Observation of the Higgs boson decay to bottom quarks

A journey into the quest, and prospects for the next challenges.

Paolo Francavilla - INFN Pisa

17/11/2018 - Seminario di fenomenologia delle particelle elementari - Genova

Istituto Nazionale di Fisica Nucleare

Its majesty, the Standard Model

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

- Great success in the description of Nature.

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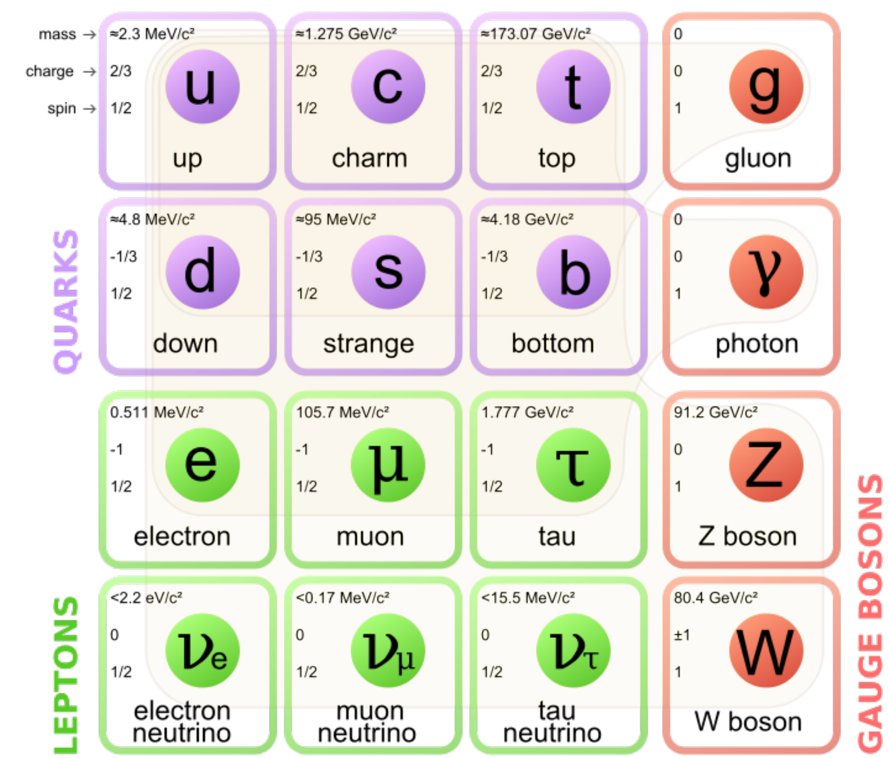
- First part is governed by gauge symmetries.
  - Gauge boson, Fermions, and their interactions



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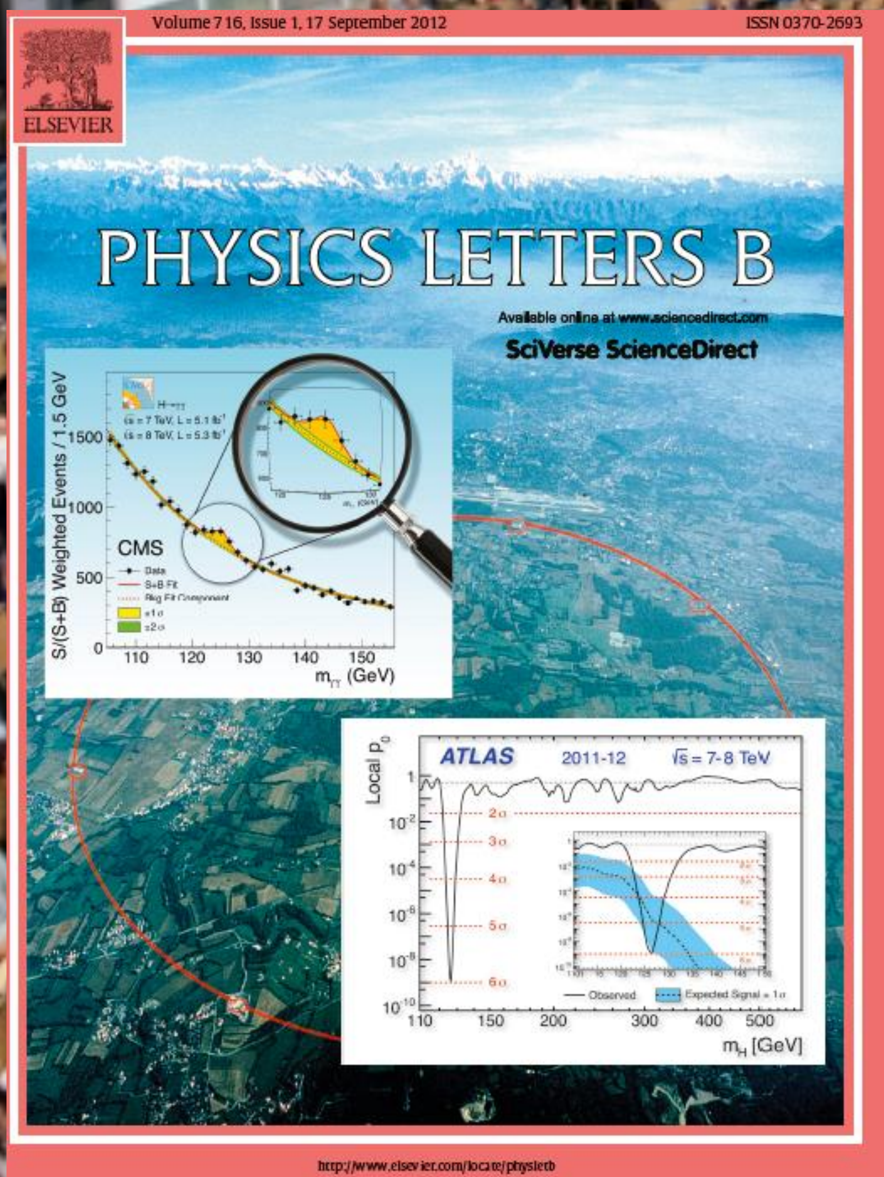
$$+ |D_\mu \phi|^2 - V(\phi)$$

- Great success in the description of Nature.
- First part is governed by gauge symmetries.
    - Gauge boson, Fermions, and their interactions
- Second part probably less "elegant", more mysterious.
    - Breaking of symmetries
    - Generation of masses
    - Large number of parameters
    - **A new scalar boson**

From the discovery to the end of Run1



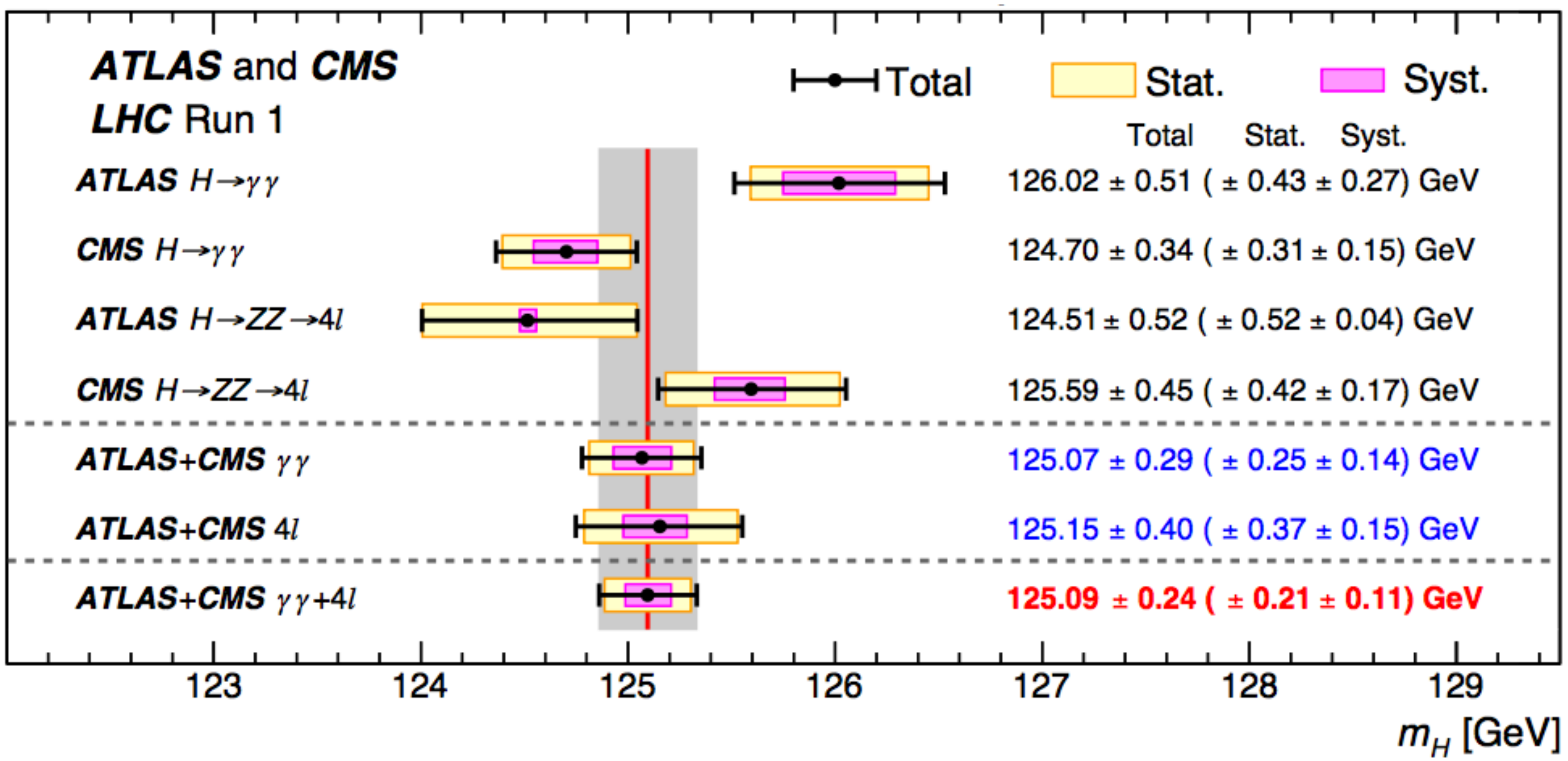
- Discovery of the Higgs boson
- Precise determination of the Higgs boson mass
- Observation of decays in vector bosons
- Observation of Yukawa couplings to τ leptons
- First determination of Higgs couplings (with precisions of 20-40%)

Higgs Boson Mass

- **What is the Higgs mass?**

Phys. Rev. Lett. 114, 191803 (2015)

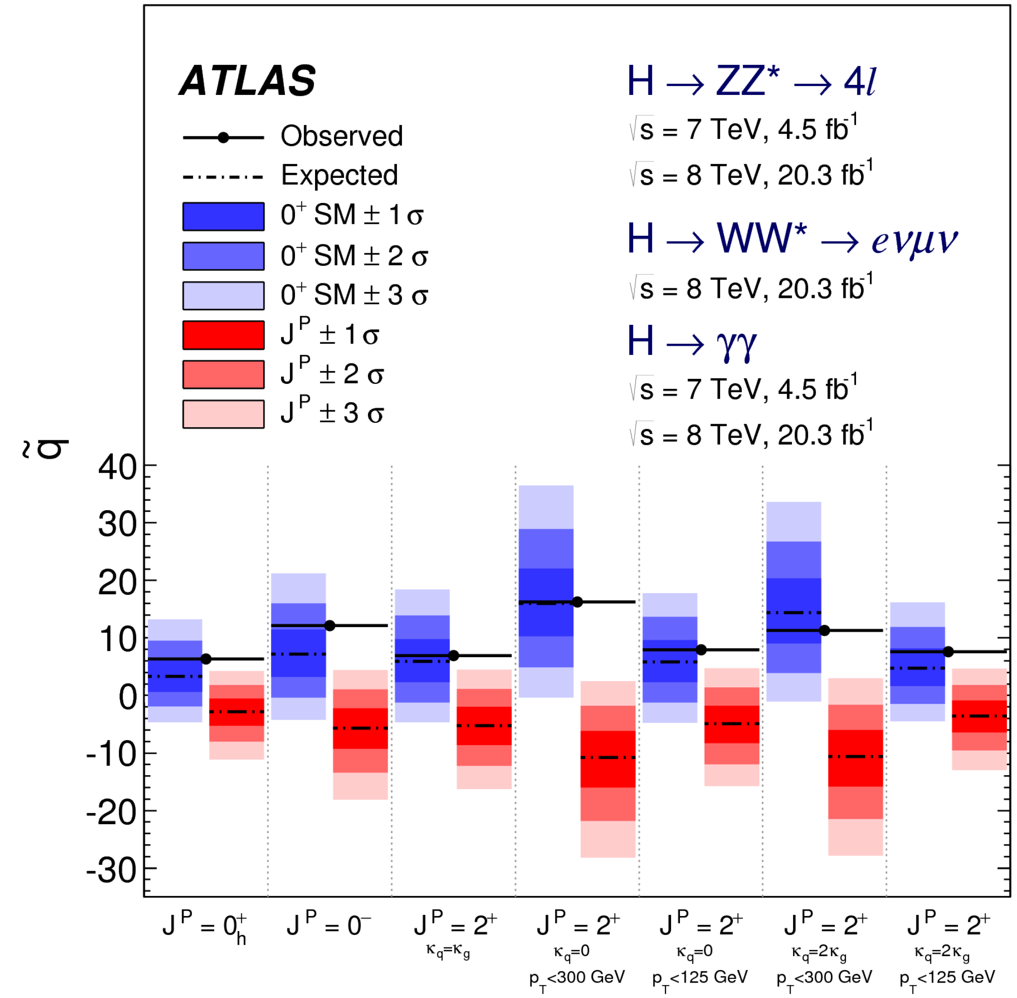
- Measured with 0.2% precisions!



- **Complete SM parameters**
  - no sign of discrepancy between γγ and ZZ

Higgs Boson Spin and CP

Eur. Phys. J. C75 (2015) 476



SPIN:

- **First fundamental(?) spin 0 particle!**
- **Spin 1** excluded by observation of H→γγ
- **Spin 2** tests in different variations (i.e. graviton) → All excluded at 95% CL

CP ODD or CP EVEN?

- **Pure CP-odd state excluded at 95% CL**
- **Tests of mixture of CP-even with contribution from CP-odd disfavoured**

$$\mathcal{L}_0^V = \Big\{\cos(\alpha)\kappa_{SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\}X_0.$$

SM

BSM CP-even

BSM CP-odd

Higgs couplings

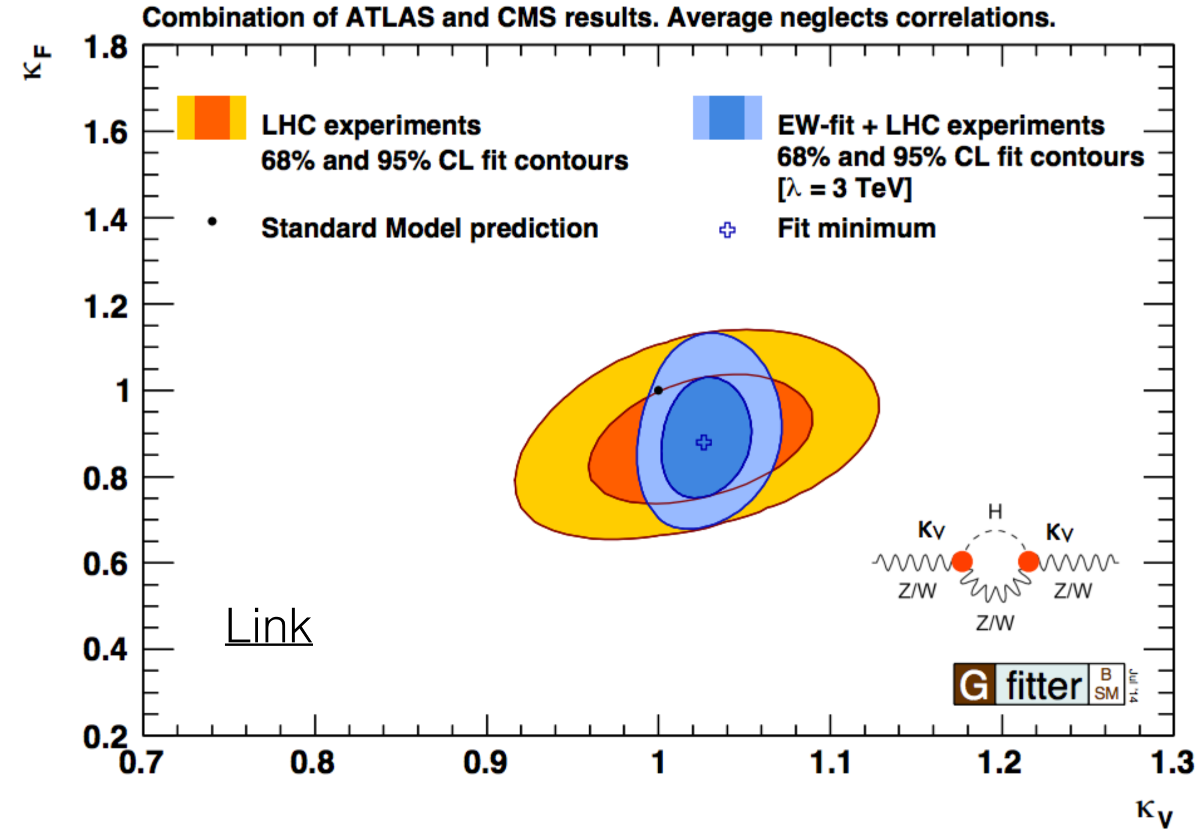
- **What are the Higgs couplings?**
- Use LO "kappa" framework

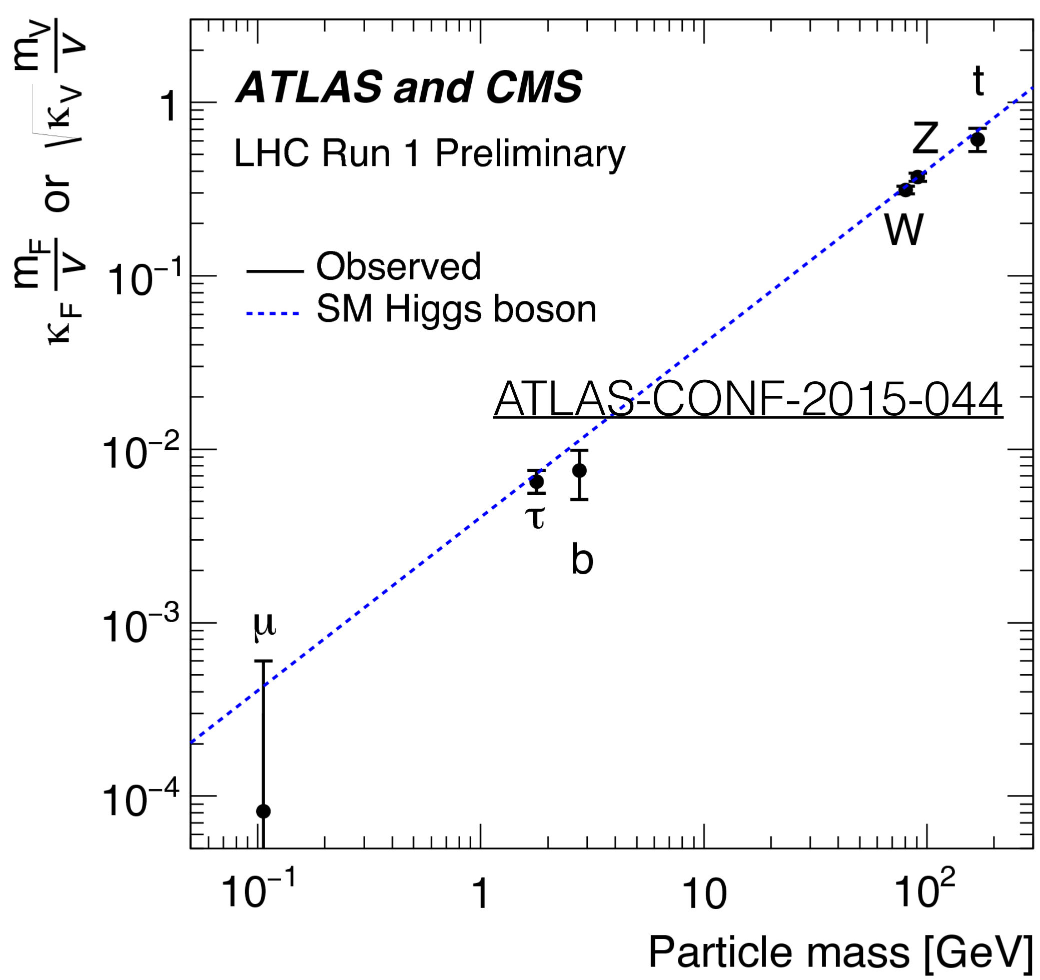
$$\mathcal{L} = \kappa_W \frac{2m_W^2}{v} W^+_\mu W^-_\mu H + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z_\mu H - \sum_f \kappa_f \frac{m_f}{v} f\bar{f}H$$
$$+ c_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^a_{\mu\nu} H + c_\gamma \frac{\alpha}{\pi v} A_{\mu\nu} A_{\mu\nu} H$$

- Each channels : $\sigma_{i\to h}(\kappa_j)\Gamma_{h\to f}(\kappa_j)/\Gamma_{tot}(\kappa_j)$
- $i \to h$: production $h \to f$: decay mode
- **Explore as many channels to determine the kappas**

Higgs couplings

Very specific coupling structure, especially for fermions!

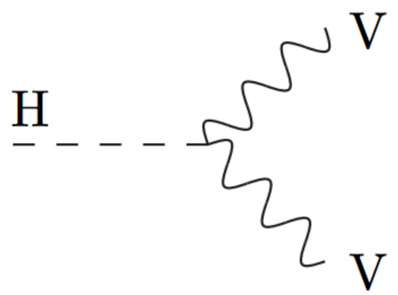




Global EW fit has ~no effect on determination of κ_F

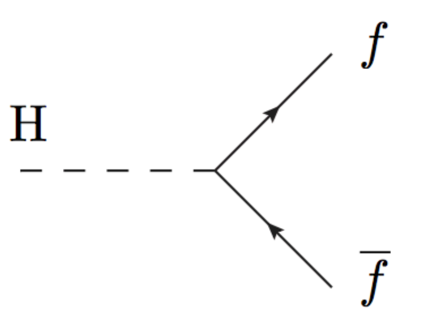
Experimental LHC information on Yukawa couplings essential to fully characterise the observed Higgs boson.

(Some of the) open questions



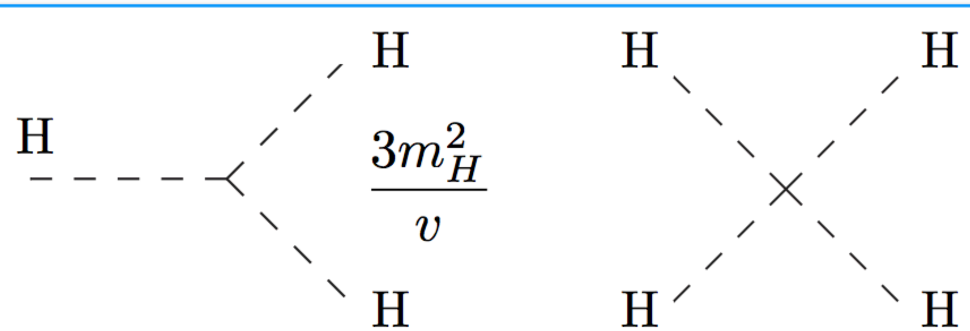
$\frac{2m_V^2}{v}$ $+ |D_\mu \phi|^2$

Is the Standard Model structure in the Higgs sector correct?
Are the structure/values of the couplings with the V bosons as predicted as in the SM?



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

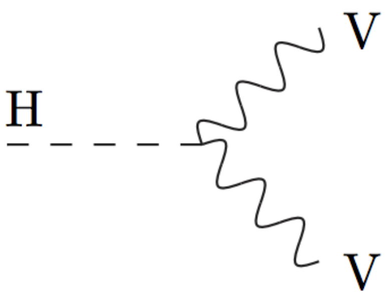
Fermion masses not requested by the EWSB.
Is the H responsible for the fermion masses?
For all the fermion masses?
Why are the families so different?



$\frac{3m_H^2}{v}$ $\frac{3m_H^2}{v^2}$ $V(\phi)$

What do we know of the real shape of the potential?

(Some of the) open questions



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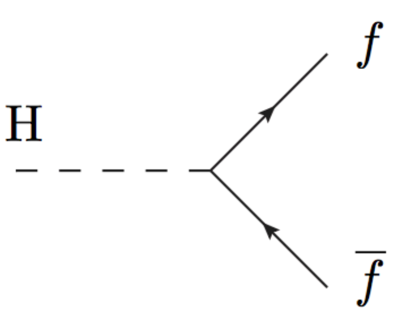

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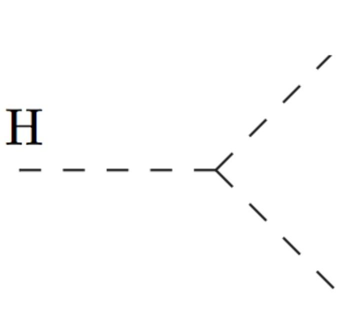
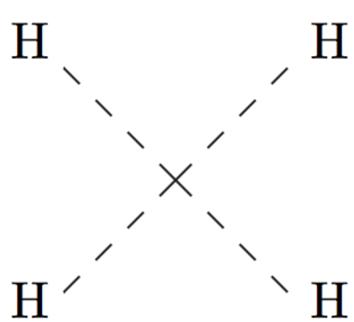


$$\frac{3m_H^2}{v}$$



$$\frac{3m_H^2}{v^2}$$

$V(\phi)$

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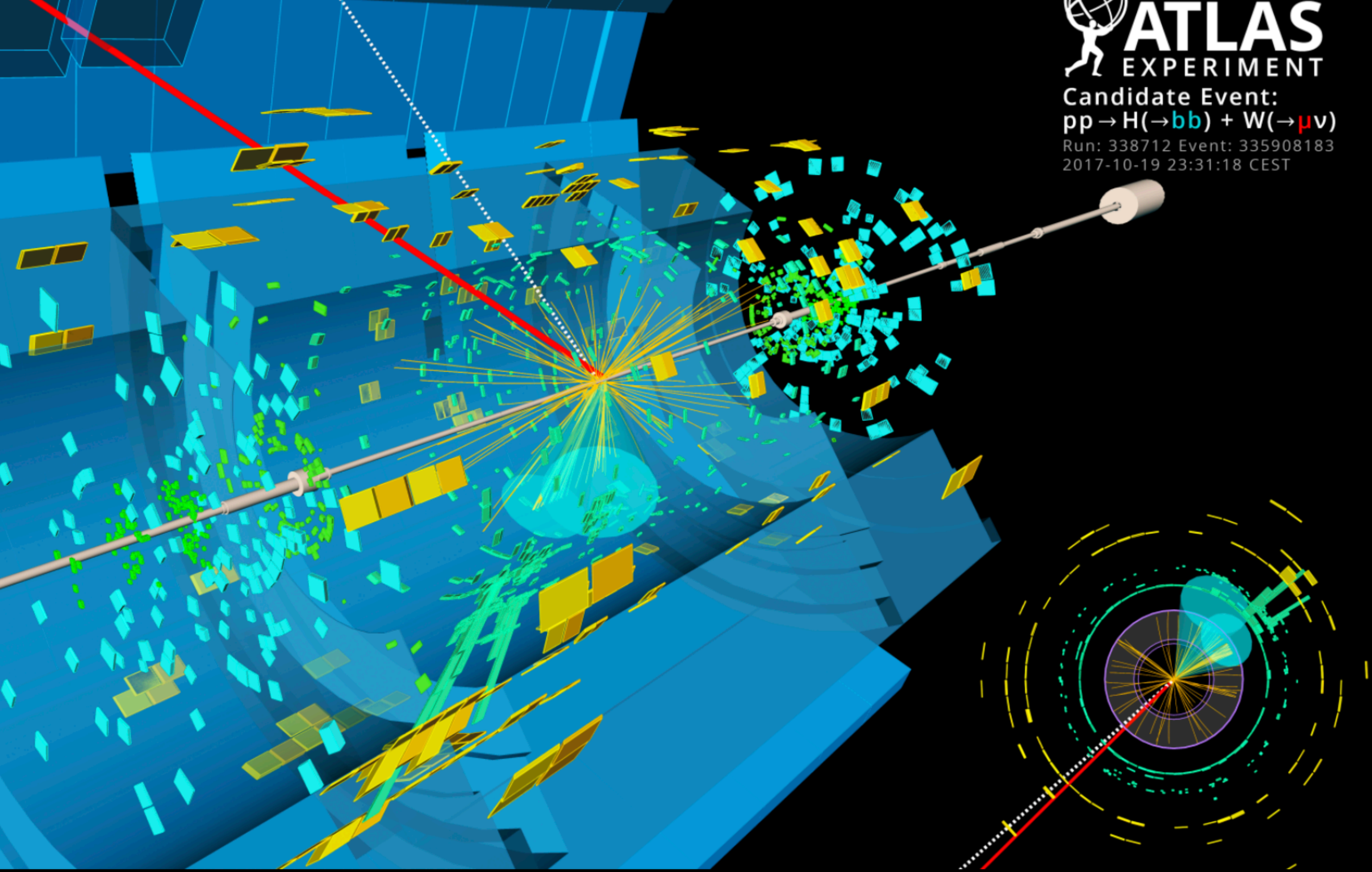
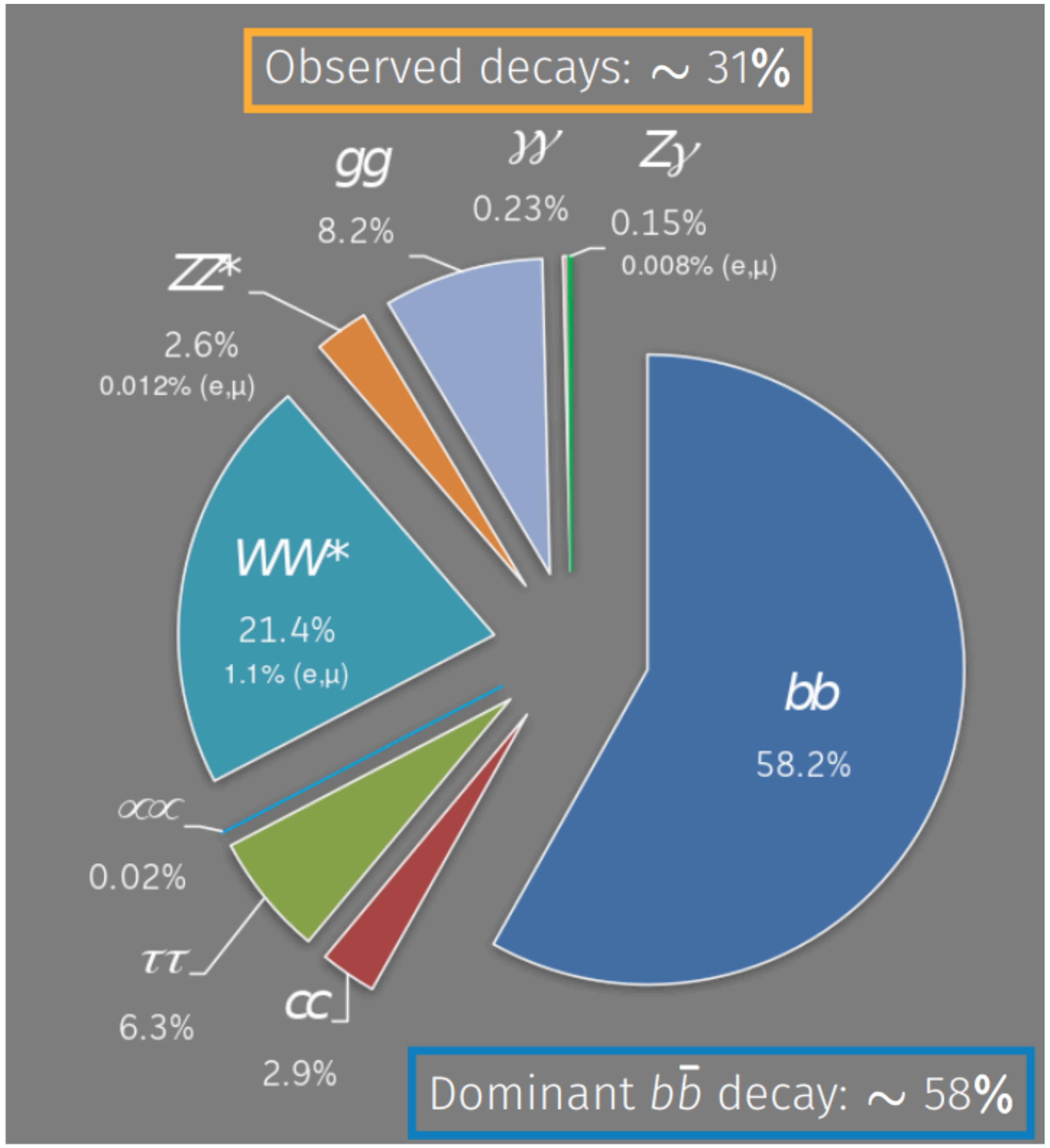

ATLAS
EXPERIMENT
Candidate Event:
pp → H(→bb) + W(→μν)
Run: 338712 Event: 335908183
2017-10-19 23:31:18 CEST

Higgs to bb

Higgs Boson decay modes

- Higgs boson branching ratios
- Many decay modes accessible at the LHC
    - Decays to γγ and gg thanks to loops
    - 31% of them already observed
    - WW, ZZ, γγ, ττ

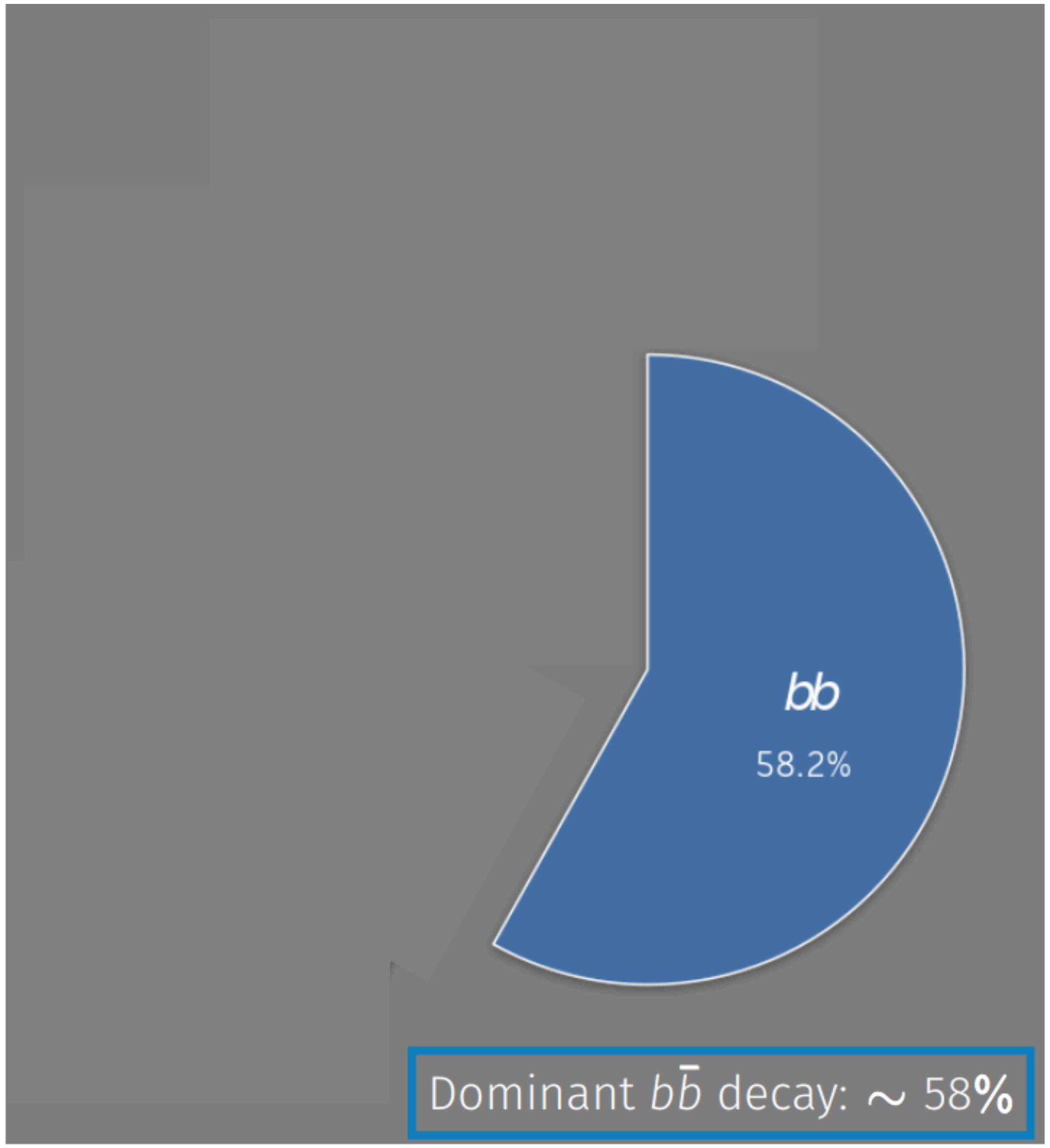


Higgs Boson decay modes

Why is interesting to observe H→bb?

- To establish the fate of the Higgs boson
  - Expected to be ~58% of the total width
- To control the Higgs Yukawa sector

	down-type	up-type
quark	**bottom**	top
lepton	τ	



- Model dependent estimation of the total width (not directly measurable at the LHC)
  - Only ratio of BR (couplings) are truly model independent at the LHC
  - Absolute coupling measurement requires assumptions on the total width (i.e. no BSM decays)
  - a term accounting for 58% of the total has a dominant effect on all the coupling determination

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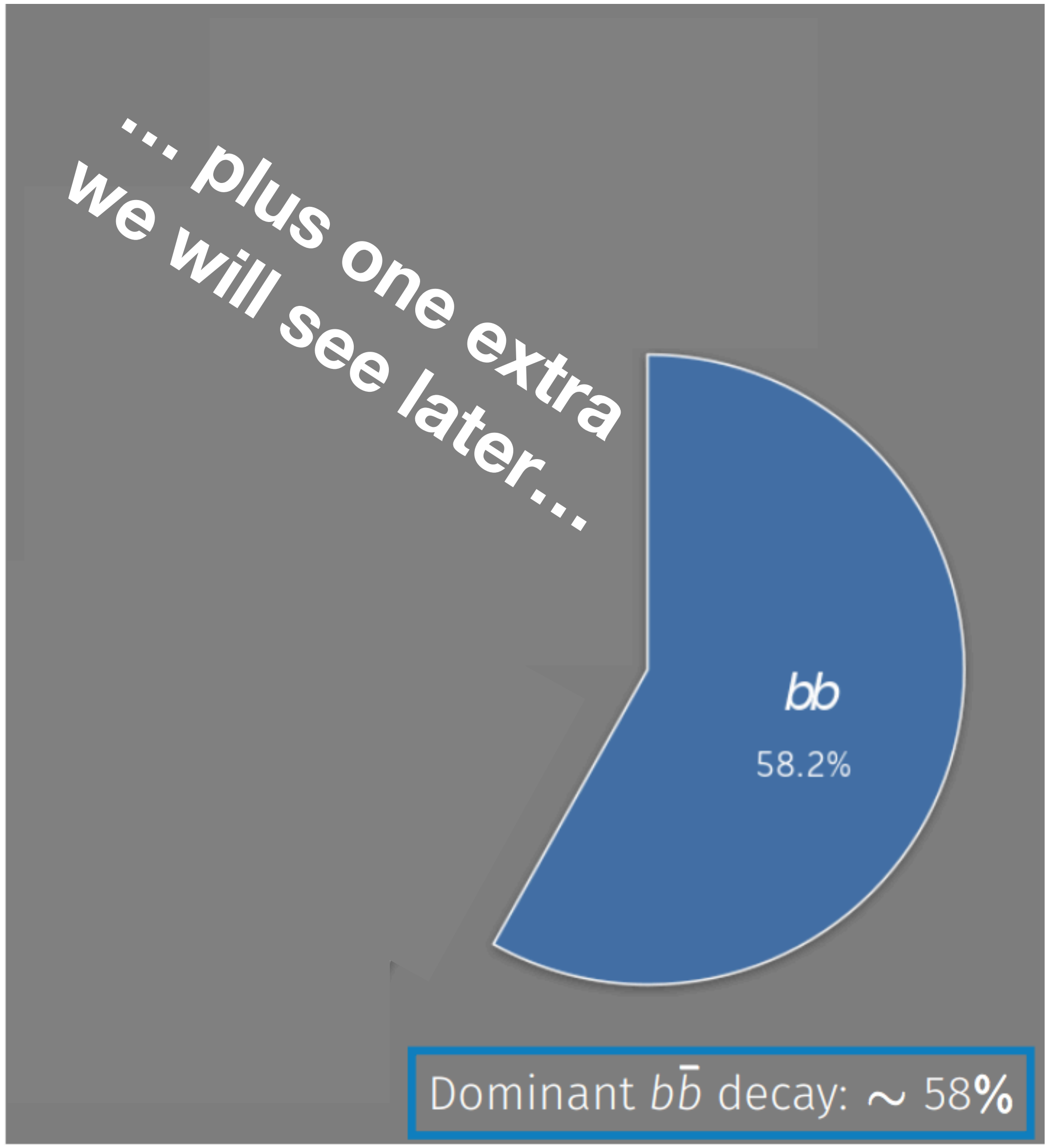
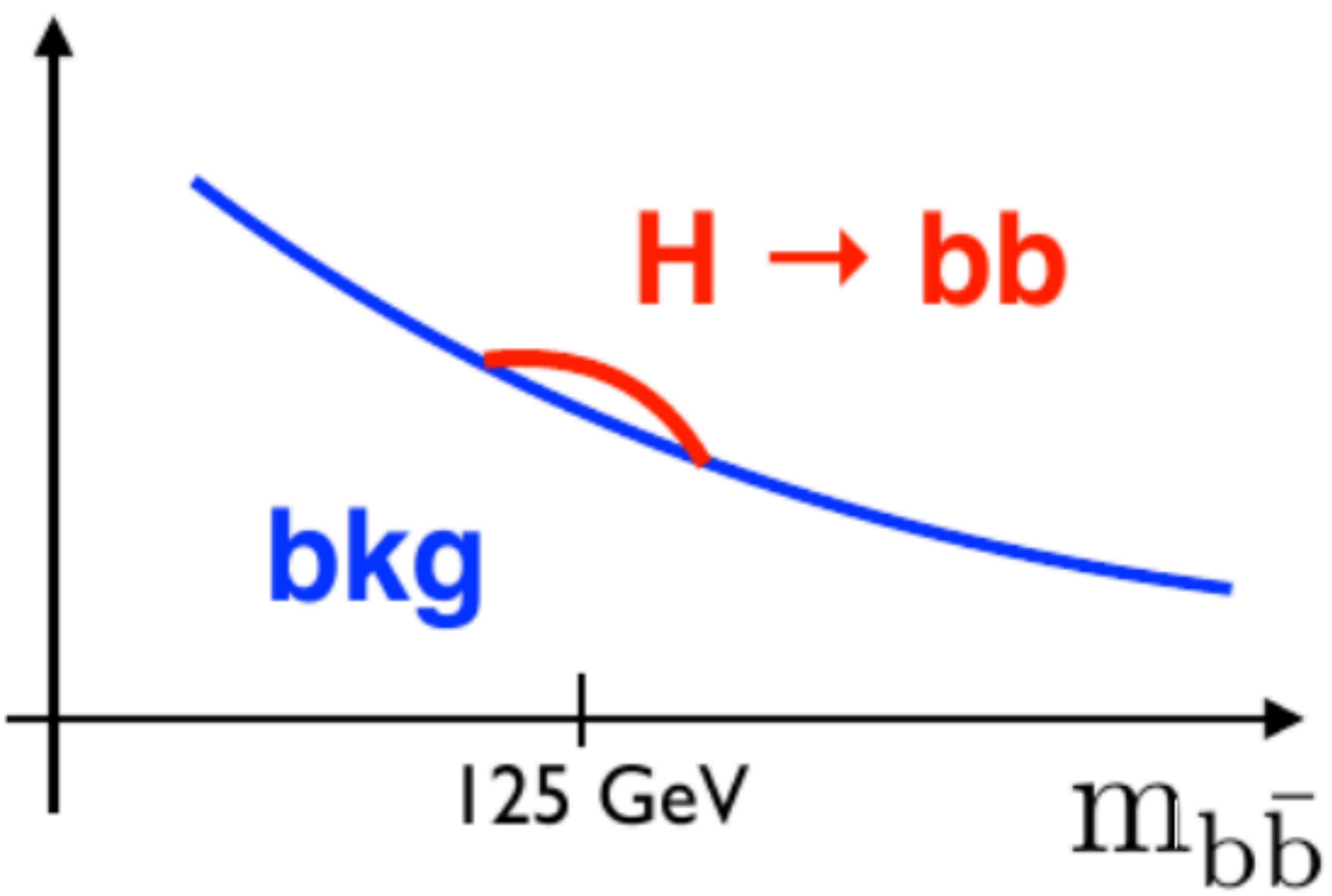


Inclusive search of H→bb: How to

aka Why it took so long to find the largest Higgs boson decay mode?



First idea: search a bump on a smooth(?) background

Does it work?

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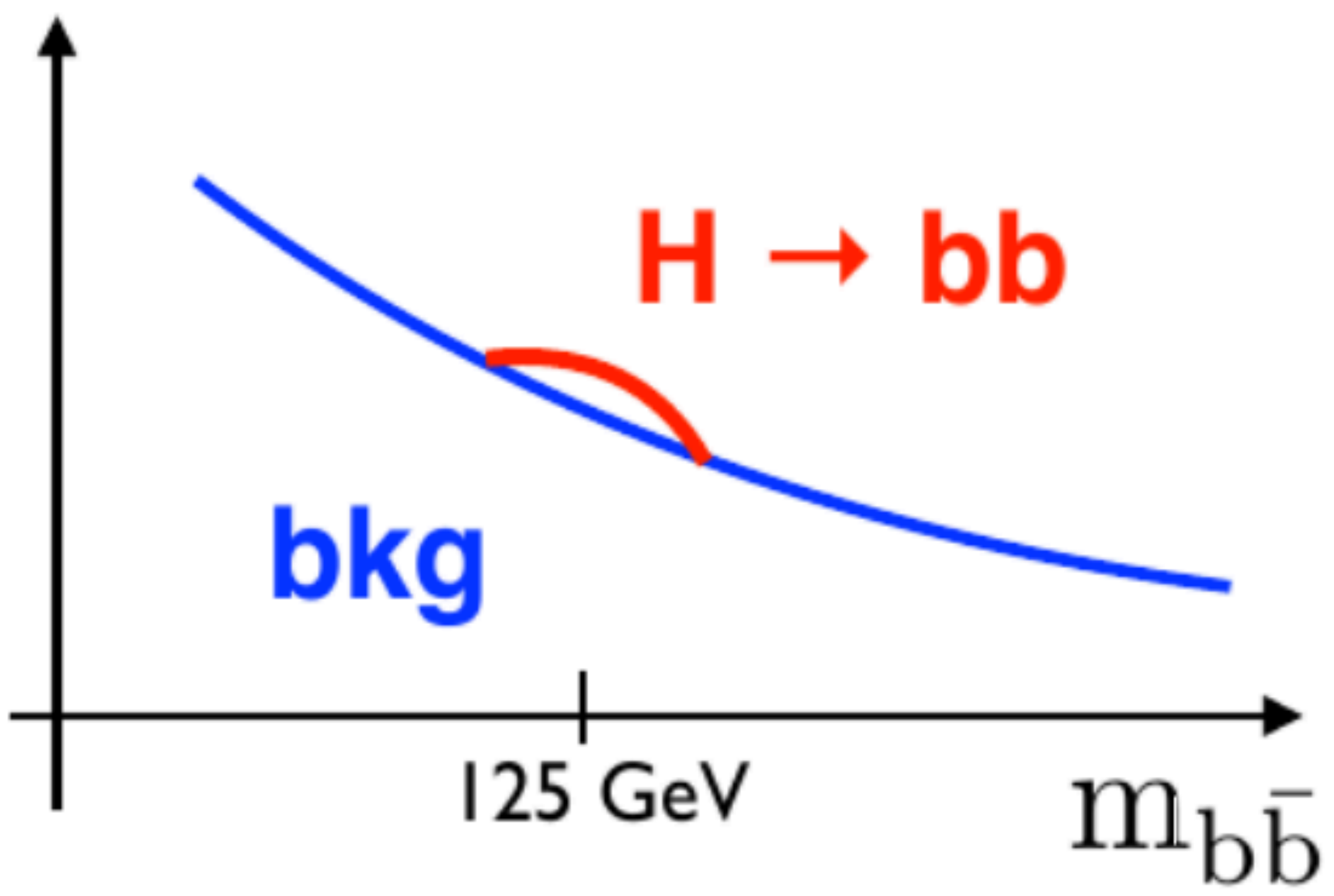
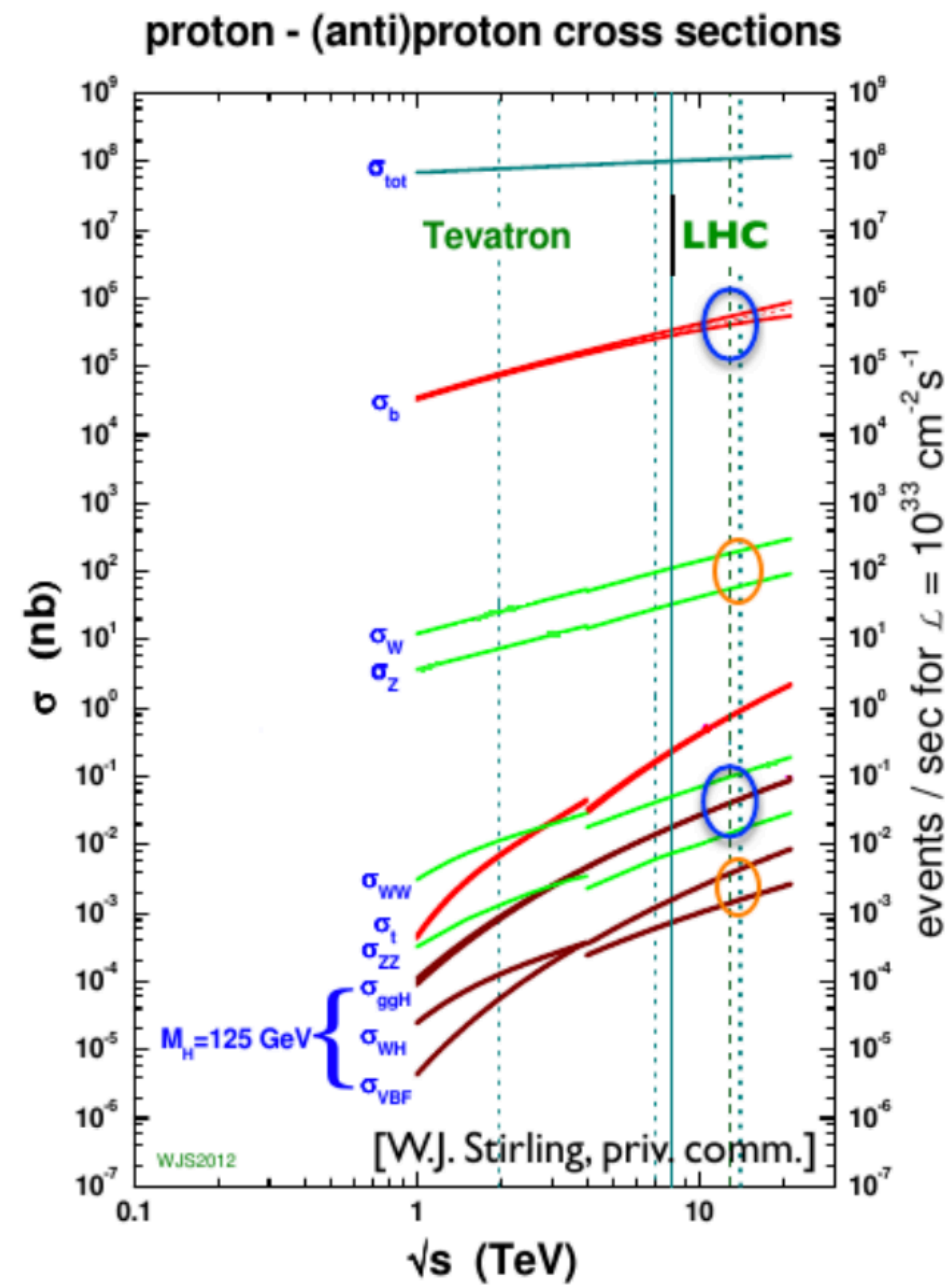
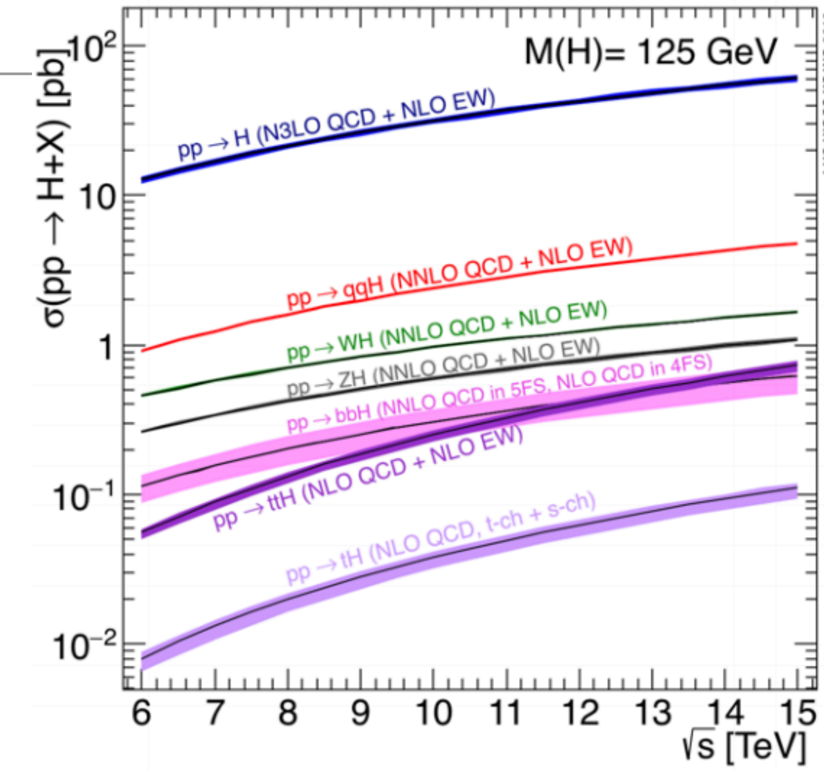




Background of multi-b-jet production is many order of magnitude higher

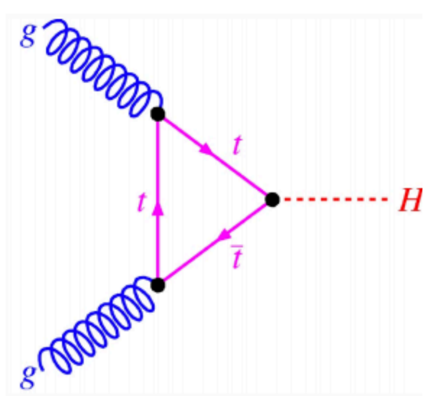
Not that easy, indeed….

Higgs Boson production at the LHC



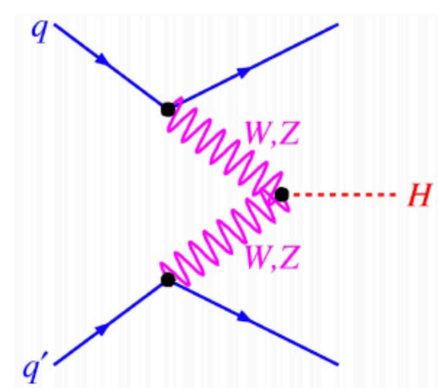
Higgs boson production

- 4 main challenge at the LHC
- Total cross section σ_H= 56 pb at 13 TeV
- ~7 million Higgs Bosons produced in ATLAS in Run2



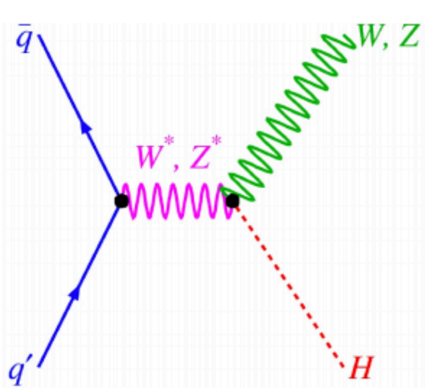
Gluon Gluon Fusion
88%

Only possible in boosted regime
(***Experts here in Genova!***)



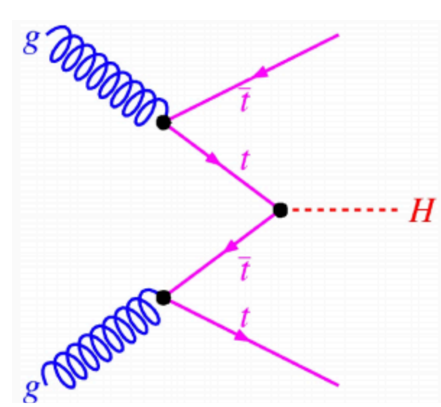
Vector Boson Fusion
7%

VBF Inclusive search
+ exclusive VBF+γ search
(***Experts here in Genova!***)



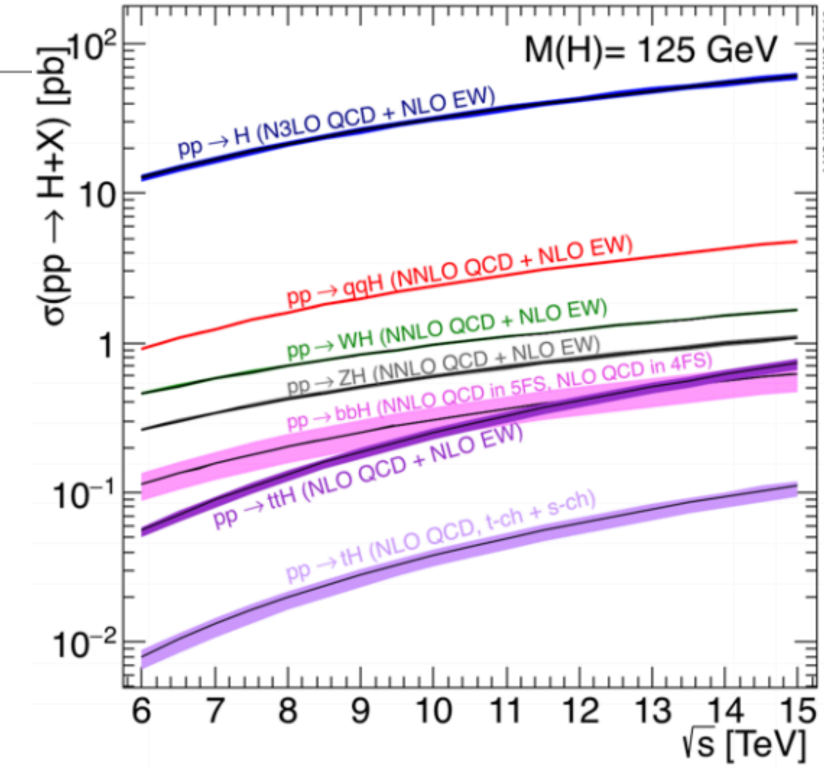
VH (WH,ZH)
3%

most sensitive channel
I will focus mostly on this



ttH
1%
Also important for top-top-Higgs Yukawa coupling

Higgs Boson production at the LHC



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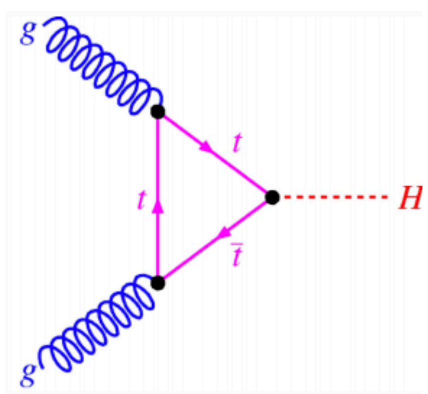

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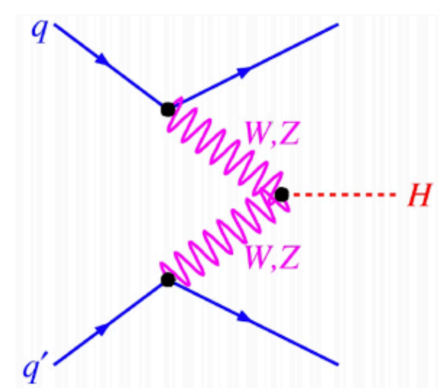

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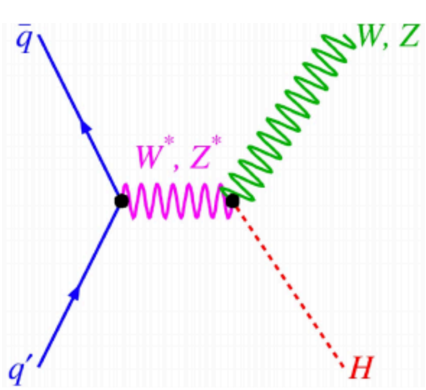

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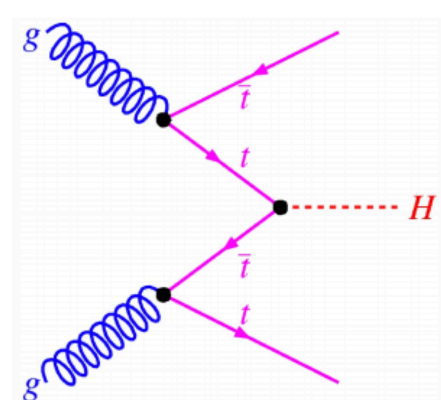
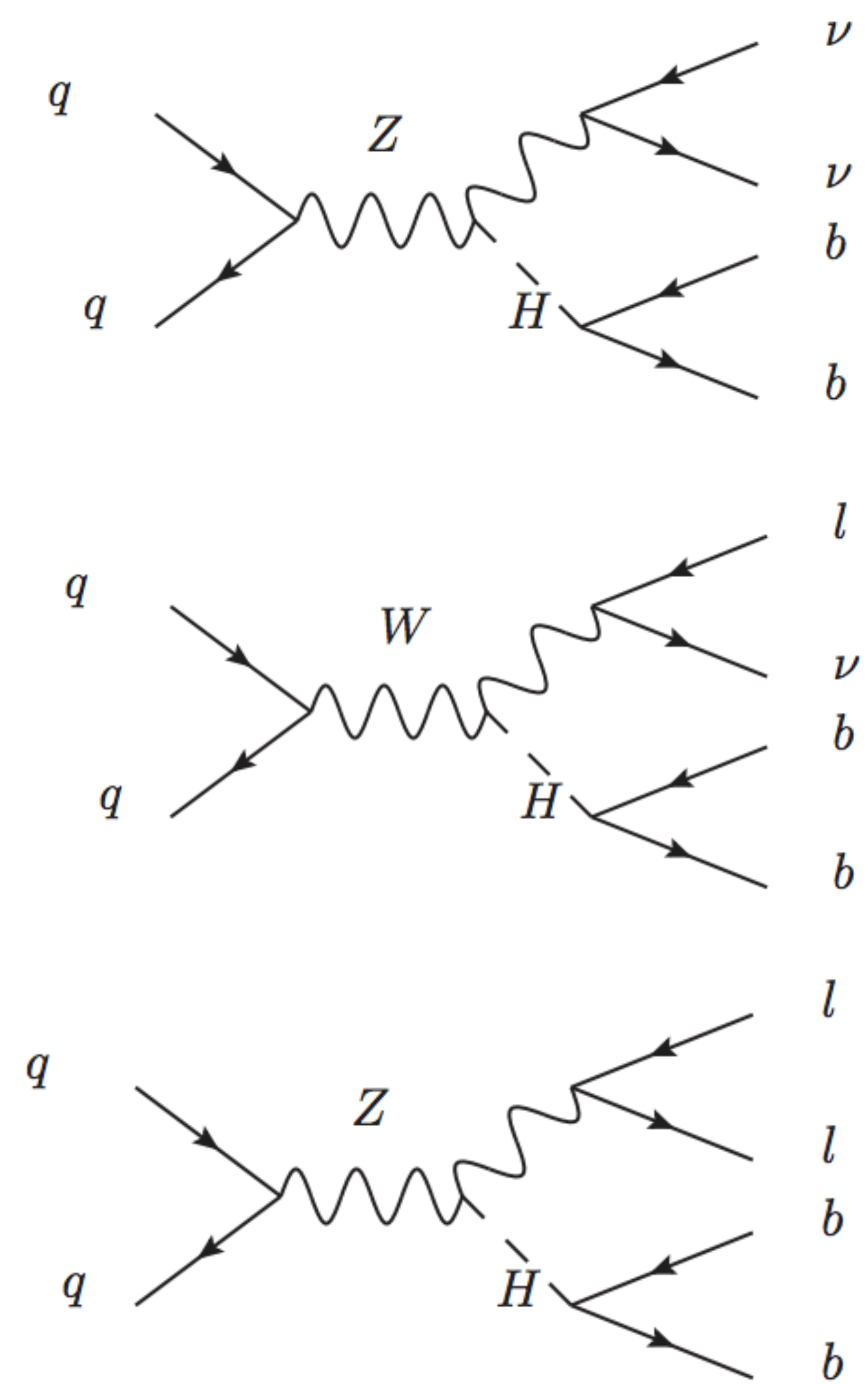


ttH
1%
Also important for top-top-Higgs Yukawa coupling

Higgs boson produced in association with a vector boson

Processes:

- pp→ZH *and* pp→WH *production*
  - Leptonic decays of Z/W for bkg rejection and trigger
  - 3 channels: 0,1,2 electrons, muons
- H→bb *decay*
  - 2 high p_T b-jets
  - Possible additional jets



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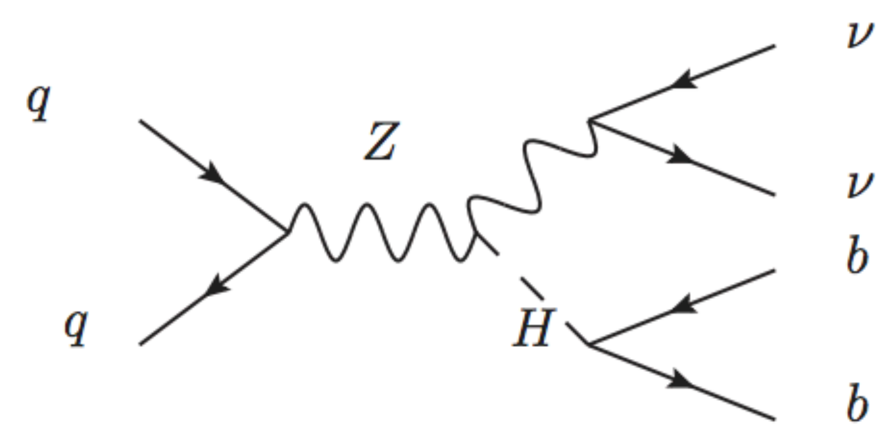
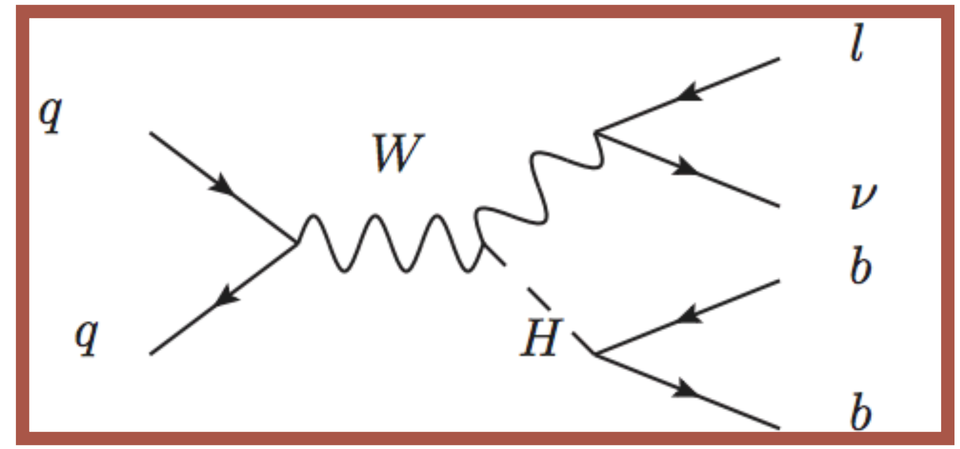
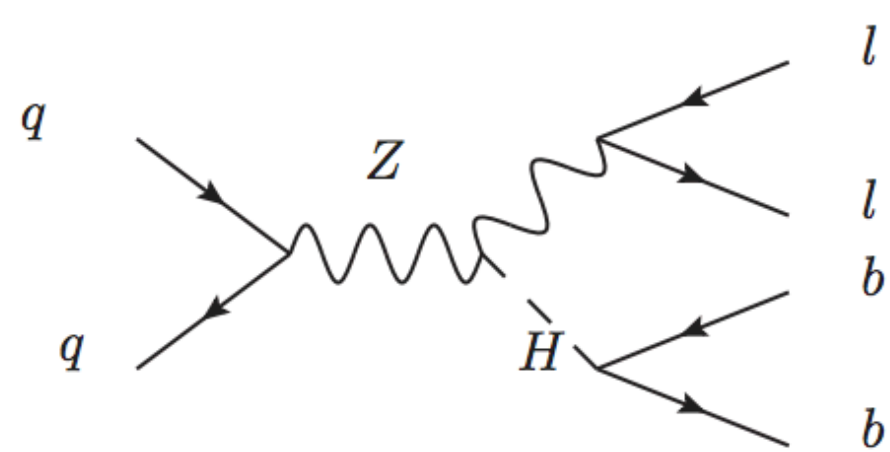
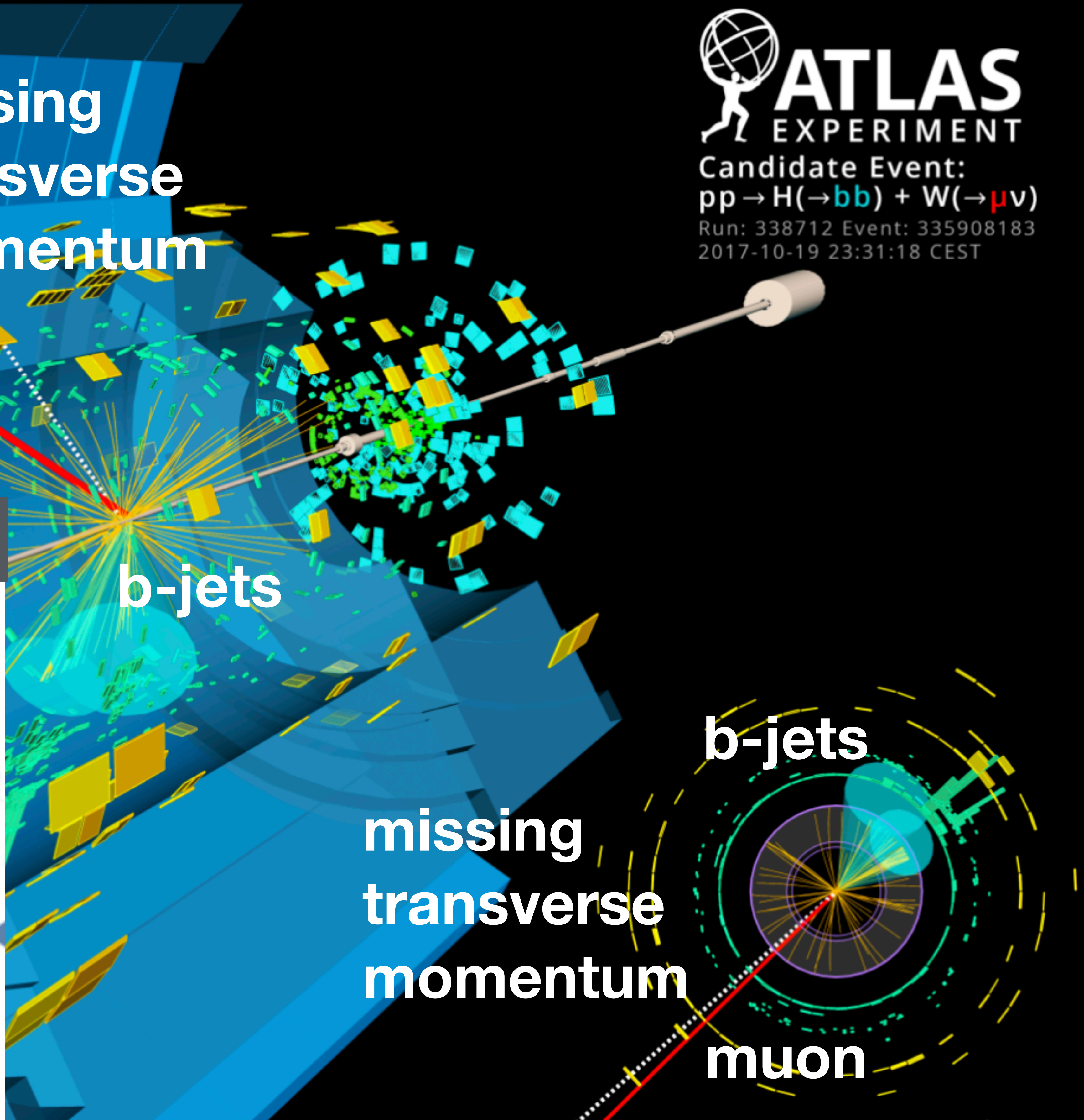
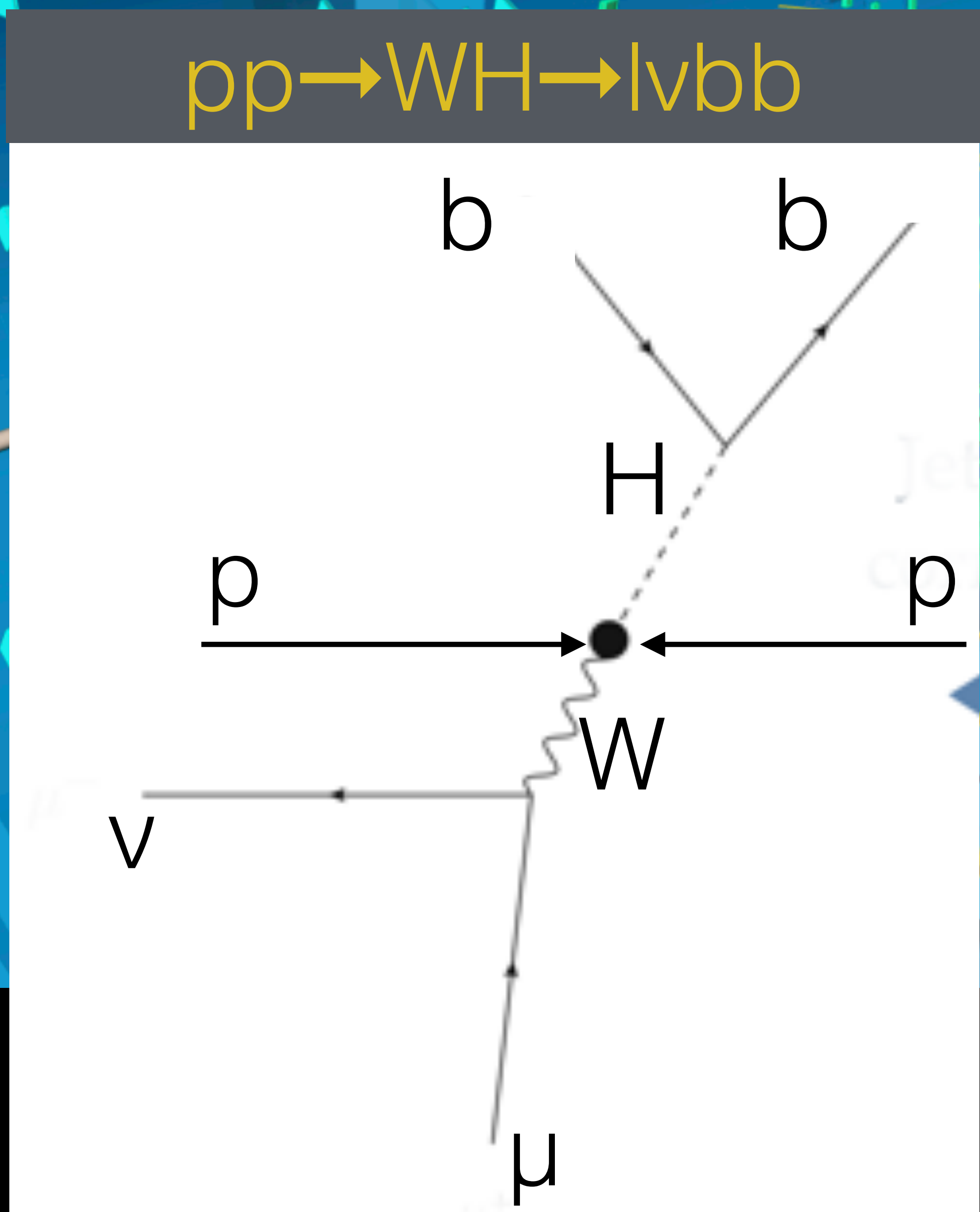








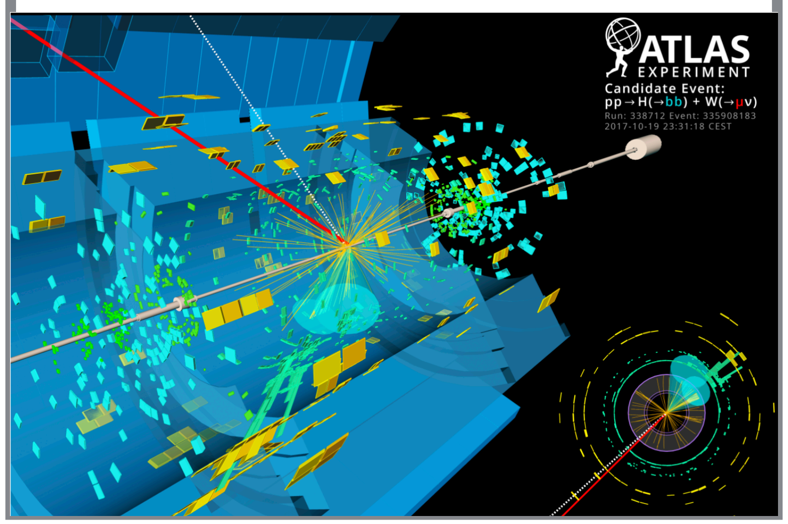


Building the analysis

The *VH* analysis selection in 1 slide

pp→WH

WH→lvbb (269 fb@13TeV)



Trigger: single e or E_T^{miss} trigger

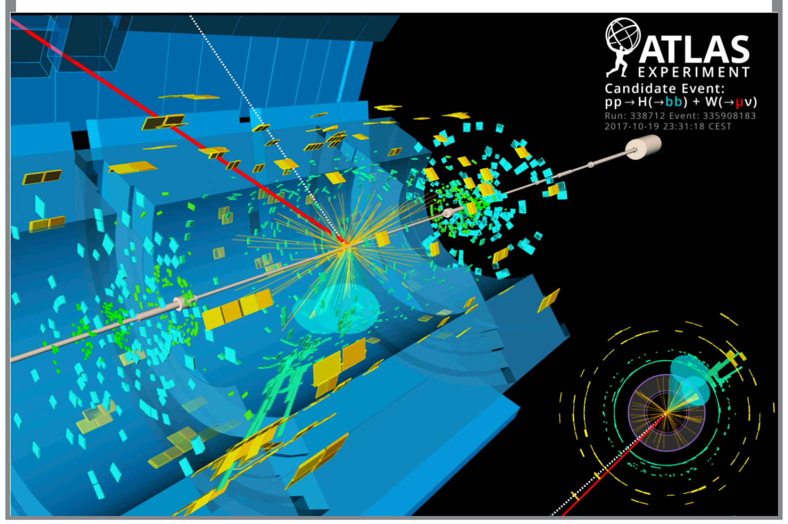
p_T(W)>150 GeV
well defined isolated e or μ (25-27 GeV)
2,3 jets (45,25 GeV)
2 leading jets b-tagged (70%WP)
multi jet suppressed MET>30 GeV

W+ Heavy Flavour jets CR:
m_{bb}<75 GeV and m_{lvb}>225 GeV

The *VH* analysis selection in 2 slides…

pp→WH

WH→lνbb (269 fb@13TeV)



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Back of the envelop calculation:

- σ(p_T(W)>150 GeV)/σ(*tot*) ~ 16%
- b-tagging eff. = 0.7^2 ~ 50%
- e/μ channel / W lepton decays ~67%
- jets/E_T^{miss}/lepton selection ~20%

SM signal for 79.8 fb^{-1}: 230 evt (221)

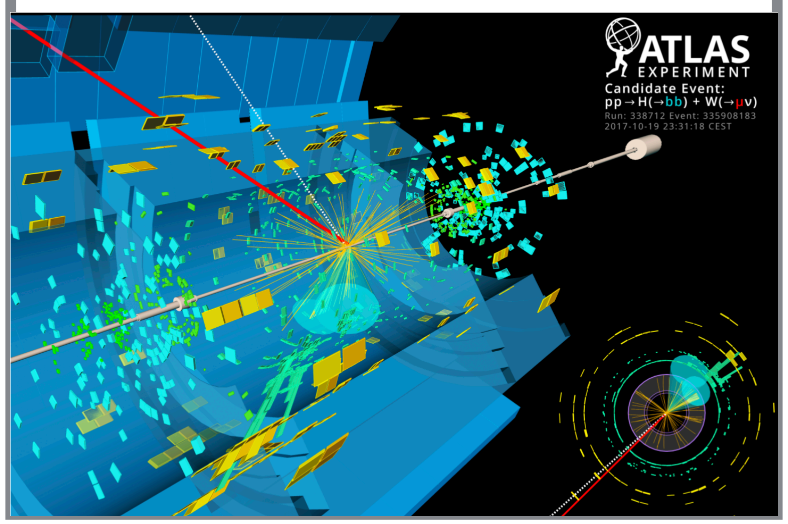
Total background: 78k evt

s/(s+b)=0.3% **s/sqrt(b)~1**

Ok… the *VH* analysis selection in 3 slides!
0-,1-,2-lepton channels

pp→WH

WH→lνbb (269 fb@13TeV)



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p_T(W)>150 GeV
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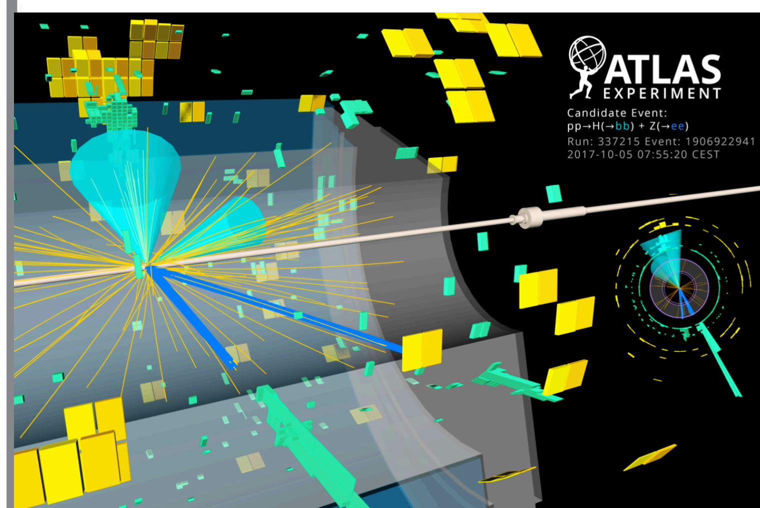
2,3 jets (45,25 GeV)
2 leading jets b-tagged (70%WP)
multi jet suppressed MET>30 GeV

W+ Heavy Flavour jets CR:
m_{bb}<75 GeV and $m_{lνb}$>225 GeV

pp→ZH

ZH→llbb (34.8 fb@13TeV)

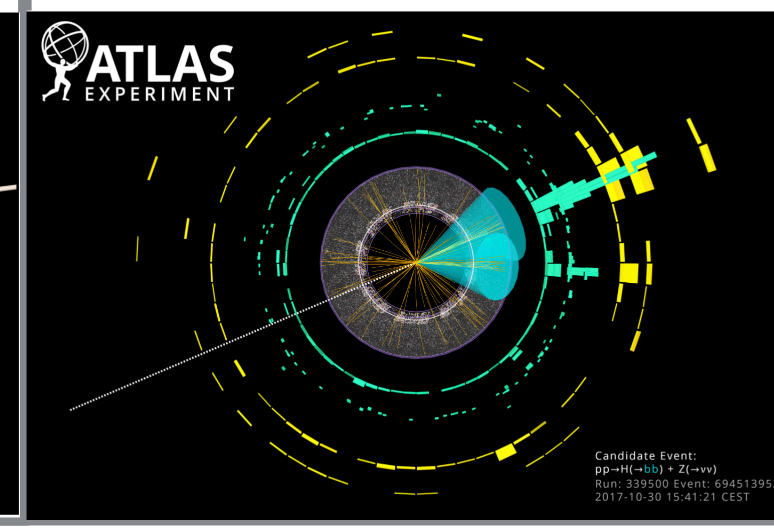


Trigger: single lepton trigger

p_T(Z)/GeV [75,150] and >150
2e or 2μ (27,7 GeV)
81<m_{ll}/GeV<101
2,≥3 jets (45,25 GeV)
2 leading jets b-tagged (70%WP)

top CR:
opposite flavour events

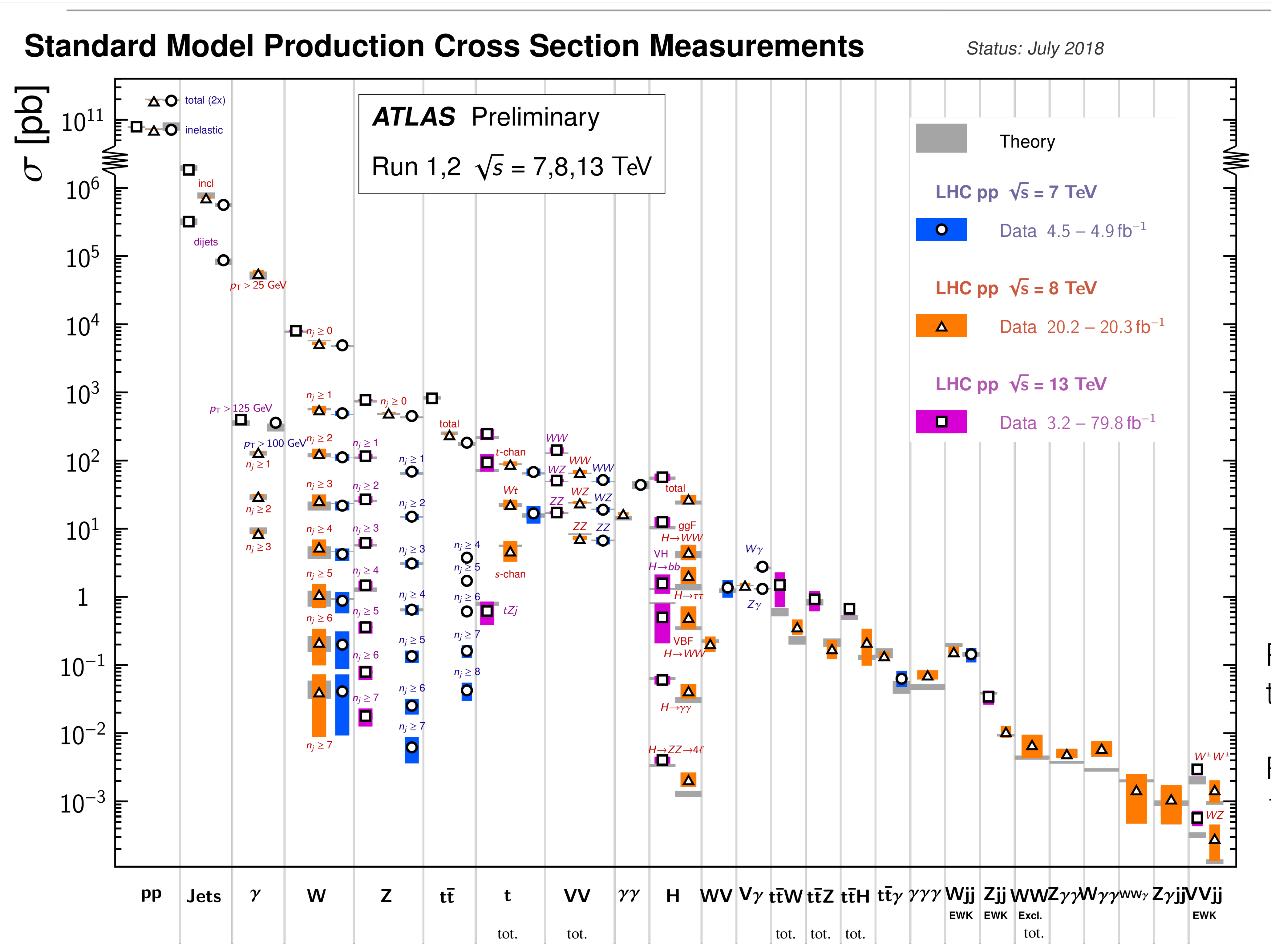
ZH→ννbb (103.4 fb@13TeV)



Trigger: E_T^{miss} trigger

MET=p_T(Z)>150 GeV
lepton veto (7 GeV)
2,3 jets (45,25 GeV)
2 leading jets b-tagged (70%WP)
multi jet suppressed by dedicated angular cuts

VH: Main Backgrounds - The Standard Model!!!

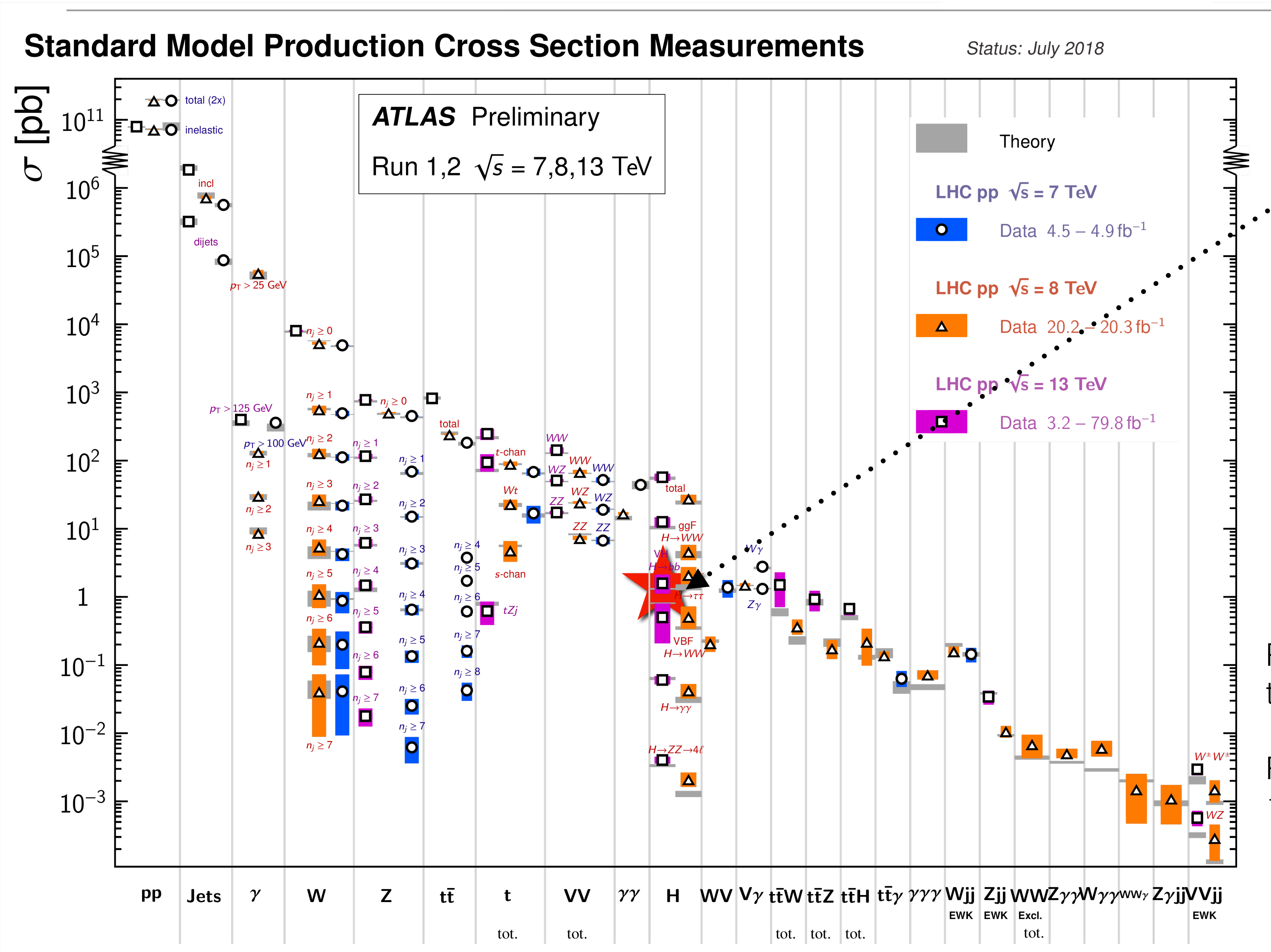


PS:
this table is impressive!

Predictions on spot over 10^{14} orders of magnitude!

VH, H → $b\bar{b}$ (μ=1.06)

VH: Main Backgrounds



Our goal!

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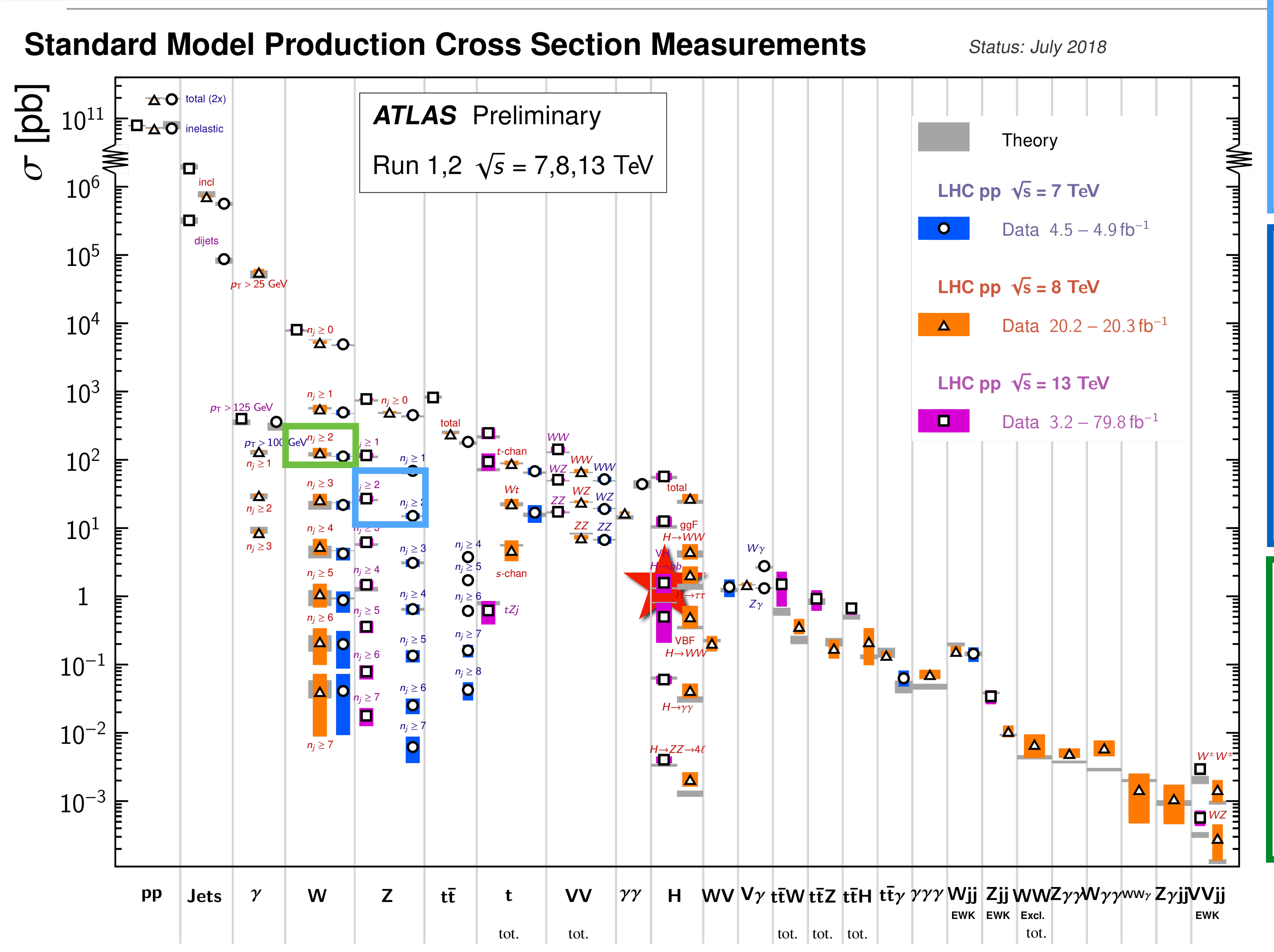
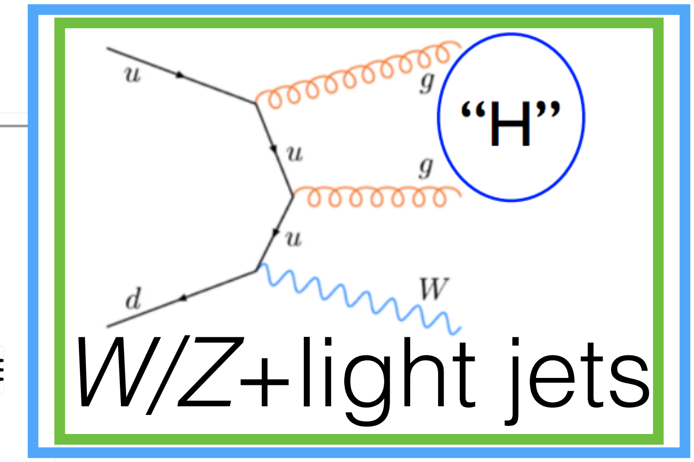
VH: Main Backgrounds

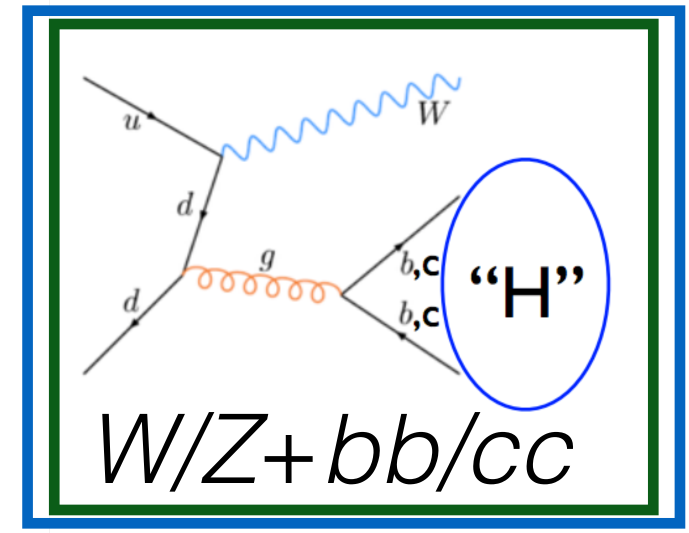
VH, H → $b\bar{b}$ (μ=1.06)

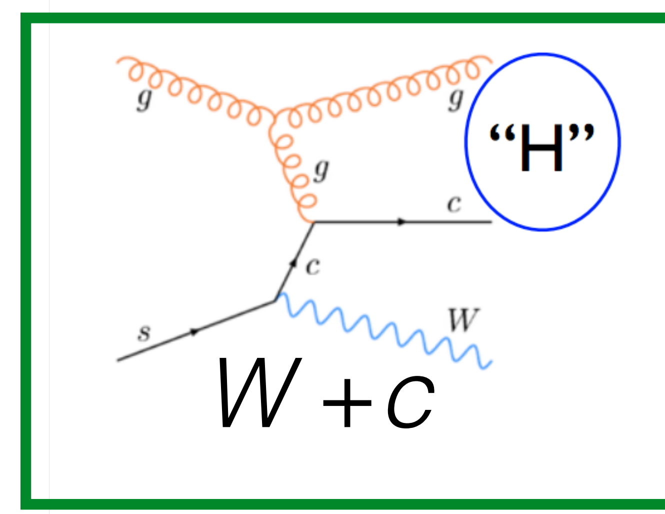
W+jets

Z+jets









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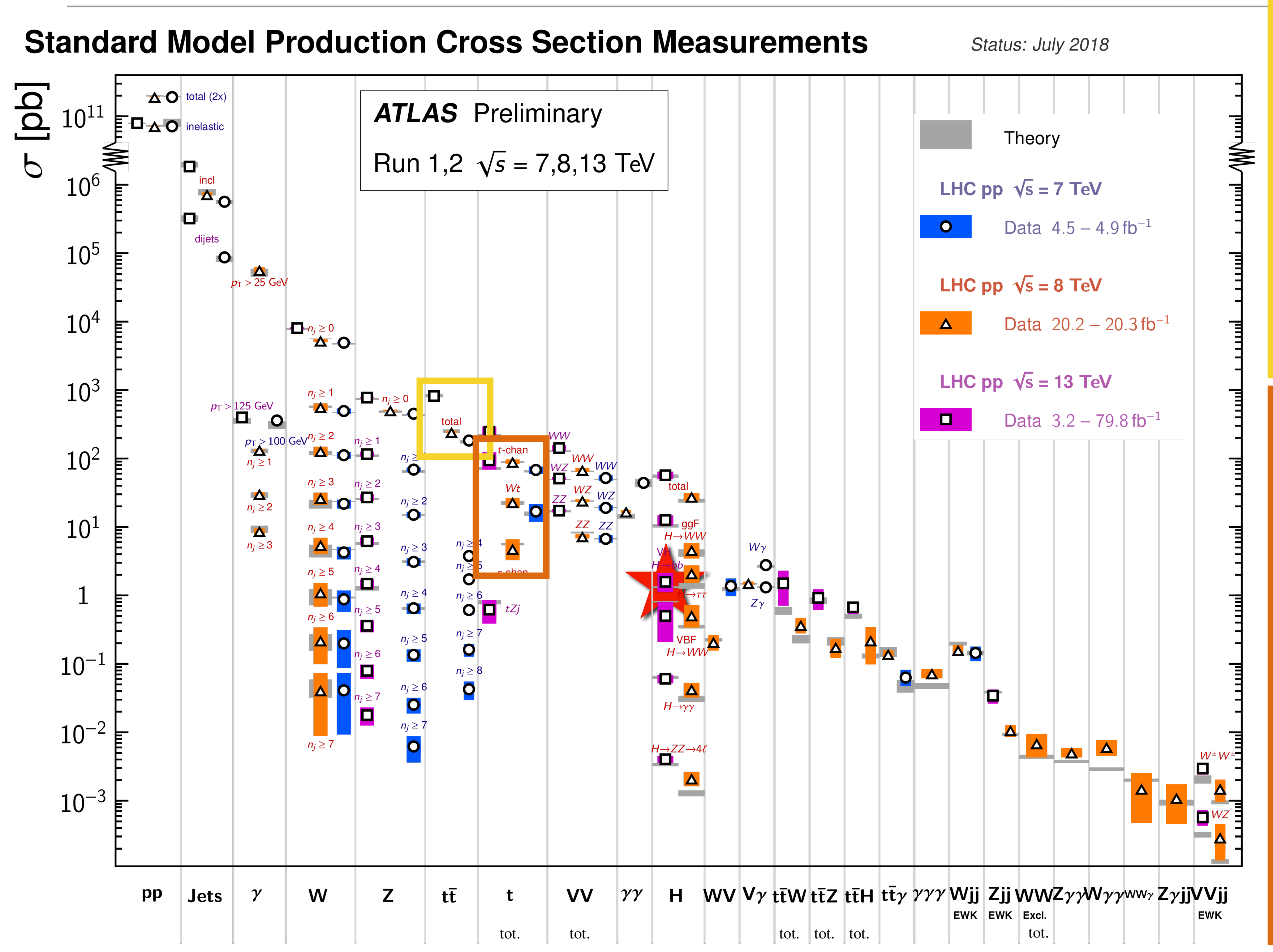
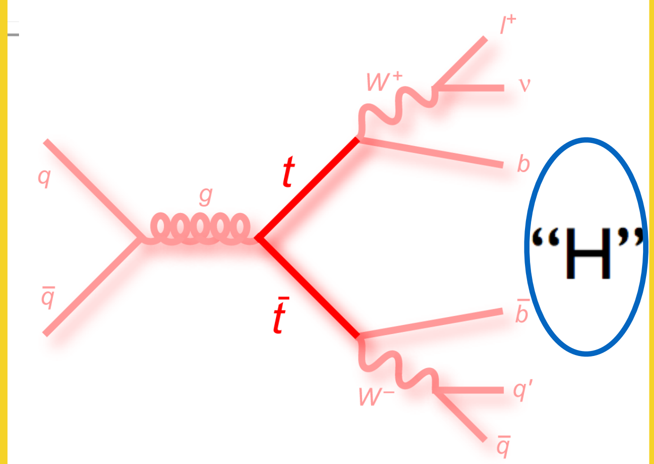
VH: Main Backgrounds

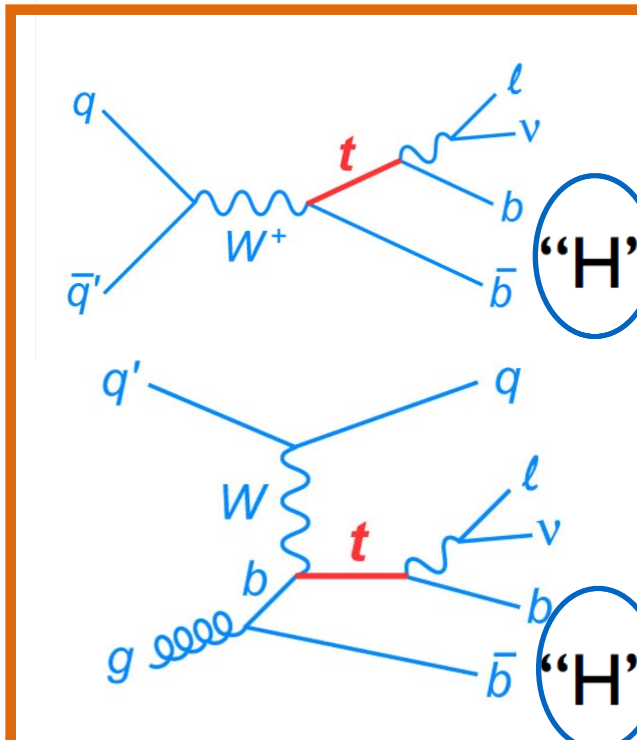
VH, H → $b\bar{b}$ (μ=1.06)

$t\bar{t}$
Single top
Multijet
W+jets
Z+jets





tt background



Single top

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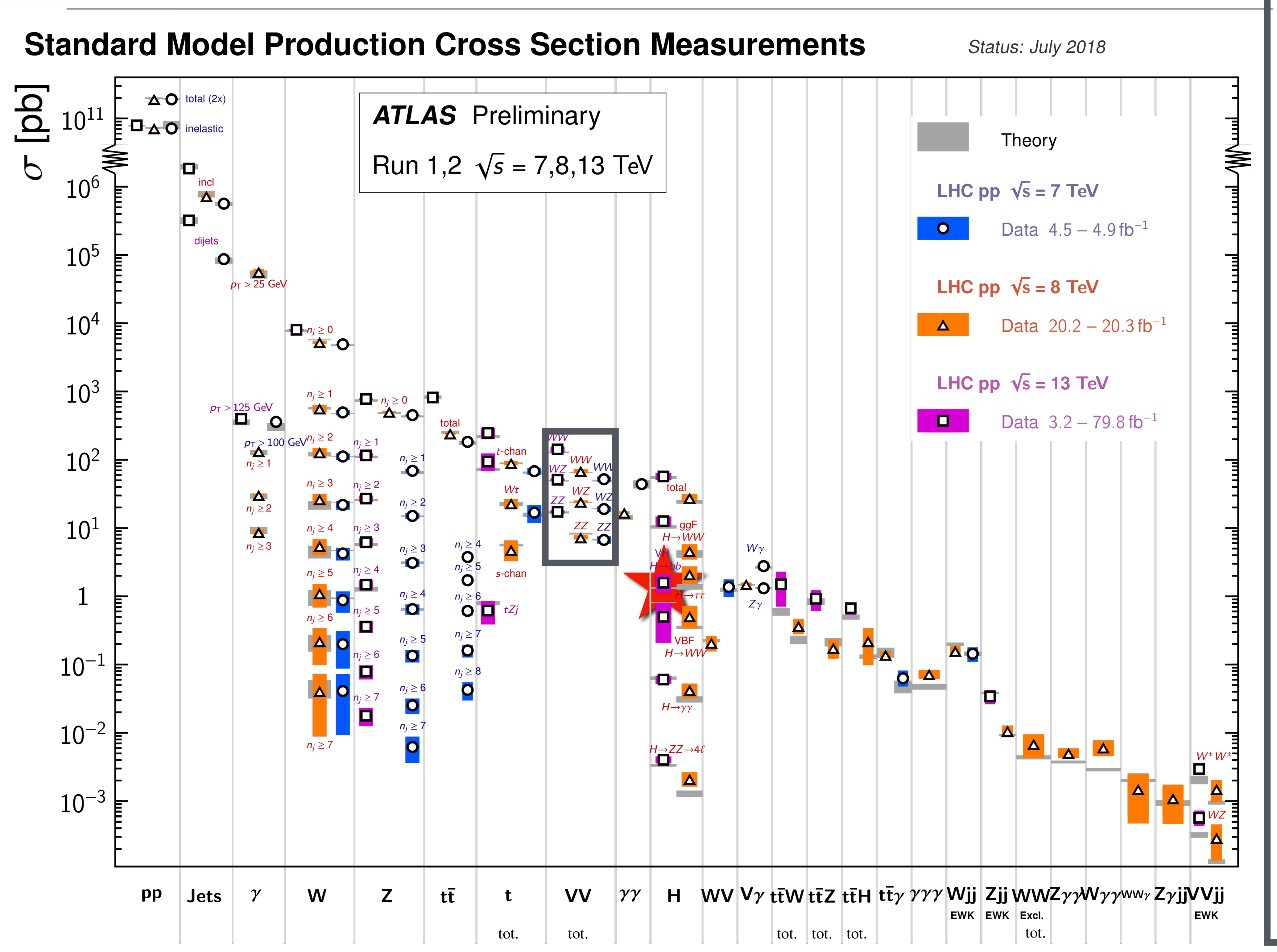
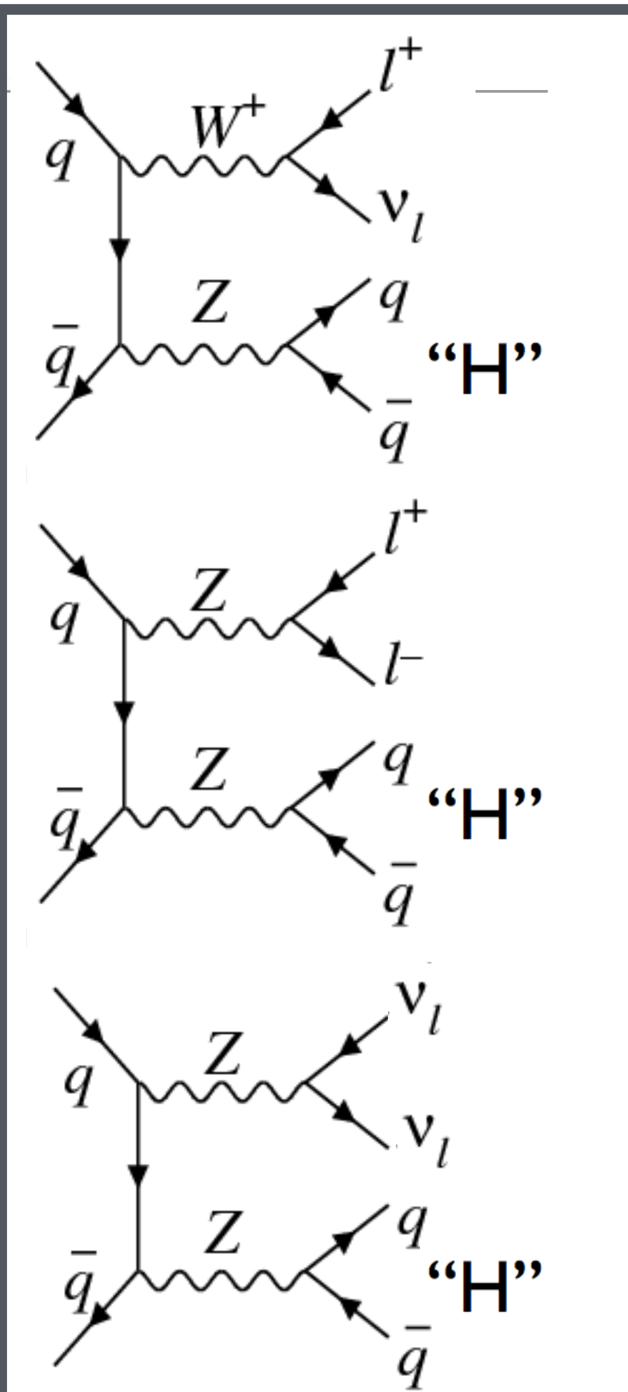
- VH, H → $b\bar{b}$ (μ=1.06)
- Diboson
- $t\bar{t}$
- Single top
- Multijet
- W+jets
- Z+jets

VH: Main Backgrounds





Diboson possible candle

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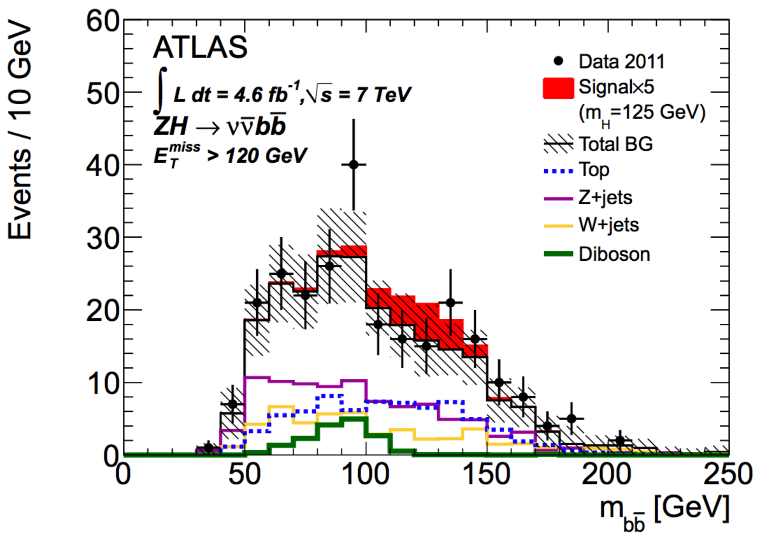
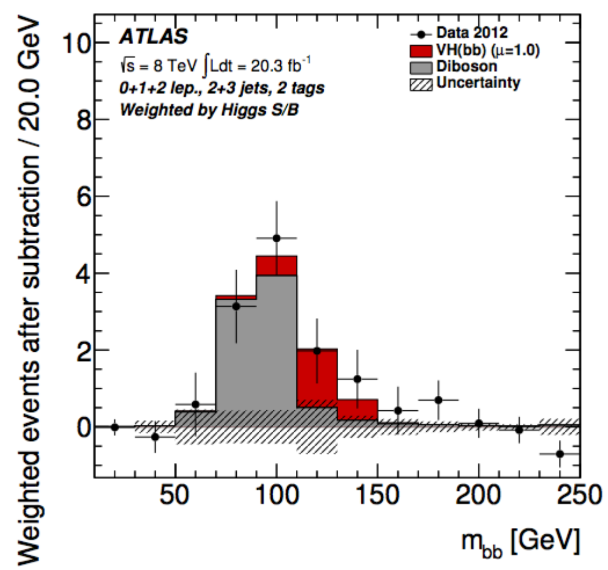
Pre-summer 2018

Early Run1



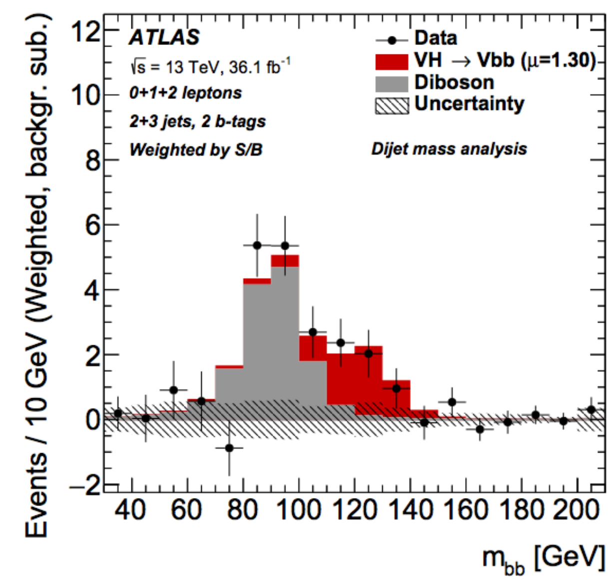
- ATLAS: arXiv:1207.0210
  7TeV data
  Limit ~ 4.5×SM
- CMS: arXiv:1202.4195
  7TeV data
  Limit ~ 6×SM
- Tevatron legacy: arXiv:1207.6436
  2.8σ at 125 GeV (1.5σ exp.)
  3.1σ in full mass range

Run1 Legacy



- ATLAS: arXiv:1409.6212
  1.4σ (2.6σ exp.)
  $\mu^{bb}_{VH} = 0.52 \pm 0.38$
- CMS: arXiv:1310.3687
  2.1σ (2.5σ exp.)
  $\mu^{bb}_{VH} = 0.89 \pm 0.45$
- LHC Combination: arXiv:1606.02266
  2.6σ (3.7σ exp.)
  $\mu^{bb} = 0.70 \pm 0.28$

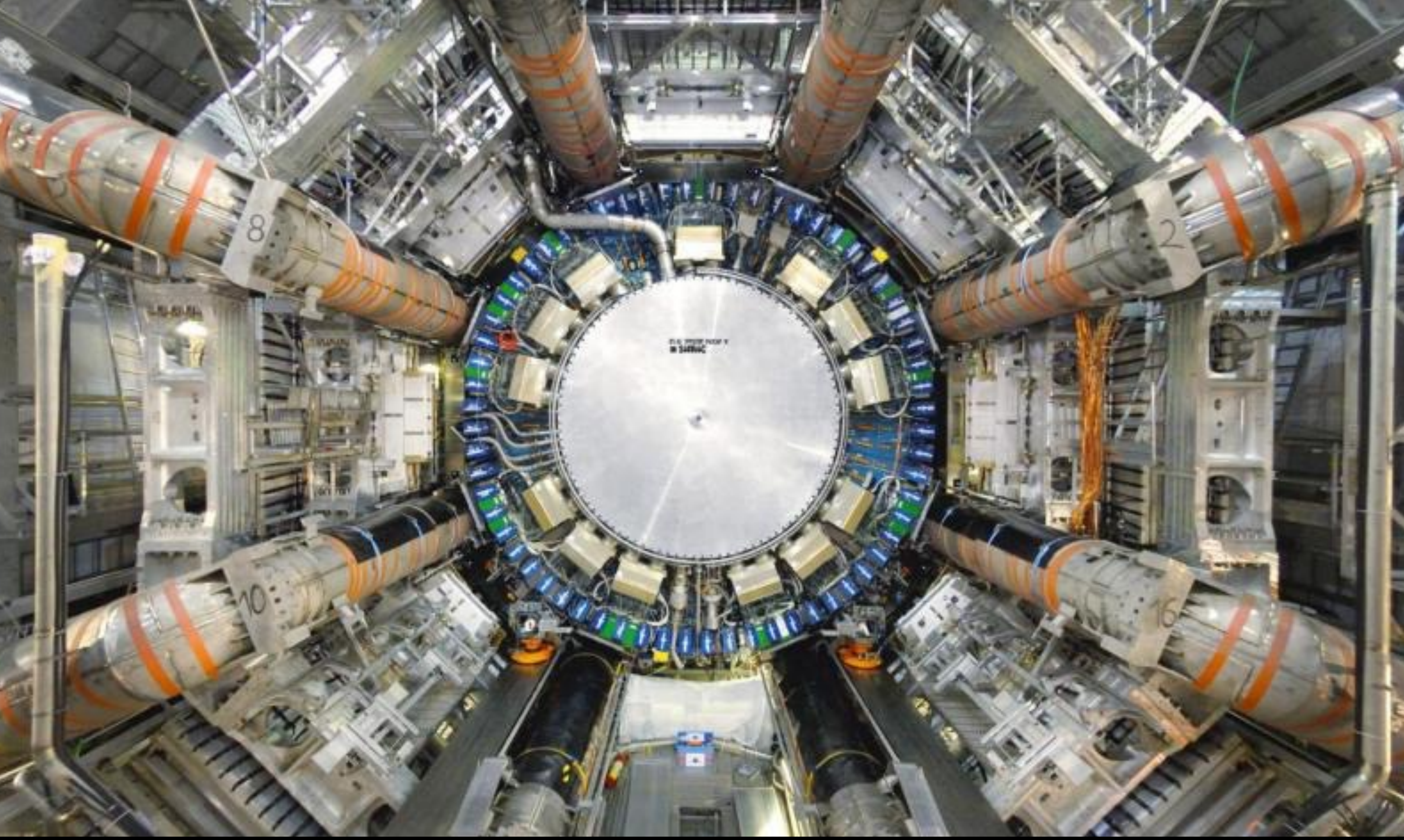
Run2 2015-2017



- ATLAS: arXiv:1708.03299
  Evidence at 3.5σ (3.0σ exp.)
  $\mu^{bb}_{VH} = 1.20 \pm 0.38$
- CMS: arXiv:1709.07497
  Evidence at 3.3σ (2.8σ exp.)
  $\mu^{bb}_{VH} = 1.2 \pm 0.40$

And in the other searches?

Analysis	Dataset	Ebs. limit	Exp. limit	signal strength	arXiv
CMS ggF	Run-2	5.8	3.3	2.3±1.7	1709.05543
ATLAS VBF	Run-1	4.4	5.4	-0.8±2.3	1606.02181
CMS VBF	Run-1	5.5	2.5	2.8±1.5	1506.01010
ATLAS VBF	Run-2	5.9	3.0	3.0±1.7	1807.08639
ATLAS ttH	Run-1	3.4	2.2	1.5±1.1	1503.05066
CMS ttH	Run-1	4.2	3.3	1.2±1.6	1502.02485
ATLAS ttH	Run-2	2.0	1.2	0.84±0.63	1712.08895
CMS ttH	Run-2	1.5	0.9	0.72±0.45	1804.03682



Experimental challenges

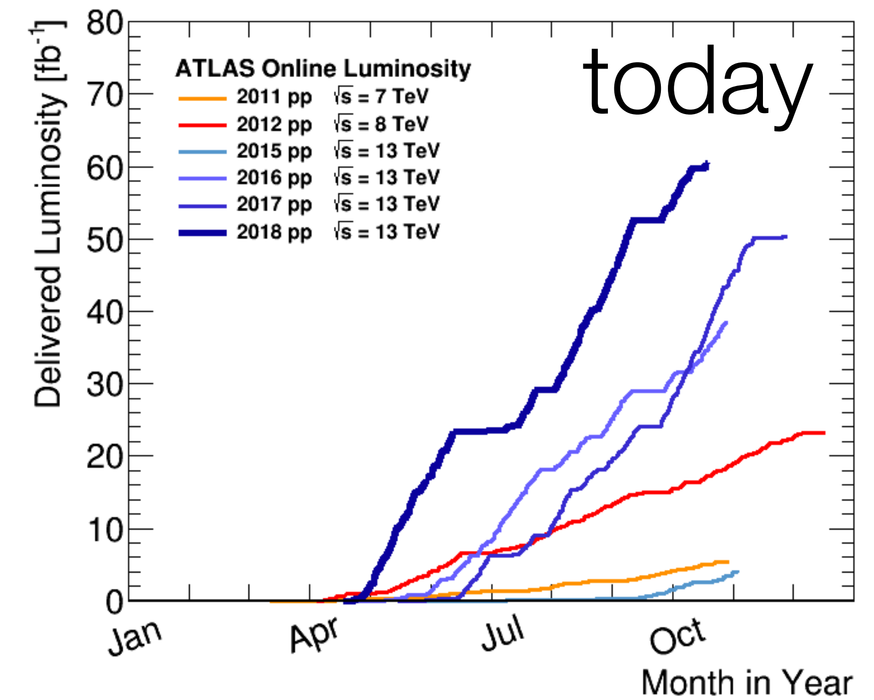
First ingredient:
Low S/B ⇒ Large dataset needed

Dataset in ATLAS:

- Run 1: 5 fb^{-1} at 7 TeV 20 fb^{-1} at 8 TeV
- Run 2: 80 fb^{-1} at 13 TeV analyses

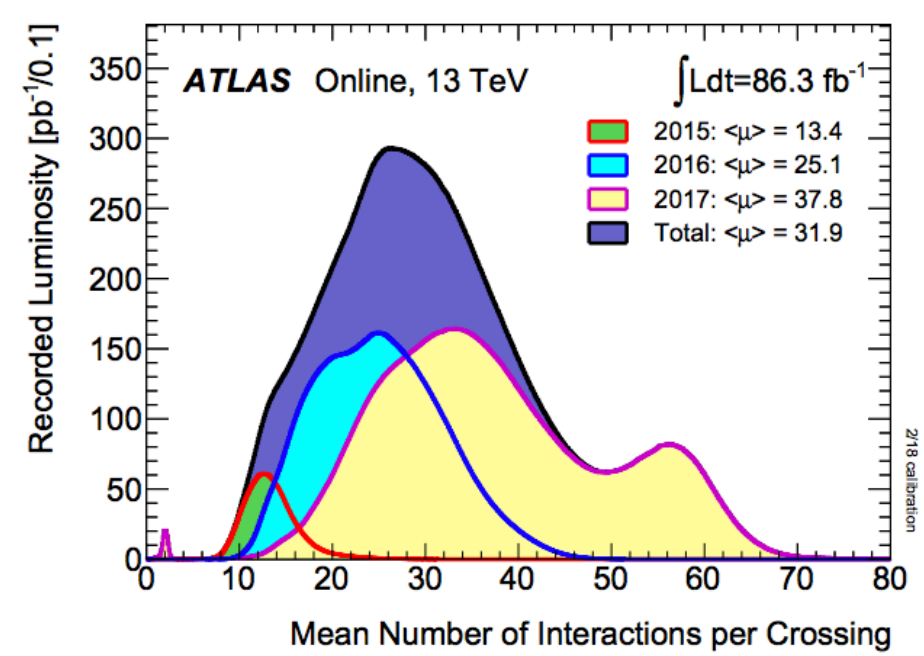
Downside: high rate of pile-up

- Challenges for trigger, jets, b-tagging

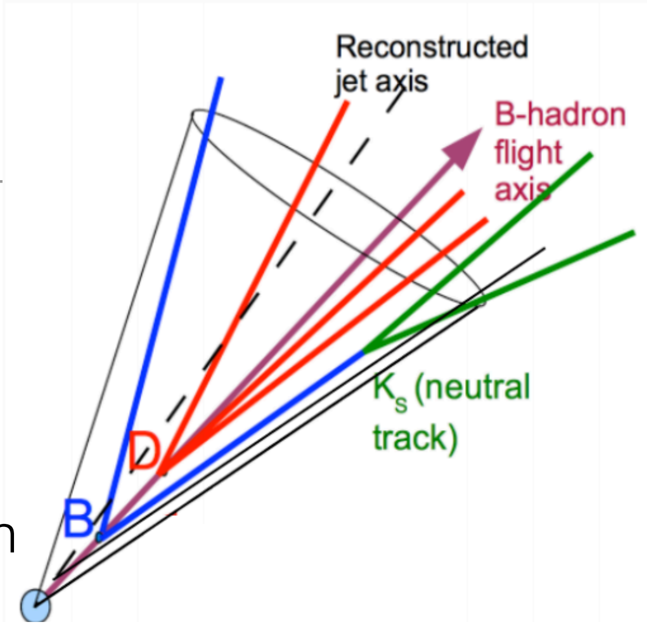


ATLAS pp 25ns run: June 5-November 10 2017										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.9	99.3	99.5	99.4	99.9	97.8	99.9	100	100	99.2
Good for physics: 93.6% (43.8 fb^{-1})										

Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at √s=13 TeV between June 5 – November 10 2017, corresponding to a delivered integrated luminosity of 50.4 fb^{-1} and a recorded integrated luminosity of 46.8 fb^{-1}. The toroid magnet was off for some runs, leading to a loss of 0.5 fb^{-1}. Analyses that don't require the toroid magnet can use these data.



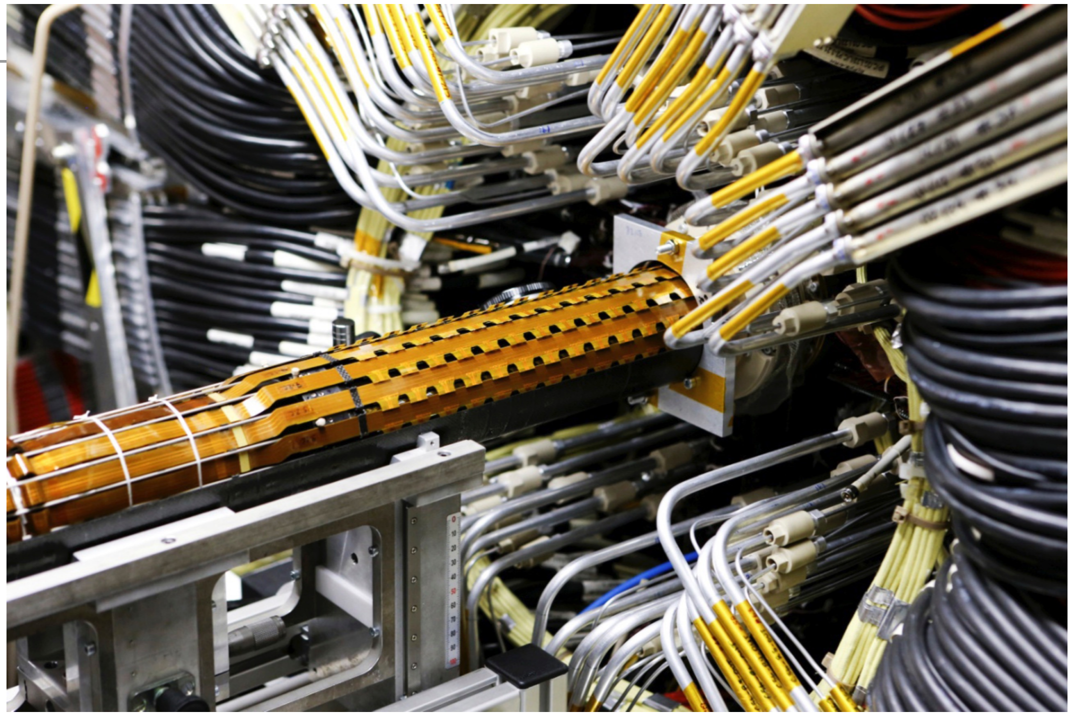
Second ingredient: B-tagging

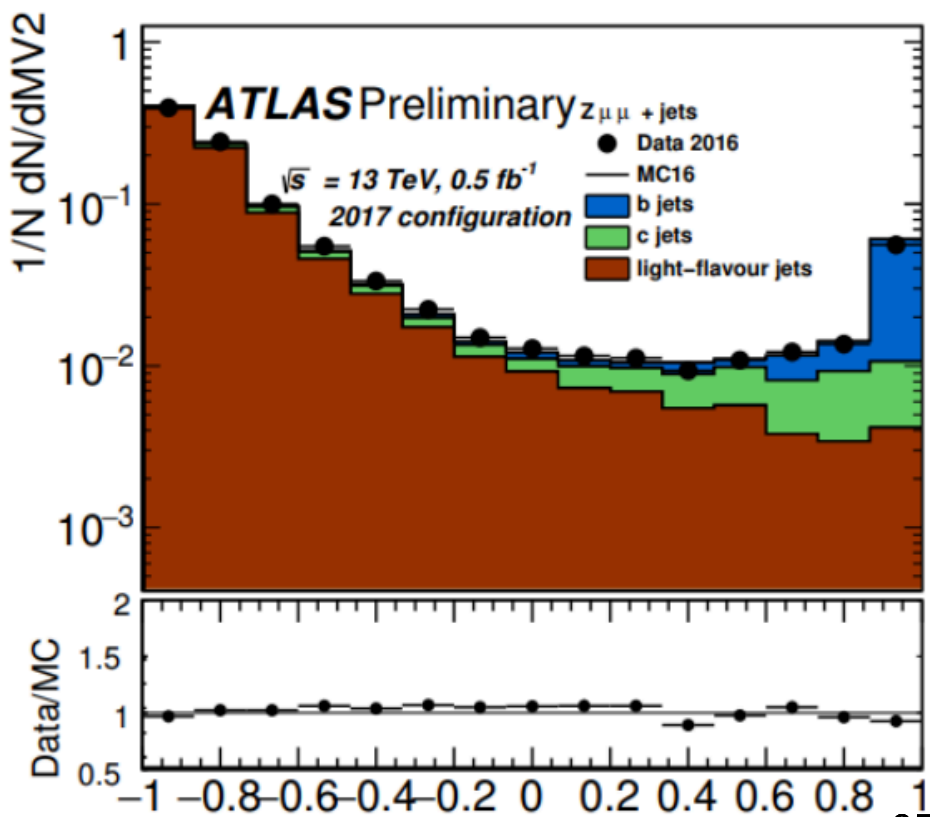


- Depends critically on the excellent operation of the tracker
- Performance in Run2 relying on
  - New IBL detector installed in LS 1(2013-2014)
  - Tracking optimised for high PU and hight p_T environment
  - Better ML algorithms
- Run2 performance
  - Rejection of light/ c jets 300/8 at 70% b-jets efficiency
  - Well modelled in simulation
  - Good performance even at high pile-up

In Run2: Insertable b-layer
- Additional pixel layer R~3.3 cm
- Pixel size 50x250 μm

ATLAS “b”-layer:
- R~5.1 cm, pixel size 50x400 μm

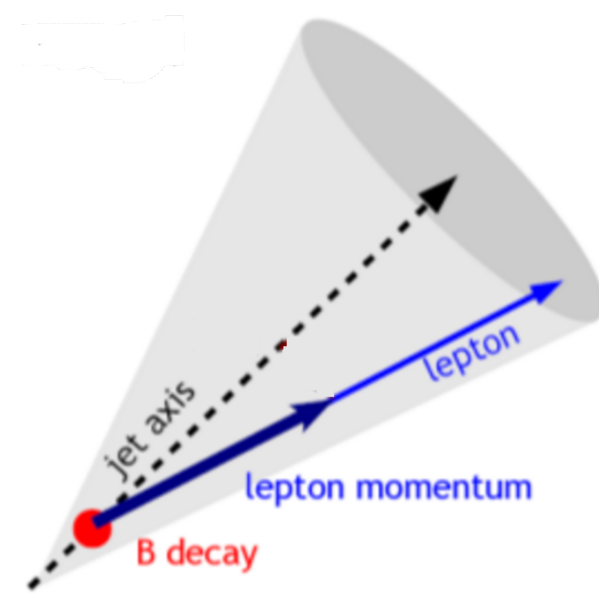


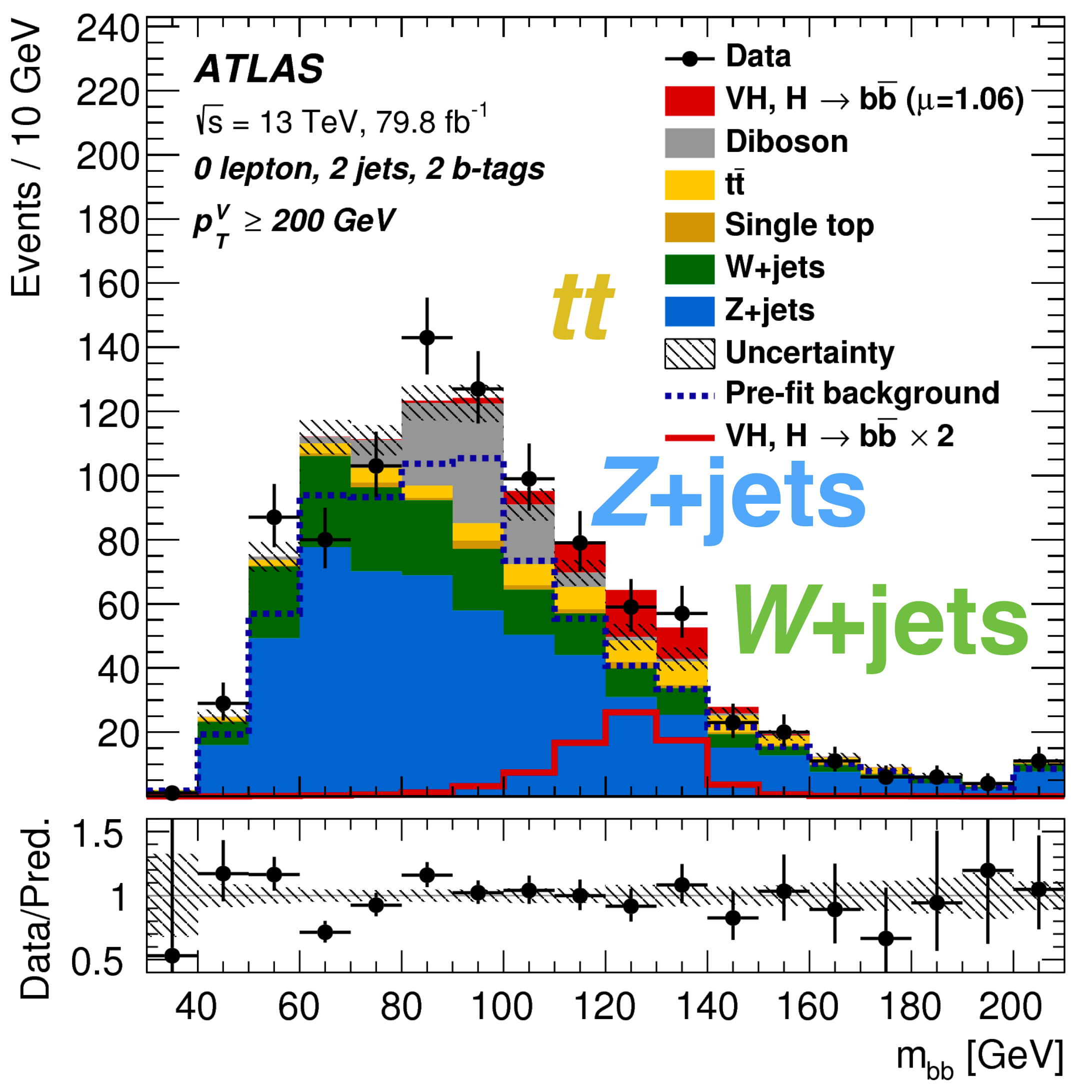


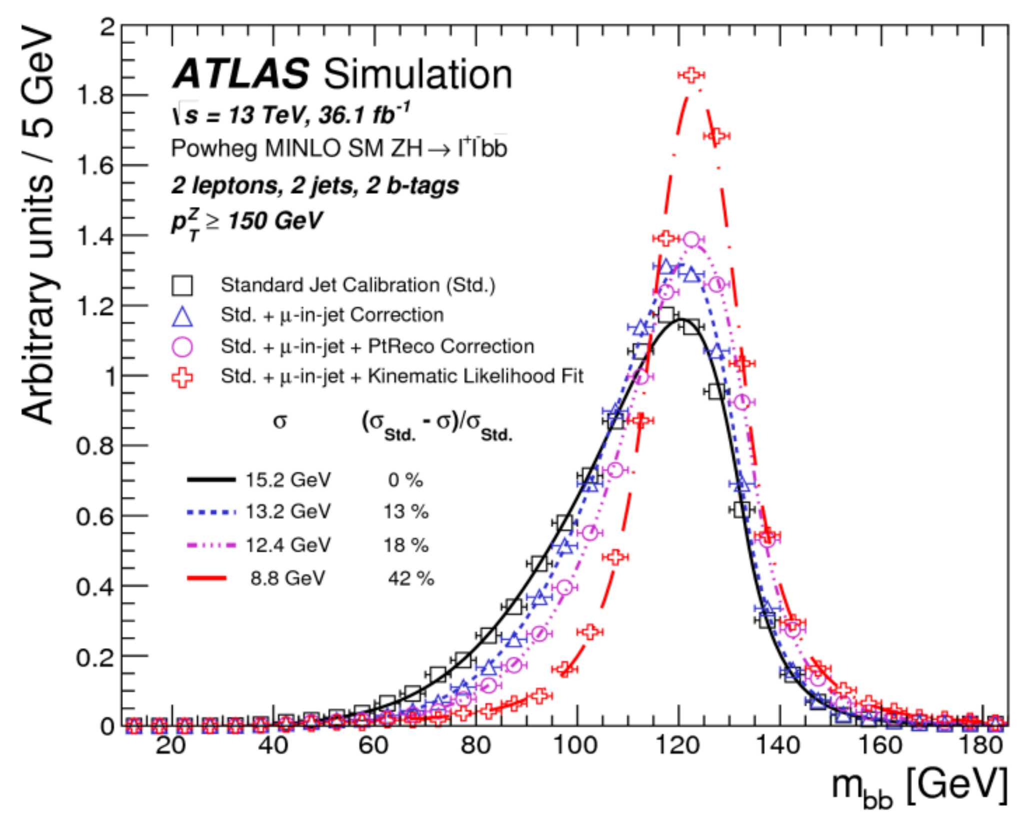
Third ingredient: Mass resolution

Sharpening signal mass peak improve sensitivity:

- Add muon in jet for semi-leptonic decays
- Apply resolution correction based on energy response on signal
- Use kinematic constrains to improve the resolution (2 leptons)

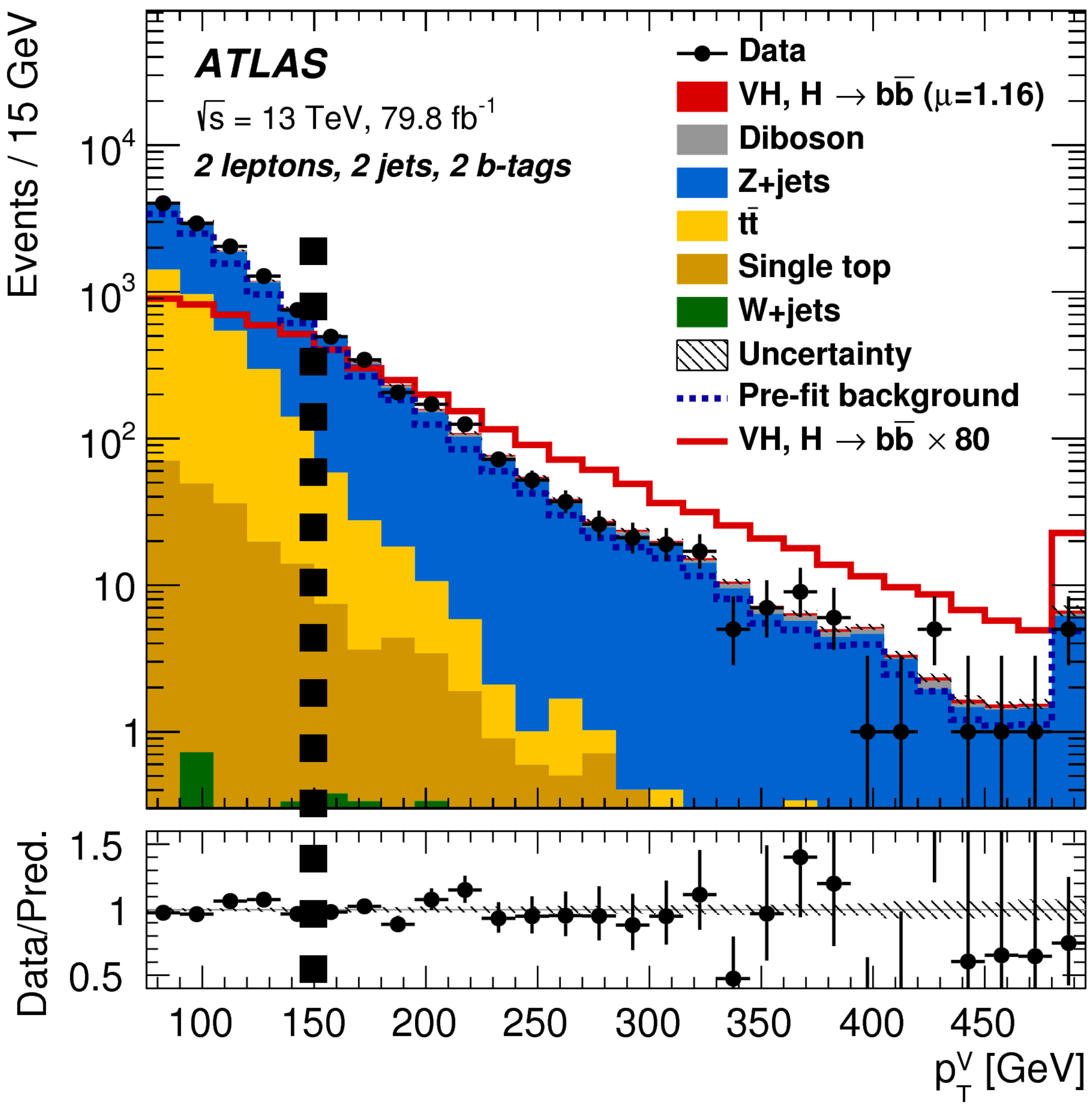




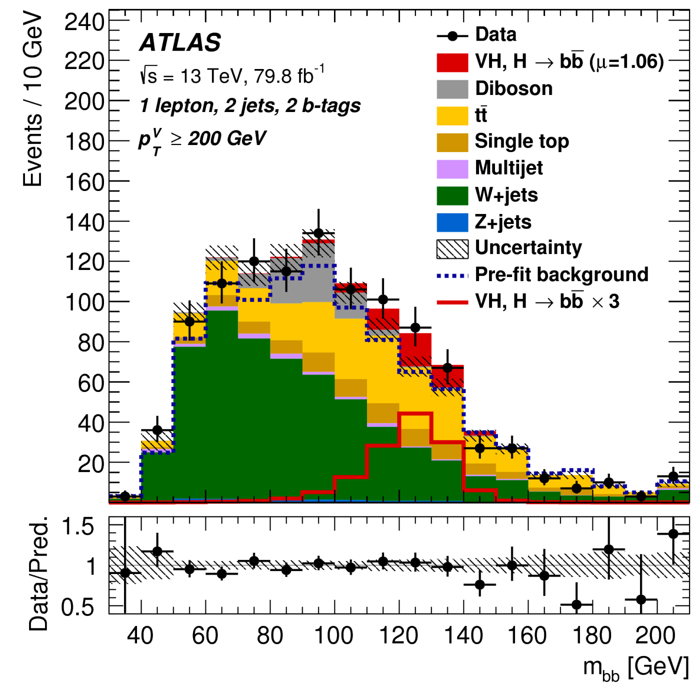


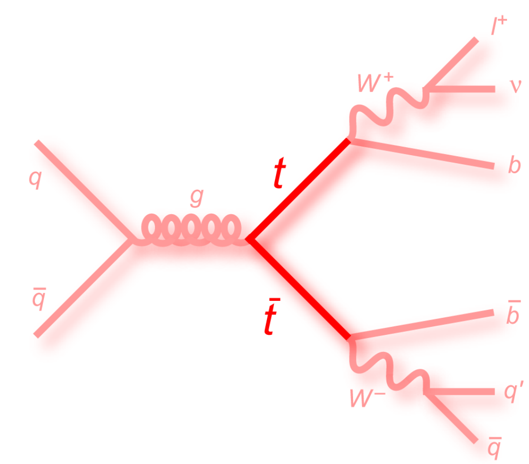
Fourth ingredient:
Topology criteria

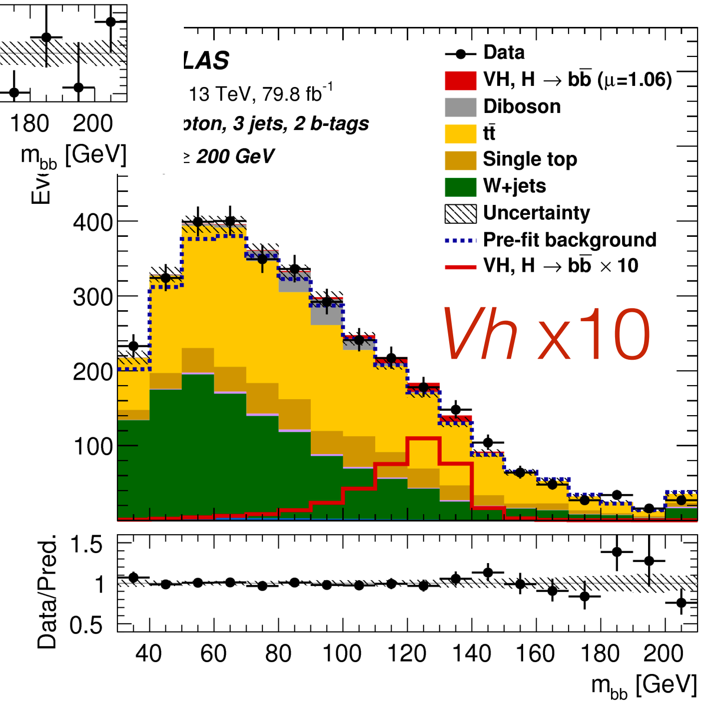
Improved signal to background separation using information on the ***W/Z p*T.**



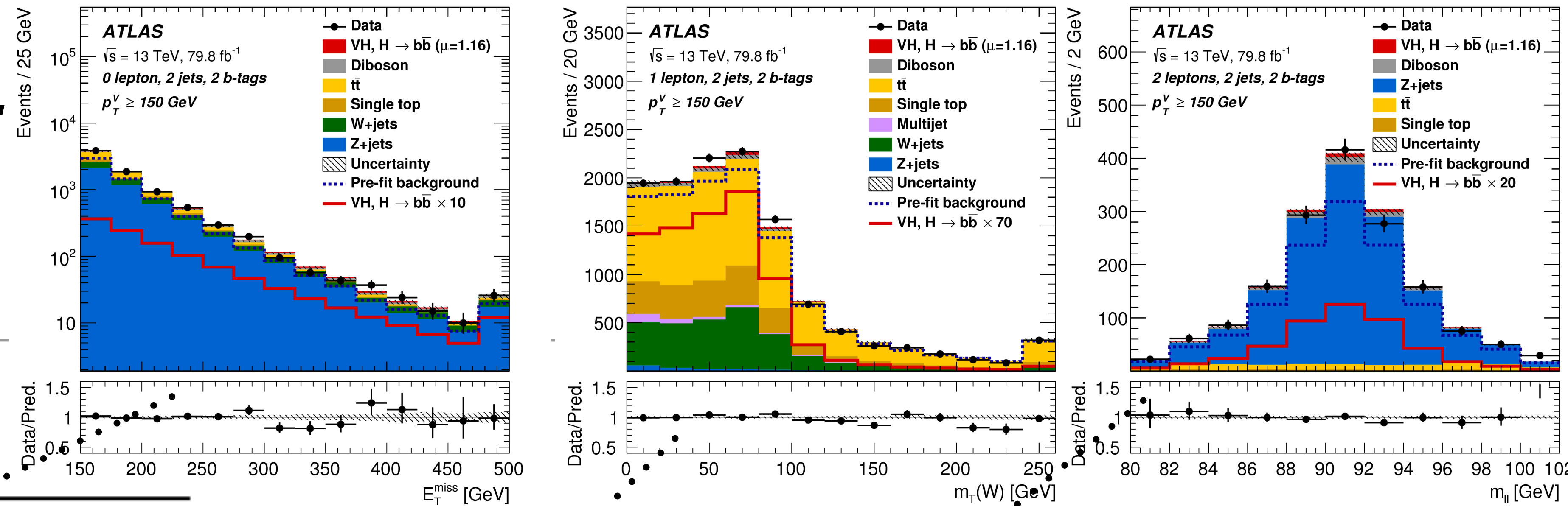
Separation in 2 and 3 jets category allow a **better sensitivity** and an improvement in handling the ***tt* background**





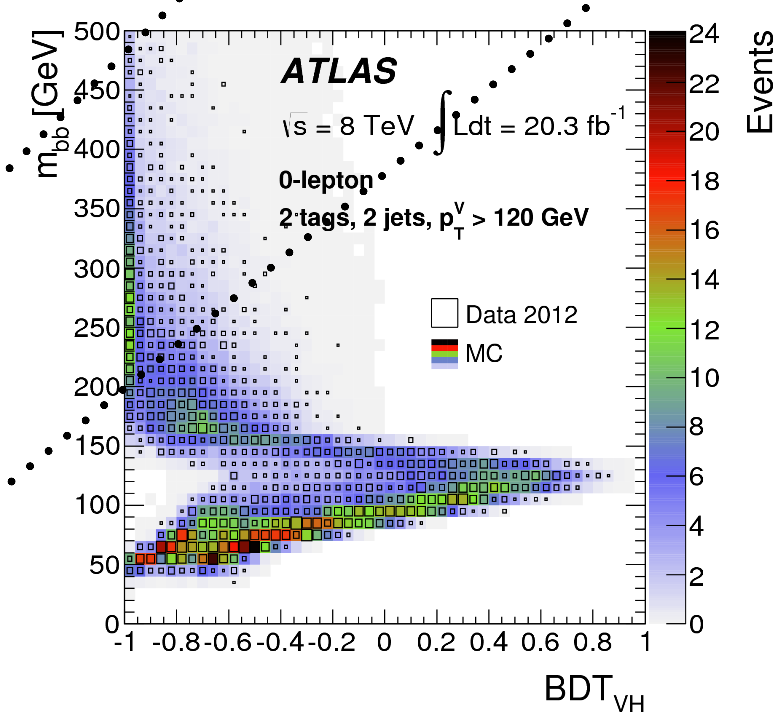


Fifth ingredient: MVA

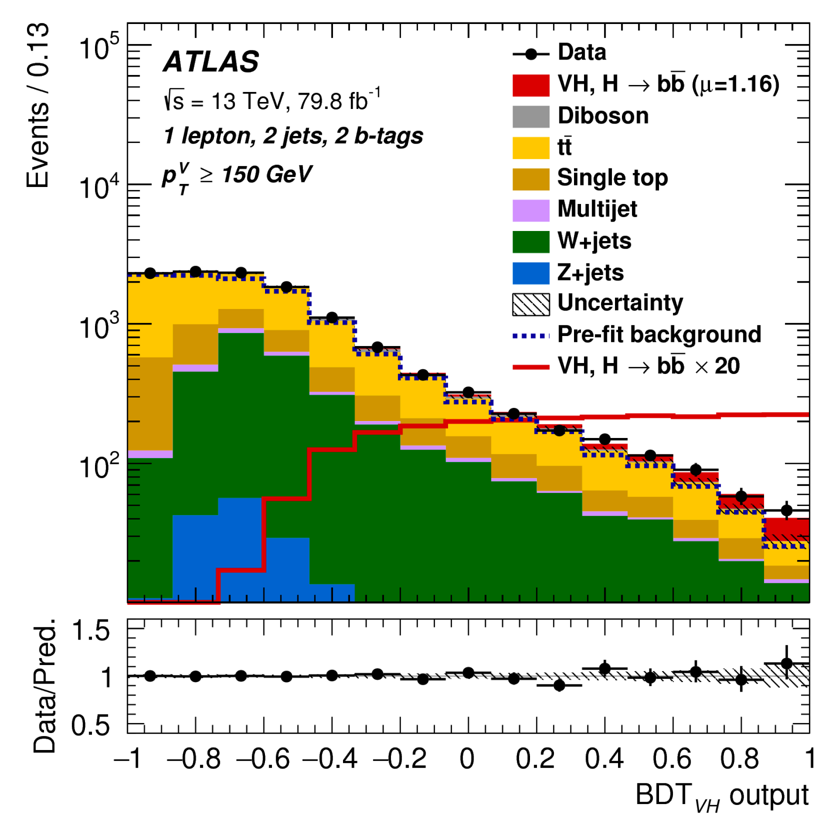


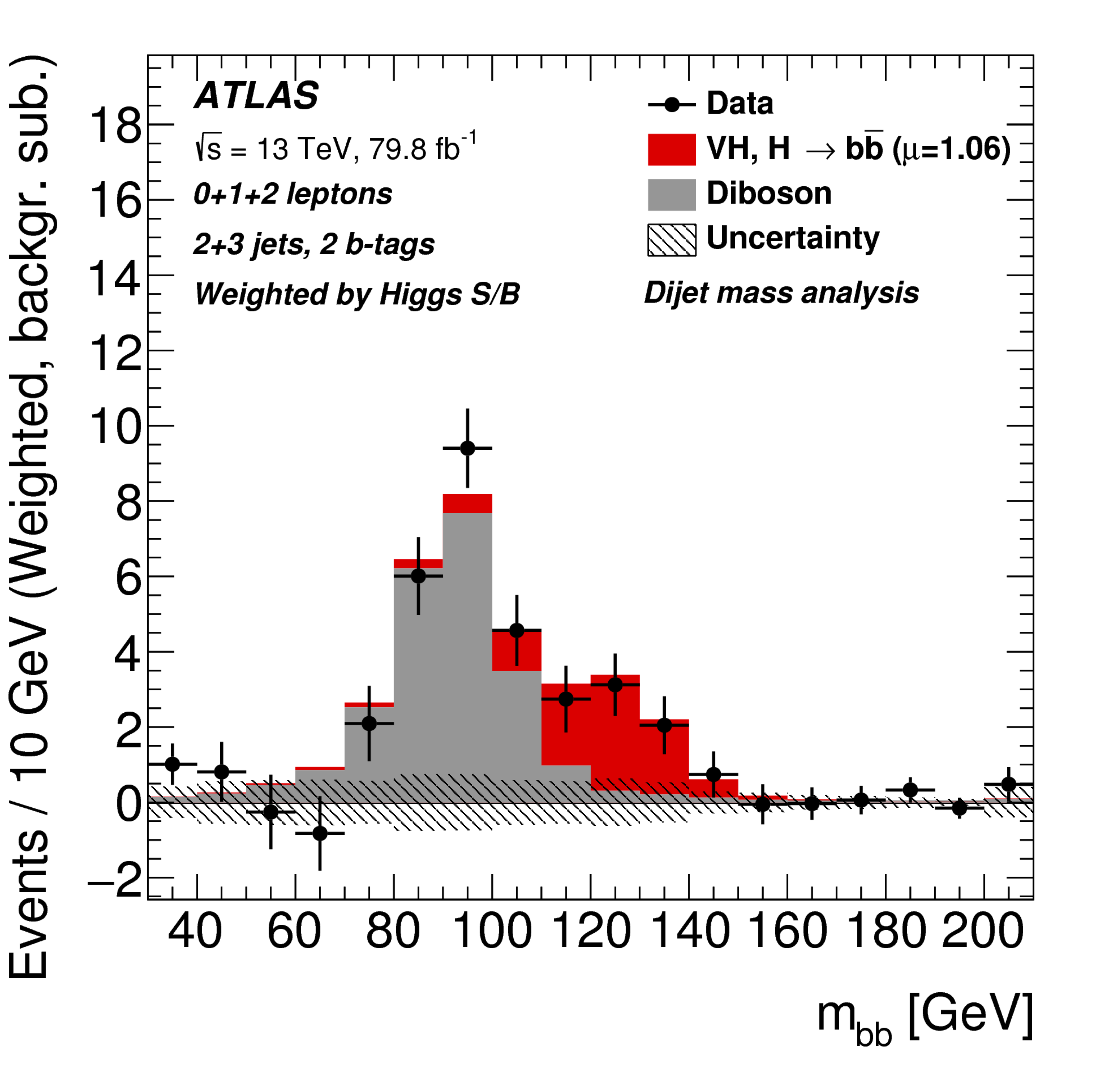
Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	$\times$	$\times$
E_T^{miss}	$\times$	$\times$	
$p_T^{b_1}$	$\times$	$\times$	$\times$
$p_T^{b_2}$	$\times$	$\times$	$\times$
m_{bb}	$\times$	$\times$	$\times$
$\Delta R(\vec{b_1}, \vec{b_2})$	$\times$	$\times$	$\times$
$\lvert\Delta\eta(\vec{b_1},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

Loose selection and BDT as final discriminant



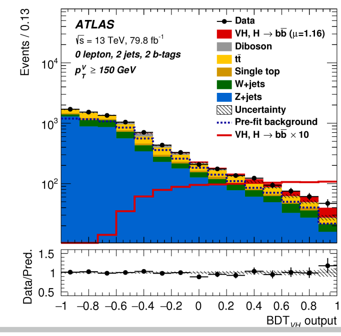
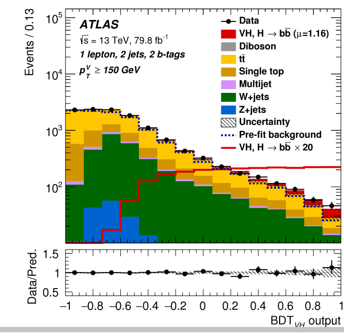
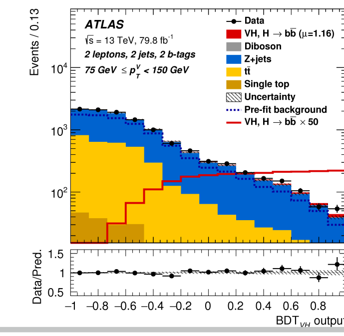
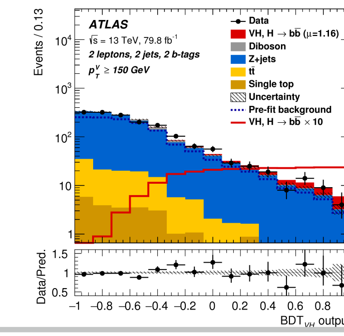
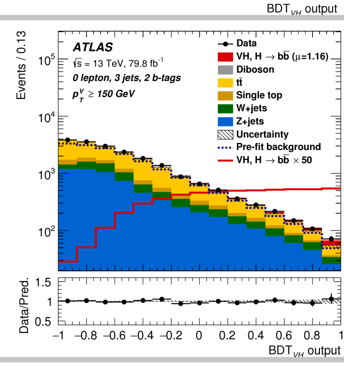
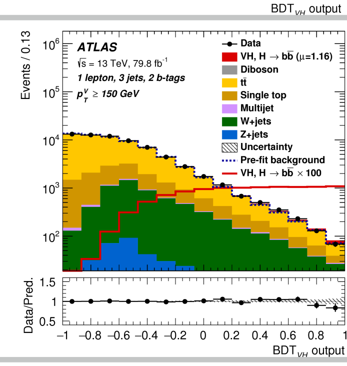
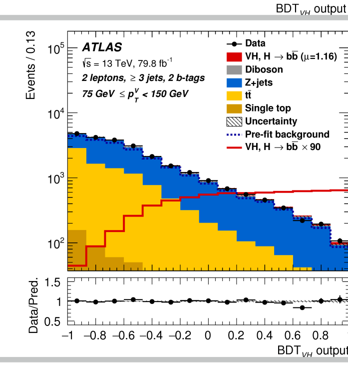
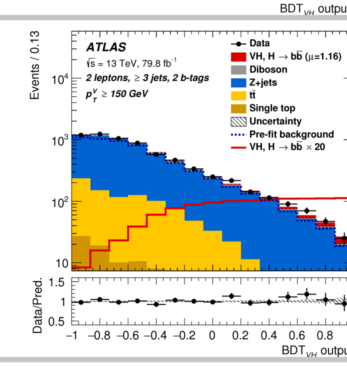
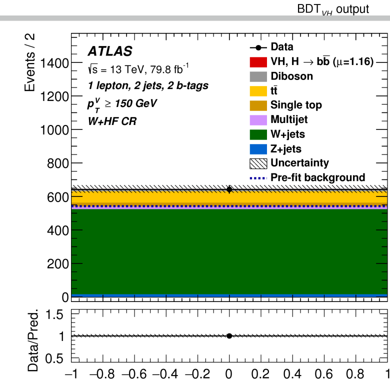
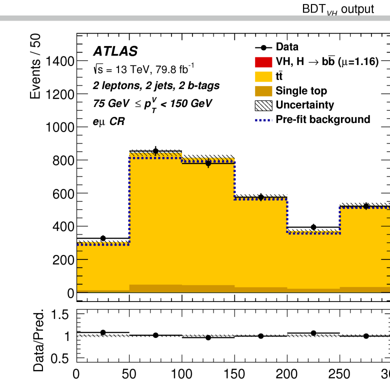
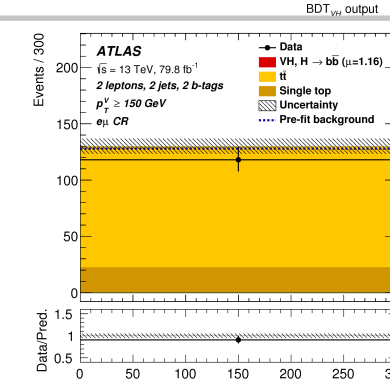
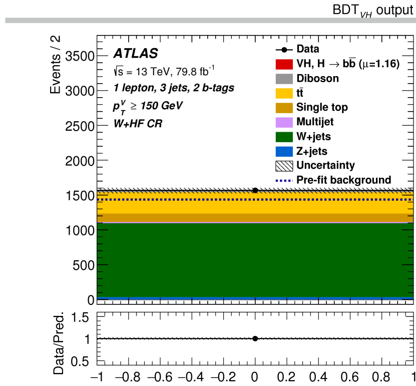
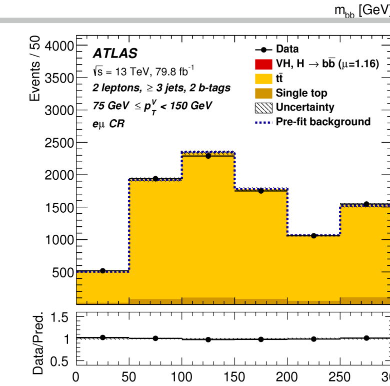
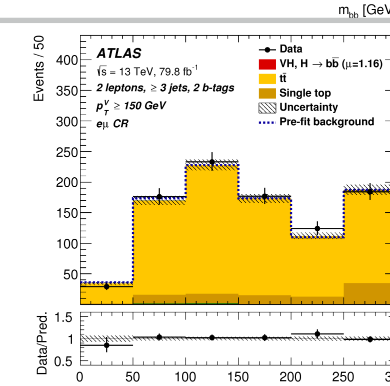
BDT output





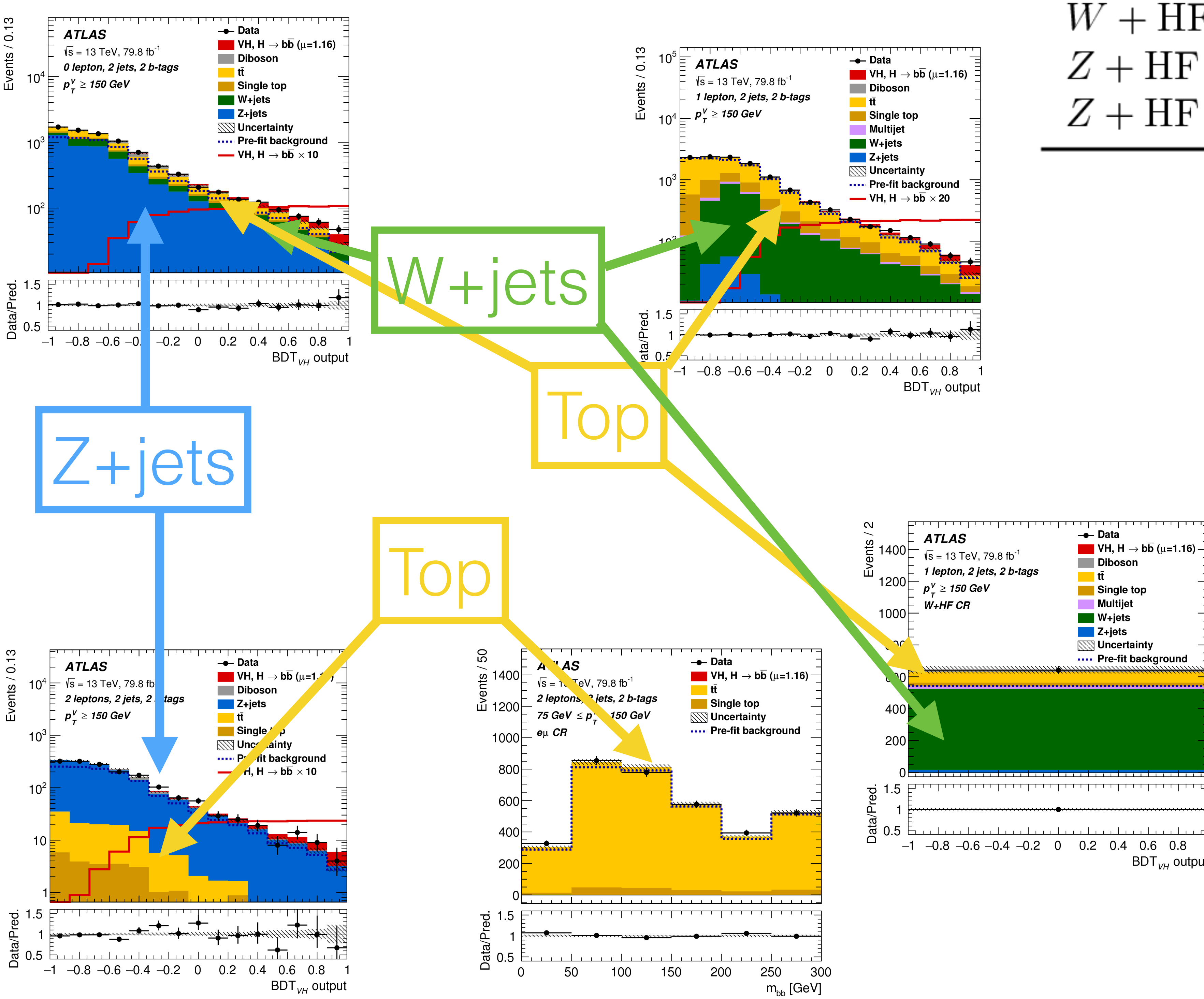
The Analysis

All the regions

	0-lepton $p_T(Z)>150$ GeV	1-lepton $p_T(W)>150$ GeV	2-lepton $75<p_T(Z)<150$ GeV	2-lepton $p_T(Z)>150$ GeV
SR 2-jets				
SR 3-jets				
CR 2-jets	Data VH, $H \to b\bar{b}$ (μ=1.06) Diboson $t\bar{t}$ Single top Multijet W+jets Z+jets Uncertainty Pre-fit background VH, $H \to b\bar{b}$			
CR 3-jets				

One fit to rule them all

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



- Common nuisance parameters across regions
  - Analysis designed with similar phase space in the three channels
- **W+jets** has dedicated CR
- **Z+jets** extrapolated from low $p_T(Z)$ regions in 2-leptons
- **tt** has dedicate CR for 2-lept.

  Extrapolated from 1-lep 3jets for 0-/1-lept.
- Systematics on extrapolation of backgrounds between regions

Systematics

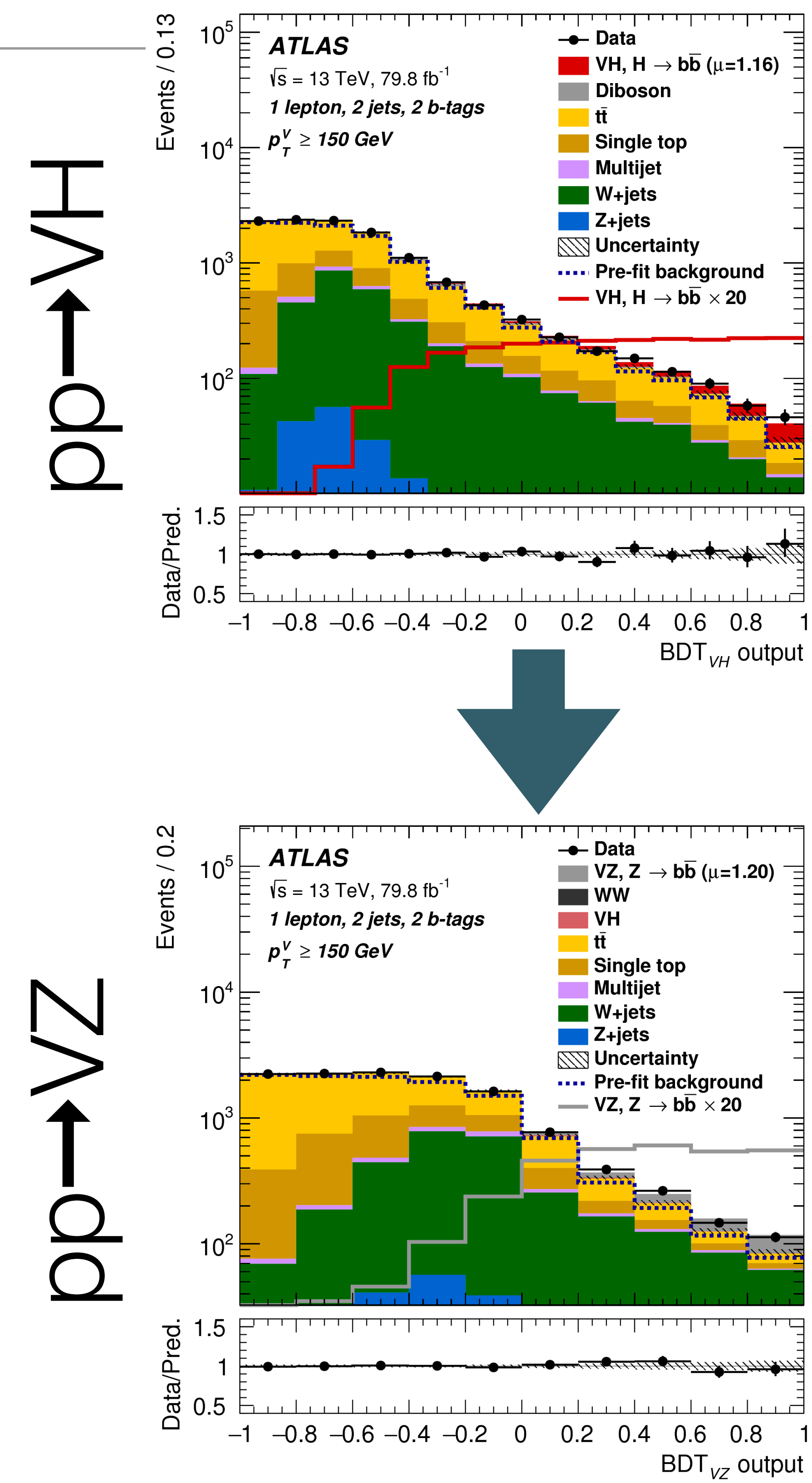
Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	b-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

Analysis dominated by systematic uncertainties

- b-tagging both b and c jet tagging calibration
- Background modelling Z+jets, W+jets, tt
- Mainly shape and extrapolation uncertainties
- Signal modelling little impact on significance
- MC stats

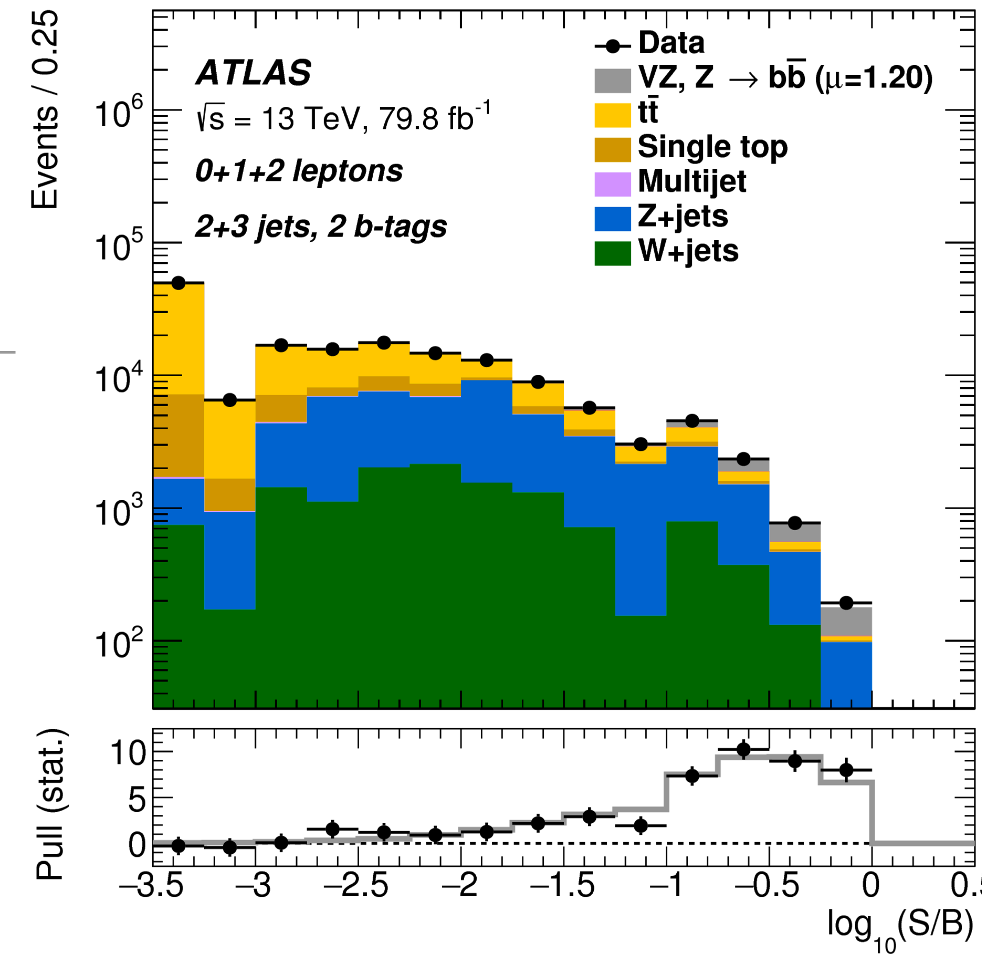
We have our standard candle: pp→VZ

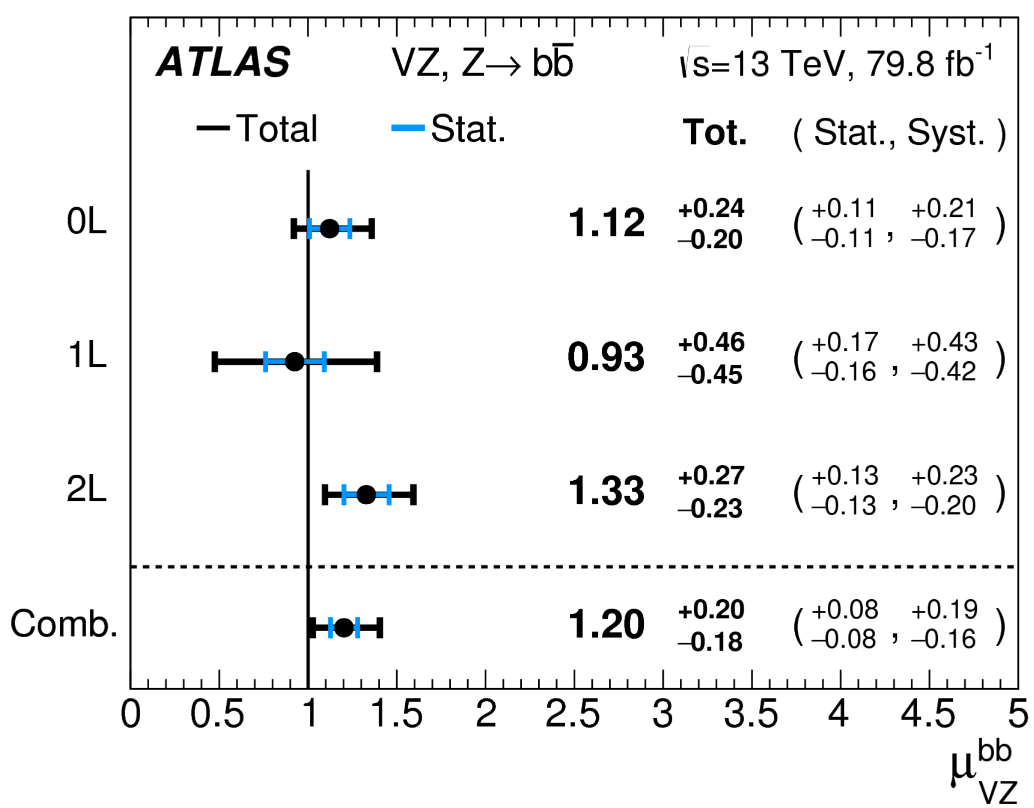
- Diboson production final state, with a Z→bb is very similar to our H→bb signal
    - Diboson already measured in other final states
    - We can validate the goodness of the analysis:
        - Keep the analysis as it is, just retrain the BDT to look for VZ
    - Robust validation of background model and associated uncertainties
- VH analysis prepared blinded
- VZ cross check performed before unblinding

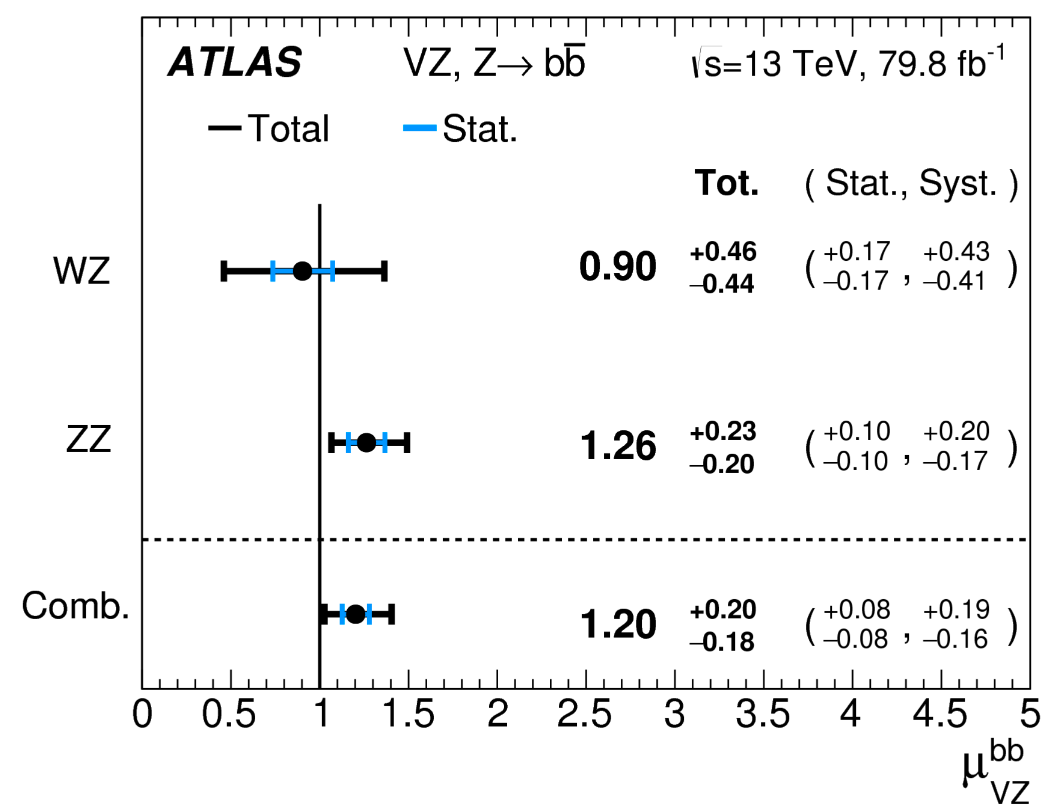


VZ Results

- Very robust diboson result
- Good agreement between channels
- Much better sensitivity for ZZ than WZ:
  - Combinatorics
  - Impact of lower $p_T(V)$ regions in 2-leptons





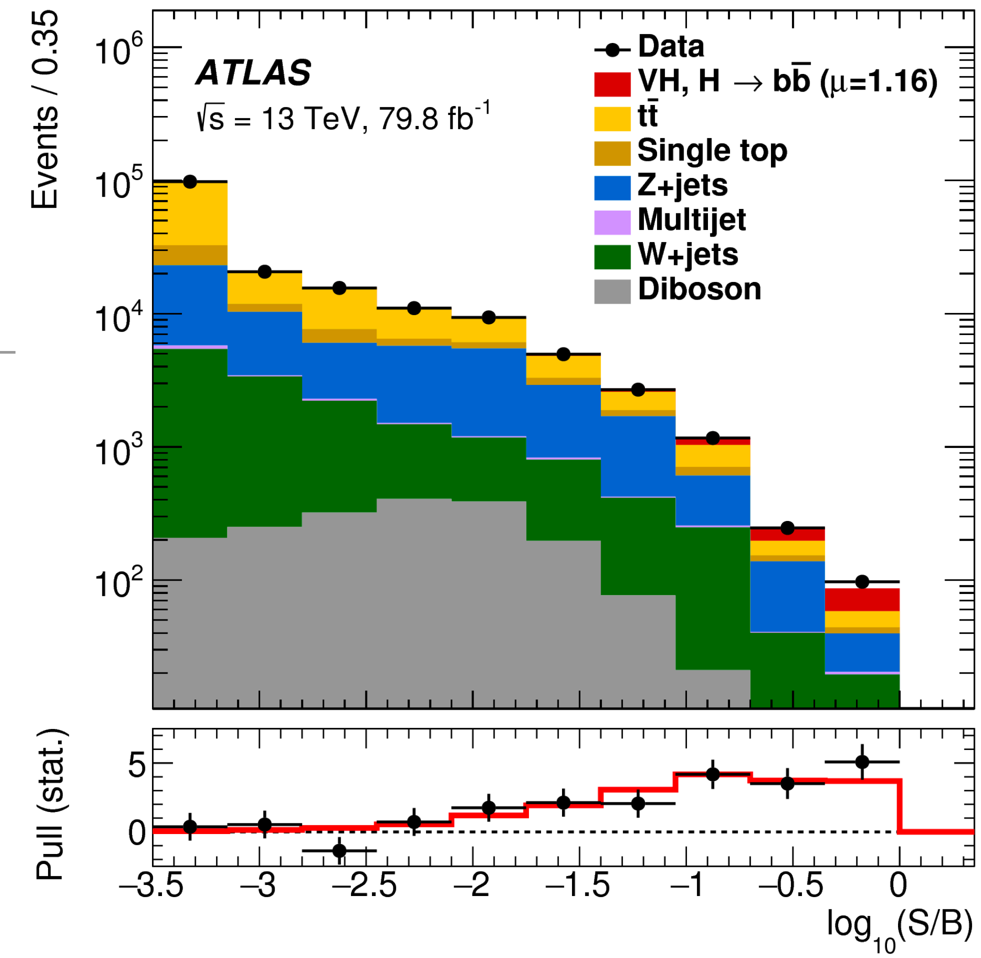


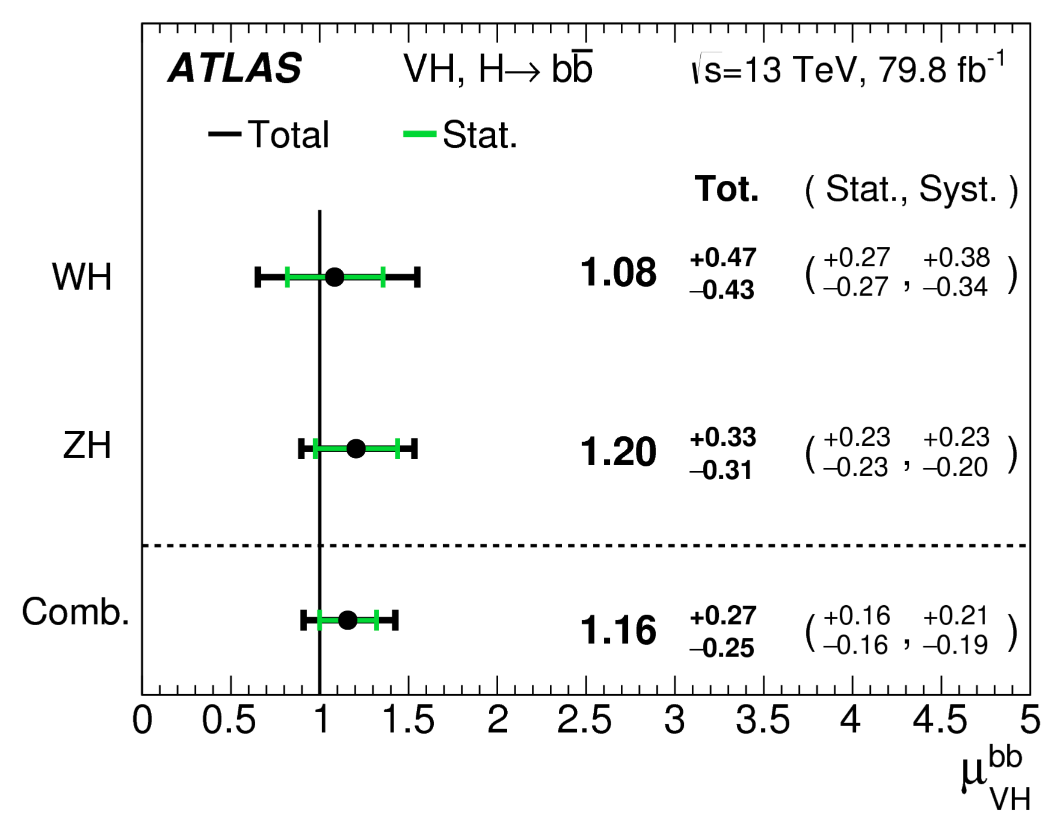
VH Results

- Significance of pp➞VH,H➞bb:

  4.9σ (4.3σ exp.)

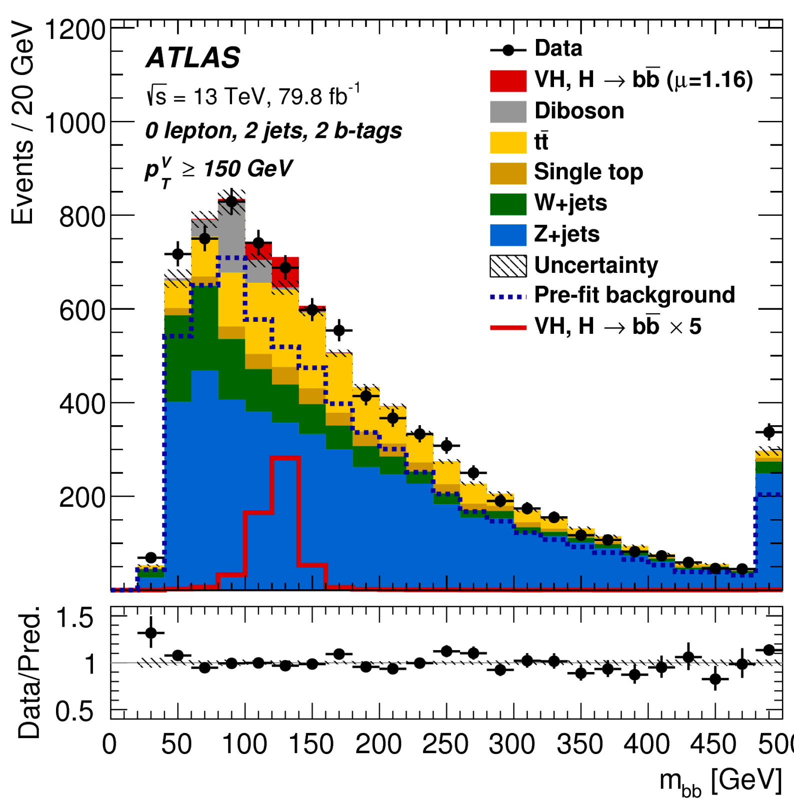
- Signal strength compatible with SM
- Lepton channels compatible at 80%
- Individual production mode significances:
  - pp➞WH: 2.5σ (2.3σ exp.)
  - pp➞ZH: 4.0σ (3.5σ exp.)



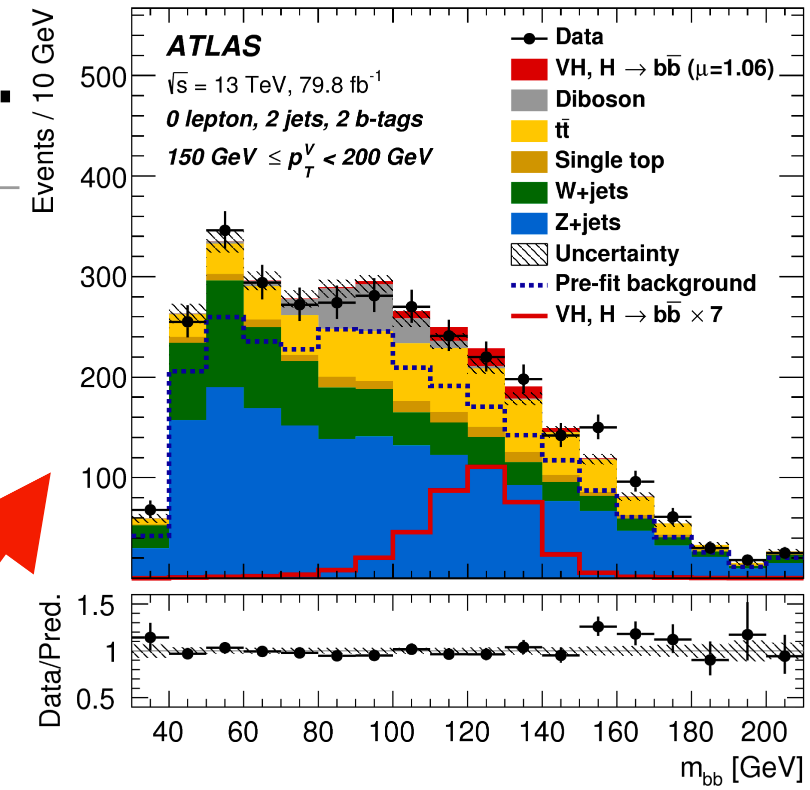


But H→bb has a nice resonance…

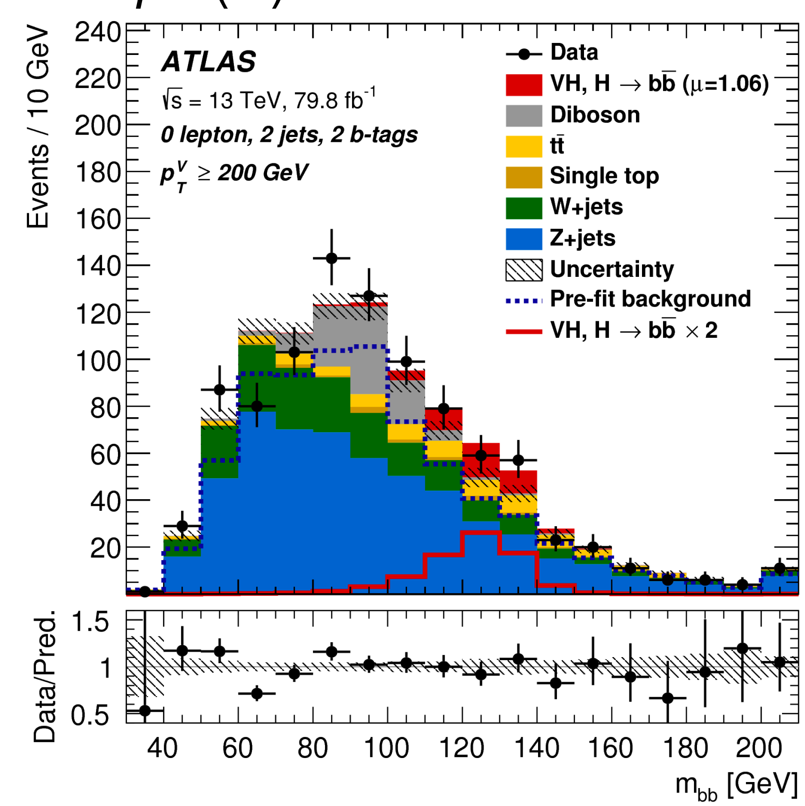
- Why not to look for a resonance in the m_{bb} spectrum?
- Important cross-check of robustness
- split in $p_T(V)$ and make use of ΔR(bb) (~angular sep.)
    - important variables in the BDT
- Cuts on m_T(W) (1-lep) and E_T^{miss} significance (2-lep)



150<p_T(V)/GeV<200

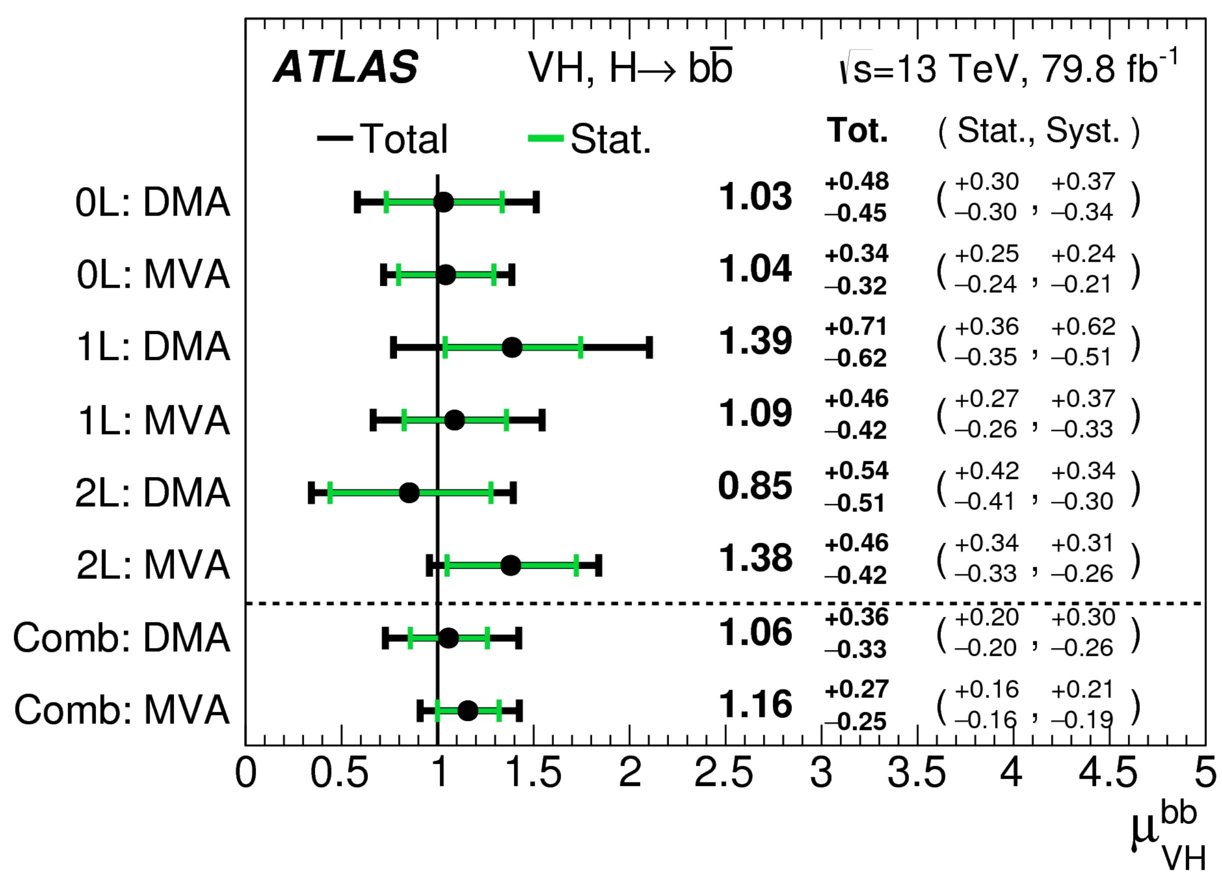


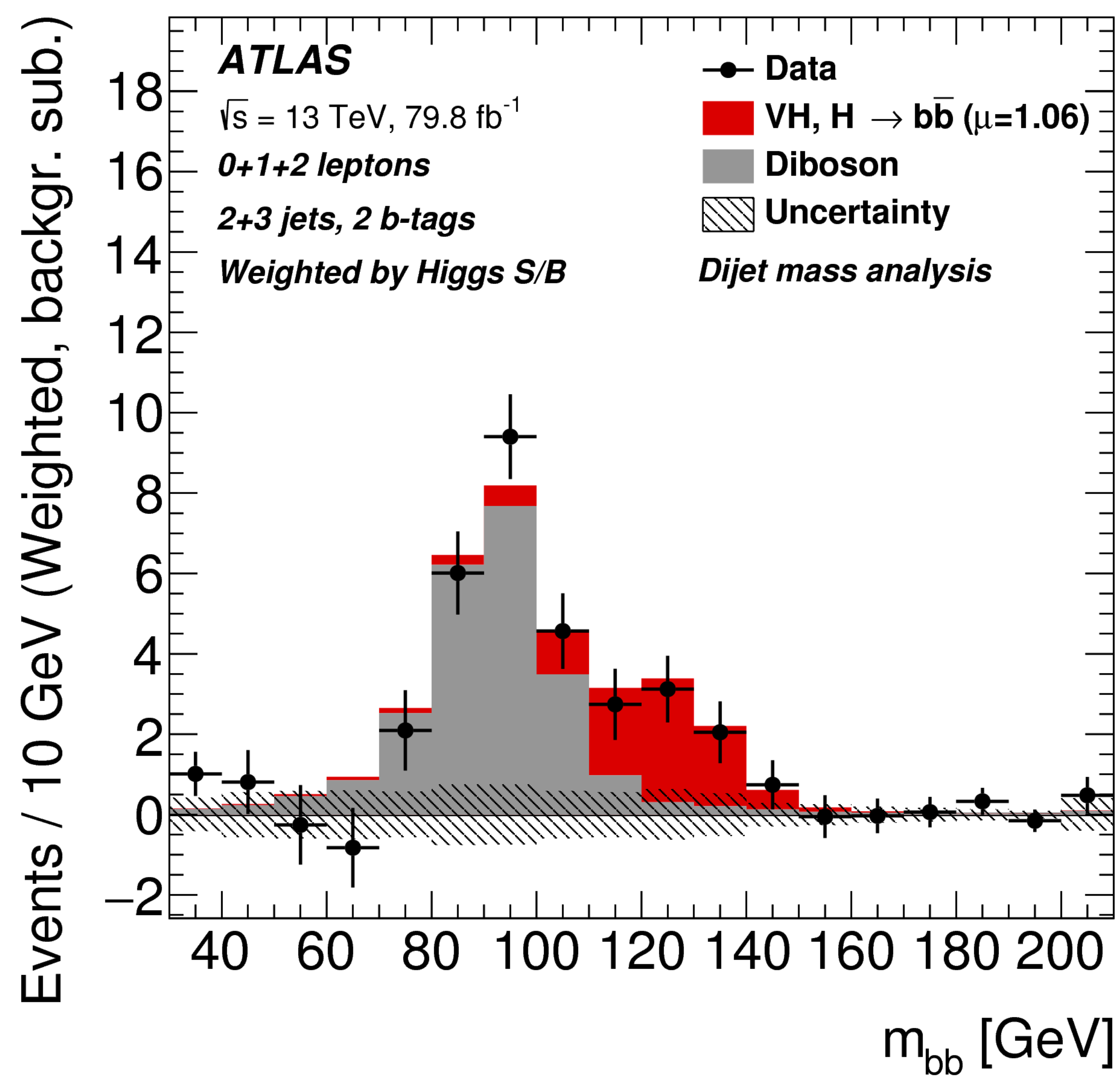
p_T(V)>200 GeV



Result of the fit of the m_{bb} shape

- Evidence at 3.6σ (3.5σ exp)
  - ~20% less sensitivity than MVA
  - Signal strength consistent with MVA in all the channels





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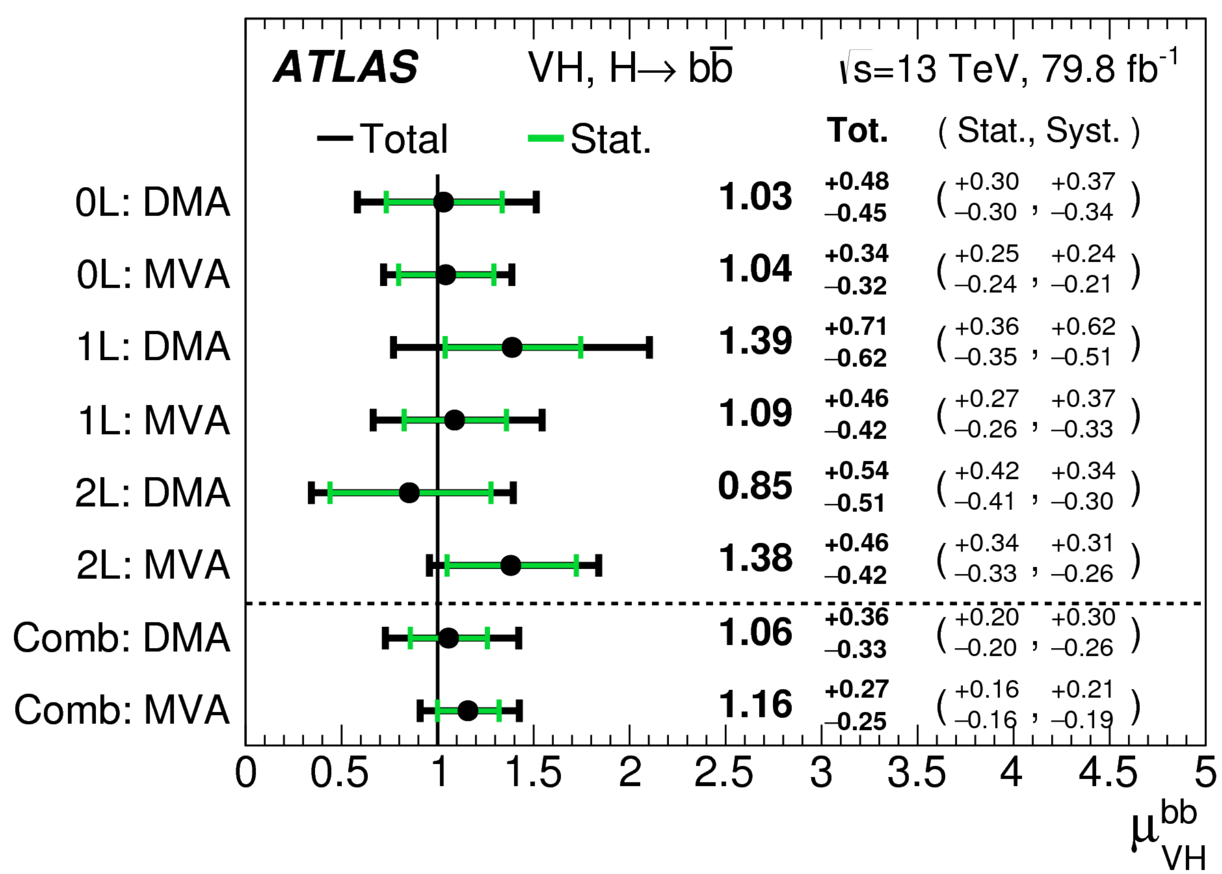
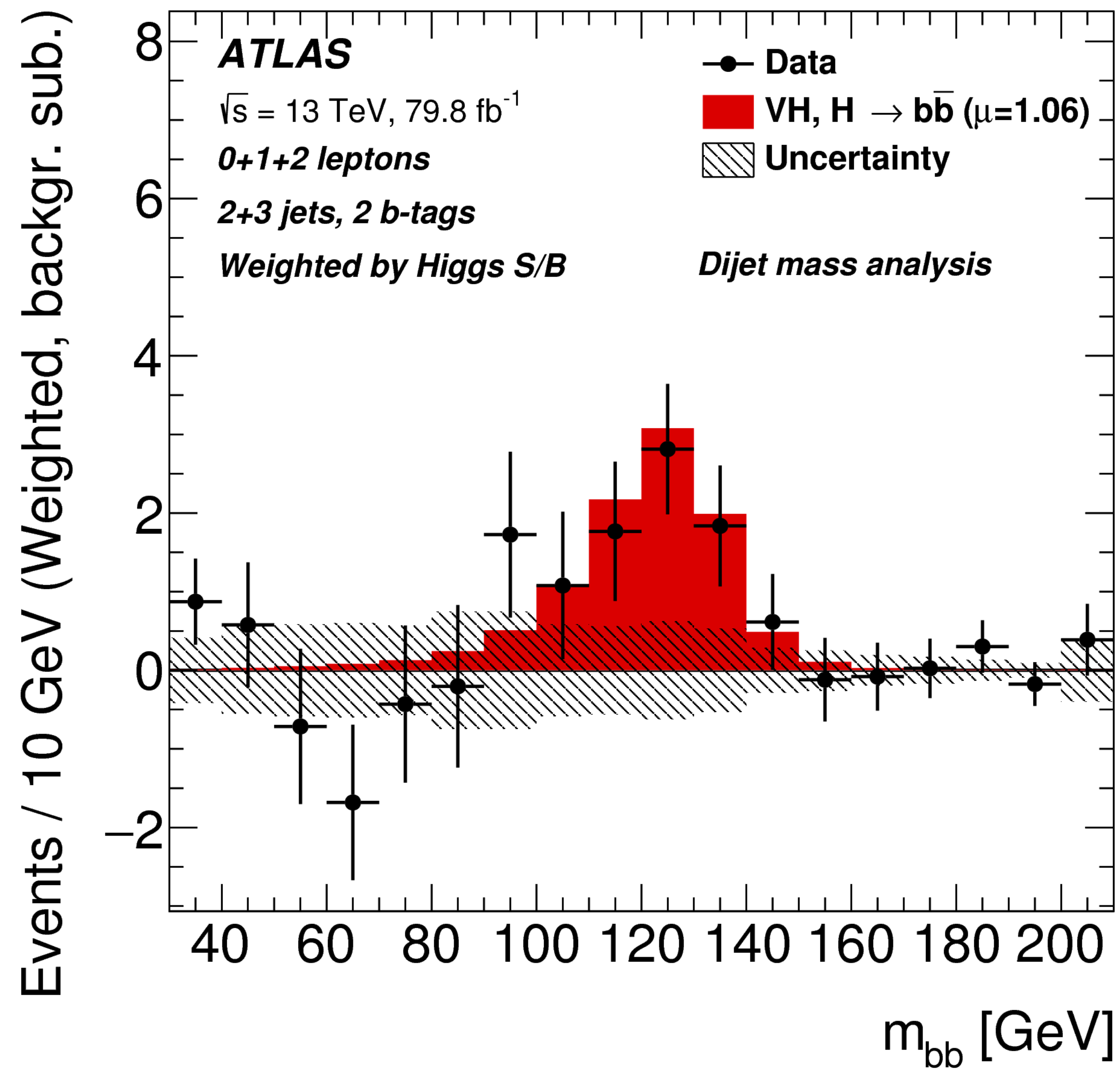


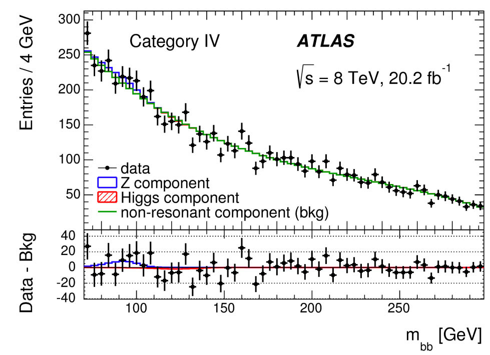


What about the other H→bb channels?

- Combine Run1 and Run2 analyses targeting all the production modes
  - Note: VBF and ttH Run2 ~35 fb^{-1} of data
- Result assume SM Higgs boson production cross sections

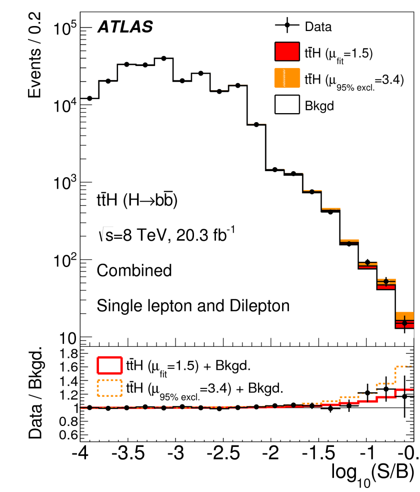
VBF Run1

JHEP 11 (2016) 112



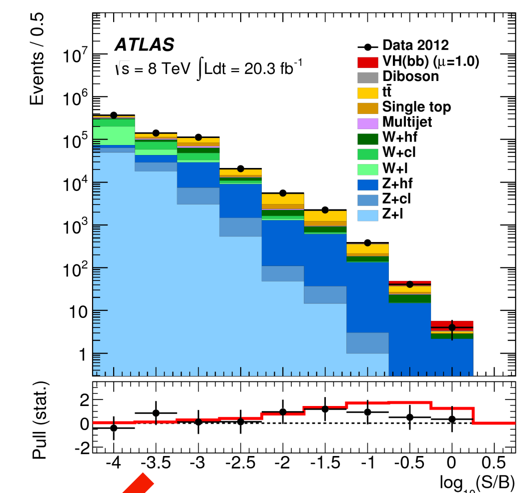
ttH Run1

Eur. Phys. J. C (2015) 75:349



VH Run1

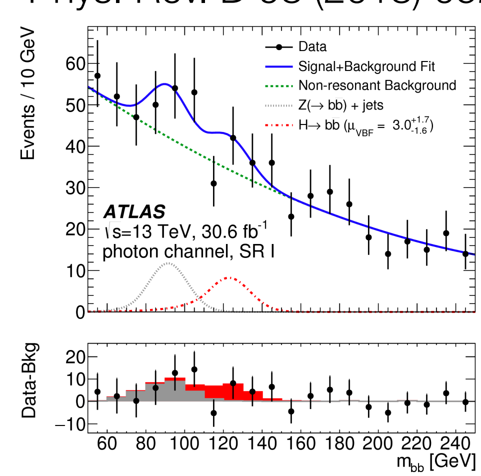
JHEP01(2015)069



Combination!!!

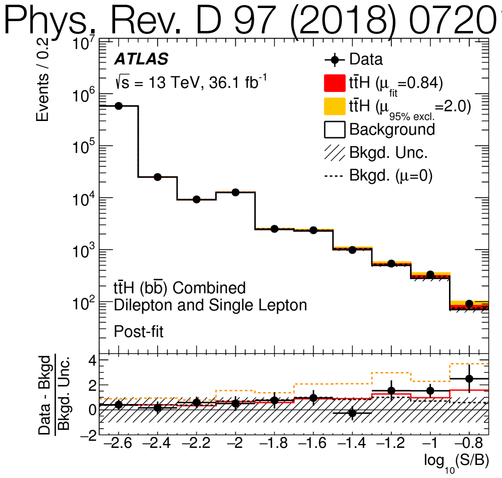
VBF Run2

Phys. Rev. D 98 (2018) 052003



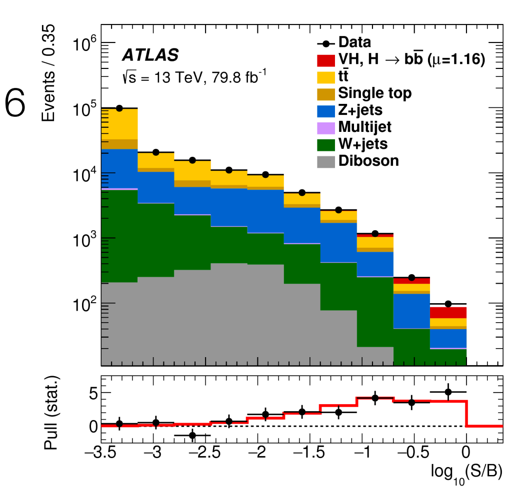
ttH Run2

Phys. Rev. D 97 (2018) 072016



VH Run2

Phys. Lett. B 786 (2018) 59



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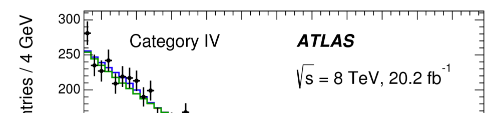
- Combine Run1 and Run2 analyses targeting all the production modes
    - Note: VBF and ttH Run2 ~35 fb^{-1} of data
- Result assume SM Higgs boson production cross sections
- **Results:**
    - Observation of H➞bb

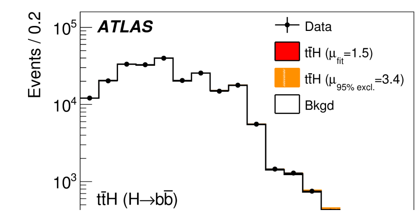
      5.4σ (5.5σ exp.)

      $\mu_{H\rightarrow bb} = 1.01 \pm 0.20$
    - Contributions from the other channels:
        - VBF (1.5σ) ttH (1.9σ)
    - Compatibility 6 measurements: 54%

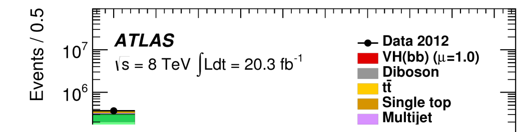
VBF Run1
JHEP 11 (2016) 112

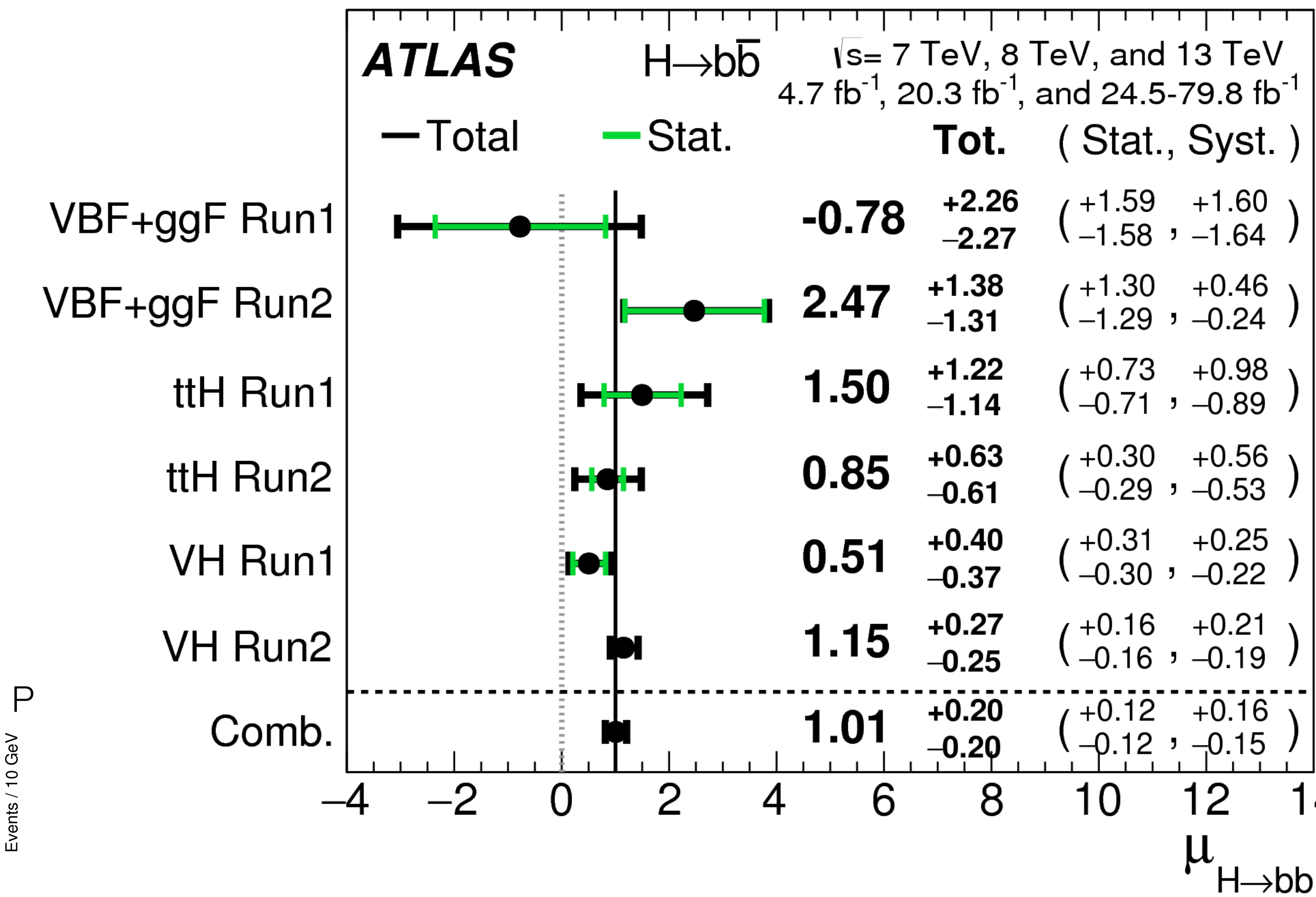


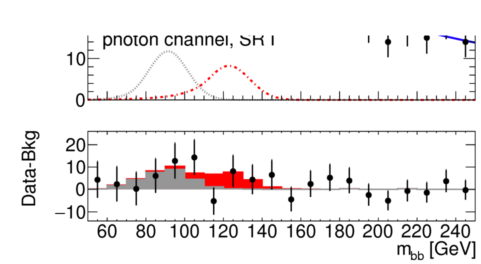
ttH Run1
Eur. Phys. J. C (2015) 75:349

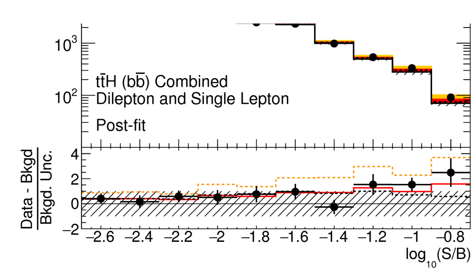


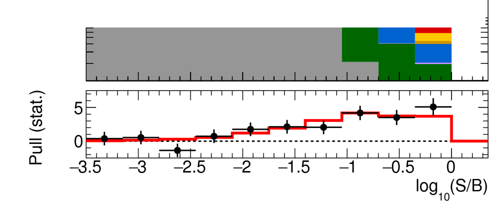
VH Run1
JHEP01(2015)069











9

Can we say something about pp→VH?

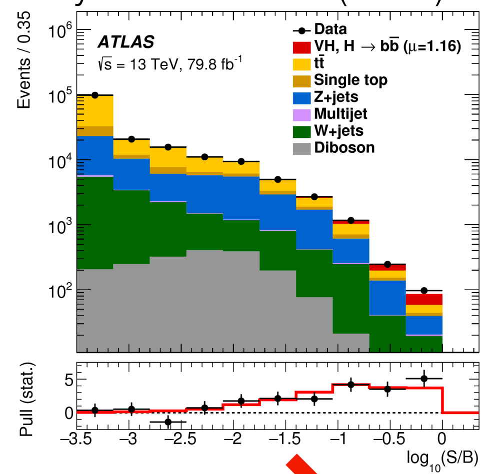
- Combine Run2 analyses in bb,γγ,4l final states
    - Note: updated analysis with 2015-17 data
- Result assume SM Higgs boson BR
- **Results:**
    - Observation of pp→VH

      5.3σ (4.8σ exp.)

      $\mu_{pp\to VH}$ =1.13 ± 0.24
    - Contributions from the other channels:
        - 4l (1.1σ) γγ (1.9σ)
    - Compatibility 3 measurements: 96%

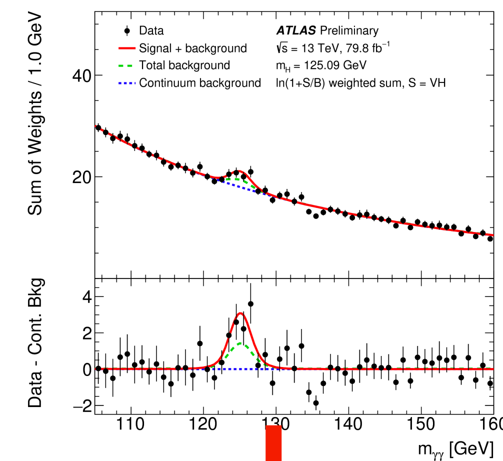
H→bb

Phys. Lett. B 786 (2018) 59



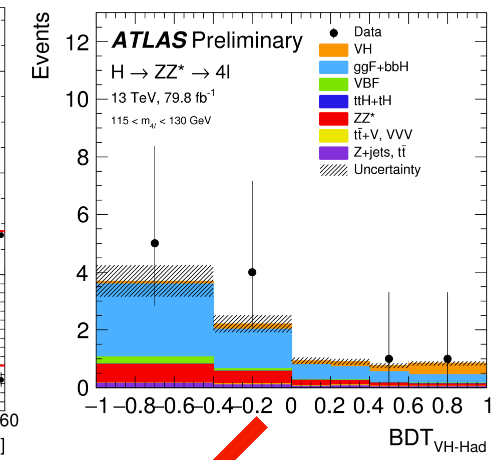
H→γγ

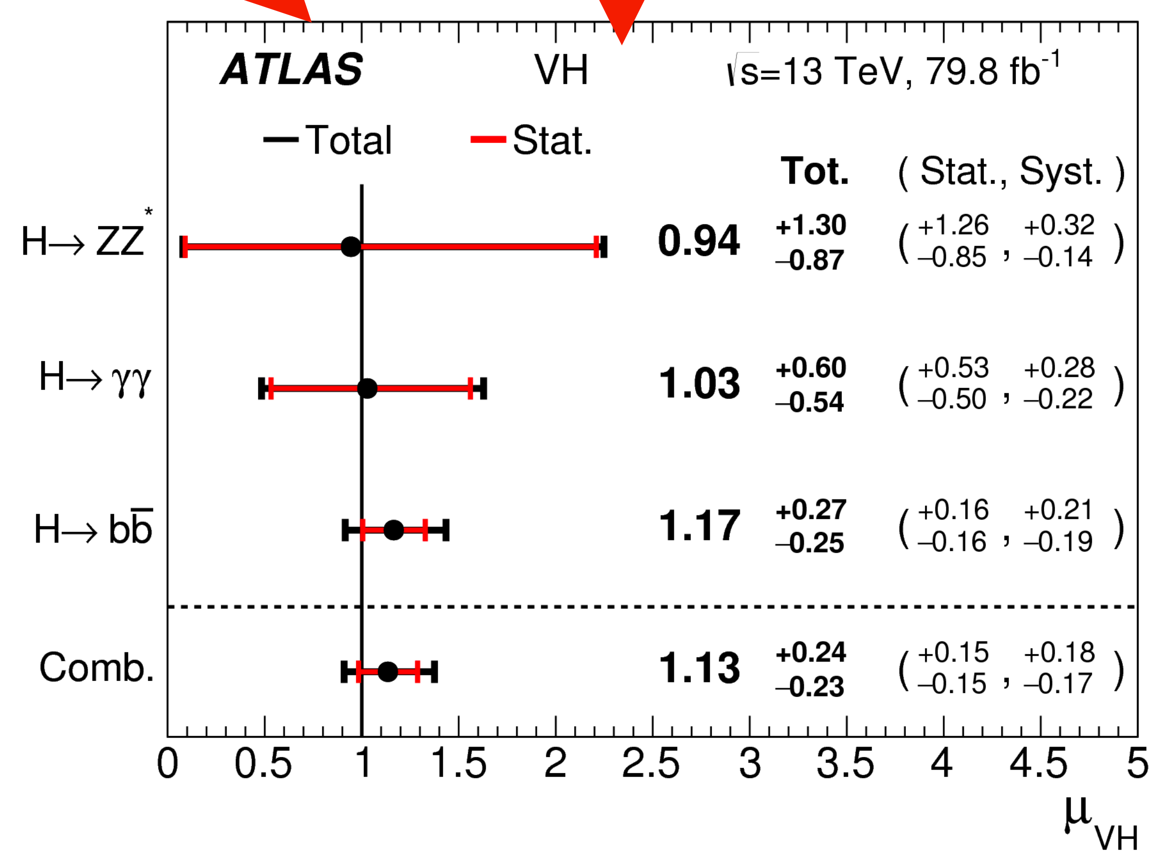
ATLAS-CONF-2018-028

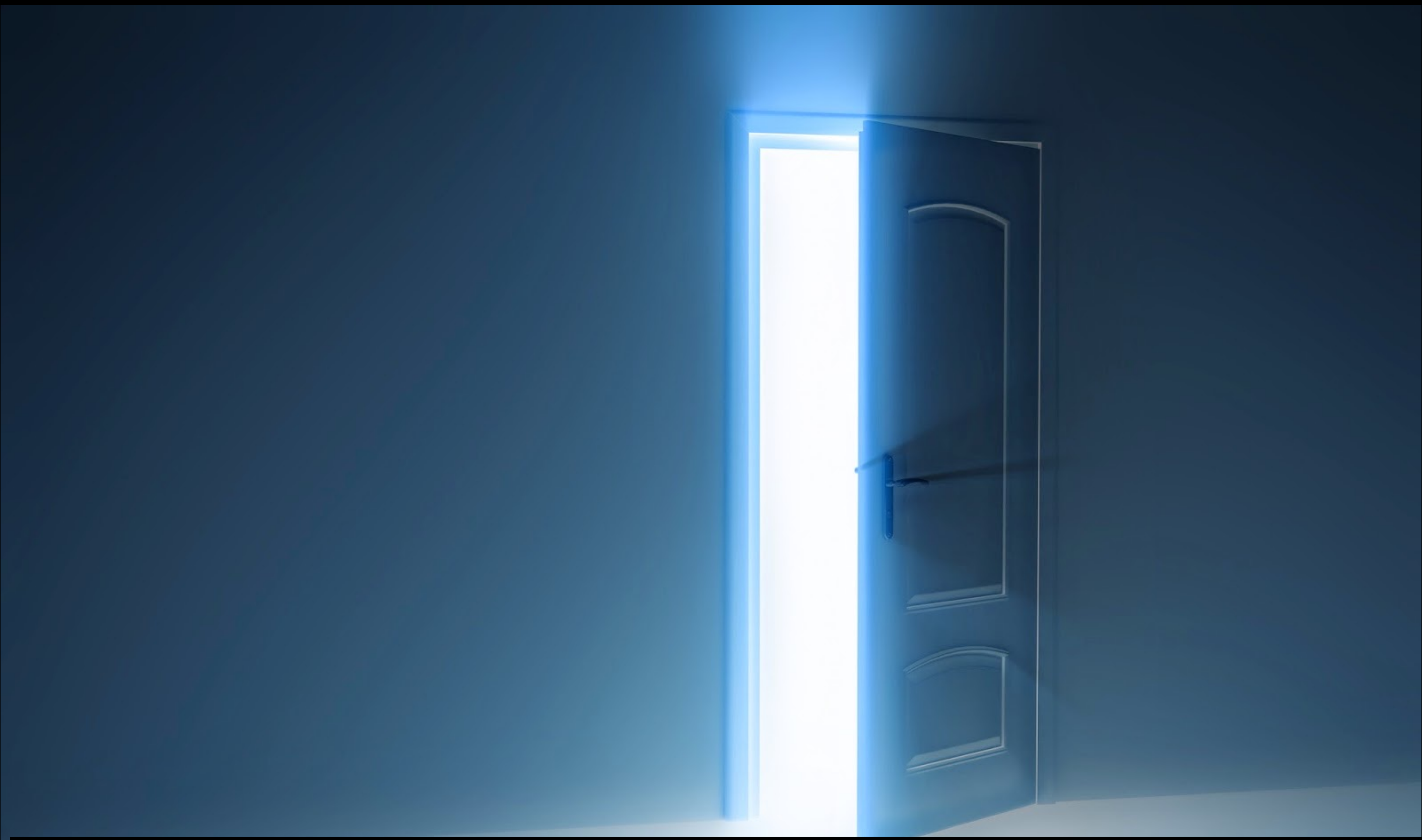


H→4l

ATLAS-CONF-2018-018







Prospects

2017-2018: The year of the Yukawa sector

Production		Decays	
ggF	LHC Run1	γγ	
VBF	ICHEP2016CHICAGO	ZZ*	LHC Run1
VH	ICHEP2018 SEOUL XXXIX INTERNATIONAL CONFERENCE ON high Energy PHYSICS JULY 4 - 11, 2018 COEX, SEOUL	WW*	
ttH	LHCP Bologna 2018	ττ	EPS EUROPEAN PHYSICAL SOCIETY HEP2017
		bb	ICHEP2018 SEOUL XXXIX INTERNATIONAL CONFERENCE ON high Energy PHYSICS JULY 4 - 11, 2018 COEX, SEOUL

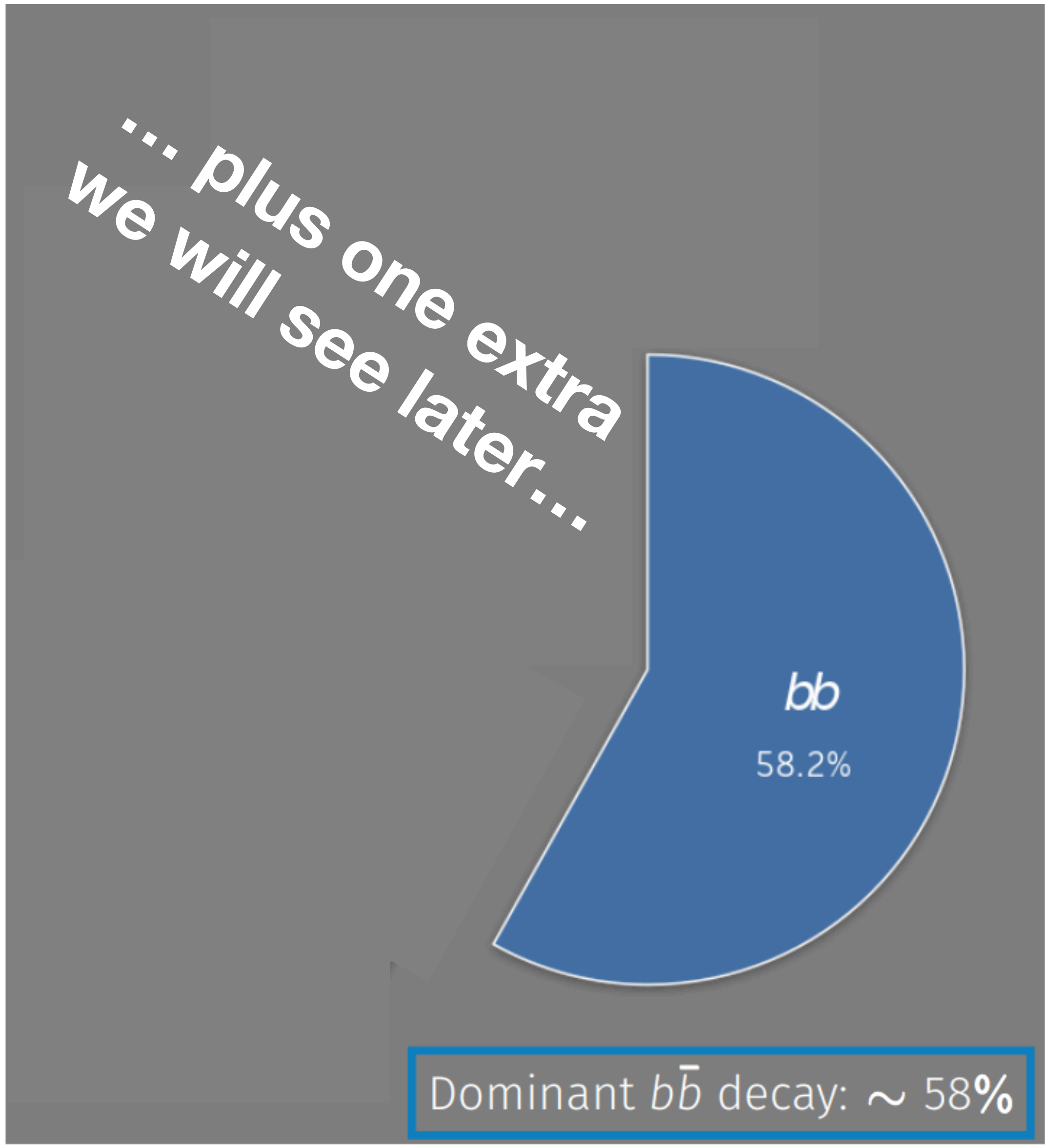
- Run2 is already opening new frontiers in the Higgs Physics
  - Yukawa sector (top, bottom, τ)

Higgs Boson decay modes

Why is interesting to observe H→bb?

- To establish the fate of the Higgs boson
  - Expected to be ~58% of the total width
- To control the Higgs Yukawa sector

	down-type	up-type
quark	**bottom**	top
lepton	τ	



- Model dependent estimation of the total width (not directly measurable at the LHC)
  - Only ratio of BR (couplings) are truly model independent at the LHC
  - Absolute coupling measurement requires assumptions on the total width (i.e. no BSM decays)
  - a term accounting for 58% of the total has a dominant effect on all the coupling determination

Higgs Boson decay modes

Why is

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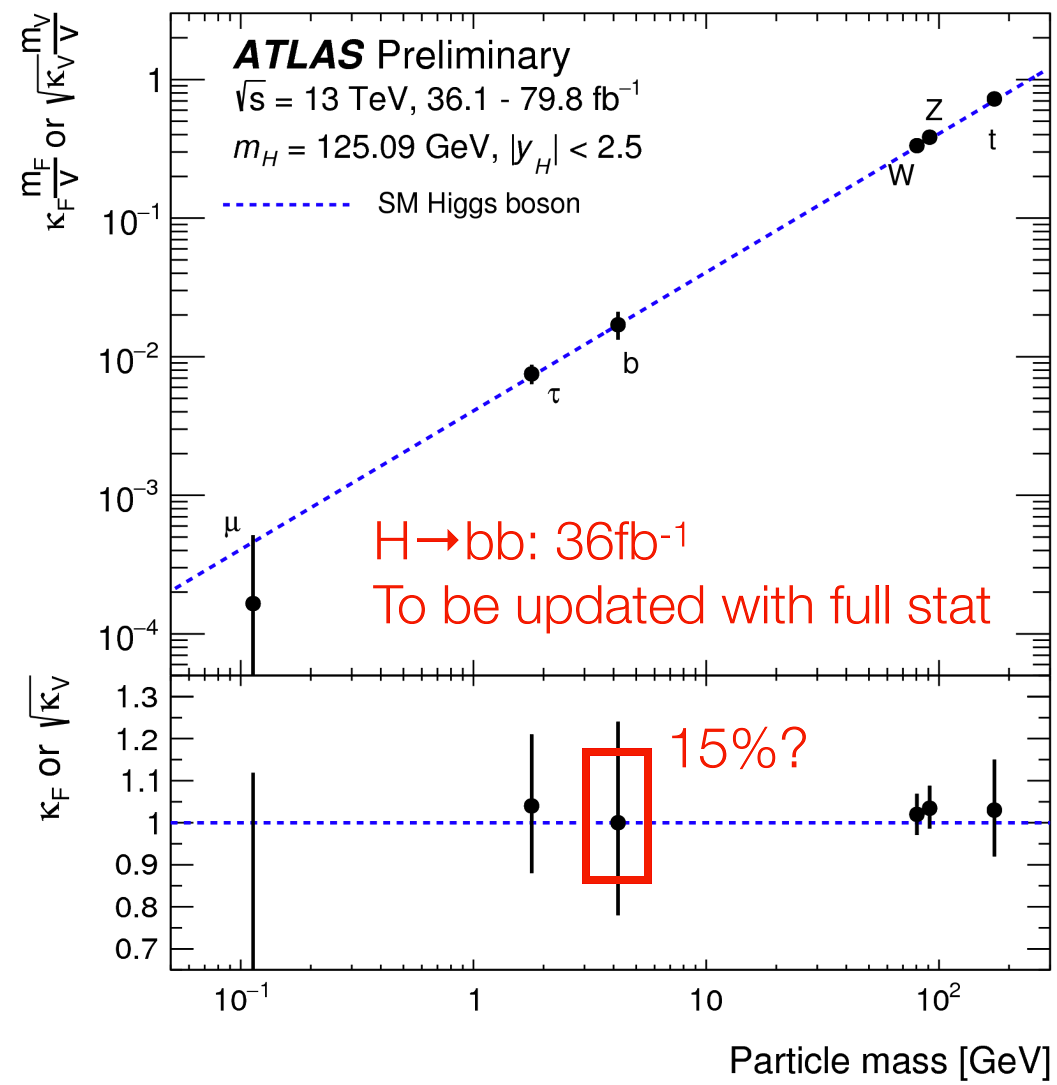
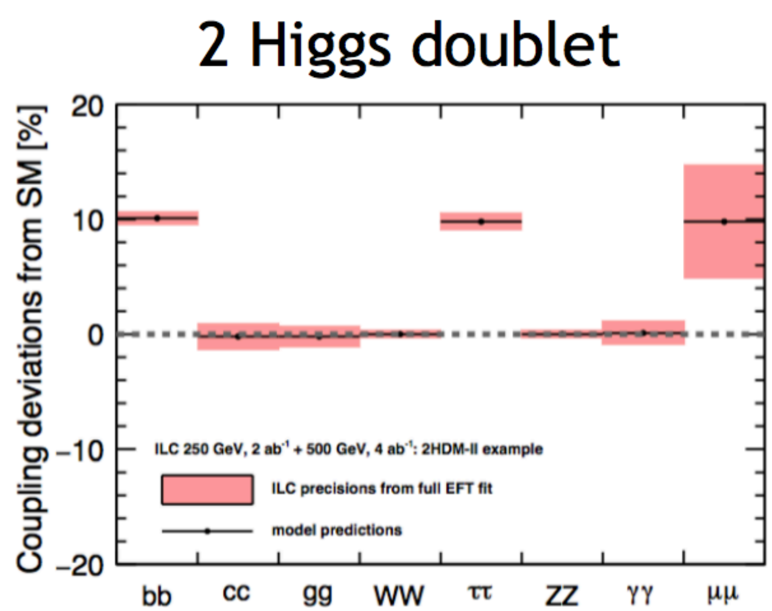
Projections for the future:

Can we reach 5% in H→bb?
Depends on how well we dominate systematics

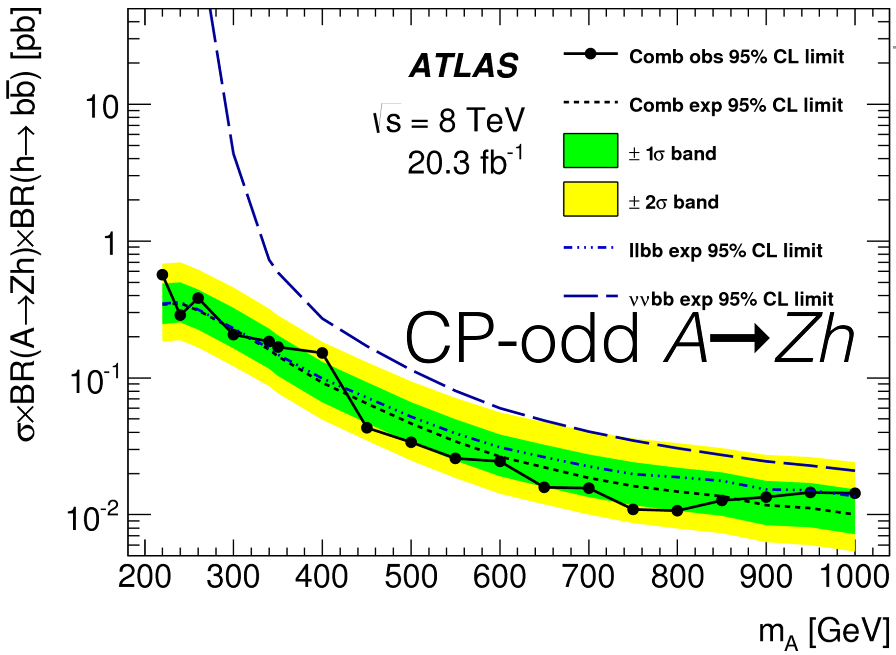
Can highlight new physics in the Yukawa sector

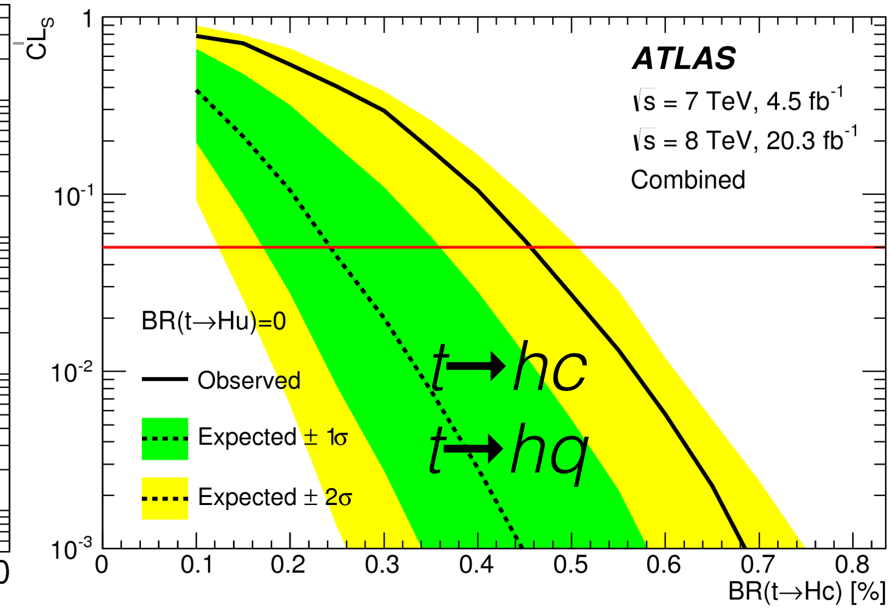


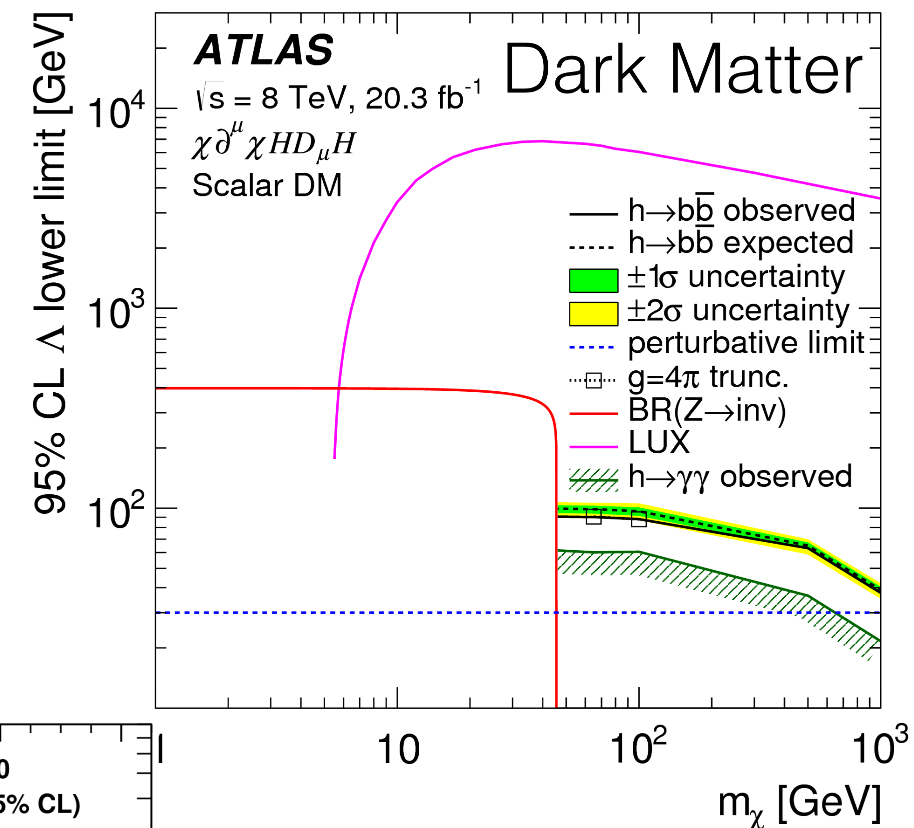
Peskin @ ICFA2017

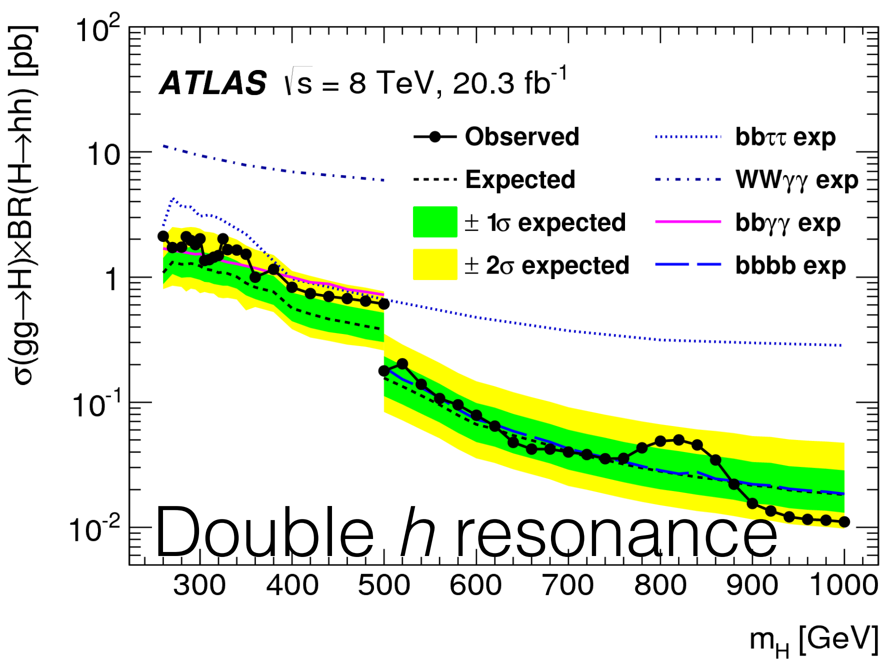


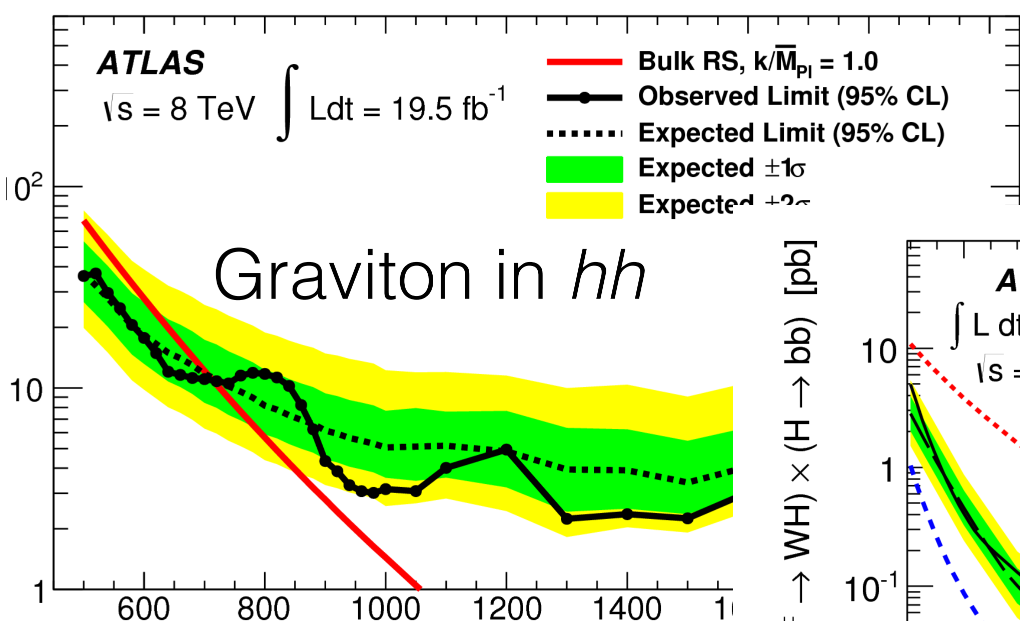
The extra motivation….H➞bb in searches
NOTE: This is Run1!!! …pletora of results in Run2

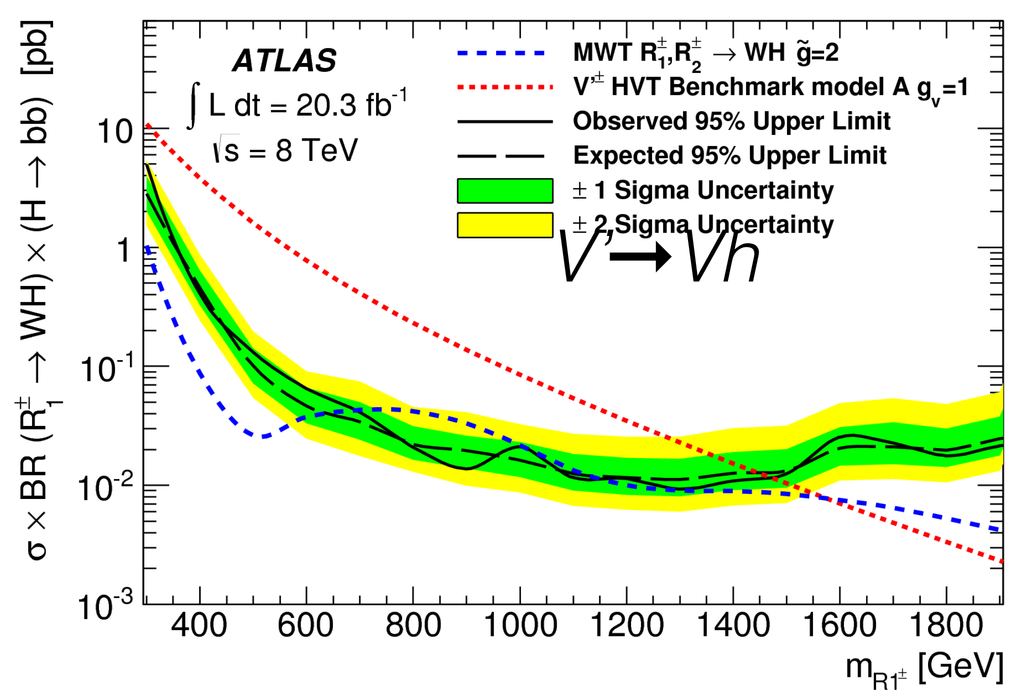






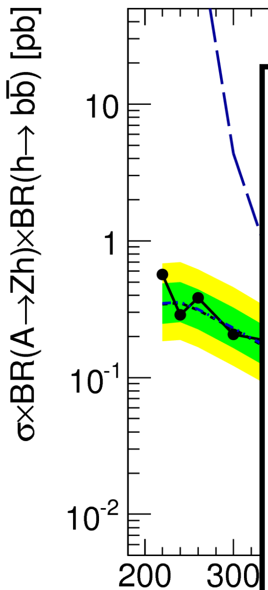


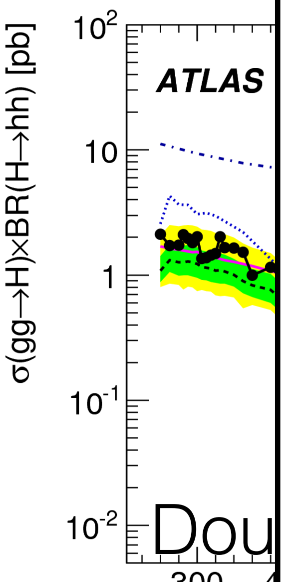


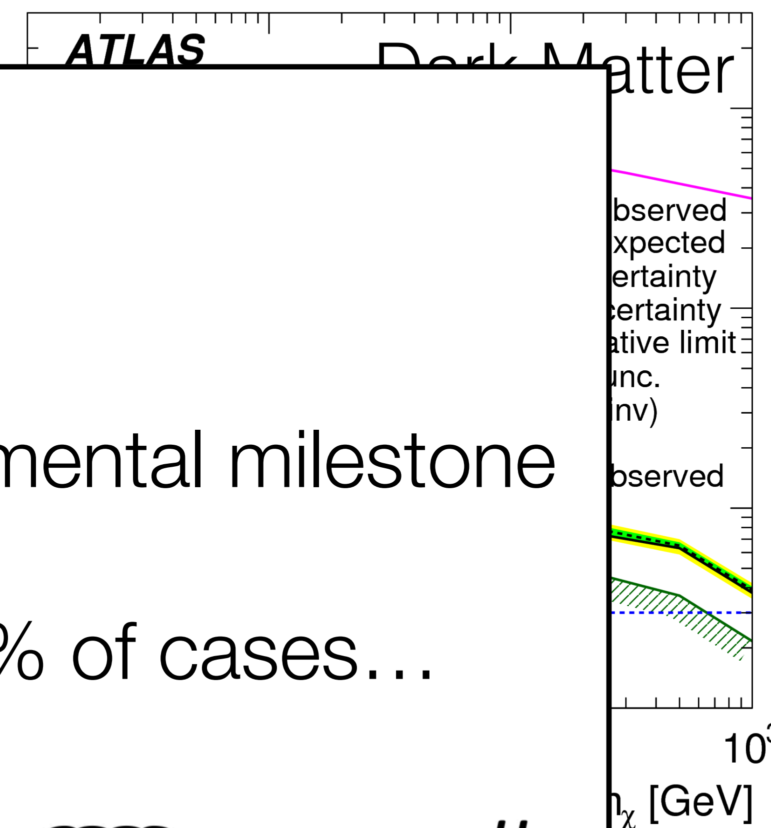


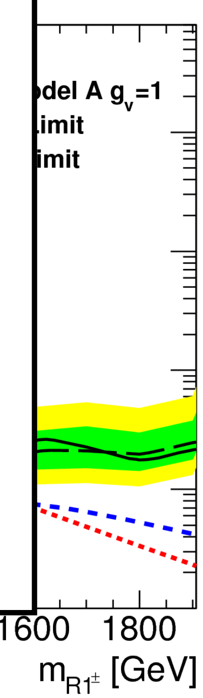
Just a small selection (just from ATLAS)…
In searches involving the Higgs boson,
H➞bb good tool to get sensitivity thanks to the large BR

The extra motivation….H→bb in searches
NOTE: This is Run1!!! …pletora of results in Run2







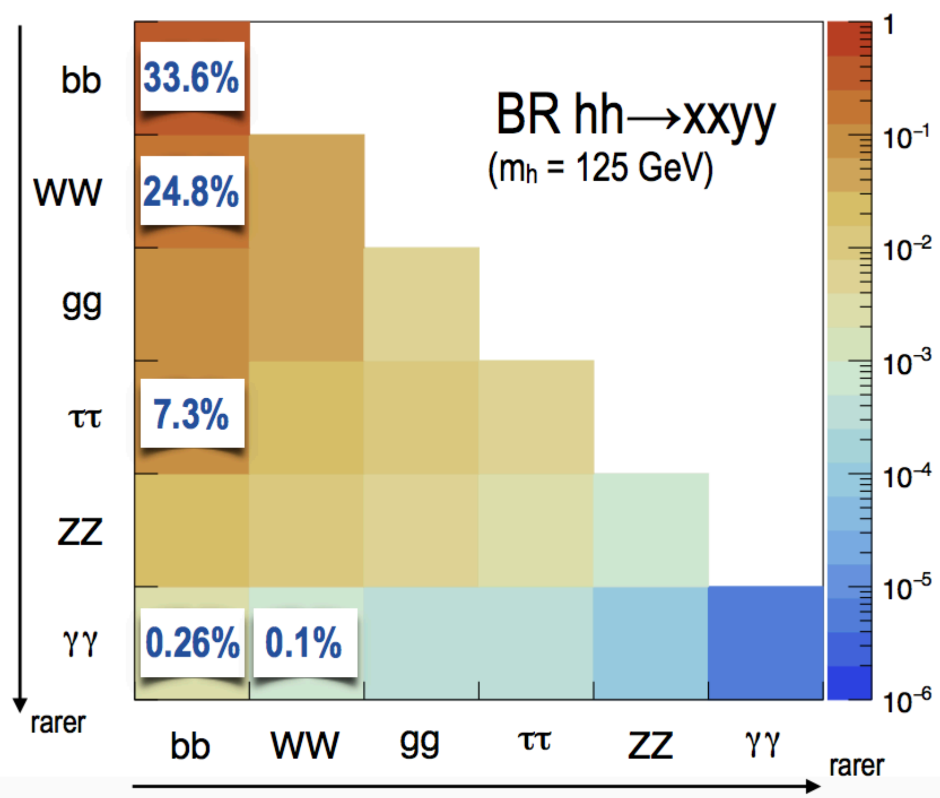


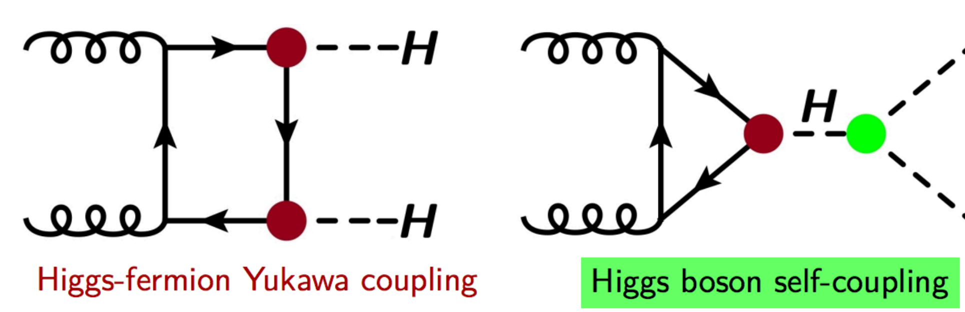
Few considerations:

What do we know about the Higgs potential?

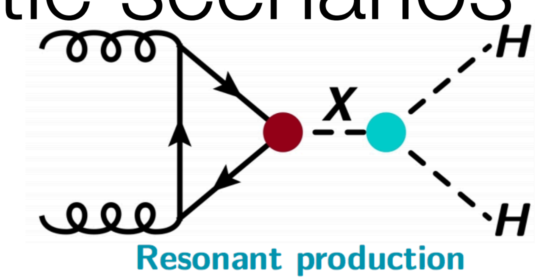
Measuring double Higgs production is a fundamental milestone

pp→HH at least one in H→bb in more than 80% of cases…





or more exotic scenarios



Just a
In sear
H→bb

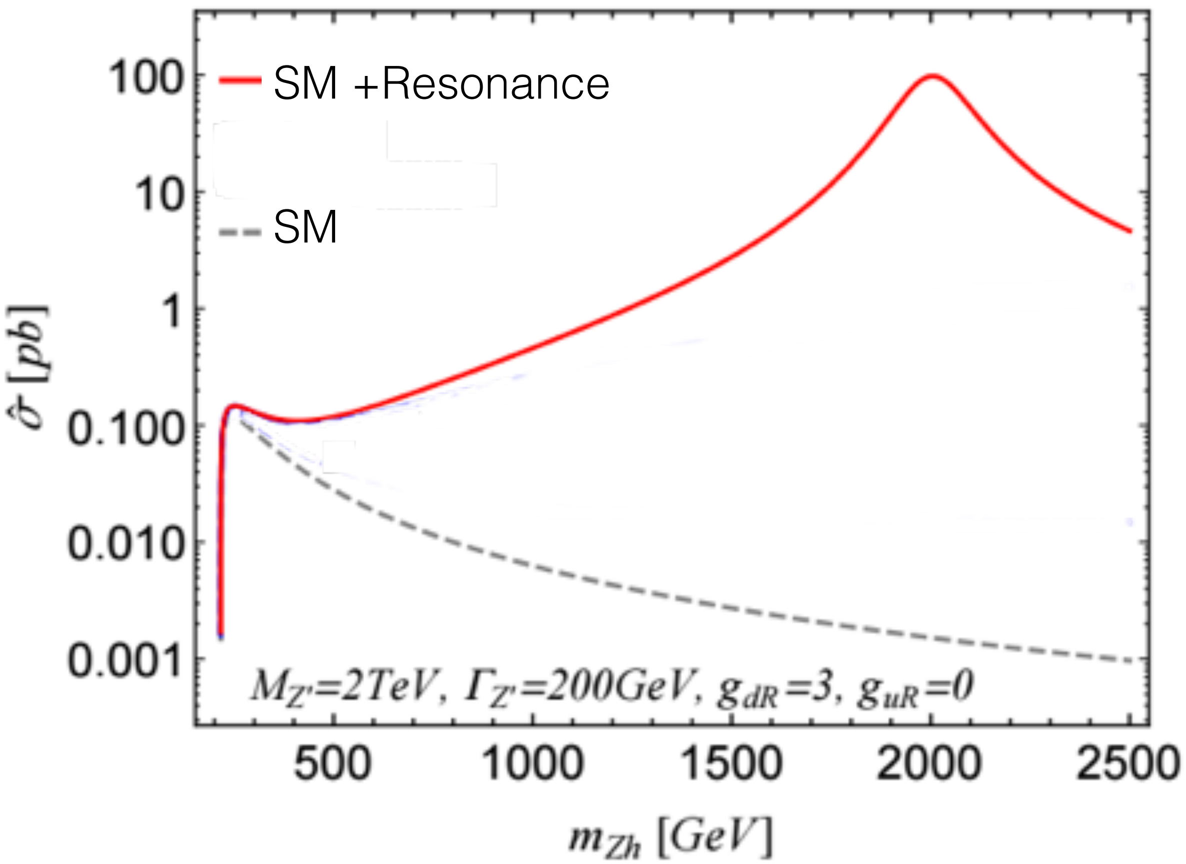
Run2: The HVV coupling in production

Production		Decays	
ggF	LHC Run1	$\gamma\gamma$	
VBF	ICHEP2016 CHICAGO	ZZ^*	LHC Run1
VH	ICHEP2018 SEOUL	WW^*	
ttH	LHCP Bologna 2018	$\tau\tau$	EPS HEP2017
		bb	ICHEP2018 SEOUL

- Run2 is already opening new frontiers in the Higgs Physics
    - Yukawa sector (top, bottom, τ)
    - Couplings with vector boson in production mode (VBF, VH)

Producing pp➞VH beyond the Standard Model

Adaptation from http://arxiv.org/pdf/1512.06135v1.pdf



Several BSM models predict the existence of new resonances decaying into VH

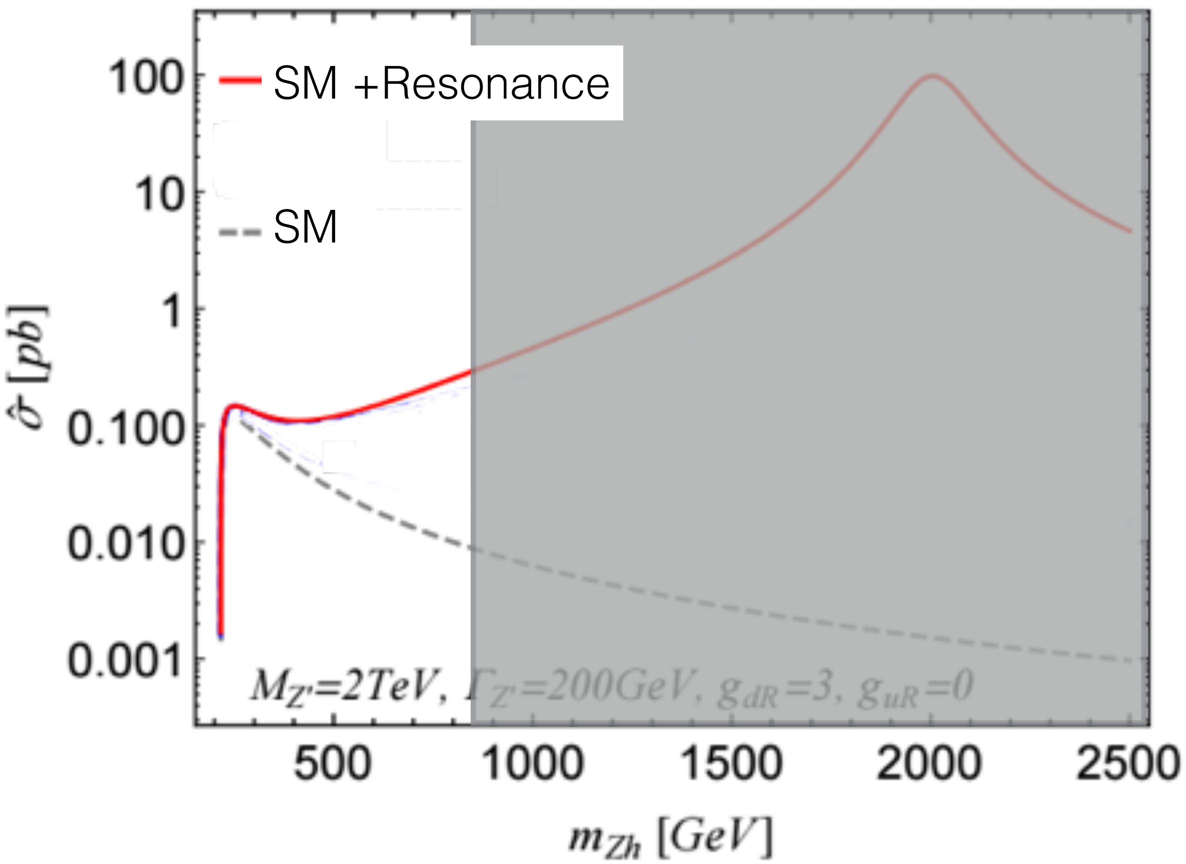
Some of the most famous one:

- 2HDM (pp➞A➞ZH)
  A is the CP odd scalar foreseen in the model
- HVT (pp➞Z'➞ZH, pp➞W'➞WH)
  Z' and W' are new vectors of the models
- Others…

Searches done in Run1 and with partial Run2 dataset.

No deviations found so far (but we always have to be open to surprises…)

Deviations from SM



If we have a resonance, which is beyond our present reach,
what happens to the VH cross section?

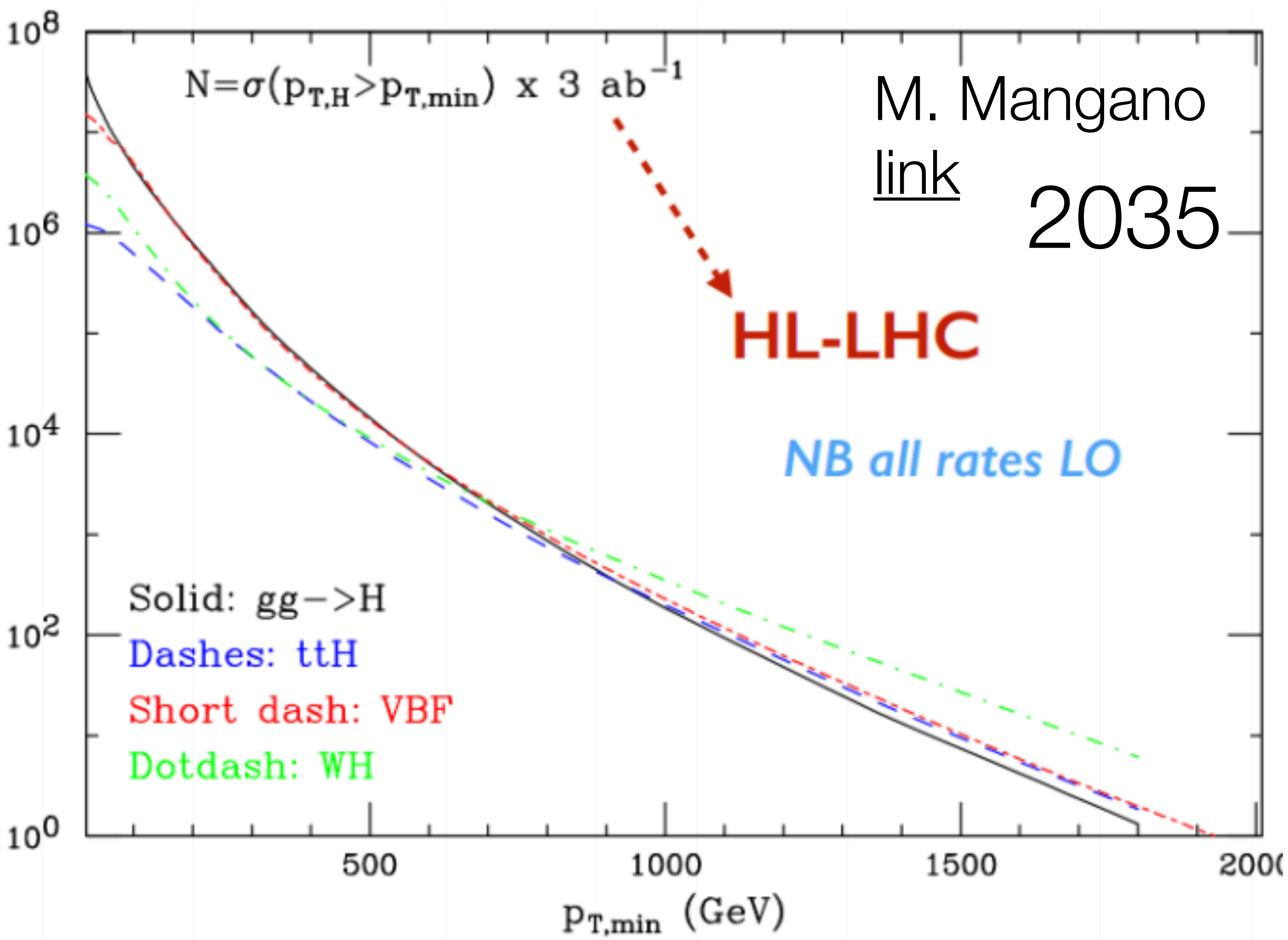
Can the measurement of the VH cross sections give information on the physics at higher scales?

Complementary approach to the direct search.

Are these effects changing the HVV couplings measured in the Higgs decays in WW and ZZ?

First consideration from the SM…

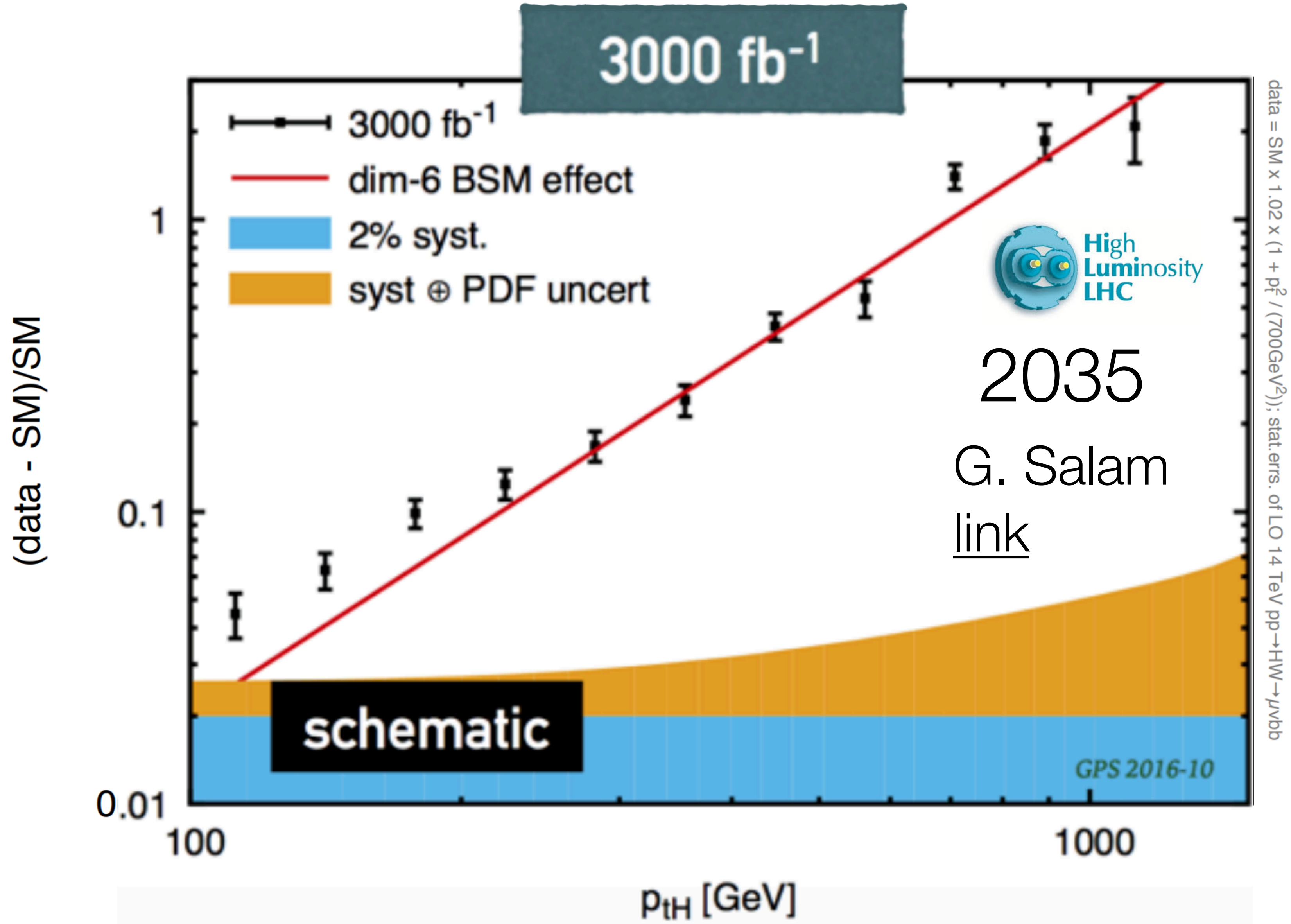
- Higgs production in the SM at High p_T



Above 800 GeV ggF is not anymore the dominant production mode

VH becomes more and more interesting!

…and beyond the SM?



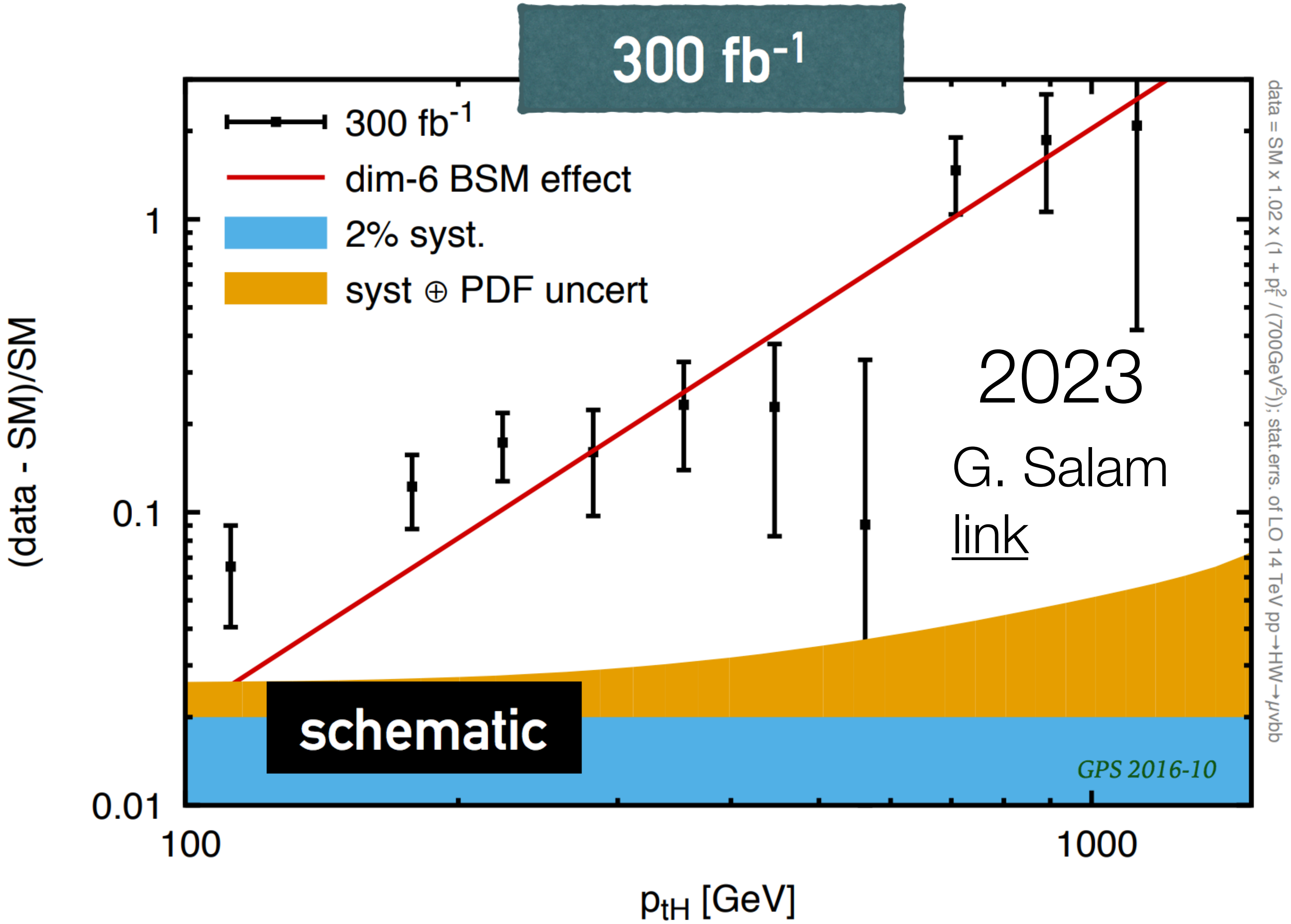
2035

G. Salam

link

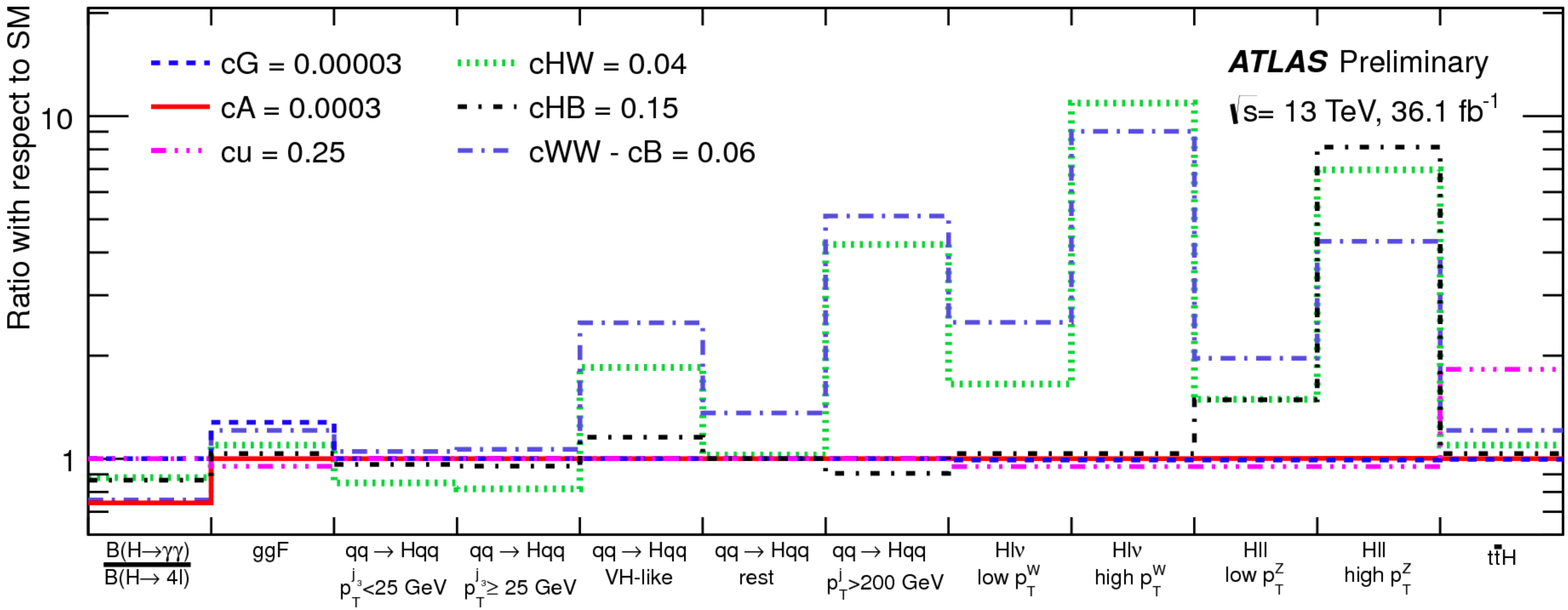
With the luminosity of HL-LHC the difference between the SM and the BSM is striking!

…and beyond the SM?



Moderate and high p_T's have similar statistical significance
it's useful to understand whole p_T range

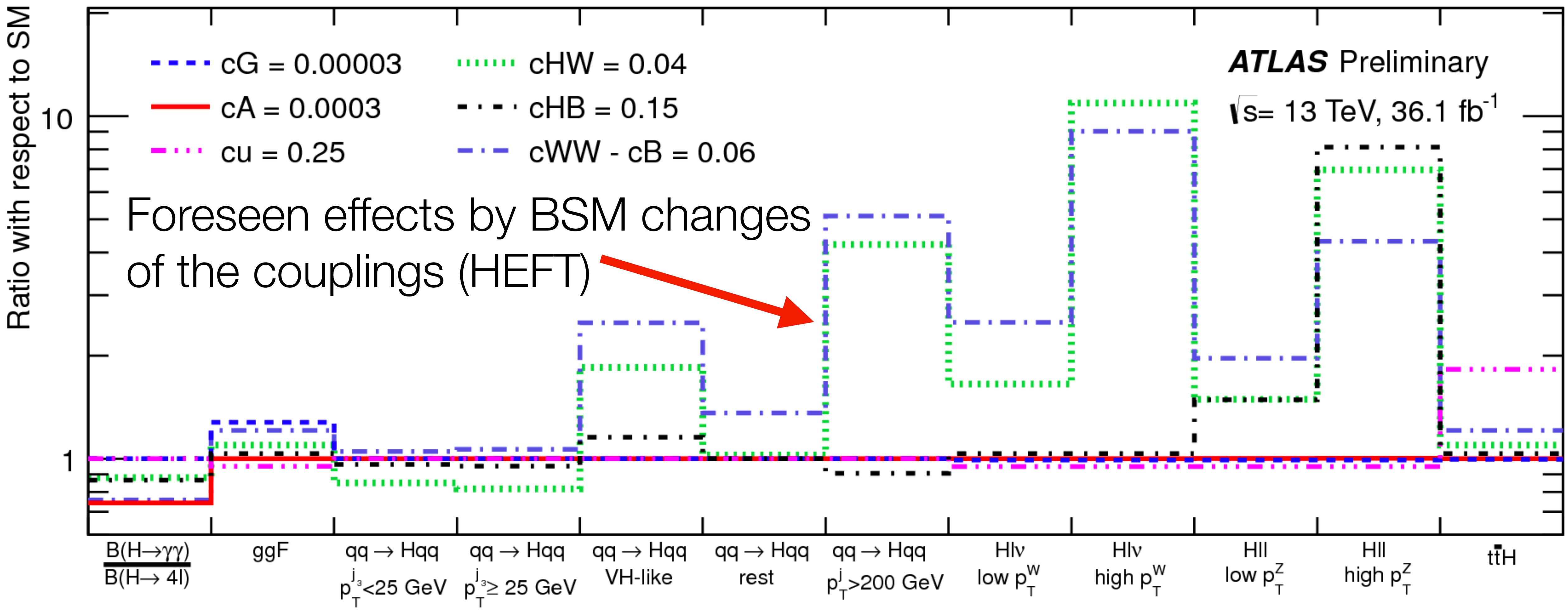
…and today?



Exclusive kinematic regions of Higgs production

γγ+4l

…and today?



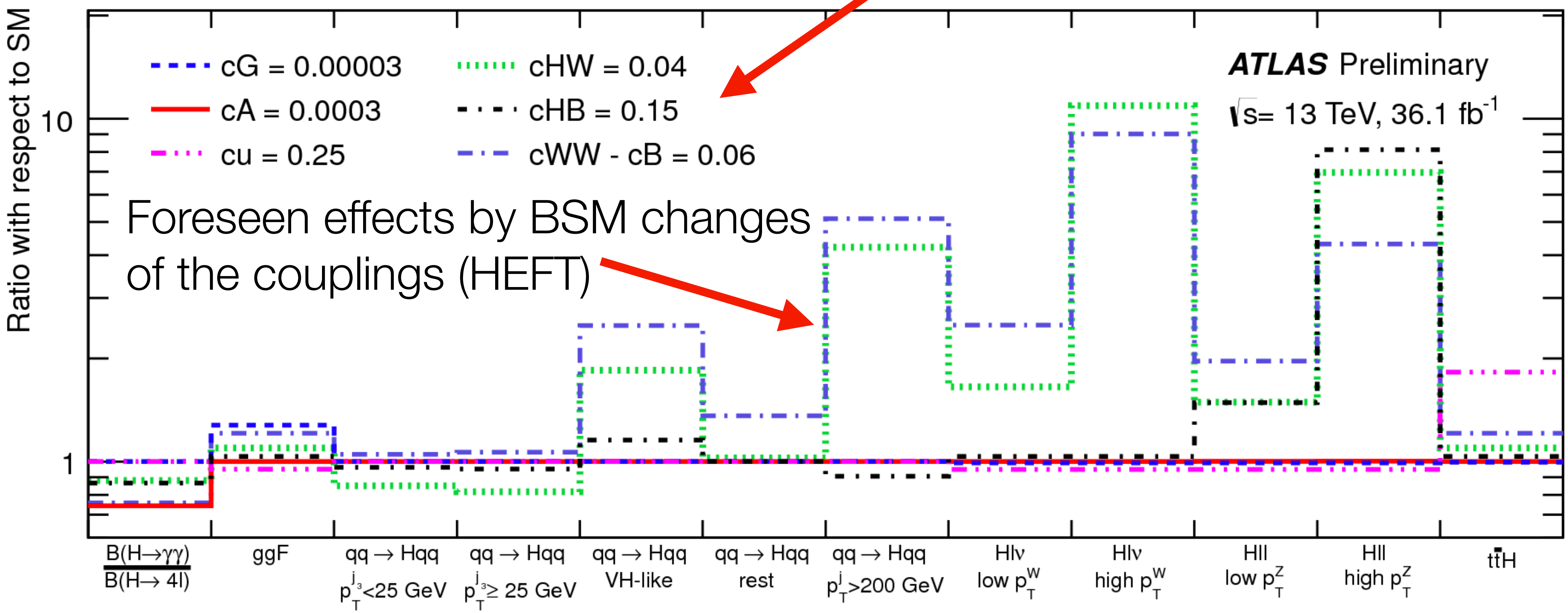
Foreseen effects by BSM changes of the couplings (HEFT)

Exclusive kinematic regions of Higgs production

…and today?

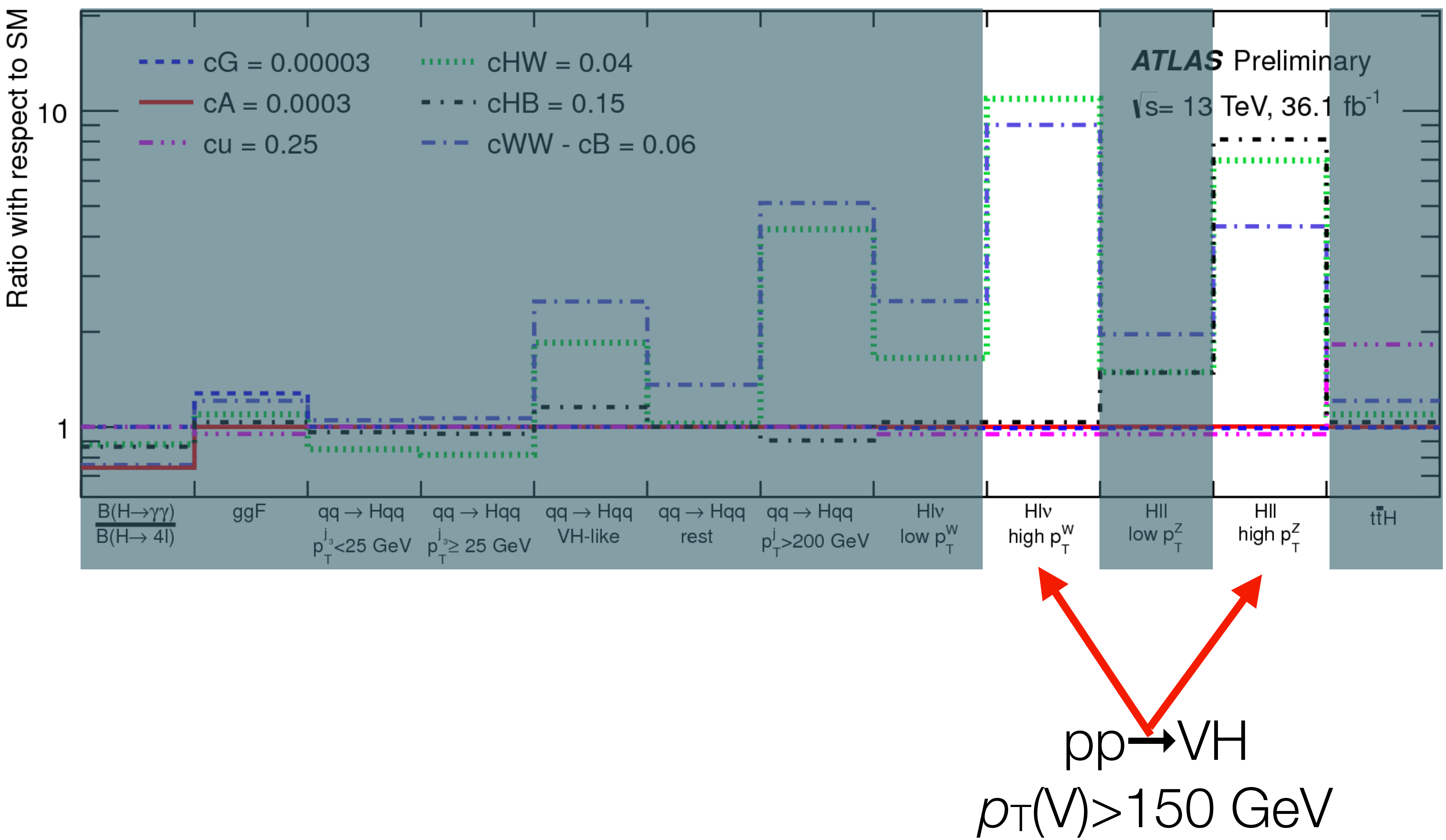
Limits from existing analysis

Foreseen effects by BSM changes of the couplings (HEFT)



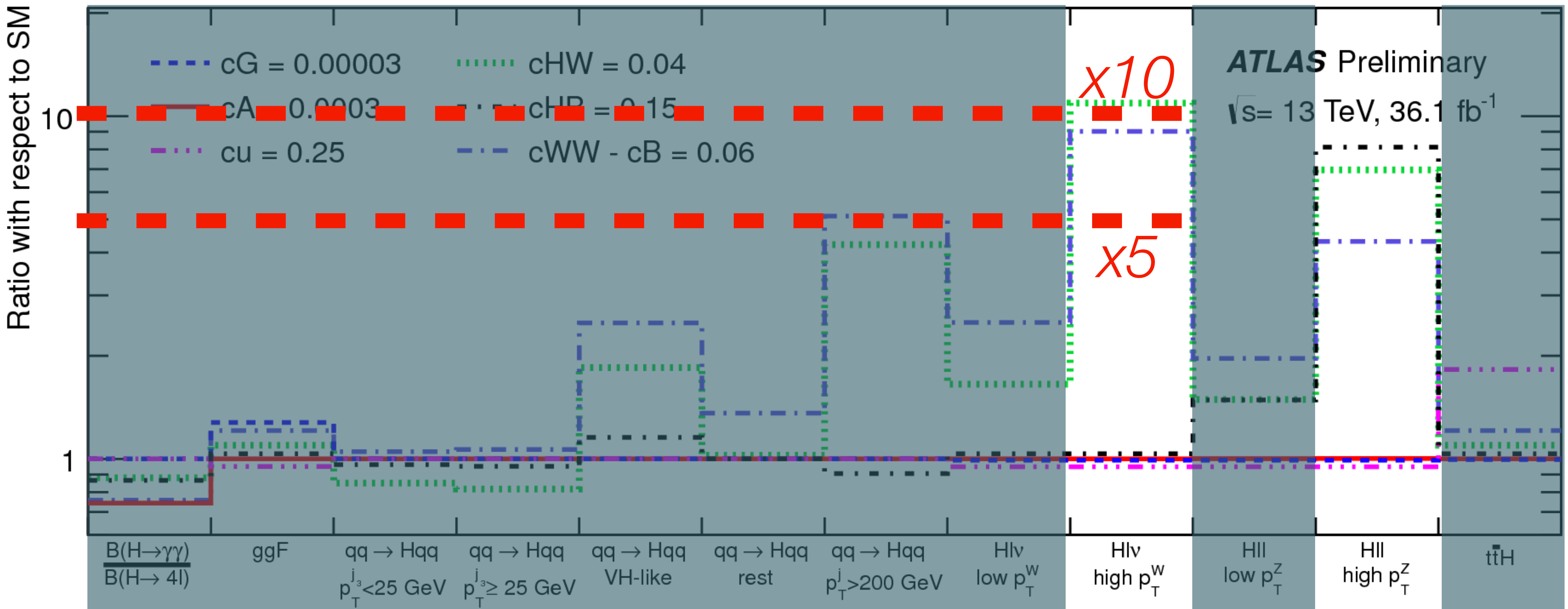
Exclusive kinematic regions of Higgs production

…and today?



Ratio with respect to SM
cG = 0.00003
cA = 0.0003
cu = 0.25
cHW = 0.04
cHB = 0.15
cWW - cB = 0.06
ATLAS Preliminary
√s= 13 TeV, 36.1 fb⁻¹
10
1
B(H→γγ) / B(H→ 4l)
ggF
qq → Hqq $p_T^{j_3}$<25 GeV
qq → Hqq $p_T^{j_3}$≥ 25 GeV
qq → Hqq VH-like
qq → Hqq rest
qq → Hqq p_T^j>200 GeV
Hlν low p_T^W
Hlν high p_T^W
Hll low p_T^Z
Hll high p_T^Z
tt̄H
pp→VH
$p_T(V)$>150 GeV

…and today?



Current precision in H➞bb: 40%!!!

Already today we can give important information
Can we go a bit more differential?
At which $p_T(V)$ can we arrive?
Stay tuned!

pp➞VH
$p_T(V)$>150 GeV

Conclusions

Production		Decays	
ggF	✓	γγ	✓
VBF	✓	ZZ*	✓
VH	✓	WW*	✓
ttH	✓	ττ	✓
		bb	✓

VH(bb) analysis with 80 fb^{-1} of Run-2 data

- $\mu^{bb}_{VH} = 1.16 \pm 0.26$, with a significance of 4.9σ

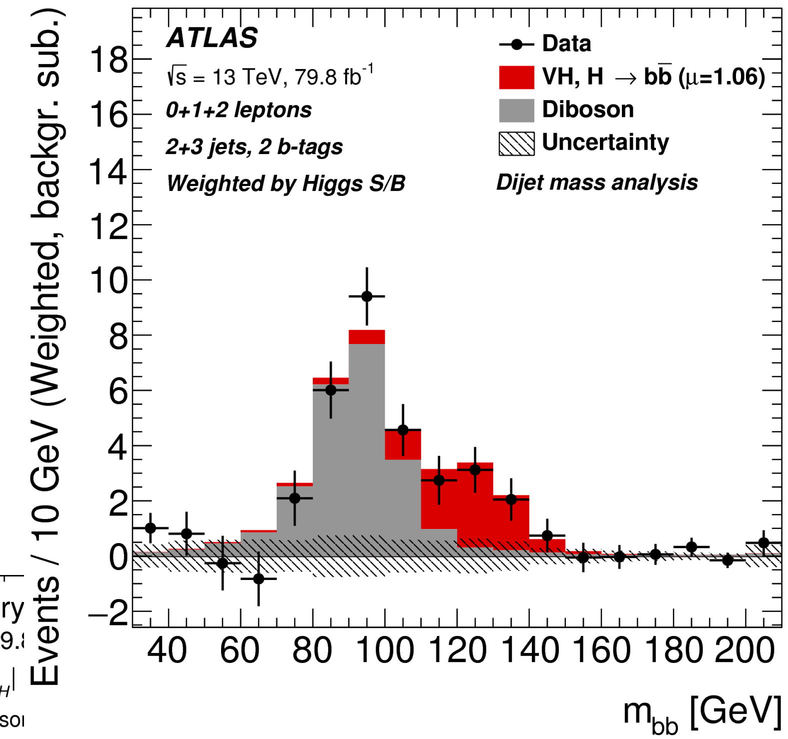
Observation of H→bb decays 5.4σ

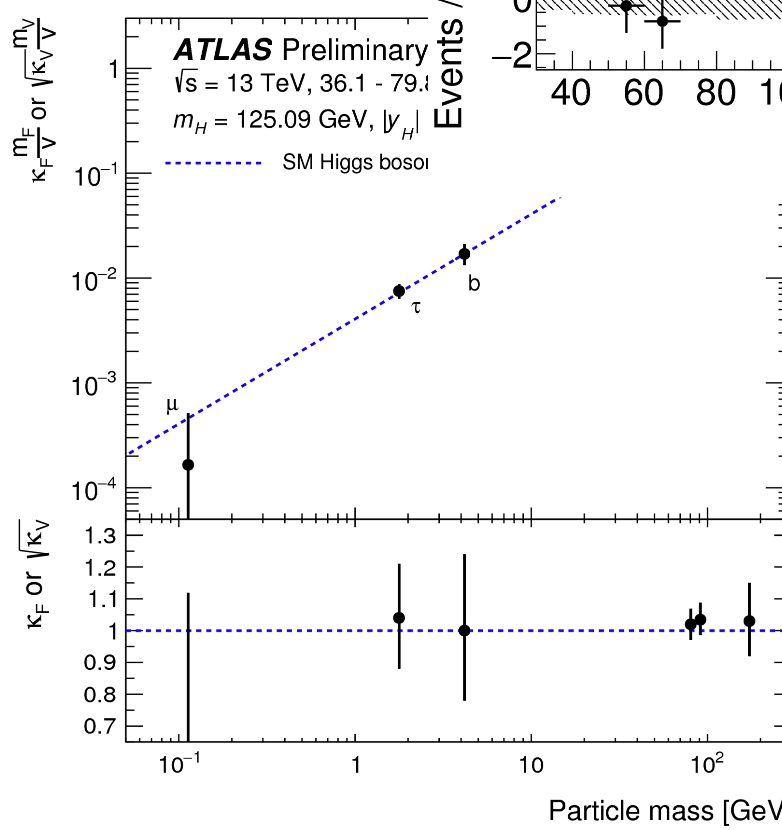
- $\mu_{H\to bb} = 1.01 \pm 0.20$
  in combination with ttH and VBF prod. modes
- 89% of the Higgs boson BR is now observed !

Observation of pp→VH production 5.3σ

- $\mu_{VH} = 1.13 \pm 0.24$
  in combination with γγ and 4l analyses
- All main production modes now observed !

Phys. Lett. B 786 (2018) 59: arXiv:1808.08238





Backup

H$\rightarrow$bb analysis details

pp→VH, H→bb Generators

Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order
Signal, mass set to 125 GeV and $b\bar{b}$ branching fraction to 58%					
$qq \to WH$ $\to \ell\nu b\bar{b}$	Powheg-Box v2 [76] + GoSam [79] + MiNLO [80,81]	NNPDF3.0NLO$^{(\star)}$ [77]	Pythia 8.212 [68]	AZNLO [78]	NNLO(QCD)+ NLO(EW) [82–88]
$qq \to ZH$ $\to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2 + GoSam + MiNLO	NNPDF3.0NLO$^{(\star)}$	Pythia 8.212	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$^{(\star)}$	Pythia 8.212	AZNLO	NLO+ NLL [89–93]
Top quark, mass set to 172.5 GeV					
$t\bar{t}$	Powheg-Box v2 [94]	NNPDF3.0NLO	Pythia 8.230	A14 [95]	NNLO+NNLL [96]
s-channel	Powheg-Box v2 [97]	NNPDF3.0NLO	Pythia 8.230	A14	NLO [98]
t-channel	Powheg-Box v2 [97]	NNPDF3.0NLO	Pythia 8.230	A14	NLO [99]
Wt	Powheg-Box v2 [100]	NNPDF3.0NLO	Pythia 8.230	A14	Approximate NNLO [101]
Vector boson + jets					
$W \to \ell\nu$	Sherpa 2.2.1 [71, 102, 103]	NNPDF3.0NNLO	Sherpa 2.2.1 [104, 105]	Default	NNLO [106]
$Z/\gamma^* \to \ell\ell$	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					
$qq \to WW$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$qq \to WZ$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$qq \to ZZ$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$gg \to VV$	Sherpa 2.2.2	NNPDF3.0NNLO	Sherpa 2.2.2	Default	NLO

$pp \rightarrow VH$, $H \rightarrow bb$ Event selection

MVA

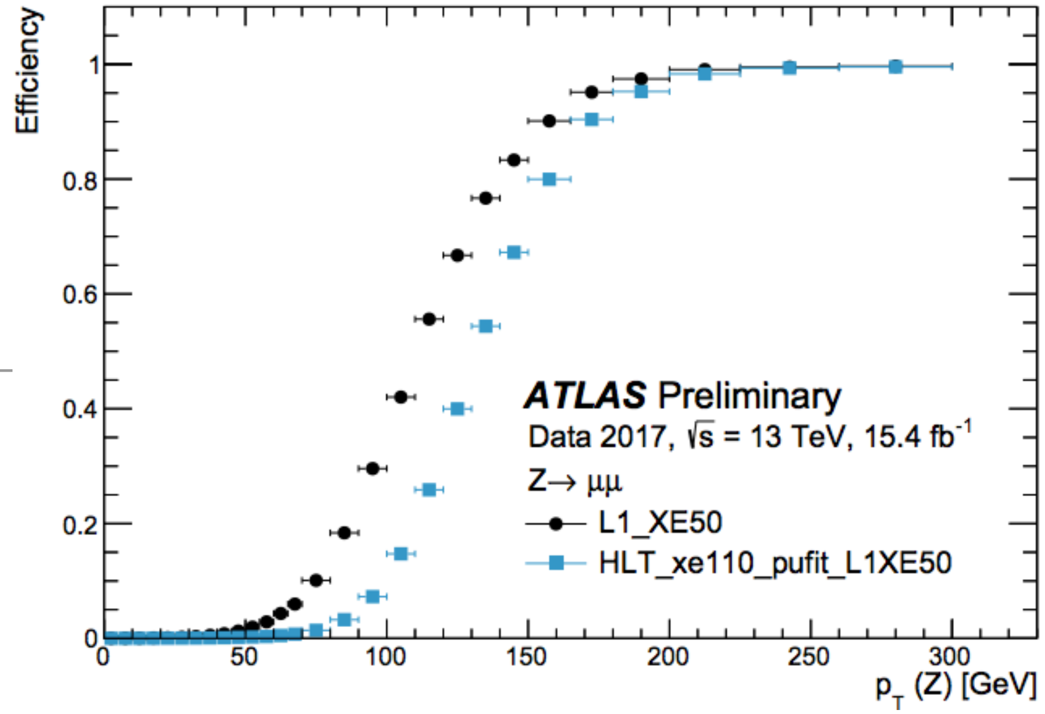
Selection	0-lepton	1-lepton e sub-channel	1-lepton μ sub-channel	2-lepton
Trigger	E_T^{miss}	Single lepton	E_T^{miss}	Single lepton
Leptons	0 *loose* leptons with $p_T > 7$ GeV	1 *tight* electron $p_T > 27$ GeV	1 *tight* muon $p_T > 25$ GeV	2 *loose* leptons with $p_T > 7$ GeV ≥ 1 lepton with $p_T >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

Additional cuts for m_{bb} shape analysis

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

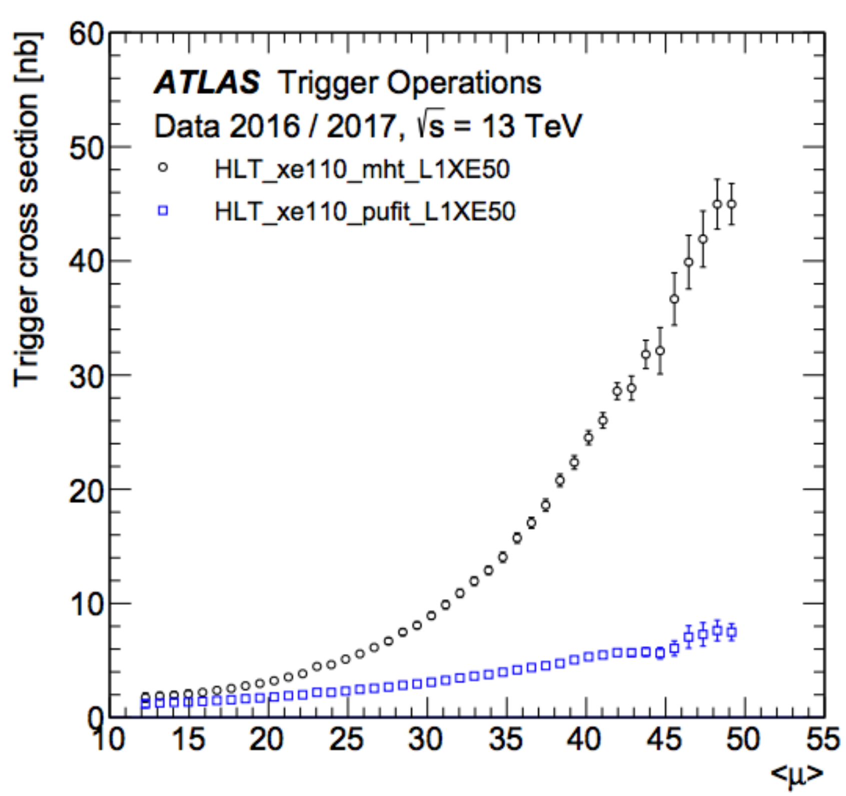
p_T^V regions			
p_T^V	$75 - 150$ GeV (2-lepton only)	$150 - 200$ GeV	> 200 GeV
$\Delta R(\vec{b}_1, \vec{b}_2)$	<3.0	<1.8	<1.2

E_T^{miss} Trigger



E_T^{miss} Trigger

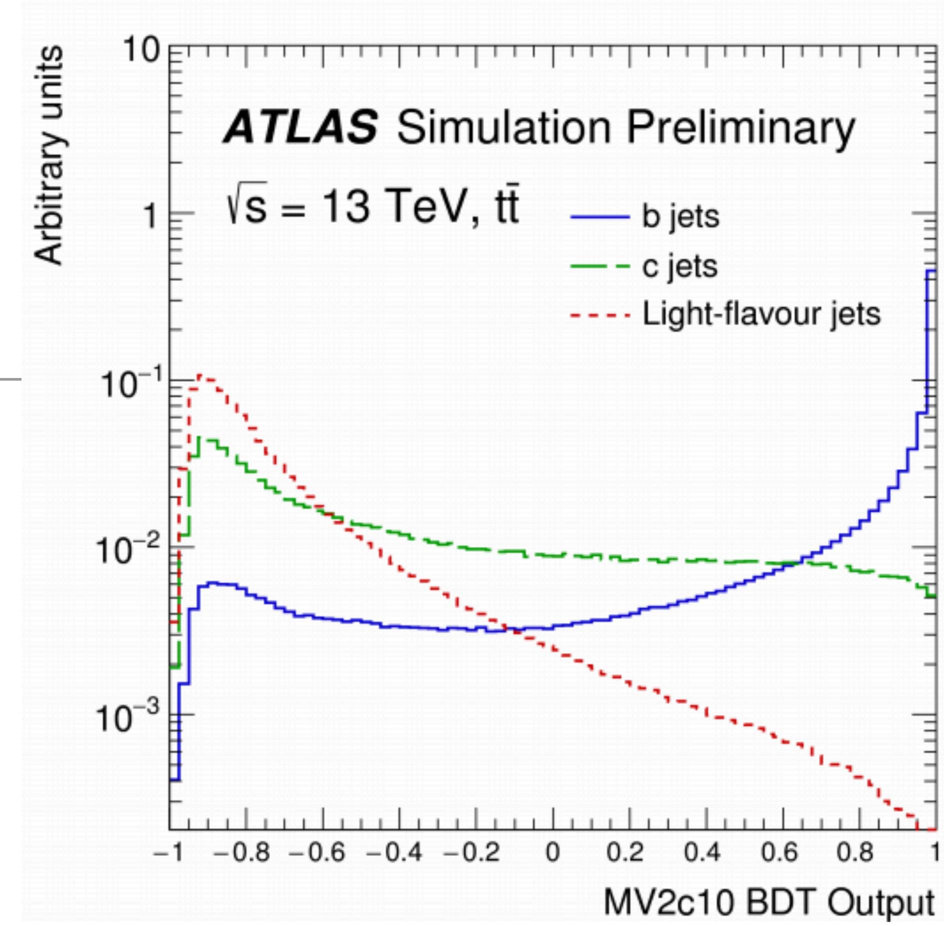
- Key item for high efficiency in 0-lepton channel
- Efficiency ~80% for E_T^{miss} >150 GeV, >95% for E_T^{miss} >200 GeV
- Efforts to limit increase of rate with pile-up
- Sufficiently large trigger bandwidth allocated
- Efficiency measurement in Z, W and tt events



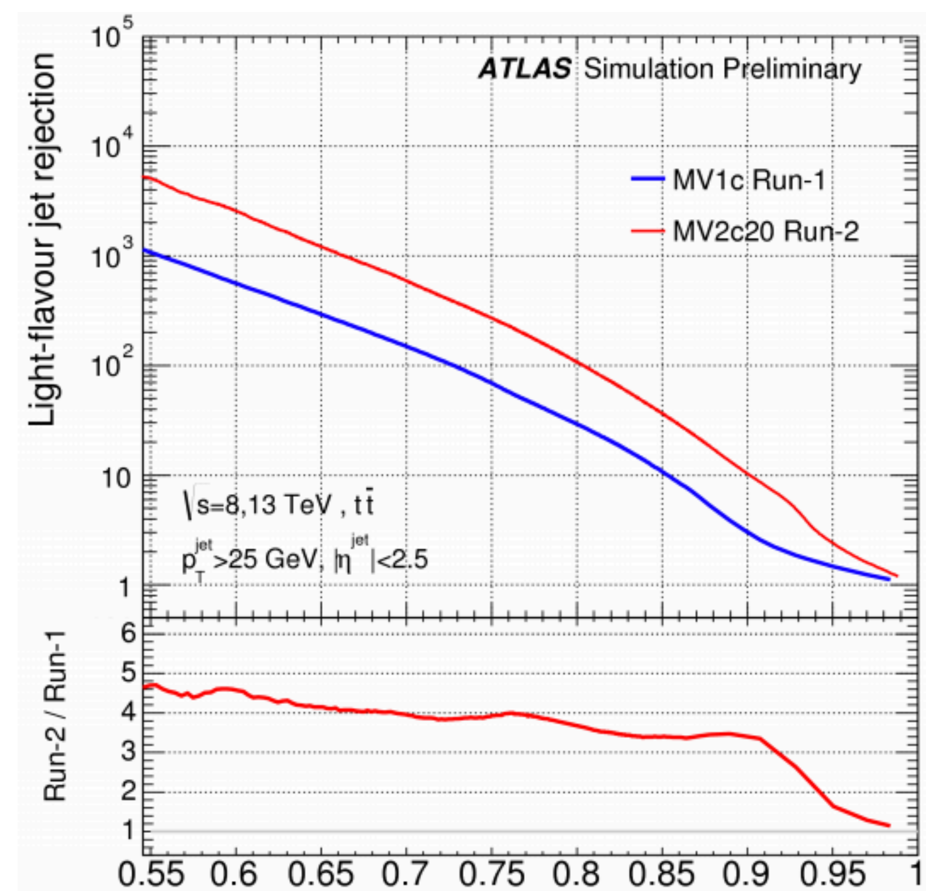
E_T^{miss} trigger in 1-muon channel

- Muons not used in E_T^{miss} calculation at trigger level
- De-facto, E_T^{miss} trigger is a p_T(W) trigger in the muon channel
- More efficient (>90%) than single-muon trigger (~80%) at p_T(W)>150 GeV

B-tagging from Run1 to Run2



- Typical performance: 70%,8.2%, 0.3% for b, c, light jets efficiency
- Large improvement compared to Run 1
  - Tracking optimisation for high-pu environment
  - Improved MVA algorithms
  - Insertion of IBL



pp→VH, H→bb Signal XS and event yields - SR

Process	$\sigma \times \mathcal{B}$ [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$qq \to ZH \to \ell\ell b\bar{b}$	29.9	<0.1	0.1	6.0
$gg \to ZH \to \ell\ell b\bar{b}$	4.8	<0.1	0.2	13.5
$qq \to WH \to \ell\nu b\bar{b}$	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	–	–

	0-lepton $p_T^V > 150\,GeV$, 2-b-tag		1-lepton $p_T^V > 150\,GeV$, 2-b-tag		2-lepton $75\,GeV < p_T^V < 150\,GeV$, 2-$b$-tag		2-lepton $p_T^V > 150\,GeV$, 2-b-tag	
Process	2-jet	3-jet	2-jet	3-jet	2-jet	≥3-jet	2-jet	≥3-jet
$Z + ll$	17 ± 11	27 ± 18	2 ± 1	3 ± 2	14 ± 9	49 ± 32	4 ± 3	30 ± 19
$Z + cl$	45 ± 18	76 ± 30	3 ± 1	7 ± 3	43 ± 17	170 ± 67	12 ± 5	88 ± 35
Z + HF	4770 ± 140	5940 ± 300	180 ± 9	348 ± 21	7400 ± 120	14160 ± 220	1421 ± 34	5370 ± 100
$W + ll$	20 ± 13	32 ± 22	31 ± 23	65 ± 48	< 1	< 1	< 1	< 1
$W + cl$	43 ± 20	83 ± 38	139 ± 67	250 ± 120	< 1	< 1	< 1	< 1
W + HF	1000 ± 87	1990 ± 200	2660 ± 270	5400 ± 670	2 ± 0	13 ± 2	1 ± 0	4 ± 1
Single top quark	368 ± 53	1410 ± 210	2080 ± 290	9400 ± 1400	188 ± 89	440 ± 200	23 ± 7	93 ± 26
$t\bar{t}$	1333 ± 82	9150 ± 400	6600 ± 320	50200 ± 1400	3170 ± 100	8880 ± 220	104 ± 6	839 ± 40
Diboson	254 ± 49	318 ± 90	178 ± 47	330 ± 110	152 ± 32	355 ± 68	52 ± 11	196 ± 35
Multi-jet e sub-ch.	–	–	100 ± 100	41 ± 35	–	–	–	–
Multi-jet μ sub-ch.	–	–	138 ± 92	260 ± 270	–	–	–	–
Total bkg.	7850 ± 90	19020 ± 140	12110 ± 120	66230 ± 270	10960 ± 100	24070 ± 150	1620 ± 30	6620 ± 80
Signal (post-fit)	128 ± 28	128 ± 29	131 ± 30	125 ± 30	51 ± 11	86 ± 22	28 ± 6	67 ± 17
Data	8003	19143	12242	66348	11014	24197	1626	6686

pp→VH, H→bb Event yields - CR

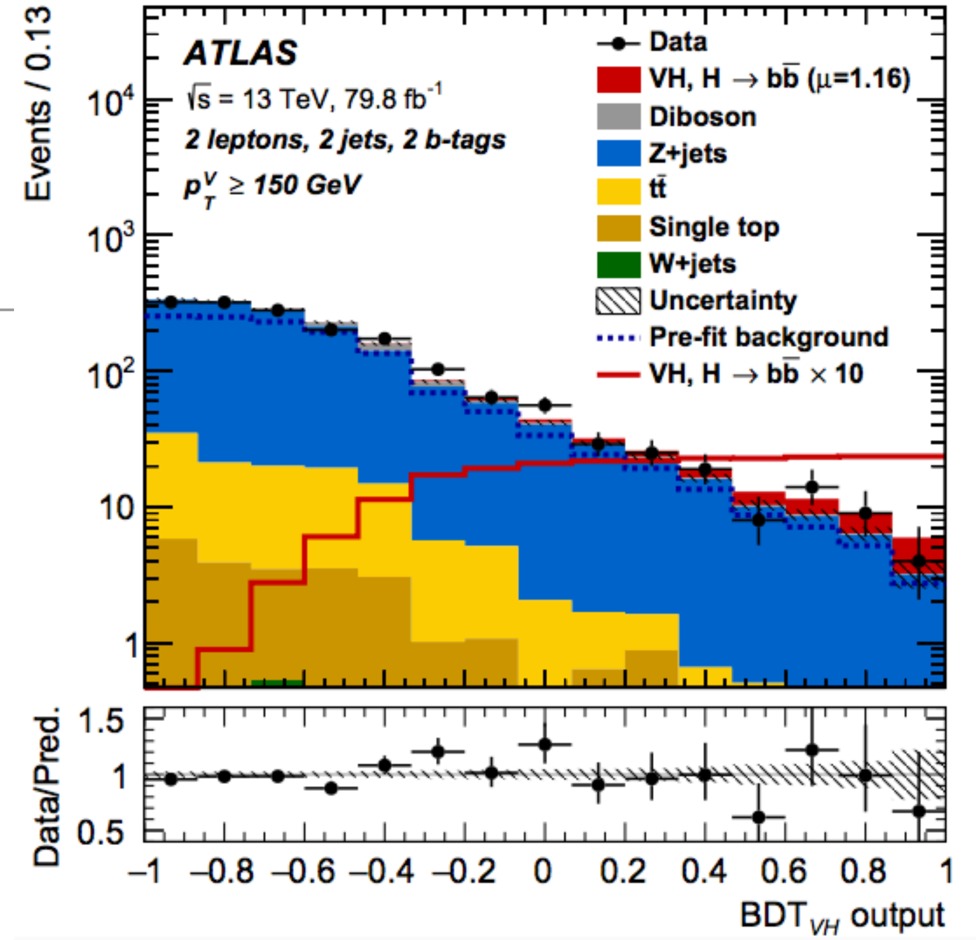
	1-lepton $p_T^V > 150\,GeV$, 2-b-tag		2-lepton $75\,GeV < p_T^V < 150\,GeV$, 2-$b$-tag		2-lepton $p_T^V > 150\,GeV$, 2-b-tag	
Process	2-jet	3-jet	2-jet	≥3-jet	2-jet	≥3-jet
Z + HF	15.1 ± 1.4	33 ± 2.5	2.5 ± 0.2	2.1 ± 0.2	< 1	< 1
$W + ll$	2.1 ± 1.5	3.8 ± 2.6	–	–	–	–
$W + cl$	8.4 ± 4.1	13.5 ± 6.6	–	< 1	–	–
W + HF	498 ± 34	1044 ± 92	2.5 ± 0.3	8.4 ± 1.0	< 1	3.3 ± 0.4
Single top quark	23.8 ± 5.4	122 ± 23	189 ± 90	450 ± 210	22.4 ± 7.1	93 ± 27
$t\bar{t}$	68 ± 18	307 ± 77	3243 ± 98	8690 ± 210	107.3 ± 6.7	807 ± 37
Diboson	13.4 ± 3.7	22.6 ± 7.5	–	< 1	–	< 1
Multi-jet e sub-ch.	8.3 ± 8.5	3.6 ± 2.9	–	–	–	–
Multi-jet μ sub-ch.	6.9 ± 4.6	13 ± 13	–	–	–	–
Total bkg.	644 ± 23	1563 ± 39	3437 ± 58	9153 ± 95	130.1 ± 6.7	905 ± 27
Signal (post-fit)	< 1	2.3 ± 0.6	< 1	< 1	< 1	< 1
Data	642	1567	3450	9102	118	923

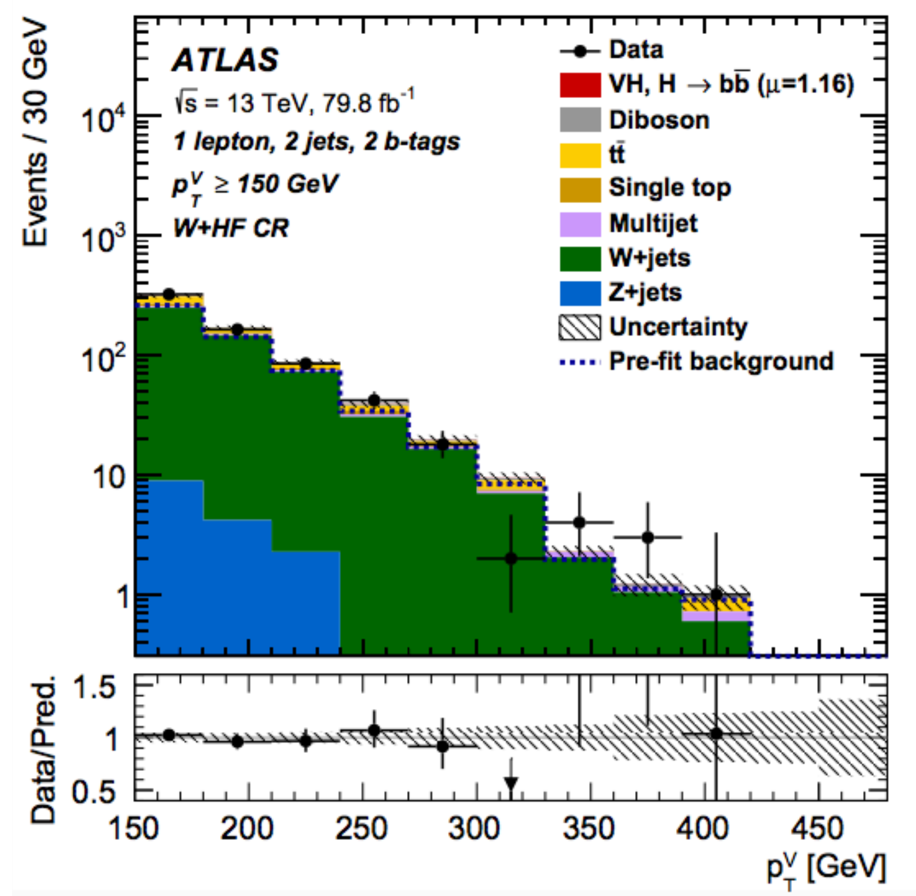
Background modelling

Z + jets	
$Z + ll$ normalisation	18%
$Z + cl$ normalisation	23%
Z + HF 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
W + jets	
$W + ll$ normalisation	32%
$W + cl$ normalisation	37%
W + HF 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)
m_{bb}, p_{T}^{V}	S
$t\bar{t}$ (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
Single top-quark	
Cross-section	4.6% (s-channel), 4.4% (t-channel), 6.2% (Wt)
Acceptance 2-jet	17% (t-channel), 55% ($Wt(bb)$), 24% (Wt(other))
Acceptance 3-jet	20% (t-channel), 51% ($Wt(bb)$), 21% (Wt(other))
m_{bb}, p_{T}^{V}	S (t-channel, $Wt(bb)$, Wt(other))
Multi-jet (1-lepton)	
Normalisation	60 – 100% (2-jet), 90 – 140% (3-jet)
BDT template	S

V+jets modelling

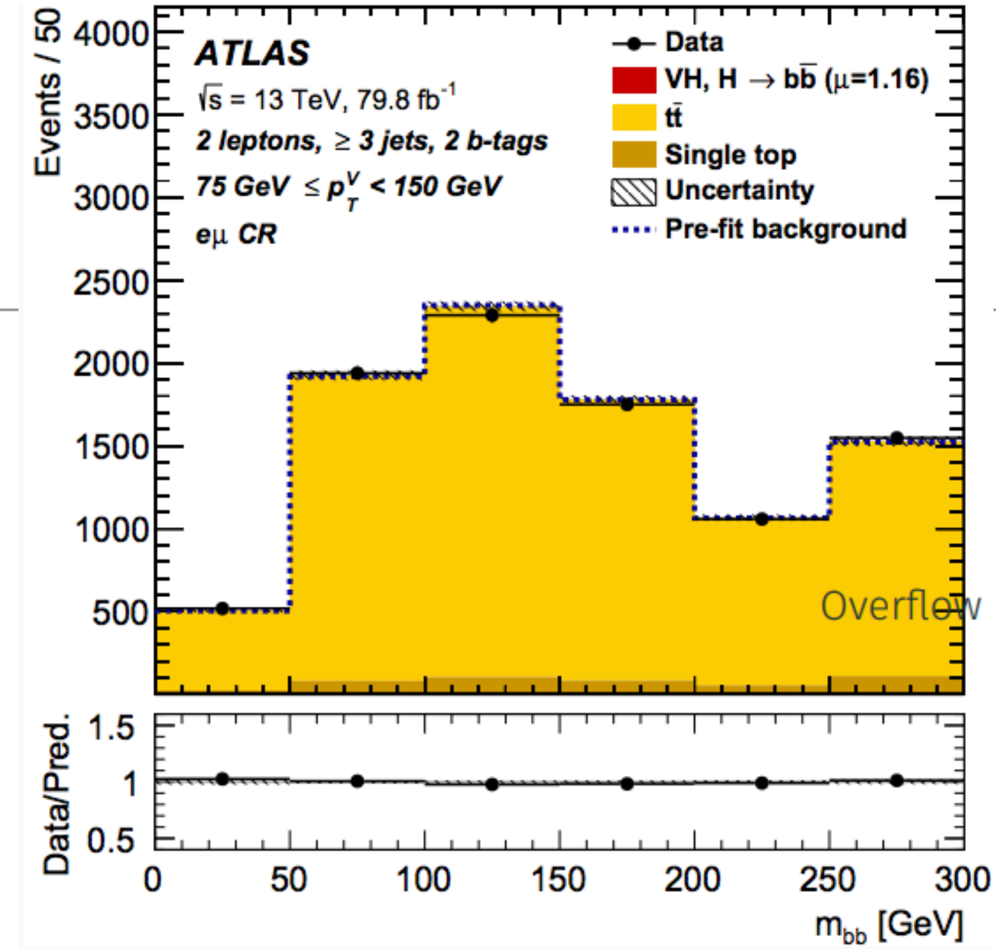
- Rely on MEPS@NLO (multi-jet merging at NLO, up to 2 extra jets@NLO)
- 2 leptons low $p_T(Z)$ can constrain Z normalisation and shapes
- 1 lepton W+HF CR contrains W normalisation
- **NOTE**: for both Z+hf and W+hf, normalisation 20-30% bigger than predictions
- Extrapolation to 0-lepton and 1-lepton SR
- Uncertainties on flavour compositions
- BDT shapes uncertainties through propagation of variations on m_{bb} and $p_T(V)$

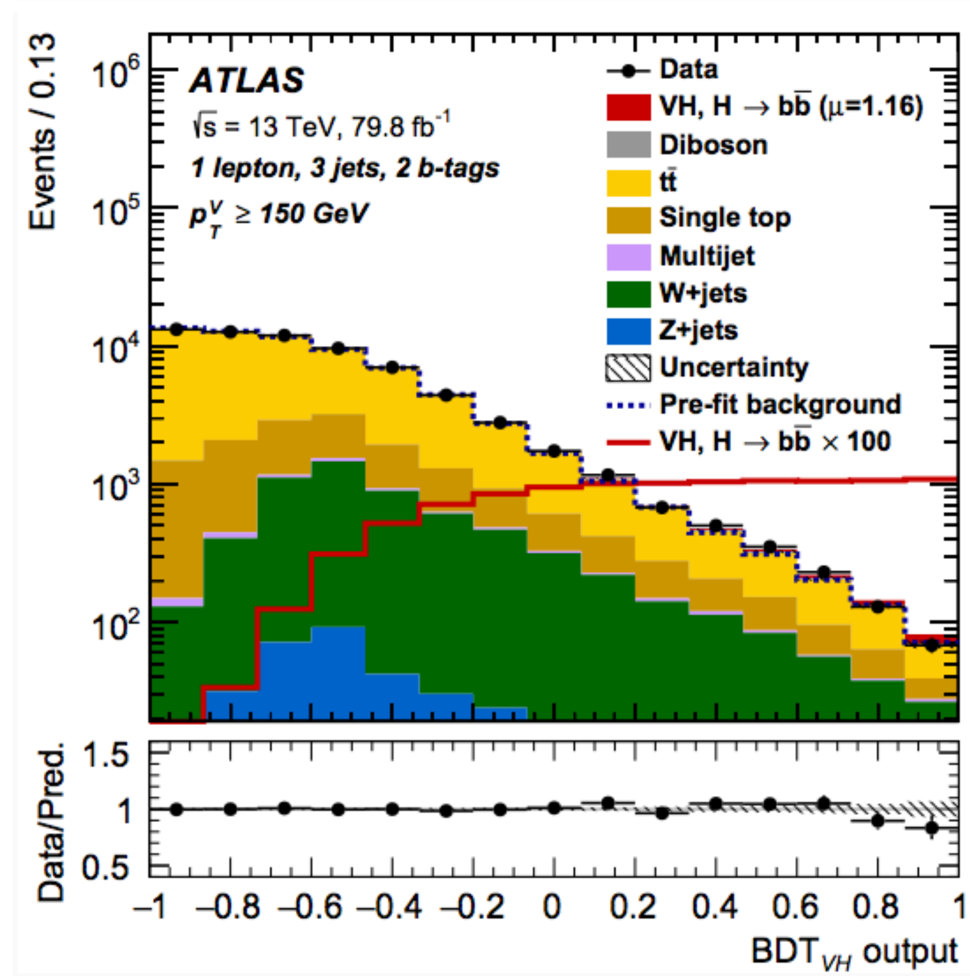




tt modelling

- Separate 2 leptons from 0/1 leptons
  Different phase space
- 2 leptons:
  - all leptons and jets in acceptance
  - eμ CR very pure
- 0/1 leptons:
  - some jets and/or leptons not reconstructed
  - 1-lepton 3 jet regions dominated by tt (almost a CR)
- Normalisation factor: ~1.0
- Extrapolation to 0/1 lepton regions
- BDT shapes uncertainties through propagation of variations on m_{bb} and $p_T(V)$





Diboson and Signal modelling

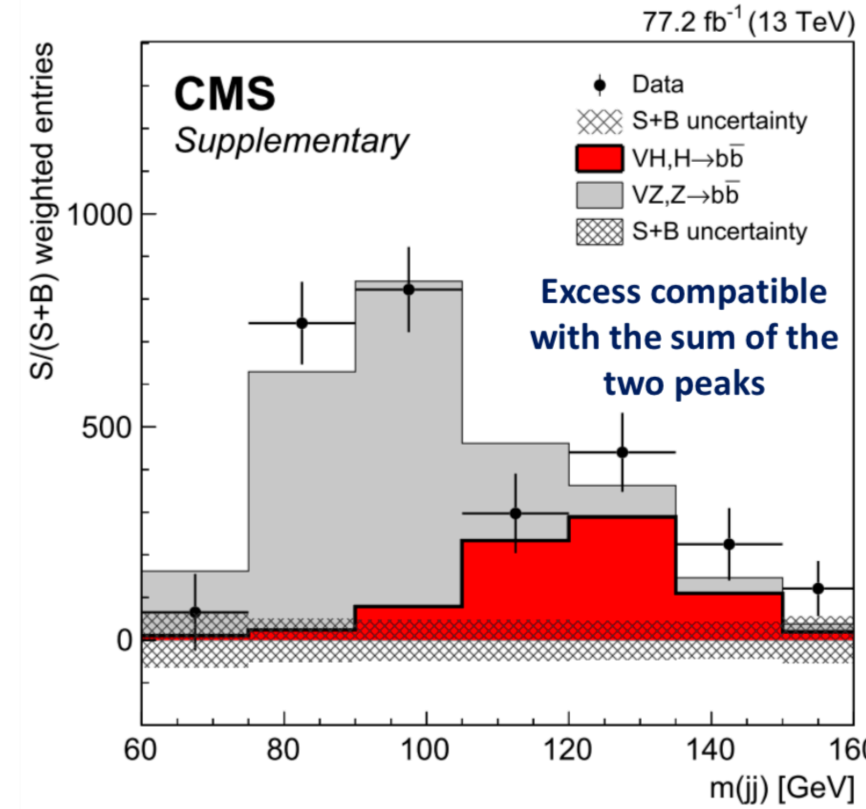
ZZ	
Normalisation	20%
0-to-2 lepton ratio	6%
Acceptance from scale variations	10 – 18%
Acceptance from PS/UE variations for 2 or more jets	6%
Acceptance from PS/UE variations for 3 jets	7% (0-lepton), 3% (2-lepton)
m_{bb}, p_{T}^{V}, from scale variations	S (correlated with WZ uncertainties)
m_{bb}, p_{T}^{V}, from PS/UE variations	S (correlated with WZ uncertainties)
m_{bb}, from matrix-element variations	S (correlated with WZ uncertainties)
WZ	
Normalisation	26%
0-to-1 lepton ratio	11%
Acceptance from scale variations	13 – 21%
Acceptance from PS/UE variations for 2 or more jets	4%
Acceptance from PS/UE variations for 3 jets	11%
m_{bb}, p_{T}^{V}, from scale variations	S (correlated with ZZ uncertainties)
m_{bb}, p_{T}^{V}, from PS/UE variations	S (correlated with ZZ uncertainties)
m_{bb}, from matrix-element variations	S (correlated with ZZ uncertainties)
WW	
Normalisation	25%

Signal	
Cross-section (scale)	0.7% (qq), 27% (gg)
Cross-section (PDF)	1.9% ($qq \to WH$), 1.6% ($qq \to ZH$), 5% (gg)
$H \to b\bar{b}$ branching fraction	1.7%
Acceptance from scale variations	2.5 – 8.8%
Acceptance from PS/UE variations for 2 or more jets	2.9 – 6.2% (depending on lepton channel)
Acceptance from PS/UE variations for 3 jets	1.8 – 11%
Acceptance from PDF+α_{S} variations	0.5 – 1.3%
m_{bb}, p_{T}^{V}, from scale variations	S
m_{bb}, p_{T}^{V}, from PS/UE variations	S
m_{bb}, p_{T}^{V}, from PDF+α_{S} variations	S
p_{T}^{V} from NLO EW correction	S

H➞bb in CMS

Phys. Rev. Lett. 121, 121801 (2018)

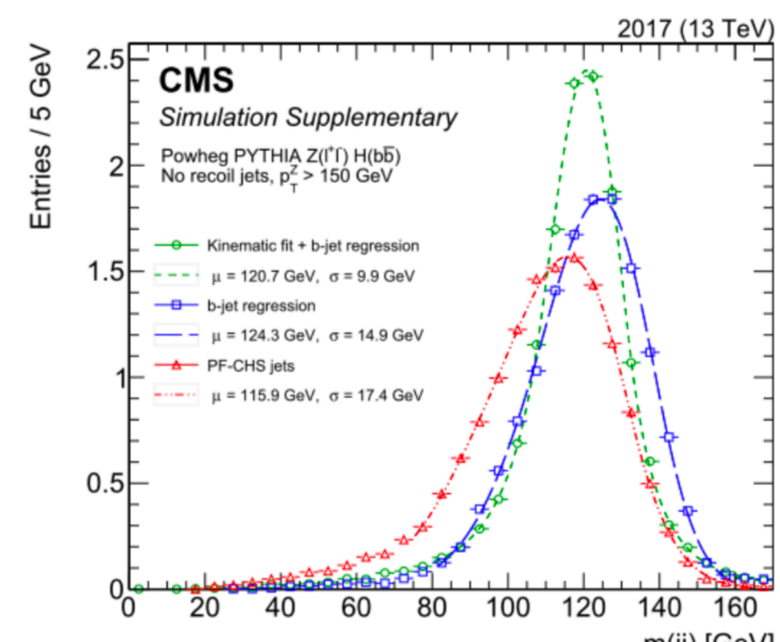
H→bb in CMS
Analysis strategy



- ATLAS and CMS adopted very similar strategy, with some differences:
  - **CMS had a Pixel detector upgraded for 2017 data taking**
    - Probably more robust to keep the 2017 dataset separate from the 2015-2016, and combined afterword.
  - **Optimization and design of each control region for each individual channel**
    - As a result CMS has different normalisation factors for the s physics process, depending on the phase-space/channel

Process	$Z(\nu\nu)$H	$W(\ell\nu)$H	$Z(\ell\ell)$H low-p_T	$Z(\ell\ell)$H high-p_T
W + udscg	1.04 ± 0.07	1.04 ± 0.07	–	–
W + b	2.09 ± 0.16	2.09 ± 0.16	–	–
W + b$\bar{\text{b}}$	1.74 ± 0.21	1.74 ± 0.21	–	–
Z + udscg	0.95 ± 0.09	–	0.89 ± 0.06	0.81 ± 0.05
Z + b	1.02 ± 0.17	–	0.94 ± 0.12	1.17 ± 0.10
Z + b$\bar{\text{b}}$	1.20 ± 0.11	–	0.81 ± 0.07	0.88 ± 0.08
t$\bar{\text{t}}$	0.99 ± 0.07	0.93 ± 0.07	0.89 ± 0.07	0.91 ± 0.07

  - **CMS uses multi variate regression to improve the m_{bb} resolution**
    - performances in ATLAS and CMS very simular
  - **CMS uses of b-tagging information as part of in their MVA input variables**
    - In ATLAS this has been tested, and it could be something to be considered for the future analysis
  - **In the full combination, CMS added the ggF boosted analysis (for ATLAS is work in progress)**

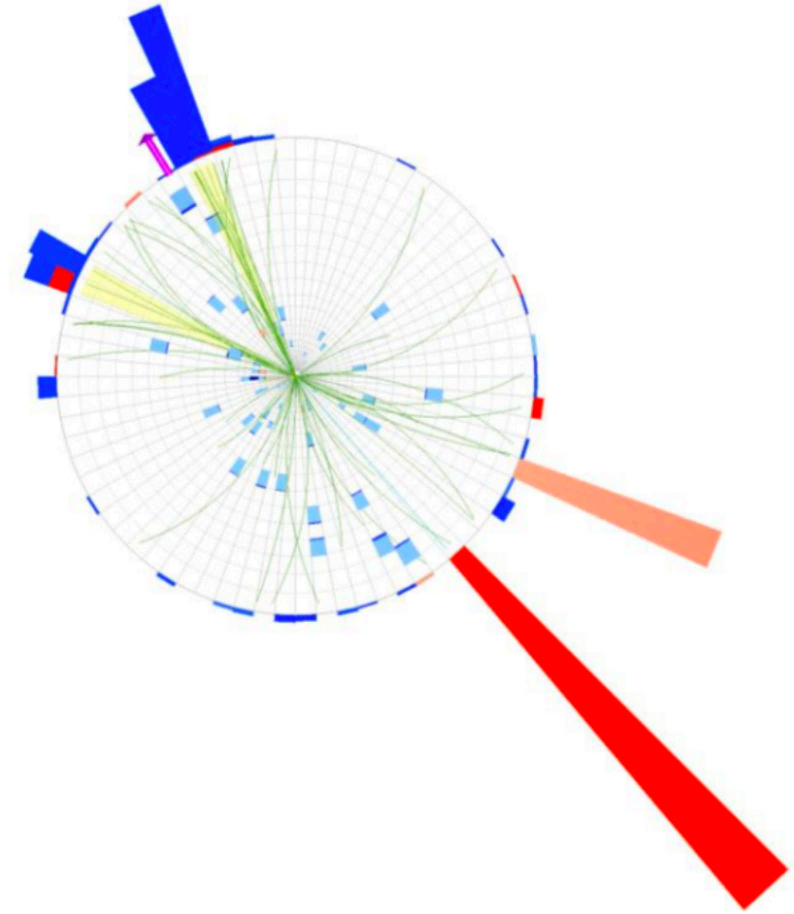


2018

Phys. Rev. Lett. 121, 121801 (2018)

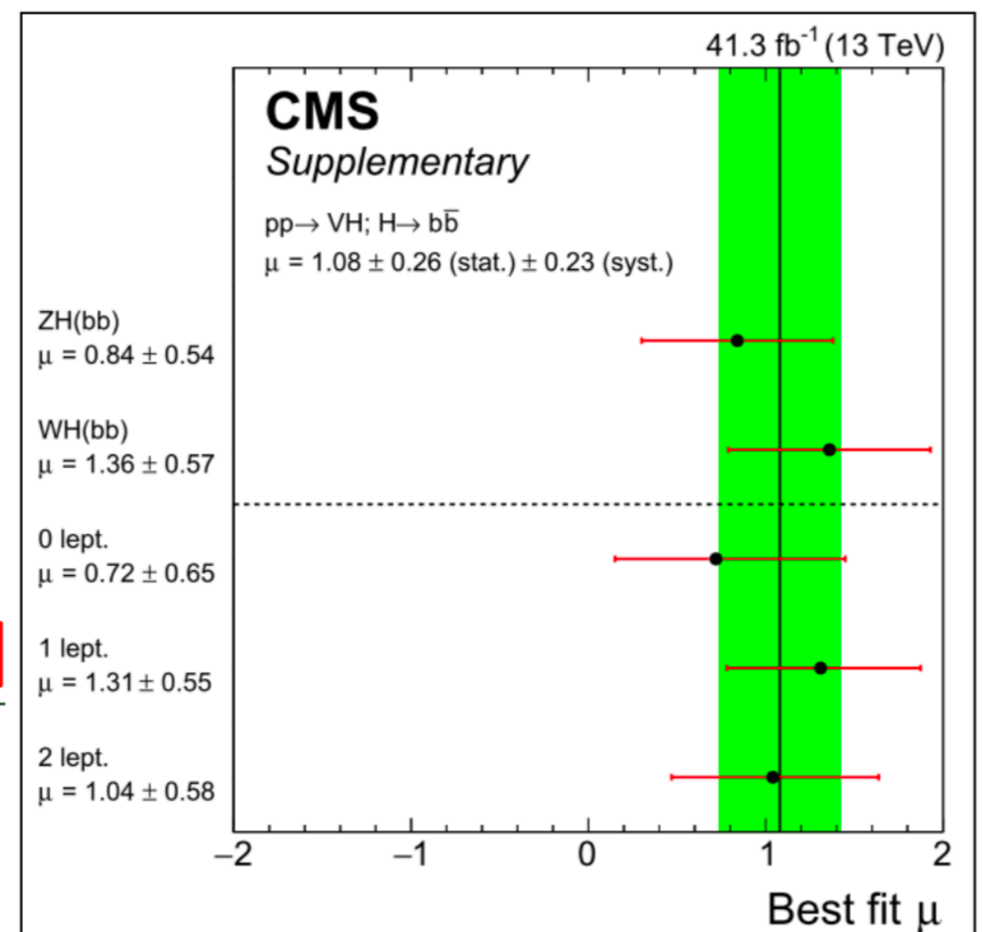
H→bb in CMS 2017

Uncertainty source	$\Delta\mu$	
Statistical	+0.26	−0.26
Normalization of backgrounds	+0.12	−0.12
Experimental	+0.16	−0.15
b-tagging efficiency and misid	+0.09	−0.08
V+jets modeling	+0.08	−0.07
Jet energy scale and resolution	+0.05	−0.05
Lepton identification	+0.02	−0.01
Luminosity	+0.03	−0.03
Other experimental uncertainties	+0.06	−0.05
MC sample size	+0.12	−0.12
Theory	+0.11	−0.09
Background modeling	+0.08	−0.08
Signal modeling	+0.07	−0.04
Total	+0.35	−0.33



CMS Experiment at LHC, CERN
Data recorded: Sun Aug 20 13:16:45 2017 CDT
Run/Event: 301472 / 634226645
Lumi section: 664

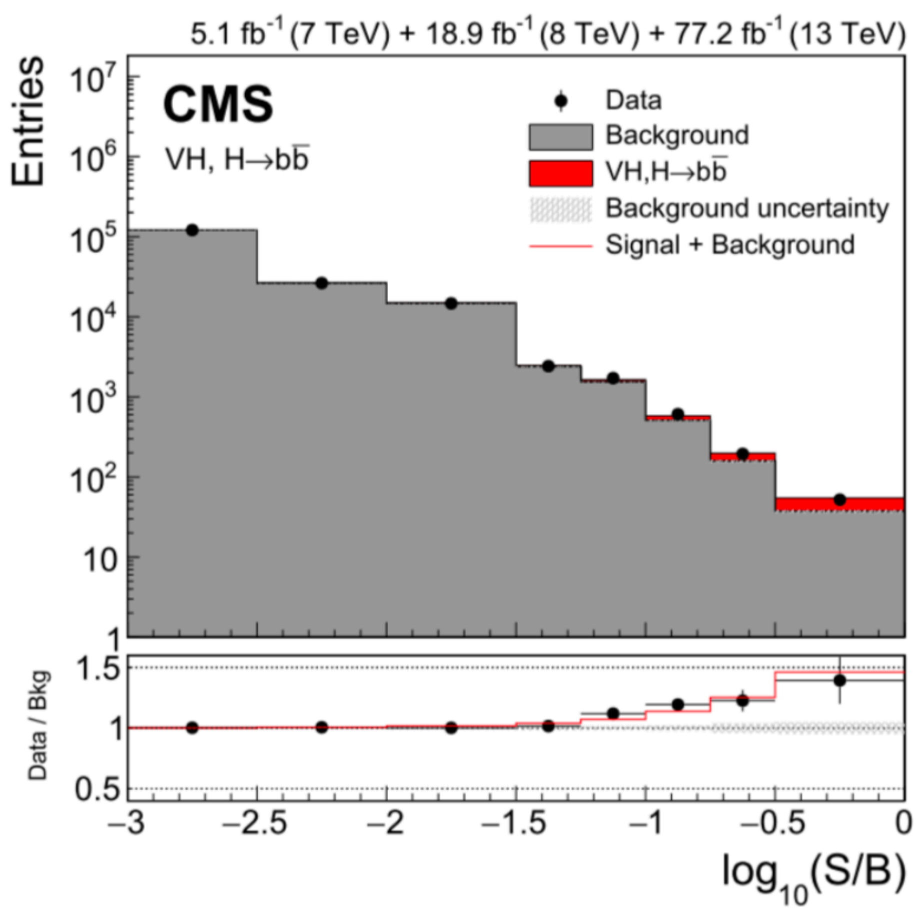
	Significance (σ)		
Data set	Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
2016	2.8	3.3	1.2 ± 0.4

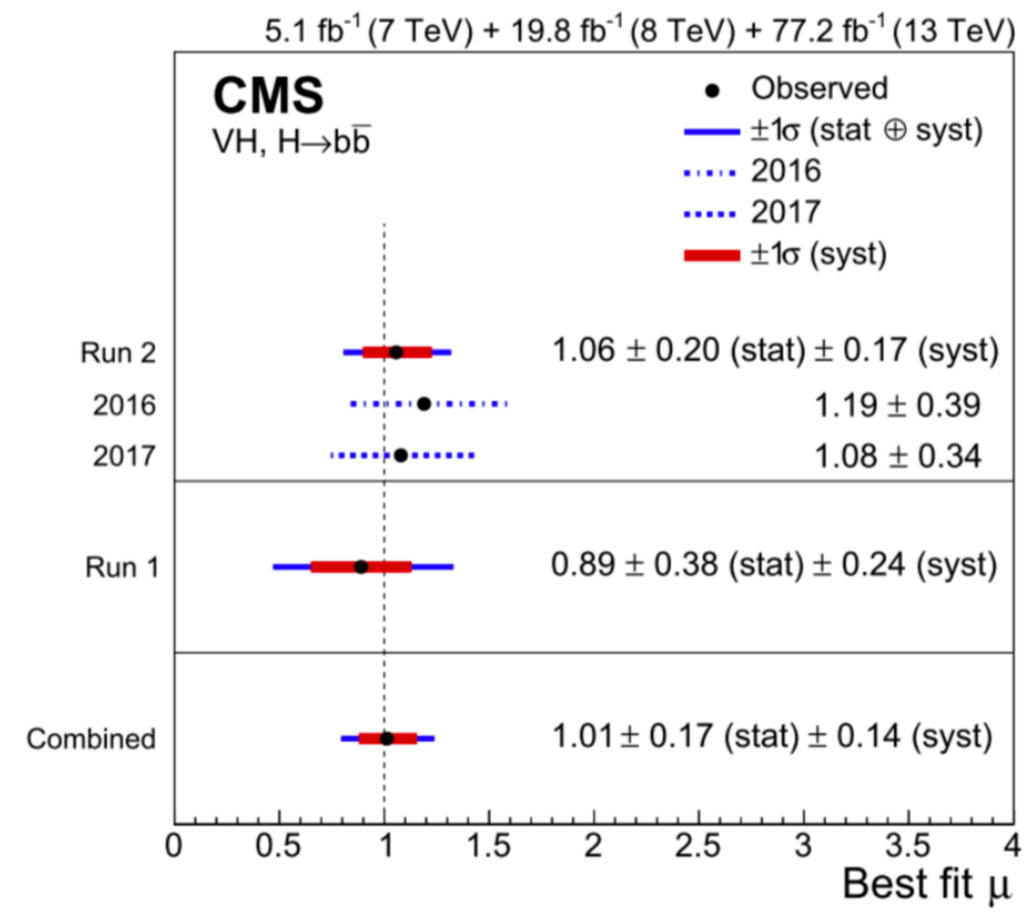


Phys. Rev. Lett. 121, 121801 (2018)

H→bb in CMS
pp→VH Combination

	Significance (σ)		
Data set	Expected	Observed	Signal strength
2017	3.1	3.3	1.08 ± 0.34
Run 2 (2016+2017)	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23

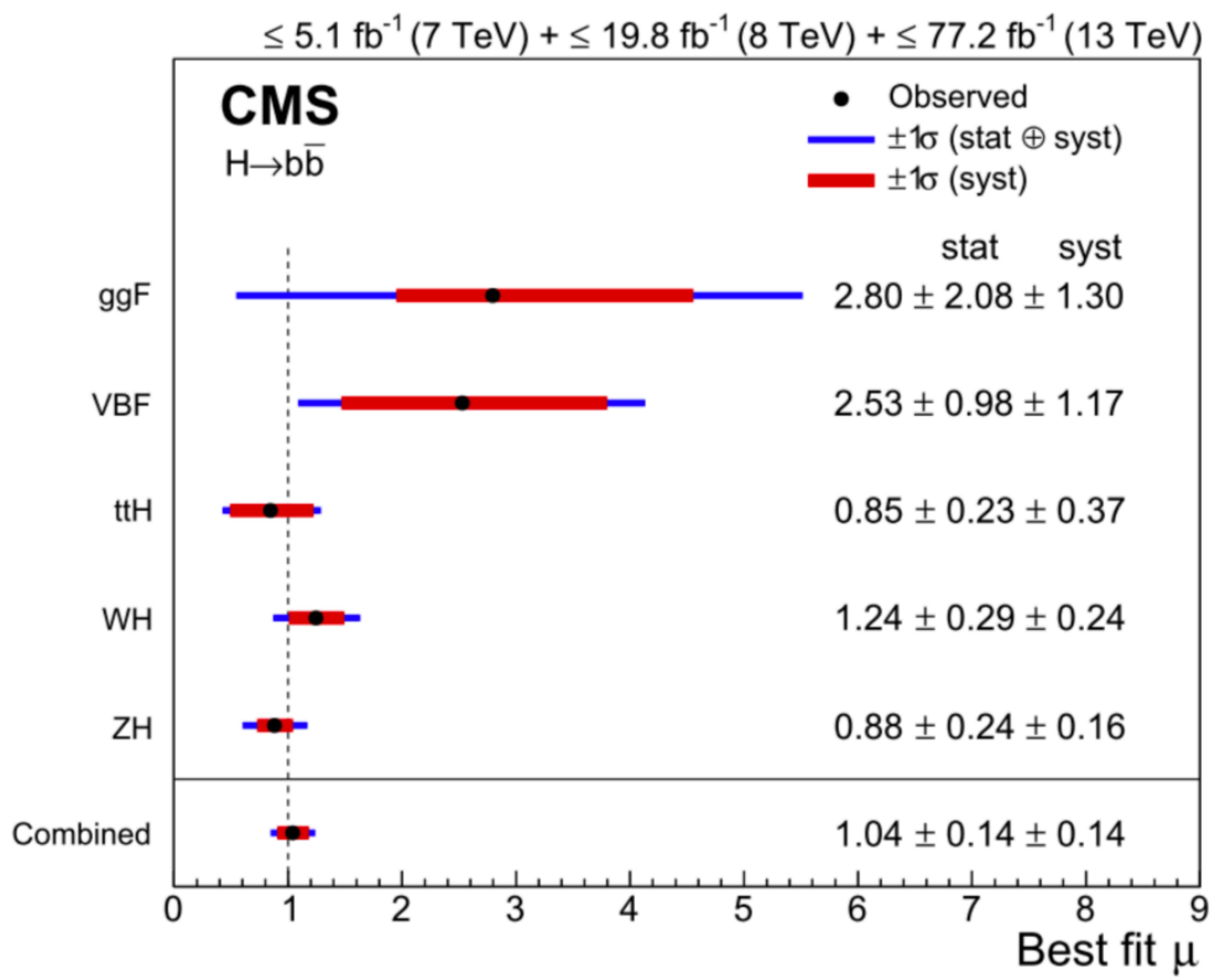




Phys. Rev. Lett. 121, 121801 (2018)

H→bb in CMS

H→bb Combination



Significance

5.5σ expected

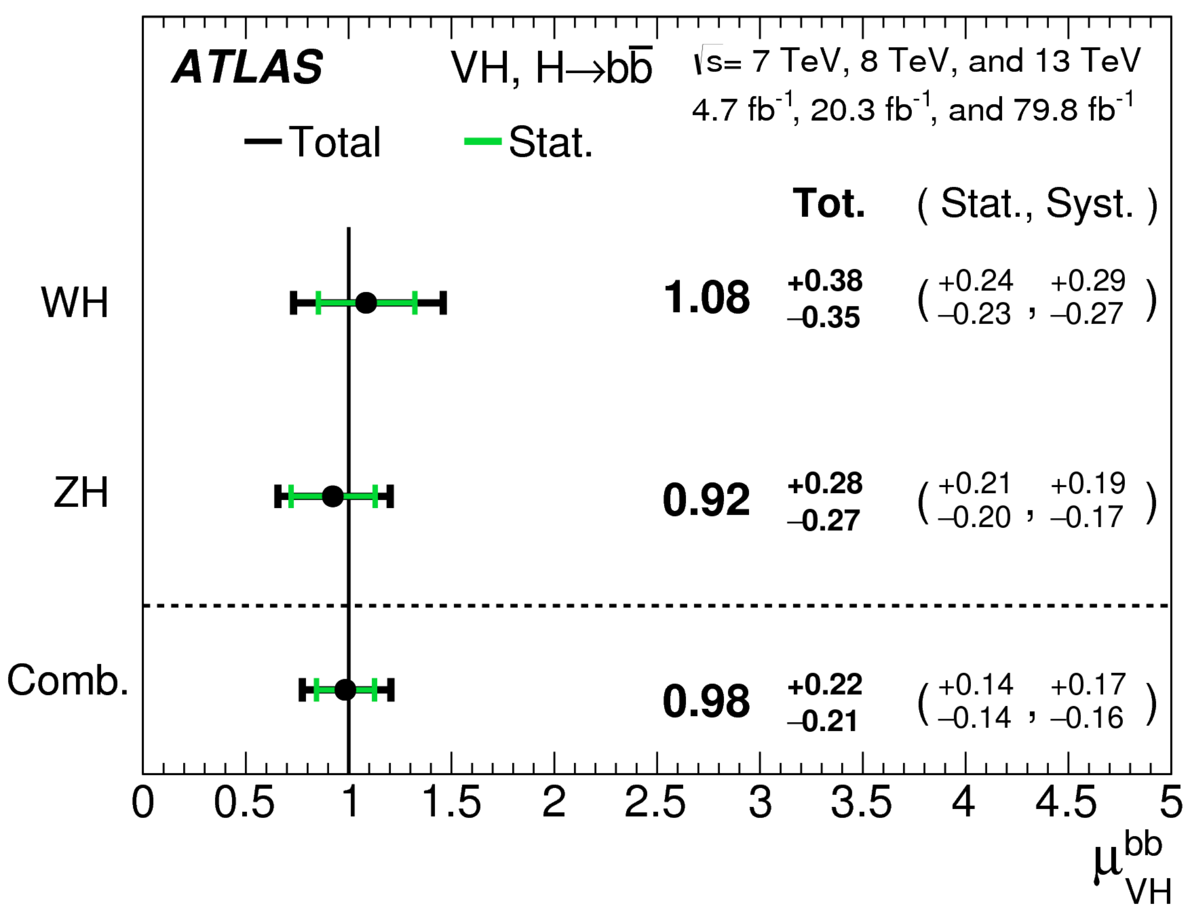
5.6σ observed

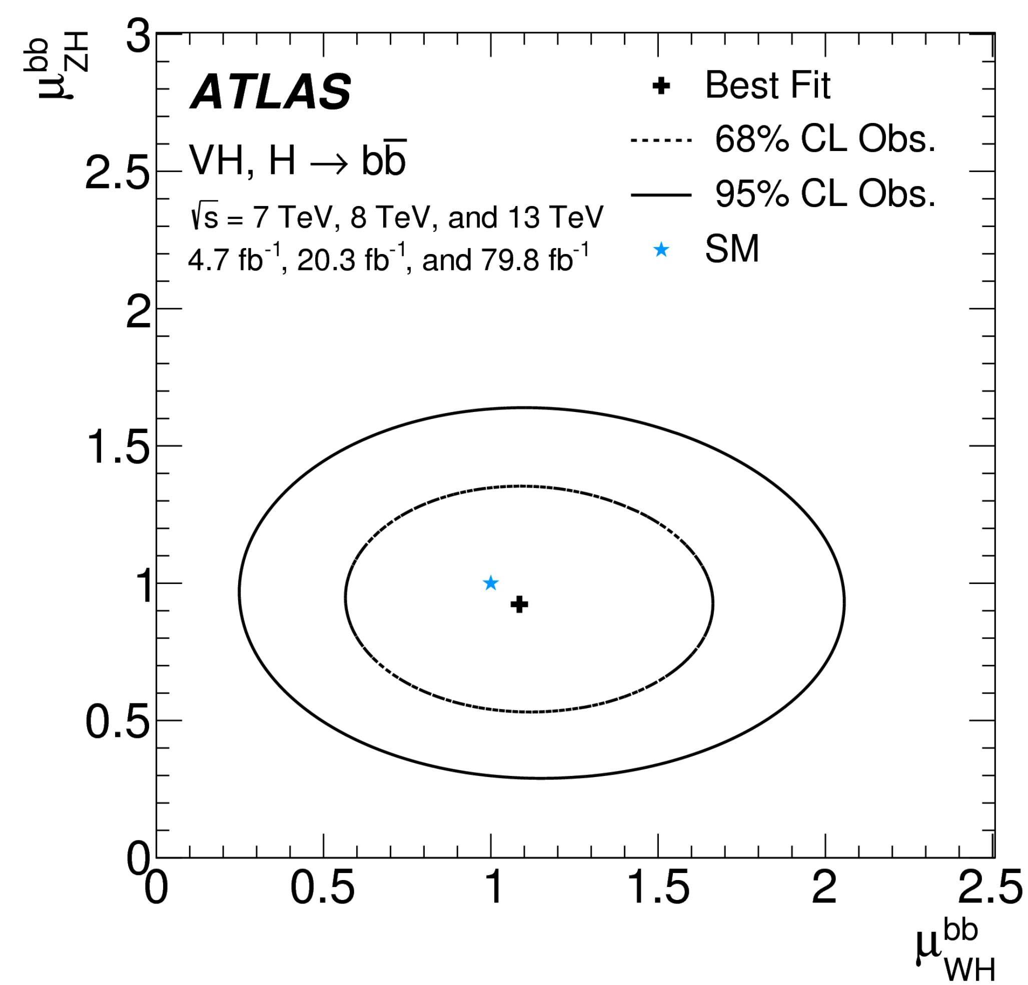
Observation of the H→bb decay by the CMS Collaboration

Combinations

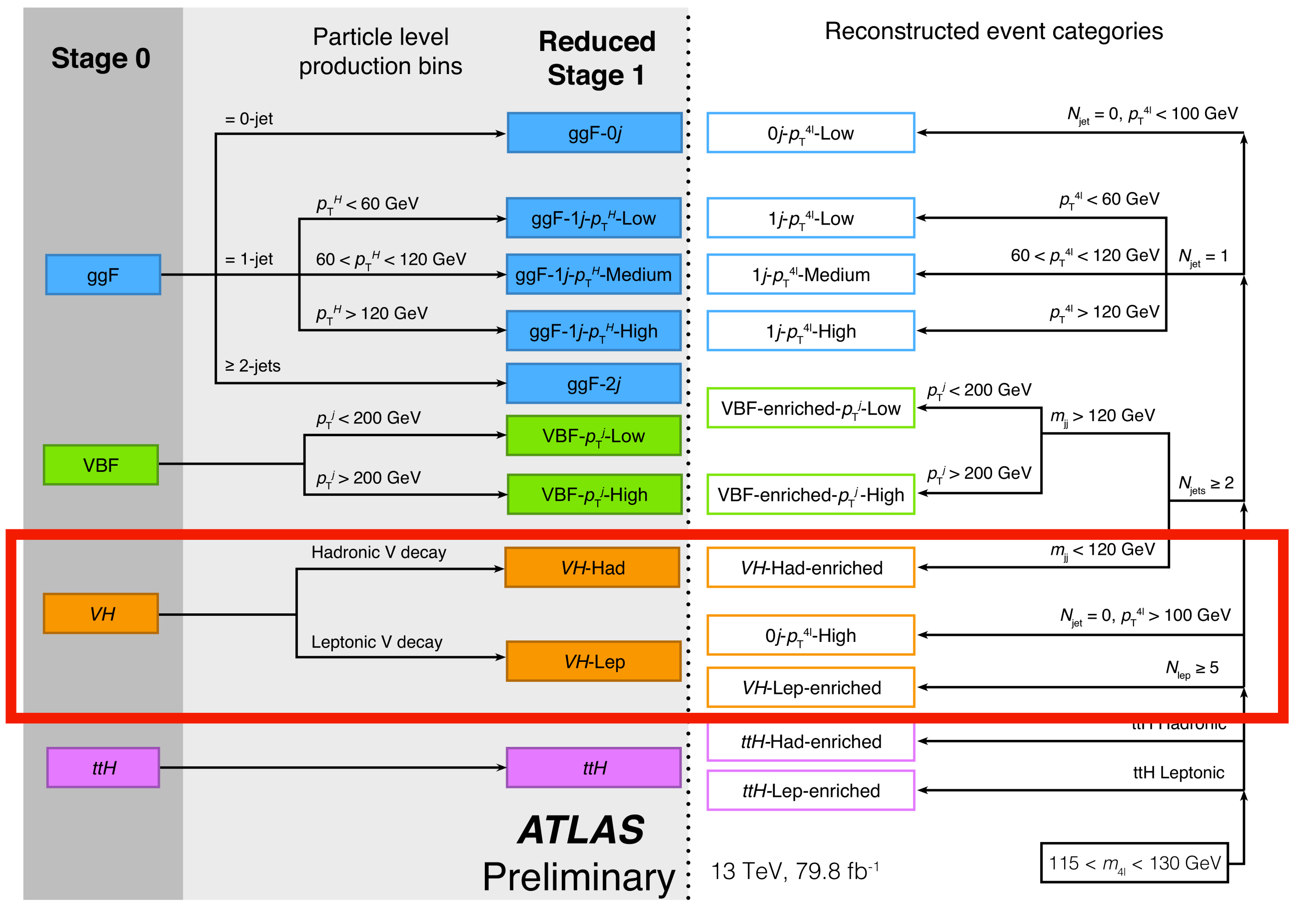
pp→VH, H→bb Run1+Run2 combination

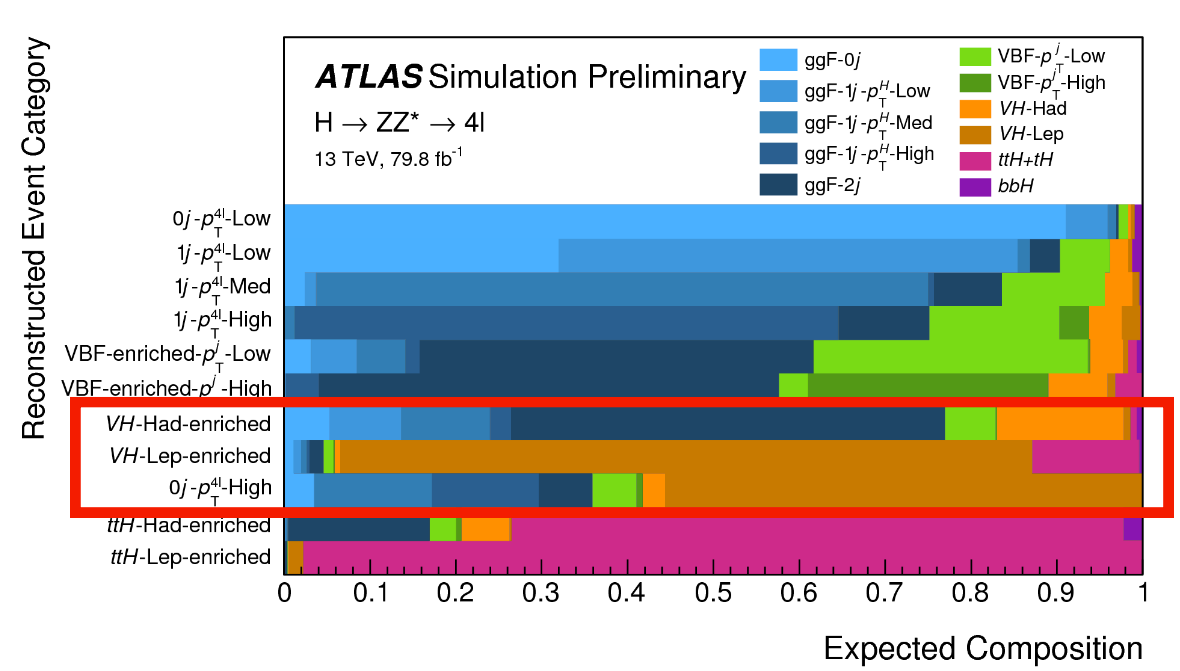
Combination of Run1 and Run2 VH, Hbb searches
Sensitivity: 4.9σ (5.1σ exp)

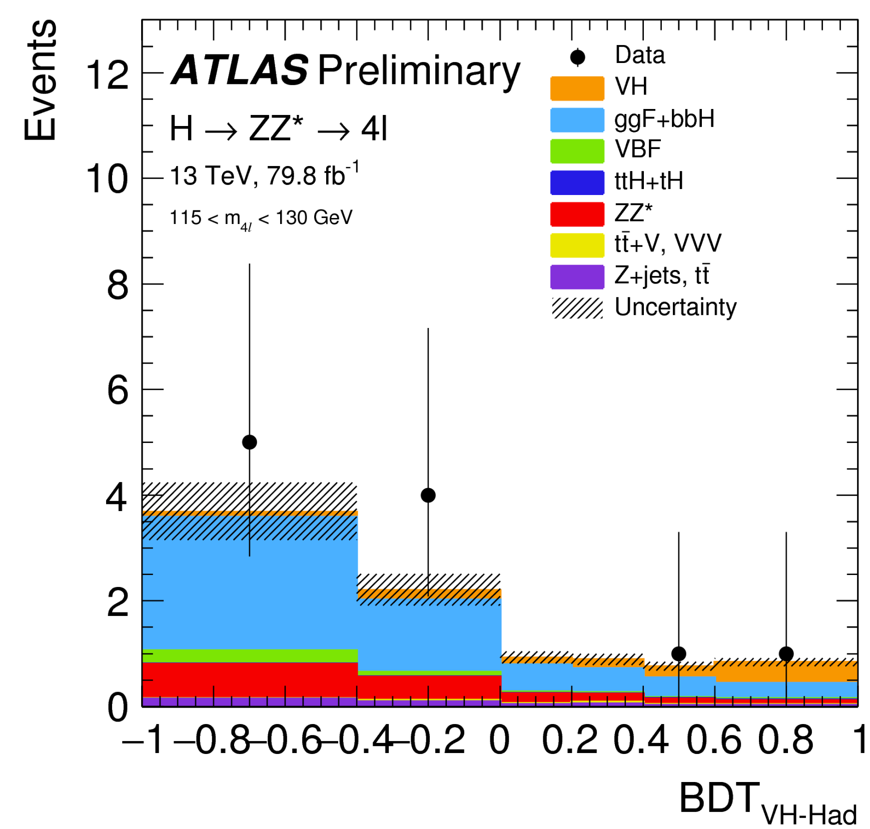




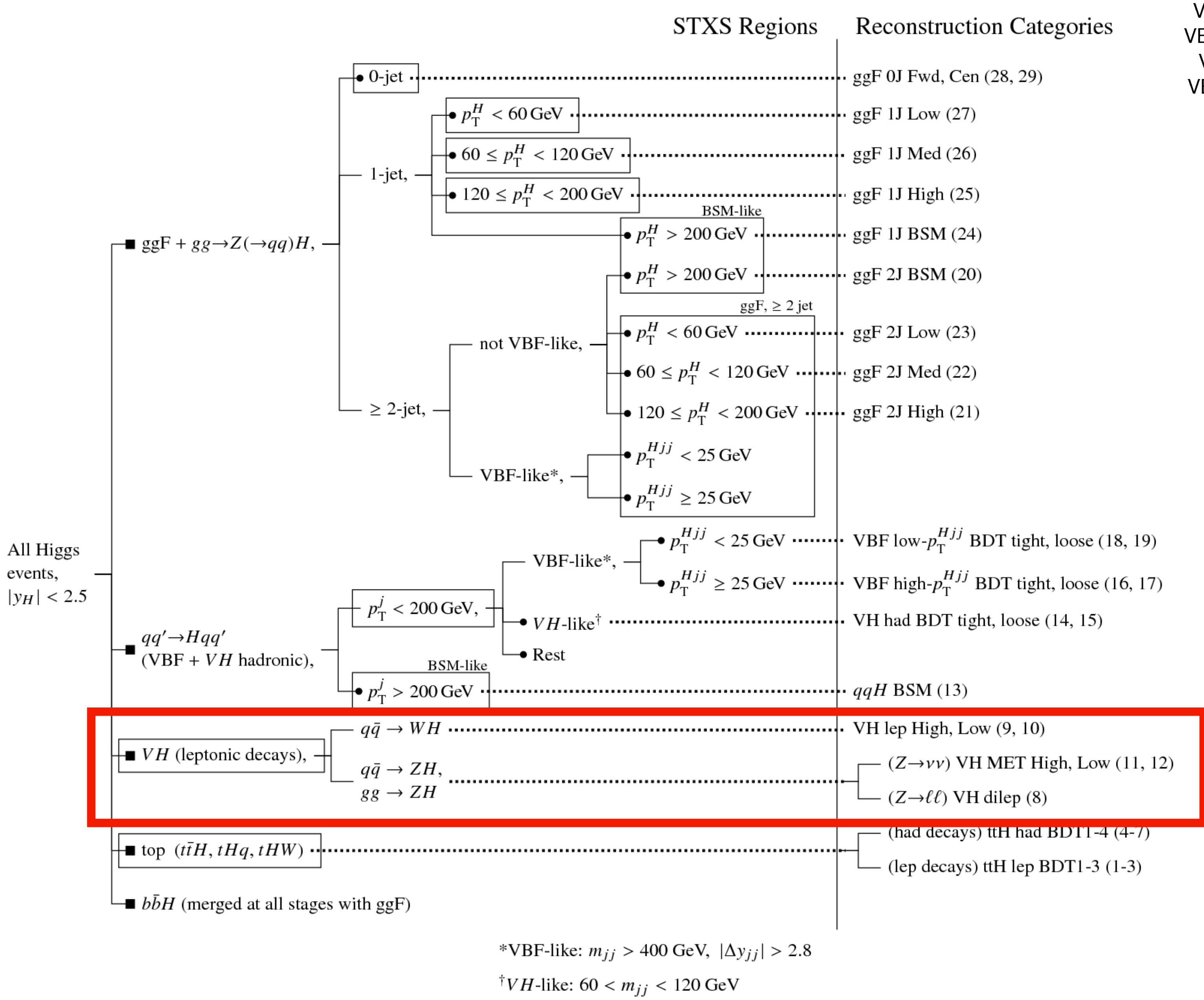
pp→VH, H→4l


Stage 0
Particle level production bins
Reduced Stage 1
Reconstructed event categories
ggF
VBF
VH
ttH
= 0-jet
= 1-jet
≥ 2-jets
ggF-0j
ggF-1j-pTH-Low
ggF-1j-pTH-Medium
ggF-1j-pTH-High
ggF-2j
VBF-pTj-Low
VBF-pTj-High
Hadronic V decay
Leptonic V decay
VH-Had
VH-Lep
ttH
0j-pT4l-Low
1j-pT4l-Low
1j-pT4l-Medium
1j-pT4l-High
VBF-enriched-pTj-Low
VBF-enriched-pTj-High
VH-Had-enriched
0j-pT4l-High
VH-Lep-enriched
ttH-Had-enriched
ttH-Lep-enriched
ttH Leptonic
115 < m4l < 130 GeV
ATLAS Preliminary
13 TeV, 79.8 fb-1

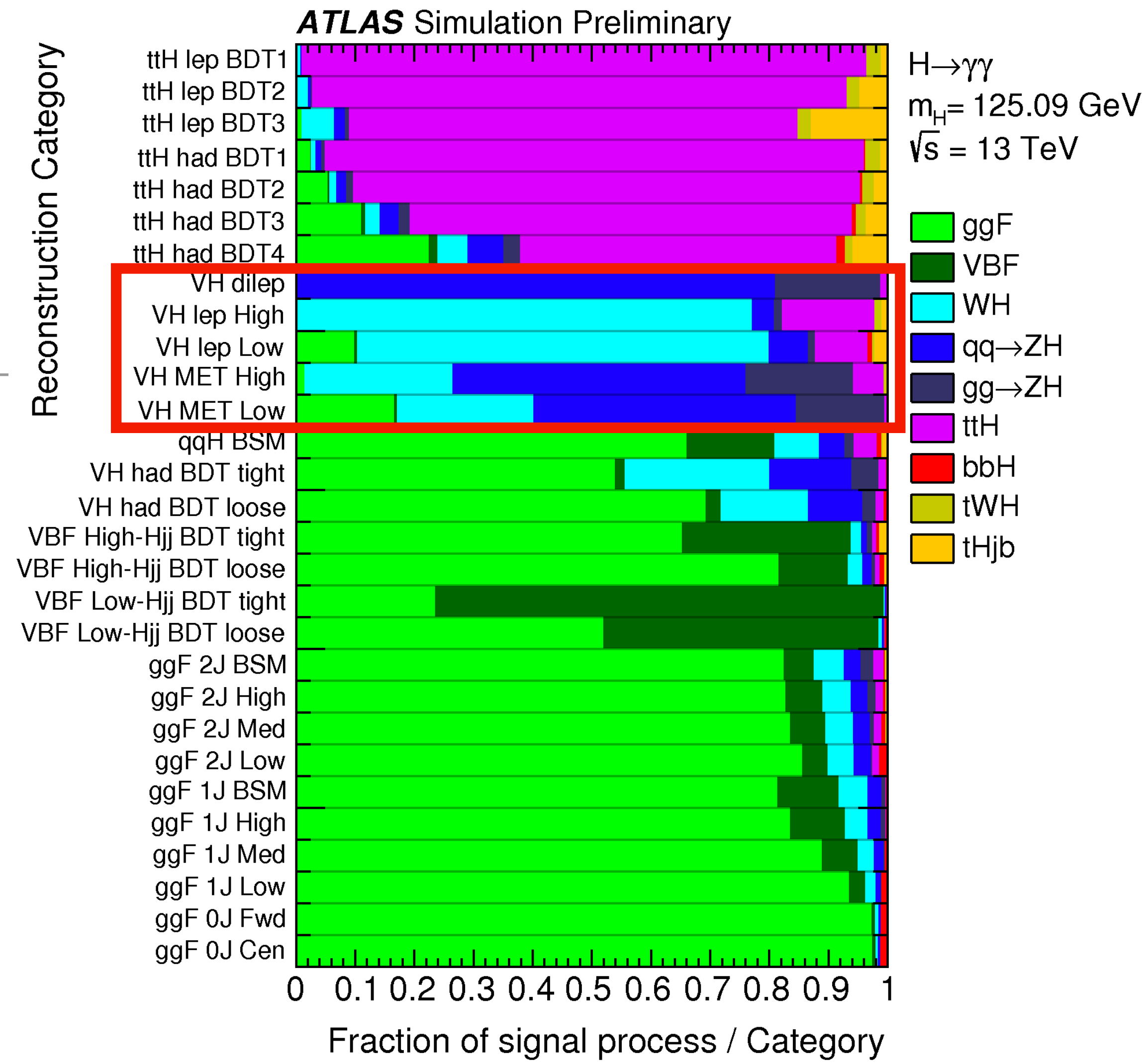

ATLAS Simulation Preliminary
H → ZZ* → 4l
13 TeV, 79.8 fb-1
ggF-0j
ggF-1j-pTH-Low
ggF-1j-pTH-Med
ggF-1j-pTH-High
ggF-2j
VBF-pTj-Low
VBF-pTj-High
VH-Had
VH-Lep
ttH+tH
bbH
Reconstructed Event Category
0j-pT4l-Low
1j-pT4l-Low
1j-pT4l-Med
1j-pT4l-High
VBF-enriched-pTj-Low
VBF-enriched-pTj-High
VH-Had-enriched
VH-Lep-enriched
0j-pT4l-High
ttH-Had-enriched
ttH-Lep-enriched
Expected Composition


ATLAS Preliminary
H → ZZ* → 4l
13 TeV, 79.8 fb-1
115 < m4l < 130 GeV
Data
VH
ggF+bbH
VBF
ttH+tH
ZZ*
tt̄+V, VVV
Z+jets, tt̄
Uncertainty
Events
BDTVH-Had

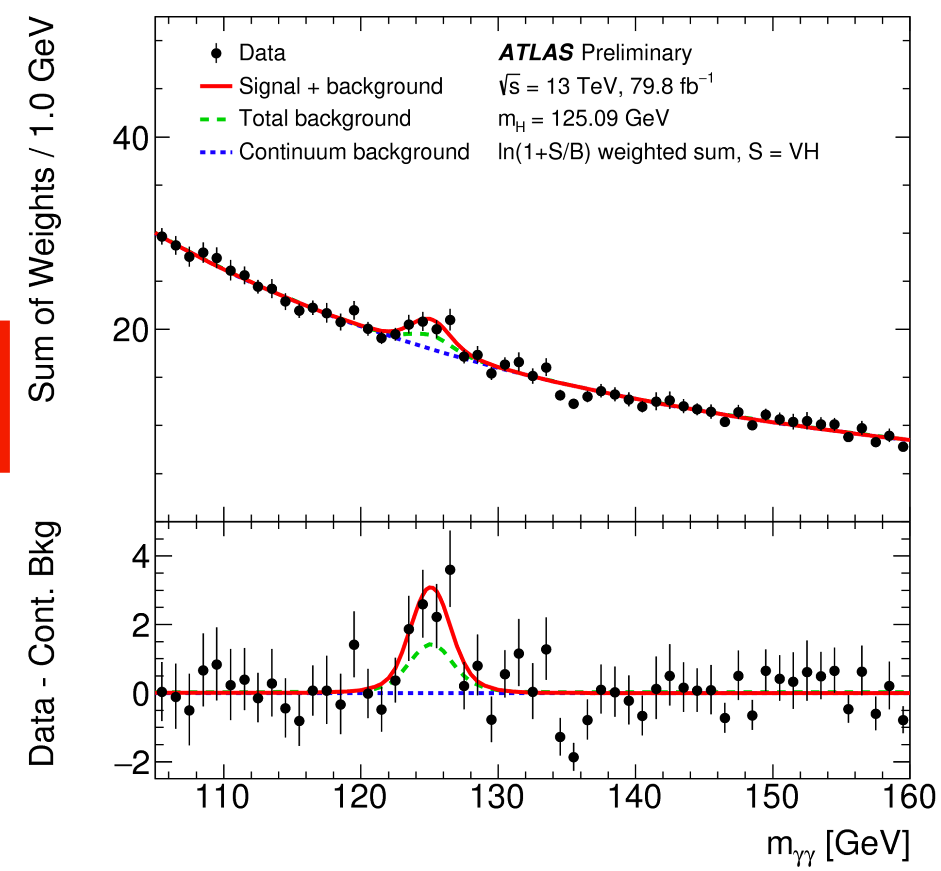
pp→VH, H→γγ



STXS Regions
Reconstruction Categories
All Higgs events, $|y_H| < 2.5$
ggF + $gg \to Z(\to qq)H$,
0-jet
ggF 0J Fwd, Cen (28, 29)
1-jet,
$p_T^H < 60$ GeV
ggF 1J Low (27)
$60 \le p_T^H < 120$ GeV
ggF 1J Med (26)
$120 \le p_T^H < 200$ GeV
ggF 1J High (25)
BSM-like
$p_T^H > 200$ GeV
ggF 1J BSM (24)
$p_T^H > 200$ GeV
ggF 2J BSM (20)
ggF, ≥ 2 jet
≥ 2-jet,
not VBF-like,
$p_T^H < 60$ GeV
ggF 2J Low (23)
$60 \le p_T^H < 120$ GeV
ggF 2J Med (22)
$120 \le p_T^H < 200$ GeV
ggF 2J High (21)
VBF-like*,
$p_T^{Hjj} < 25$ GeV
$p_T^{Hjj} \ge 25$ GeV
$qq' \to Hqq'$ (VBF + VH hadronic),
$p_T^j < 200$ GeV,
VBF-like*,
$p_T^{Hjj} < 25$ GeV
VBF low-p_T^{Hjj} BDT tight, loose (18, 19)
$p_T^{Hjj} \ge 25$ GeV
VBF high-p_T^{Hjj} BDT tight, loose (16, 17)
VH-like†
VH had BDT tight, loose (14, 15)
Rest
BSM-like
$p_T^j > 200$ GeV
qqH BSM (13)
VH (leptonic decays),
$q\bar{q} \to WH$
VH lep High, Low (9, 10)
$q\bar{q} \to ZH$, $gg \to ZH$
$(Z \to \nu\nu)$ VH MET High, Low (11, 12)
$(Z \to \ell\ell)$ VH dilep (8)
top ($t\bar{t}H$, tHq, tHW)
(had decays) ttH had BDT1-4 (4-7)
(lep decays) ttH lep BDT1-3 (1-3)
$b\bar{b}H$ (merged at all stages with ggF)
*VBF-like: $m_{jj} > 400$ GeV, $|\Delta y_{jj}| > 2.8$
†VH-like: $60 < m_{jj} < 120$ GeV

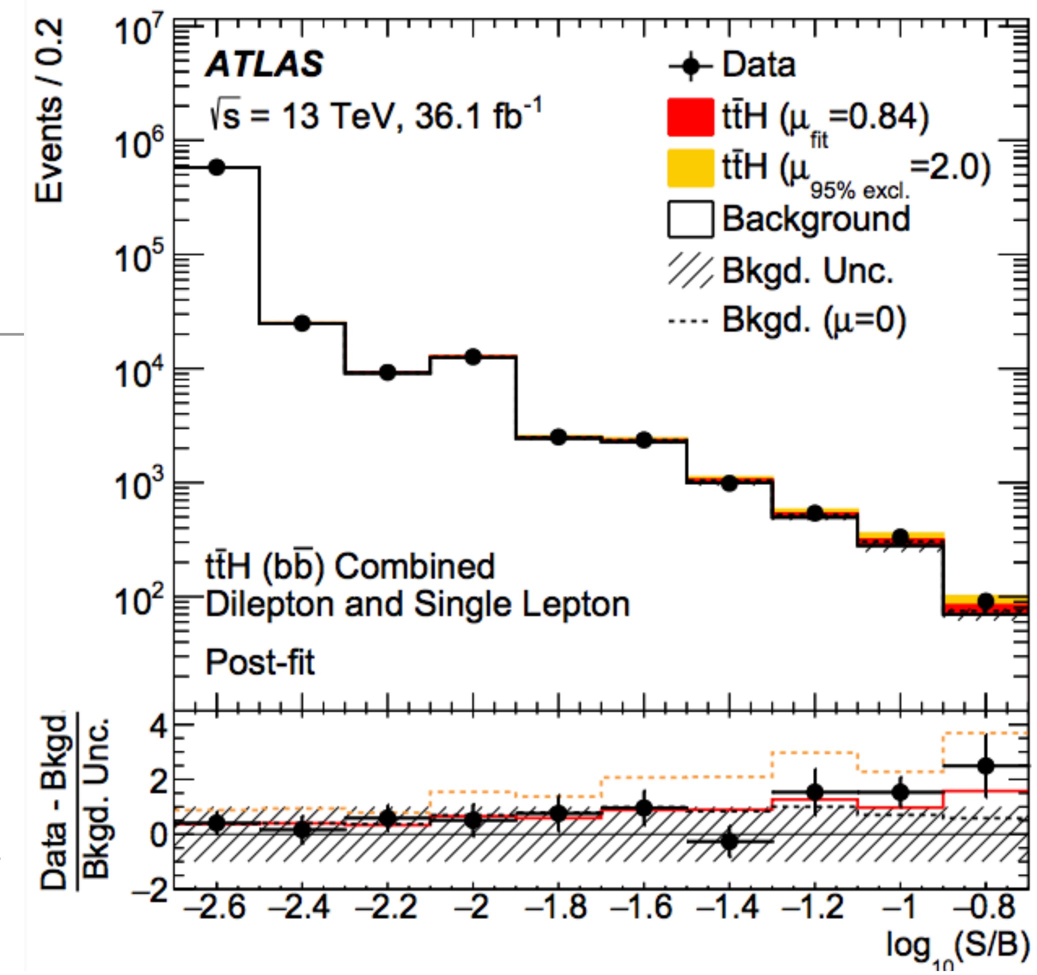


ATLAS Simulation Preliminary
H→γγ
m_H= 125.09 GeV
$\sqrt{s}$ = 13 TeV
Reconstruction Category
ttH lep BDT1
ttH lep BDT2
ttH lep BDT3
ttH had BDT1
ttH had BDT2
ttH had BDT3
ttH had BDT4
VH dilep
VH lep High
VH lep Low
VH MET High
VH MET Low
qqH BSM
VH had BDT tight
VH had BDT loose
VBF High-Hjj BDT tight
VBF High-Hjj BDT loose
VBF Low-Hjj BDT tight
VBF Low-Hjj BDT loose
ggF 2J BSM
ggF 2J High
ggF 2J Med
ggF 2J Low
ggF 1J BSM
ggF 1J High
ggF 1J Med
ggF 1J Low
ggF 0J Fwd
ggF 0J Cen
ggF
VBF
WH
qq→ZH
gg→ZH
ttH
bbH
tWH
tHjb
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Fraction of signal process / Category



Data
Signal + background
Total background
Continuum background
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 79.8 fb^{-1}
m_H = 125.09 GeV
ln(1+S/B) weighted sum, S = VH
Sum of Weights / 1.0 GeV
40
20
Data - Cont. Bkg
4
2
0
−2
110 120 130 140 150 160
$m_{\gamma\gamma}$ [GeV]

ttH, H→bb in Run2

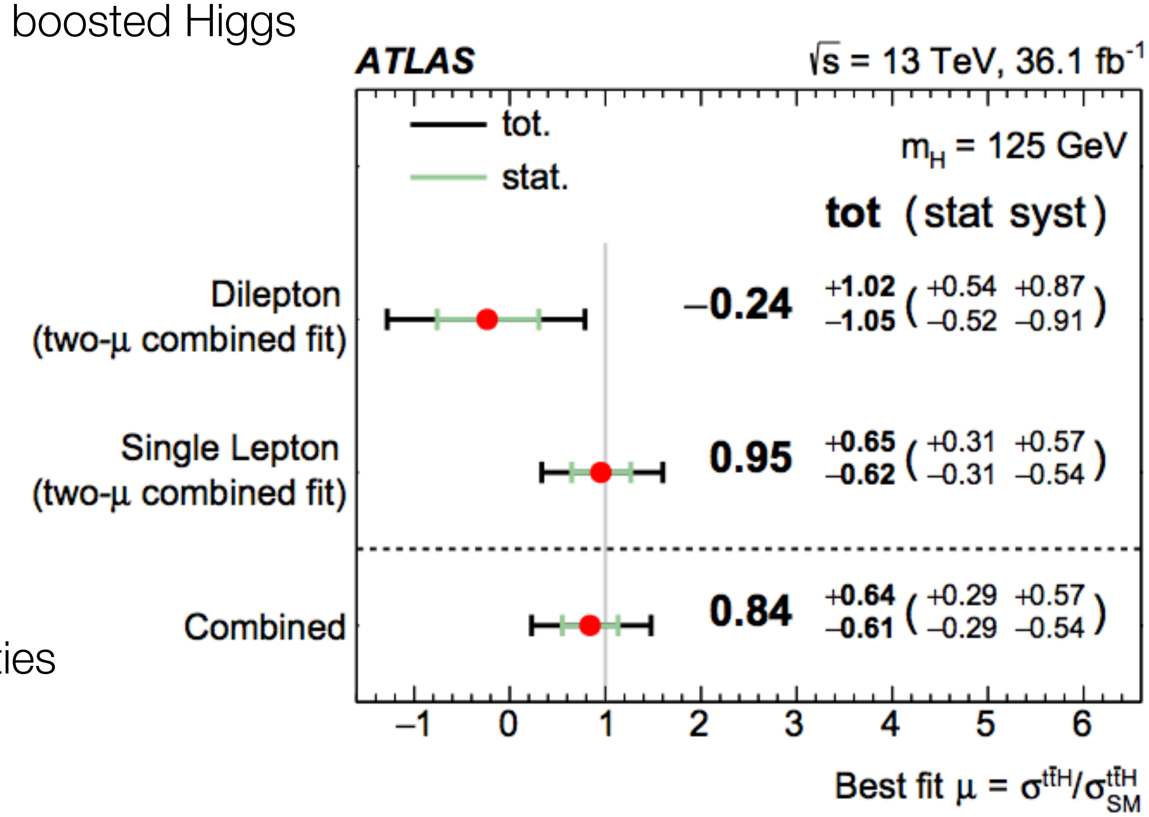


Run-2 Analysis

- Semi-leptonic and di-leptonic tt decays
- Many jets and b-jets in final state
- Use of powerful ML techniques
    - to resolve the combinatorics: best matching of jets to W, top, Higgs
    - final classification BDT to separate ttH from backgrounds
- Simultaneous fit of 9 SR and 110 CR, including a category with boosted Higgs

Results:

- μ= 0.84 +0.64 - 0.61
- Sensitivity 1.4σ (1.6σ exp)
    - Correspond to a limit of 2 SM
- Large impact from the tt+bb modelling
- Also quite sensitive to b-tagging and jet energy scale uncertainties



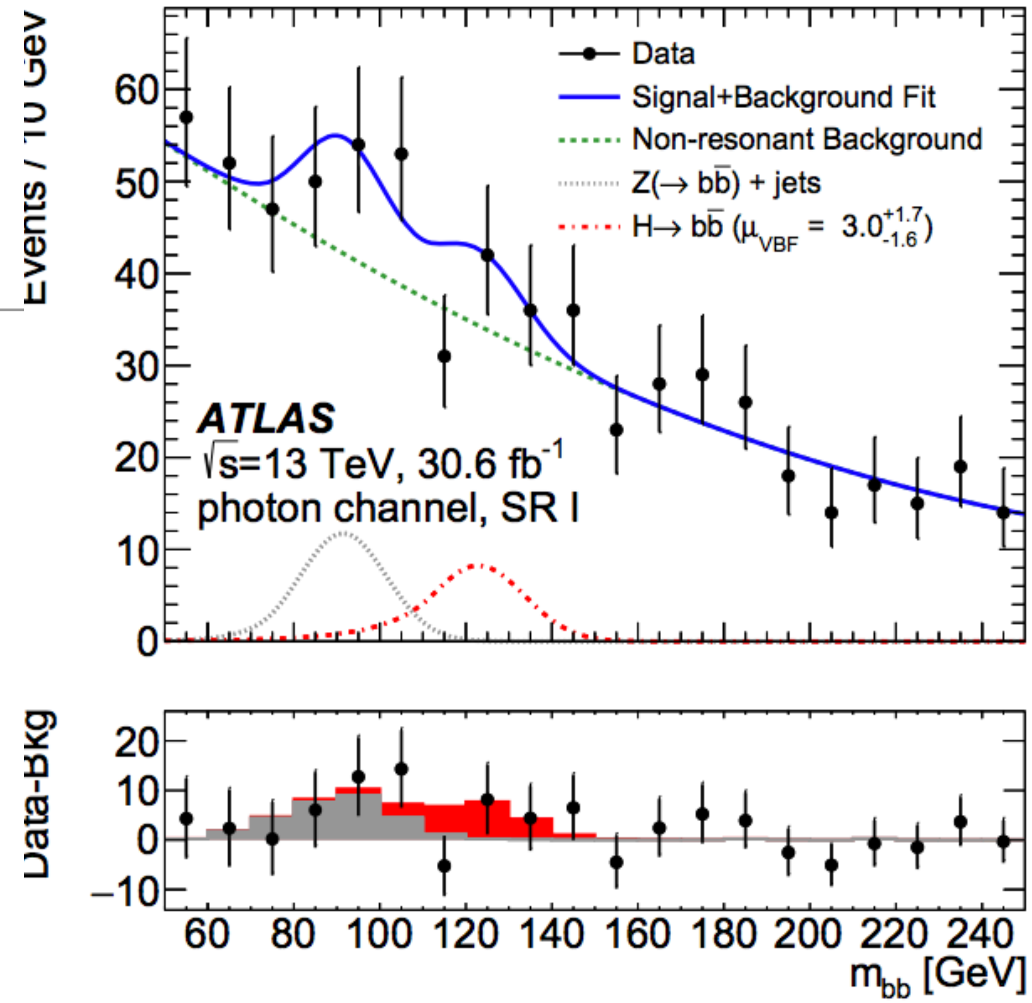
VBF, H→bb in Run2

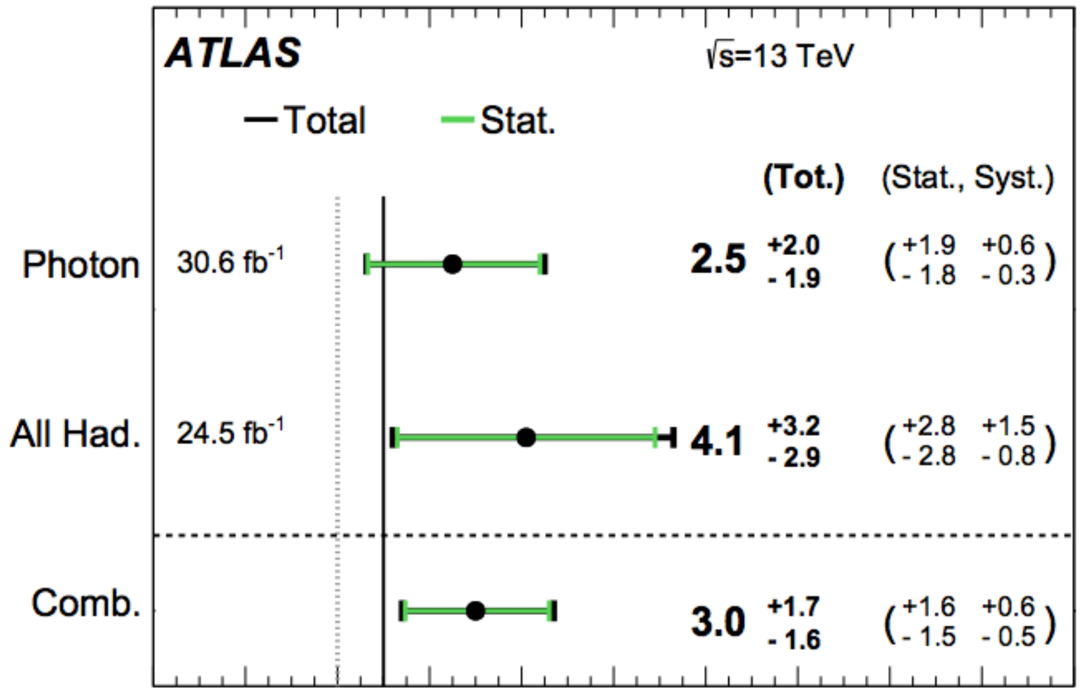
Run-2 Analysis

- Use both inclusive and exclusive VBF+γ categories
    - Exclusive final state: better S/B, higher trigger efficiency
    - Inclusive category further split depending on number of central jets
- BDTs using kinematic variables uncorrelated with H mass to categorise in S/B
- Then simultaneous fit of 9 m_{bb} distributions

Results

- μ=3.0+1.7-1.6
- Sensitivity 1.9σ (0.7σ exp)
- Sensitivity limited by data statistics (especially in VBF+γ)

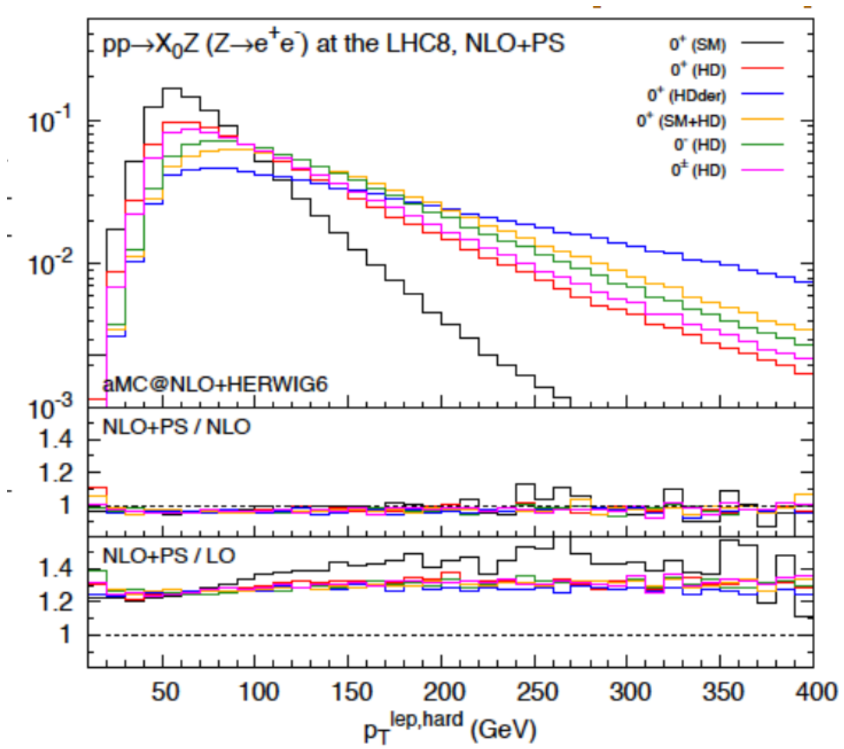




VH - EFT

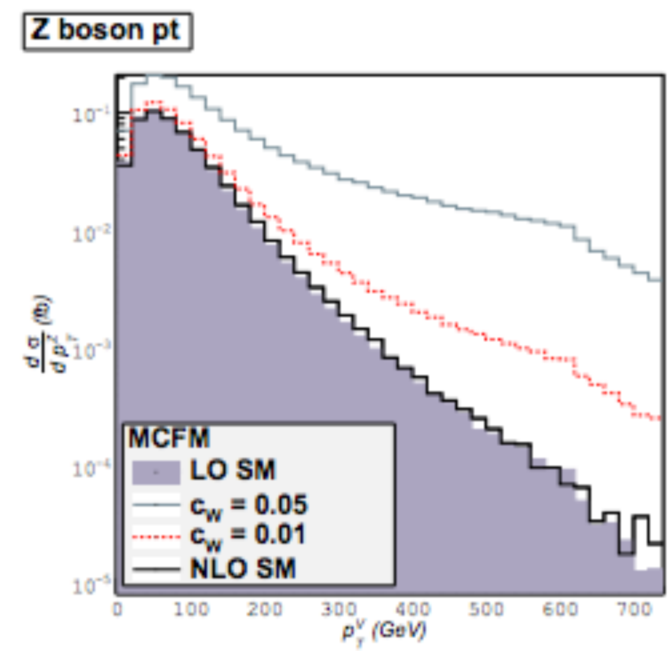
Deviations from SM

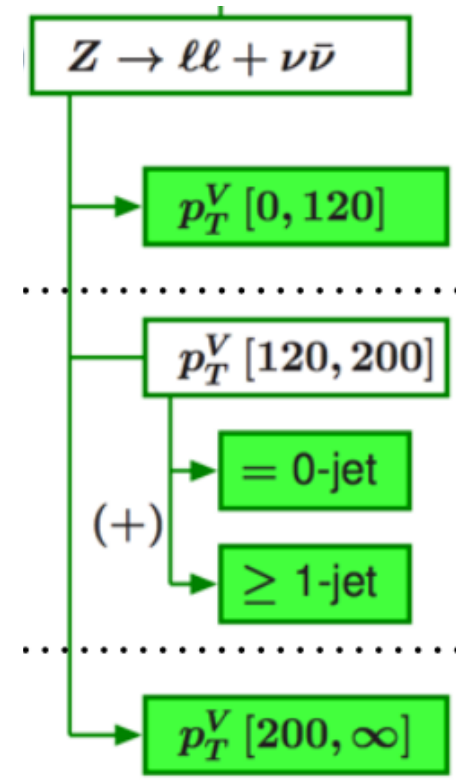
Higgs characterisation
EPJC74 (2014) 1, 2710 Maltoni, Mawatari, Zaro



$$
\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\big] \\
& - \tfrac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\
& - \tfrac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\
& - \tfrac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\big] \\
& - \tfrac{1}{4}\tfrac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\big] \\
& - \tfrac{1}{2}\tfrac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\big] \\
& - \tfrac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, A_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} \\
& \qquad + \big(\kappa_{H\partial W} W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.\big)\big]\Big\} X_0 \,, \qquad (1)
\end{aligned}
$$

Complete Higgs Sector Constraints on Dimension-6 Operators (just using *Vh*)
JHEP07(2014)036 - Ellis, Sanz, You





Measure the effect with:

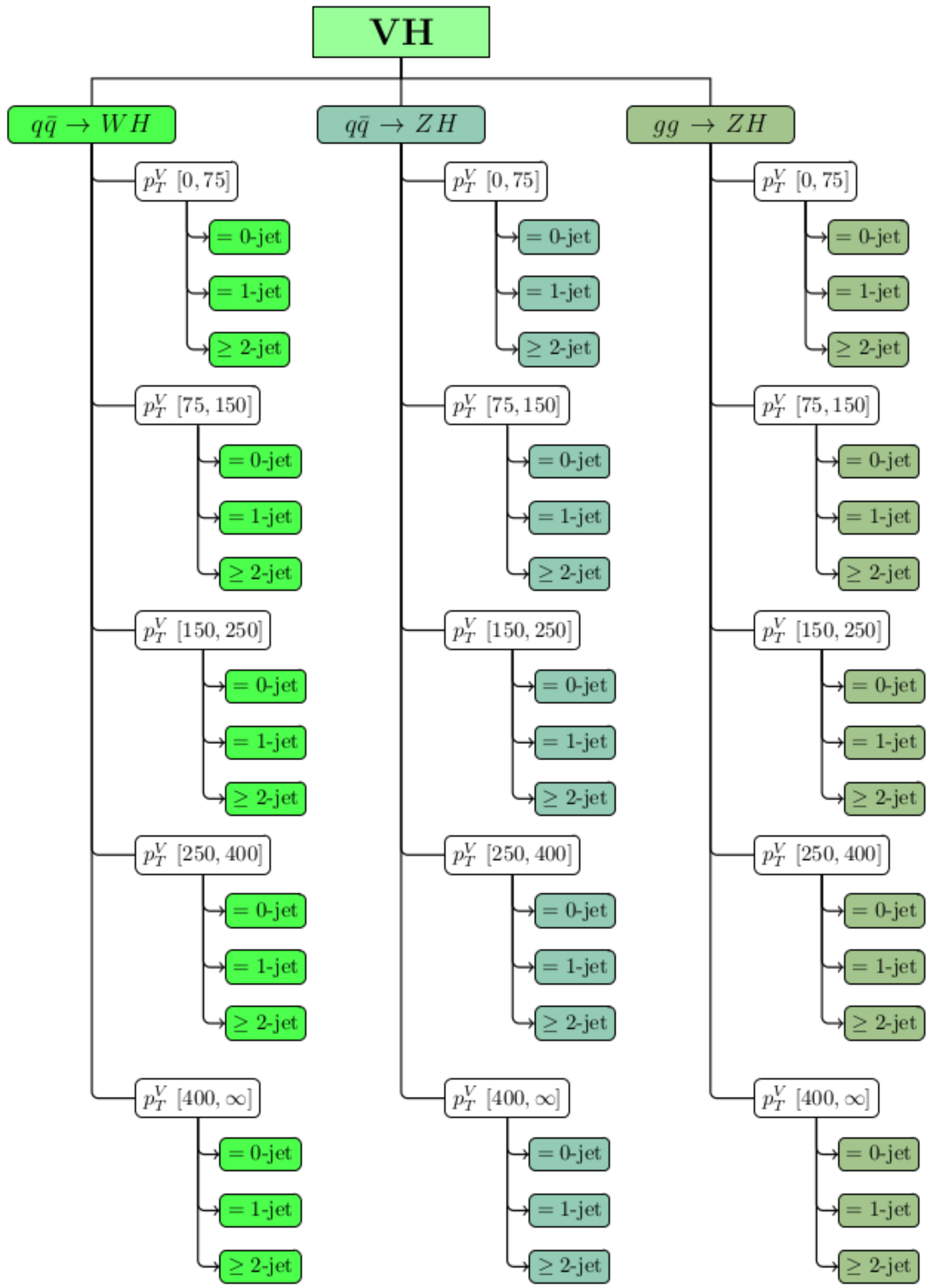
a) differential fiducial cross sections (not easy for H→bb)

b) differential simplified cross sections (the challenge)
- discussed in LH2015, in YR4, first results at LHC

c) Use of pseudo-observables (a la LEP) -
Greljo,Isidori,Lindert,Marzocca ZU-TH-47-15

d) Report constrains and limits on coefficients of HEFT Dim-6 operators
- different tools already available.

STXS: the ultimate splitting



We will not measure all these bins, but they can be used to develop a model of the signal TH systematics which can be treated in the measurements

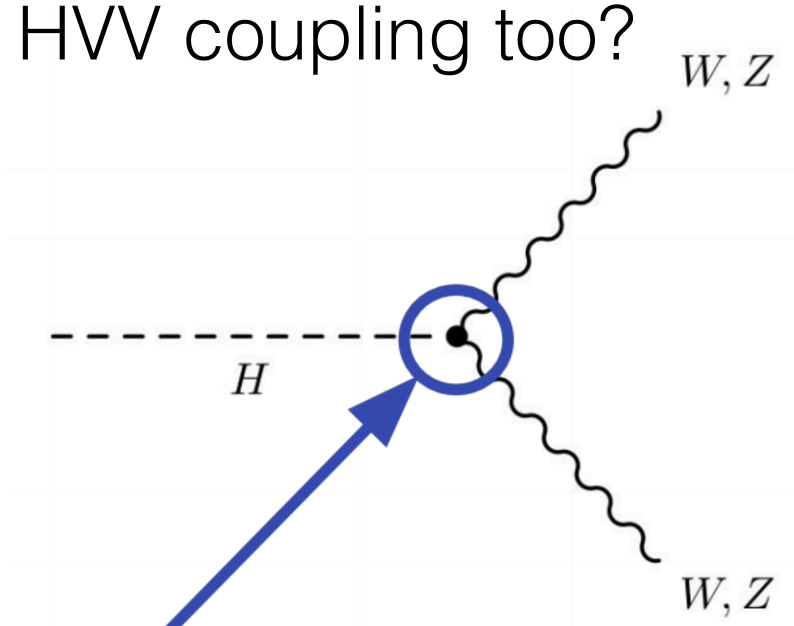
Deviation from the SM - HEFT

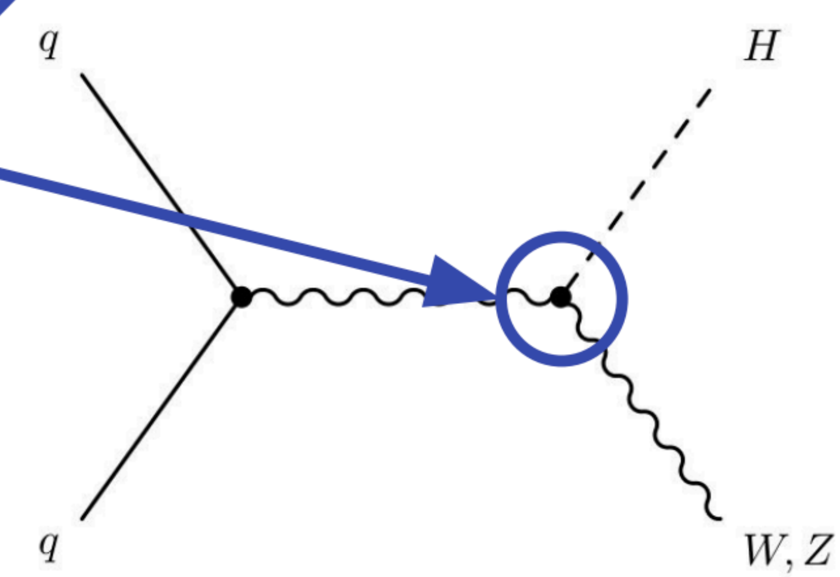
Will it change the HVV coupling too?

$$\mathcal{L}_{BSM} \xrightarrow[(E \ll M)]{} \mathcal{L}_{\text{eff}} \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots$$

$$\mathcal{L}_6 = \sum_i c_i \frac{\mathcal{O}_i}{M^2}$$

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





HEFT and STXS

- Since the bins of the STXS are pre-defined, we can calculate the expected variations due to the presence of dim6 operators:

- Master formula: σ(c$_i$)=σ^{SM} (1+$\Sigma_i A_i c_i$+ $\Sigma_{ij} B_{ij} c_i c_j$)

interference   pure BSM*

Cross-section region	$\sum_i A_i c_i$
$q\bar{q} \to Hl\nu$ ($p_T^V < 150$ GeV)	$-1.0\text{cH} + 34\text{cWW} + 11\text{cHW} + 24\text{cpHQ} + 2.0\text{cpHL}$
$q\bar{q} \to Hl\nu$ ($150 \leq p_T^V < 250$ GeV, 0 jets)	$-1.0\text{cH} + 76\text{cWW} + 51\text{cHW} + 67\text{cpHQ} + 2.0\text{cpHL}$
$q\bar{q} \to Hl\nu$ ($150 \leq p_T^V < 250$ GeV, ≥ 1 jet)	$-1.0\text{cH} + 71\text{cWW} + 46\text{cHW} + 61\text{cpHQ} + 2.0\text{cpHL}$
$q\bar{q} \to Hl\nu$ ($p_T^V \geq 250$ GeV)	$-1.0\text{cH} + 200\text{cWW} + 170\text{cHW} + 190\text{cpHQ} + 2.0\text{cpHL}$
$q\bar{q} \to Hll$ ($p_T^V < 150$ GeV)	$-1.0\text{cH} - 4.0\text{cT} + 30\text{cWW} + 8.4\text{cB} + 8.5\text{cHW}$ $+2.5\text{cHB} + 0.032c_\gamma - 1.9\text{cHQ} + 23\text{cpHQ} + 5.2\text{cHu}$ $-2.0\text{cHd} - 0.96\text{cHL} + 2.0\text{cpHL} - 0.23\text{cHe}$
$q\bar{q} \to Hll$ ($150 \leq p_T^V < 250$ GeV, 0 jets)	$-1.0\text{cH} - 4.0\text{cT} + 62\text{cWW} + 18\text{cB} + 38\text{cHW}$ $+11\text{cHB} - 5.0\text{cHQ} + 61\text{cpHQ} + 14\text{cHu} - 5.2\text{cHd}$ $-0.98\text{cHL} + 2.1\text{cpHL} - 0.23\text{cHe}$
$q\bar{q} \to Hll$ ($150 \leq p_T^V < 250$ GeV, ≥ 1 jet)	$-1.0\text{cH} - 4.0\text{cT} + 58\text{cWW} + 17\text{cB} + 33\text{cHW}$ $+9.9\text{cHB} - 4.6\text{cHQ} + 56\text{cpHQ} + 14\text{cHu} - 4.6\text{cHd}$ $-0.99\text{cHL} + 2.1\text{cpHL} - 0.24\text{cHe}$
$q\bar{q} \to Hll$ ($p_T^V \geq 250$ GeV)	$-1.0\text{cH} - 4.0\text{cT} + 150\text{cWW} + 46\text{cB} + 130\text{cHW}$ $+38\text{cHB} - 14\text{cHQ} + 170\text{cpHQ} + 42\text{cHu} - 14\text{cHd}$ $-0.98\text{cHL} + 2.1\text{cpHL} - 0.24\text{cHe}$

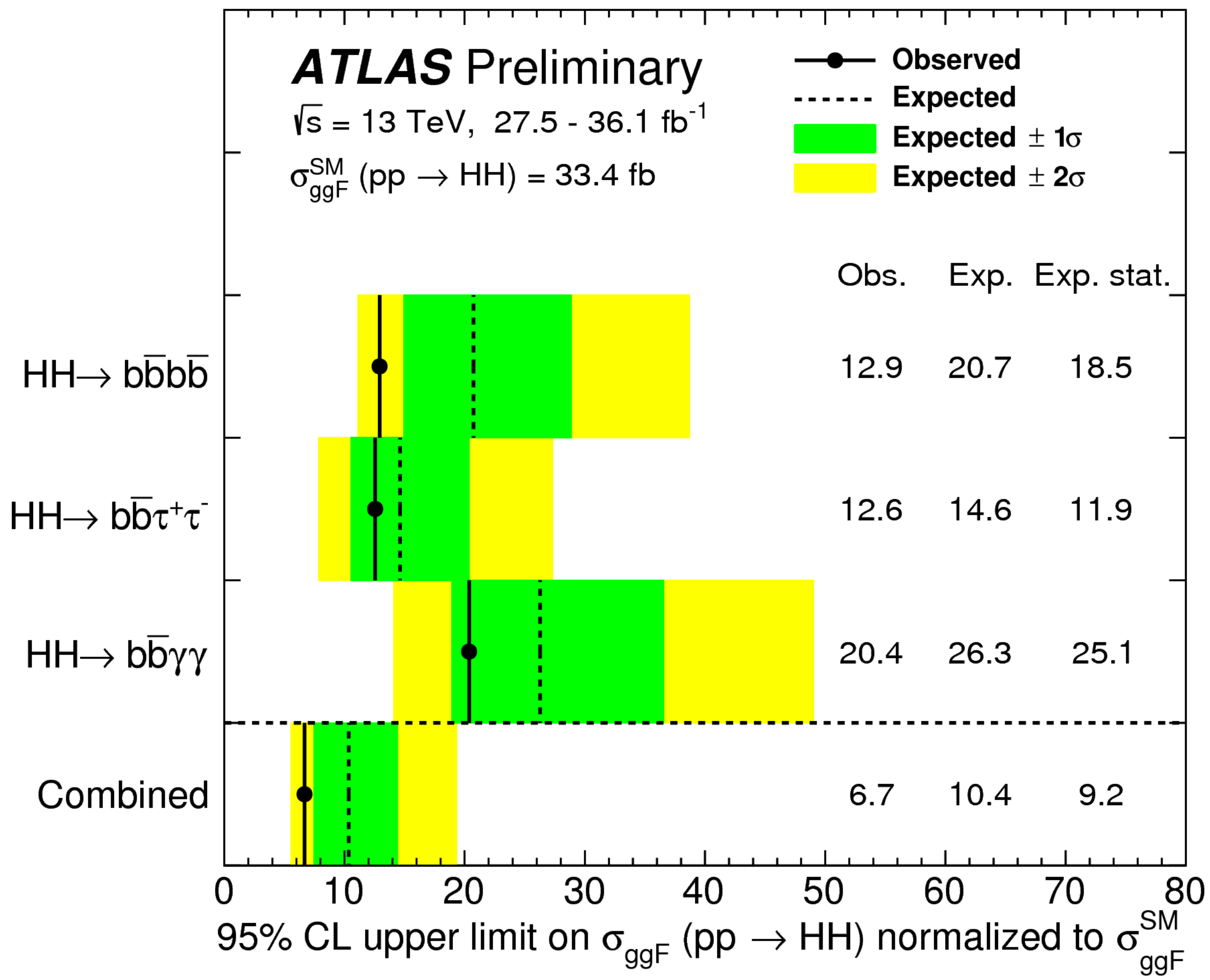
Deviation from the SM: CP odd operators

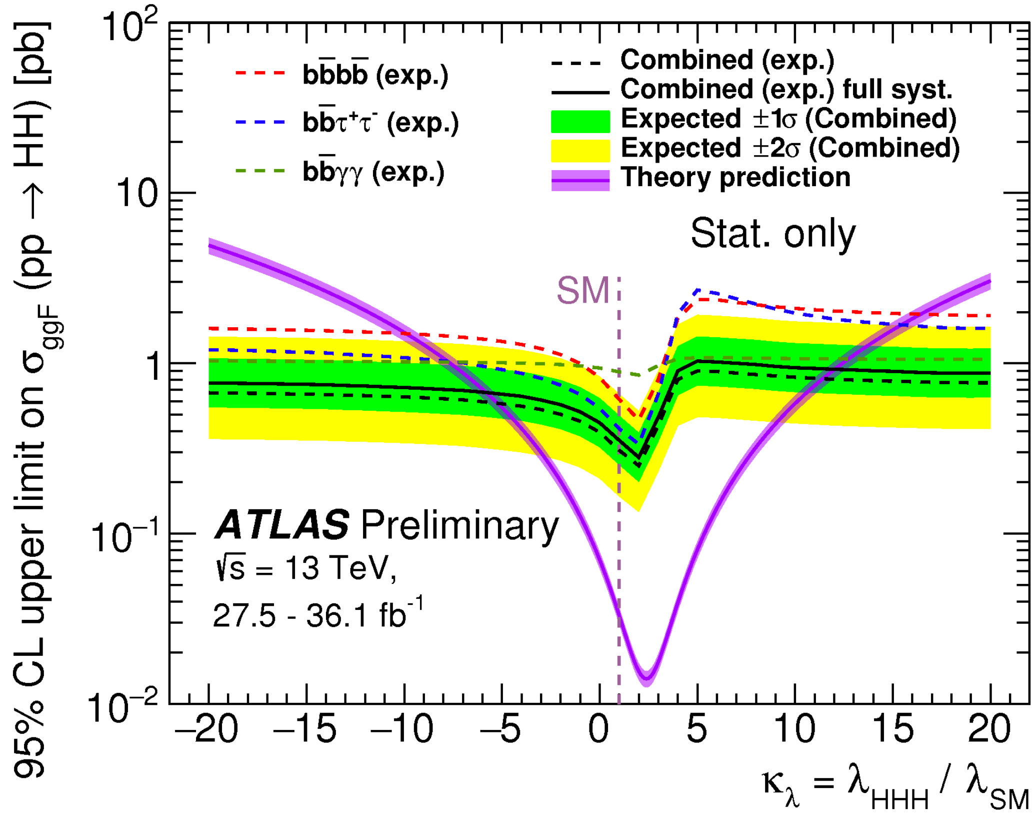
- 15 operators affect Higgs physics
  - 4 are CP odd
- These are usually neglected in STXS interpretations
  - Effects are degenerate with the one due to the other operators for these observables
- Studies on dedicated observables on-going

HEL operator	Coefficient
$\mathcal{O}_g = \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\frac{c_g}{\Lambda^2} = \frac{g_s^2}{m_W^2}$ cG
$\tilde{\mathcal{O}}_g = \lvert H\rvert^2 G^A_{\mu\nu} \tilde{G}^{A\mu\nu}$	$\frac{\tilde{c}_g}{\Lambda^2} = \frac{g_s^2}{m_W^2}$ tcG
$\mathcal{O}_\gamma = \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\frac{c_\gamma}{\Lambda^2} = \frac{g'^2}{m_W^2}$ cA
$\tilde{\mathcal{O}}_\gamma = \lvert H\rvert^2 B_{\mu\nu} \tilde{B}^{\mu\nu}$	$\frac{\tilde{c}_\gamma}{\Lambda^2} = \frac{g'^2}{m_W^2}$ tcA
$\mathcal{O}_u = y_u \lvert H\rvert^2 \bar{Q}_L H^\dagger u_R + \text{h.c.}$	$\frac{c_u}{\Lambda^2} = \frac{\text{cu}}{v^2}$
$\mathcal{O}_d = y_d \lvert H\rvert^2 \bar{Q}_L H d_R + \text{h.c.}$	$\frac{c_d}{\Lambda^2} = \frac{\text{cd}}{v^2}$
$\mathcal{O}_\ell = y_\ell \lvert H\rvert^2 \bar{L}_L H \ell_R + \text{h.c.}$	$\frac{c_\ell}{\Lambda^2} = \frac{\text{cl}}{v^2}$
$\mathcal{O}_H = \frac{1}{2}\left(\partial^\mu \lvert H\rvert^2\right)^2$	$\frac{c_H}{\Lambda^2} = \frac{\text{cH}}{v^2}$
$\mathcal{O}_6 = \left(H^\dagger H\right)^3$	$\frac{c_6}{\Lambda^2} = \frac{\lambda}{v^2}$ c6
$\mathcal{O}_{HW} = i\,(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\frac{c_{HW}}{\Lambda^2} = \frac{g}{m_W^2}$ cHW
$\tilde{\mathcal{O}}_{HW} = i\,(D^\mu H)^\dagger \sigma^a (D^\nu H) \tilde{W}^a_{\mu\nu}$	$\frac{\tilde{c}_{HW}}{\Lambda^2} = \frac{g}{m_W^2}$ tcHW
$\mathcal{O}_{HB} = i\,(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\frac{c_{HB}}{\Lambda^2} = \frac{g'}{m_W^2}$ cHB
$\tilde{\mathcal{O}}_{HB} = i\,(D^\mu H)^\dagger (D^\nu H) \tilde{B}_{\mu\nu}$	$\frac{\tilde{c}_{HB}}{\Lambda^2} = \frac{g'}{m_W^2}$ tcHB
$\mathcal{O}_W = \frac{i}{2}\left(H^\dagger \sigma^a D^\mu H\right) D^\nu W^a_{\mu\nu}$	$\frac{c_W}{\Lambda^2} = \frac{g}{m_W^2}$ cWW
$\mathcal{O}_B = \frac{i}{2}\left(H^\dagger D^\mu H\right) \partial^\nu B_{\mu\nu}$	$\frac{c_B}{\Lambda^2} = \frac{g'}{m_W^2}$ cB

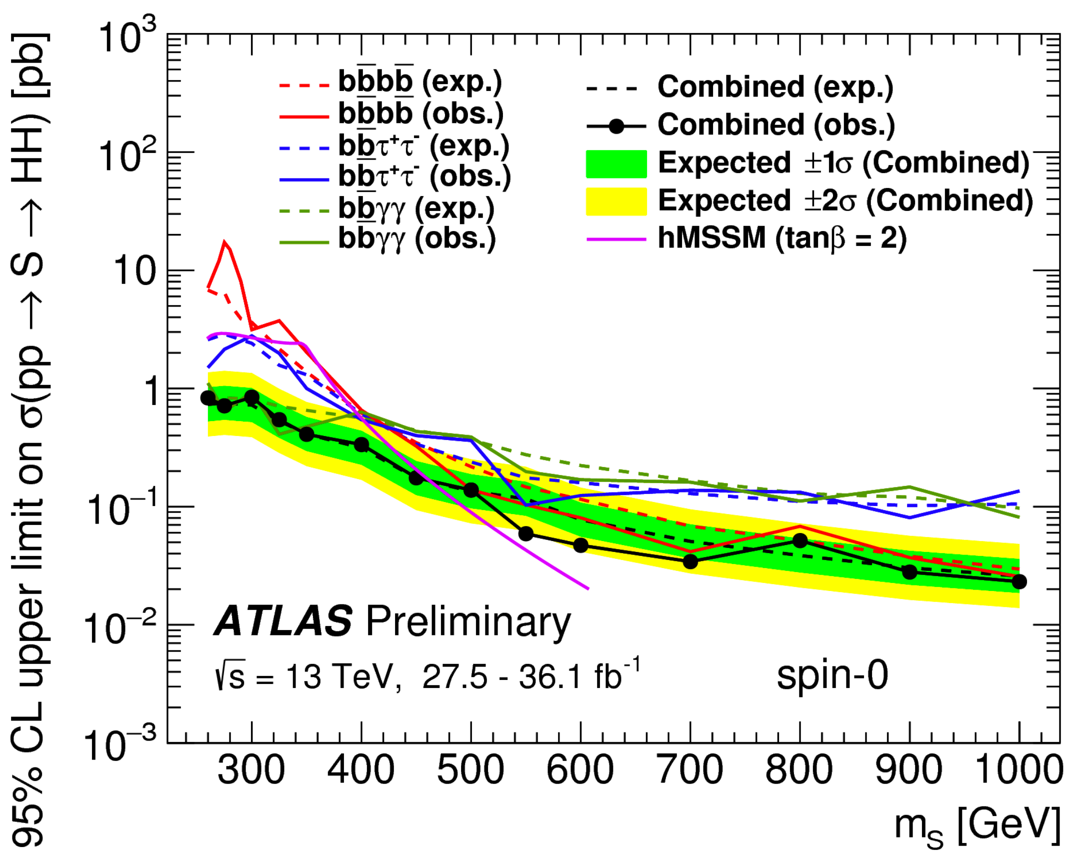
Double Higgs

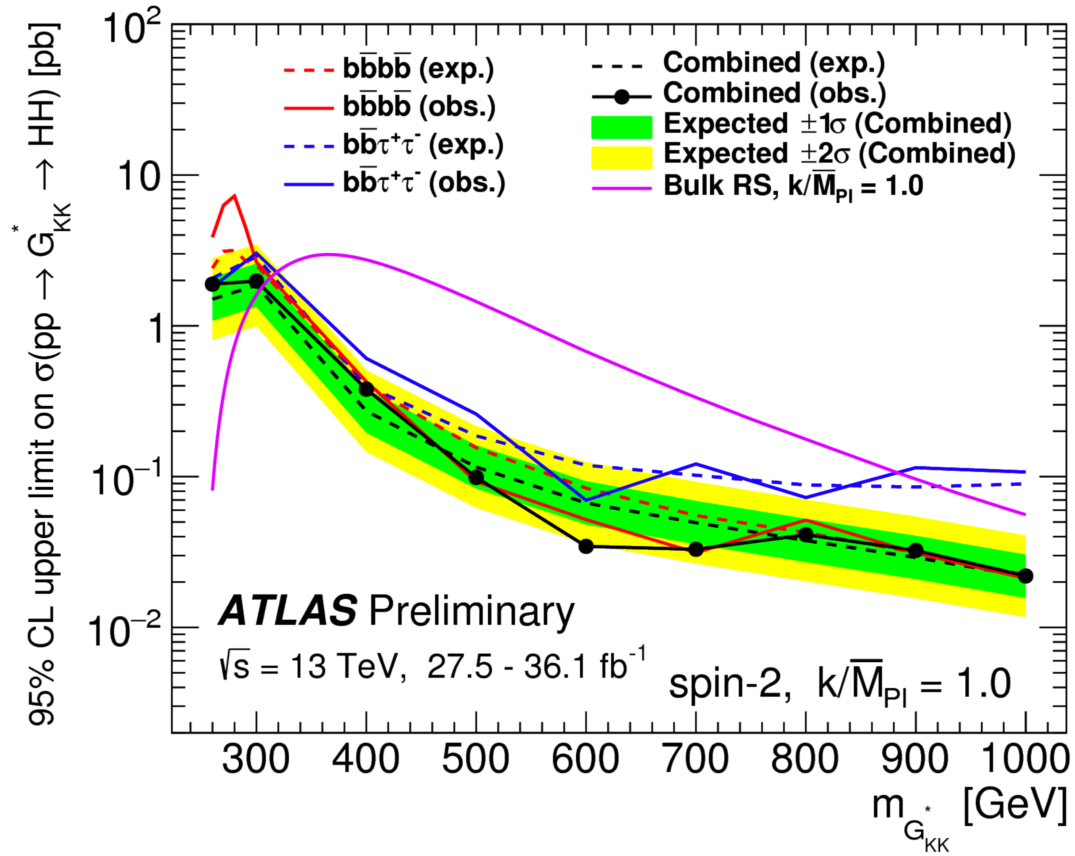
Double Higgs - SM

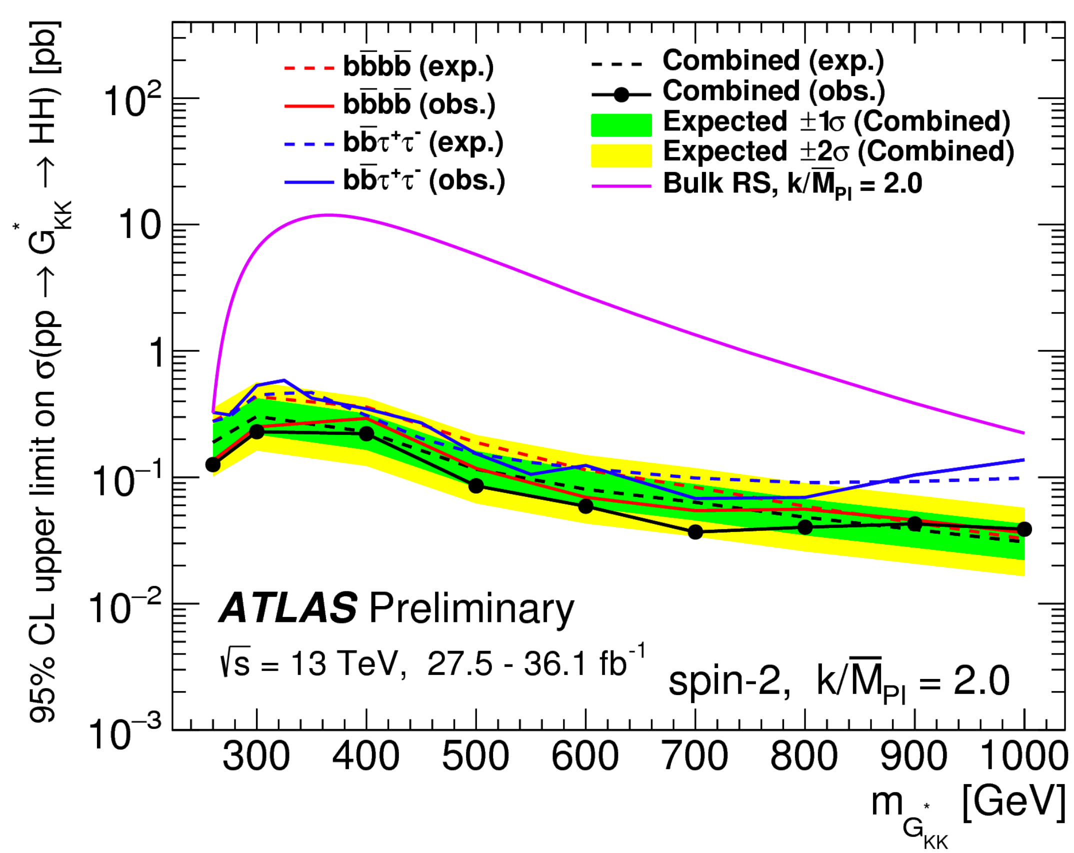




Double Higgs BSM

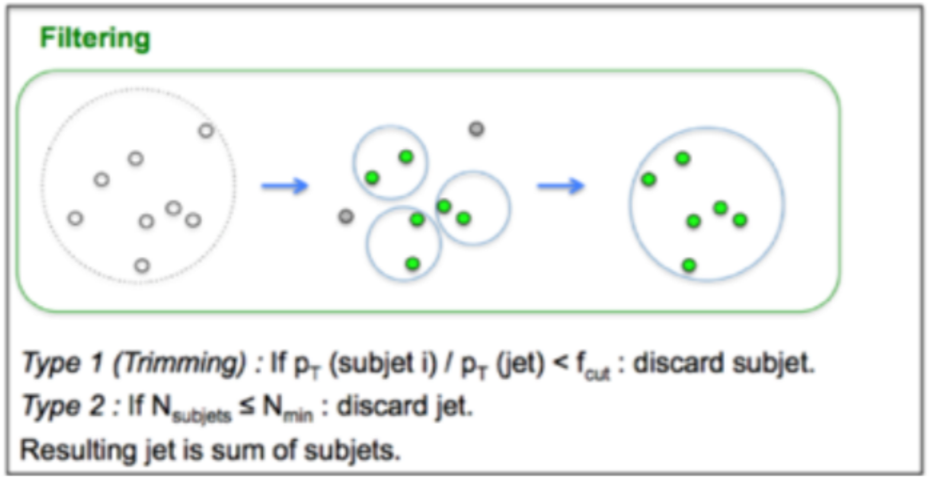






Resonance Search, the first Run2 $H \rightarrow bb$ result

Higgs and jet substructures



- **Λ > 700-800 GeV ~ $p_T(h)$ > 300-400 GeV**
- For **$p_T(h)$ > 400 GeV**, Higgs decay particles start to be reconstructed in a **single jet of *R*~1.0 (Large-*R* jet)**
- **Anti-kt with *R*=1.0** preferred in ATLAS
- **Suppress PU and UE** on the measurement of the **large-*R* jet mass** (*key observable*) **→ *"trimming"***
- And *b*-tagging?
  ***b*-tagging on jets built from tracks** with anti-kt with *R*=0.2 used.
  Track-jets matched to the large-*R* jets.
- Technique very interesting for searches.

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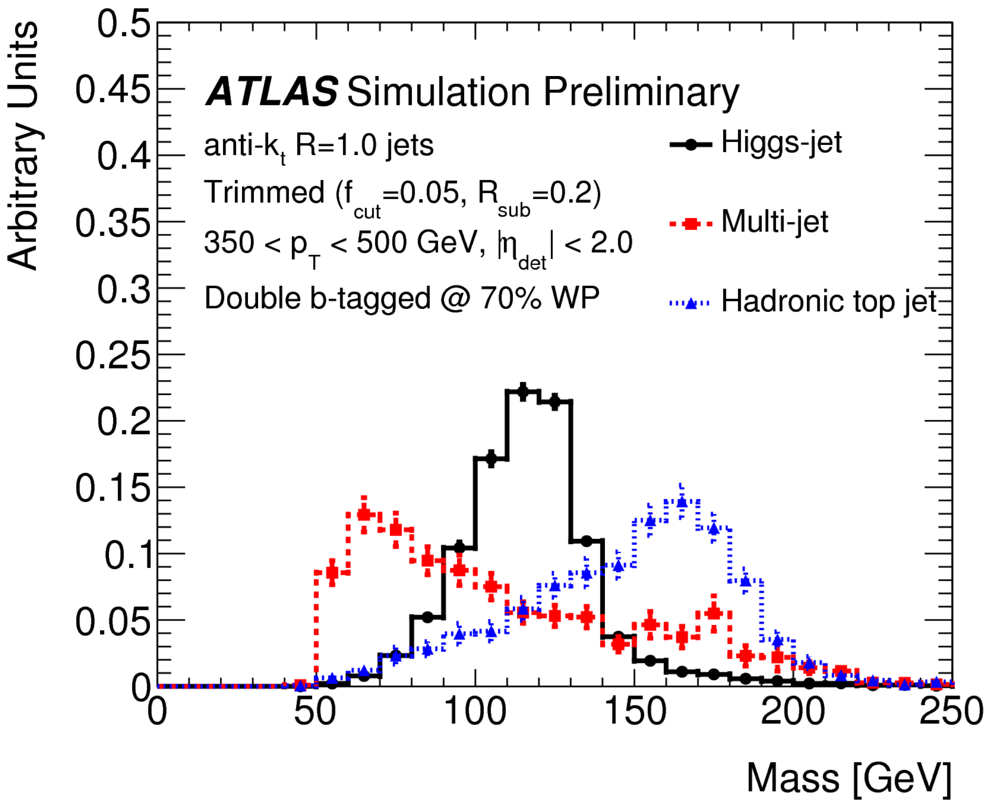
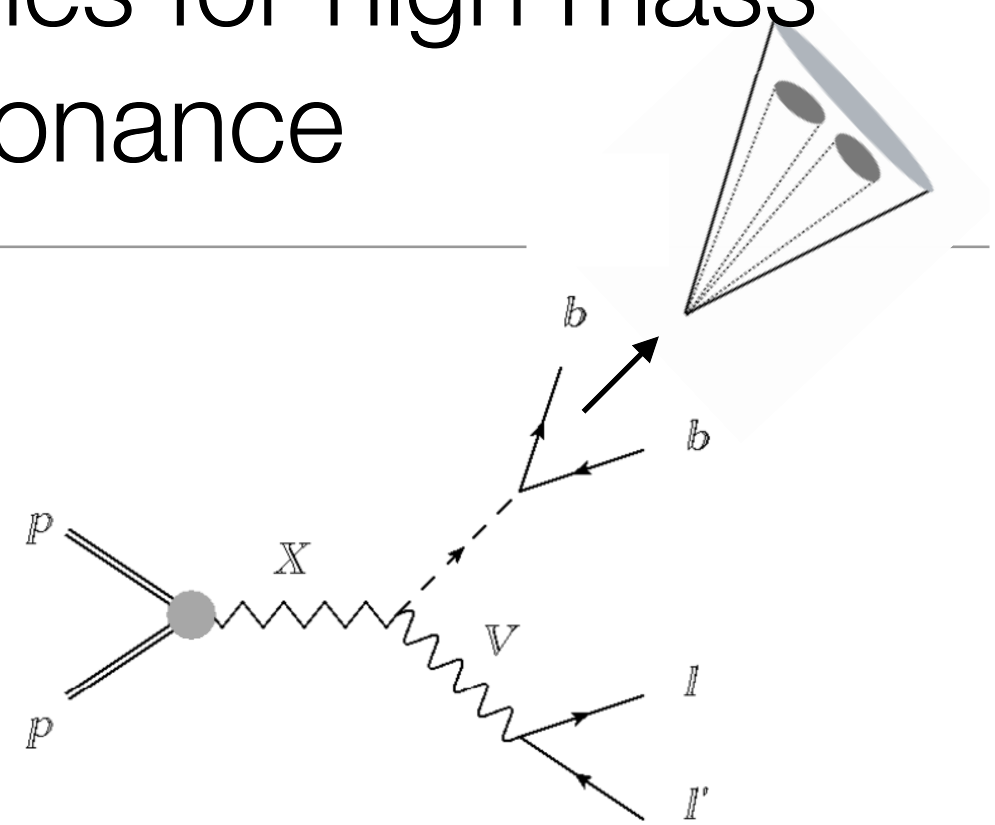
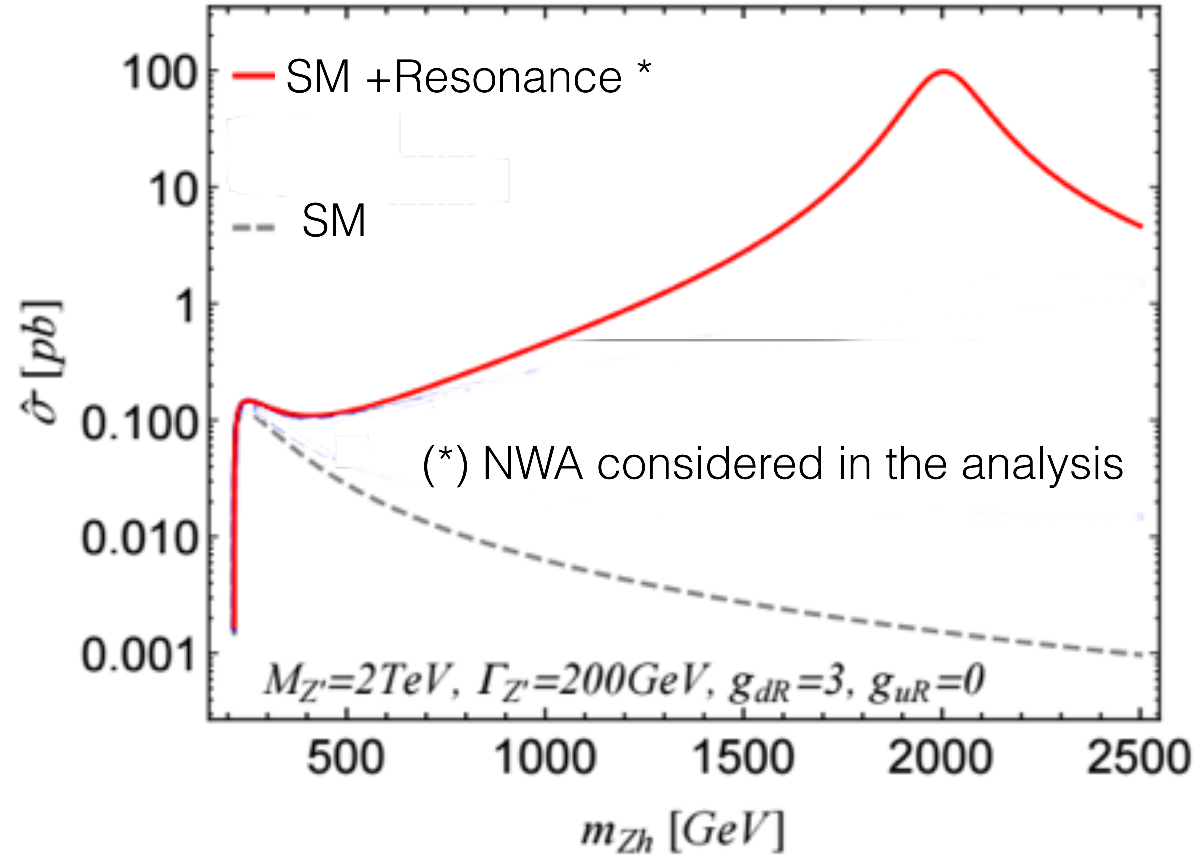


Adaptation from http://arxiv.org/pdf/1512.06135v1.pdf

Searches for high mass *Vh* resonance





Looking for a resonance *W'* or *Z'* decaying in *Vh.*

Analysis optimised for $m_{W'/Z'}$>1 TeV.

Events selected if there is a **large-R jet** with **p_T(j)>250 GeV** with **75<m(j)<145 GeV** (95% efficient) **1- or 2-tags** on associated track jets.

3 lepton channels:
- 0-lepton ($Z\rightarrow\nu\nu$);
- 1-lepton ($W\rightarrow l\nu$);
- 2-lepton ($Z\rightarrow ll$).

2 tag categories:
- 1-tag
- 2-tag

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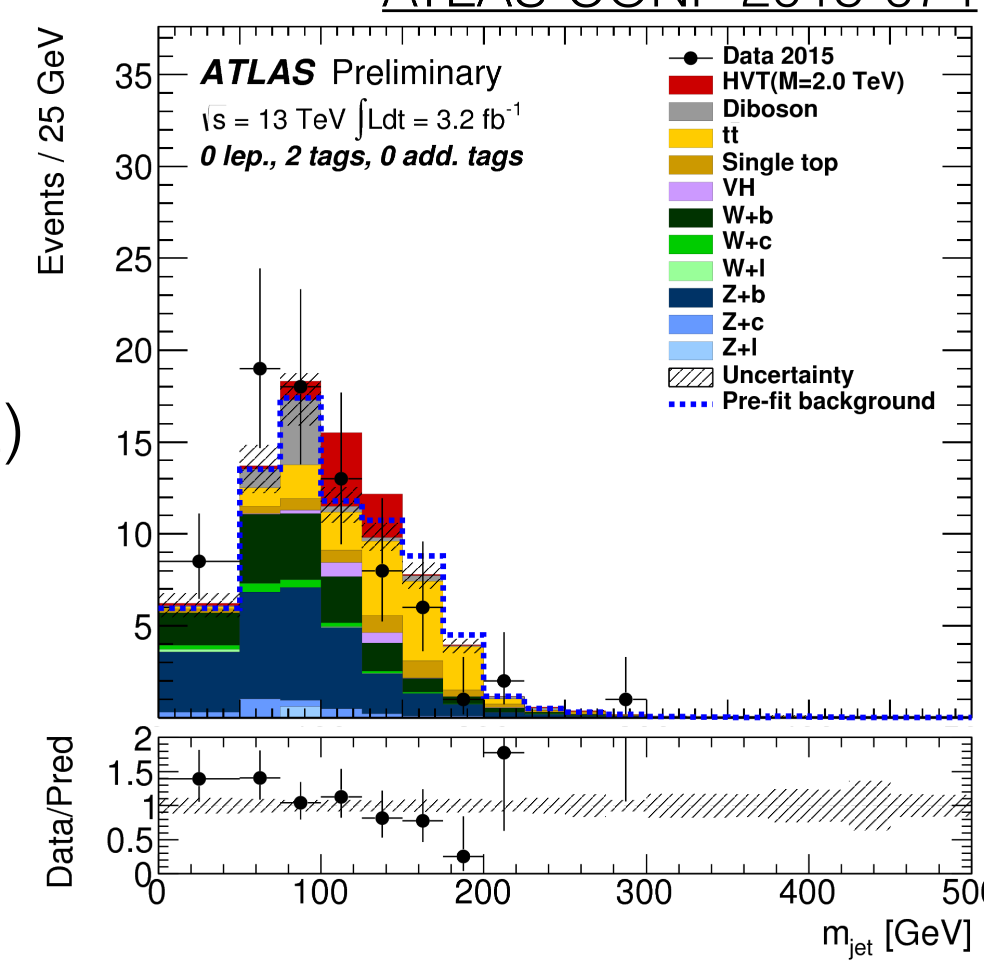
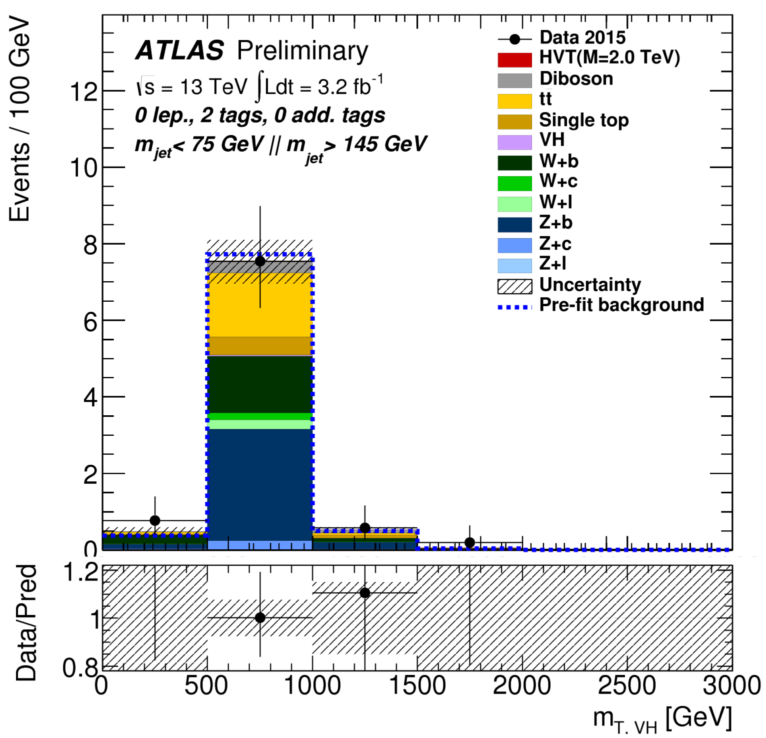
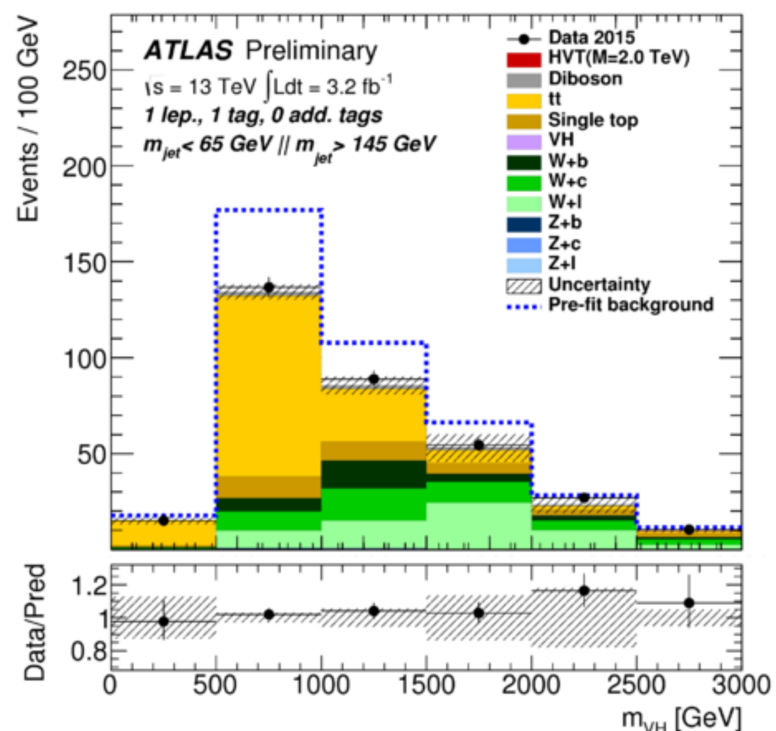
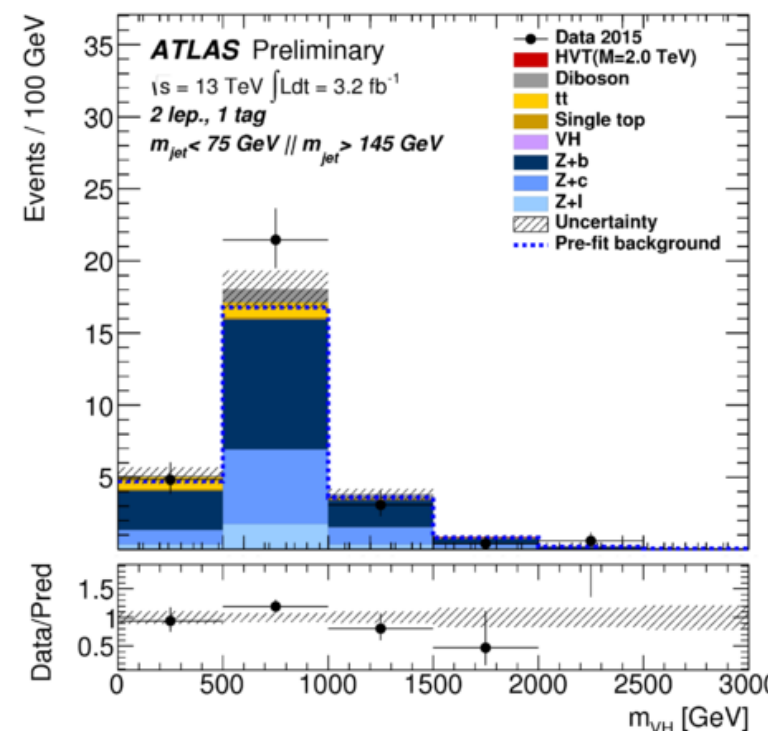
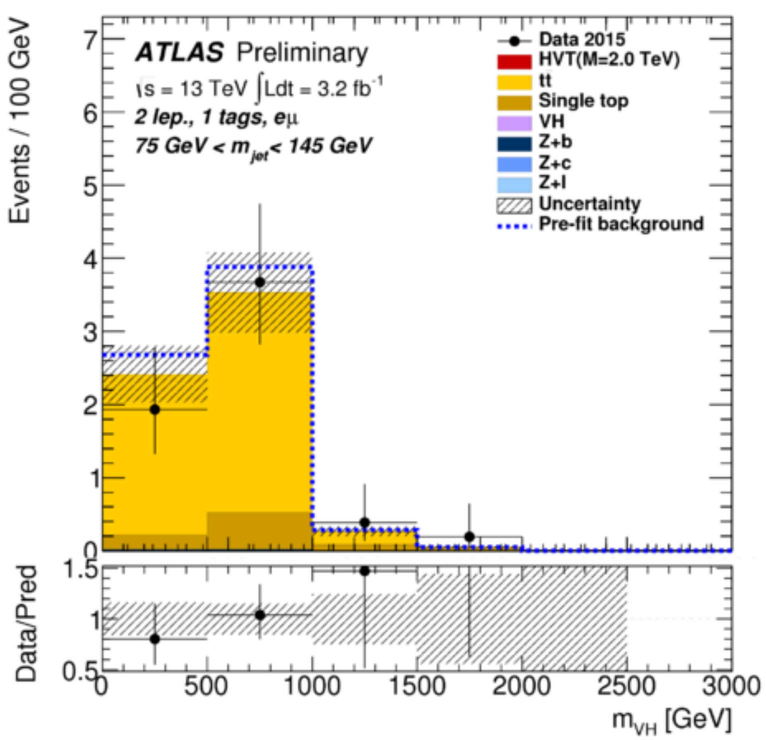


Backgrounds and Control Regions









Simultaneous profile likelihood fit for each channel

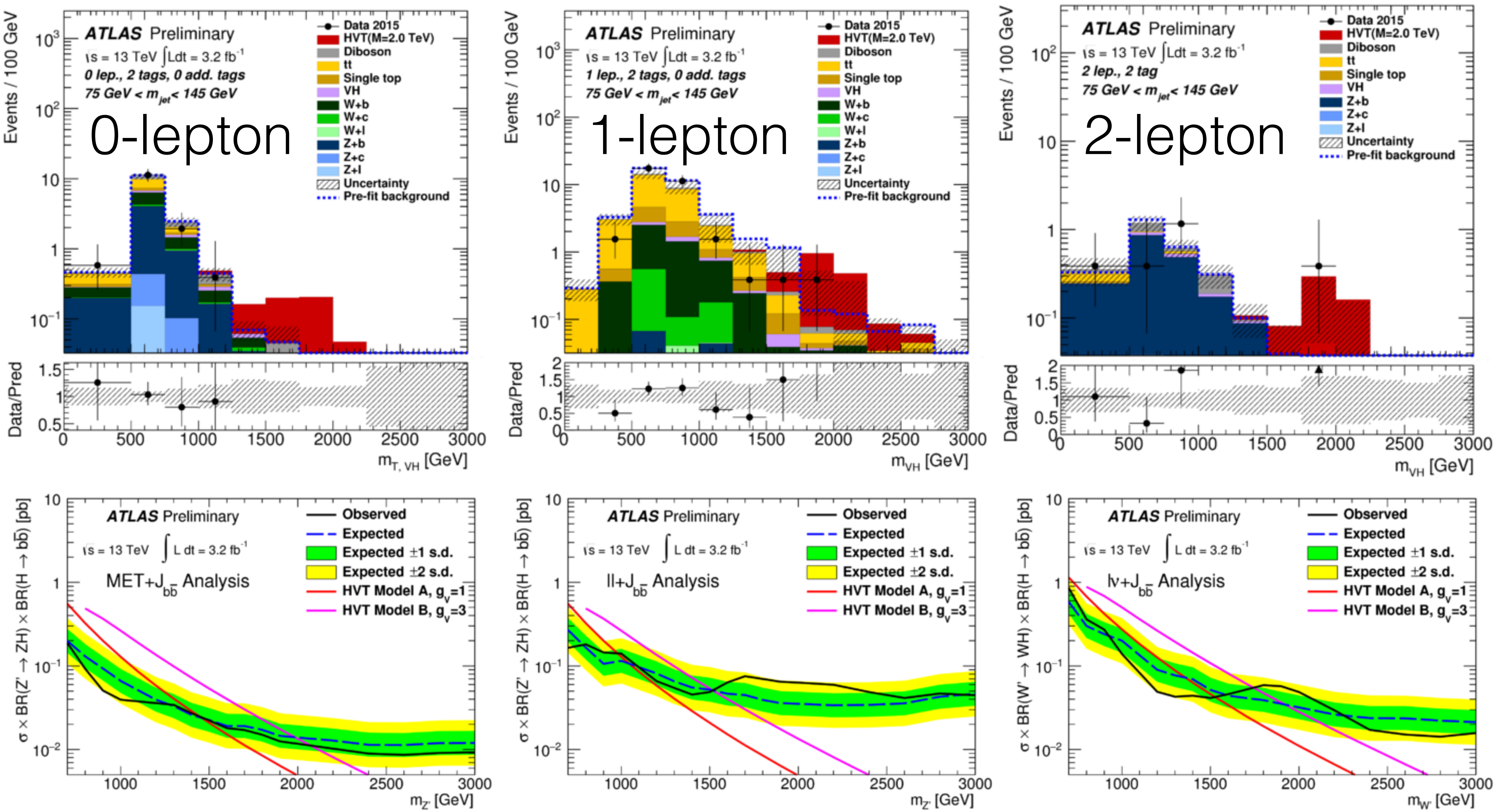
2 signal regions (2 tag - 1 tag) per channel

4-6 control regions (side-bands m(J)) per channel

Already controlling our favorite backgrounds in vast regions of phase space

Paolo Francavilla

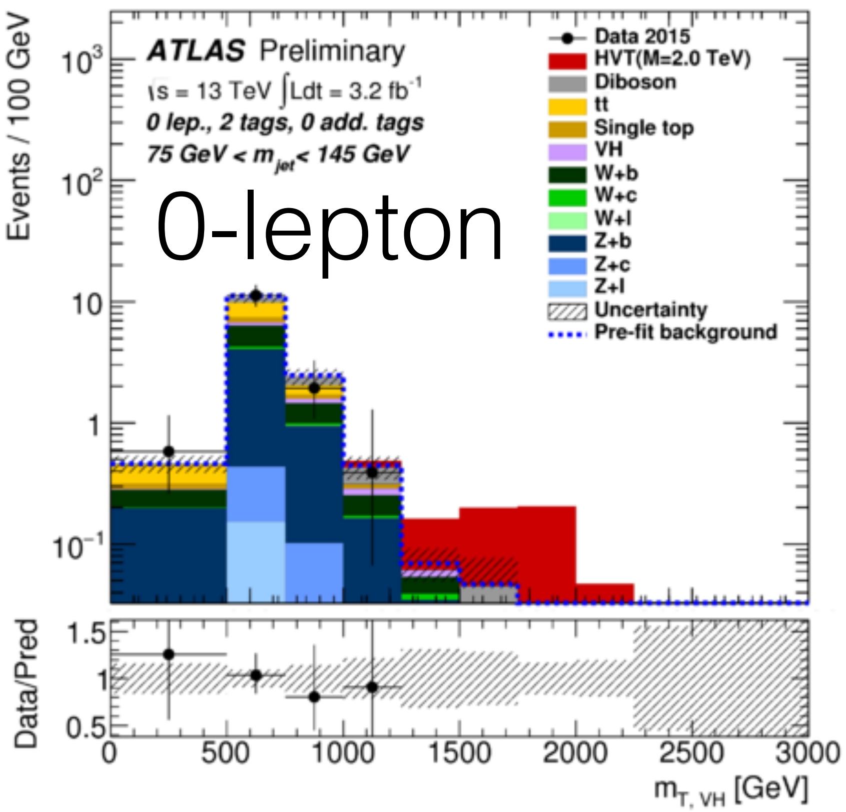
Results

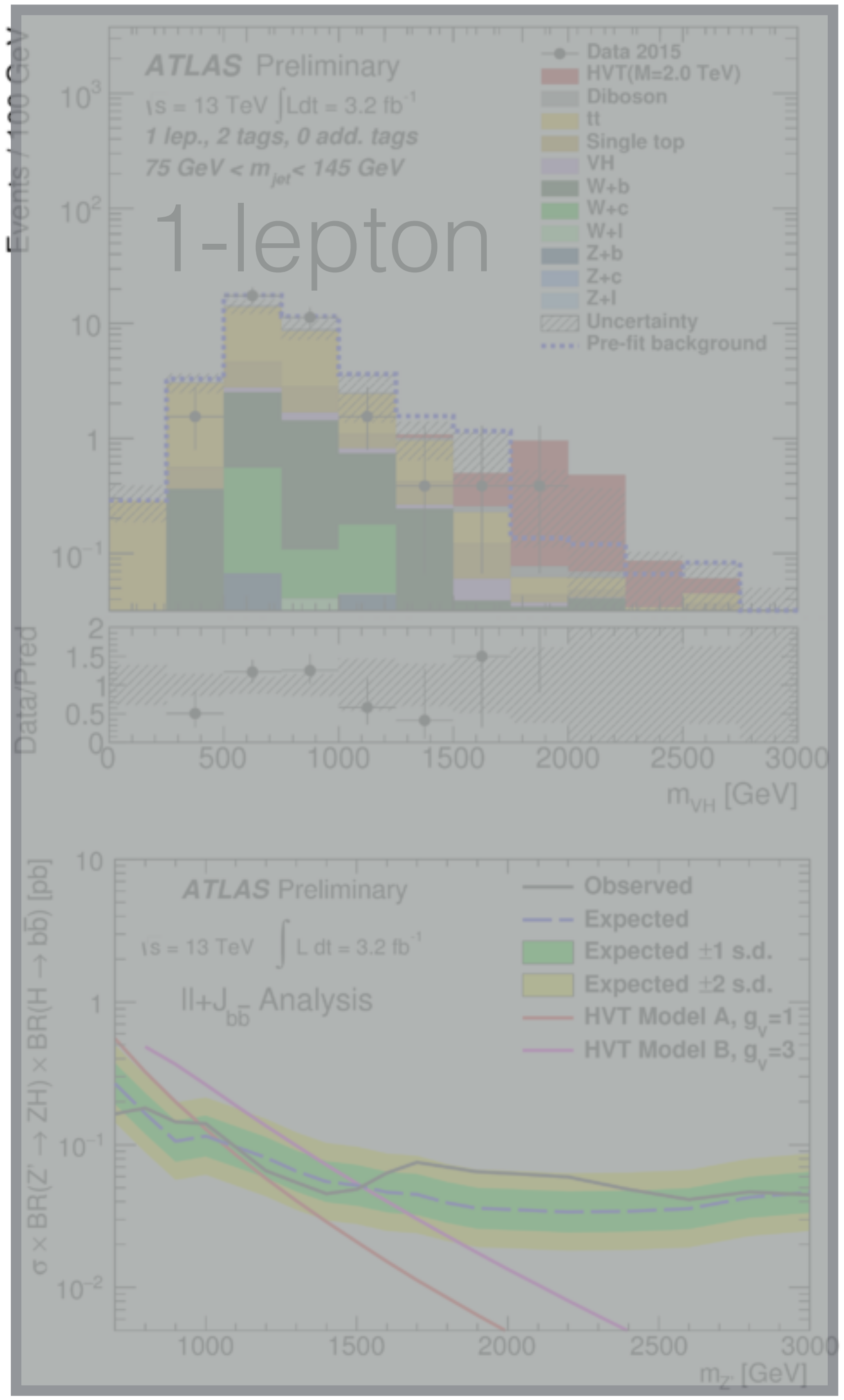


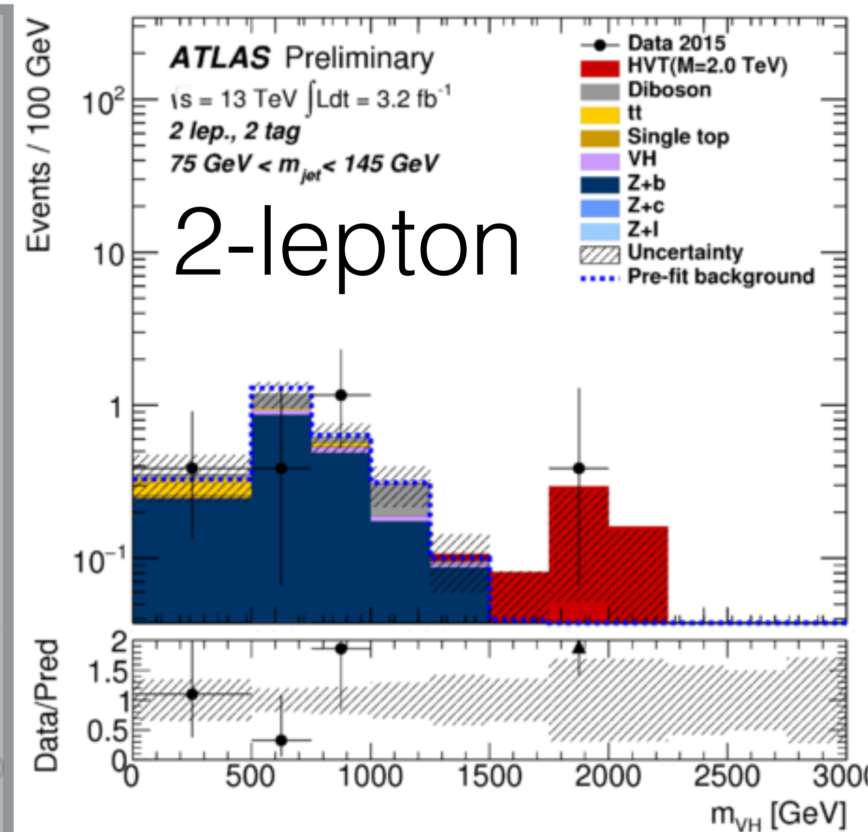
Extended Run1 limits for m(V')>1.5 TeV

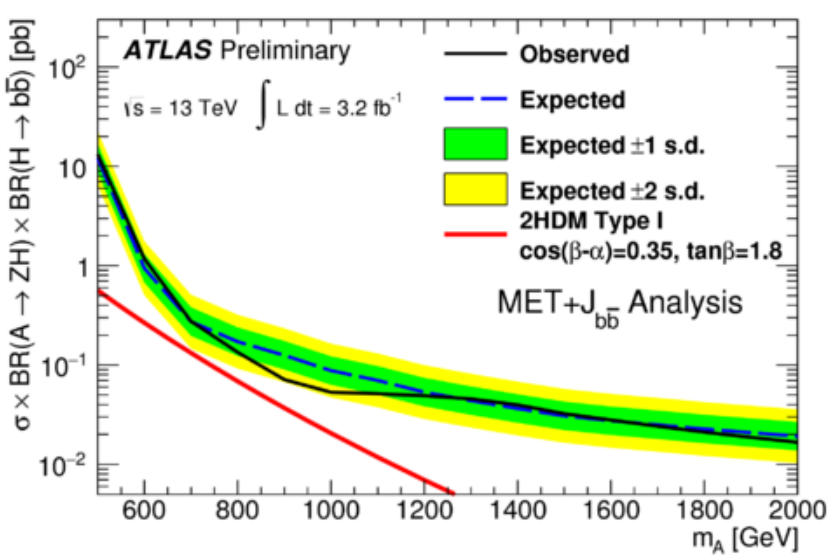
First LHC Run2 public result on $h \rightarrow b\bar{b}$ physics

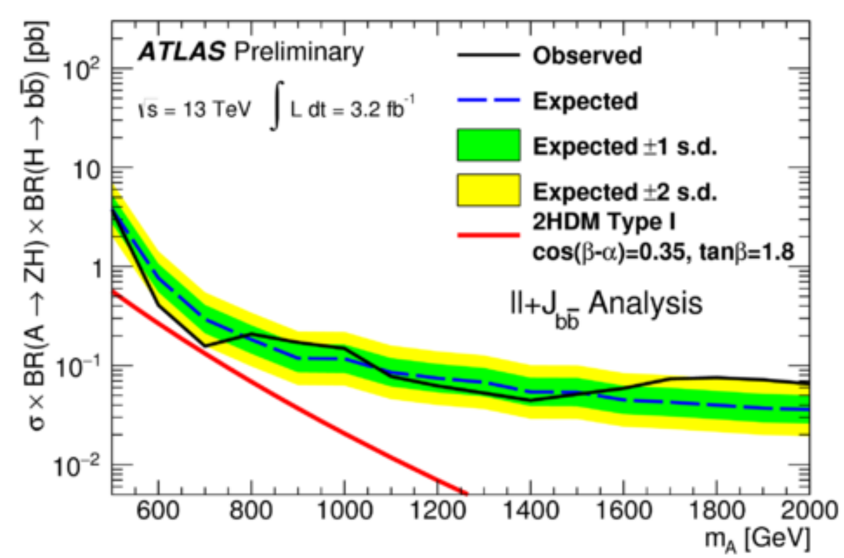
Results











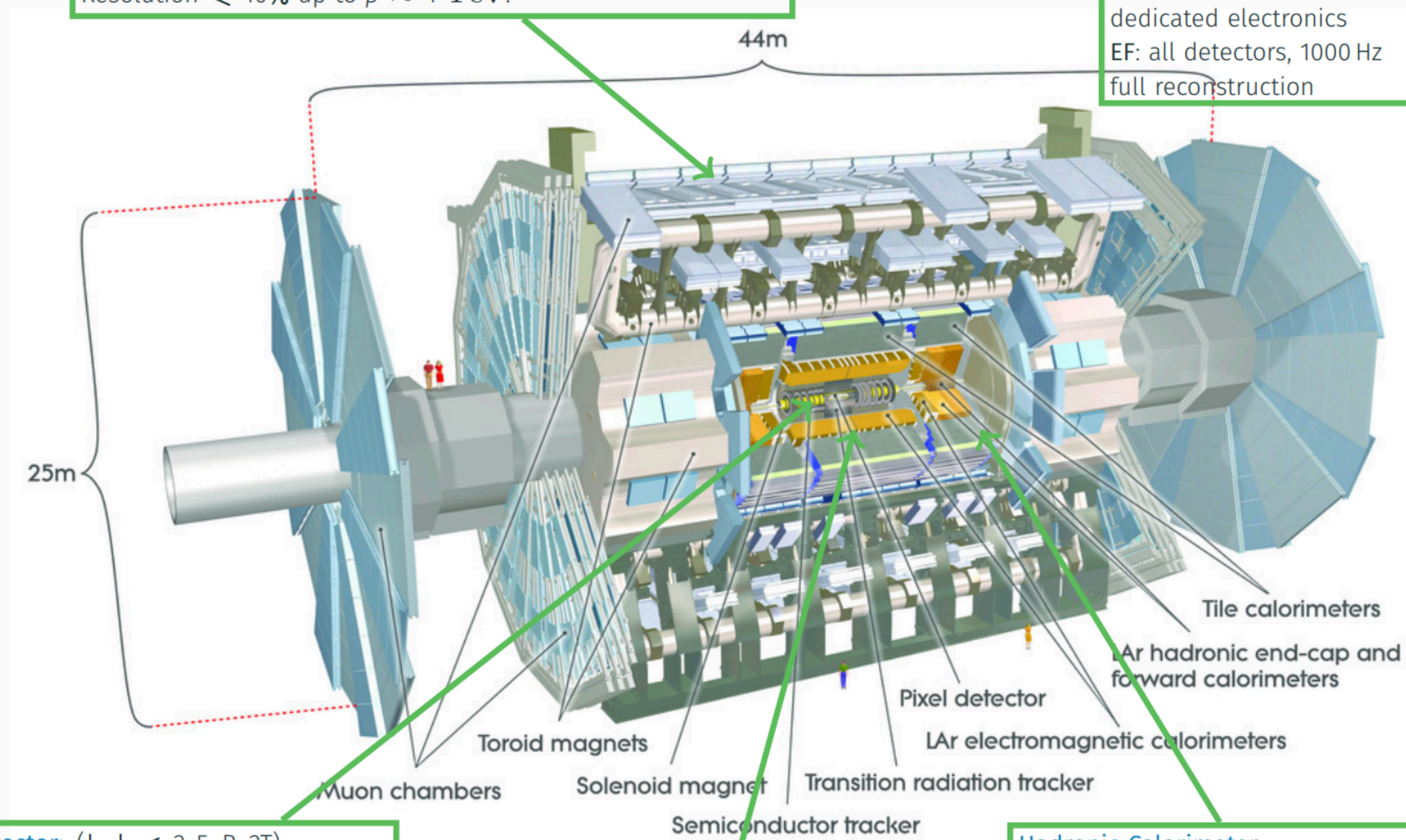
First glimpse at search of CP-odd scalar *A→Zh*

Extending the search at lower masses, and combining the channels

ATLAS Detector in 1 slide

Muon Spectrometer: ($|\eta| < 2.7$)
Air toroid with drift chambers,
Provides μ trigger and momentum measurement,
Resolution $< 10\%$ up to $p \sim 1\,\mathrm{TeV}$.

Trigger System:
3 levels
L1: calo and muons, 100 kHz
dedicated electronics
EF: all detectors, 1000 Hz
full reconstruction



Inner Detector: ($|\eta| < 2.5$, B=2T)
Si Pixels, SCT, TRT
Precision tracking,
Vertex reconstruction,
e/π separation
$\sigma/p_T \sim 3.8\,10^{-4} p_T \oplus 0.015$

EM Calorimeter: ($|\eta| < 3.2$)
Pb-LAr, accordion structure
Provides trigger on e/γ,
Identification and measurement
$\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

Hadronic Calorimeter:
Scint/Fe tiles in barrel ($|\eta| < 1.7$)
W/Cu-LAr in endcaps ($|\eta| < 4.9$)
Provides jet trigger and energy measurement,
$\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$
Hermetic coverage for MET