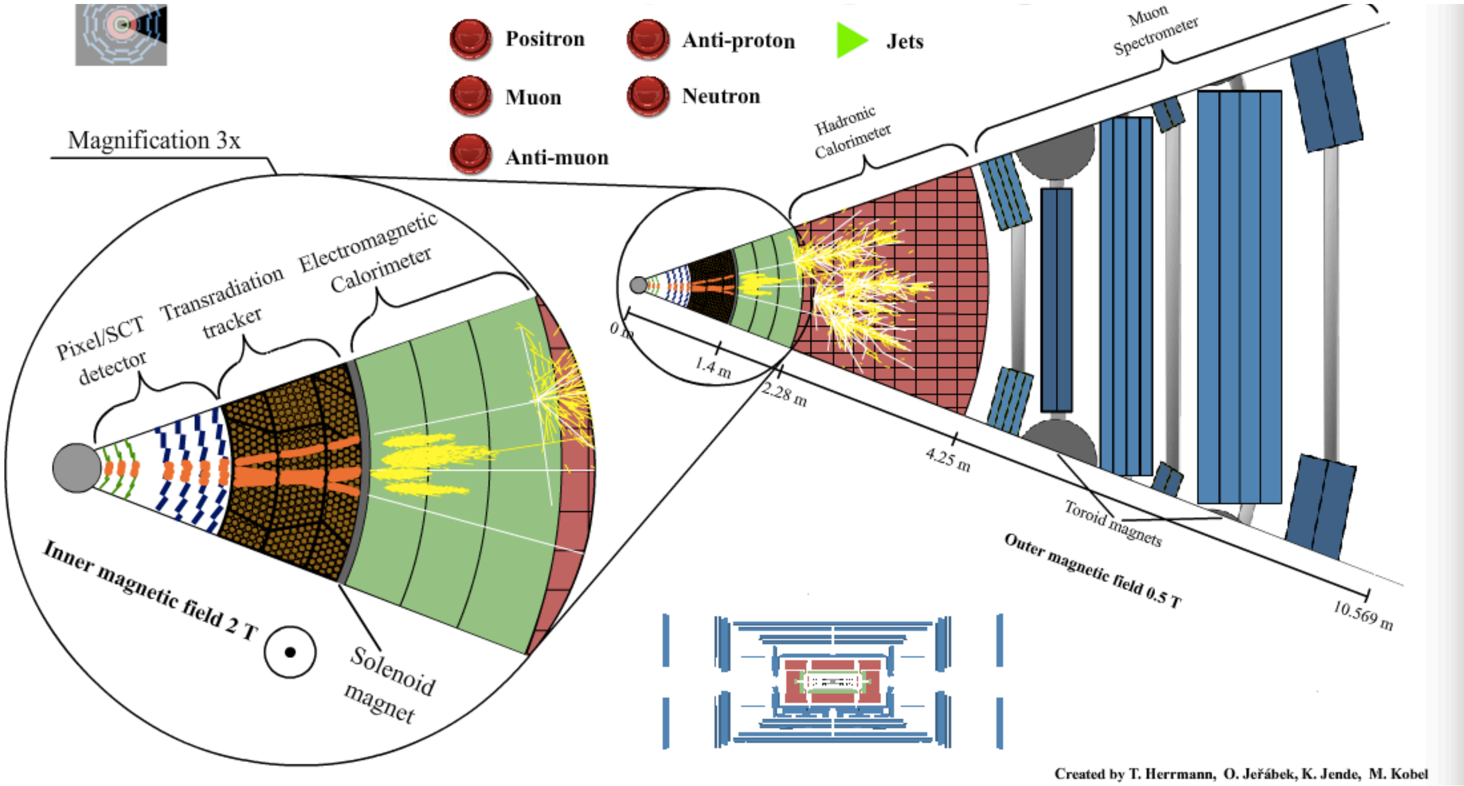


Identification of particles in ATLAS



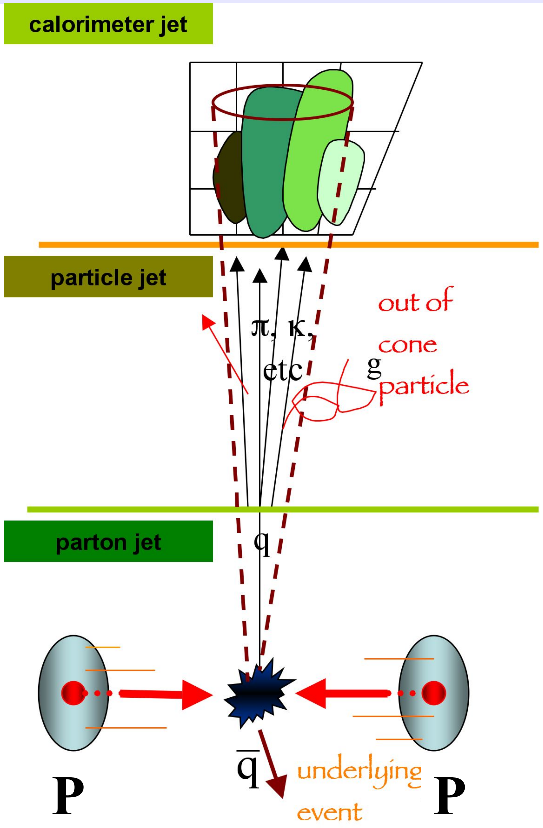
Jets

- Quarks/gluons hadronize producing a colimated spray of particles: jets



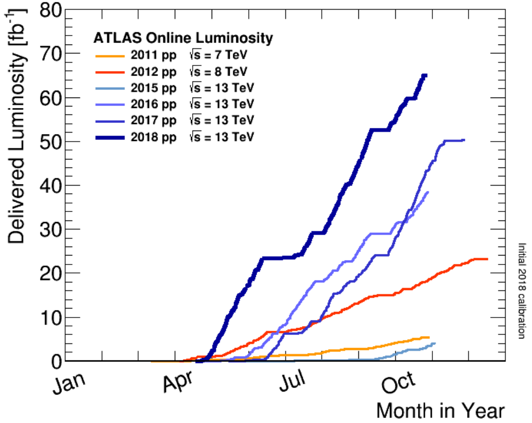
Jets reconstruction and calibration

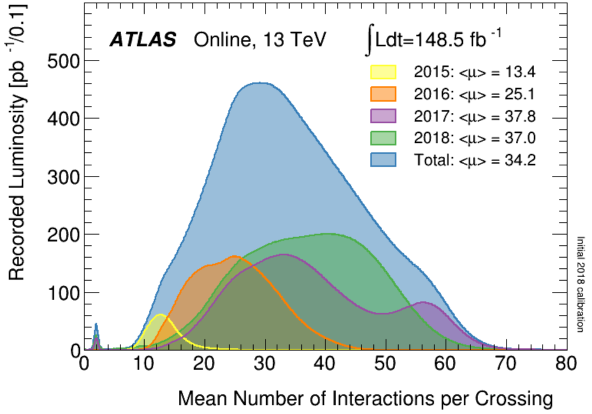
- Complex underlying physics
  - spectator interactions
  - initial and final state gluons
  - energy from different pp interactions
  - different types of jets: light quarks,
  - gluons, b/c/t
- Complex detector properties:
  - non-linear energy response
  - non-instrumented regions,
  - dead material
  - invisible energy
- Algorithm effects:
  - Out of cone radiation, infrared safeness



ATLAS and LHC operation

- Integrated luminosity
  - 158 fb^{-1} delivered
  - 140 fb^{-1} recorded
- Average pile-up at 13 TeV
  - 34.2 interactions/BX



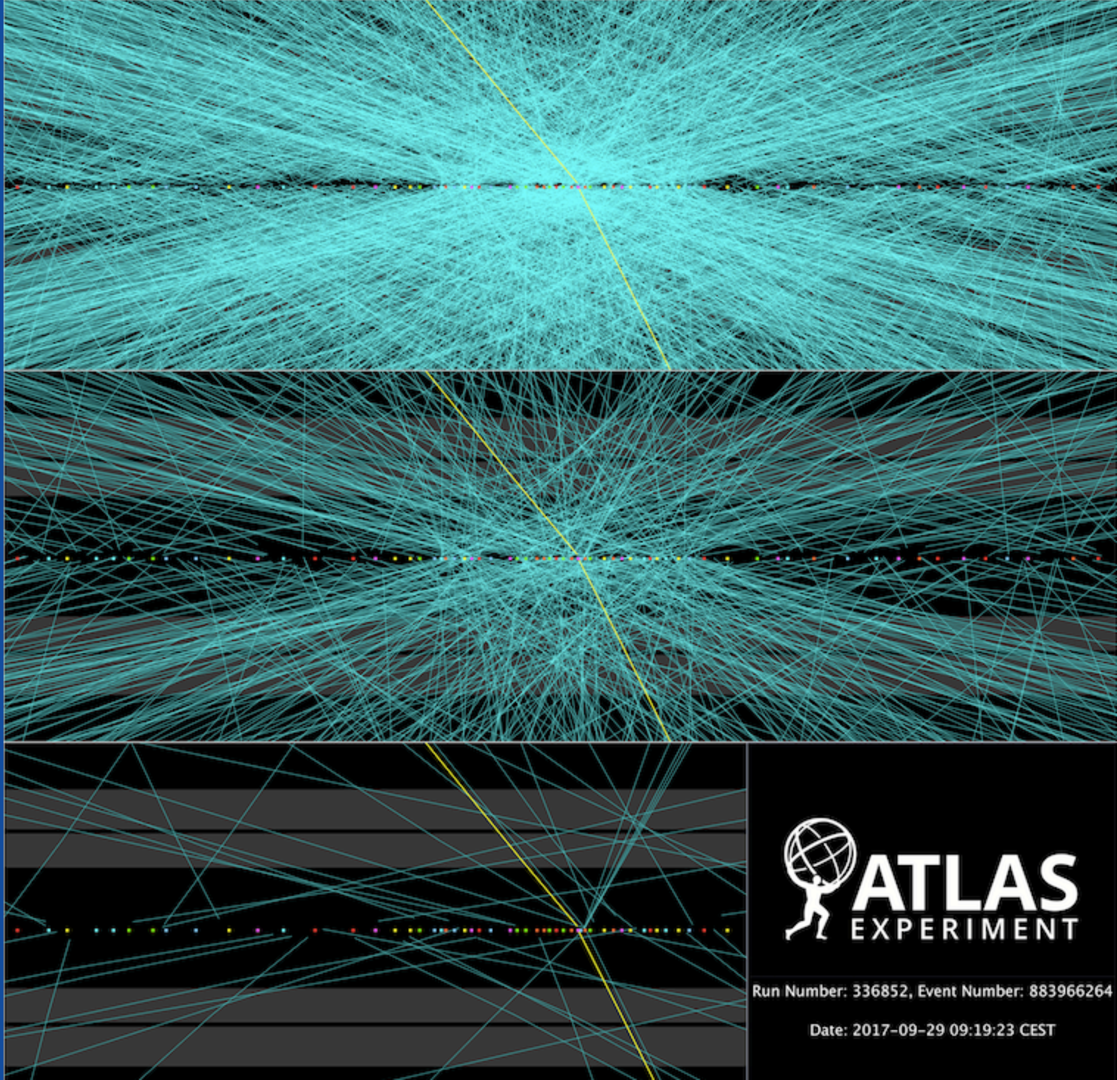


ATLAS pp data: April 25-October 24 2018										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.8	100	99.7	100	99.8	99.7	100	100	100	99.6
Good for physics: 97.5% (60.1 fb^{-1})										

Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions at $\sqrt{s}$=13 TeV between April 25 – October 24 2018, corresponding to a delivered integrated luminosity of 63.8 fb^{-1} and a recorded integrated luminosity of 61.7 fb^{-1}. Dedicated luminosity calibration activities during LHC fills used 0.7% of recorded data and are included in the inefficiency. The luminosity includes 193 pb^{-1} of good data taken at an average pileup of μ=2.

Pile-up

- Event with a Z→$\mu\mu$ decay plus 65 additional pp interactions
- Very difficult to reconstruct and distinguish different particles



Standard Model backgrounds

Production cross section of

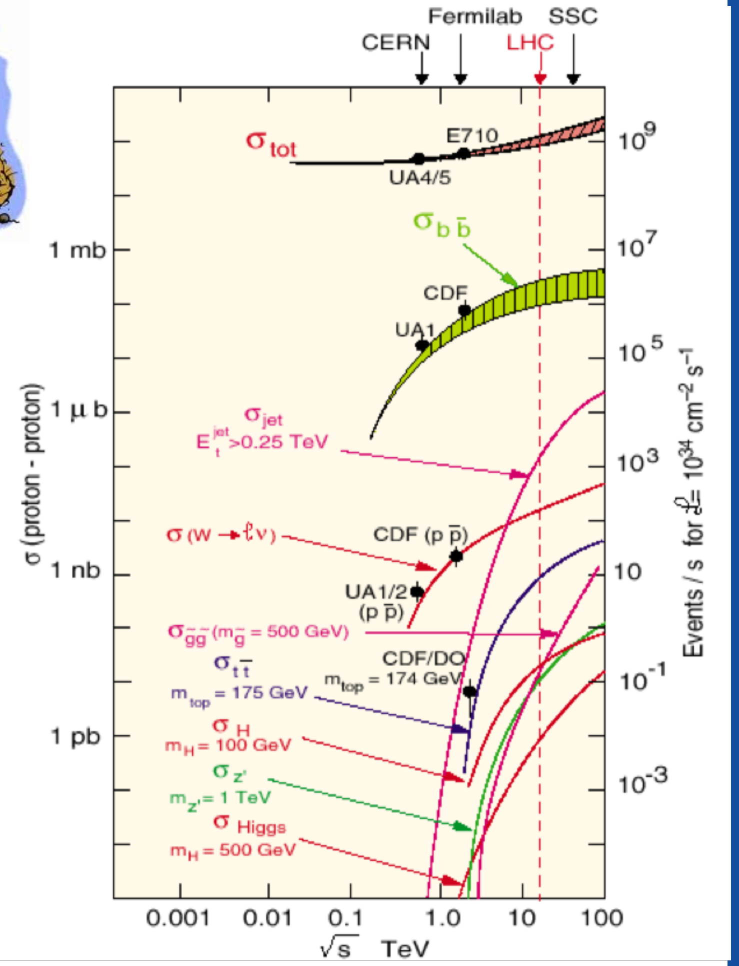
- Jets ~10^8 larger than σ_H
- B-jets ~10^7 times larger than σ_H
- W-bosons: nearly 10000 times higher than σ_H

We need

- Clear experimental signatures in the detector

For H→bb search:

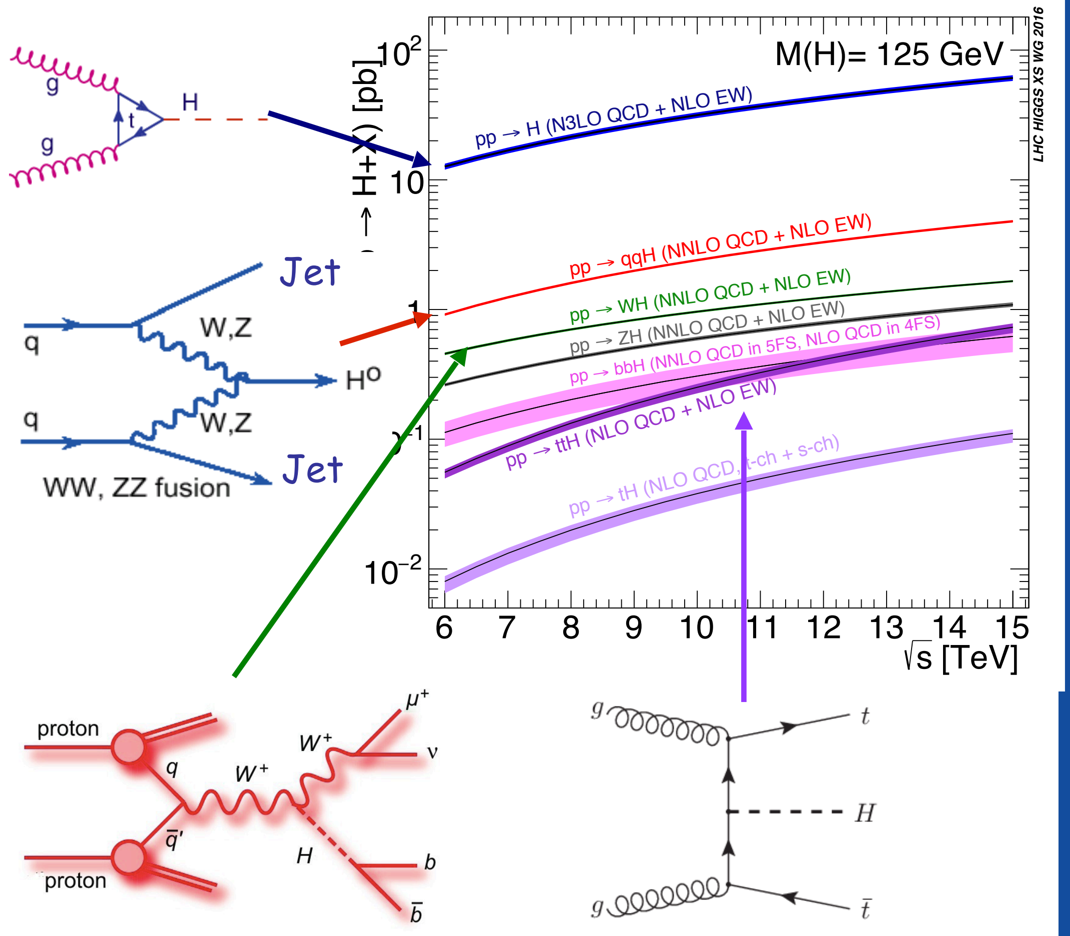
- Use sub-dominant production modes
- Associated production with vector bosons
- Vector boson fusion



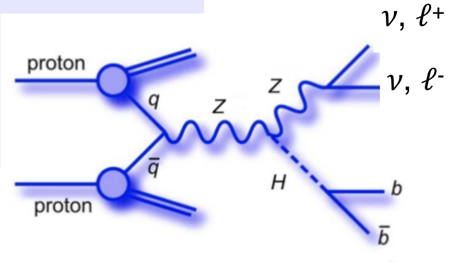
Higgs production at the LHC

- Dominant gluon-gluon fusion
- Sub-dominant:
  - Vector boson fusion
  - WH and ZH associated production
  - ttH associated production

At the LHC… can only measure production and decay together

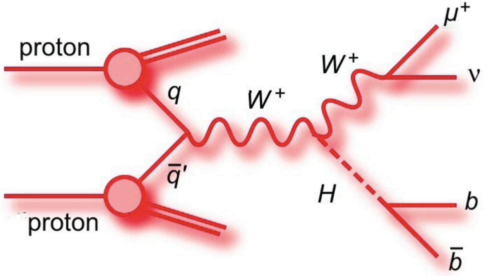


H→bb decay

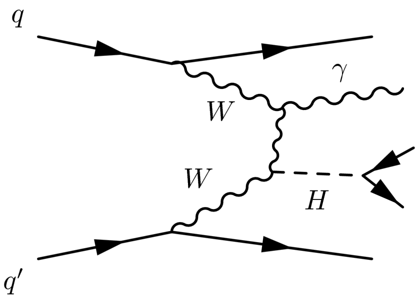


Searches performed using sub-dominant production modes:

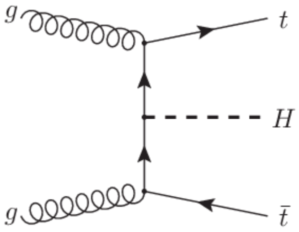
- WH and ZH associated production (VH)
  - Three different channels: 0, 1 and 2 charged leptons



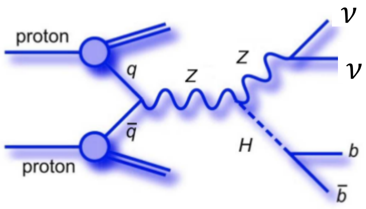
- VBF analysis
  - Considered final states with/out additional γ
    - Final state photon helps reducing the background due to interference effects for the background

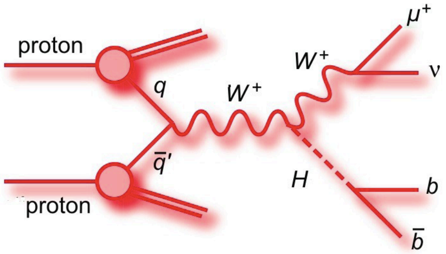


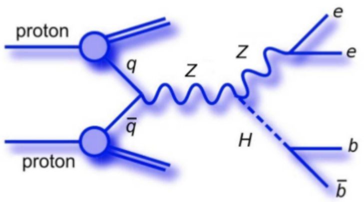
- ttH production



VH(bb) searches: 3 channels







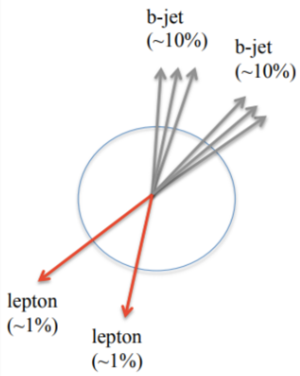
- 0-lepton:
  - $E_T^{miss} > 150$ GeV
- 1-lepton:
  - e/μ, p_T>25 GeV
  - Tight isolation
  - Missing E_T >30 GeV (e chn)
  - $p_T^V > 150$ GeV
- 2-leptons:
  - Isolated ee, μμ
  - p_T^1>25 GeV, p_T^2>7 GeV
  - $p_T^V > 75$ GeV
  - m_{ll} compatible with m_Z

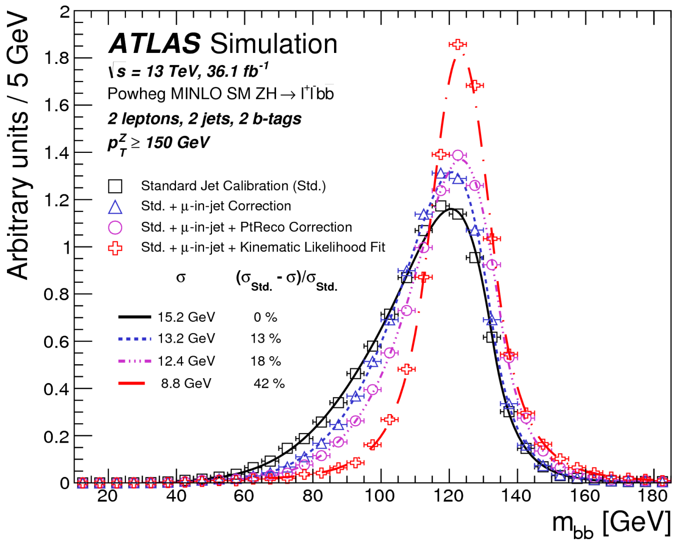
Plus:

- Two jets
  - anti-kT with R=0.4
  - P_T^{j1}>45 GeV
  - p_T^{j2}>20 GeV
- B-tagging
  - Eff: 70%, light jet mistag rate: 0.3%,
  - charm mistag rate: 8%
- Analysis categories:
  - 2/3 jets (0/1lepton)
  - 2/≥3jets (2lept.)
  - p_T^V bins
    - 75-150, > 150 GeV (2lepton)
    - >150 GeV (0/1lepton)

Invariant mass resolution

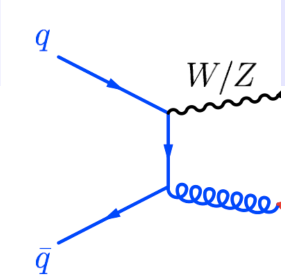
- Mass resolution improvements
  - b-jets need dedicated calibration
  - Add muons in the vicinity (semi-lep. decays)
  - Simple average jet pT correction. Accounts for neutrinos, and interplay of resolution and pT spectrum effects.
- Improvement ~ 18%
- Kinematic fit for leptons:
  - Profit from the good lepton resolution
  - Constraint jet kinematics
  - Improvement ~40%

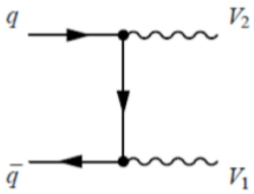


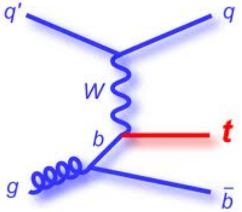


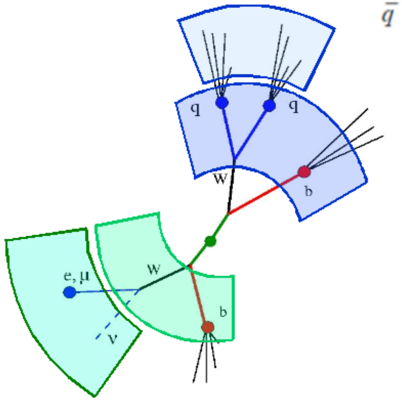
Main backgrounds

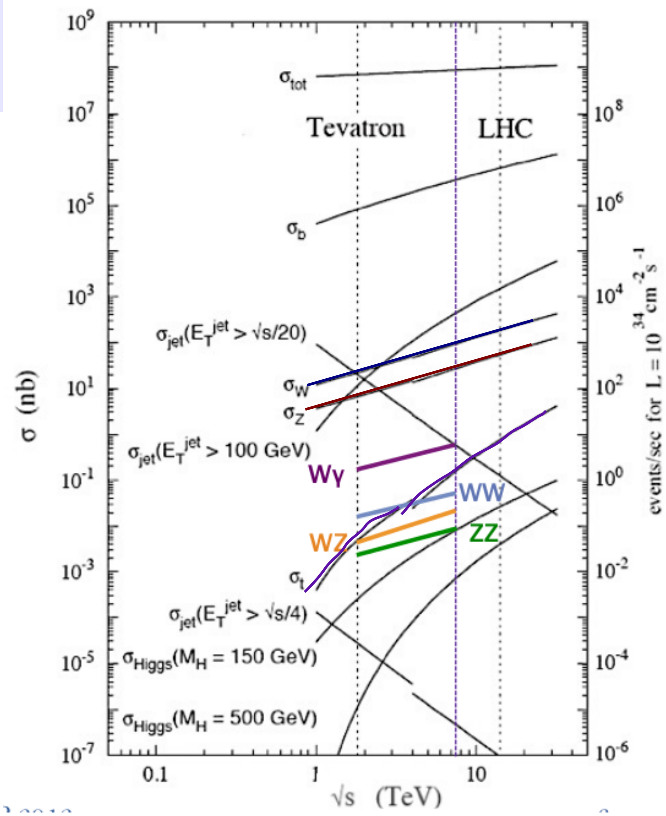
- W+jets, Z+jets production
- Di-boson production
  - WW, WZ, ZZ
- Top production:
  - t-tbar
  - Single top











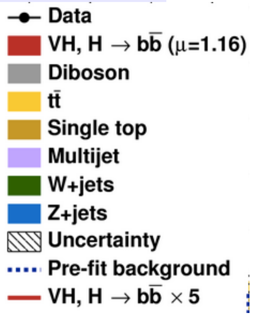
VH(bb) Main backgrounds

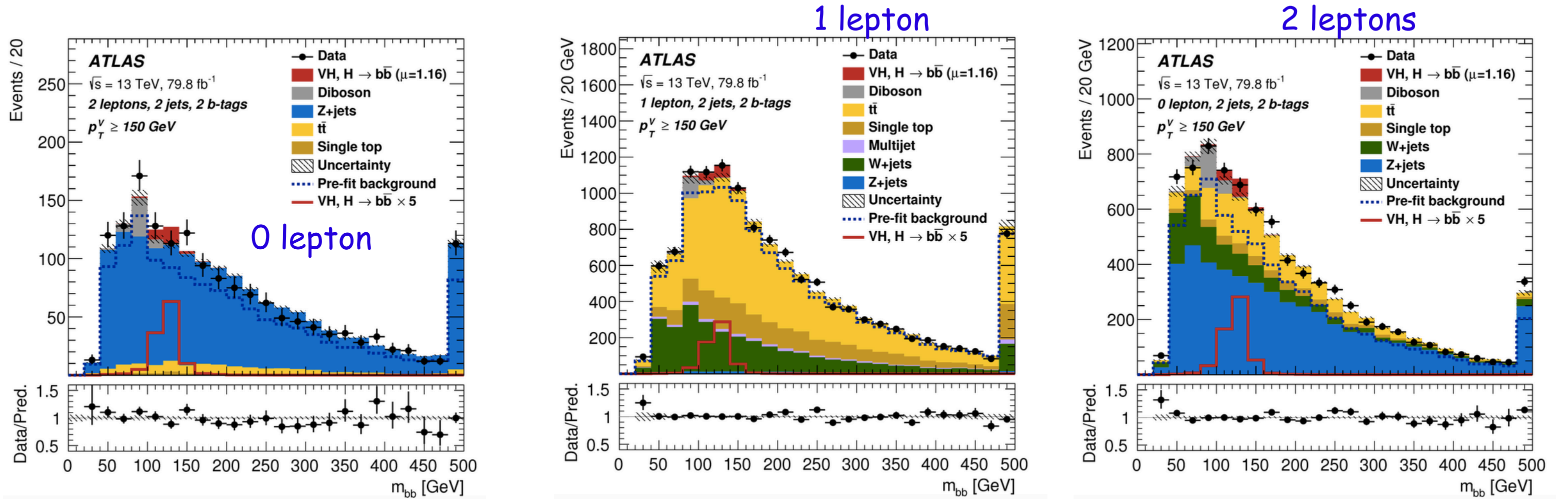
➢ Dominant backgrounds dependent on channel

Z+bjets dominates in 0, 2 lepton channels

Top quark and W+jets in 1 lepton channel

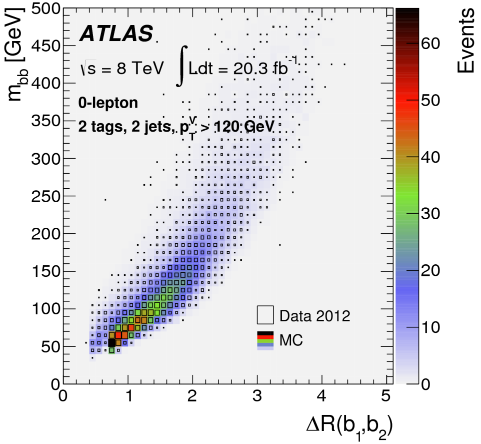
Multi-jet important in 1 lepton channel





Multi-variate analysis

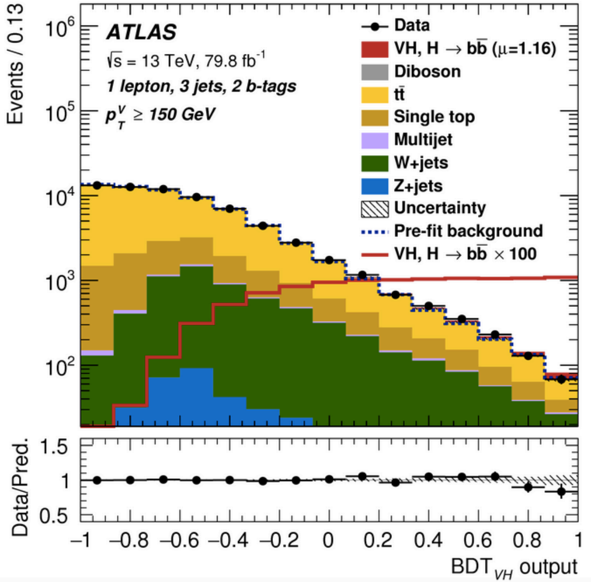
- Boosted decision tree (BDT)
  - Combine many different variables
  - Trained in 8 categories:
    - 3 lepton, 2/3 jets, low/high p_T^V bin (2 lepton channel)
- Most discrimination from m_{bb} and $\Delta R(b_1,b_2)$
  - New in run 2: m_{Top}, $|\Delta Y(V,H)|$
  - → +7% in sensitivity



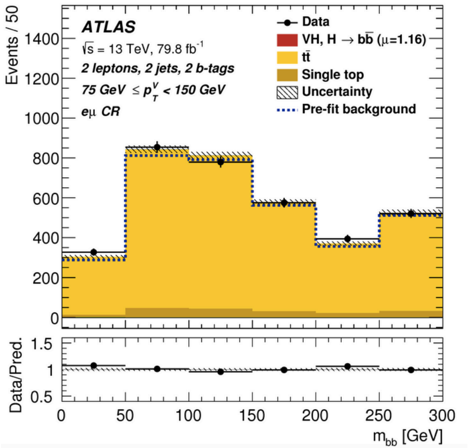
Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	×	×
E_T^{miss}	×	×	
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(\vec{b_1},\vec{b_2})$	×	×	×
$\lvert\Delta\eta(\vec{b_1},\vec{b_2})\rvert$	×		
$\Delta\phi(\vec{V},\vec{bb})$	×	×	×
$\lvert\Delta\eta(\vec{V},\vec{bb})\rvert$			×
m_{eff}	×		
$\min[\Delta\phi(\vec{\ell},\vec{b})]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
$E_T^{miss}/\sqrt{S_T}$			×
m_{top}		×	
$\lvert\Delta Y(\vec{V},\vec{bb})\rvert$		×	
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

VH(bb) Combined fit

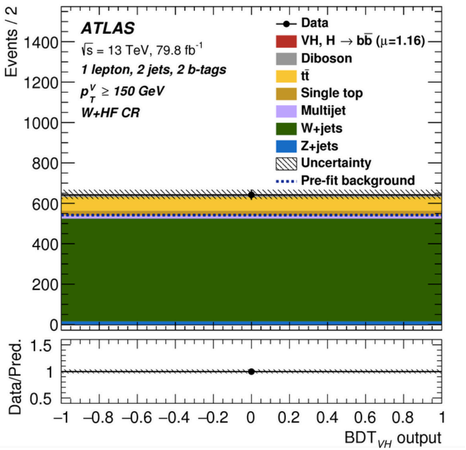
- Signal strength from profiled likelihood fit
  - Take into account all event categories
- Use BDT discriminant as input
- Control regions to constrain the backgrounds



eμ control region



W+HF control region



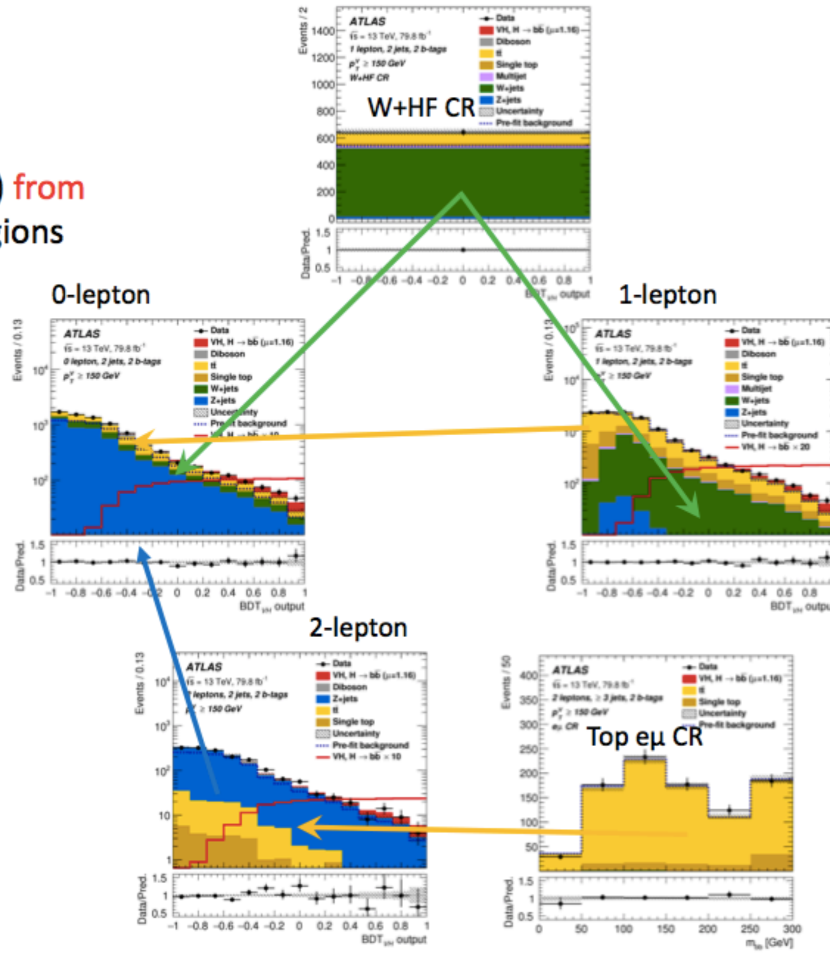
Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.98 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	1.06 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	0.95 ± 0.06
$W+$HF 2-jet	1.19 ± 0.12
$W+$HF 3-jet	1.05 ± 0.12
$Z+$HF 2-jet	1.37 ± 0.11
$Z+$HF 3-jet	1.09 ± 0.09

Background modelling

- Use state-of-the-art MC generators (except MJ which is modelled in 1-lepton using a data-driven method)
- Constrain (shape and normalization) from data by using high purity control regions
- Main background normalizations floating in the fit

Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.98 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	1.06 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	0.95 ± 0.06
$W+$HF 2-jet	1.19 ± 0.12
$W+$HF 3-jet	1.05 ± 0.12
$Z+$HF 2-jet	1.37 ± 0.11
$Z+$HF 3-jet	1.09 ± 0.09

- Parametrize extrapolation uncertainties across regions as uncertainties on ratios of yields
- Shape uncertainties on BDTs



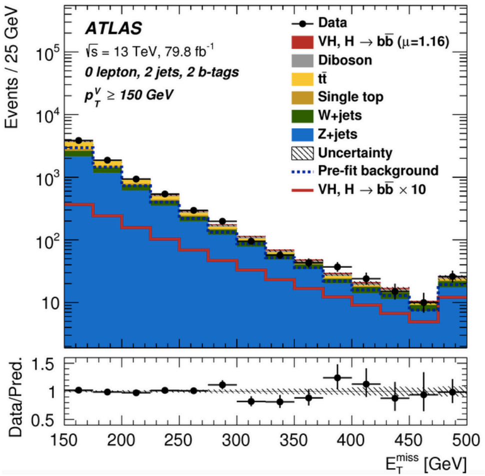
Slide from Y. Ma (LAL)

Post-fit distributions

➢ Control regions are used to constrain the backgrounds

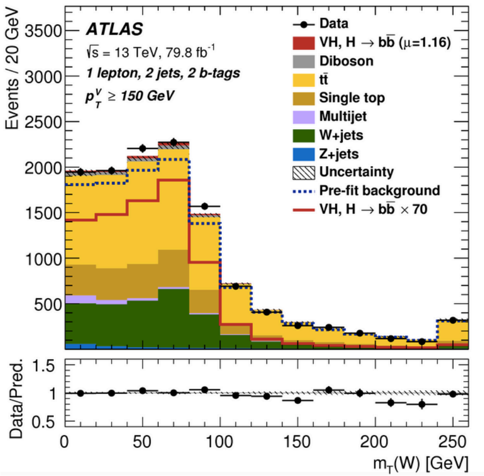
E_T^{miss}

0 lep, 2jets, 2btags



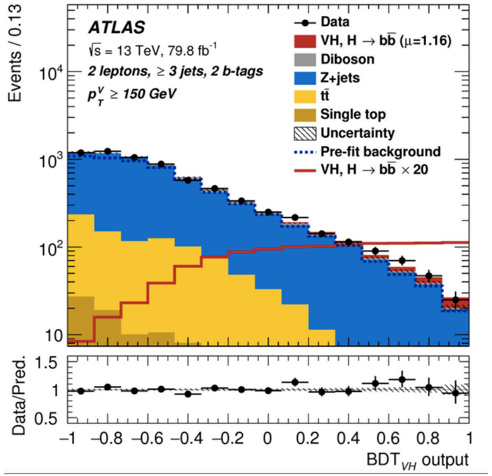
W transverse mass

1 lep., 3jets, 2 btags



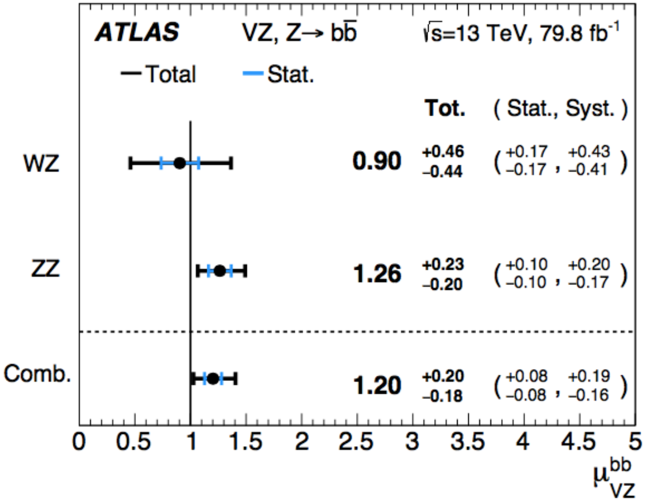
2 leptons, 2 tags, 2 jets

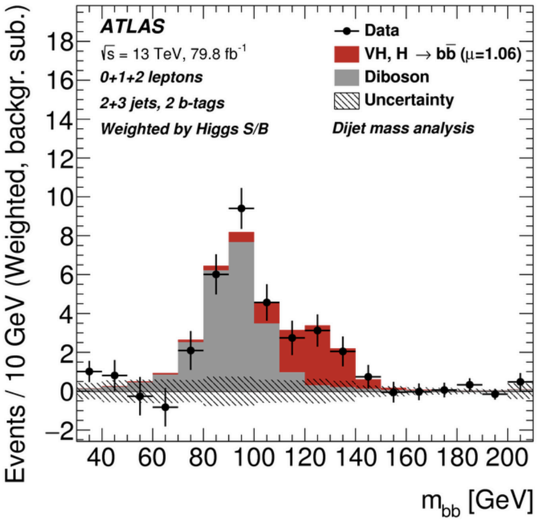
BDT discriminant



Diboson VZ (Z→bb) "search"

- Search for the known signal Z→bb (diboson search)
  - Test the fit and the all the analysis procedures





Systematic uncertainties

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-flavour 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
Multi-jet		0.005
MC statistical		0.070

Analysis dominated by systematic uncertainties

Measured by impact on signal strength (μ)

Many important sources !

b-tagging both b and c jet tagging calibration

- Resp. ∼3% and ∼10% per jet

Background modelling Z+hf, W+hf, $t\bar{t}$

- Mainly shape and extrapolation uncertainties

Signal modelling little impact on significance

- Dominated by systematic uncertainties on the acceptance

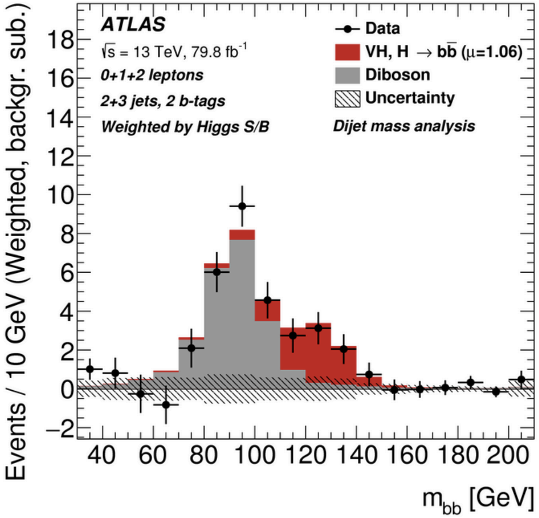
MC stats never-ending race between data stat and MC stat

- Use of dedicated MC filters
- Not easy in all cases, e.g $t\bar{t}$ phase space in 0/1-lepton

Slide from N. Morange

Di-jet mass analysis

- 3.6σ observed
- 3.5σ expected



$$\mu_{VH}^{bb} = 1.06^{+0.36}_{-0.33} = 1.06 \pm 0.20(\text{stat.})^{+0.30}_{-0.26}(\text{syst.})$$

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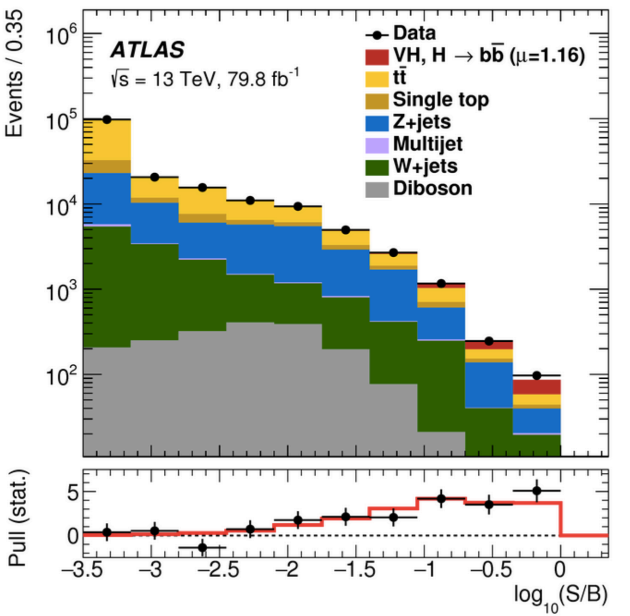
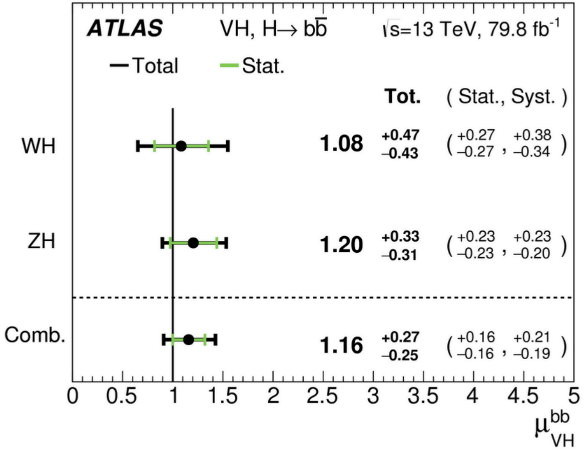
WH and ZH with H→bb results

- 79 fb^{-1} of pp collisions at $\sqrt{s}$= 13 TeV
  - 4.9σ evidence observed (4.3σ expected)
  - systematic uncertainties start to dominate!!

$$\mu^{bb}_{VH} = 1.16^{+0.27}_{-0.25} = 1.16 \pm 0.16(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$$





Dominant systematics from b-tagging, background normalisation & modelling (W+jets, Z+jets, top)

$H \to bb$ Run 1 + Run 2 combination

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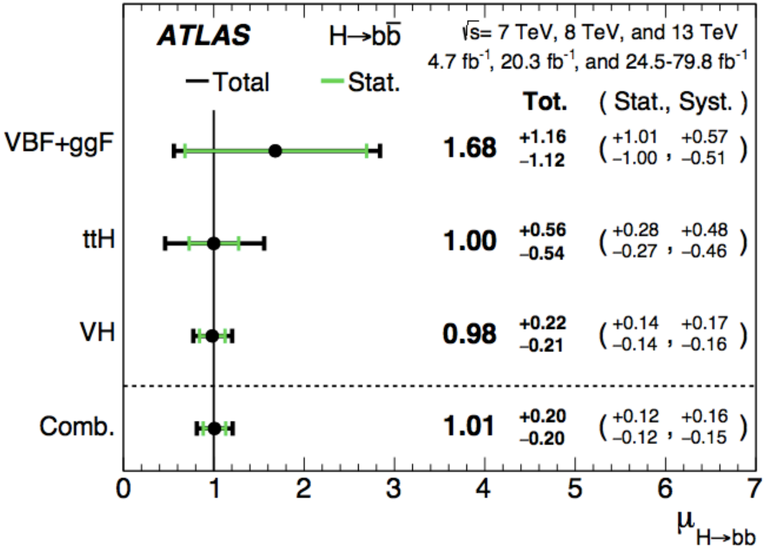
- Includes ttH and vector boson fusion (with H->bb) channels
- 5.4σ observation!! (5.5σ expected)



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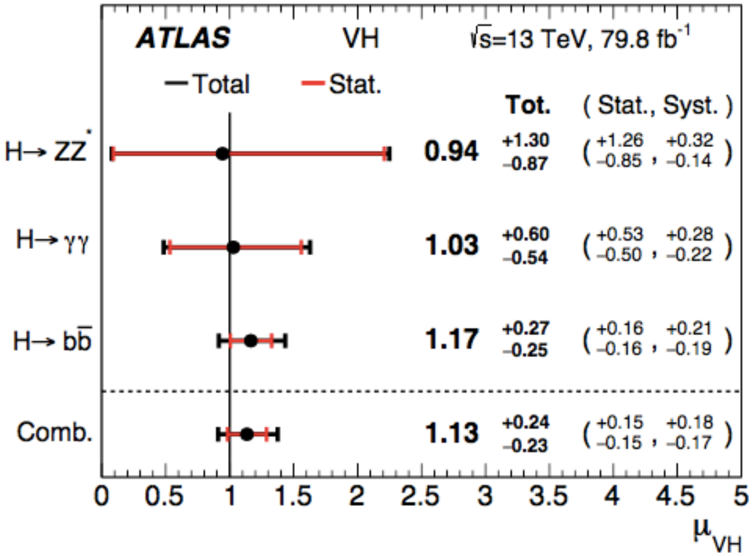
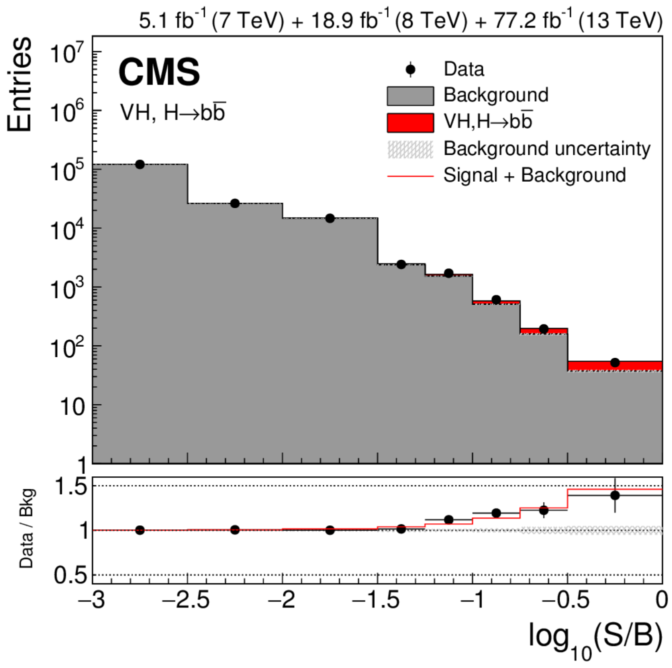
Observation of VH production

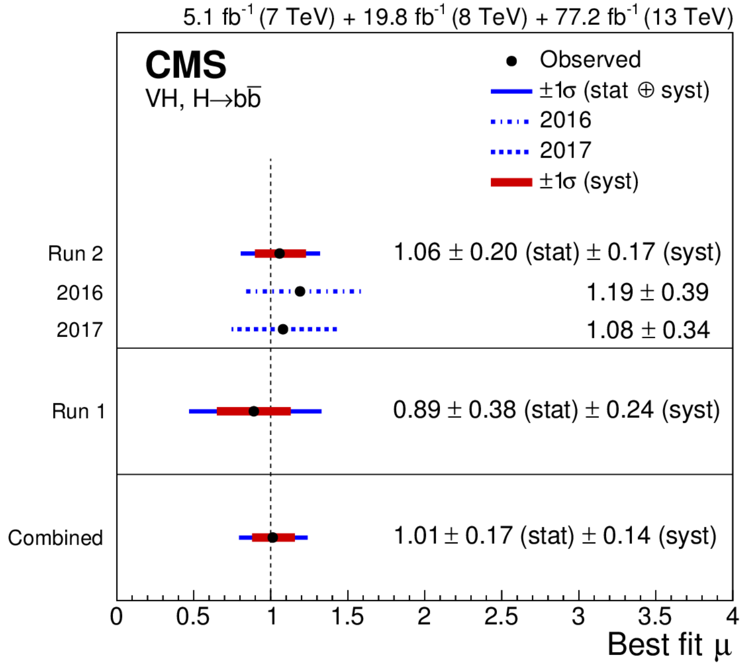
- Combination of H→bb with two more channels
  - Four leptons (ZZ*)
  - γγ
- Direct observation of the Higgs produced in association with vector bosons!



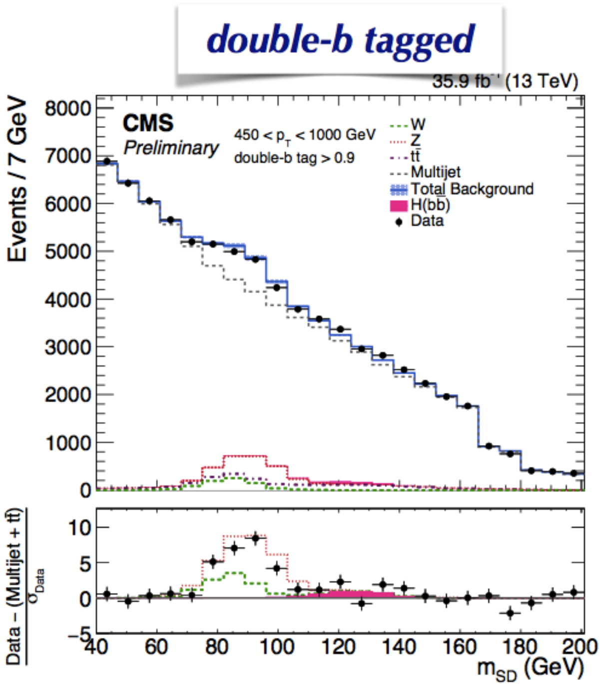
Channel	Significance	
	Exp.	Obs.
$H \to ZZ^* \to 4\ell$	1.1	1.1
$H \to \gamma\gamma$	1.9	1.9
$H \to b\bar{b}$	4.3	4.9
VH combined	4.8	5.3

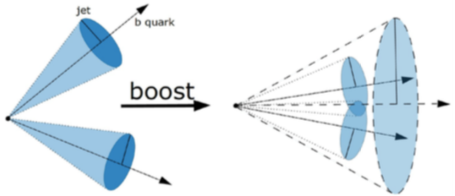
CMS VH with H→bb observation



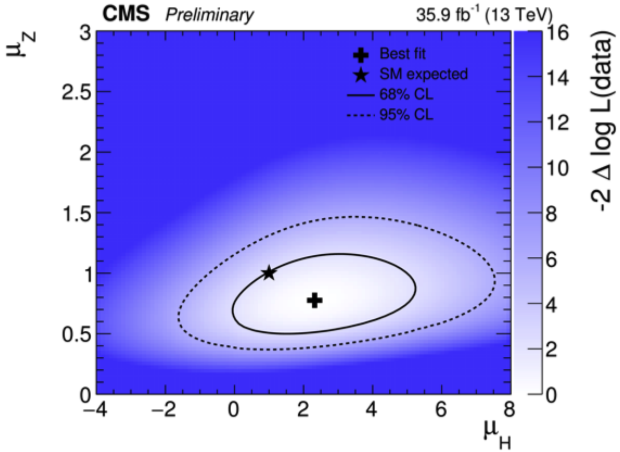


CMS inclusive H → bb search





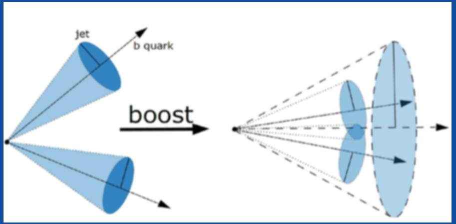
- ➢ Simultaneous fit to search for Z → bb and H → bb signals

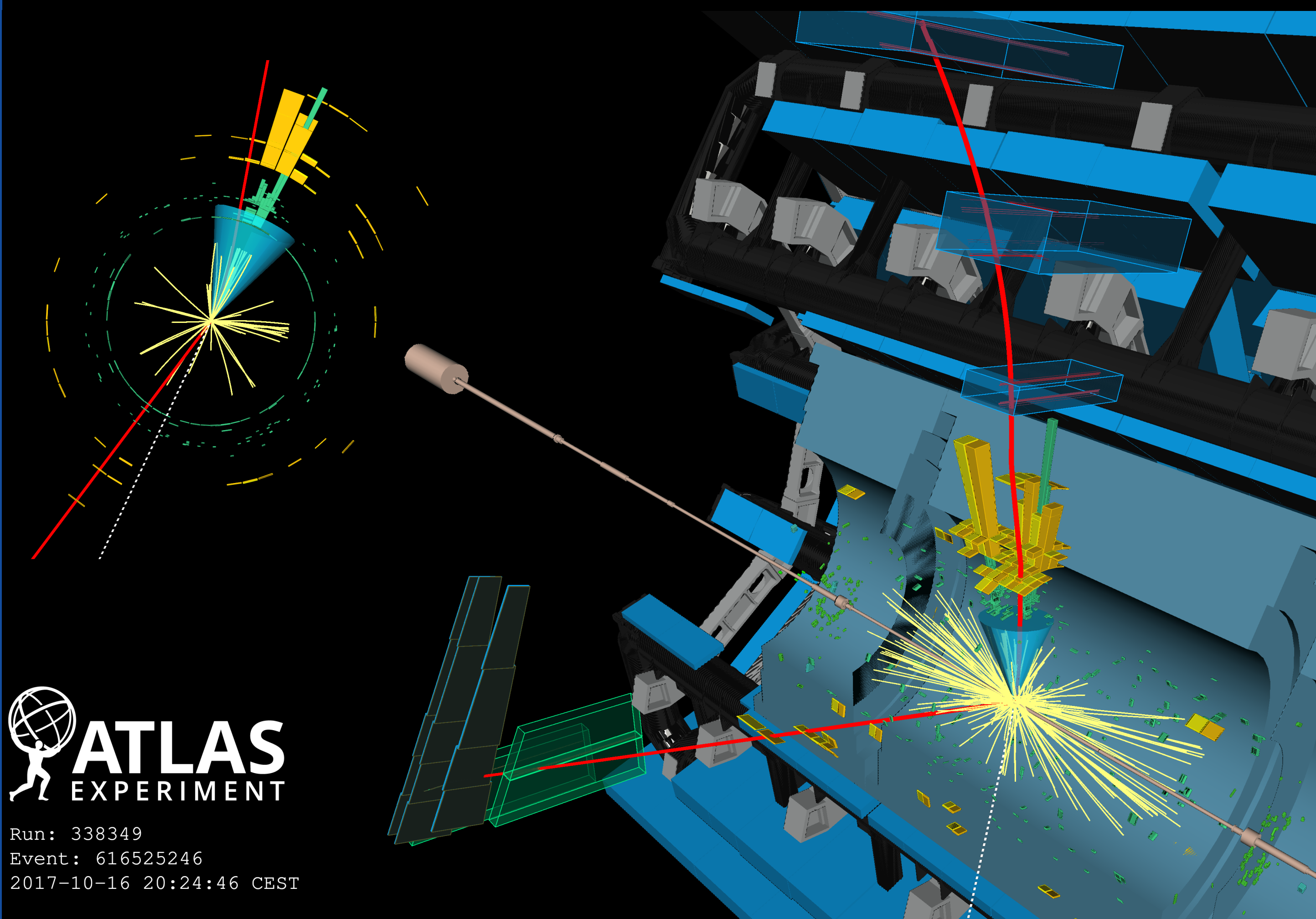


	H	Z
Observed best fit	$\mu_H = 2.3^{+1.8}_{-1.6}$	$\mu_Z = 0.78^{+0.23}_{-0.19}$
Expected significance	0.7σ ($\mu_H = 1$)	5.8σ ($\mu_Z = 1$)
Observed significance	1.5σ	5.1σ

Boosted H→bb Decay (VH production)

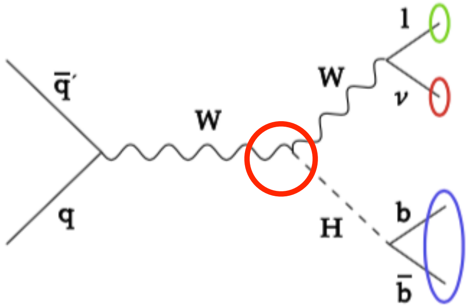
More sensitive to new physics effects!





New physics in the hWW vertex?

- New physics can modify the hWW vertex structure
  - Will affect cross sections
    - Particularly at high p_T!!
  - CP-even and CP-odd operators
    - CP odd operators can introduce CP violation
    - Angular observables to disentangle these contributions in future!



$$i\Gamma^{\mu\nu}_{HWW}(k_1, k_2) = i(g_2 m_W)\left[g^{\mu\nu}\left(1 + a_W - \frac{b_{W1}}{m_W^2}(k_1 \cdot k_2)\right) + \frac{b_{W1}}{m_W^2}\, k_1^\nu k_2^\mu + \frac{c_W}{m_W^2}\epsilon^{\mu\nu\rho\sigma} k_{1_\rho} k_{2_\sigma}\right]$$

ATLAS VH boosted studies

Binned profile likelihood fit in m_J in **14 regions**

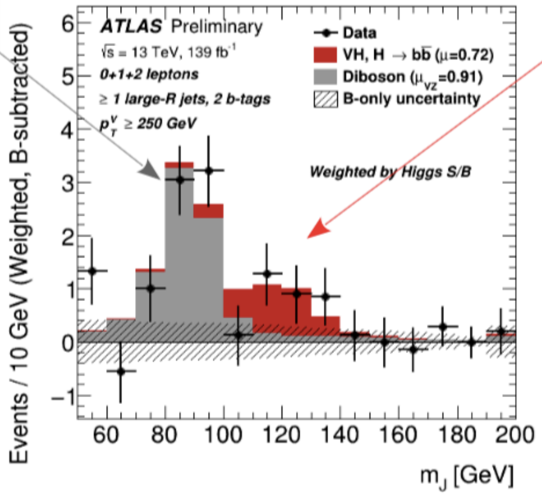
→ *simultaneously* extracting **VH(→bb)** and VZ(→bb) signal strengths

H.Arnold, Seminar @ CERN

Yesterday!

$\mu_{VZ}^{bb} = 0.91^{+0.29}_{-0.23} = 0.91 \pm 0.15(\text{stat.})^{+0.25}_{-0.17}(\text{syst.})$

Obs. (exp.) significance: 5.2 (5.7) σ



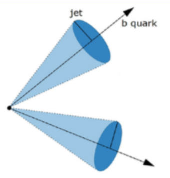
$\mu_{VH}^{bb} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})$

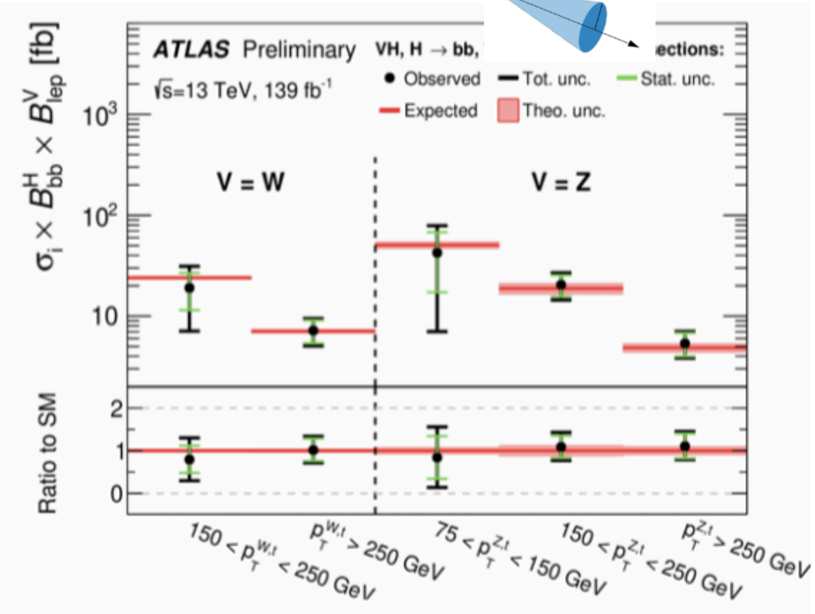
Obs. (exp.) significance: 2.1 (2.7) σ

- **Good compatibility**
  - between signal strengths in different channels / regions
  - With the SM prediction
- Analysis *statistically* limited
- Leading systematic uncertainties: m_J resolution, background modelling and MC stat. unc.

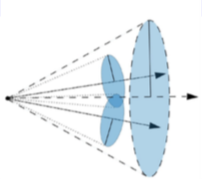
Cross section as a function of $p_T(V)$

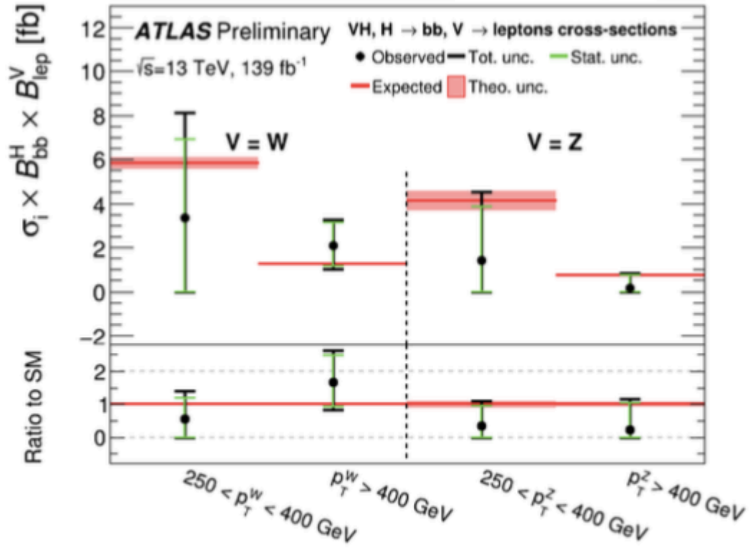
- Resolved analysis





- Boosted analysis



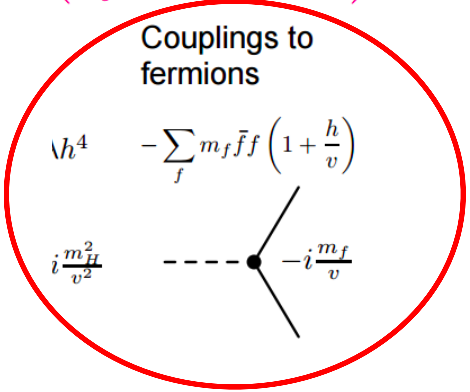


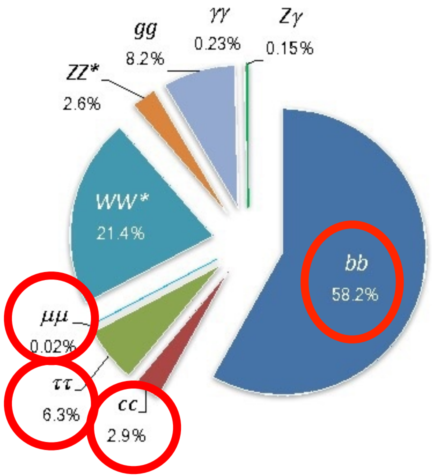
Higgs couplings to fermions

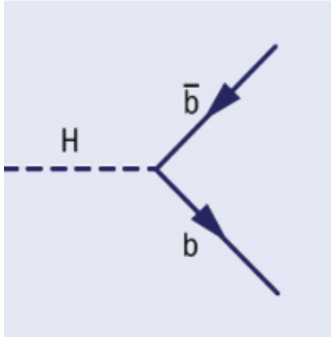
$(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.})$

- Couplings to fermions
- Experimental measurements:

  Decay rates to quarks & leptons







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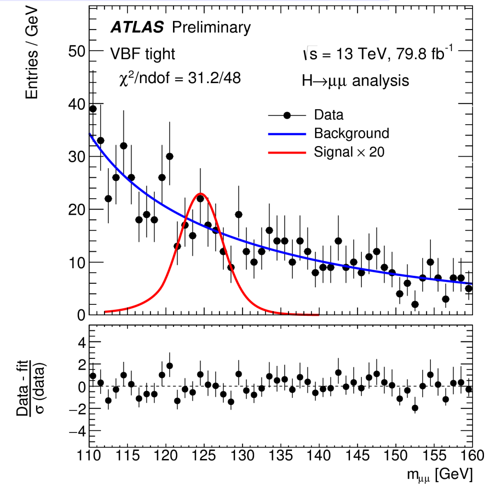
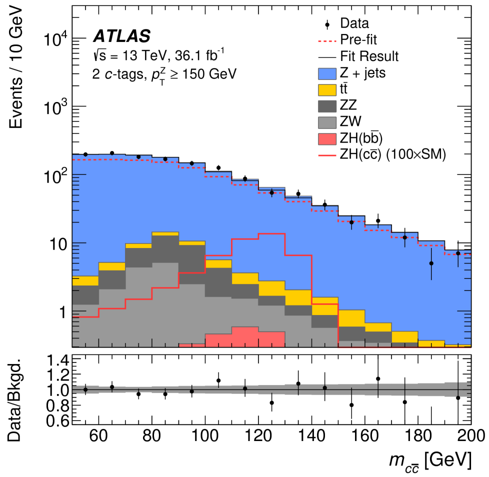
Second generation: H→$\mu\mu$ and H→cc

- H→$\mu\mu$
  - Very low branching fraction but sensitivity reaching close to SM
- H→cc:
  - Extremely challenging: huge backgrounds
  - Similar strategy as VH with H→bb
  - Expected sensitivity ~150×SM

	$\int \mathscr{L} dt$	95% CL upper limit	
		Expected	Observed
H→$\mu\mu$	78.9 fb^{-1}	2×SM	1.5×SM
H→cc	36.1 fb^{-1}	150^{+80}_{-40}	110×SM





Higgs couplings to fermions

$$(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.})$$

- Couplings to fermions
- Experimental measurements:

  Decay rates to quarks & leptons

  Top quark coupling:

    Indirect: gg fusion production mode

      But model dependent —> need direct probes!

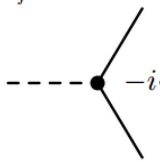
    ttH associated production

  Rare decays

Couplings to fermions

λh^4 $\quad -\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$

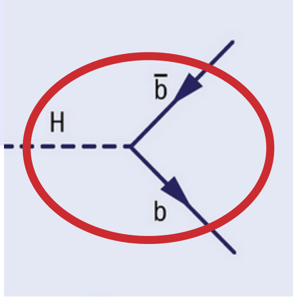
$i\frac{m_H^2}{v^2}$



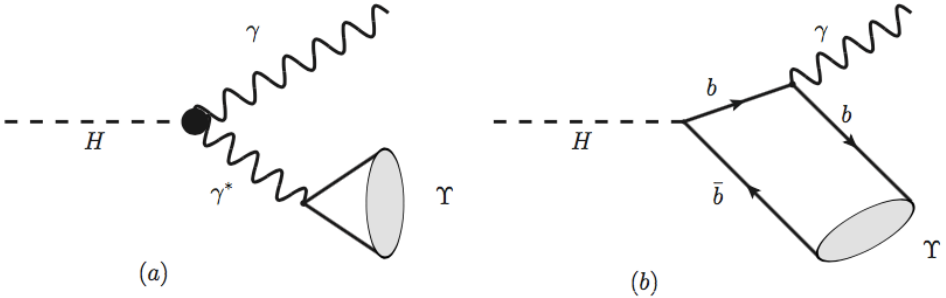
$-i\frac{m_f}{v}$

t,b, …

Probing the Hbb coupling



- Questions
  - Is it really as the SM predicts?
  - What is the sign of the coupling?
  - Are there anomalous components?
- Probing the sign of the Hbb coupling:
  - Decay H→$\Upsilon\gamma$
    - Interference between two difference diagrams results in very low BR
    - Can be enhanced if the sign of the coupling is the opposite!
    - Very difficult channel —> will need HL-LHC



T. Modak et al.
Phys.Rev. D94 (2016) no.7, 075017

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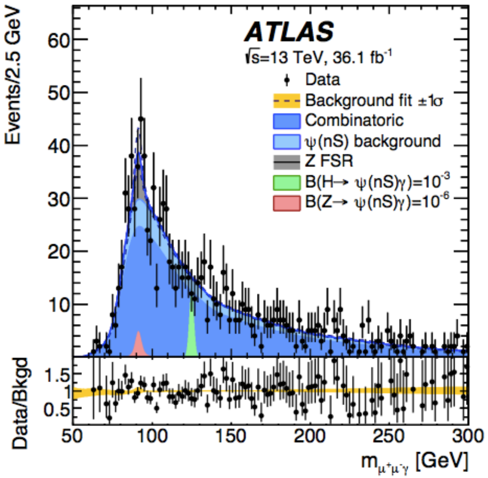
Hcc and Hbb vertices

- Rare decays sensitive to Hcc or Hbb vertex
  - Direct and indirect contributions
- Could be enhanced due to BSM physics
- No signal observed →imposed limits on BR



- ATLAS

BR ($H \to J/\Psi\gamma$) ~3×10^{-6} BR ($H \to \Upsilon\gamma$) ~9×10^{-8}

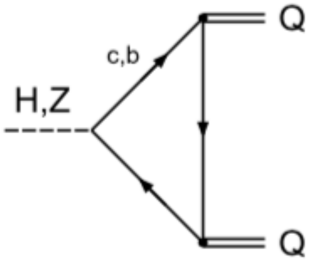
Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to J/\psi\,\gamma)\,[\,10^{-4}\,]$	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H \to \psi\,(2S)\,\gamma)\,[\,10^{-4}\,]$	$15.6^{+7.7}_{-4.4}$	19.8
$\mathcal{B}(Z \to J/\psi\,\gamma)\,[\,10^{-6}\,]$	$1.1^{+0.5}_{-0.3}$	2.3
$\mathcal{B}(Z \to \psi\,(2S)\,\gamma)\,[\,10^{-6}\,]$	$6.0^{+2.7}_{-1.7}$	4.5
$\mathcal{B}(H \to \Upsilon(1S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.4}_{-1.4}$	4.9
$\mathcal{B}(H \to \Upsilon(2S)\,\gamma)\,[\,10^{-4}\,]$	$6.2^{+3.0}_{-1.7}$	5.9
$\mathcal{B}(H \to \Upsilon(3S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.5}_{-1.4}$	5.7

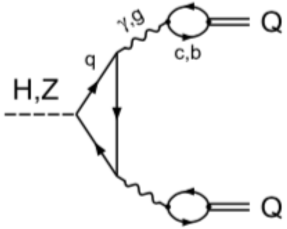
- CMS

Channel	Polarization	$\mathcal{B}$(Z (H) → J/ψγ) at 95% CL
$Z \to J/\psi\,\gamma$	Unpolarized	$1.4\ (1.6^{+0.7}_{-0.5}) \times 10^{-6}$
	Transverse	$1.5\ (1.7^{+0.7}_{-0.5}) \times 10^{-6}$
$H \to J/\psi\,\gamma$	Longitudinal	$1.2\ (1.4^{+0.6}_{-0.4}) \times 10^{-6}$
	Transverse	$7.6\ (5.2^{+2.4}_{-1.6}) \times 10^{-4}$

CMS search for H→J/ψ J/ψ, H→ΥΥ

- Expected BR~10^{-9}, 10^{-8}
- Search performed by CMS recently
  - Z channel used as reference
    - Important also to understand theoretical calculations/uncertainties



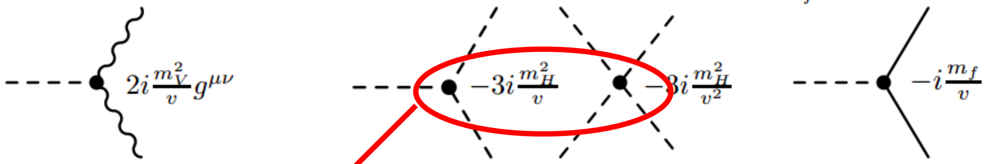


Process	Observed	Expected
$\mathcal{B}(H \to J/\psi J/\psi)$	1.8×10^{-3}	$(1.8^{+0.2}_{-0.1}) \times 10^{-3}$
$\mathcal{B}(H \to \Upsilon\Upsilon)$	1.4×10^{-3}	$(1.4 \pm 0.1) \times 10^{-3}$
$\mathcal{B}(Z \to J/\psi J/\psi)$	2.2×10^{-6}	$(2.8^{+1.2}_{-0.7}) \times 10^{-6}$
$\mathcal{B}(Z \to \Upsilon\Upsilon)$	1.5×10^{-6}	$(1.5 \pm 0.1) \times 10^{-6}$

Higgs self interactions

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

Couplings to EW gauge bosons	Higgs self-couplings	Couplings to fermions
$[m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0] \cdot \left(1+\frac{h}{v}\right)^2$	$-\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4$	$-\sum_f m_f \bar{f} f \left(1+\frac{h}{v}\right)$



$m_H = \sqrt{2}\mu = \sqrt{\lambda}v$ (v = vacuum expectation value)

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- ✴ Higgs potential
- ✴ Experimental measurements:
  - Higgs mass
  - HH production

Phys. Rev. Lett. 121 (2018) 191801

Eur. Phys. J. C 78 (2018) 1007

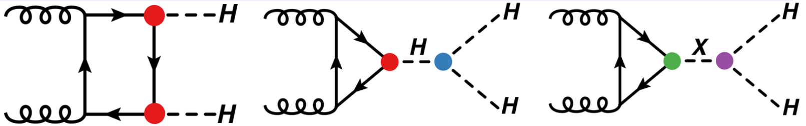
arXiv:1811.11028 JHEP 11 (2018) 040

arXiv:1811.04671 arXiv:1804.06174

ATLAS-CONF-2018-043

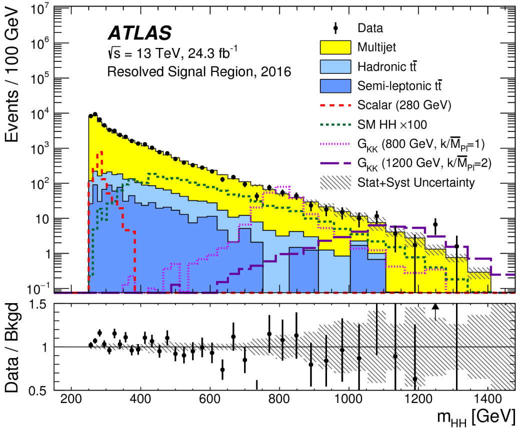
Phys. Rev. Lett. 121 (2018) 191801
arXiv:1804.06174
JHEP 11 (2018) 040

Search for di-Higgs production

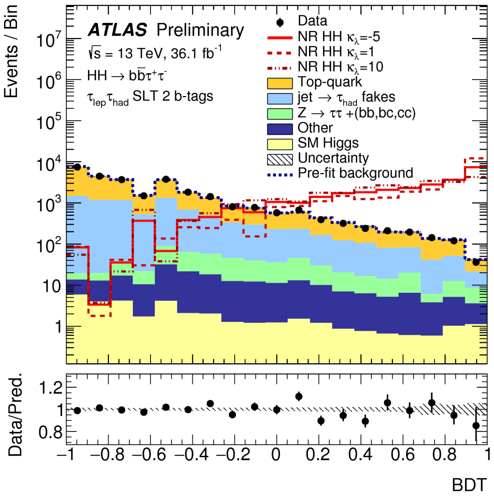


- Sensitive to Higgs self coupling and new physics
- Many different final states studied
  - WW*WW*, bbbb, $bb\tau\tau$, $bb\gamma\gamma$, bbWW*
- No signal observed yet

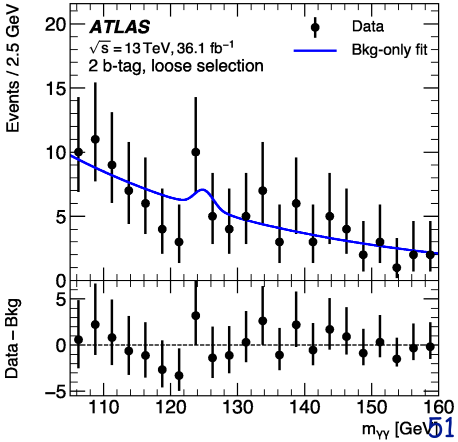
HH→bbbb



HH→bbττ



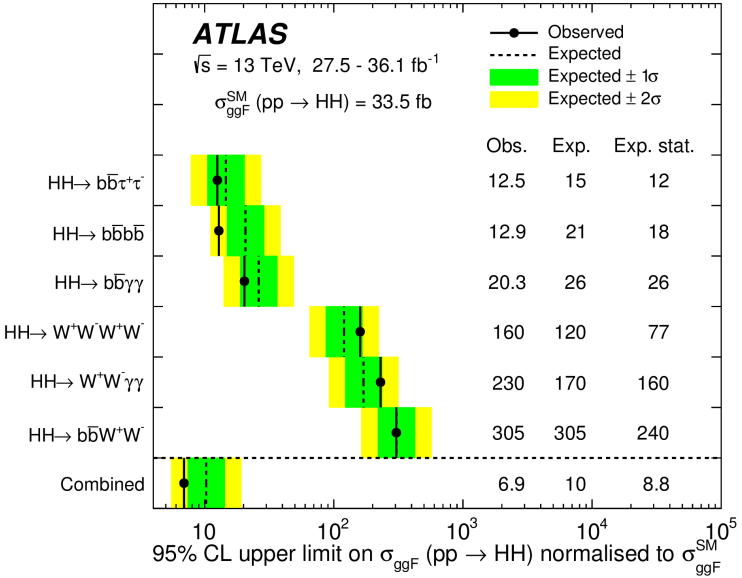
HH→bbγγ

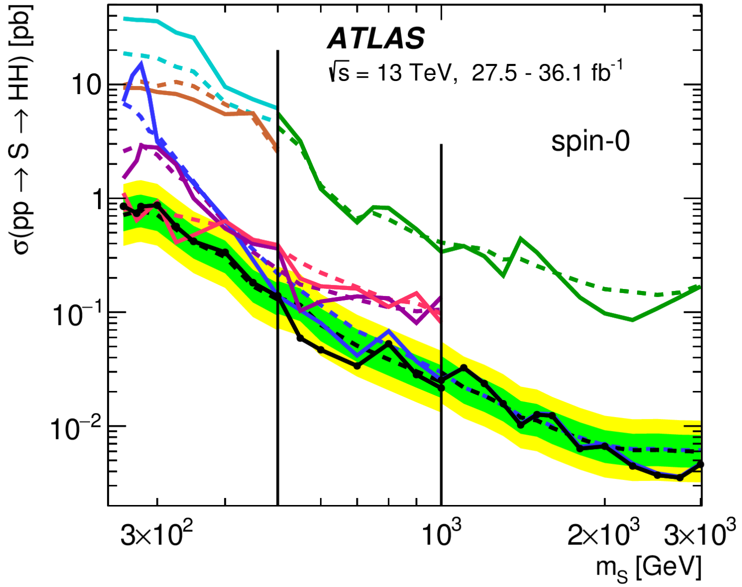


Combination of di-Higgs searches

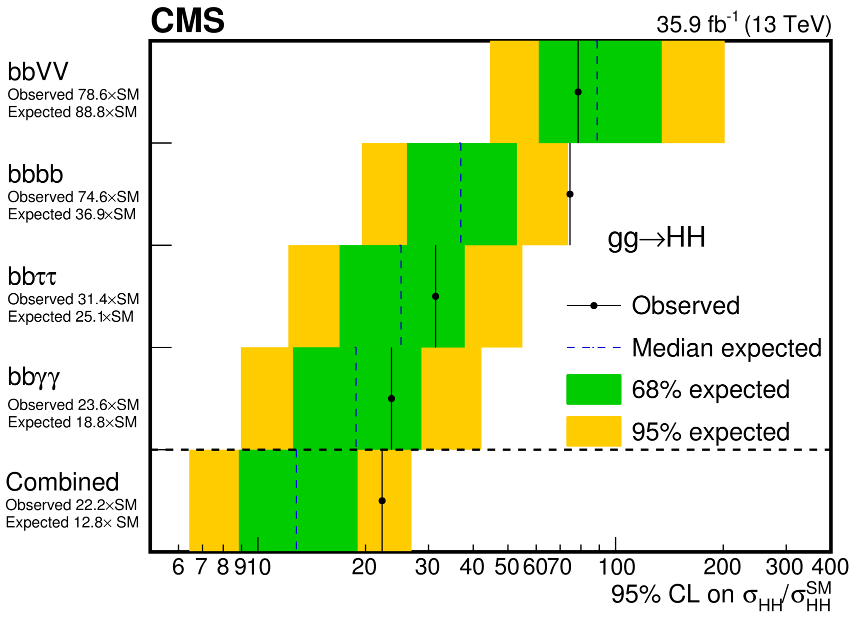
ATLAS-CONF-2018-043

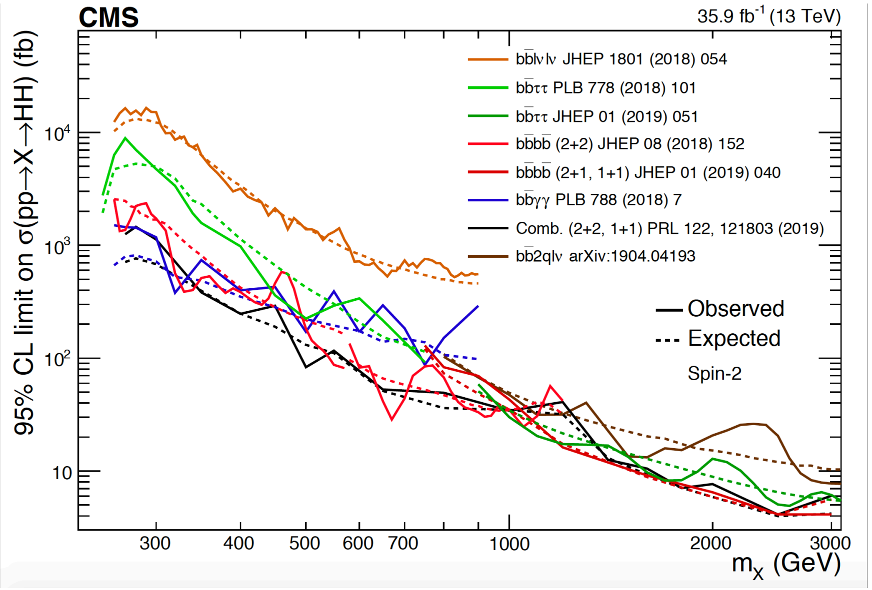
- Channels included: bbbb, $bb\tau\tau$, $bb\gamma\gamma$
- Integrated luminosity: 36 fb-1





CMS combination



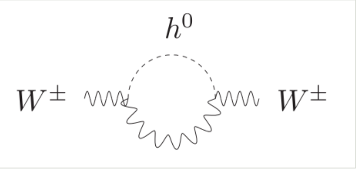


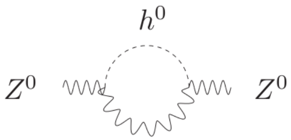
Electroweak fits

- But… are all the pieces of the SM fitting correctly???

Corrections to Electroweak observables

- Electroweak observables are sensitive to masses of top quark and Higgs through radiative corrections





$$M_W^2 = \rho\, M_Z^2 \cos^2\theta_W$$

$$(\rho-1) \sim M_{top}^2$$

$$(\rho-1) \sim \ln M_H$$

Sensitivity to Higgs mass is only logarithmic: Need ultra-precise measurements!

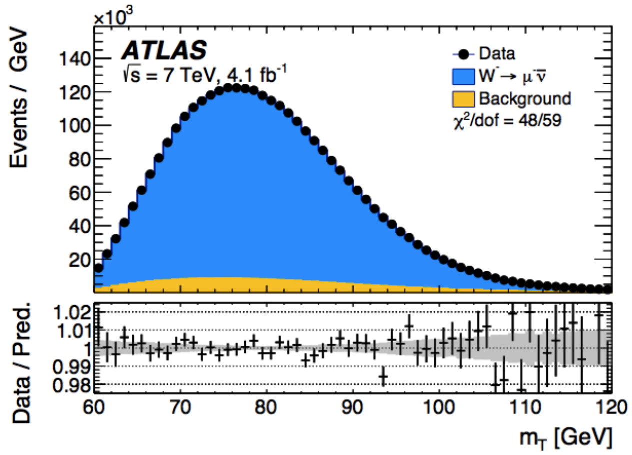
- Precise measurements of electroweak observables can be used to constraint the Higgs boson mass or test internal coherence of the model!!

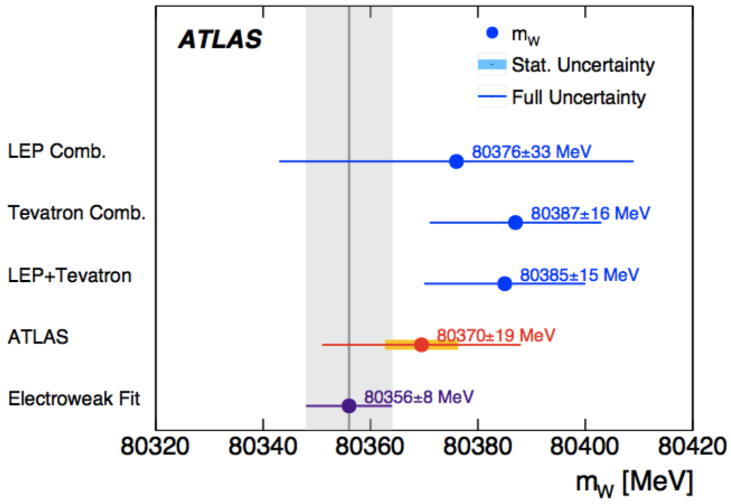
W boson mass measurement

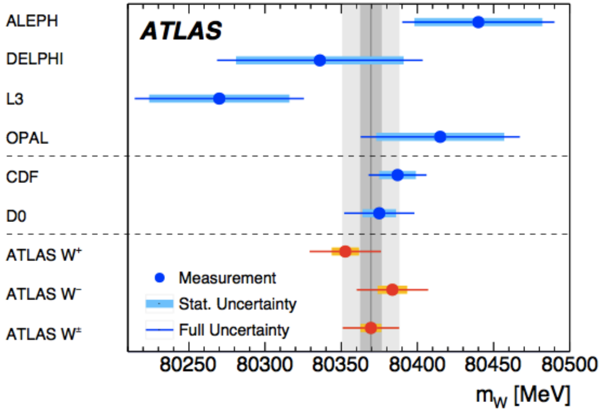
- High precision measurement

  Data from 2011 only!

- Consistency test of the SM

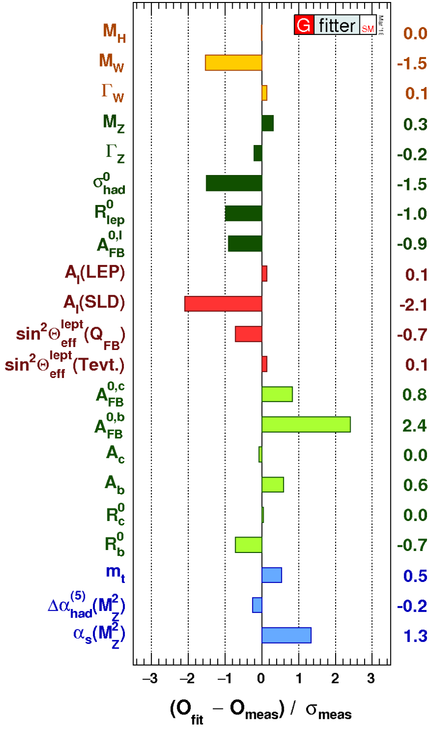


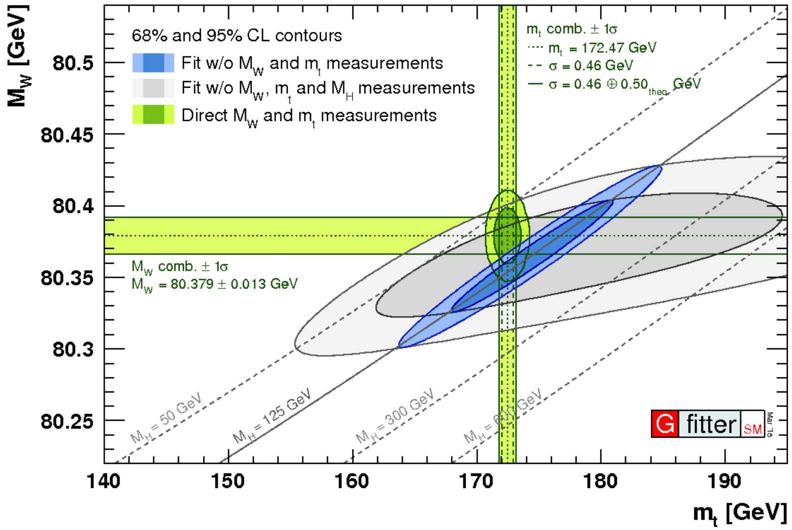




m_W, m_t, m_H

- Long list of parameters used



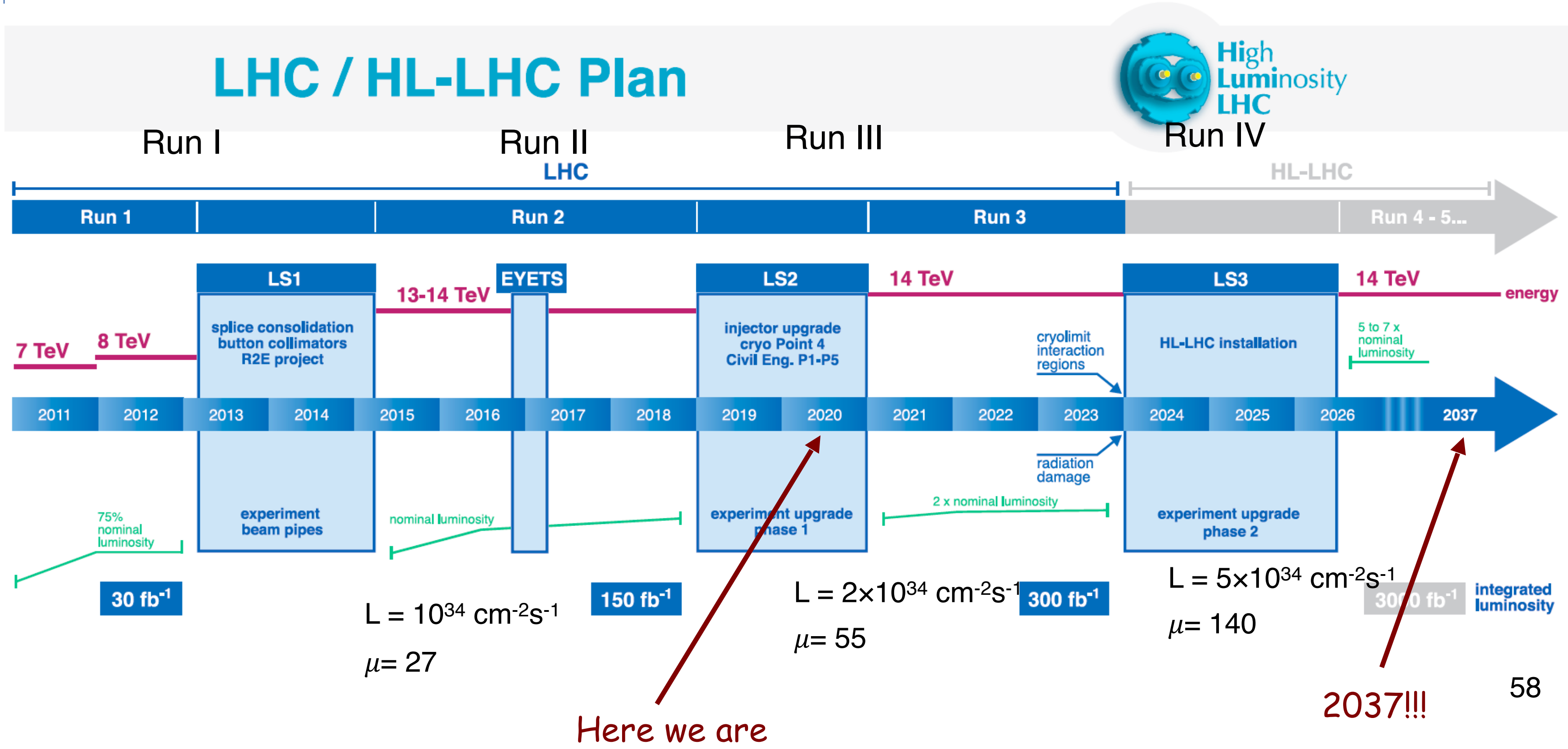


- Best fit mass for Higgs boson:

$$M_H = 90^{+21}_{-18}\ \text{GeV}$$

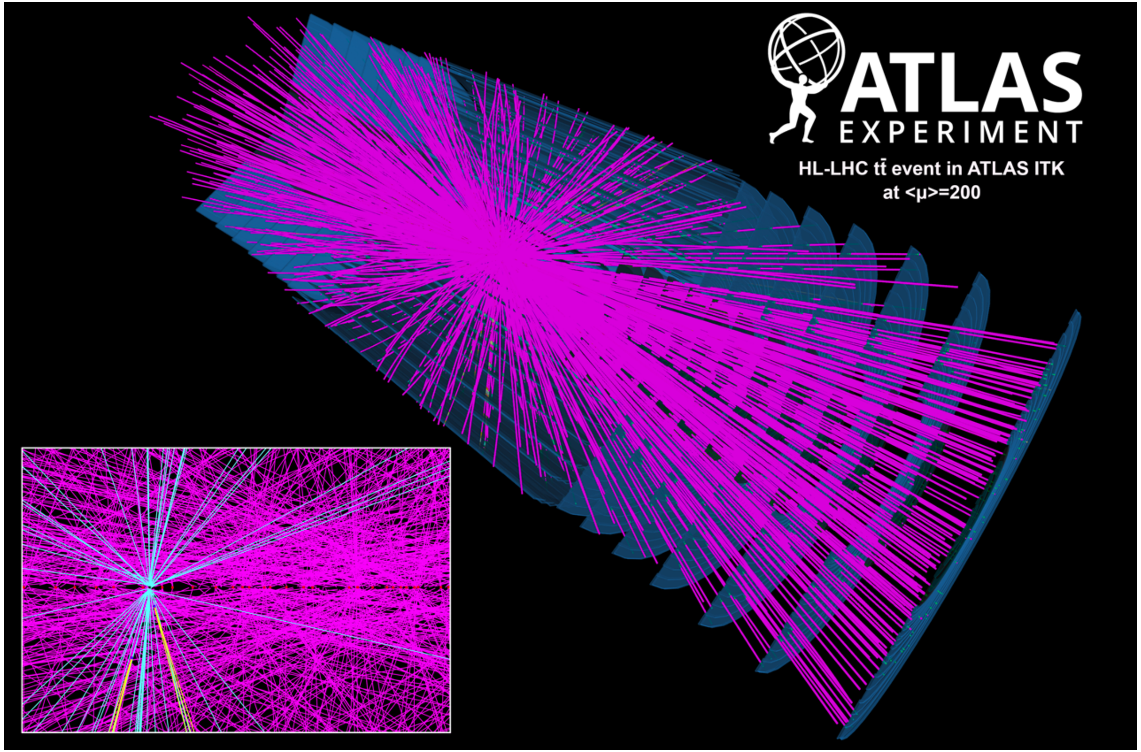
- Compatible with observation within 1.7σ

Future perspectives



Huge pile-up!!

- Will require upgraded detectors!!

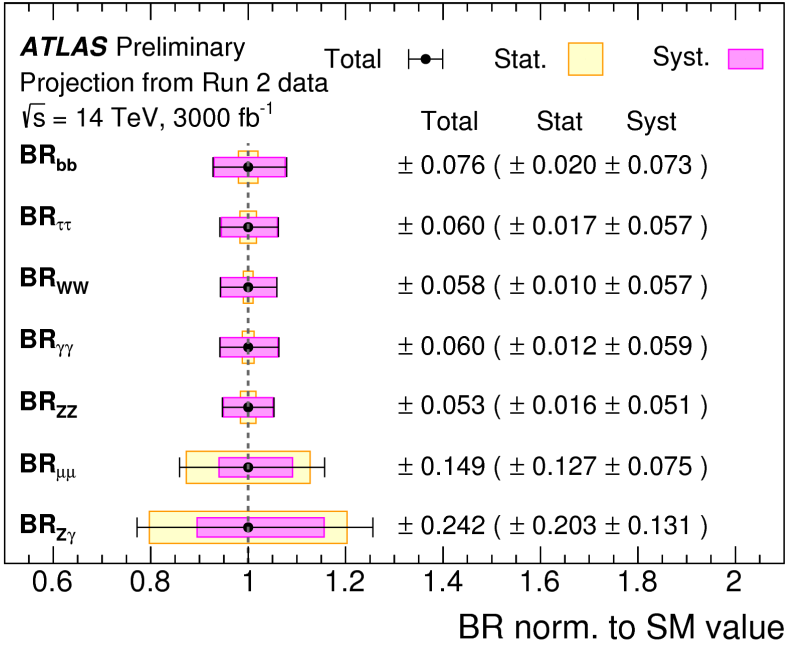


High-Lumi LHC perspectives

- Uncertainties below 10% for most channels
- Continue to probe

  SM predictions

  or… find new physics!!



Conclusions

- The Higgs boson provides an optimal ground to probe the SM predictions and search for new physics!
- Outstanding performance of the LHC and the CMS and ATLAS detectors
  - Large increase in the available pp collisions
- A wealth of new results on SM Higgs boson studies
  - Main decay and production modes now observed in each experiment!!
    - Direct observation of the Higgs coupling to top and bottom quarks
    - Observation of VH, VBF production
- All results are compatible with SM predictions
- Searches for new physics and additional Higgs bosons continue
  - Much more data to come!

Thanks!

Acknowledgments

REPÚBLICA PORTUGUESA

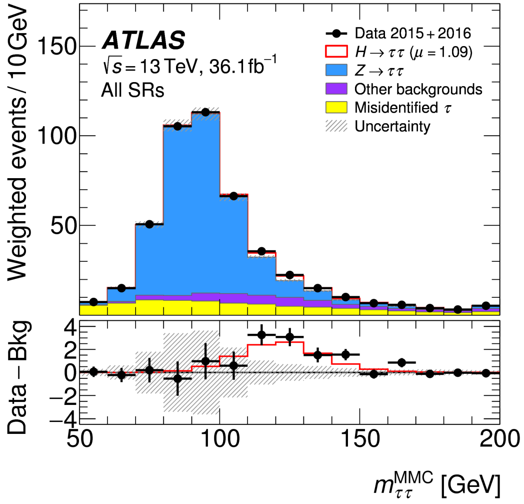
FCT Fundação para a Ciência e a Tecnologia

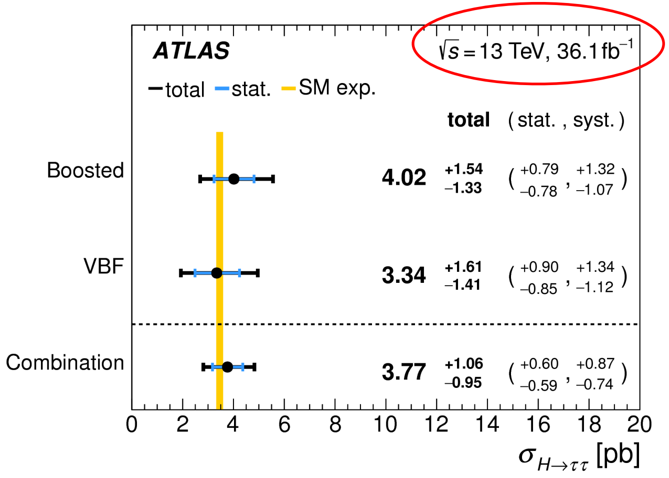
Backup

arXiv:1811.08856

ATLAS observation of H→$\tau\tau$

- 13 different signal regions considering
  - Final state of the τ decays
  - VBF optimised category
  - Boosted H ($p_T^{\tau\tau}$>100 GeV) category, dominated by ggF



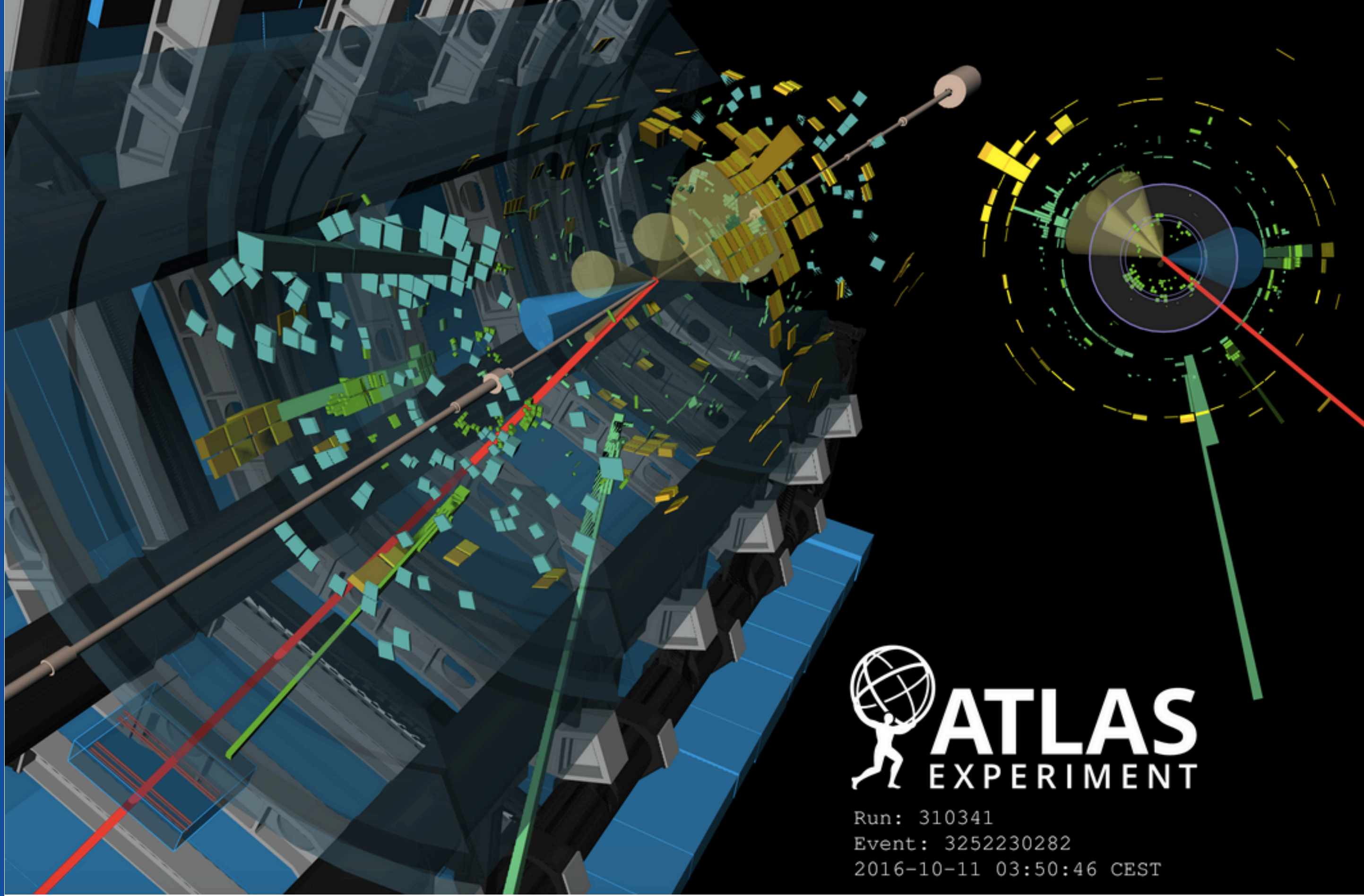


★ Run 1+Run2 combined significance: 6.4σ observed (5.4σ expected)

Search for ttH production

Direct probe of the top Yukawa coupling

Very difficult channel: many possible final states, many particles, combinatorics, …



Observation of ttH production

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- Direct probe of the top Yukawa coupling
- Use all available final states:
  - H→bb, H→$\gamma\gamma$, multi-leptons (H→$\tau\tau$, H
    H→ZZ* →4ℓ
- Combined Run 1 & Run 2 significance:
  - Expected: 5.1σ
  - Observed: 6.5σ
- Dominant systematic uncertainties
  - tt+HF background in H→bb
  - Non-prompt/fake lepton in multi-lepton channel
  - Signal modelling
  - Jet energy scale