Charm and bottom Yukawa couplings: experimental searches

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On behalf of the LHCb, ATLAS and CMS Collaborations
CERN

Workshop on physics of the high luminosity LHC, and perspectives at a high energy LHC

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Introduction

Deviations in the Yukawa couplings would be an indication of new physics

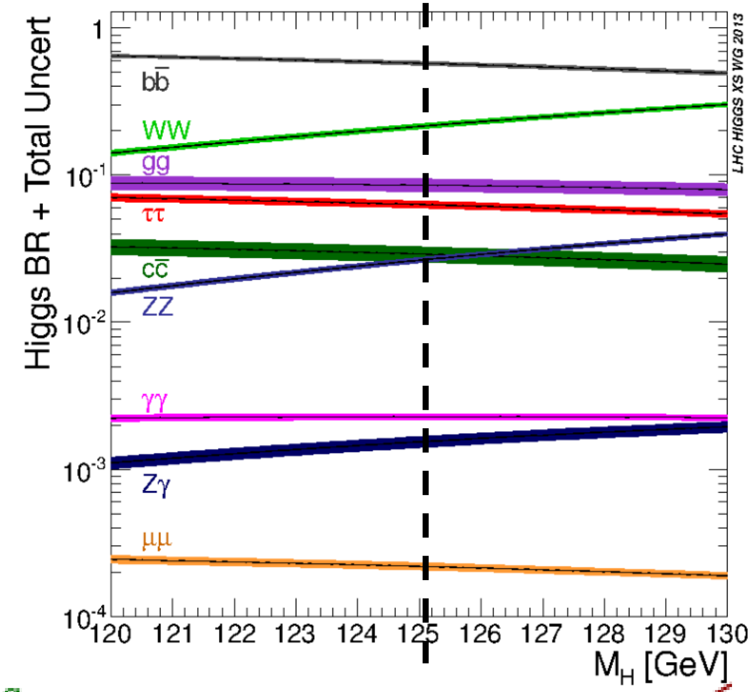
The decay channel $H \rightarrow b\bar{b}/c\bar{c}$ provides an important way to probe the yukawa coupling for b/c quarks

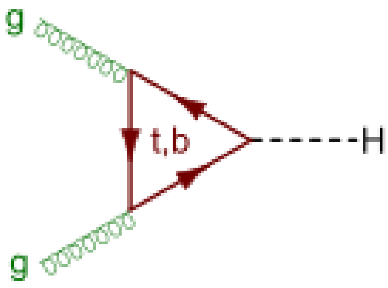
$H \rightarrow b\bar{b}$:

- Dominant contribution to the total decay width (highest branching ratio - 58%)
- Searched for in all cases by ATLAS and CMS

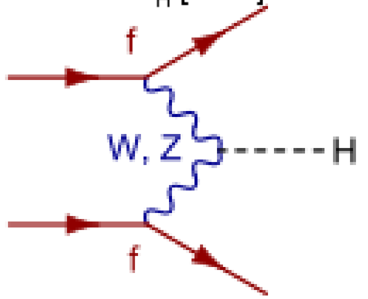
$H \rightarrow c\bar{c}$ is much more challenging

- ~20 times smaller branching ratio than $H \rightarrow b\bar{b}$

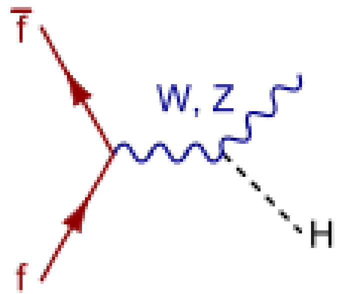




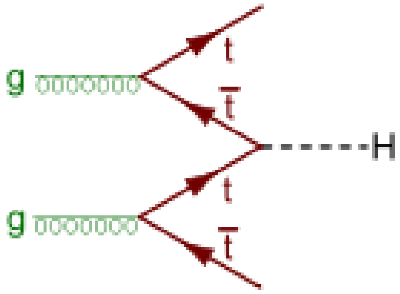
Gluon-gluon fusion



Vector boson fusion



Higgs strahlung



Top fusion

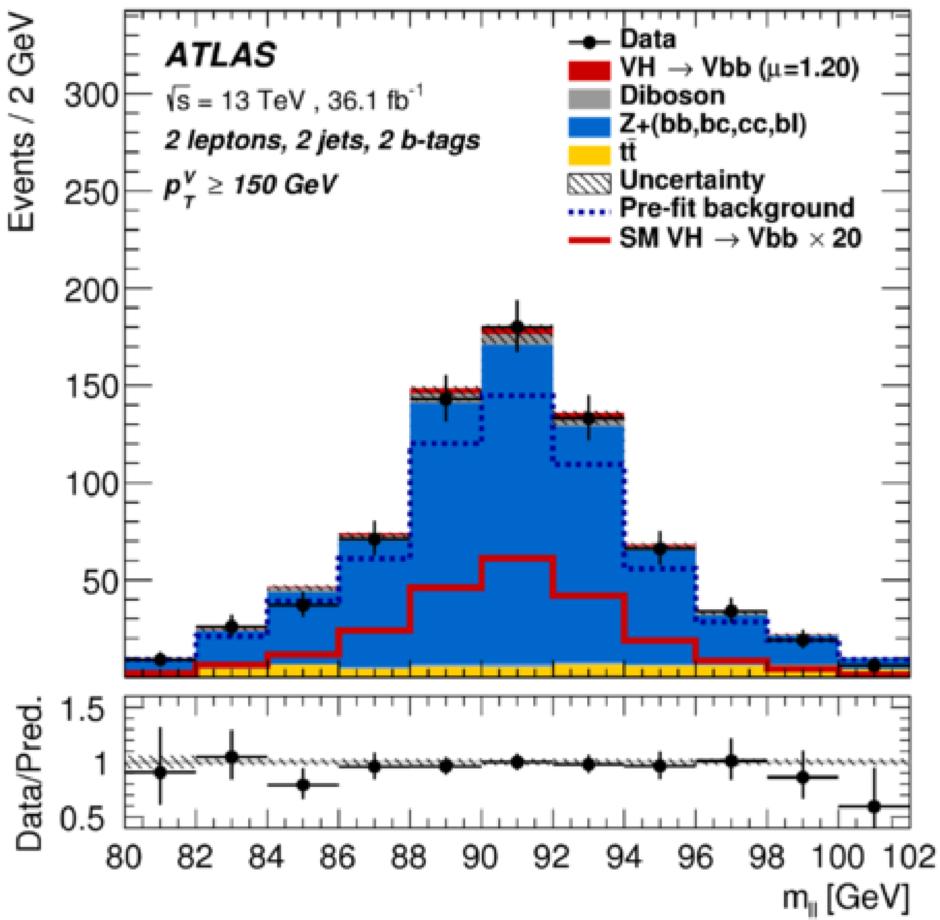
List of recent papers (not exhaustive)

- Search for the Standard Model Higgs boson produced by vector-boson fusion and decaying to bottom quarks in $\sqrt{s}$=8 TeV pp collisions with the ATLAS detector (JHEP 11 (2016) 112)
- Search for the Standard Model Higgs boson decaying into $b\bar{b}$ produced in association with top quarks decaying hadronically in pp collisions at $\sqrt{s}$=8 TeV with the ATLAS detector (*JHEP 05 (2016) 160*)
- Search for the associated production of a Higgs boson with a single top quark in proton-proton collisions at $\sqrt{s}$ = 8 TeV (JHEP 06 (2016) 177)
- Evidence for the H→$b\bar{b}$ decay with the ATLAS detector (Submitted to JHEP - **arXiv:1708.03299**)
- Evidence for the Higgs boson decay to a bottom quark-antiquark pair (CMS-HIG-16-044 - Submitted to PLB)
- Inclusive search for a highly boosted Higgs boson decaying to a bottom quark-antiquark pair (CMS-HIG-17-010 - Submitted to PRL)
- Search for H → $b\bar{b}$ or $c\bar{c}$ in association with a W or Z boson in the forward region of pp collisions (LHCb-CONF-2016-006)
- Search for Higgs and Z Boson Decays to J/ψγ and Υ(nS)γ with the ATLAS Detector (Phys. Rev. Lett. 114 (2015) 121801)
- Search for Higgs and Z Boson Decays to φγ with the ATLAS Detector (Phys. Rev. Lett. 117, 111802)

VH(bb) @ ATLAS

- Full 2015 and 2016 analysis (36.1fb^{-1})
- Selection based in the topology of V (0,1 and 2 e or μ) and ≥ 2 jets
- Jets are b-tagged using an optimized algorithm:
  - average 70% b-jet tagging efficiency
  - nominal light-flavour (u,d,s-quark and gluon) and c-jet misidentification efficiencies of 0.3% and 8.2%, respectively
- Dedicated correction is applied to improve the m($b\bar{b}$) resolution

$ZH(llb\bar{b})$,Z+HF, ttbar

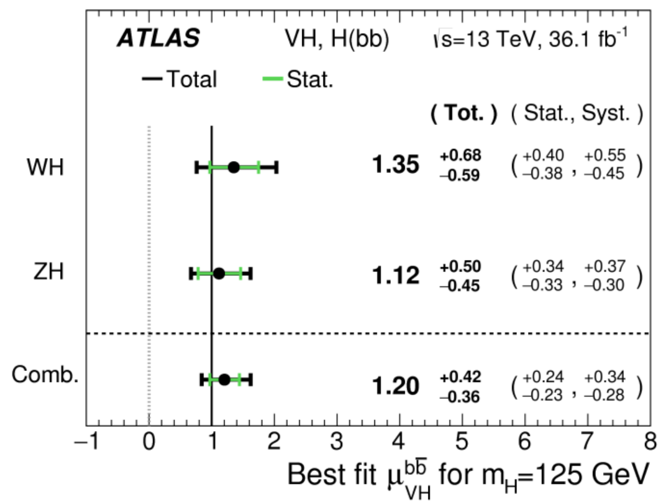


arXiv:1708.03299 submitted to JHEP

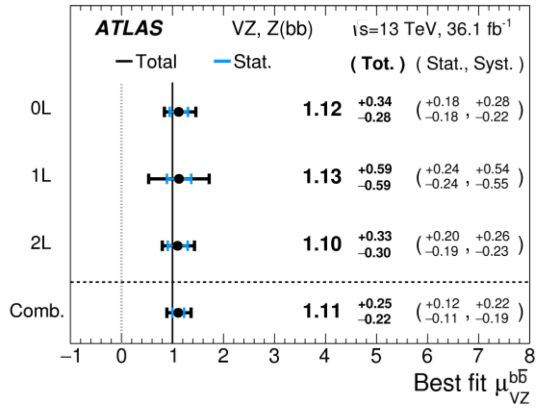
VH(bb) @ ATLAS

[arXiv:1708.03299](https://arxiv.org/abs/1708.03299) **submitted to JHEP**

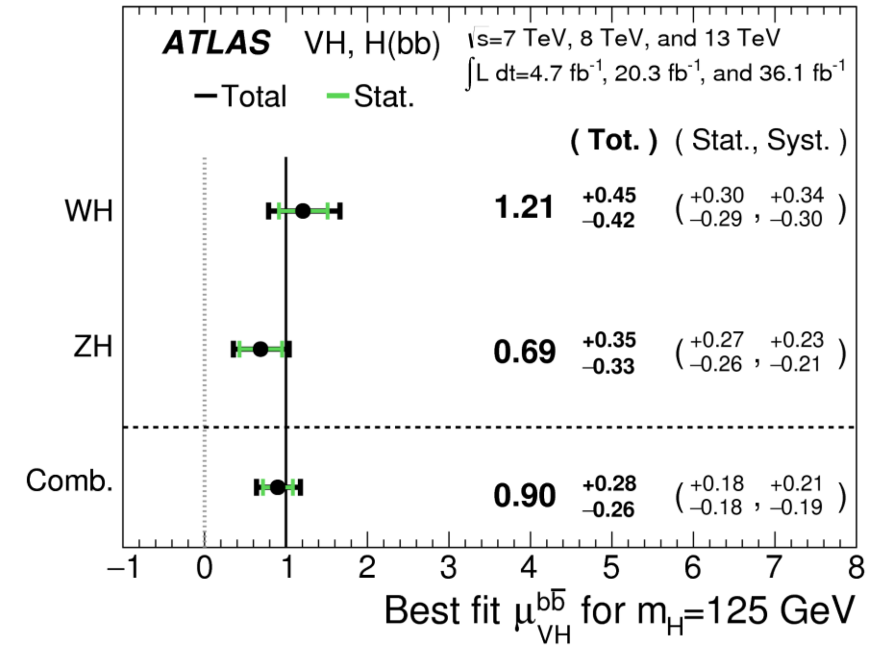
Run II



VZ analysis cross check



Run I + Run II



Observed 3.6 σ
Expected 4.0 σ

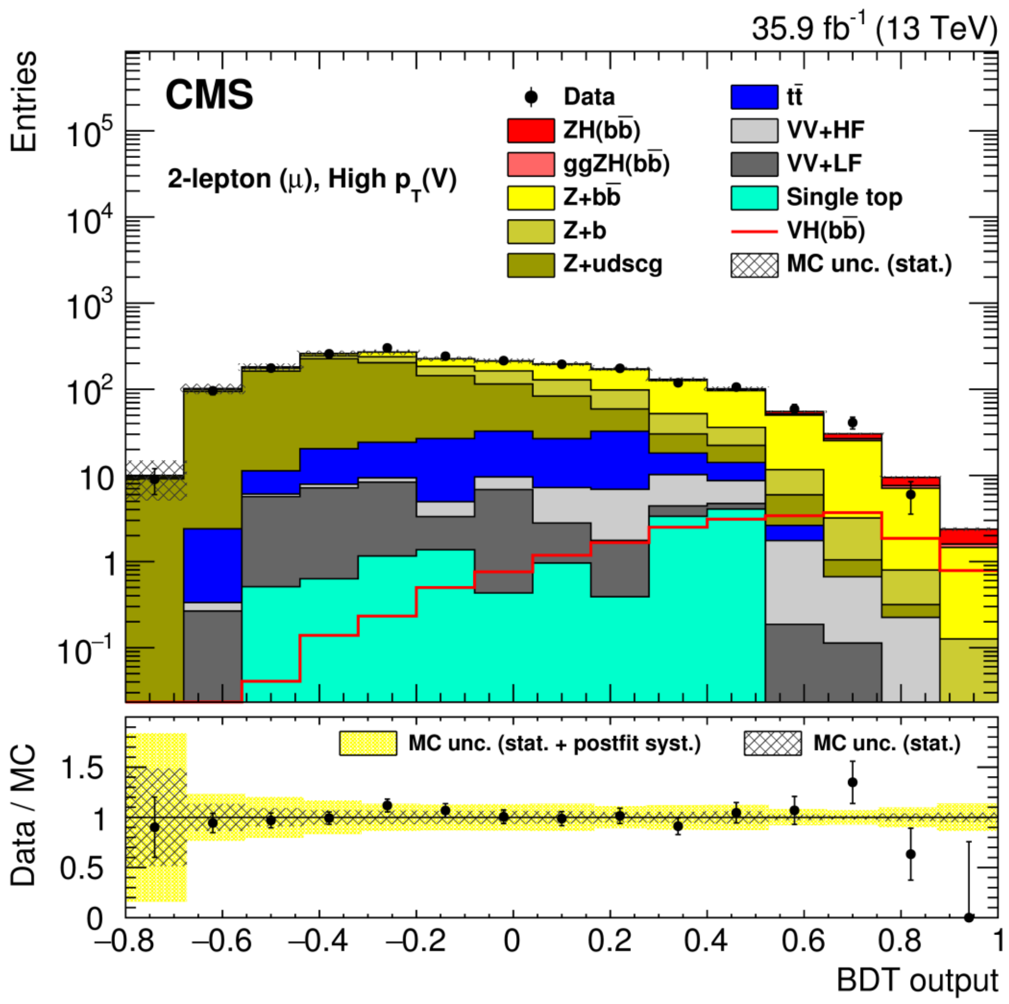
Consistent with the value of the Yukawa coupling for the bottom quarks in the Standard Model

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

VH(bb) @ CMS

arXiv:1709.07497 **submitted to PLB**

- Full 2015 and 2016 analysis (35.9fb^{-1}, 13 TeV)
- Selection and performance similar to ATLAS
- Powerful b-tagging:
  - 50-75 % efficiency for b-jets
  - Misidentification 5-25% and 0.15-0.3% for c-jets and light jets respectvely
- Dedicated correction to improve the di-b-jet mass
- Di-b-jet mass sidebands are used as control regions



VH(bb) @ CMS

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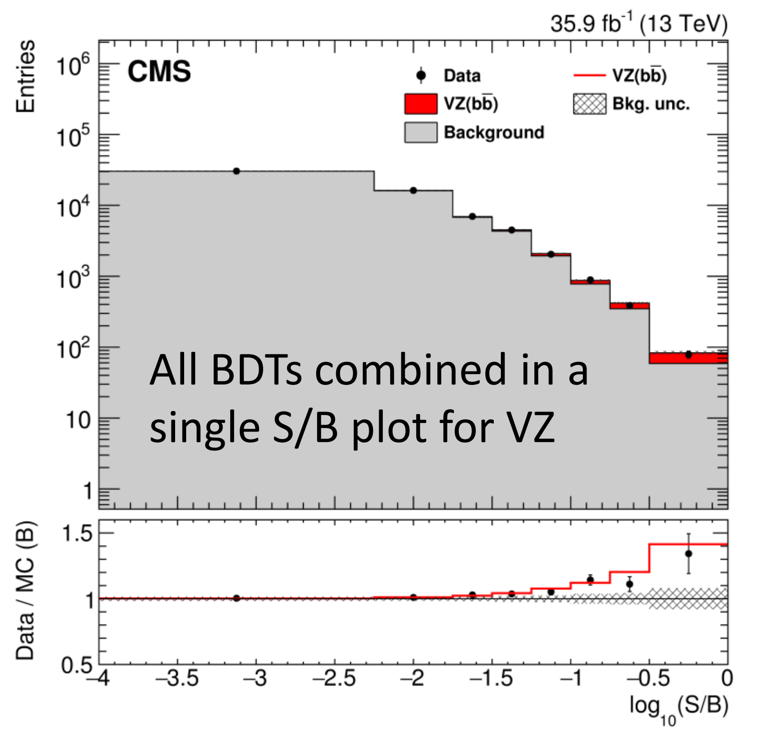
VZ validation



Channels	Significance expected	Significance observed
0-lepton	3.1	2.0
1-lepton	2.6	3.7
2-lepton	3.2	4.5
Combined	4.9	5.0

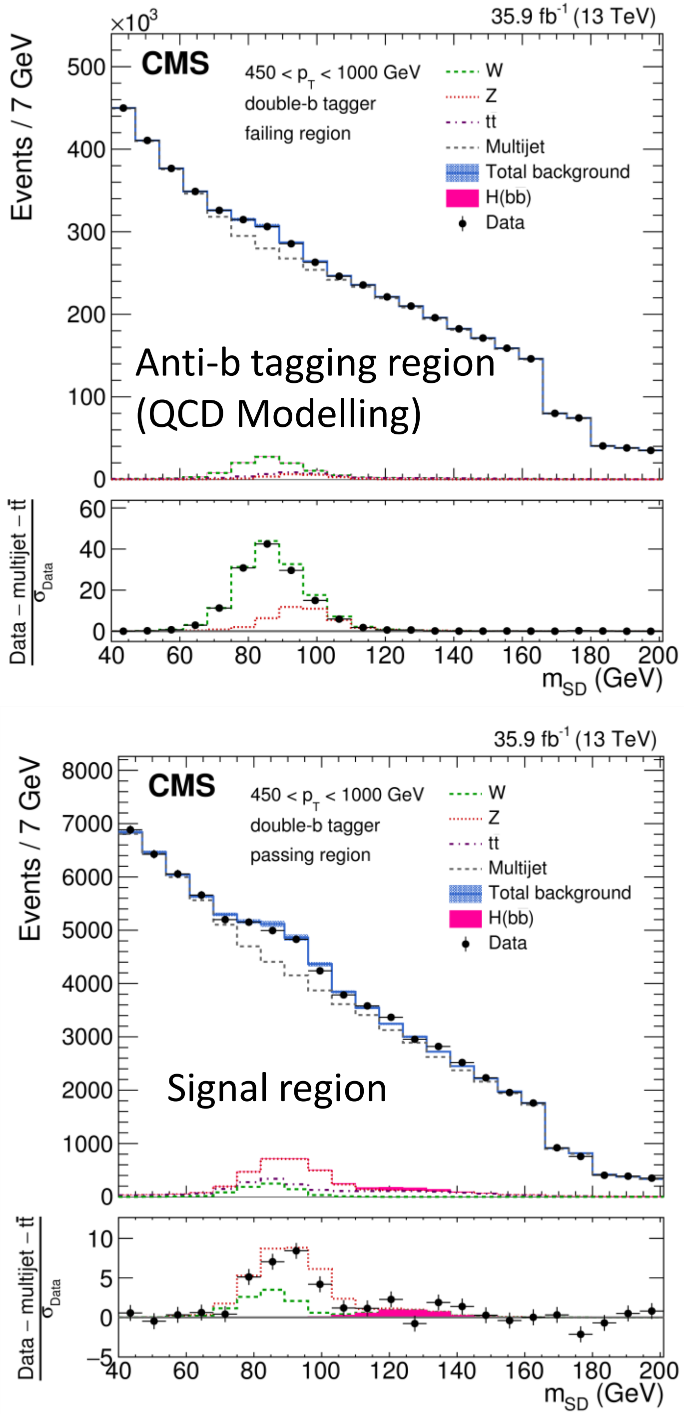
Data used	Significance expected	Significance observed	Signal strength observed
Run 1	2.5	2.1	$0.89^{+0.44}_{-0.42}$
Run 2	2.8	3.3	$1.19^{+0.40}_{-0.38}$
Combined	3.8	3.8	$1.06^{+0.31}_{-0.29}$

Source	Type	Individual contribution to the μ uncertainty (%)
Scale factors ($t\bar{t}$, V+jets)	norm.	9.4
Size of simulated samples	shape	8.1
Simulated samples' modeling	shape	4.1
b tagging efficiency	shape	7.9
Jet energy scale	shape	4.2
Signal cross sections	norm.	5.3
Cross section uncertainties (single-top, VV)	norm.	4.7
Jet energy resolution	shape	5.6
b tagging mistag rate	shape	4.6
Integrated luminosity	norm.	2.2
Unclustered energy	shape	1.3
Lepton efficiency and trigger	norm.	1.9

Boosted H(bb) @ CMS

arXiv:1709.05543
submitted to PRL

- Single fat jet
  - anti-kt R=0.8, $p_T > 450\ GeV$
- Lepton and E_{Tmiss} vetoed to avoid contamination from top and Standard Model Electroweak
- Special b-tagging identifies two B-hadron within the fat jet
- Dedicated algorithm to remove pile-up effects (PUPPI)
- Grooming (soft-drop mass) removes soft radiation from the jet (m_{SD})
- N-subjetiness is used to require jets with two subjets (remove part of the QCD backgroud)
  - Uncorrelated with the jet mass distribution



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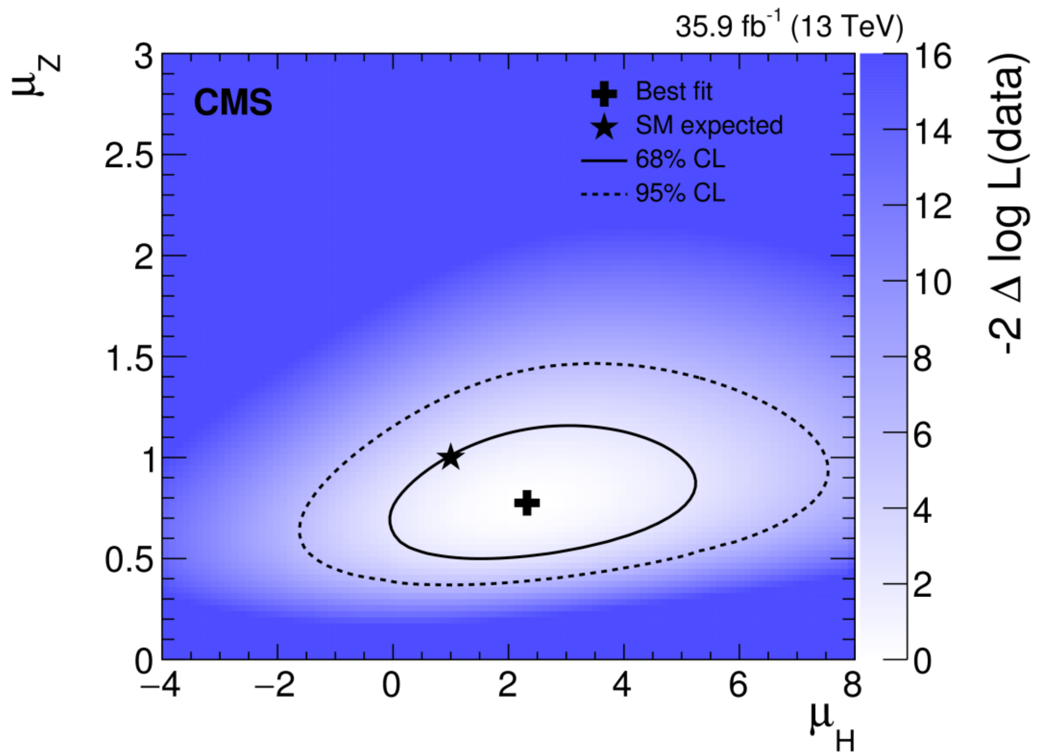


Systematic source	W/Z	H
Integrated luminosity	2.5%	2.5%
Trigger efficiency	4%	4%
Pileup	<1%	<1%
$N_2^{1,\mathrm{DDT}}$ selection efficiency	4.3%	4.3%
Double-b tag	4% (Z)	4%
Jet energy scale / resolution	10/15%	10/15%
Jet mass scale (p_T)	0.4%/100 GeV (p_T)	0.4%/100 GeV (p_T)
Simulation sample size	2–25%	4–20% (ggF)
H p_T correction	—	30% (ggF)
NLO QCD corrections	10%	—
NLO EW corrections	15–35%	—
NLO EW W/Z decorrelation	5-15%	—

	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

First observation of the Z+jet using a single fat jet topology

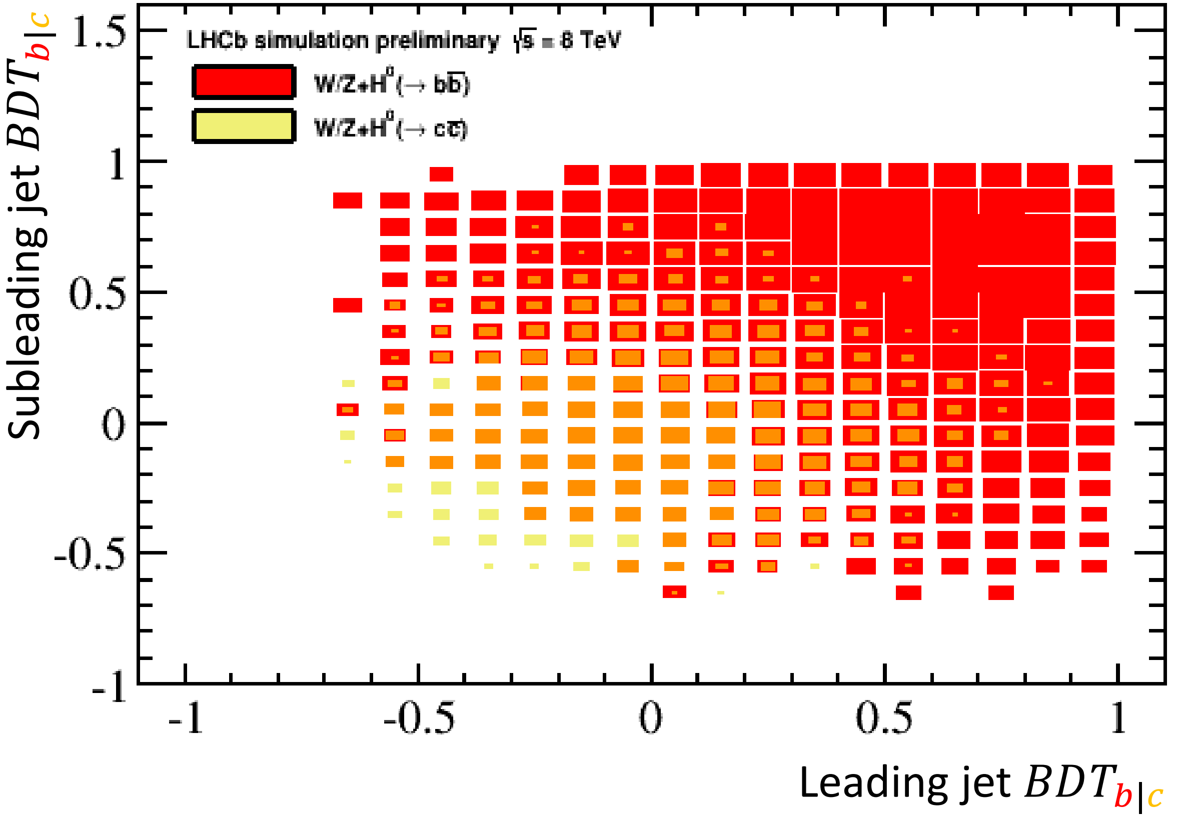
Search for the VH($b\bar{b}$ or $c\bar{c}$) @ LHCb

LHCB-CONF-2016-006

- 2012 Data (2 fb^{-1} @ 8 TeV)
- Selection:
  - Z/W decays into muons or electrons
  - $p_T^l >$ 20 GeV, 2.0 < η^μ < 4.5 (2.0 < η^e < 4.25)
  - $20\ \text{GeV} < p_T^j < 100\ \text{GeV},\ 2.2 < \eta^j < 4.2$
- For the Z/W+H($c\bar{c}$), an additional requirement is applied to the BDT(b|c)
  - ~90% of Z/W+H($b\bar{b}$) is removed
  - ~60% of Z/W+H($c\bar{c}$) efficiency
- The di-c-tag efficiency for the criteria used in VH[$c\bar{c}$] was about 2%
- Set the following limits:

$$\sigma[\mathrm{V} + \mathrm{H}^0(\mathrm{b\bar{b}})] < 1.6\ \mathrm{pb\ at\ 95\ \%\ CL} \quad (50 \times \mathrm{SM})$$
$$\sigma[\mathrm{V} + \mathrm{H}^0(\mathrm{c\bar{c}})] < 9.4\ \mathrm{pb\ at\ 95\ \%\ CL}\ (6200 \times \mathrm{SM})$$

First experimental limit set on the $\sigma[V + H(c\bar{c})]$



Dominant systematic Unc.	Signal	Backgrounds
Theory	3.2%	28.3-32.4%
b-tagging	17.8-18.3%	14.7-16.1%
Jet energy	6.7-8%	7-7.5%
MC statistics	7.5-10.8%	34.4-50%

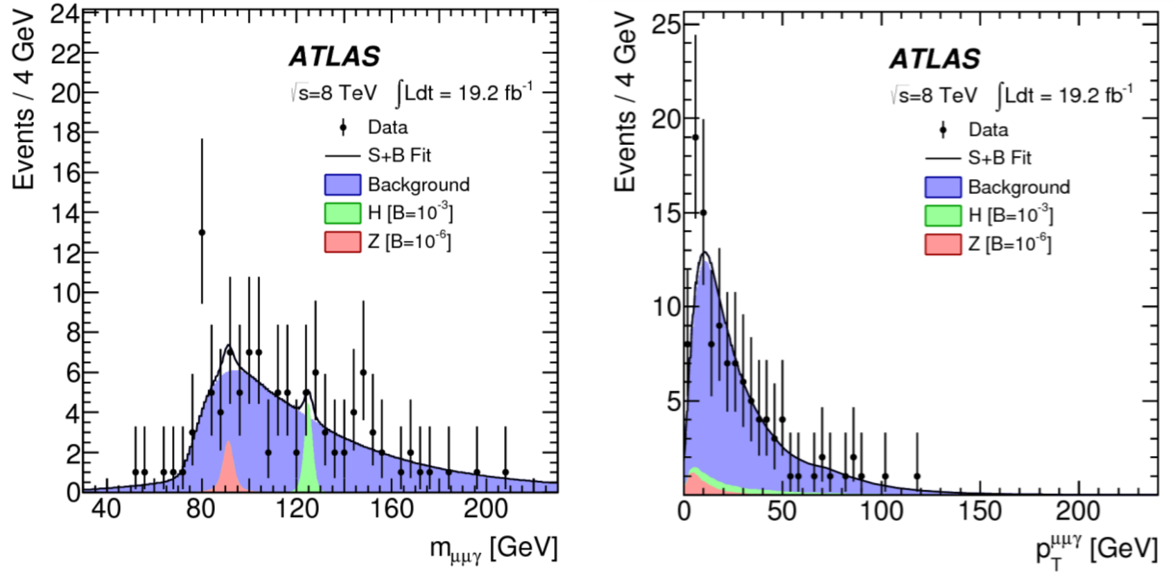
H/Z→J/$\psi\gamma$ @ ATLAS

Phys.Rev.Lett. 114 (2015) no.12, 121801

- Probe H coupling to charm quarks which is sensitive to BSM physics
- Expected branching fractions:
  - BR($H \to J/\psi\gamma$) = $2.8 \pm 0.2 \times 10^{-6}$
  - BR(Z $\to J/\psi\gamma$) = $9.96 \pm 1.86 \times 10^{-8}$
- $\sqrt{s} = 8$ TeV (20.3fb^{-1})
- Main background comes from QCD
- Systematic dominated by luminosity (2.8%) and trigger efficiency (1.7%)
- The upper limit for BR($H \to J/\psi\gamma$) is around $540 \times$ SM prediction

95% CL_s Upper Limits	
$Z \to J/\psi\gamma[10^{-6}]$	
Expected	$2.0^{+1.0}_{-0.6}$
Observed	2.6

Simultaneous fit with the expected limits

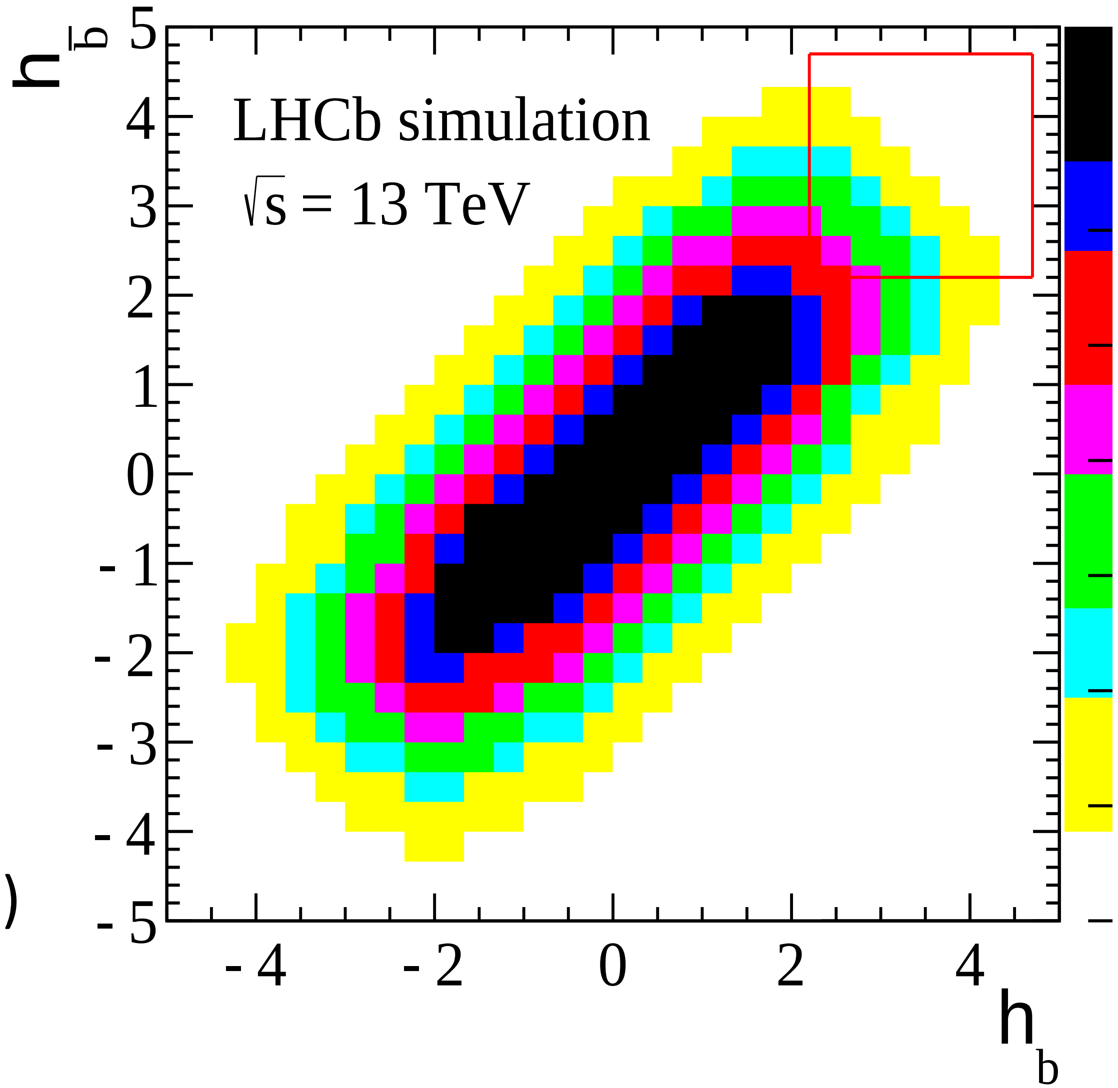


$H \to J/\psi\gamma[10^{-3}]$	
Expected	$1.2^{+0.6}_{-0.3}$
Observed	1.5
$\sigma(pp \to H) \times BR(H \to J/\psi\gamma)$[fb]	
Expected	26^{+12}_{-7}
Observed	33

PROSPECTS for HL-LHC

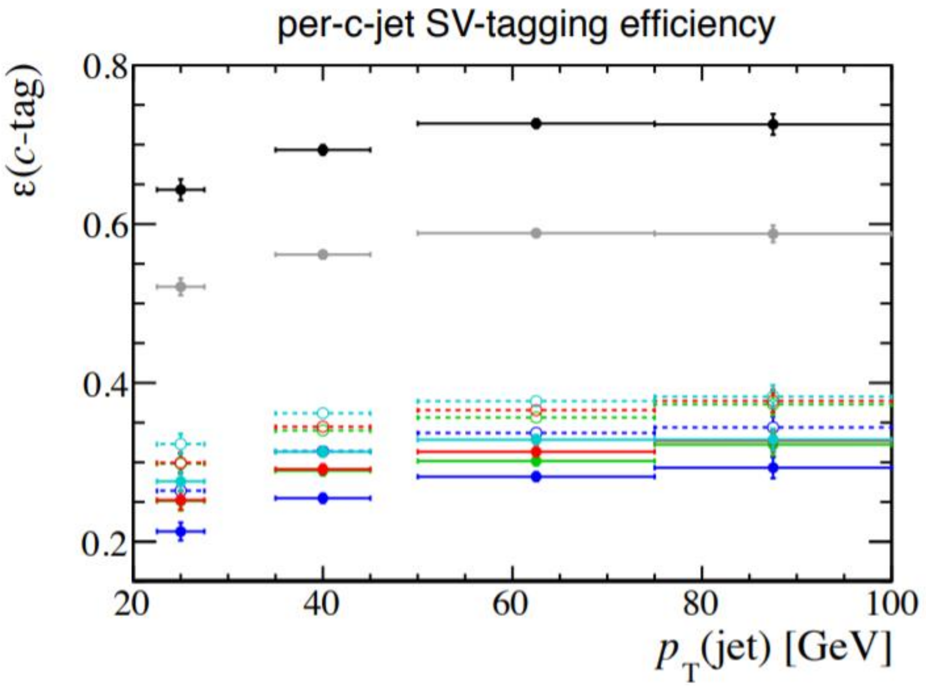
Prospects: H→ $c\bar{c}$ @ LHCb

- Lower luminosity than ATLAS/CMS but unique capabilities for discrimination between b- and c-jets
- LHCb acceptance covers ~5% of the associated production of W/ZH @ 13 TeV
  - When the two jets are in acceptance, the lepton from W/Z tends to be in acceptance as well (~60%)
  - More boosted Higgs is better for LHCb
- Ignoring any improvements in the analysis or detector, the extrapolation of the limit obtained at 8 TeV to 300fb^{-1} @ 14 TeV gives ~50 × BR(SM)



Prospects: H→ $c\bar{c}$ @ LHCb

The c-tagging efficiency will be better in the Phase II due to improvements in the secondary vertex resolution



Perfect detector, i.e. has true SV in kinematic fiducial region.

Perfect IP resolution, but including RECO efficiency (assumed to be same as Run 1, which may not be true), etc.

Phase-II Scenario 2 (RF removed)
Phase-II Scenario 1 (Pixel 4x smaller)
Run 3
Run1
Solid: IP $X^2 > 16$ (as in Run 1)
Dashed: IP $X^2 > 9$

More information in the Flavour WG: session 4 - LHCb material reduction impact (G. M. Ciezarek)

- Considering the improvements in the c-jet tagging and the detector Phase-II, the limit in the branching ratio can be pushed down to 5-10 × BR(SM)

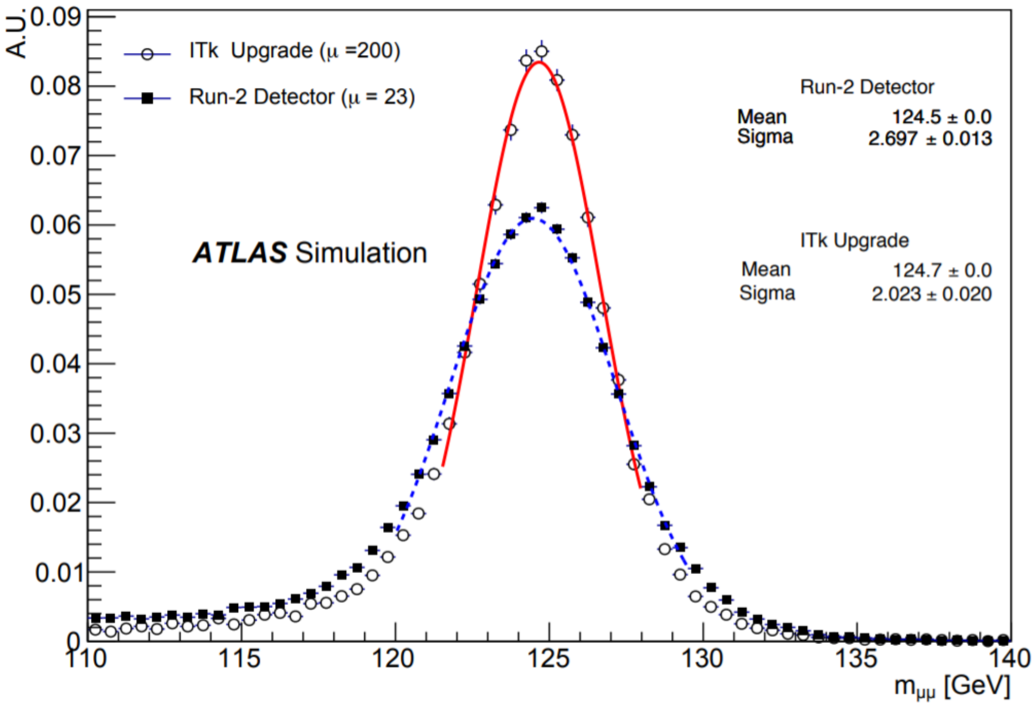
M. Williams and P. Ilten

Prospects: H/Z→J/$\psi\gamma$ @ ATLAS

- Extrapolation obtained considering the same detector performance in Run I
- The requirements in the p_T^{γ} and $p_T^{\mu\mu}$ were raised to increase the background rejection
- Multivariate analysis has been introduced to increase the sensitivity

ATL-PHYS-PUB-2015-043

Prospects	300 fb^{-1}	3000 fb^{-1}	SM
$\mathrm{BR}(Z \to J/\psi\gamma)[10^{-7}]$	$7.0^{2.7}_{-2.0}$	$4.4^{+1.9}_{1.1}$	$4\times$
$\mathrm{BR}(H \to J\psi\gamma)[10^{-6}]$	153^{69}_{-43}	44^{+19}_{-12}	$15\times$
$\sigma(pp \to H) \times BR(H \to J/\psi\gamma)$	$8.6^{+2.4}_{-3.7}$	$2.5^{+0.7}_{-1.0}$	$15\times$

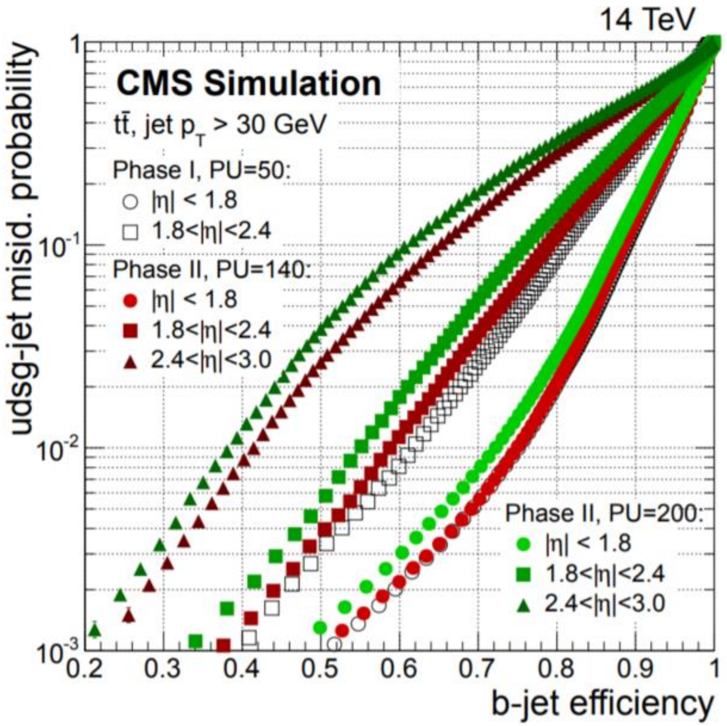


Improvements in the dimuon mass resolution will allow to achieve better limits (ATLAS-TDR-025)

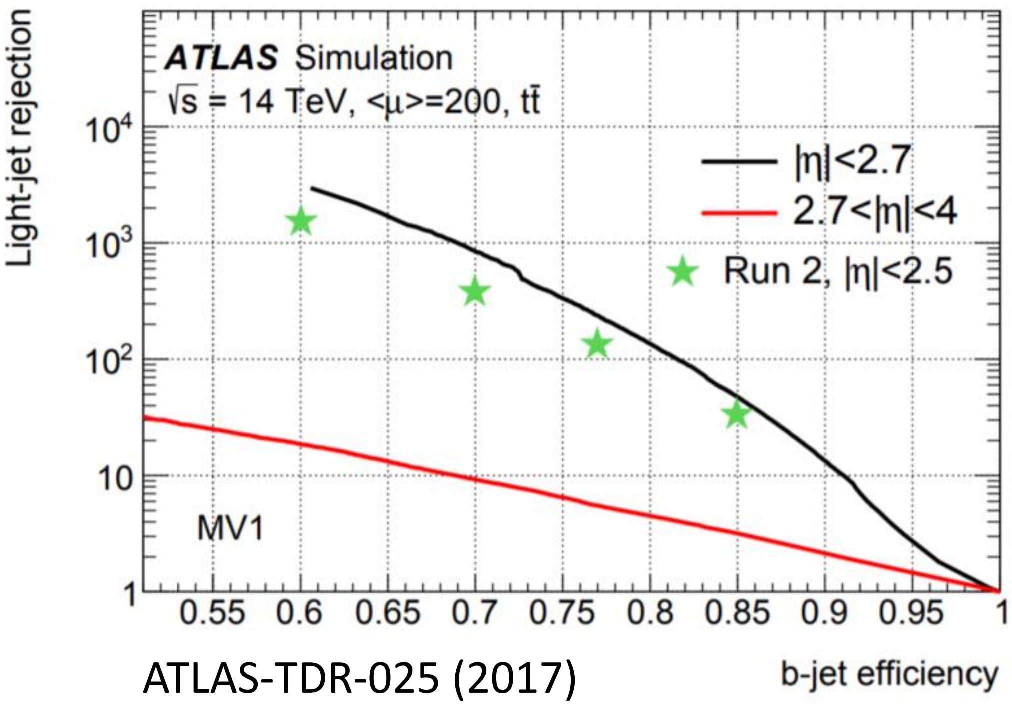
Prospects: VH($b\bar{b}$)

- Powerful b-tagging in the Phase II
- Extrapolation to 3000fb^{-1}:
  - Based in the Run I analysis strategy with higher p_T requirement
  - Only the one and two lepton selections are considered
  - The expected significance is 8.8-9.6σ (signal strength about 15%)

ATL-PHYS-PUB-2014-011



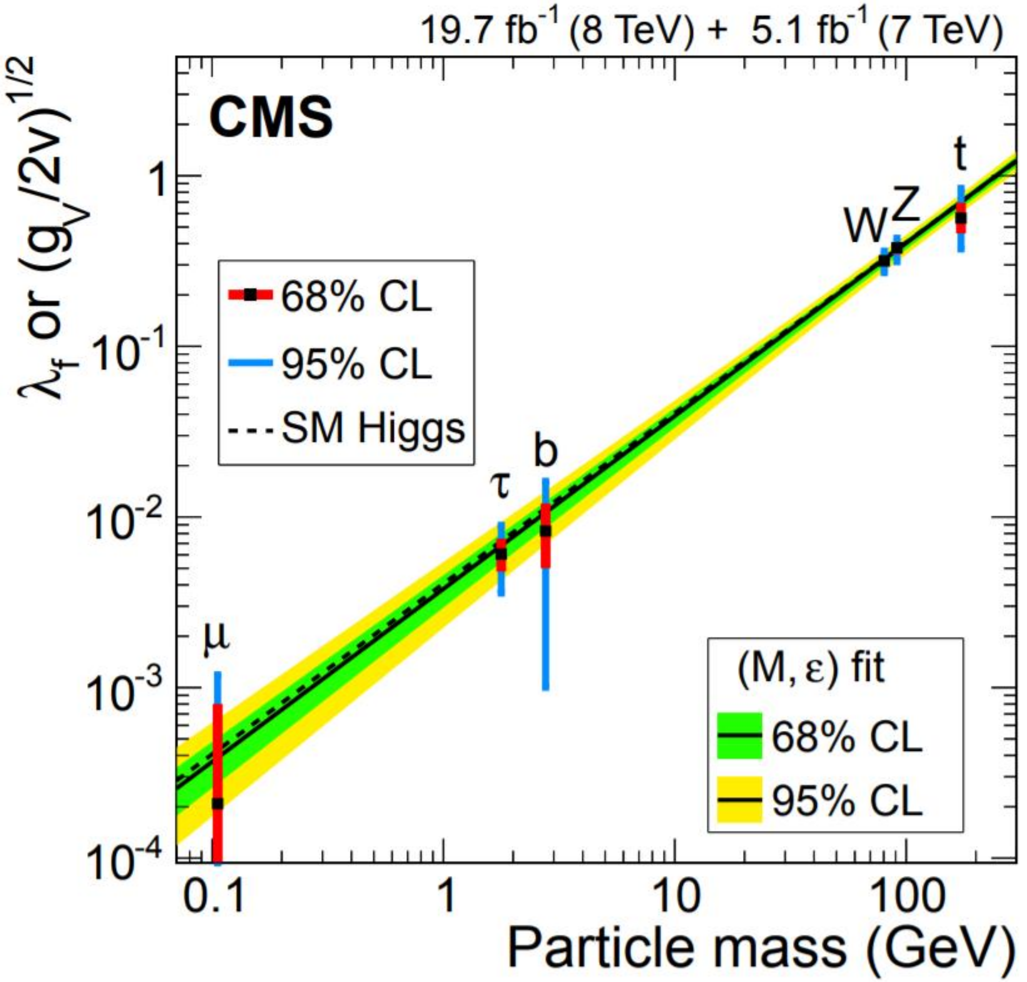
CERN-LHCC-2015-19

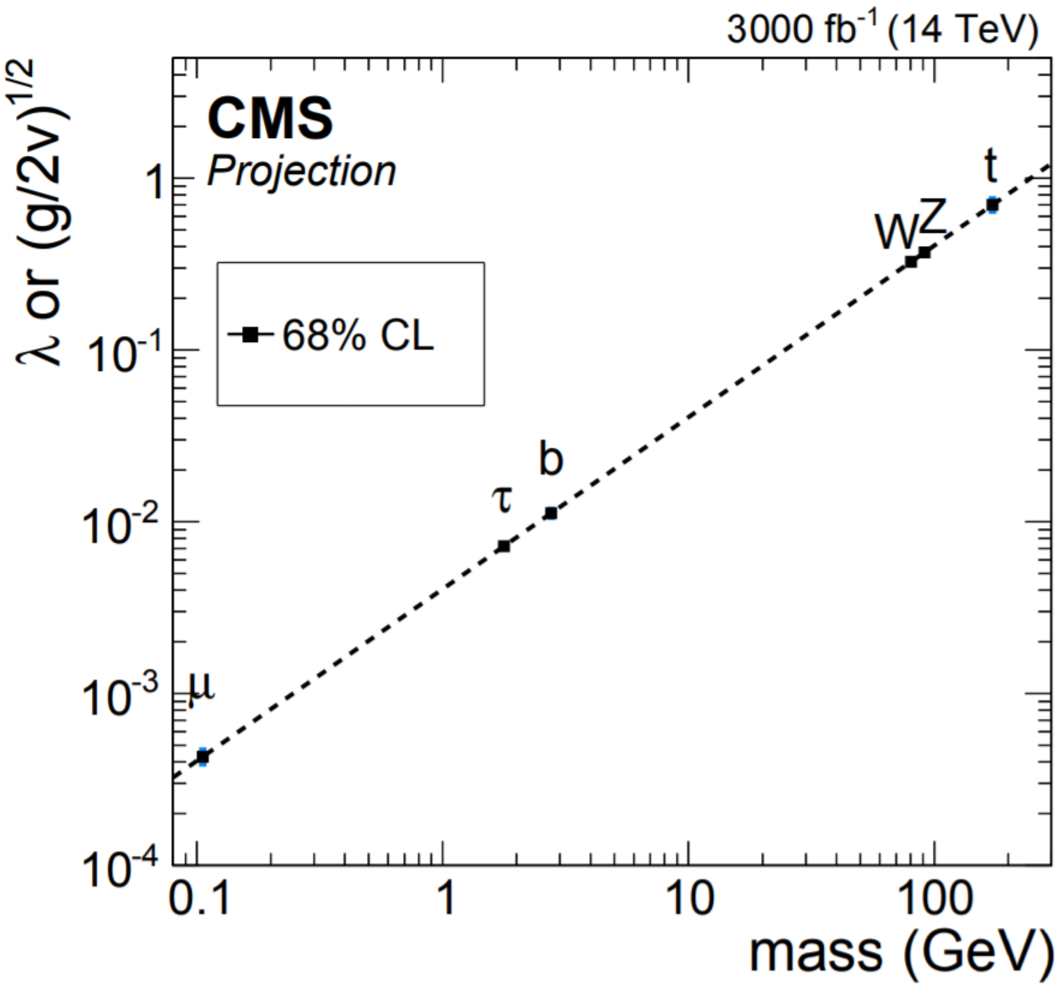


ATLAS-TDR-025 (2017)

Prospects: couplings

CMS Phase-II Upgrade Technical Proposal, LHCC-P-008

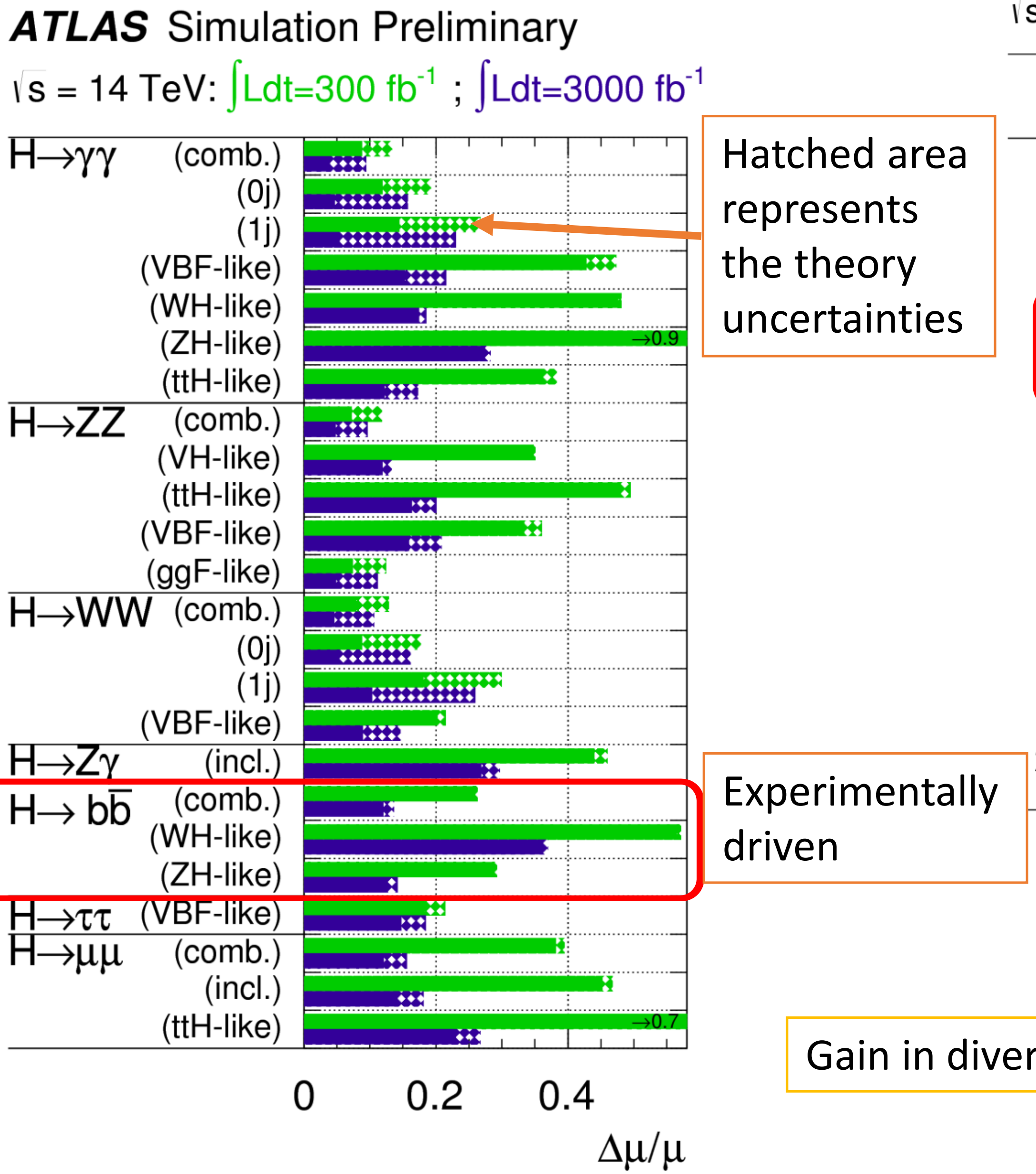


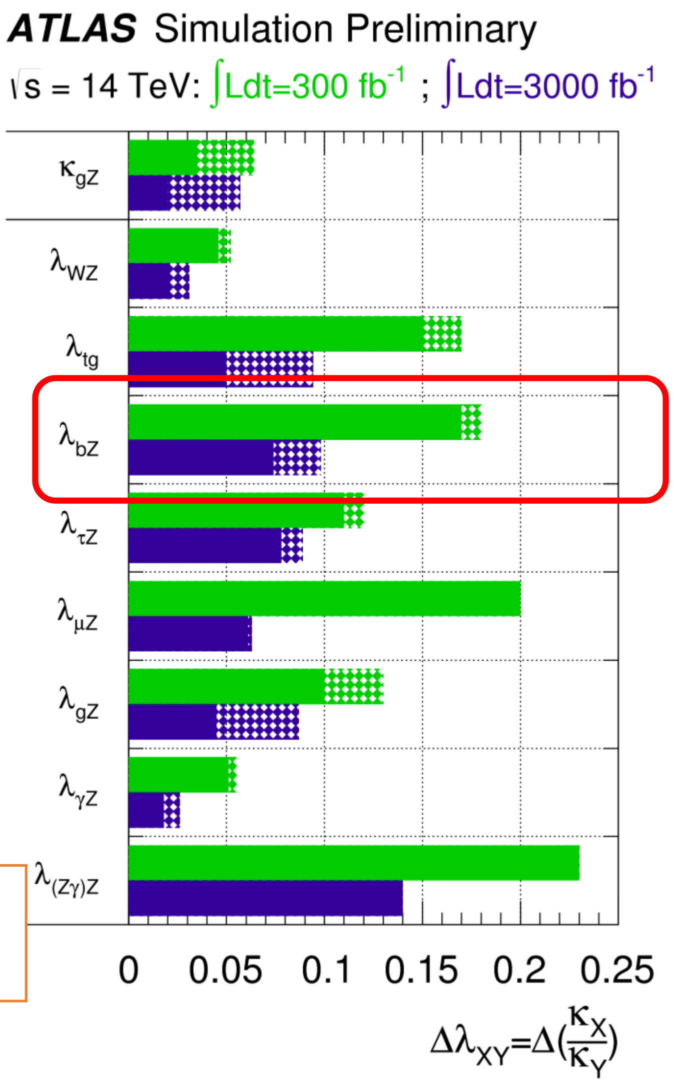


Compared to a precision of about 20% on Higgs boson couplings with Run I data, several percent precision can be reached for most coupling measurements (HL-LHC).

Prospects: couplings

ATL-PHYS-PUB-2014-016





Gain in diversity of production mechanisms

The factors k_i are couplings modifiers with respect to the SM predictions. Therefore, there is a dependency with k_i^2 for the cross sections and branching ratios, e.g.:

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = k_g^2$$

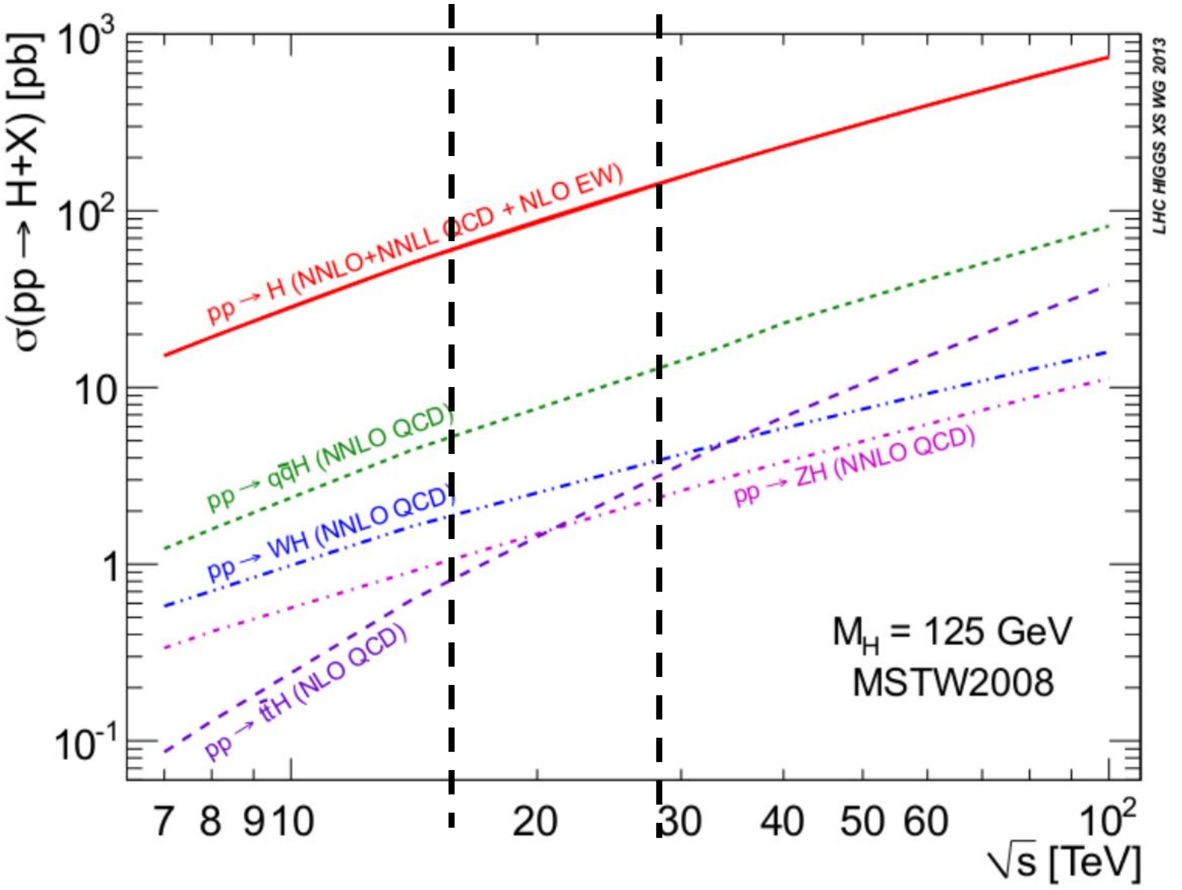
$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = k_b^2$$

Conclusion

- The H $(b\bar{b})$ analyses are close to the observation (5σ)
  - The statistics will double when the 2017 data is included
- Most of the couplings will be at several percent level at HL-LHC $(3000\ \mathrm{fb}^{-1})$
  - Not the case for H$(c\bar{c})$
- LHCb has unique prospects for H$(c\bar{c})$

	Cross section (14 TeV)	Increase factor* (14 TeV-> 27 TeV)	Acceptance ratio increase @ LHCb (14 TeV -> 27 TeV)
ggH	50.3 pb	× 2.8	× 1.4
VBF	4.4 pb	× 3.1	× 1.5
VH	2.5 pb	× 2.4	× 2.0

*Linearly extrapolated



Backup slides

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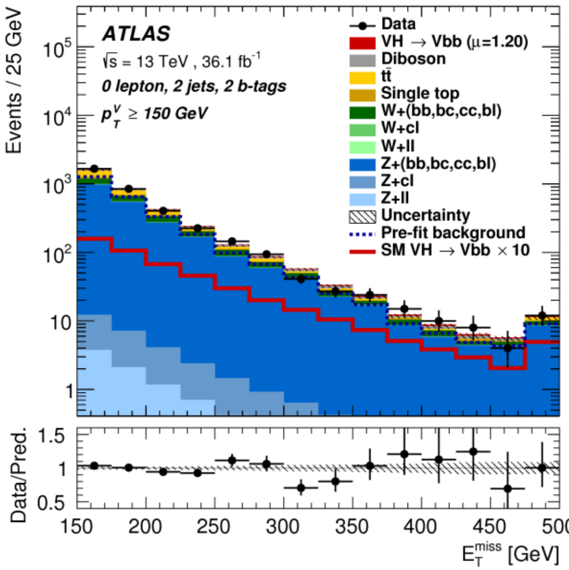
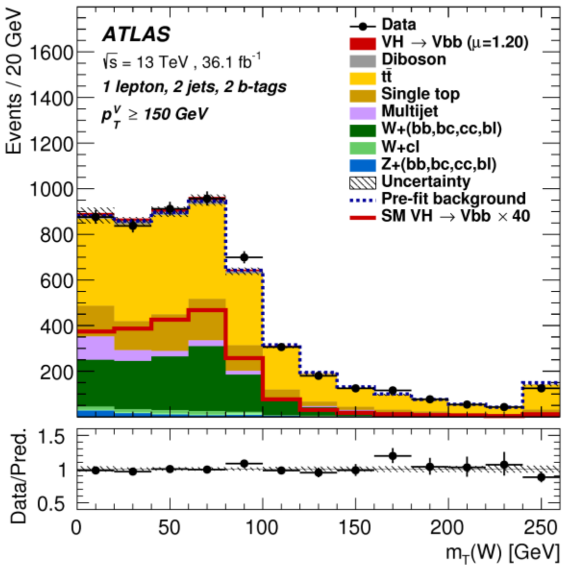
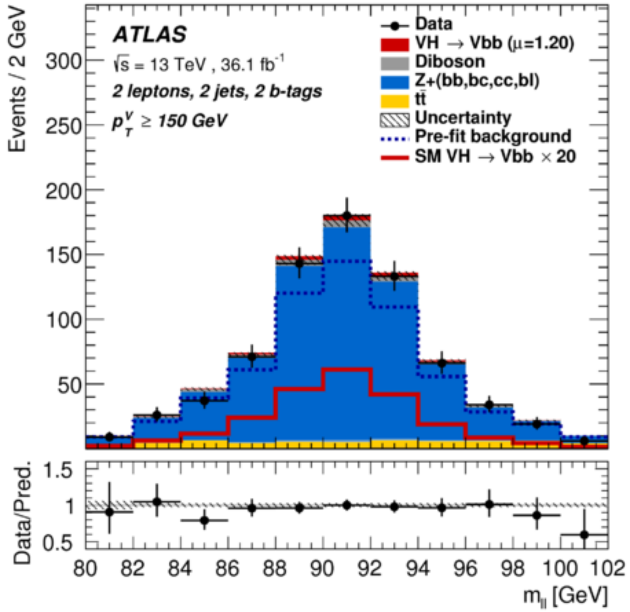
$Z(\nu\nu)/W(\tau nu)H(b\bar{b})$ +,Z+HF, W+HF, ttbar



$WH(l\nu b\bar{b})$, W+HF, ttbar, top



$ZH(llb\bar{b})$,Z+HF, ttbar



arXiv:1708.03299 **submitted**

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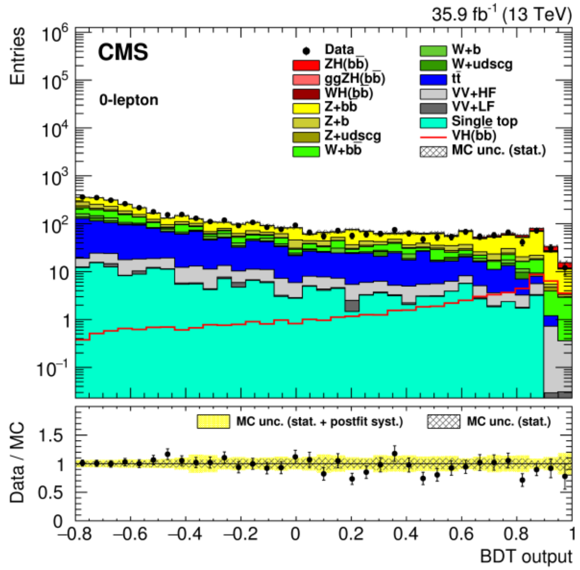
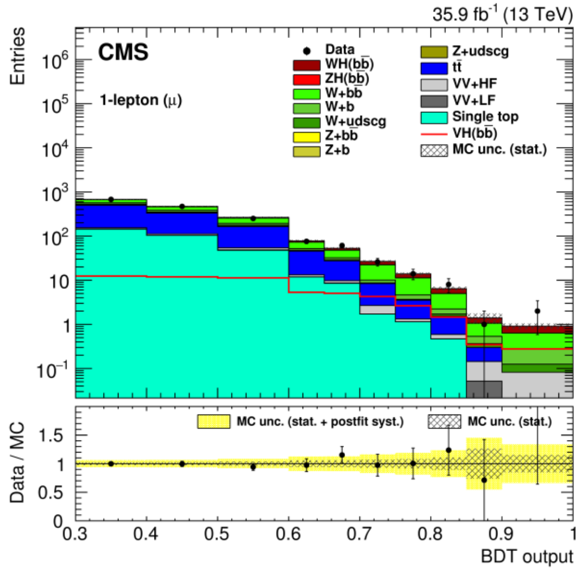
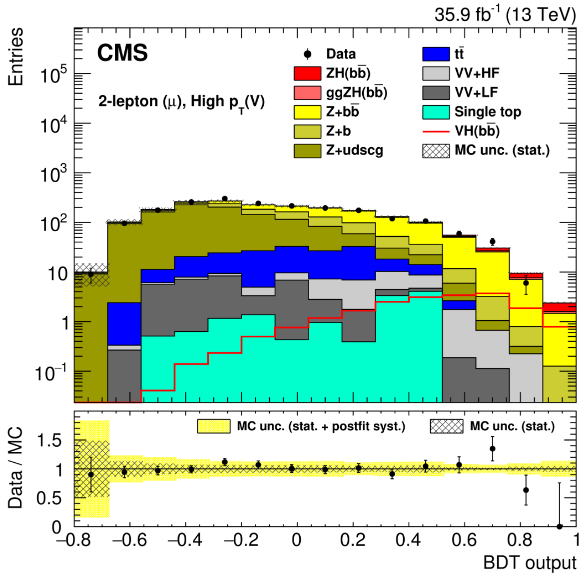
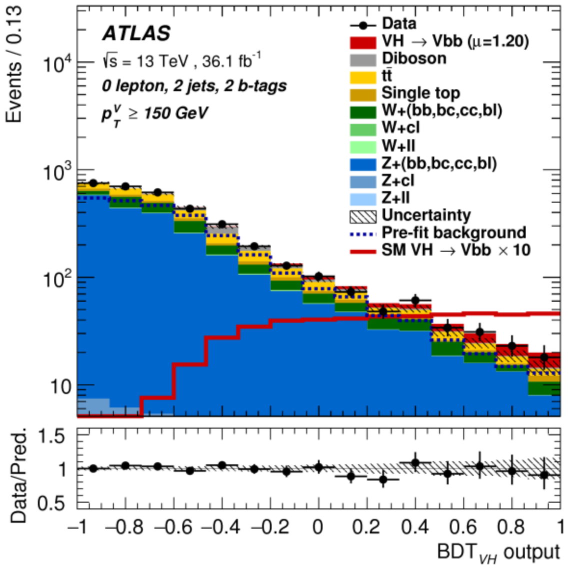


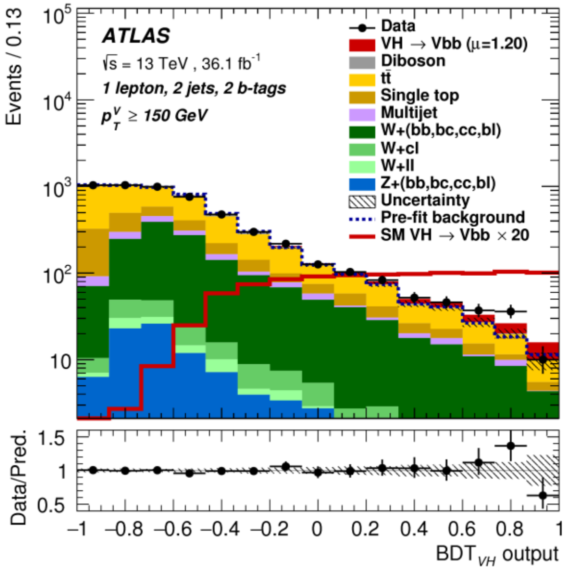


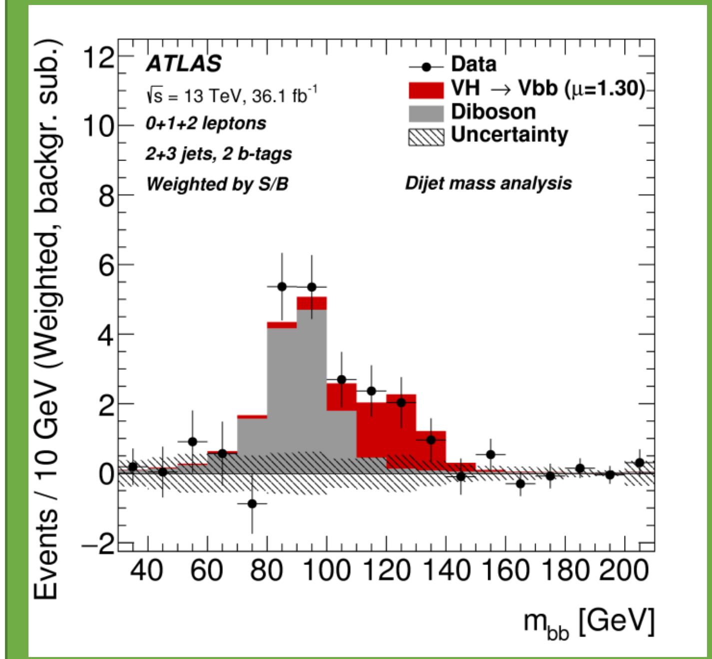


VH(bb) @ ATLAS

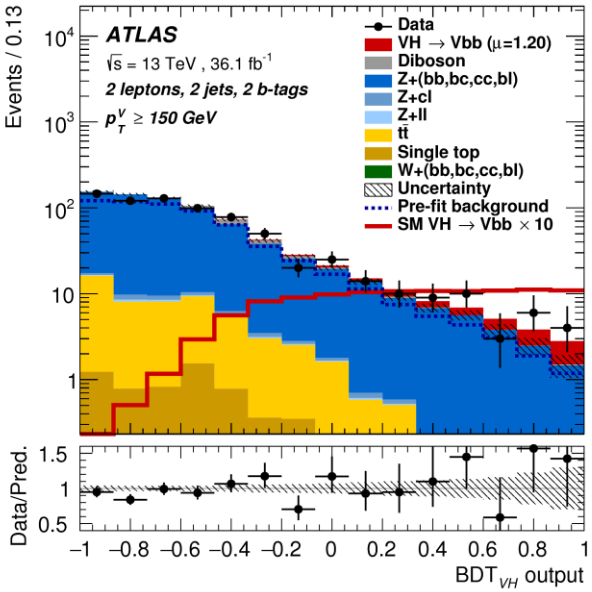
- Final selection using BDT VH(bb)



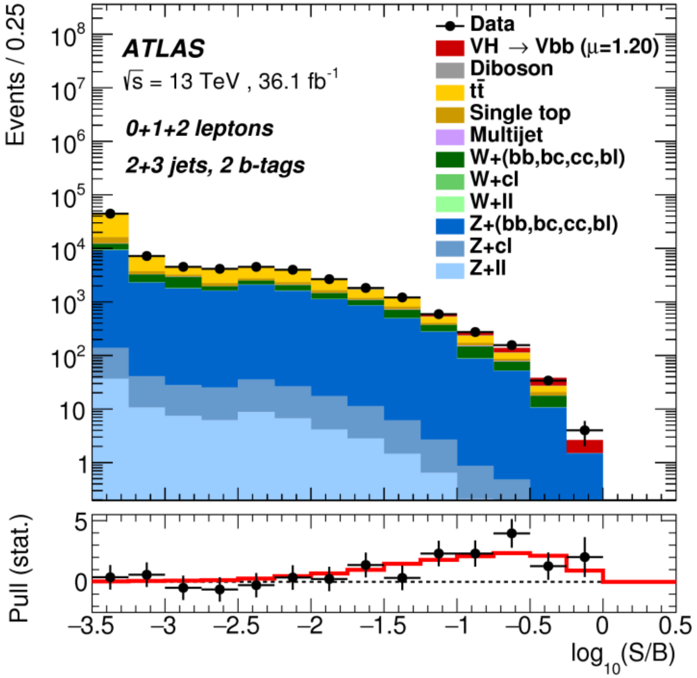




Crosscheck done using the dijet mass analysis with additional cuts to improve the S/B ratio



Combined



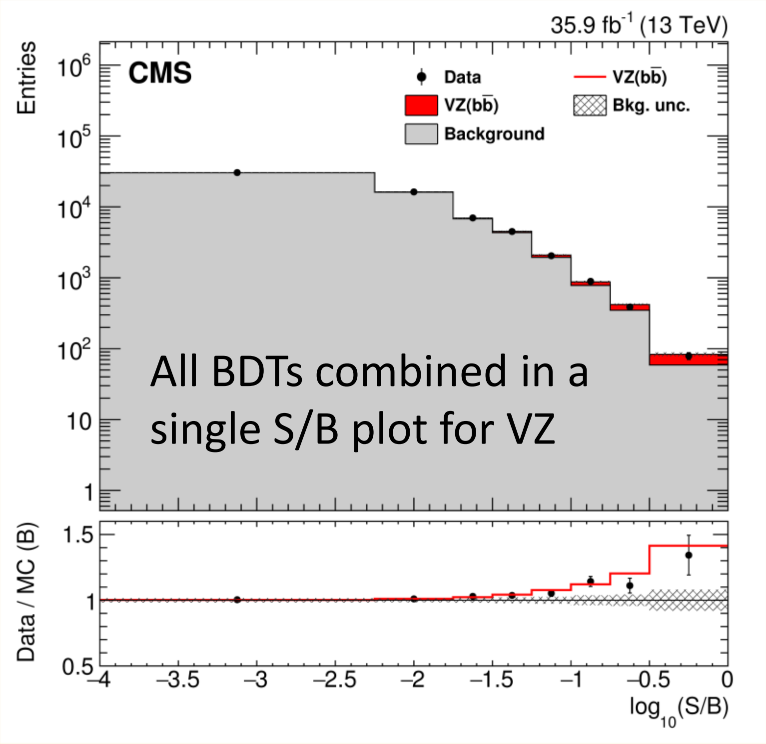
difficult is to model correctly many different backgrounds over a large phase space, so systematics are a concern

arXiv:1708.03299 submitted

VH(bb) @ CMS

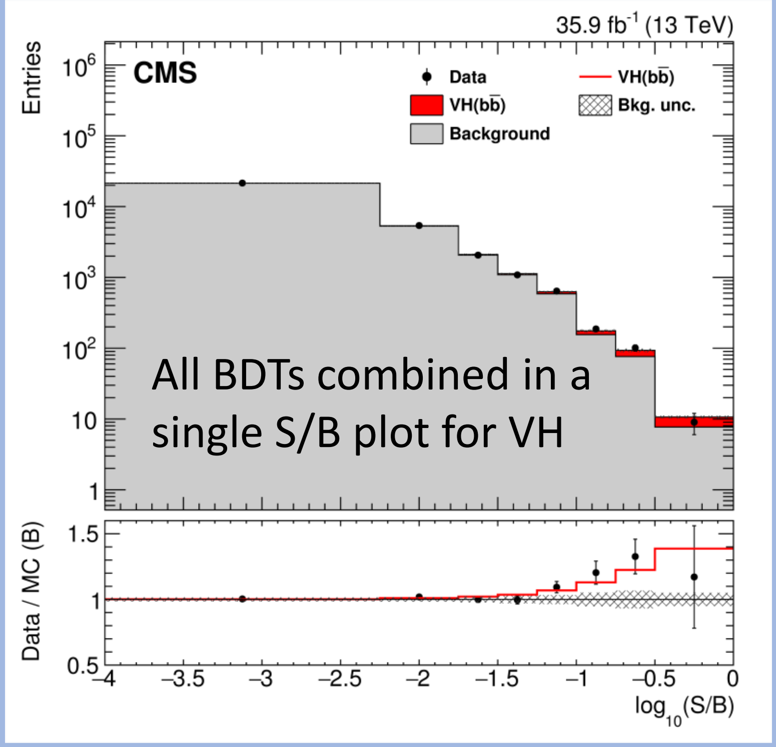
arXiv:1708.03299 submitted

VZ validation

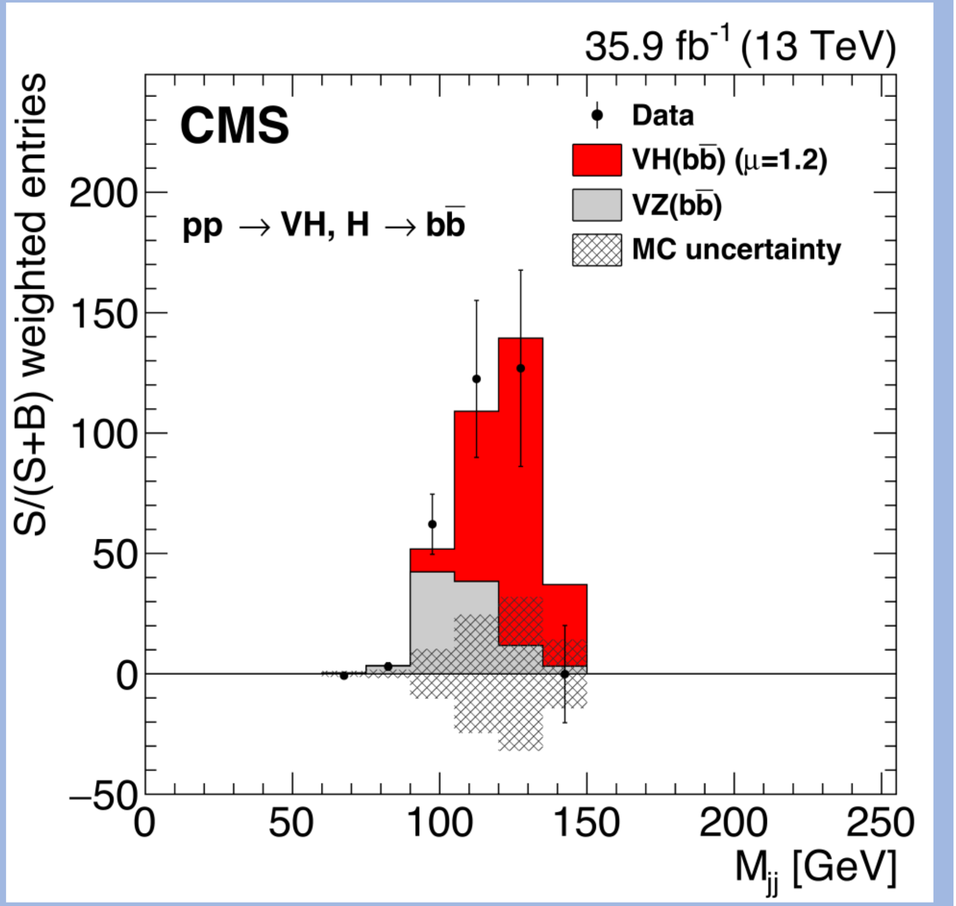


Channels	Significance expected	Significance observed
0-lepton	3.1	2.0
1-lepton	2.6	3.7
2-lepton	3.2	4.5
Combined	4.9	5.0

VH



Channels	Significance expected	Significance observed
0-lepton	1.5	0.0
1-lepton	1.5	3.2
2-lepton	1.8	3.1
Combined	2.8	3.3



Process	√s = 14 TeV	√s = 33 TeV	√s = 40 TeV	√s = 60 TeV	√s = 80 TeV	√s = 100 TeV
ggF [a]	50.35 pb	178.3 pb (3.5)	231.9 pb (4.6)	394.4 pb (7.8)	565.1 pb (11.2)	740.3 pb (14.7)
VBF [b]	4.40 pb	16.5 pb (3.8)	23.1 pb (5.2)	40.8 pb (9.3)	60.0 pb (13.6)	82.0 pb (18.6)
WH [c]	1.63 pb	4.71 pb (2.9)	5.88 pb (3.6)	9.23 pb (5.7)	12.60 pb (7.7)	15.90 pb (9.7)
ZH [c]	0.904 pb	2.97 pb (3.3)	3.78 pb (4.2)	6.19 pb (6.8)	8.71 pb (9.6)	11.26 pb (12.5)
ttH [d]	0.623 pb	4.56 pb (7.3)	6.79 pb (11)	15.0 pb (24)	25.5 pb (41)	37.9 pb (61)
bbH [e]	0.581 pb	2.13 pb (3.7)	2.77 pb (4.8)	4.69 pb (8.1)	6.65 pb (11)	8.64 pb (15)
gg → HH[f]*(λ=1)*	33.8 fb	207 fb (6.1)	298 fb (8.8)	609 fb (18)	980 fb (29)	1.42 pb (42)

PDF is NNLO(NLO) MSTW2008 set. Numbers in () parentheses are the cross-section ratio wrt 14 TeV.

a) NNLO+NNLL QCD + NLO EW corrections. QCD scale and PDF+α_S uncertainties remain constant about +-8% for both (D. de Florian).

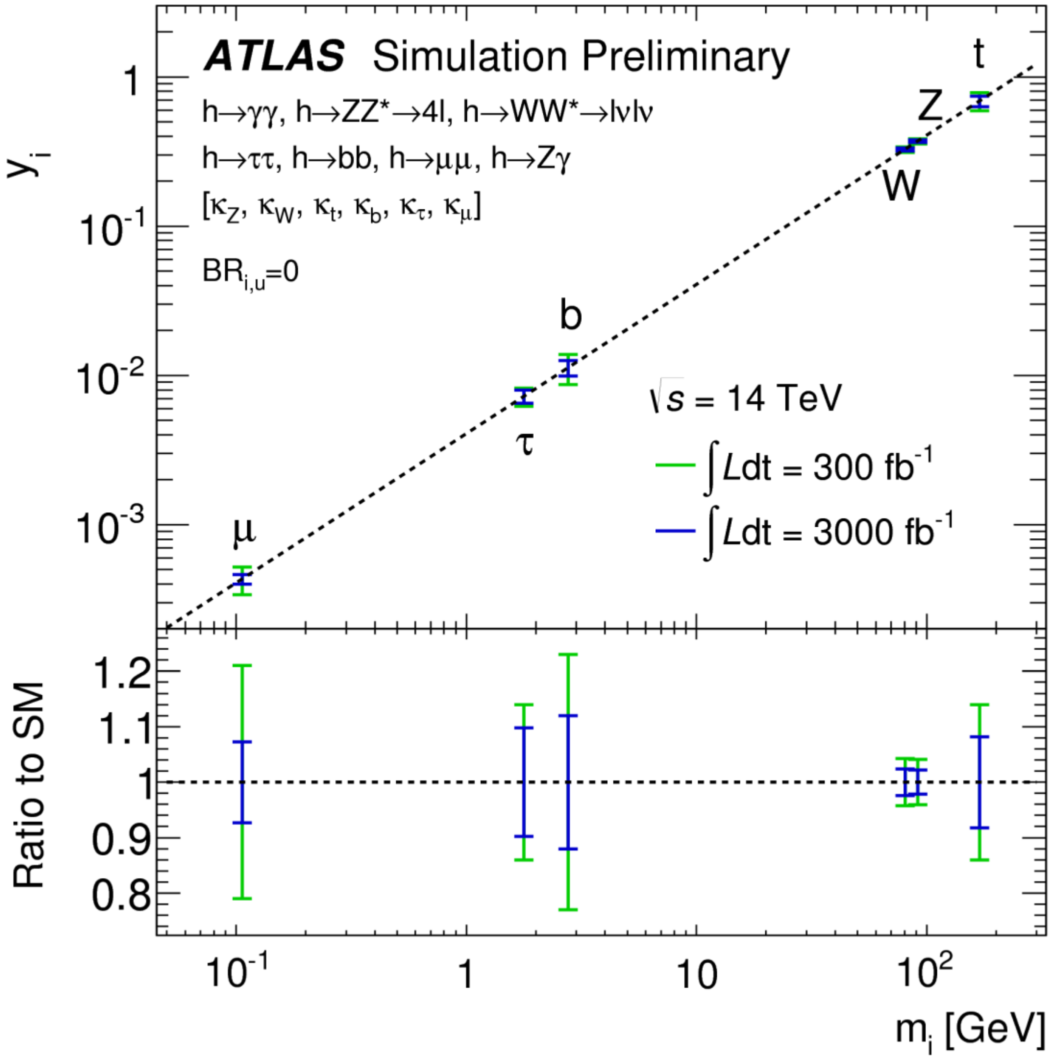
b) NNLO QCD only with VBF@NNLO (M. Zaro).

c) NNLO QCD only with VH@NNLO (R. Harlander).

d) NLO QCD. (M. Spira).

e) NNLO QCD in 5FS (R. Harlander).

f) NLO QCD with HPAIR. The central scale is the invariant mass of the Higgs pair. The scale is varied by a factor 2 up and down. (M. Spira).



Bosons $y_{V,i} = \sqrt{K_{V,i} \frac{g_{V,i}}{2v}} = \sqrt{K_{V,i}} \frac{m_{V,i}}{v}$

Fermions $y_{F,i} = K_{F,i} \frac{g_{F,i}}{\sqrt{2}} = K_{F,i} \frac{m_{F,i}}{v}$

H/Z→J/$\psi\gamma$ @ ATLAS

Phys.Rev.Lett. 114 (2015) no.12, 121801

95% CL_s Upper Limits	
$Z \to J/\psi\gamma[10^{-6}]$	
Expected	$2.0^{+1.0}_{-0.6}$
Observed	2.6
$H \to J/\psi\gamma[10^{-3}]$	
Expected	$1.2^{+0.6}_{-0.3}$
Observed	1.5
$\sigma(pp \to H) \times BR(H \to J/\psi\gamma)[fb]$	
Expected	26^{+12}_{-7}
Observed	33

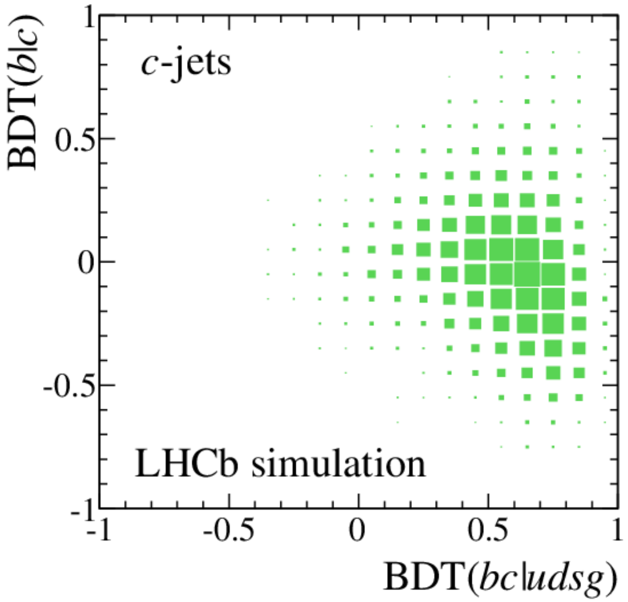
The upper limit for BR($H \to J/\psi\gamma$) is around $540 \times$ SM prediction

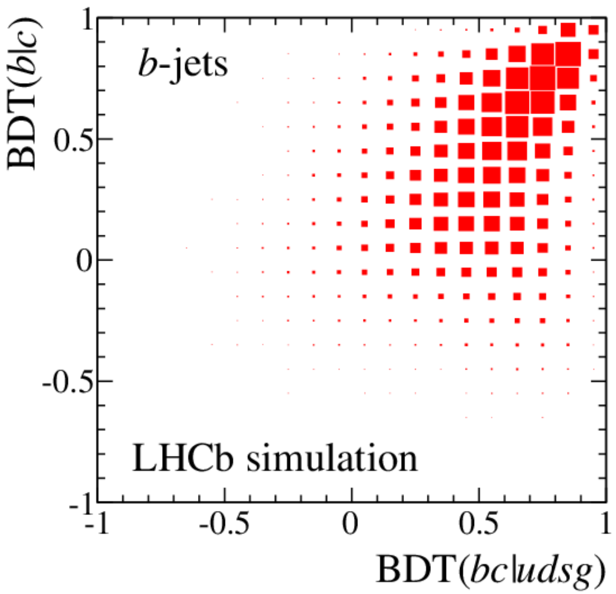
Systematic uncertainties	
Trigger Efficiency	1.7%
Photon reconstruction and identification efficiency	0.5-0.7%
Muon reconstruction and identification efficiency	0.4%
Integrated luminosity	2.8%
Photon energy	0.2%

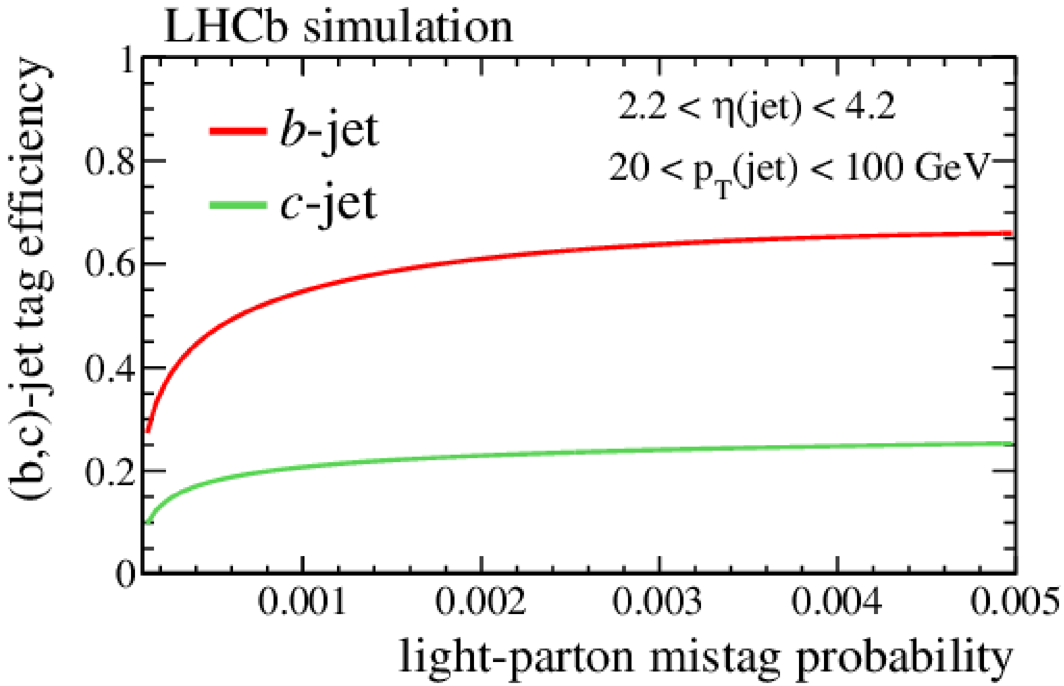
Tagging @ LHCb

[J. Instrum. 10 (2015) P06013](#)

- Powerful heavy quark tagging
- For jets with $20\text{ GeV} < p_T^j < 100\text{ GeV}$ and $2.2 < \eta^j < 4.2$:
  - Efficiency of b-jet tagging $\sim$ 65%
  - Efficiency of c-jet tagging $\sim$ 20%
  - Misidentification of a light-jet $\sim$ 0.3%







Search for the VH($b\bar{b}$ or $c\bar{c}$) @ LHCb

LHCB-CONF-2016-006

- Possible enhancements of the H($c\bar{c}$) SM predictions have been suggested by

G. Perez et al. Phys. Rev. D92 (2015) 033016 arXiv: 1503.00290

$$\sigma\left[V + H^0\left(b\bar{b}\right)\right] < 1.6\, pb\ at\ 95\ \%\ CL \quad (50 \times \text{SM})$$
$$\sigma\left[V + H^0\left(c\bar{c}\right)\right] < 9.4\, pb\ at\ 95\ \%\ CL\ (6200 \times SM)$$

First experimental limit set on the $\sigma\left[V + H\left(c\bar{c}\right)\right]$

Dominant systematic Unc.	Signal	Backgrounds
Theory	3.2%	28.3-32.4%
b-tagging	17.8-18.3%	14.7-16.1
Jet energy	6.7-8%	7-7.5%
MC statistics	7.5-10.8%	34.4-50%

Z/W+H($b\bar{b}$) distributions with μ in the final state