



LABORATÓRIO DE INSTRUMENTAÇÃO  
E FÍSICA EXPERIMENTAL DE PARTÍCULAS  
*partículas e tecnologia*

# [ HIGGS Physics $H \rightarrow b\bar{b}$ case study ]

Rute Pedro | 8th April  
LIP Course on Physics at the LHC

**FCT** Fundação  
para a Ciência  
e a Tecnologia

Lisb@20<sup>20</sup>

**COMPETE**  
2020  
PROGRAMA OPERACIONAL COMPETIVIDADE E INTERNACIONALIZAÇÃO

PORTUGAL  
2020

UNIÃO EUROPEIA  
Fundo Europeu de  
Desenvolvimento Regional

 **ATLAS**  
EXPERIMENT

# Today's plan: case study of the $H \rightarrow b\bar{b}$ decay



What's special about it

Role of W/Z H production

Search at the LHC

Journey towards observation

Snooping through the window

$H \rightarrow b\bar{b}$  : what  
makes it special?

# Reminder: Standard Model Lagrangian

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

Kinetic term for the Gauge fields and interaction between gluons, and W/Z bosons

$$+ i \bar{\Psi} \not{D} \Psi + h.c.$$

Kinetic term for the Fermions and interaction between Fermions and the Gauge fields

$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$$

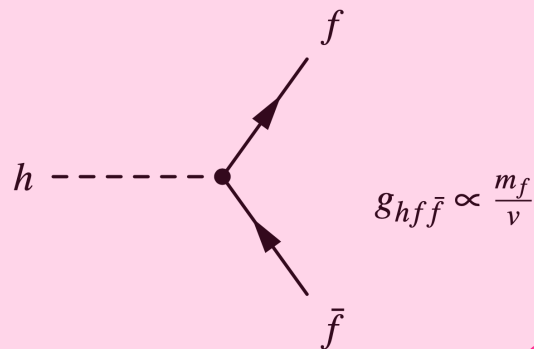
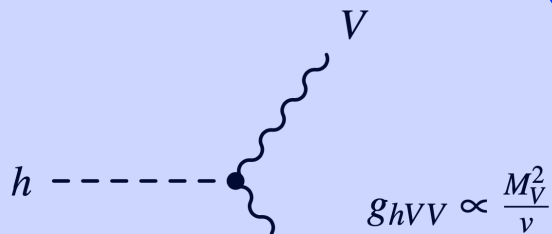
Yukawa couplings and mass terms for Fermions

$$+ \frac{1}{2} D_\mu \phi |^2 - V(\phi)$$

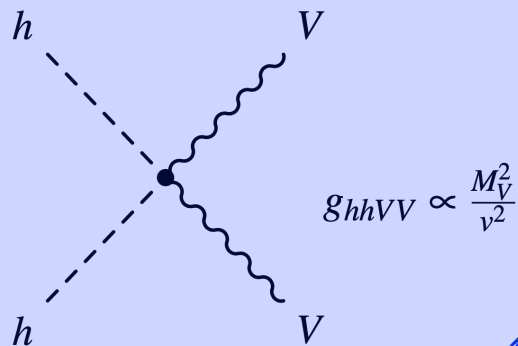
Higgs mechanism: couplings to W/Z, W/Z mass terms, Higgs self-couplings and Higgs potential

# Reminder: Higgs couplings

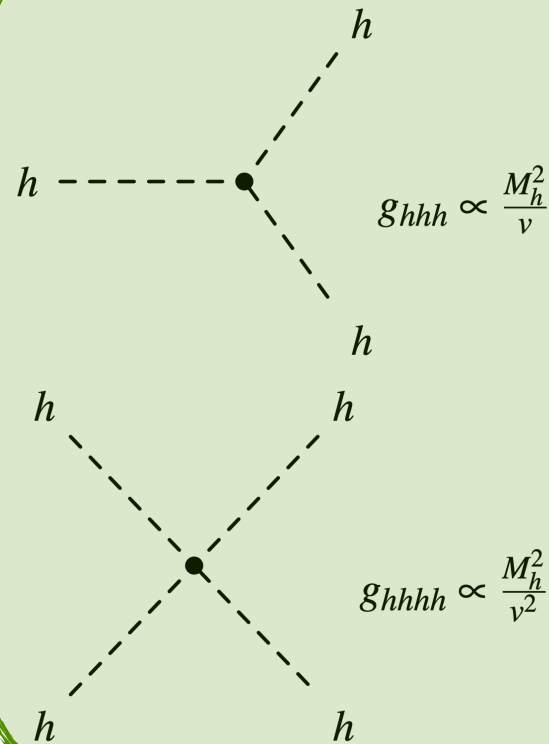
Self-interactions



Yukawa



To gauge bosons

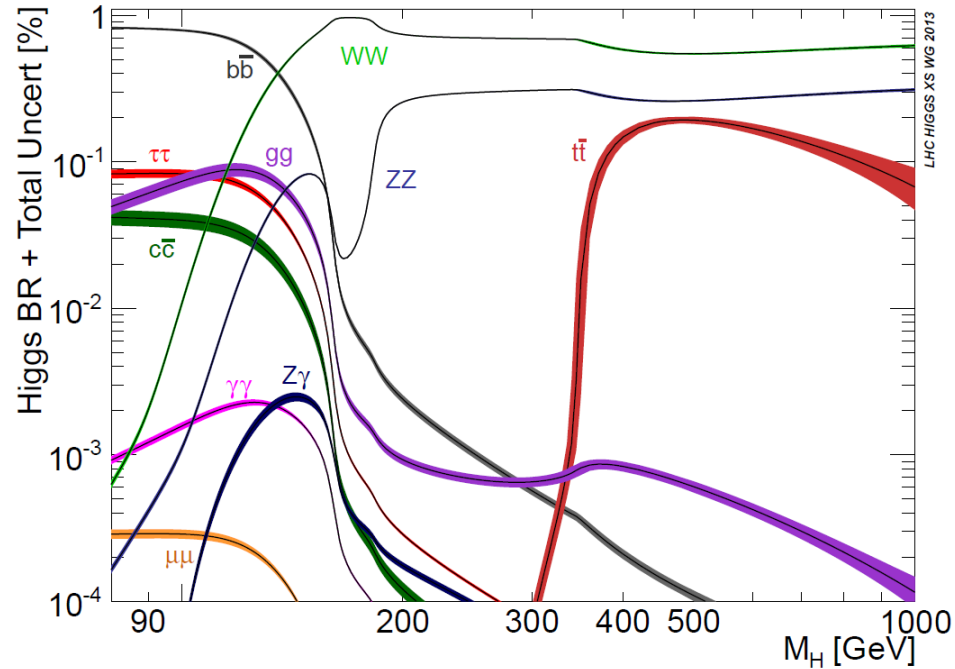


# Reminder: Higgs decay

- Depends on  $m_h$ , not predicted by theory
- Two competing contributions to the partial width  $\Gamma_i$ :
  - Increases with coupling strength (with  $m_f$  or  $m_V^2$ )
  - Decreases with  $m_f/m_h$  or  $m_V/m_h$

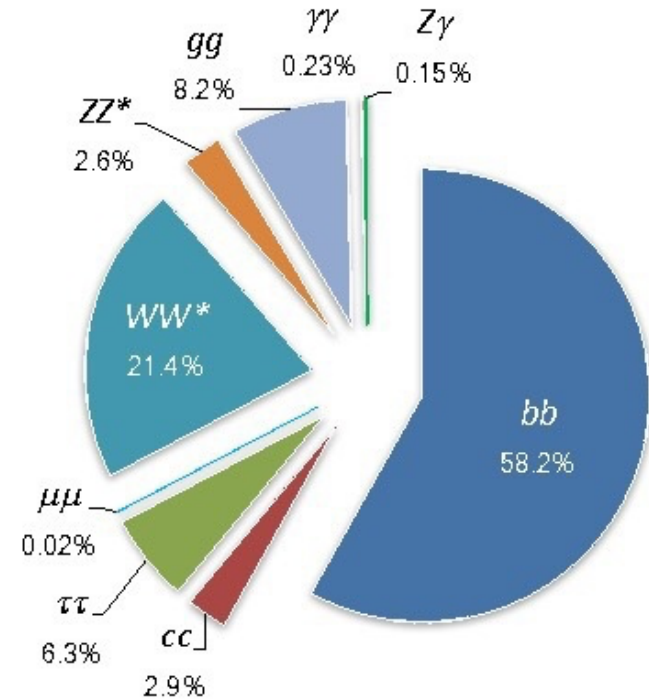
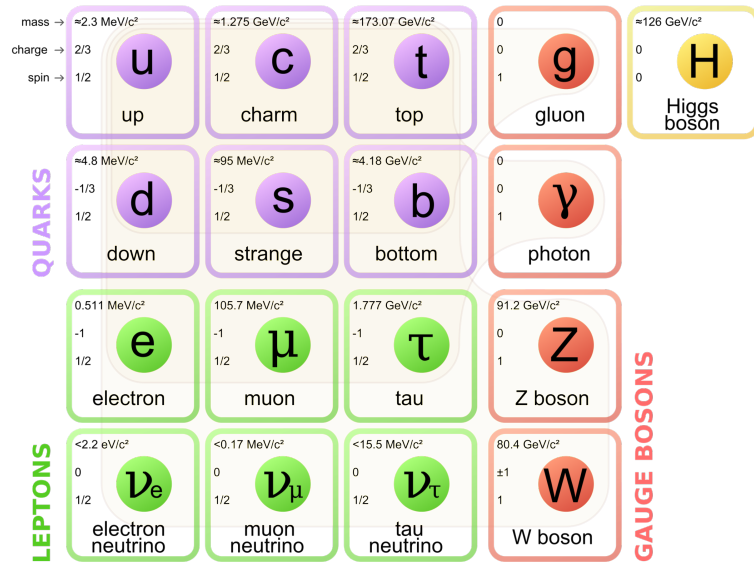
$$\Gamma(h \rightarrow f\bar{f}) \propto m_f^2 m_h \sqrt{1-x} \quad , \text{ with } x = 4m_f^2/m_h^2$$

$$\Gamma(h \rightarrow VV) \propto m_h^3 \left(1-x + \frac{3}{4}x^2\right) \sqrt{1-x} \quad , \text{ with } x = 4m_V^2/m_h^2$$



- Branching ratio  $\frac{\Gamma_i}{\sum \Gamma_i}$

# $H \rightarrow b\bar{b}$ largest branching ratio

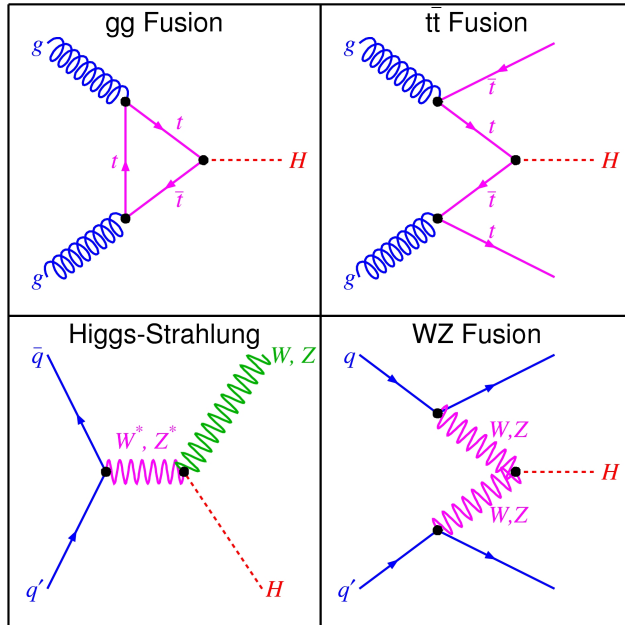


- For  $m_h \sim 125 \text{ GeV}$ : b-quarks are the heaviest particles such that  $2m < m_h$
- $H \rightarrow b\bar{b}$  dominates the Higgs width
- Measuring it is fundamental to probe non-SM Higgs decays

**$H \rightarrow b\bar{b}$  and W/Z**

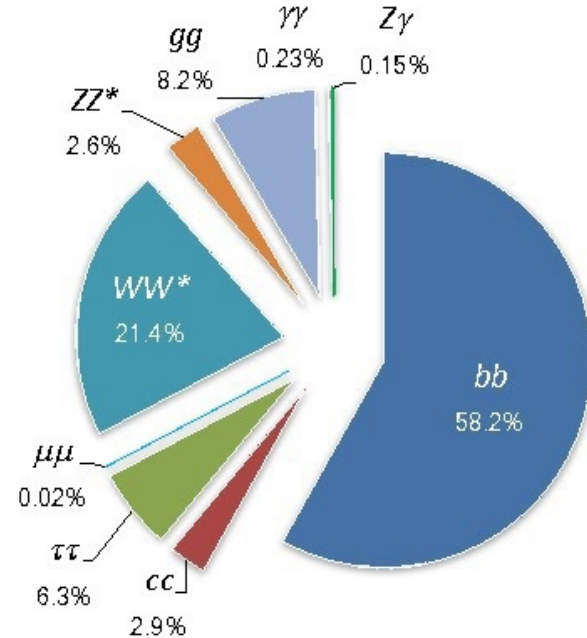
**associated production:  
a long marriage story**

# Search "channels"



Production mode

(depends on initial state particles:  $pp, p\bar{p}, e^+e^-$ )

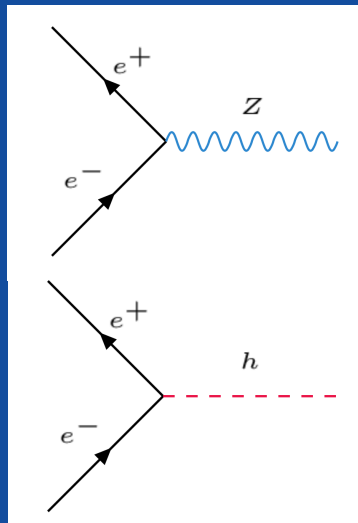


Decay mode

(Branching ratios depend on Higgs mass)

# LEP

$e^+e^-$  collider (narrow width approximation):

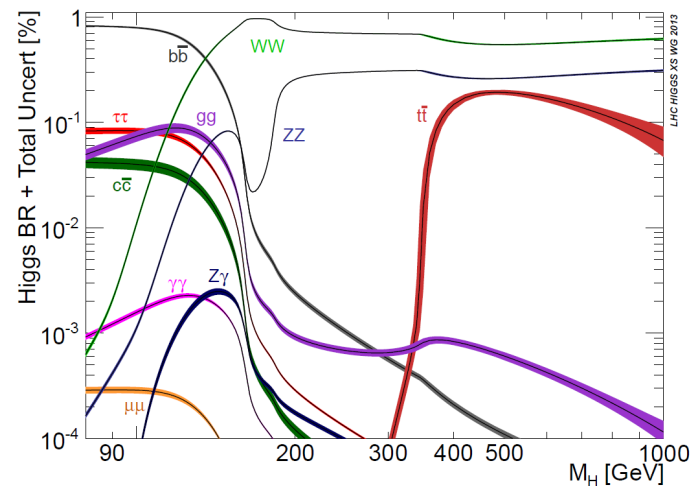
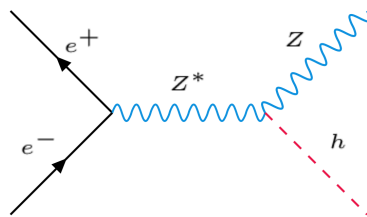


$$\sigma(e^+e^- \rightarrow Z) = 0.0671 \frac{\pi}{2} \delta(E_{CM}^2 - m_Z^2)$$

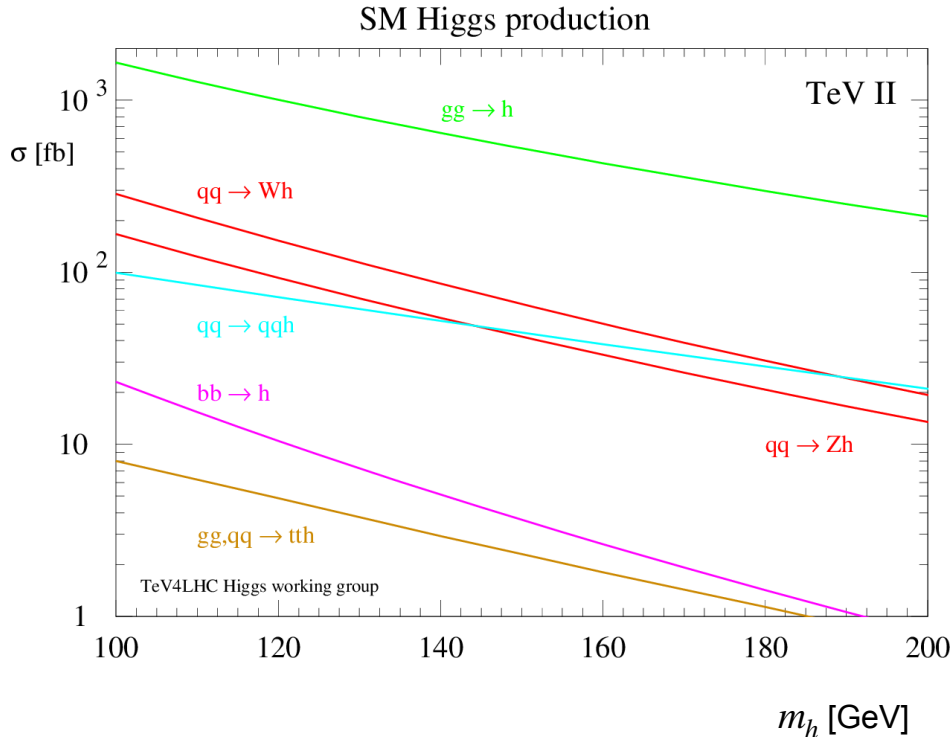
$$\sigma(e^+e^- \rightarrow H) = 4.31 \times 10^{-12} \frac{\pi}{2} \delta(E_{CM}^2 - m_H^2)$$

(suppressed by small electron-Higgs coupling)

- The solution:  $e^+e^- \rightarrow ZH$ ,  $E_{CM} > m_Z + m_H$
- Maximum  $E_{CM}$  reached at LEP: 206 GeV
  - Could only probe H production:  $m_H < E_{CM} - m_Z = 206 - 91 = 115$  GeV
  - $H \rightarrow b\bar{b}$  by far the dominant decay mode



# Tevatron



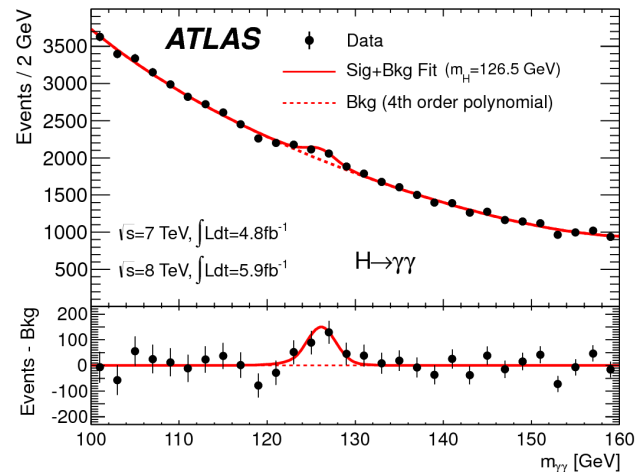
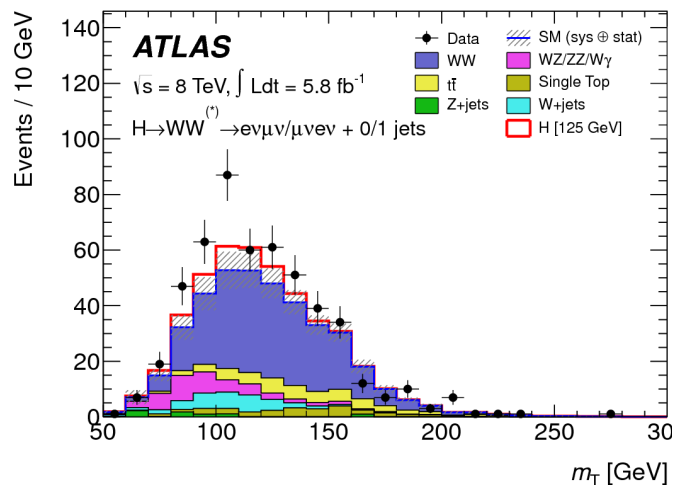
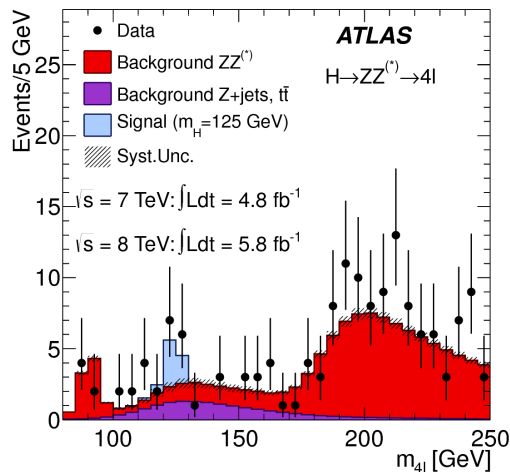
- $p\bar{p}$  collider, for low Higgs mass:
  - $gg \rightarrow H$  (via loop): large cross-section but very small sensitivity
  - Golden channel is W/ZH production and  $H \rightarrow b\bar{b}$  decay
  - Tevatron legacy Higgs result combining all data from both CDF and D0 experiments: Higgs evidence on this channel

**$H(\rightarrow b\bar{b})$  at the LHC**

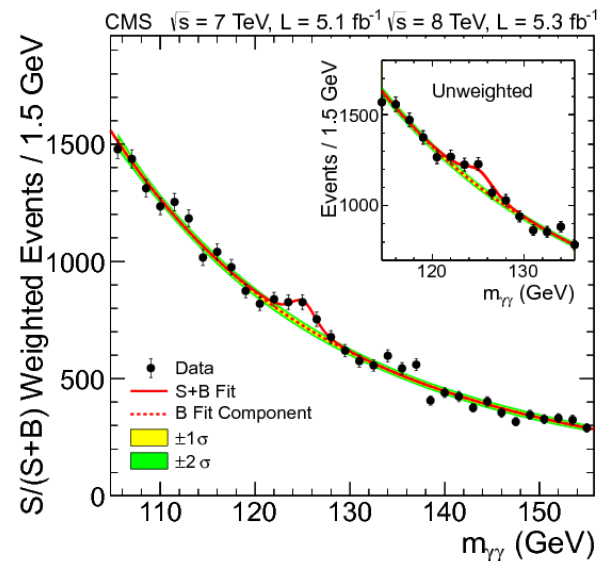
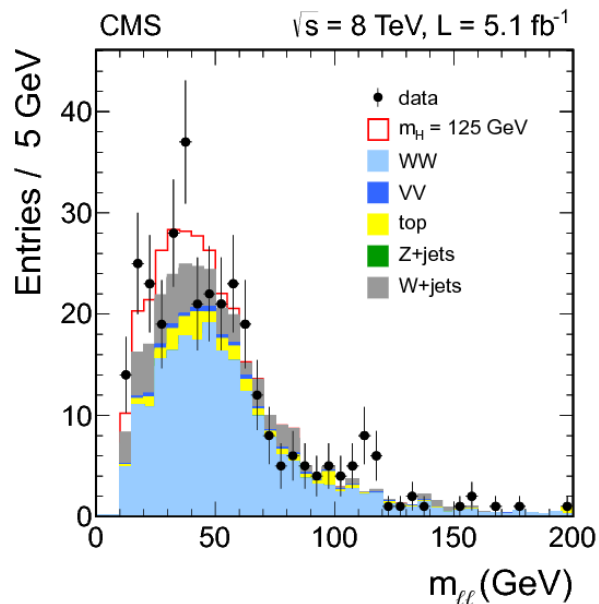
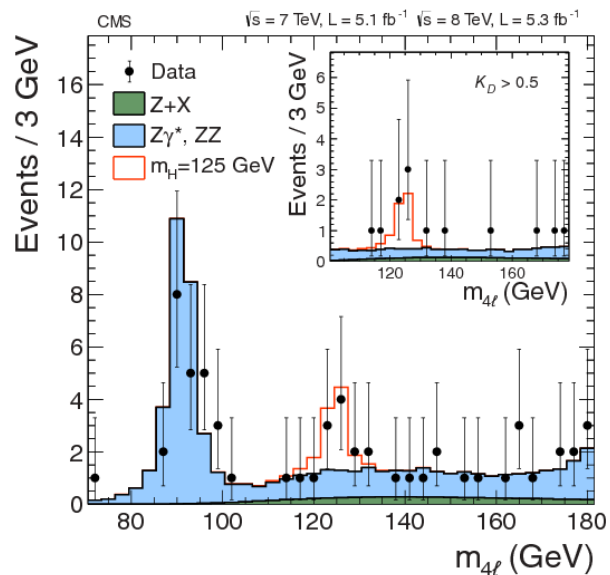
# Higgs discovery - ATLAS

## 2012

- Golden channels for Higgs discovery  $H \rightarrow ZZ$ ,  $H \rightarrow WW$ ,  $H \rightarrow \gamma\gamma$
- We measured the Higgs mass and determined the charge
- Tested against non-SM spin/parity hypothesis



# Higgs discovery - CMS

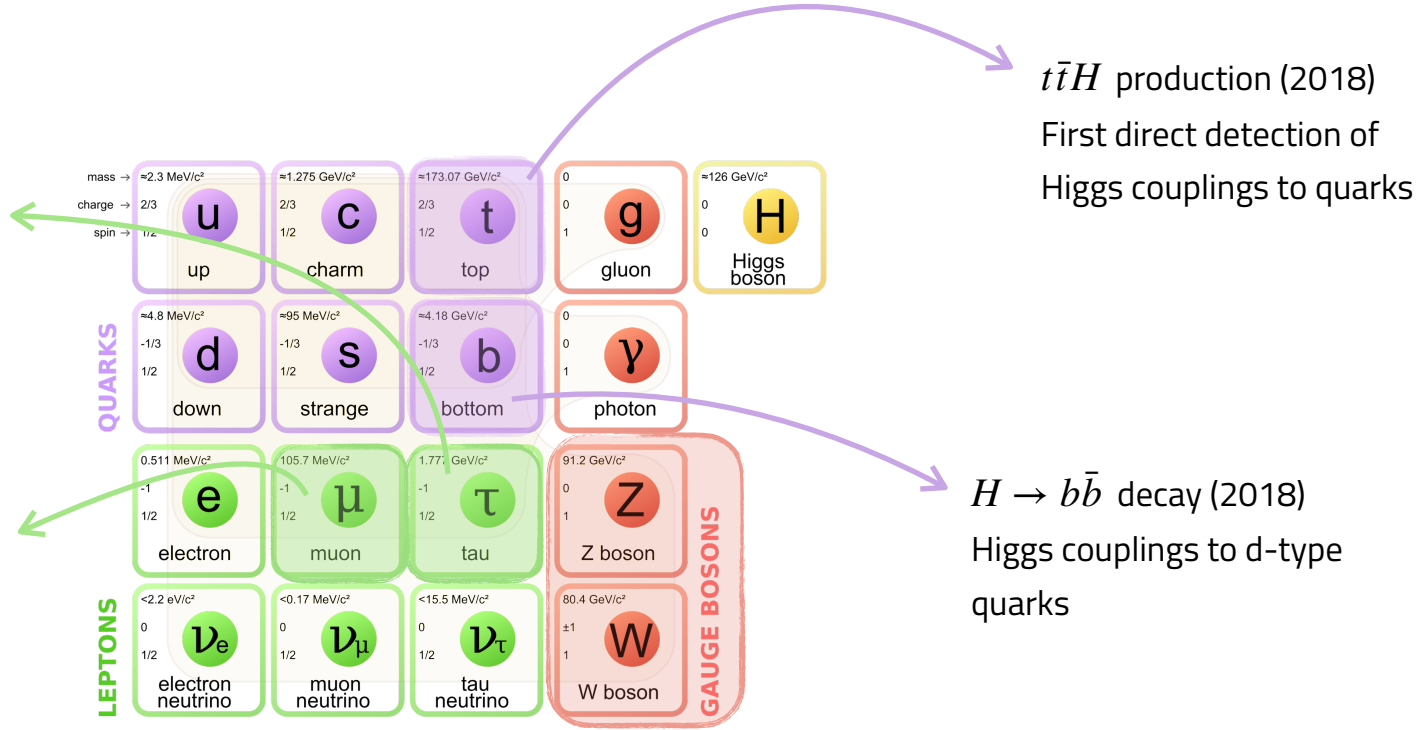


- Independently by the two experiments

# Higgs and the Fermion sector

$H \rightarrow \tau \bar{\tau}$  decay (2017)  
First direct detection of a Yukawa coupling

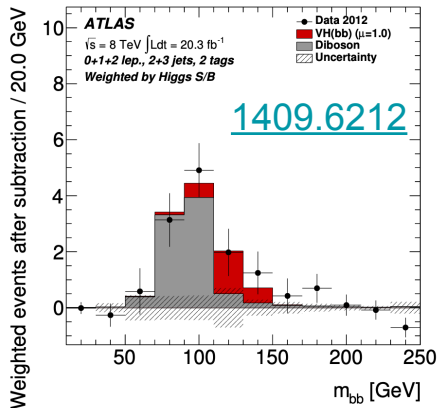
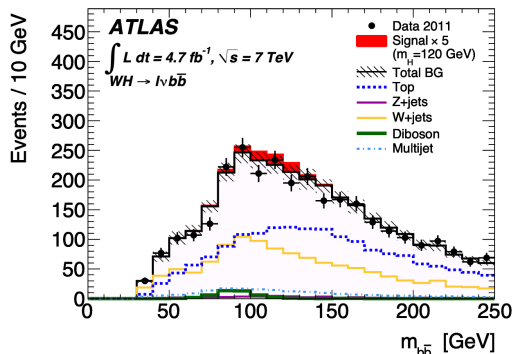
$H \rightarrow \mu \bar{\mu}$  decay (2020)  
Evidence of couplings with 2nd fermion generation



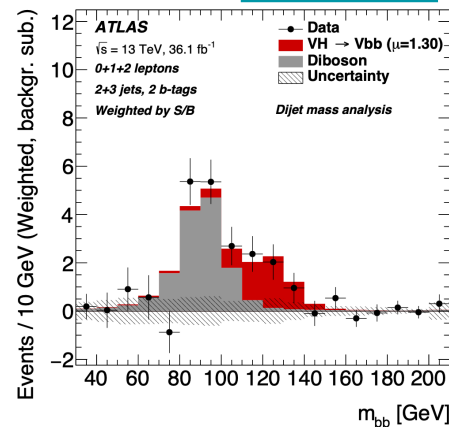
Higgs discovery (2012)

# $H \rightarrow b\bar{b}$ across the years

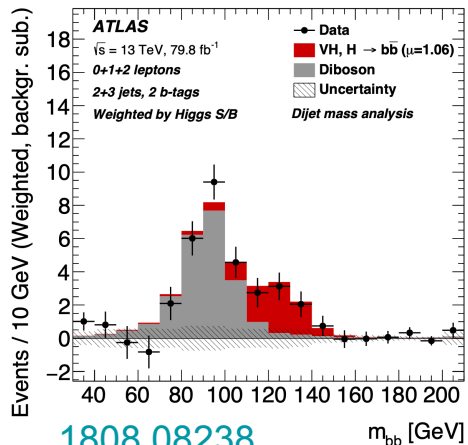
[1207.0210](#)



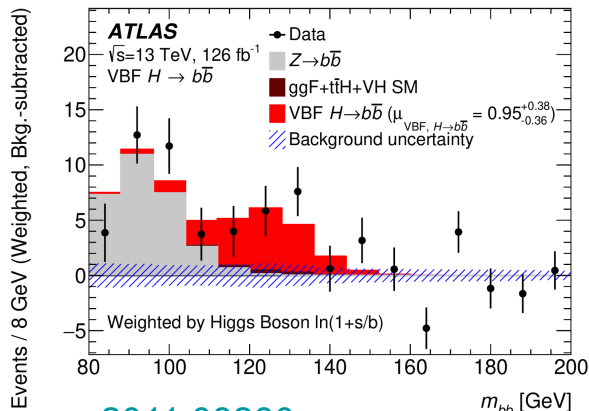
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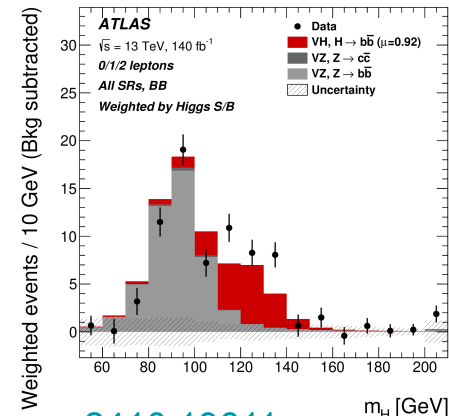
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[1808.08238](#)



[2011.08280](#)

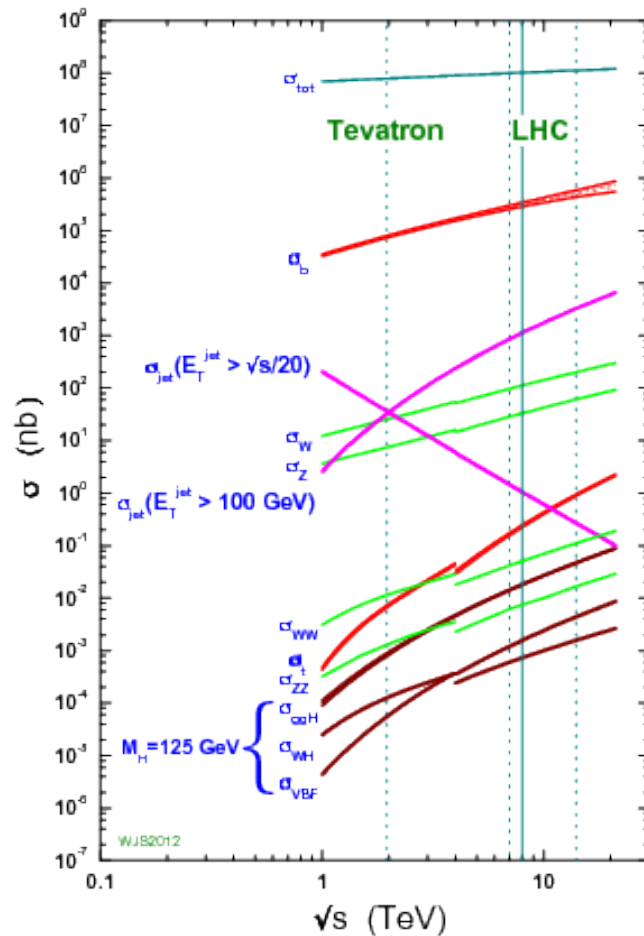
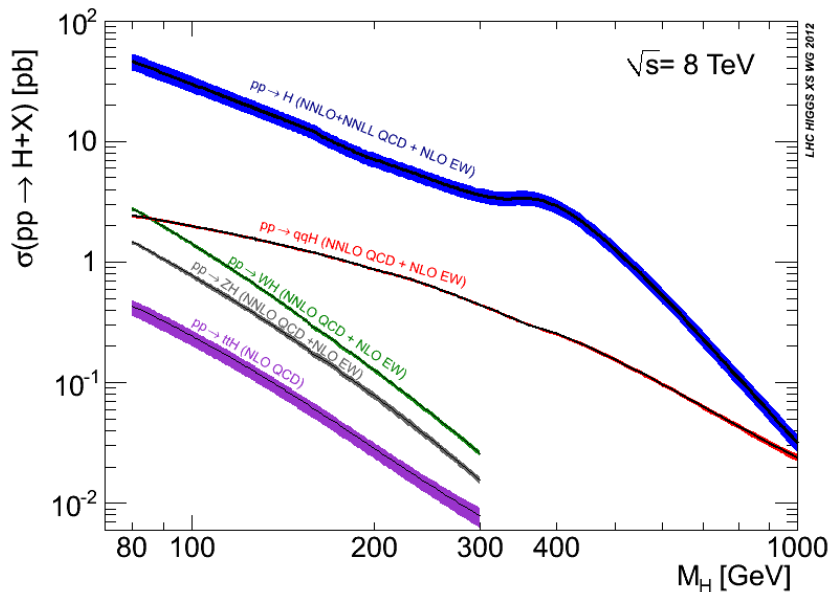


[2410.19611](#)

# $H \rightarrow b\bar{b}$ observation at the LHC

## Why did it take so long?

It all comes down to  $\frac{S}{\sqrt{B}}$  ...

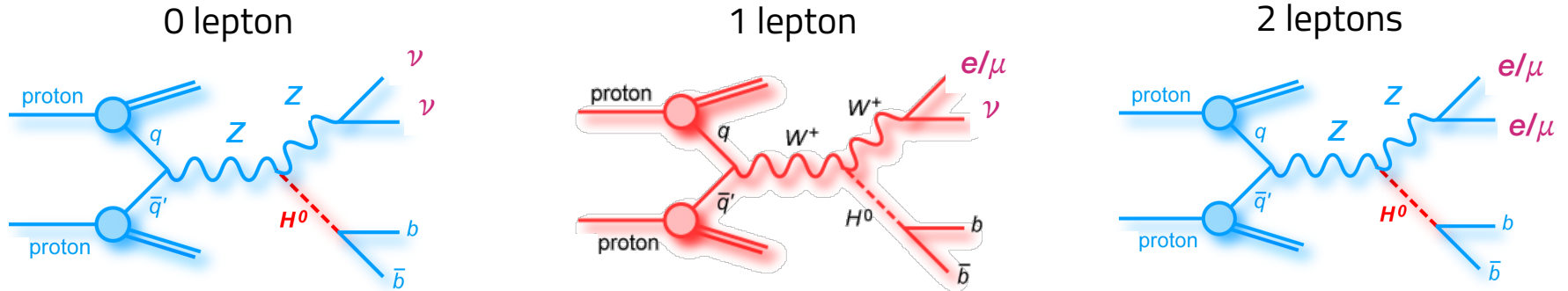


| A journey towards

$H \rightarrow b\bar{b}$  observation

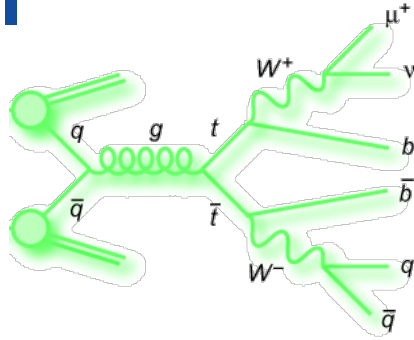
with ATLAS

# Signal topology

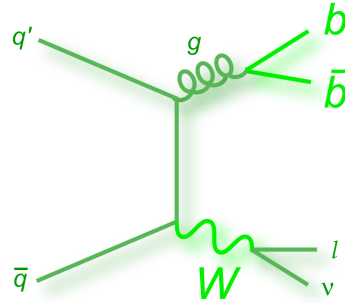


- W/Z associated production: use leptonic decay of W/Z to trigger the signal
- Mode most sensitive to  $H \rightarrow b\bar{b}$
- At least one high  $p_T$  jet
- 2 jets identified as the hadronisation of b-quarks ("*b-tagging*")
- 0, 1 or 2 isolated electrons/muons ("*leptons*")

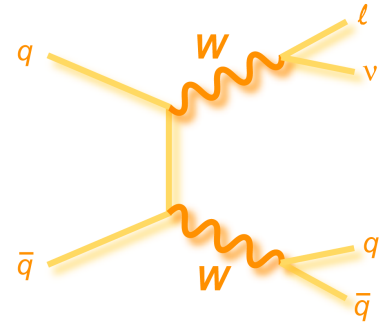
# Background processes



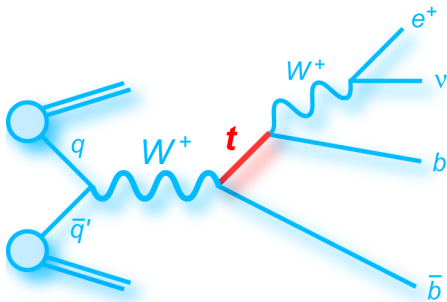
top pairs



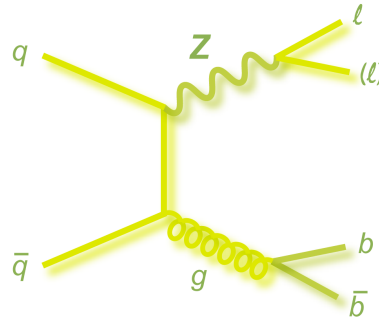
W+jets



vector boson pairs



top



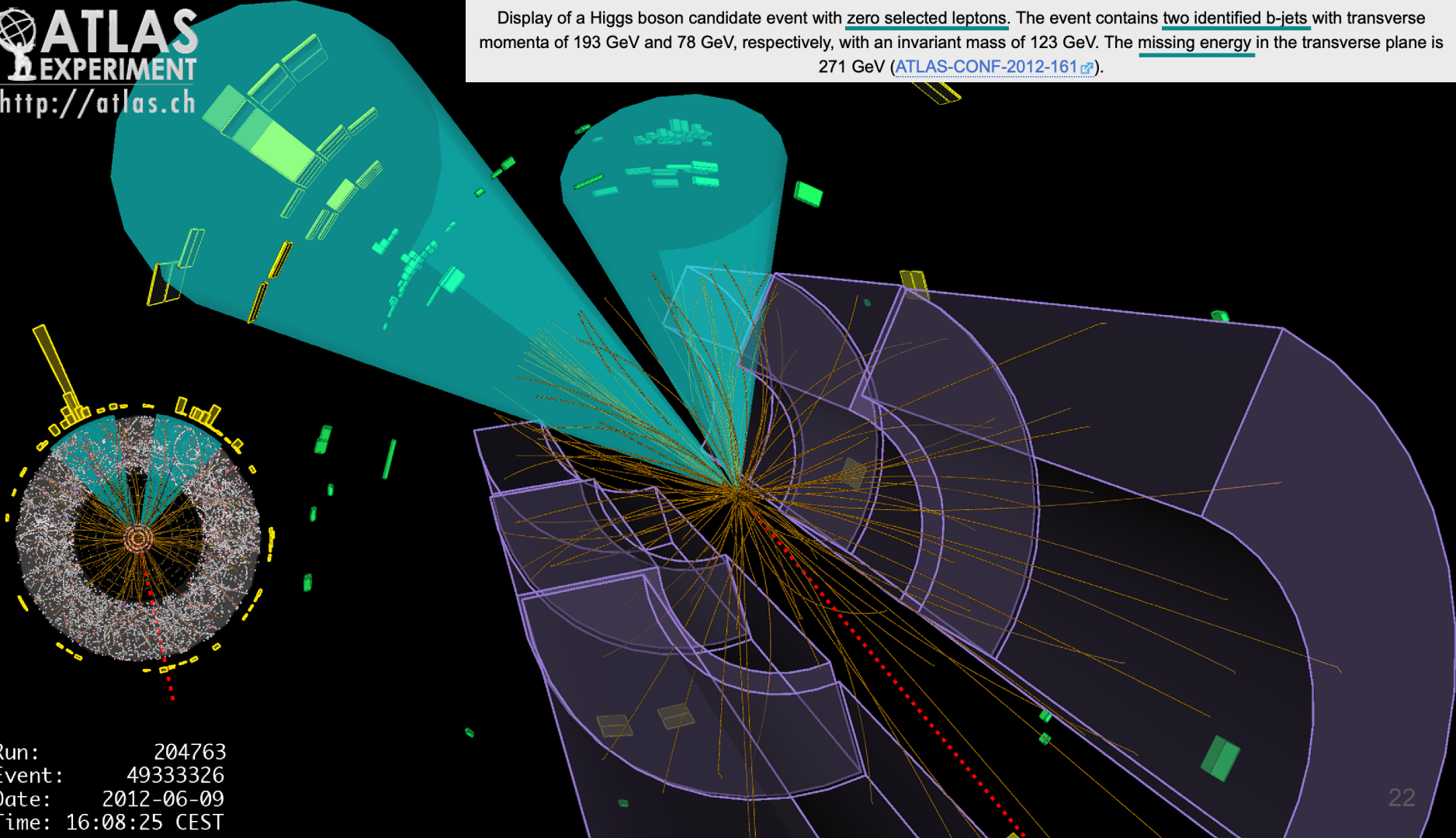
Z+jets

- Similar final state than signal
- Much larger cross-section
- Exemplifying decay chain, remember:
  - $Z \rightarrow q\bar{q}l\ell^+\ell^-\nu\bar{\nu}$
  - $W^- \rightarrow q'\bar{q}l\ell^-\bar{\nu}$
  - $t \rightarrow W^+b$  (>99%)

# Key factors for identifying $W/ZH(H \rightarrow b\bar{b})$

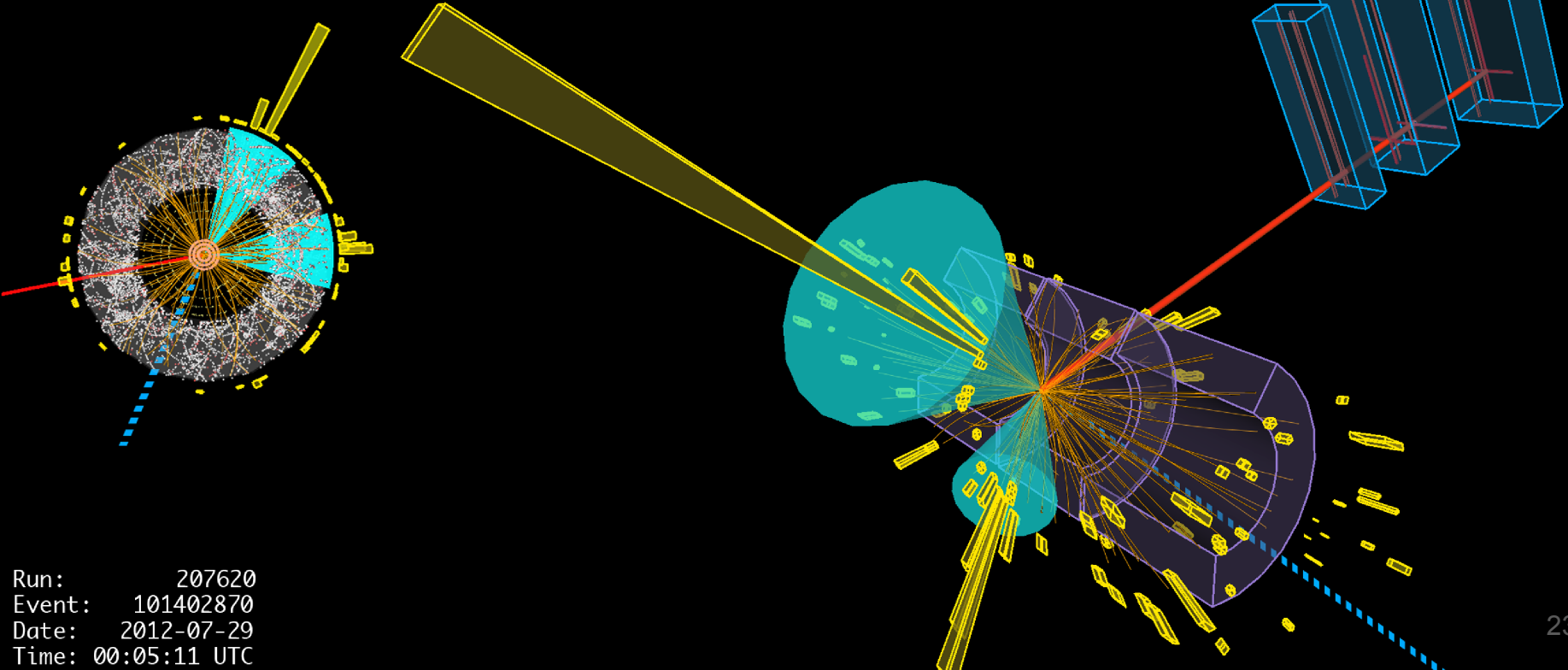
- Higgs candidate: 2 b-jets
  - Jet finding
  - b-tagging
  - $m_{bb}$  resolution
- (0 lepton)  $Z \rightarrow \nu\bar{\nu}$ :
  - Neutrinos are weakly interacting: yield missing energy
- (1 lepton)  $W^\pm \rightarrow \ell^\pm\nu$  and (2 lepton)  $Z \rightarrow \ell\bar{\ell}$ :
  - Reconstruct and identify electrons and muons

Display of a Higgs boson candidate event with zero selected leptons. The event contains two identified b-jets with transverse momenta of 193 GeV and 78 GeV, respectively, with an invariant mass of 123 GeV. The missing energy in the transverse plane is 271 GeV ([ATLAS-CONF-2012-161](#)).

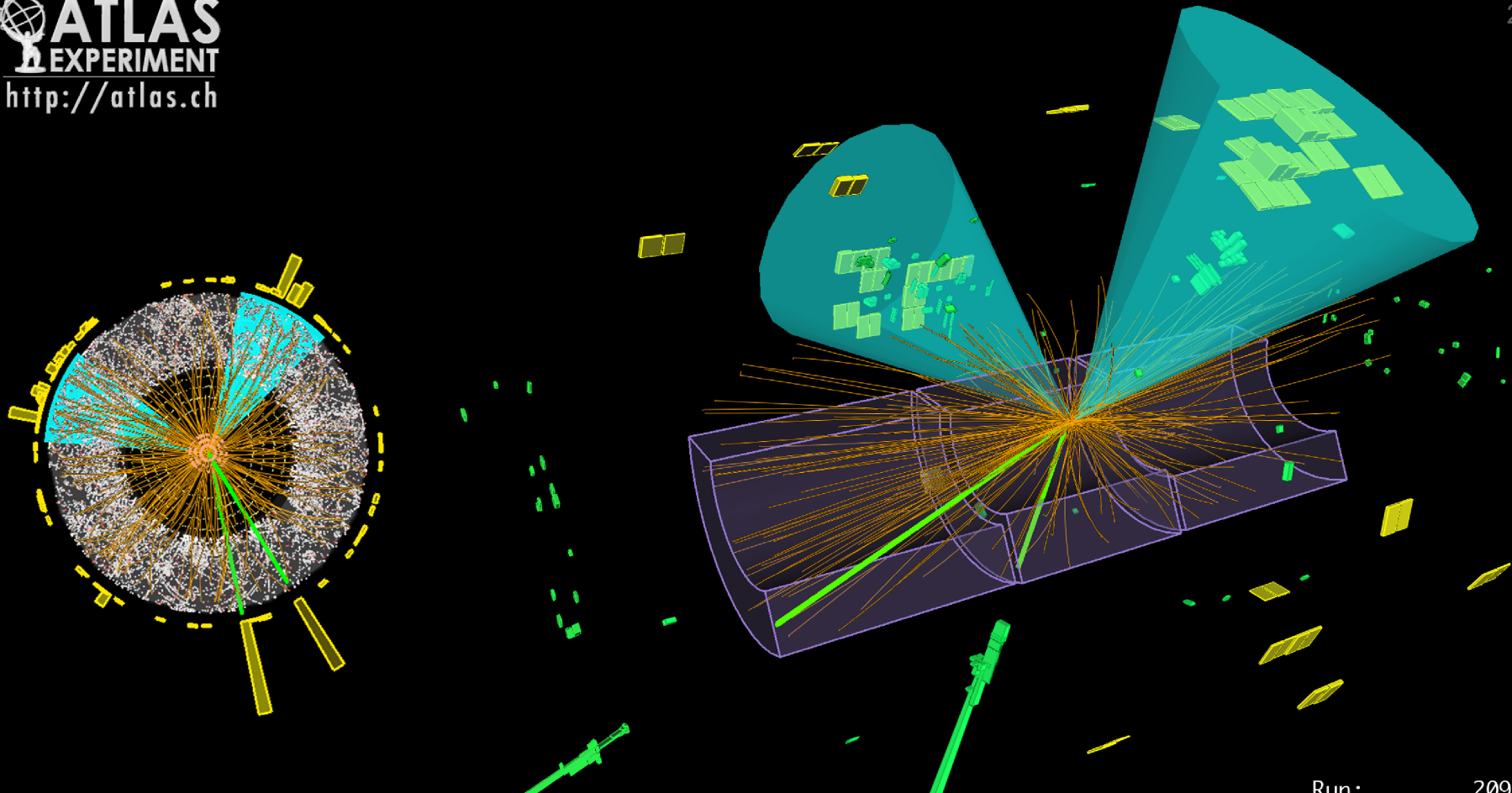


Run: 204763  
Event: 49333326  
Date: 2012-06-09  
Time: 16:08:25 CEST

Display of a Higgs boson candidate event with one selected lepton. The two identified b-jets have transverse momenta of 149 GeV and 86 GeV, respectively, with an invariant mass of 109 GeV. The identified muon has a transverse momentum of 96 GeV, the missing energy in the transverse plane is 139 GeV, resulting in a transverse momentum of the W boson candidate of 209 GeV



Run: 207620  
Event: 101402870  
Date: 2012-07-29  
Time: 00:05:11 UTC

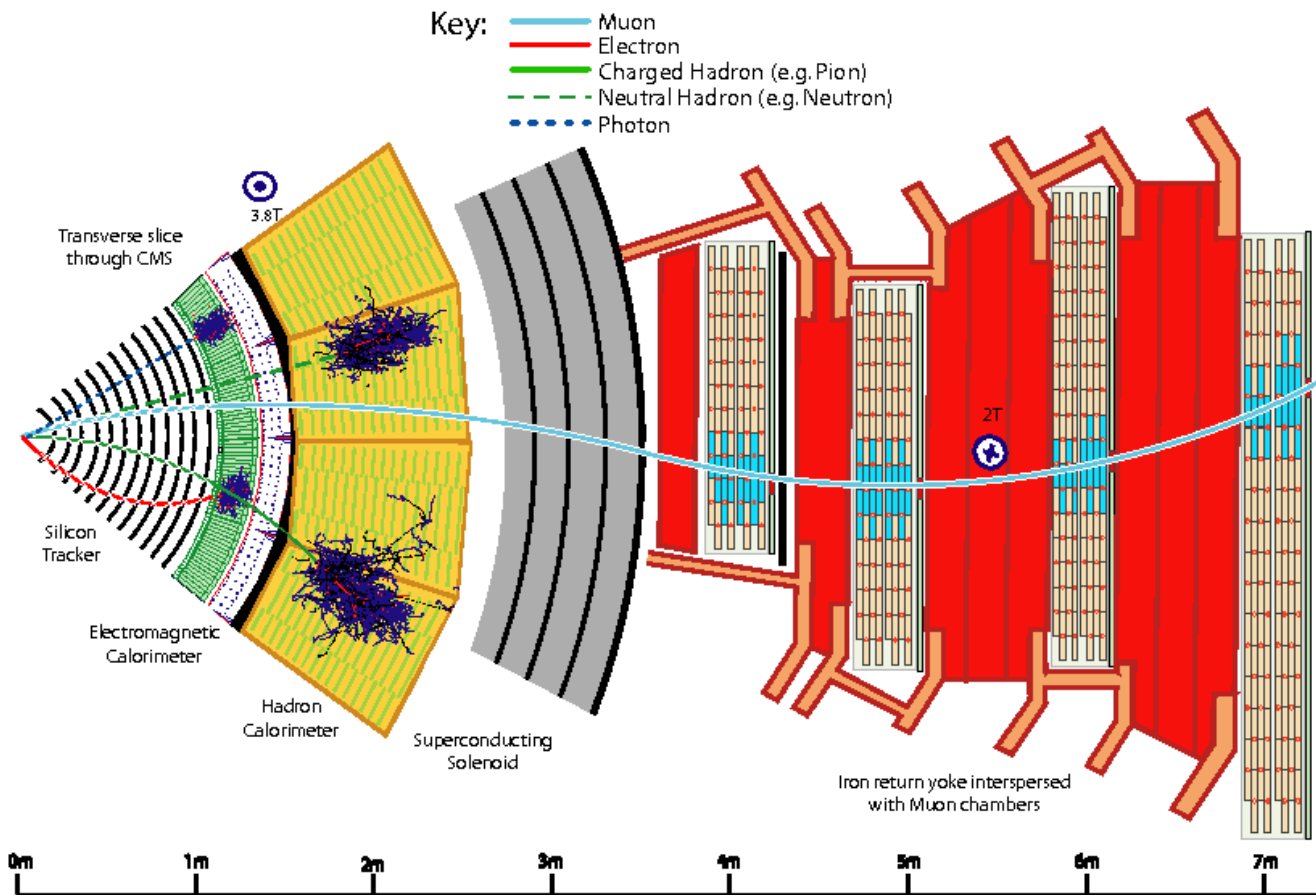


Display of a Higgs boson candidate event with two selected leptons. The two identified b-jets have transverse momenta of 70 GeV and 65 GeV, respectively, with an invariant mass of 122 GeV. The identified leptons have transverse momenta of 63 GeV and 54 GeV, respectively, resulting in a transverse momentum of the Z boson candidate of 115 GeV ([ATLAS-CONF-2012-161](#)).

Run: 209787  
Event: 144100666  
Date: 2012-09-05  
Time: 03:57:49 UTC

# Anatomy of a collider event

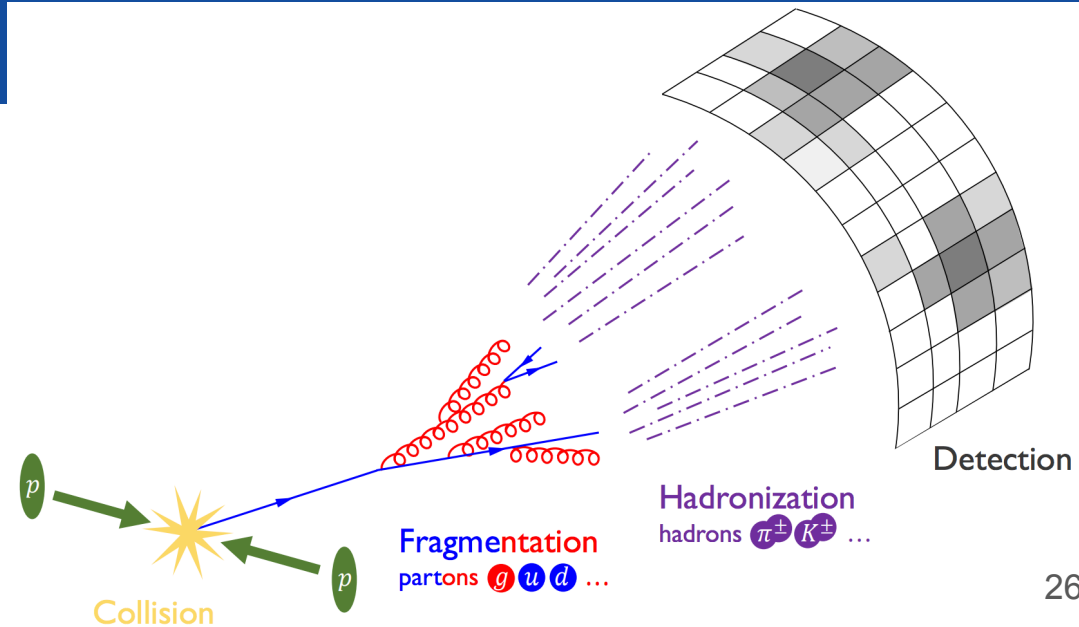
- Identify collision vertices and particles:
  - Track-finding
  - Electron/muon ID/reconstruction
  - Jet clustering
- Measure energy, momenta, electric charge
- Jet flavour
- Event topology



# Jets

- Quarks/gluons exist confined in bound states (hadrons)
- When produced freely (eg. decay/collision product) they give rise to a shower of particles: jet
  - Fragmentation and hadronisation processes
  - Parametrised by a few phenomenological models

- We infer the quark/gluon properties from the measurement of jets
- Jet clustering from detected cell energy deposits or particle tracks
- Anti-kt algorithm: combines closer/softer particles first

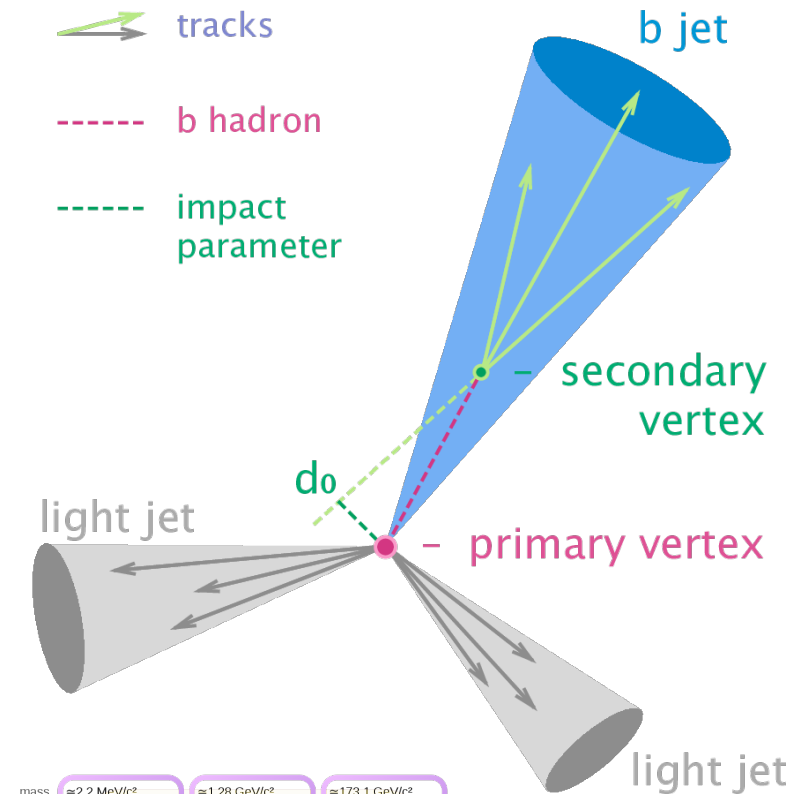


# Jet Flavour identification

Explore unique characteristics of heavy flavour-jets

- “Large” lifetime of b/c-hadrons ( $\sim$ ps)
- Displaced secondary vertex
- Track displacement  $d_0$  (and  $z_0$ )
- Soft lepton from b/c hadron decay

Relies on Inner tracking system



mass charge spin	$\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$
	<b>u</b> up	<b>c</b> charm	<b>t</b> top
<b>QUARKS</b>	$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 96 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 4.18 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom

# BDT for jet flavour identification

## MV2

Per-jet probability of originating from {b, c, g/u/d/s} partons

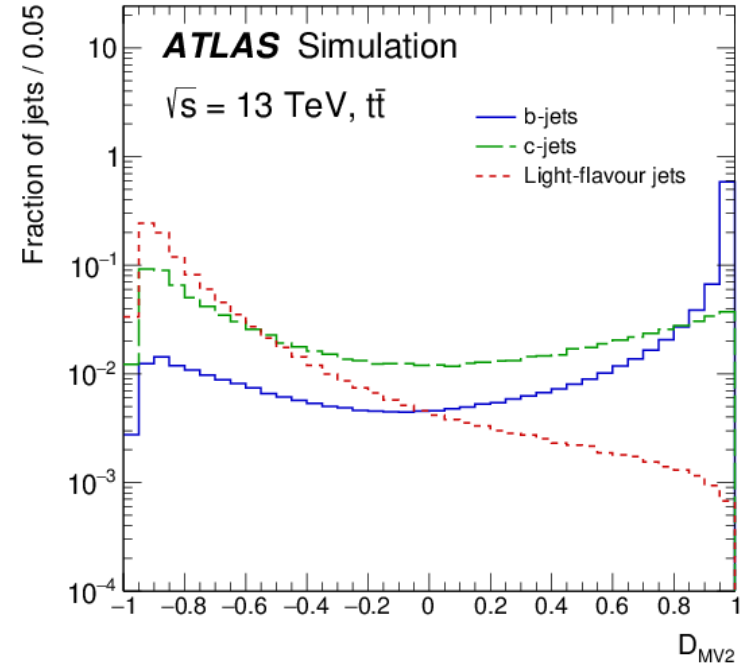
Boosted Decision Tree with many input variables

- Number of secondary vertices (SV)
- Number of tracks from SV
- SV mass
- Radial distance  $\Delta R(\text{track}, \text{jet})$
- Jet  $p_T, \eta$
- $d_0, \dots$

Rejection factor of 300 (light-jets) and 8 (c-jets) for 70% b-jet efficiency

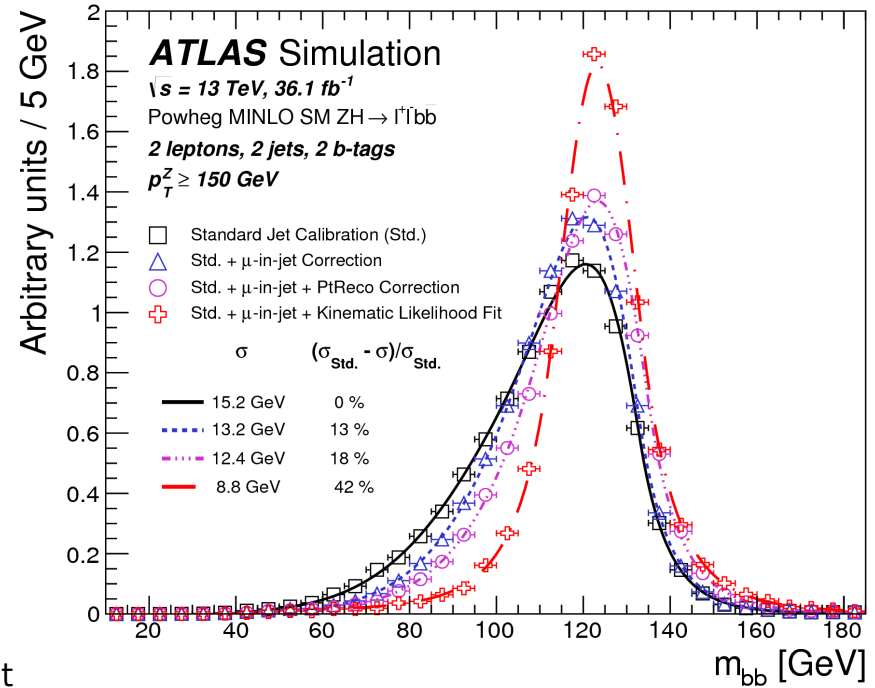
Stable performance as a function of pile-up

More sophisticated algorithms now, including deep learning



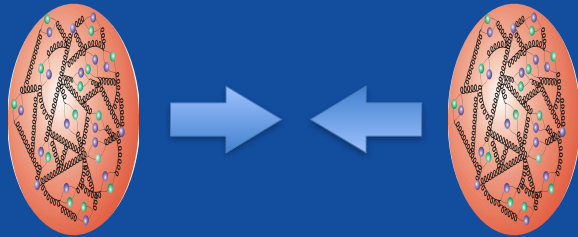
# $m_{bb}$ resolution

- Important to get the narrowest possible peak to be sensitive to it
- Higgs candidate formed by the system of 2 b-jets
  - $b_1 : (\vec{p}_{b_1}, E_{b_1})$
  - $b_2 : (\vec{p}_{b_2}, E_{b_2})$
  - $H : m_{bb}^2 = (E_{b_1} + E_{b_2})^2 + ||\vec{p}_{b_1} + \vec{p}_{b_2}||^2$
- Driven by precision and accuracy of jet energy measurement
- Several improvements (up to 42%):
  - Add  $\vec{p}$  of muon closes to jet axis (account for semi-leptonic decays of hadron in jets)
  - Jet pT correction to account for energy loss due to neutrino emission (derived from signal simulation)
  - $ZH \rightarrow \ell\bar{\ell}b\bar{b}$ : use of  $Z \rightarrow \ell\bar{\ell}$  recoiling against the  $H \rightarrow b\bar{b}$  to constrain jet kinematics



# Missing “Energy”

Associated with undetected particles: neutrinos, non-SM candidates for dark matter



Initial momentum in the transverse plane:  $\vec{0}$

After collision missing momentum will be:  $-\sum_i \vec{p}_{T_i}$

Rely mainly on the energy deposits in the calorimeters and on muon momentum measurements

- Many components:
  - Electrons, photons, tau-leptons, jets, muons
  - Calorimeter energy deposits/tracks not associated with any of the objects above

# Online event trigger

- Remember: it's impossible to record all the events, collision rate is 40 MHz!

Selection	0-lepton	1-lepton		2-lepton
		<i>e</i> sub-channel	$\mu$ sub-channel	
Trigger	$E_T^{\text{miss}}$	Single lepton	$E_T^{\text{miss}}$	Single lepton
Leptons	0 <i>loose</i> leptons with $p_T > 7$ GeV	1 <i>tight</i> electron $p_T > 27$ GeV	1 <i>tight</i> muon $p_T > 25$ GeV	2 <i>loose</i> leptons with $p_T > 7$ GeV $\geq 1$ lepton with $p_T > 27$ GeV
$E_T^{\text{miss}}$	$> 150$ GeV	$> 30$ GeV	–	–
$m_{\ell\ell}$	–	–	–	$81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$
Jets	Exactly 2 / Exactly 3 jets		Exactly 2 / $\geq 3$ jets	
Jet $p_T$			$> 20$ GeV for $ \eta  < 2.5$ $> 30$ GeV for $2.5 <  \eta  < 4.5$	
<i>b</i> -jets			Exactly 2 <i>b</i> -tagged jets	
Leading <i>b</i> -tagged jet $p_T$			$> 45$ GeV	
$H_T$	$> 120$ GeV (2 jets), $> 150$ GeV (3 jets)		–	–
$\min[\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{j}_{\text{ets}})]$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)		–	–
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{b}\vec{b})$	$> 120^\circ$		–	–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^\circ$		–	–
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p}_T^{\text{miss}})$	$< 90^\circ$		–	–
$p_T^V$ regions	$> 150$ GeV		$75 \text{ GeV} < p_T^V < 150 \text{ GeV}$ , $> 150 \text{ GeV}$	
Signal regions	–	$m_{bb} \geq 75 \text{ GeV}$ or $m_{\text{top}} \leq 225 \text{ GeV}$		Same-flavour leptons Opposite-sign charges ( $\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75 \text{ GeV}$ and $m_{\text{top}} > 225 \text{ GeV}$		Different-flavour leptons Opposite-sign charges

# Offline event selection

- Common selection criteria

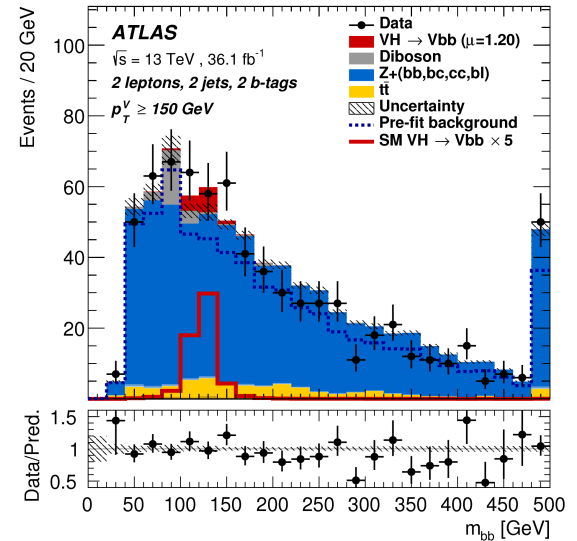
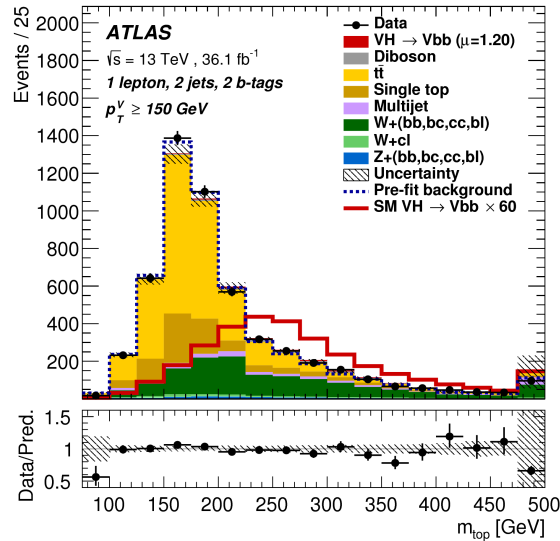
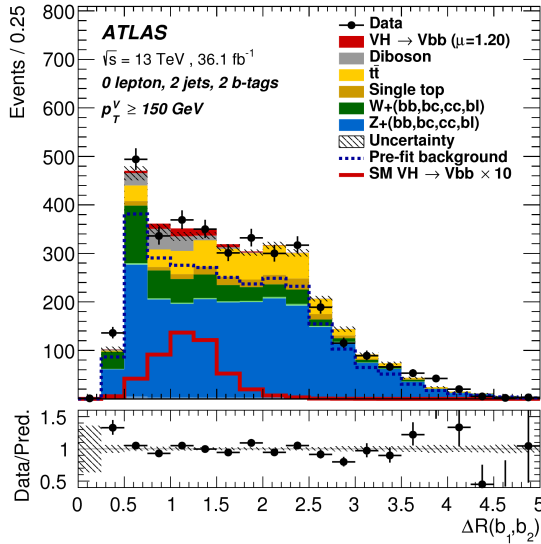
Selection	0-lepton		1-lepton		2-lepton
			<i>e</i> sub-channel	$\mu$ sub-channel	
Trigger	$E_T^{\text{miss}}$		Single lepton	$E_T^{\text{miss}}$	Single lepton
Leptons	0 <i>loose</i> leptons with $p_T > 7$ GeV		1 <i>tight</i> electron $p_T > 27$ GeV	1 <i>tight</i> muon $p_T > 25$ GeV	2 <i>loose</i> leptons with $p_T > 7$ GeV $\geq 1$ lepton with $p_T > 27$ GeV
$E_T^{\text{miss}}$	$> 150$ GeV		$> 30$ GeV	–	–
$m_{\ell\ell}$	–		–	–	$81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$
Jets	Exactly 2 / Exactly 3 jets		$> 20$ GeV for $ \eta  < 2.5$ $> 30$ GeV for $2.5 <  \eta  < 4.5$		Exactly 2 / $\geq 3$ jets
Jet $p_T$			Exactly 2 <i>b</i> -tagged jets $> 45$ GeV		
<i>b</i> -jets					
Leading <i>b</i> -tagged jet $p_T$					
$H_T$	$> 120$ GeV (2 jets), $> 150$ GeV (3 jets)		–		–
$\min[\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{j}_{\text{ets}})]$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)		–		–
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{b}\vec{b})$	$> 120^\circ$		–		–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^\circ$		–		–
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p}_T^{\text{miss}})$	$< 90^\circ$		–		–
$p_T^V$ regions	$> 150$ GeV				$75 \text{ GeV} < p_T^V < 150 \text{ GeV}$ , $> 150 \text{ GeV}$
Signal regions	–		$m_{bb} \geq 75 \text{ GeV}$ or $m_{\text{top}} \leq 225 \text{ GeV}$		Same-flavour leptons Opposite-sign charges ( $\mu\mu$ sub-channel)
Control regions	–		$m_{bb} < 75 \text{ GeV}$ and $m_{\text{top}} > 225 \text{ GeV}$		Different-flavour leptons Opposite-sign charges

# Signal regions

- Designed to maximise  $S/\sqrt{B}$

Selection	0-lepton	1-lepton		2-lepton
		$e$ sub-channel	$\mu$ sub-channel	
Trigger	$E_T^{\text{miss}}$	Single lepton	$E_T^{\text{miss}}$	Single lepton
Leptons	0 <i>loose</i> leptons with $p_T > 7$ GeV	1 <i>tight</i> electron $p_T > 27$ GeV	1 <i>tight</i> muon $p_T > 25$ GeV	2 <i>loose</i> leptons with $p_T > 7$ GeV $\geq 1$ lepton with $p_T > 27$ GeV
$E_T^{\text{miss}}$	$> 150$ GeV	$> 30$ GeV	–	–
$m_{\ell\ell}$	–	–	–	$81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$
Jets	Exactly 2 / Exactly 3 jets		Exactly 2 / $\geq 3$ jets	
Jet $p_T$			$> 20$ GeV for $ \eta  < 2.5$ $> 30$ GeV for $2.5 <  \eta  < 4.5$	
$b$ -jets			Exactly 2 $b$ -tagged jets	
Leading $b$ -tagged jet $p_T$			$> 45$ GeV	
$H_T$	$> 120$ GeV (2 jets), $> 150$ GeV (3 jets)		–	–
$\min[\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{j}_{\text{ets}})]$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)		–	–
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{b}\vec{b})$	$> 120^\circ$		–	–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^\circ$		–	–
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p}_T^{\text{miss}})$	$< 90^\circ$		–	–
$p_T^V$ regions		$> 150$ GeV		$75 \text{ GeV} < p_T^V < 150 \text{ GeV}, > 150 \text{ GeV}$
Signal regions	–	$m_{bb} \geq 75 \text{ GeV}$ or $m_{\text{top}} \leq 225 \text{ GeV}$		Same-flavour leptons Opposite-sign charges ( $\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75 \text{ GeV}$ and $m_{\text{top}} > 225 \text{ GeV}$		Different-flavour leptons Opposite-sign charges

# Discriminating signal from background



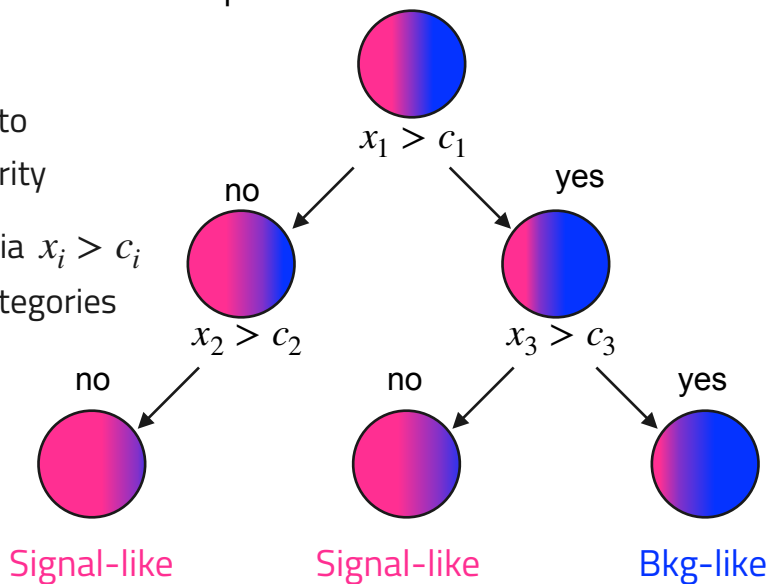
- For signal, the 2 b-jets come from the Higgs decay and are kinematically correlated

- (1 lepton) Attempt to reconstruct the t-quark invariant mass (system  $\ell\nu b$ ): background peak at 175 GeV

- $m_{bb}$

# Boosted Decision Tree for signal identification

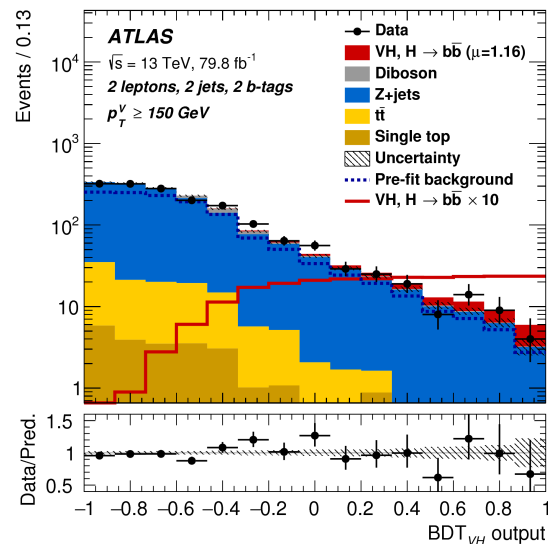
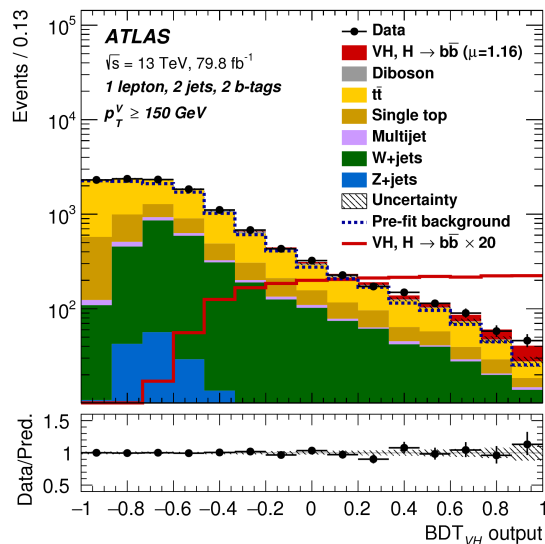
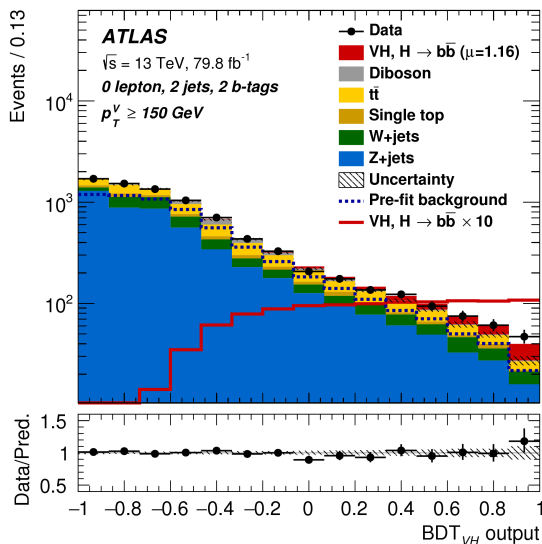
- BDT trained on simulated signal and background events
- Improve background and signal separation of the events exploring a multidimensional space
- Partitions the data to increase sample purity
- Finds optimal criteria  $x_i > c_i$  to separate data categories



Variable	0-lepton	1-lepton	2-lepton
$p_T^V$	$\equiv E_T^{\text{miss}}$	×	×
$E_T^{\text{miss}}$	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
$m_{bb}$	×	×	×
$\Delta R(\vec{b}_1, \vec{b}_2)$	×	×	×
$ \Delta\eta(\vec{b}_1, \vec{b}_2) $	×		
$\Delta\phi(\vec{V}, \vec{bb})$	×	×	×
$ \Delta\eta(\vec{V}, \vec{bb}) $			×
$m_{\text{eff}}$	×		
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		×	
$m_T^W$		×	
$m_{\ell\ell}$			×
$m_{\text{top}}$		×	
$ \Delta Y(\vec{V}, \vec{bb}) $		×	
Only in 3-jet events			
$p_T^{\text{jet}_3}$	×	×	×
$m_{bbj}$	×	×	×

# Boosted Decision Tree for signal identification

- BDT output discriminant
- Signal-to-Background ratio (S/B) up to 30% in most sensitive bins



# Background control regions

- To obtain pure samples on specific backgrounds

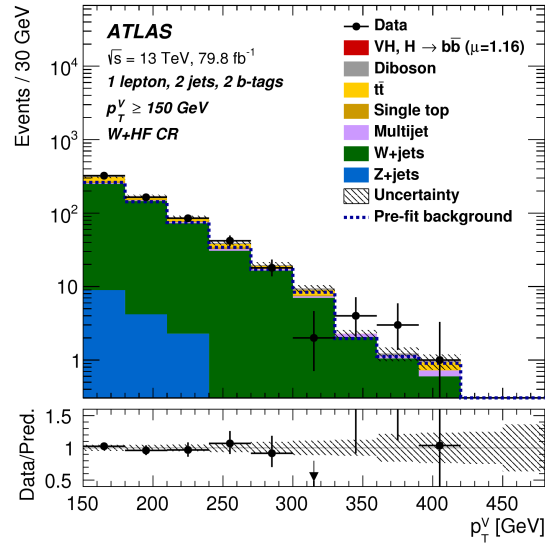
Selection	0-lepton	1-lepton		2-lepton
		<i>e</i> sub-channel	$\mu$ sub-channel	
Trigger	$E_T^{\text{miss}}$	Single lepton	$E_T^{\text{miss}}$	Single lepton
Leptons	0 <i>loose</i> leptons with $p_T > 7$ GeV	1 <i>tight</i> electron $p_T > 27$ GeV	1 <i>tight</i> muon $p_T > 25$ GeV	2 <i>loose</i> leptons with $p_T > 7$ GeV $\geq 1$ lepton with $p_T > 27$ GeV
$E_T^{\text{miss}}$	$> 150$ GeV	$> 30$ GeV	–	–
$m_{\ell\ell}$	–	–	–	$81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$
Jets	Exactly 2 / Exactly 3 jets			Exactly 2 / $\geq 3$ jets
Jet $p_T$	$> 20$ GeV for $ \eta  < 2.5$ $> 30$ GeV for $2.5 <  \eta  < 4.5$			
<i>b</i> -jets	Exactly 2 <i>b</i> -tagged jets			
Leading <i>b</i> -tagged jet $p_T$	$> 45$ GeV			
$H_T$	$> 120$ GeV (2 jets), $> 150$ GeV (3 jets)		–	–
$\min[\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{j}_{\text{ets}})]$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)		–	–
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{b}\vec{b})$	$> 120^\circ$		–	–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^\circ$		–	–
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p}_T^{\text{miss}})$	$< 90^\circ$		–	–
$p_T^V$ regions	$> 150$ GeV		$75 \text{ GeV} < p_T^V < 150 \text{ GeV}, > 150 \text{ GeV}$	
Signal regions	–	$m_{bb} \geq 75 \text{ GeV}$ or $m_{\text{top}} \leq 225 \text{ GeV}$		Same-flavour leptons Opposite-sign charges ( $\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75 \text{ GeV}$ and $m_{\text{top}} > 225 \text{ GeV}$		Different-flavour leptons Opposite-sign charges

# Background control regions

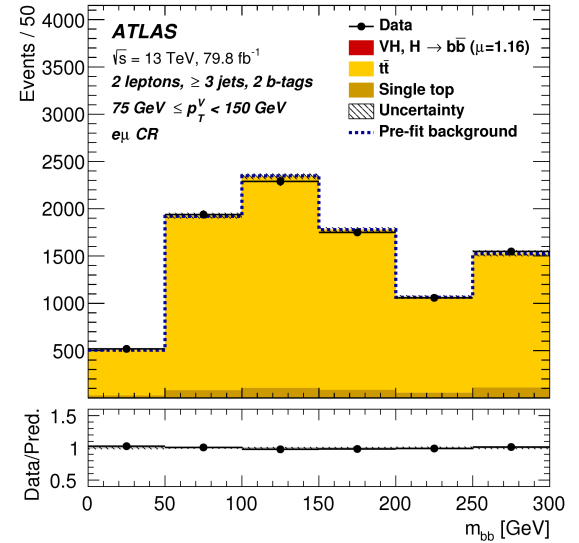
Control regions

$m_{bb} < 75 \text{ GeV}$  and  $m_{top} > 225 \text{ GeV}$

Different-flavour leptons  
Opposite-sign charges



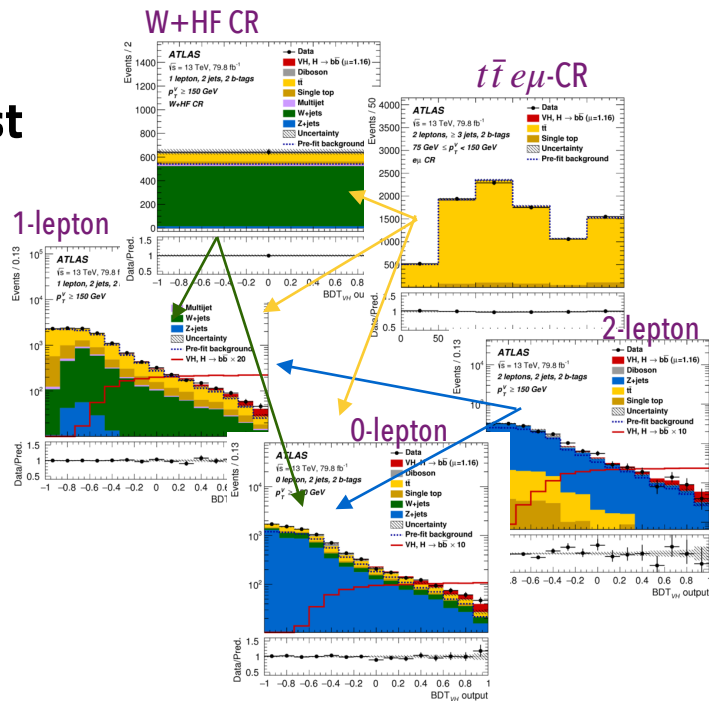
- Enriched in W+jets



- Enriched in top pairs

# Statistical analysis: signal hypothesis test and signal measurement

- Background and signal estimate with Monte-Carlo simulation
- Adjust simulation to data, fit parameters
  - Dominant backgrounds normalisation
  - Signal strength factor  $\mu = \frac{N_{obs}}{N_{exp}}$
- Simultaneous profile likelihood binned fit to all regions
  - Inputs: BDT output (SR),  $m_{bb}$  ( $t\bar{t} e\mu$ -CR) and yield (W+HF CR)
  - Floating normalisation of dominant backgrounds
  - Total number of SR+CR: 14



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

# Statistical data analysis

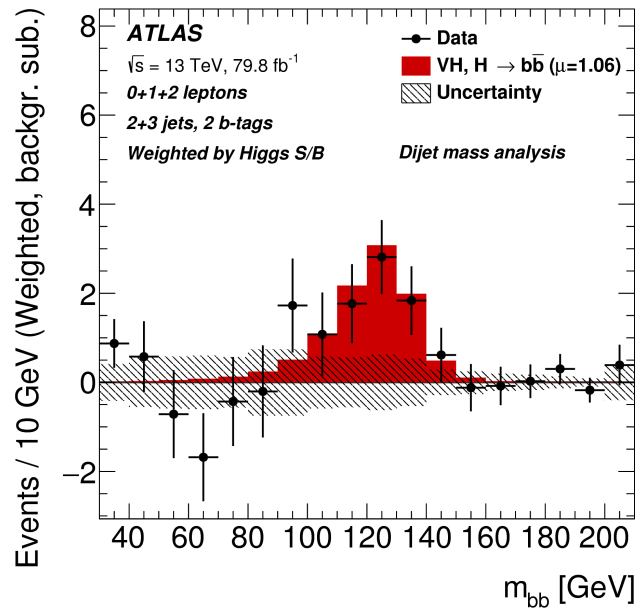
- Uncertainties
  - Simulation (statistics, modelling)
  - Theoretical (eg. cross-section)
  - Experimental (eg. jet energy)
  - (Plus data statistical uncertainties)
- Enter the fit as “nuisance parameters”, i.e., with an a priori value to be constrained by data
- Impact of each uncertainty source quantified as a signal strength uncertainty  $\sigma_\mu$

Source of uncertainty	$\sigma_\mu$	
Total	0.259	
Statistical	0.161	
Systematic	0.203	
Experimental uncertainties		
Jets	0.035	
$E_T^{\text{miss}}$	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	

# Results

- Remember...
  - $p_0$  probability that the signal hypothesis is fake
- Analysed 79.8 fb<sup>-1</sup> of 13 TeV pp data
  - Observed (expected) significance: 4.9 $\sigma$  (4.3 $\sigma$ )
  - Almost there, but didn't reach the "5 $\sigma$ " to claim observation
  - $\mu = 1.16^{+0.27}_{-0.25}$
- Cross-checked with pure "cut-based" analysis
  - $\mu = 1.06$ , 3.6 $\sigma$  (notice significance gain with BDT)
- All measurements compatible with SM ( $\mu = 1$ )

Signal strength	Signal strength	$p_0$		Significance	
		Exp.	Obs.	Exp.	Obs.
0-lepton	$1.04^{+0.34}_{-0.32}$	$9.5 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$	3.1	3.3
1-lepton	$1.09^{+0.46}_{-0.42}$	$8.7 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	2.4	2.6
2-lepton	$1.38^{+0.46}_{-0.42}$	$4.0 \cdot 10^{-3}$	$3.3 \cdot 10^{-4}$	2.6	3.4
$VH, H \rightarrow b\bar{b}$ combination	$1.16^{+0.27}_{-0.25}$	$7.3 \cdot 10^{-6}$	$5.3 \cdot 10^{-7}$	4.3	4.9

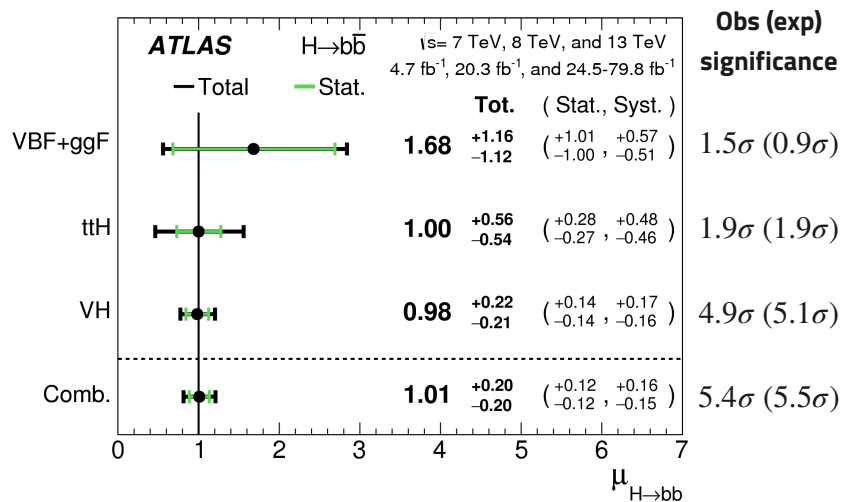


# Combination with other channels:

## Habemus $H \rightarrow b\bar{b}$ !!!

- Observation of  $H \rightarrow b\bar{b}$ 
  - $VH(H \rightarrow b\bar{b})$  combination of Run 1&2 data
  - Combination with other production modes: ttH, VBF+gluon fusion (ggF)

- $H \rightarrow b\bar{b}$  dominant in VH observation ( $5.3\sigma$ )
  - Combined with  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ^* \rightarrow 4l$

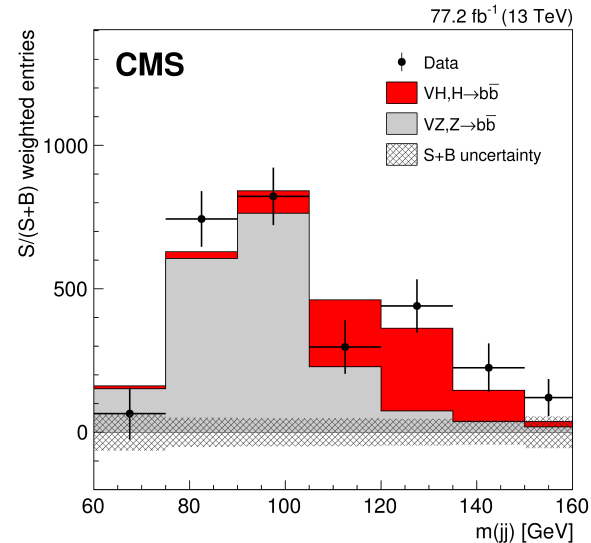
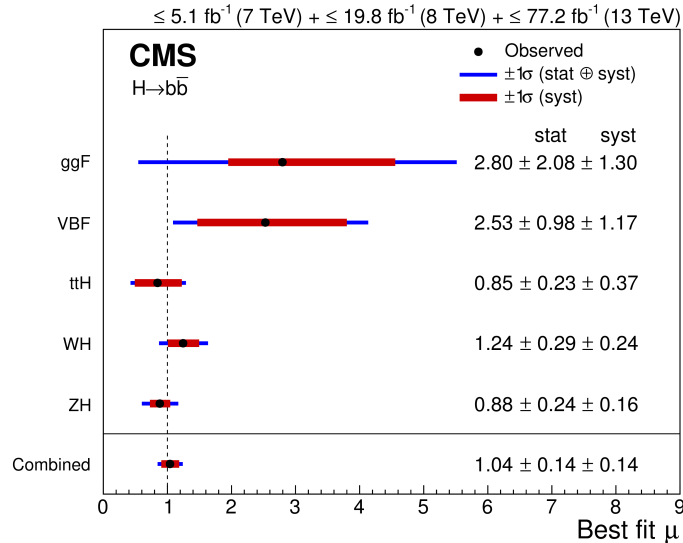


Channel	Significance	
	Exp.	Obs.
$H \rightarrow ZZ^* \rightarrow 4l$	1.1	1.1
$H \rightarrow \gamma\gamma$	1.9	1.9
$H \rightarrow b\bar{b}$	4.3	4.9
VH combined	4.8	5.3

- All measurements compatible with SM ( $\mu = 1$ )

# CMS counterpart

- Analysis of Run 1&2 pp data
  - Combination of  $VH(H \rightarrow bb)$  with other  $H \rightarrow bb$  searches in different production modes
  - Observed (expected) significance:  $5.6\sigma$  ( $5.5\sigma$ )
  - $\mu = 1.04 \pm 0.20$



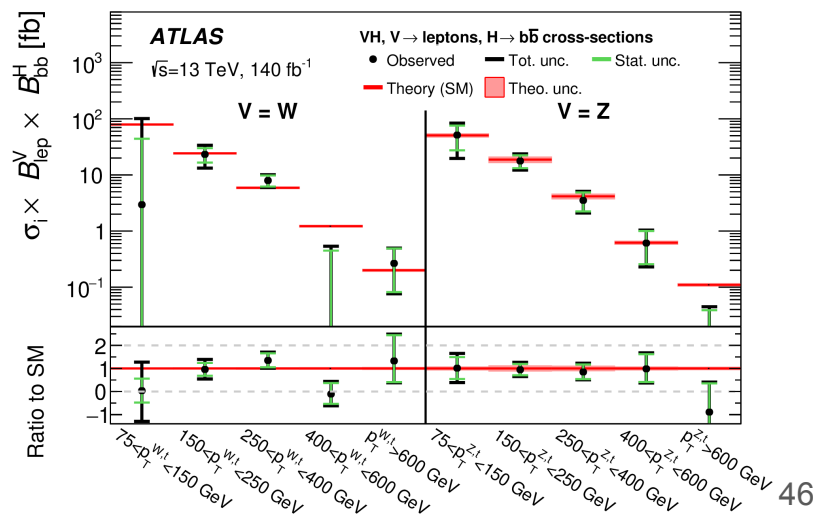
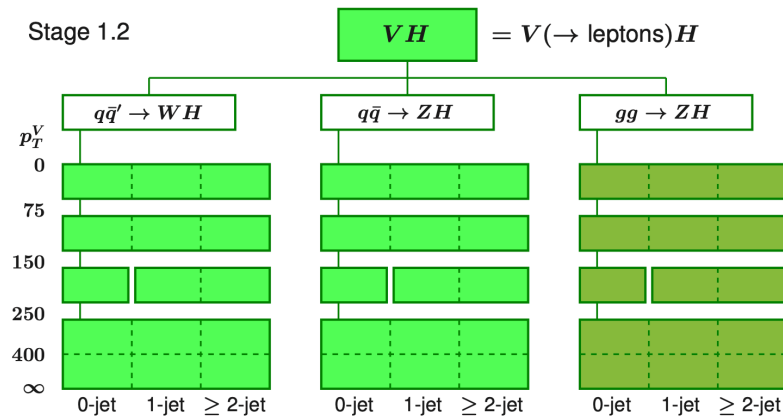
| **Snooping through  
the  $H \rightarrow b\bar{b}$  window**

# What's next?

- Use  $H \rightarrow b\bar{b}$  to measure Higgs properties
  - Towards differential cross-section
  - Investigate the HVV and Hbb interaction vertex
  - Higgs boosted regime
- What we may expect from the High Luminosity-LHC

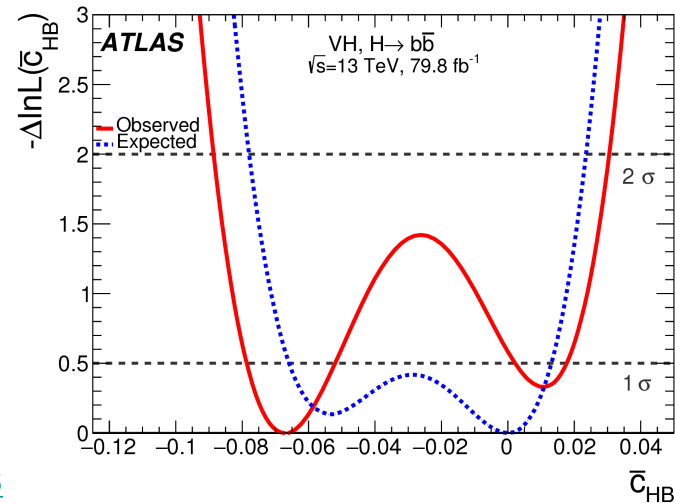
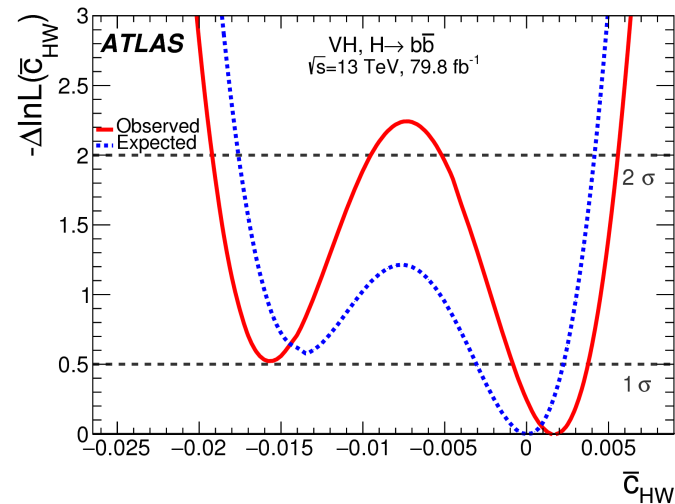
# Differential cross-section measurements

- Simplified Template Cross Section framework
  - Measure  $\sigma$  in exclusive regions of the phase space
  - Increasing granularity with acquired data
- Probe kinematic properties of Higgs boson in more detail
- All measurements compatible with SM
- Towards measurement of differential  $\sigma_{VH}$ 
  - $\sigma_{VH}$  as a function of  $p_T^V$



# Effective Field Theory interpretation of VH cross-section measurements

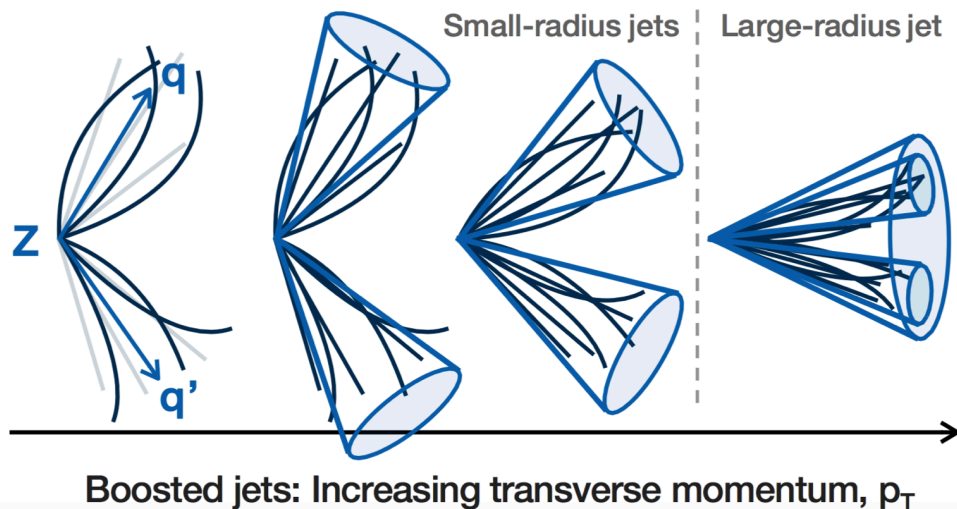
- Investigate the HVV interaction vertex
- EFT framework
  - Model anomalous Higgs couplings adding extra terms to the SM Lagrangian:  $\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \mathcal{L}_{BSM}$
  - Use cross-section measurements to constrain the strength of new operators:  $\sigma_{EFT} = \sigma_{SM} + \sigma_{BSM} + \sigma_{int}$
  - $c_{HW}$  and  $c_W$  regulate new interaction between H and W/Z bosons
  - $c_{HB}$  and  $c_B$  scale new interactions with Z (affect only  $\sigma_{ZH}$  and not  $\sigma_{WH}$ )
  - SM limit:  $c \rightarrow 0$
- $c$  limited to few percent at 95% CL



# Higgs “Boosted” Regime

Collisions with large energy transfer are more sensitive to New Physics effects

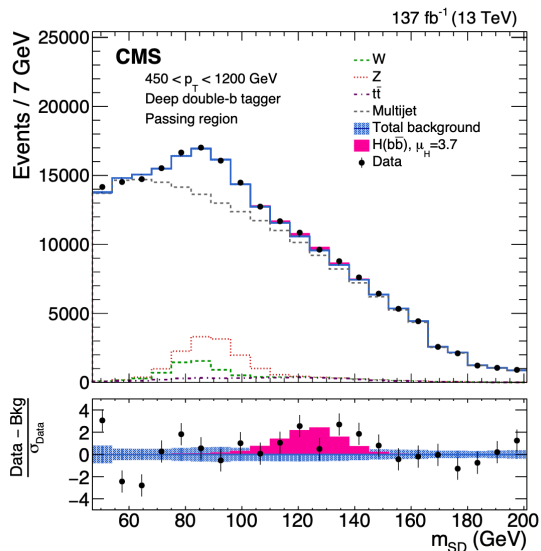
- Higgs produced with large momentum (boosted)
- Hadronically decaying particles lead to large-jets, unable to resolve two jets



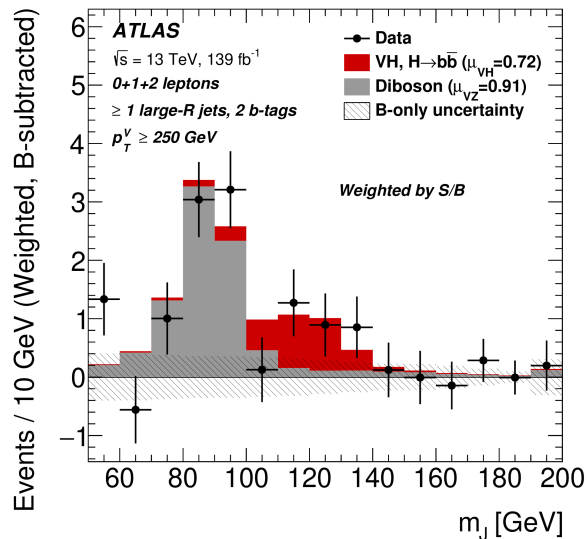
- Signal reconstructed has a large-R jet
- 2 b-tagged sub-jets inside large-R jet (reconstructed from tracks)
- Other techniques being explored, e.g. using Deep Neural Networks

# "Boosted" $H \rightarrow b\bar{b}$

- $S/\sqrt{B}$  is larger for high momentum
  - Search inclusive in all production modes
  - Observed (expected) significance:  $2.5\sigma$  ( $0.7\sigma$ )



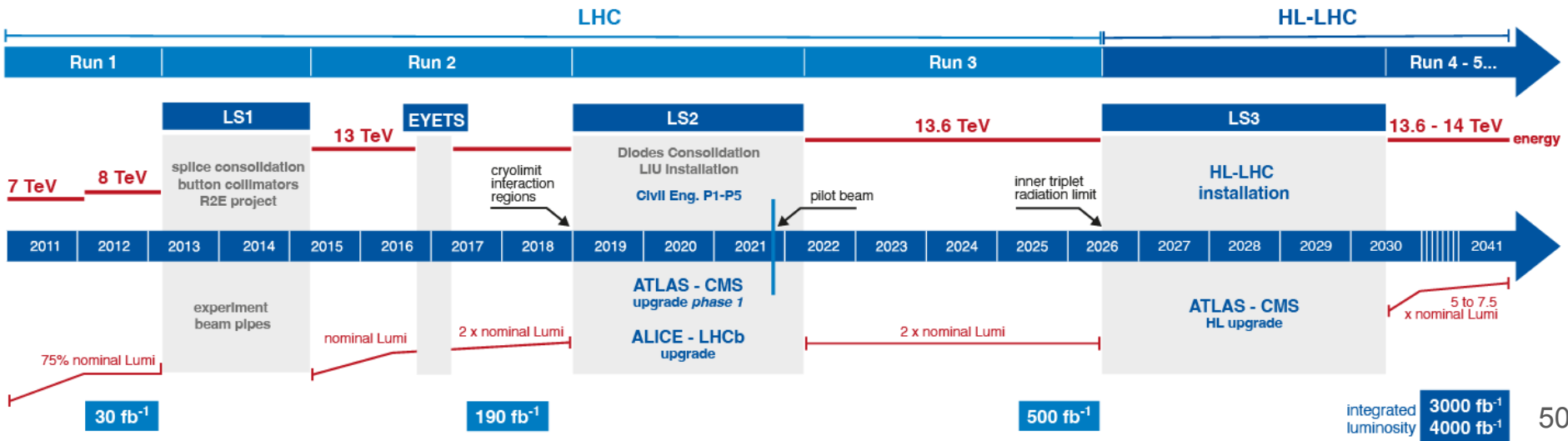
- Associated W/Z production
  - $p_{TJ} > 250$  GeV
  - Observed (expected) significance:  $2.1\sigma$  ( $2.7\sigma$ )
  - $\mu = 0.72^{+0.39}_{-0.36}$  (SM-compatible)



# High Luminosity-LHC upgrade

The HL-LHC upgrade will increase the instantaneous luminosity by a factor of 5 to 7

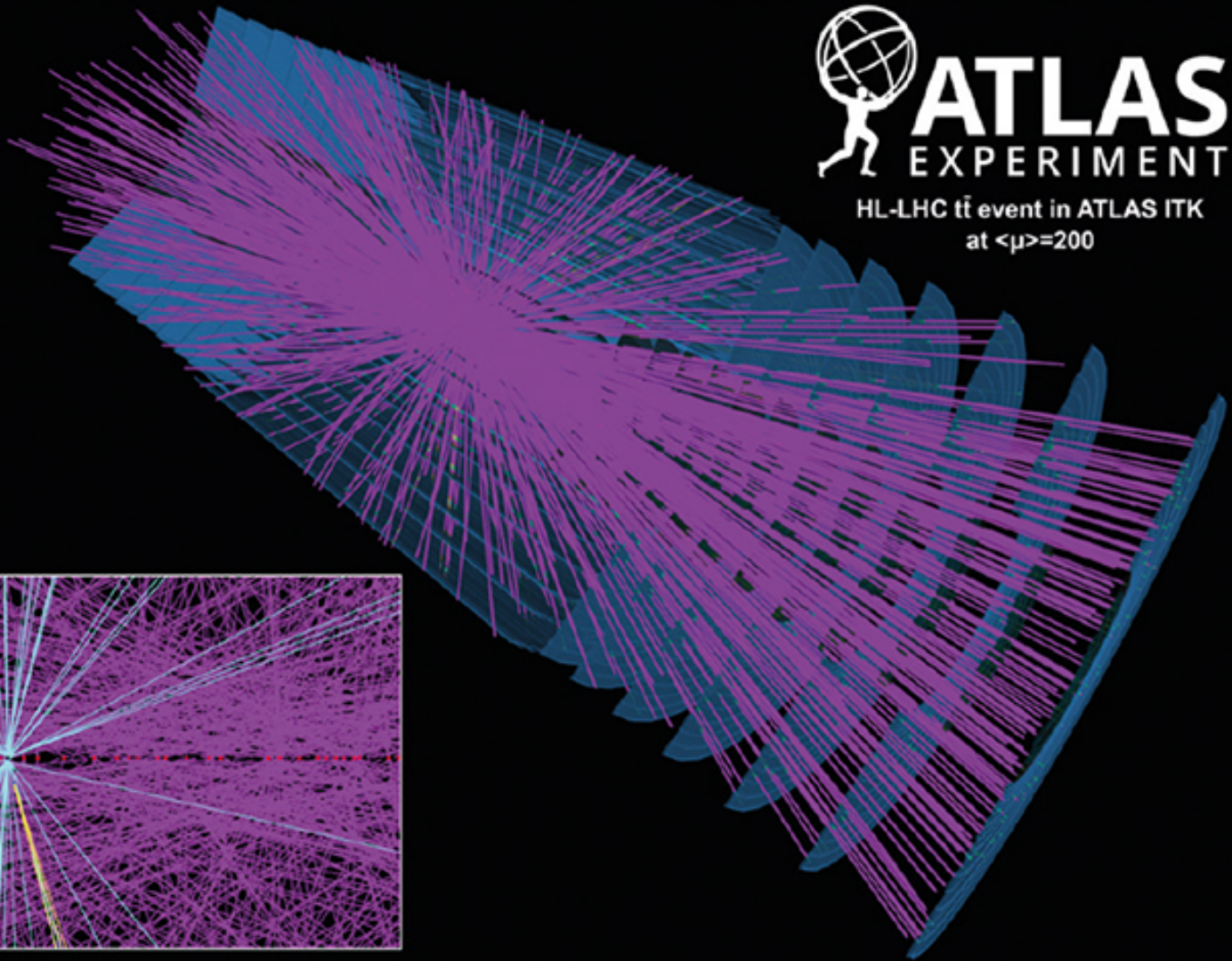
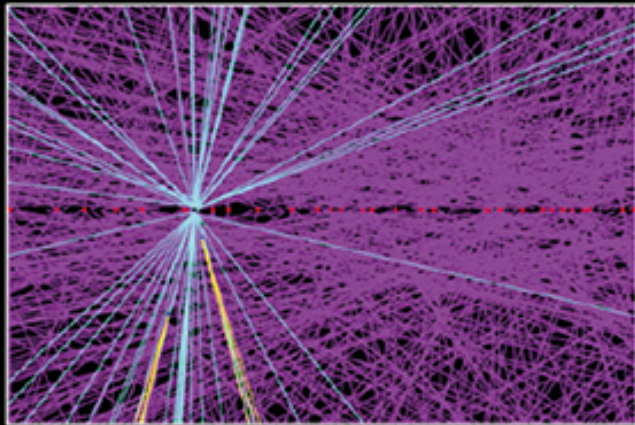
- A lot more data to analyse: 3000/4000 fb<sup>-1</sup>
- Will reduce statistical uncertainty of the measurements
- High pile-up: simultaneous collisions per bunch crossing 33 → 140
- Noisy environment: ambiguous track reconstruction, collision vertex finding, pile-up energy subtraction,...





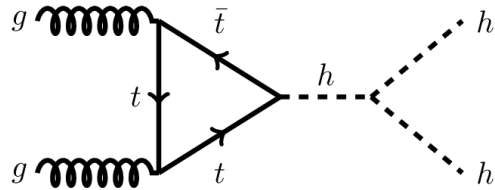
# ATLAS EXPERIMENT

HL-LHC  $t\bar{t}$  event in ATLAS ITK  
at  $\langle\mu\rangle=200$



# HL-LHC prospects

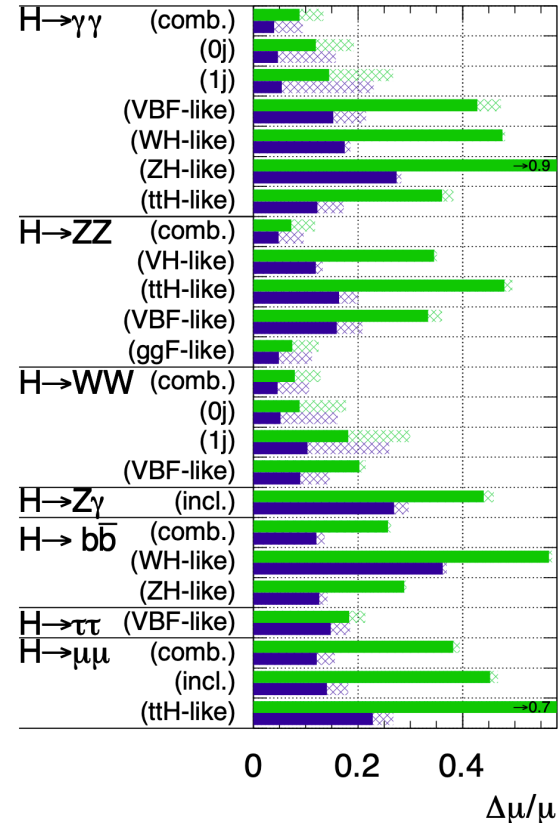
- Sensitivity to Higgs rare processes
  - $H \rightarrow \mu\bar{\mu}$ ,  $H \rightarrow Z\gamma$
  - Higgs self-coupling via di-Higgs production



- More precise measurements

## ATLAS Simulation Preliminary

$\sqrt{s} = 14$  TeV:  $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$  ;  $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$





# Thanks!

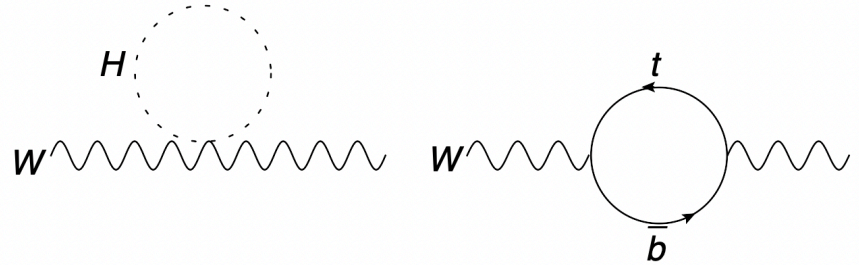
Any questions?

You can find me at [rute@lip.pt](mailto:rute@lip.pt)

# On the importance of precision measurements

# Precise tests of SM internal consistency

- The SM has many parameters but not all of them are independent
- Eg: W mass:
  - Sub %-level radiative correction dependent on  $M_{top}^2$  and  $\ln M_H$
- Precise measurements of electroweak observables can be used to test internal coherence of the model!!
  - Most sensitive measurements:  $M_{top}, M_W, M_H$



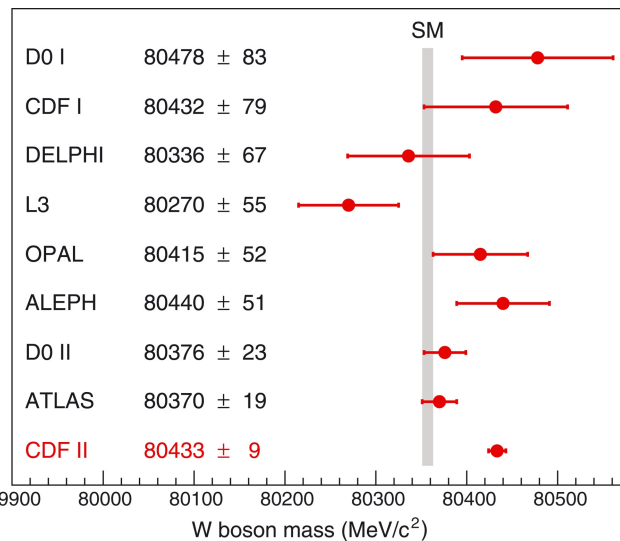
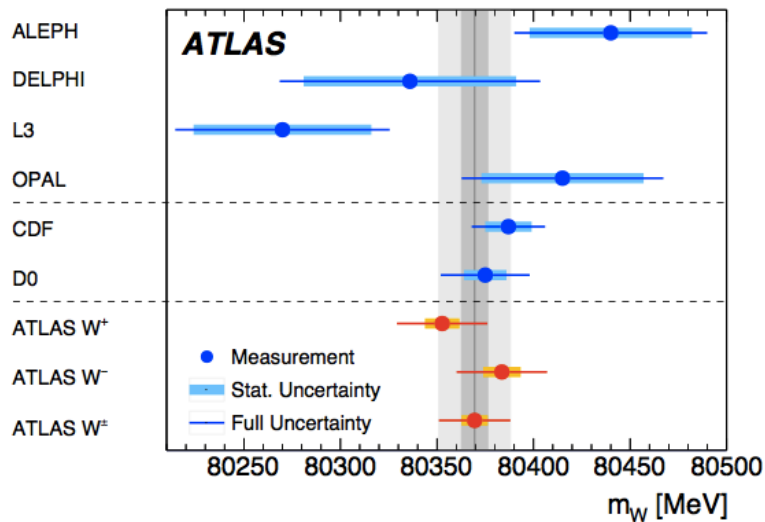
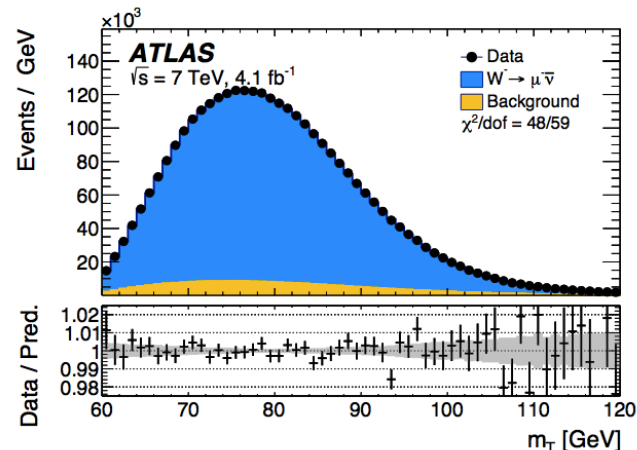
$$M_W^2 = \rho M_Z^2 \cos^2 \theta_W$$

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

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

# W boson mass measurement

- High precision measurement  $\rightarrow$  low pile-up
  - Data from 2011 only!
- Consistency test of the SM



Hot news:  
 Last week CDF-II  
 published a new  
 measurement with  
 record precision  
 incompatible with SM  
 expectations