中國科學院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Study on ATLAS alternative Higgs productions (VBF H->bb & VBF H->WW)

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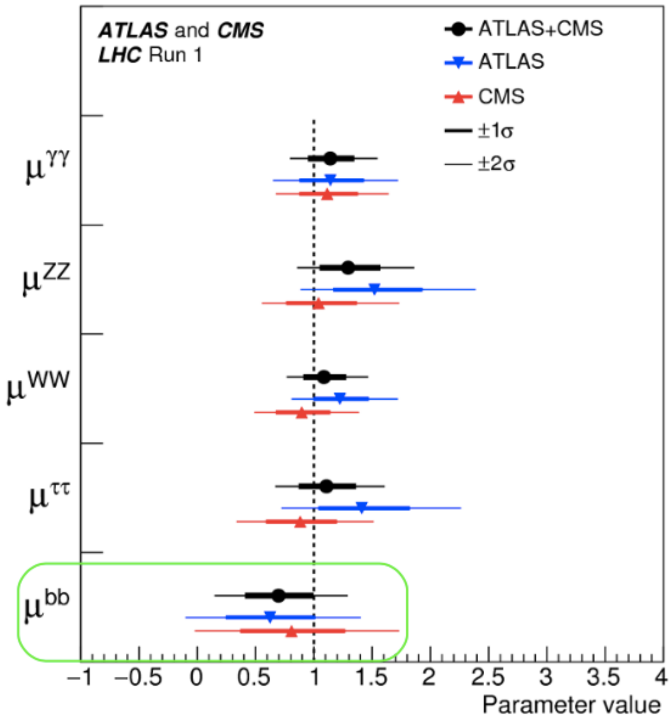
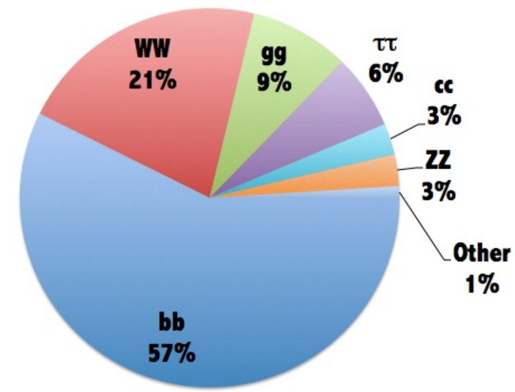
Higgs-bottom Yukawa couplings

- **H→bb has the largest branching ratio (~58%)**
- **Evidence of fermionic decays in Run 1:**

H → bb: 2.6σ (expected 3.7σ)



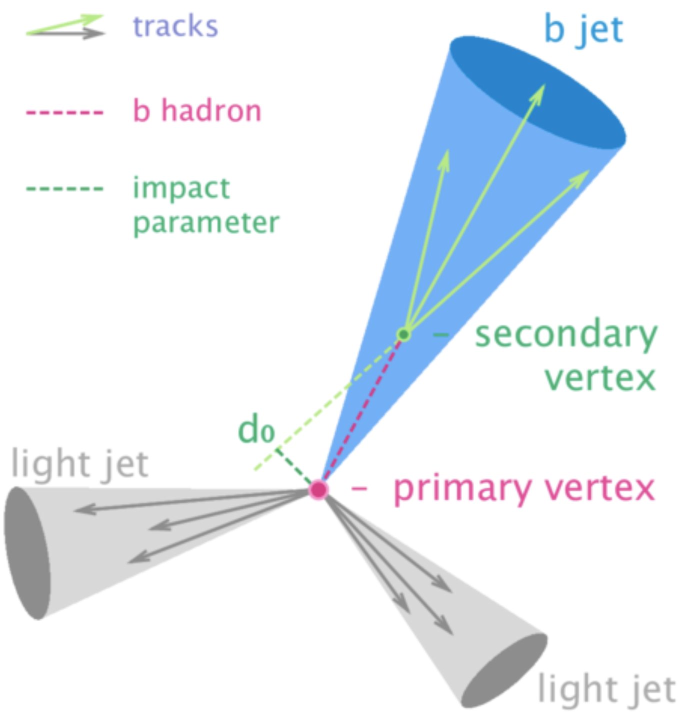
Higgs decays at m_H=125GeV

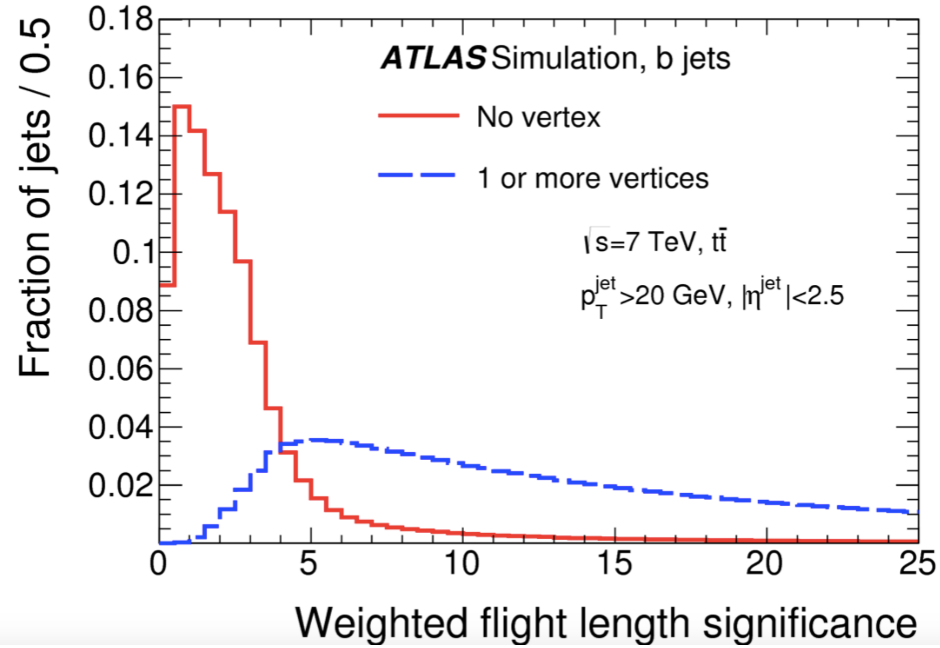


channel	Reference	Integrated Lumiosity
VH($b\bar{b}$)	**arXiv:1708.03299**	36 fb^{-1} (13TeV)
VBF H(bb)γ	ATLAS-CONF-2016-063	12.5 fb^{-1} (13TeV)

How to Identify b quark jets in ATLAS

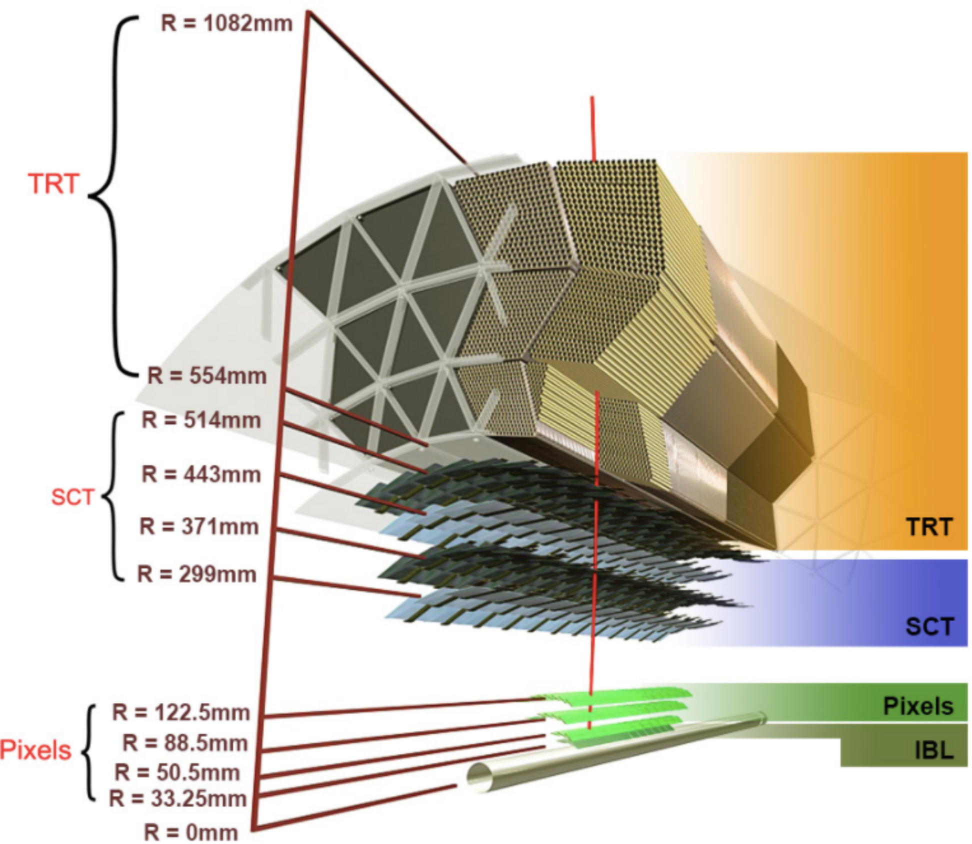
- **Two ways to Identify b jets**
  - **impact parameters**
  - **secondary vertex from B decay**

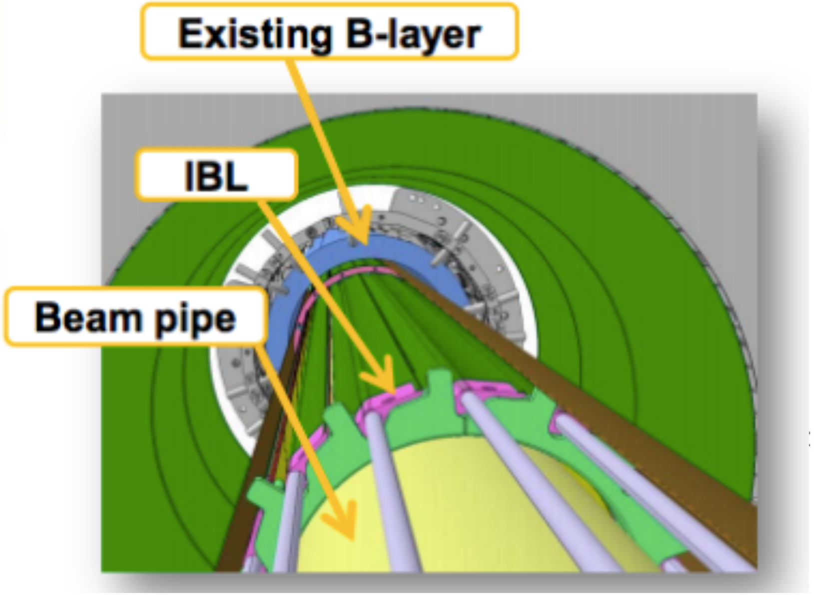




ATLAS Detector upgrade from run 1 to run 2

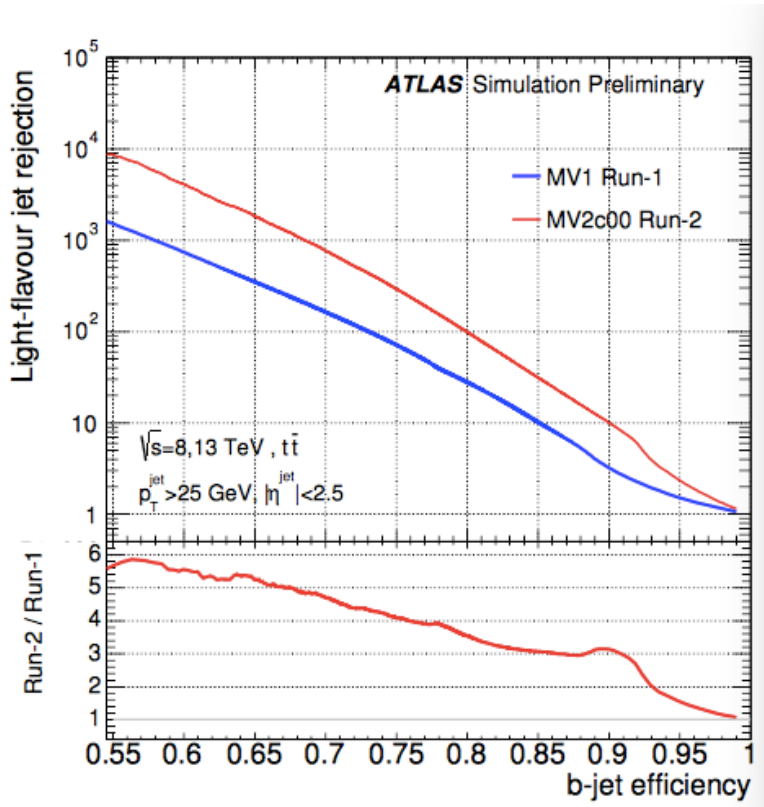
- **IBL = New Insertable pixel B-Layer at R=33 mm**

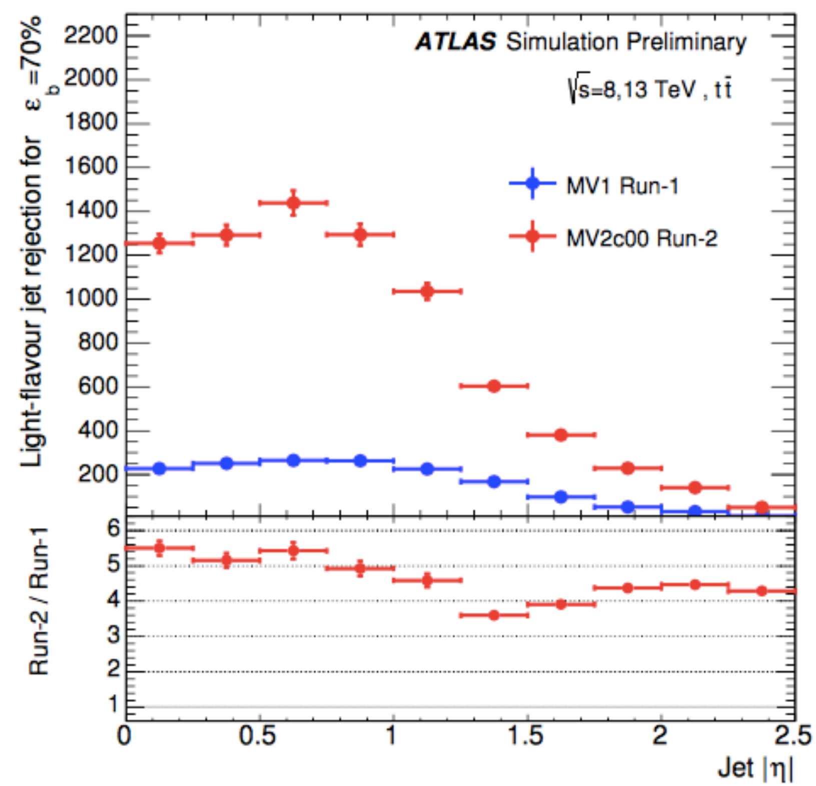




B tagging performance Improvement after upgrade

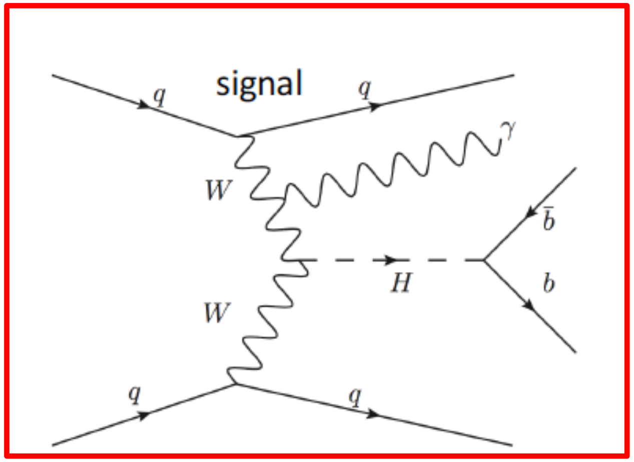
- **Light jet rejection power increases by a factor of 10**

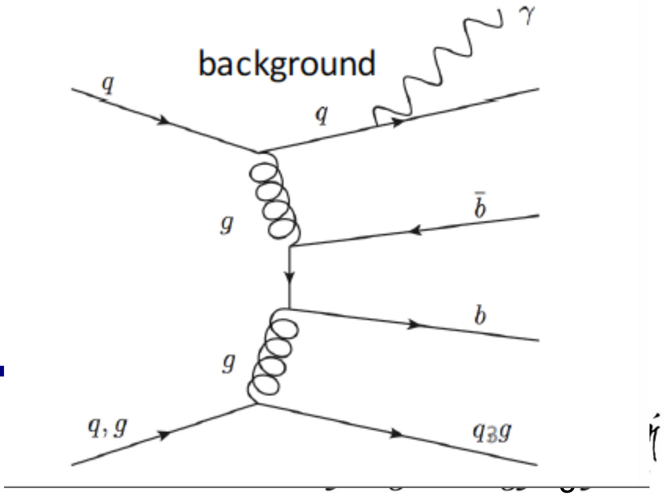




VBF H(bb)γ final state

- Search for H->bb in VBF events containing a central photon
- Advantages of requiring a photon
  - extra handle for trigger
  - suppresses QCD background
  - Sensitive to WWH VBF production
  - not sensitive to ZZH VBF





ATLAS-CONF-2016-063

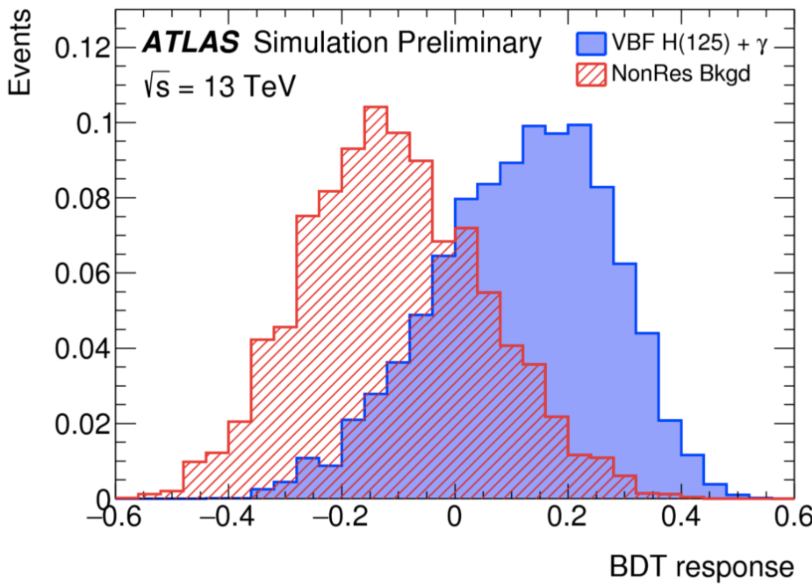
VBF H(bb)γ event selection

ATLAS-CONF-2016-063

- **Trigger:**
  - L1 trigger: single photon (pT > 25 GeV)
  - High level trigger: 4 jets pT > 35 GeV, mjj> 700 GeV
- **Offline Selection:**
  - Tight ID photon, pT > 30 GeV
  - 4 jets with pT> 40 GeV
  - 2 central(|η|<2.5) b-tagged jets
  - pT(bb)>80GeV
  - mjj> 800 GeV
- **BDT discriminant**

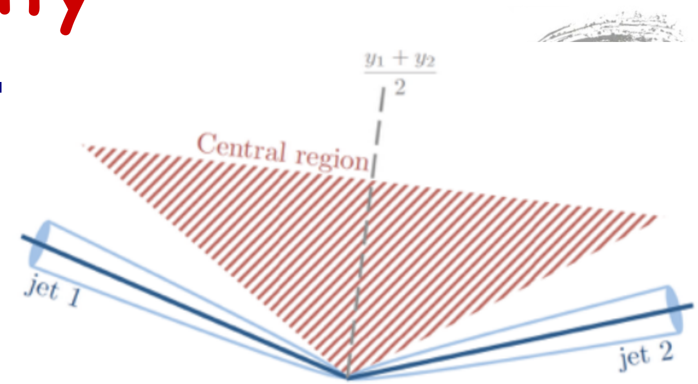
$$\Delta R(jet, \gamma), m_{jj}, \Delta\eta_{jj}, H_T^{soft}, jet\ width, \gamma\ centrality, p_T^{balance}$$

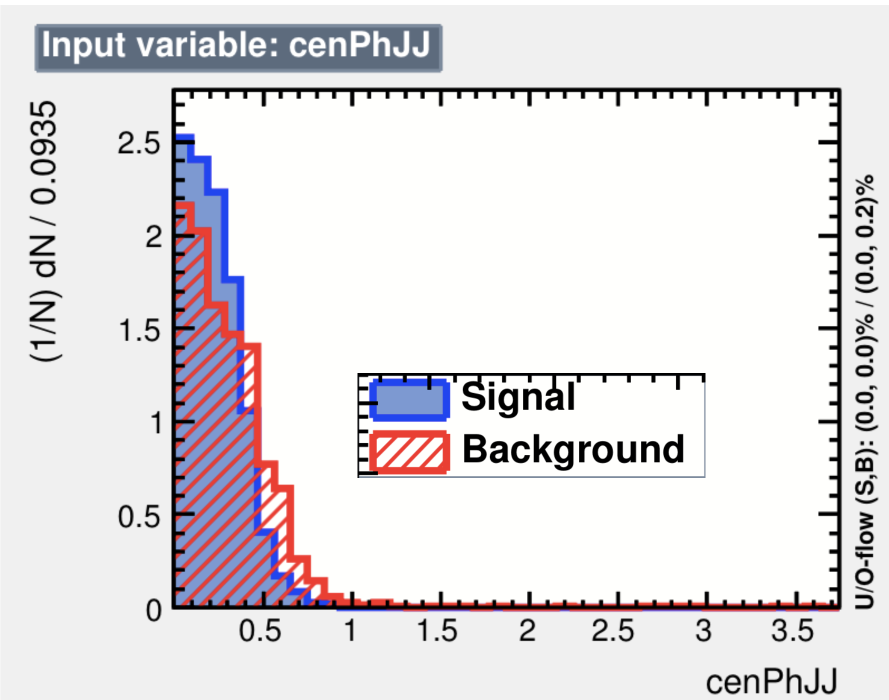
- **Define 3 regions with different S/B**
- **Fit m_{bb} in 3 regions**

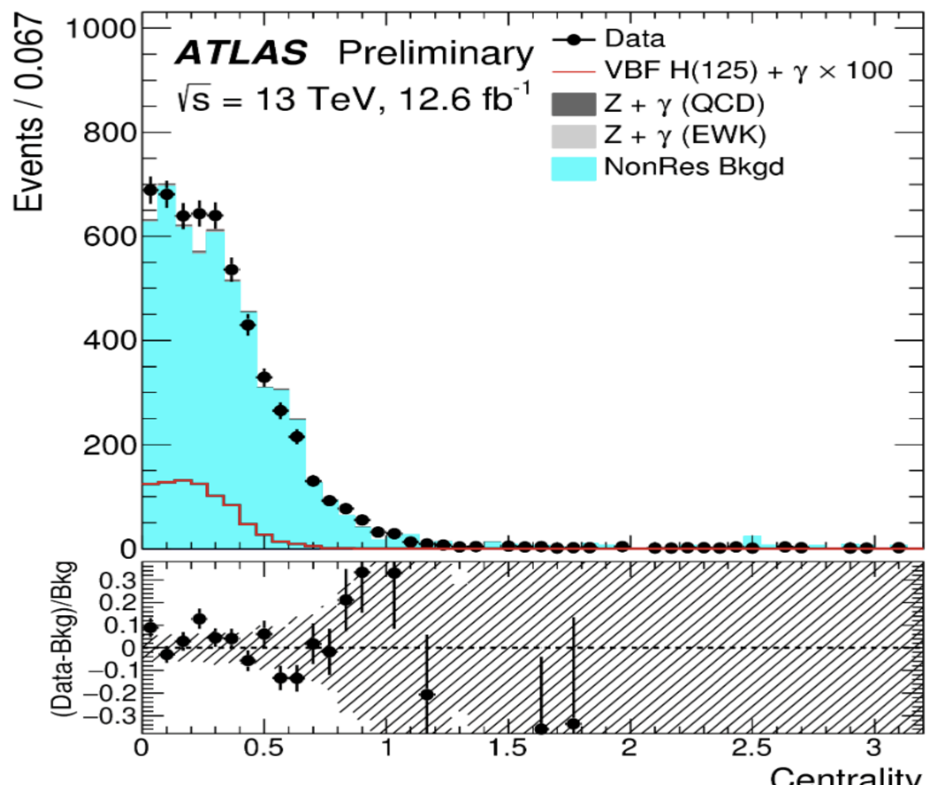


VBF H(bb)γ MVA Input varialbe: photon centrality

$$centrality(\gamma) = \left| \frac{y_\gamma - \frac{y_{j_1}+y_{j_2}}{2}}{y_{j_1} - y_{j_2}} \right|$$

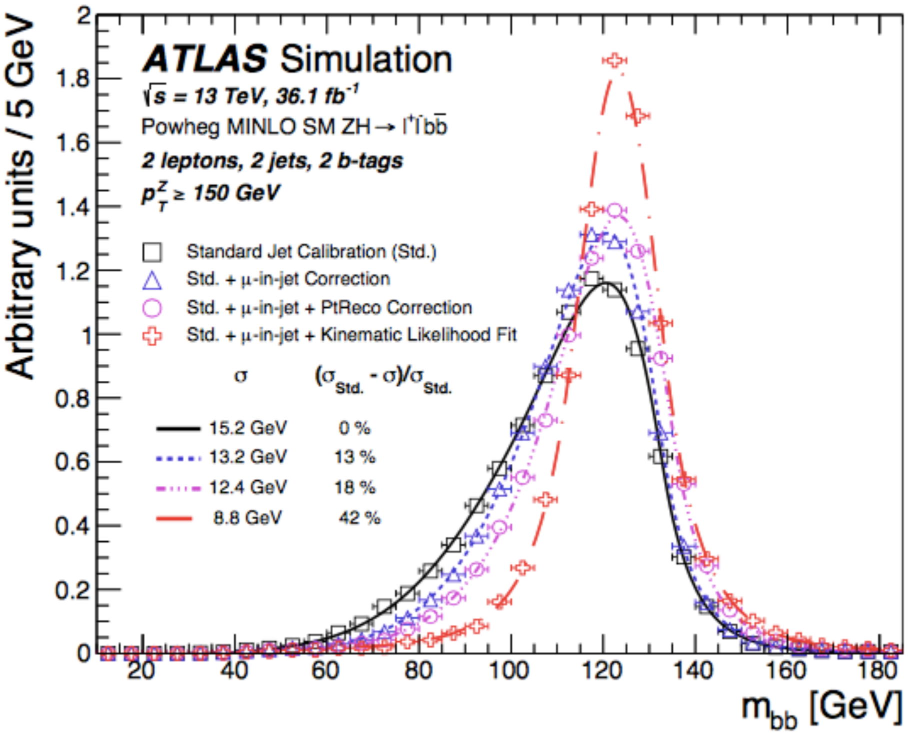






B jet energy corrections

- Using ATLAS default jet energy calibrations
  - Higgs mass resolution is not great
  - Asymmetry in mass, long tail in low mass region
- Dedicated B jet calibration
  - Muon-in-jets corrections
  - Kinematic likelihood



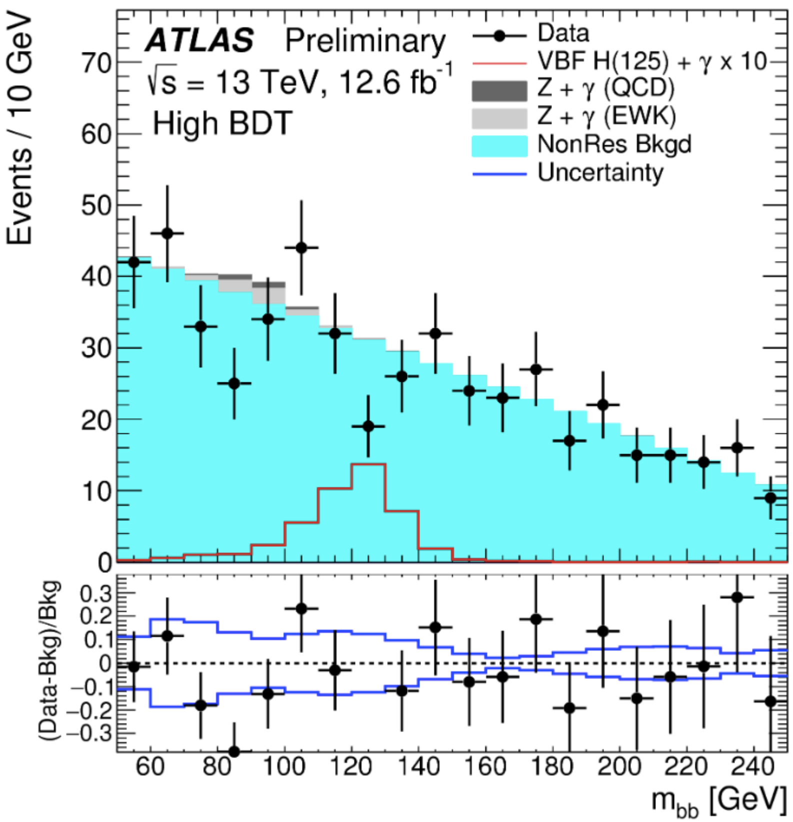
VBF H(bb)γ signal extraction

ATLAS-CONF-2016-063

- Non-resonant background (γ+jets) estimated with 2nd order polynomial fit.

Statistics uncertainty in mbb sideband region dominated

High BDT score region



Result	$H(\to b\bar{b}) + \gamma jj$	$Z(\to b\bar{b}) + \gamma jj$
Expected significance	0.4	1.3
Expected p-value	0.4	0.1
Observed p-value	0.9	0.4
Expected limit	$6.0^{+2.3}_{-1.7}$	$1.8^{+0.7}_{-0.5}$
Observed limit	4.0	2.0
Observed signal strength μ	$-3.9^{+2.8}_{-2.7}$	0.3 ± 0.8

VBF H（bb）γ production cross section limit

- Expected 95% CL limit:

  $6.0^{+2.3}_{-1.7}$

- Observed 95% CL limit:

  $4\times(\sigma\times BR)^{SM}$

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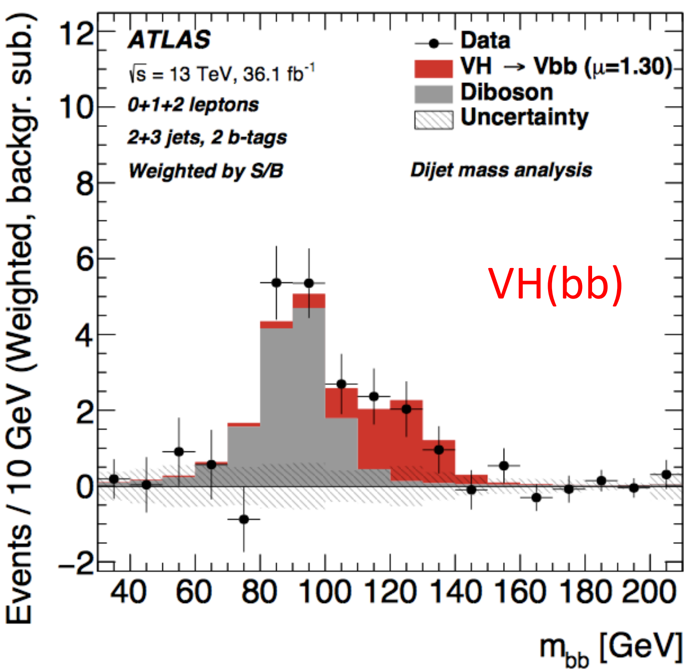
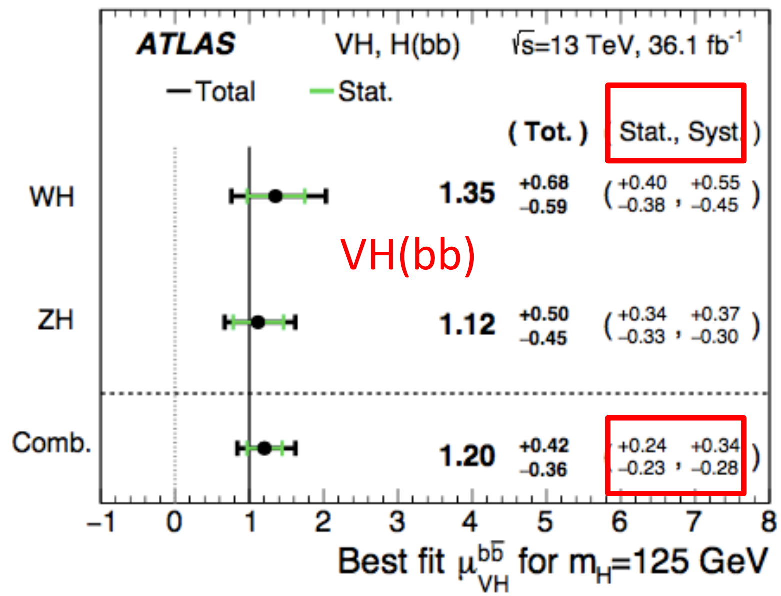
Latest results on H(bb)

- Combined signal strength with 36 fb-1 at $\sqrt{s}$= 13 TeV
  - VH(bb): 3.5 σ observed significance (3.0 σ expected)
    - Systematics dominated, very hard to reach 5 σ with run 2 data
  - VBF (bb) & VBF H(bb)γ : 1.8 σ observed significance (0.8 σ expected)
    - Statistics dominated, will catch up with VH
    - Combination of VBF and VH are more likely to reach 5 σ





VBF H->WW

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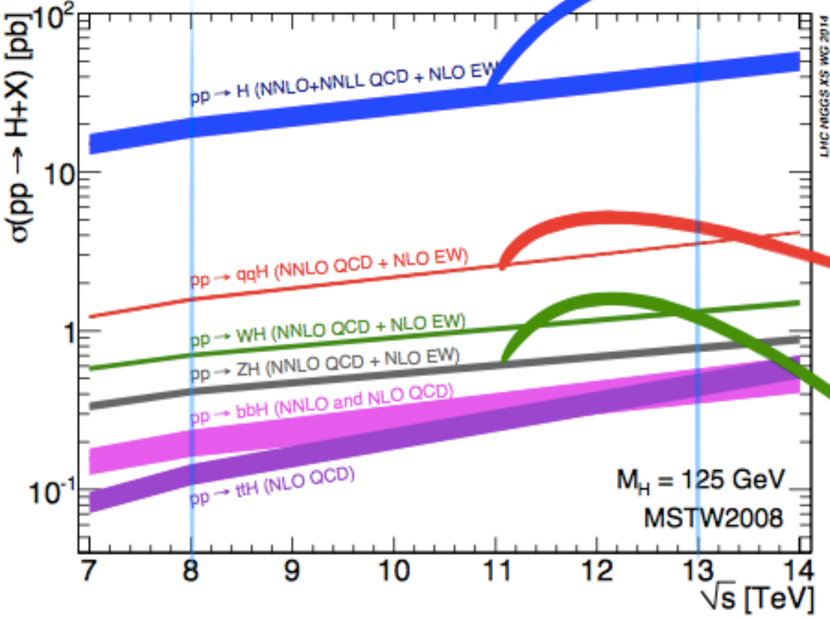
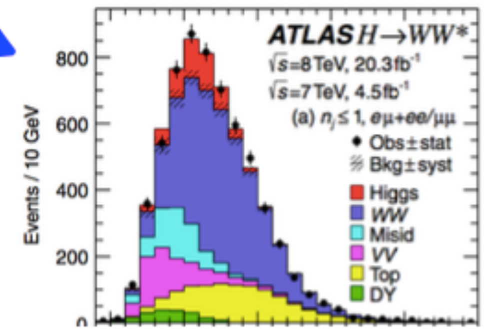
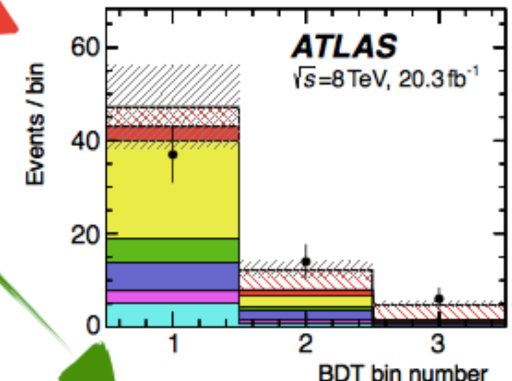
H→WW*→lνlν @ RunI

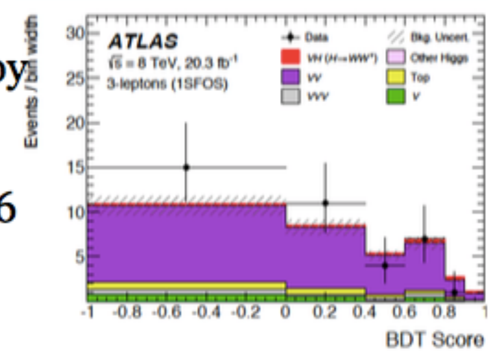




Confirmed:
5.8 σ
μ_{ggF}=1.02

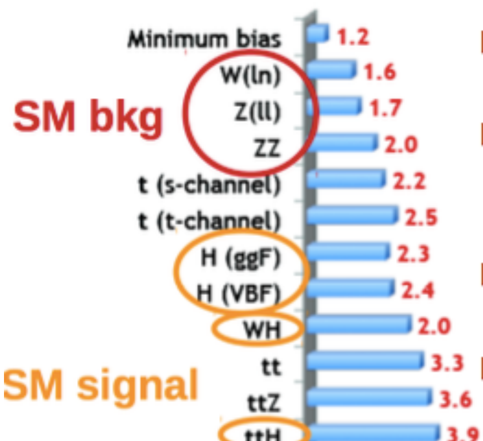


Evidence:
3.2 σ
μ_{VBF}=1.27



Search:
2.5 σ
μ_{VH}=3

13 / 8 TeV ratio



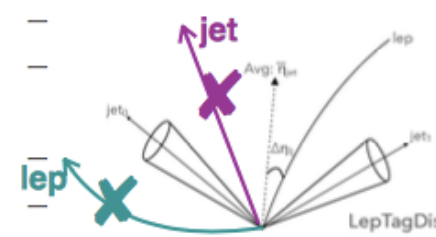
- Higgs XS increases by factor 2.3
- Background typically increases by factor 1.9 (3.3 for tt)
- Significance scales as $S/\sqrt{B} \rightarrow$ 1.6
- Sensitivity for 10/fb @ 13 TeV corresponds to full Run 1 dataset

Event Selection

Main backgrounds:

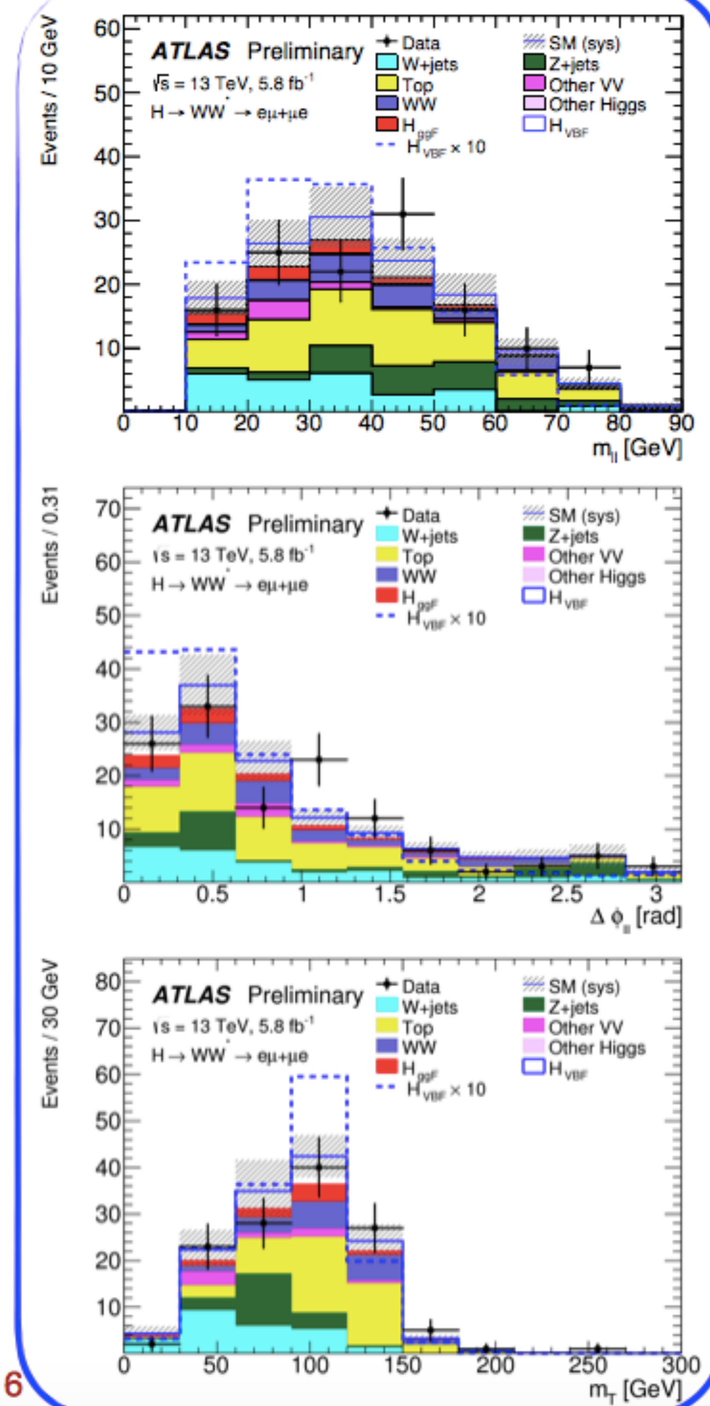
- **ggF** estimated with MC simulation
- **WW:** estimated with MC simulation
- **Top** and **Z→ττ**: shape form MC simulation, NF estimated with data
- **W+jets**: data-driven from events with one lepton satisfying only loose but failing tight ID criteria; fake factors measured in a di-jet sample

	Signal region	$Z\to\tau\tau$ CR	Top-quark CR
Preselection	Two isolated leptons ($\ell = e, \mu$) with opposite charge $p_{\mathrm{T}}^{\mathrm{lead}} > 25GeV$ ($p_{\mathrm{T}}^{\mathrm{lead}} > 22GeV$ for muons in 2015), $p_{\mathrm{T}}^{\mathrm{sublead}} > 15GeV$ $m_{\ell\ell} > 10GeV$, $N_{\mathrm{jet}} \geq 2$		
	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 1$
A BDT is trained at this level. Eight discriminant variables are used: $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, m_{T}, Δy_{jj}, m_{jj}, $p_{\mathrm{T}}^{\mathrm{tot}}$, $\sum_{\ell,j} m_{\ell j}$, and $\eta_{\ell}^{\mathrm{centrality}}$			
Selection	$m_{\tau\tau} < 66.2GeV$	$\lvert m_{\tau\tau} - m_Z \rvert < 25GeV$	–
	–	$m_{\ell\ell} < 80GeV$	–
	OLV applied	CJV applied	BDT > -0.8	–
	SR1: $-0.8 < \mathrm{BDT} \leq 0.7$	–	–
	SR2: $0.7 < \mathrm{BDT} \leq 1$	–	–



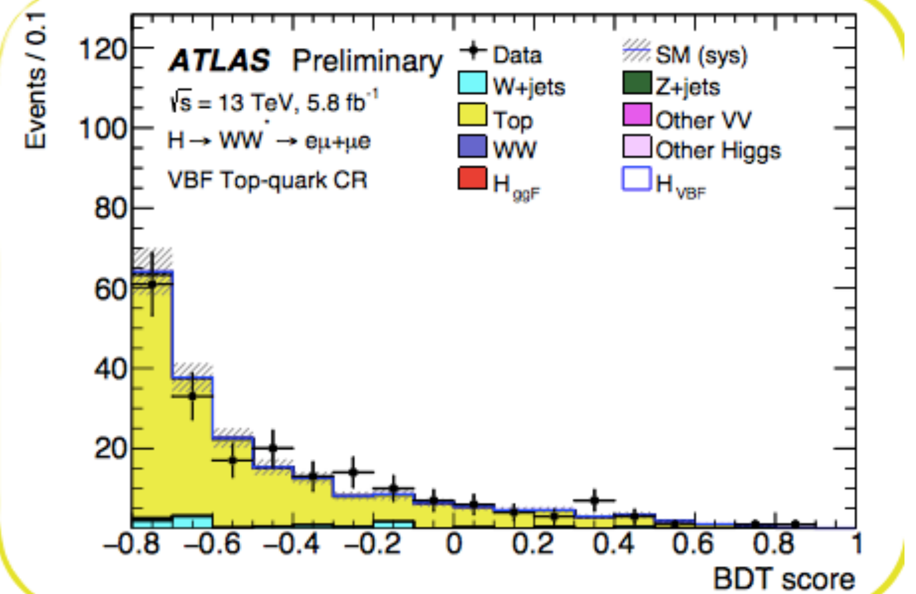
MVA Analysis

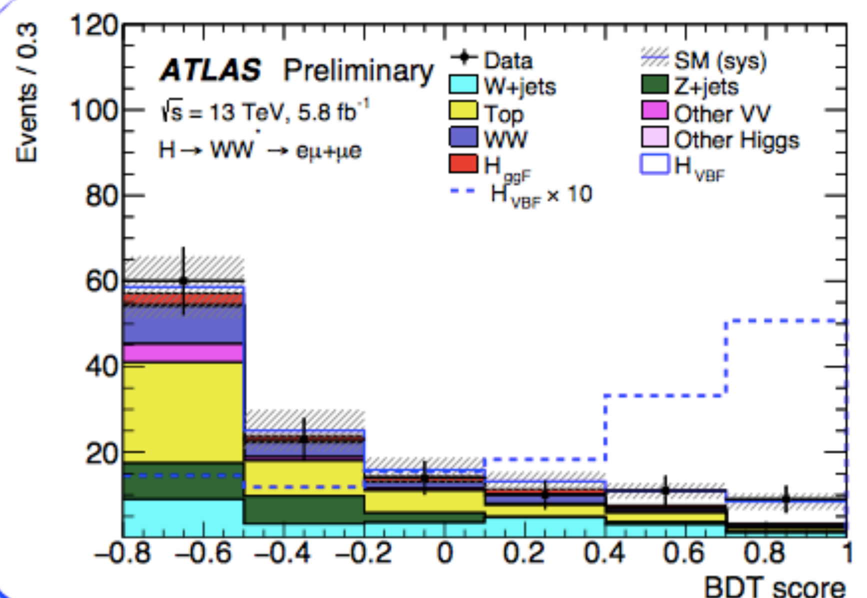
- The analysis uses a BDT to classify an event as signal- or background-like:
  - Signal: VBF
  - Bkg: Top,VV, Z+jets and ggF
- The training is performed after $N_{b\text{-jet}}=0$
- It uses information related to the production and decay topology
  - ➡ Leptons: m_{ll}, $\Delta\phi_{ll}$,m_T
  - Jets: m_{jj}, Δy_{jj}
  - Jets/Leptons: $\eta_{centrality}$, $\sum M_{lj}$, p_T^{tot}

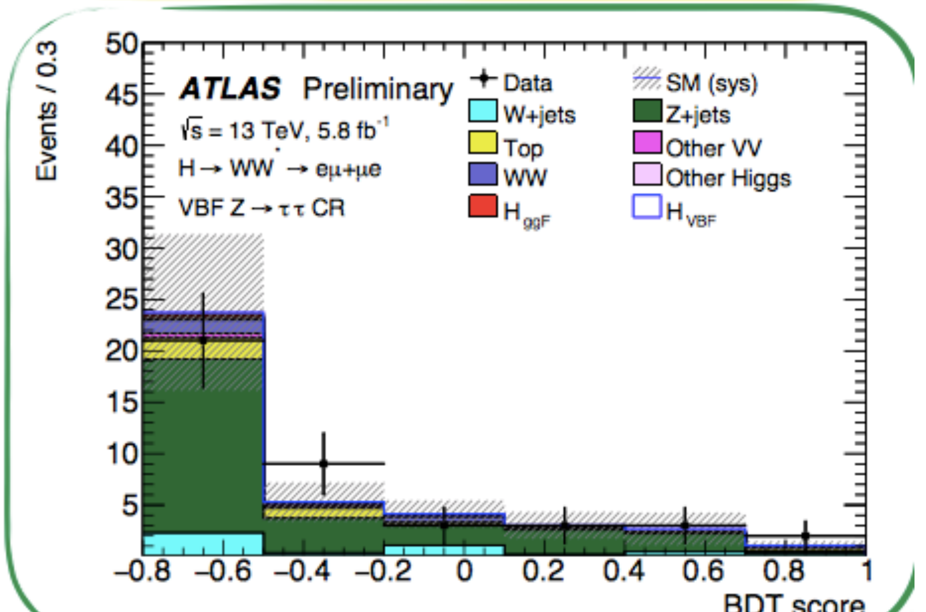


BDT Modelling

- BDT modelling has been checked in the Top and Z→ττ CRs and SR
  - Good data/MC region in all the regions
- Important shape different between signal and background in SR





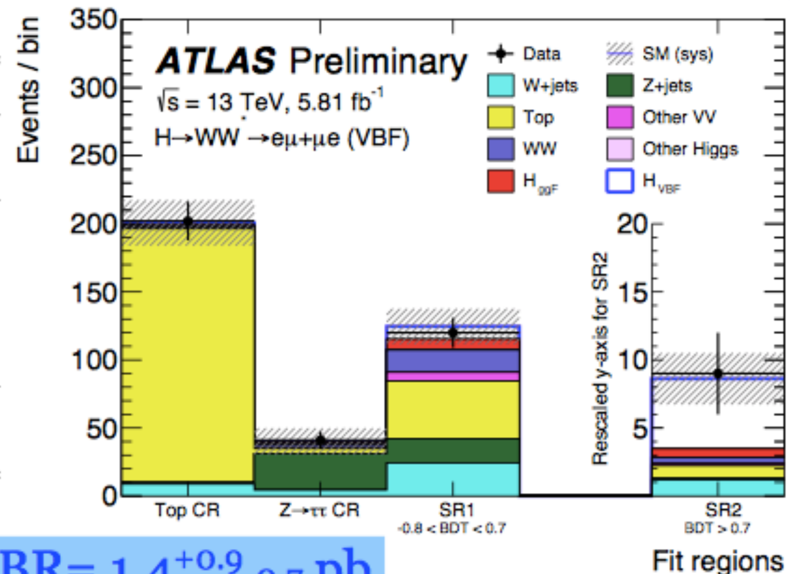


VBF H->WW result

- observed (expected) significance
  - 1.9σ (1.2σ) with 5.8 fb^{-1} data
- Statistics dominated
  - ~60% stat.
  - ~30% syst.

Source	$\Delta\mu_{\mathrm{VBF}}/\mu_{\mathrm{VBF}}$ [%]
Statistical	+60 / -50
Fake factor, sample composition	+18 / -15
MC statistical	±15
VBF generator	+14 / -5
WW generator	+11 / -7
QCD scale for ggF signal for $N_{\mathrm{jet}} \geq 3$	+8 / -7
Jet energy resolution	+8 / -7
b-tagging	+8 / -6
Pile-up	+8 / -6
QCD scale for ggF signal for $N_{\mathrm{jet}} \geq 2$	±6
JES flavour composition	+6 / -4
WW renormalisation scale	±5
Total systematic	+33 / -26
Total uncertainty	+70 / -50

Category	SR1	SR2	Top CR	Z+jets CR
VBF	9.3 ± 3.6	5.1 ± 1.8	1.7 ± 0.6	1.1 ± 0.4
Other Higgs	8.0 ± 4.0	0.7 ± 0.4	1.1 ± 0.2	1.2 ± 0.0
WW	13.0 ± 8.0	0.4 ± 0.2	1.4 ± 0.5	2.0 ± 0.9
Other VV	6.6 ± 2.6	0.2 ± 0.1	0.2 ± 0.0	0.8 ± 0.2
Top quark	42.2 ± 7.6	0.9 ± 0.7	186 ± 17	3.6 ± 1.6
W+jets	24.3 ± 9.2	1.2 ± 0.7	8.8 ± 4.0	4.4 ± 2.2
Z+jets	18.0 ± 9.9	0.1 ± 0.1	1.3 ± 1.0	27 ± 10
Total background	115 ± 13	3.5 ± 1.9	199 ± 17	38.8 ± 9.8
Observed	120	9	202	41



- SR with 2 bins
- CRs with 1 bin

$\mu_{\mathrm{VBF}}=1.7^{+1.1}_{-0.9}$ → $\sigma_{\mathrm{VBF}}\times \mathrm{BR}= 1.4^{+0.9}_{-0.7}$ pb

Summary

- **The search for the Higgs decays to b-quarks in ALTAS**
  - VBF H(bb)γ: first ATLAS result (ever)
  - VH(bb) : observed (expected) significance: 3.5 σ(3.0 σ)
  - Combination of VBF and VH is likely to reach 5 σ with full run 2 data

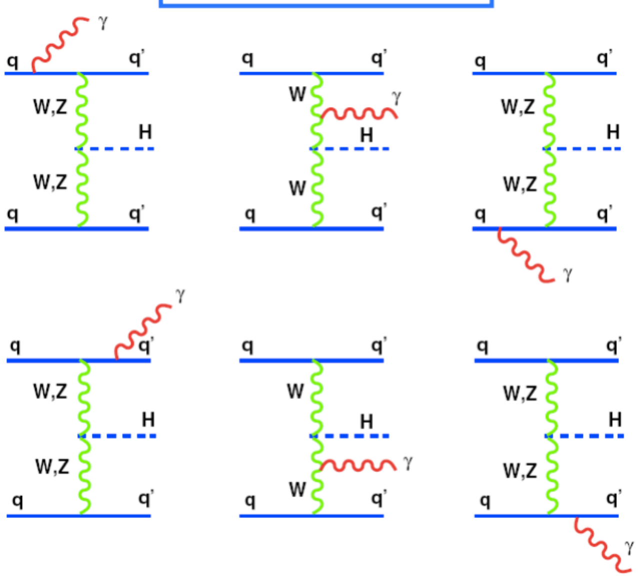
- **VBF H(WW)**
  - observed (expected) significance 1.9σ (1.2σ) with 5.8 fb^{-1} data
  - Likely to reach 3σ ~4σ with full run 2 data

Introduction

Inspired by Barbara Mele's paper
http://arxiv.org/abs/hep-ph/0702119

- Introduce a new channel in VBF H->bb
- pp->h(bb) jj +γ
  - Measurement of bbH and WWH coupling
  - By requiring a central photon
    - S/B ratio is much better than VBF H->bb

$\boxed{qq \to qq\, H + \gamma}$



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MC Samples

- Signal samples (VBF H(->bb)+γ):
  - generated with Madgraph, parton shower by Pythia8
- Z(bb)γ+jets (resonance background)
  - EWK VBF H(->bb)+γ
  - generated with Madgraph, parton shower by Pythia8
  - QCD VBF H(->bb)+γ
  - generated with Madgraph, parton shower by Pythia8

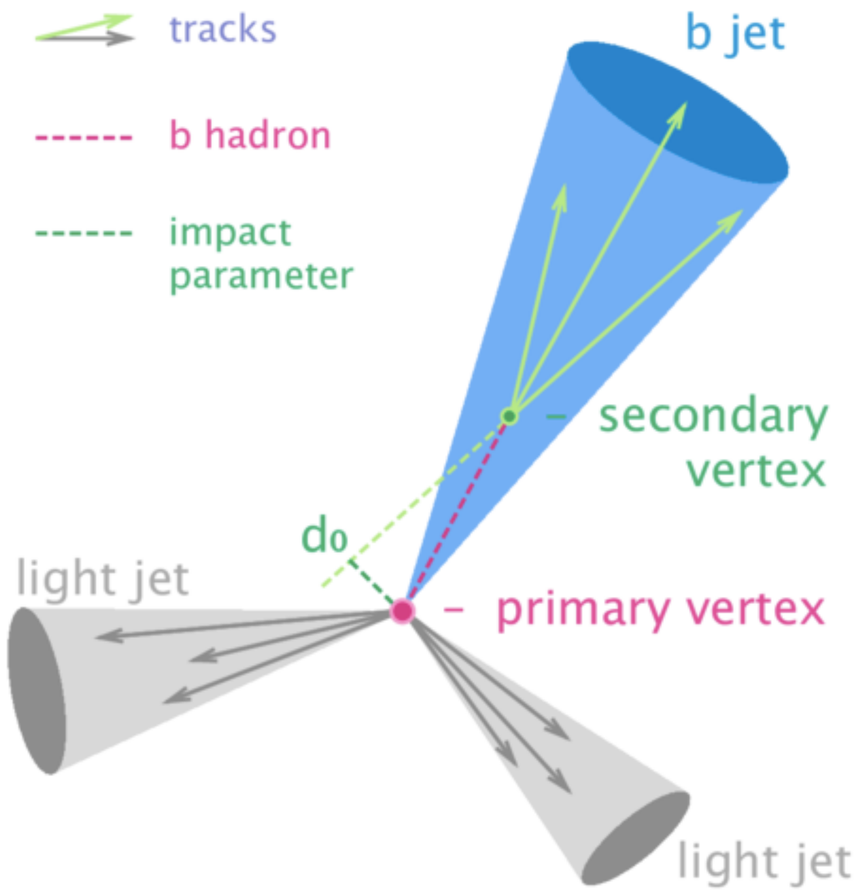
– QCD γbb+jets (Non resonance background)
  - generated with Madgraph, parton shower by Pythia8
  - For MVA training

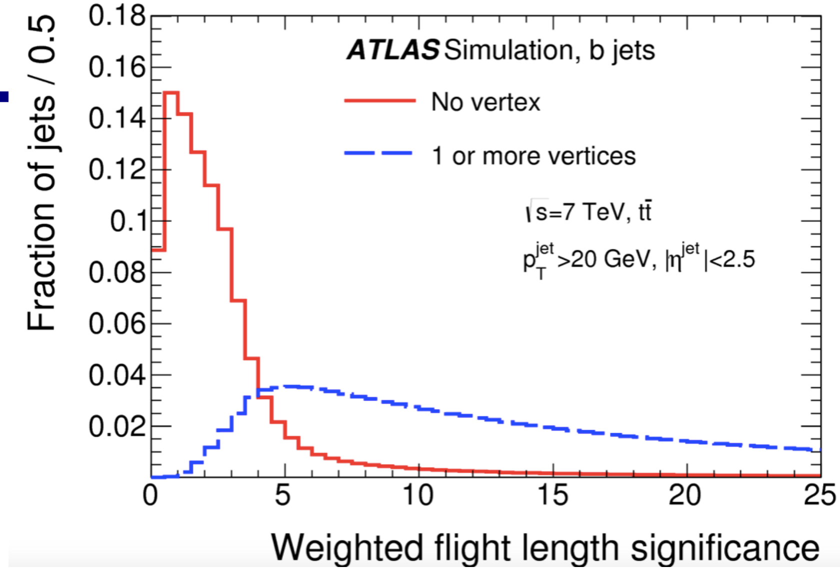
Trigger

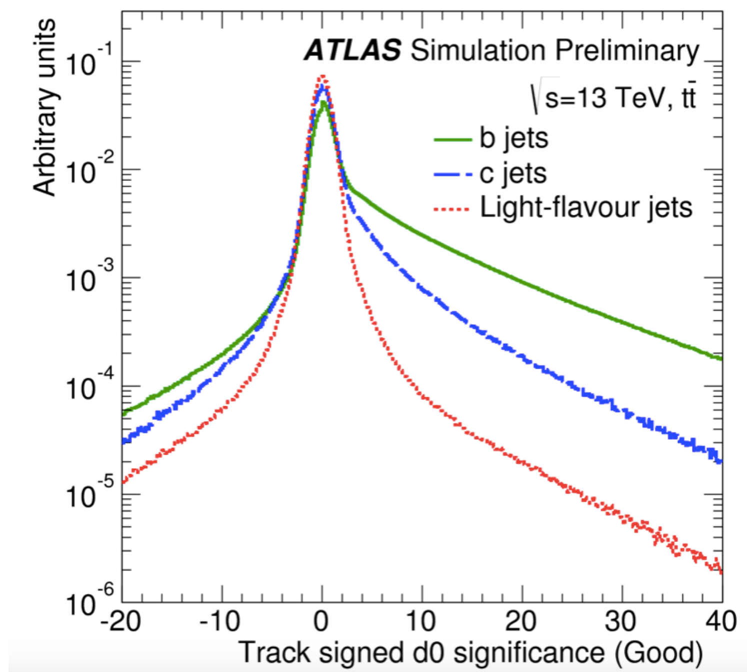
- Threshold for single photon trigger and 4jets triggers are high.
  - Single photon: trigger EF_g120_loose (ET>120GeV. too high)
  - General 4jet triggers : ET>100GeV (too high)
- Dedicated trigger developed in 2015 for this analysis.
- Analysis is mainly based on VBF0b trigger.
  - L1 item : L1EM22VHI (trigger on EM object with ET>22GeV)
  - HLT :
    - Medium ID photon, pT >25GeV
    - 4 HLT jets pT >35GeV, |eta|<4.9
    - Mjj>700GeV

Nick name	Trigger name	Integrated lumiosity
VBF0b	HLT_g25_medium_L1EM22VHI_4j35_0eta490_invm700	2.5 fb-1 (2015) 10.1 fb-1 (2016)

How to Identify b quark jets in ATLAS







jets

decay

Impact of each systematics

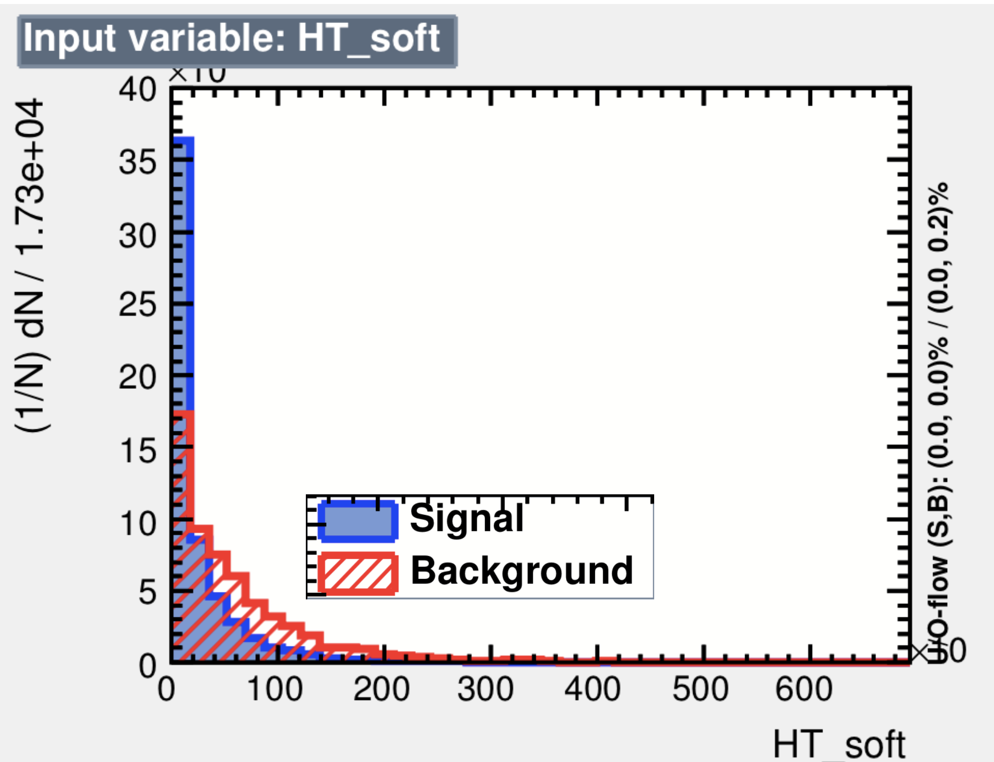
- Non-resonance background systematics is the leading systematics.

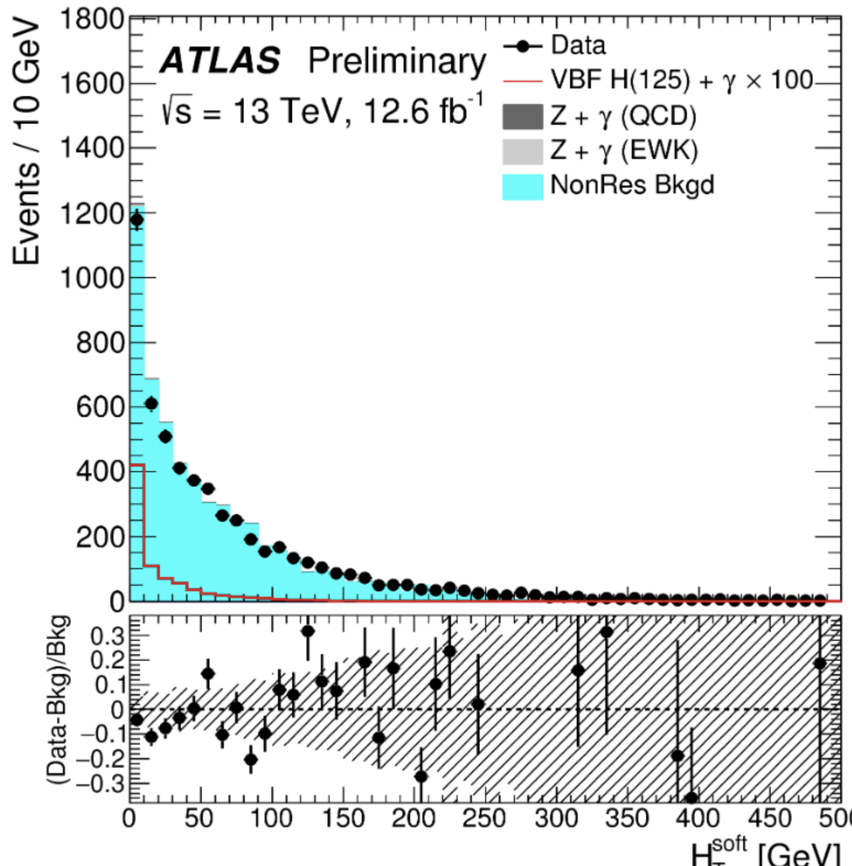
Uncertainty source	Uncertainty $\Delta\mu$
Non-resonant background uncertainty in medium-BDT region	0.22
Non-resonant background uncertainty in high-BDT region	0.21
Non-resonant background uncertainty in low-BDT region	0.17
Parton shower uncertainty on $H + \gamma$ acceptance	0.16
QCD scale uncertainty on $H + \gamma$ cross section	0.13
Jet energy uncertainty from calibration across η	0.10
Jet energy uncertainty from flavour composition in calibration	0.09
Integrated luminosity uncertainty	0.08

MVA Input varialbe: H_T^{soft}

- **Low QCD activity in rapidity gap of two VBF jets for VBF**

H_T^{soft}: the scalar sum p_T of the soft TrackJets with $p_T > 7$ GeV (HT_soft) .





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Major Background process

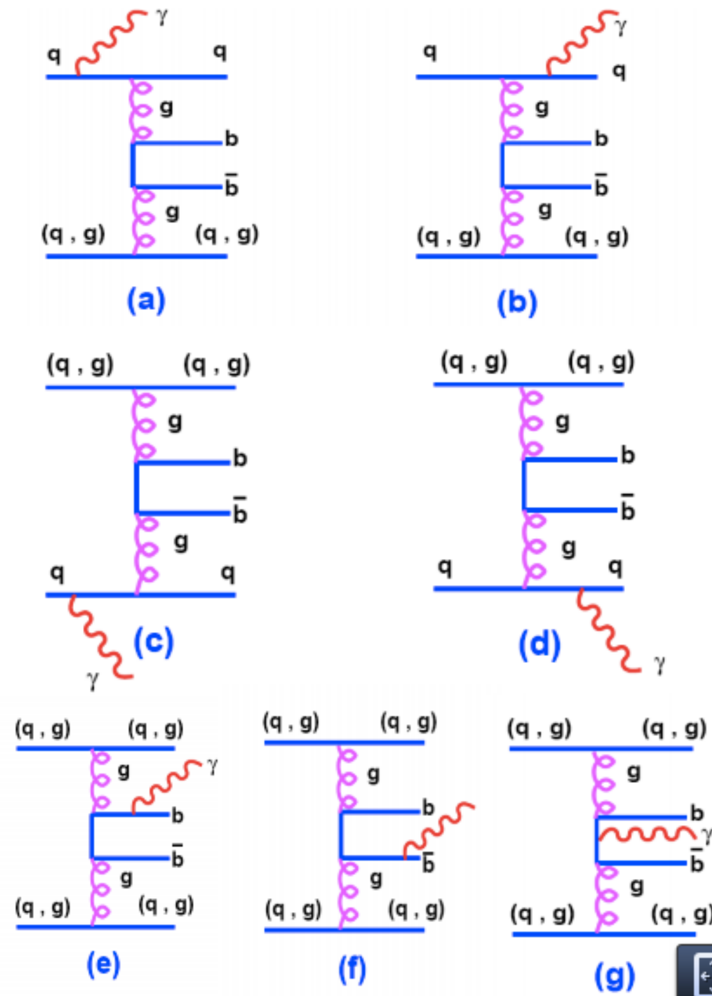
- **QCD pbbjj +γ production**

Inspired by Barbara Mele's paper
http://arxiv.org/abs/hep-ph/0702119

bckg is less active by requiring a central photon

dynamical effect:
destructive interference
for gamma at large angles
a) + b) and c)+ d)

dominant effect, but suppressed by the b-quark electric charge



Event pre-selection

Selection	Requirement
Derivation	HIGG5D3
Trigger	HLT_g25_medium_L1EM22VHI_4j35_0eta490_invm700
Event quality (data only)	pass GRL no Tile, LAr, SCT and Core error
Primary Vertex	At least one primary vertex
Photon	≥ 1 photon
Jets	≥ 4 jets ($p_T > 40$ GeV, $\mid \eta \mid < 4.5$) ≥ 2 jets in $\mid \eta \mid < 2.5$ (central jets)
Higgs signal jet (BB)	two central jets with highest MV2c10 weights
VBF jets (JJ)	pair of non-signal jets with highest invariant mass
b-jets	2 b-tagged jets (tagged on the BB pair with MV2c10 at 77% fixed cut working point)
m_{JJ}	$m_{JJ} > 800$ GeV
$p_T(BB)$	$p_T(BB) > 80$ GeV

MVA studies

- **BDT training samples:**
  - signal: HbbjjaSM125 (direct tag)
  - background: NonResbbjja (truth tag)

$$p_T^{balance} = \frac{(p^{b_1} + p^{b_2} + p^{j_1} + p^{j_2} + p^{\gamma})_T}{p_T^{b_1} + p_T^{b_2} + p_T^{j_1} + p_T^{j_2} + p^{\gamma}}$$

$$centrality(\gamma) = \left| \frac{y_\gamma - \frac{y_{j_1}+y_{j_2}}{2}}{y_{j_1} - y_{j_2}} \right|$$

- **11 BDT input variables:**

variable	definition
dRB1Ph, dRB2Ph, dRJ1Ph, dRJ2Ph	angular separation between the selected jets and the photon
mJJ, dEtaJJ	kinematics of the VBF jets
WidthJ1, WidthJ2	calorimeter jet width of the VBF jets
pTBal	pT balancing variable for selected final state objects
cenPhJJ	centrality of the photon with respect to the VBF jets
HT_soft	scalar sum pT of the soft TrkJets (pT>7GeV)

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m_{bb} Fit configurations

- **H+γ fit configuration**
  - H+γ normalization μ_{H} is **the parameter of interest.**
  - H+γ and Z+γ shape from MC simulation
  - Z+γ normalization from MC predictions
    - The normalization of are from MC simulation.
  - **Non-resonance background is fitted as 2^nd order polynomial**

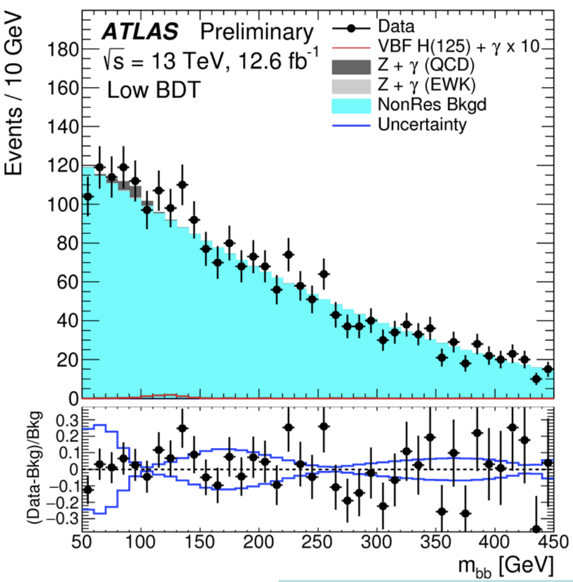
- **Z+γ fit configuration**
  - **EWK Z(bb)γ+jets and QCD Z(bb)γ+jets are considered as signal**
  - H+γ and Z+γ shape from MC simulation
  - H+γ is normalization from MC simulation

$$\mathcal{L}(\mu,\theta)=\prod_{j=1}^{N}\frac{(\mu s_j(\theta)+b_j(\theta))^{n_j}}{n_j!}e^{-(\mu s_j(\theta)+b_j(\theta))}\prod_{i=1}^{Q}f_X(\theta_i|\bar{\theta}_i,\sigma_{\theta_i})\prod_{l=1}^{P}\mathcal{G}_X(\theta_l|\bar{\theta}_l,\sigma_{\theta_l})$$

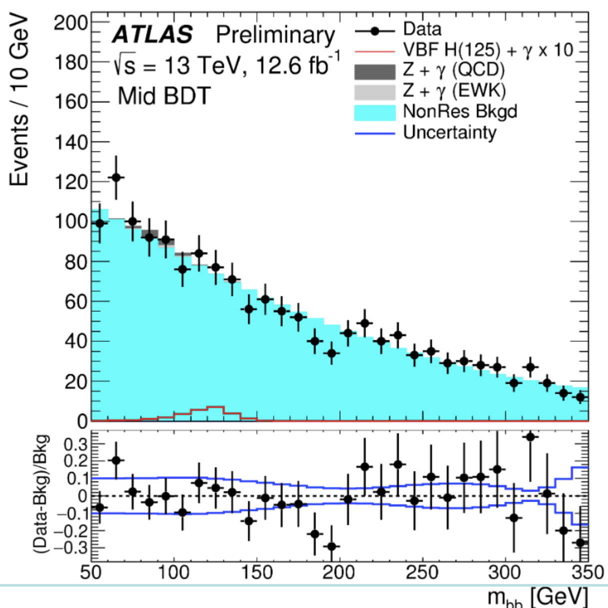
m_{bb} fit

Mbb fit with 3 category : high/medium/low BDT region

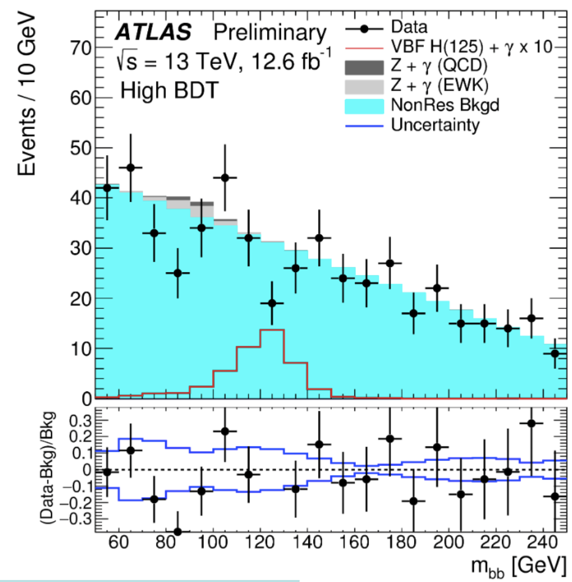
Low BDT



Medium BDT



High BDT



BDT categories	BDT score	mBB fit range
low	BDT < -0.1	[50, 450] GeV
medium	-0.1 < BDT < 0.1	[50, 350] GeV
high	BDT > 0.1	[50, 250] GeV

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Result

ATLAS-CONF-2016-063

- **H+γ fit configuration**
  - H+γ normalization μ_{H} is the parameter of interest.
  - Z+γ normalization and Z+γ shape from MC simulation
- **Z+γ fit configuration**
  - EWK Z(bb)γ+jets and QCD Z(bb)γ+jets are signal
  - H+γ normalization and H+γ shape from MC simulation

Result	$H(\to b\bar{b}) + \gamma jj$	$Z(\to b\bar{b}) + \gamma jj$
Expected significance	0.4	1.3
Expected p-value	0.4	0.1
Observed p-value	0.9	0.4
Expected limit	$6.0\ ^{+2.3}_{-1.7}$	$1.8\ ^{+0.7}_{-0.5}$
Observed limit	4.0	2.0
Observed signal strength μ	$-3.9\ ^{+2.8}_{-2.7}$	$0.3\ \pm 0.8$

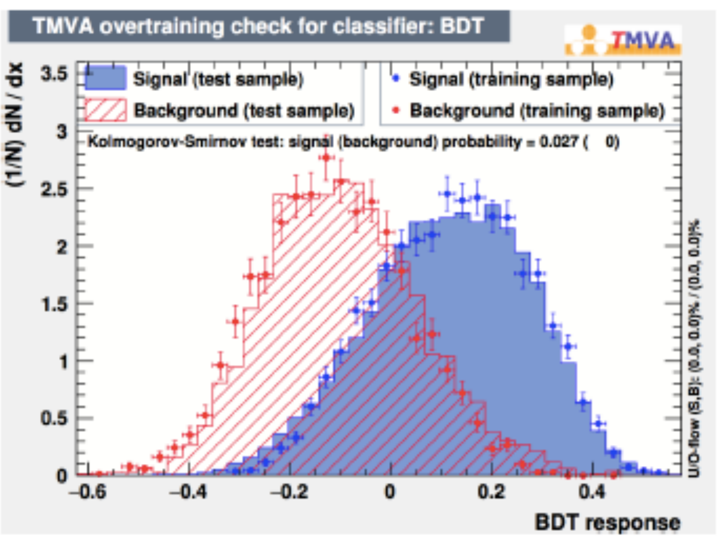
Systematic uncertainties

- Theoretical uncertainties for H+gamma and Z+gamma
  - QCD scale systematics
  - Parton shower systematics
- Non-resonance background systematics
  - Statistics in mbb sideband region
- Experimental uncertainties
  - Jet systematics (Jet energy scale)
  - B-tagging efficiency systematics

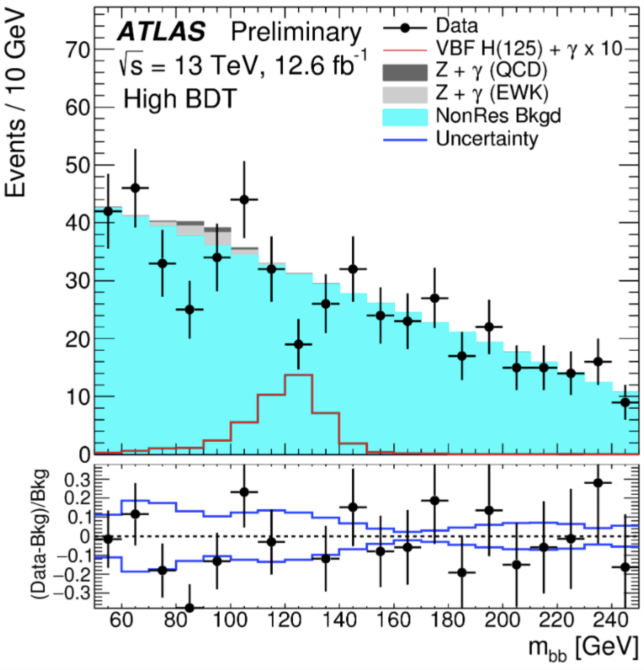
Analysis strategy

- Pre-selection cut
- MVA analysis (boosted decision tree)
  - category the events into three category
- Extract signal from m_{bb} fit

use a BDT to separate the signal and non-resonant background

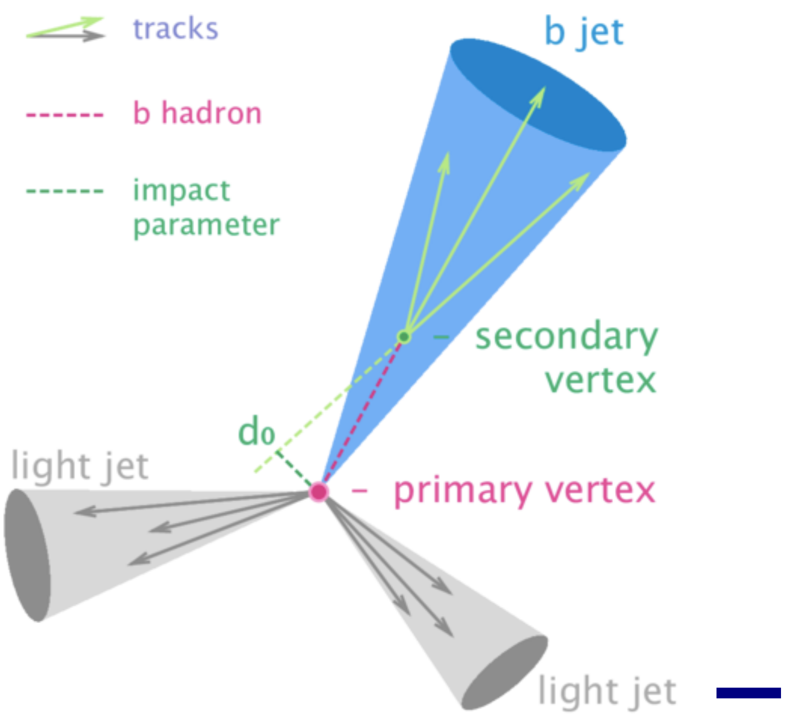


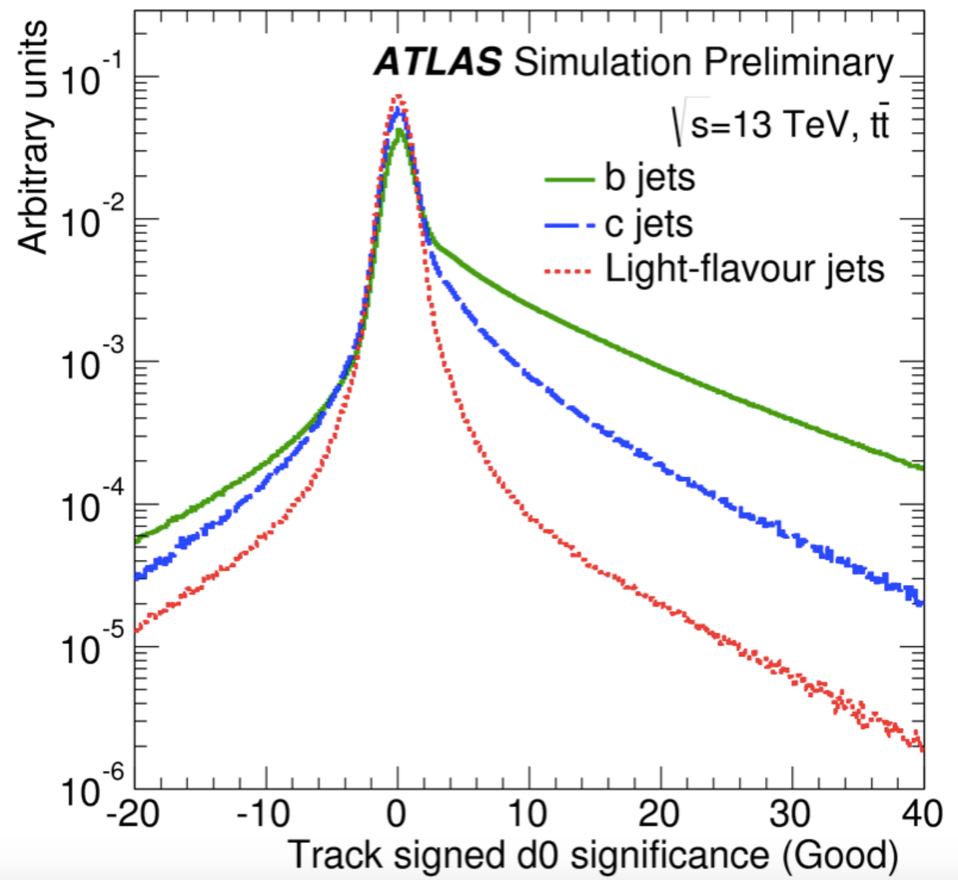
Perform fit in m_{bb} spectrum



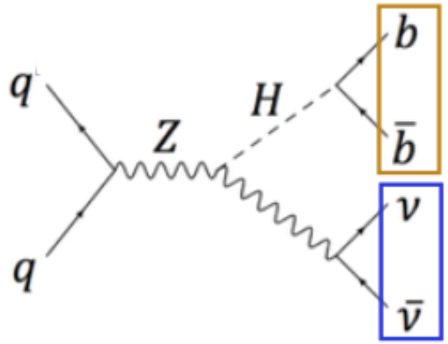
How to Identify b quark jets in ATLAS(1)

- Two ways to Identify b jets
  - impact parameters
  - secondary vertex from B decay

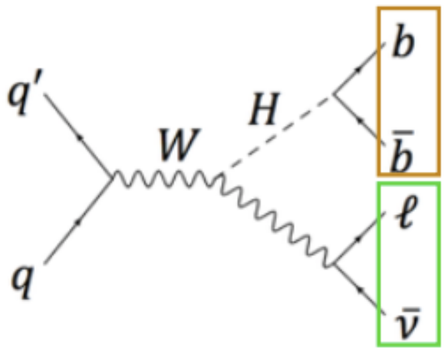




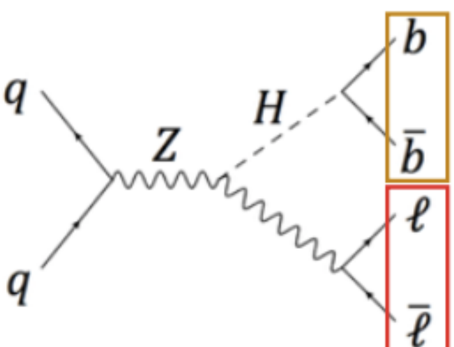
VH(bb): 3 channels



- **0-lepton:**
  - E_T^{miss} > 150 GeV



- **1-lepton:**
  - e/μ, p_T>25 GeV
  - Tight isolation
  - Missing E_T
  - p_T^V > 150 GeV



- **2-leptons:**
  - Isolated ee, μμ
  - p_T^1>25 GeV, p_T^2>7 GeV
  - No missing E_T,
  - m_{ll} compatible with m_Z

- Two jets
  - anti-kT with R=0.4
  - P_T^{j1}>45 GeV
  - p_T^{j2}>20 GeV
- Improved b-tagging with respect to Run 1:
  - Eff: 70%, light jet rejection: 380, charm rejection: 12
- Analysis categories:
  - 2/3 jets (0/1lepton)
  - 2/≥3jets (2lept.)
  - P_T^V </> 150 GeV (2lept)

VH(bb) background

- **Z+bjets dominates in 0, 2 lepton channels**
- **Top quark and W+jets in 1 lepton channel**
- **Multi-jet background**
  - **negligible in 0/2 lepton channels after anti-QCD cuts**
  - **Data-driven estimate in 1 lepton channel**

0 Lepton 1 Lepton 2 Lepton