The ‘beauty’ of the Higgs Boson

(at ATLAS)

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from ~10 years ago …

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Studio delle prestazioni del rivelatore a pixel dell'esperimento ATLAS in preparazione alla presa dati

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Nella figura 2.8 è riportato con maggiore dettaglio l'andamento della "significatività" per la scoperta del bosone di Higgs in funzione della sua massa; essa descrive la probabilità che un particolare segnale fisico osservato sia interpretabile come una pura fluttuazione statistica del fondo.

ATLAS physics TDR plot

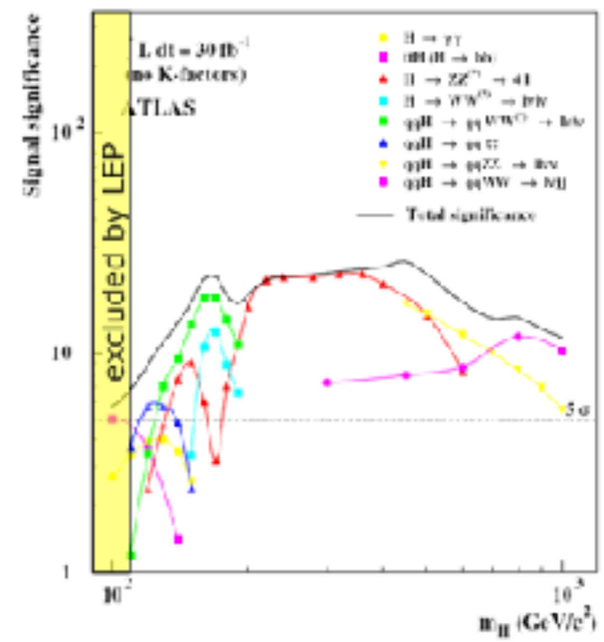


Figura 2.8: Significatività statistica dei vari canali per la rivelazione del bosone di Higgs del MS in funzione della sua massa dopo una luminosità integrata di 30 fb^{-1} corrispondenti a 3 anni alla luminosità iniziale.

30 fb^{-1} in the first 3 years of LHC

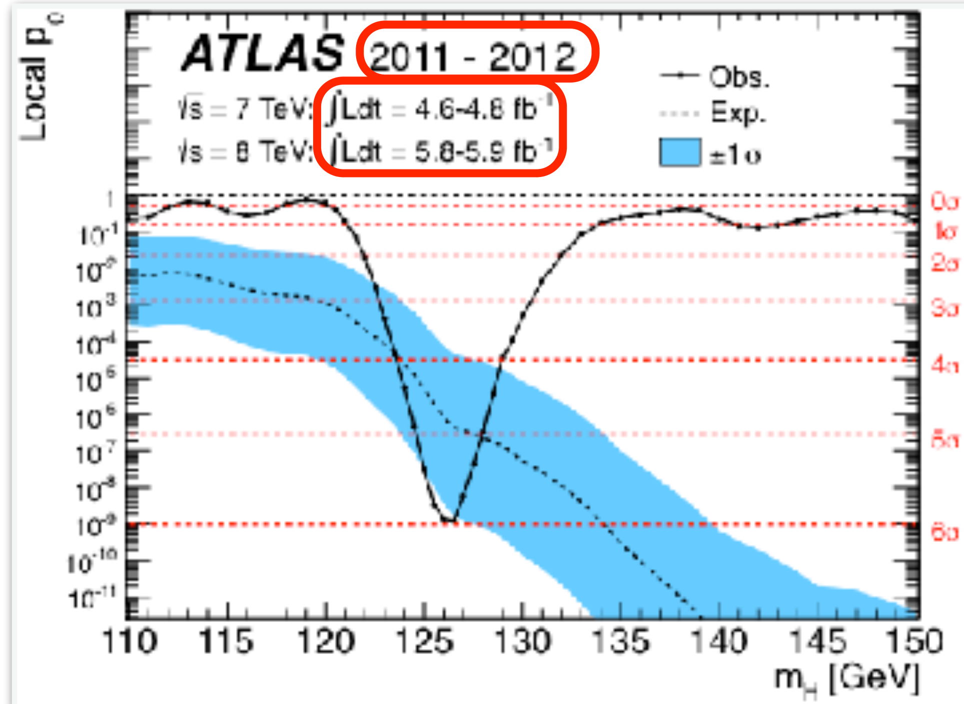
La significatività viene espressa in unità di deviazioni standard della distribuzione del segnale: una maggiore significatività rappresenta una maggiore separazione del segnale dal fondo considerato.

42 CAPITOLO 2. L'ESPERIMENTO ATLAS

Poiché il limite per la scoperta di nuovi fenomeni è fissato a cinque sigma rispetto al fondo[16], il grafico suggerisce che il bosone di Higgs potrà essere scoperto in meno di tre anni di presa dati alla luminosità iniziale per qualunque valore della sua massa.

the Higgs boson could be discovered in <3 year of data-taking for any possible value of its mass

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

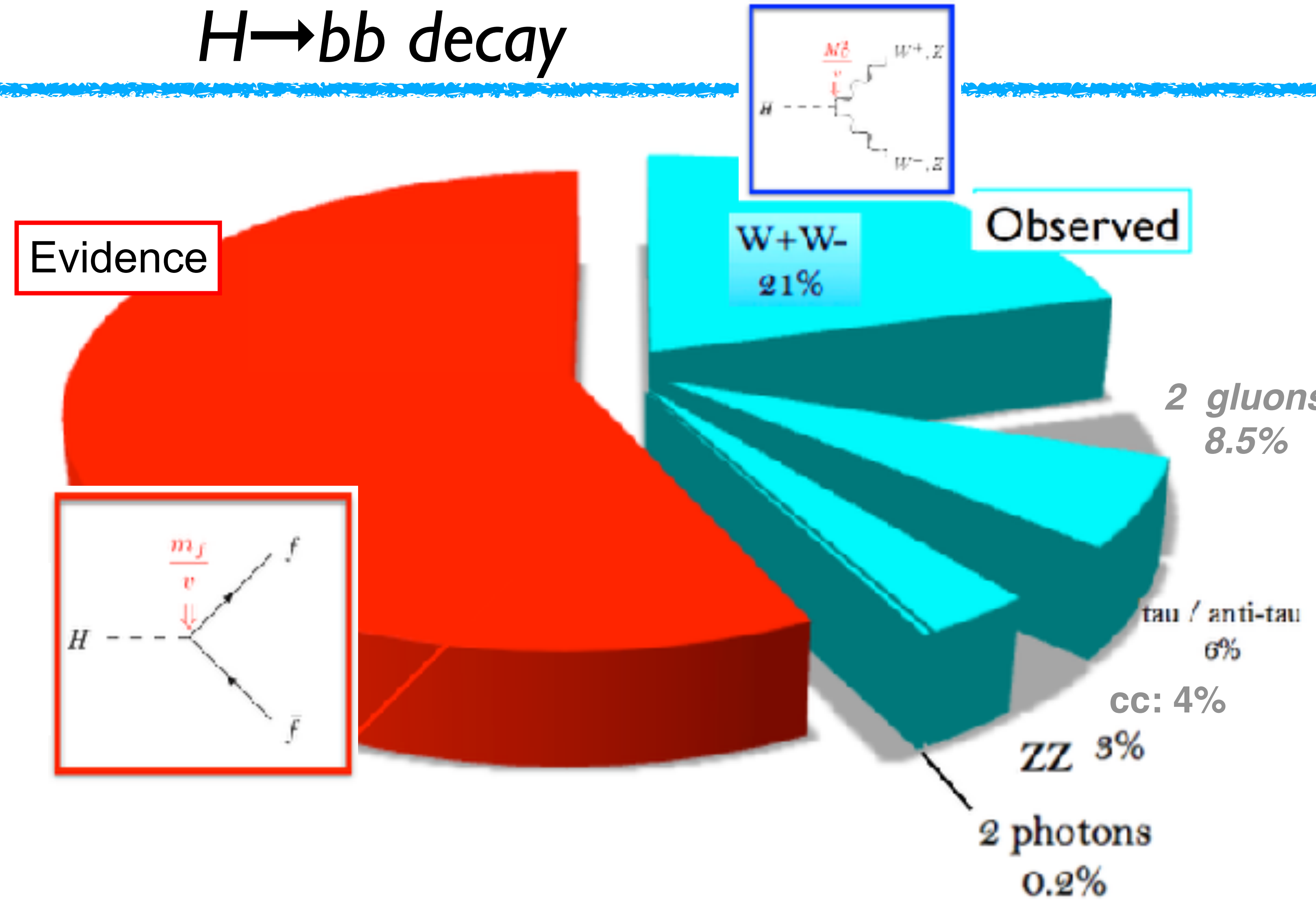


- With the discovery of a SM-like Higgs boson in 2012, *the SM is now complete*.
- Several years of measurements devoted to characterise in detail the new particle:
  - *0.2% uncertainty on its mass*
  - *spin 0 and CP parity*
  - *coupling to vector bosons and taus established*
  - *measurements driven by leading production modes*

So far, no sign of deviation with respect to the Standard Model Higgs boson

- New playground to understand the consistency of the SM and explore new physics effects

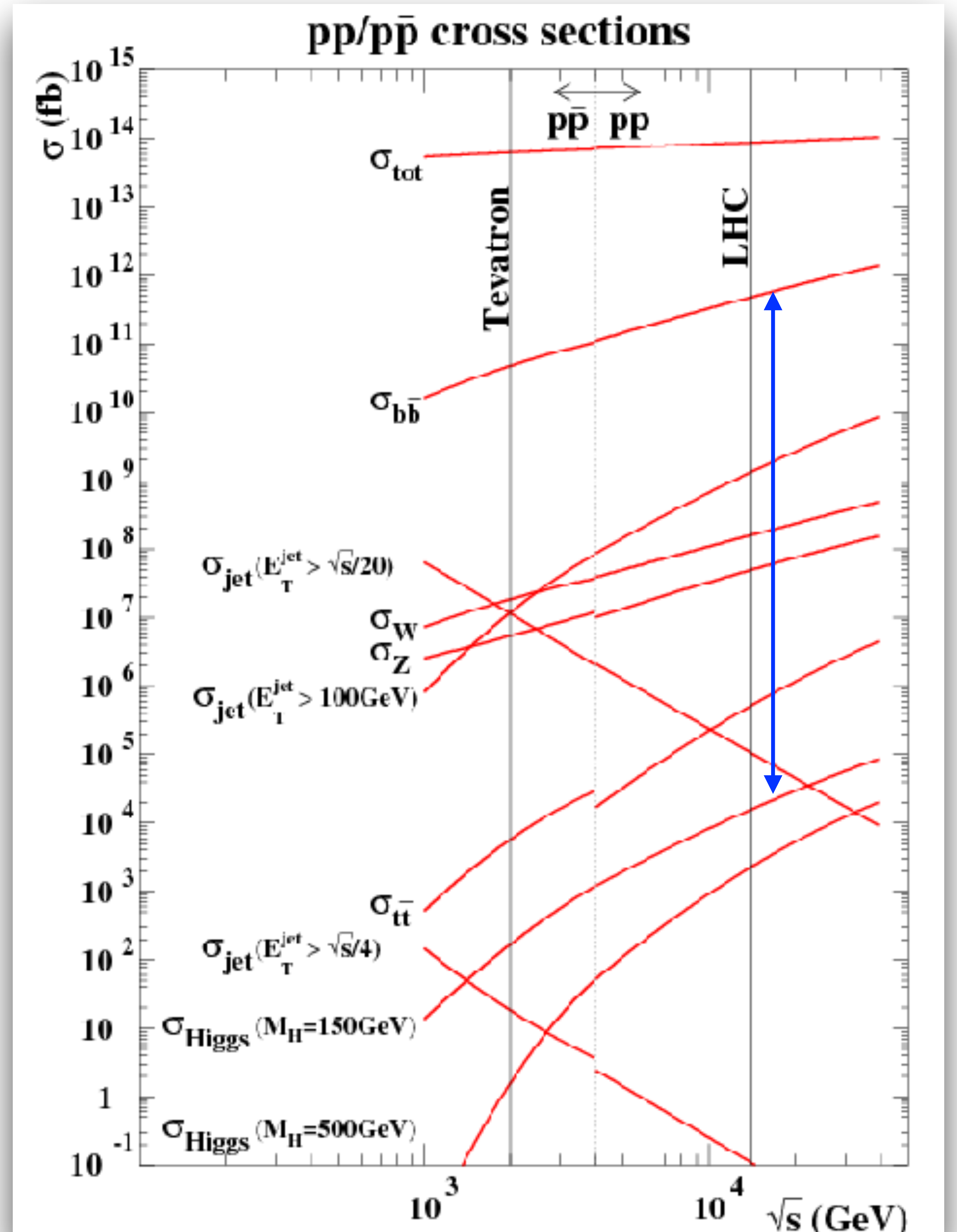
H→bb decay



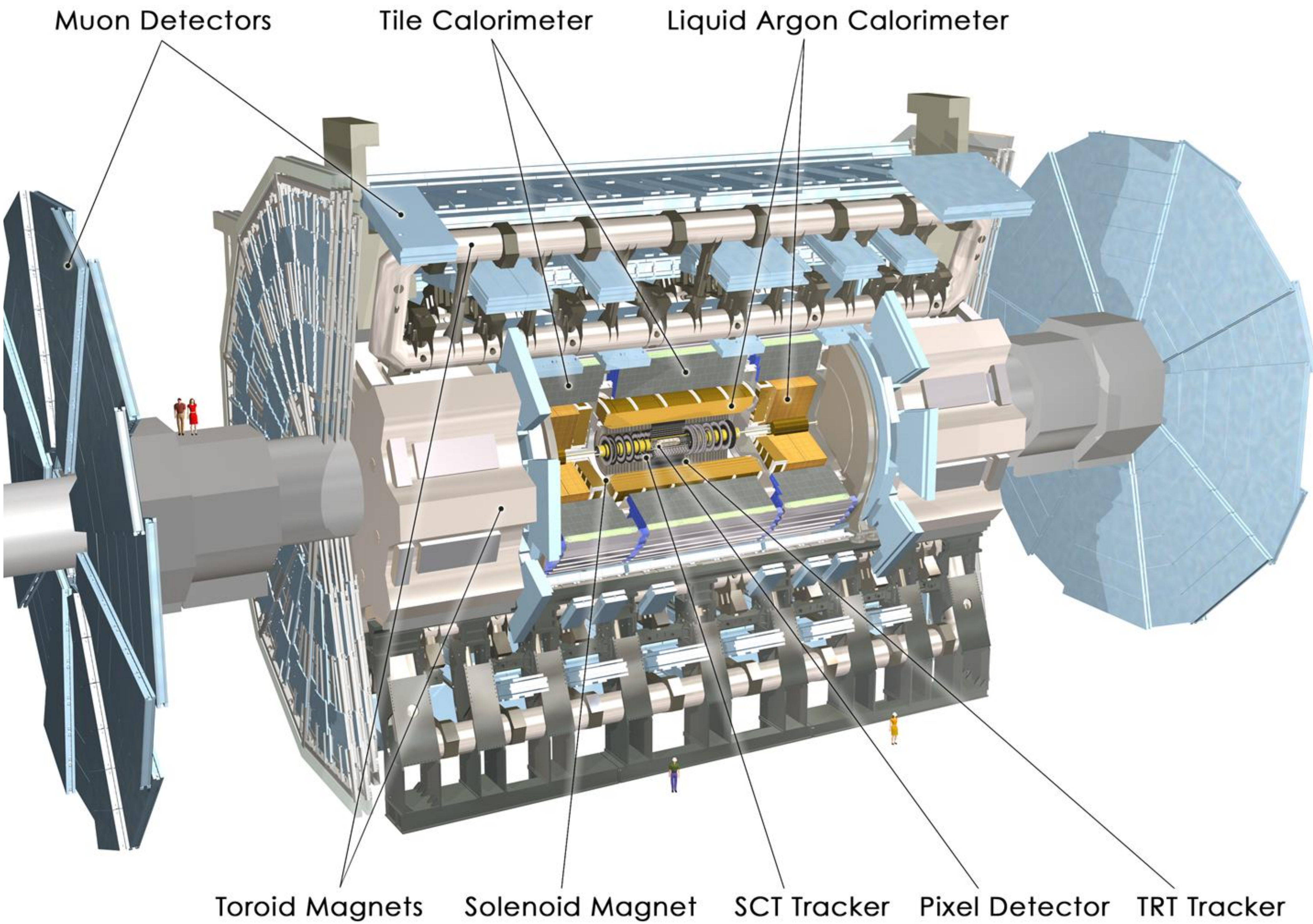
- ✦ *Higgs boson width*: ***4 MeV***

- ✦ ***Largest Higgs boson decay mode: 58%:***
  - direct probe of Higgs boson-to-quarks interactions (together with ttH)
  - most accessible decay to quarks
- ✦ ***Largest contribution to Higgs boson decay width:***
  - key ingredient in absolute decay rate analysis
  - deviation from SM behaviour could easily accommodate room for new physics (invisible decays)
  - preferential H→bb coupling in some beyond the Standard Model (BSM) scenarios

- ***Overwhelming QCD di-jet background at the LHC:***
  - several orders of magnitude larger background (even when considering b-jets)
  - high cross section incompatible with the constrain of the trigger budget of the experiments
- Solution to both points:
  - rely on ***associated Higgs boson production***
- *Increase in centre of mass energy not always helps.* 8TeV ->13 TeV:
  - ttbar: x4
  - inclusive Higgs boson: x2

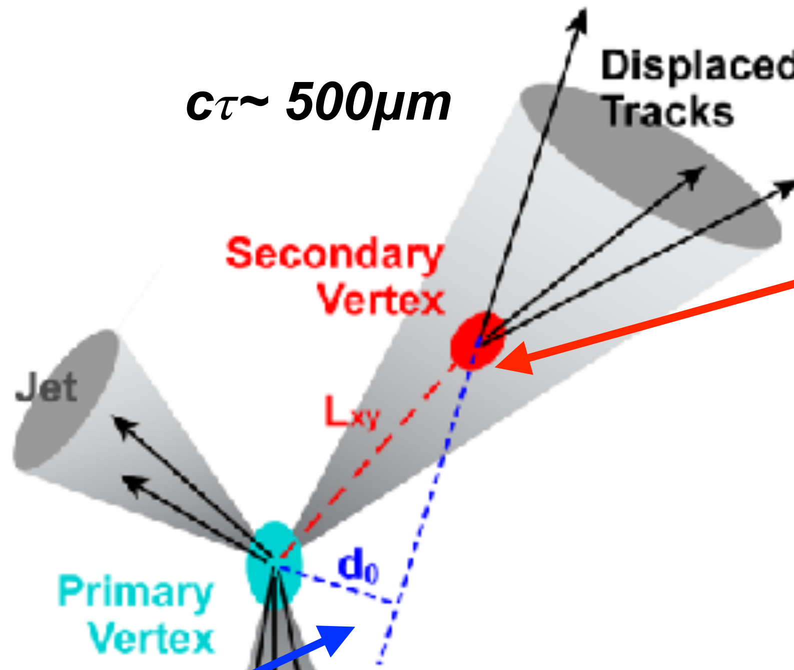


Intermezzo: “how to identify H→bb decays”



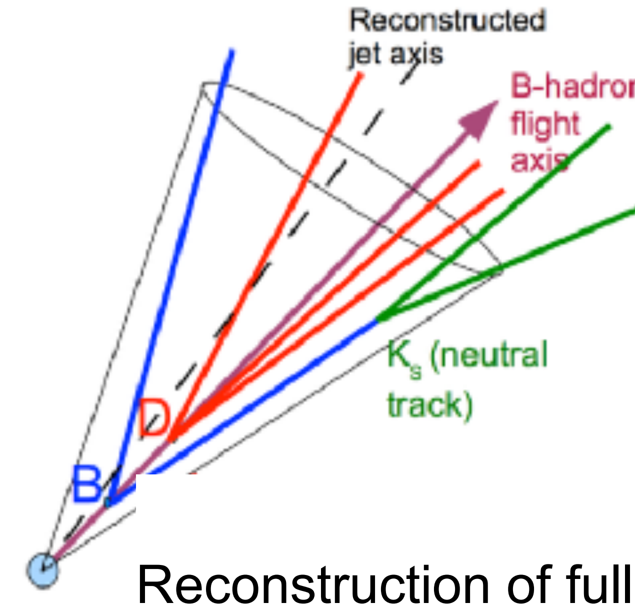
b-tagging in ATLAS

- ***B-tagging***: identifying jets containing B-hadrons



Likelihood-based track impact parameter significance: ***IPTagger***

Inclusive secondary vertex reconstruction: ***SV***



Reconstruction of full B->D hadron decay chain: ***JetFitter***

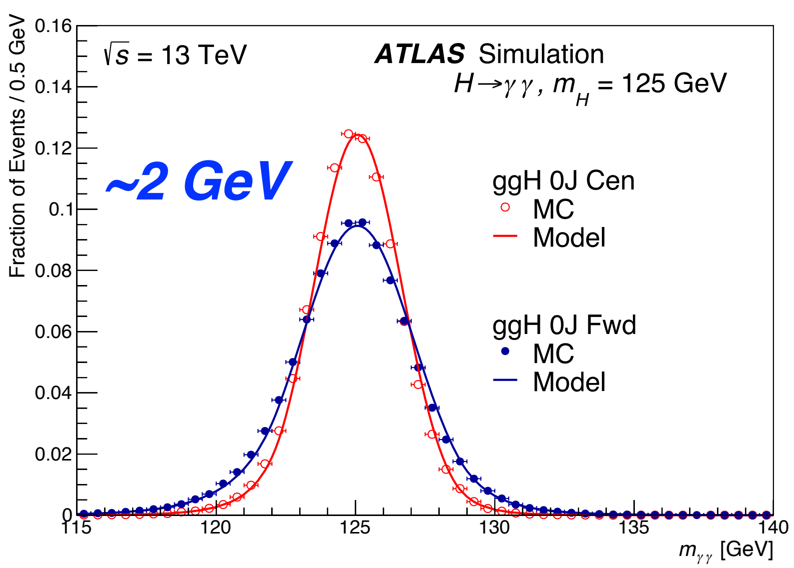
features of the algorithms combined with multivariate techniques

b-jet eff.	c-jet mis-tag	light jet mis-tag
60%	~3%	<0.1%
70%	~8%	0.3%
77%	~16%	0.7%
85%	~33%	3%

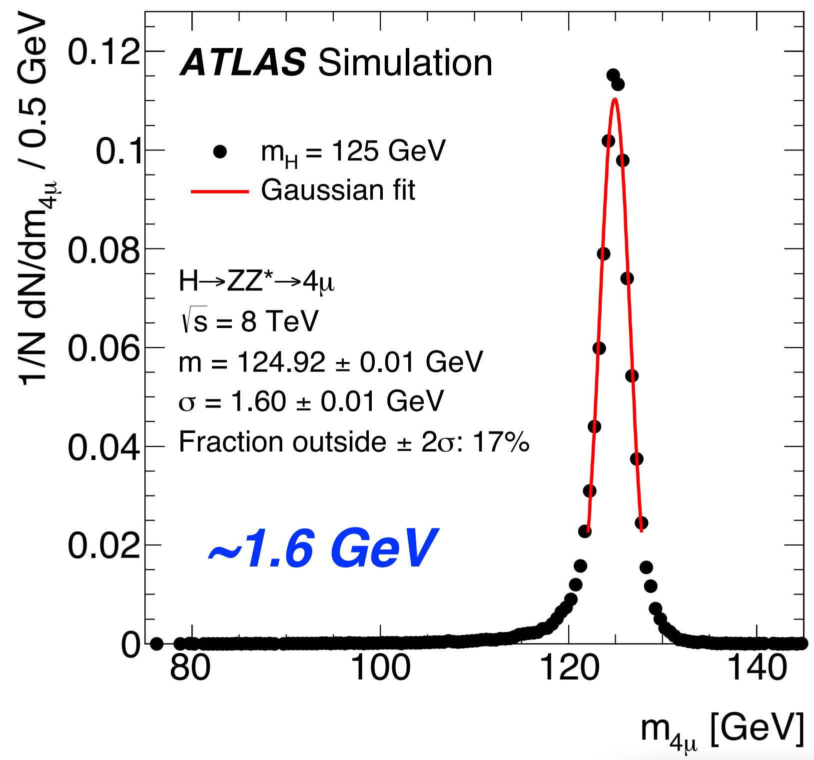
- Efficiency measured with data-driven techniques:
  - ***b-jets***: unc ~2% in [50-100] GeV
  - **c-jets**: unc ~10% in [25-140] GeV
  - **light-jets**: unc ~60% in [25-500] GeV

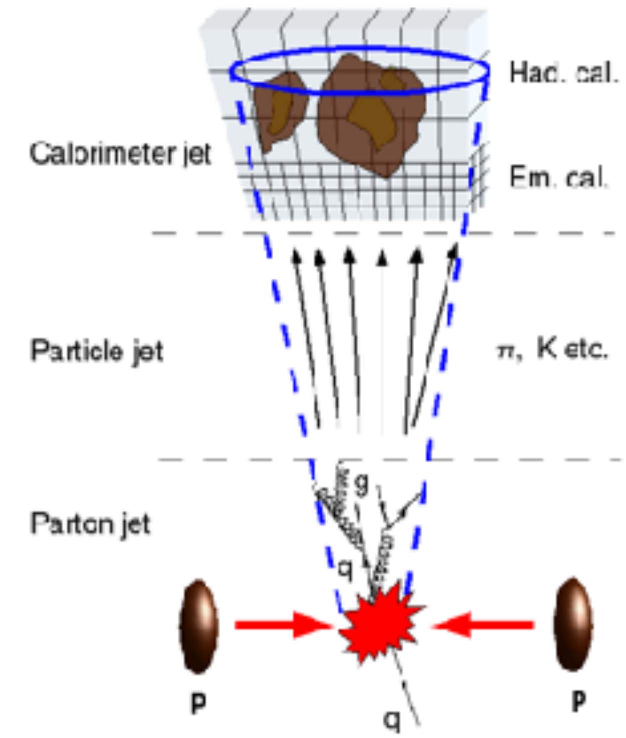
m_{bb} calibration

H->γγ

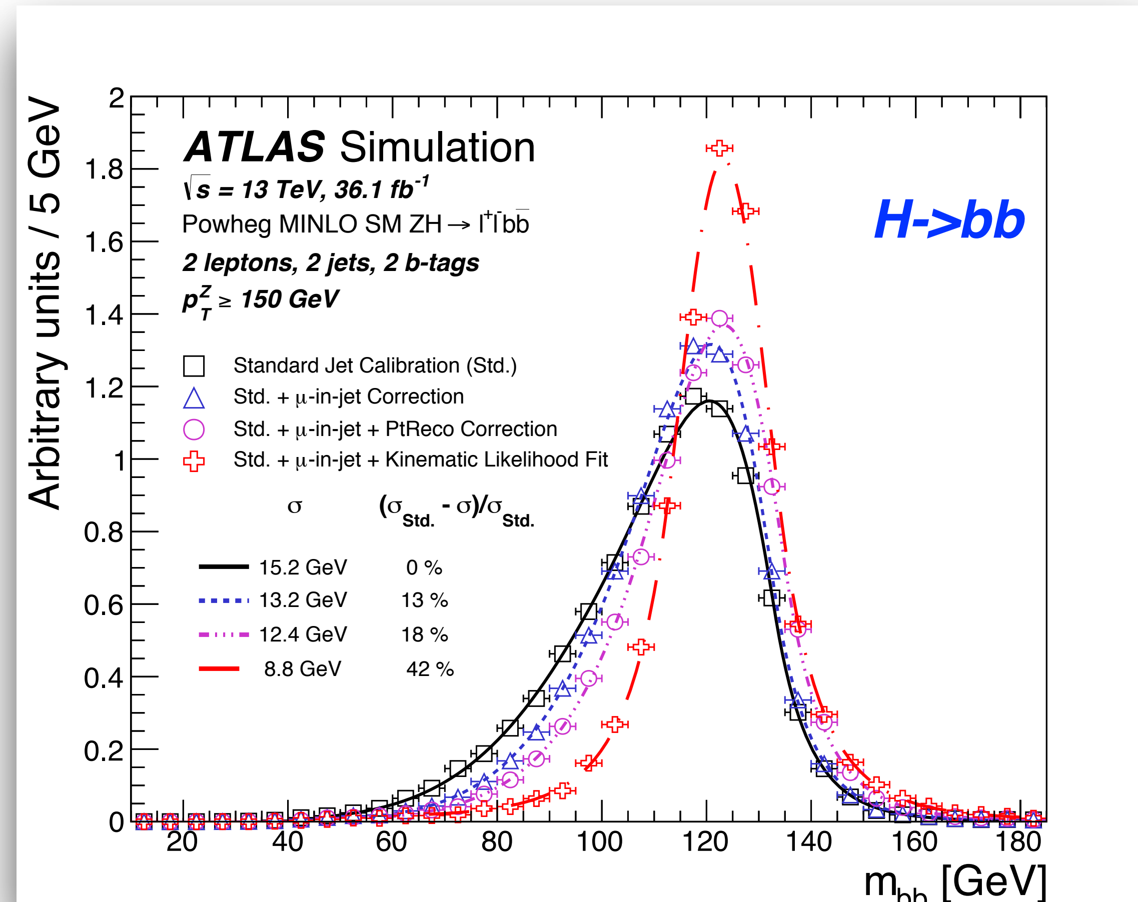


H->ZZ->4l

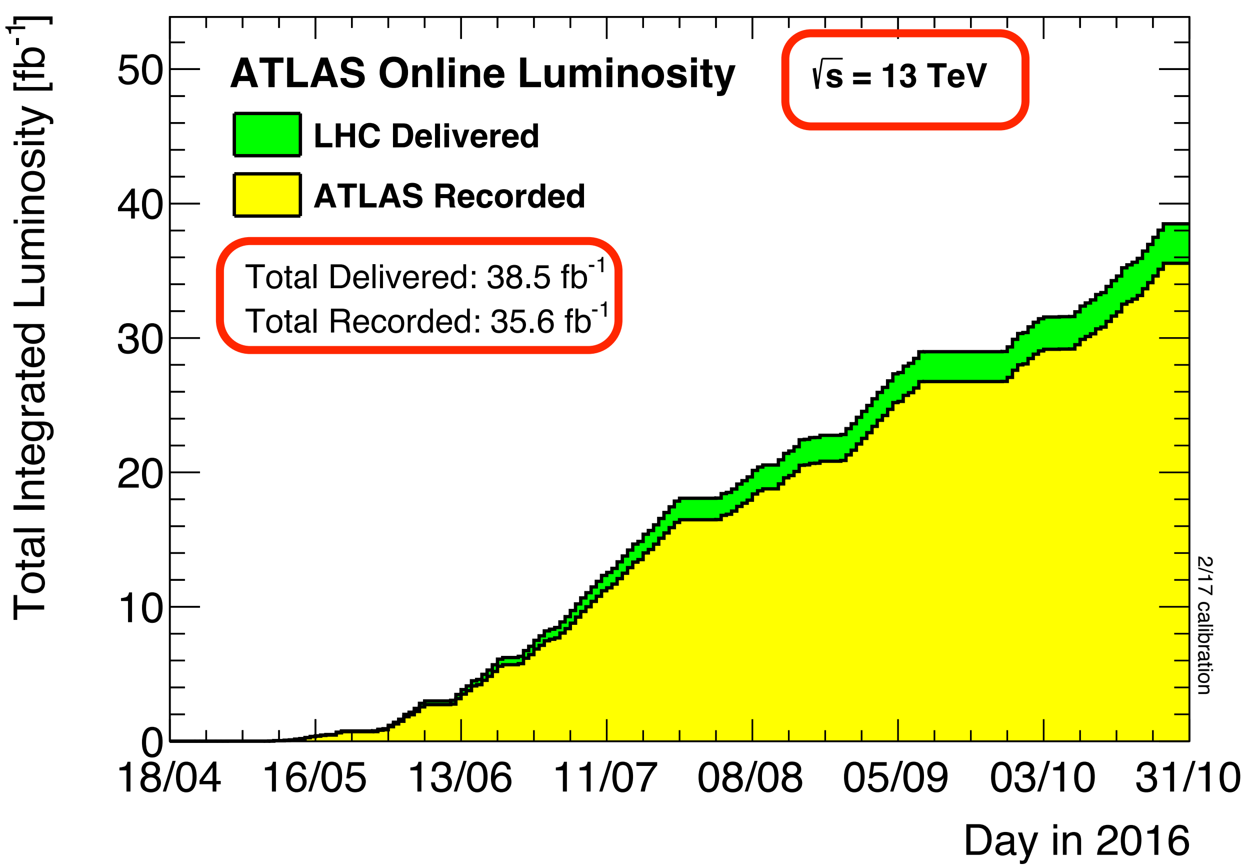


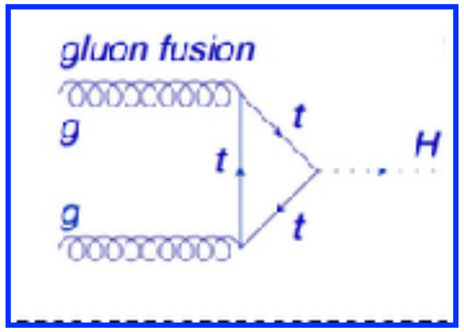


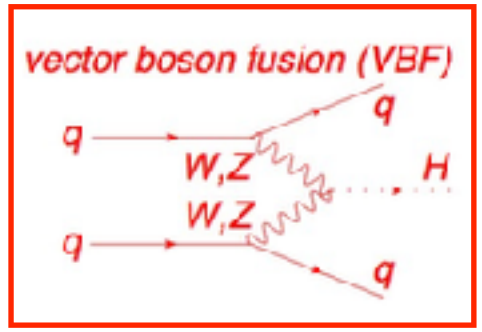
- Improving ***m_{bb}* resolution** on top of default Anti-kt R=0.4 calorimeter jet reconstruction performance:
  - **adding soft muon** (when found inside the jet cone) to jet 4-momentum: **+13%**
  - additional scaling of jet momentum (**p_T correction**) to compensate from missing neutrino: **+5%**
  - ***kinematic likelihood fit*** to constrain jet response: only if topology allows

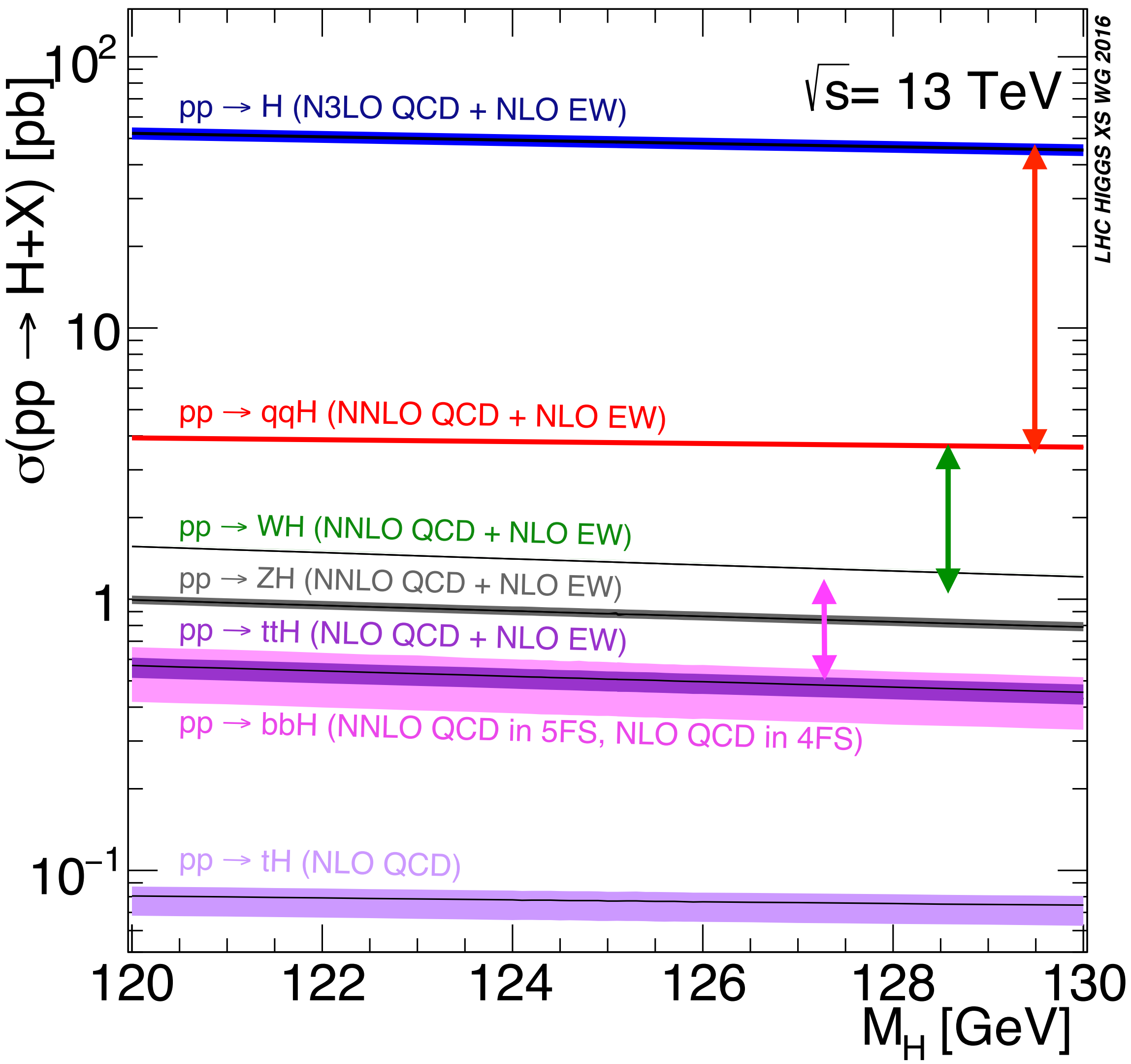


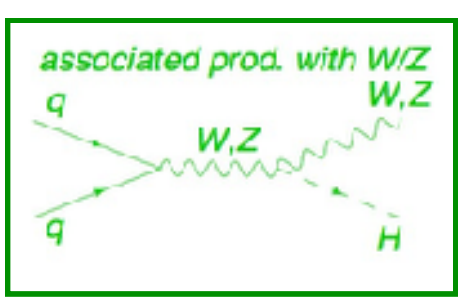
SM H→bb analyses

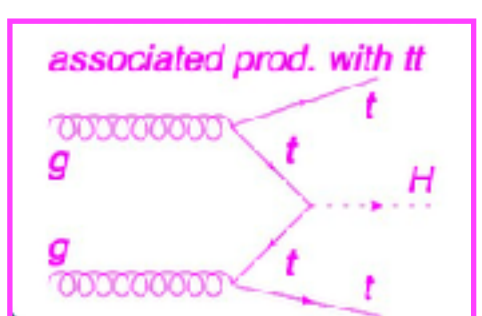










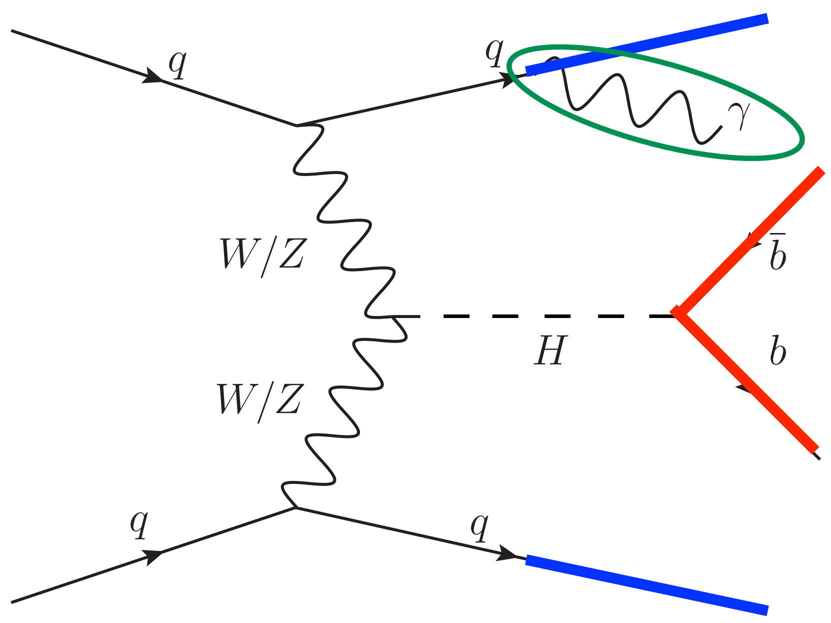


H→bb: how?

- ***gluon fusion***:
  - overwhelming multi-jet background
  - only limited to very high p_T
- ***Vector Boson Fusion***: 1/10 of total cross section
  - forward jets topology helps reducing the background
  - fully hadronic final state still maintain many experimental difficulties (trigger)
- ***VH production***: 1/20 of total cross section
  - can use leptonic decays of V for triggering/background reduction
  - *GOLDEN H->bb channel at hadronic machines*
- ***ttH***: 1/100 of total cross section
  - can rely on leptonic decays of top quarks for triggering/background reduction
  - complicated combinatorics: difficult to extract a mass peak already for the signal

VBF H→bb + photon

- Very characteristic final state:
  - 2 b-tagged jets
  - 2 forward jets with large rapidity gap / m_{jj}
  - 1 high p_T photon: reduce background, easier triggering

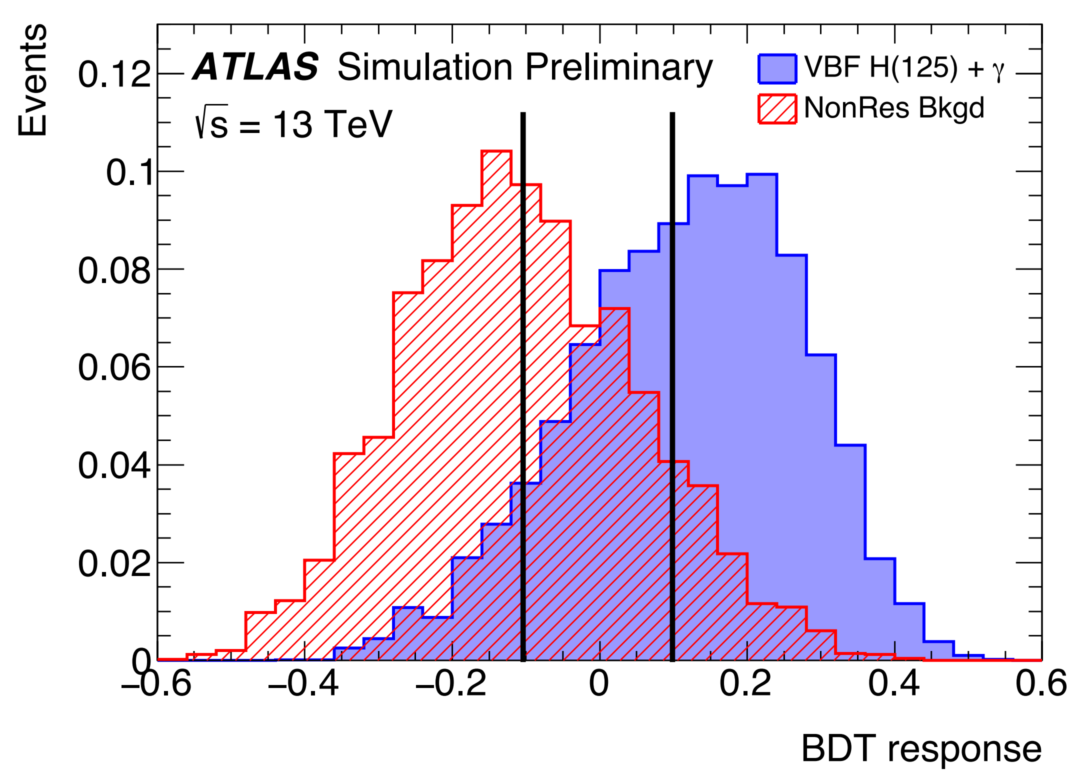


- Fitting m_{bb} spectrum in bins of boosted decision tree:

observed σ*BR/(σ*BR)$_{SM}$ < 4.0

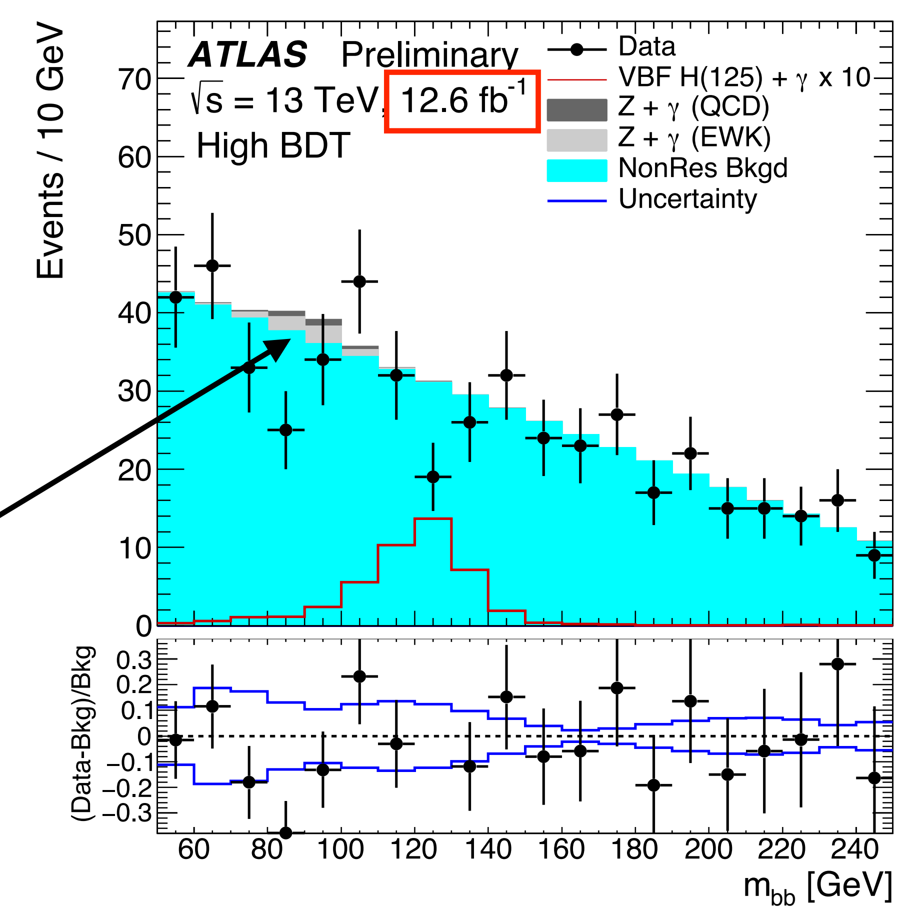
expected σ*BR/(σ*BR)$_{SM}$ < 6.0

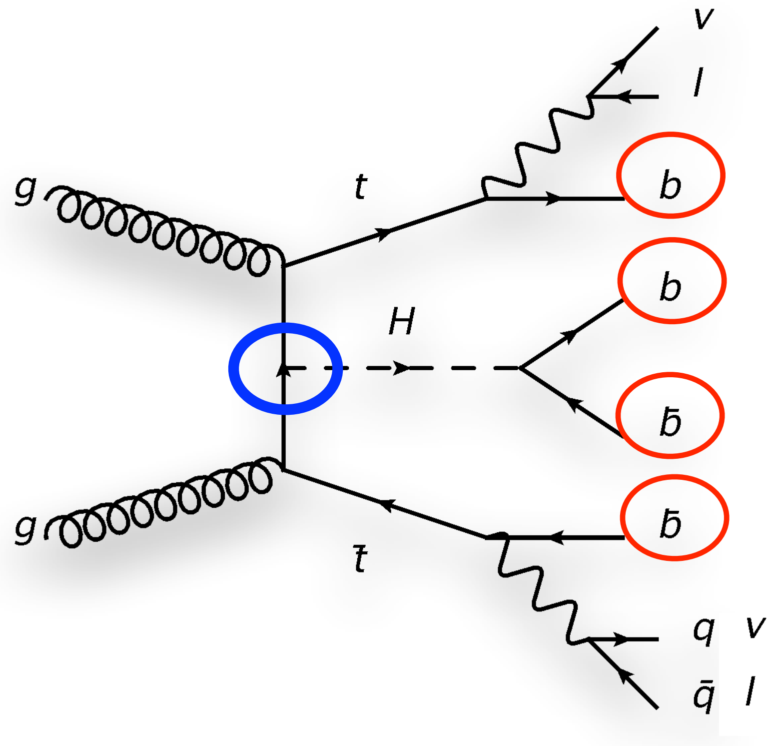
- Signal strength: μ_{VBF}=(-3.9 ± 2.8) stat. dominated



- Measurement of VBF Z->bb + γ as validation

μ_{VBFzbb}=(0.3 ± 0.8)



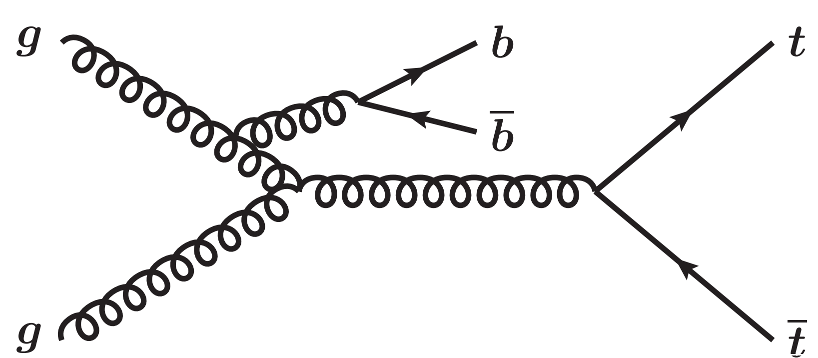


✦ Preferred gateway to ***top Yukawa coupling*** measurement

✦ 'Crowded' final state with multiple possibilities given by ttbar decay products:

- *consider events with only one (1L) or two (2L) leptons in the final state*
- *categorising events according to the number of reconstructed jets*
- ***heavily relying on flavour tagging information***

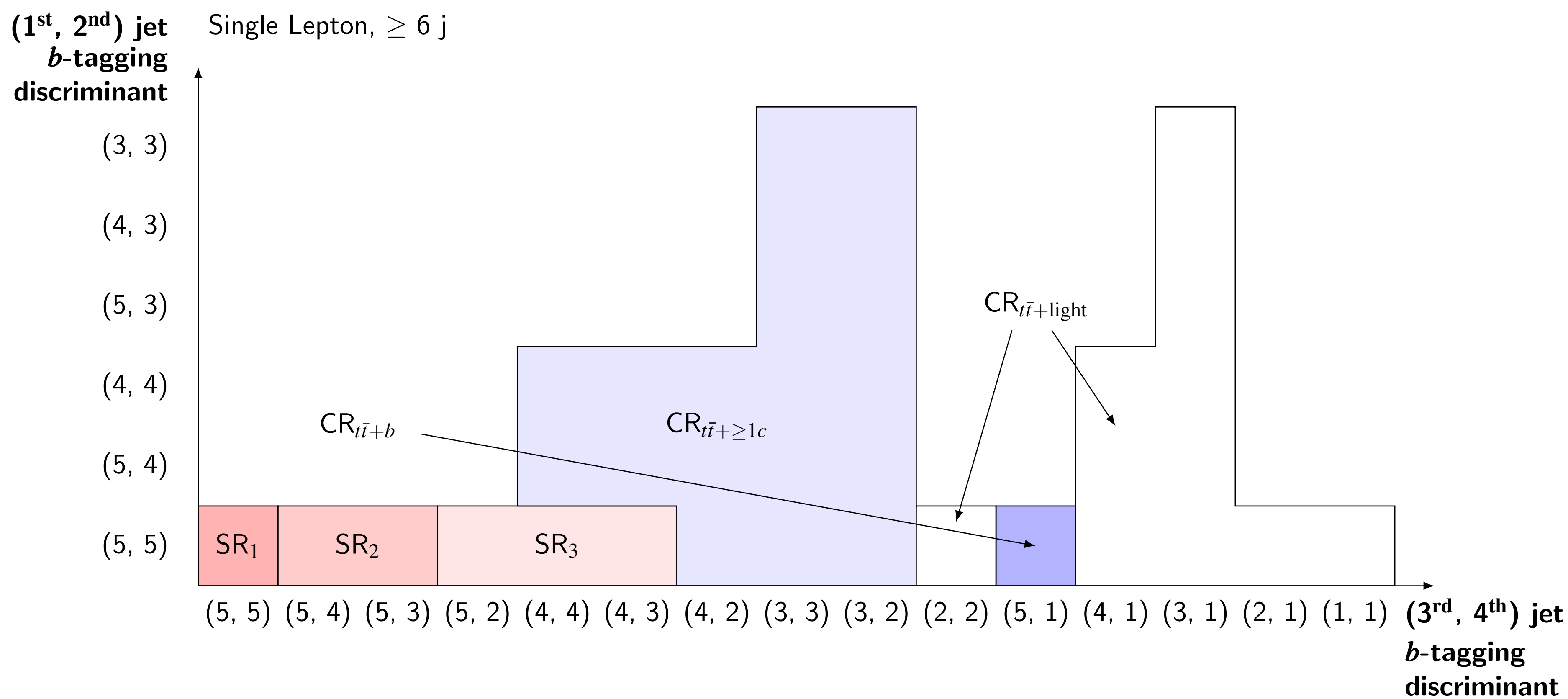
✦ Large and difficult to control irreducible tt+bb background



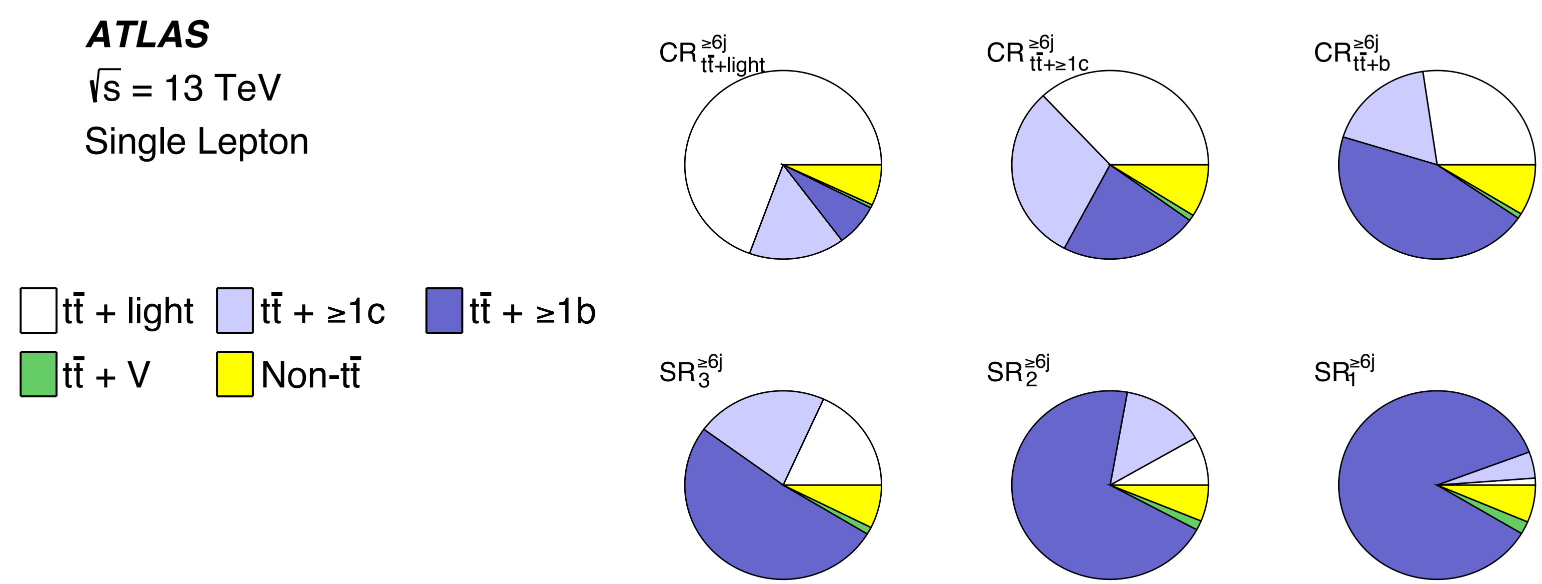
Run2: $t\bar{t}H$ ($H \to b\bar{b}$)

[Phys. Rev. D 97 (2018) 072016]

- (for a given jet multiplicity) **Categorise events according to the b-tagging score of the jets:**
  - *increase signal acceptance, exploit different S/B [and S/sqrt(B)] in each region*

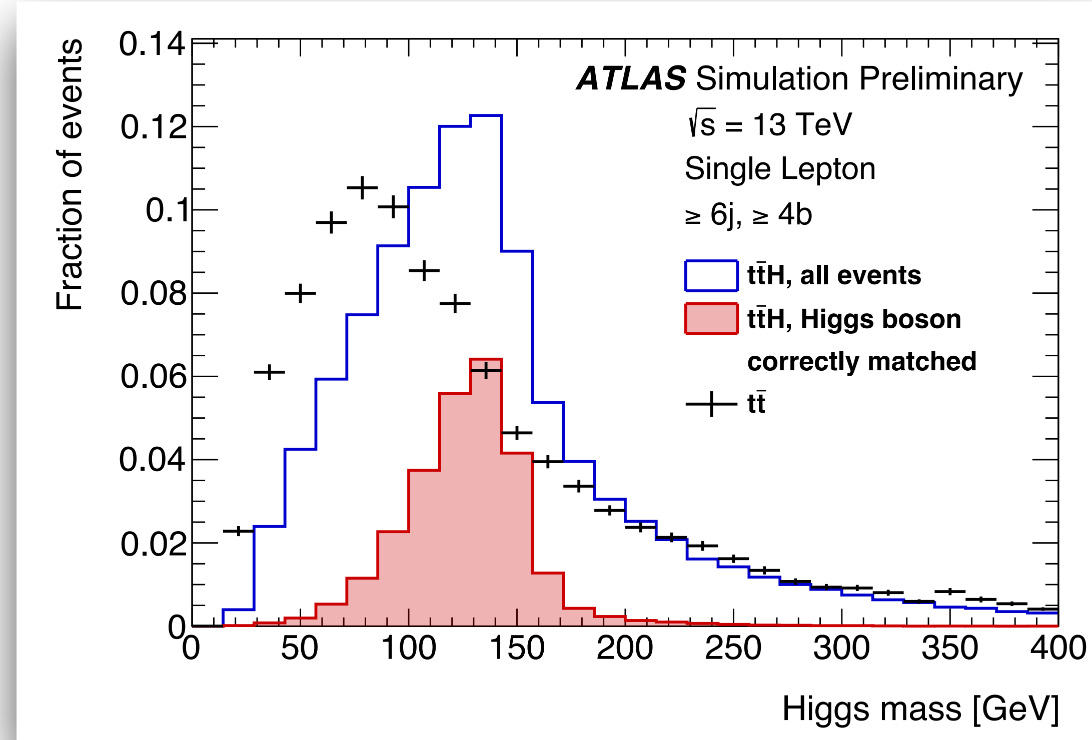


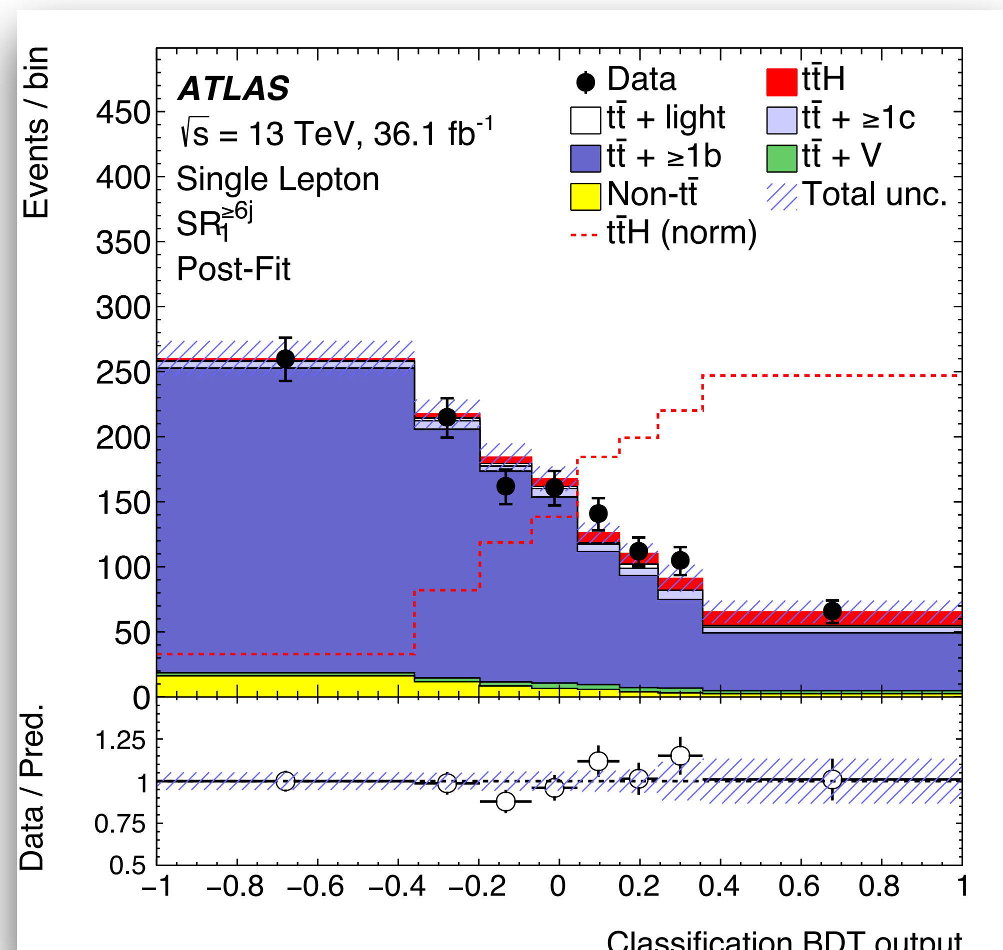
- *Very different background composition in each regions*
  - *used to constrain the normalisation*



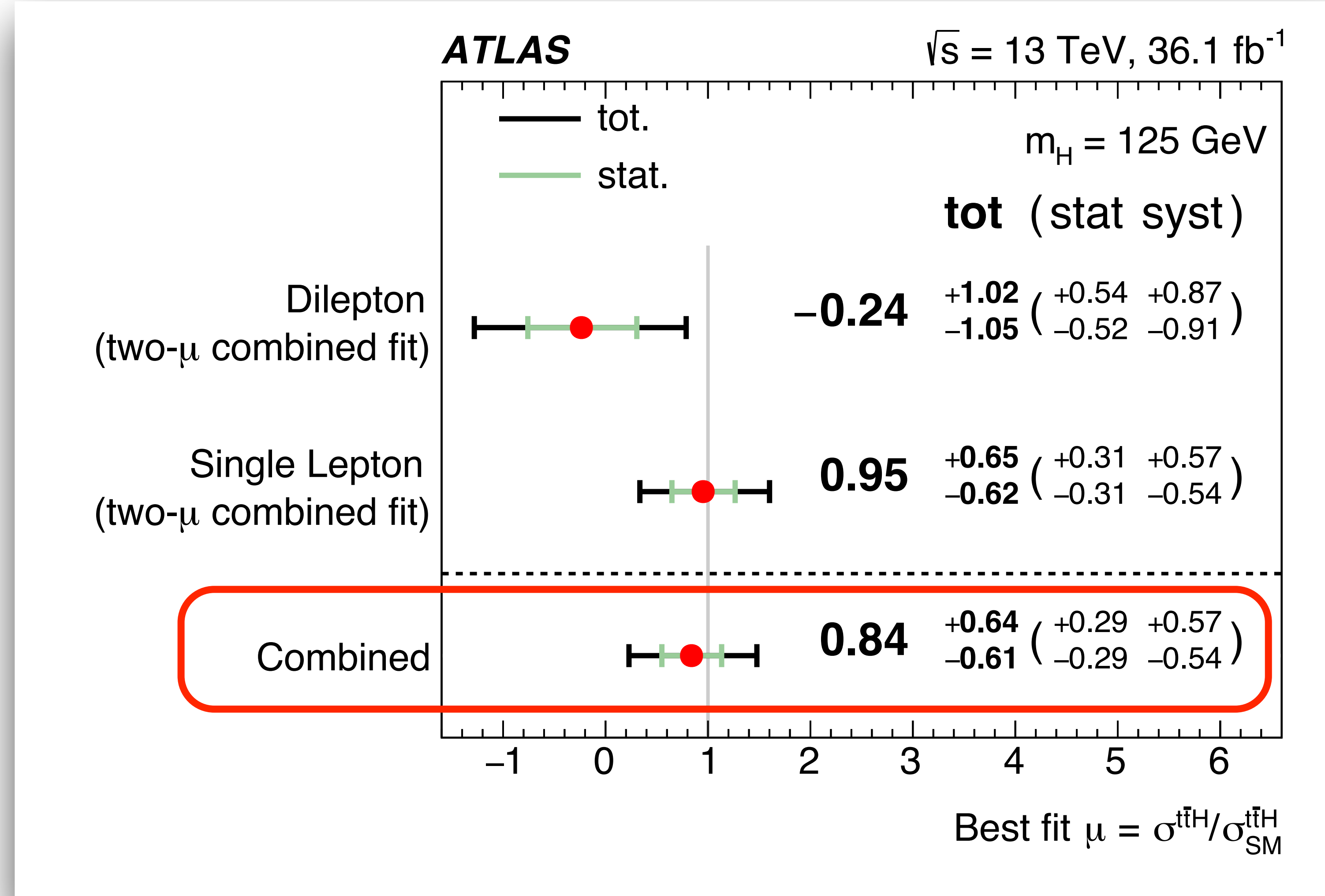
$t\bar{t}H$ ($H\to b\bar{b}$): discriminant

- 4b in the final state complicates combinatorics:
  - *only 30% of Higgs boson correctly reconstructed inside the signal —> can't directly rely on the mass peak*
  - *will improve at high p_T topologies*





- Final discriminant in signal regions: BDT
  - *jet kinematic variables*
  - *global event variables*
  - *jet b-tagging scores*
  - *event reconstruction through additional BDT: assigning reconstructed jets to partons in ttbar/ ttH decay*
  - *Likelihood/MEM discriminant (signal VS ttbb)*



***1.4* (1.6) observed (expected) significance**
w.r.t. no Higgs hypothesis

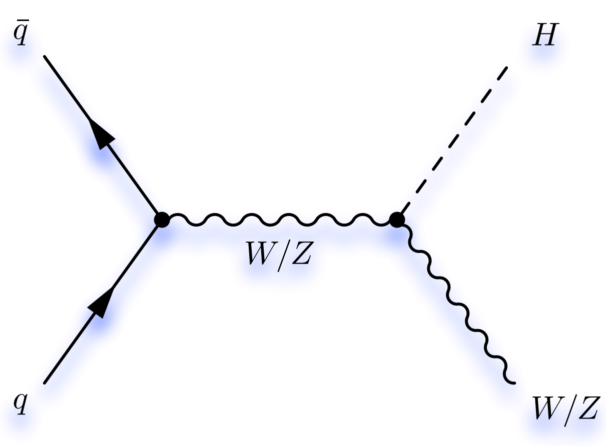
- At 95% CL, for m_H=125 GeV:

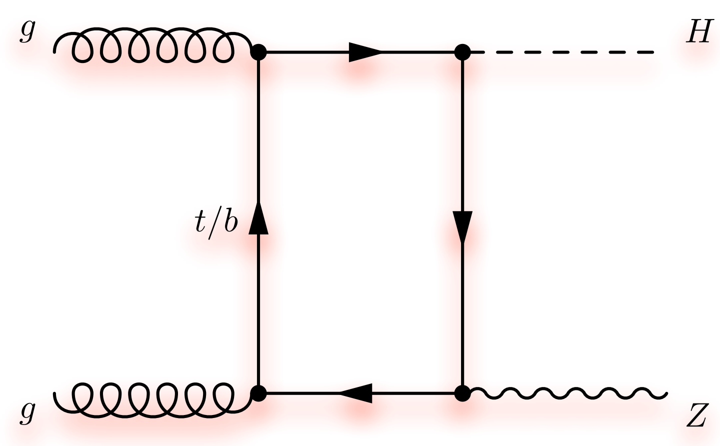
observed σ*BR/(σ*BR)$_{SM}$ < 4.0
expected σ*BR/(σ*BR)$_{SM}$ < 1.9

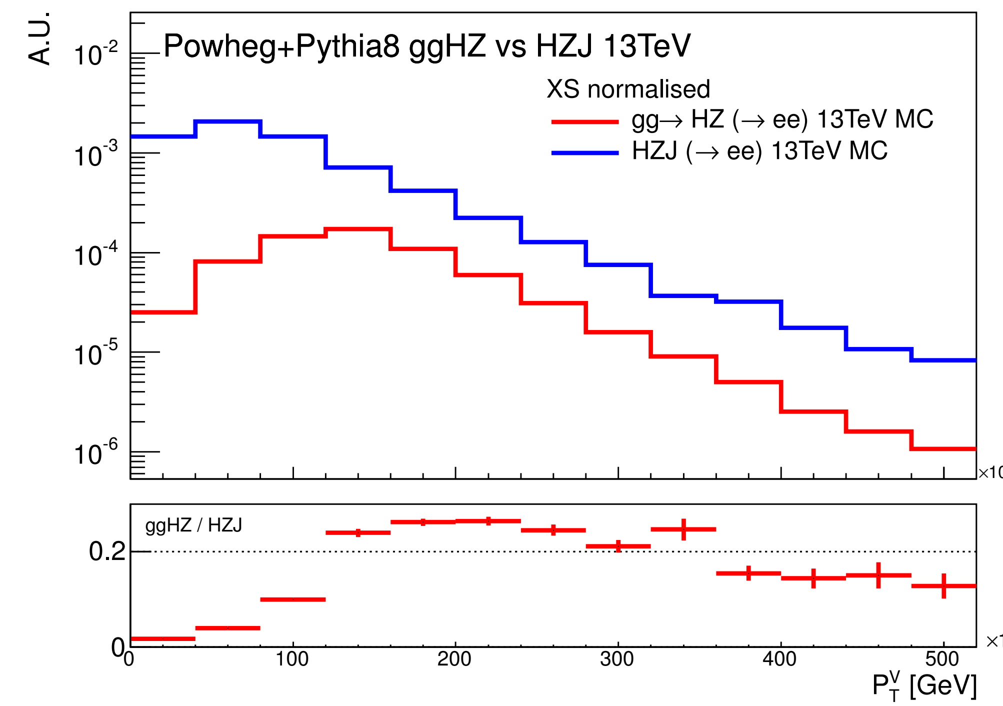
- Analysis dominated by systematic uncertainties: MC modelling of $tt+b\bar{b}$ background, **mis-tag of c and light jets**

VH, H→bb analysis

VH associated production



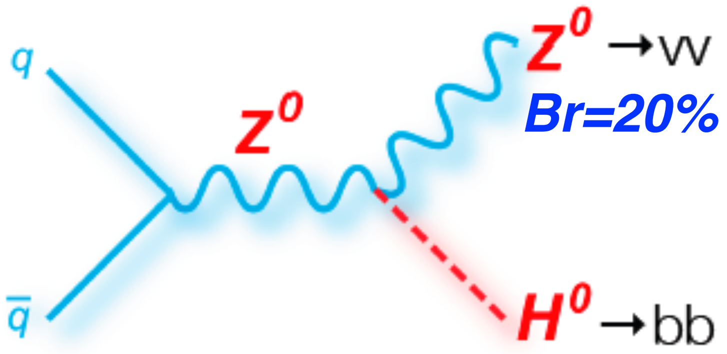


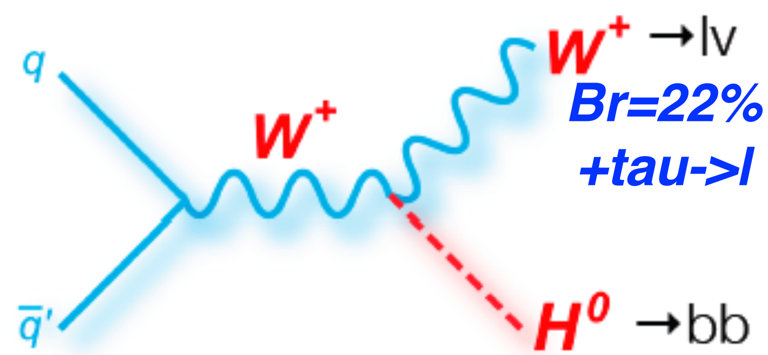


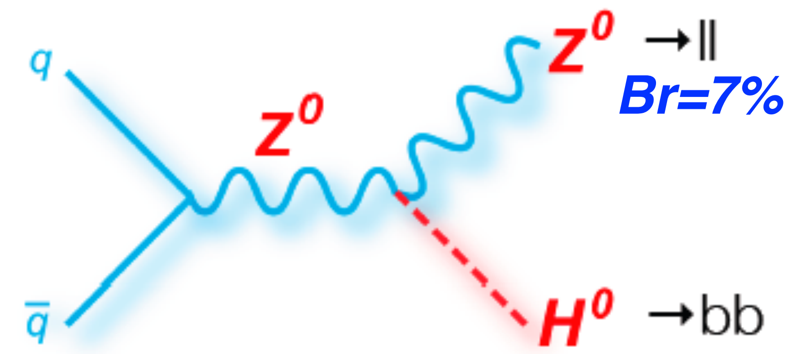
- Associated production with vector boson often considered a **“golden channel” for H->bb**:
  - pure EWK diagram at LO
  - production xSection predicted quite precisely from the theory point of view: NNLO QCD + NLO EWK
  - can exploit leptonic decay leptonic decays of vector boson for an easy triggering / background reduction
  - mostly fully reconstructed/low multiplicity final state

- (WH+ZH)*Br(H->bb) ~ 1.3 pb —> **45k Higgs events in 36 fb^{-1}**:
  - need to add V->ll’ BR + reconstruction + tight event selection to make the signal more visible

- **3 main channels**: very different way to reconstruct the vector boson candidate







0-lepton:

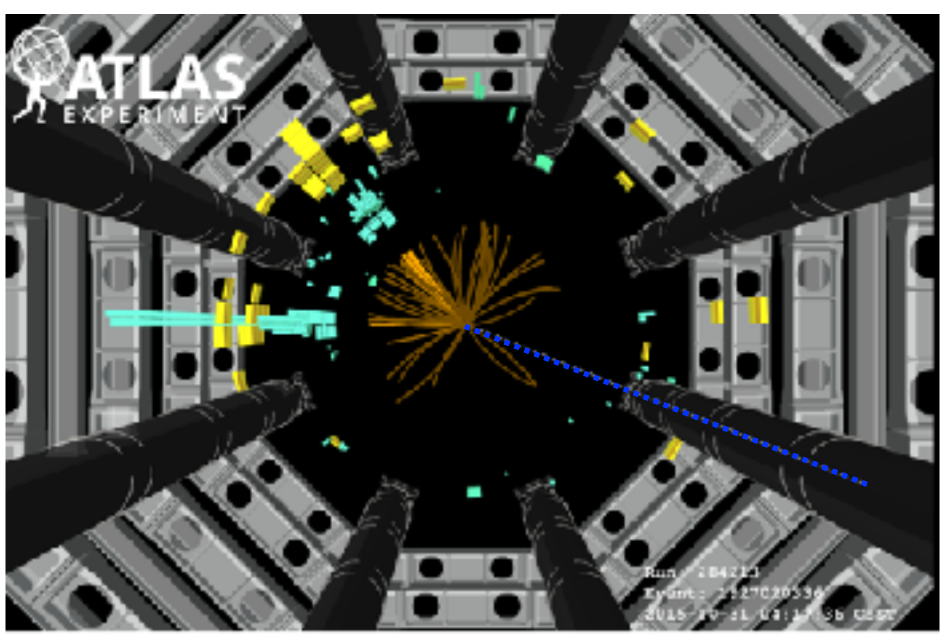
- mainly Z->vv but also W->tau
- V p_T = MET

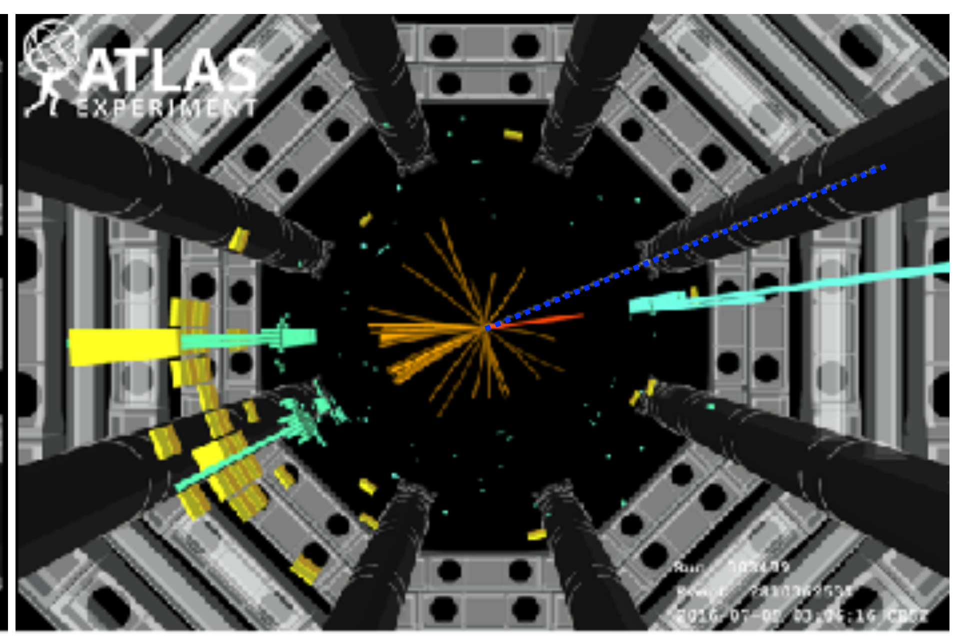
1-lepton (l=e,mu):

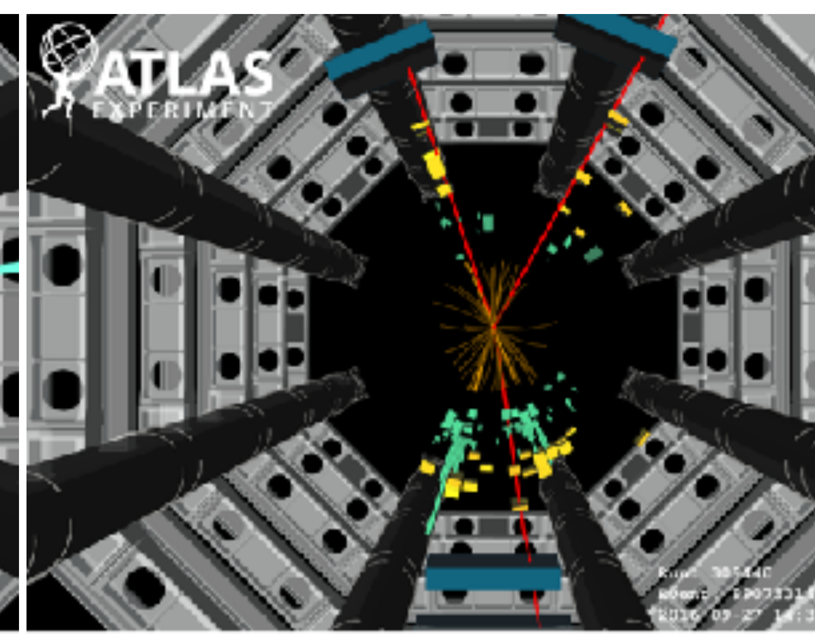
- mainly W->lv
- V p_T = p_T(l,MET)

2-lepton (l=e,mu):

- same flavour, mainly Z->ll
- V p_T = p_T ll



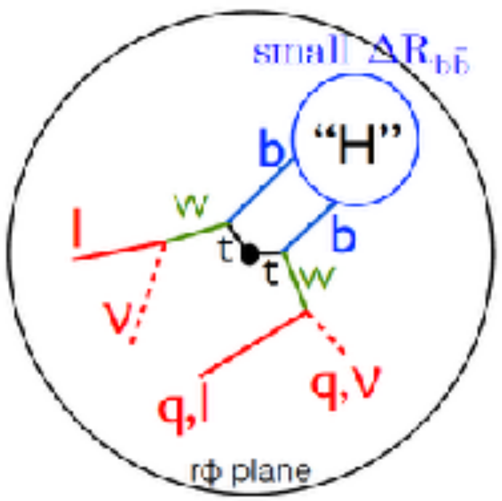




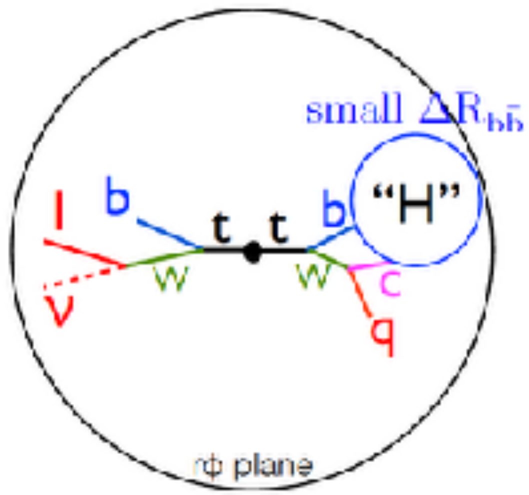
VHbb: selection

- Common aspects among channels:
  - triggering on vector boson object: MET trigger (0L, 1L-μ) , single lepton trigger (1L-e, 2L)
  - exactly 2 central ($|\eta|<2.5$) b-tagged jets (70% b-jet efficiency)
  - categorising events as a function of additional jets

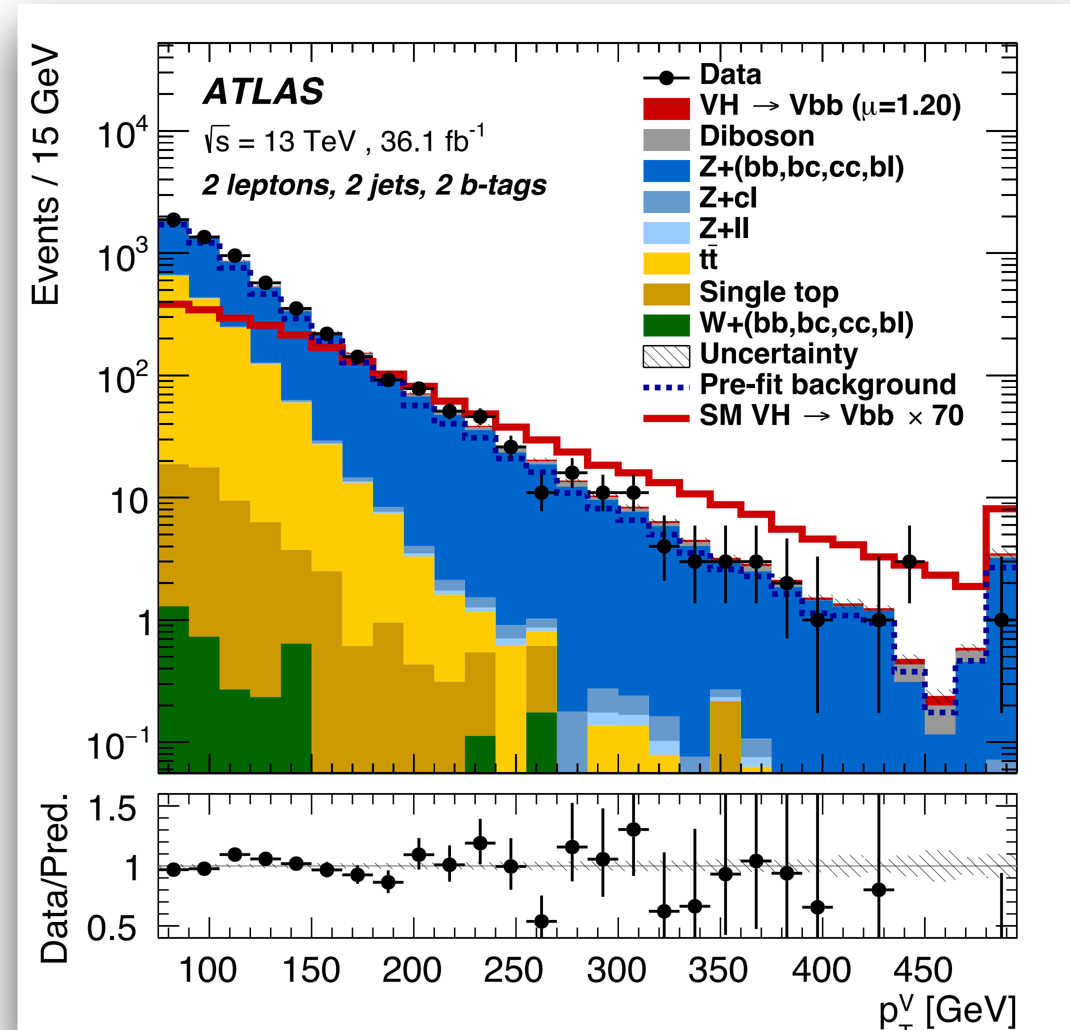
- Hight V p_T selection strongly suppresses certain background topologies:



low p_T(V/H)



high p_T(V/H)

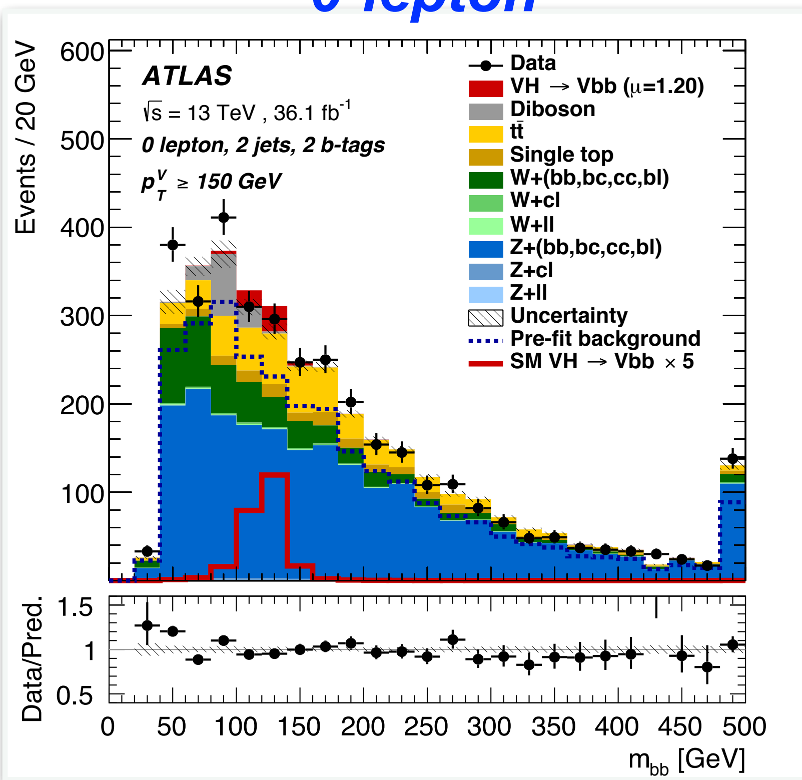


- Chosen cut values:
  - ***0-Lepton:*** **V p_T > 150 GeV** [imposed by MET trigger]
  - ***1-Lepton:*** **V p_T > 150 GeV** [considerably reduced multi-jet background]
  - ***2-Lepton:*** **V p_T > 75 GeV** [split signal region at 150 GeV]

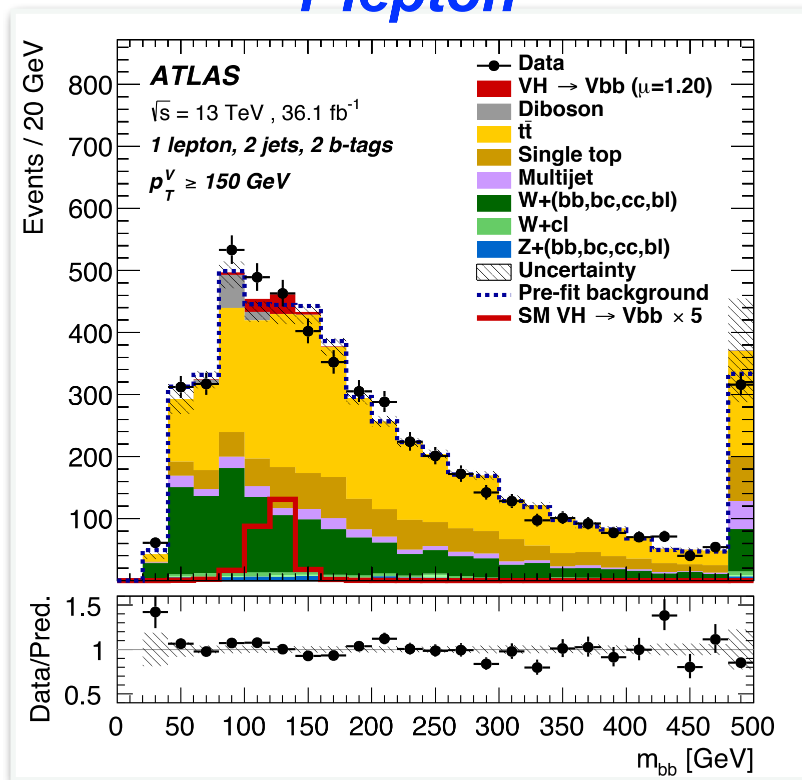
- Overall acceptance for signal: 1-7%

- Different **background composition** in each channel

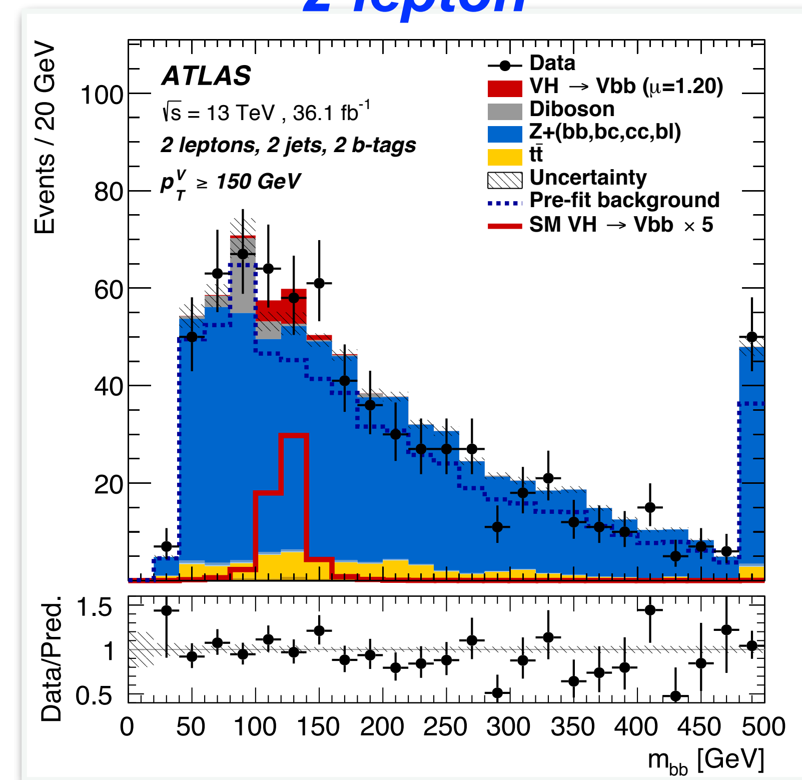
0-lepton



1-lepton



2-lepton

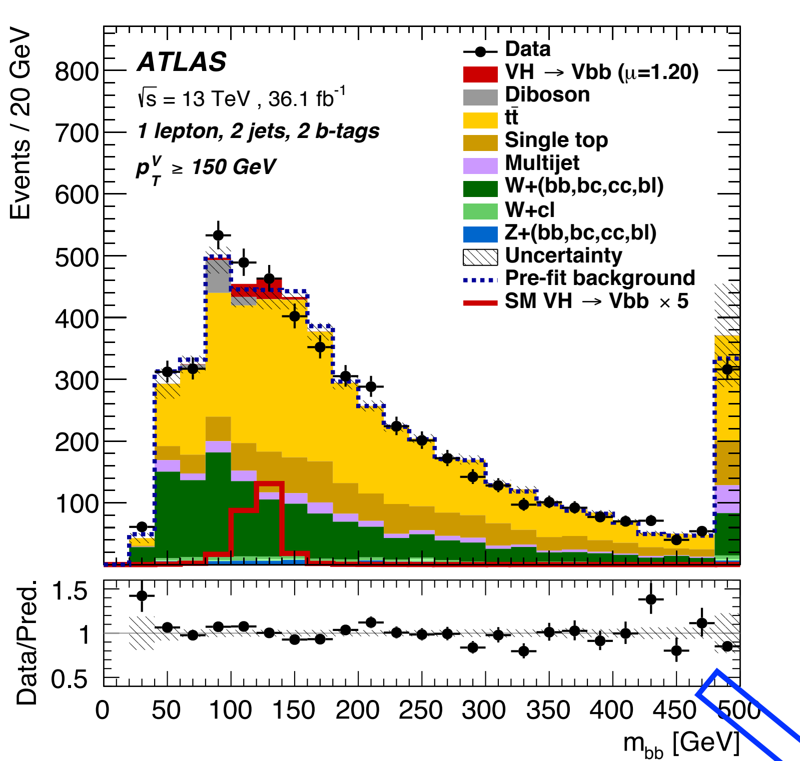


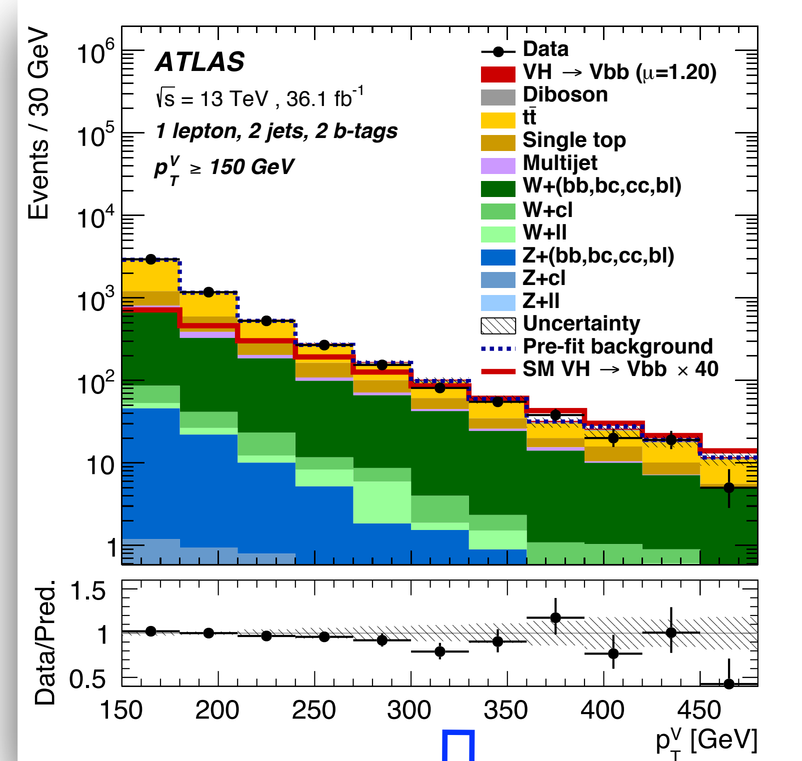
- ***V+jet***: dominated by Z+bb, W+bb
  - ***Z+hf***: 0L and 1L , ***W+hf***: 0L and 1L
- ***ttbar***: present in every channel
  - very different topology of selected events between 0L/1L and 2L channels

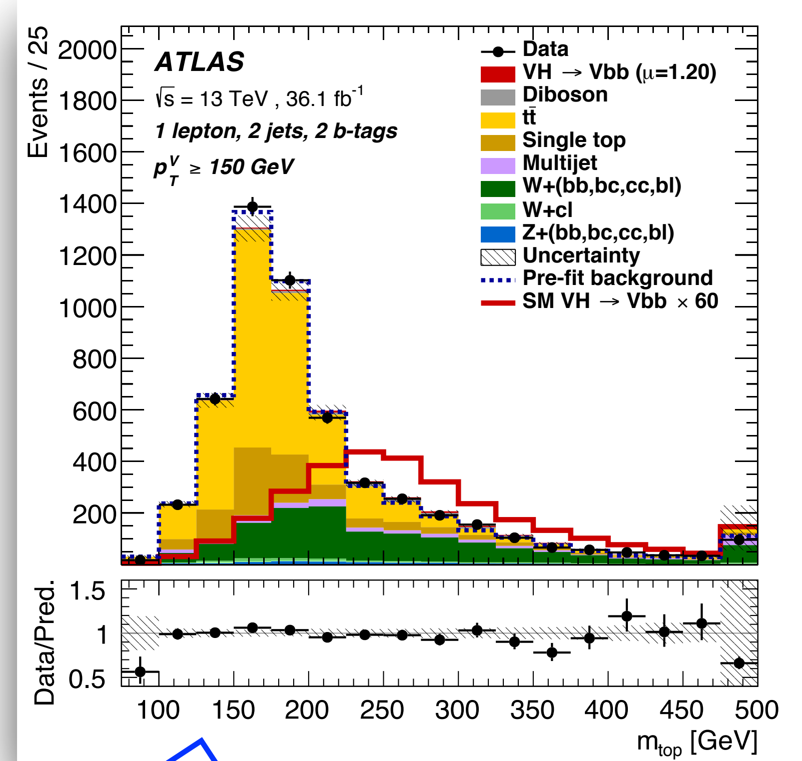
Floating normalisation uncertainties determined from control regions

- Resonant *VZ, Z->bb* background: used to validate the analysis procedure
- ***Single top*** and ***QCD multi-jet background***: subdominant contributions only present in 1L channel

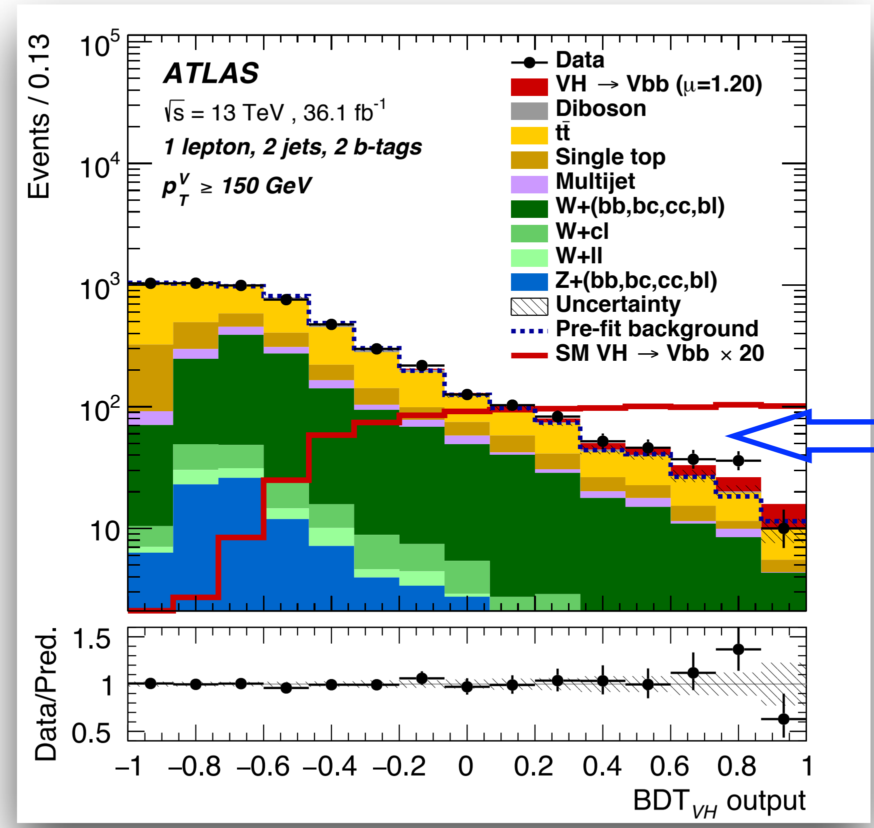
Multivariate discriminant





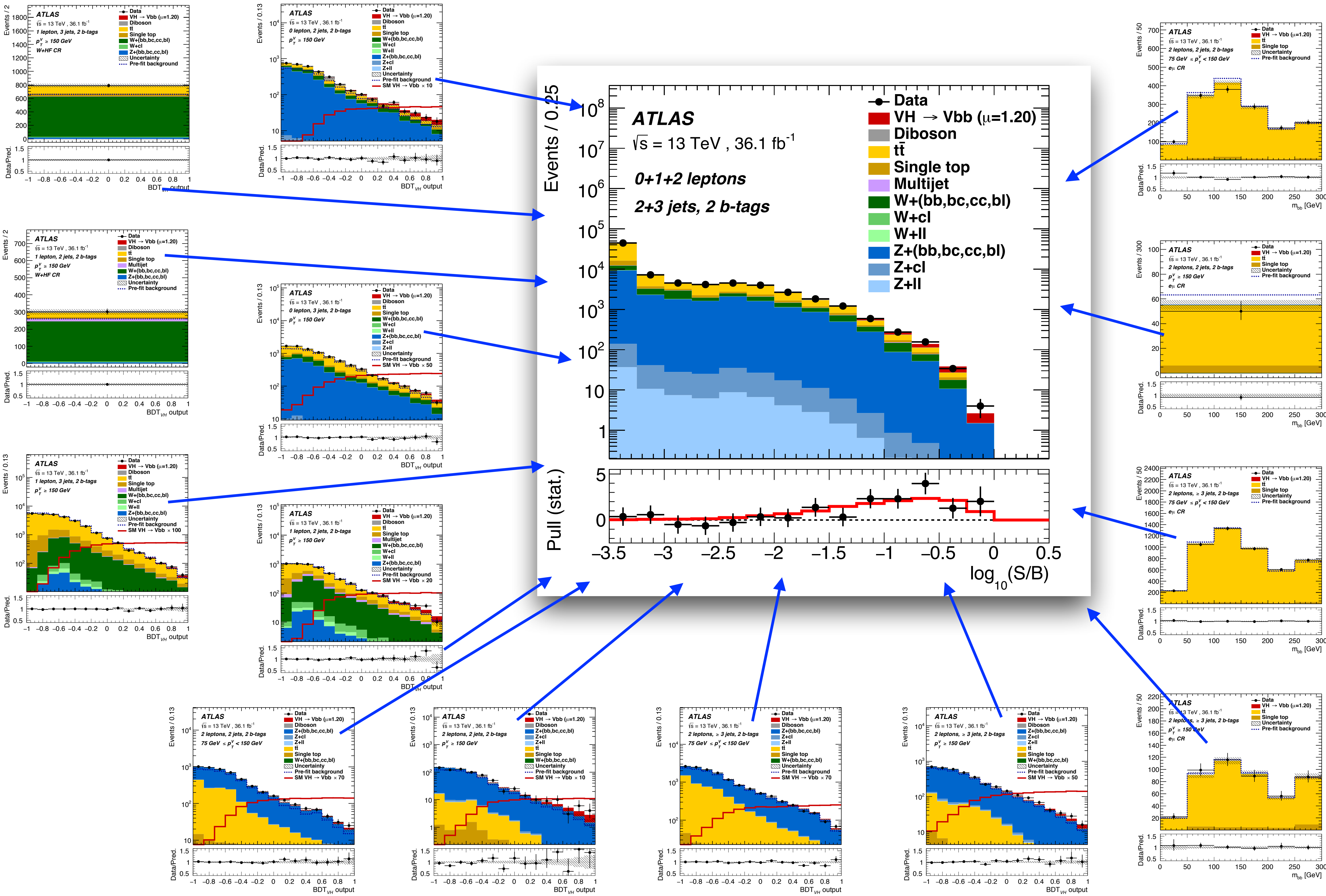


Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(\vec{b}_1, \vec{b}_2)$	×	×	×
$\|\Delta\eta(\vec{b}_1, \vec{b}_2)\|$	×		
$\Delta\phi(\vec{V}, \vec{bb})$	×	×	×
$\|\Delta\eta(\vec{V}, \vec{bb})\|$			×
m_{eff}	×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

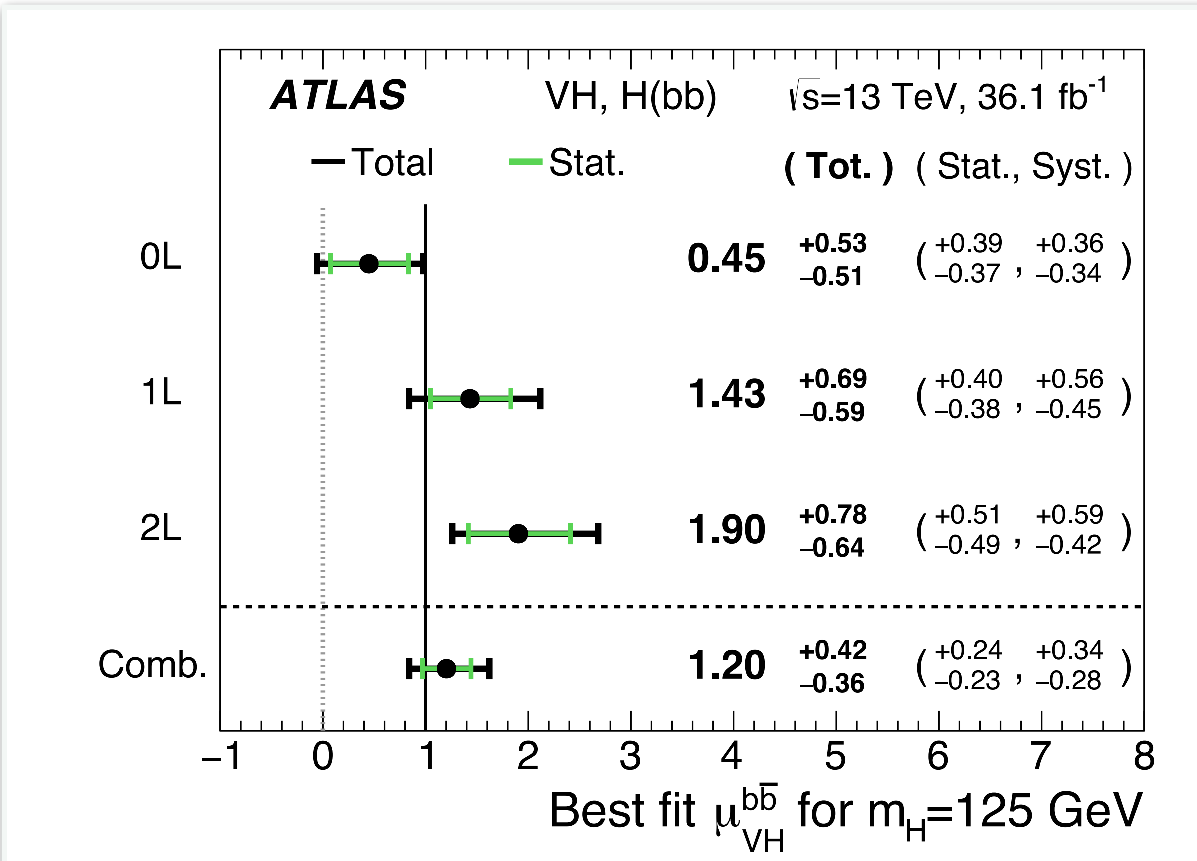


- S/B ~ few %
- combining multiple input variables into a boosted decision tree
- discriminant trained independently in each analysis region

Putting it all together



Putting al together (2)



$$\mu = 1.20^{+0.24}_{-0.23}(\text{stat.})^{+0.34}_{-0.28}(\text{syst.})$$

evidence of H->bb through VH associated production

Dataset	p_0		Significance	
	Exp.	Obs.	Exp.	Obs.
0-lepton	4.2%	30%	1.7	0.5
1-lepton	3.5%	1.1%	1.8	2.3
2-lepton	3.1%	0.019%	1.9	3.6
Combined	0.12%	0.019%	3.0	3.5

- Good complementarity among the various channel: ***compatibility of individual channels = 10%***
- Result compatible with SM prediction (NNLO QCD+NLO EWK inclusive cross section + acceptance from NLO generator)

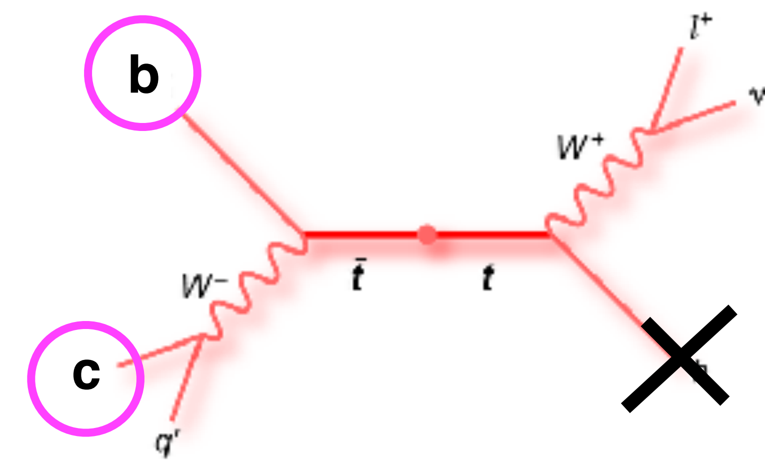
Uncertainty breakdown

Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
E_T^{miss}		0.03
Leptons		0.01
b-tagging	b-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
Floating normalisations		0.07
Z + jets		0.07
W + jets		0.07
$t\bar{t}$		0.07
Single top quark		0.08
Diboson		0.02
Multijet		0.02
MC statistical		0.13

- ***Analysis systematically dominated*** : syst. component represent 61% of total error [does not mean that it will not shrink with luminosity]

- ***Signal modelling systematics***: dominated by acceptance effects
  - do not impact the significance of the measured signal

- ***Detector systematics effects***
  dominated by flavour tagging
  [sensitivity to c-jet mis-tag from ttbar events]



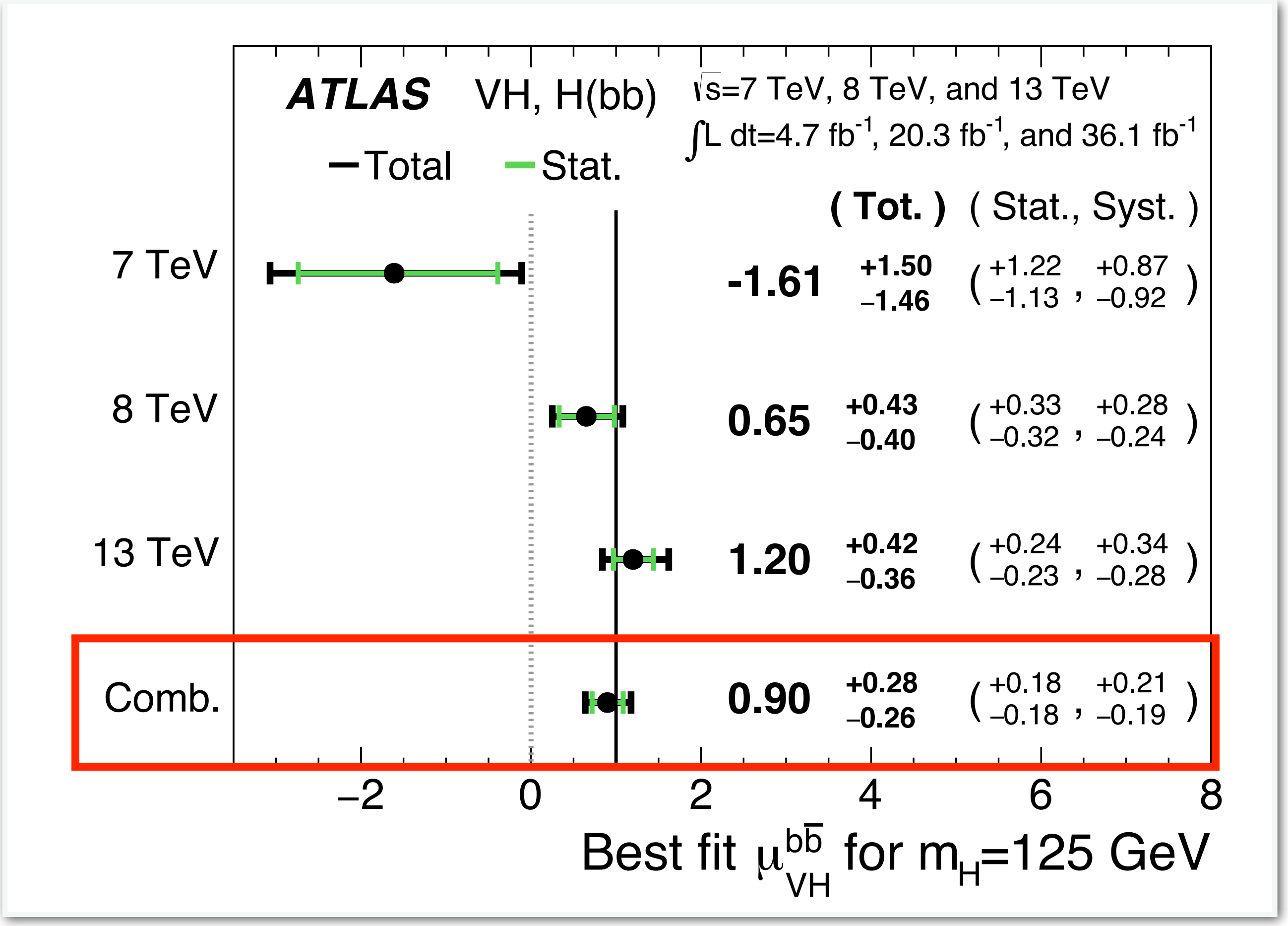
- Similar contribution from ***modelling uncertainty*** of various processes:
  - ***W+jets***: W p_T shape uncertainty
  - ***Z+jets***: mbb shape uncertainty
  - ***single top***: diagram subtraction VS diagram removal in Wt production

- ***MC statistics:*** mainly for ttbar and Z+hf

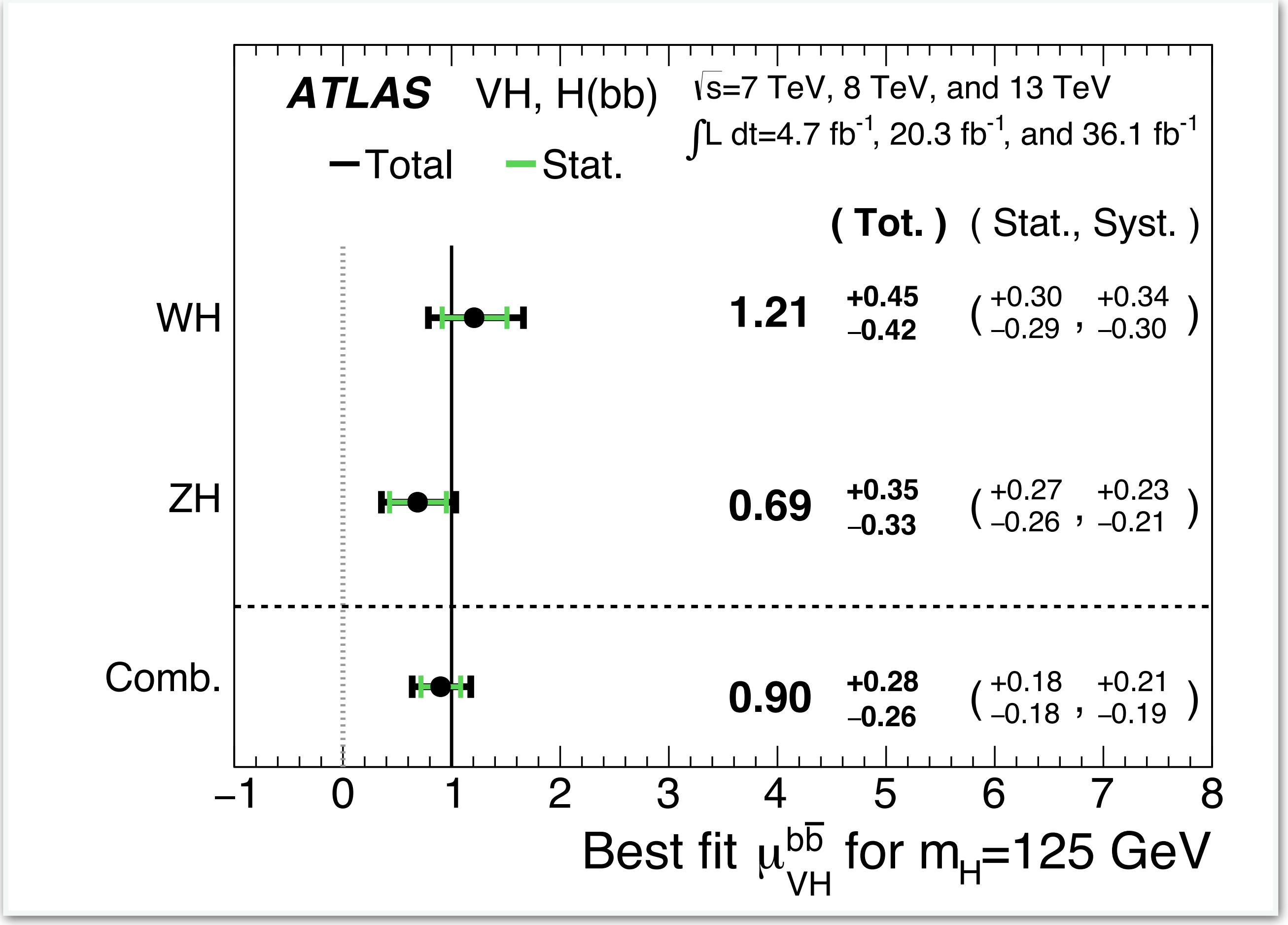
Run I + Run2

✦ Majority of systematic uncertainties considered uncorrelated due to change in detector / object reconstruction techniques / MonteCarlo samples / analysis strategy

compatibility 7.0%

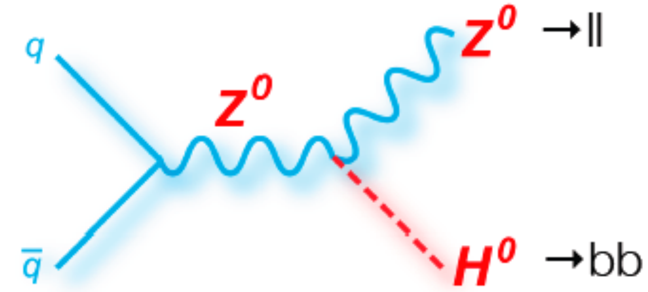


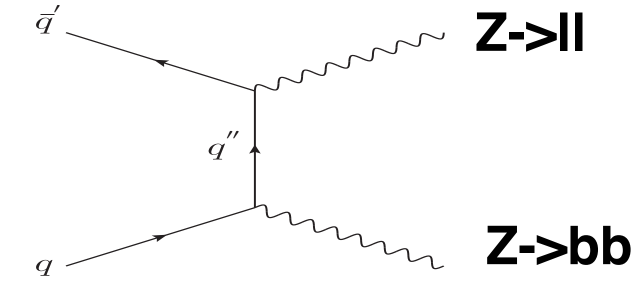
WH-ZH correlation: ~1%

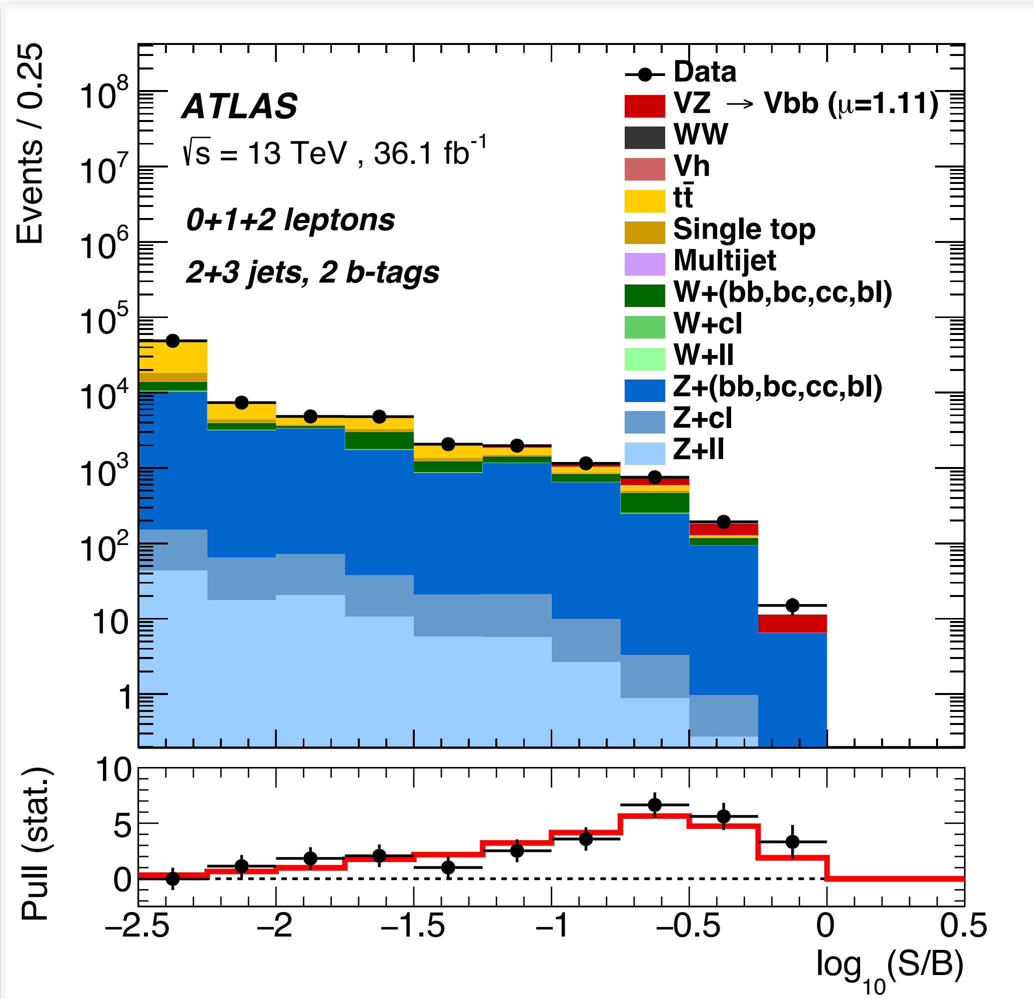


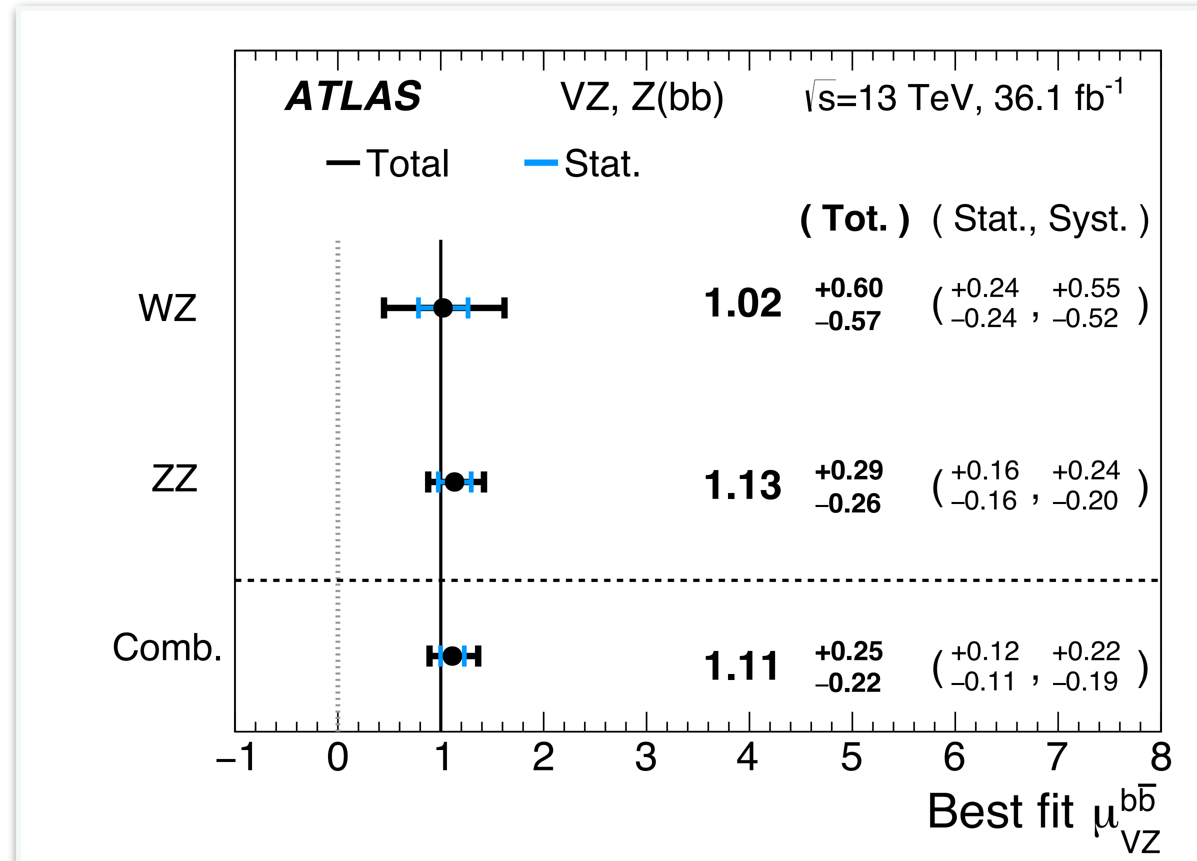
	Run1	Run2	Run1+Run2
exp. significance	2.6 s.d	3.0 s.d	4.00 s.d
obs. significance	1.4 s.d	3.5 s.d	3.57 s.d
signal strength	$0.51^{+0.40}_{-0.37}$	$1.20^{+0.41}_{-0.36}$	$0.91^{+0.28}_{-0.26}$

- Re-training BDT in order to isolate diboson signal







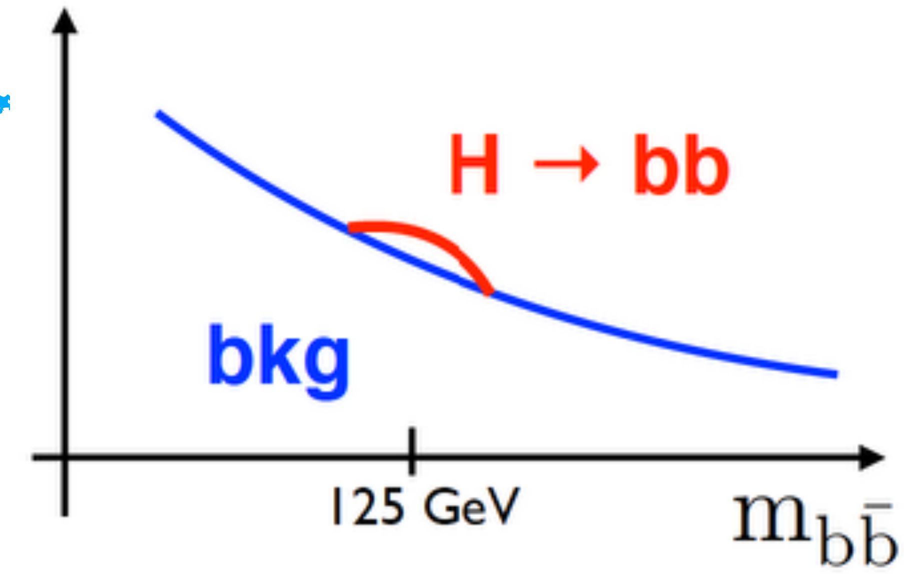


- Expected significance: 5.3 σ , *Observed significance: 5.8 σ*

$$\mu_{VZ} = 1.11^{+0.12}_{-0.11}(\text{stat.})^{+0.22}_{-0.19}(\text{syst.})$$

observation of diboson production in VZ->ll'bb final state

A more 'intuitive' analysis

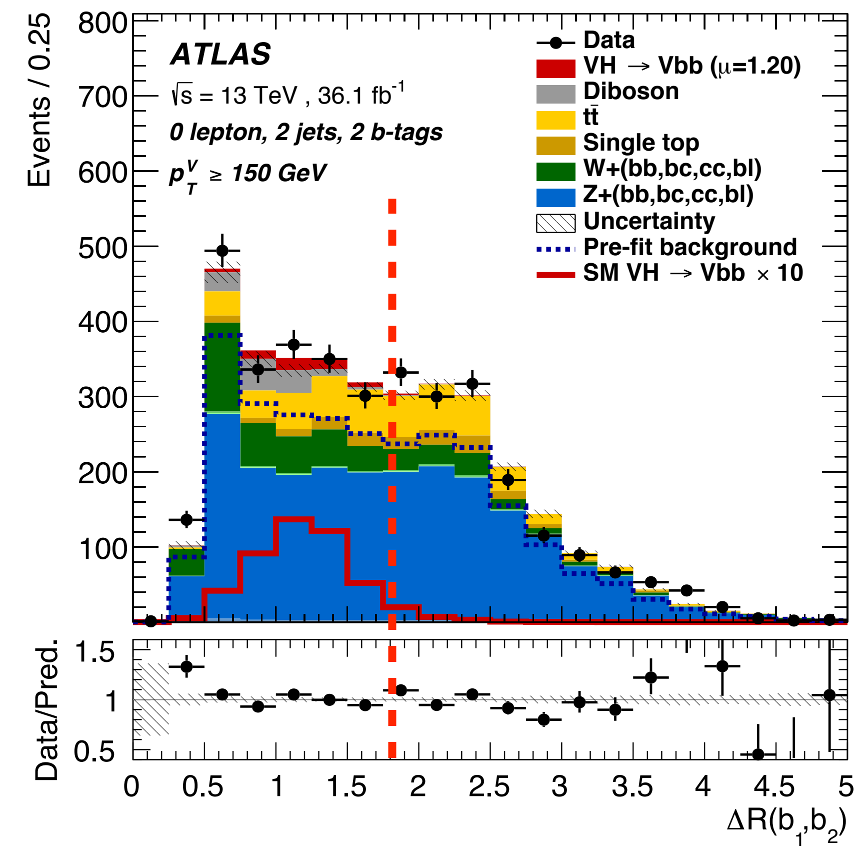


- The dream of every theorist: ***"can you perform the analysis without the BDT black box fitting the m_{bb} spectrum?"***

- Tighter selection cuts (mostly against ttbar):

Selection	0-lepton	1-lepton	2-lepton
	Channel		
m_T^W	-	< 120 GeV	-
$E_T^{miss}/\sqrt{S_T}$	-	-	$< 3.5\sqrt{\text{GeV}}$

	p_T^V regions		
p_T^V	(75, 150] GeV (2-lepton only)	(150, 200] GeV	(200, ∞) GeV
$\Delta R(\vec{b}_1, \vec{b}_2)$	<3.0	<1.8	<1.2

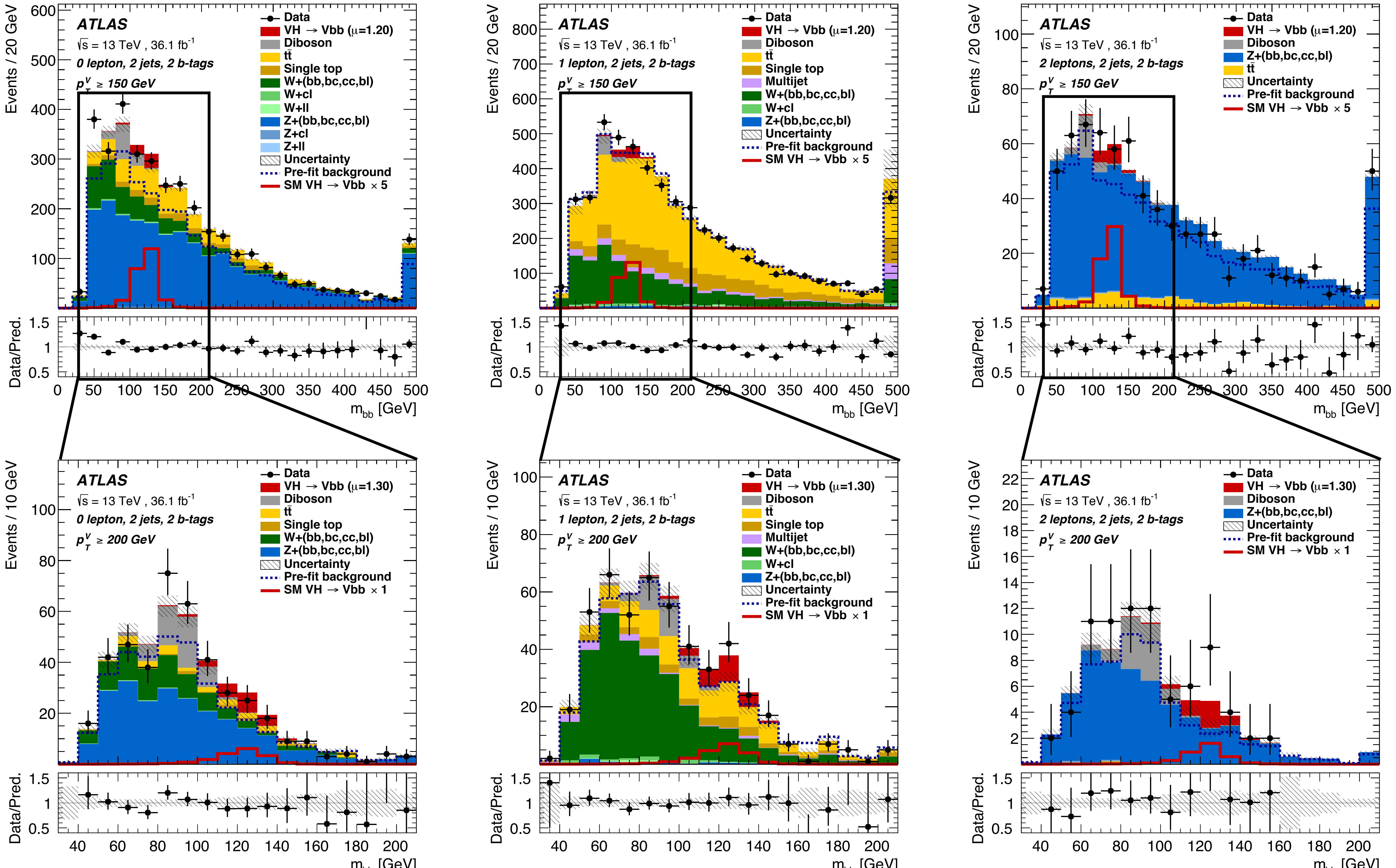


- Further region splitting according to V p_T:

Channel	SR/CR	75 GeV< p_T^V <150 GeV: 2 jets	75 GeV< p_T^V <150 GeV: 3 jets	150 GeV< p_T^V <200 GeV: 2 jets	150 GeV< p_T^V <200 GeV: 3 jets	p_T^V > 200 GeV: 2 jets	p_T^V > 200 GeV: 3 jets
		Categories					
0-lepton	SR	-	-	m_{bb}	m_{bb}	m_{bb}	m_{bb}
1-lepton	SR plus W + HF CR	-	-	m_{bb}	m_{bb}	m_{bb}	m_{bb}
2-lepton	SR	m_{bb}	m_{bb}	m_{bb}	m_{bb}	m_{bb}	m_{bb}
2 lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield*	$m_{bb}{}^{\dagger}$	Yield*	$m_{bb}{}^{\dagger}$

A more 'intuitive' analysis (2)

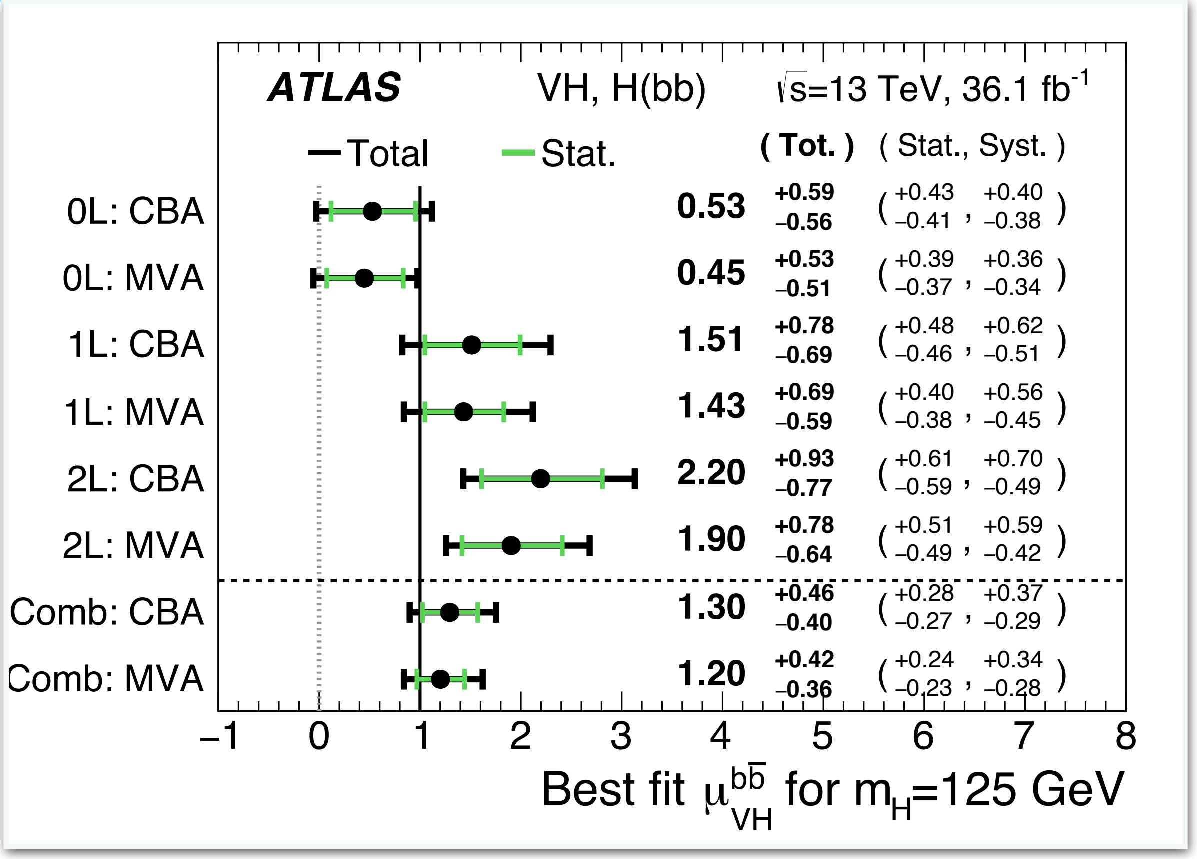
✦ MVA analysis selection



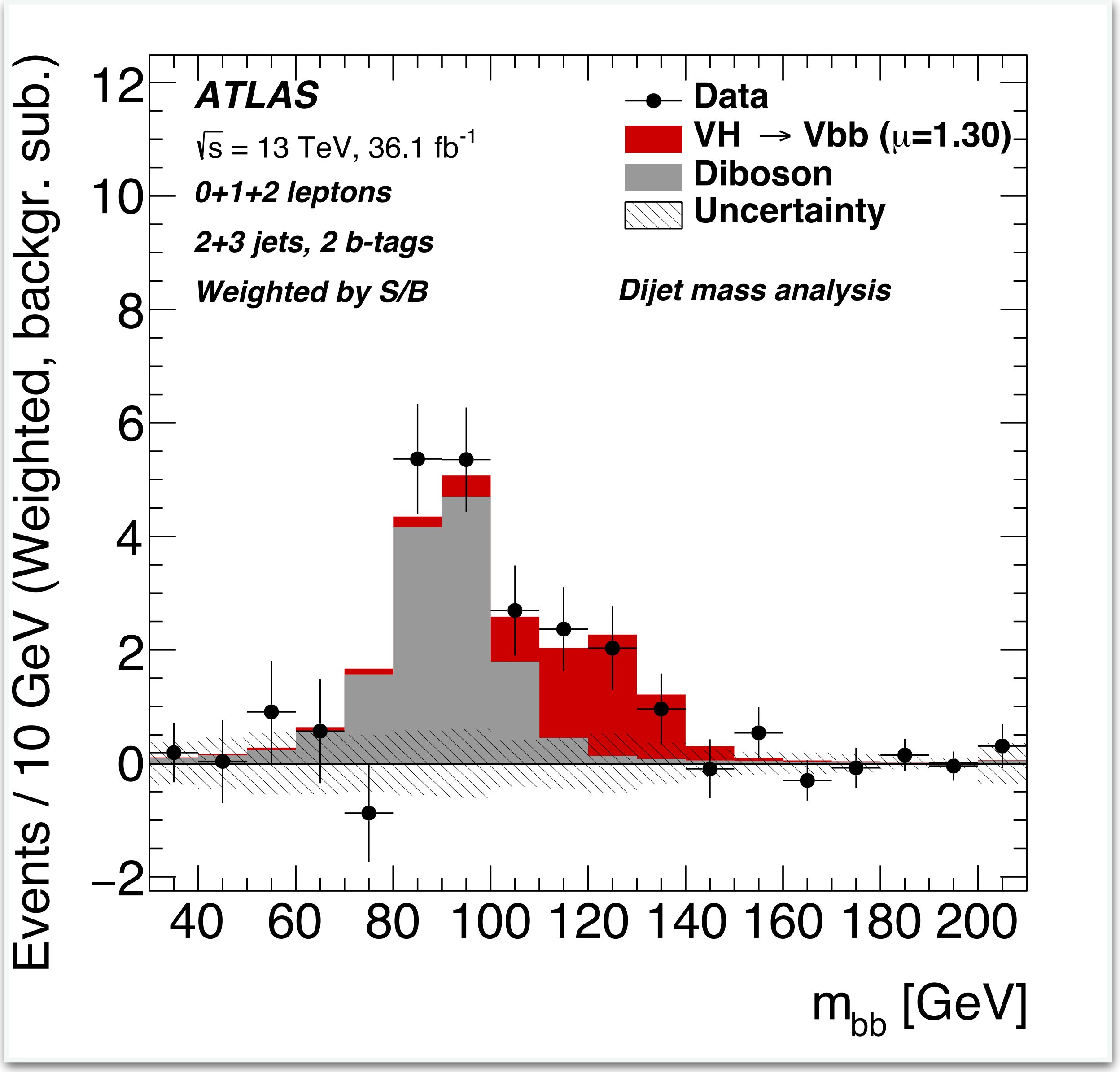
✦ di-jet analysis selection

- Extremely consistent results between MVA and di-jet mass analysis

- Combining 14 m_{bb} distributions weighted by their S/B



sign.	Exp.	Obs.
MVA	3.0 σ	3.5 σ
di-jet	2.8 σ	3.5 σ



$$\mu = 1.30^{+0.28}_{-0.27}(\text{stat.})^{+0.37}_{-0.29}(\text{syst.})$$

H->bb : full snapshot

- CMS too has a very comprehensive program for measuring H->bb (very consistent set of results)

process	Year	experiment	exp. sig.	obs. sig.	signal strength
VH	Run2 (36ifb)	ATLAS	3.0 s.d.	3.5 s.d.	1.2 ± 0.4
		CMS	2.8 s.d.	3.3 s.d.	1.2 ± 0.4
	Run1 (20ifb) + Run2 (36ifb)	ATLAS	**4.0 s.d.**	**3.6 s.d.**	**0.90 ± 0.27**
		CMS	**3.8 s.d.**	**3.8 s.d.**	**1.06 ± 0.30**
VBF+gam	Run2 (12.6ifb)	ATLAS	0.4 s.d.		-3.9 ± 2.8
VBF	Run2 (2.3ifb)	CMS			-3.7 ± 2.5
ttH	Run2 (36ifb)	ATLAS	1.6 s.d.	1.4 s.d.	0.8 ± 0.6
		CMS	2.2 s.d.	1.6 s.d.	0.7 ± 0.45
ggH	Run2 (36ifb)	CMS	0.7 s.d.	1.5 s.d.	2.3 ± 1.8

ATLAS+CMS Run1 combination

Decay channel	ATLAS+CMS	ATLAS	CMS
μ^{bb}	$0.70\,^{+0.29}_{-0.27}$	$0.62\,^{+0.37}_{-0.37}$	$0.81\,^{+0.45}_{-0.43}$

CMS Run2 combination

$H \to bb$		
Best fit value	Uncertainty Stat.	Uncertainty Syst.
$1.12\,^{+0.29}_{-0.28}$	$^{+0.19}_{-0.19}$	$^{+0.22}_{-0.20}$

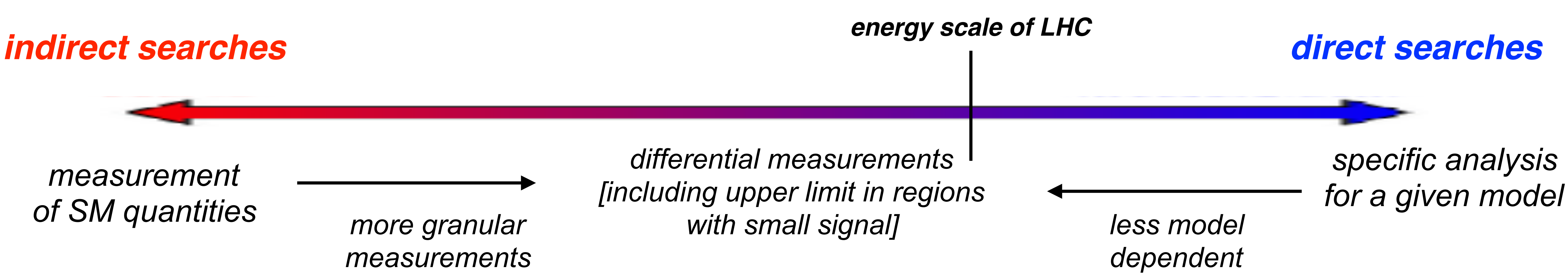
H->bb as a tool for new physics searches

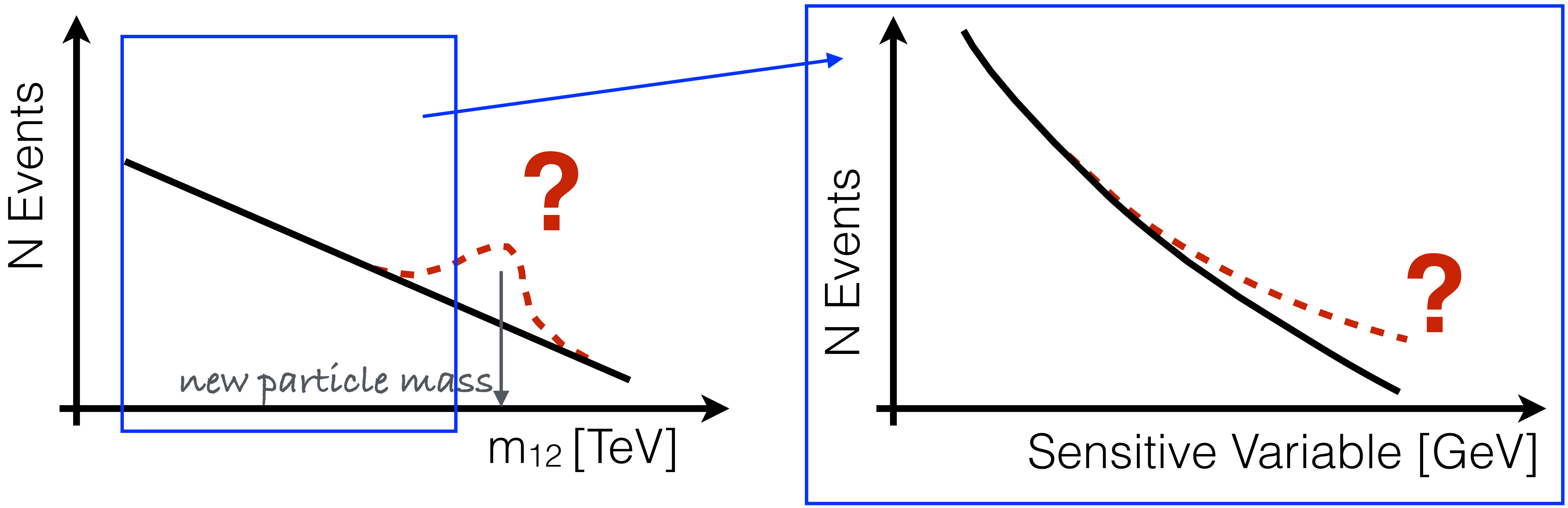
H_{bb} as a tool for BSM searches

- **Direct searches**:
  - *new physics signature include SM Higgs boson or SM Higgs-boson-like particles in final states:*
  - *consider simplified models as a prototype for a large variety of models: heavy vector triplets, vector-like quarks, Higgs+invisible, SUSY EWK decay chains, di-Higgs resonances*

- **Indirect searches**:
  - *modified interaction of Higgs boson can be revealed through deviations of production/decays with respect to SM*
  - *often interpreted in the context of effective field theory (EFT)*

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i c_i^{(6)} O_i^{(6)} / \Lambda^2$$



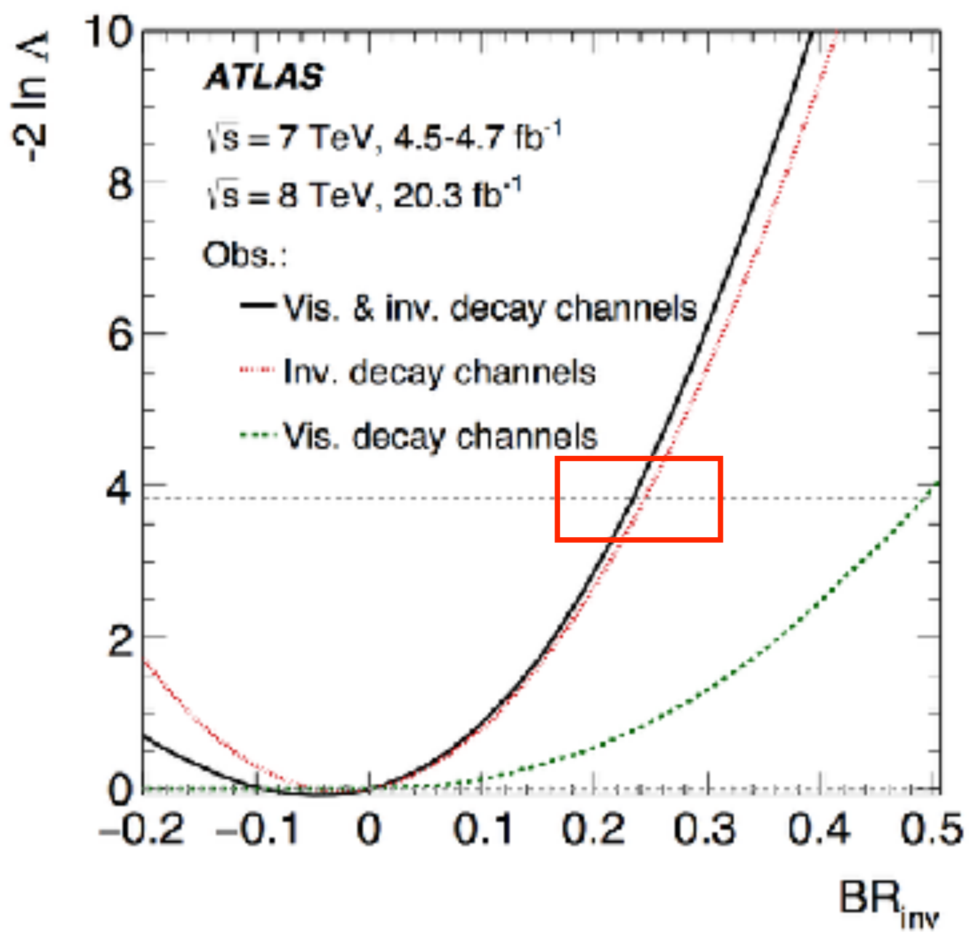


- While not being the cleanest channel, ***H->bb has some key advantages***:
  - fully reconstructed Higgs boson with distinct recognisable features
  - largest possible statistics: good feature when looking for small signals

- Express production and decay of Higgs boson in terms of simple modifiers of couplings with known SM particles: *assuming that effect of new physics modifies the rate but not the type of interaction*

Production	Loops	Interference	Expression in fundamental coupling-strength s	
$\sigma(ggF)$	✓	b–t	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	-	-	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim$	κ_W^2
$\sigma(q\bar{q} \to ZH)$	-	-	$\sim$	κ_Z^2
$\sigma(gg \to ZH)$	✓	Z–t	$\kappa_{ggZH}^2 \sim$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	$\sim$	κ_b^2
$\sigma(ttH)$	-	-	$\sim$	κ_t^2

Partial decay width				
$\Gamma_{b\bar{b}}$	-	-	$\sim$	κ_b^2
Γ_{WW}	-	-	$\sim$	κ_W^2
Γ_{ZZ}	-	-	$\sim$	κ_Z^2
$\Gamma_{\tau\tau}$	-	-	$\sim$	κ_τ^2
$\Gamma_{\mu\mu}$	-	-	$\sim$	κ_μ^2
$\Gamma_{\gamma\gamma}$	✓	W–t	$\kappa_\gamma^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma_{Z\gamma}$	✓	W–t	$\kappa_{Z\gamma}^2 \sim$	$1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$
Total decay width				
Γ_H	✓	$W-t$ $b-t$	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 - 0.00022 \cdot \kappa_\mu^2$



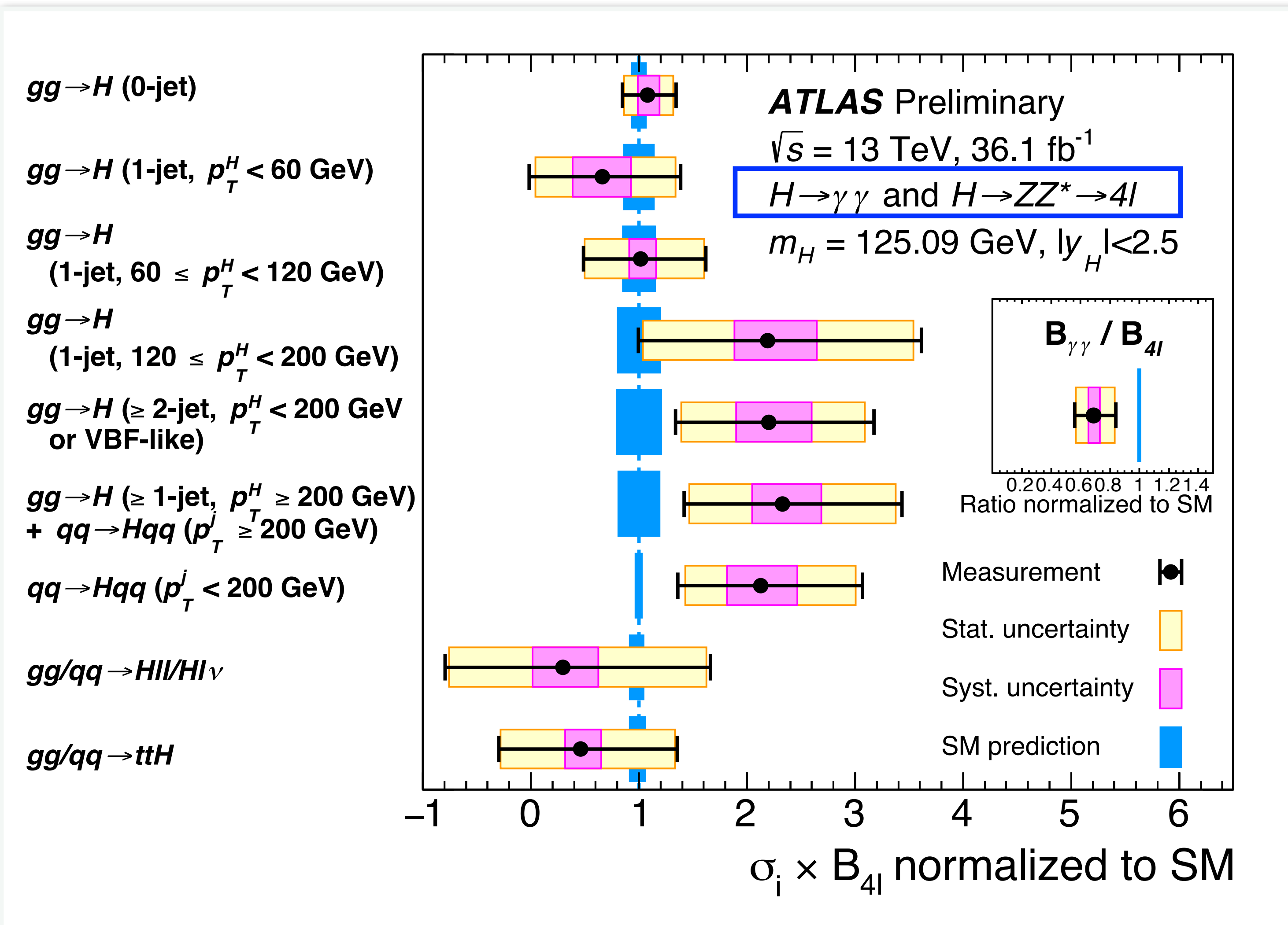
- Introducing new parameter for Higgs-to-invisible branching ratio:

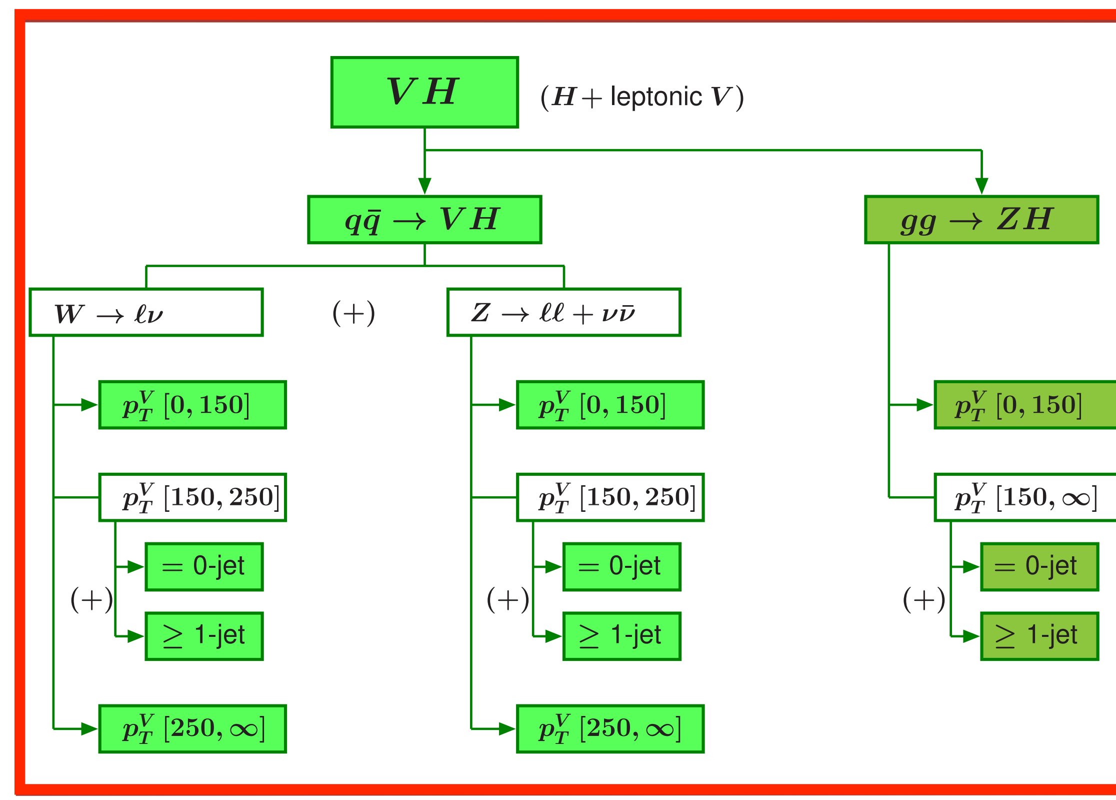
$$Br(H\to xx) = \kappa^2_{xx} / \kappa^2_H * (1-\mathbf{Br_{inv}})$$

- Simultaneous fit to all Higgs boson production and decay measurements can help setting upper limit Br_{inv}:
  - ***Br_{inv}<49% @ 95% CL level***
  - *improving by 10%* the limit from direct H->invisible searches …. and making it less model dependent

Going more differential

- Simplified template cross section: *slice the truth phase space in some bins with physics/ experimentally inspired boundaries*
- Not a proper differential cross section measurement but ***reducing the signal modelling uncertainties in each truth region and providing more inputs for a signal re-interpretation***





- VH leptonic categories are split along the main direction of the VHbb analysis (Vp_T, nJet)

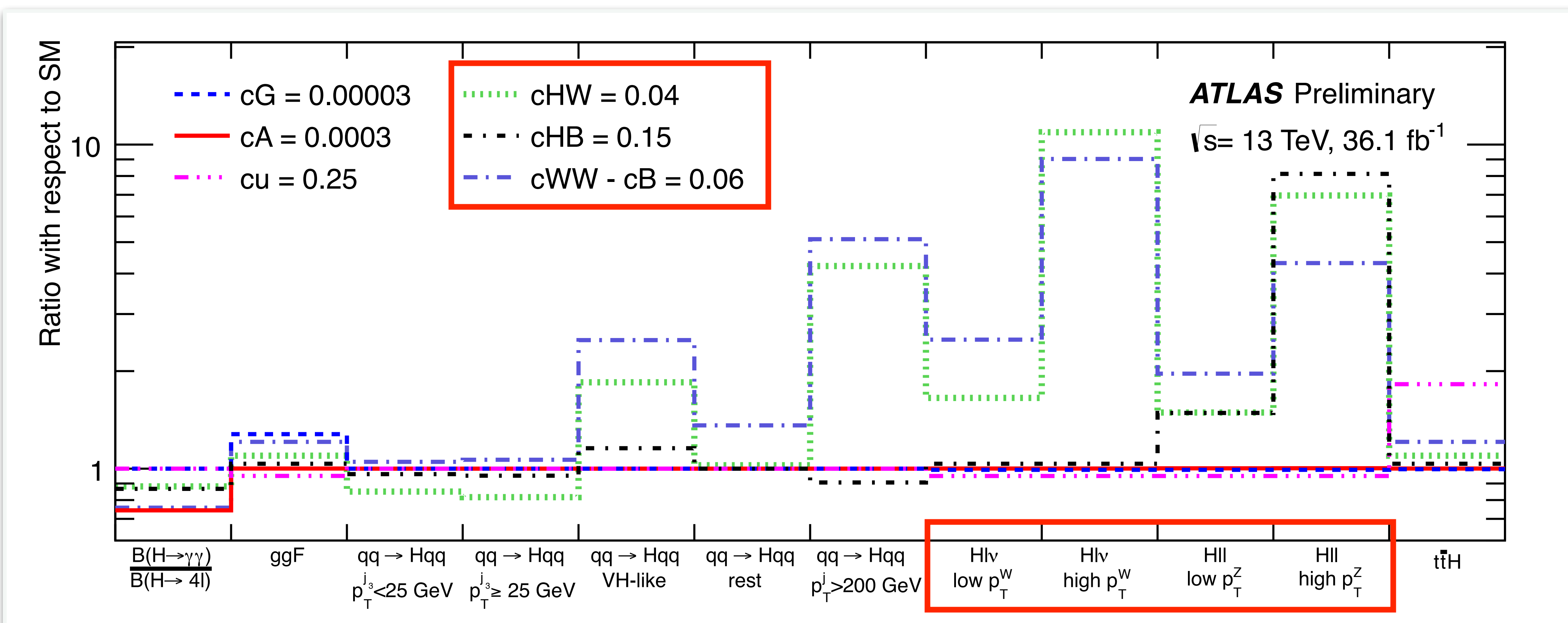
Going more differential: EFT

- VH production very sensitive to anomalous Higgs-Vector boson interactions

- ***"Sensitivity" VS "Precision" balance***:
  - *effects are small on quantities we can measure very precisely*
  - *effects are much larger in tails where the precision of the measurements in less high*

7 / 59 dim 6 operators

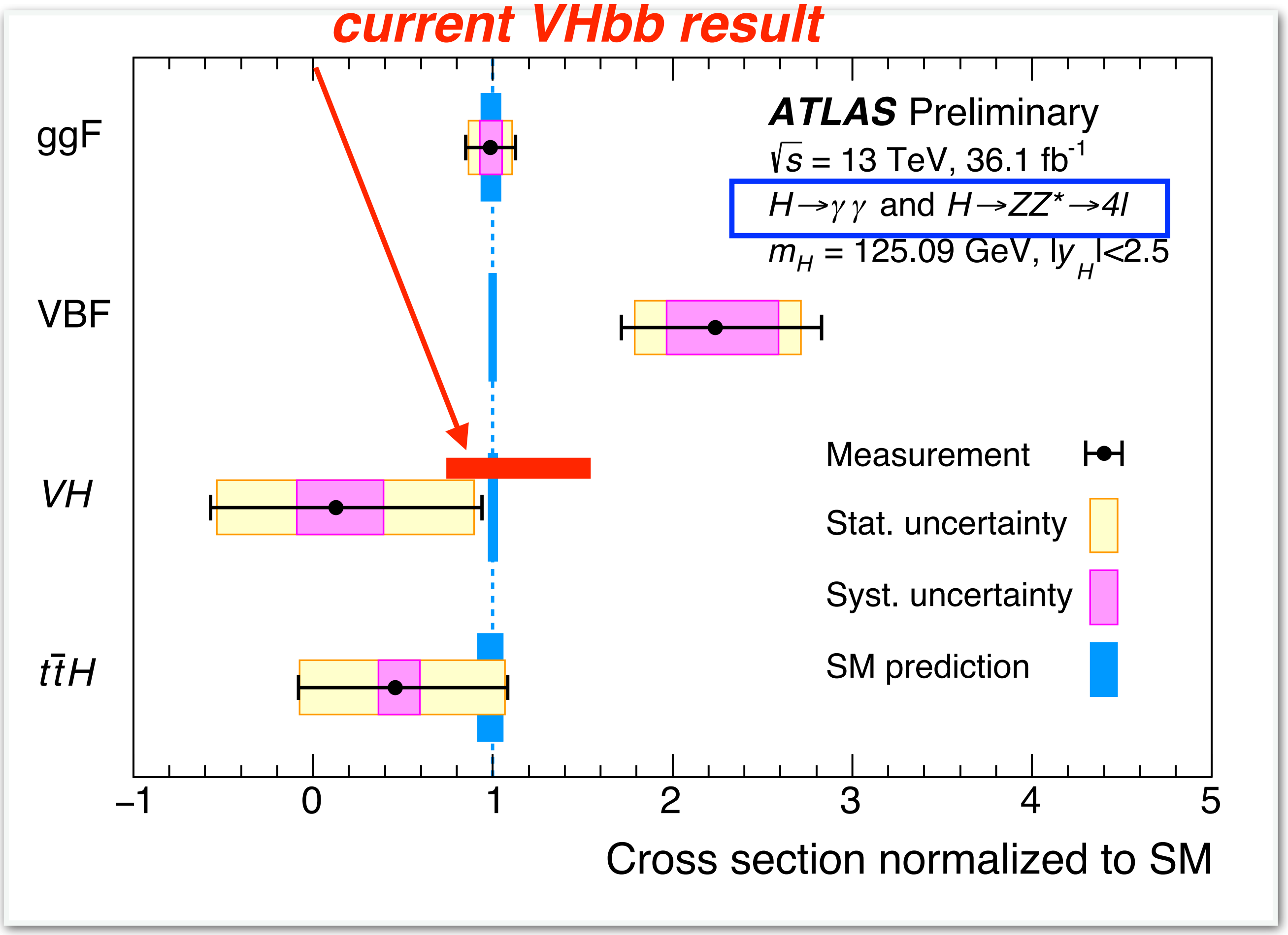
Operator	Expression	HEL coefficient	Vertices
O_g	$\|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	$cG = \frac{m_W^2}{g_s^2}\bar{c}_g$	Hgg
O_γ	$\|H\|^2 B_{\mu\nu} B^{\mu\nu}$	$cA = \frac{m_W^2}{g'^2}\bar{c}_\gamma$	$H\gamma\gamma, HZZ$
O_u	$y_u \|H\|^2 \bar{u}_l H u_R + \text{h.c.}$	$cu = v^2 \bar{c}_u$	$Ht\bar{t}$
O_{HW}	$i\,(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$cHW = \frac{m_W^2}{g}\bar{c}_{HW}$	HWW, HZZ
O_{HB}	$i\,(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$cHB = \frac{m_W^2}{g'}\bar{c}_{HB}$	HZZ
O_W	$i\,(H^\dagger \sigma^a D^\mu H) D^\nu W^a_{\mu\nu}$	$cWW = \frac{m_W^2}{g}\bar{c}_W$	HWW, HZZ
O_B	$i\,(H^\dagger D^\mu H)\,\partial^\nu B_{\mu\nu}$	$cB = \frac{m_W^2}{g'}\bar{c}_B$	HZZ

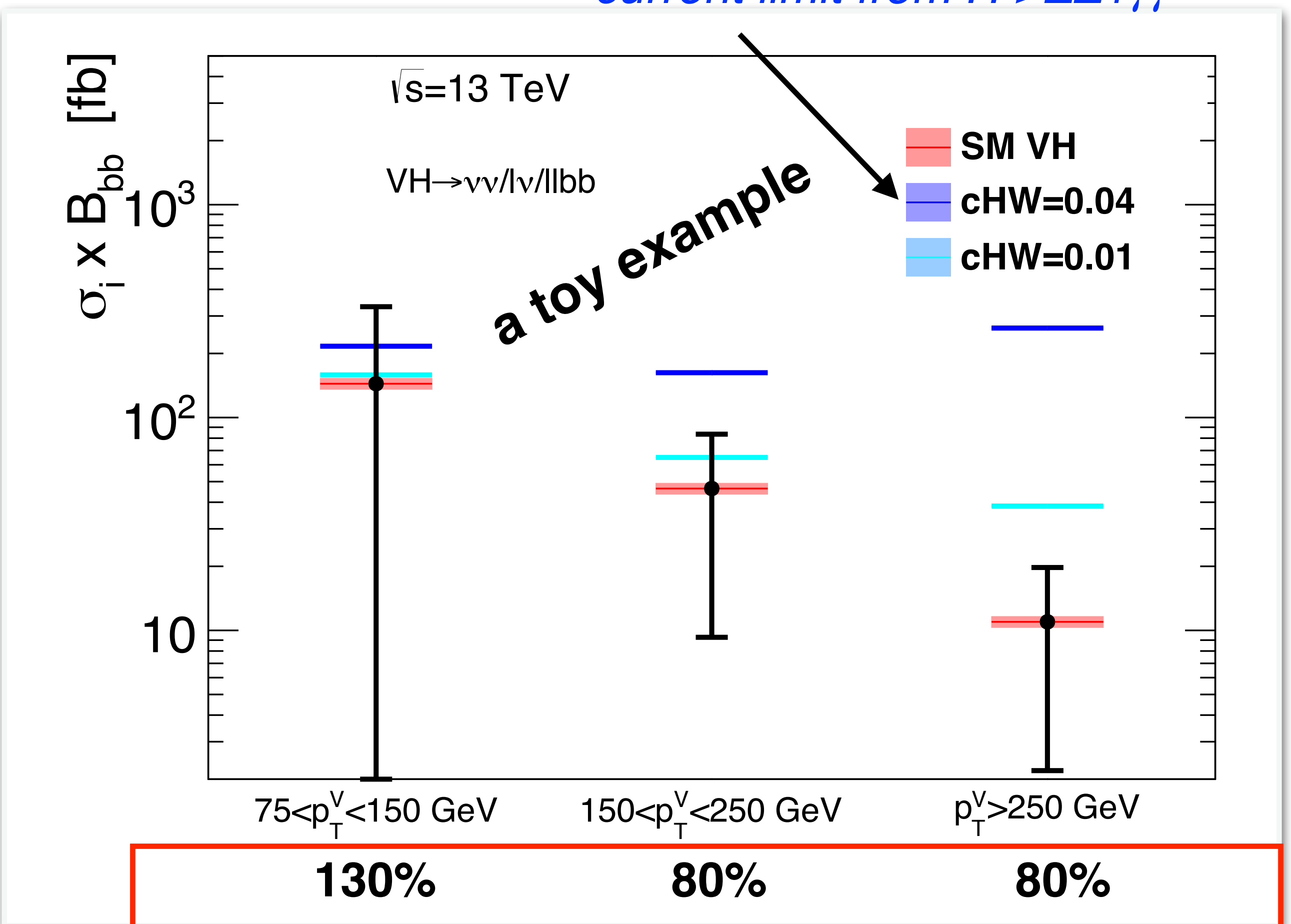


p_T^W>150 p_T^Z>150

Going more differential (3)

- *For VH production Hbb analysis will remain the* ***leading source of information*** *for some time*
- Due to the analysis event selection, ***VHbb analysis is already exploring high p_T regime***





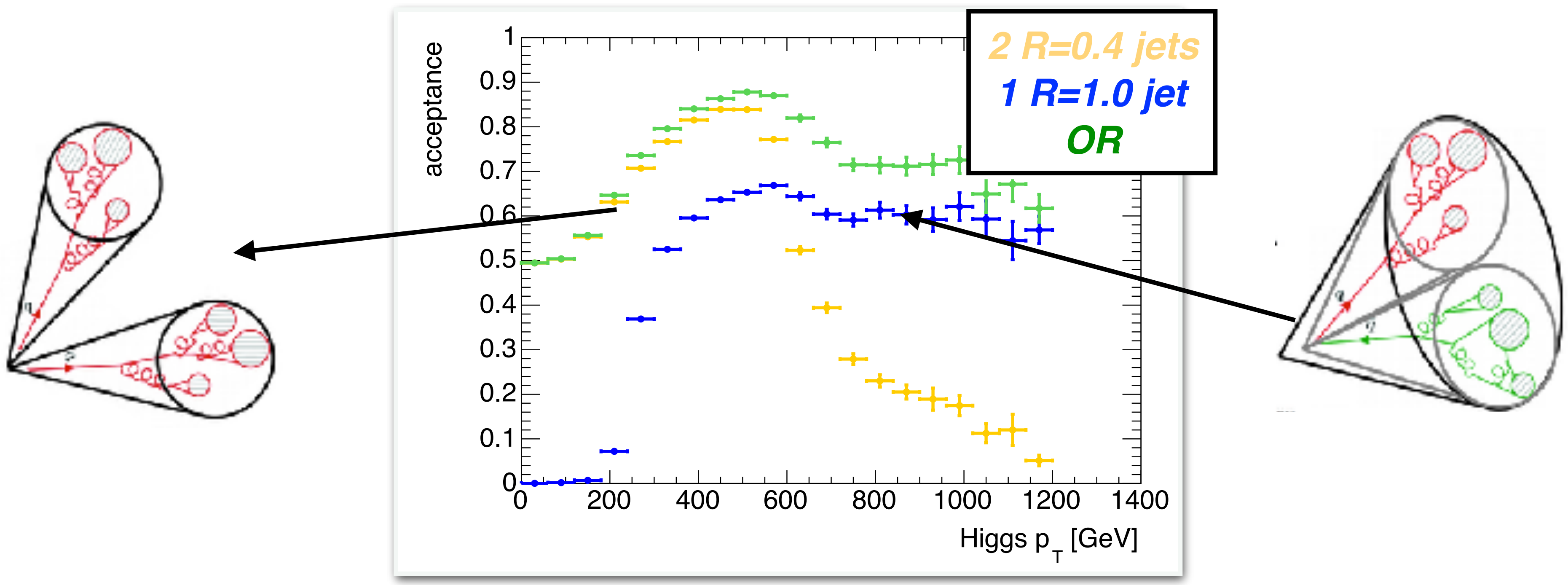
"What if" uncertainties from VHbb analysis in the near future

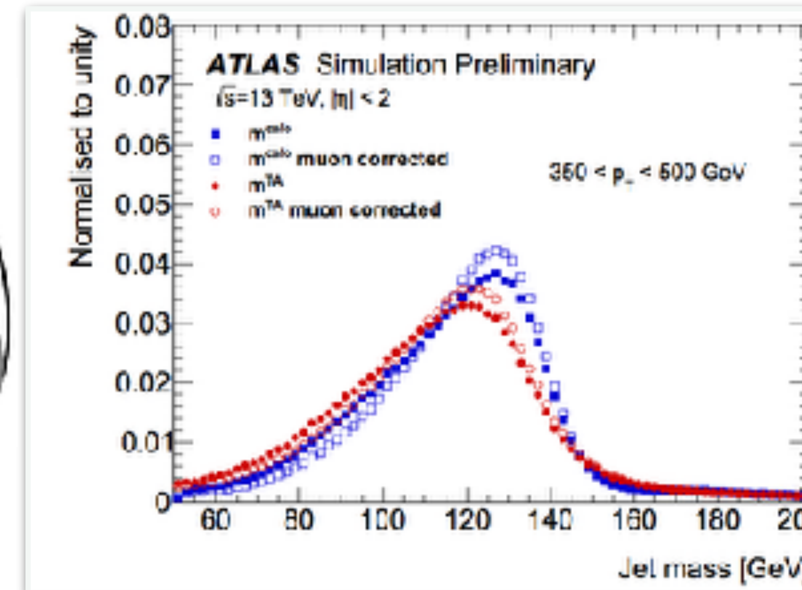
- High pT VH(bb) analysis is competitive with more precise / inclusive measurements from other decay channels since they are exploring higher energy scales …….

can we push it even further?

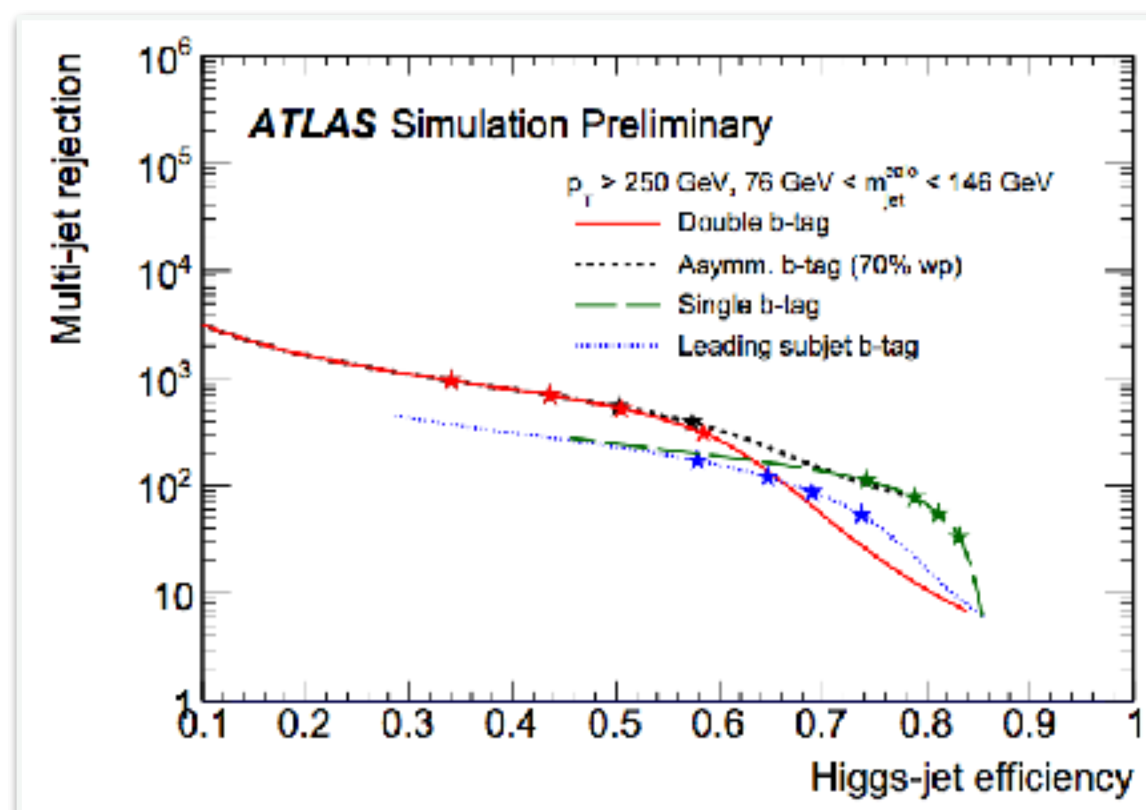
The push for high p_T: experiment

- As Higgs boson p_T increases:
  - failing to resolve b-jet with R=0.4 jets —> **capture the entire decay with larger R=1.0 jet**





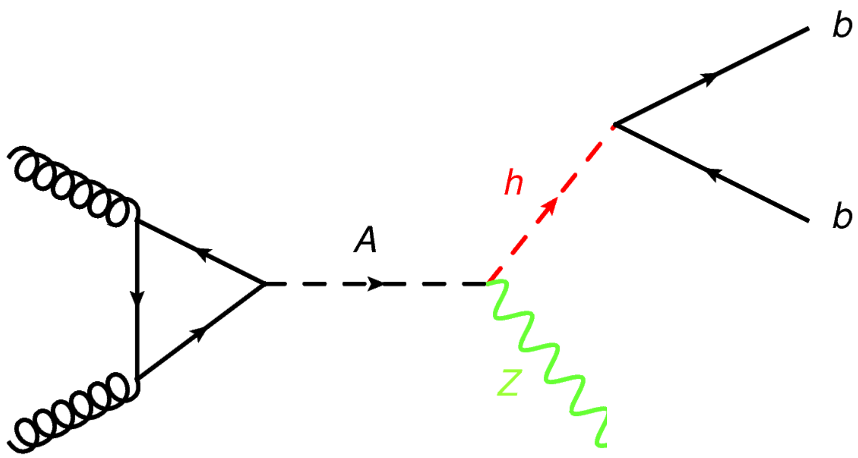
- **Sub structure b-tagging**:
  - *identify 2 R=0.2 track jets (PU resistant) inside largeR jets and apply b-tagging selection*
  - *once 2 sub-jets have been identified, more standard jet substructure techniques (τ_{12}) lose most of their discriminating power*



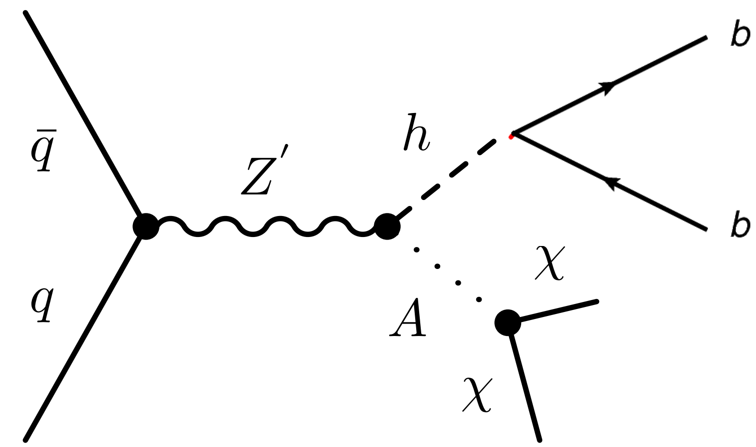
Direct searches example

- ***VH resonance***

A: pseudo scalar Higgs in 2HDM



- ***Higgs+MET analysis***



Z':new interaction mediator

A: dark matter candidate

- Identical final state of SM VH analysis: VH resonance (0L,2L SR), Higgs+MET (0L SR)

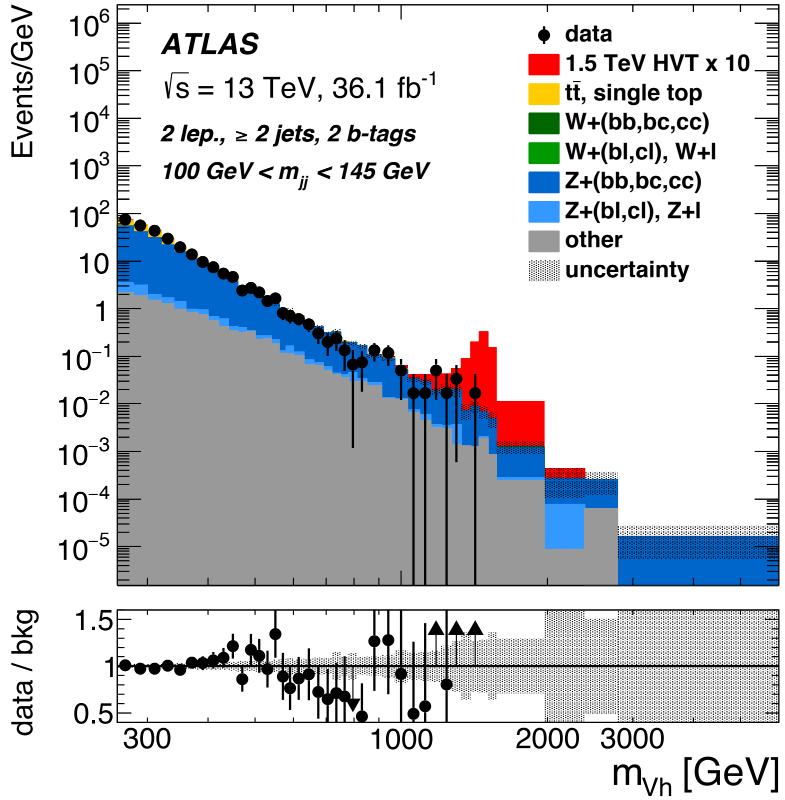
- Both analyses are considering two regimes
  - ***'Resolved' regime****: Higgs boson identified as two separate b-tagged jets*
  - ***'Boosted' regime****: Higgs boson identified as a R=1.0 jets (p_T>200GeV) with b-tagged track jets*

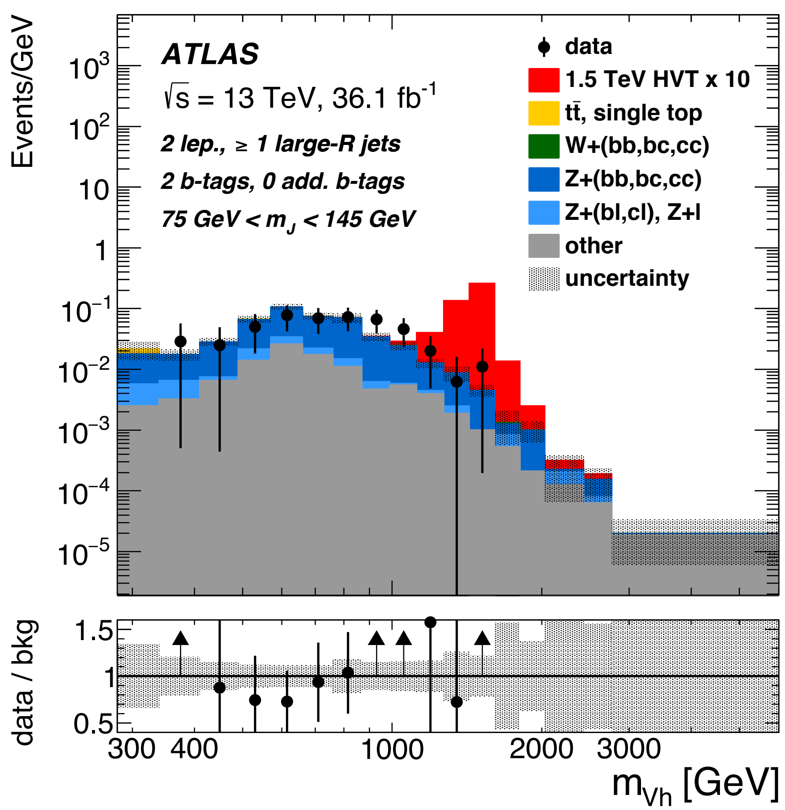
Resolved-Boosted separation**:**

"priority resolved"	E_T^{miss}>500 GeV

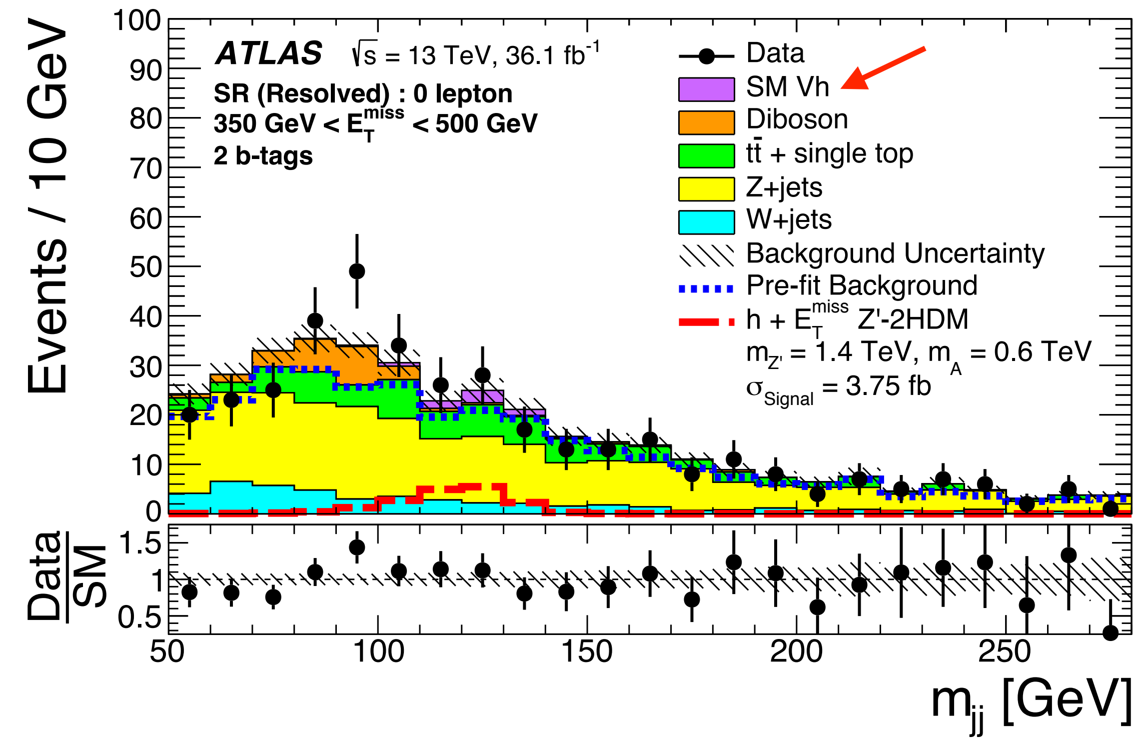
- In the 'boosted' regime considering large radius just with one or two b-tagged sub-jets:
  - *recovering acceptance at high p_T but clearly losing in rejection*

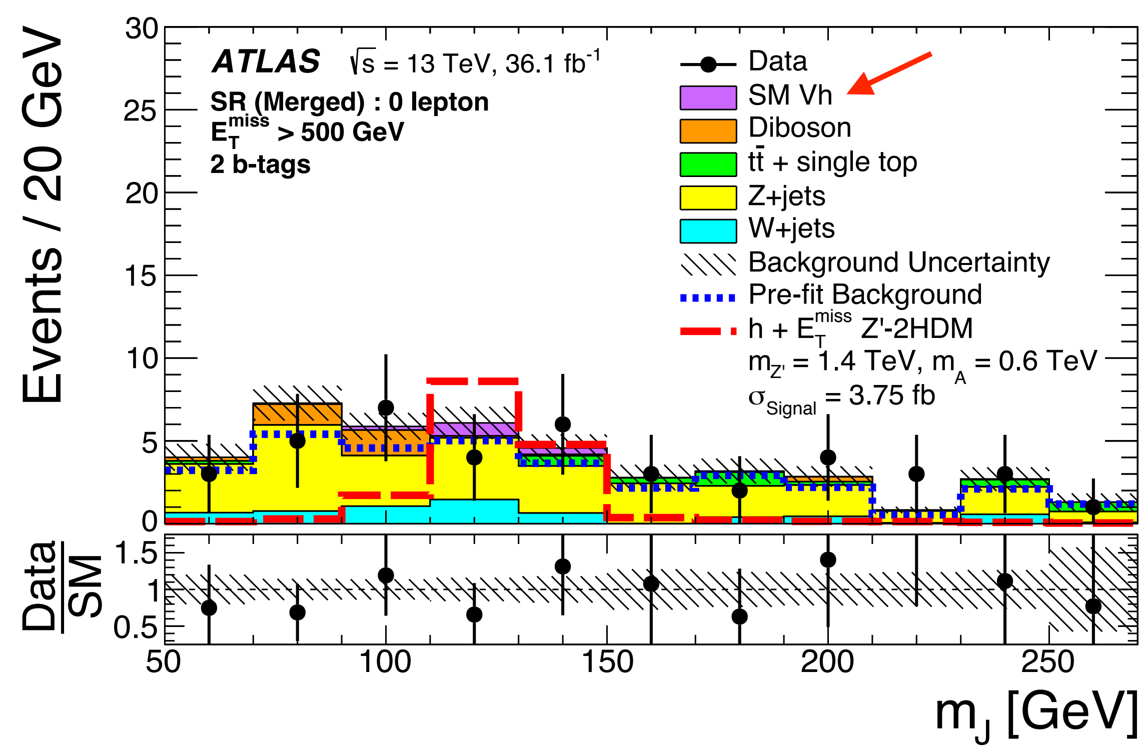
- Selecting an m_{jj}/m_J window and looking for a peak in m_{VH}



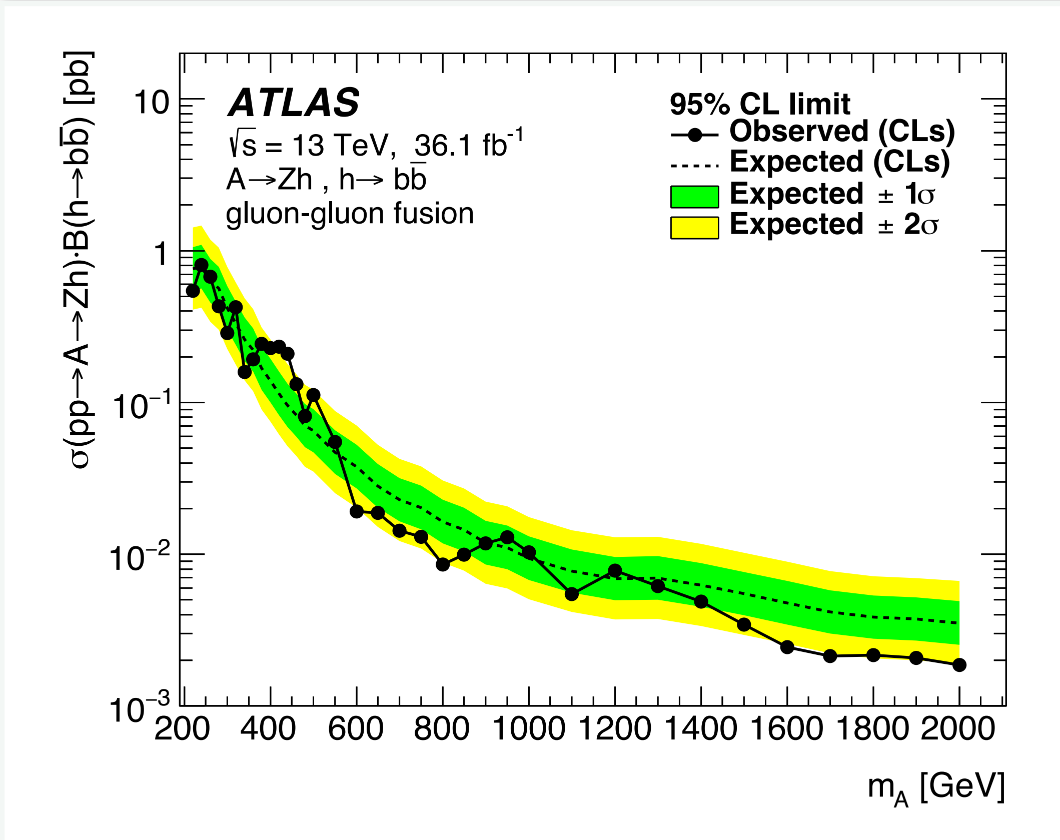


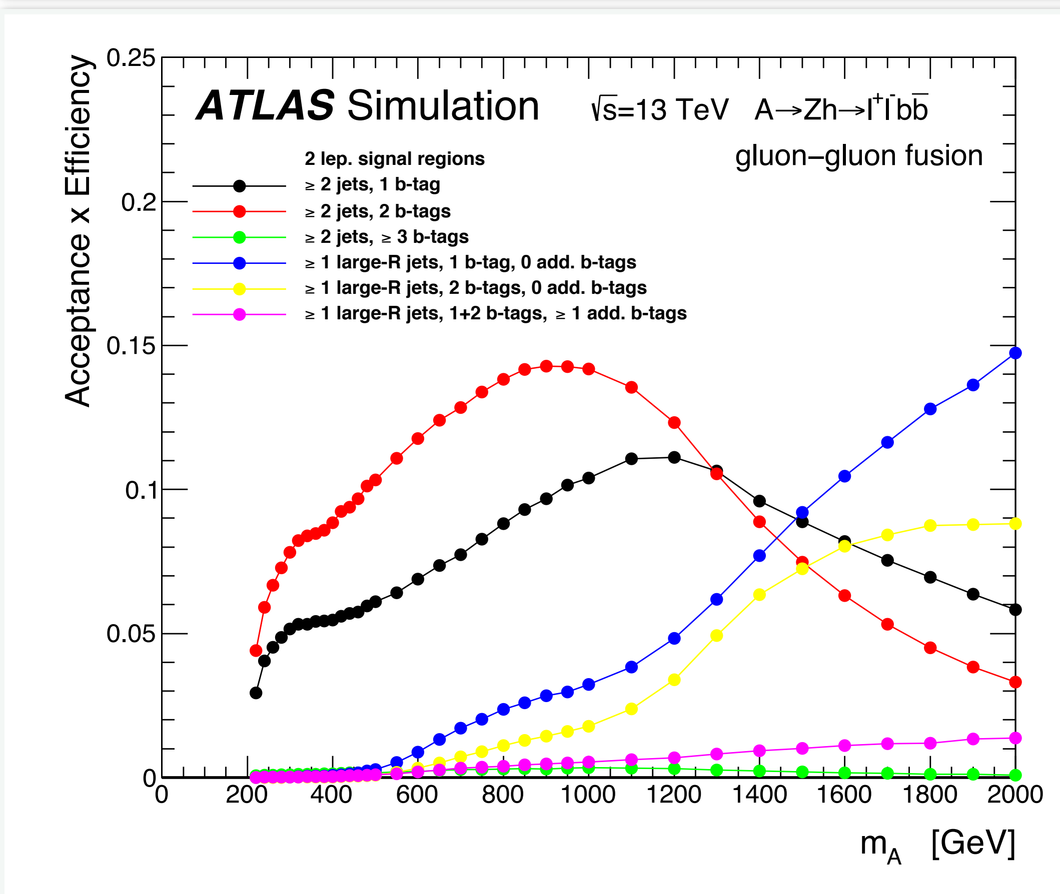
- Fitting m_{jj}/m_J in multiple E_T^{miss} bins



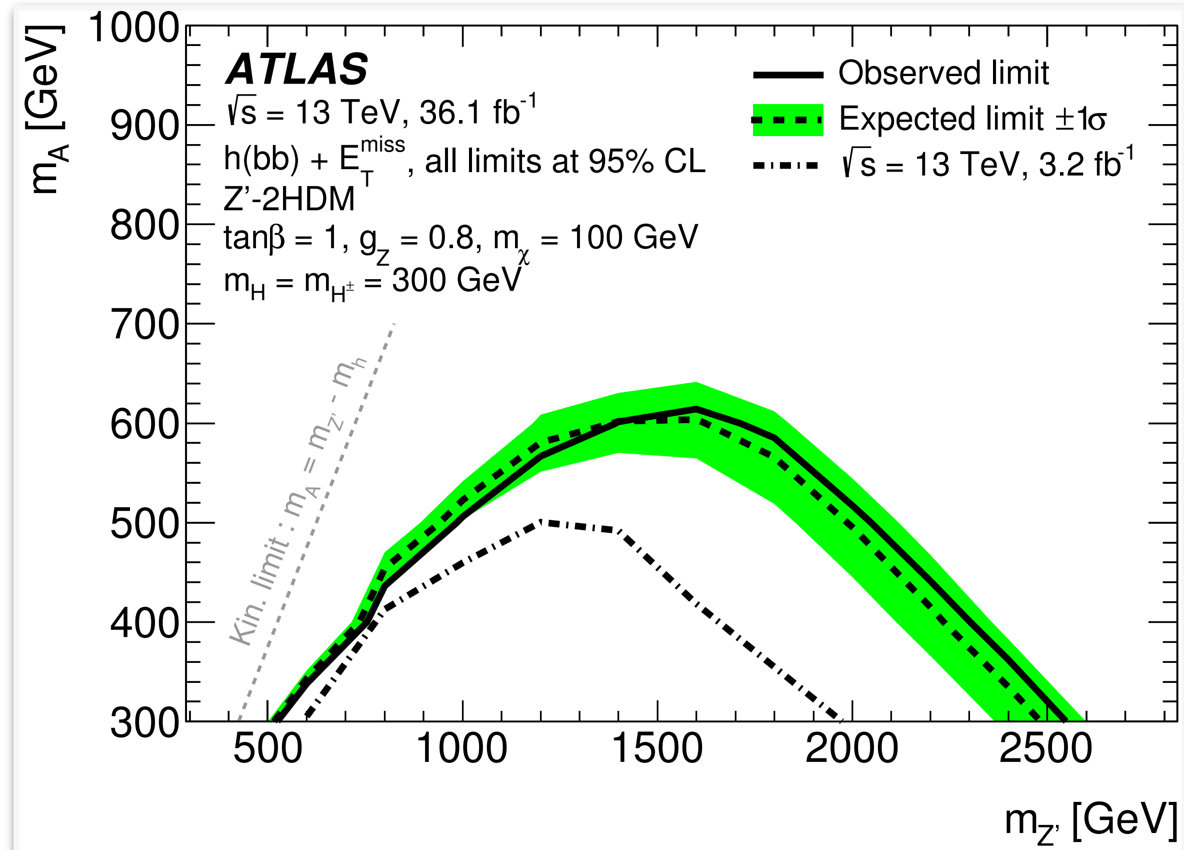


Direct searches example (2)

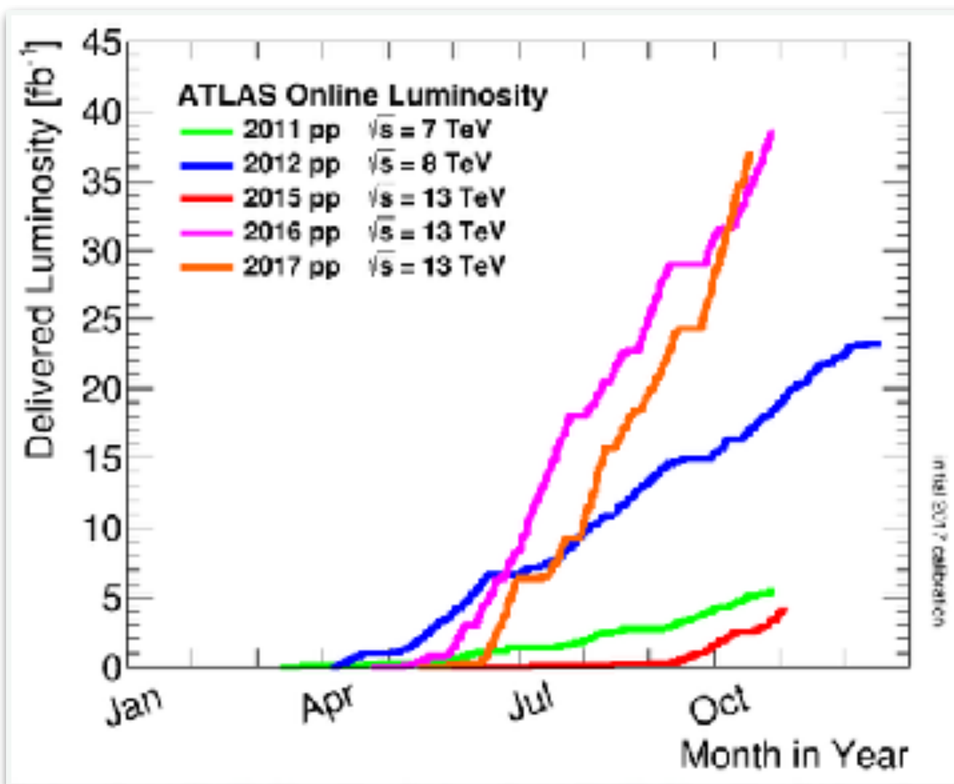




- ✦ Push sensitivity into multi TeV regime



- ***ATLAS is closing in on the investigation of the most 'popular' Higgs boson decay mode:***
  - ***3-sigma evidence*** of H->bb in VH production mode
  - steady progress of H->bb analyses in VBF and ttH production
  - within the uncertainty of the measurement (~30%) the Standard Model still stands
  - working hard to obtain ***observation of H->bb before the end of Run2***



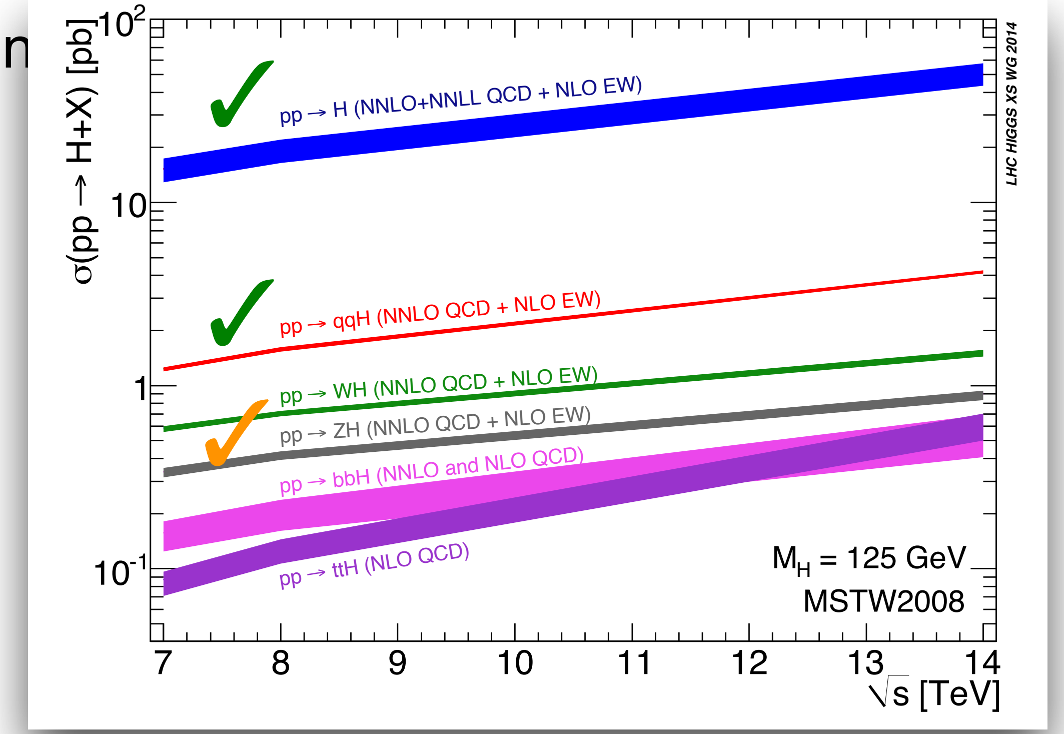
- **H->bb is turning in a mature tool to explore for the presence of new physics:**
  - more sophisticated techniques to identify the presence of a H->bb final state over a large p_T spectrum
  - pursuing both direct searches and more model-independent approaches (differential cross section, simplified template cross section, EFT interpretation)
  - more data is already there for statistics-limited analyses

!!!! Stay tuned for upcoming results !!!!

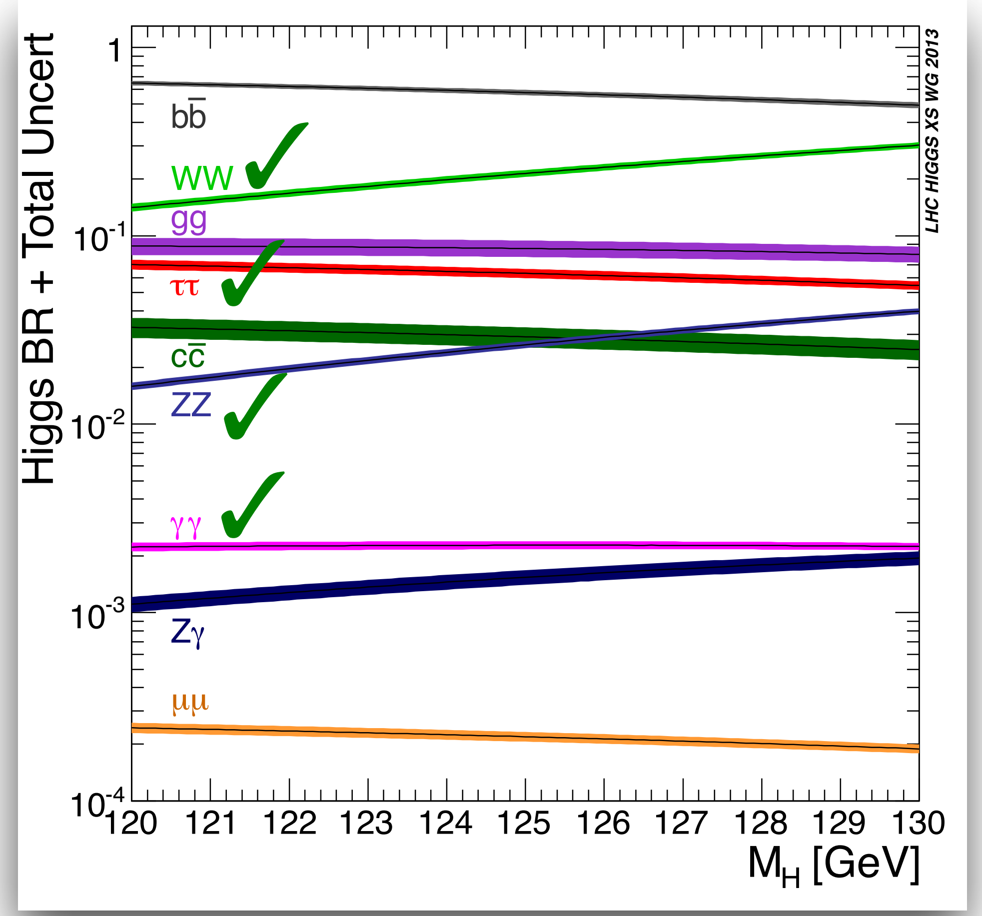
BackUp

Current experimental status

✦ ***Run1 legacy results:*** being confirmed by Run2 measuremen



- 2012 discovery and precise measurement driven by *gluon fusion* production mode [indirect probe of coupling to quarks]
- 5.4 s.d. observation of *vector boson fusion production*
- 3.5 s.d. evidence for *VH production*
- observation of *direct decay into bosonic final states* (WW,ZZ,γγ) well established
- observation of *decay into tau pair* confirmed coupling to fermions (leptons)
- mass measurement now at <3% uncertainty
- spin / parity
- “re-discovery” of Higgs boson signal at 13TeV started with bosonic channels (ZZ and γγ)



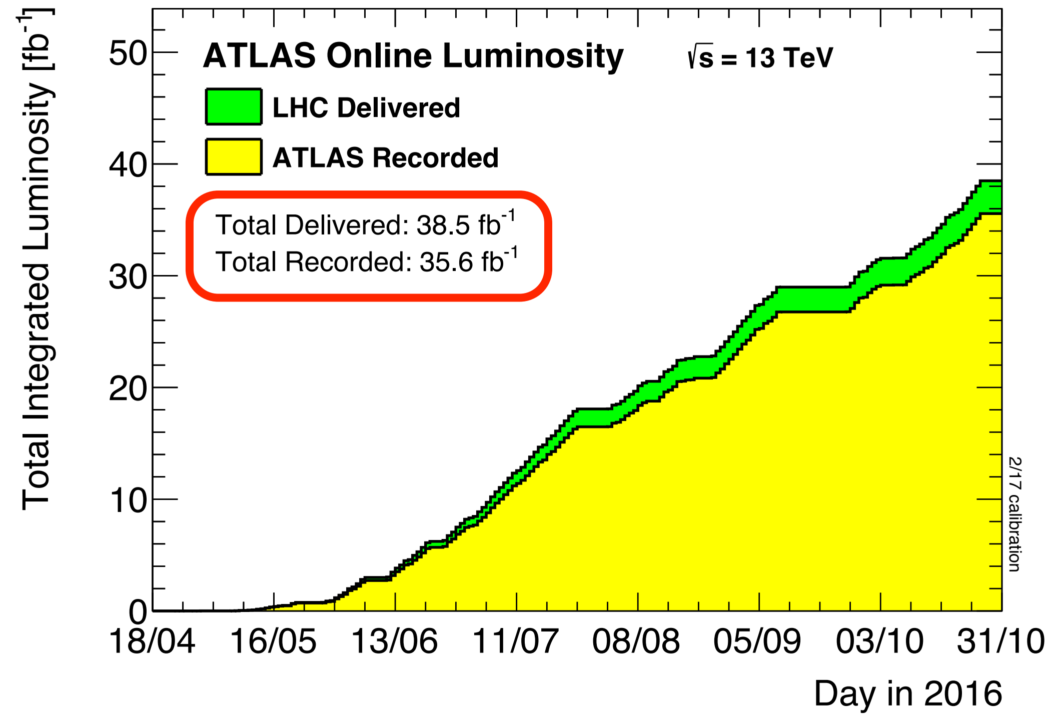
$H \to bb$ status before LHC Run2

(*) 3.1 s.d. global

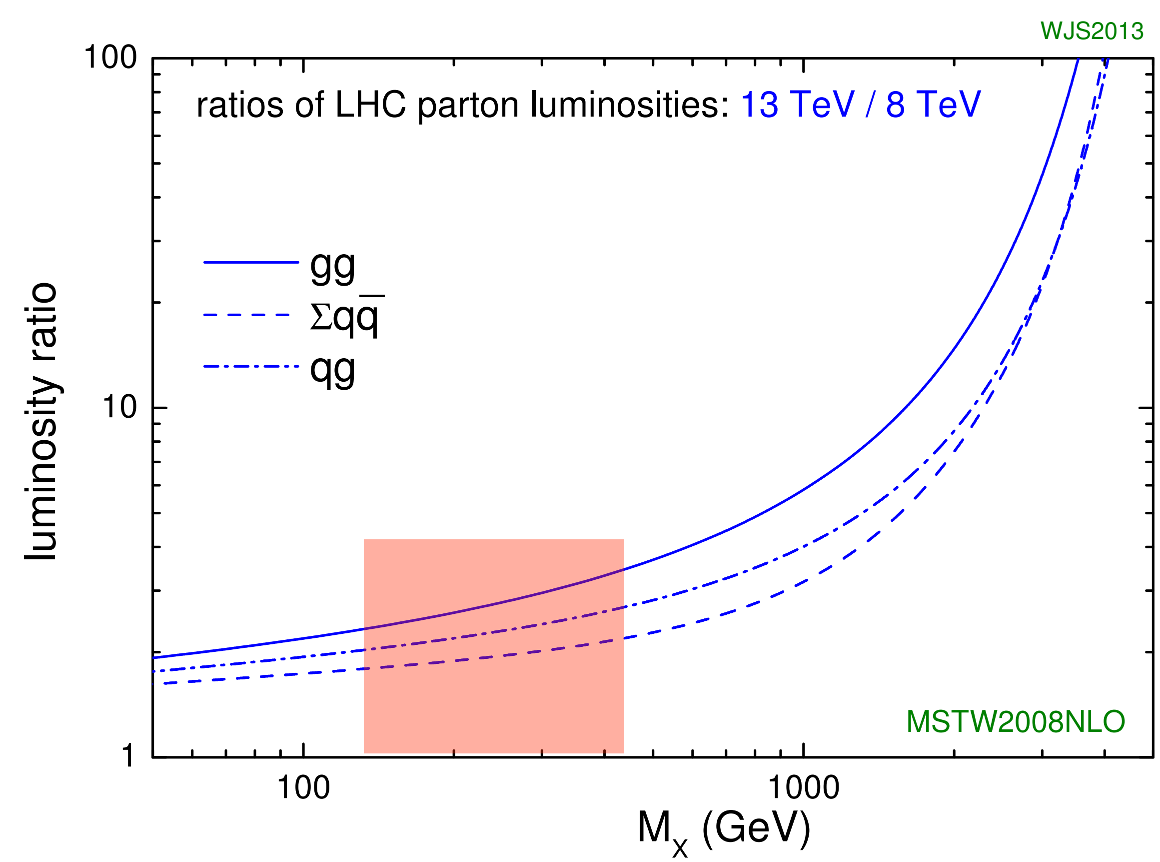
process	experiment	exp. sig.	obs. sig.	signal strength
VH	ATLAS	2.6 s.d.	1.4 s.d.	0.5 ± 0.4
	CMS	2.5 s.d.	2.1 s.d.	0.9 ± 0.4
	TEVATRON	1.5 s.d.	2.8 s.d. (*)	1.9 ± 0.8
VBF	ATLAS			-0.8 ± 2.3
	CMS	0.8 s.d.	2.0 s.d.	2.8 ± 1.5
ttH	ATLAS	1.1 s.d.	1.35 s.d.	1.5 ± 1.1
	CMS			1.2 ± 1.6
VH+ttH	ATLAS+CMS	3.7 s.d.	2.6 s.d.	0.70 ± 0.28

- VH is clearly the most sensitive channel
- Small deficit w.r.t. SM predictions prevent to reach evidence

- Very successful LHC Run in 2015+2016



- Increase in centre-of-mass energy (8TeV ->13 TeV) does not always help:
  - VH/VBF : x2
  - ttH : x4
  - ttbar : x3.2

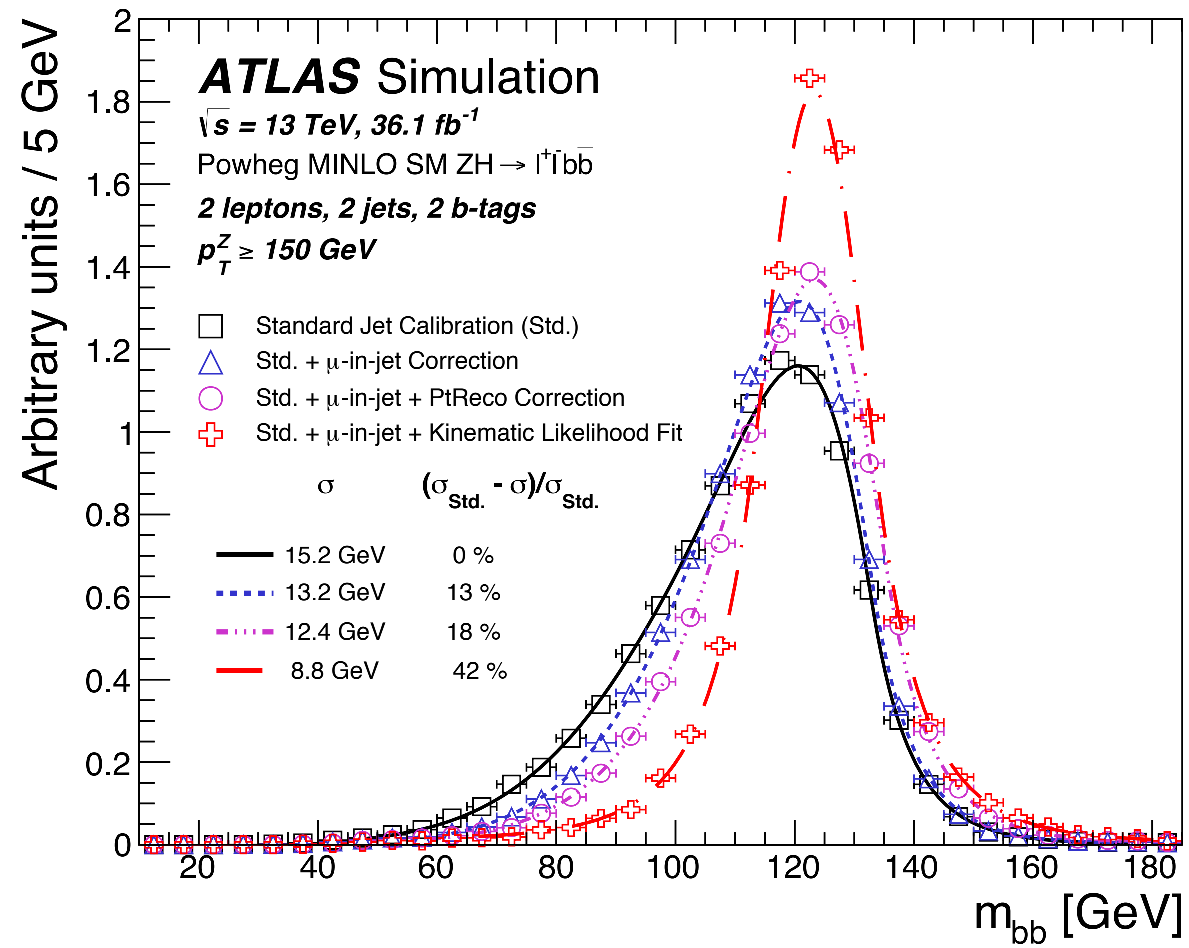


m_{bb} calibration

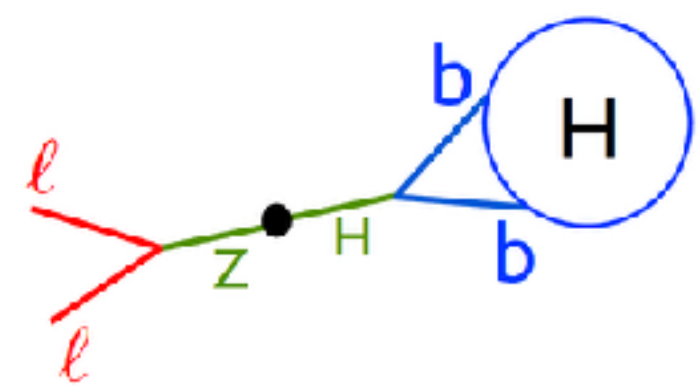
- Standard jet calibration corrects energy deposits in the calorimeter to the scale truth particle jets built from stable and interacting particles (R=0.4)

- In b-jets, semileptonic b-hadron decays (20% of total) produce **muons and neutrinos not considered in the jet calibration**

- Improving m_{bb} resolution by:
  - **adding soft muon** (when found inside the jet cone) to jet 4-momentum: **+13%**
  - additional scaling of jet momentum (**p_T correction**) to compensate from missing neutrino: **+5%**
  - ***kinematic likelihood fit*** to constrain jet response: only if topology allows

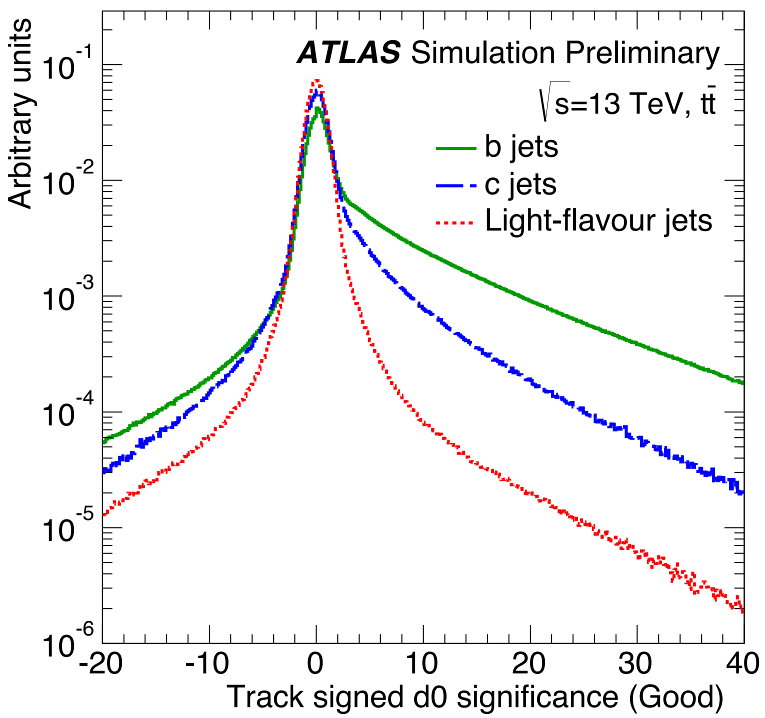


- Kinematic likelihood fit:
  - balancing di-b-jet momentum against Z->ll pT
  - additional 20% better resolution in 2 jets event

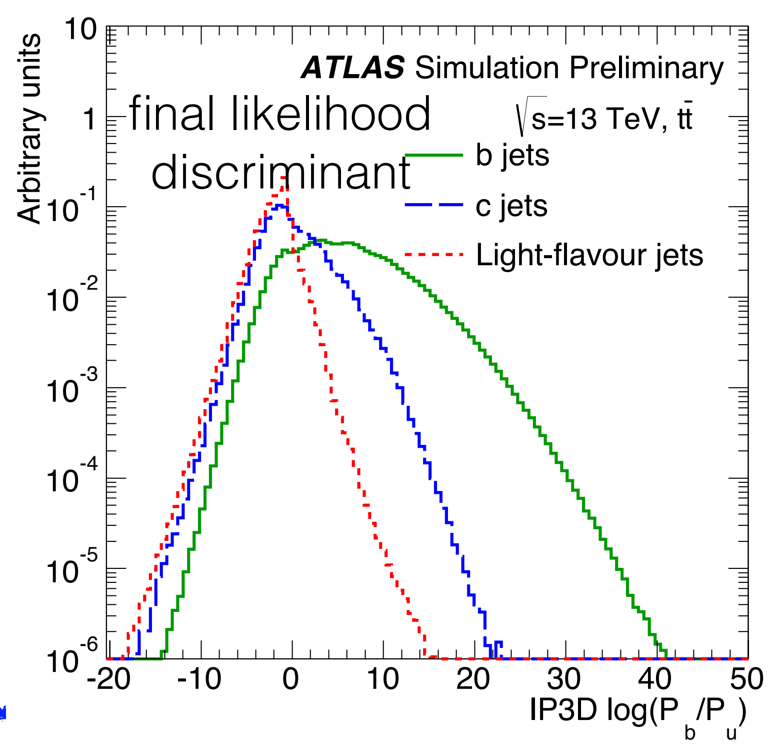


Algorithms highlights

IPTagger

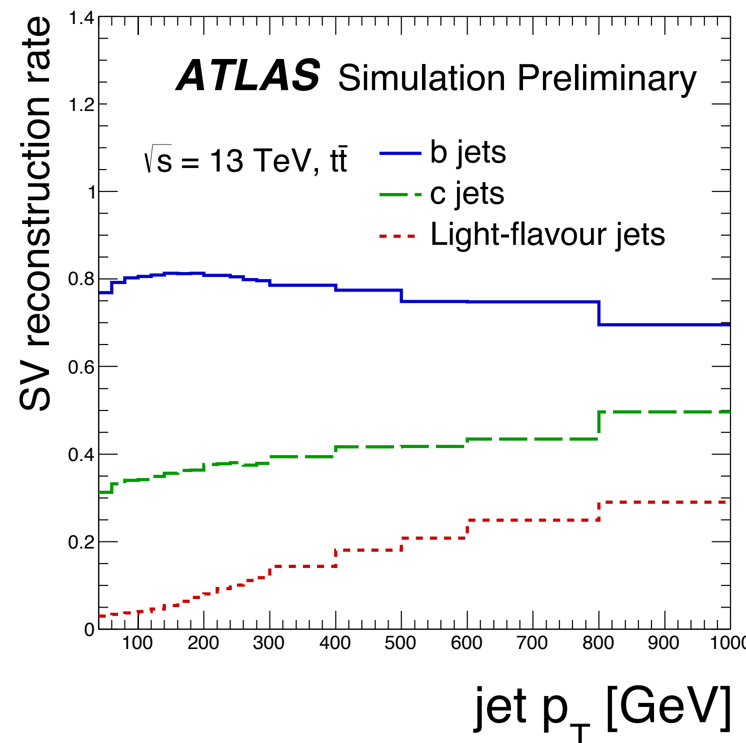


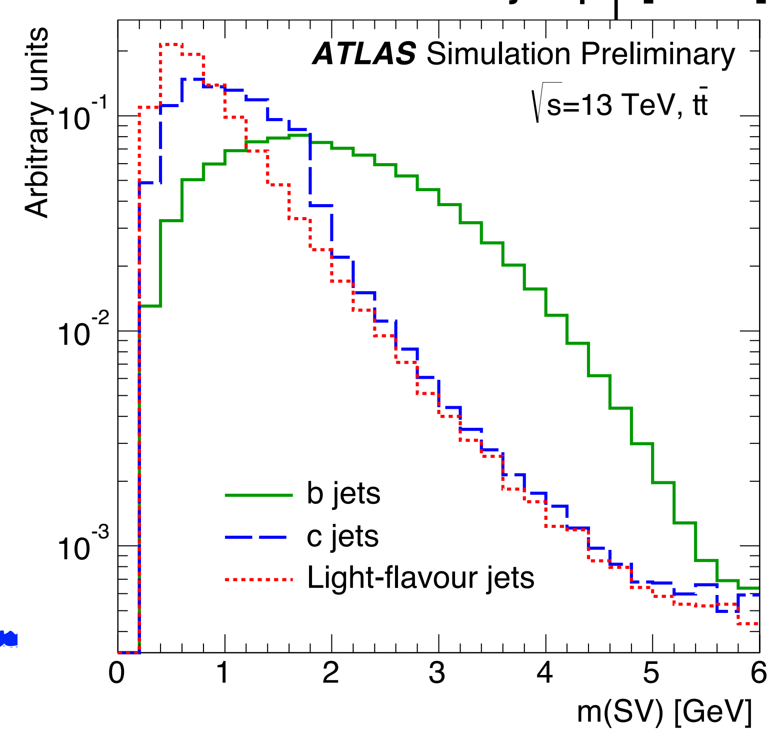
From single track PDF …. to combined likelihood discriminant



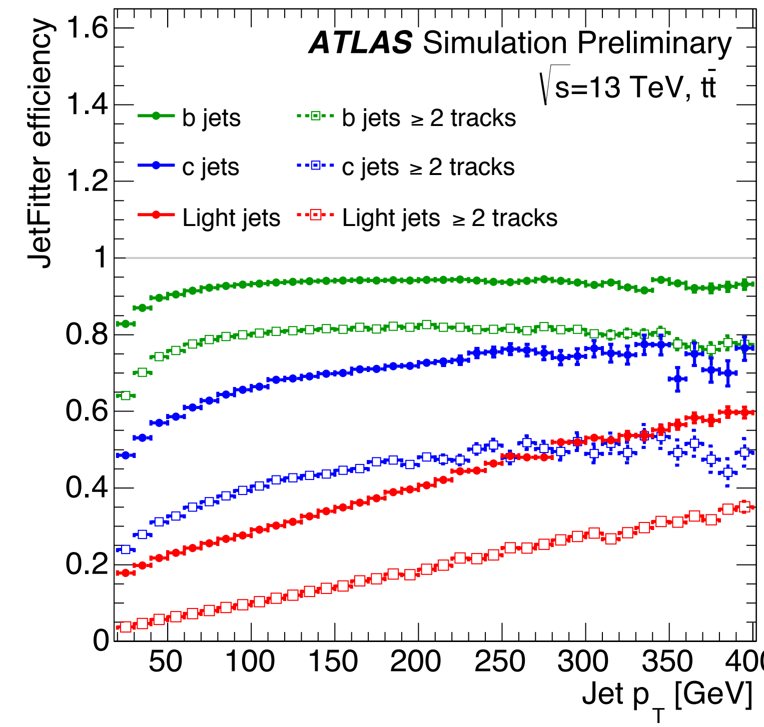
SV *and* ***JetFitter*** *can be considered as 'two complementary approaches" for secondary vertices reconstruction*

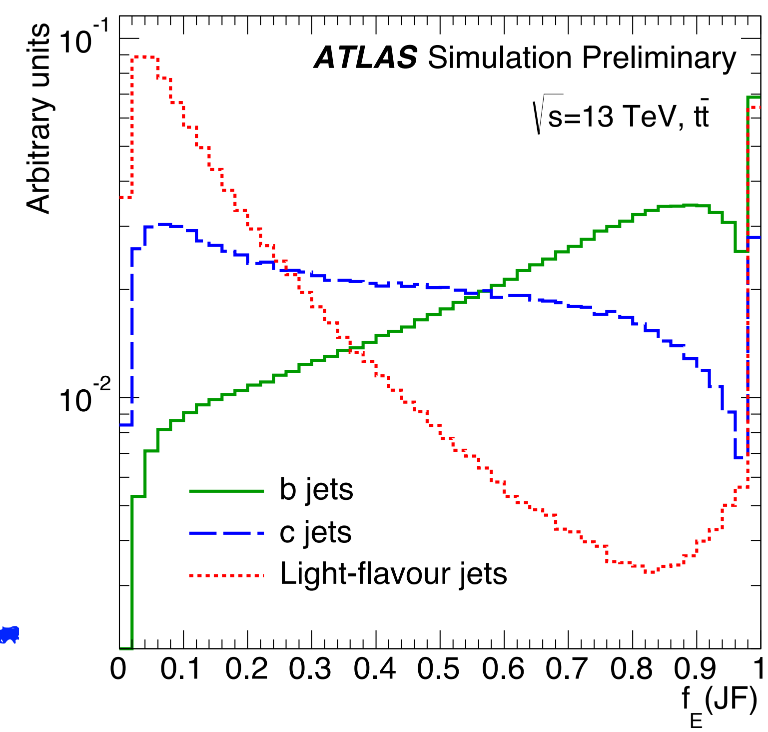
high purity, low efficiency





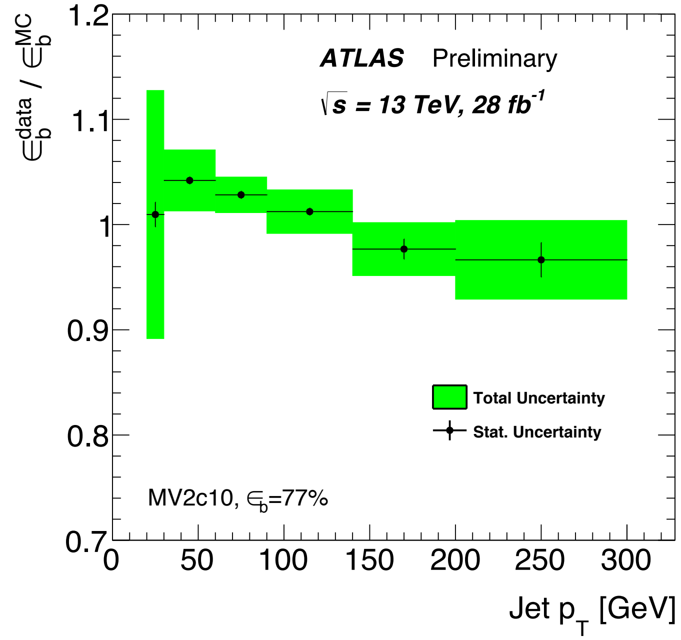
low purity, high efficiency



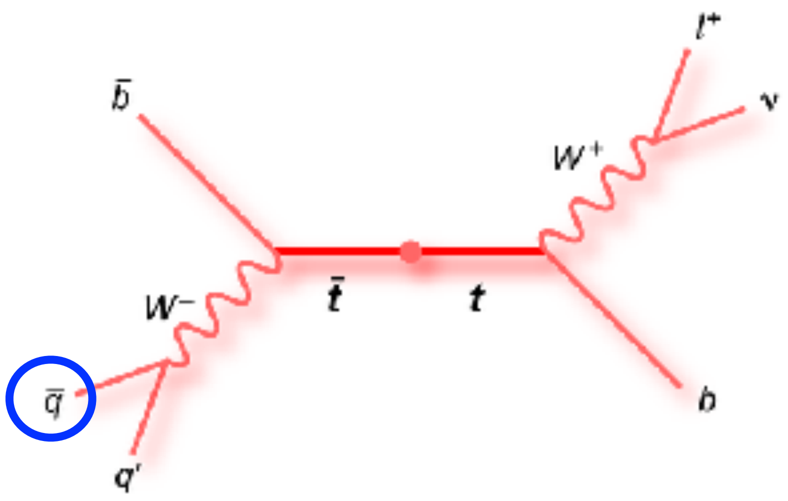


Dao Valerio

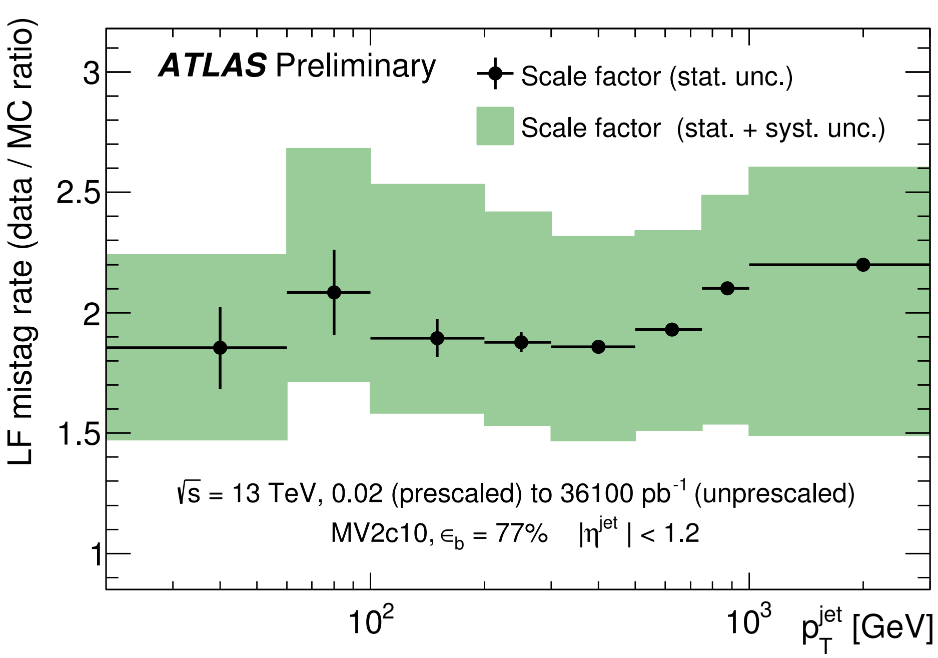
flavour tagging calibration



- **b-jet calibration**: di-leptonic ttbar events are a pure source of b-jets
  - 2 complementary methods (tag & probe, PDF) yield compatible results
  - <2% uncertainty in the central p_T region thanks to additional MVA selection which increases the purity

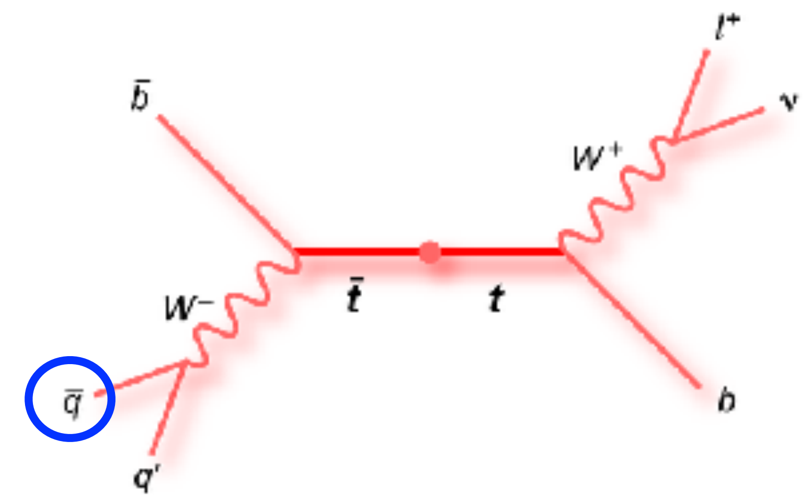


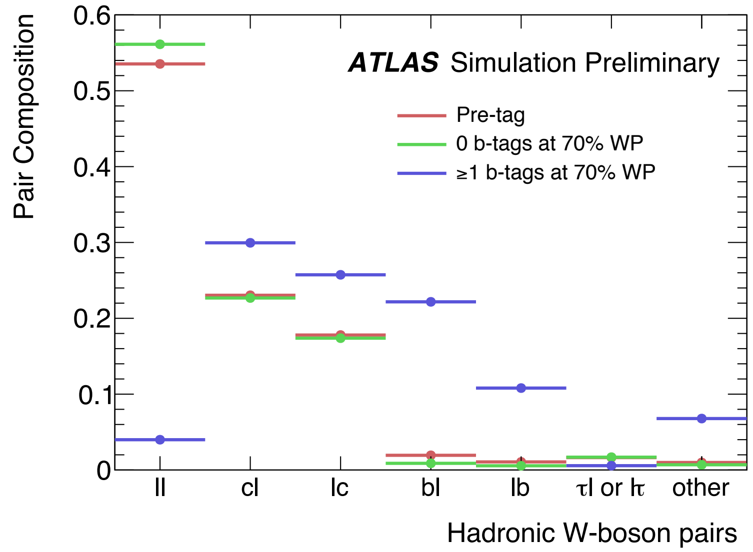
- **c-jet calibration**: relying on a c-jet sample from W->cs in ttbar l+jets events
  - completely inclusive in D-hadron decay —> no need for complicated extrapolation on decay multiplicity
  - W-jets identified through a kinematic reconstruction of the event

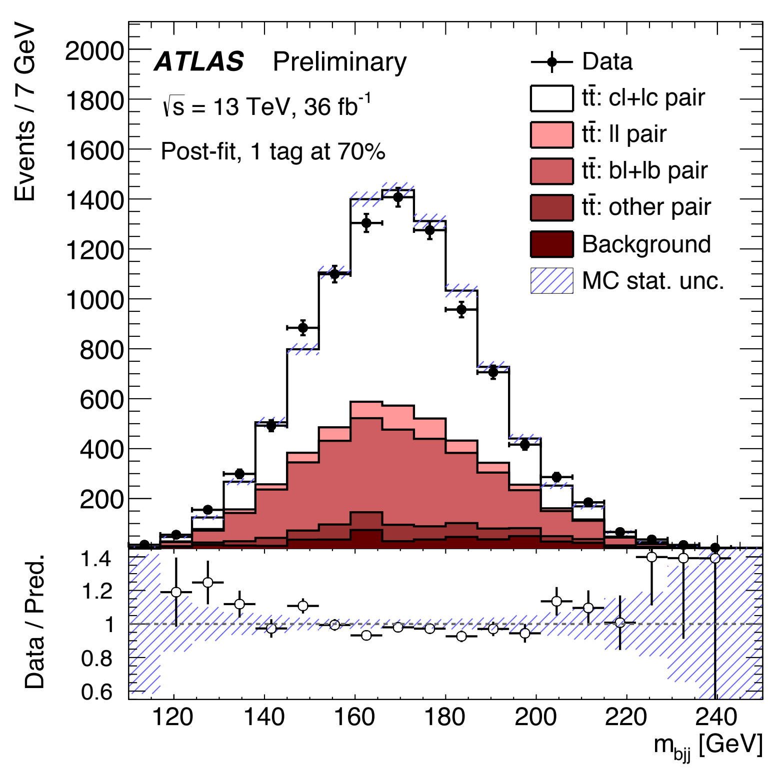


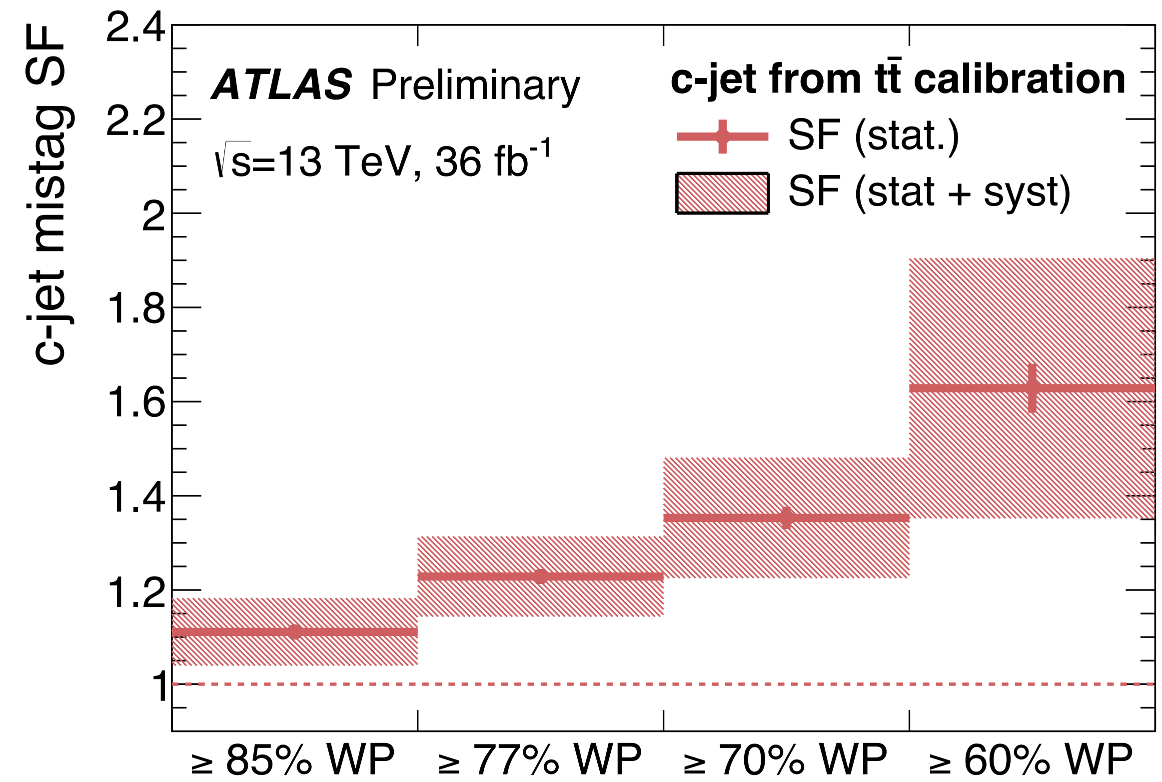
- **light-jet calibration**: di-jet sample has very high statistics
  - negative tag method (like CMS): flip the sign of impact parameter when building the tagger to suppress b-jet contamination (light-jet is symmetric in first approximation)
  - main problem: very good tagger performance for tight WP produce a significant b-jet contamination

- ***c-jet calibration:*** relying on a c-jet sample from W->cs in ttbar l+jets events
  - completely inclusive in D-hadron decay —> no need for complicated extrapolation on decay multiplicity
  - W-jets identified through a kinematic reconstruction of the event





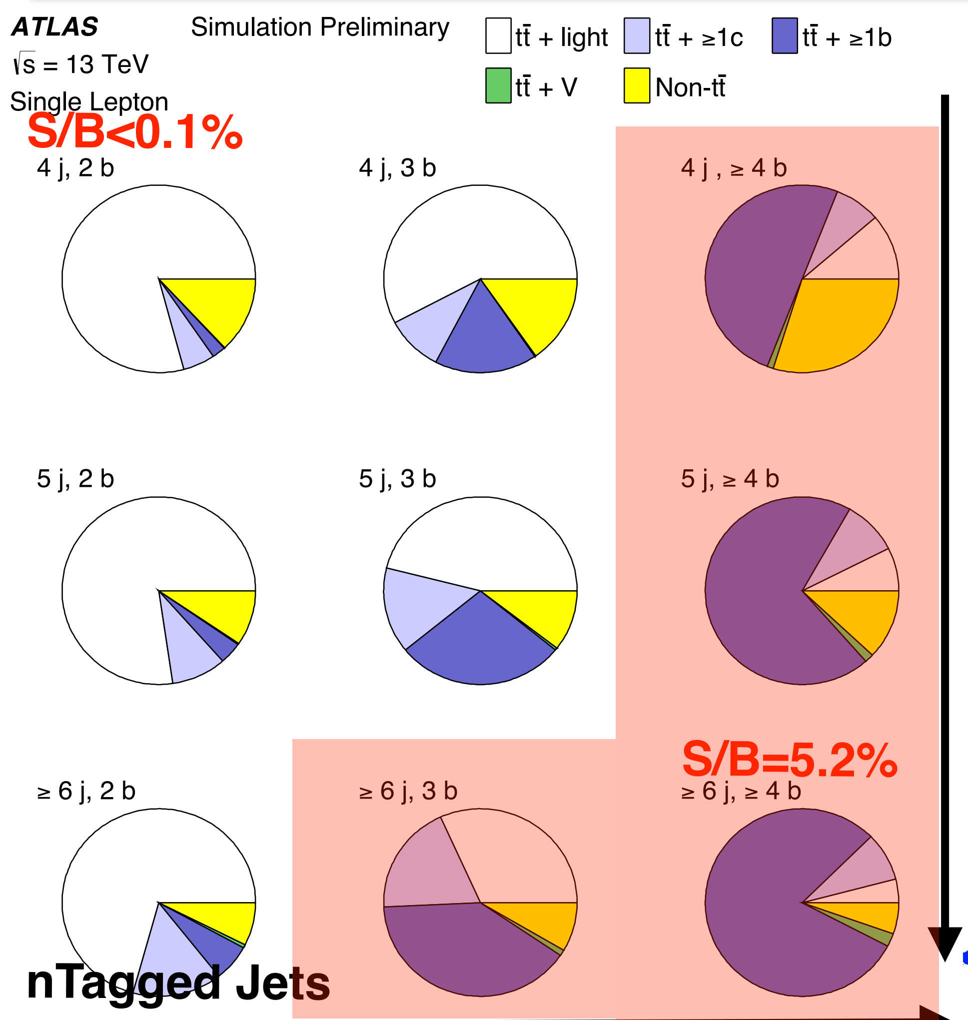




$t\bar{t}H$ (H->$b\bar{b}$): strategy

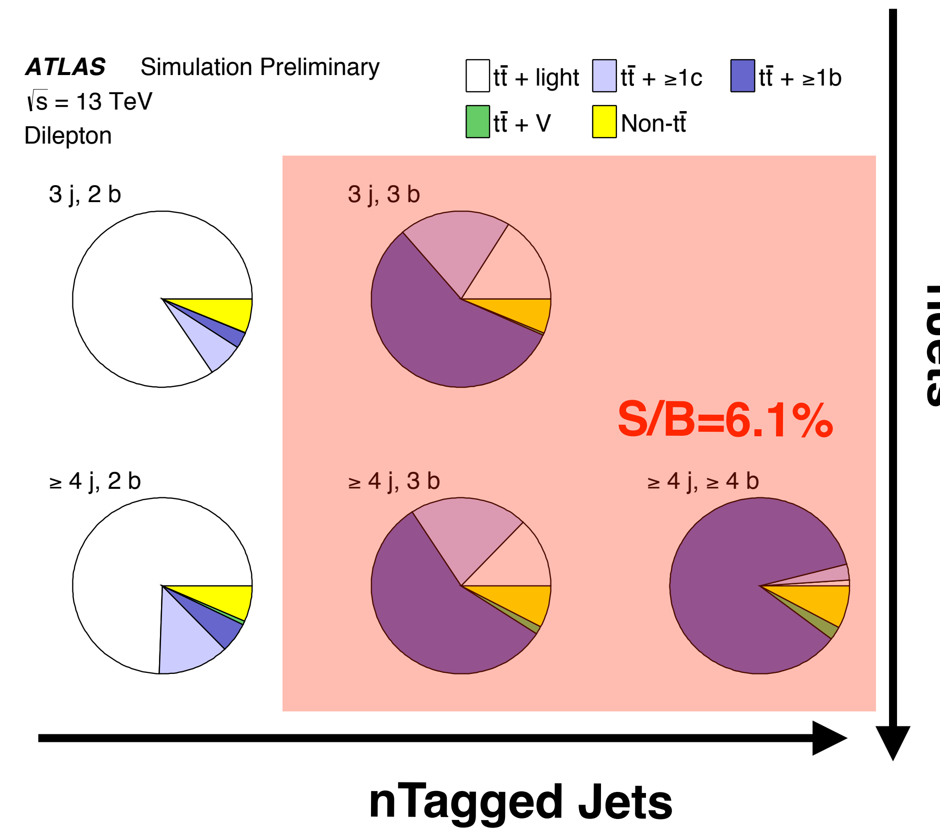
- Both ATLAS and CMS classify events ***according to jet and b-tagged jets multiplicity(*) …..***:
  - *also consider signal events with missing jets / b-tagged jets (efficiency ~70%)*
  - *exploit different S/B [and S/sqrt(B)] in each region*
  - ***very different background composition in each regions***: different effect of systematics in each region

- ….. but then the approaches diverge:
  - ***ATLAS:*** also considering large statistics background dominated control regions (better understanding/constraining of common systematics). Single discriminant fitted in each region.



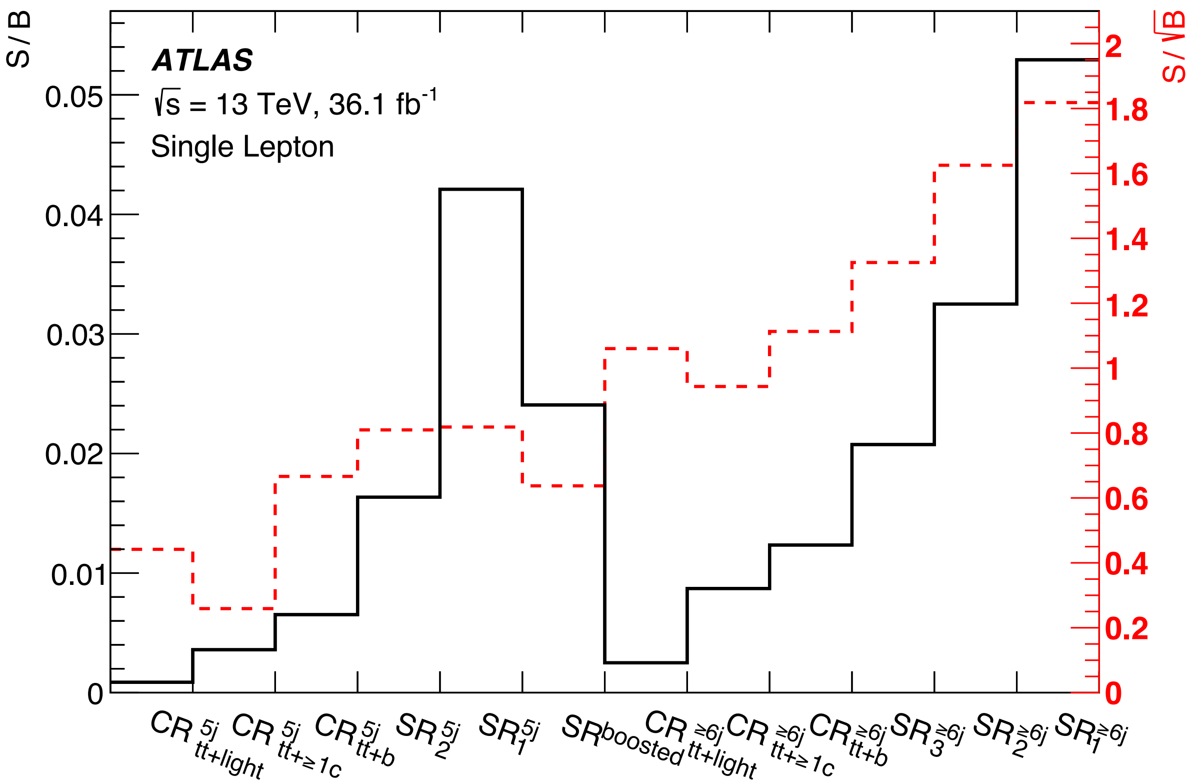
No numbers from CMS to quantify increase of S/B due to BDT categorisation

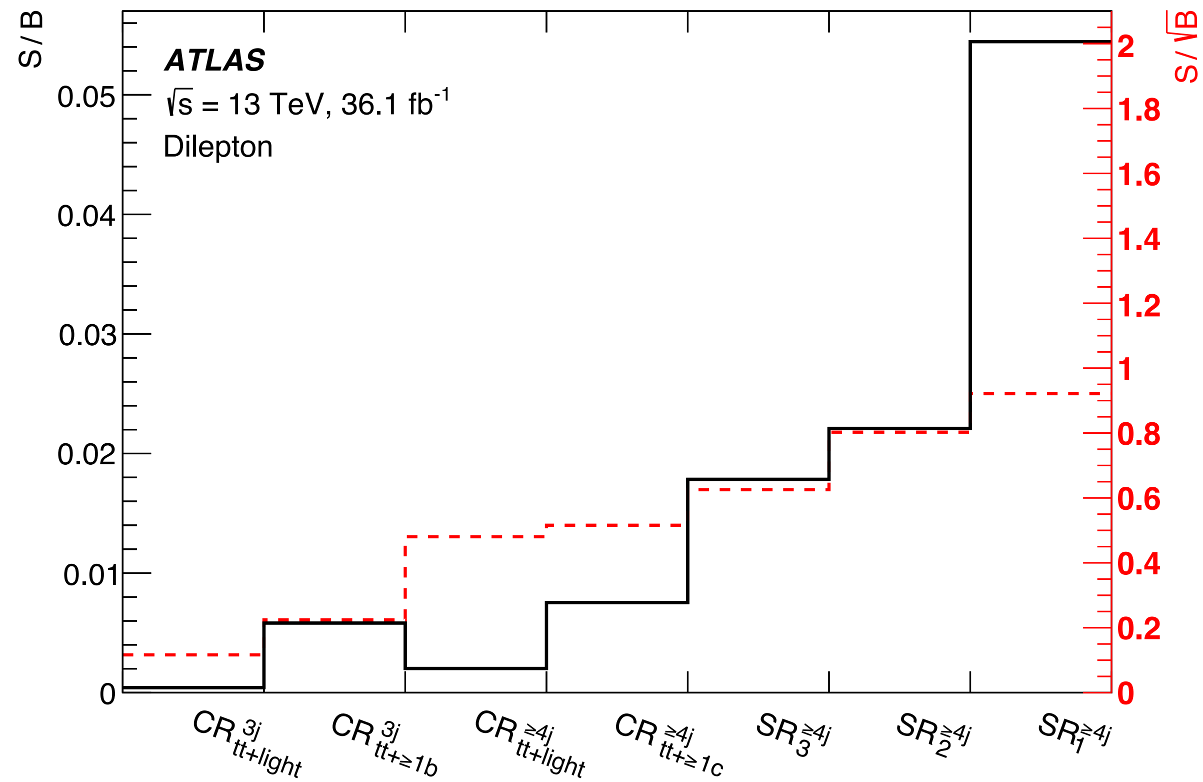
(*) jet and b-tagged jets definition/performance differ in ATLAS and CMS better b-tagging performance in ATLAS



$t\bar{t}H$ ($H \to b\bar{b}$): strategy

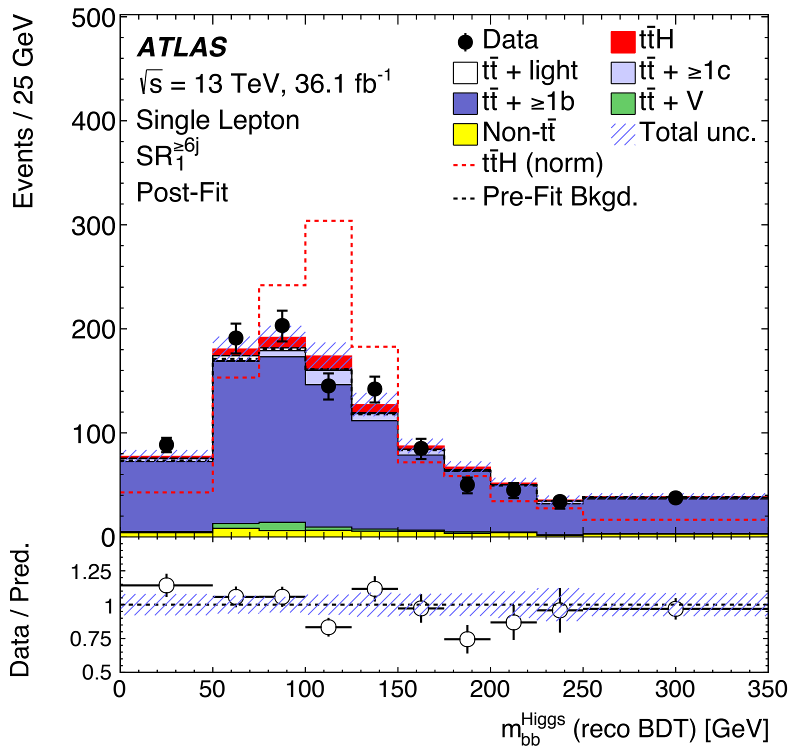
- l+jets
- di-lepton

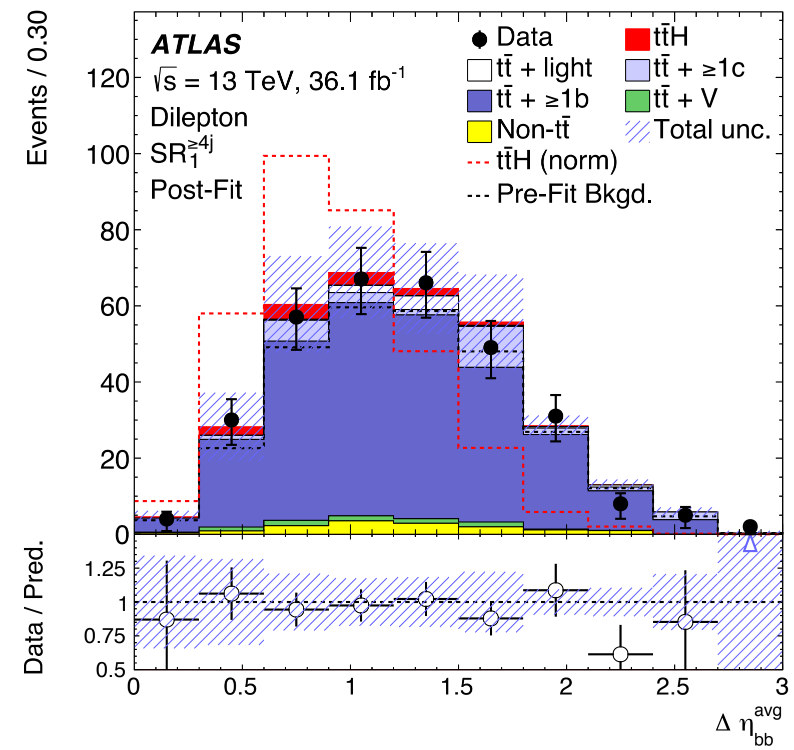


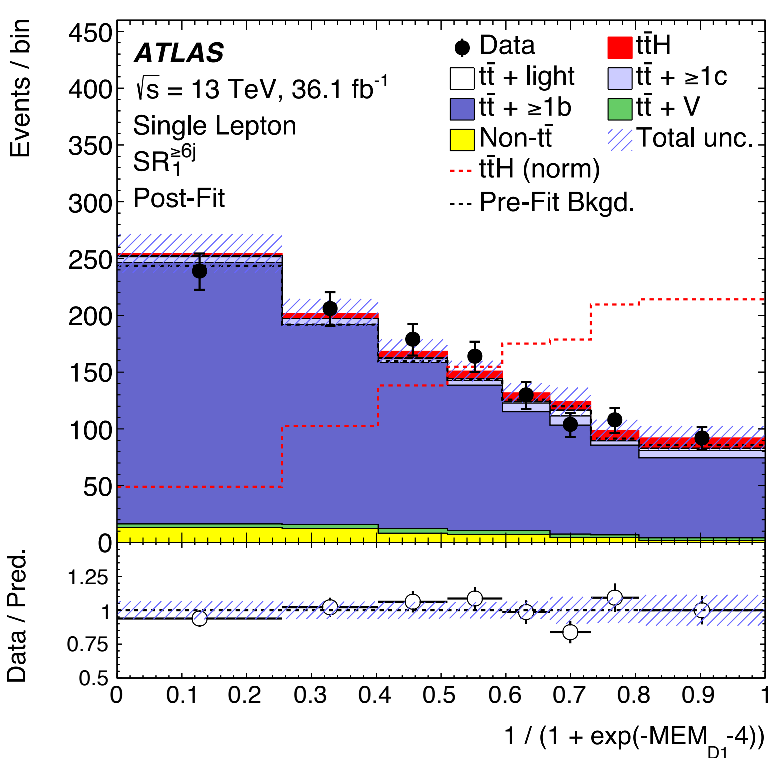


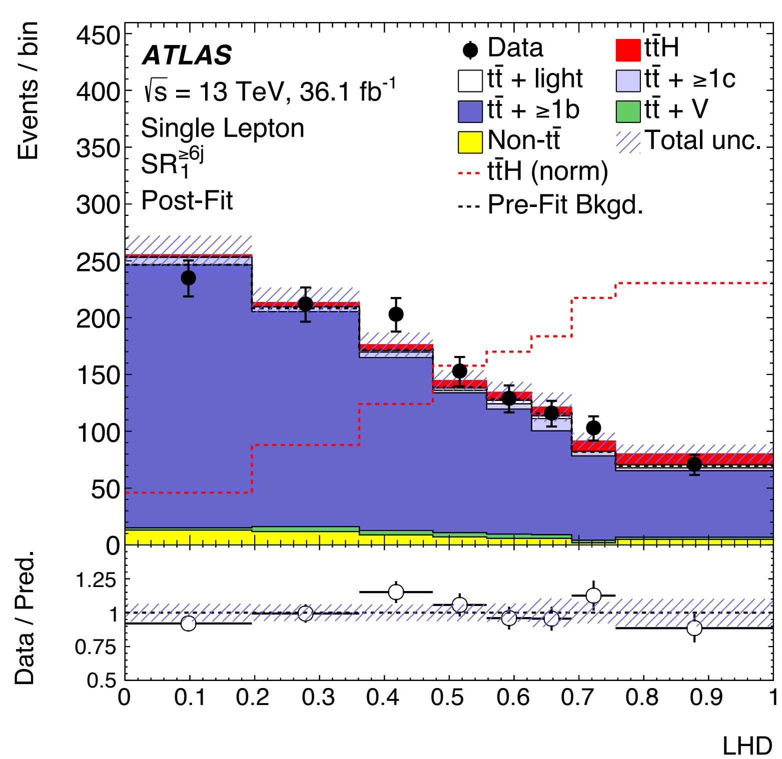
$t\bar{t}H$ ($H \to b\bar{b}$): discriminant

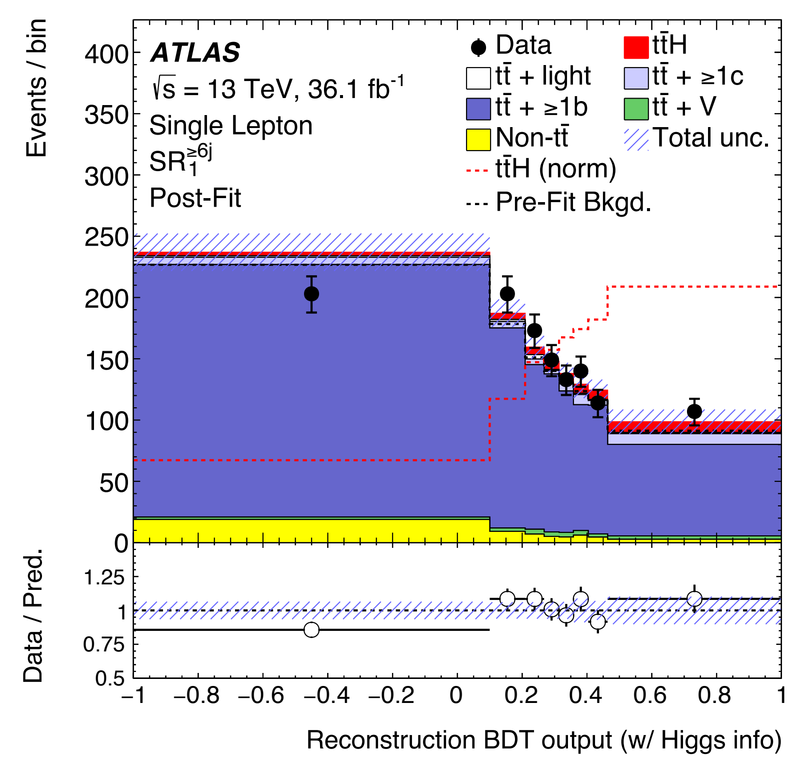
- Disclaimer: *"given the low S/B it will be close to impossible to extract the signal without heavily relying on multivariate techniques"*



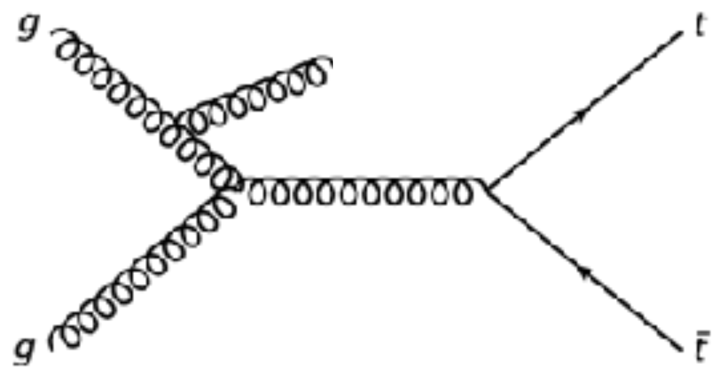


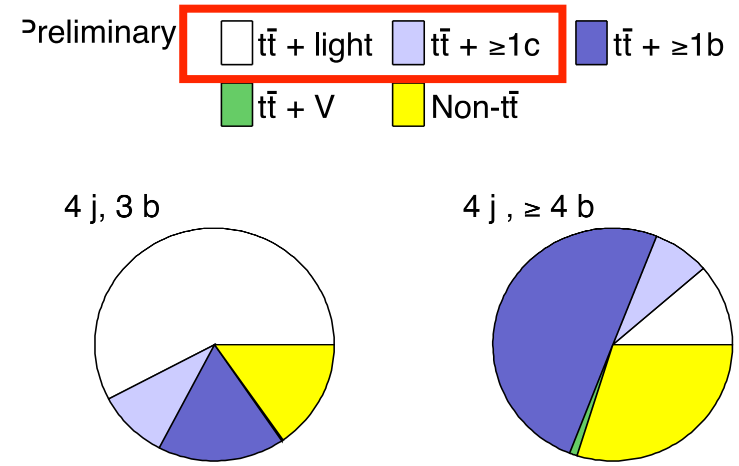






$t\bar{t}H$ ($H\to b\bar{b}$): background





- Main reducible background: ***ttbar+light / ttbar+c jets***
  - *crucial to model jet multiplicity :* extra jets mis-tagged as b-jets
  - ***ATLAS****: Powheg(NLO)+Pythia6 (h_{damp}=1)* reweighted to NNLO prediction for top p_T/ttbar p_T

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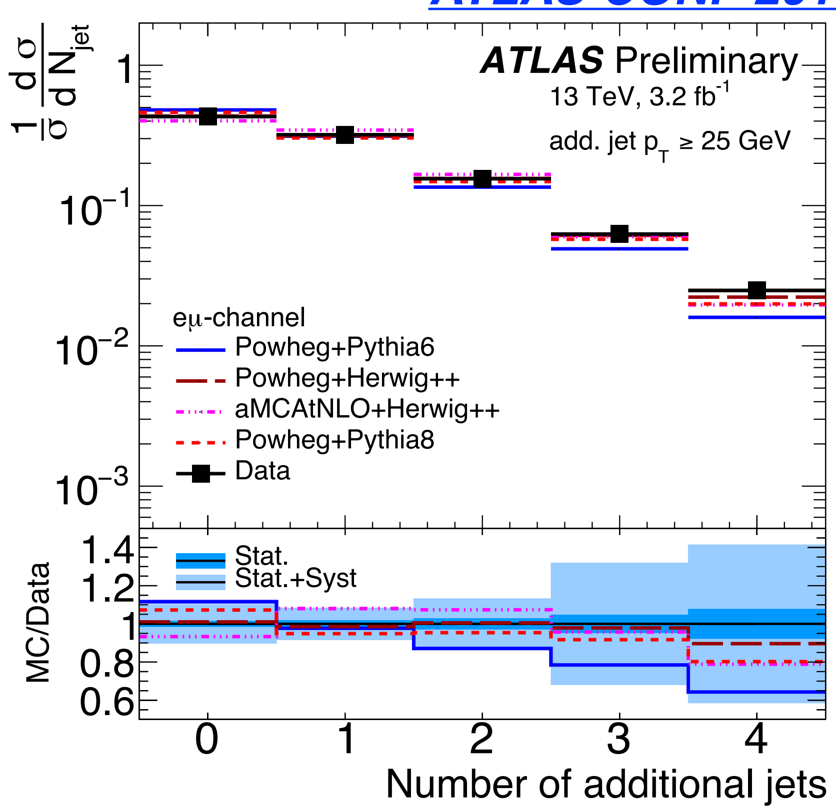
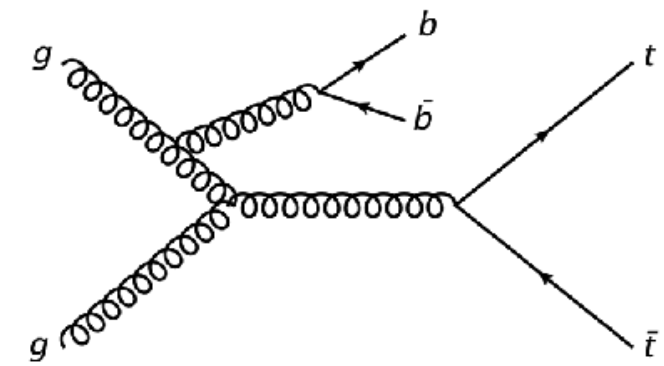
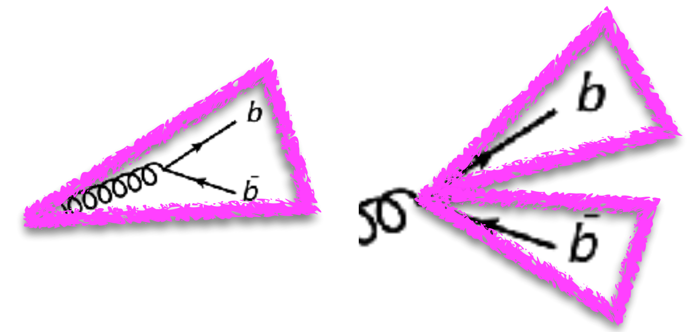
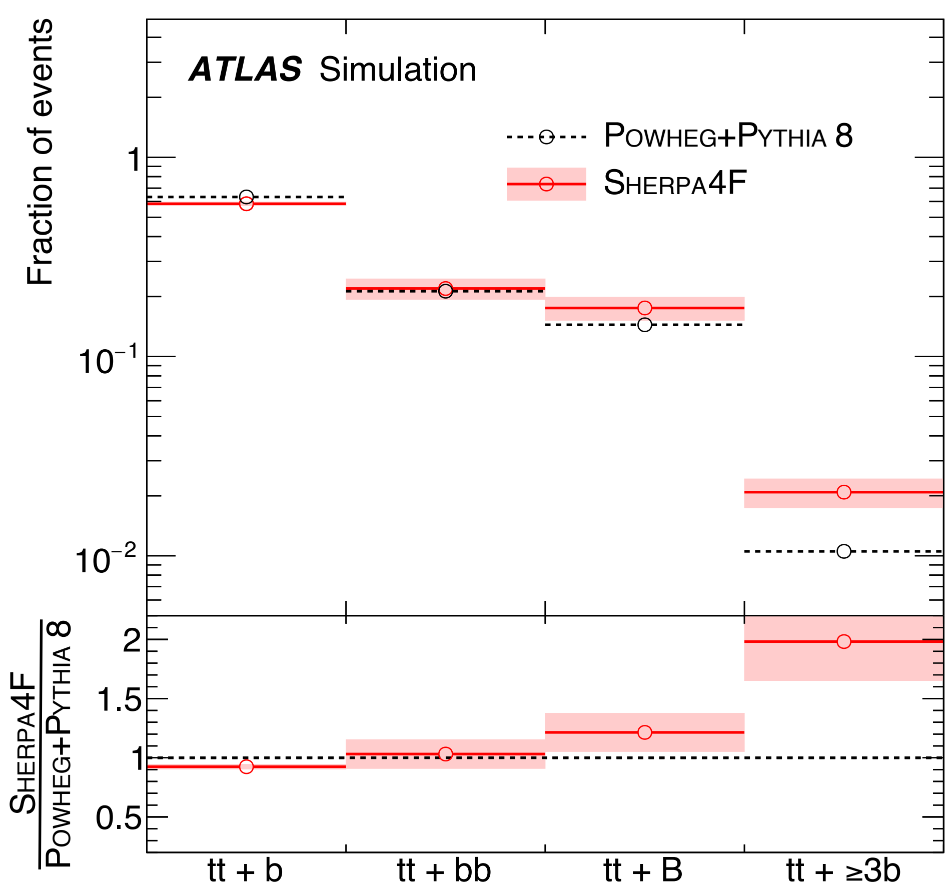


theorist not so happy with us modelling high multiplicity with NLO inclusive generators

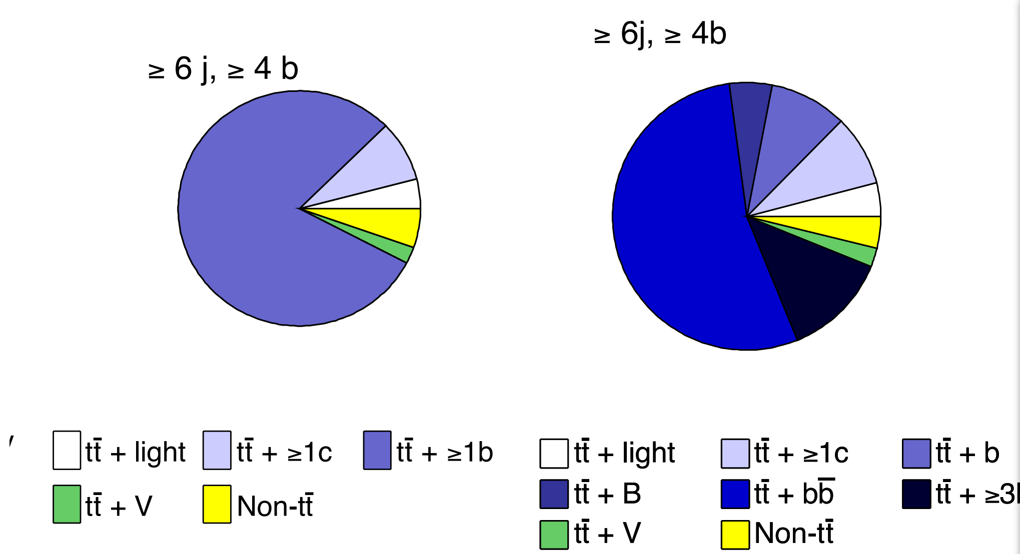
- Main reducible background: ***ttbar+b(b)***
  - *theoretically very challenging:* α_s^4, large object multiplicity, multiple scales, contribution from gluon splitting (PS VS LO)
  - *experimentally very challenging:* dominant only in signal-like region, constrained through relative normalisation across regions (strongly depends on the possibility to resolve gluon splitting
  - ***ATLAS**: same Powheg+Pythia6 generator but REWEIGHTED to Sherpa OpenLoop tt+bb NLO predictions* [both shapes and categories]







- **Same** categorisation for ATLAS and CMS:
  - b= 1 b-hadron jet, B/2b= 2 b-hadron jet
  - ***ATLAS**: categorisation is not used in the plots since common normalisation* [but used for implementation of systematics]



tt+HF sys: "too much VS too little?"

ATLAS:

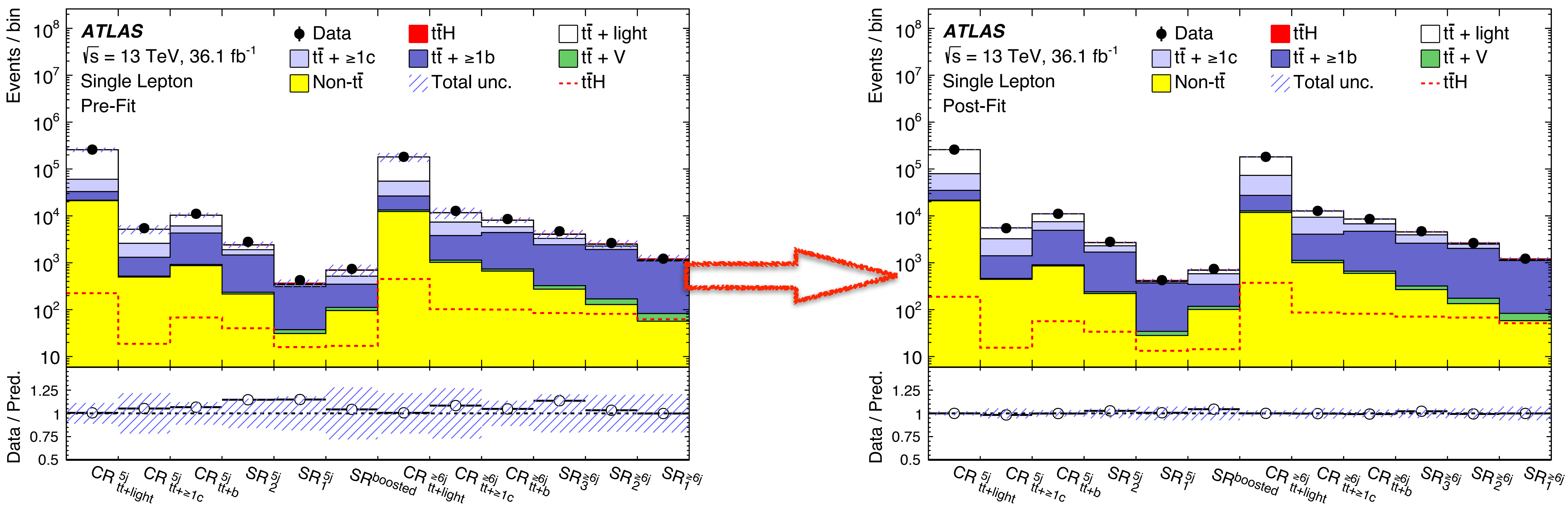
- free-floating normalisation of tt+≥1b and tt+≥1c [no bias on preferred central value]
- modelling of ttbar pt_T/top p_T from higher order generator NNLO, parton shower (Pythia6 VS Herwig), Powheg scale variations
- uncertainties from NLO tt+bb predictions: Sherpa internal variations, and Sherpa VS aMC@NLO
- all uncertainties uncorrelated among tt+≥1b, tt+≥1c, tt+light (but correlated among categories)
- uncertainties are allowed to change the relative composition/shape of the tt+≥1b categories

Systematic source	Description	$t\bar{t}$ categories
$t\bar{t}$ cross-section	Up or down by 6%	All, correlated
$k(t\bar{t}+\geq 1c)$	Free-floating $t\bar{t}+\geq 1c$ normalization	$t\bar{t}+\geq 1c$
$k(t\bar{t}+\geq 1b)$	Free-floating $t\bar{t}+\geq 1b$ normalization	$t\bar{t}+\geq 1b$
SHERPA5F vs. nominal	Related to the choice of NLO event generator	All, uncorrelated
PS & hadronization	POWHEG+HERWIG 7 vs. POWHEG+PYTHIA 8	All, uncorrelated
ISR / FSR	Variations of μ_R, μ_F, h_{damp} and A14 Var3c parameters	All, uncorrelated
$t\bar{t}+\geq 1c$ ME vs. inclusive	MG5_aMC@NLO+HERWIG++: ME prediction (3F) vs. incl. (5F)	$t\bar{t}+\geq 1c$
$t\bar{t}+\geq 1b$ SHERPA4F vs. nominal	Comparison of $t\bar{t}+b\bar{b}$ NLO (4F) vs. POWHEG+PYTHIA 8 (5F)	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ renorm. scale	Up or down by a factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ resumm. scale	Vary μ_Q from $H_T/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ global scales	Set μ_Q, μ_R, and μ_F to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ shower recoil scheme	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ PDF (MSTW)	MSTW vs. CT10	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ PDF (NNPDF)	NNPDF vs. CT10	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ UE	Alternative set of tuned parameters for the underlying event	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 3b$ normalization	Up or down by 50%	$t\bar{t}+\geq 1b$

$t\bar{t}H$ ($H \to b\bar{b}$): plot comparison

These are very complicated fits:

- *profiling systematic uncertainties*: O(50-100) parameters determined simultaneously together with the signal strength [most of them with prior constraints]
- the fit will constrain the total signal+background uncertainty at the level of the data stat. uncertainty
- post-fit good data/mc agreement is almost a tautology: very little information given about the effect of the fit on the sys parameters

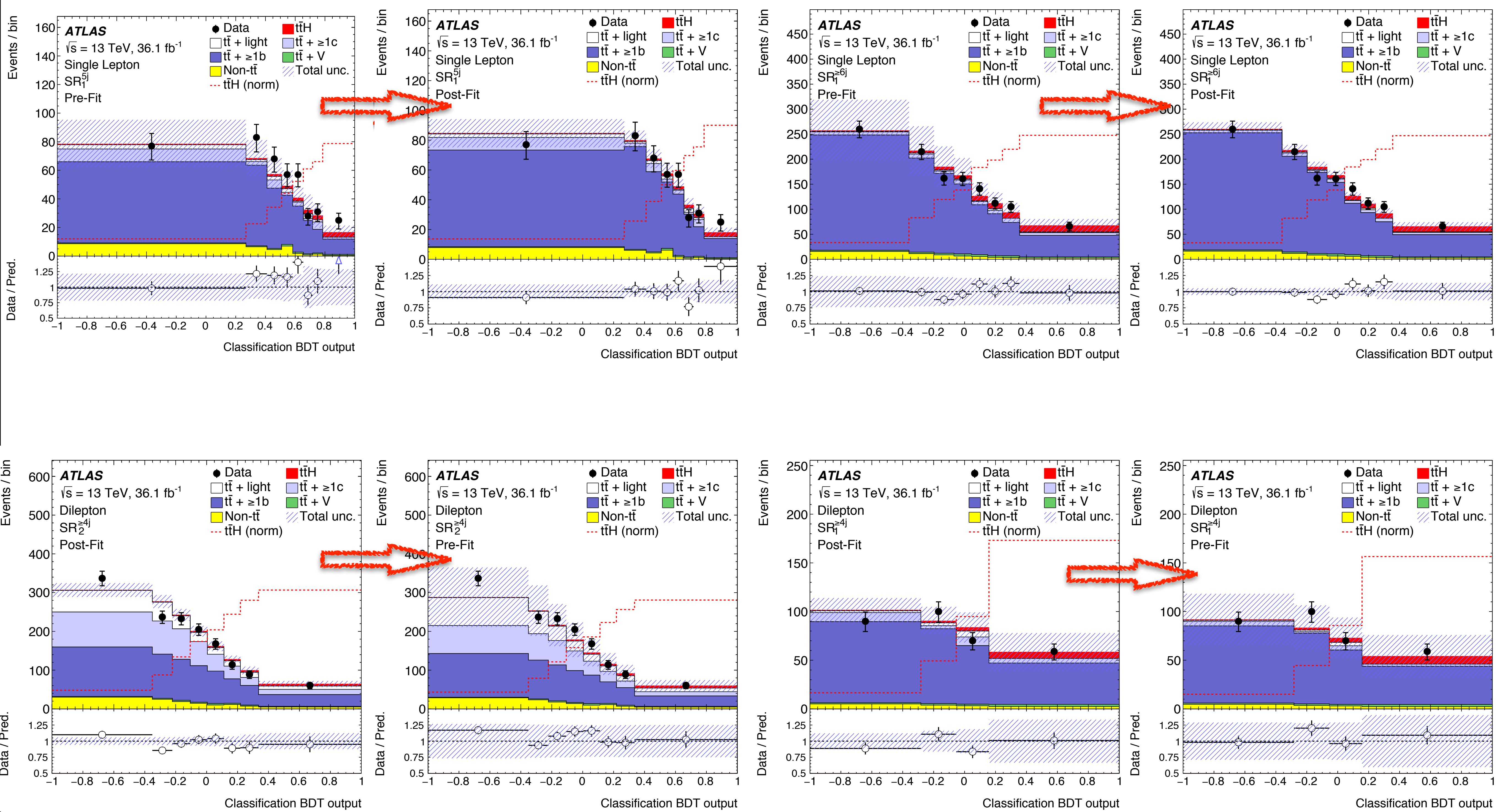


Normalisation factors for tt+HF:

- ***tt+b:* 1.30 ± 0.18** , ***tt+c:* 1.31 $^{+0.53}_{-0.40}$**

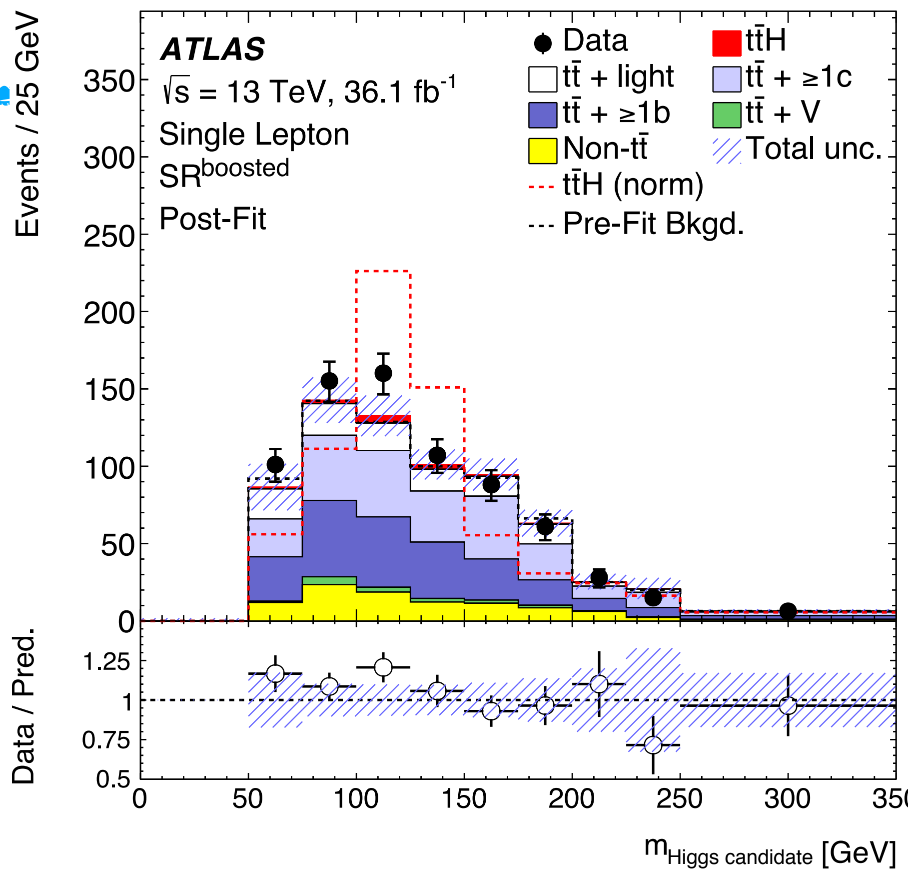
$t\bar{t}H$ (H->$b\bar{b}$): plot comparison (2)

Most sensitive regions: only a small subset of the 27 regions used in the analysis

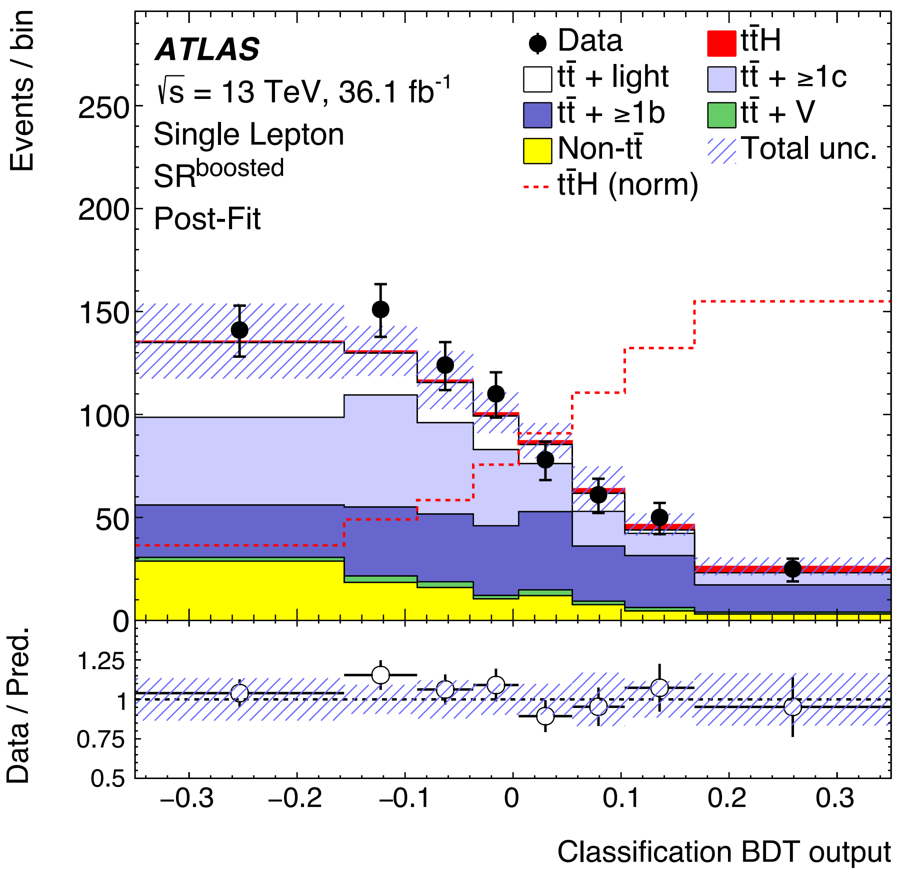


ttHbb: boosted

- *l+jets final state*
- Re-clustering Akt4 calo jets into Akt10 calo jets:
  - Higgs candidate: p_T>200 GeV, at least 2 b-tagged sub-jets
  - top candidate: p_T>250 GeV, at least 2 sub-jets, only one b-tagged

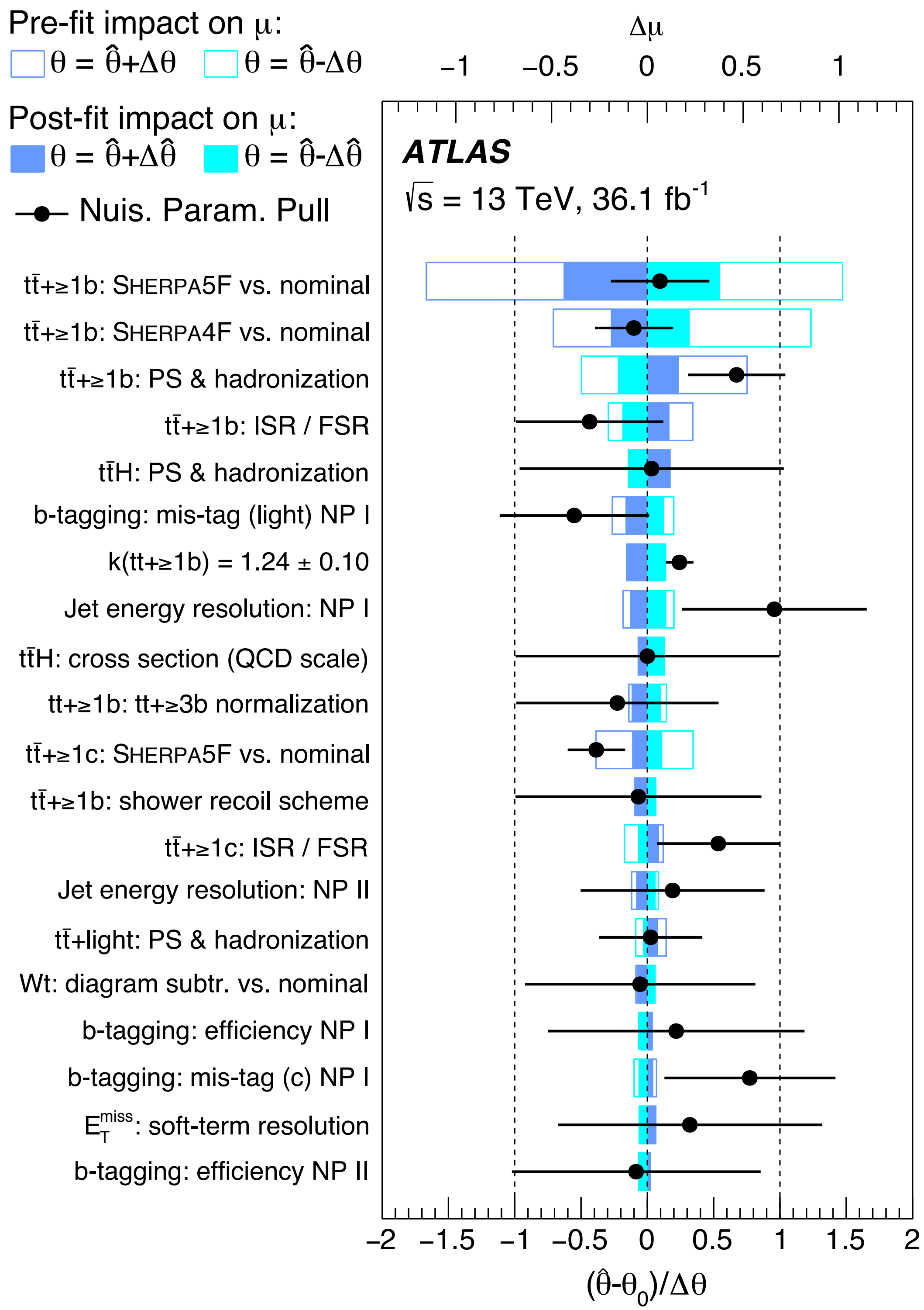


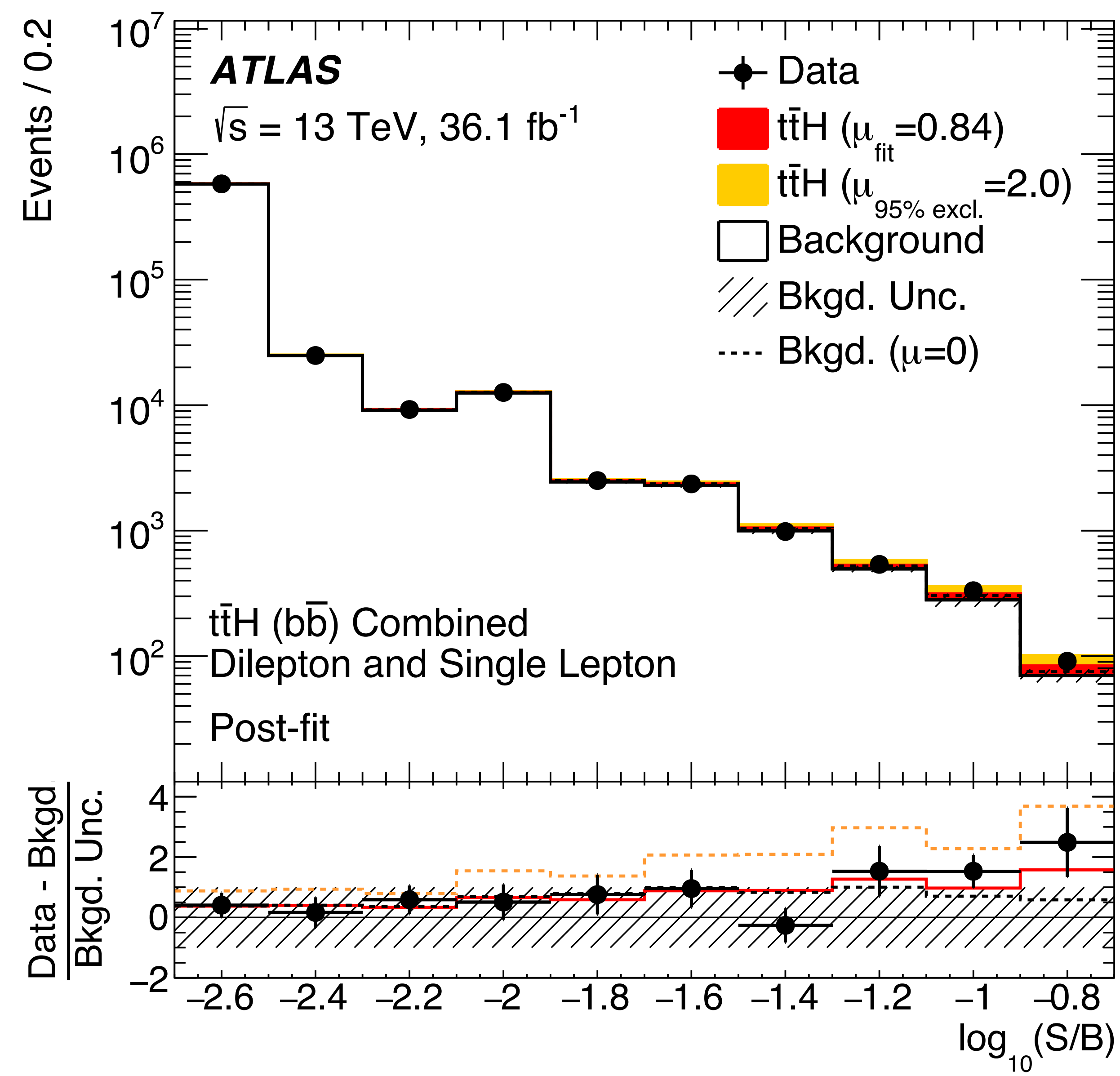
- *Pro:*
  - reduced combinatorial —> mass peak more visible
  - concentrating on higher pt regime [although still requiring Akt4 as starting point]



- *(temporarily) Con't:*
  - lower statistics
  - need to have looser event selection in other to have enough events —> larger reducible background contamination

ttHbb: more results





The full fit model

- Likelihood fit performed simultaneously to all signal and control regions:
  - main fit parameter: **signal strength $\mu = XS^{VH}/XS_{SM}^{VH}$**
  - free floating normalisation of leading backgrounds (W+bb, Z+bb, ttbar)
    - separate normalisation in 2 and 3 jet bins: avoid any assumption on uncertainty dependence over jet multiplicity
    - ttbar normalisation uncorrelated between 0-lepton/1-lepton and 2-lepton
  - additional systematic uncertainties included in the likelihood as constrained nuisance parameters: allowing the data to control the uncertainties

- Detector-related uncertainties can modify both the normalisation and the discriminant shape of the various process

- Modelling uncertainties: computed as envelope / sum in quadrature of a complete set of MC parameter variations
  - for leading backgrounds: **extrapolation uncertainties across regions** (CR->SR, 1L->0L, 2L->0L)
  - **flavour composition** uncertainties for V+jets
  - for small background/signal/diboson (we can't fully control uncertainties them from data yet): full set of **uncertainties on cross section and acceptance** [the latter is obtained with Stewart-Tackmann method when radiation is involved]
  - **shape uncertainties**:
    - parameterised independently as a function of m_{bb} and V p_T [leading variables in the BDT]
    - largest shape among all the possible variation: careful monitoring of effects across regions and for different systematics
  - systematic uncertainties on shape and acceptance are treated as uncorrelated

- In total: 141 analysis bins, 146 nuisance parameters …..

VHbb: MC

Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order ace2.5cm
Signal					
$qq \to WH$ $\to \ell\nu b\bar{b}$	POWHEG-BOX v2 [19] + GOSAM [22] + MINLO [23,24]	NNPDF3.0NLO$^{(\star)}$ [20]	PYTHIA8.212 [13]	AZNLO [21]	NNLO(QCD)+ NLO(EW) [25,26,27,28,29,30,31]
$qq \to ZH$ $\to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	POWHEG-BOX v2 + GOSAM + MINLO	NNPDF3.0NLO$^{(\star)}$	PYTHIA8.212	AZNLO	NNLO(QCD)$^{(\dagger)}$+ NLO(EW)
$gg \to ZH$ $\to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	POWHEG-BOX v2	NNPDF3.0NLO$^{(\star)}$	PYTHIA8.212	AZNLO	NLO+ NLL [32,33,34,35,36]
Top quark					
$t\bar{t}$	POWHEG-BOX v2 [37]	NNPDF3.0NLO	PYTHIA8.212	A14 [38]	NNLO+NNLL [39]
s-channel	POWHEG-BOX v1 [40]	CT10 [41]	PYTHIA6.428 [42]	P2012 [43]	NLO [44]
t-channel	POWHEG-BOX v1 [40]	CT10f4	PYTHIA6.428	P2012	NLO [45]
Wt	POWHEG-BOX v1 [46]	CT10	PYTHIA6.428	P2012	NLO [47]
Vector boson + jets					
$W \to \ell\nu$	SHERPA 2.2.1 [16,48,49]	NNPDF3.0NNLO	SHERPA 2.2.1 [50,51]	Default	NNLO [52]
$Z/\gamma^* \to \ell\ell$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NNLO
$Z \to \nu\nu$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NNLO
Diboson					
WW	SHERPA 2.1.1	CT10	SHERPA 2.1.1	Default	NLO
WZ	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO
ZZ	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO

VHbb: event selection

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 medium 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 or 3 jets			Exactly 2 or ≥ 3 jets
Jet p_T		> 20 GeV		
b-jets		Exactly 2 b-tagged jets		
Leading b-tagged jet p_T		> 45 GeV		
H_T	> 120 (2 jets), > 150 GeV (3 jets)	–		–
$\min[\Delta\phi(E_T^{miss}, \text{jets})]$	$> 20°$ (2 jets), $> 30°$ (3 jets)	–		–
$\Delta\phi(E_T^{miss}, bb)$	$> 120°$	–		–
$\Delta\phi(b_1, b_2)$	$< 140°$	–		–
$\Delta\phi(E_T^{miss}, E_{T,trk}^{miss})$	$< 90°$	–		–
p_T^V regions	> 150 GeV			(75, 150] GeV, > 150 GeV

- ***Optimised jet pt selection***
- A series of cuts to ***reduce the multijet background***
- in 0L and 1L ***restricting to <4 jets*** to reduce ttbar background
- ***m_{ll} cut in 2L strongly reduces ttbar —> allows to consider ≥4 jet events***

- **Signal acceptance**:
  - O(few %) manly due to V pT selection

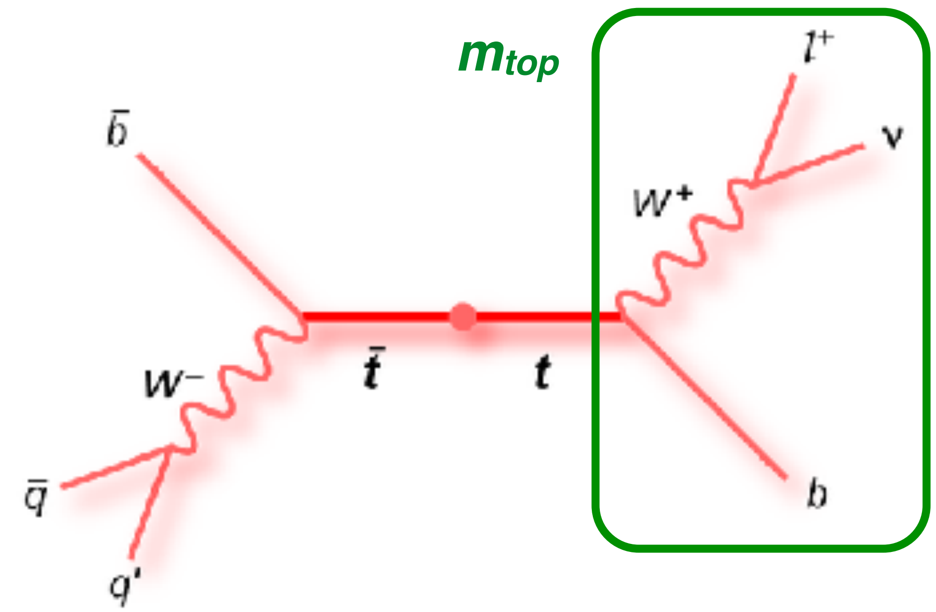
$m_H = 125$ GeV at $\sqrt{s} = 13$ TeV		Acceptance [%]		
Process	Cross-section × B [fb]	0-lepton	1-lepton	2-lepton
$qq \to ZH \to \ell\ell b\bar{b}$	29.9	< 0.1	< 0.1	7.0
$gg \to ZH \to \ell\ell b\bar{b}$	4.8	< 0.1	< 0.1	15.7
$qq \to WH \to \ell\nu b\bar{b}$	269.0	0.2	1.0	–
$qq \to ZH \to \nu\nu b\bar{b}$	89.1	1.9	–	–
$gg \to ZH \to \nu\nu b\bar{b}$	14.3	3.5	–	–

VHbb: analysis regions

- **8 SRs, 6 CRs**

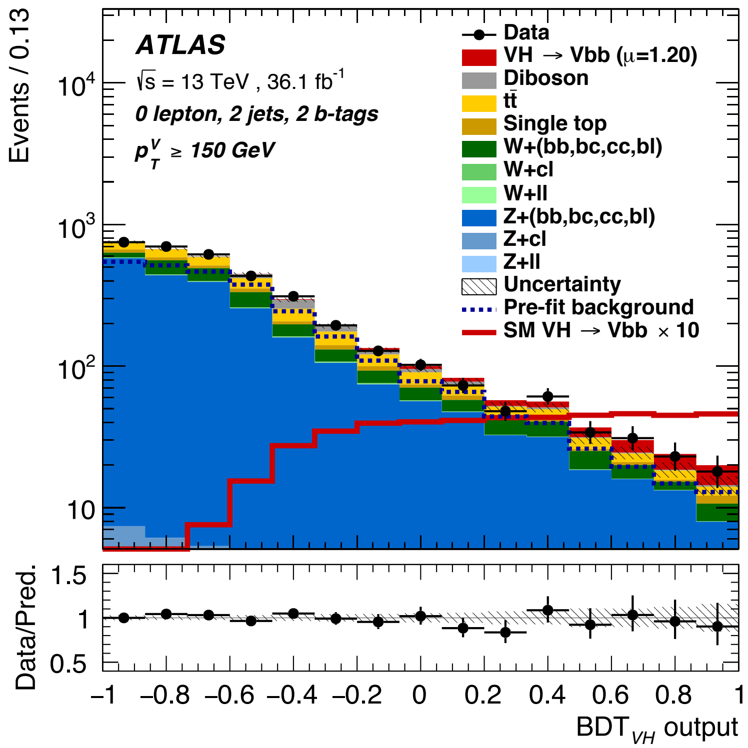
Channel	SR/CR	Categories			
		$75\text{ GeV} < p_T^V < 150\text{ GeV}$		$p_T^V > 150\text{ GeV}$	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR	-	-	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	W + HF CR	-	-	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}

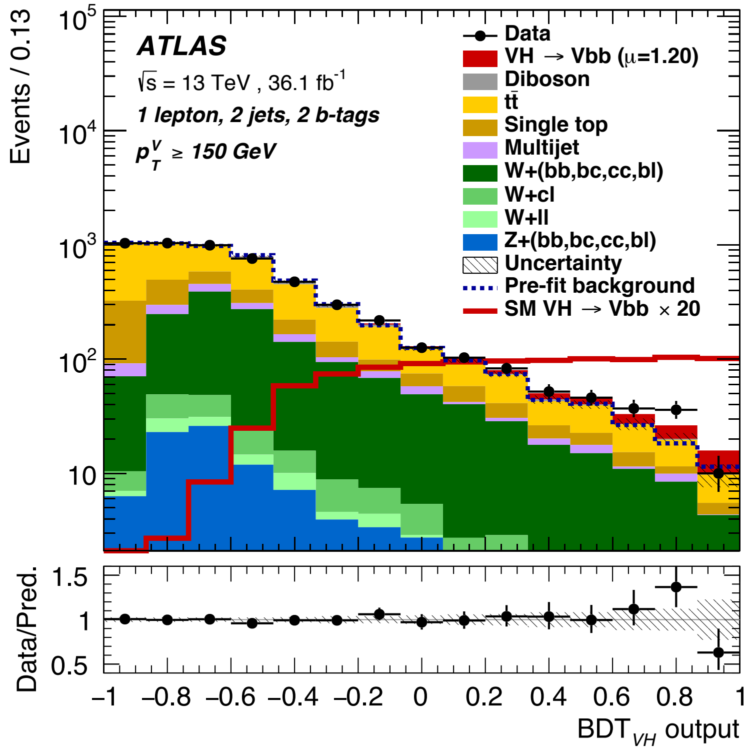
- ***WCR*** in 1-lepton: disentangle W+jets and ttbar in 1-lepton
  - m_{bb} <75 GeV : reduce signal contamination
  - m_{top} >225 : reduce ttbar contamination
  - 77% purity: but clearly extrapolations are needed

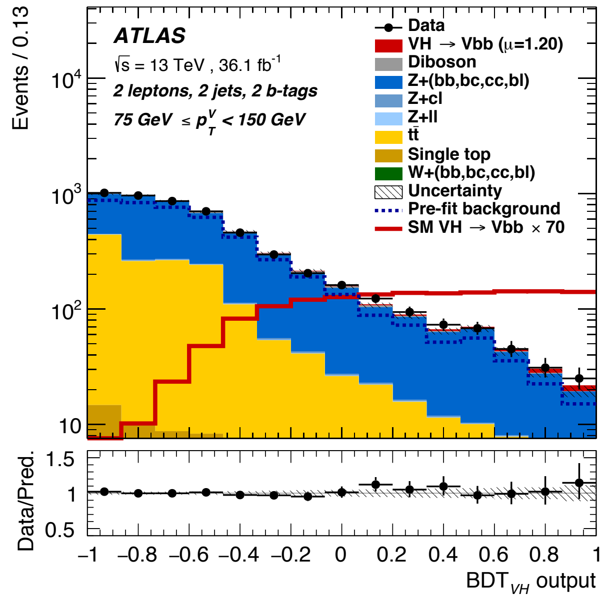


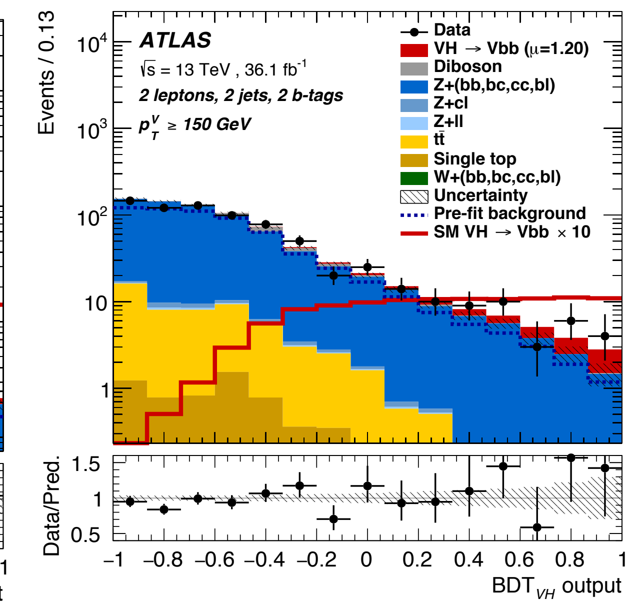
- **top CRs** in 2-lepton: exactly the same selection but e+μ final state
  - 99% pure in ttbar, no signal contamination
  - practically no theoretical extrapolation between CR and SR

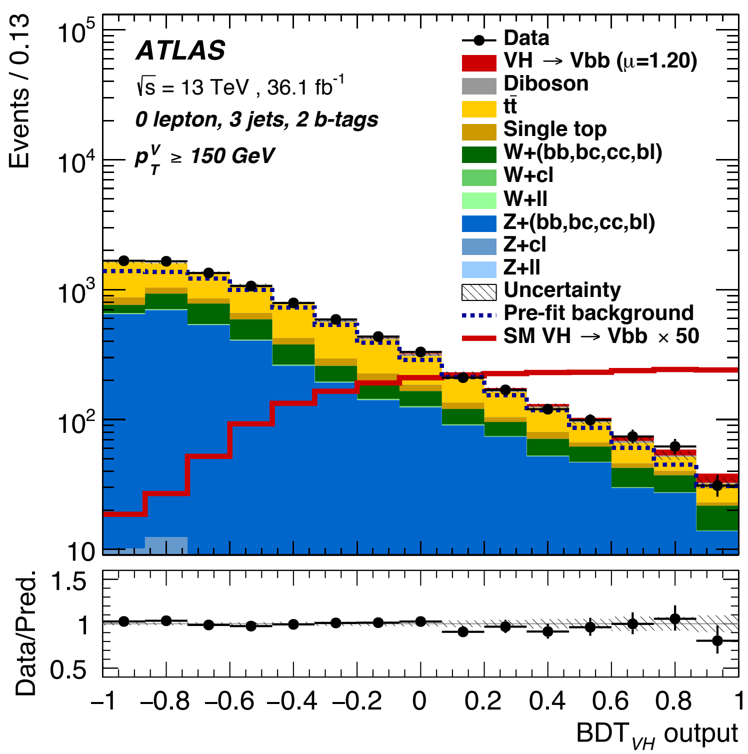
Multivariate discriminant (2)

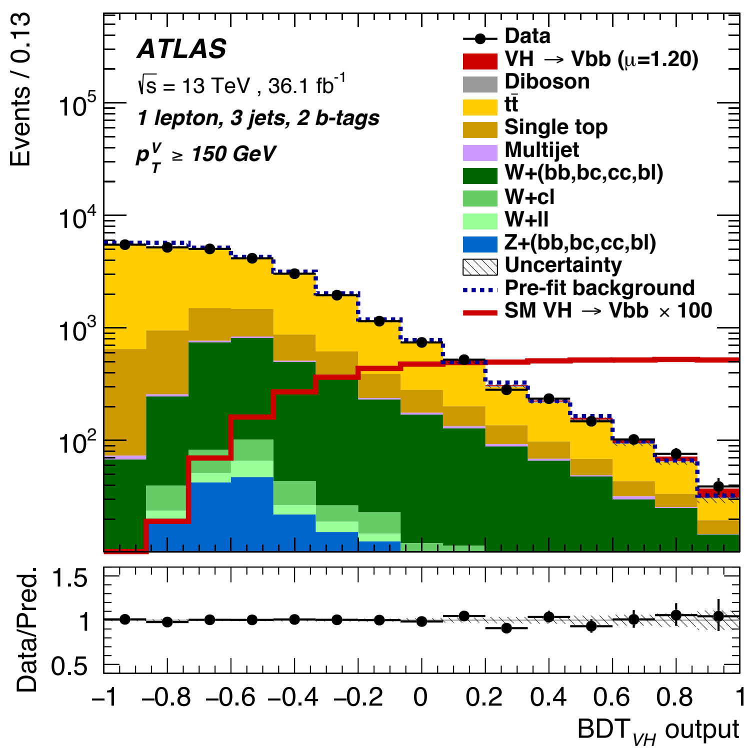


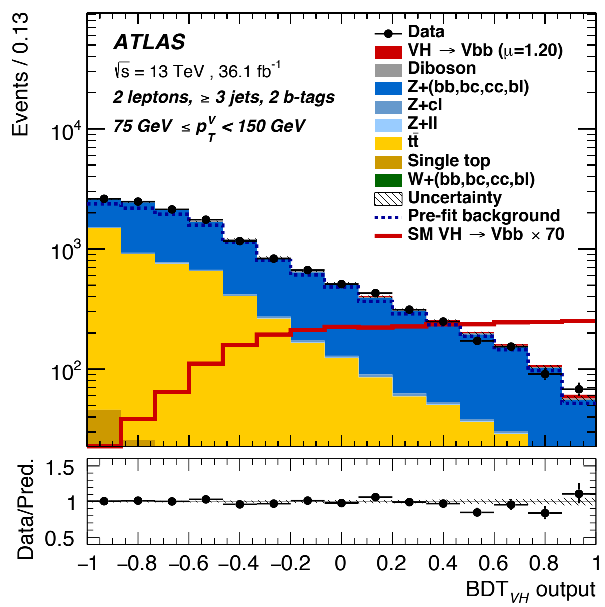


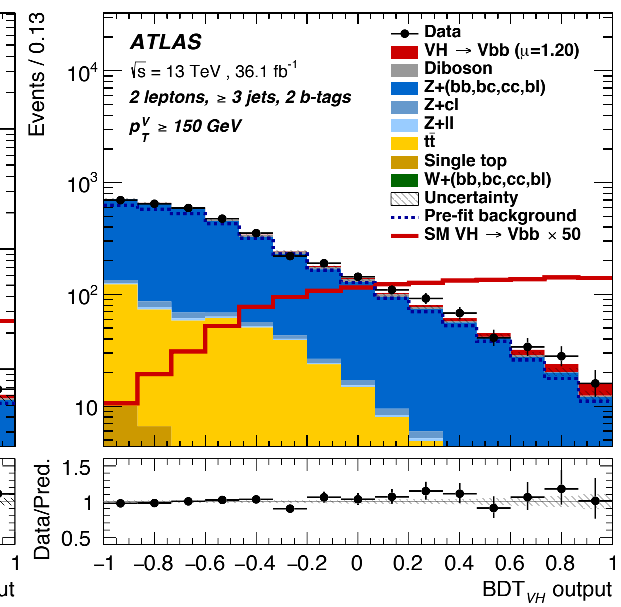




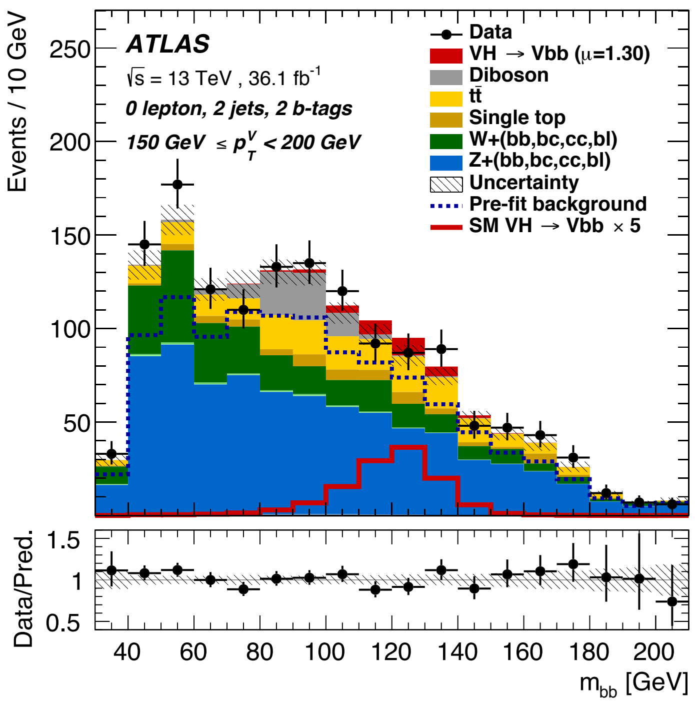


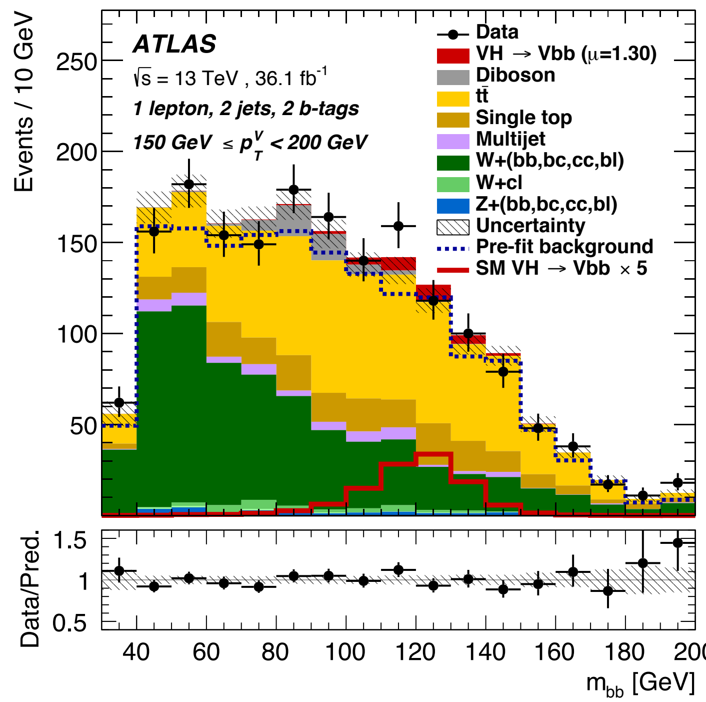


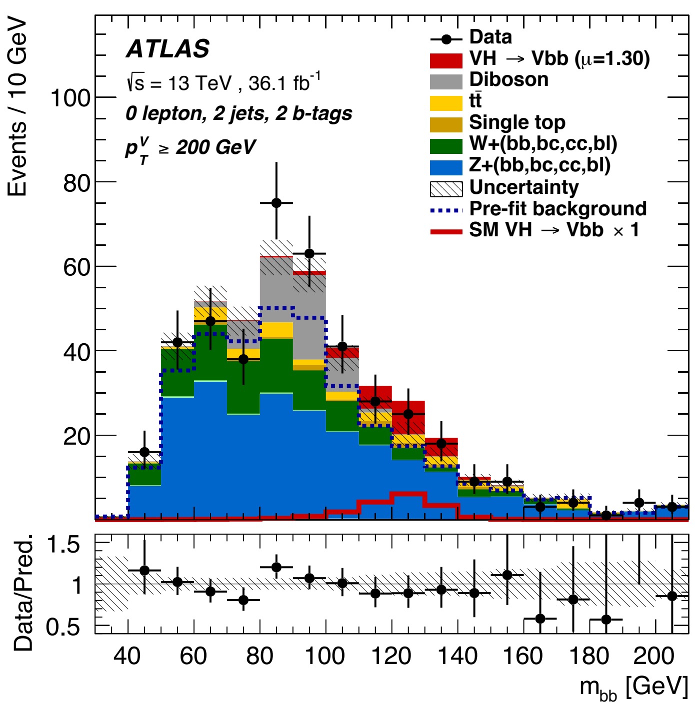


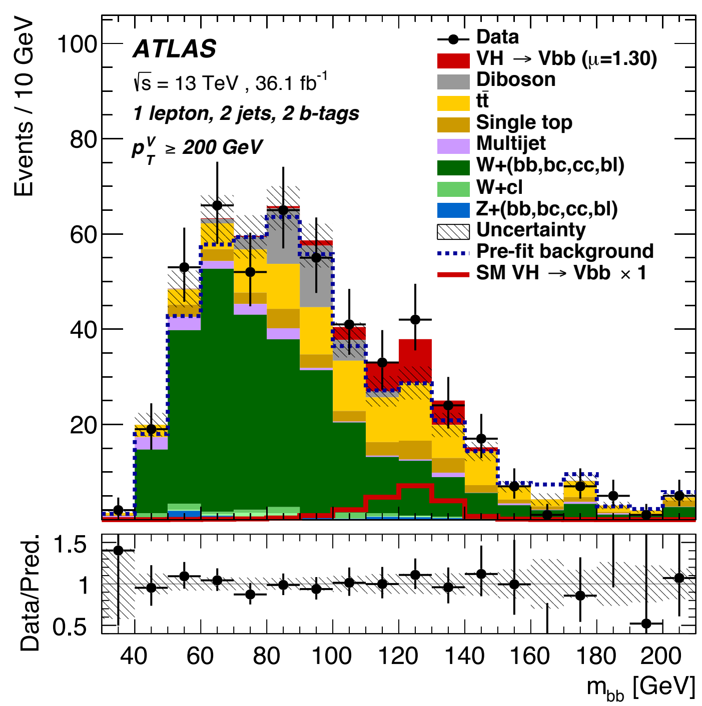


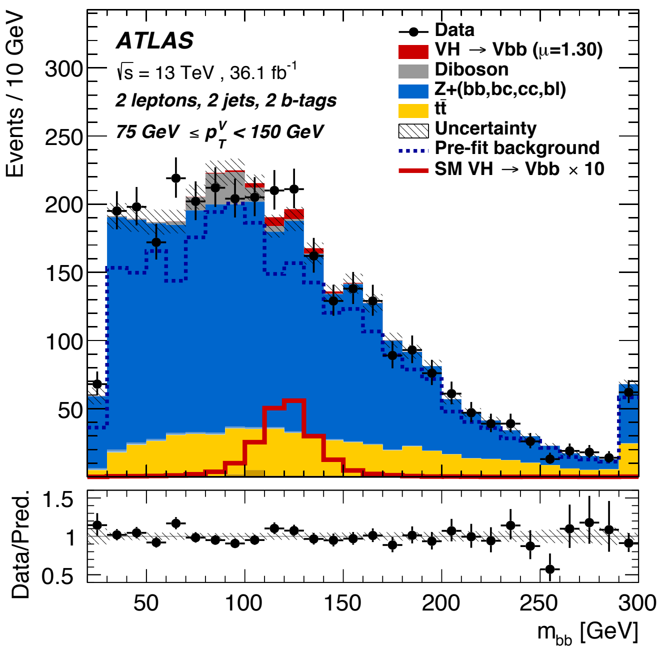
di-jet mass analysis: 2J

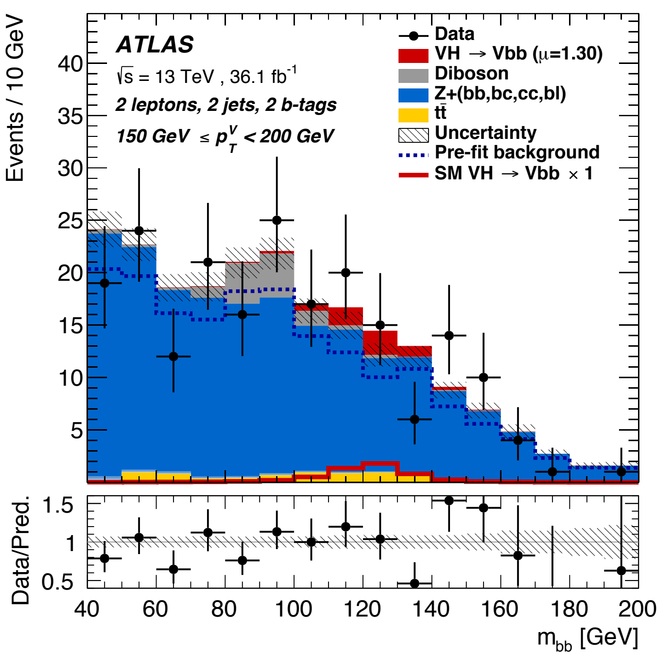


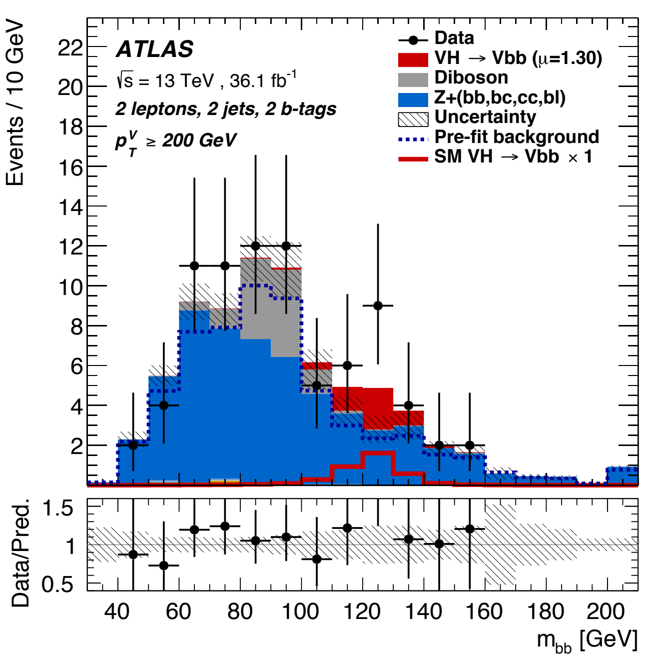




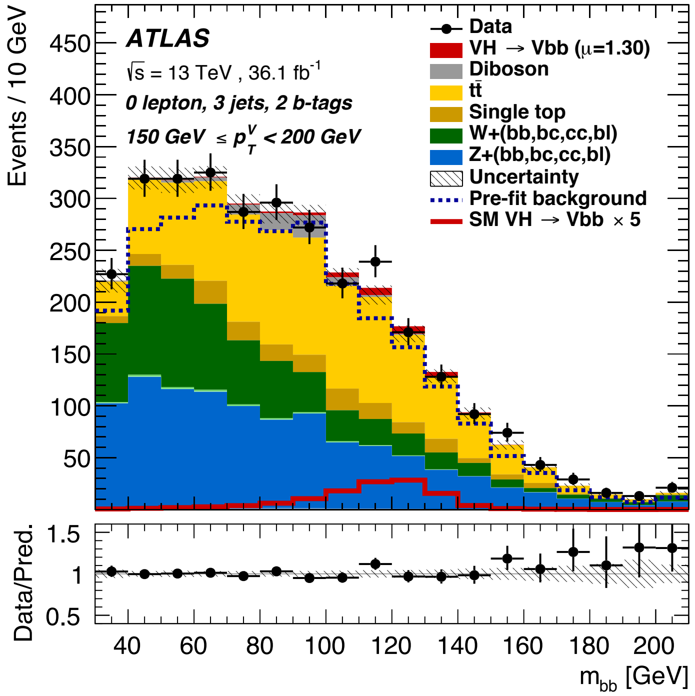


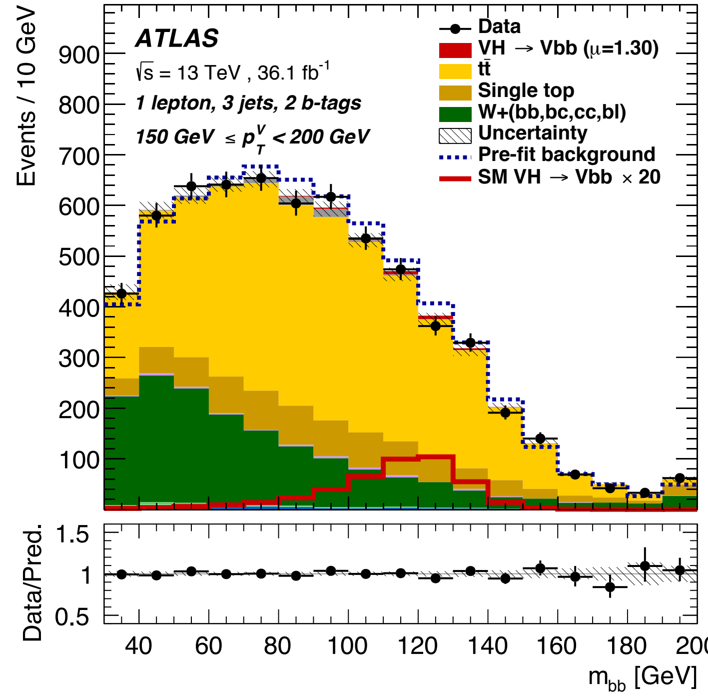


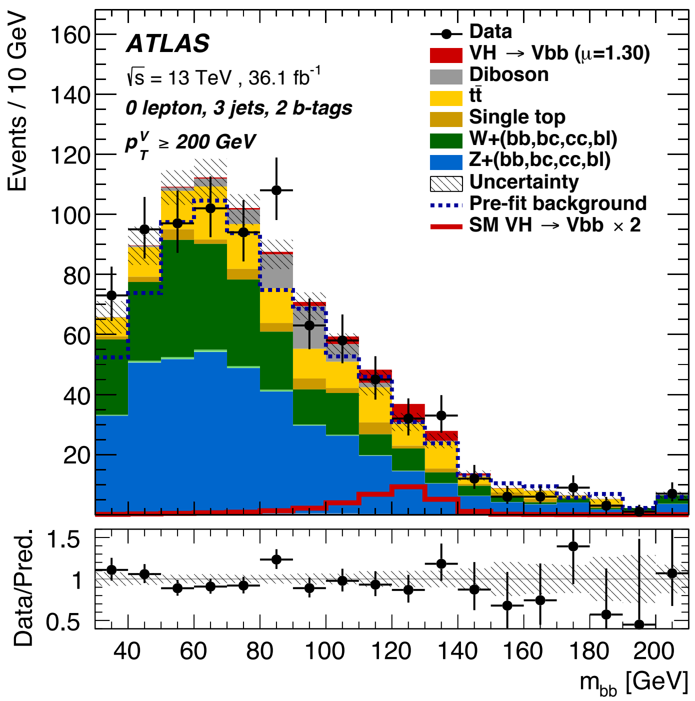


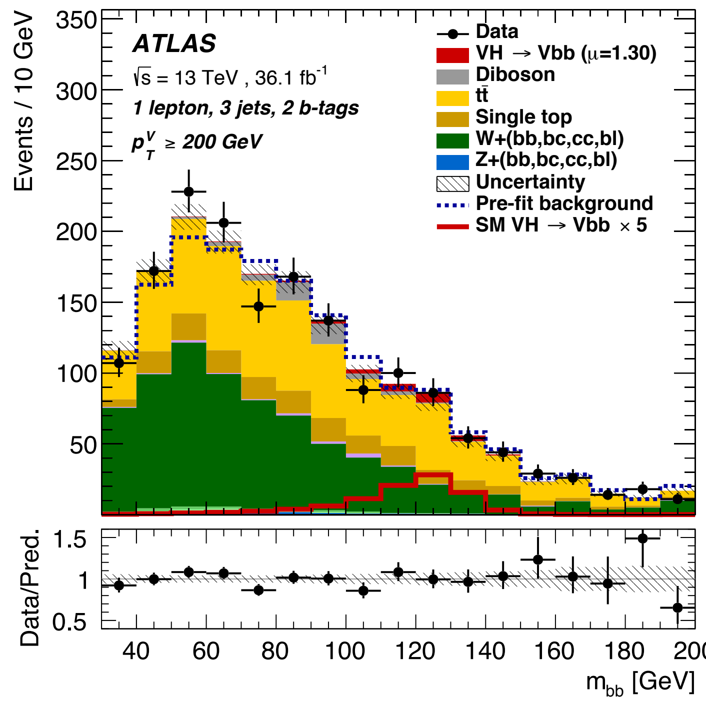


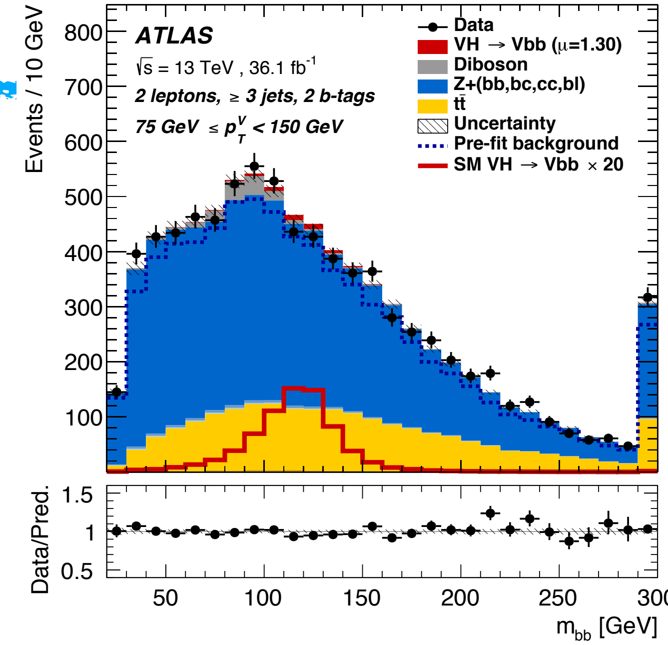
di-jet mass analysis: 3J

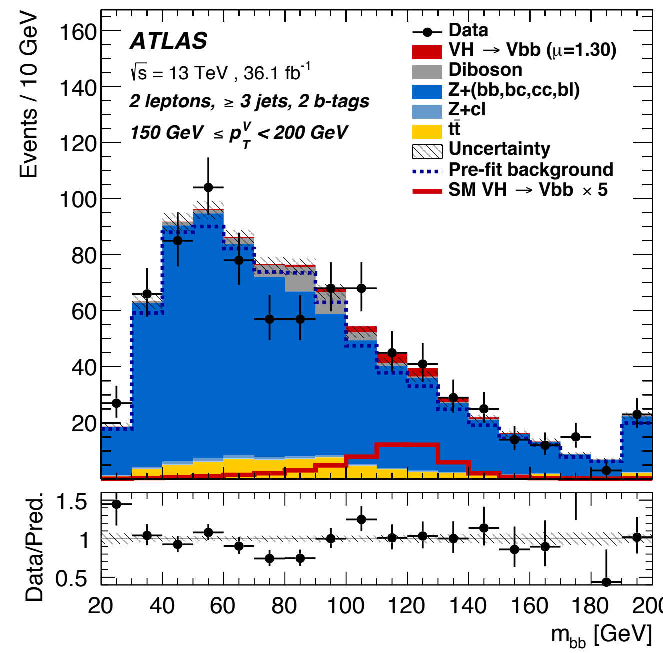


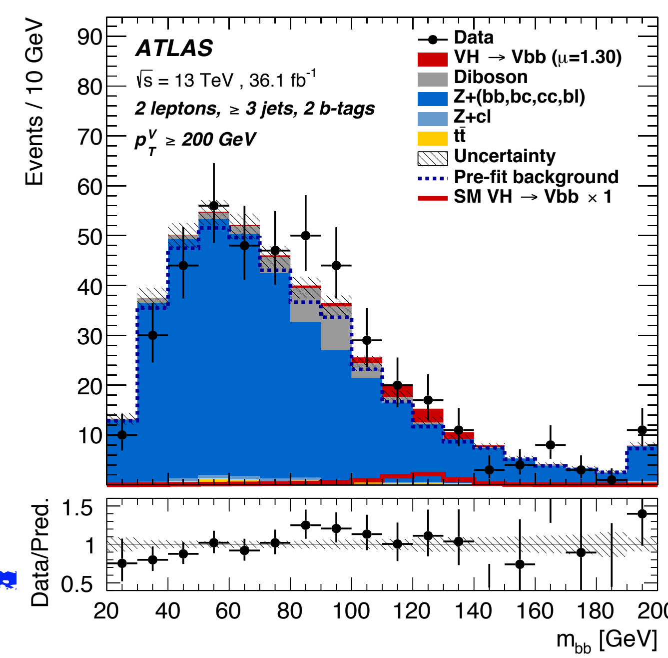












- Possible effects (components) of modelling uncertainties:
  - ***overall normalisation***: common effect to all analyses regions
    - inclusive cross section uncertainties for small background
    - free-floating overall normalisation factor for backgrounds that can be controlled from data (free of any initial bias)
  - ***acceptance uncertainties***: effect on selection efficiency for a given region
    - for processes without free-floating normalisation / signal: effect full selection from inclusive sample
    - for processes without free-floating normalisation: relative effect from main region controlling the normalisation to any other region
  - ***shape uncertainties***: effect on the shape of the fitted distribution
    - effects estimated at “truth level” as a function of 2 key variables: m_{bb} and V p_T
    - leading (uncorrelated) variables in the final multivariate discriminant
    - parametric effect of variation is applied coherently to other variables thought event-by-event reweighing

- While evaluated from the envelope of a series of well defined generator parameter comparisons [see later] … ***acceptance and shape effects are considered as uncorrelated*** in the profile likelihood fit implementation:
  - clearly identify the effect of the particular uncertainty
  - conservative approach that prevents large variation in one “variable” to be constrained by the data and uncontrollably propagated to the rest of the fit

Signal uncertainties

- Only concentrating in acceptance uncertainties as effect of shape uncertainties on the overall result is small

		Signal
	Cross-section (scale)	0.7% (qq), 27% (gg)
	Cross-section (PDF)	1.9% ($qq \to WH$), 1.6% ($qq \to ZH$), 5% (gg)
	Branching ratio	1.7 %
	Acceptance from scale variations (var.)	2.5 – 8.8% (Stewart–Tackmann jet binning method)
(*)	Acceptance from PS/UE var. for 2 or more jets	10.0 – 13.9% (depending on lepton channel)
(**)	Acceptance from PS/UE var. for 3 jets	12.9 – 13.4% (depending on lepton channel)
	Acceptance from PDF+α_S var.	0.5 – 1.3%

(*): overall acceptance for ≥2 jets events , (**): overall acceptance for (≥)3 jets / 2jets events

- Take home messages / questions:
  - **effect of PDF uncertainties is clearly subletting at the moment**
  - **effect of scale variation amplified in ST prescription by the large fraction of events with 3 or more jets (3rd jet p_T>20GeV)**
  - **strong effect of parton shower variation on acceptance: both overall acceptance (Pythia8 VS Herwig7) and 3J/2J ratio (Pythia8 tuning). Low 3rd jet pt more sensitive to parton shower?**

The full fit model

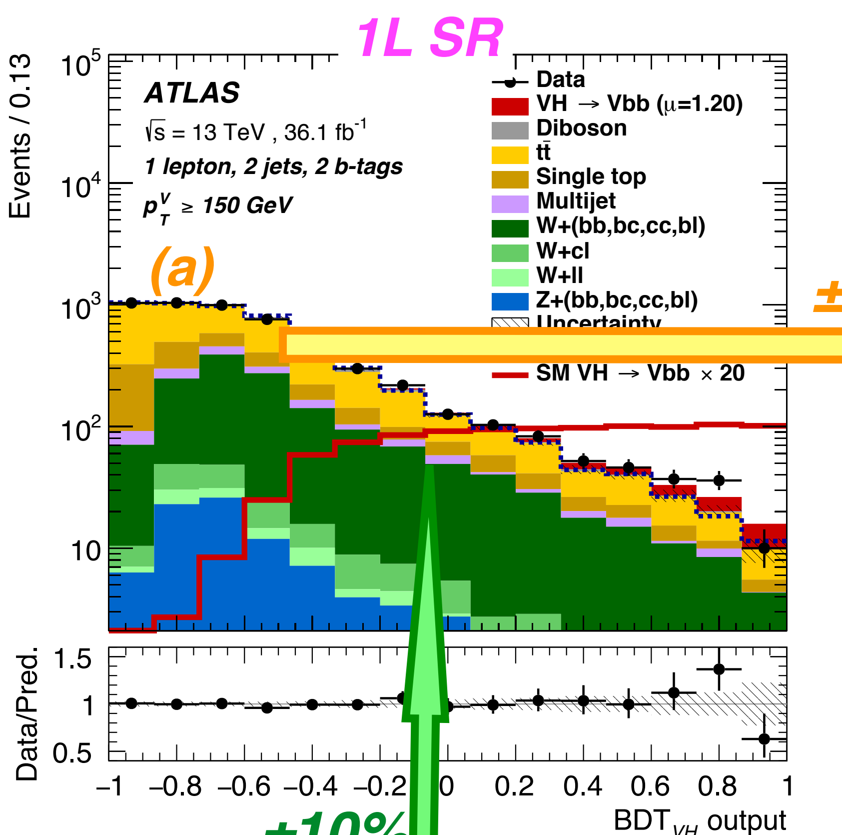
- Likelihood fit performed simultaneously to all signal and control regions:
  - main fit parameter: **signal strength $\mu = XS^{VH}/XS_{SM}^{VH}$**
  - **free floating normalisation of leading backgrounds** (W+bb, Z+bb, ttbar)
    - separate normalisation in 2 and 3 jet bins
    - ttbar normalisation uncorrelated between 0-lepton/1-lepton and 2-lepton
  - additional systematic uncertainties included in the likelihood as constrained nuisance parameters: **allowing the data to control the uncertainties**

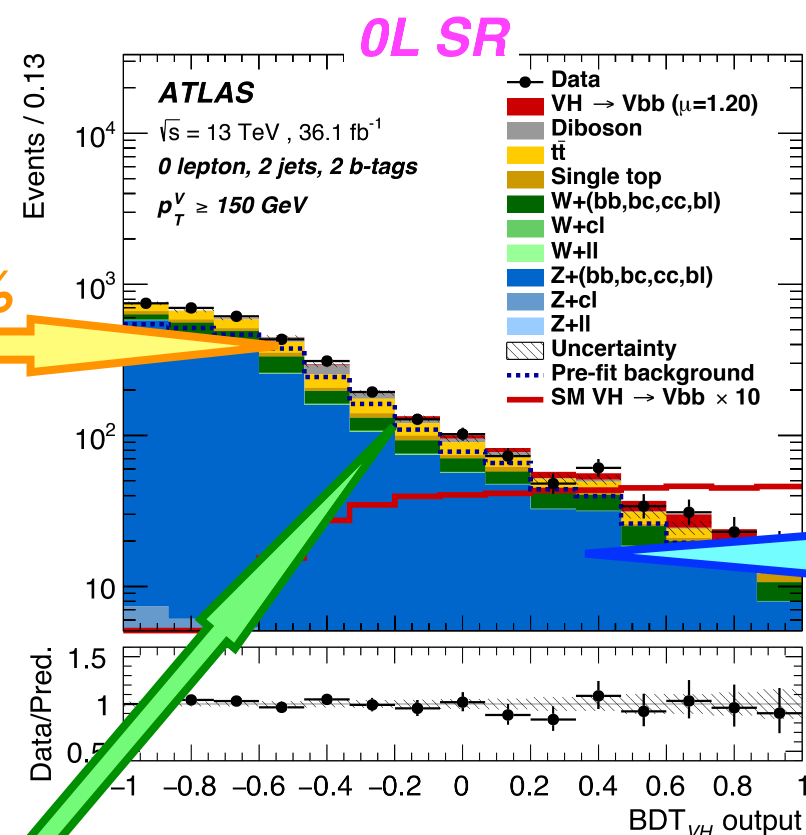
- Modelling uncertainties:
  - for leading backgrounds: **extrapolation uncertainties across regions** (CR->SR, 1L->0L, 2L->0L)
  - **flavour composition** uncertainties for V+jets
  - for small background/signal/diboson: full set of **uncertainties on cross section and acceptance**
  - **shape uncertainties**:
    - parameterised independently as a function of m_{bb} and V p_T [leading variables in the BDT]
    - largest shape among all the possible variation
  - systematic uncertainties on shape and acceptance are treated as uncorrelated

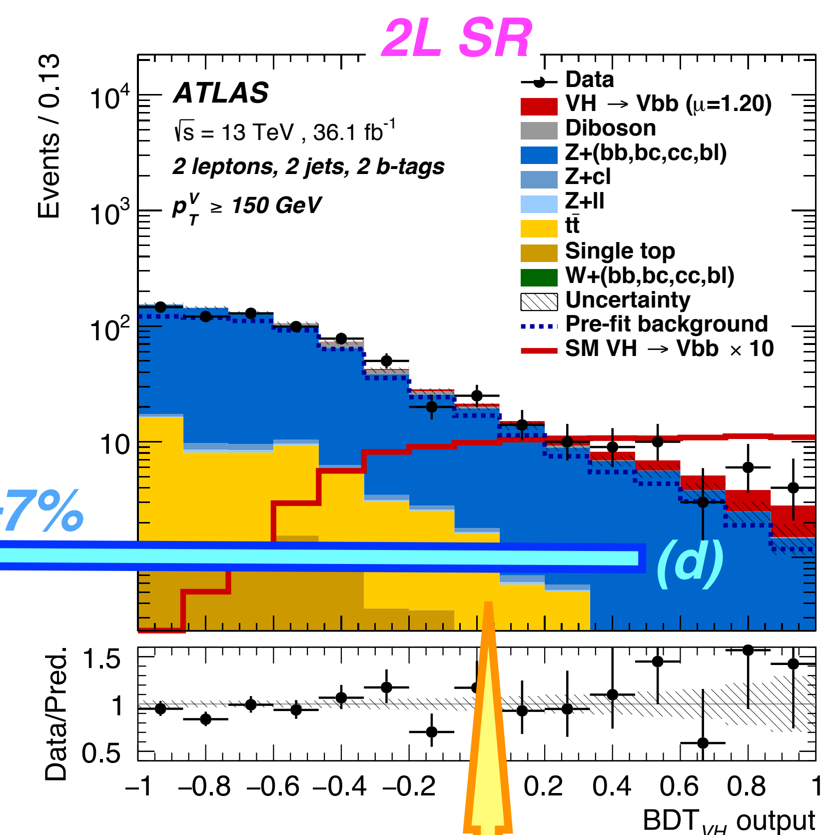
- **In total**: 141 analysis bins, 146 nuisance parameters …..

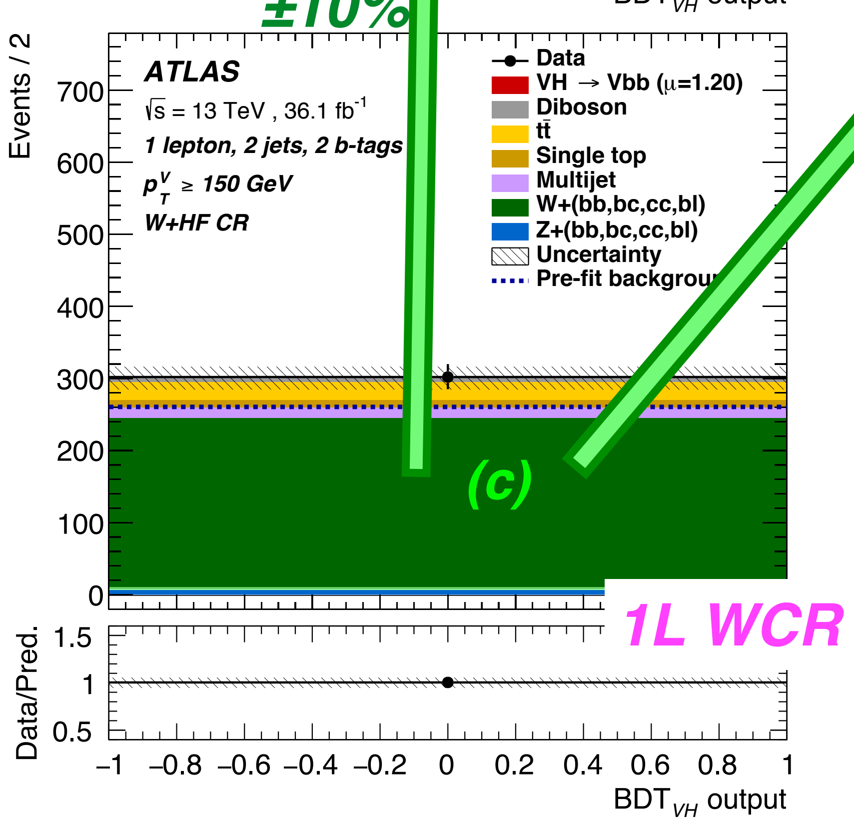
The full fit model (2)

- Warning: slightly simplified version, only 1 jet multiplicity bin shown

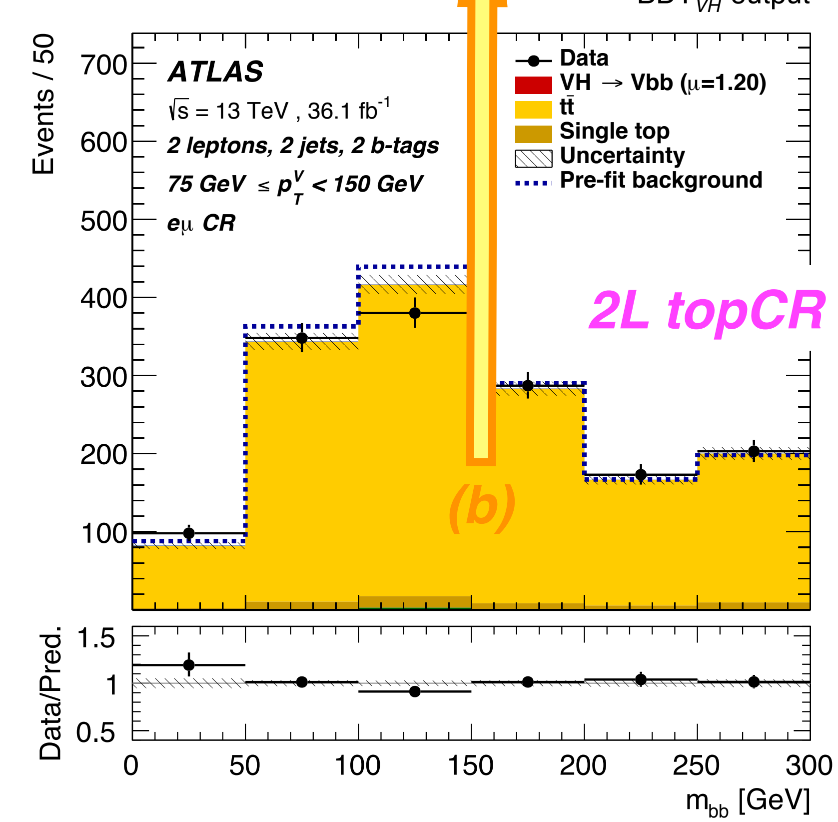








	Process	Normalisation factor
(a)	$t\bar{t}$ 0- and 1-lepton	0.90 ± 0.08
(b)	$t\bar{t}$ 2-lepton 2-jet	0.97 ± 0.09
	$t\bar{t}$ 2-lepton 3-jet	1.04 ± 0.06
(c)	W + HF 2-jet	1.22 ± 0.14
	W + HF 3-jet	1.27 ± 0.14
(d)	Z + HF 2-jet	1.30 ± 0.10
	Z + HF 3-jet	1.22 ± 0.09



W+jets modelling uncertainties

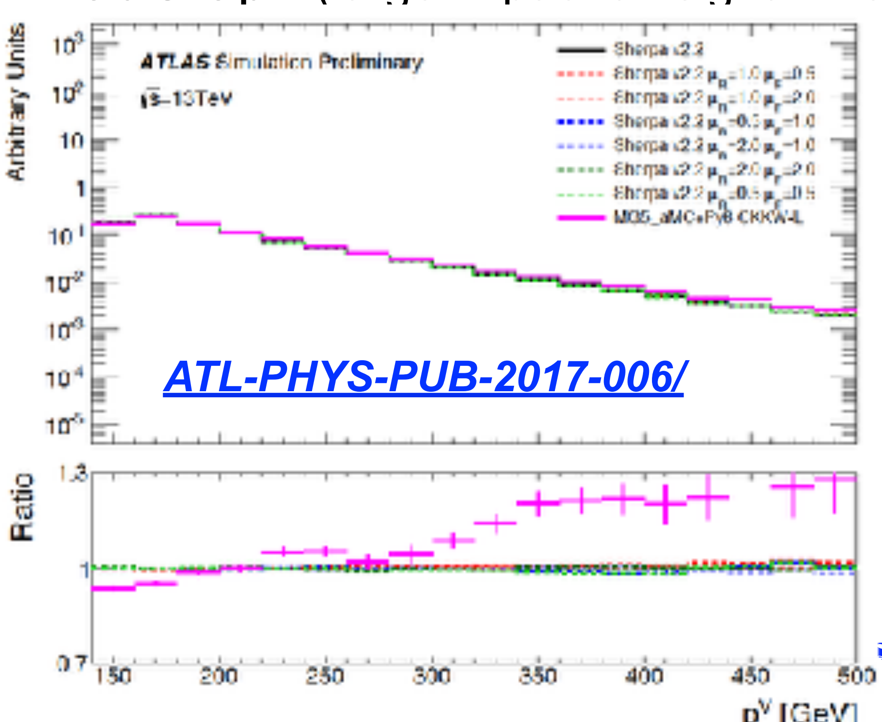
- Nominal sample: ***Sherpa 2.2.1 5F MEPS@NLO*** (0,1,2 parton @NLO, 3,4 @LO)
- Uncertainties variations:
  - fact/ren scale and PDF variations in Sherpa 2.2.1 sample —> subleading effect on shape
  - ckkw and matching scale variation in Sherpa 2.1 sample —> small effect but statistically limited
  - comparison with MadGraph+Pythia8 5F MEPS@LO (up to 4 partons)

	W + jets
$W + ll$ normalisation	32%
$W + cl$ normalisation	37%
$W + bb$ normalisation	Floating (2-jet, 3-jet)
$W + bl$-to-$W + bb$ ratio	26% (0-lepton) and 23% (1-lepton)
$W + bc$-to-$W + bb$ ratio	15% (0-lepton) and 30% (1-lepton)
$W + cc$-to-$W + bb$ ratio	10% (0-lepton) and 30% (1-lepton)
0-to-1 lepton ratio	5%
W + HF CR to SR ratio	10% (1-lepton)

- *analysis dominated by W+bb contribution* (uncertainties on flavour composition are subdominant)
- *floating normalisation of W+HF separately in 2 and 3jets*

W + HF 2-jet	1.22 ± 0.14
W + HF 3-jet	1.27 ± 0.14

- Shape uncertainties are dominated by comparison between Sherpa and MadGraph. Leading contribution to analysis sensitivity comes from differences in W p_T spectrum between Sherpa and MadGraph (large impact on signal-like tail of the BDT)



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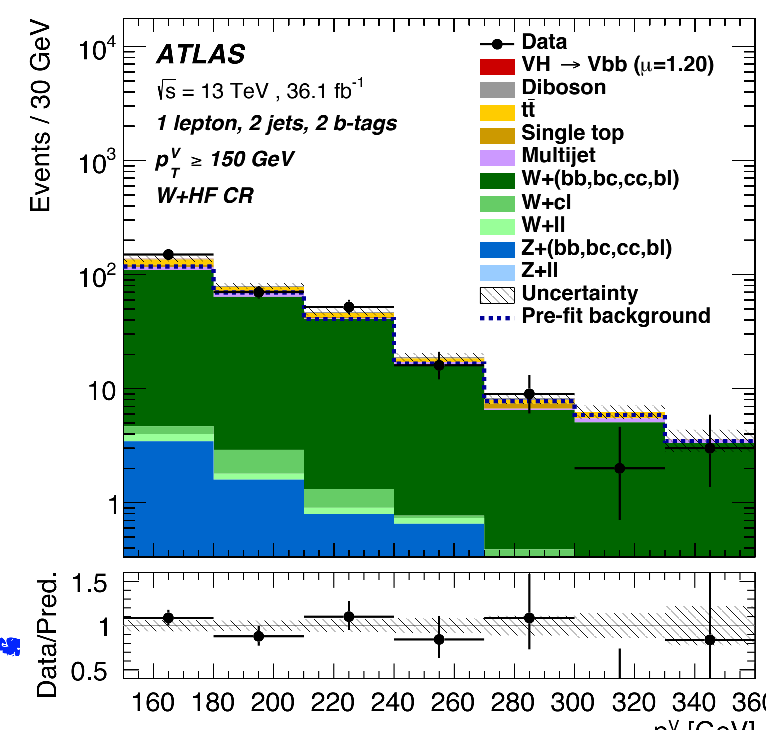
- with more data, the difference could be reduced in the dedicated WCR (not used in current iteration of the analysis)
- … but is such a difference expected??



Z+jets modelling uncertainties

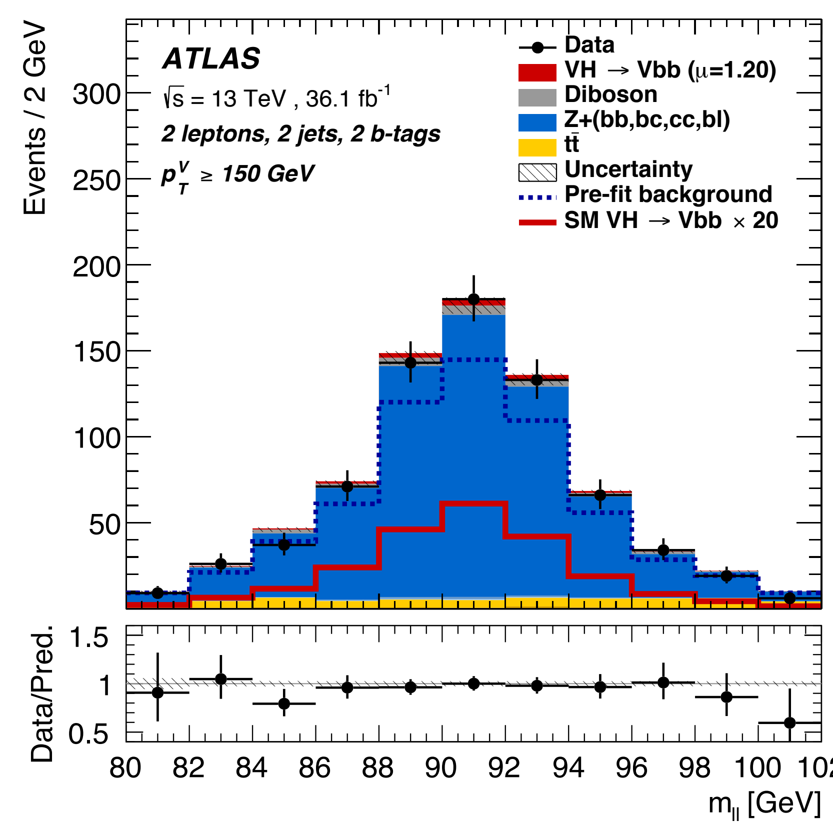
- Exactly same prescriptions as for W+jets in terms of available MC and variations

	Z + jets
$Z + ll$ normalisation	18%
$Z + cl$ normalisation	23%
$Z + bb$ normalisation	Floating (2-jet, 3-jet)
$Z + bc$-to-$Z + bb$ ratio	30 – 40%
$Z + cc$-to-$Z + bb$ ratio	13 – 15%
$Z + bl$-to-$Z + bb$ ratio	20 – 25%
0-to-2 lepton ratio	7%
m_{bb}, p_T^V	S

- *analysis dominated by Z+bb contribution* (uncertainties on flavour composition are subdominant)
- *floating normalisation of W+HF separately in 2 and 3jets*: Sherpa NLO 5F MC consistently underestimates the data as for the W+HF case

Z + HF 2-jet	1.30 ± 0.10
Z + HF 3-jet	1.22 ± 0.09

- 2-lepton SR quite pure in Z+HF thanks to the mll window around the Z peak
- (contrary to W+HF) Z+HF Shape uncertainties extracted in subset of SR:
  - m_{bb} [100-150] veto to remove signal contribution
  - $E_T^{miss}/\mathrm{sqrt}(H_T)<3.5$ to further minimise ttbar contamination
  - data-MC difference taken as the variation for the shape uncertainties: reduced effect w.r.t. MC-MC comparison



- normalisation mainly driven by 2-lepton channel:
  - extrapolation uncertainties to 0-lepton channel computed from MC inputs only using the in the V p_T>150GeV bin

ttbar modelling uncertainties

- 2 different phase space for ttbar in the analysis:
  - ***0+1 lepton***: 4-jet veto selects mainly events with missing ttbar decay products (very different from final state of usual ttbar measurements)
  - ***2 lepton***: more natural ttbar decay topology: 2lep + 2b-jets (+ jets)

  every uncertainty is considered decorrelated between 0+1 lepton and 2-lepton regions

- Nominal sample: ***Powheg (V2)+Pythia8*** (hdamp=1.5*mtop)

- Alternative samples:
  - Parton Shower: Powheg+Herwig7, MatrixElement: aMC@NLO+Pythia8
  - radiation settings (hdamp, μ_R, μ_F, shower tune)

$t\bar{t}$ (all are uncorrelated between the 0+1 and 2-lepton channels)	
$t\bar{t}$ normalisation	Floating (0+1 lepton, 2-lepton 2-jet, 2-lepton 3-jet)
0-to-1 lepton ratio	8%
2-to-3-jet ratio	9% (0+1 lepton only)
W + HF CR to SR ratio	25%
m_{bb}, p_T^V	S

- *Normalisation factors consistent with unity*

$t\bar{t}$ 0- and 1-lepton	0.90 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	0.97 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	1.04 ± 0.06

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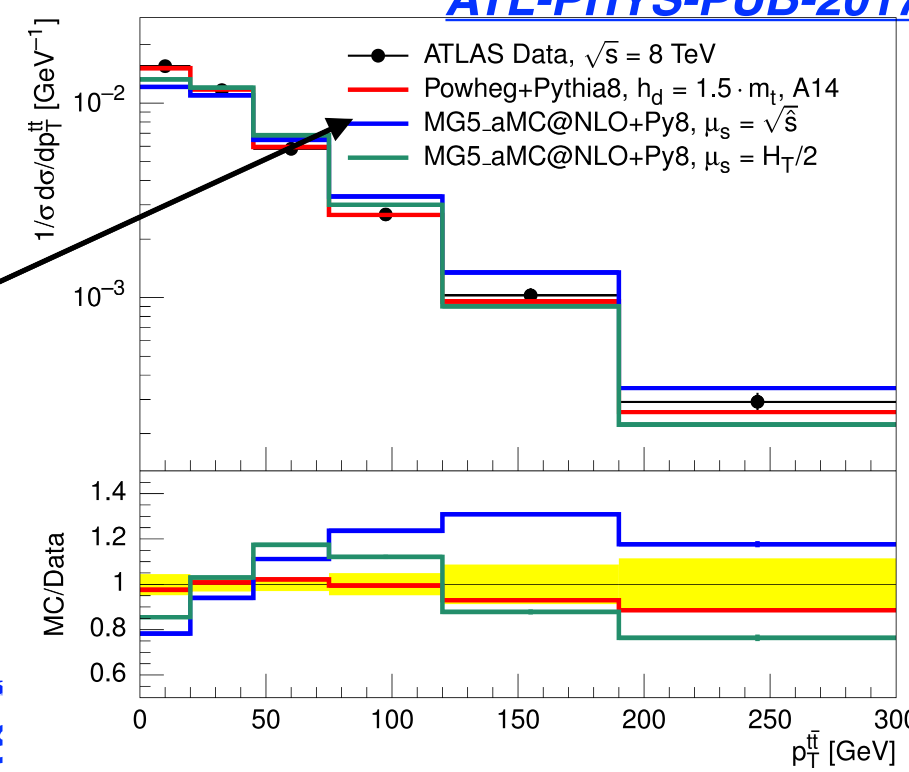
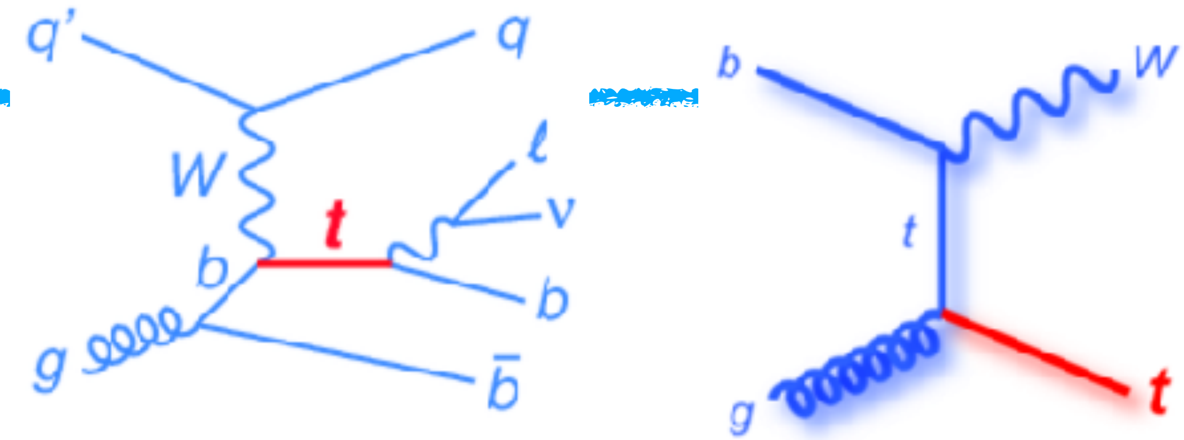


- Extrapolation and shape uncertainties effects *dominated by the differences between Powheg and aMC@NLO*:
  - 2-lepton channel manages to reduce the impact of the uncertainties thanks to the dedicated control region
  - in 0-1 lepton channel: main SR has the largest top contribution

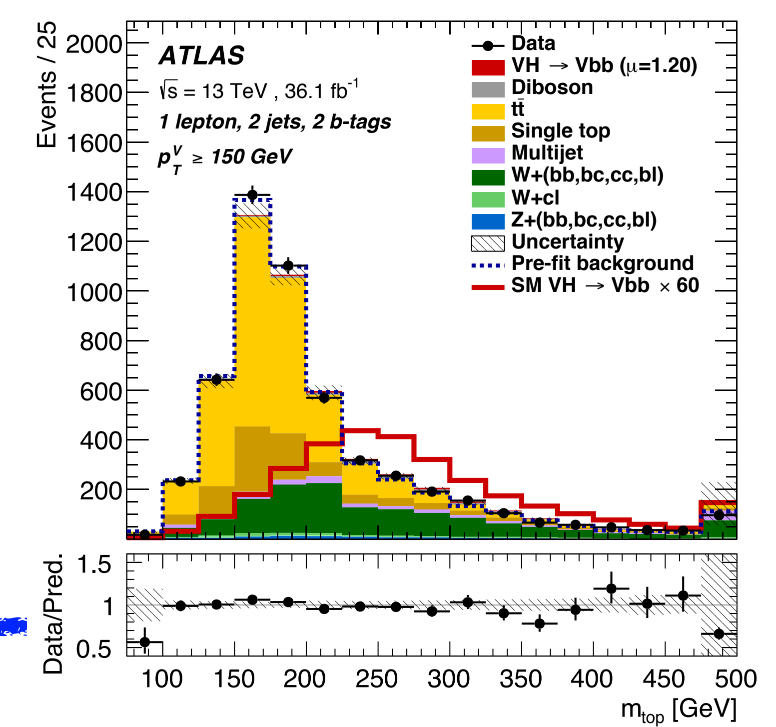
single top modelling



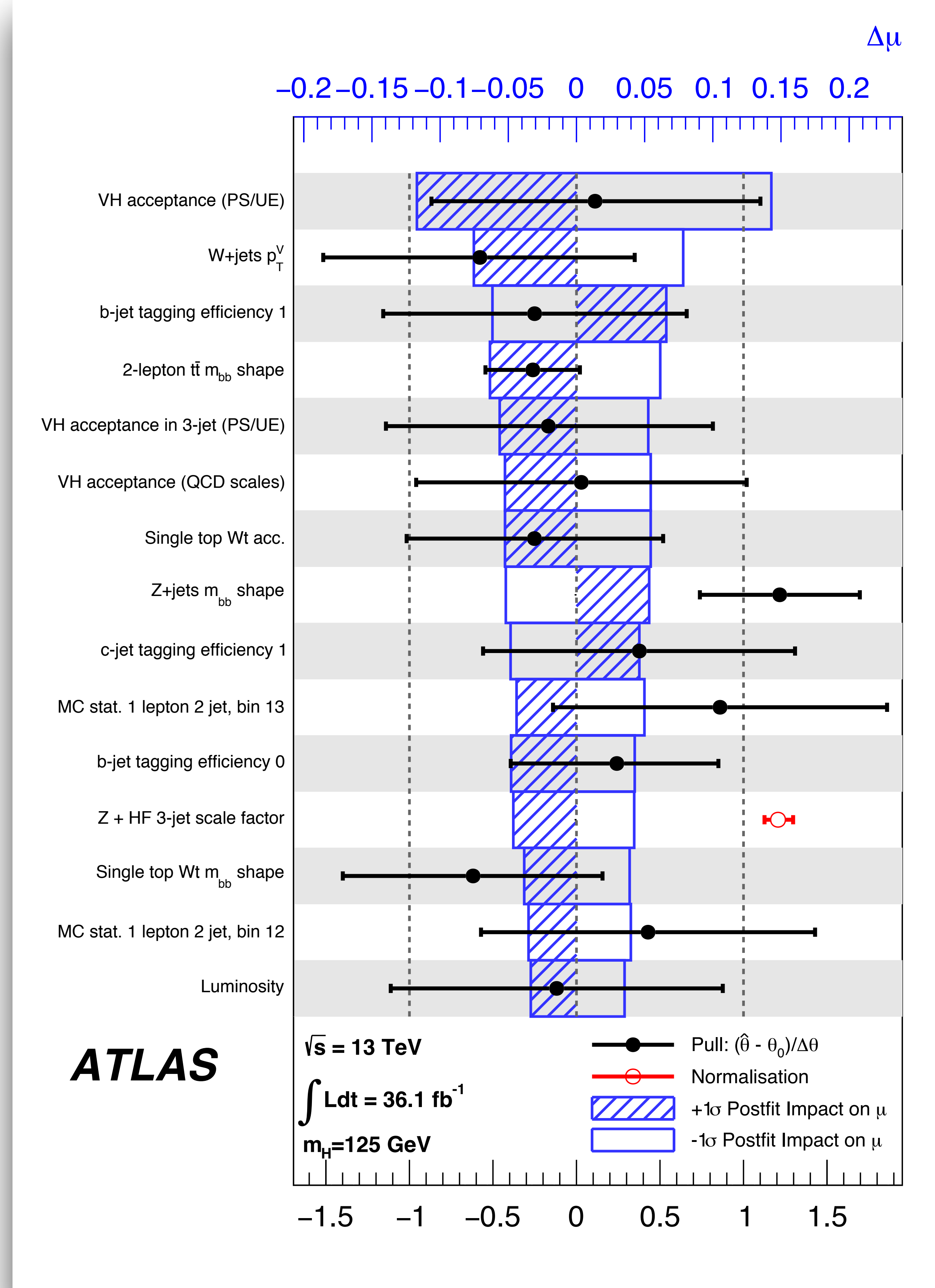
- Solely relevant in the 1-lepton channel:
  - 50/50 contribution between t-channel and Wt
  - Wt more important since it has more signal-like features
- Nominal sample: ***Pohweg+Pythia6*** (diagram removal procedure for Wt)
- Alternative samples:
  - Powheg+Herwig++
  - radiation settings: (hdamp+PS tune)
  - aMC@NLO+Herwig++
  - diagram subtraction procedure for Wt

	Single top quark
Cross-section	4.6% (*s*-channel), 4.4% (*t*-channel), 6.2% (*Wt*)
Acceptance 2-jet	17% (*t*-channel), 35% (*Wt*)
Acceptance 3-jet	20% (*t*-channel), 41% (*Wt*)
m_{bb}, p_T^V	S (*t*-channel, *Wt*)

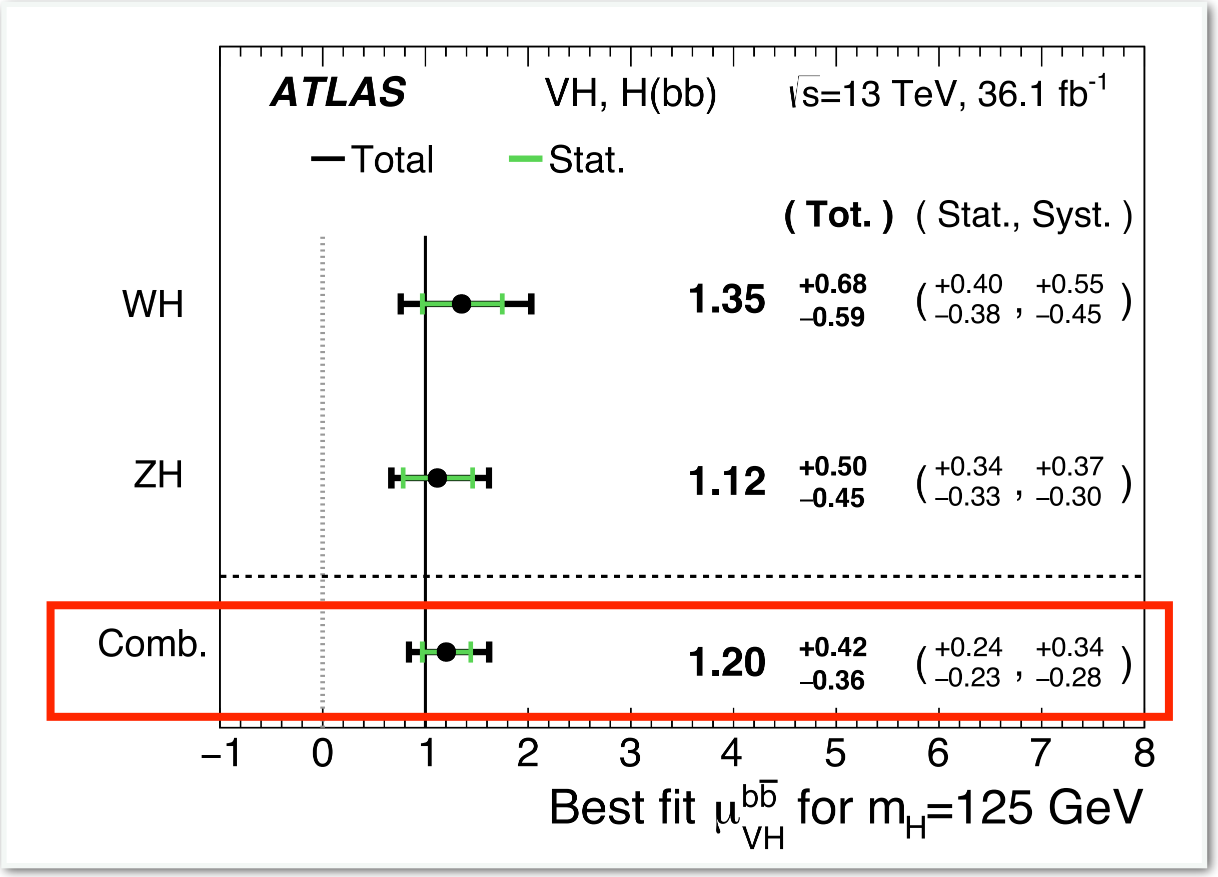
- Wt uncertainties completely driven by comparison of DR-DS schema:
  - strong shape difference in many kinematic quantities (mbb, V pT)
  - further sensitive variable: m_{top} (proxy from) used both in MVA and region definition
- More coherent attempt at Wt+ttbar production being studied in ATLAS, but not yet incorporated in the analysis (see P. Thompson's talk)



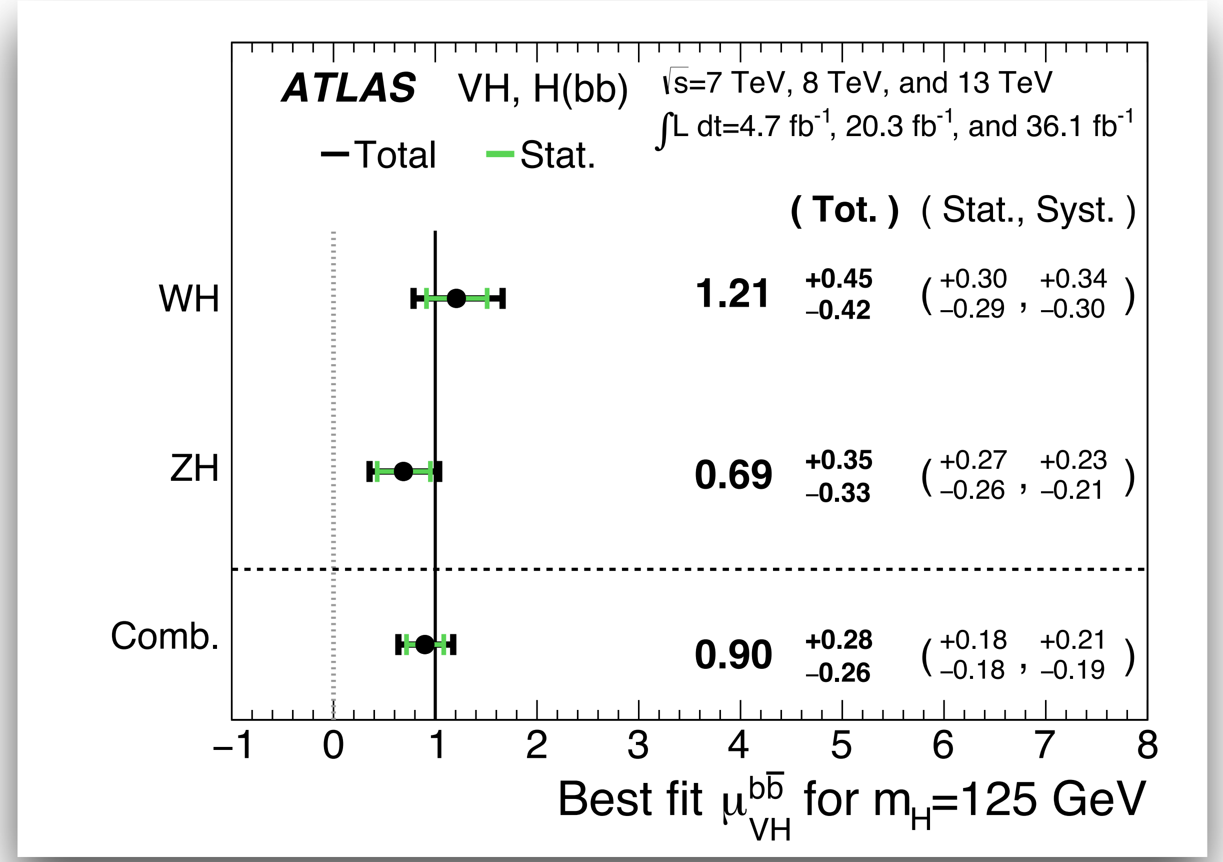
Ranking plot

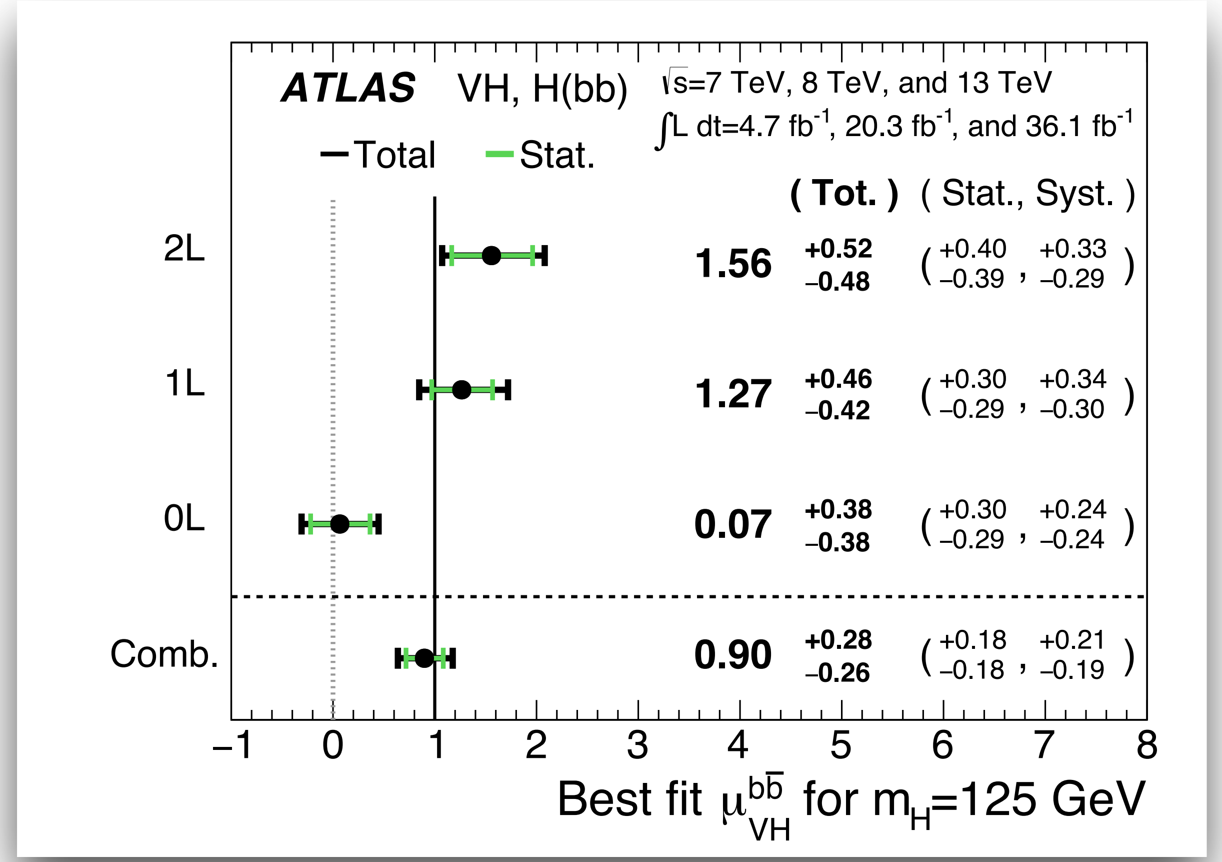


Cross-checks



Run I + Run2 (2)





- **WH-ZH compatibility in combination: 75%**
- **~1% correlation**

- **Channel compatibility in combination: 1.5%**

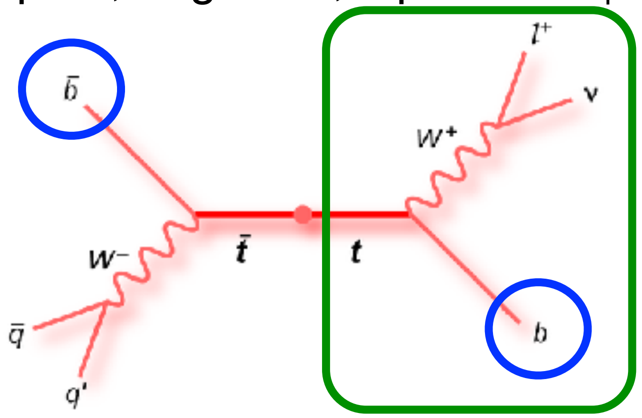
- 0-lepton and 2-lepton while both dominated by ZH, covers different portion of the phase space (2-lepton extends down to lower V p_T)

Signal regions	0-lepton		1-lepton		2-lepton			
	$p_T^V > 150$ GeV, 2-b-tag		$p_T^V > 150$ GeV, 2-b-tag		75 GeV $< p_T^V <$ 150 GeV, 2-b-tag		$p_T^V > 150$ GeV, 2-b-tag	
Sample	2-jet	3-jet	2-jet	3-jet	2-jet	≥3-jet	2-jet	≥3-jet
$Z + ll$	9.0 ± 5.1	15.5 ± 8.1	< 1	–	9.2 ± 5.4	35 ± 19	1.9 ± 1.1	16.4 ± 9.3
$Z + cl$	21.4 ± 7.7	42 ± 14	2.2 ± 0.1	4.2 ± 0.1	25.3 ± 9.5	105 ± 39	5.3 ± 1.9	46 ± 17
Z + HF	2198 ± 84	3270 ± 170	86.5 ± 6.1	186 ± 13	3449 ± 79	8270 ± 150	651 ± 20	3052 ± 66
$W + ll$	9.8 ± 5.6	17.9 ± 9.9	22 ± 10	47 ± 22	< 1	< 1	< 1	< 1
$W + cl$	19.9 ± 8.8	41 ± 18	70 ± 27	138 ± 53	< 1	< 1	< 1	< 1
W + HF	460 ± 51	1120 ± 120	1280 ± 160	3140 ± 420	3.0 ± 0.4	5.9 ± 0.7	< 1	2.2 ± 0.2
Single top quark	145 ± 22	536 ± 98	830 ± 120	3700 ± 670	53 ± 16	134 ± 46	5.9 ± 1.9	30 ± 10
$t\bar{t}$	463 ± 42	3390 ± 200	2650 ± 170	20640 ± 680	1453 ± 46	4904 ± 91	49.6 ± 2.9	430 ± 22
Diboson	116 ± 26	119 ± 36	79 ± 23	135 ± 47	73 ± 19	149 ± 32	24.4 ± 6.2	87 ± 19
Multi-jet e sub-ch.	–	–	102 ± 66	27 ± 68	–	–	–	–
Multi-jet μ sub-ch.	–	–	133 ± 99	90 ± 130	–	–	–	–
Total bkg.	3443 ± 57	8560 ± 91	5255 ± 80	28110 ± 170	5065 ± 66	13600 ± 110	738 ± 19	3664 ± 56
Signal (fit)	58 ± 17	60 ± 19	63 ± 19	65 ± 21	25.6 ± 7.8	46 ± 15	13.6 ± 4.1	35 ± 11
Data	3520	8634	5307	28168	5113	13640	724	3708

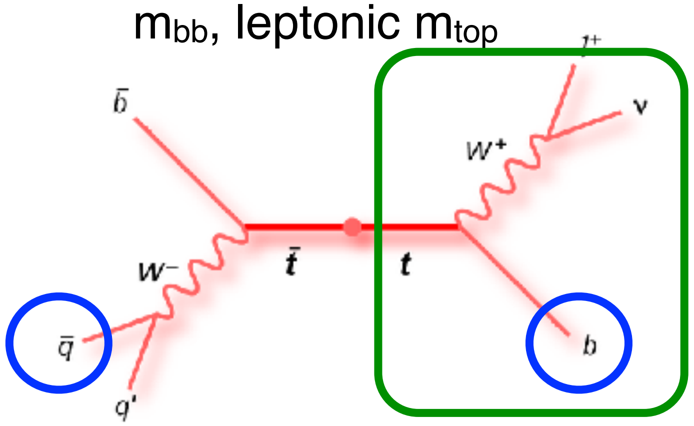
Control regions	1-lepton		2-lepton			
	$p_T^V > 150$ GeV, 2-tag		75 GeV $< p_T^V <$ 150 GeV, 2-tag		$p_T^V > 150$ GeV, 2-tag	
Sample	2-jet	3-jet	2-jet	≥3-jet	2-jet	≥3-jet
$Z + ll$	< 1	< 1	< 1	< 1	< 1	< 1
$Z + cl$	–	< 1	< 1	< 1	< 1	< 1
Z + HF	6.6 ± 0.7	19.3 ± 1.4	2.1 ± 0.2	2.8 ± 0.2	< 1	1.2 ± 0.1
$W + ll$	1.1 ± 0.1	2.9 ± 0.1	–	–	–	–
$W + cl$	2.6 ± 1.1	8.7 ± 3.7	–	–	–	–
W + HF	234 ± 21	594 ± 45	3.0 ± 0.3	2.7 ± 0.3	< 1	< 1
Single top quark	10.3 ± 2.8	40 ± 14	50 ± 15	127 ± 45	5.8 ± 1.8	27.9 ± 9.8
$t\bar{t}$	24.8 ± 7.8	107 ± 29	1437 ± 41	4852 ± 85	48.8 ± 3.8	431 ± 21
Diboson	5.6 ± 1.9	12.1 ± 4.2	–	< 1	–	–
Multi-jet e sub-ch.	8.2 ± 5.3	2.2 ± 5.6	–	–	–	–
Multi-jet μ sub-ch.	6.8 ± 5.1	3.7 ± 5.4	–	–	–	–
Total bkg.	300 ± 16	791 ± 27	1492 ± 37	4985 ± 68	55.2 ± 3.9	461 ± 19
Signal (fit)	< 1	1.2 ± 0.4	< 1	< 1	< 1	< 1
Data	302	790	1489	4967	50	470

ttbar in 1L

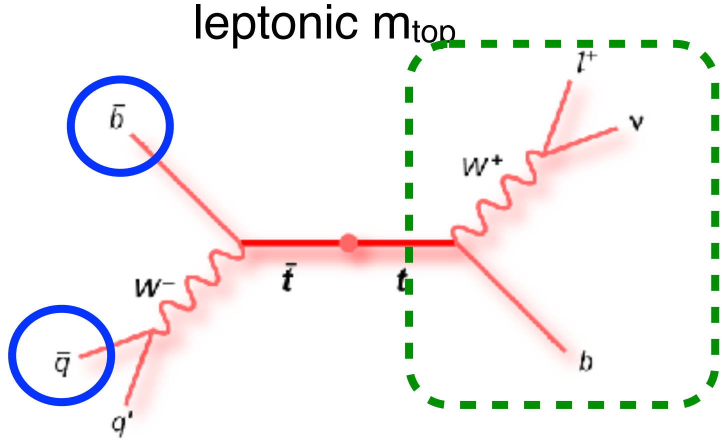
ttbar_bb: similar for ttbar dilepton, large m_{bb}, leptonic m_{top}



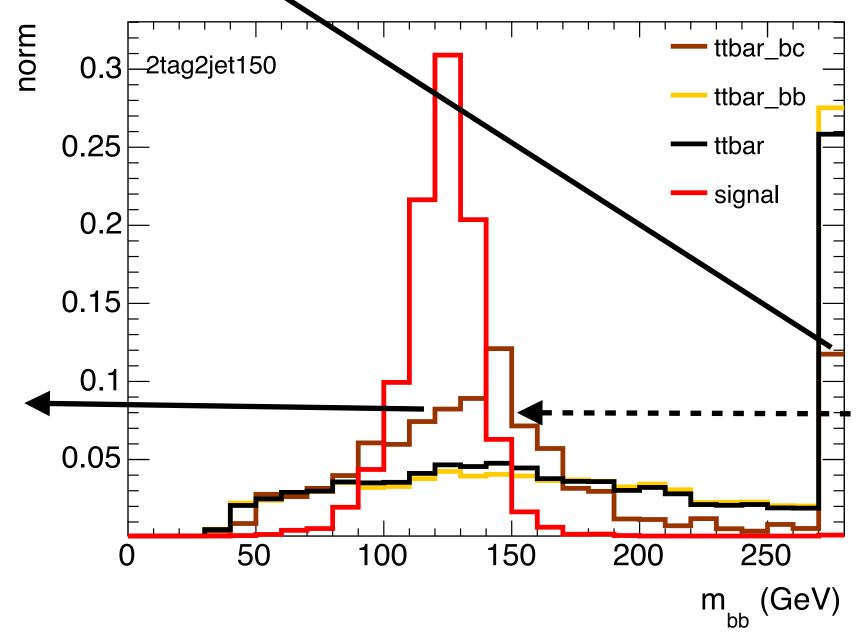
ttbar_bc (1): less likely for dilepton (unless tt+c), still large m_{bb}, leptonic m_{top}

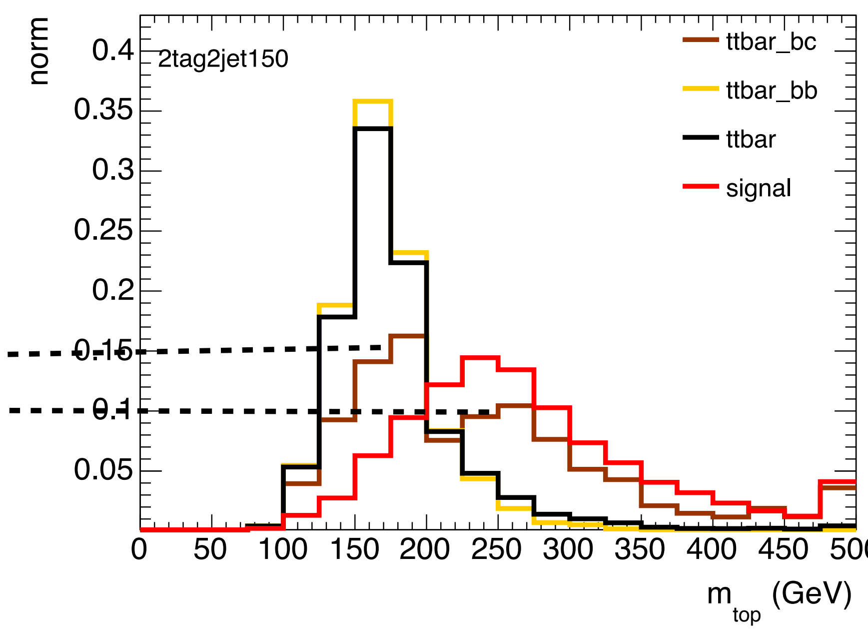


ttbar_bc (2): less likely for dilepton (unless tt+c), smaller m_{bb}, no leptonic m_{top}

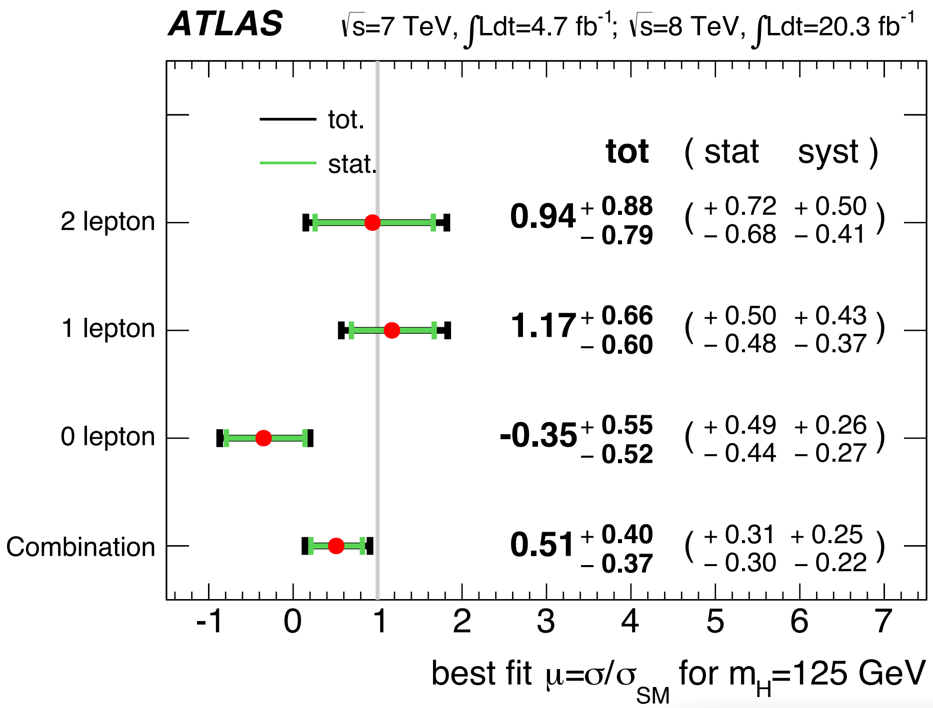


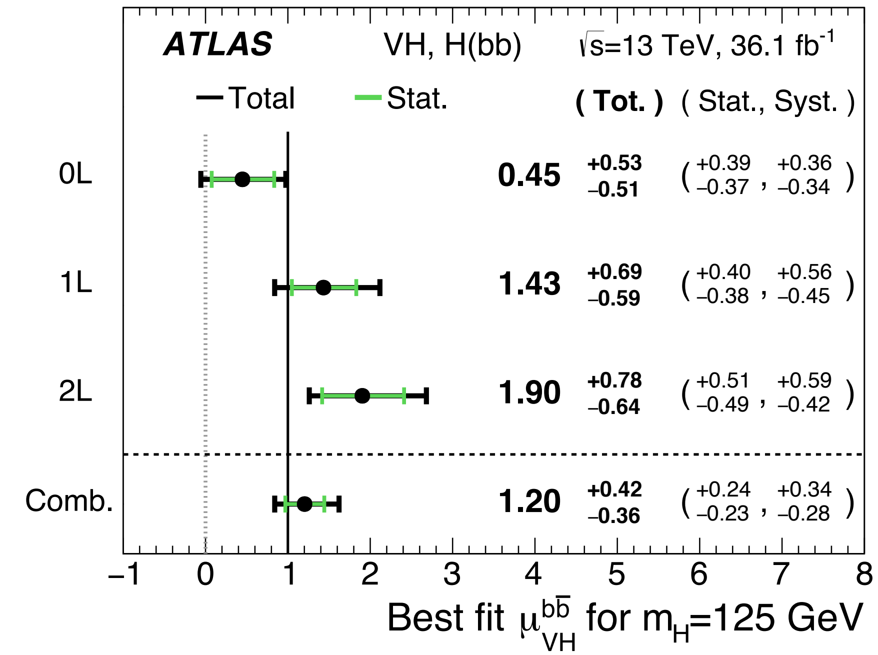
- Different types of ttbar events can pass the 1L selection:
  - classified by the flavour of the selected jets
  - ttbar_bb:
    - dominant category (include also di-leptonic contribution)
    - invariant mass of b-jet is large
    - further discriminated with ***leptonic top reconstruction*** (mtop)
  - ttbar_bc:
    - hadronic W is the largest source of c-jet
    - much smaller contribution but brings dependency on c-jet calibration
    - …. but ttbar_bc (2) is significantly more signal-like in mbb and mtop

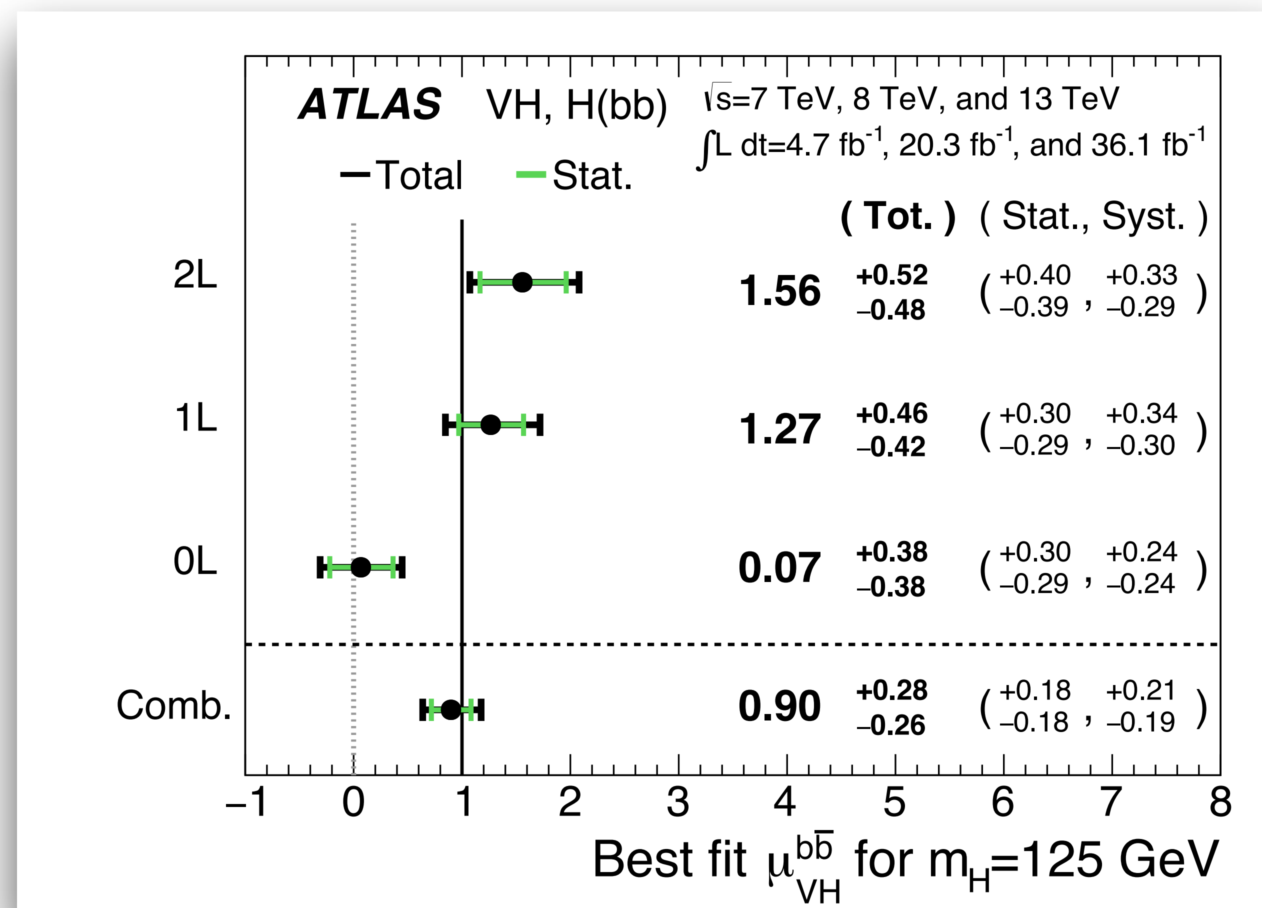




Something to keep an eye on







- **Channel compatibility in combination: 1.5%**

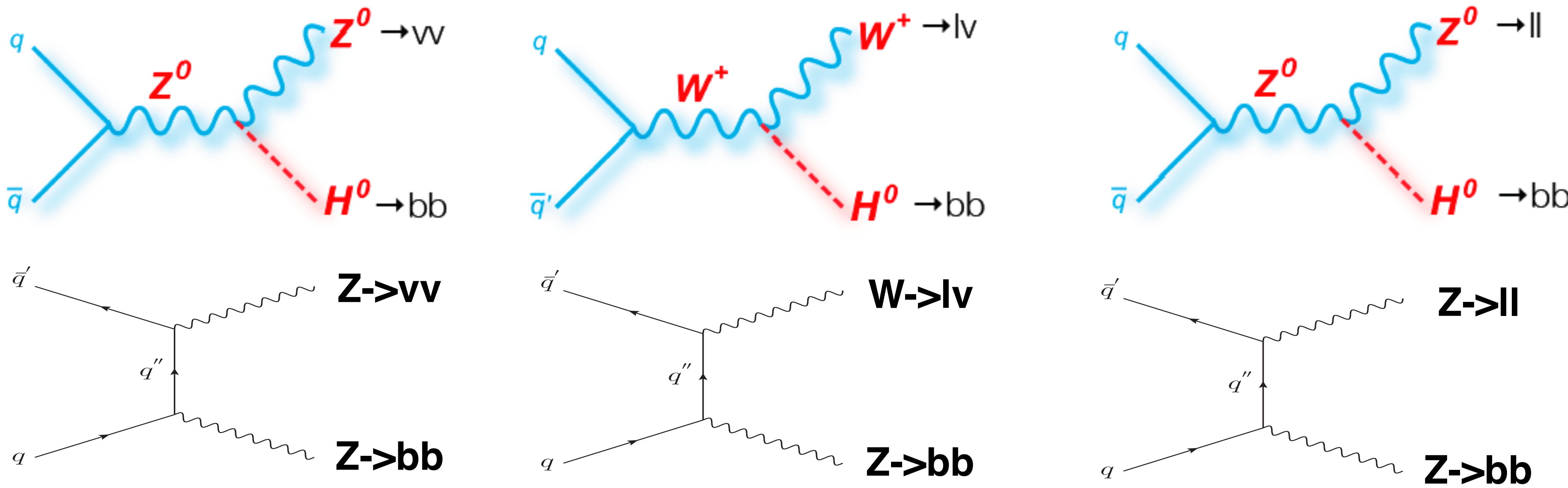
- 0-lepton and 2-lepton while both dominated by ZH, covers different portion of the phase space (2-lepton extends down to lower V p_T)

✦ Validating the MVA analysis: **V+Z->bb** is irreducible background with a peak in m_{bb}

Larger x-sec for VZ

$Br(H_{bb})/Br(Z_{bb})$~4

High V p_T selection favours VH



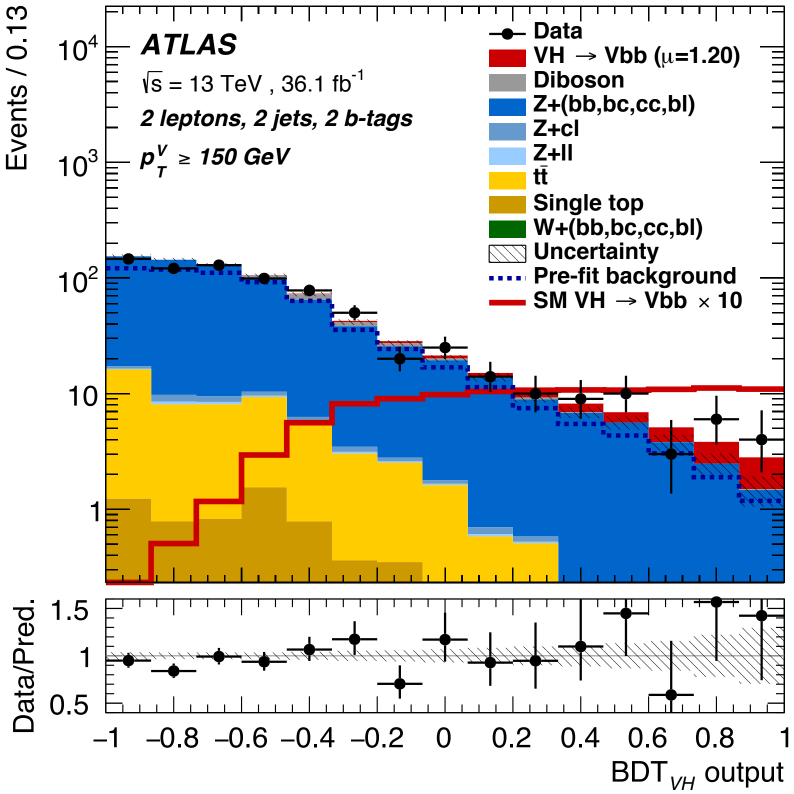
✦ yields ratio in SR: *ZZ/ZH~2* *WZ/WH~1* *ZZ/ZH~2-3*

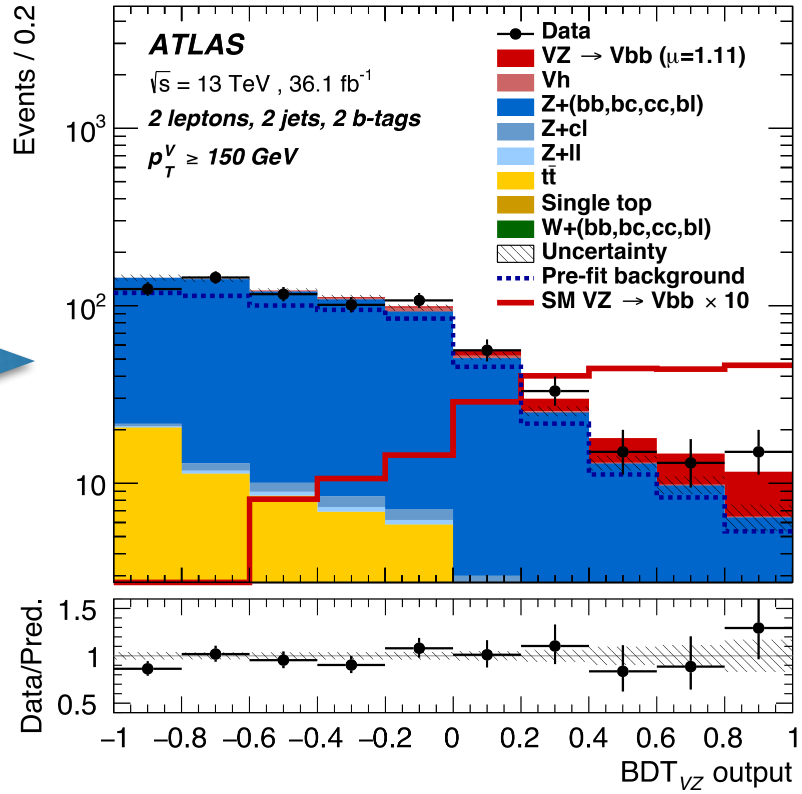
✦ Same region definition

✦ Same event selection

✦ Same analysis model

✦ BDT is retrained (with the SAME variables) for diboson VS background separation



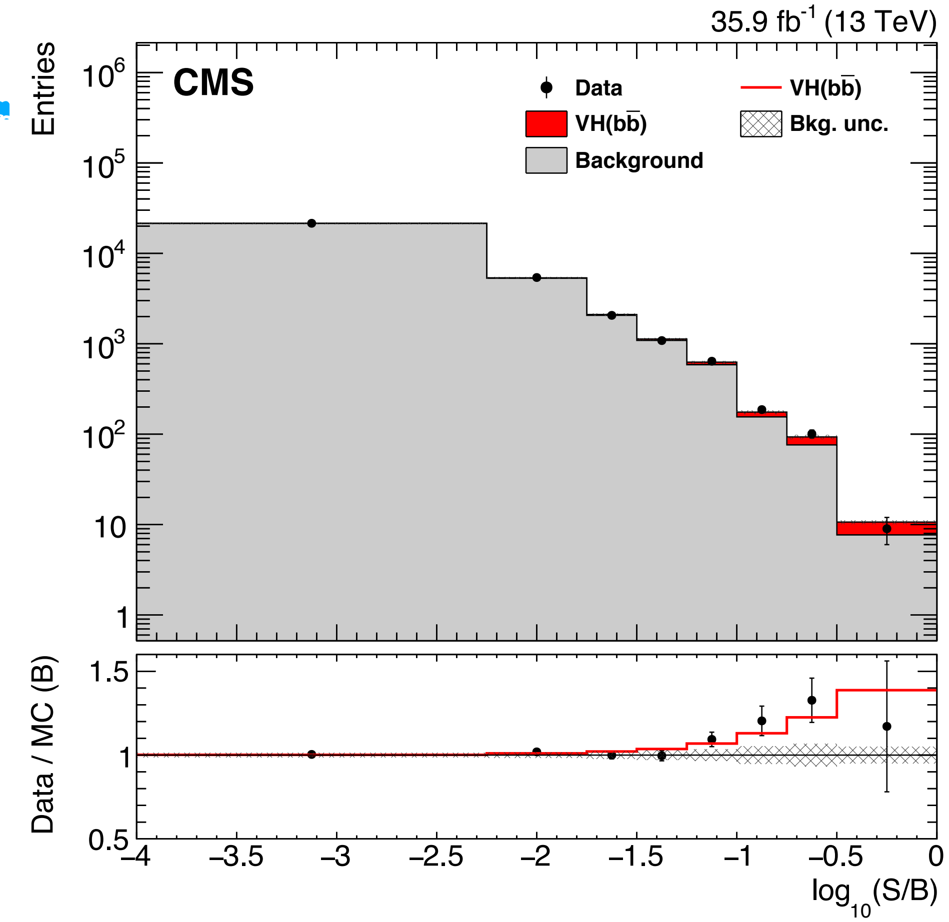


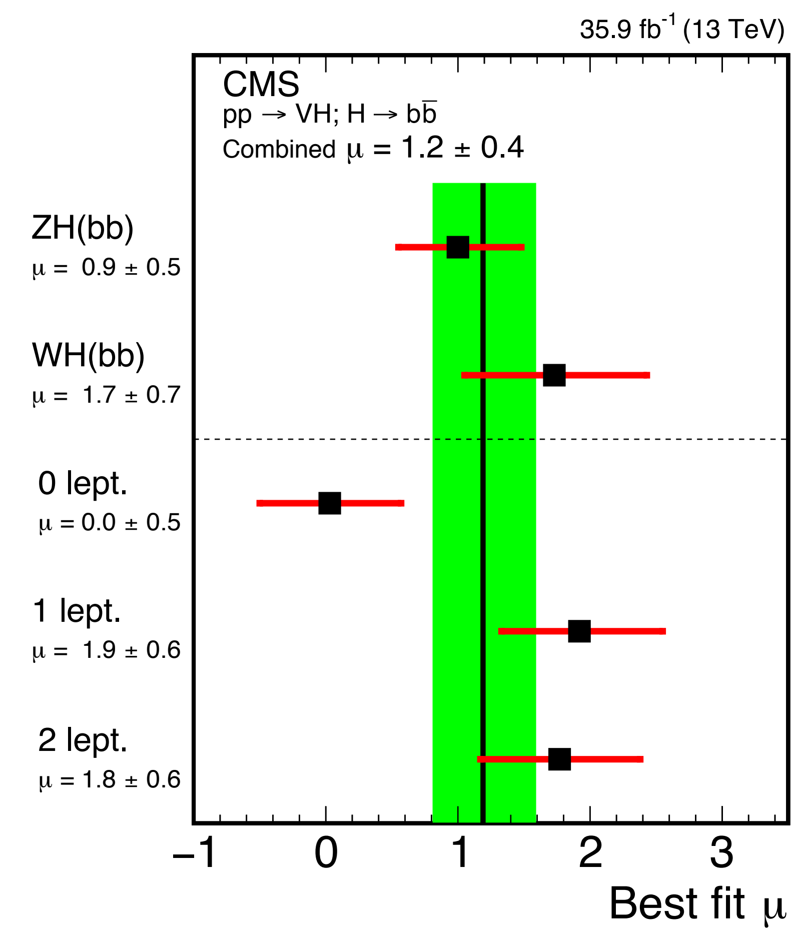
VHbb: ATLAS VS CMS

- Analysis also performed by CMS ([Phys. Lett. B 780 (2018) 501]) : identical dataset and Run1+Run2 combination

	ATLAS	CMS
Run2 exp. sig	3.0 s.d.	2.8 s.d.
Run2 obs. sig	3.5 s.d.	3.3 s.d.
Run2 μ_{VHbb}	1.2 ± 0.4	1.2 ± 0.4
Run1+Run2 exp. sig	4.0 s.d.	3.8 s.d.
Run1+Run2 obs. sig	3.6 s.d.	3.8 s.d.
Run1+Run2 μ_{VHbb}	0.90 ± 0.27	1.06 ± 0.30

- Quite some different analysis choices by CMS (tighter preselection, many more control regions) … but similar sensitivity **… and compatible measured signal strength**



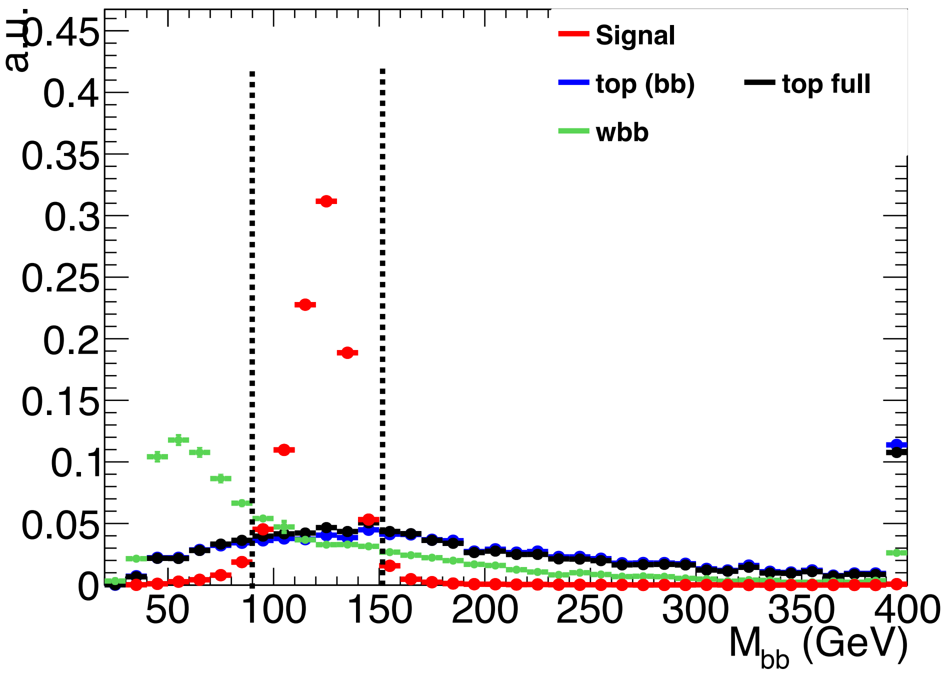


event selection

- ATLAS:

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 medium 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 or 3 jets			Exactly 2 or ≥ 3 jets
Jet p_T	> 20 GeV			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_T	> 45 GeV			
H_T	> 120 (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\vec{E}_T^{miss}, \vec{jets})]$	$> 20°$ (2 jets), $> 30°$ (3 jets)	–		–
$\Delta\phi(\vec{E}_T^{miss}, \vec{bb})$	$> 120°$	–		–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140°$	–		–
$\Delta\phi(\vec{E}_T^{miss}, \vec{E}_{T,trk}^{miss})$	$< 90°$	–		–
p_T^V regions	> 150 GeV			(75, 150] GeV, > 150 GeV
Signal regions	✓	$m_{bb} \geq 75$ GeV or $m_{top} \leq 225$ GeV		Same-flavour leptons Opposite-sign charge ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{top} > 225$ GeV		Different-flavour leptons

- Even more complicated is the *mbb window definition*: CMS defines the SR in relatively narrow m_{bb} window … while ATLAS is not applying any cut on it



- Furthermore, in the SR, CMS is fitting the BDT after already cutting on it??

- CMS

Variable	0-lepton	1-lepton	2-lepton
$p_T(V)$	> 170	> 100	$[50, 150], > 150$
$M(\ell\ell)$	-	-	$[75, 105]$
p_T^ℓ	-	$(> 25, > 30)$	> 20
$p_T(j_1)$	> 60	> 25	> 20
$p_T(j_2)$	> 35	> 25	> 20
$p_T(jj)$	> 120	> 100	-
$M(jj)$	$[60, 160]$	$[90, 150]$	$[90, 150]$
$CMVA_{max}$	> 0.9432	> 0.9432	> -0.5884
$CMVA_{min}$	> -0.5884	> -0.5884	> -0.5884
N_{aj}	< 2	< 2	-
N_{al}	$= 0$	$= 0$	-
E_T^{miss}	> 170	-	-
Anti-QCD	Yes	-	-
$\Delta\phi(V, H)$	> 2.0	> 2.5	> 2.5
$\Delta\phi(E_T^{miss}, E_T^{miss}{}_{trk})$	< 0.5	-	-
$\Delta\phi(E_T^{miss}, \ell)$	-	< 2.0	-
Lepton Isolation	-	< 0.06	-
Event BDT	> -0.8	> 0.3	> -0.8

Variable	Channels utilizing
$M(\mathrm{jj})$: dijet invariant mass	All
$p_T(\mathrm{jj})$: dijet transverse momentum	All
$p_T(V)$: vector boson transverse momentum	All
$\mathrm{CMVA_{max}}$: value of CMVA for the Higgs boson daughter with largest CSV value	2-lepton, 0-lepton
$\mathrm{CMVA_{min}}$: value of CMVA for the Higgs boson daughter with second largest CSV value	All
$\mathrm{CMVA_{add}}$: value of CMVA for the additional jet with largest CSV value	0-lepton
$\Delta\phi(\mathrm{V,H})$: azimuthal angle between V and dijet	All
$p_T(j)$: transverse momentum of each Higgs boson daughter	2-lepton, 0-lepton
$p_T(\mathrm{add.})$: transverse momentum of leading additional jet	0-lepton
$\Delta\eta(\mathrm{jj})$: difference in η between Higgs boson daughters	2-lepton, 0-lepton
$\Delta R(\mathrm{jj})$: distance in η–ϕ between Higgs boson daughters	2-lepton
N_{aj}: number of additional jets N.B. definition slightly different per channel	1-lepton, 2-lepton
$p_T(\mathrm{jj})/p_T(\mathrm{V})$: p_T balance between Higgs boson candidate and vector boson	2-lepton
M_Z: Z boson mass	2-lepton
SA5: number of soft activity jets with $p_T > 5\,\mathrm{GeV}$ *basically track jets*	All
M_t: reconstructed top quark mass	1-lepton
$\Delta\phi(E_T^{miss}, \ell)$: azimuthal angle between E_T^{miss} and lepton	1-lepton
E_T^{miss}: missing transverse energy	1-lepton, 2-lepton
$m_T(W)$: W transverse mass	1-lepton
$\Delta\phi(\mathrm{jj})$: difference in ϕ between Higgs boson daughters	0-lepton
$\Delta\phi(E_T^{miss}, \mathrm{jet.})$: azimuthal angle between E_T^{miss} and the closest jet with $p_T > 30\,\mathrm{GeV}$	0-lepton

BDT

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

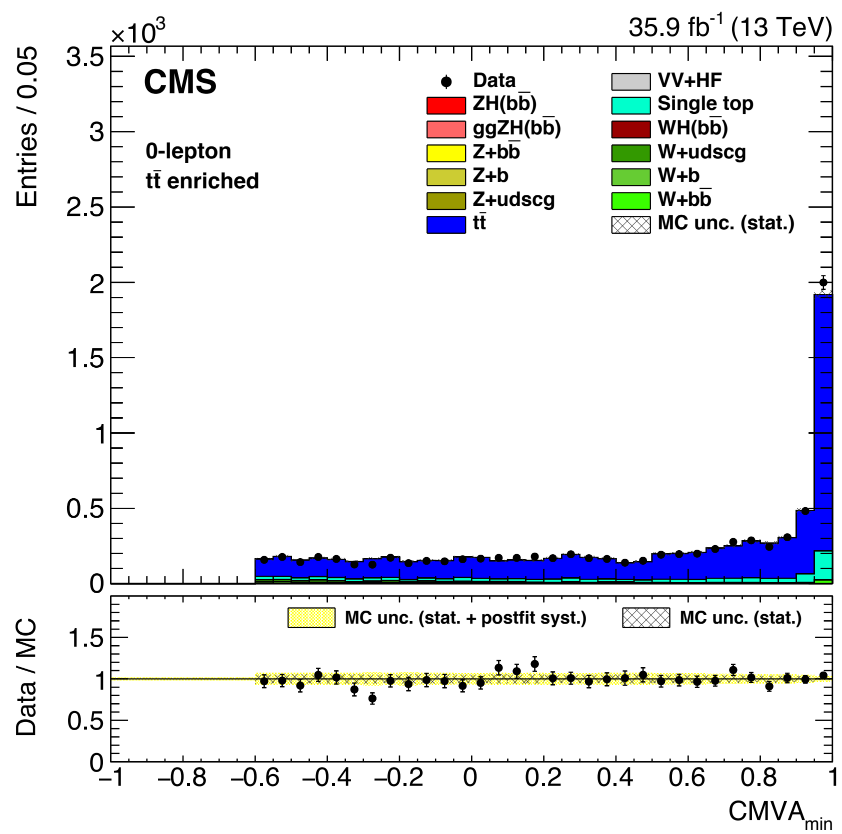
- New variables from CMS:
  - PCB b-tagging: with pros' and cons
  - pT(jj): but then why also having ptjj/PtV if you have both already?
  - soft track jets (more effective against ttbar?)
  - some redundant variable for extra QCD rejection?

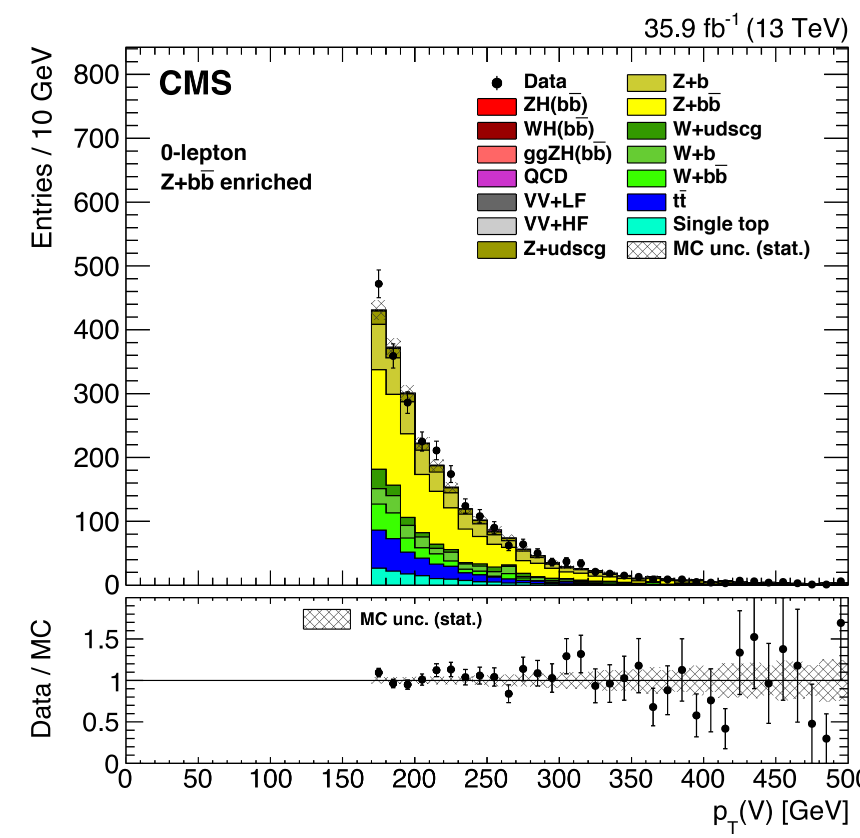
Region definition: 0L

- **0L**: similar bb / Vpt selection as SR
  - ***ttbar CR***: this is actually a 1L+4jets selection (??) with looser cut on METcleaning
  - ***Z+light CR***:
    - anti-tight b-tag selection
    - removing 4j events
  - ***Z+HF CR***:
    - using mbb sidebands
    - removing >3j events

Variable	$t\bar{t}$	Z+LF	Z+HF
V decay category	$W(\ell\nu)$	$Z(\nu\nu)$	$Z(\nu\nu)$
$p_T(j_1)$	>60	>60	>60
$p_T(j_2)$	>35	>35	>35
$p_T(jj)$	>120	>120	>120
p_T^{miss}	>170	>170	>170
$\Delta\phi(V,jj)$	>2	>2	>2
$N_{a\ell}$	≥ 1	=0	=0
N_{aj}	≥ 2	≤ 1	≤ 1
$M(jj)$	—	—	$\notin [60-160]$
$CMVA_{max}$	$>CMVA_M$	$<CMVA_M$	$>CMVA_T$
$CMVA_{min}$	$>CMVA_L$	$>CMVA_L$	$>CMVA_L$
$\Delta\phi(j,\vec{p}_T^{miss})$	—	>0.5	>0.5
$\Delta\phi(\vec{p}_T^{miss},\vec{p}_T^{miss}(trk))$	—	<0.5	<0.5
$\min\Delta\phi(j,\vec{p}_T^{miss})$	$<\pi/2$	—	—

- Comments:
  - huge stat. in top CR … but the extrapolation might be huge … (both through nJet and nLep)
  - Z+HF region not that pure
  - there are always some non trivial njet extrapolation involved in their definition of CR



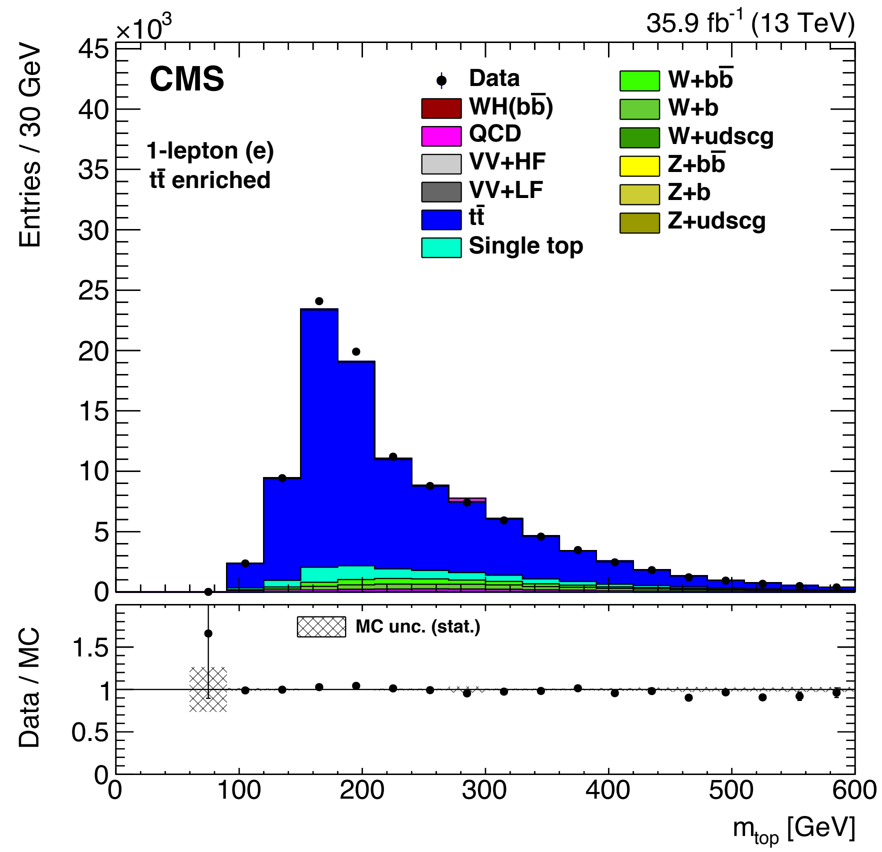


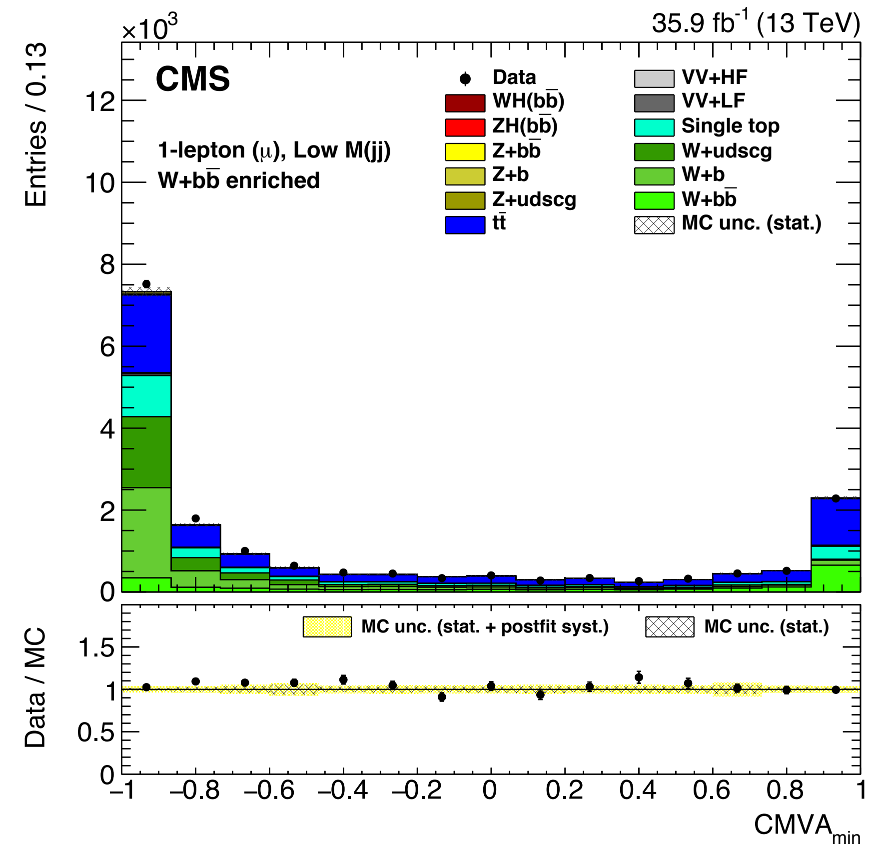
Region definition: 1L

- **1L**: similar bb / Vpt selection as SR
  - ***ttbar CR***: 4J selection + mbb<250 [need to check orthogonality with 0L top CR]
  - ***W+light CR***:
    - anti-tight b-tag selection
    - 2j events
    - mbb<250
  - ***W+HF CR***:
    - using mbb sidebands
    - 2j events only

Variable	$t\bar{t}$	W+LF	W+HF
$p_T(j_1)$	>25	>25	>25
$p_T(j_2)$	>25	>25	>25
$p_T(jj)$	>100	>100	>100
$p_T(V)$	>100	>100	>100
$CMVA_{max}$	$>CMVA_T$	$[CMVA_L, CMVA_M]$	$>CMVA_T$
N_{aj}	>1	—	$=0$
$N_{a\ell}$	$=0$	$=0$	$=0$
$\sigma(p_T^{miss})$	—	>2.0	>2.0
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	<2	<2	<2
$M(jj)$	<250	<250	<90, $[150, 250]$

- Comments:
  - huge stat. in top CR … but the extrapolation might be huge … (thgouth nJet)
  - W+HF CR is a bit of a mess [and it's further split in low and high mjj]
  - there are always some non trivial njet extrapolation involved in their definition of CR

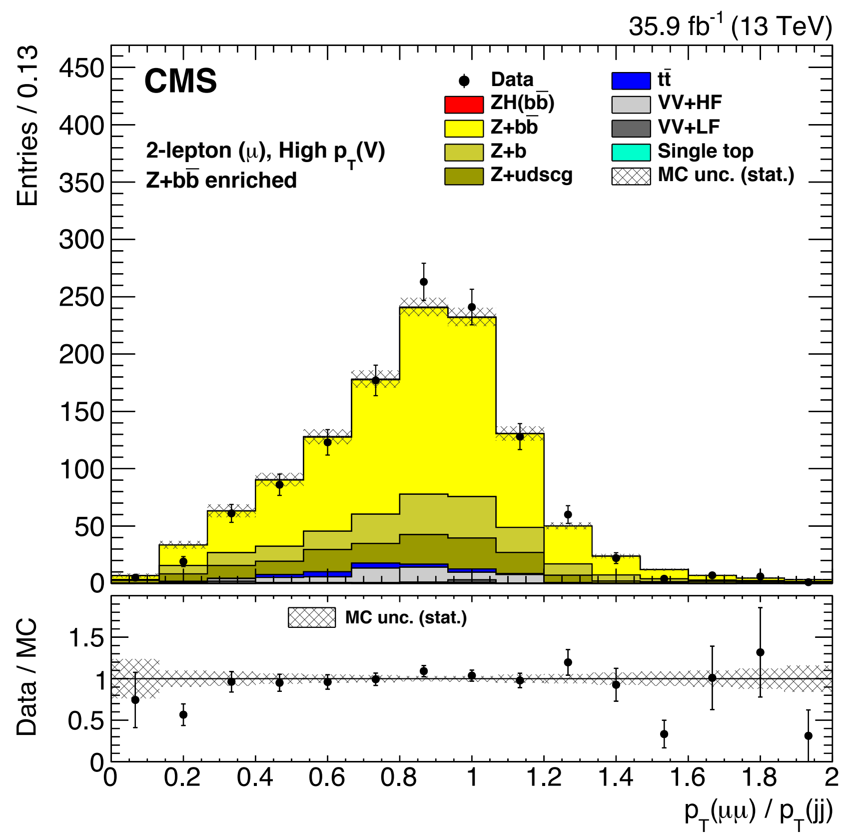


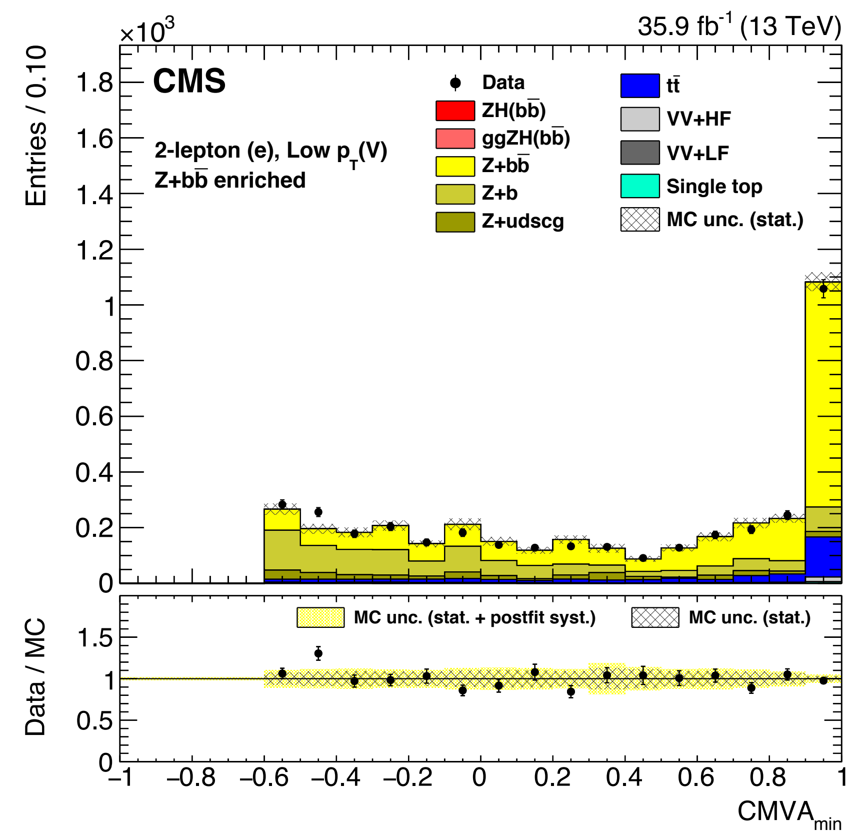


Region definition: 2L

- **2L**: similar bb / Vpt selection as SR
  - tighter btag selection in tt and Z+hf
  - ***ttbar CR***: mll sidebands
  - ***Z+light CR***:
    - anti-tight b-tag selection
    - 2j events
    - mbb<250
  - ***Z+HF CR***:
    - using mbb sidebands
    - METsig cuts
    - tighter mll

Variable	$t\bar{t}$	Z+LF	Z+HF
$p_T(jj)$	> 100	> 100	-
$p_T(V)$	$[50, 150], > 150$	$[50, 150], > 150$	$[50, 150], > 150$
$CMVA_{max}$	> 0.9432	< 0.9432	> 0.9432
$CMVA_{min}$	> -0.5884	< -0.5884	> -0.5884
N_{aj}	-	-	-
N_{al}	-	-	-
E_T^{miss}	-	-	< 60
$\Delta\phi(V,H)$	-	-	> 2.5
$M(\ell\ell)$	$\notin [0, 10], \notin [75, 120]$	$[75, 105]$	$[85, 97]$
$M(jj)$	-	-	$\notin [90, 150]$





- Comments:
  - why using mll extrapolation in topCR when you have em?
  - not a fantastic purity in the Zhf CR

"***Sensitivity*** might not require extreme ***Precision***"

M. Mangano's talk

$$\delta O_Q \sim \left(\frac{Q}{\Lambda}\right)^2$$

size of deviation

scale of your analysis

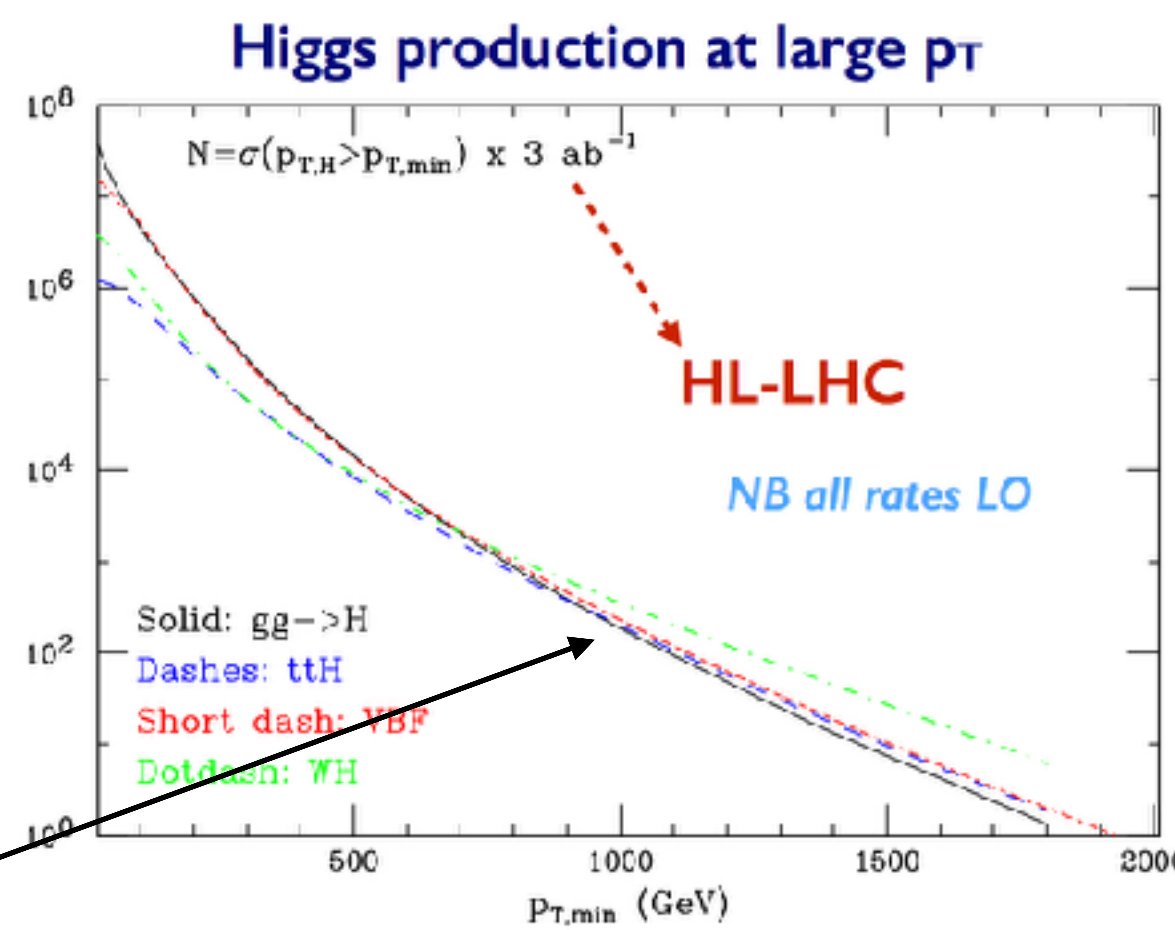
NP scale

- Probing higher scale in the analysis makes you mode ***sensitive*** to NP therefore you can afford to be less **precise**

- One example:
  - *3% uncertainty for p_T>150GeV : probes scales up to 890 GeV*
  - *10% uncertainty for p_T>600GeV : probes scales up to 1800 TeV*
  - *an analysis 3 times less precise has twice the sensitivity*

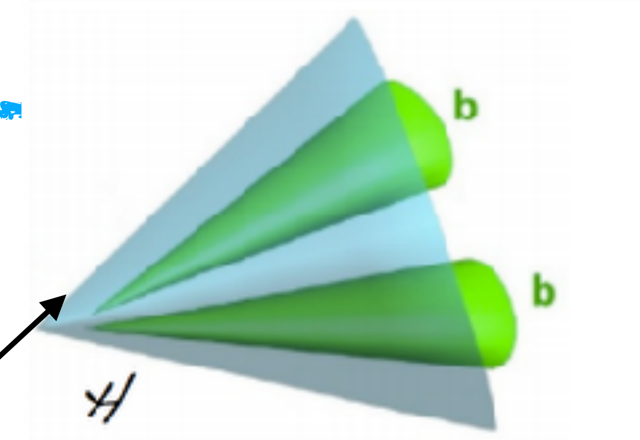
- High pT VH analysis could become competitive with inclusive H->WW measurement

- ***As Higgs p_T increases, VH becomes more and more competitive with ggF as dominate Higgs production mode***



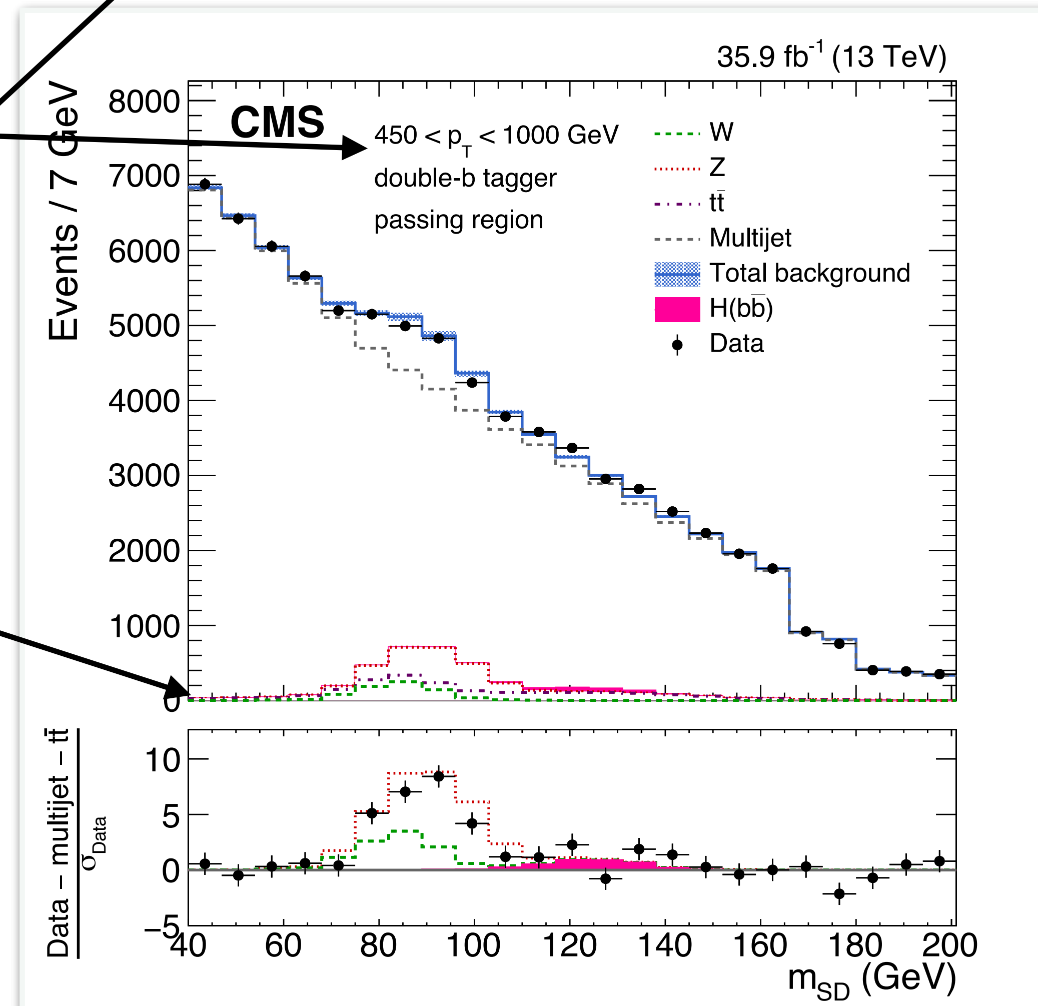
ggF H->bb

- From CMS: [Phys. Rev. Lett. 120 (2018) 071802]



Search for $gg \to H \to b\bar{b}$ historically **deemed impossible**

- Throwing everything at it:
  - fat jet selection: ideal to capture boosted decay at high p_T
  - double b-tagging inside the fat-jet: reconstructing 2 secondary vertices/decay chain
  - various substructure techniques based on calorimetry/particle flow:
    - soft drop mass
    - cut on substructure variable
  - actual fit is performed in multiple jet pt bins: some assumptions needed on the pt spectrum dependency

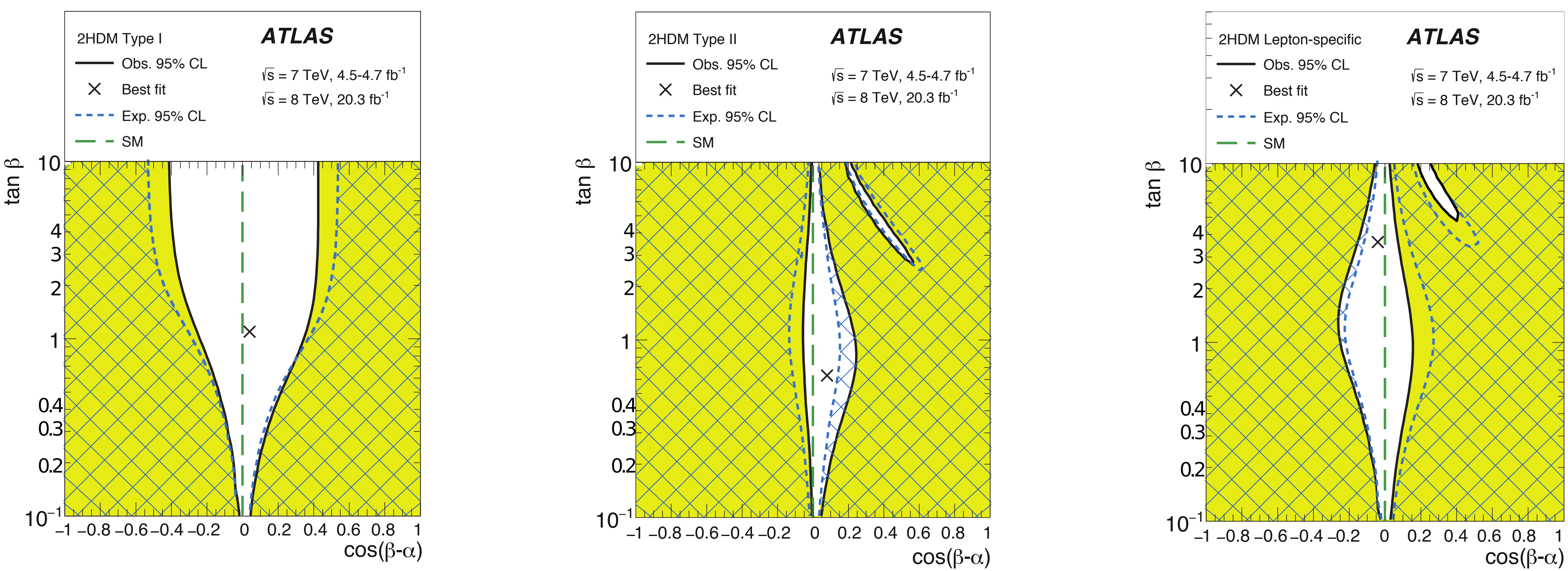


- Very good proof of principle for Z->bb …. 1.5 sigma excess for H->bb [and a lot of discussion on high pt higgs predictions]

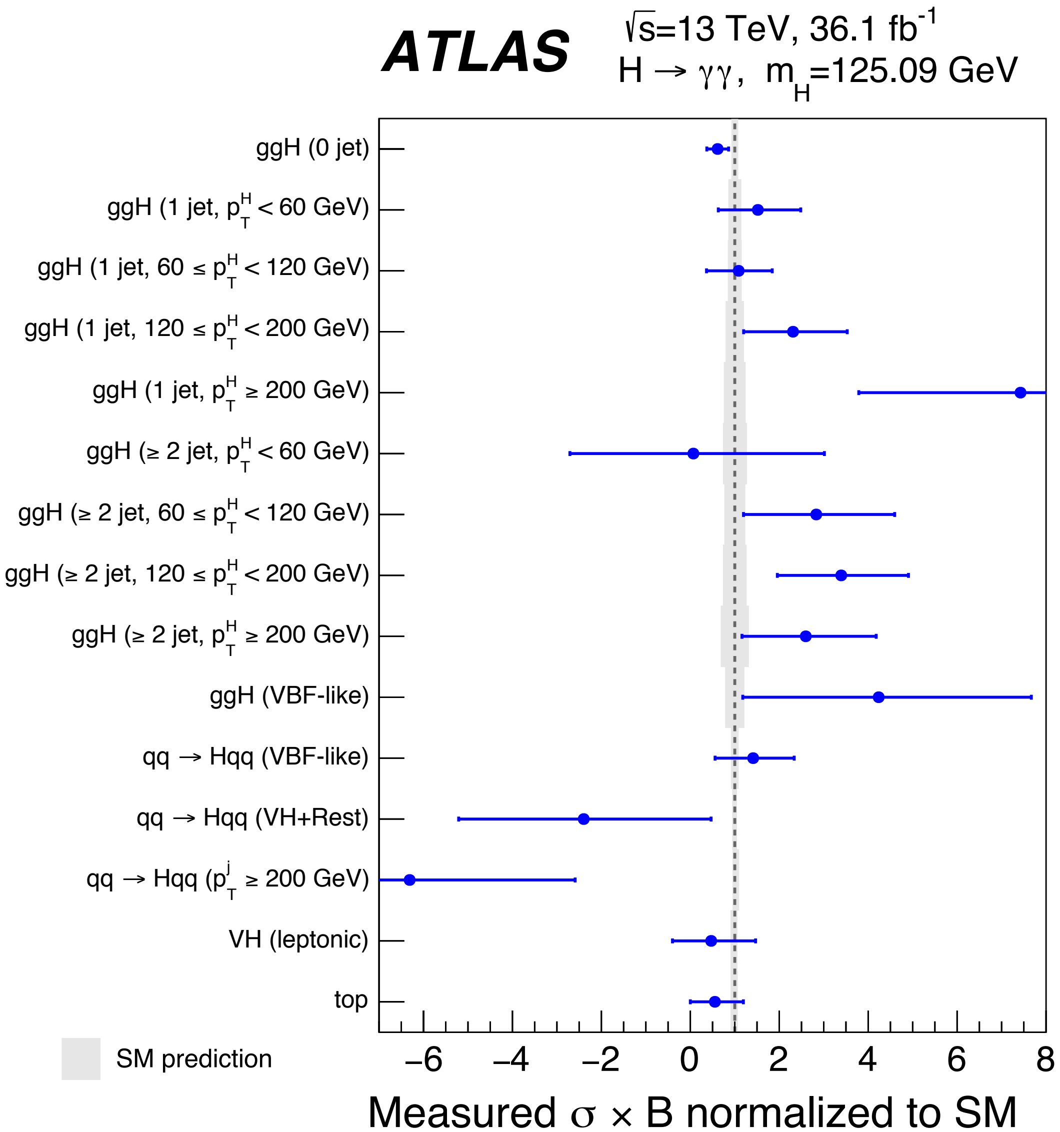
	H	H no p_T corr.	Z
Observed signal strength	$2.3^{+1.8}_{-1.6}$	$3.2^{+2.2}_{-2.0}$	$0.78^{+0.23}_{-0.19}$
Expected UL signal strength	< 3.3	< 4.1	—
Observed UL signal strength	< 5.8	< 7.2	—
Expected significance	0.7σ	0.5σ	5.8σ
Observed significance	1.5σ	1.6σ	5.1σ

- 2HDM: extension of the SM to 5 Higgs bosons (2 CP-even, 1 CP-odd, 2 charged)
- *h = lightest CP-even*. Can parameterise deviation of couplings as a function of 2 mixing parameters

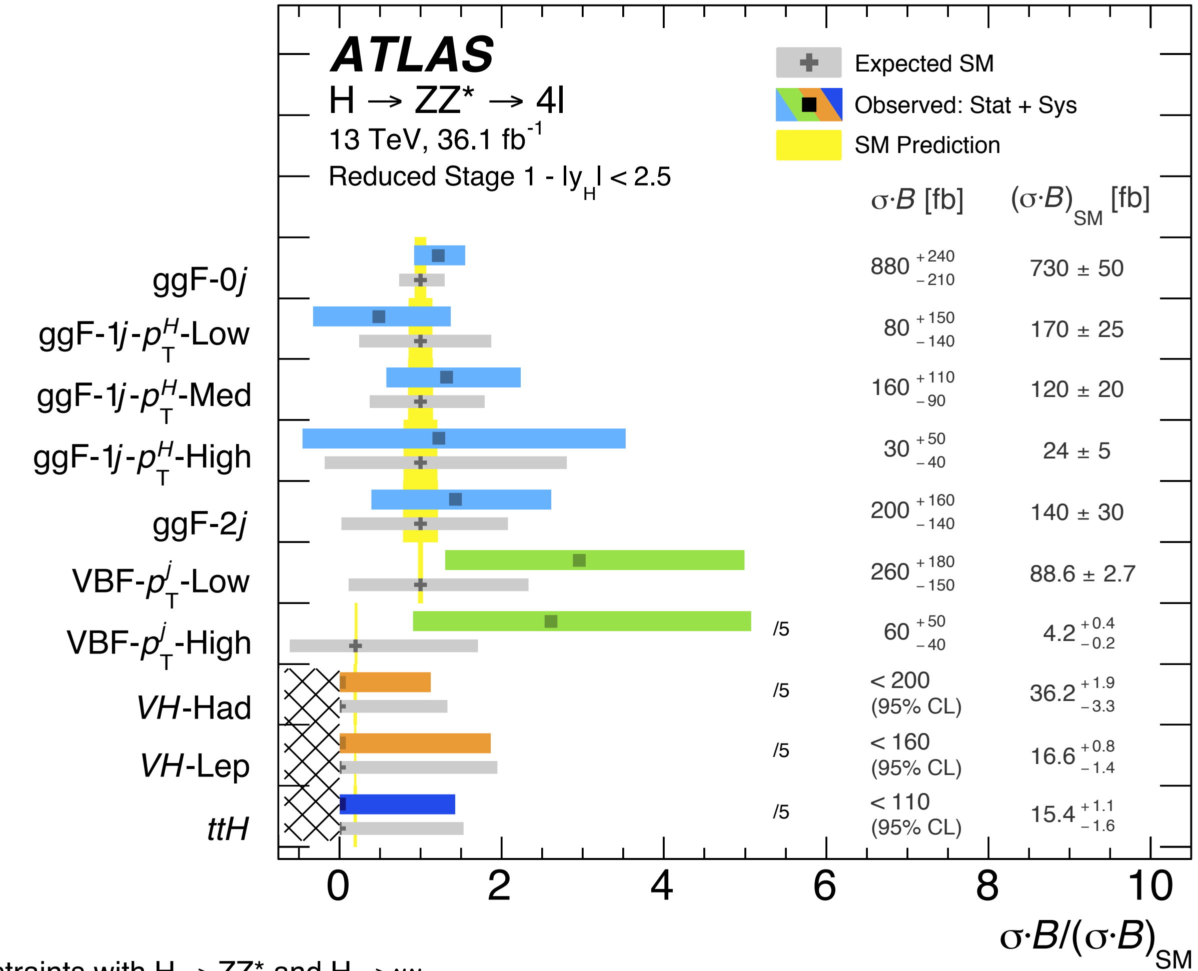
	2HDM type I	type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$



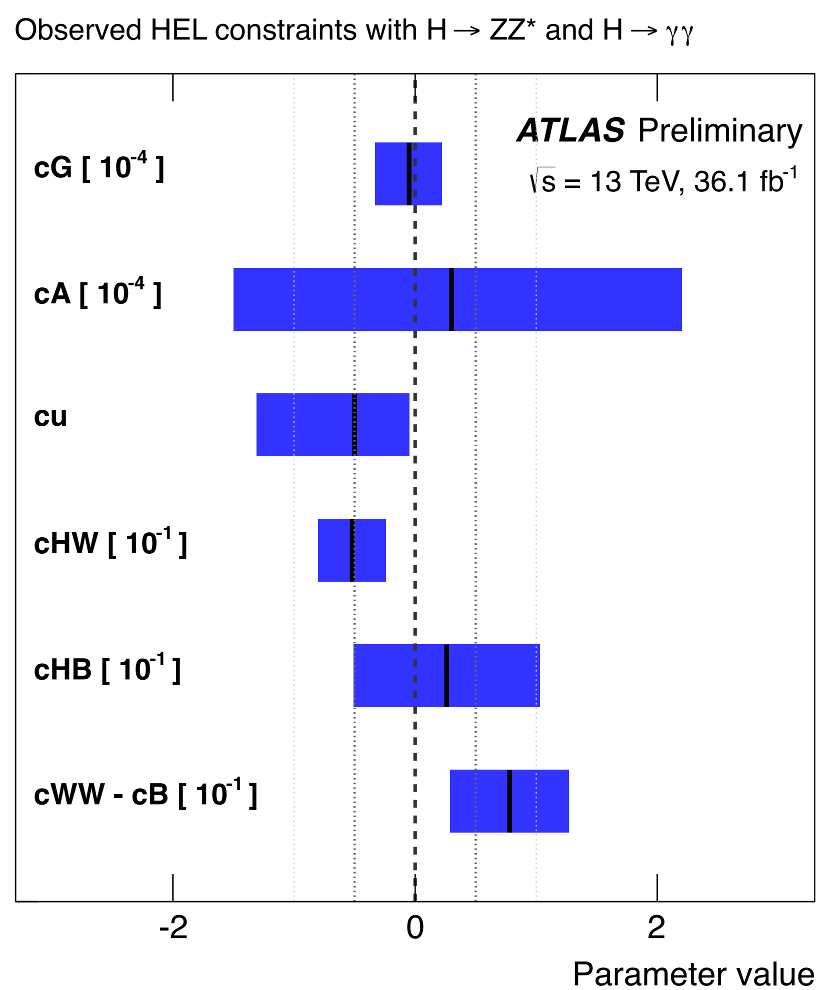
EFT in VH



ATLAS
√s=13 TeV, 36.1 fb-1
H → γγ, mH=125.09 GeV
ggH (0 jet)
ggH (1 jet, pTH < 60 GeV)
ggH (1 jet, 60 ≤ pTH < 120 GeV)
ggH (1 jet, 120 ≤ pTH < 200 GeV)
ggH (1 jet, pTH ≥ 200 GeV)
ggH (≥ 2 jet, pTH < 60 GeV)
ggH (≥ 2 jet, 60 ≤ pTH < 120 GeV)
ggH (≥ 2 jet, 120 ≤ pTH < 200 GeV)
ggH (≥ 2 jet, pTH ≥ 200 GeV)
ggH (VBF-like)
qq → Hqq (VBF-like)
qq → Hqq (VH+Rest)
qq → Hqq (pTj ≥ 200 GeV)
VH (leptonic)
top
SM prediction
−6 −4 −2 0 2 4 6 8
Measured σ × B normalized to SM



ATLAS
H → ZZ* → 4l
13 TeV, 36.1 fb-1
Reduced Stage 1 - |yH| < 2.5
Expected SM
Observed: Stat + Sys
SM Prediction
σ·B [fb]
(σ·B)SM [fb]
ggF-0j
ggF-1j-pTH-Low
ggF-1j-pTH-Med
ggF-1j-pTH-High
ggF-2j
VBF-pTj-Low
VBF-pTj-High
VH-Had
VH-Lep
ttH
880 +240 −210
730 ± 50
80 +150 −140
170 ± 25
160 +110 −90
120 ± 20
30 +50 −40
24 ± 5
200 +160 −140
140 ± 30
260 +180 −150
88.6 ± 2.7
/5
60 +50 −40
4.2 +0.4 −0.2
/5
< 200 (95% CL)
36.2 +1.9 −3.3
/5
< 160 (95% CL)
16.6 +0.8 −1.4
/5
< 110 (95% CL)
15.4 +1.1 −1.6
0 2 4 6 8 10
σ·B/(σ·B)SM



Observed HEL constraints with H → ZZ* and H → γγ
ATLAS Preliminary
√s = 13 TeV, 36.1 fb-1
cG [10-4]
cA [10-4]
cu
cHW [10-1]
cHB [10-1]
cWW - cB [10-1]
-2 0 2
Parameter value

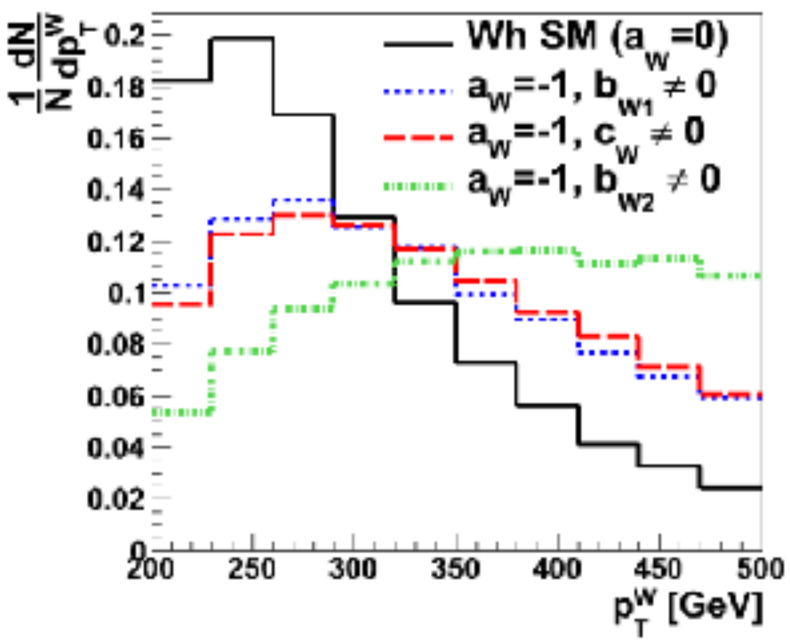
EFT in VH

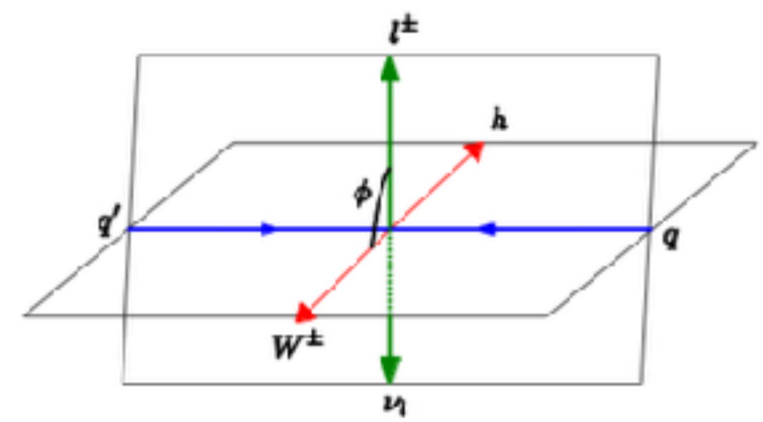
- Boosted regime only

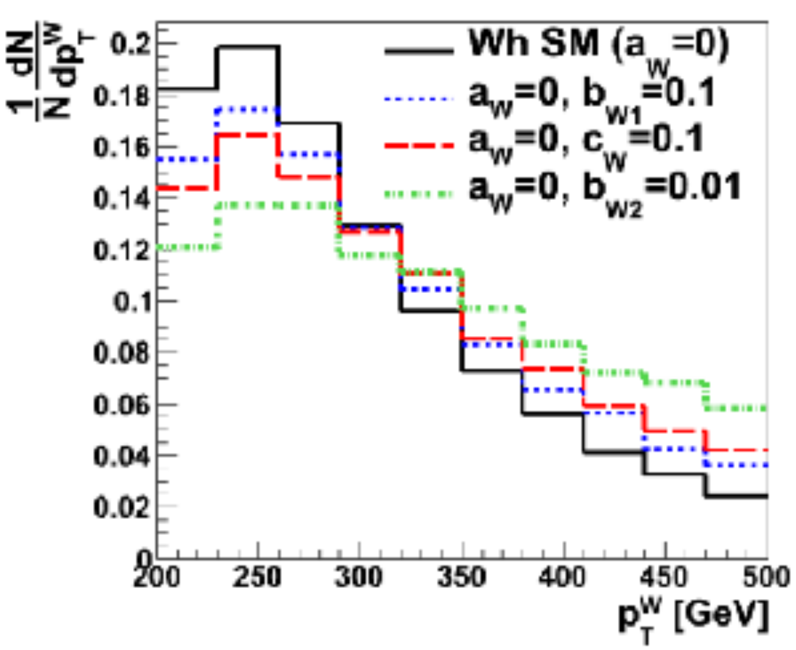
$$\mathcal{O}_{WW} = \frac{g_2^2\, b_{WW}}{4\Lambda^2}\,\Phi^\dagger\Phi W^i_{\mu\nu}W^{i\mu\nu}\,, \qquad \tilde{\mathcal{O}}_{WW} = \frac{g_2^2\, c_{WW}}{4\Lambda^2}\,\Phi^\dagger\Phi W^i_{\mu\nu}\tilde{W}^{i\mu\nu}\,,$$

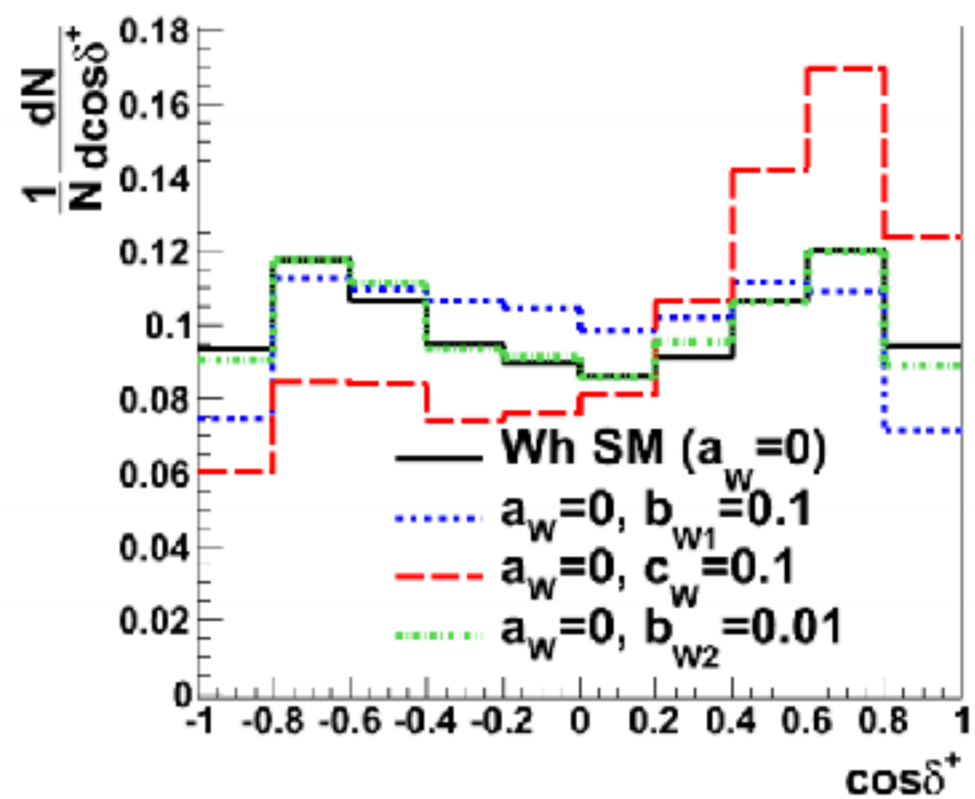
$$\mathcal{O}_{hW} = \frac{i g_2\, b_{hW}}{\Lambda^2}\,(D^\nu W_{\mu\nu})^k\left(\Phi^\dagger\sigma^k \overleftrightarrow{D}^\mu\Phi\right).$$

$$i\Gamma^{\mu\nu}_{hWW}(k_1,k_2) = i\,(g_2 m_W)\left[\eta^{\mu\nu}\left(1+a_W-\frac{b_{W1}}{m_W^2}(k_1\cdot k_2)+\frac{b_{W2}}{m_W^2}(k_1^2+k_2^2)\right) + \frac{b_{W1}}{m_W^2}\,k_1^\nu k_2^\mu - \frac{b_{W2}}{m_W^2}\,(k_1^\mu k_1^\nu + k_2^\mu k_2^\nu) + \frac{c_W}{m_W^2}\,\epsilon^{\mu\nu\rho\sigma}k_{1\rho}k_{2\sigma}\right];$$









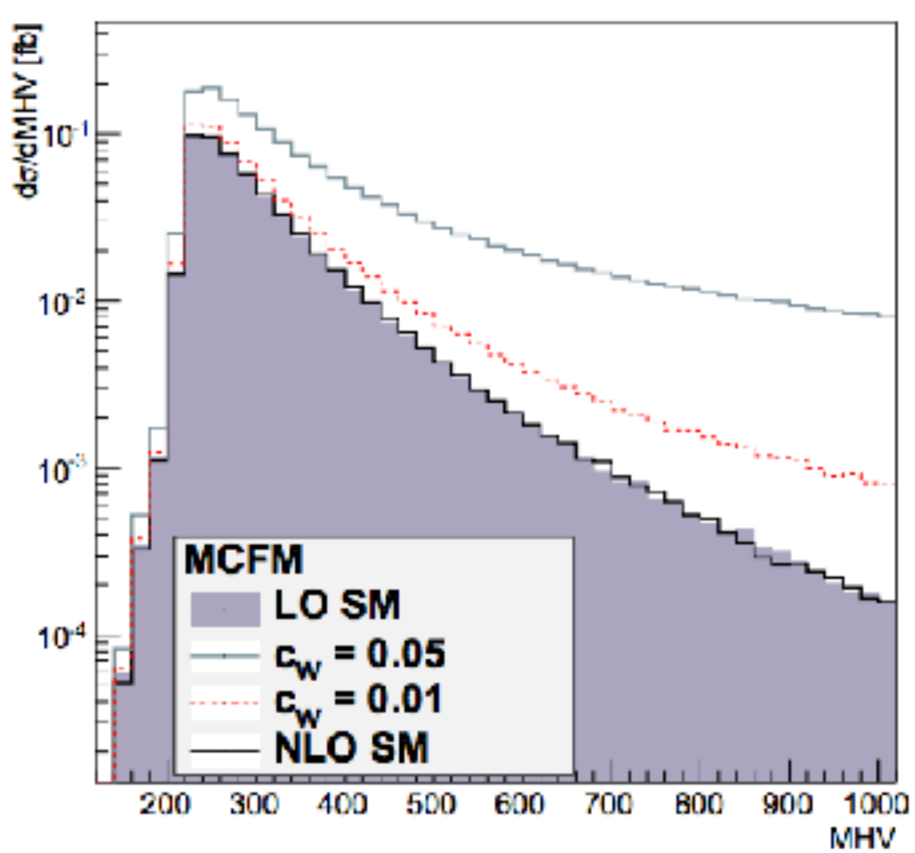
EFT in VH (2)

arxiv:1409.5449

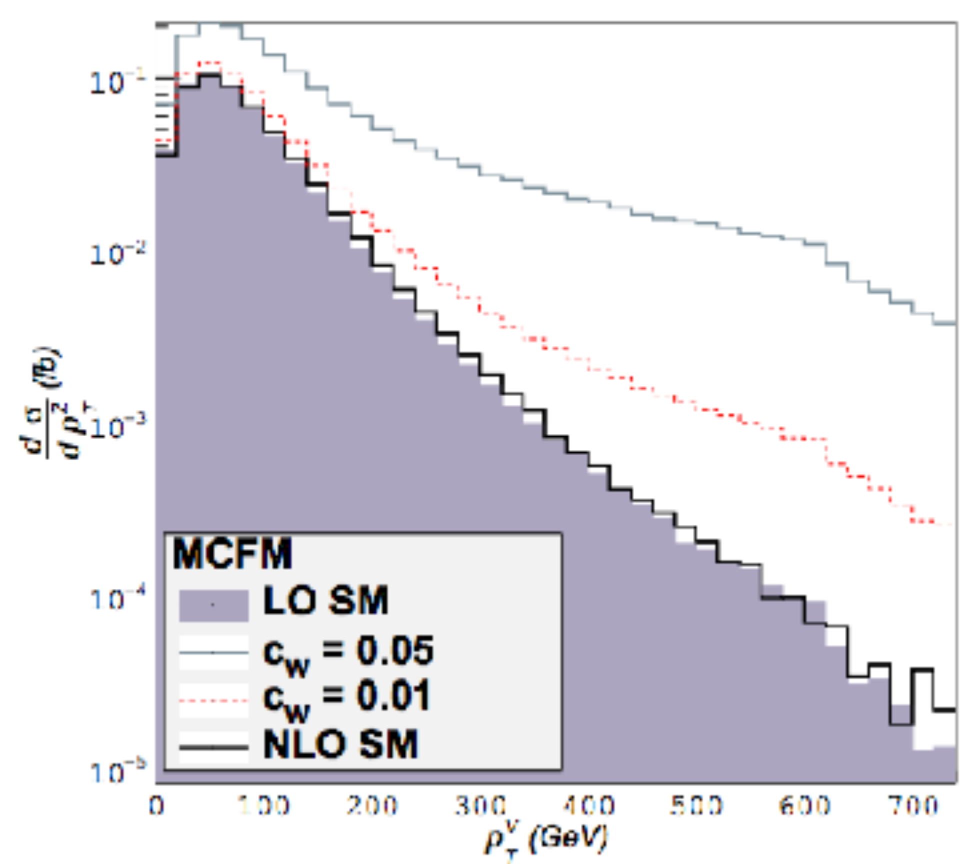
- Dim-6 operators only

$$
\begin{aligned}
\mathcal{L} \supset\ & \frac{\bar{c}_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{g'^2\ \bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\ \bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu} \\
+\ & \frac{2ig\ \bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\right]W^k_{\mu\nu} + \frac{ig'\ \bar{c}_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu} \\
+\ & \frac{ig\ \bar{c}_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu} + \frac{ig'\ \bar{c}_B}{2m_W^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu} \\
+\ & \frac{\bar{c}_t}{v^2}y_t\Phi^\dagger\Phi\ \Phi^\dagger\cdot\bar{Q}_L t_R + \frac{\bar{c}_b}{v^2}y_b\Phi^\dagger\Phi\ \Phi\cdot\bar{Q}_L b_R + \frac{\bar{c}_\tau}{v^2}y_\tau\ \Phi^\dagger\Phi\ \Phi\cdot\bar{L}_L\tau_R\,.
\end{aligned}
$$

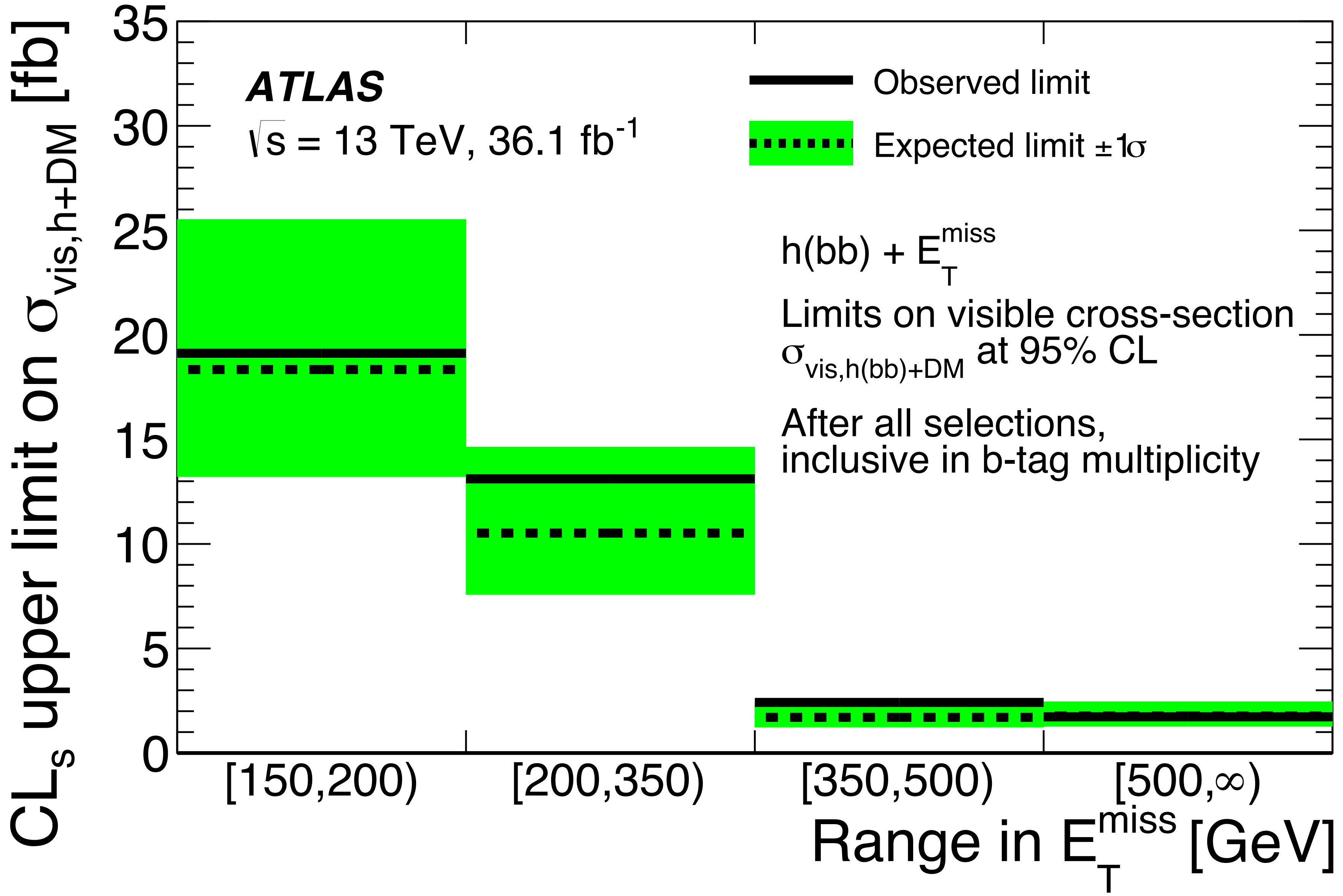
MHV



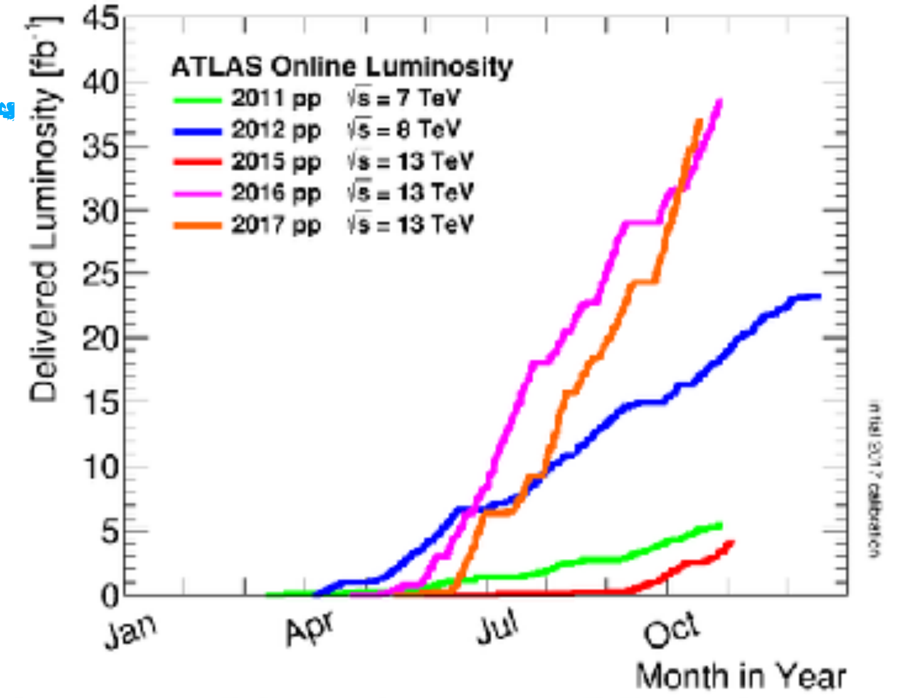
Z boson pt



- towards a model independent result

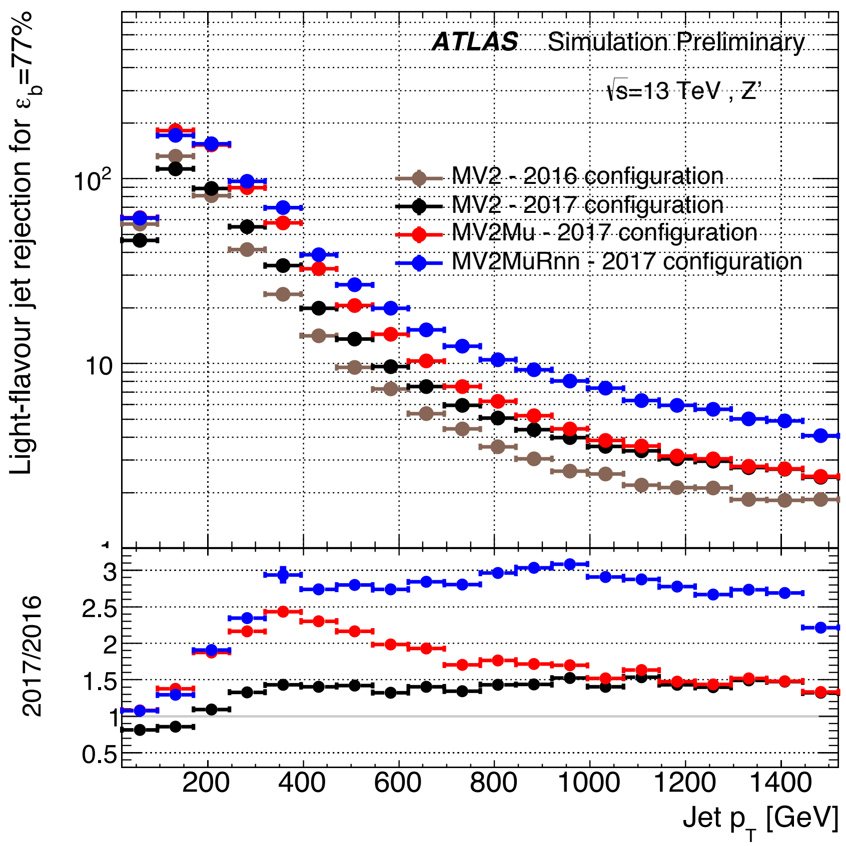


Prospects



- ✦ ***More data***: *will allow to extend the p_T range*
  - likely doubling luminosity at the end of 2017
  - up to 120 fb[-1] at the end of Run2

ATL-PHYS-PUB-2017-013/



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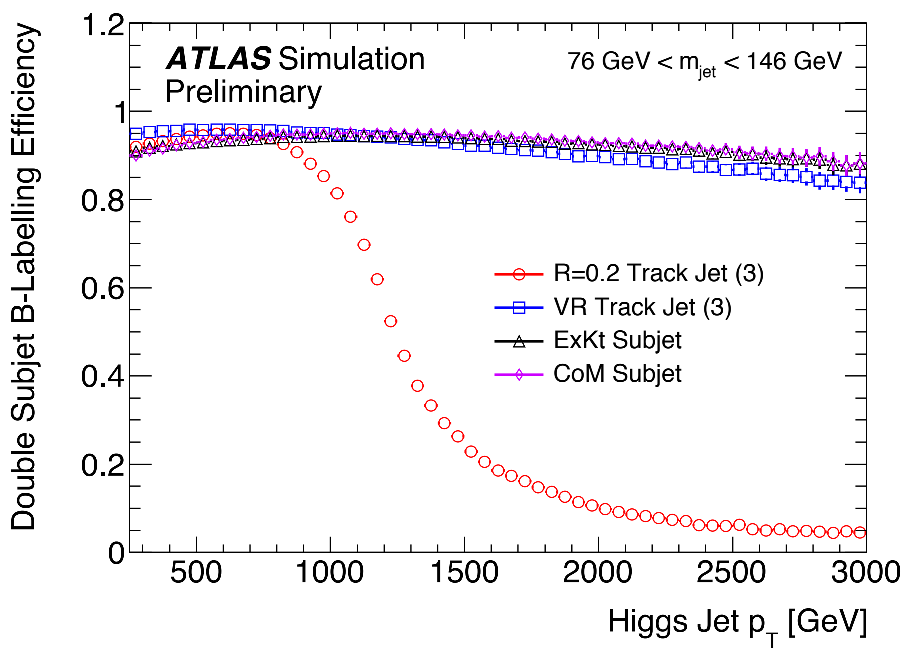
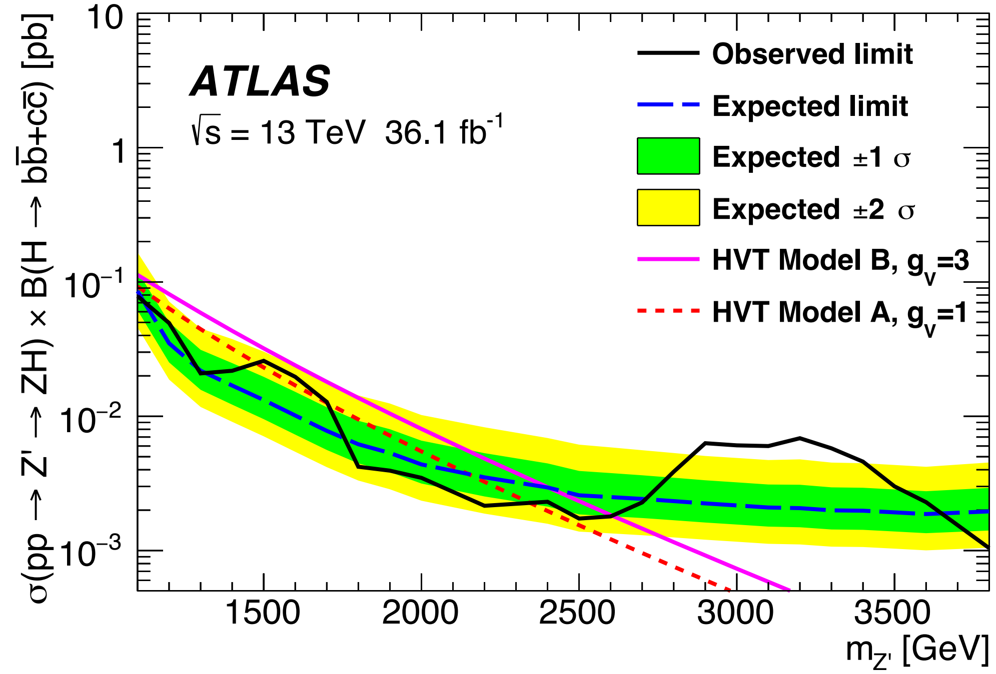
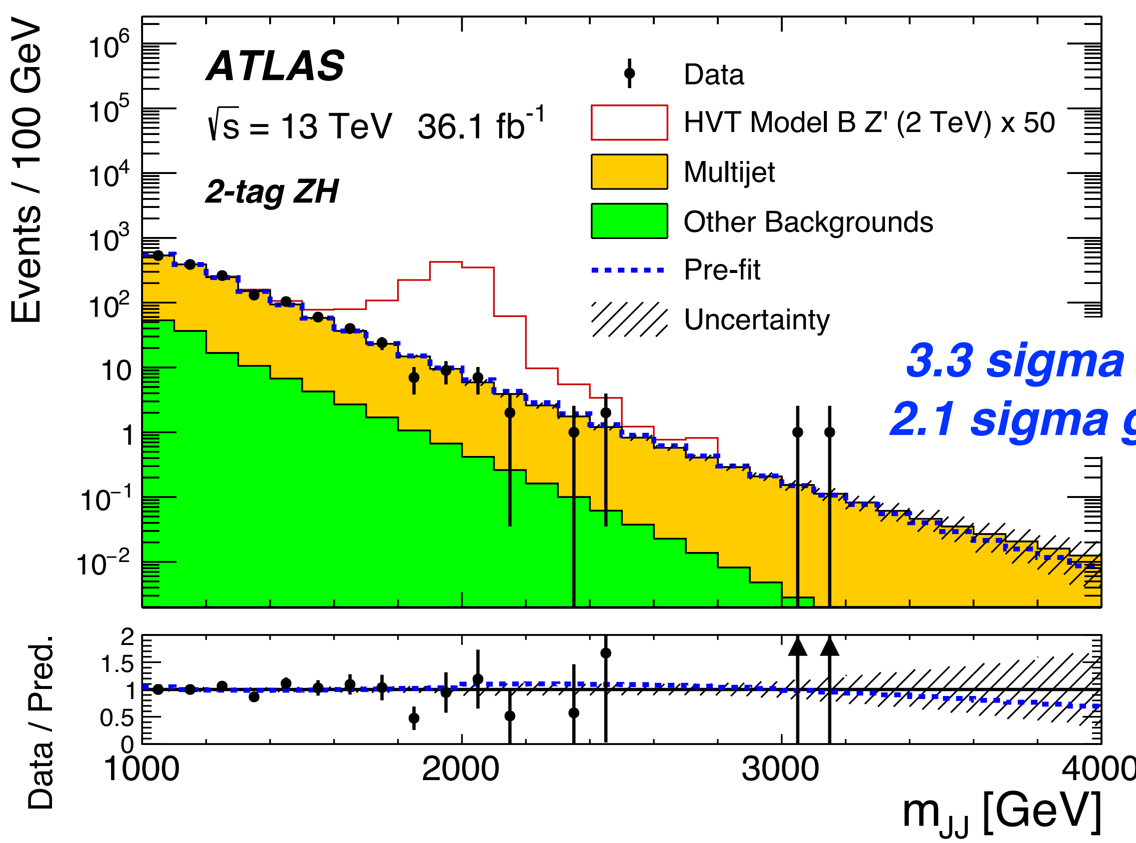


- ***Better algorithms***: *i.e. flavour tagging*
  - more attention to high pT tuning
  - incorporating more advanced machine learning techniques (deep learning, recursive networks)

- ✦ ***More/Better MonteCarlo***:
  - continue to incorporate state-of -the-art prediction from theorist
  - more MC stat. will allow more sophisticated data analysis techniques (i.e. adversarial training to have unbiased mbb distribution in the background, reducing the effect of systematic uncertainties)

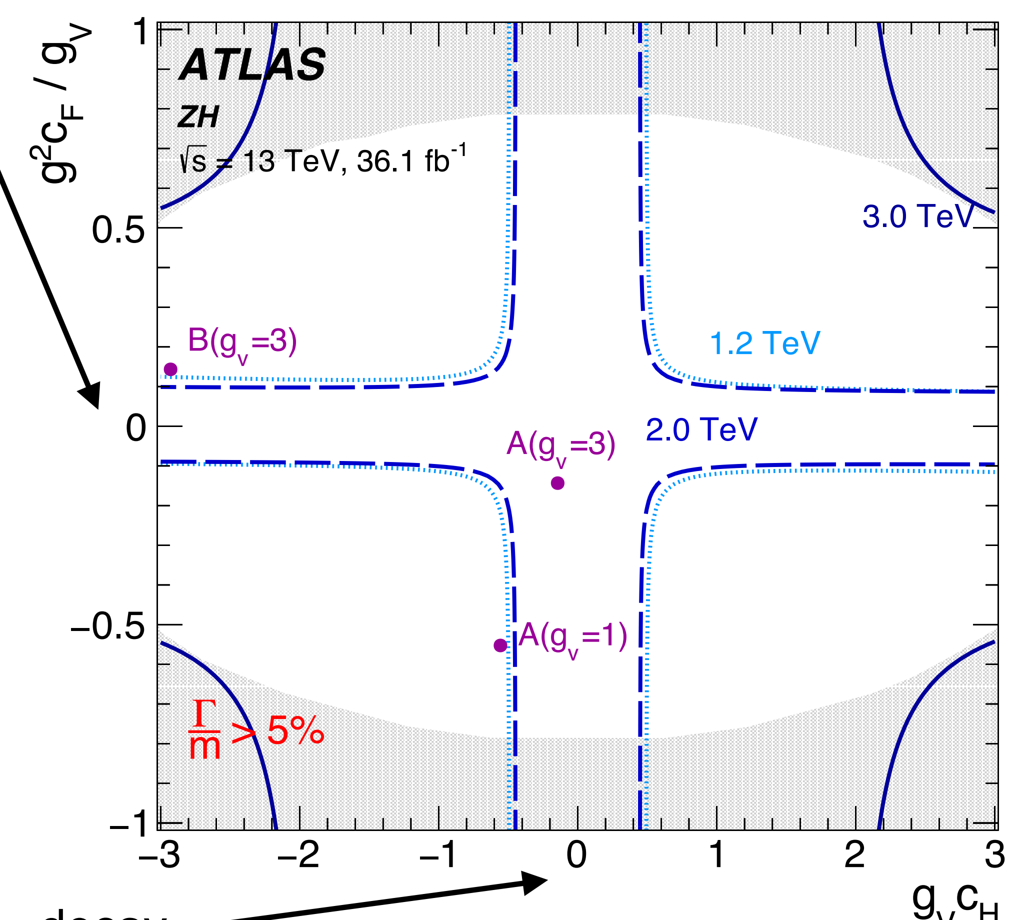
- Very problematic for the triggering point of view:
  - *restricting to very high pT (<450, 250 GeV)*
  - *2 largeR jets with substructure techniques to identify V and H bosons*
  - *selection on the mass of the 2 jets: H-Jet: 75<m_J<145 , V-jet: variable cut to maintain 50% efficiency*





3.3 sigma local
2.1 sigma global

production



decay