LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

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

Rute Pedro | 7th April

LIP Course on Physics at the LHC

Fundação para a Ciência e a Tecnologia
Lisb@20[20]
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

$H \to b\bar{b}$: 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

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

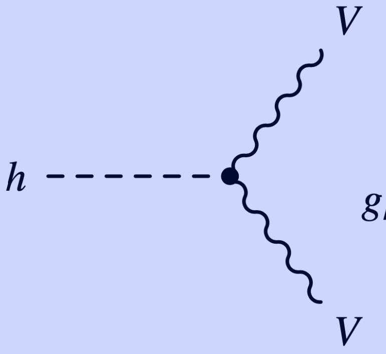
Yukawa couplings and mass terms for Fermions

$$+ |D_\mu \phi|^2 - V(\phi)$$

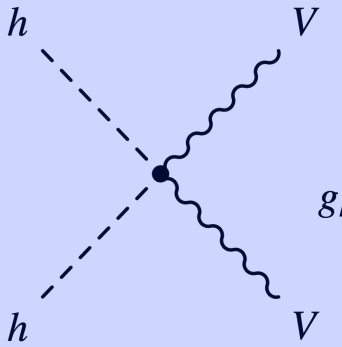
Higgs mechanism: couplings to W/Z, W/Z mass terms, Higgs self-couplings and Higgs potential

More here

Reminder: Higgs couplings

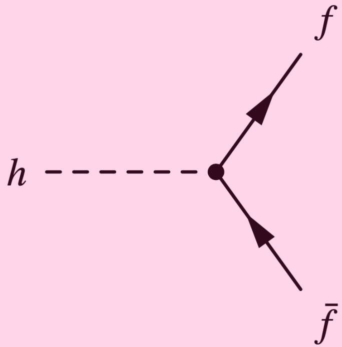


$g_{hVV} \propto \frac{M_V^2}{v}$



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

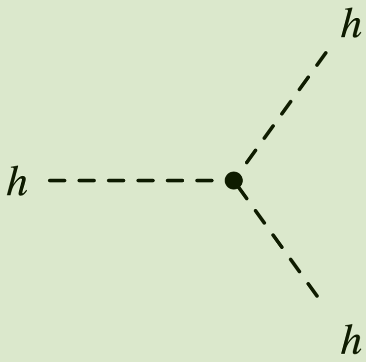
To gauge bosons



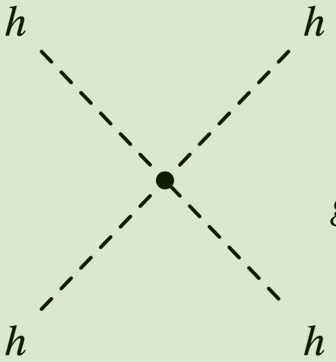
$g_{hf\bar{f}} \propto \frac{m_f}{v}$

Yukawa

Self-interactions



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

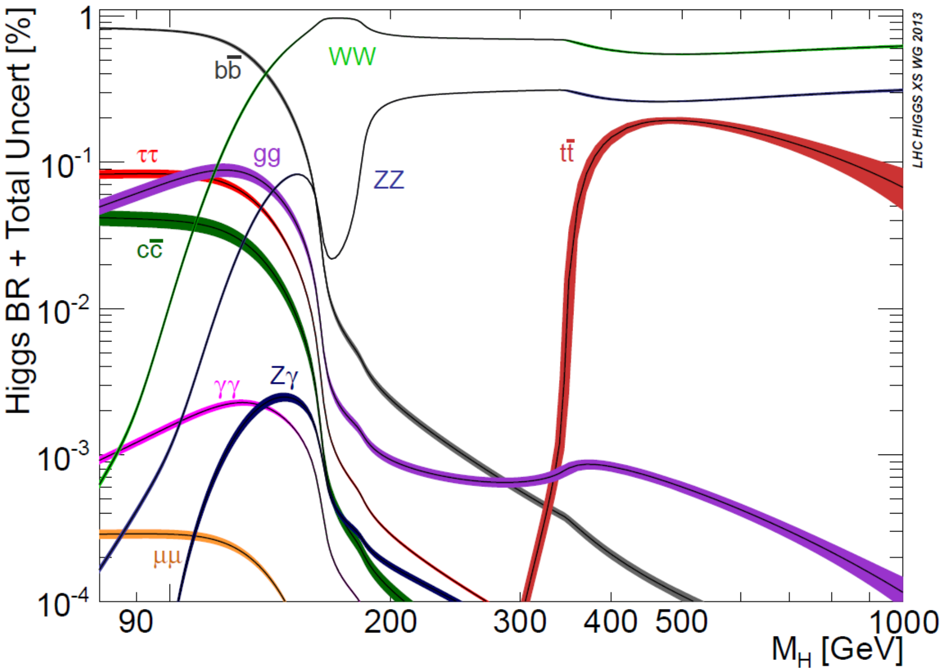


$g_{hhhh} \propto \frac{M_h^2}{v^2}$

Reminder: Higgs decay

- Depends on m_h , not predicted by theory

- Two competing contributions to the partial width Γ_i :
  - Increases with coupling strength (with m_f or m_V^2)
  - Decreases with m_f/m_h or m_V/m_h

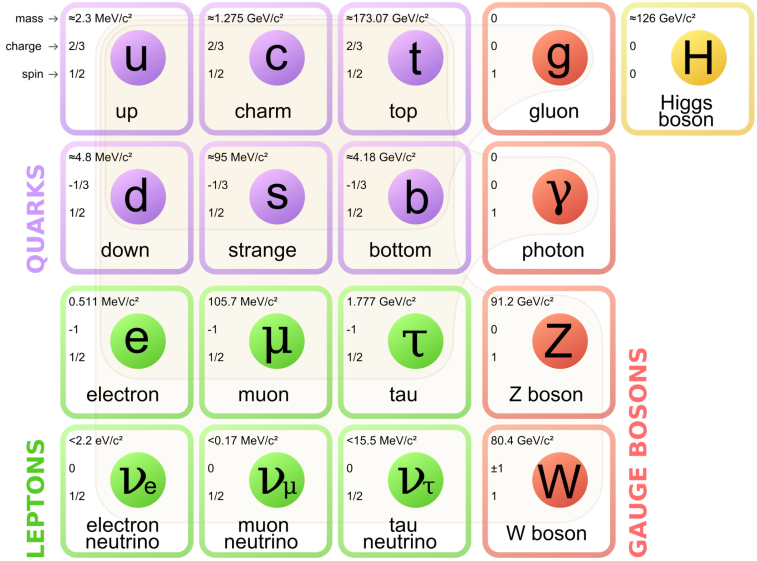


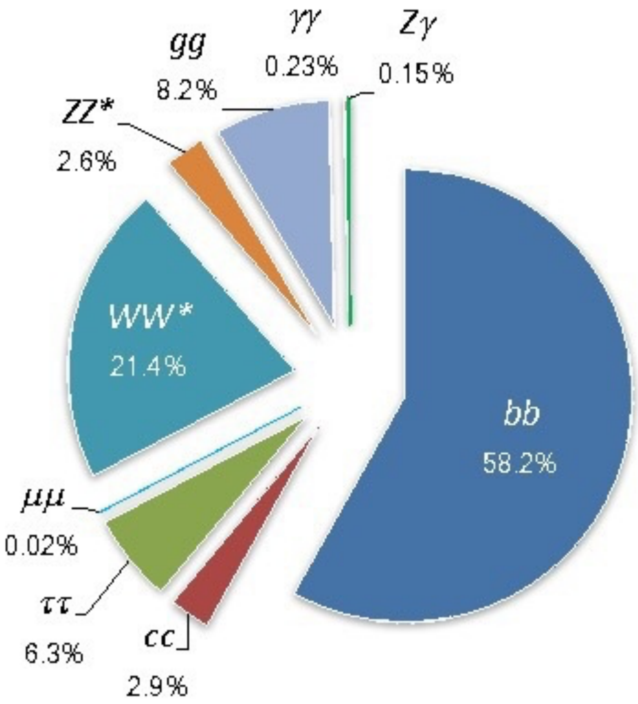
$$\Gamma(h \to f\bar{f}) \propto m_f^2 m_h \sqrt{1-x} \quad \text{, with } x = 4m_f^2/m_h^2$$

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

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

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

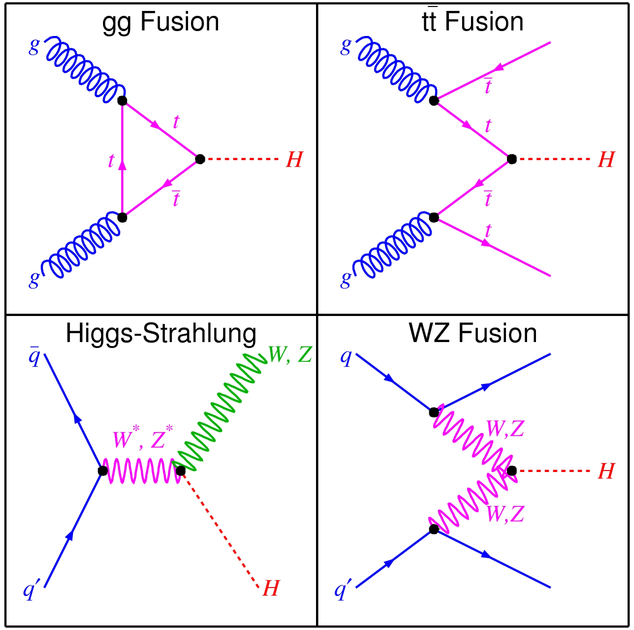




- For m_h~125 GeV: b-quarks are the heaviest particles such that $2m < m_h$
- $H \to b\bar{b}$ dominates the Higgs width
- Measuring it is fundamental to probe non-SM Higgs decays

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

Search "*channels*"



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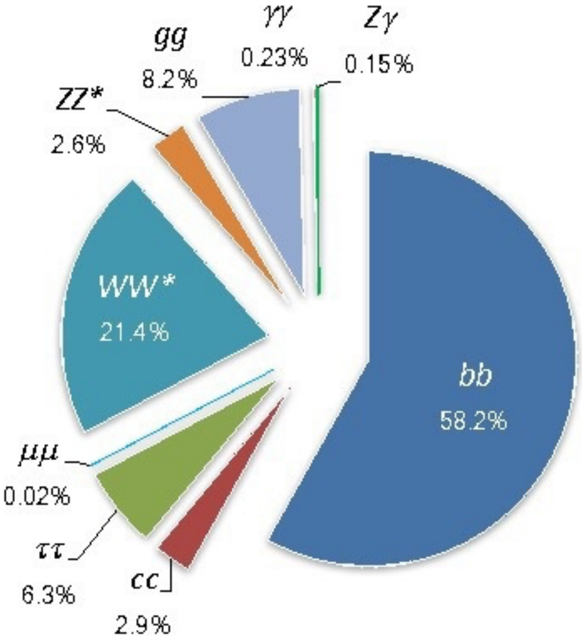


Production mode

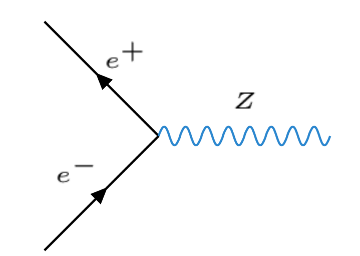
(depends on initial state particles: $pp, p\bar{p}, e^+e^-$)

Decay mode

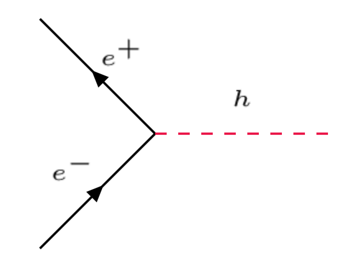
(Branching ratios depend on Higgs mass)

LEP

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



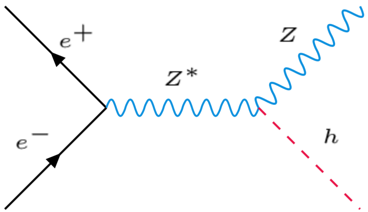
$$\sigma(e^+e^- \to Z) = 0.0671 \frac{\pi}{2} \delta(E_{CM}^2 - m_Z^2)$$



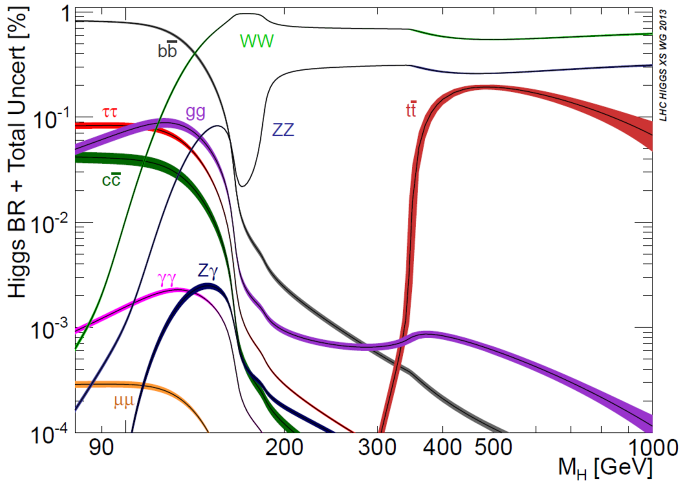
$$\sigma(e^+e^- \to H) = 4.31 \times 10^{-12} \frac{\pi}{2} \delta(E_{CM}^2 - m_H^2)$$

(suppressed by small electron-Higgs coupling)

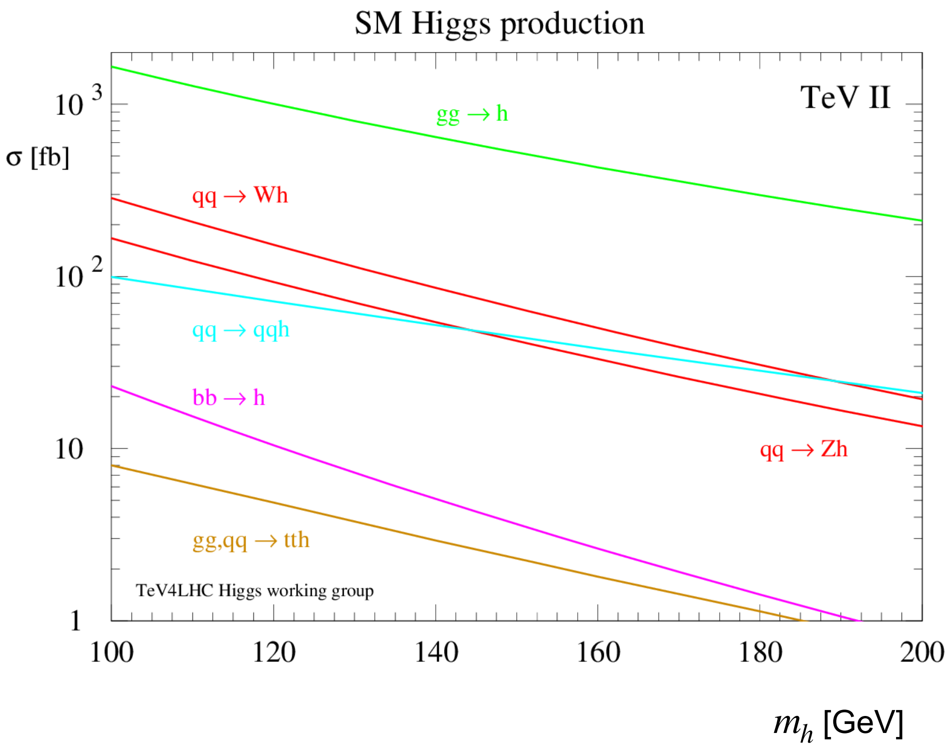
- The solution: $e^+e^- \to ZH, \quad E_{CM} > m_Z + m_H$



- 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

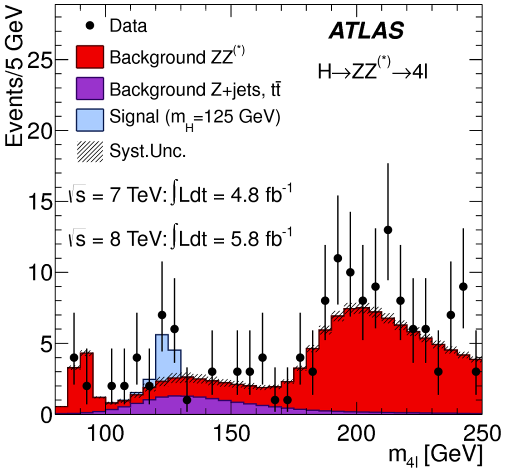


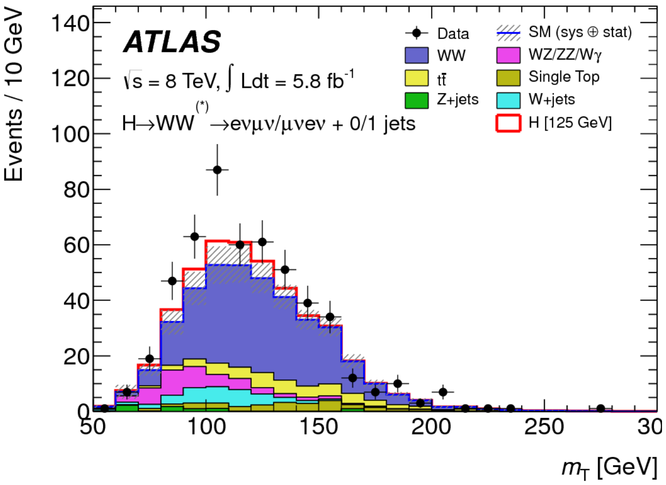
- $p\bar{p}$ collider, for low Higgs mass:
  - $gg \to H$ (via loop): large cross-section but very small sensitivity
  - Golden channel is W/ZH production and $H \to b\bar{b}$ decay
  - Tevatron legacy Higgs result combining all data from both CDF and D0 experiments: Higgs evidence on this channel

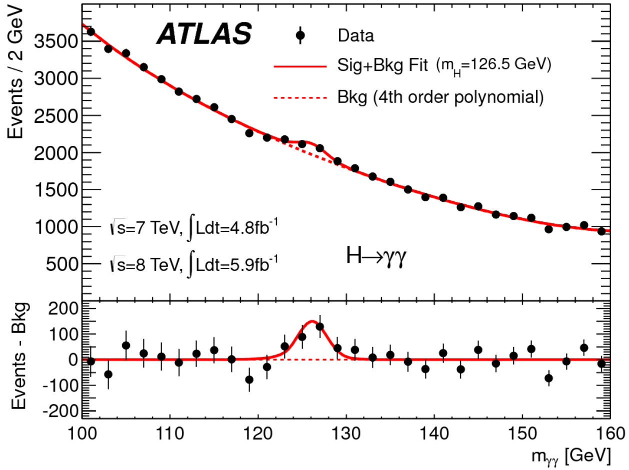
$H(\rightarrow b\bar{b})$ at the LHC

Higgs discovery - ATLAS
2012

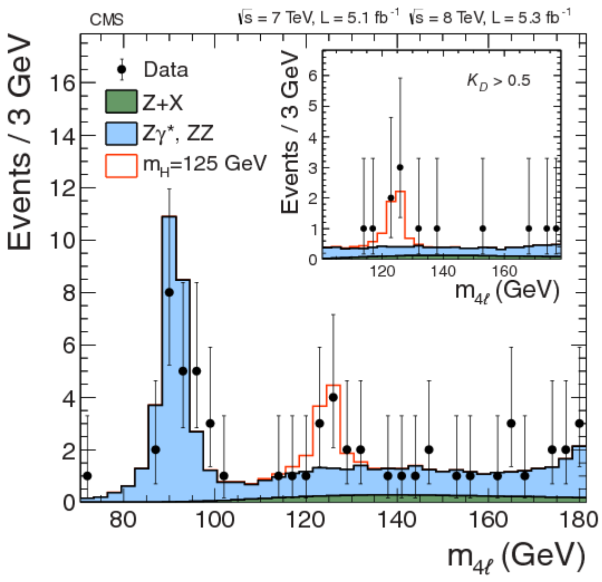
- Golden channels for Higgs discovery $H \rightarrow ZZ, \quad H \rightarrow WW, \quad H \rightarrow \gamma\gamma$
- We measured the Higgs mass and determined the charge
- Tested against non-SM spin/parity hypothesis

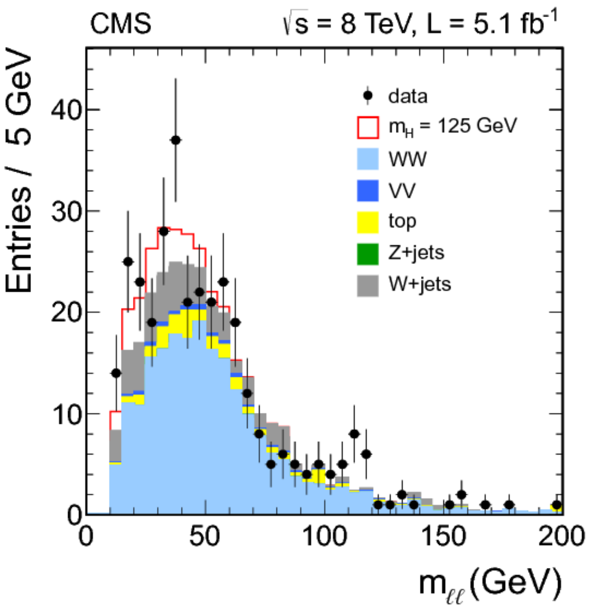


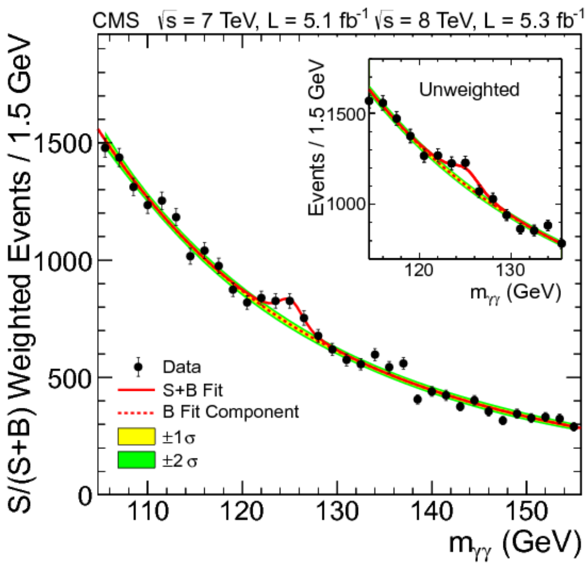




Higgs discovery - CMS







- Independently by the two experiments

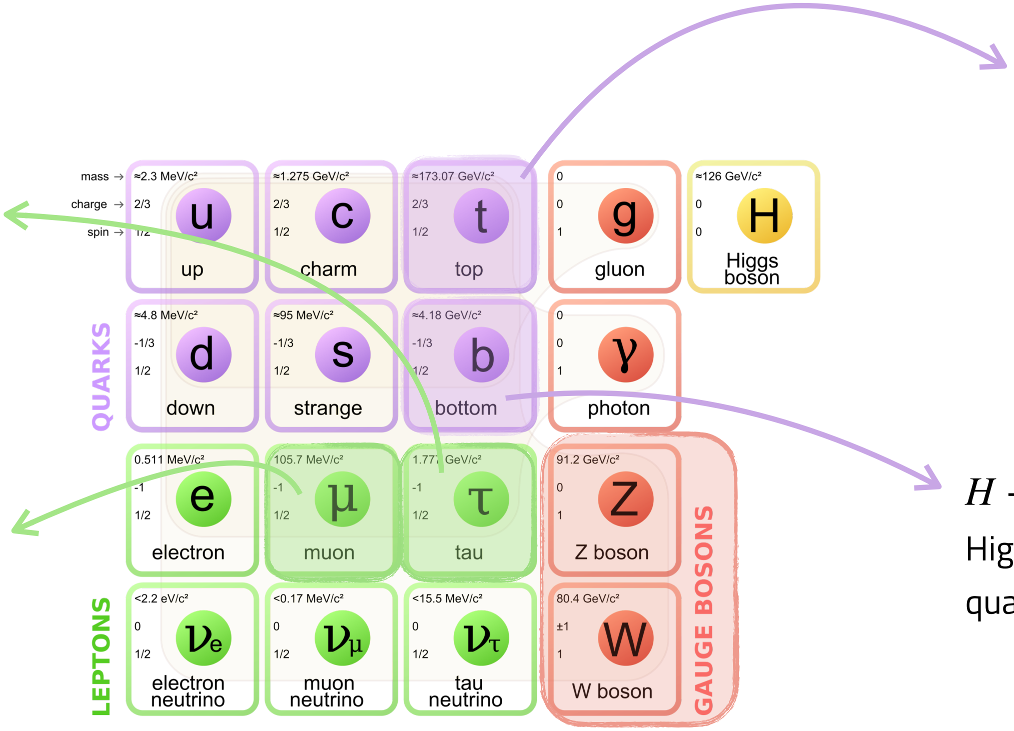
Higgs and the Fermion sector

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

First direct detection of a Yukawa coupling

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

Evidence of couplings with 2nd fermion generation



Higgs discovery (2012)

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

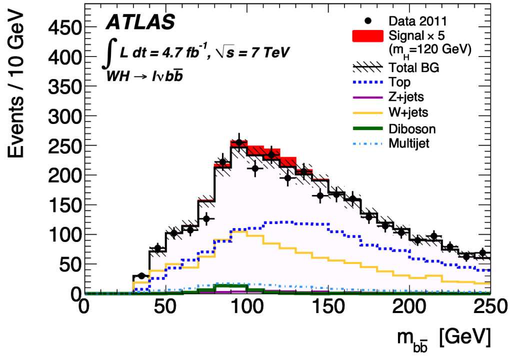
First direct detection of Higgs couplings to quarks

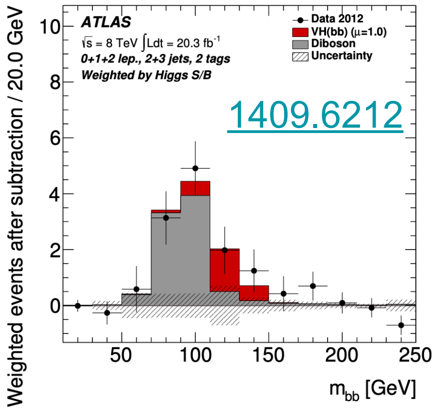
$H \to b\bar{b}$ decay (2018)

Higgs couplings to d-type quarks

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

1207.0210





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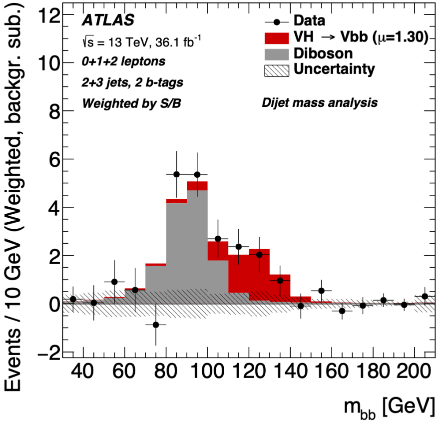

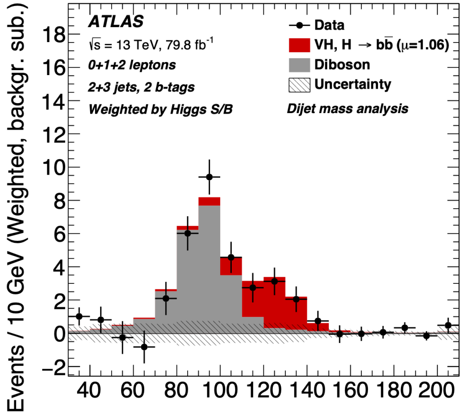

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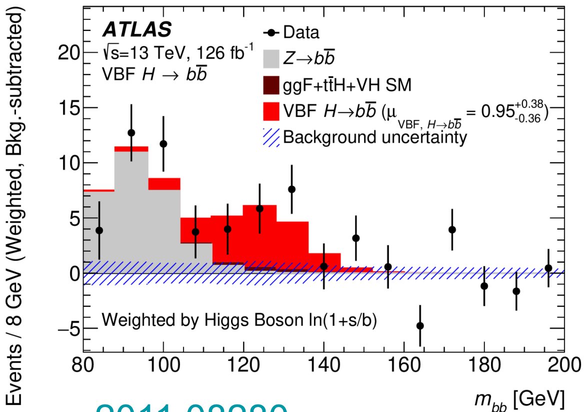

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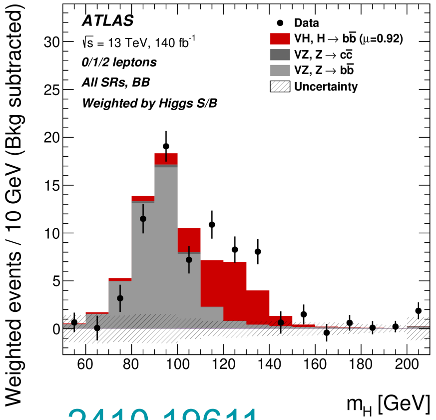

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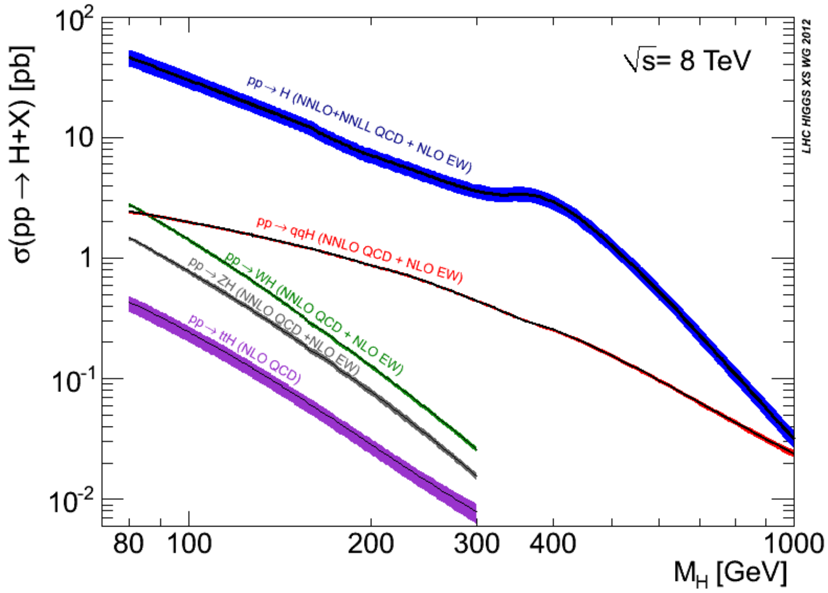
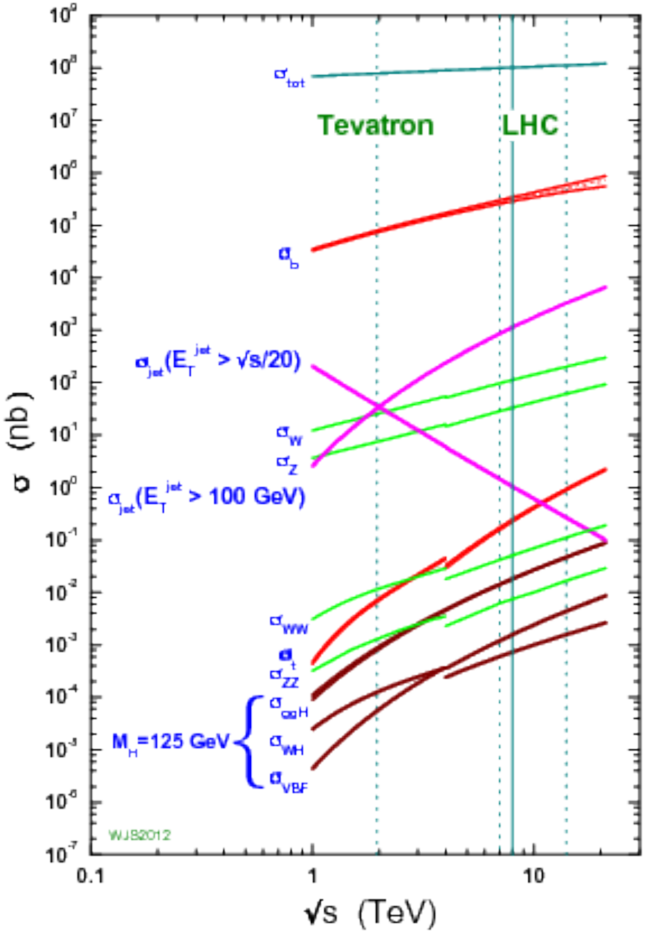
$H \to b\bar{b}$ observation at the LHC

Why did it take so long?

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

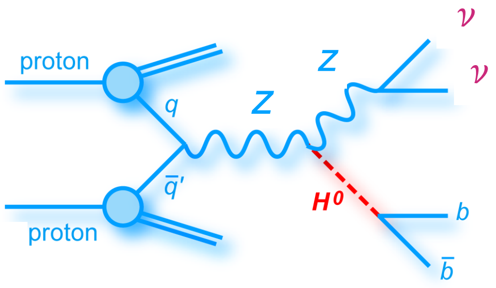




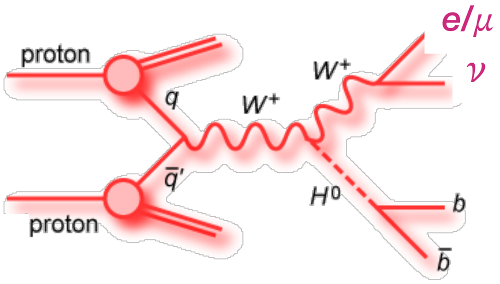
A journey towards $H \to b\bar{b}$ observation with ATLAS

Signal topology

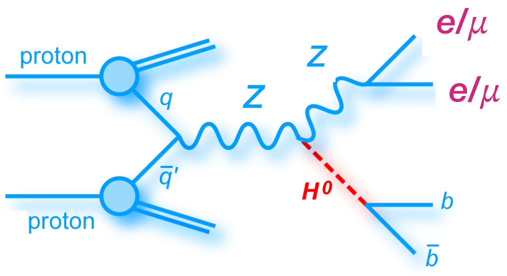
0 lepton



1 lepton

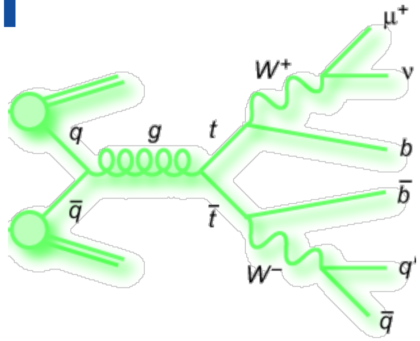


2 leptons

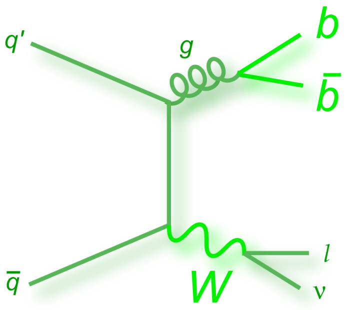


- W/Z associated production: use leptonic decay of W/Z to trigger the signal
- Mode most sensitive to $H \to b\bar{b}$
- At least one high p_T jet
- 2 jets identified as the hadronisation of b-quarks ("*b-tagging*")
- 0, 1 or 2 isolated electrons/muons ("*leptons*")

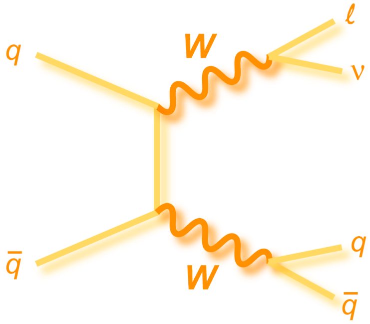
Background processes



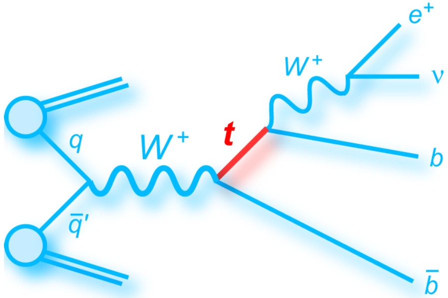
top pairs



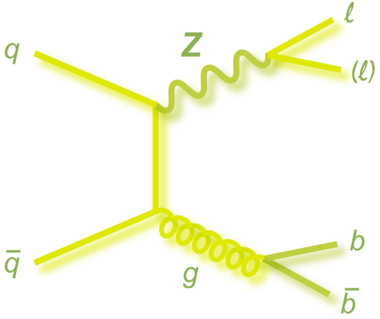
W+jets



vector boson pairs



top



Z+jets

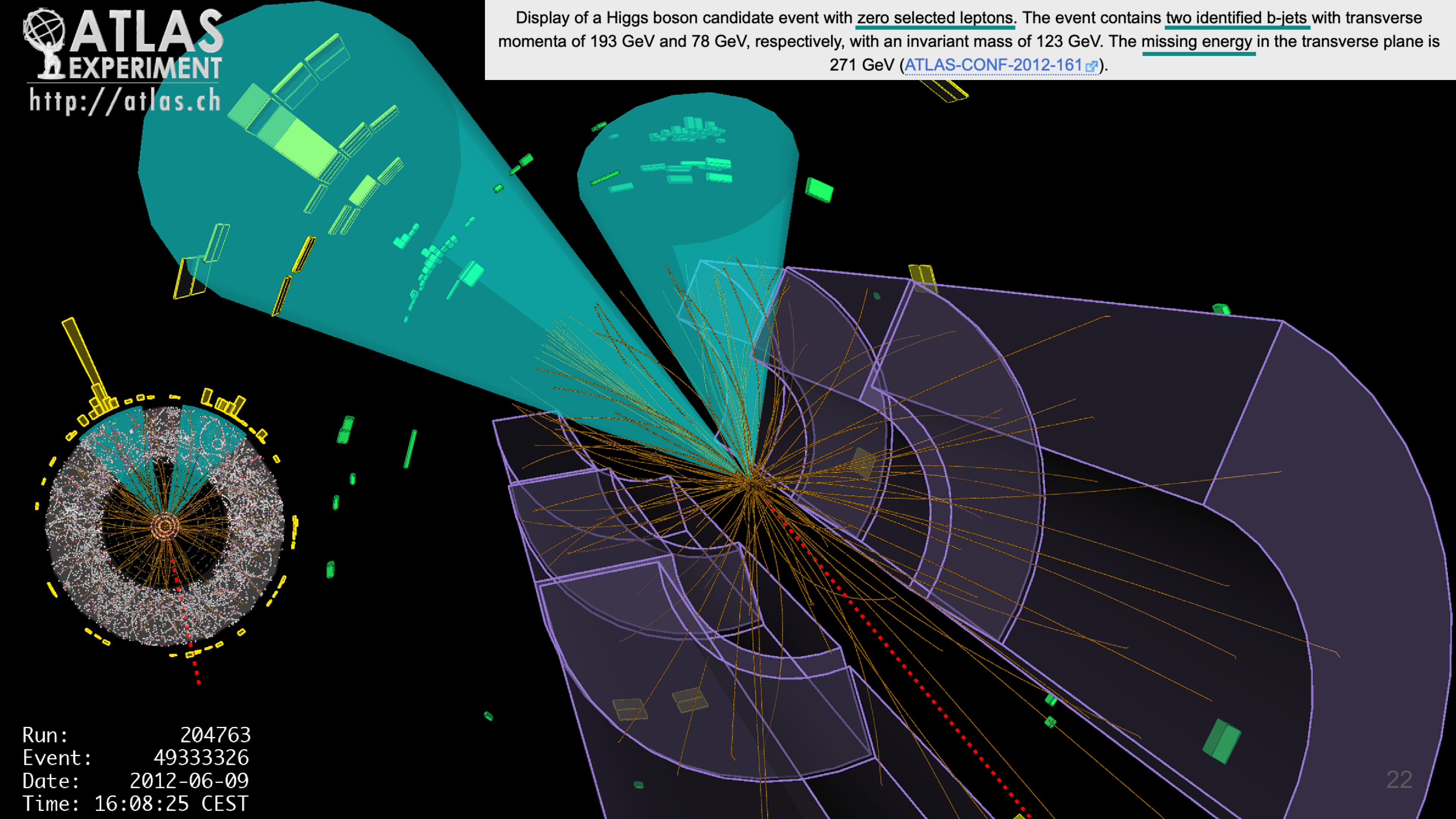
- Similar final state than signal
- Much larger cross-section
- Exemplifying decay chain, remember:
  - $Z \to q\bar{q}/\ell^+\ell^-/\nu\bar{\nu}$
  - $W^- \to q'\bar{q}/\ell^-\bar{\nu}$
  - $t \to W^+b$ (>99%)

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

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

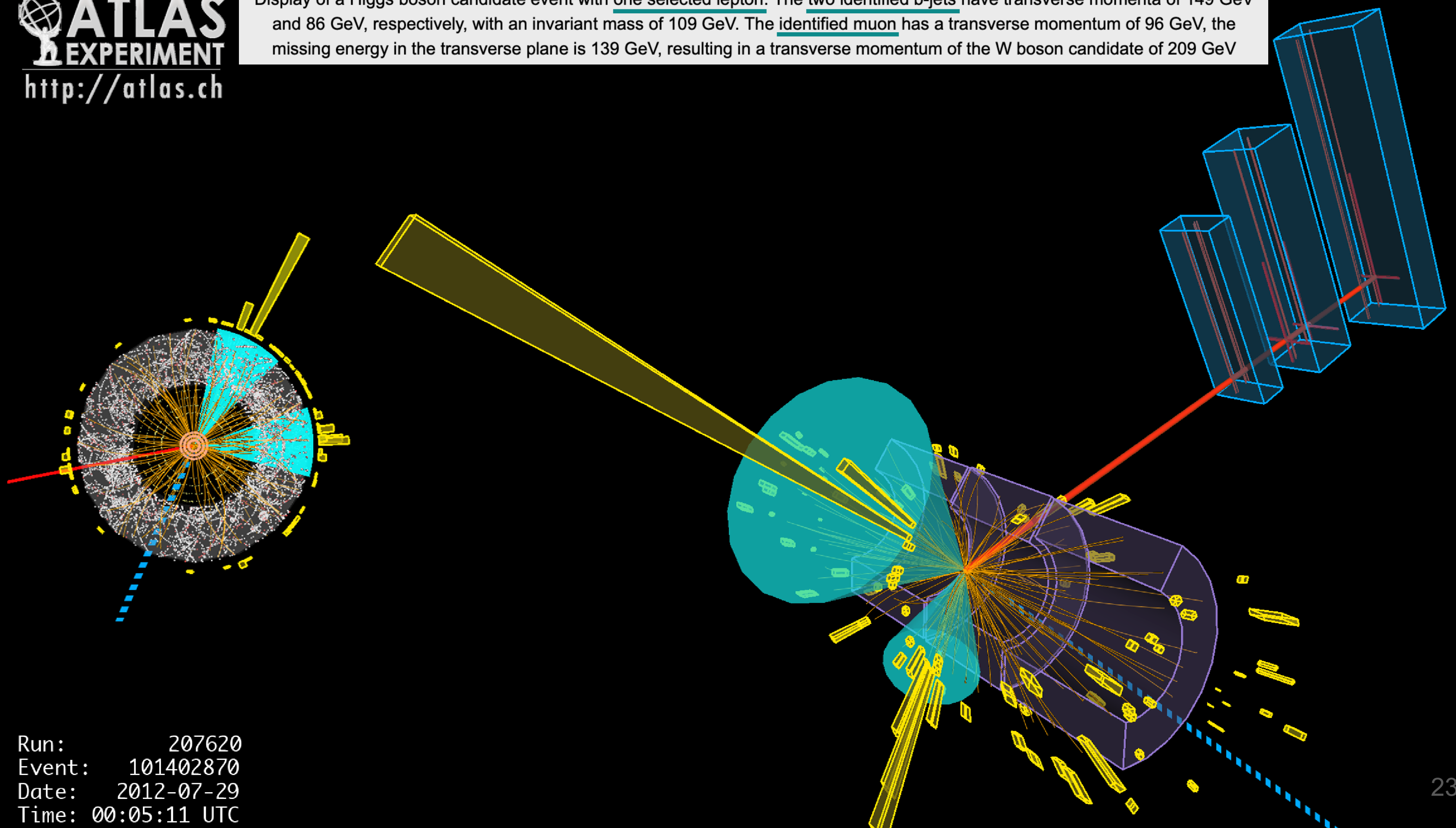
- (0 lepton) $Z \to \nu\bar{\nu}$:
  - Neutrinos are weakly interacting: yield missing energy
- (1 lepton) $W^{\pm} \to \ell^{\pm}\nu$ and (2 lepton) $Z \to \ell\bar{\ell}$:
  - Reconstruct and identify electrons and muons

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).

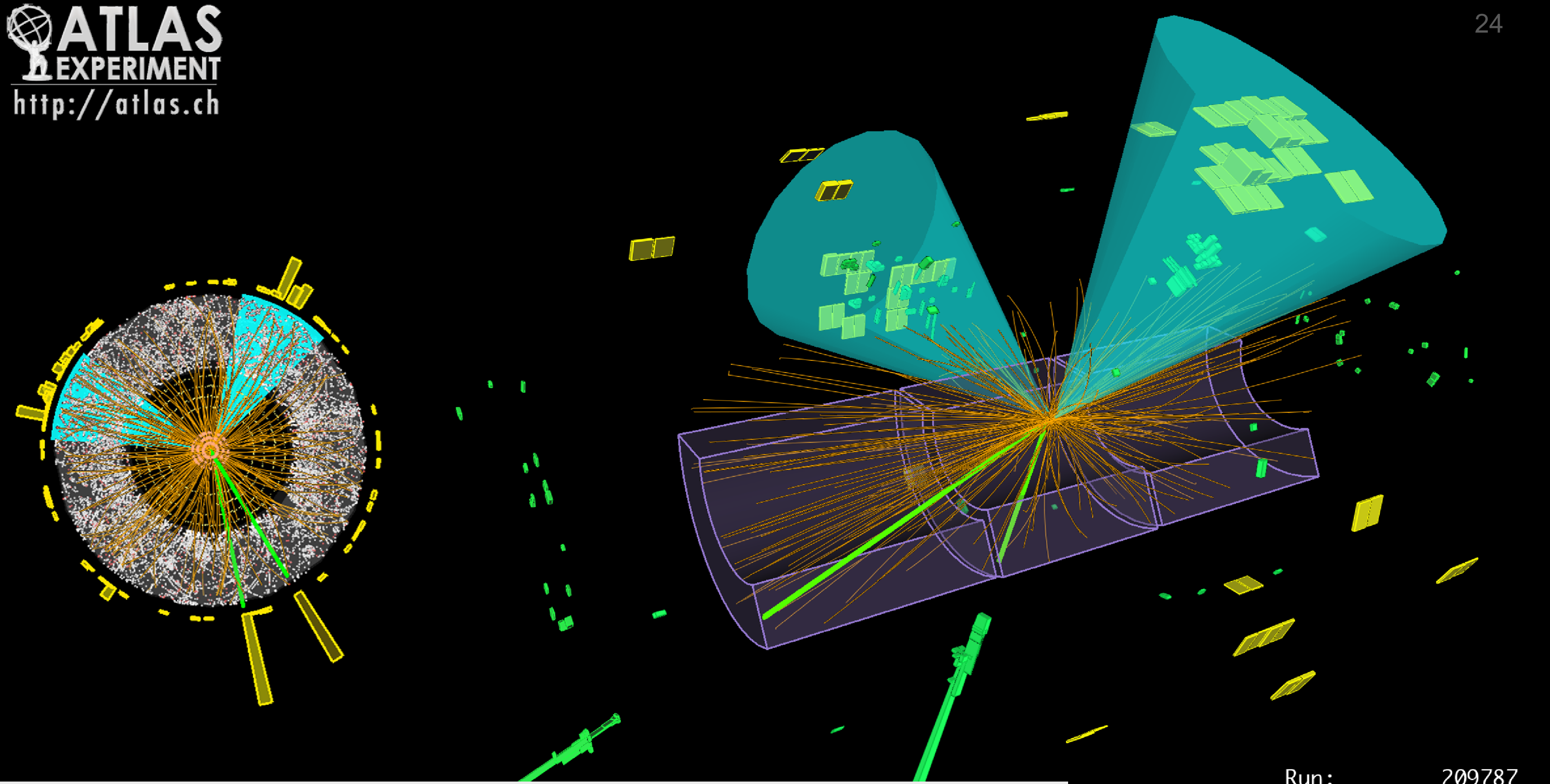


Display of a Higgs boson candidate event with one selected lepton. The two identified b-jets have transverse momenta of 149 GeV and 86 GeV, respectively, with an invariant mass of 109 GeV. The identified muon has a transverse momentum of 96 GeV, the missing energy in the transverse plane is 139 GeV,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

ATLAS EXPERIMENT
http://atlas.ch



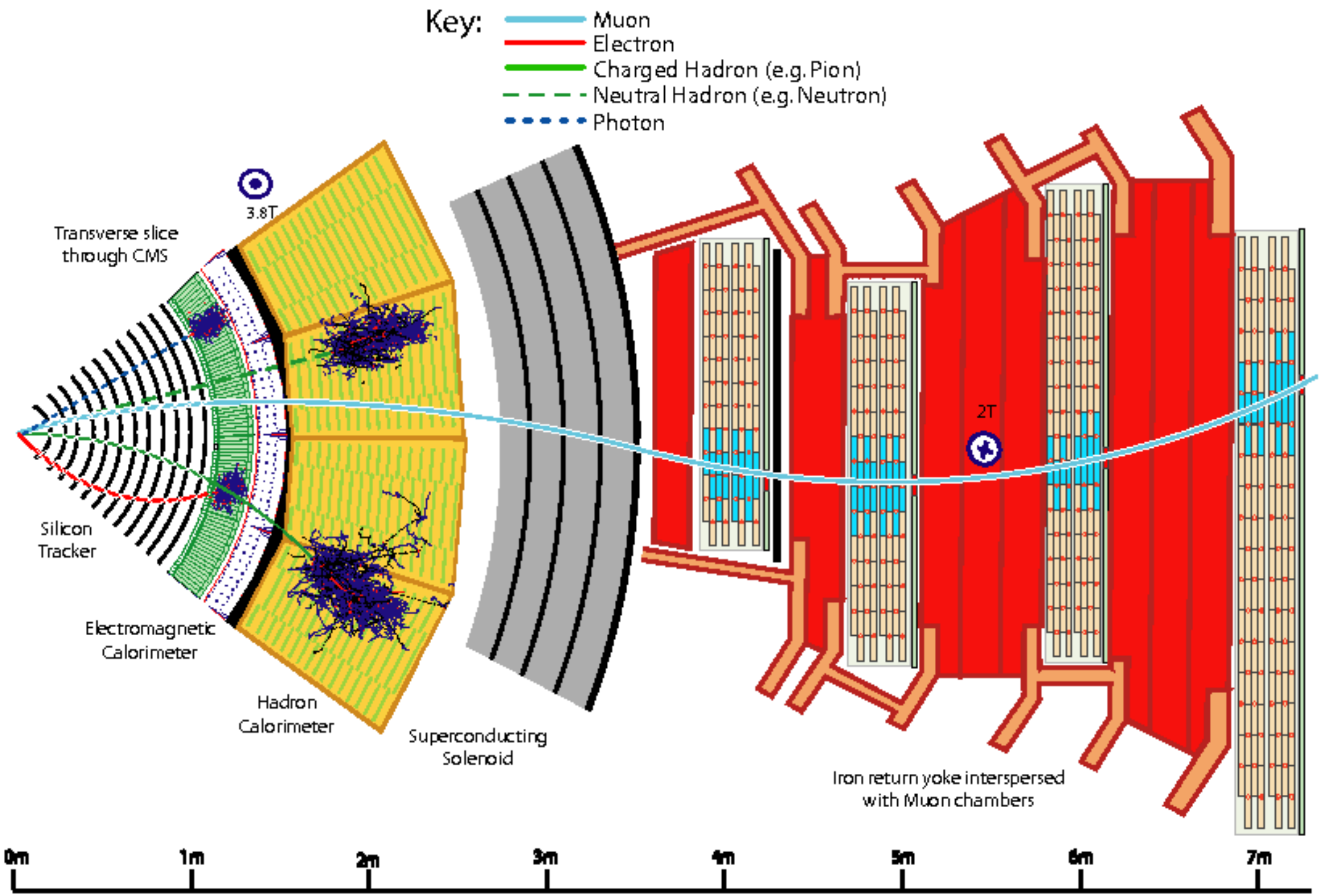
Run: 207620
Event: 101402870
Date: 2012-07-29
Time: 00:05:11 UTC



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

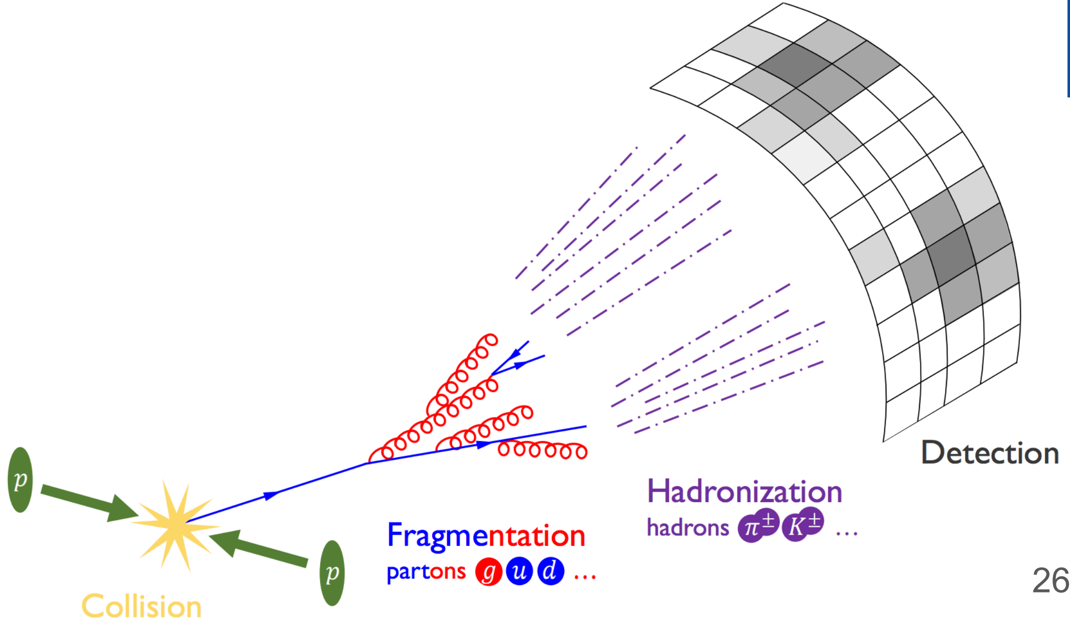
- Identify collision vertices and particles:
  - Track-finding
  - Electron/muon ID/ reconstruction
  - Jet clustering
- Measure energy, momenta, electric charge
- Jet flavour
- Event topology



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

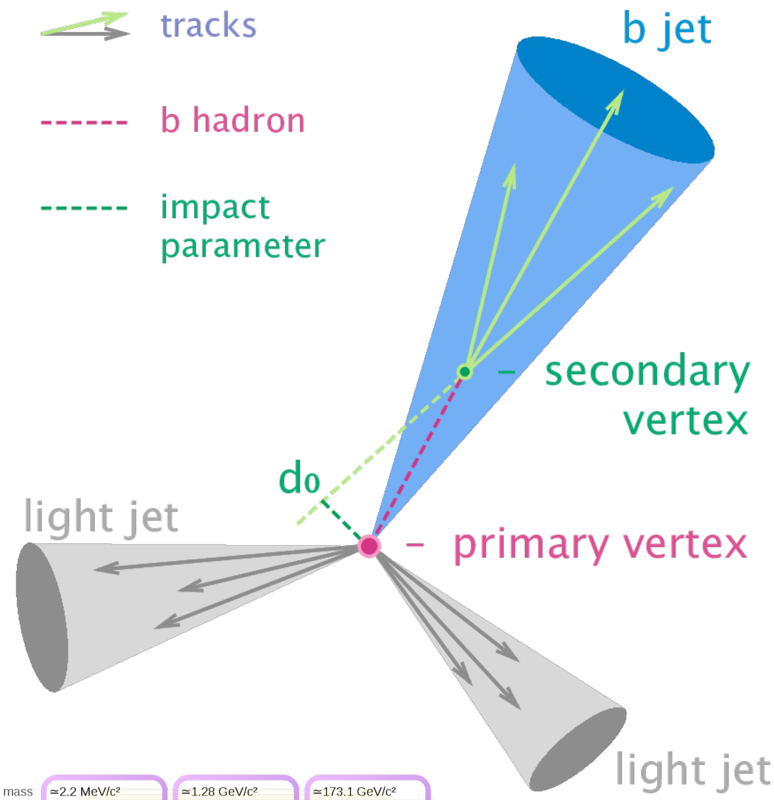


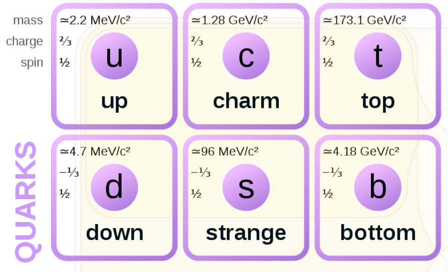
Jet Flavour identification

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





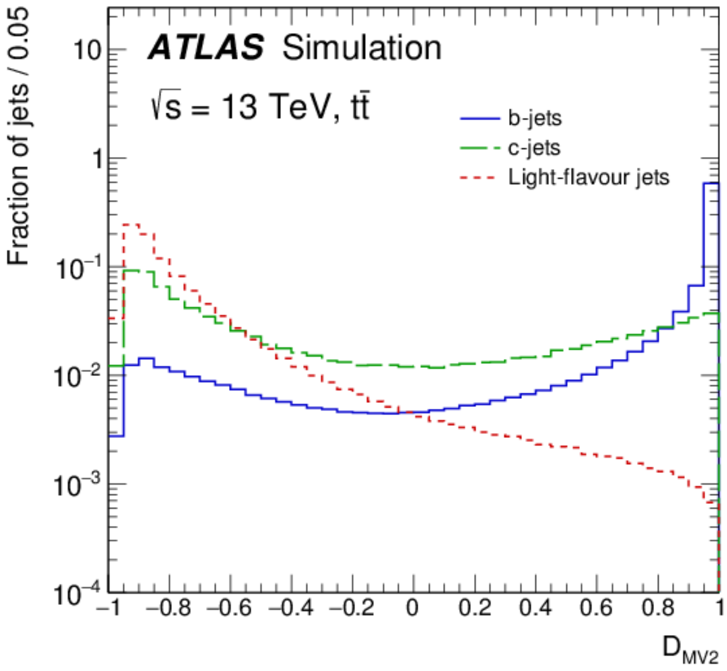
BDT for jet flavour identification

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, η
- 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

More sophisticated algorithms now, including deep learning

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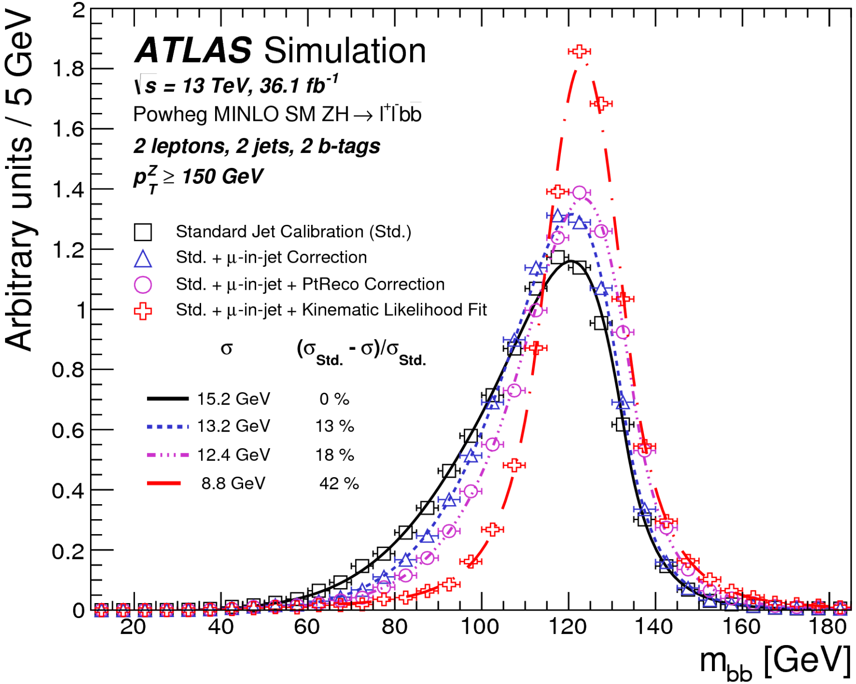
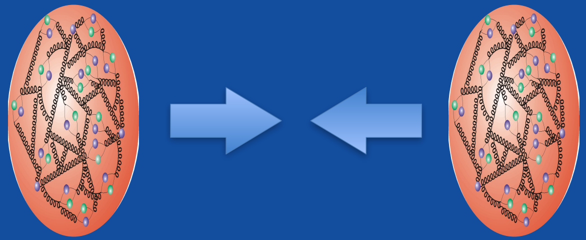
m_{bb} resolution



- 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 $\overrightarrow{p}$ 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		2-lepton
		e sub-channel	μ sub-channel	
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 ≥ 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 $\lvert\eta\rvert < 2.5$ > 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 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

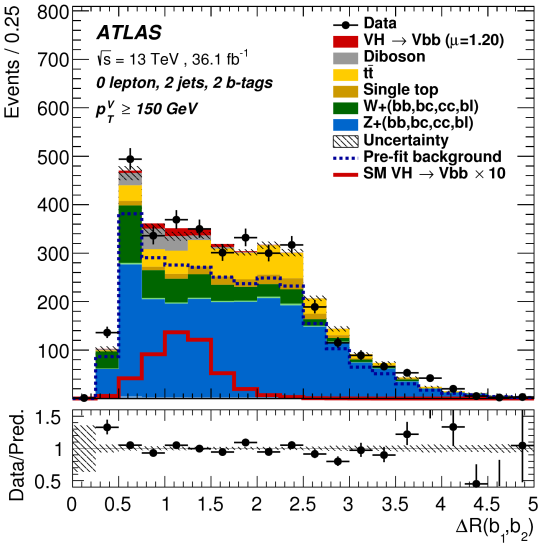
Selection	0-lepton	1-lepton: e sub-channel	1-lepton: μ sub-channel	2-lepton
Trigger	E_T^{miss}	Single lepton	E_T^{miss}	Single lepton
Leptons	0 *loose* leptons with $p_T > 7$ GeV	1 *tight* electron $p_T > 27$ GeV	1 *tight* muon $p_T > 25$ GeV	2 *loose* leptons with $p_T > 7$ GeV ≥ 1 lepton with $p_T > 27$ 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 / ≥ 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 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

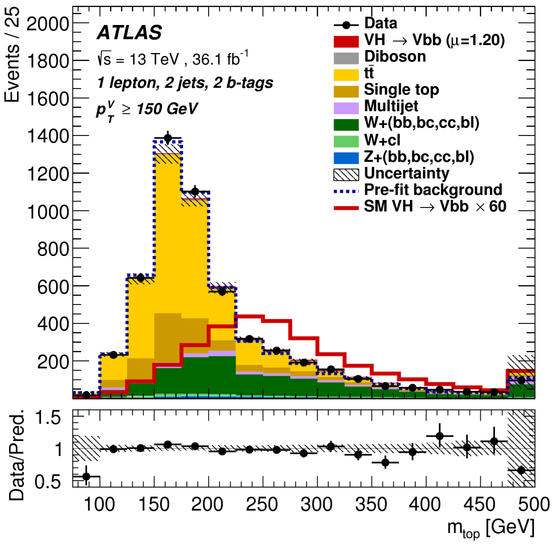
Signal regions

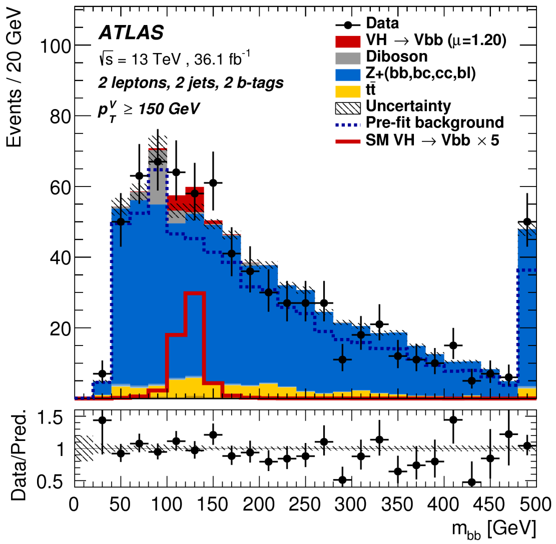
- Designed to maximise $S/\sqrt{B}$

Selection	0-lepton	1-lepton: e sub-channel	1-lepton: μ 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 ≥ 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 $\lvert\eta\rvert < 2.5$ > 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)	–		–
$\min[\Delta\phi(\vec{E}_T^{miss}, \vec{jets})]$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)	–		–
$\Delta\phi(\vec{E}_T^{miss}, \vec{bb})$	$> 120^\circ$	–		–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^\circ$	–		–
$\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{miss})$	$< 90^\circ$	–		–
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 Opposite-sign charges ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{top} > 225$ GeV		Different-flavour leptons Opposite-sign charges

Discriminating signal from background





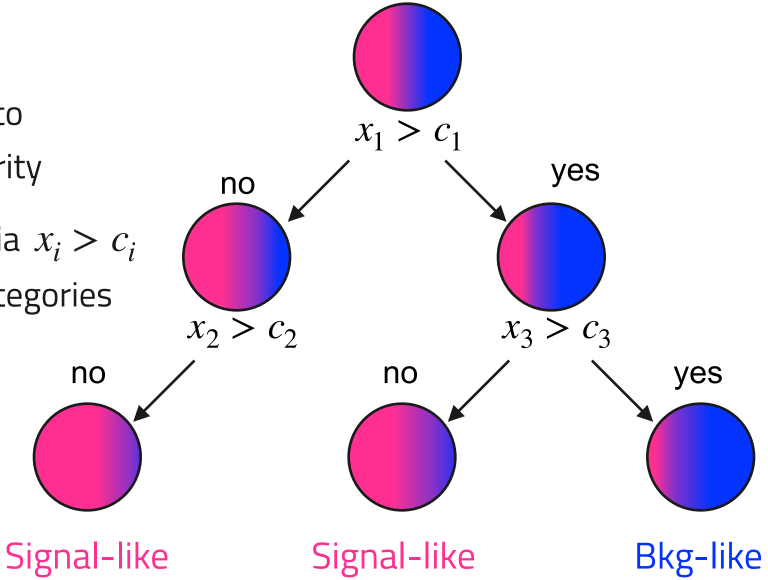


- For signal, the 2 b-jets come from the Higgs decay and are kinematically correlated
- (1 lepton) Attempt to reconstruct the t-quark invariant mass (system $\ell\nu b$): background peak at 175 GeV
- m_{bb}

Boosted Decision Tree for signal identification

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

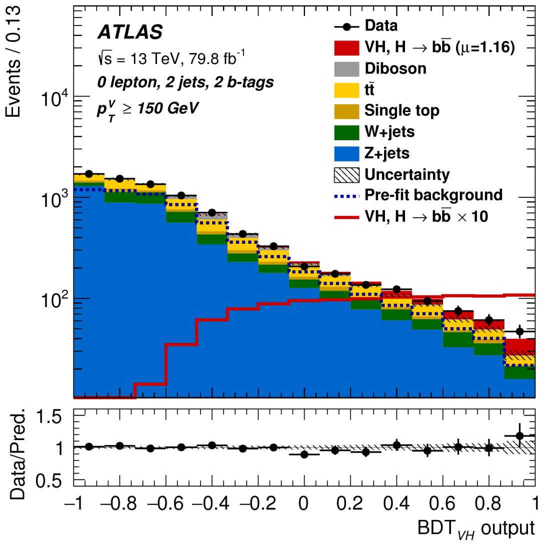
- Partitions the data to increase sample purity
- Finds optimal criteria $x_i > c_i$ to separate data categories

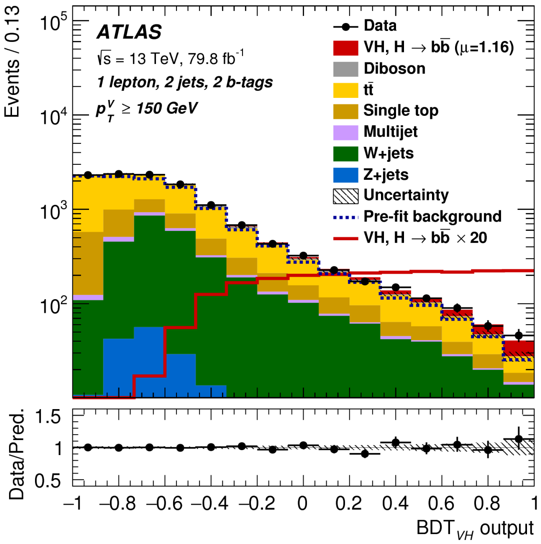


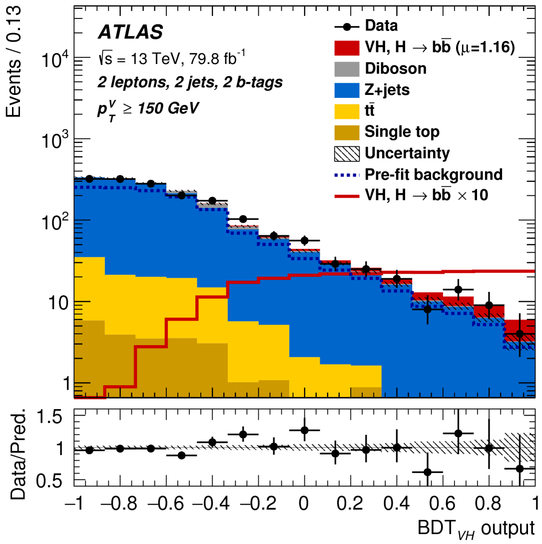
Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	$\times$	$\times$
E_T^{miss}	$\times$	$\times$	$\times$
$p_T^{b_1}$	$\times$	$\times$	$\times$
$p_T^{b_2}$	$\times$	$\times$	$\times$
m_{bb}	$\times$	$\times$	$\times$
$\Delta R(\vec{b}_1, \vec{b}_2)$	$\times$	$\times$	$\times$
$\lvert\Delta\eta(\vec{b}_1,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







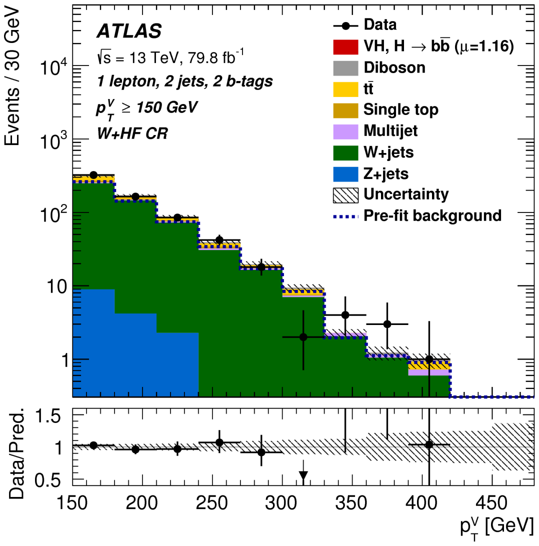
Background control regions

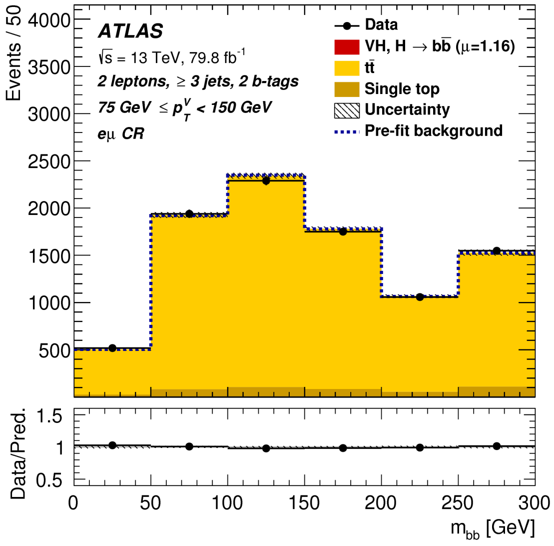
- To obtain pure samples on specific backgrounds

Selection	0-lepton	1-lepton e sub-channel	1-lepton μ 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 ≥ 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 / ≥ 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)	–		–
$\min[\Delta\phi(\vec{E}_T^{miss}, \vec{jets})]$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)	–		–
$\Delta\phi(\vec{E}_T^{miss}, \vec{bb})$	$> 120^\circ$	–		–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^\circ$	–		–
$\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{miss})$	$< 90^\circ$	–		–
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 Opposite-sign charges ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{top} > 225$ GeV		Different-flavour leptons Opposite-sign charges

Background control regions

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

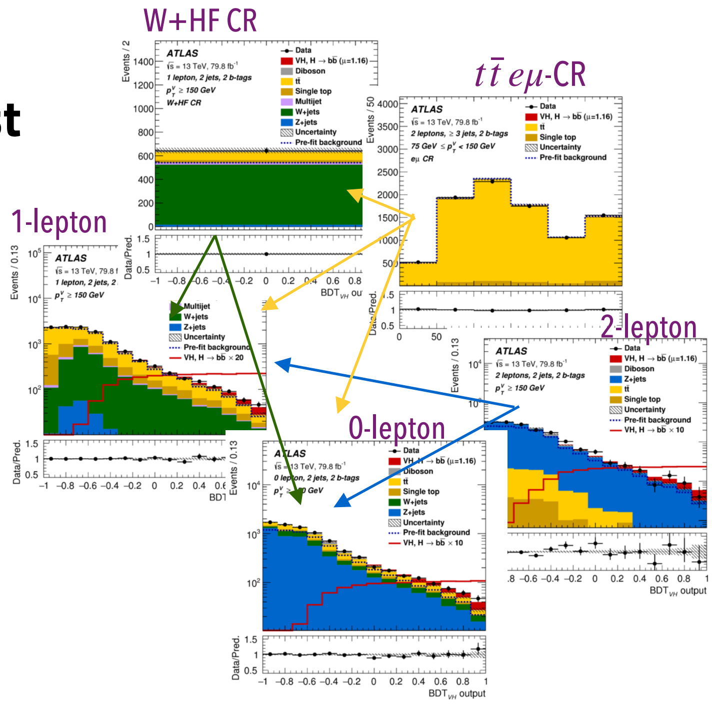




- Enriched in W+jets
- Enriched in top pairs

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 $\mu = \dfrac{N_{obs}}{N_{exp}}$
- 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 ± 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

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

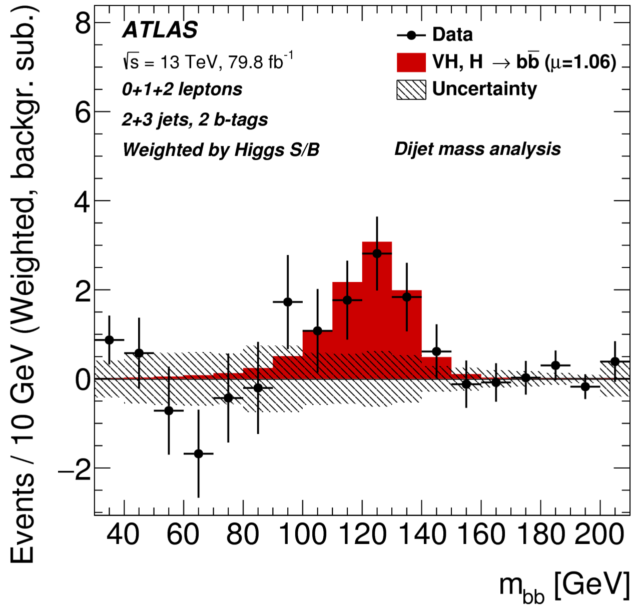
- Impact of each uncertainty source quantified as a signal strength uncertainty σ_μ

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

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: 4.9σ (4.3σ)
  - Almost there, but didn't reach the "5σ" 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 $(\mu = 1)$



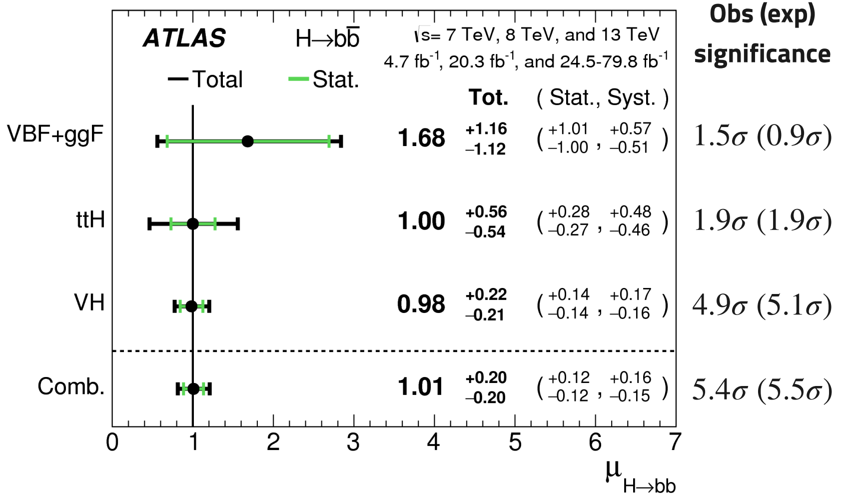
VH Run1 arXiv:1409.6212 ttH Run2 arXiv:1712.08895 VBF+ggF Run1 arXiv:1606.02181

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)



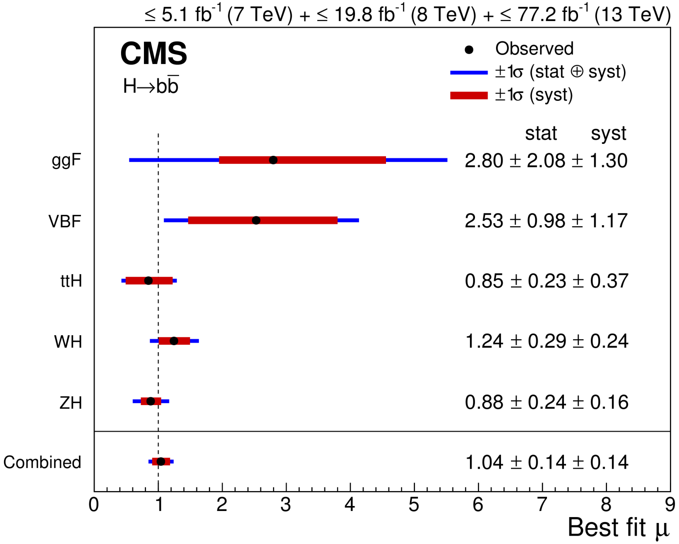
- $H \to bb$ dominant in VH observation (5.3σ)
  - Combined with $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$

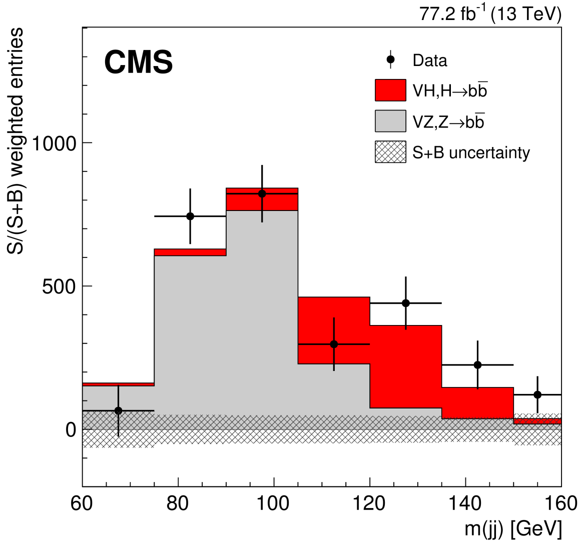
Channel	Significance Exp.	Significance Obs.
$H \to ZZ^* \to 4\ell$	1.1	1.1
$H \to \gamma\gamma$	1.9	1.9
$H \to b\bar{b}$	4.3	4.9
VH combined	4.8	5.3

- 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: 5.6σ (5.5σ)
  - $\mu = 1.04 \pm 0.20$





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

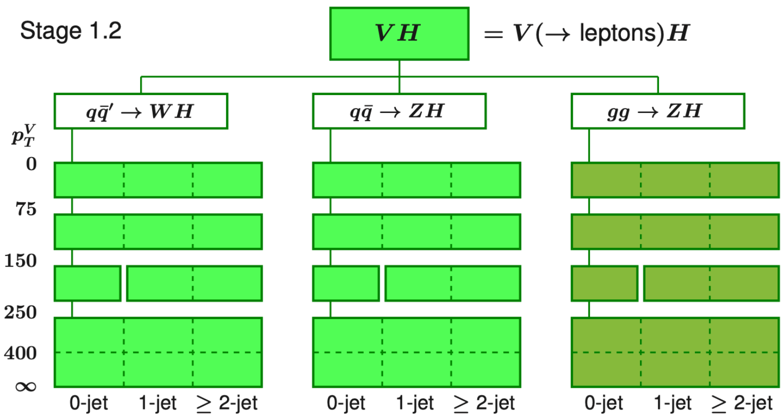
What's next?

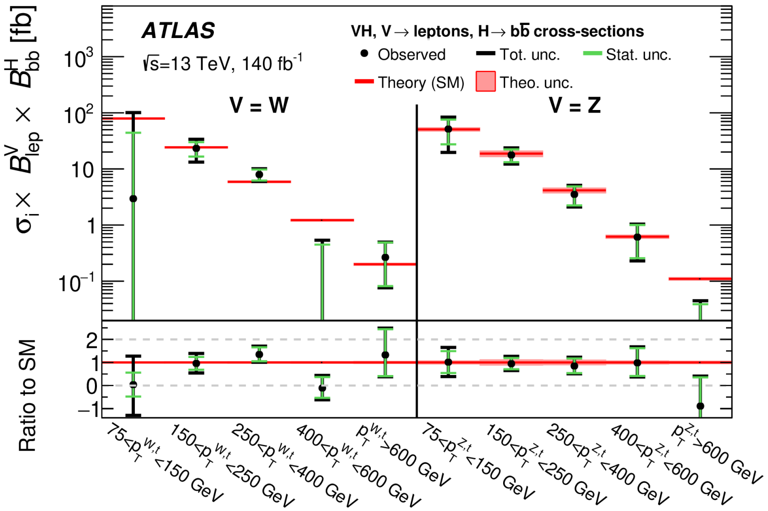
- Use $H \rightarrow b\bar{b}$ to measure Higgs properties
  - Towards differential cross-section
  - Investigate the HVV and Hbb interaction vertex
  - Higgs boosted regime

- What we may expect from the High Luminosity-LHC

Differential cross-section measurements

- Simplified Template Cross Section framework
  - Measure σ 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 σ_{VH}
  - σ_{VH} as a function of p_T^V

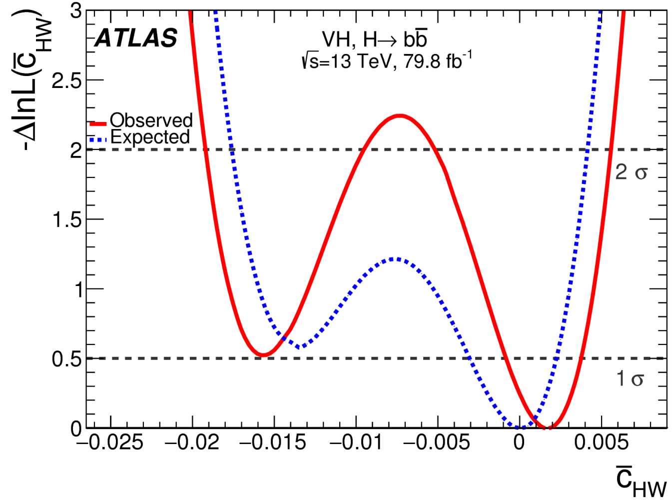


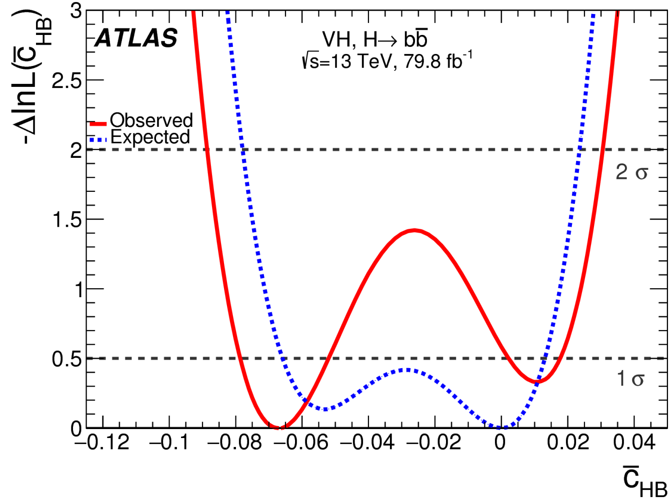


Effective Field Theory interpretation of VH cross-section measurements

- 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 σ_{ZH} and not σ_{WH})
  - SM limit: $c \to 0$
- c limited to few percent at 95% CL

arXiv:1903.04618

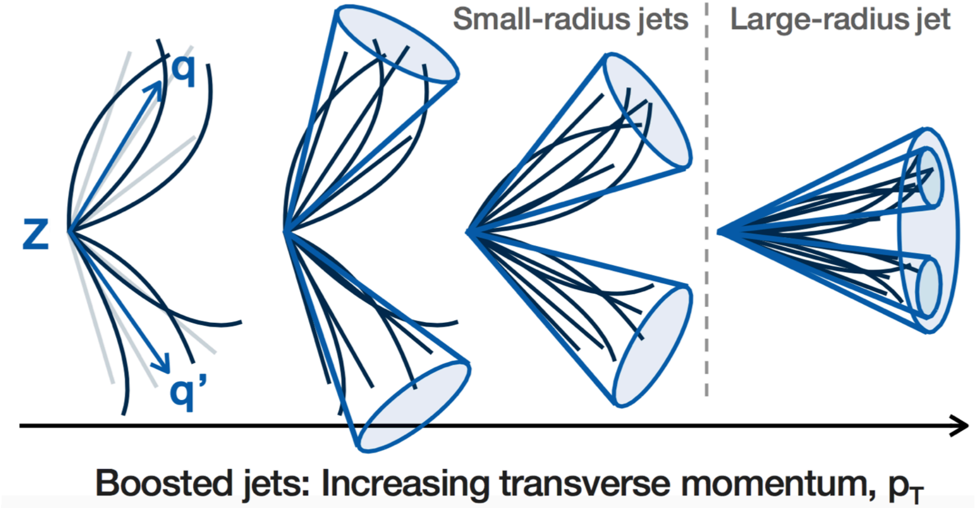




Higgs *"Boosted"* Regime

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



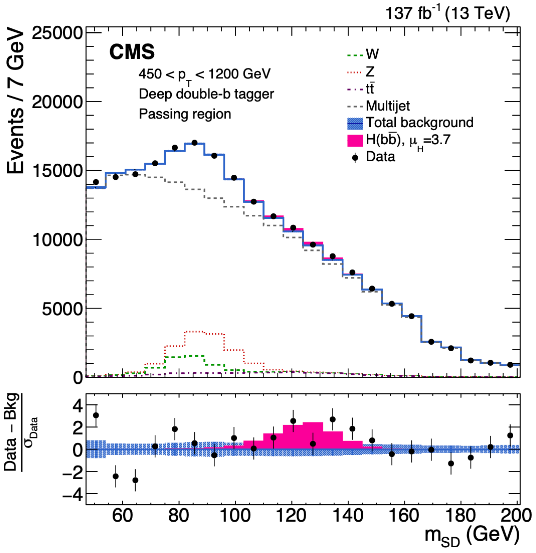
- Signal reconstructed has a large-R jet
- 2 b-tagged sub-jets inside large-R jet (reconstructed from tracks)
- Other techniques being explored, e.g. using Deep Neural Networks

JHEP12(2020)085

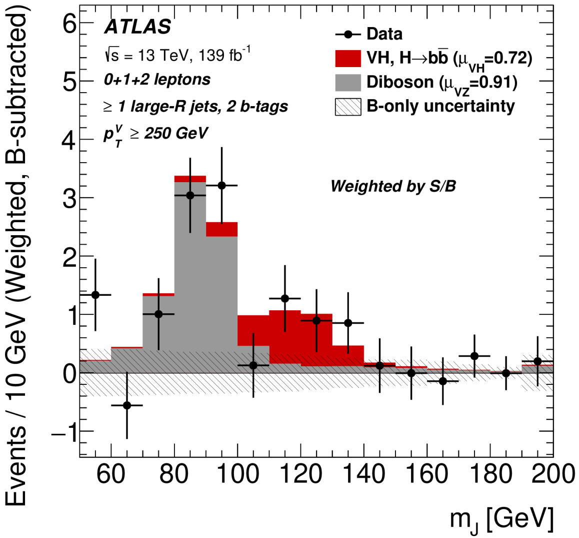
VHbb boosted 2008.02508

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

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



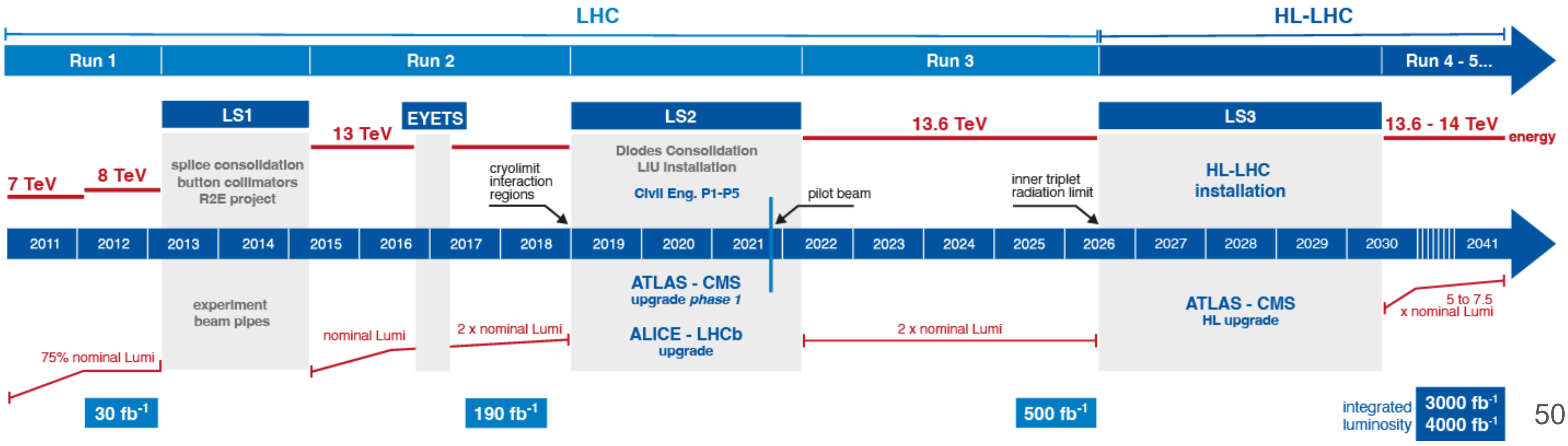
- Associated W/Z production
  - p_{TJ} > 250 GeV
  - Observed (expected) significance: $2.1\sigma\ (2.7\sigma)$
  - $\mu = 0.72^{+0.39}_{-0.36}$ (SM-compatible)

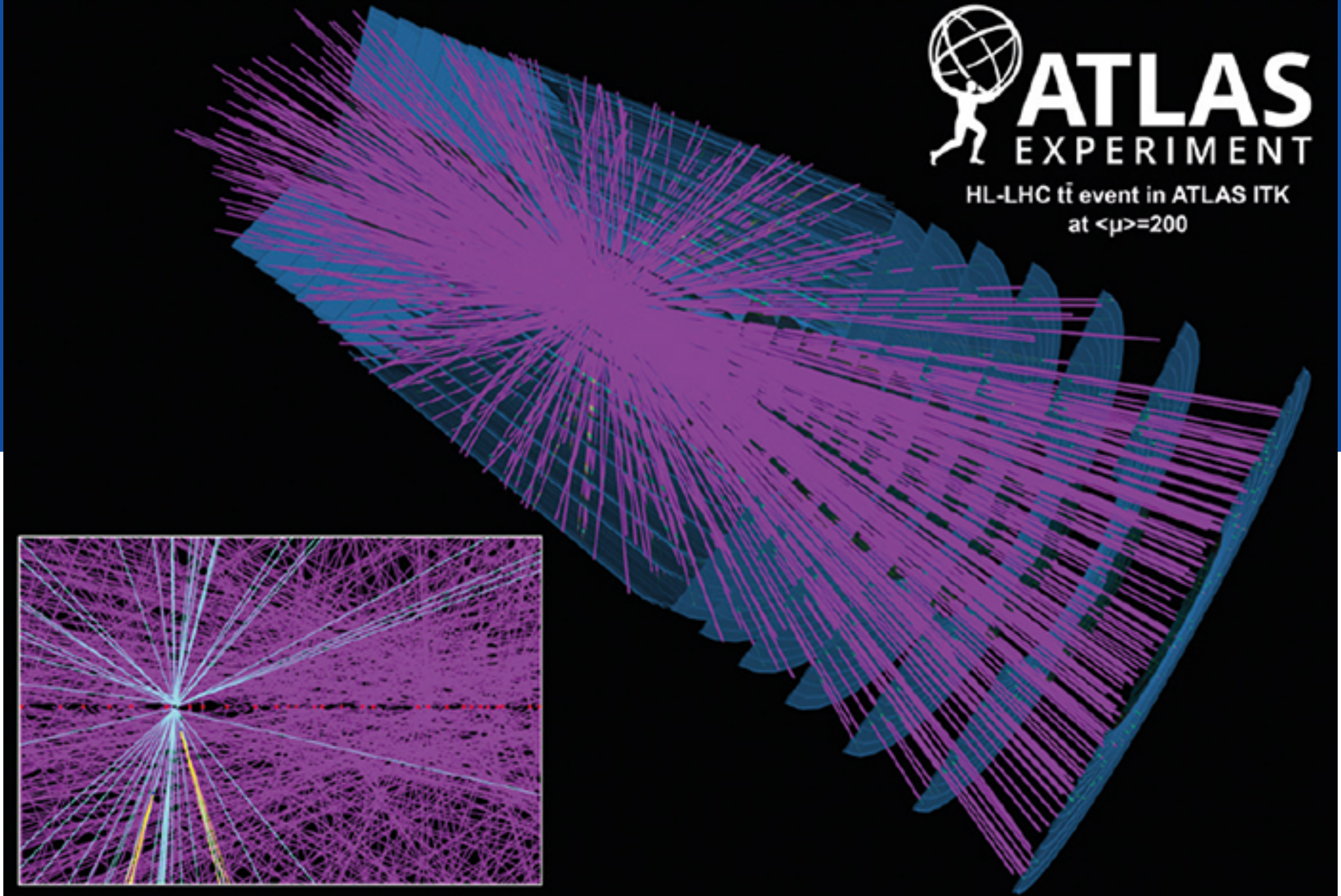


High Luminosity-LHC upgrade

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

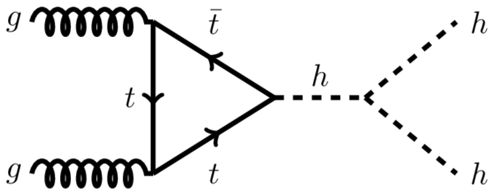
- A lot more data to analyse: 3000/4000 fb^{-1}
- Will reduce statistical uncertainty of the measurements
- High pile-up: simultaneous collisions per bunch crossing $33 \rightarrow 140$
- Noisy environment: ambiguous track reconstruction, collision vertex finding, pile-up energy subtraction,...



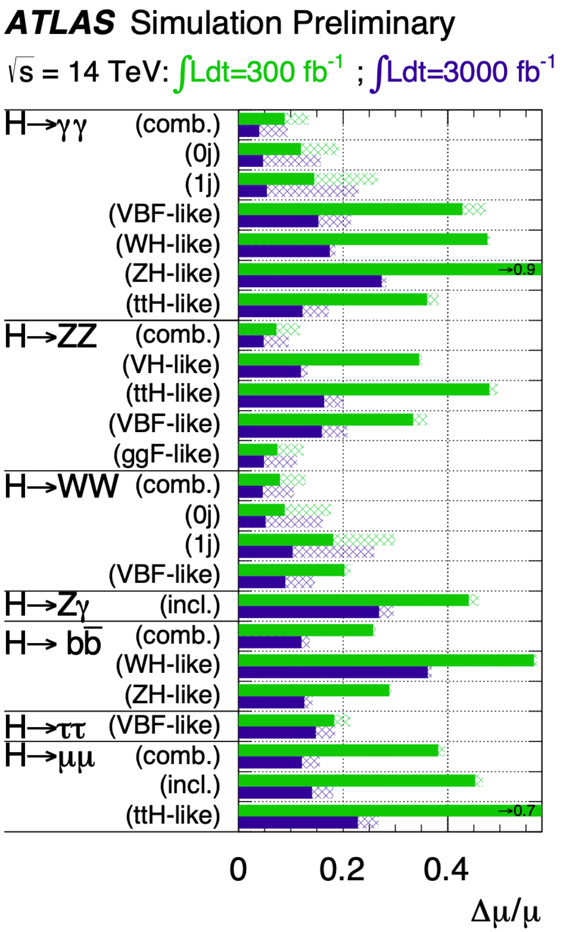

HL-LHC tt̄ event in ATLAS ITK
at <μ>=200

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!

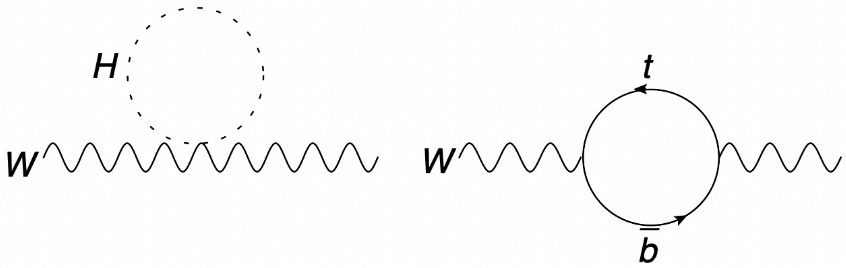
Any questions?

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^2_{top} 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



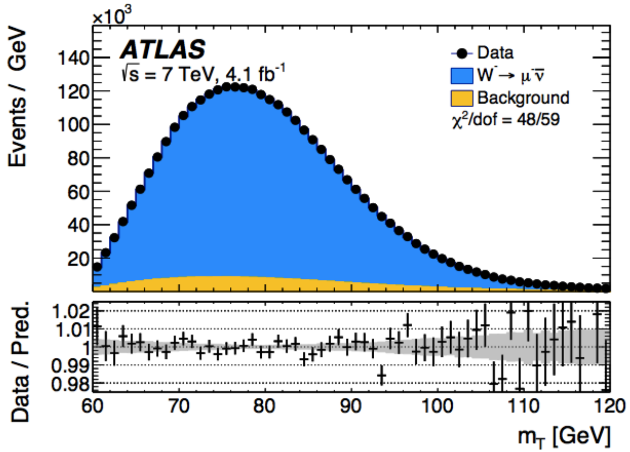
$$M_W^2 = \rho\, M_Z^2 \cos^2\theta_W$$

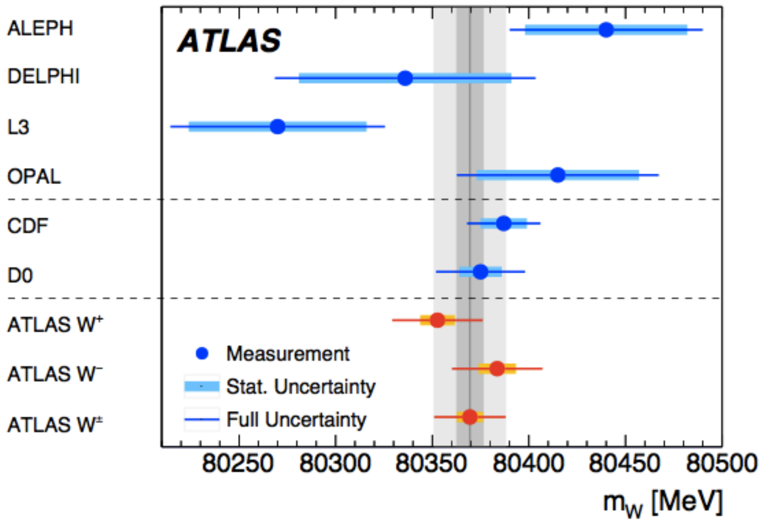
$$(\rho - 1) \sim \ln M_H$$

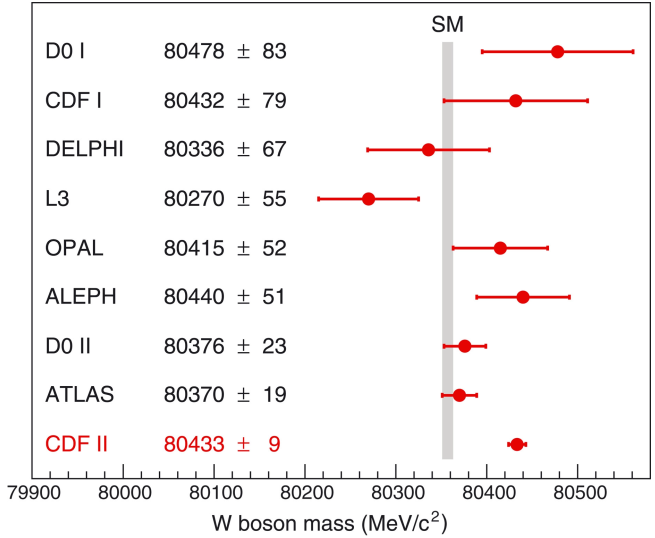
$$(\rho - 1) \sim M_{top}^2$$

W boson mass measurement

- High precision measurement —> 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