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

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

Rute Pedro | 17th April

LIP Course on Physics at the LHC

Fundação para a Ciência e a Tecnologia
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COMPETE 2020
PROGRAMA OPERACIONAL COMPETITIVIDADE E INTERNACIONALIZAÇÃO
PORTUGAL 2020
UNIÃO EUROPEIA
Fundo Europeu de Desenvolvimento Regional
ATLAS EXPERIMENT

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

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

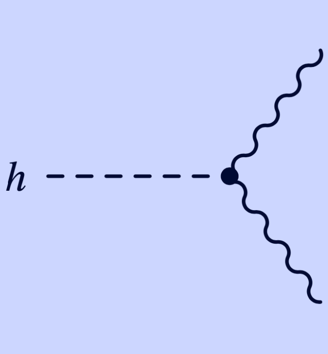
Kinetic term for the Gauge fields and interaction between gluons

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

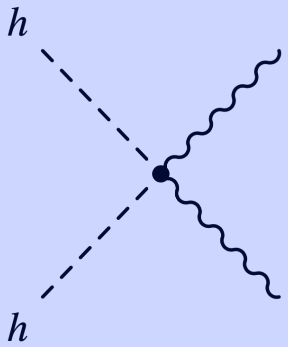
Yukawa couplings and mass terms for Fermions

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

# Reminder: Higgs couplings

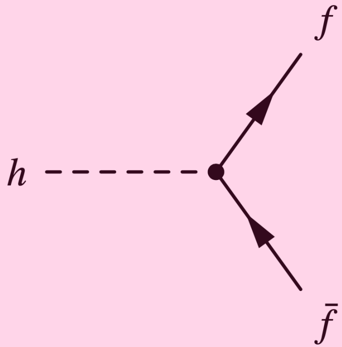



$$g_{hVV} \propto \frac{M_V^2}{v}$$




$$g_{hhVV} \propto \frac{M_V^2}{v^2}$$

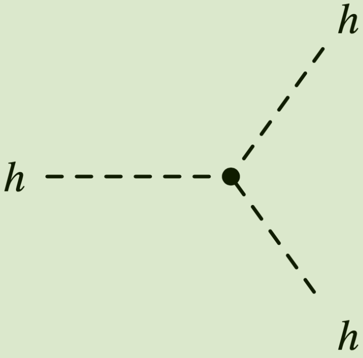
To gauge bosons



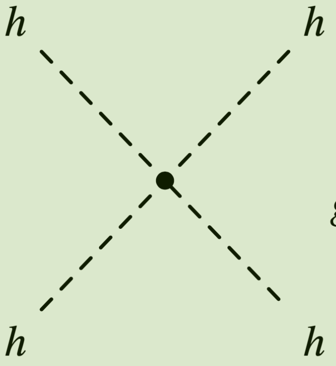

$$g_{hf\bar{f}} \propto \frac{m_f}{v}$$

Yukawa

Self-interactions



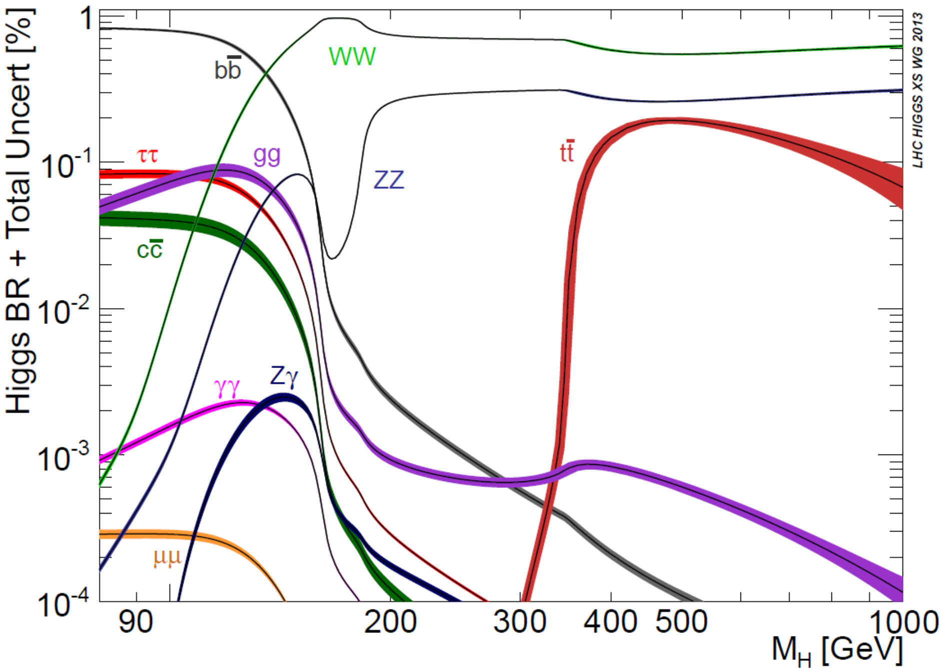

$$g_{hhh} \propto \frac{M_h^2}{v}$$




$$g_{hhhh} \propto \frac{M_h^2}{v^2}$$

# 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 $m_V/m_h$

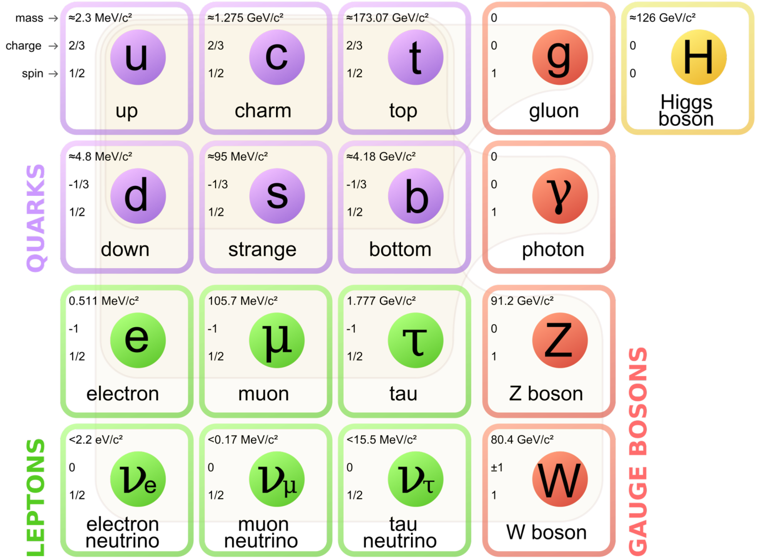


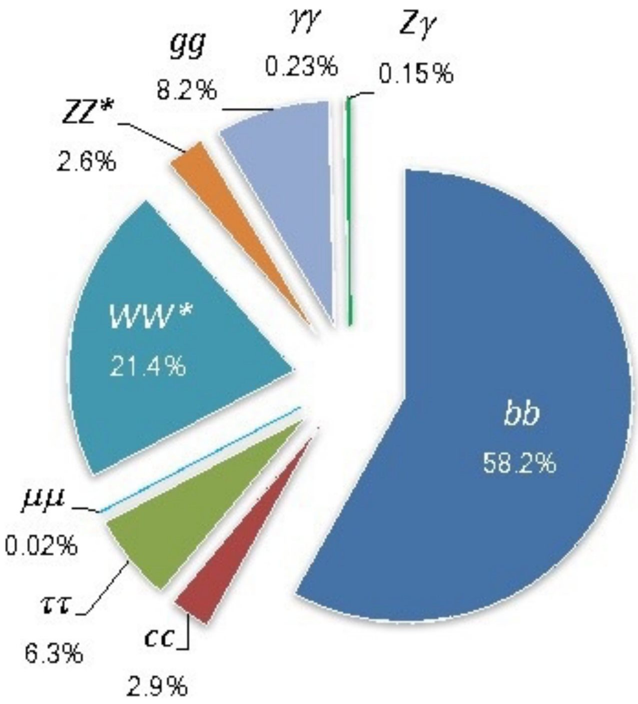

$$\Gamma(h \to f\bar{f}) \propto m_f^2 m_h \sqrt{1-x} \quad \text{, with } x = 4m_f^2/m_h^2$$

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

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

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

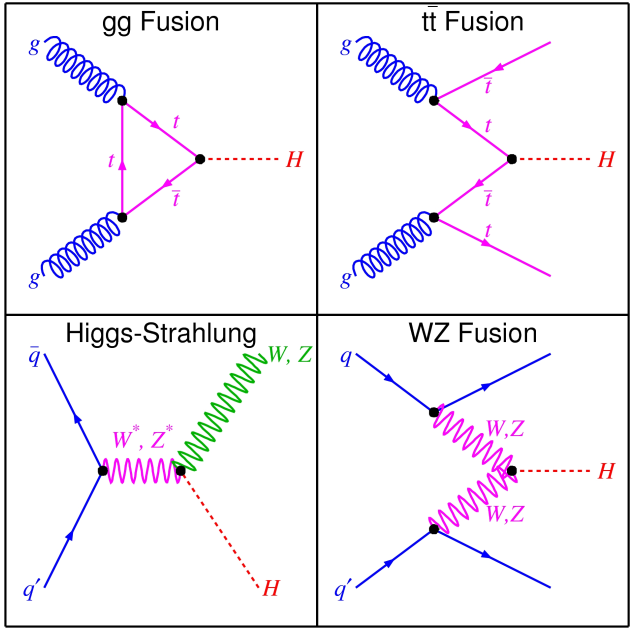



- For $m_h$~125 GeV: b-quarks are the heaviest particles such that $2m < m_h$
- $H \to b\bar{b}$ dominates the Higgs width
- Measuring it is fundamental to probe non-SM Higgs decays

# $H \rightarrow b\bar{b}$ and W/Z associated production: a long marriage story

# Search "*channels*"

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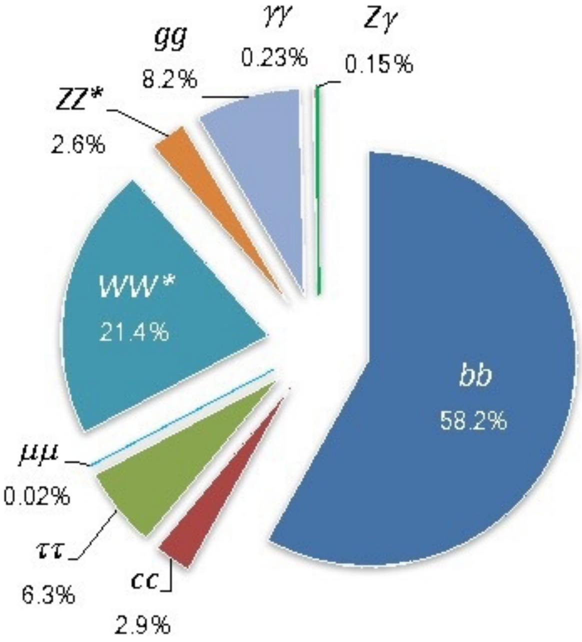



Production mode

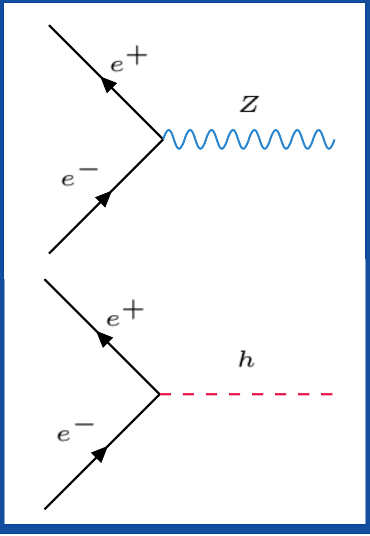
(depends on initial state particles: $pp, p\bar{p}, e^+e^-$)

Decay mode

(Branching ratios depend on Higgs mass)

# LEP

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

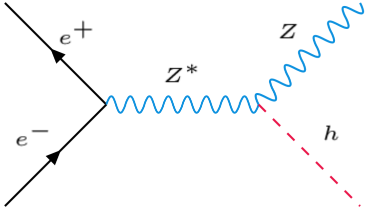



$$\sigma(e^+e^- \to Z) = 0.0671\frac{\pi}{2}\delta(E_{CM}^2 - m_Z^2)$$

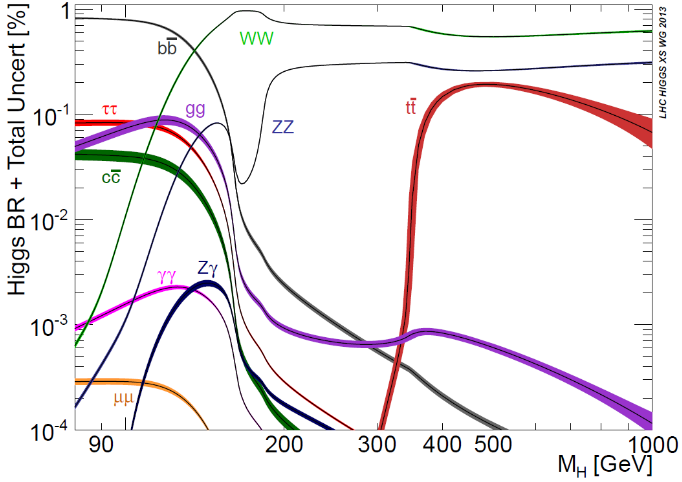
$$\sigma(e^+e^- \to H) = 4.31 \times 10^{-12}\frac{\pi}{2}\delta(E_{CM}^2 - m_H^2)$$

(suppressed by small electron-Higgs coupling)

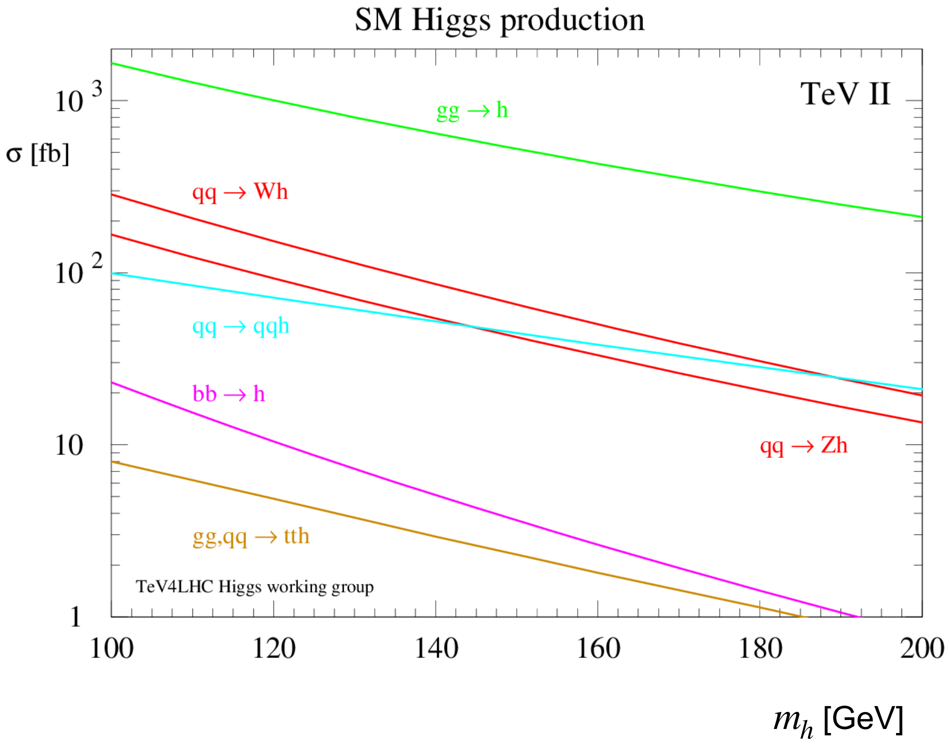
- The solution: $e^+e^- \to ZH, \quad E_{CM} > m_Z + m_H$




- Maximum $E_{CM}$ reached at LEP: 206 GeV
  - Could only probe H production: $m_H < E_{CM} - m_Z = 206 - 91 = 115$ GeV
  - $H \to b\bar{b}$ by far the dominant decay mode



# Tevatron

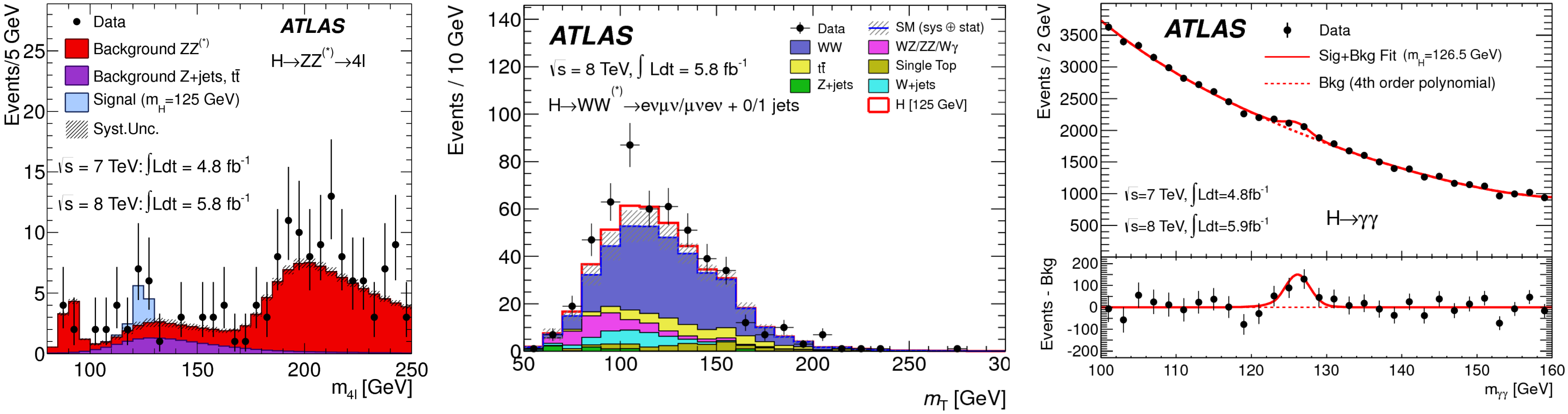



- $p\bar{p}$ collider, for low Higgs mass:
  - $gg \to H$ (via loop): large cross-section but very small sensitivity
  - Golden channel is W/ZH production and $H \to b\bar{b}$ decay
  - Tevatron legacy Higgs result combining all data from both CDF and D0 experiments: Higgs evidence on this channel

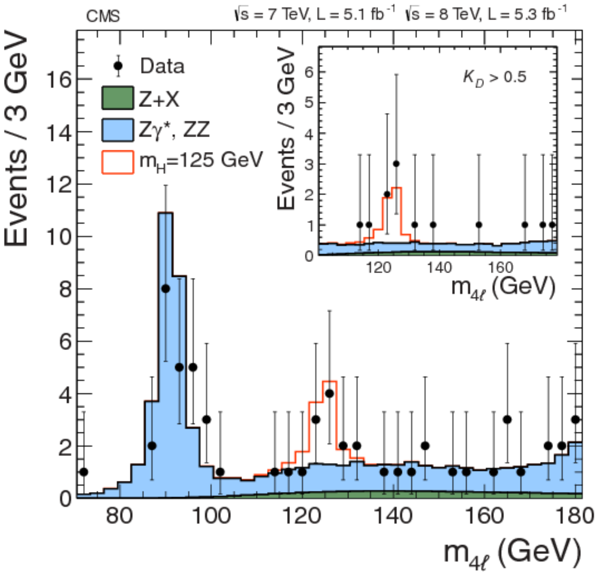
# $H(\rightarrow b\bar{b})$ at the LHC

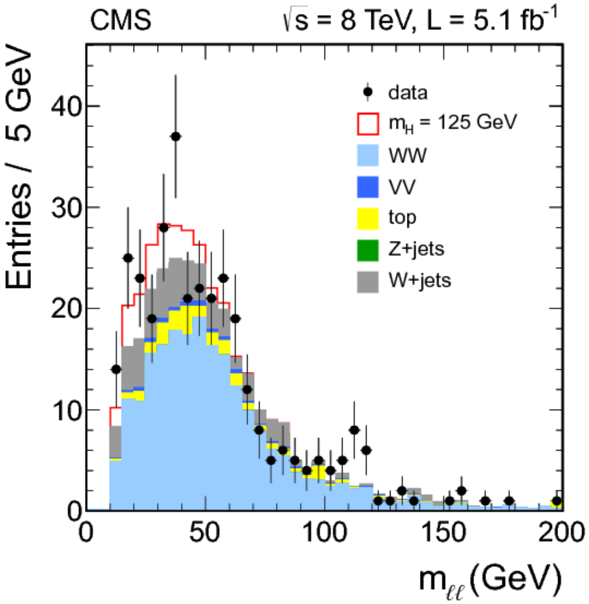
# Higgs discovery - ATLAS
## 2012

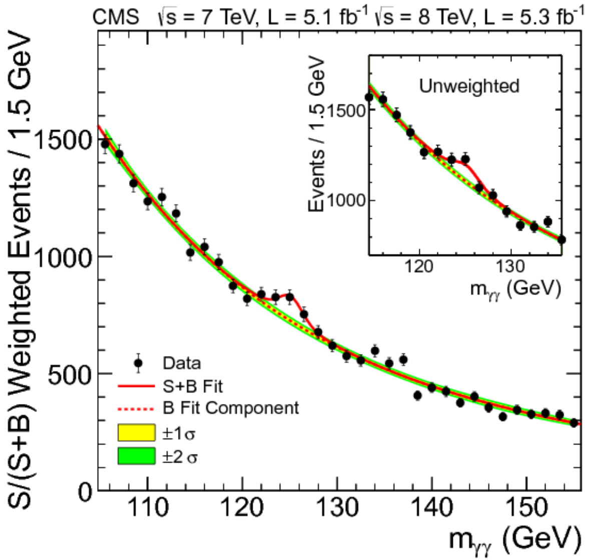
- Golden channels for Higgs discovery $H \to ZZ, \quad H \to WW, \quad H \to \gamma\gamma$
- We measured the Higgs mass and determined the charge
- Tested against non-SM spin/parity hypothesis



# Higgs discovery - CMS




- Independently by the two experiments

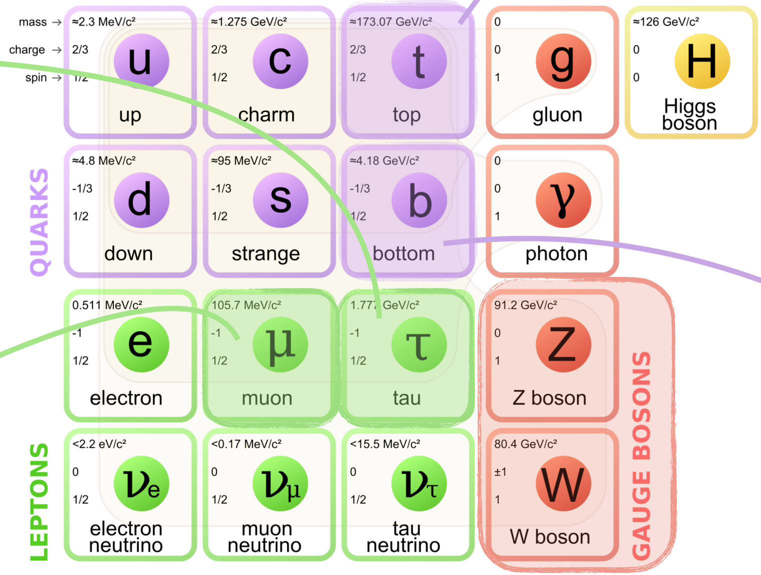
# Higgs and the Fermion sector

$H \rightarrow \tau\bar{\tau}$ decay (2017)

First direct detection of a Yukawa coupling

$H \rightarrow \mu\bar{\mu}$ decay (2020)

Evidence of couplings with 2nd fermion generation




$t\bar{t}H$ production (2018)

First direct detection of Higgs couplings to quarks

$H \rightarrow b\bar{b}$ decay (2018)

Higgs couplings to d-type quarks

Higgs discovery (2012)

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

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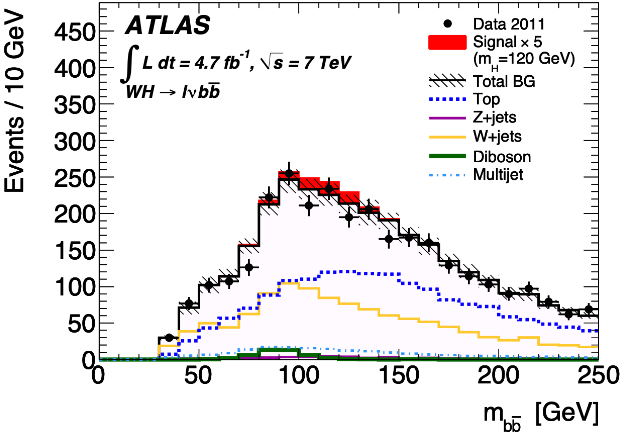


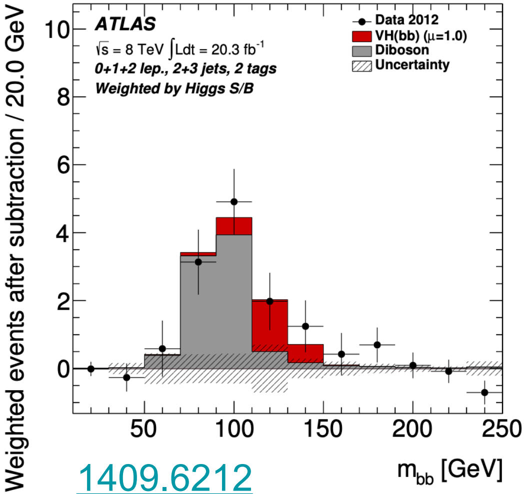


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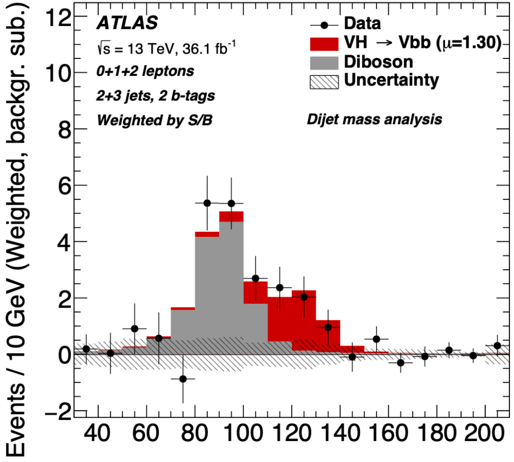


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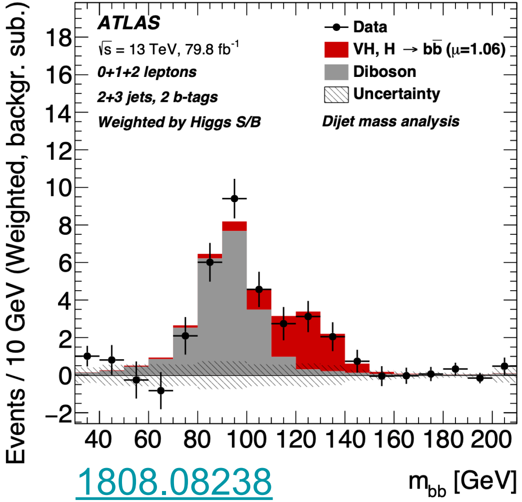


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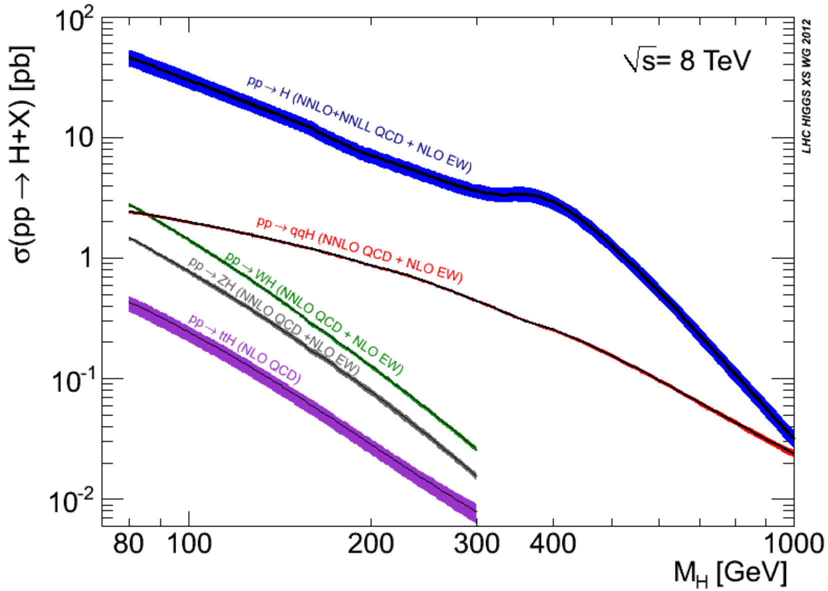
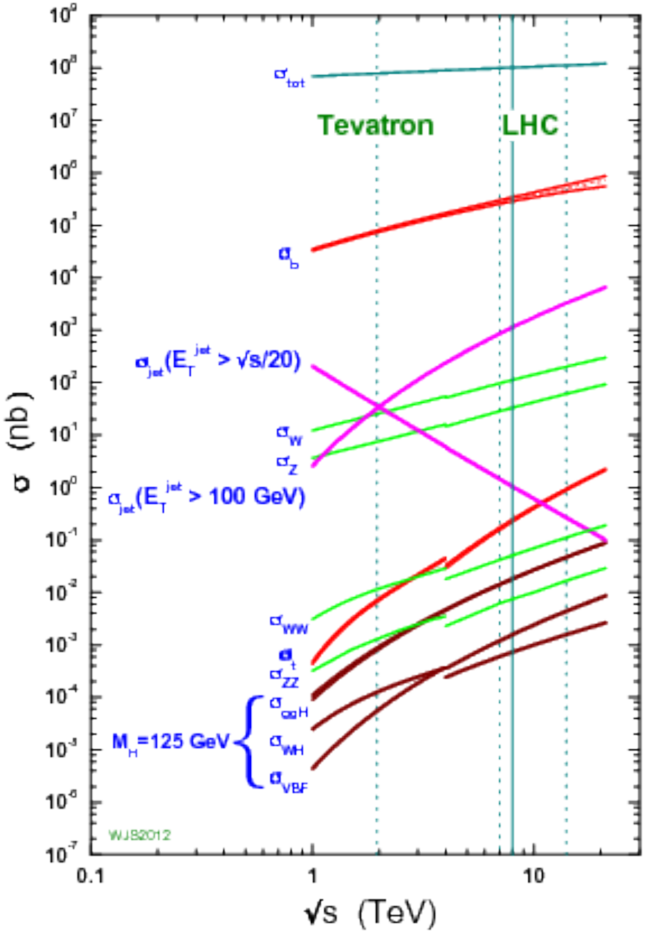
# $H \to b\bar{b}$ observation at the LHC

# Why did it take so long?

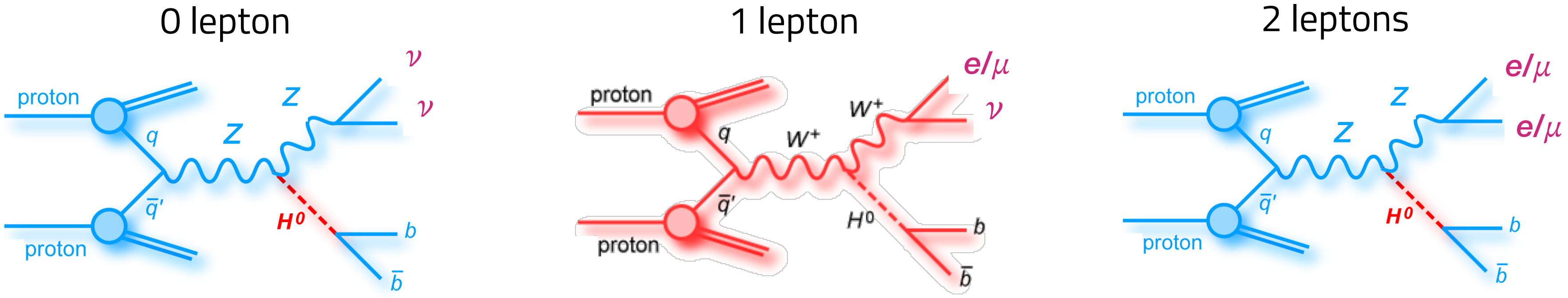
- It all comes down to $\dfrac{S}{\sqrt{B}}$ …



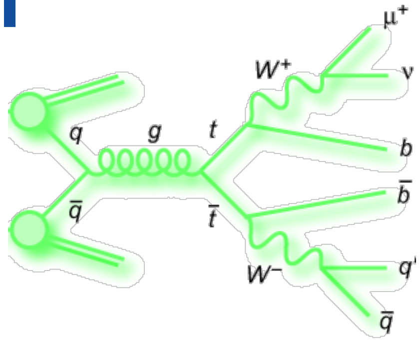
# A journey towards $H \to b\bar{b}$ observation with ATLAS

# Signal topology

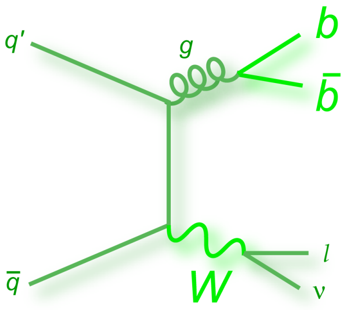



- W/Z associated production: use leptonic decay of W/Z to trigger the signal
- Mode most sensitive to $H \to b\bar{b}$
- At least one high $p_T$ jet
- 2 jets identified as the hadronisation of b-quarks ("*b-tagging*")
- 0, 1 or 2 isolated electrons/muons ("*leptons*")

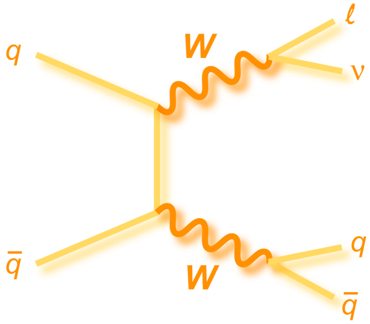
# Background processes



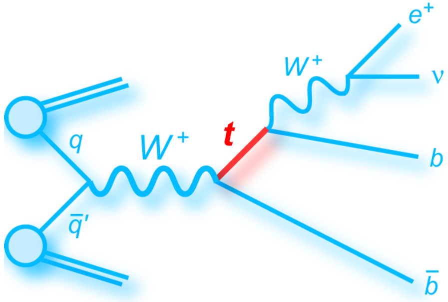

top pairs



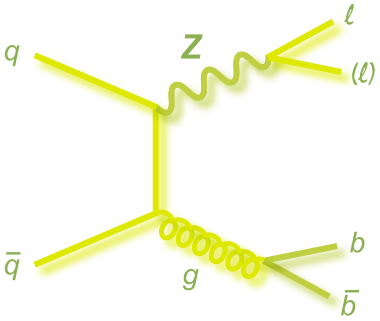

W+jets




vector boson pairs




top




Z+jets

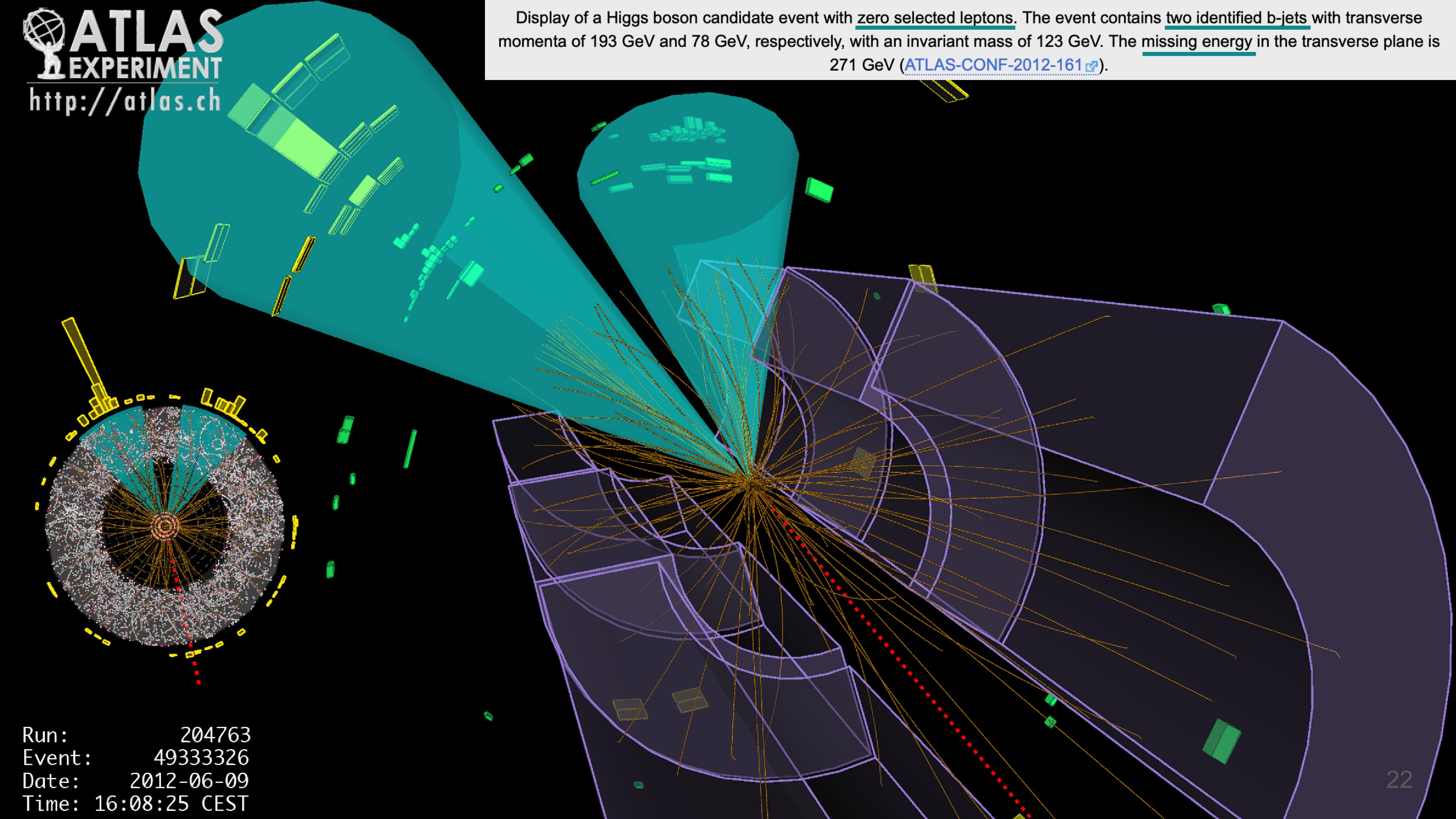
- Similar final state than signal
- Much larger cross-section
- Exemplifying decay chain, remember:
  - $Z \rightarrow q\bar{q}/\ell^{+}\ell^{-}/\nu\bar{\nu}$
  - $W^{-} \rightarrow q'\bar{q}/\ell^{-}\bar{\nu}$
  - $t \rightarrow W^{+}b$ (>99%)

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

- Higgs candidate: 2 b-jets
  - Jet finding
  - b-tagging
  - $m_{bb}$ resolution

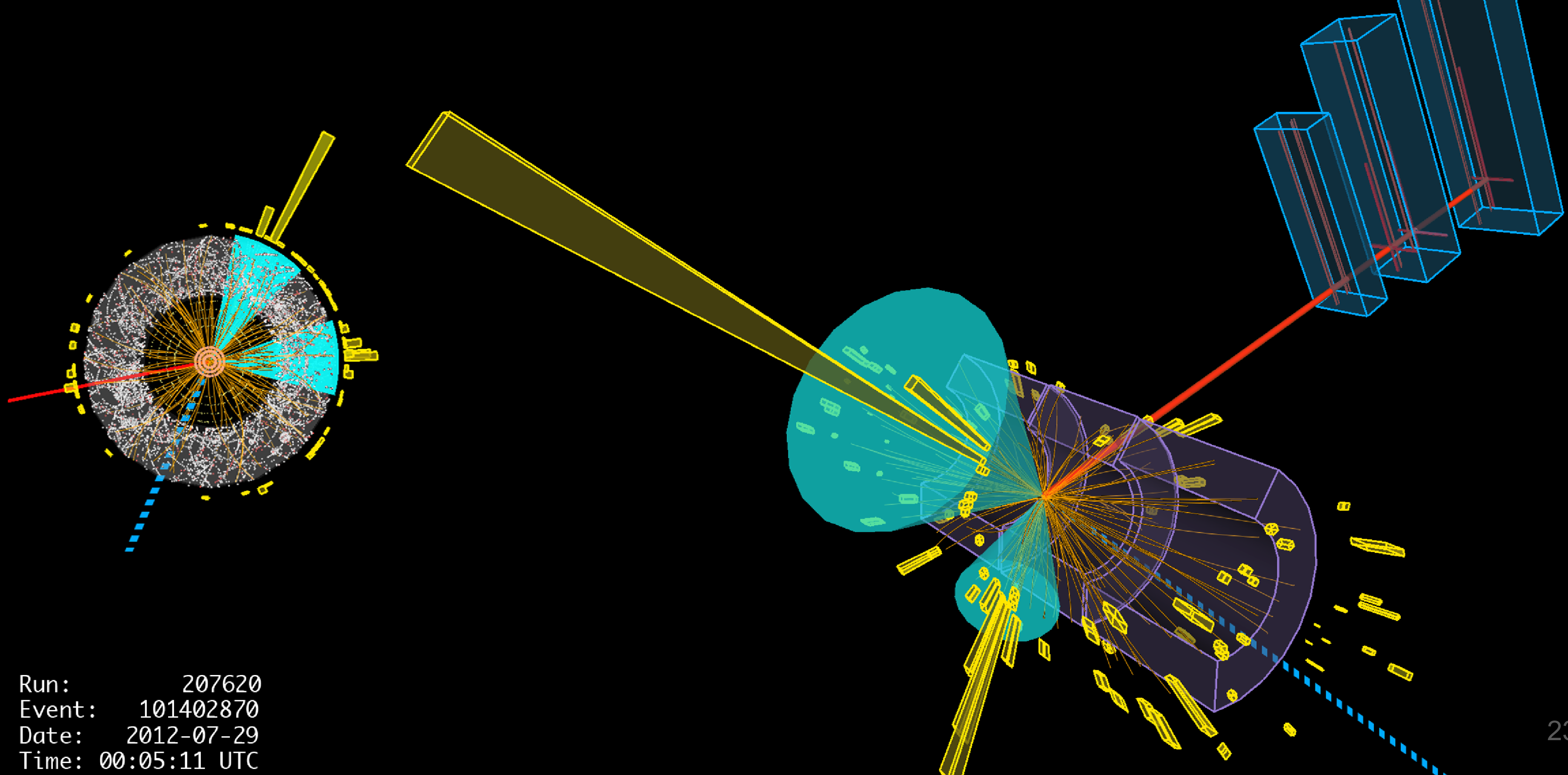
- (0 lepton) $Z \to \nu\bar{\nu}$:
  - Neutrinos are weakly interacting: yield missing energy
- (1 lepton) $W^{\pm} \to \ell^{\pm}\nu$ and (2 lepton) $Z \to \ell\bar{\ell}$:
  - Reconstruct and identify electrons and muons

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).

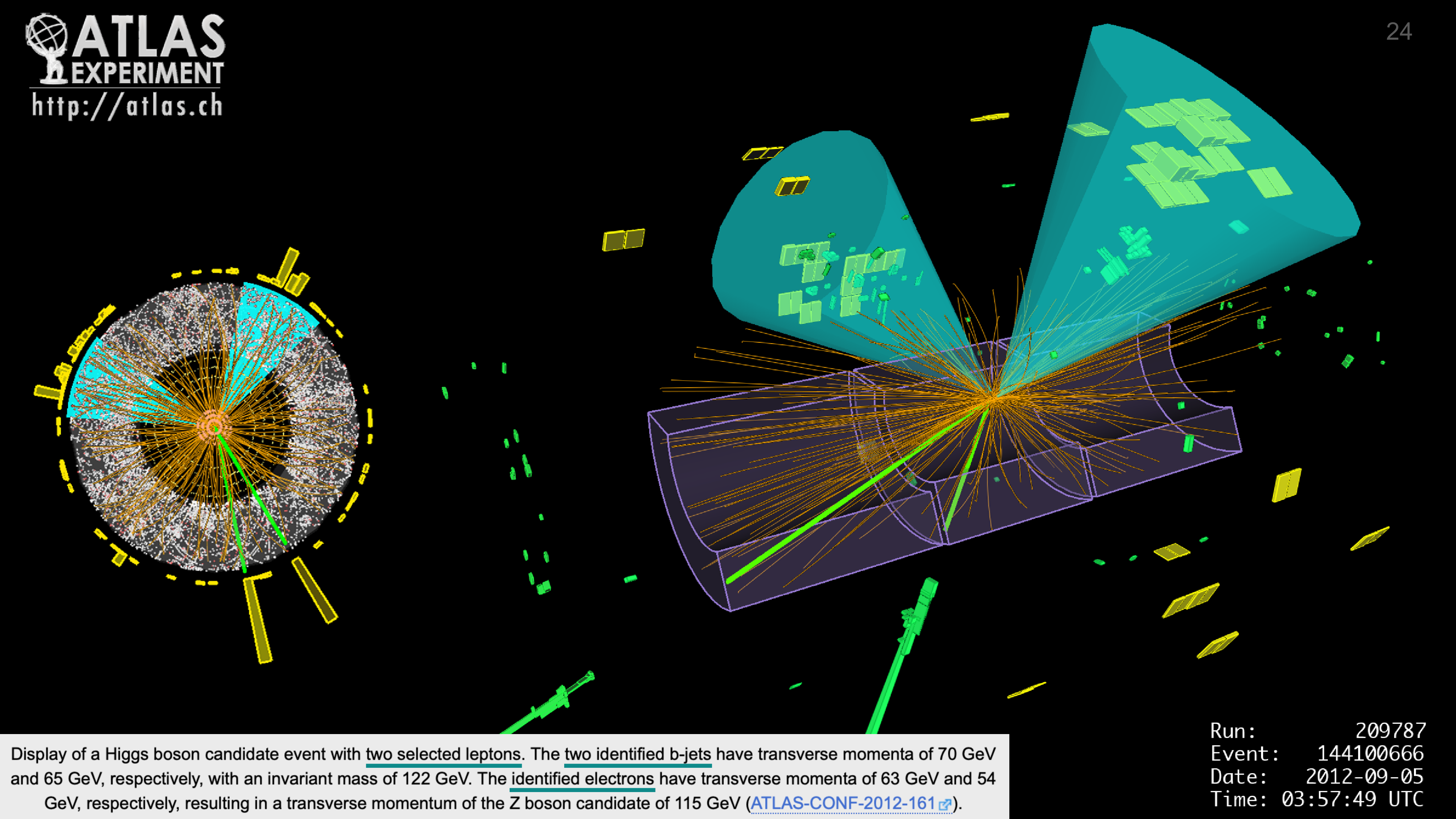


ATLAS EXPERIMENT
http://atlas.ch

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



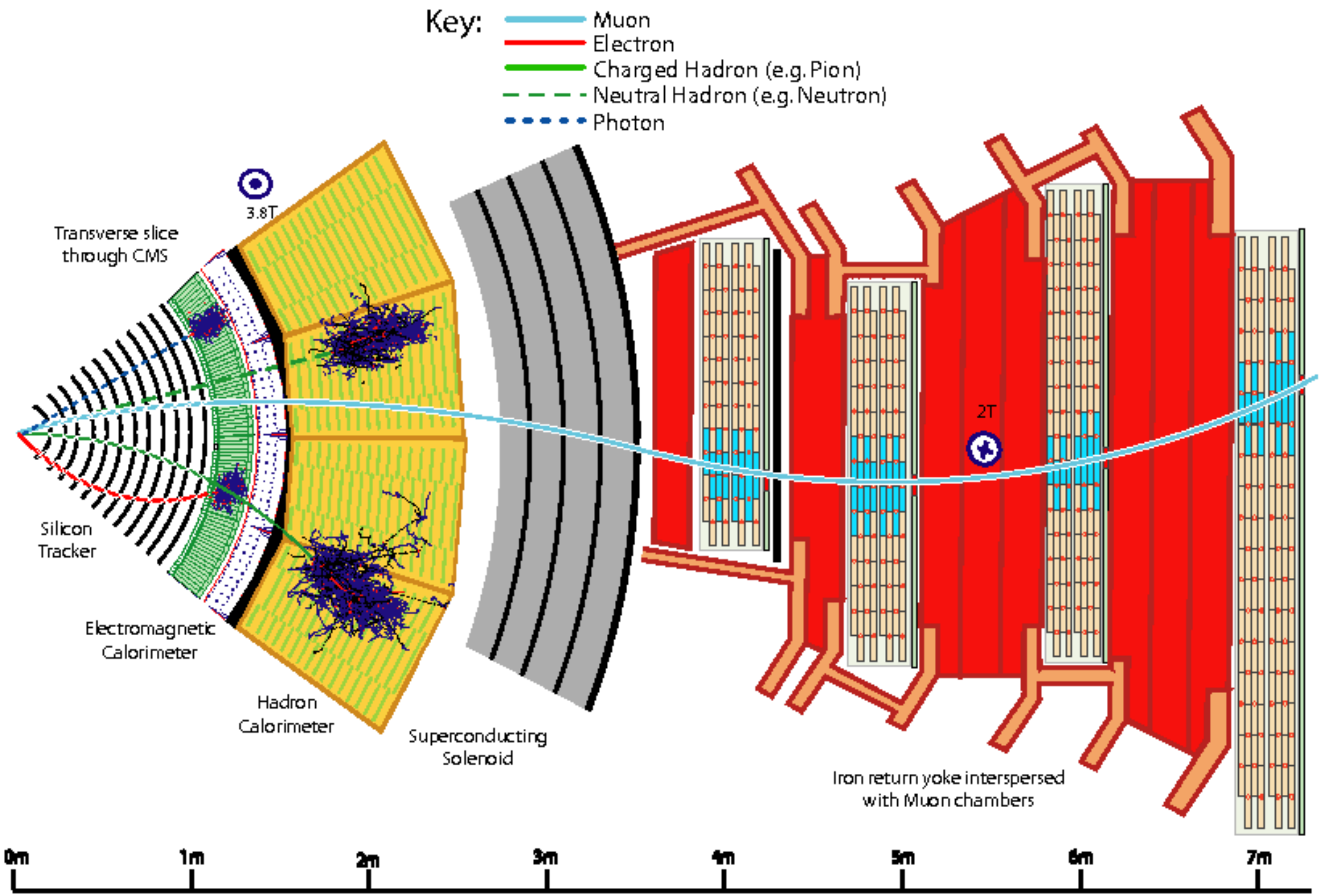
Run: 207620
Event: 101402870
Date: 2012-07-29
Time: 00:05:11 UTC




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 electrons 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).

# Anatomy of a collider event

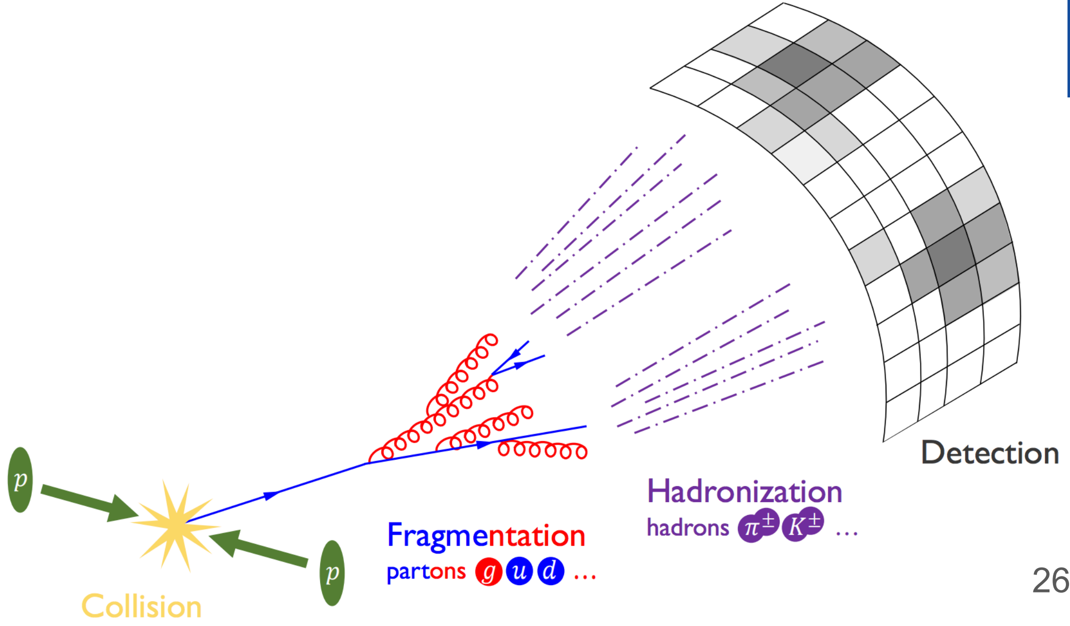
- Identify collision vertices and particles:
  - Track-finding
  - Electron/muon ID/ reconstruction
  - Jet clustering
- Measure energy, momenta, electric charge
- Jet flavour
- Event topology



# 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

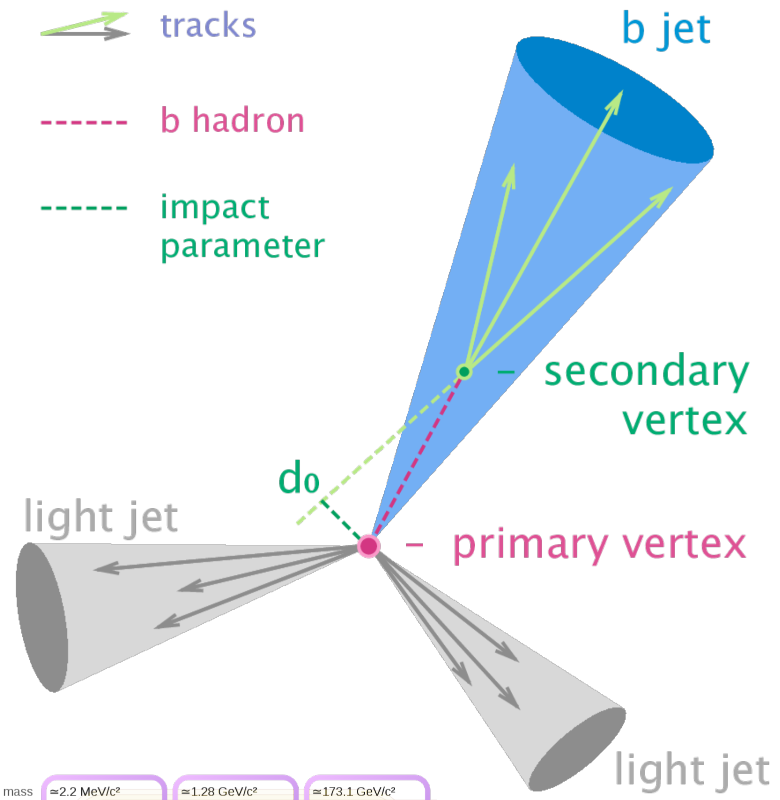


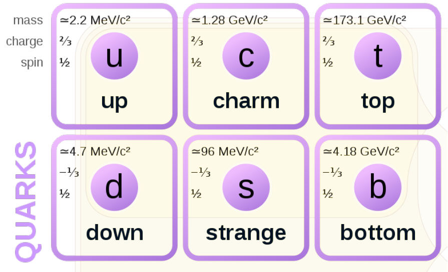
# Jet Flavour identification

Explore unique characteristics of heavy flavour-jets

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

Relies on Inner tracking system



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# BDT for jet flavour identification

## MV2

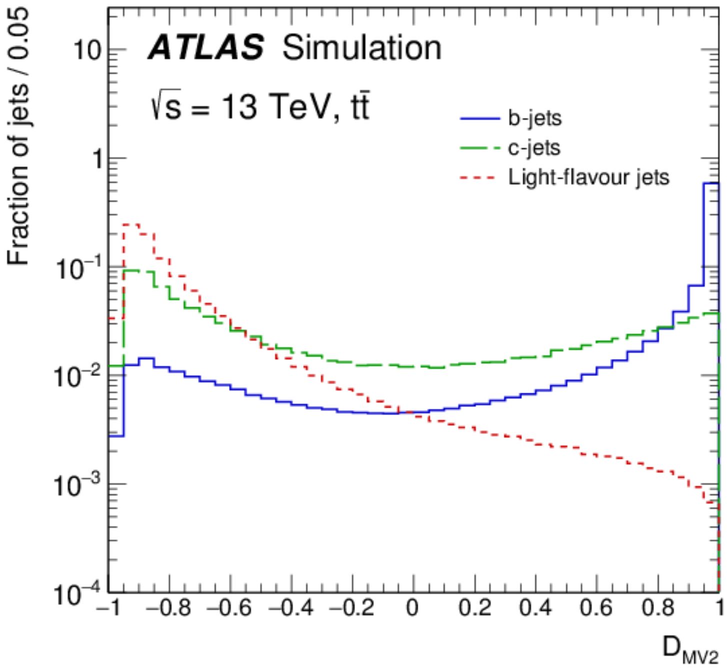
Per-jet probability of originating from {b, c, g/u/d/s} partons

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 $p_T, \eta$
- $d_0$, ...

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

Stable performance as a function of pile-up



# $m_{bb}$ resolution

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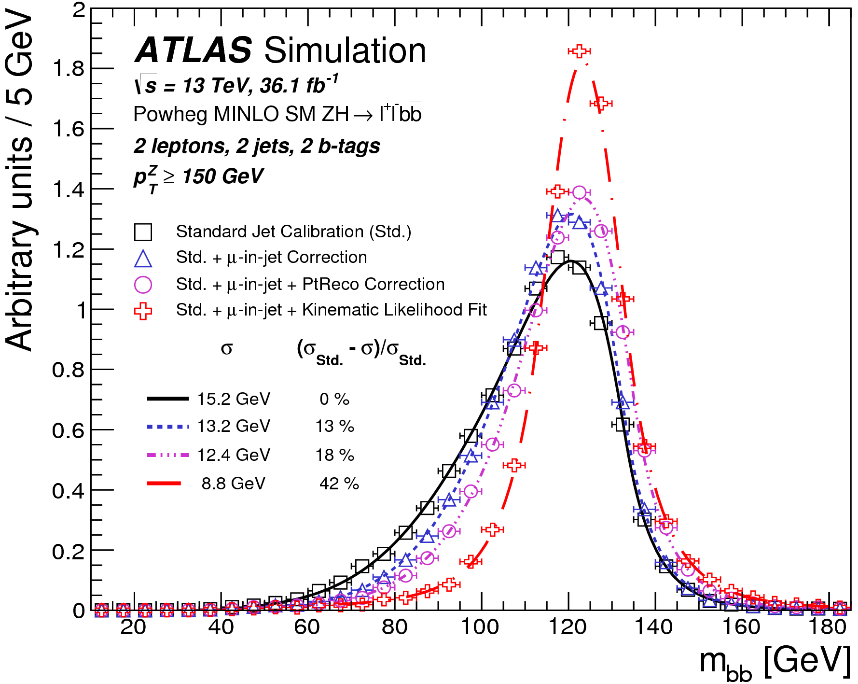
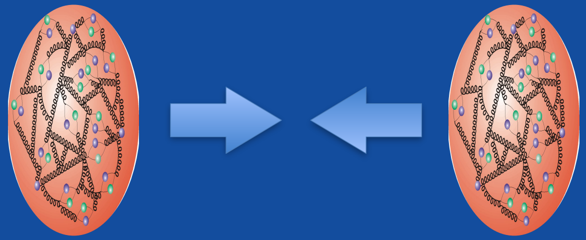
- Important to get the narrowest possible peak to be sensitive to it
- Higgs candidate formed by the system of 2 b-jets
  - $b_1 : (\vec{p}_{b_1}, E_{b_1})$
  - $b_2 : (\vec{p}_{b_2}, E_{b_2})$
  - $H : m_{bb}^2 = (E_{b_1} + E_{b_2})^2 + ||\vec{p}_{b_1} + \vec{p}_{b_2}||^2$




- Driven by precision and accuracy of jet energy measurement
- Several improvements (up to 42%):
  - Add $\overrightarrow{p}$ 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)
  - $ZH \to \ell\bar{\ell}b\bar{b}$: use of $Z \to \ell\bar{\ell}$ recoiling against the $H \to b\bar{b}$ 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: $e$ sub-channel | 1-lepton: $\mu$ sub-channel | 2-lepton |
|---|---|---|---|---|
| Trigger | $E_T^{miss}$ | Single lepton | $E_T^{miss}$ | Single lepton |
| Leptons | 0 *loose* leptons with $p_T > 7$ GeV | 1 *tight* electron $p_T > 27$ GeV | 1 *tight* muon $p_T > 25$ GeV | 2 *loose* leptons with $p_T > 7$ GeV $\geq 1$ lepton with $p_T > 27$ GeV |
| $E_T^{miss}$ | $> 150$ GeV | $> 30$ GeV | – | – |
| $m_{\ell\ell}$ | – | – | | $81 \text{ GeV} < m_{\ell\ell} < 101$ GeV |
| Jets | Exactly 2 / Exactly 3 jets | | | Exactly 2 / $\geq 3$ jets |
| Jet $p_T$ | $> 20$ GeV for $\lvert\eta\rvert < 2.5$; $> 30$ GeV for $2.5 < \lvert\eta\rvert < 4.5$ | | | |
| $b$-jets | Exactly 2 $b$-tagged jets | | | |
| Leading $b$-tagged jet $p_T$ | $> 45$ GeV | | | |
| $H_T$ | $> 120$ GeV (2 jets), $>150$ GeV (3 jets) | – | | – |
| $\min[\Delta\phi(\vec{E}_T^{miss}, \vec{jets})]$ | $> 20°$ (2 jets), $> 30°$ (3 jets) | – | | – |
| $\Delta\phi(\vec{E}_T^{miss}, \vec{bb})$ | $> 120°$ | – | | – |
| $\Delta\phi(\vec{b_1}, \vec{b_2})$ | $< 140°$ | – | | – |
| $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{miss})$ | $< 90°$ | – | | – |
| $p_T^V$ regions | $> 150$ GeV | | | $75 \text{ GeV} < p_T^V < 150$ GeV, $> 150$ GeV |
| Signal regions | – | $m_{bb} \geq 75$ GeV or $m_{top} \leq 225$ GeV | | Same-flavour leptons Opposite-sign charges ($\mu\mu$ sub-channel) |
| Control regions | – | $m_{bb} < 75$ GeV and $m_{top} > 225$ GeV | | Different-flavour leptons Opposite-sign charges |

# Offline event selection

- Common selection criteria

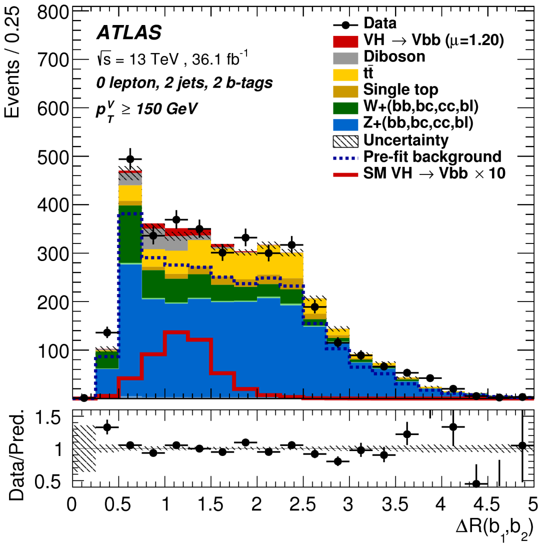
| Selection | 0-lepton | 1-lepton: $e$ sub-channel | 1-lepton: $\mu$ sub-channel | 2-lepton |
|---|---|---|---|---|
| Trigger | $E_T^{miss}$ | Single lepton | $E_T^{miss}$ | Single lepton |
| Leptons | 0 *loose* leptons with $p_T > 7$ GeV | 1 *tight* electron $p_T > 27$ GeV | 1 *tight* muon $p_T > 25$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

# Signal regions

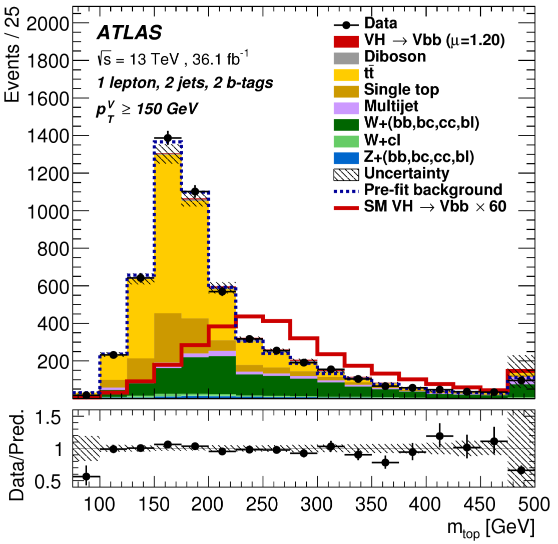
- Designed to maximise $S/\sqrt{B}$

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

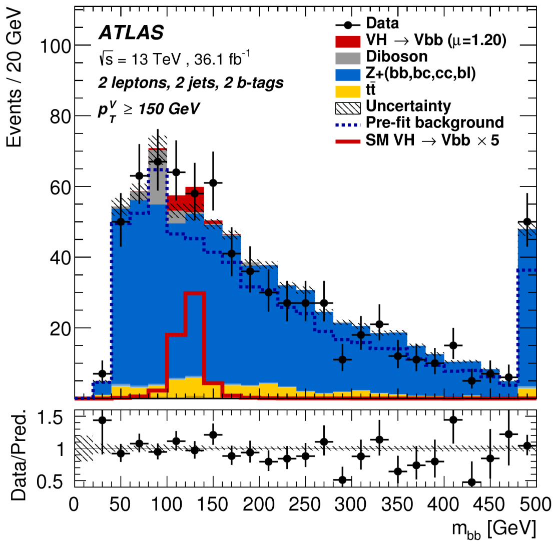
# Discriminating signal from background




- 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

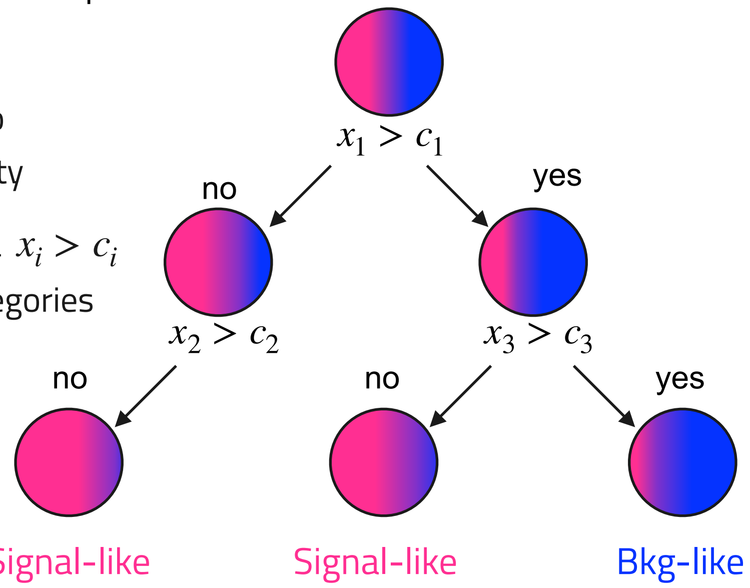



- $m_{bb}$

# Boosted Decision Tree for signal identification

- BDT trained on simulated signal and background events
- Improve background and signal separation exploring the events in a multidimensional space

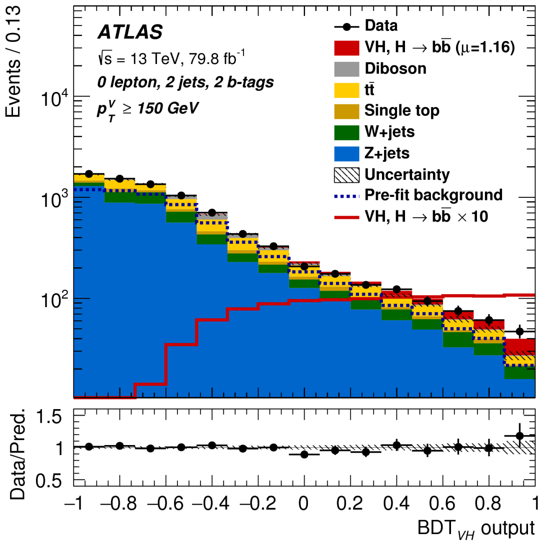
- Partitions the data to increase sample purity
- Finds optimal criteria $x_i > c_i$ to separate data categories

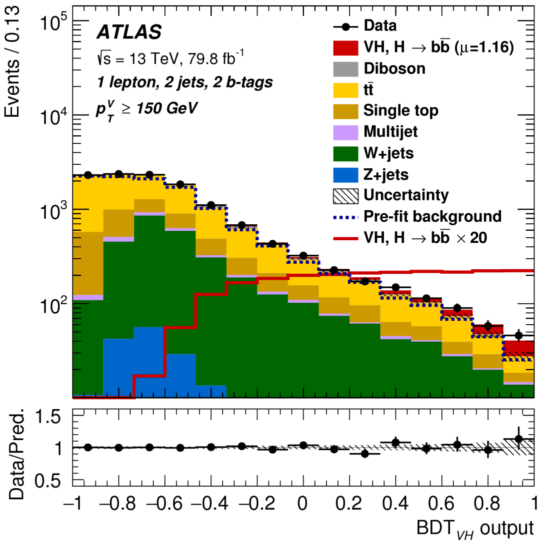


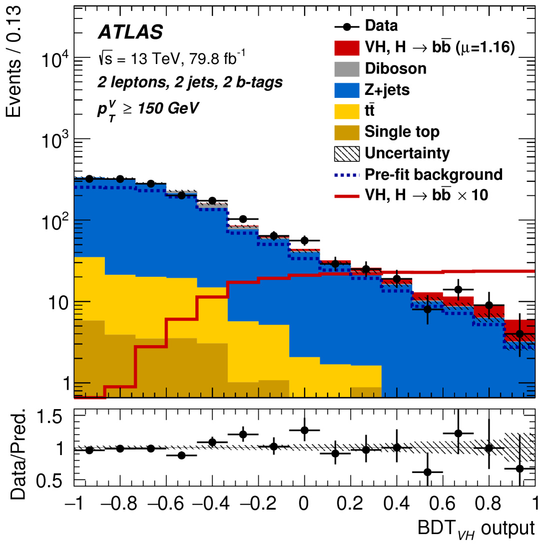

| Variable | 0-lepton | 1-lepton | 2-lepton |
|---|---|---|---|
| $p_T^V$ | $\equiv E_T^{miss}$ | $\times$ | $\times$ |
| $E_T^{miss}$ | $\times$ | $\times$ | $\times$ |
| $p_T^{b_1}$ | $\times$ | $\times$ | $\times$ |
| $p_T^{b_2}$ | $\times$ | $\times$ | $\times$ |
| $m_{bb}$ | $\times$ | $\times$ | $\times$ |
| $\Delta R(\vec{b}_1, \vec{b}_2)$ | $\times$ | $\times$ | $\times$ |
| $\|\Delta\eta(\vec{b}_1, \vec{b}_2)\|$ | $\times$ | | |
| $\Delta\phi(\vec{V}, \vec{bb})$ | $\times$ | $\times$ | $\times$ |
| $\|\Delta\eta(\vec{V}, \vec{bb})\|$ | | | $\times$ |
| $m_{eff}$ | $\times$ | | |
| $\min[\Delta\phi(\vec{\ell}, \vec{b})]$ | | $\times$ | |
| $m_T^W$ | | $\times$ | |
| $m_{\ell\ell}$ | | | $\times$ |
| $m_{top}$ | | $\times$ | |
| $\|\Delta Y(\vec{V}, \vec{bb})\|$ | | $\times$ | |
| | Only in 3-jet events | | |
| $p_T^{jet_3}$ | $\times$ | $\times$ | $\times$ |
| $m_{bbj}$ | $\times$ | $\times$ | $\times$ |

# Boosted Decision Tree for signal identification

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



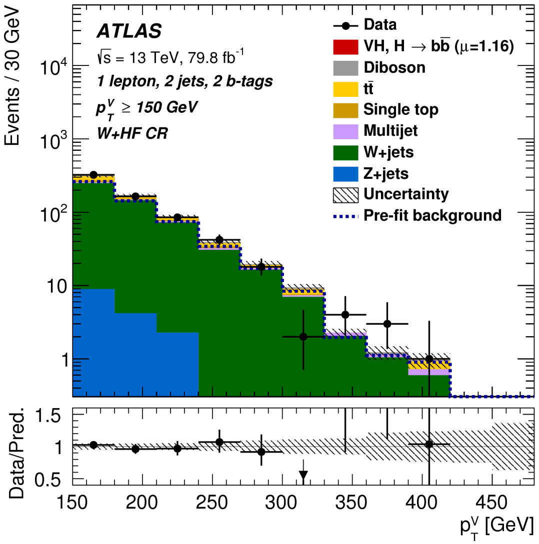
# Background control regions

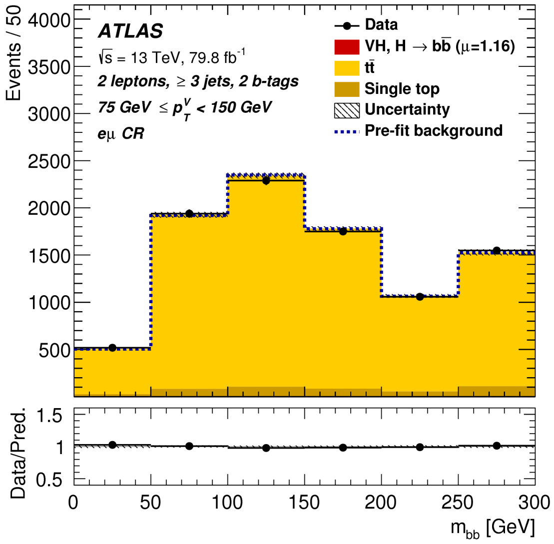
- To obtain pure samples on specific backgrounds

| Selection | 0-lepton | 1-lepton: $e$ sub-channel | 1-lepton: $\mu$ sub-channel | 2-lepton |
|---|---|---|---|---|
| Trigger | $E_{\mathrm{T}}^{\mathrm{miss}}$ | Single lepton | $E_{\mathrm{T}}^{\mathrm{miss}}$ | Single lepton |
| Leptons | 0 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV | 1 *tight* electron $p_{\mathrm{T}} > 27$ GeV | 1 *tight* muon $p_{\mathrm{T}} > 25$ GeV | 2 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV $\geq 1$ lepton with $p_{\mathrm{T}} > 27$ GeV |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ | $> 150$ GeV | $> 30$ GeV | – | – |
| $m_{\ell\ell}$ | – | – | | 81 GeV $< m_{\ell\ell} <$ 101 GeV |
| Jets | Exactly 2 / Exactly 3 jets | | | Exactly 2 / $\geq 3$ jets |
| Jet $p_{\mathrm{T}}$ | $> 20$ GeV for $\lvert\eta\rvert < 2.5$ $> 30$ GeV for $2.5 < \lvert\eta\rvert < 4.5$ | | | |
| $b$-jets | Exactly 2 $b$-tagged jets | | | |
| Leading $b$-tagged jet $p_{\mathrm{T}}$ | $> 45$ GeV | | | |
| $H_{\mathrm{T}}$ | $> 120$ GeV (2 jets), $>150$ GeV (3 jets) | – | | – |
| $\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{\mathrm{jets}})]$ | $> 20^{\circ}$ (2 jets), $> 30^{\circ}$ (3 jets) | – | | – |
| $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{bb})$ | $> 120^{\circ}$ | – | | – |
| $\Delta\phi(\vec{b_1}, \vec{b_2})$ | $< 140^{\circ}$ | – | | – |
| $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ | $< 90^{\circ}$ | – | | – |
| $p_{\mathrm{T}}^{V}$ regions | $> 150$ GeV | | | 75 GeV $< p_{\mathrm{T}}^{V} <$ 150 GeV, $> 150$ GeV |
| Signal regions | – | $m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV | | Same-flavour leptons Opposite-sign charges ($\mu\mu$ sub-channel) |
| Control regions | – | $m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV | | Different-flavour leptons Opposite-sign charges |

# Background control regions

| | | | |
|---|---|---|---|
| Control regions | – | $m_{bb} < 75$ GeV and $m_{top} > 225$ GeV | Different-flavour leptons<br>Opposite-sign charges |

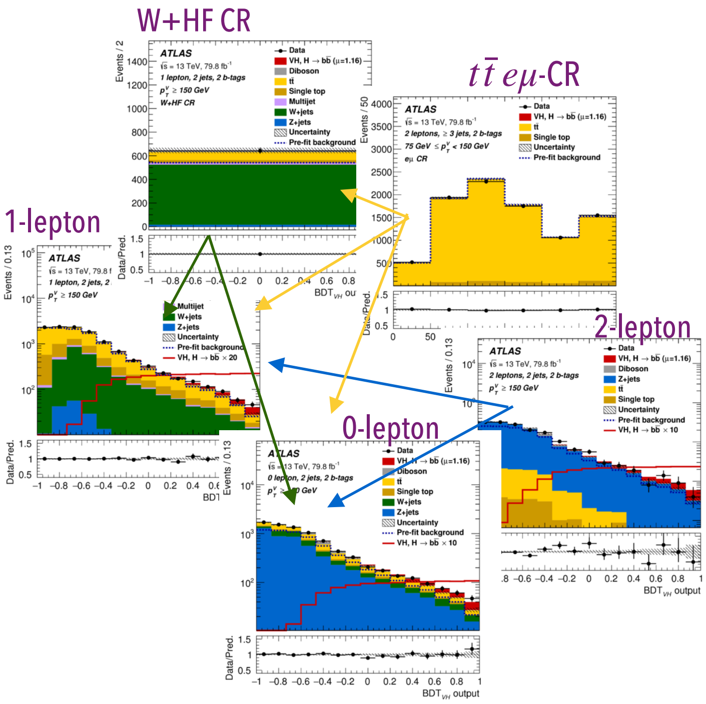



- Enriched in W+jets
- Enriched in top pairs

# Statistical data analysis

- Background and signal estimate with Monte-Carlo simulation
- Adjust simulation to data, fit parameters
  - Dominant backgrounds normalisation
  - Signal strength factor $\mu = \dfrac{N_{obs}}{N_{exp}}$
- 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

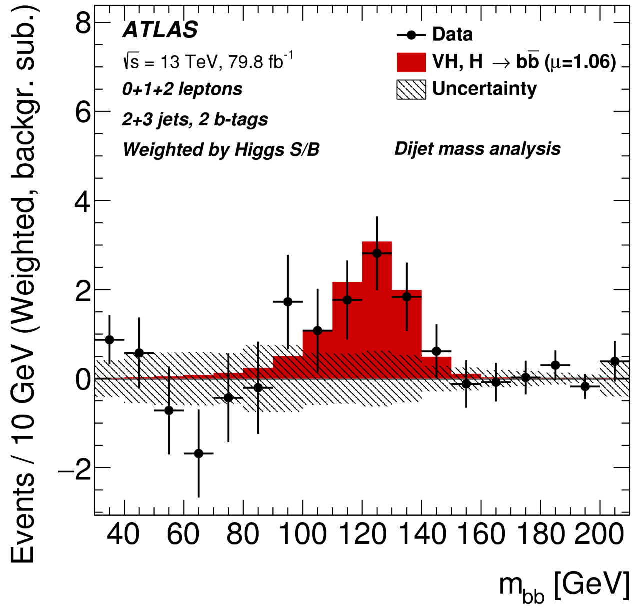
- Impact of each uncertainty source quantified as a signal strength uncertainty $\sigma_\mu$

| Source of uncertainty | | $\sigma_\mu$ |
|---|---|---|
| Total | | 0.259 |
| Statistical | | 0.161 |
| Systematic | | 0.203 |
| Experimental uncertainties | | |
| Jets | | 0.035 |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ | | 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

| 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 |
| $VH,\ H \to b\bar{b}$ combination | $1.16^{+0.27}_{-0.25}$ | $7.3 \cdot 10^{-6}$ | $5.3 \cdot 10^{-7}$ | 4.3 | 4.9 |

- Remember…
  - $p_0$ probability that the signal hypothesis is fake
- Analysed 79.8 fb$^{-1}$ 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
  - $\mu = 1.06, 3.6\sigma$ (note significance gained with BDT)
- All measurements compatible with SM $(\mu = 1)$



VH Run1 arXiv:1409.6212 ttH Run2 arXiv:1712.08895 VBF+ggF Run1 arXiv:1606.02181

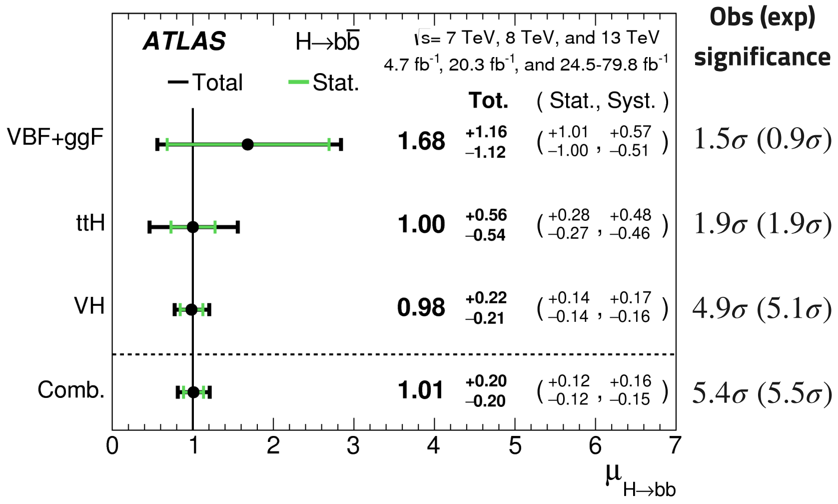
ttH Run1 arXiv:1503.05066 VBF+ggF Run2 arXiv:1807.08639

1808.08238

# Combination with other channels

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

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



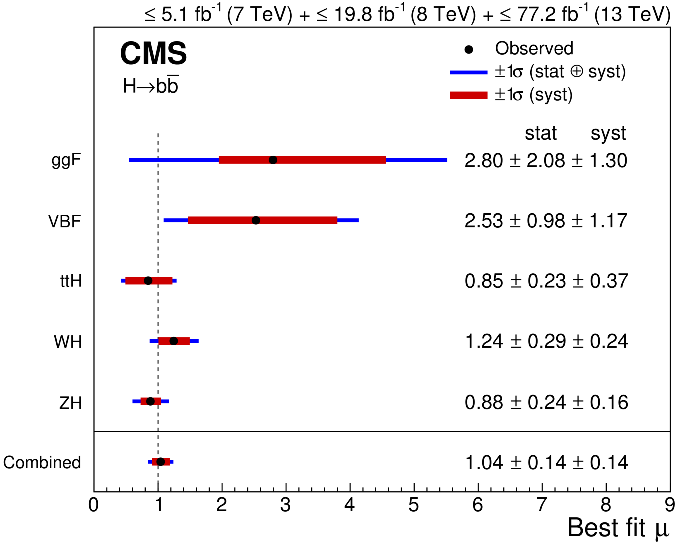

- $H \to bb$ dominant in VH observation (5.3$\sigma$)
  - Combined with $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$

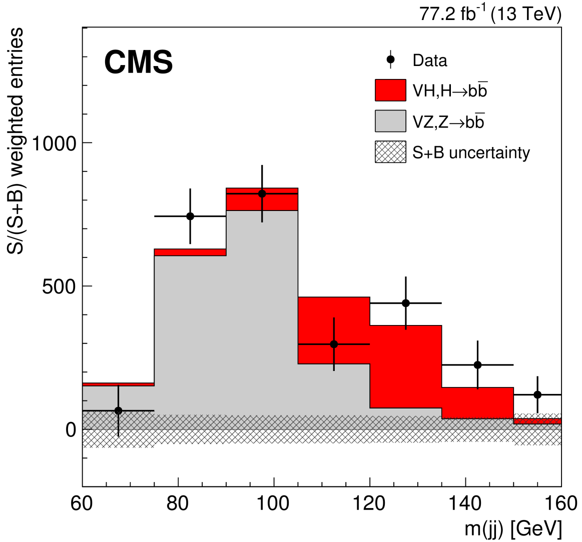
| Channel | Significance Exp. | Significance Obs. |
|---|---|---|
| $H \to ZZ^* \to 4\ell$ | 1.1 | 1.1 |
| $H \to \gamma\gamma$ | 1.9 | 1.9 |
| $H \to b\bar{b}$ | 4.3 | 4.9 |
| VH combined | 4.8 | 5.3 |

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

# CMS counterpart

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



# Snooping through the $H \to b\bar{b}$ window

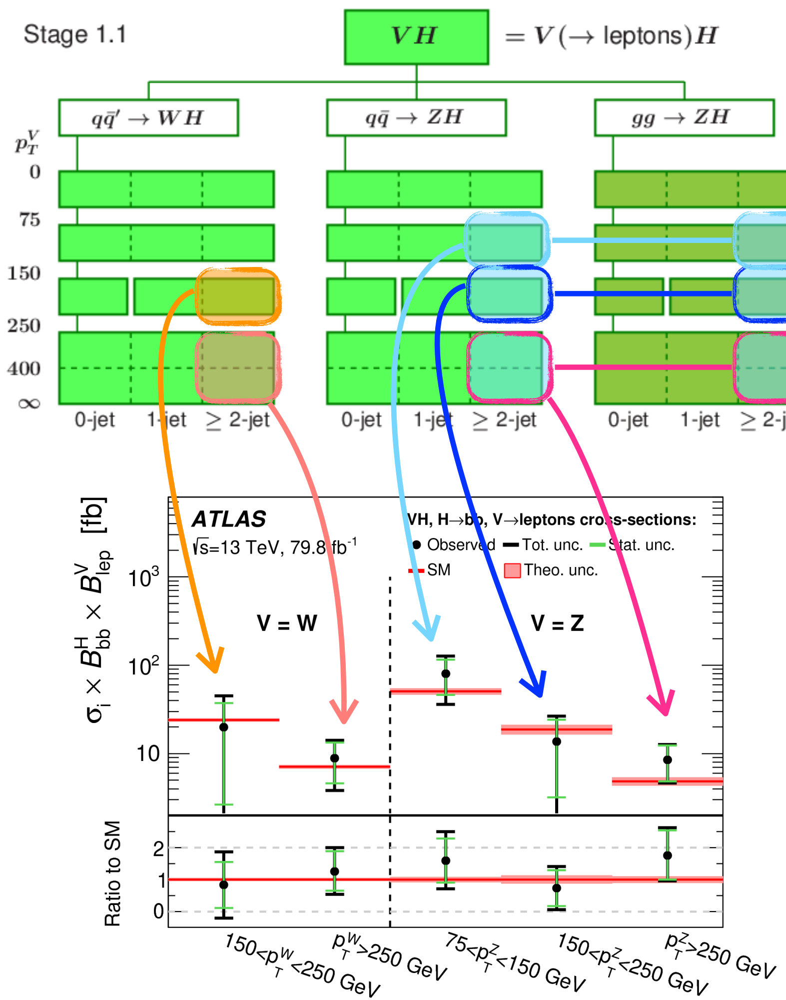
# What’s next?

- 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 arXiv:1903.04618

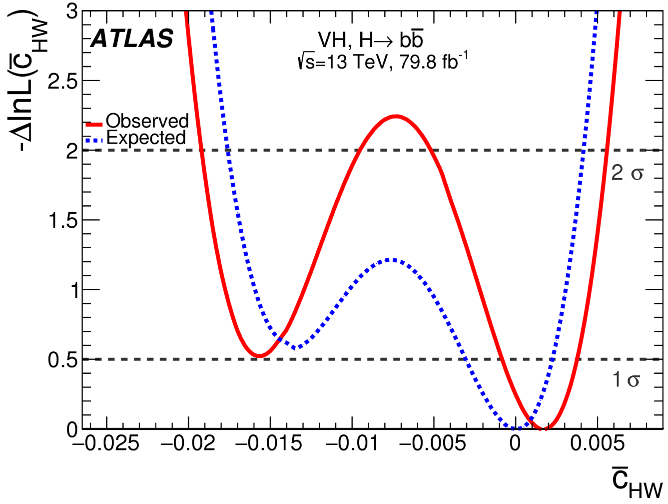
# Differential cross-section measurements

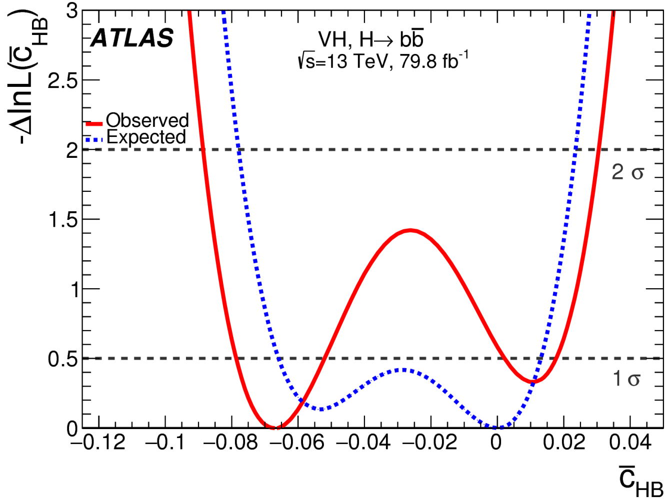
- Simplified Template Cross Section framework
  - Measure $\sigma$ in exclusive regions of the phase space
  - Increasing granularity with acquired data
- Probe kinematic properties of Higgs boson in more detail
- All measurements compatible with SM
- Towards measurement of differential $\sigma_{VH}$
  - $\sigma_{VH}$ 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: $\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \mathscr{L}_{BSM}$
  - 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: $c \to 0$
- $c$ limited to few percent at 95% CL



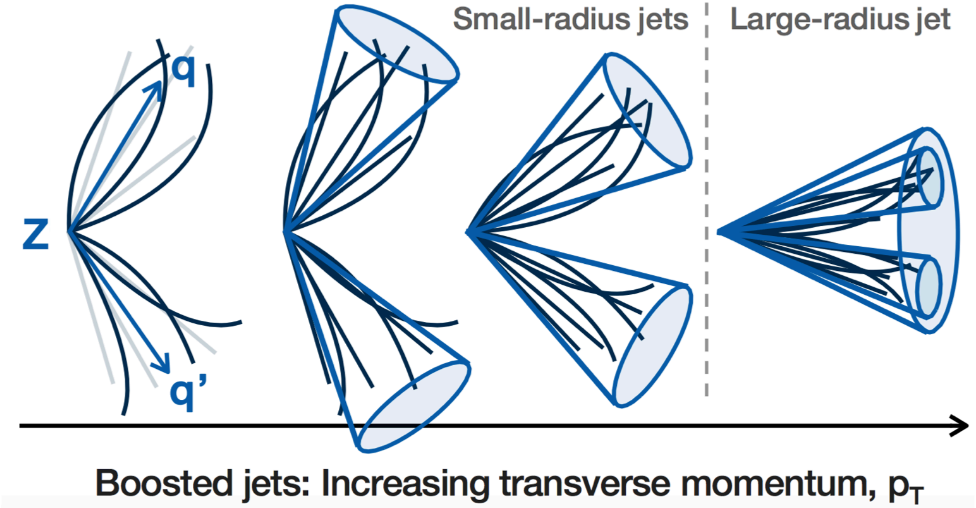




arXiv:1903.04618

# 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



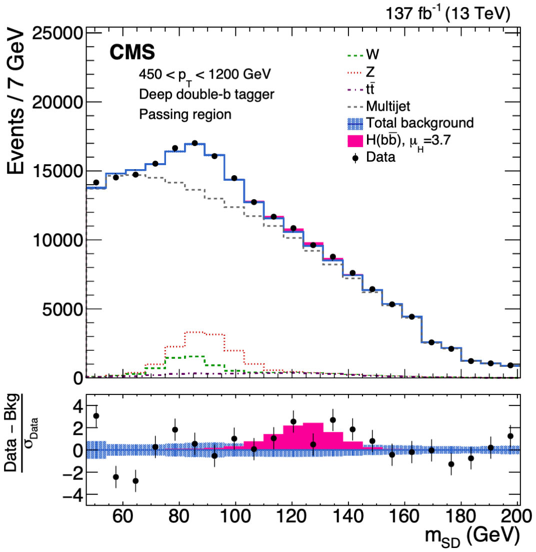

- Signal reconstructed has a large-R jet
- 2 b-tagged sub-jets inside large-R jet (reconstructed from tracks)
- Other techniques being explored, e.g. using Deep Neural Networks

JHEP12(2020)085

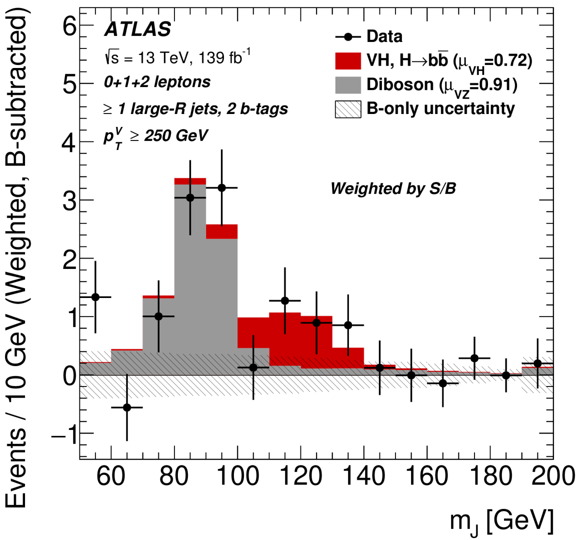
VHbb boosted 2008.02508

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

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



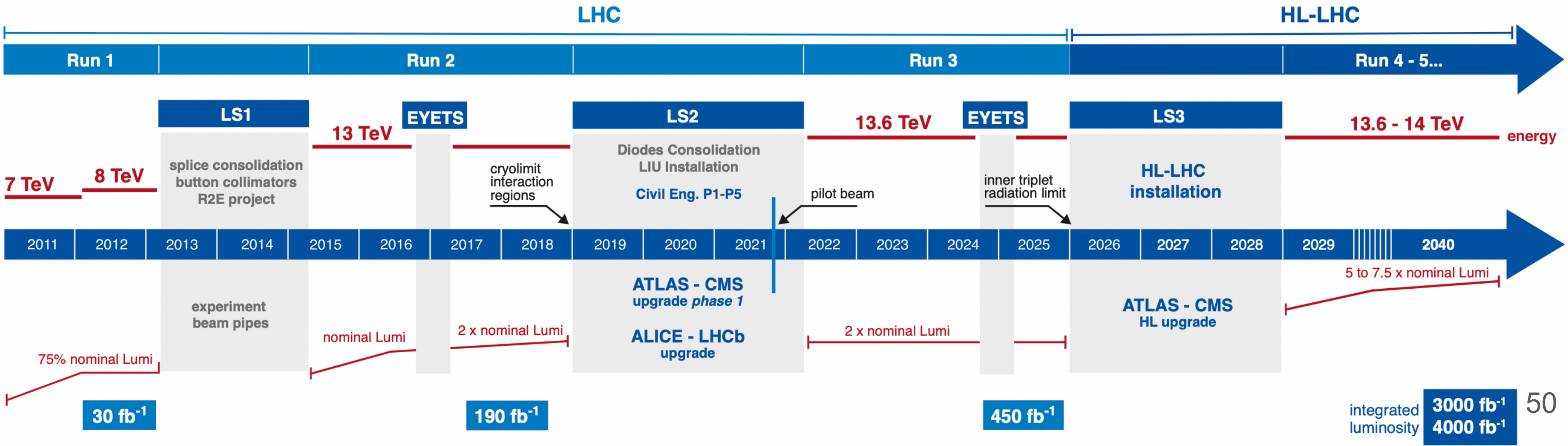

- Associated W/Z production
  - $p_{TJ}$ > 250 GeV
  - Observed (expected) significance: $2.1\sigma$ $(2.7\sigma)$
  - $\mu = 0.72^{+0.39}_{-0.36}$ (SM-compatible)

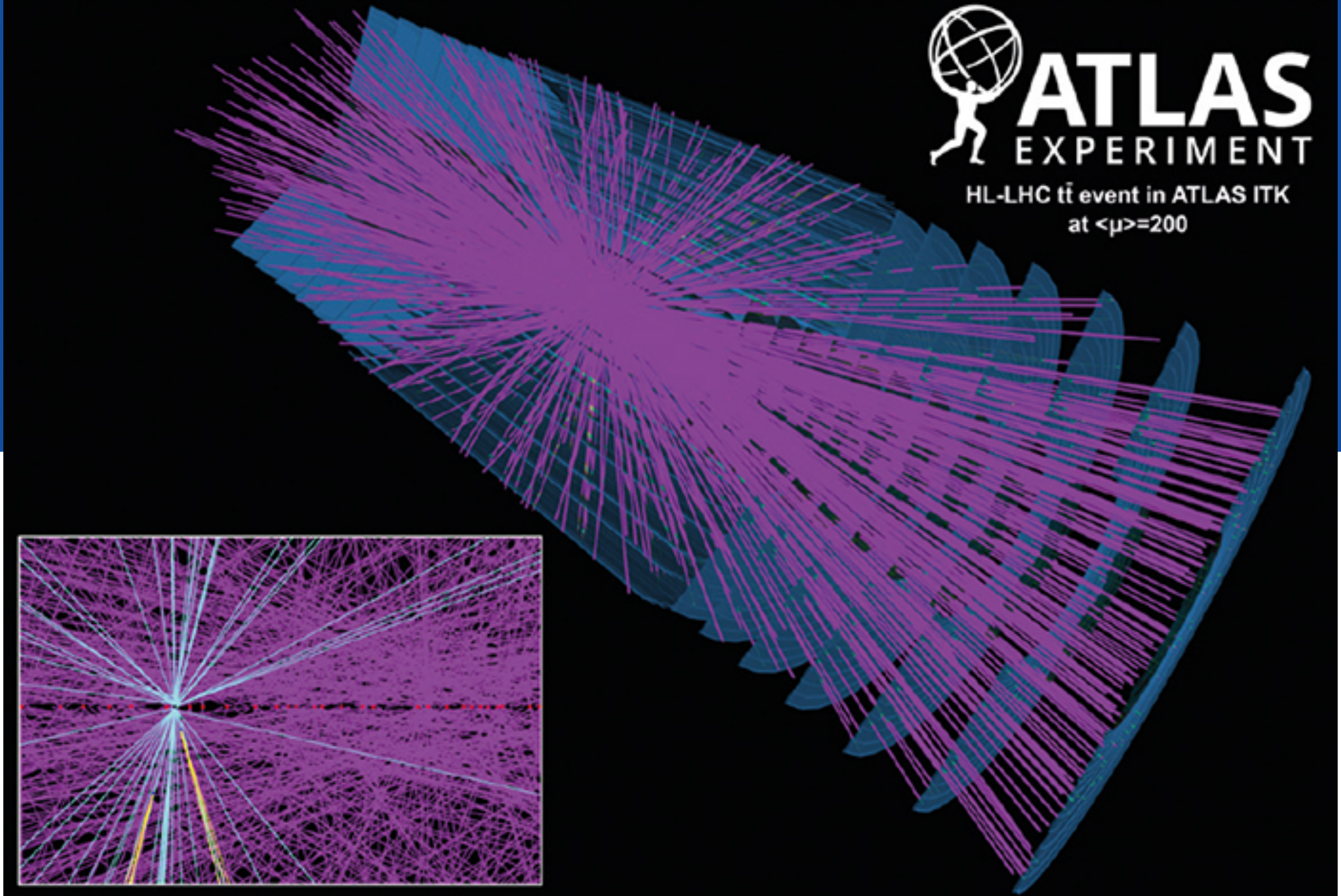


# High Luminosity-LHC upgrade

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

- A lot more data to analyse: 3000/4000 $\mathrm{fb}^{-1}$
- Will reduce statistical uncertainty of the measurements
- High pile-up: simultaneous collisions per bunch crossing $33 \rightarrow 140$
- Noisy environment: ambiguous track reconstruction, collision vertex finding, pile-up energy subtraction,...

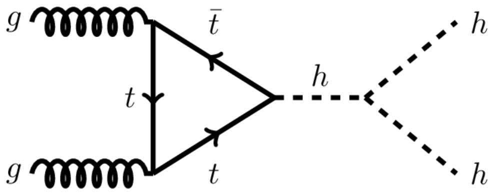



ATLAS
EXPERIMENT
HL-LHC $t\bar{t}$ event in ATLAS ITK
at <μ>=200

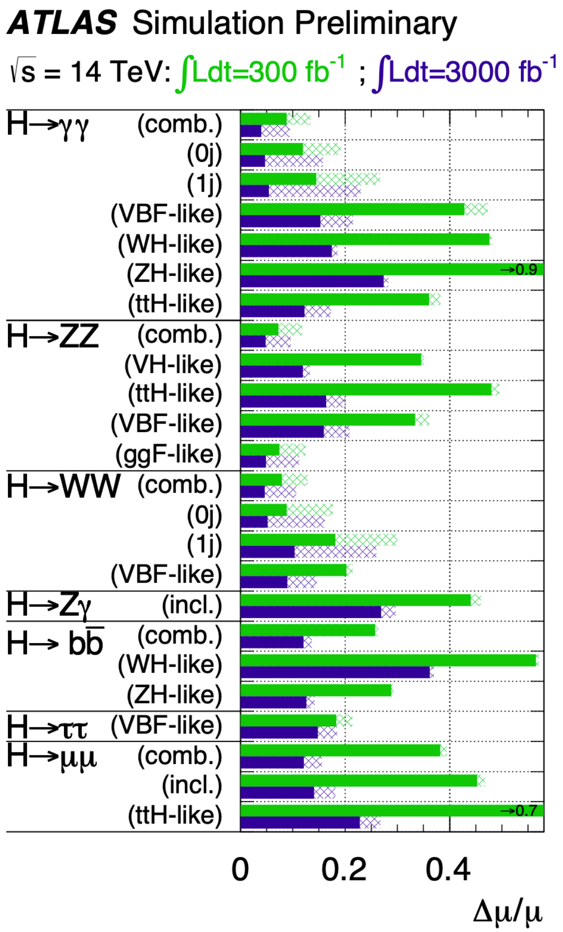
ATL-PHYS-PUB-2014-016

# HL-LHC prospects

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




- More precise measurements



# Thanks!

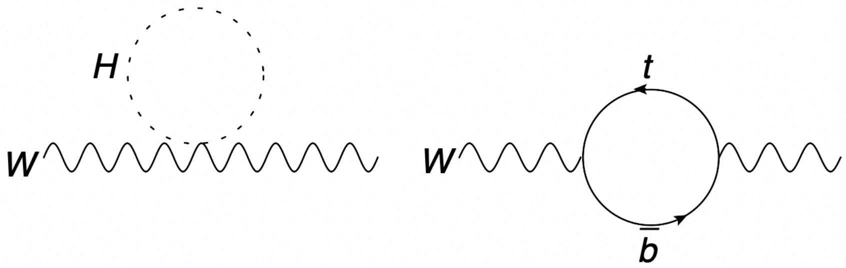
## Any questions?

You can find me at 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 $\ln M_h$




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

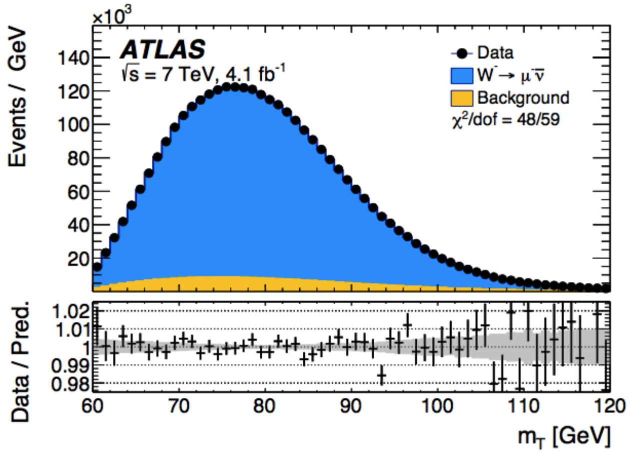
$(\rho-1) \sim \ln M_H$

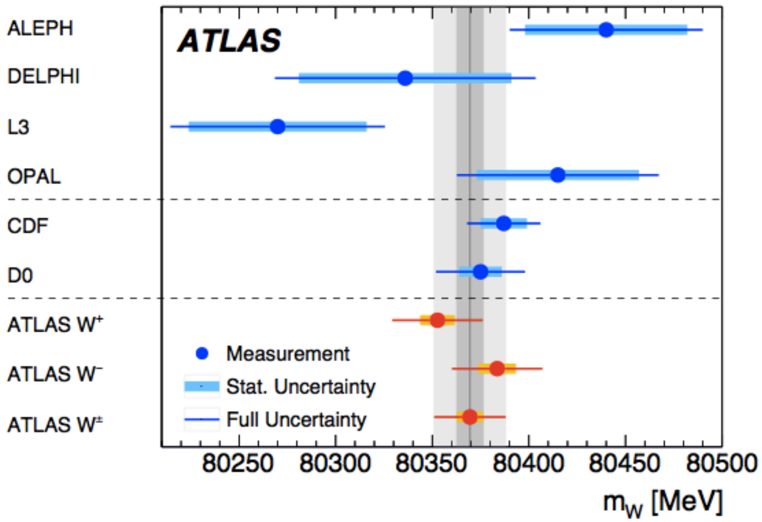
$(\rho-1) \sim M_{top}^2$

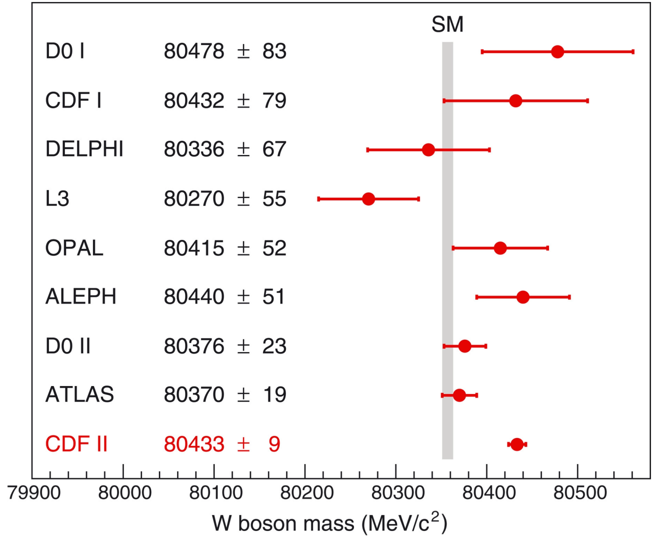
- Precise measurements of electroweak observables can be used to test internal coherence of the model!!
  - Most sensitive measurements: $M_{top}$, $M_W$, $M_H$

# W boson mass measurement

- High precision measurement —> 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