

Higgs plus Heavy Flavour: searches and measurements from Run I

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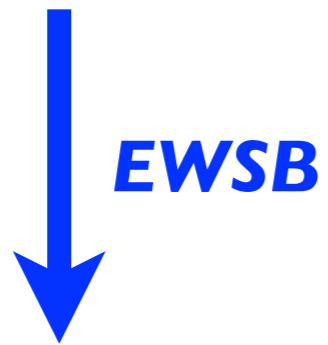
on behalf of the ATLAS and CMS Collaborations

LHCPh 2015, Sept. 4 2015, St. Petersburg

Overview

The SM Yukawa sector:

$$\lambda_{ij} \bar{\Psi}_i \Psi_j \Phi_H$$



**Flavour-diagonal
scalar interactions**

$$\lambda_\psi \bar{\psi}_L \psi_R H + h.c.$$

Overview

The SM Yukawa sector:

$$\lambda_{ij} \bar{\Psi}_i \Psi_j \Phi_H$$

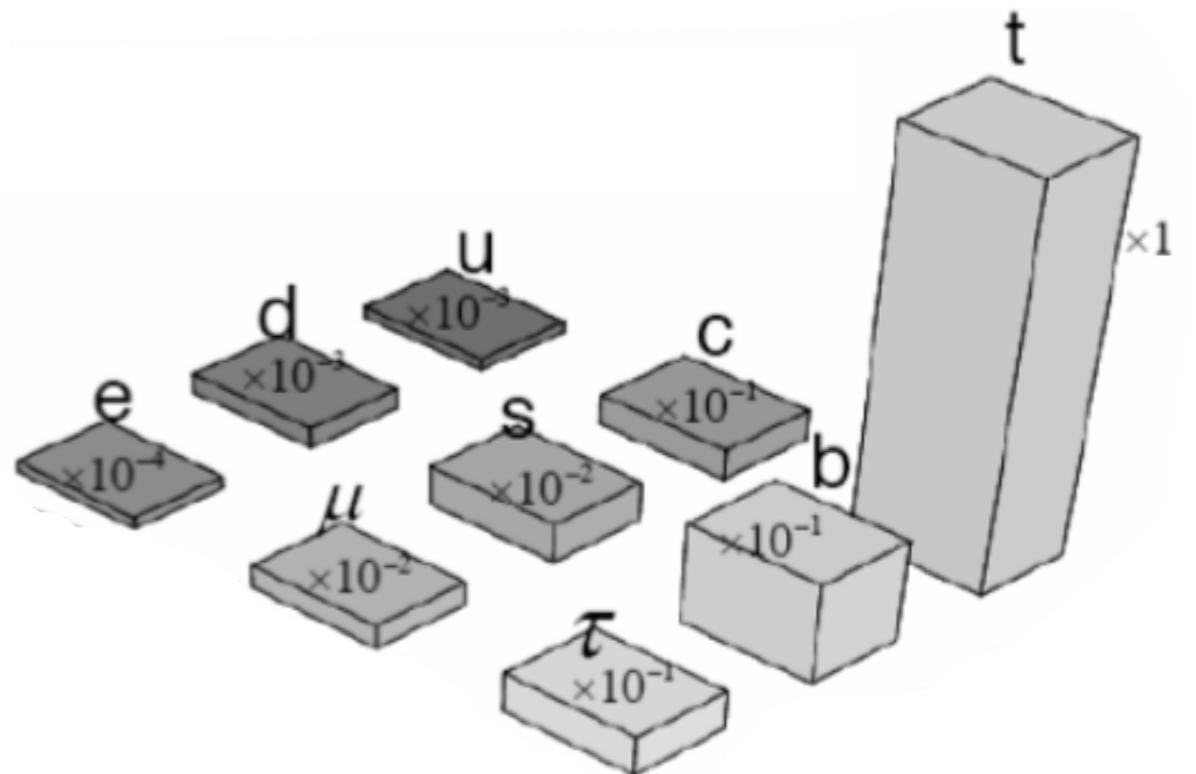
↓
EWSB

**Flavour-diagonal
scalar interactions**

$$\lambda_\psi \bar{\psi}_L \psi_R H + h.c.$$



$$\lambda_\psi = \kappa_\psi \frac{\sqrt{2} m_\psi}{v} \quad \kappa_\psi^{\text{SM}} = 1$$



Overview

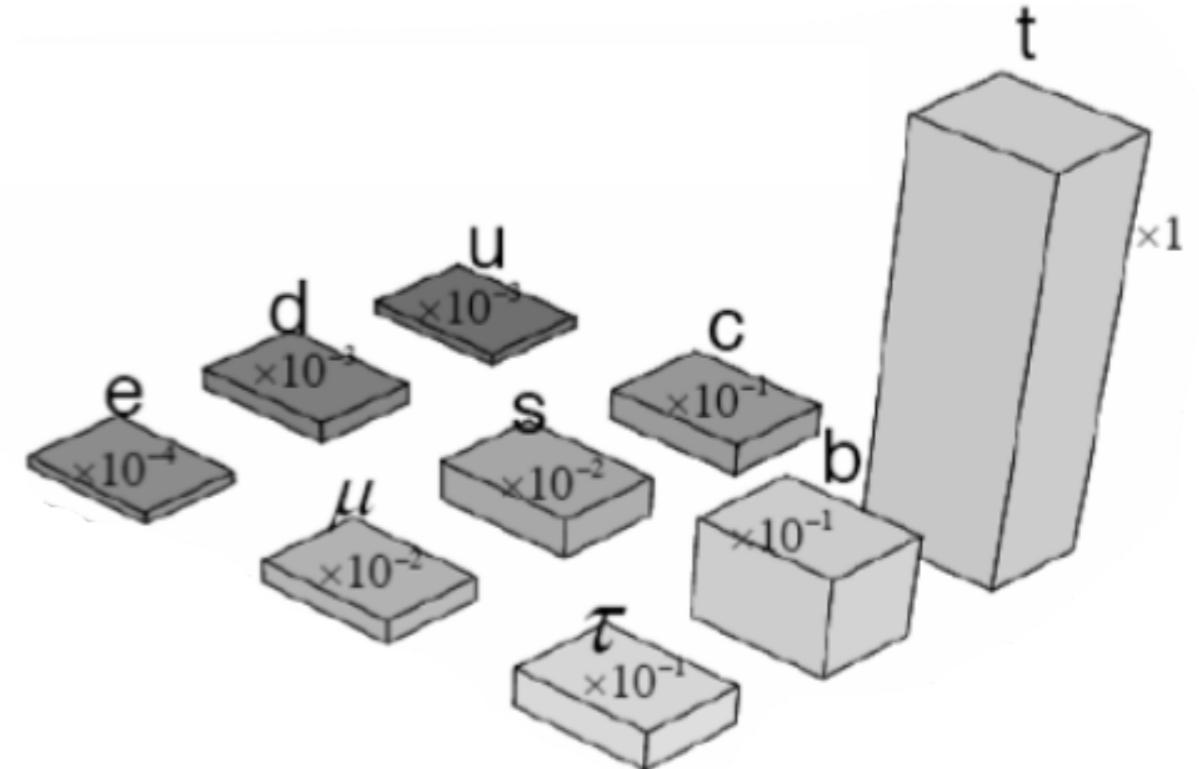
The SM Yukawa sector:

$$\lambda_{ij} \bar{\Psi}_i \Psi_j \Phi_H$$

↓
EWSB

Flavour-diagonal
scalar interactions

$$\lambda_\psi \bar{\psi}_L \psi_R H + h.c.$$



$$\lambda_\psi = \kappa_\psi \frac{\sqrt{2} m_\psi}{v}$$

$$\kappa_\psi^{\text{SM}} = 1$$

At the LHC, we measure:

$$\sigma_{xx \rightarrow H} \times \mathcal{B}(H \rightarrow yy)$$

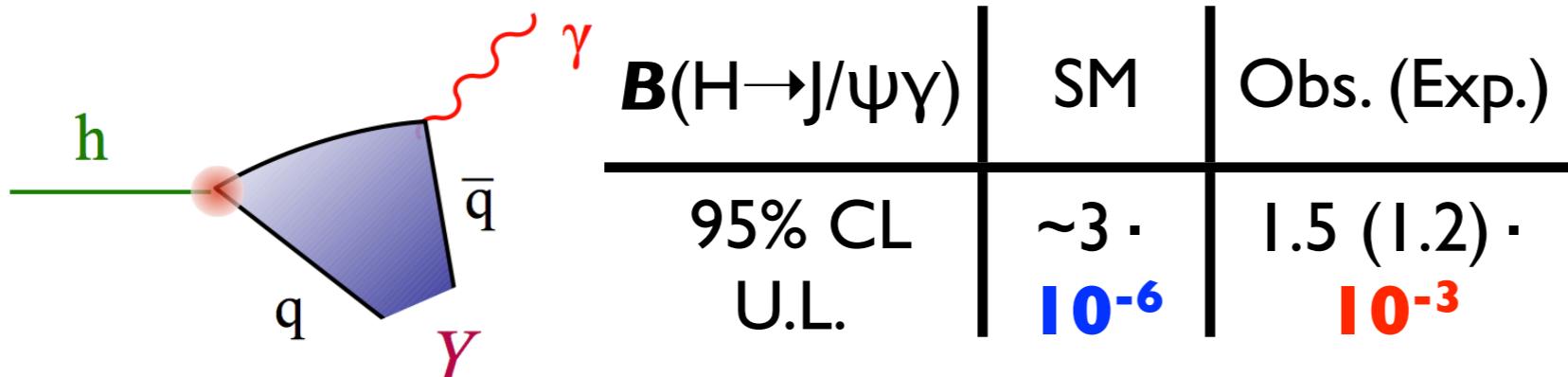
→

- ratios of κ 's
- κ 's (+ model assumptions)

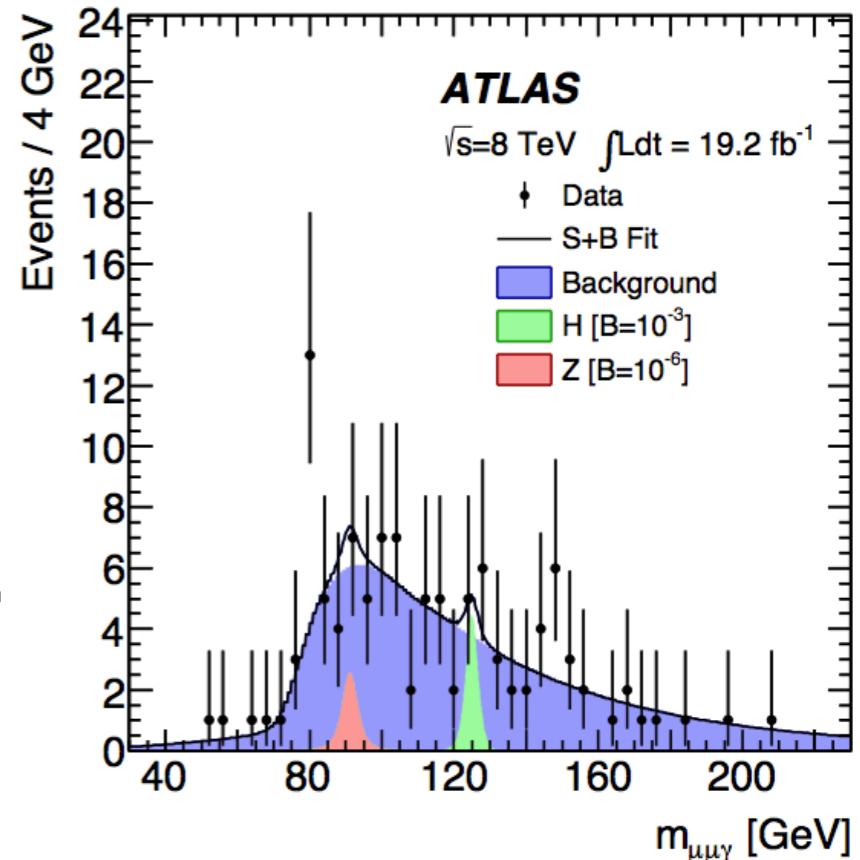
The charm and bottom Yukawa's

- **Charm quark**

- ▶ identification of $H \rightarrow cc$ decays experimentally challenging
- ▶ $H \rightarrow J/\Psi \gamma$ as a viable probe for c-H coupling
 $\rightarrow \mu\mu$



ATLAS, PRL 114 121801 (2015)
CMS, arXiv:1507.03031 (2015)

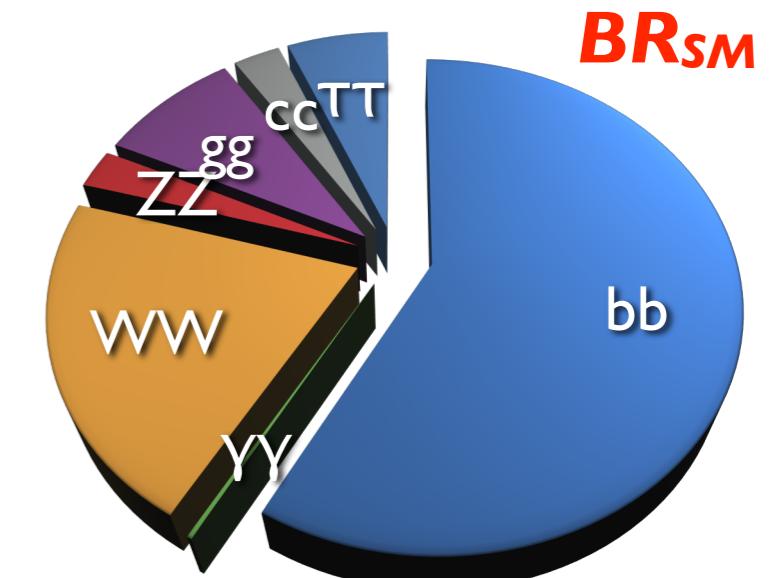


- **Bottom quark**

- ▶ accessible through $H \rightarrow bb$ decays (b tagging)
- ▶ K_b important to constrain BR_{BSM}

$$\kappa_H^2(\kappa_i, m_H) = \sum_{j = WW^{(*)}, ZZ^{(*)}, b\bar{b}, \tau^-\tau^+, \gamma\gamma, Z\gamma, gg, t\bar{t}, c\bar{c}, s\bar{s}, \mu^-\mu^+} \frac{\Gamma_j(\kappa_i, m_H)}{\Gamma_H^{\text{SM}}(m_H)}$$

$\approx 58\%$

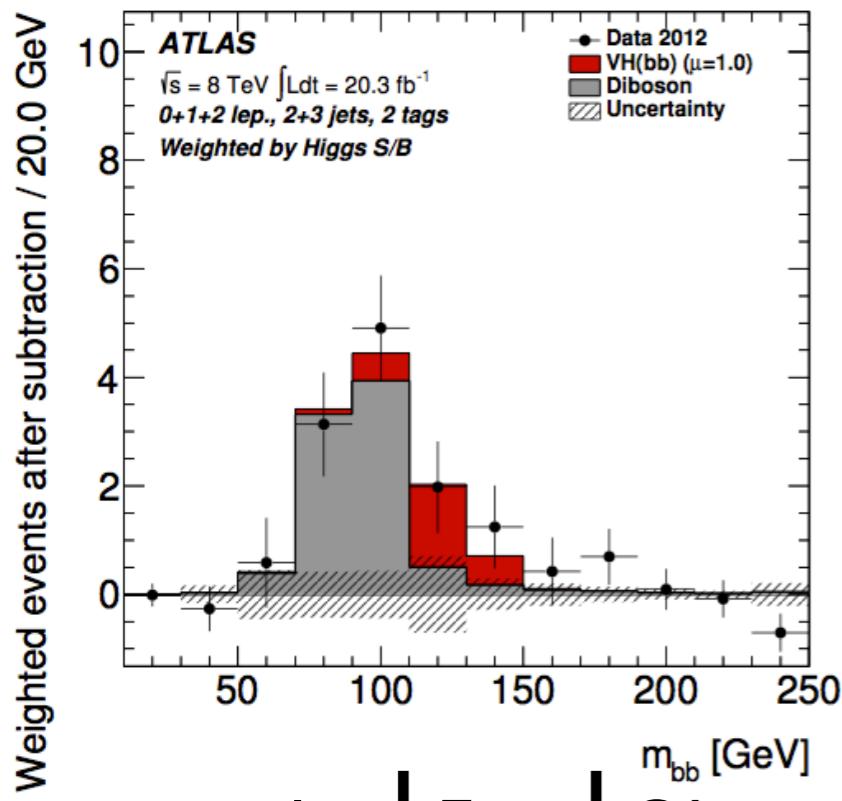


Higgs to bottom quarks

$(Z, W^\pm)H \rightarrow bb$

► 0, 1, 2-leptons + jets

CMS, PRD 89 012003 (2014)
ATLAS, JHEP 01 (2015) 069

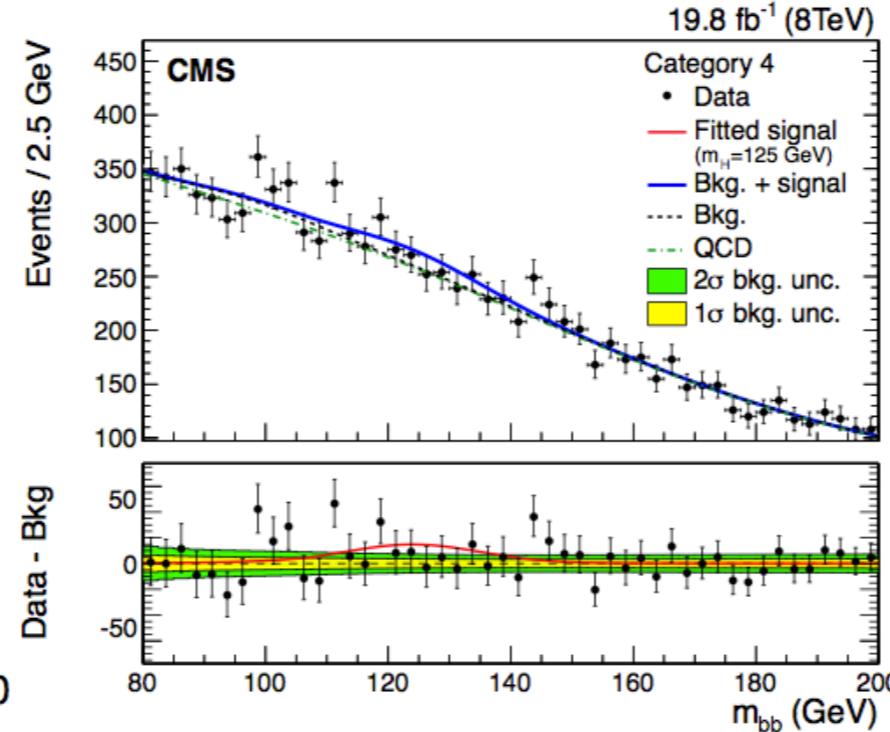


p-value	Exp.	Obs.
CMS	2.1σ	2.1σ
ATLAS	2.6σ	1.4σ

VBF $\rightarrow bb$

► 0 leptons + jets

CMS, 1506.01010,
submitted to PRD

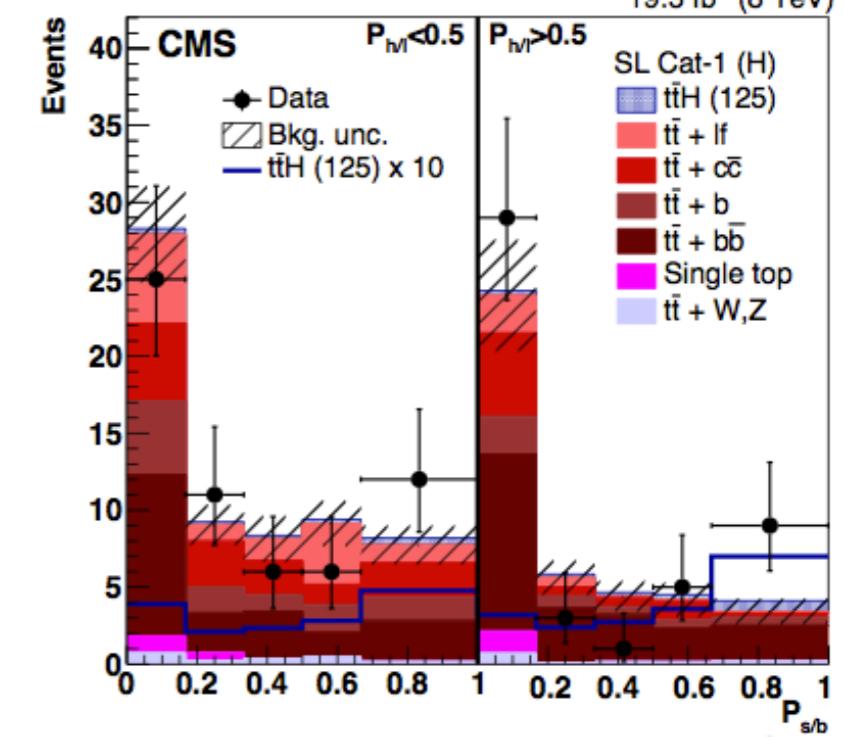


6

tth $\rightarrow bb$

► 1-2 leptons + jets

CMS, JHEP 09 (2014) 087
CMS, EPJC 75 (2015) 212
ATLAS, EPJC 75 (2015) 349



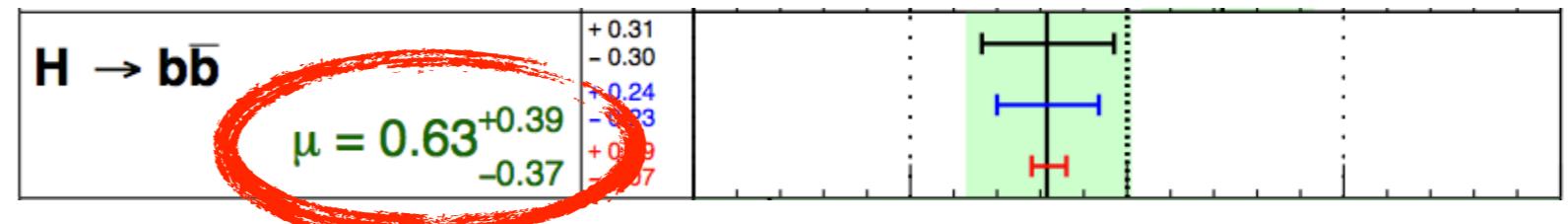
	$\mu^{95\%}$	Exp.	Obs.
CMS	<3.5	<4.1	
ATLAS	<2.2		<3.4

Results from Run I: $\mu \sigma \times BR$

- ATLAS

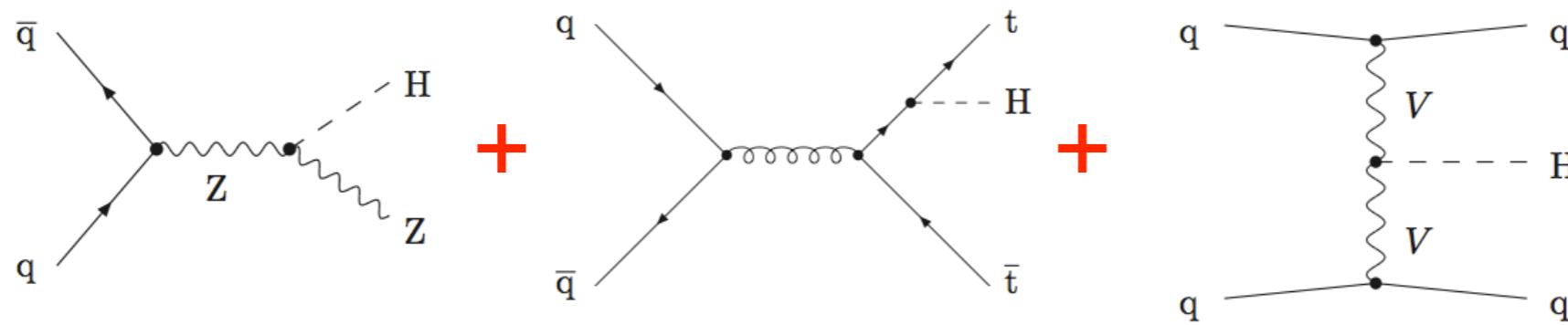
- ▶ VH + ttH

ATLAS, arXiv:1507.04548, submitted to EPJC



- CMS

- ▶ VH + ttH + VBF



CMS, arXiv:1506.01010, submitted to PRD

Channel	H → bb̄	Best fit (68% CL)		Upper limits (95% CL)		Signal significance	
		Observed	Expected	Observed	Expected	Observed	Expected
VH		0.89 ± 0.43		1.68	0.85	2.08	2.52
ttH		0.7 ± 1.8		4.1	3.5	0.37	0.58
VBF		$2.8^{+1.6}_{-1.4}$		5.5	2.5	2.20	0.83
Combined		$1.03^{+0.44}_{-0.42}$		1.77	0.78	2.56	2.70

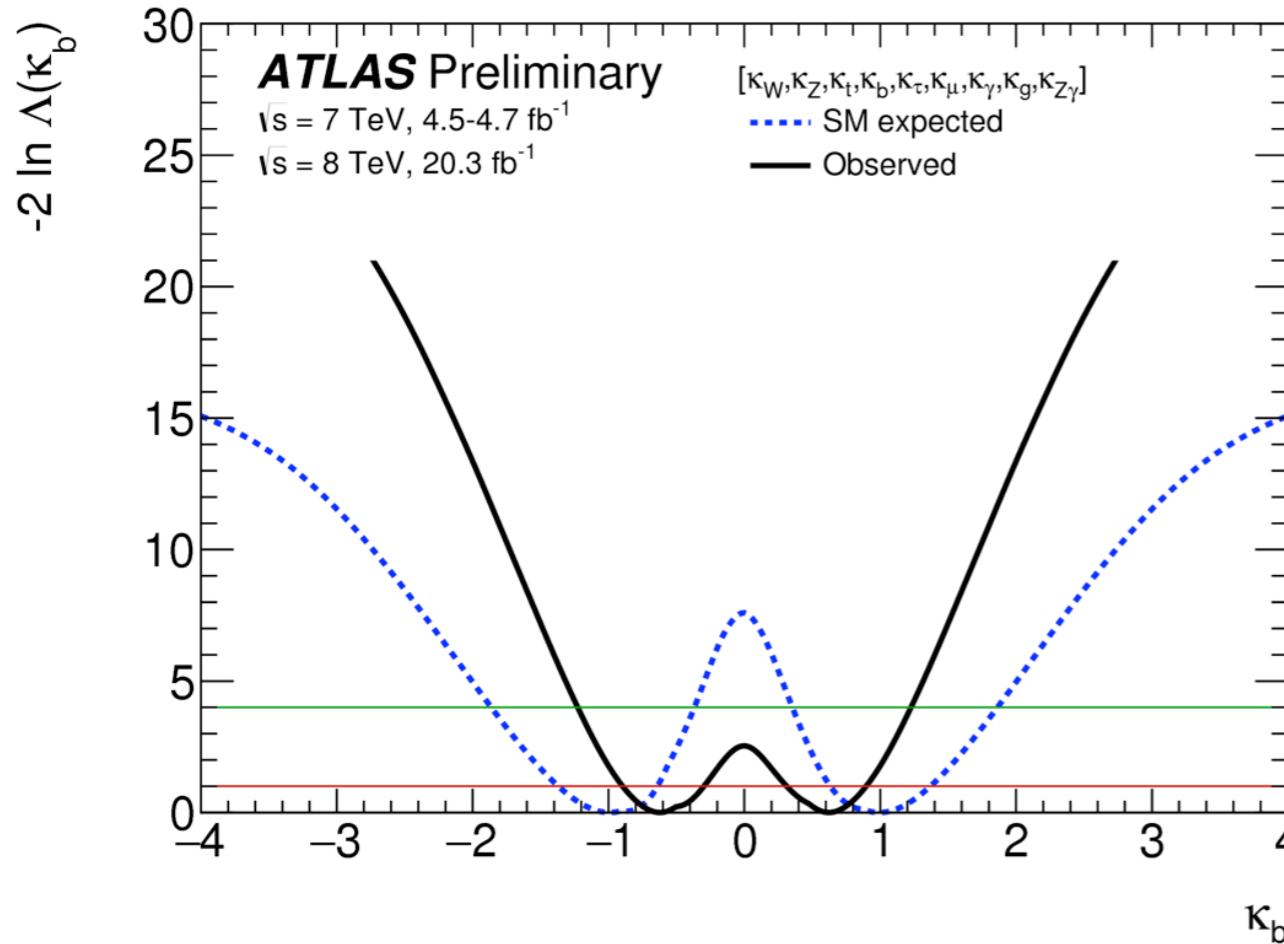
Results from Run I: K_b

Combination of all Higgs channels

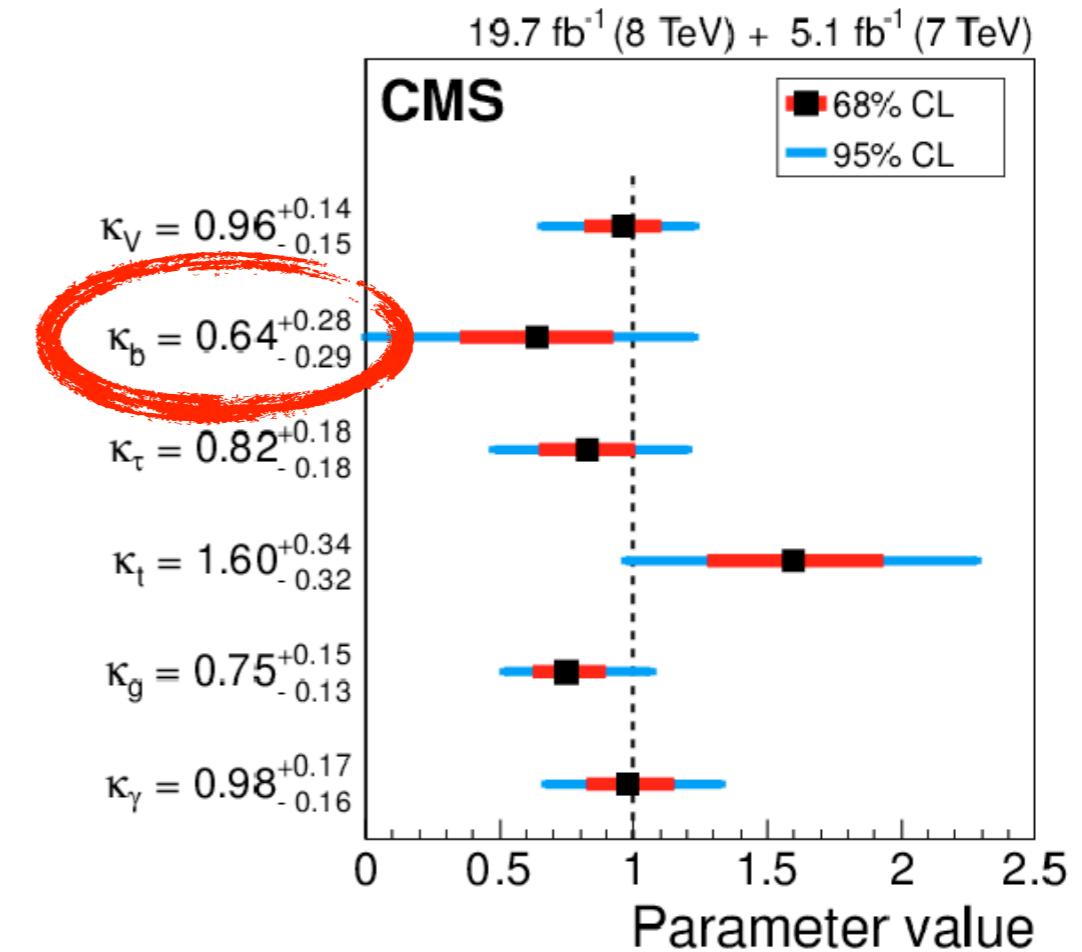
- ▶ assume $BR_{BSM} = 0$
- ▶ use effective K_g, K_γ couplings

$$\begin{array}{ll} \textbf{VH, VBF:} & \textbf{ttH:} \\ \frac{\kappa_V^2 \kappa_b^2}{\kappa_H^2 (\kappa_V^2, \kappa_b^2)} & \frac{\kappa_t^2 \kappa_b^2}{\kappa_H^2 (\kappa_V^2, \kappa_b^2)} \end{array}$$

ATLAS, arXiv:1507.04548
submitted to EPJC



CMS, EPJC 75 (2015) 212



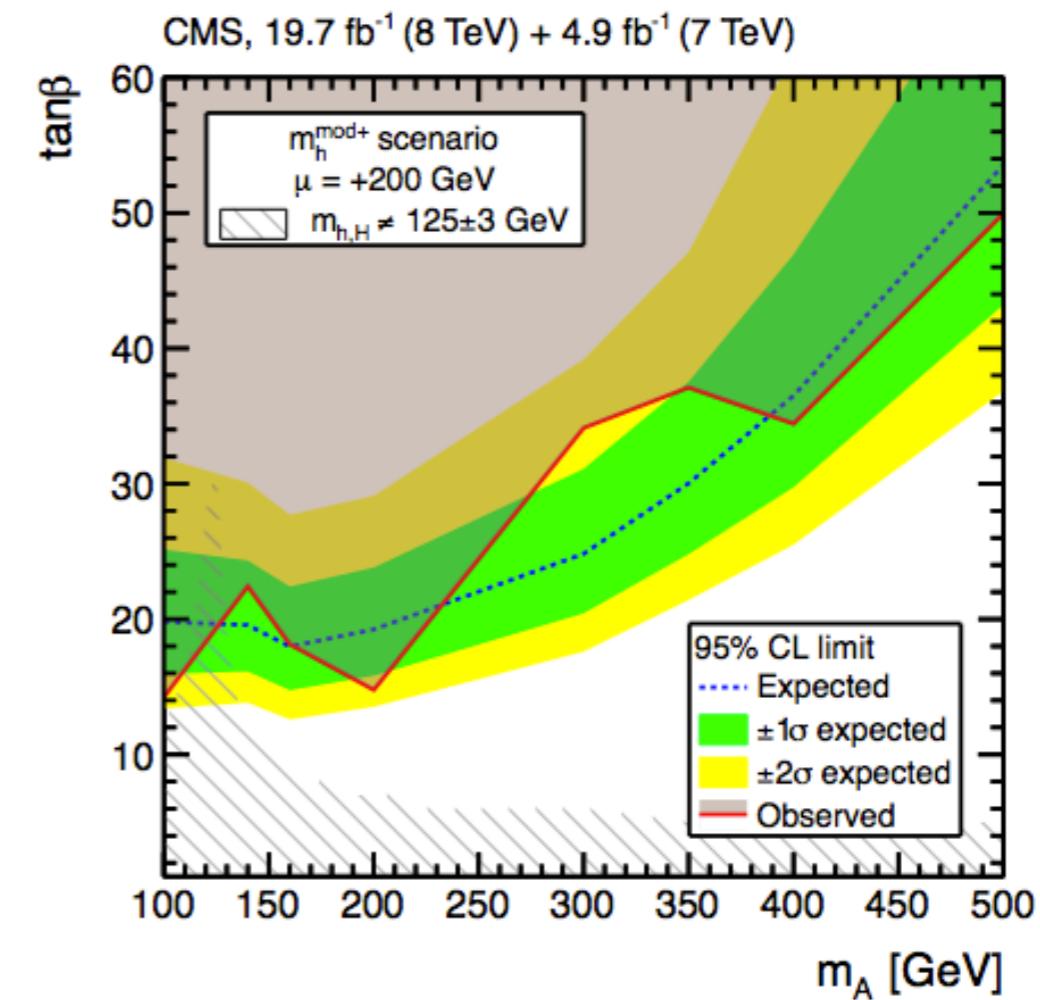
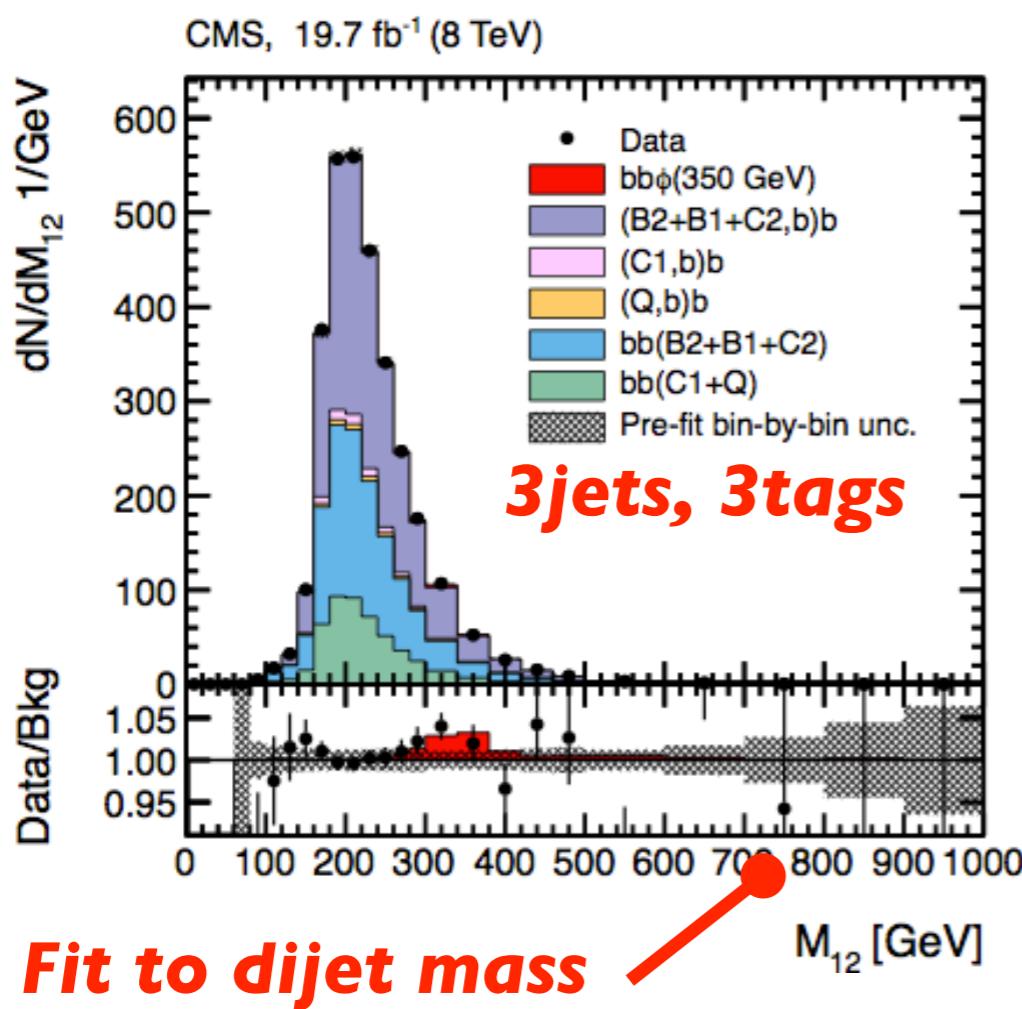
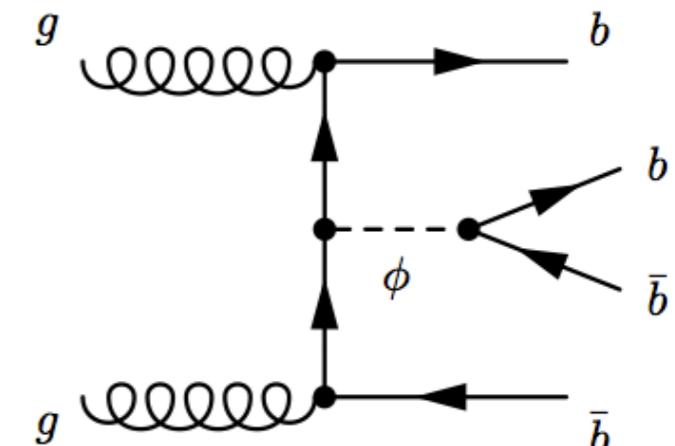
Bottom+Higgs: $bb\phi$

CMS, arXiv:1506.08329,
submitted to JHEP

Hunting $\tan^2\beta$ enhanced h/H/A production with b quarks

- ▶ $\Phi \rightarrow \tau\tau$
 - most stringent direct constraints on $(M_A, \tan\beta)$
- ▶ $\Phi \rightarrow bb$
 - enhanced sensitivity to SUSY parameters

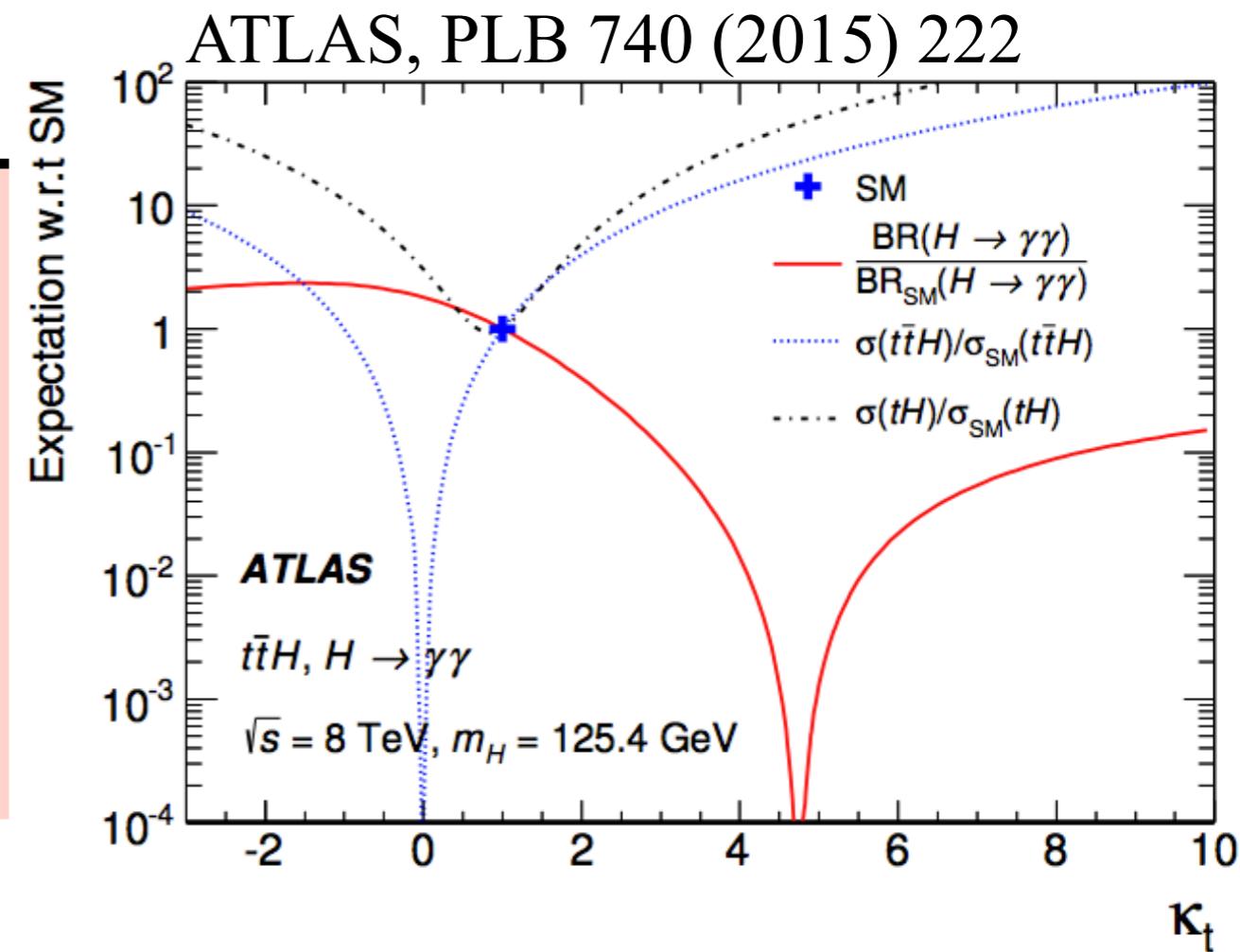
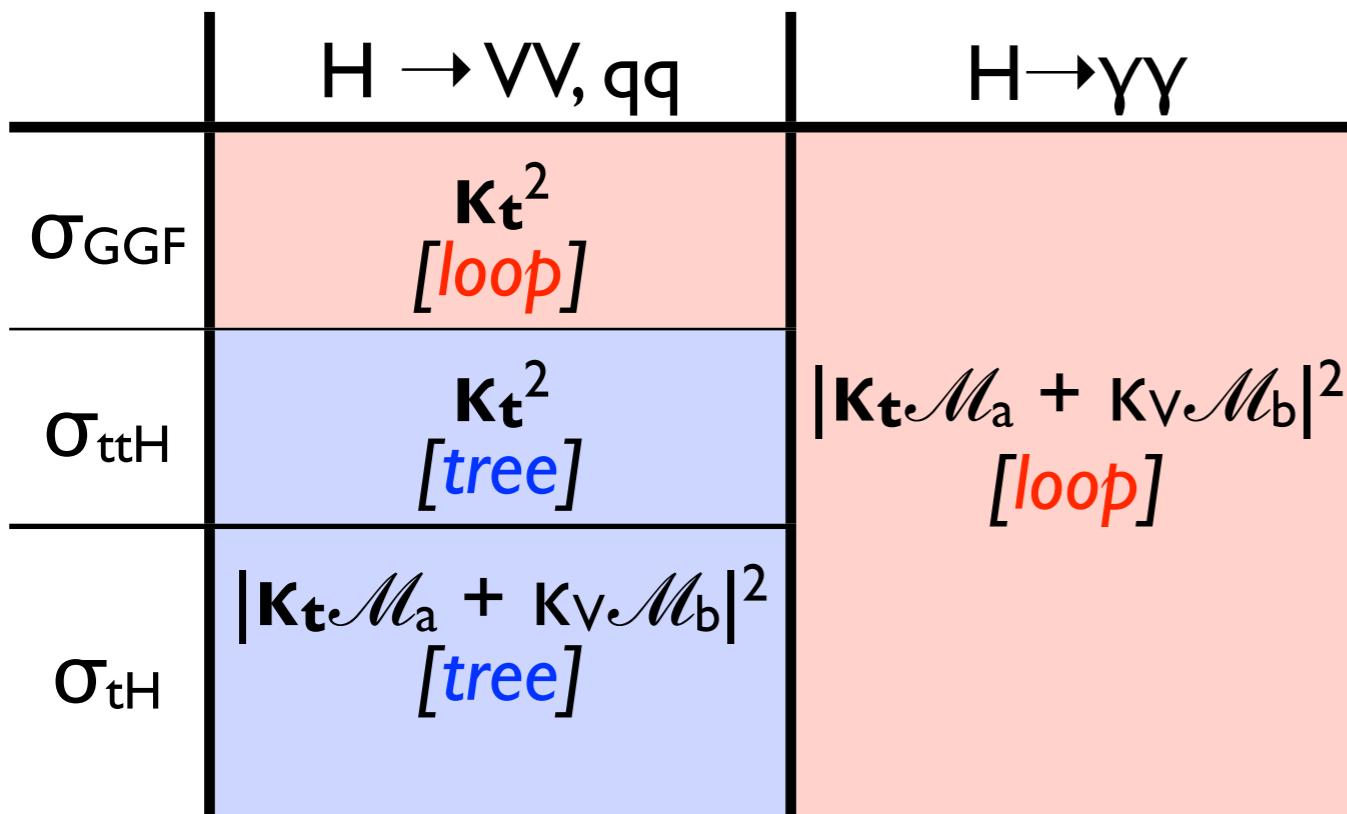
$$\sigma(b\bar{b}\phi) \times \text{BR}(\phi \rightarrow b\bar{b}) = 2 \sigma(b\bar{b}\phi)_{\text{SM}} \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \frac{9}{(1 + \Delta_b)^2 + 9}$$



The top quark Yukawa

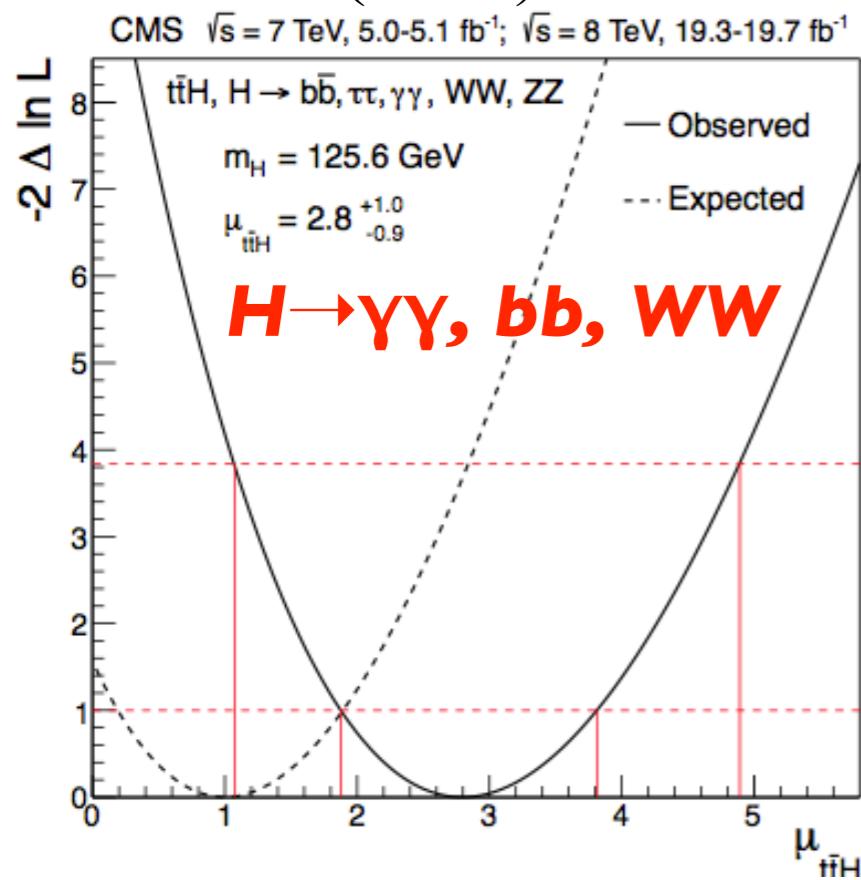
The largest [$O(1)$] coupling in the Yukawa sector

- ▶ no direct decay into top quarks
- ▶ tightest constraints from GGF and $BR(H \rightarrow \gamma\gamma)$
- ▶ complement with direct measurement

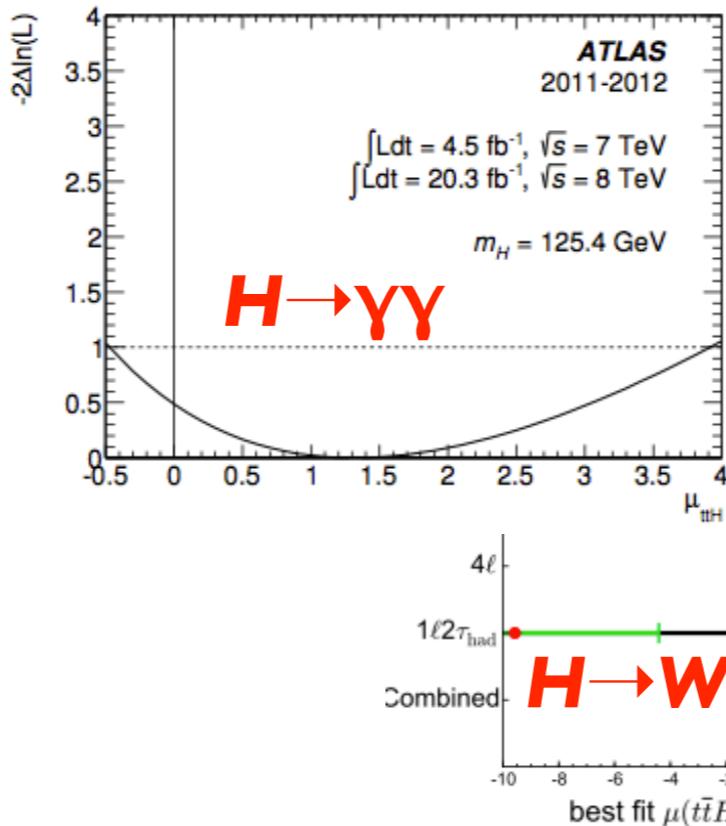


Top+Higgs: ttH

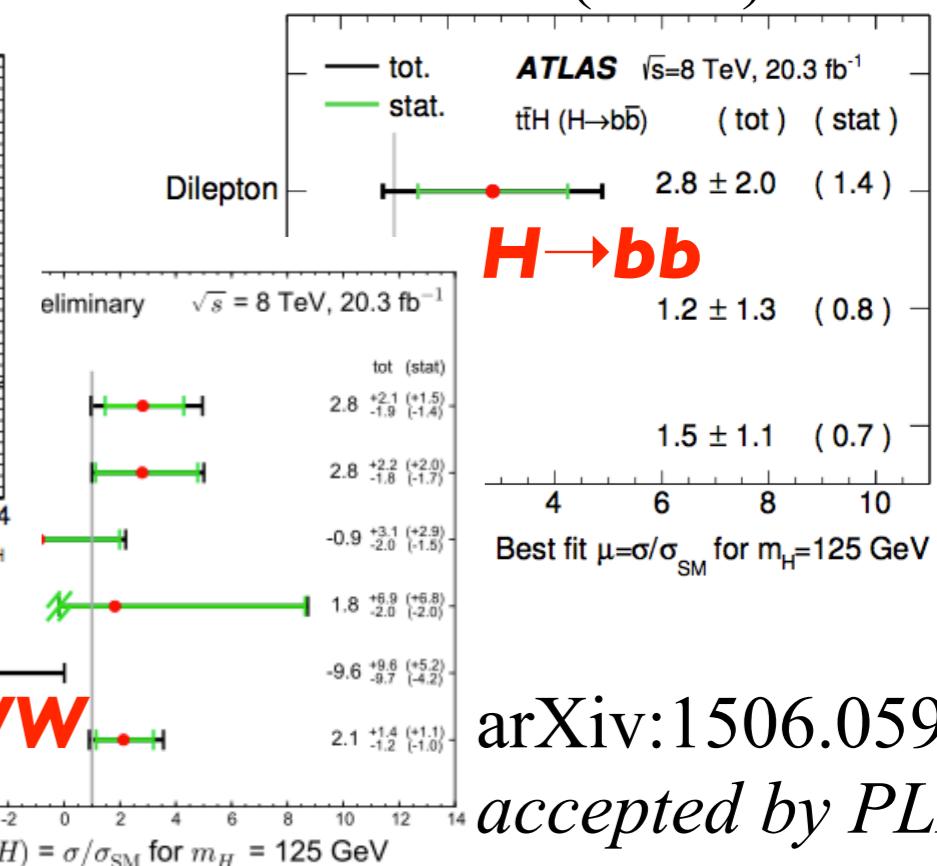
JHEP 09 (2014) 087



PLB 740 (2015) 222



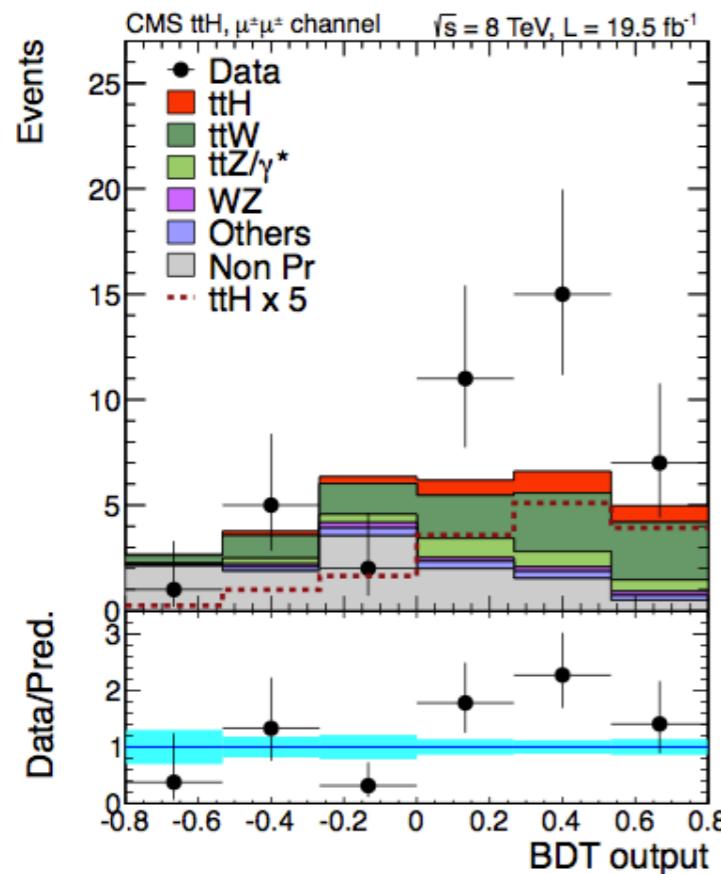
EPJC 75 (2015) 349



arXiv:1506.05988,
accepted by PLB

	Experiment	obs. (exp.) limit 95% CL	best-fit value ($\pm 1\sigma$)
H → hadrons	CMS	< 4.1 (3.5)	$0.7^{+1.9}_{-1.9}$
	ATLAS	< 3.4 (2.2)	$1.5^{+1.1}_{-1.1}$
H → photons	CMS	< 7.4 (4.7)	$2.7^{+2.6}_{-1.8}$
	ATLAS	< 6.7 (4.9)	$1.4^{+2.1}_{-1.4}$
H → leptons	CMS	< 6.6 (2.4)	$3.7^{+1.6}_{-1.4}$
	ATLAS	< 4.7 (2.4)	$2.1^{+1.4}_{-1.2}$

Top+Higgs: ttH



Largest excess in $\mu^+\mu^-$ channel

CMS, JHEP 09 (2014) 087

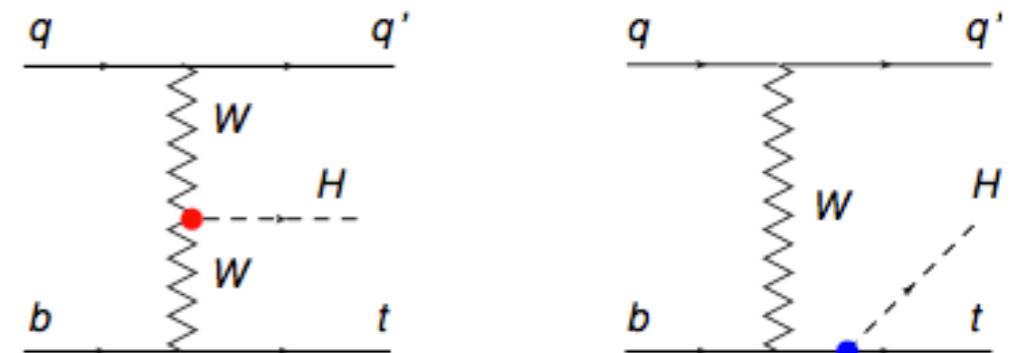
	p-value	Exp.	Obs.
CMS		1.2σ	3.6σ
ATLAS		1.5σ	2.5σ

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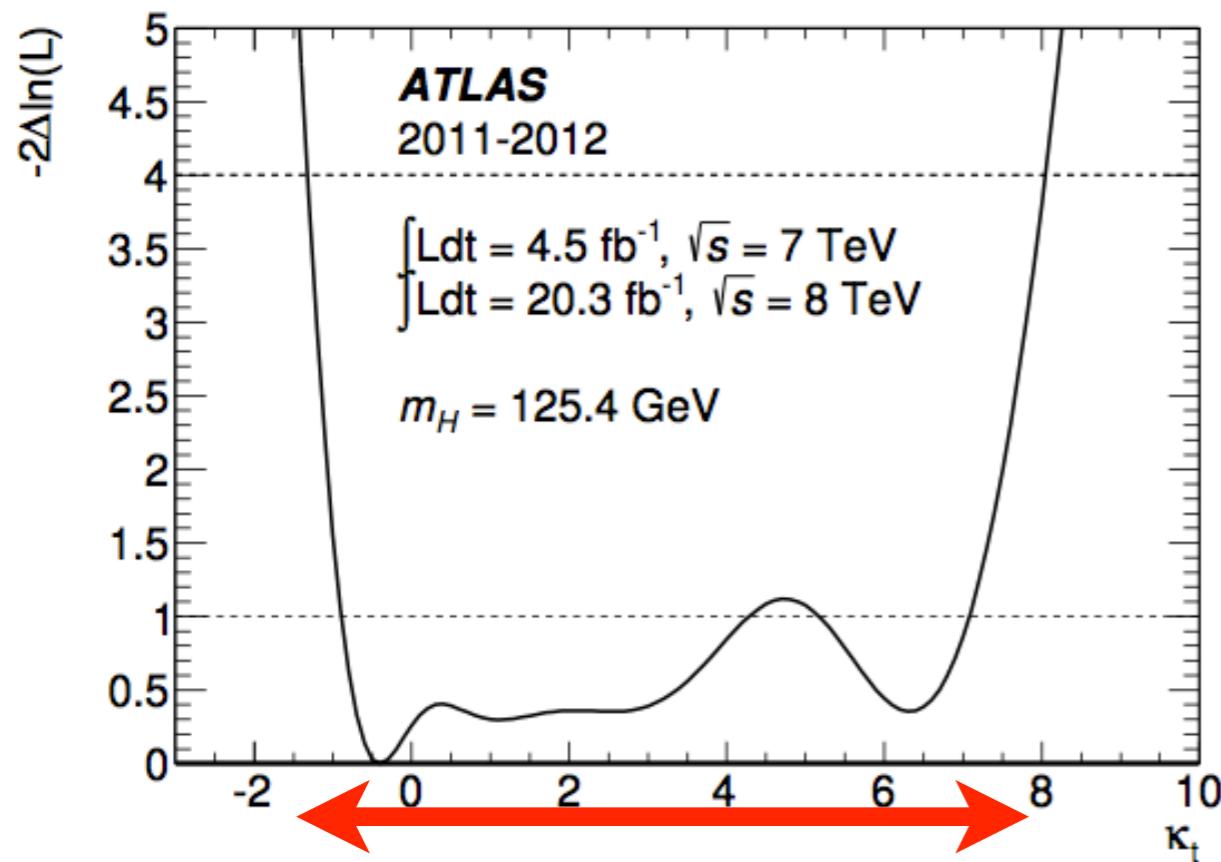
Top+Higgs: tH

Search for tHq/WtH production

- ▶ (accidentally) small in SM ($\sigma_{\text{NLO}} \sim 18 \text{ fb}$)
- ▶ sensitive to $\text{sign}(g_{HWW} \times y_t)$



ATLAS: inclusive $t(t)+H$ search



ATLAS, PLB 740 (2015) 222

CMS: optimise for tHq

$\mu^{95\%} (\kappa_t = -I)$	Obs.	Exp.
$H \rightarrow \gamma\gamma$	< 4.1	4.1
$H \rightarrow bb$	< 7.6	5.1
$H \rightarrow WW$	< 6.7	5.0

CMS, PAS-HIG-14-001

CMS, PAS-HIG-14-015

CMS, PAS-HIG-14-026

Combination to be appear soon

Results from Run I: K_t

Combination of all Higgs channels

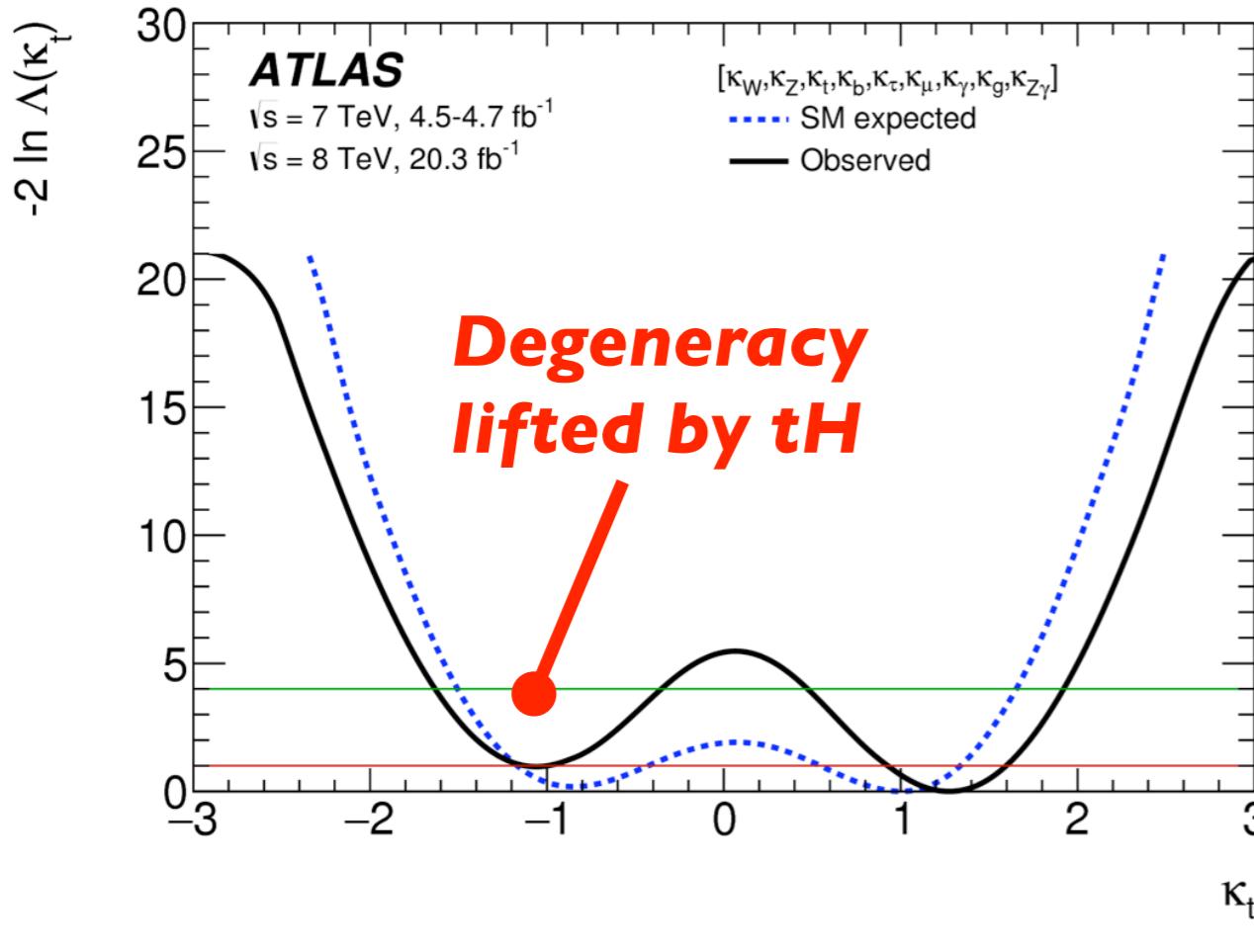
- ▶ assume $BR_{BSM} = 0$
- ▶ use effective K_g, K_Y couplings

$$t\bar{t}H \rightarrow ff: \frac{\kappa_t^2 \kappa_b^2}{\kappa_H^2(\kappa_V^2, \kappa_b^2)} \quad \frac{\kappa_t^2 \kappa_\tau^2}{\kappa_H^2(\kappa_V^2, \kappa_b^2)}$$

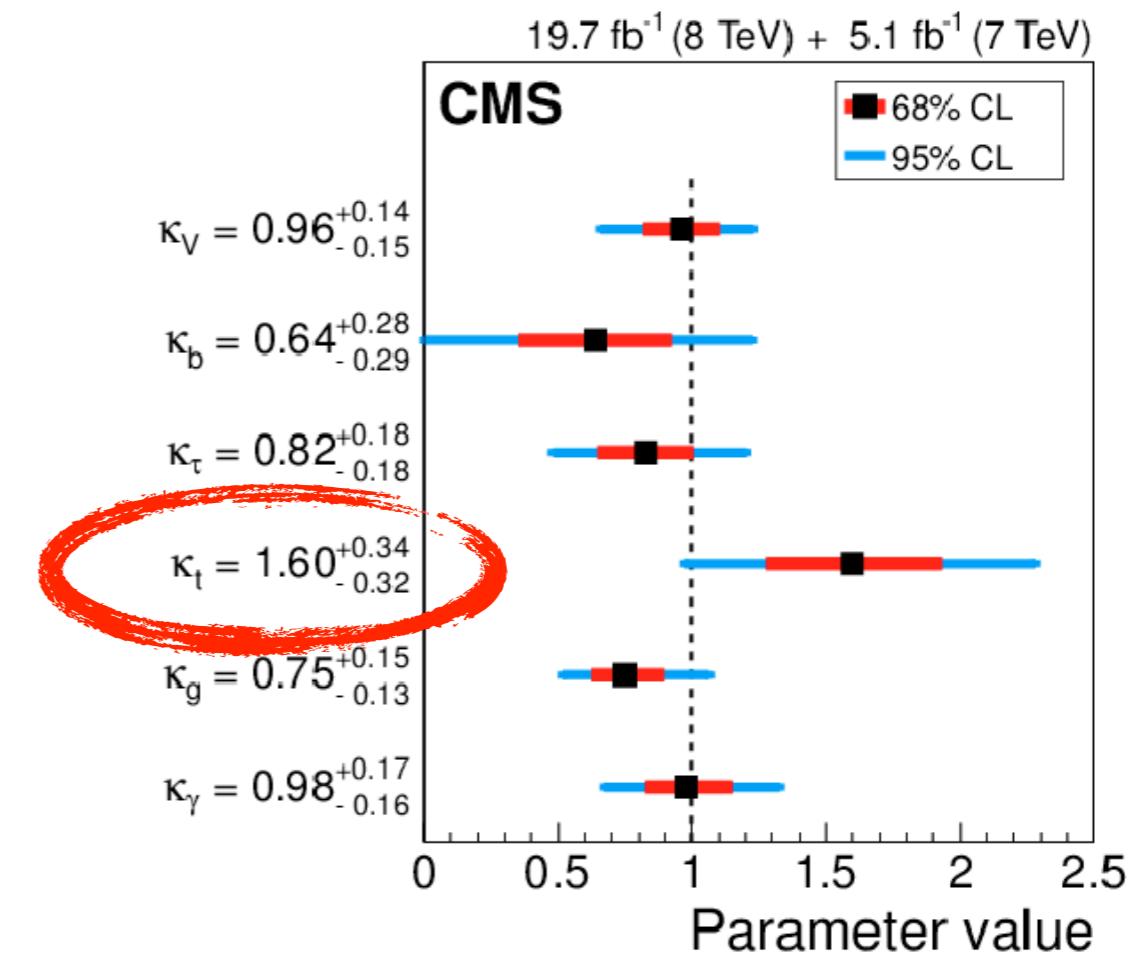
$$t\bar{t}H \rightarrow VV, \gamma\gamma: \frac{\kappa_t^2 \kappa_V^2}{\kappa_H^2(\kappa_V^2, \kappa_b^2)} \quad \frac{\kappa_t^2 \kappa_\gamma^2}{\kappa_H^2(\kappa_V^2, \kappa_b^2)}$$

$$tH \rightarrow \gamma\gamma: \frac{\kappa_{tH}^2(\kappa_t, \kappa_V) \kappa_\gamma^2}{\kappa_H^2(\kappa_V^2, \kappa_b^2)}$$

ATLAS, arXiv:1507.04548
submitted to EPJC



CMS, EPJC 75 (2015) 212



FCNC from the Yukawa sector

- FC currents from tqH interaction highly suppressed in SM
 - ▶ $BR(t \rightarrow cH) < 10^{-15}$
 - ▶ appear naturally in BSM
- Search for FC decays of top quarks
 - ▶ profit from large $\sigma(pp \rightarrow tt)$
 - constraints on FC coupling:

$$\mathcal{B} = (\lambda_{tcH}^2 + \lambda_{tuH}^2) / (g^2 \cdot |V_{tb}|^2 \cdot \chi^2)$$

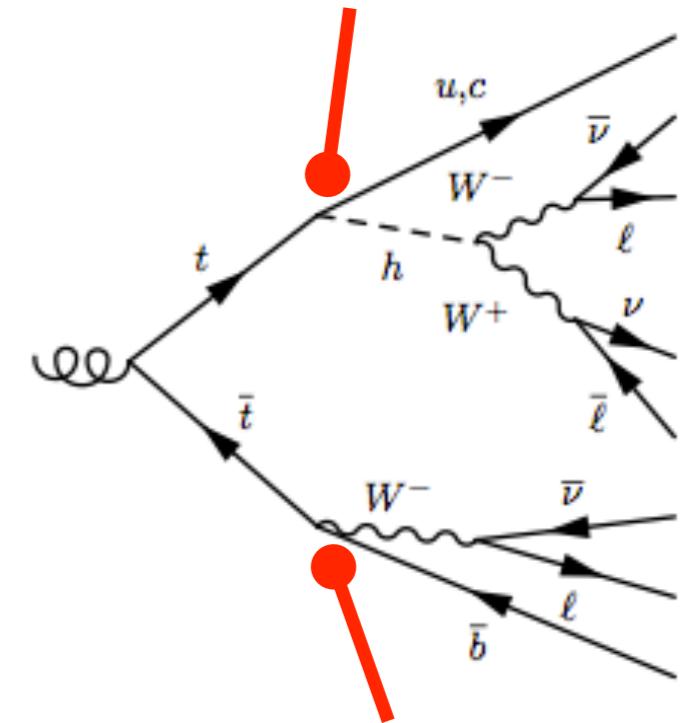
CMS, PRD 90 112013 (2013)

CMS, PAS-TOP-13-017

CMS, PAS-TOP-14-019

ATLAS, JHEP 06 (2014) 008

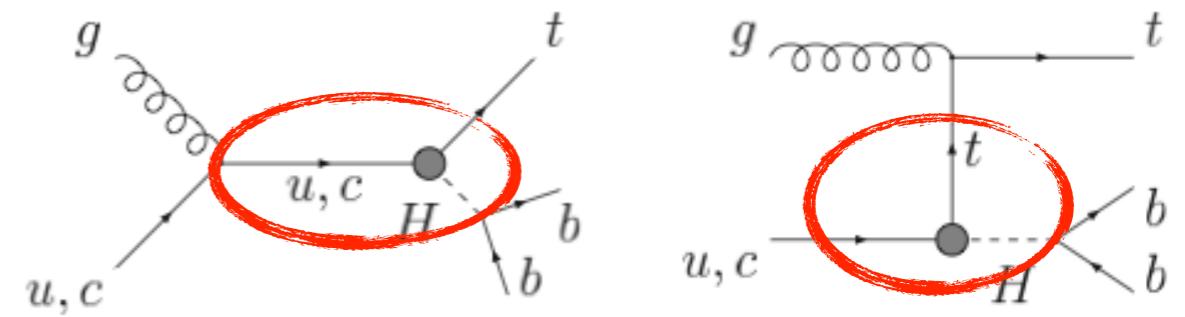
$$\lambda_{t(u,c)H} \bar{t}(u,c) H$$



$$-\frac{g}{\sqrt{2}} V_{tb} \bar{t}_L \gamma^\mu b_L W_\mu^+$$

- Single-top production
 - ▶ Run I analysis mostly focusing on tHq

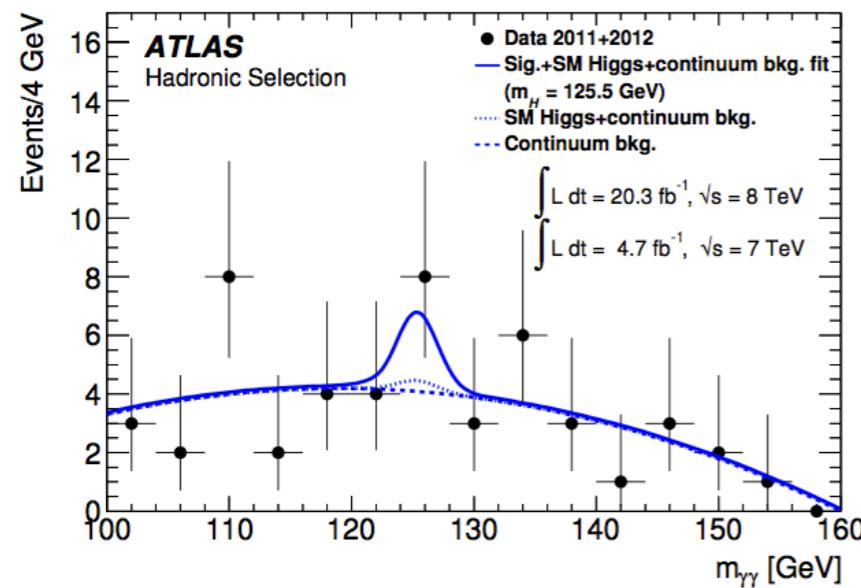
Aguilar-Saavedra, Acta Phys.Polon.
B35:2695-2710 (2004)



FCNC in top quark decays

- $H \rightarrow \gamma\gamma$

- ▶ cut-based selection (0/1 leptons)
- ▶ fit to $m_{\gamma\gamma}$ spectrum



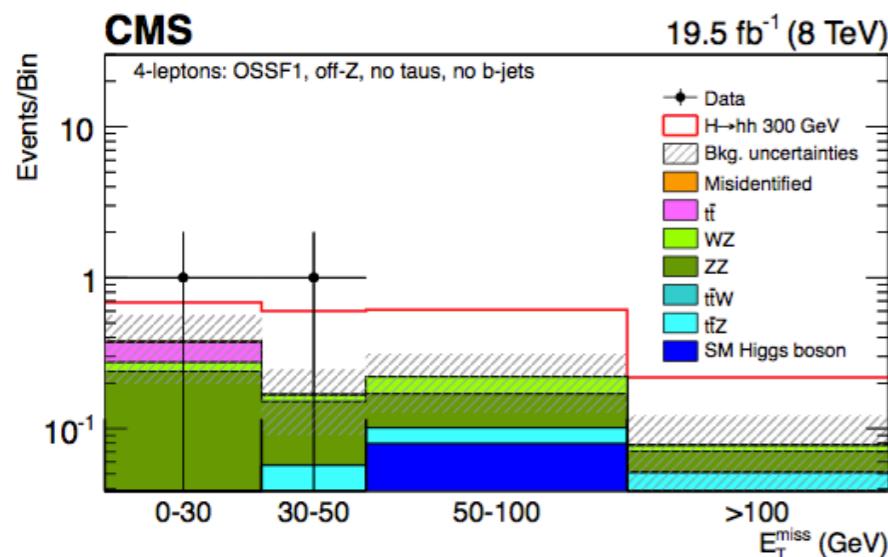
ATLAS, JHEP 06 (2014) 008
CMS, PAS-TOP-14-019

$BR(t \rightarrow cH)$ 95% CL	Exp.	Obs.
CMS	0.71%	0.47%
ATLAS	0.51%	0.79%
$\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.17$		

CMS, PRD 90 112013 (2013)
CMS, PAS-TOP-13-017

- $H \rightarrow \text{multilepton}$

- ▶ cut & count



$BR(t \rightarrow cH)$ 95% CL	Exp.	Obs.
$lll, llll$	1.17%	1.28%
$lll, llll + \gamma\gamma l$	0.65%	0.56%
$l^\pm l^\pm, lll$	0.89%	0.93%

FCNC in top quark decays

	SM	QS	2HDM	FC 2HDM	MSSM	\mathcal{R}	SUSY
$t \rightarrow uZ$	8×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}	
$t \rightarrow u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}	
$t \rightarrow ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}	
$t \rightarrow uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	—	10^{-5}	$\sim 10^{-6}$	
$t \rightarrow cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}	
$t \rightarrow c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}	
$t \rightarrow cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}	
$t \rightarrow cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$	

$$g_{qt} \simeq \frac{\sqrt{m_q m_t}}{M_W}$$

Aguilar-Saavedra, Acta Phys.Polon.
B35:2695-2710 (2004)

Summary

- Probing the Yukawa sector by measuring $\sigma(x\bar{x} \rightarrow H) \times BR(H \rightarrow yy)$

 - ▶ compatibility with SM
 - ▶ flavour structure

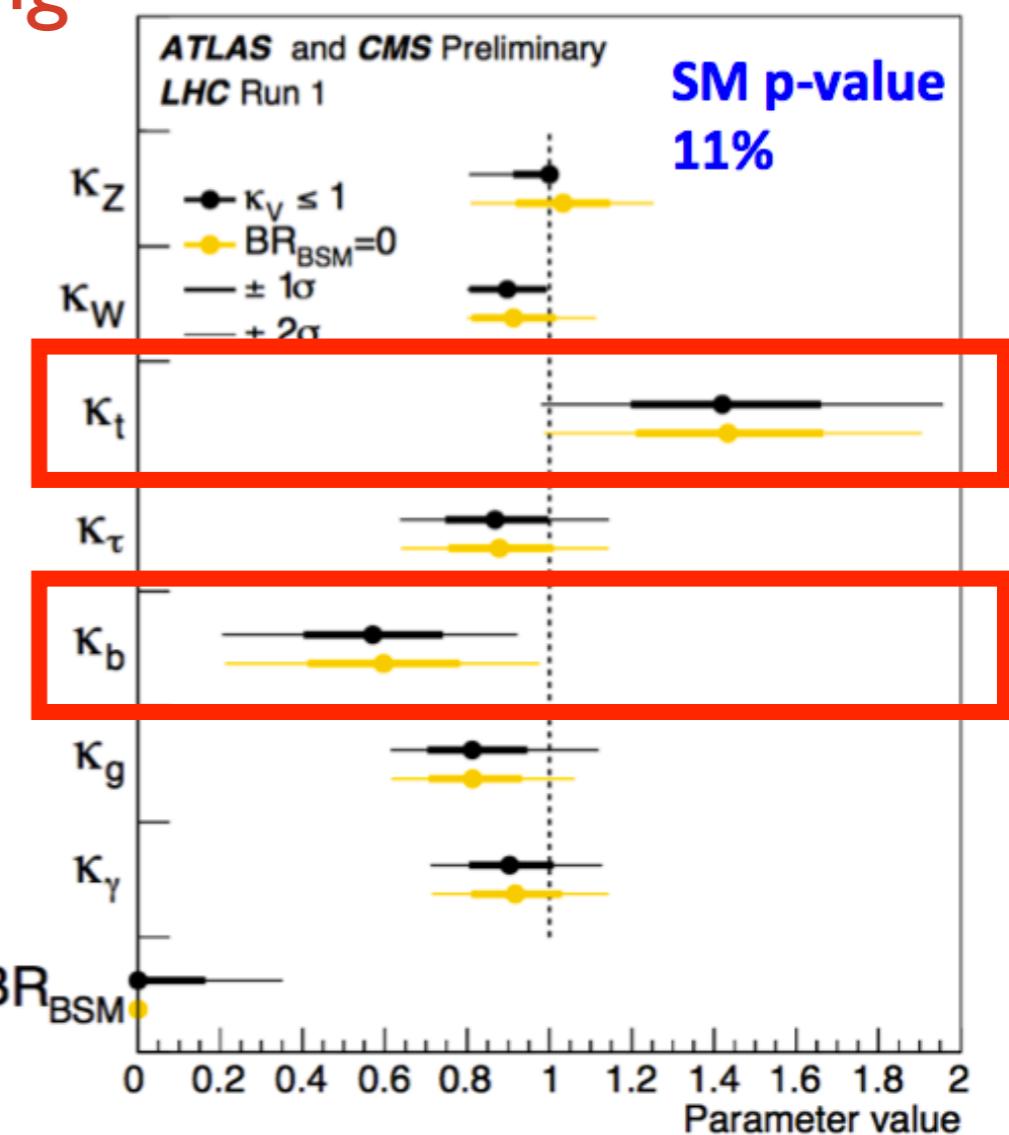
- Heavy flavour in Higgs decay

 - ▶ $H \rightarrow cc$: rare decays □
 - $BR_{SM} \sim 10^{-6}$; from Run I: $\sim 10^{-3}$ □
→ null test of SM
 - ▶ $H \rightarrow bb$
 - ATLAS+CMS: **2.6 σ** (3.7 σ)

- Heavy flavour in Higgs production

 - ▶ expected Run I top+Higgs sensitivity: $\sim 1.5\sigma$ /experiment
 - slight excess over SM expectation to be reassessed with 13 TeV data
 - ▶ FCNC in top decays
 - $BR_{SM} \sim 10^{-15}$; from Run I: $\sim 10^{-3}$ → null test of the SM
 - close to sensitivity for some BSM models

from Marco Pieri's talk



Back up

Overview

The SM Yukawa sector:

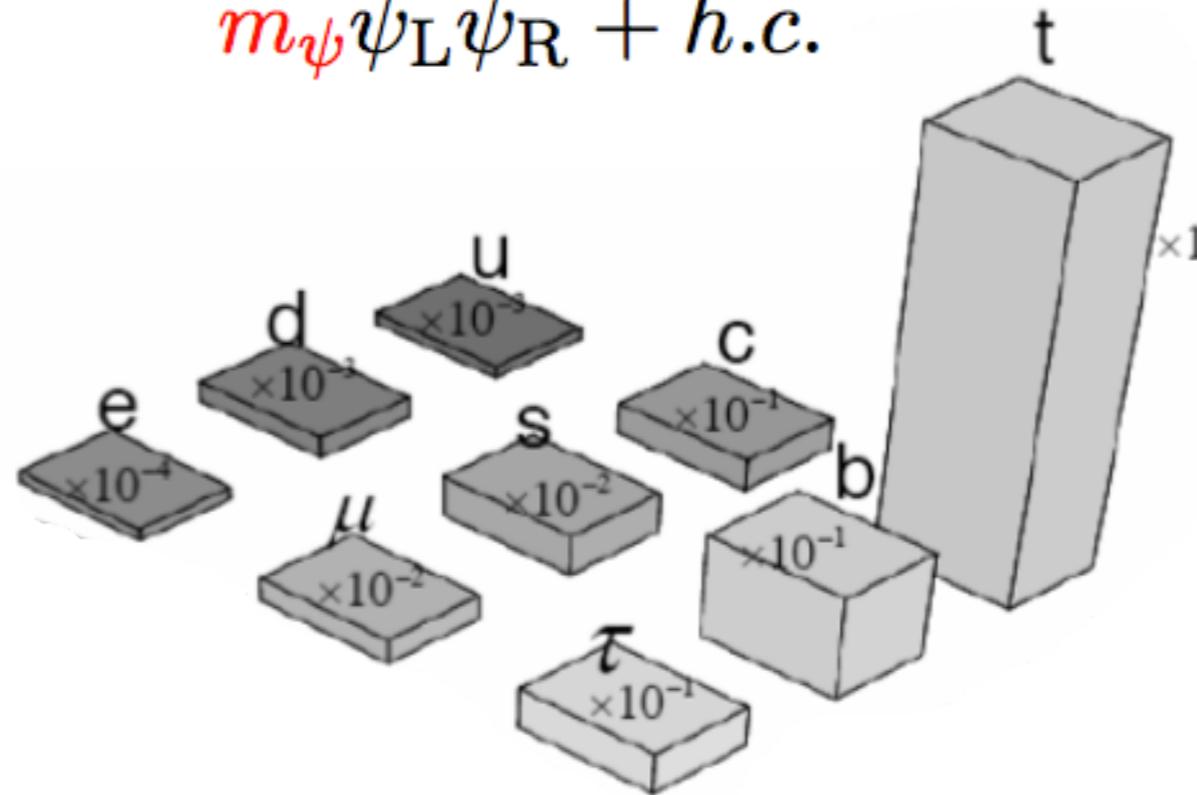
$$\lambda_{ij} \bar{\Psi}_i \Psi_j \Phi_H$$

mass matrix

$$m_\psi \bar{\psi}_L \psi_R + h.c.$$

flavour diagonal scalar interactions

$$\lambda_\psi \bar{\psi}_L \psi_R H + h.c.$$



$$\lambda_\psi = \kappa_\psi \frac{\sqrt{2} m_\psi}{v}$$

$$\boxed{\kappa_\psi^{\text{SM}} = 1}$$

FCNC from the Yukawa sector

- FC currents from tHq interaction highly suppressed in SM

► $\text{BR}(t \rightarrow cH) < 10^{-15}$

- H-mediated FCNC in several BSM extensions

- already at tree-level
 - extended Higgs sectors, extra quark singlets
- >> I enhancements from extra loops
 - e.g.: $\text{BR} \sim 10^{-5}$ in MSSM
- in general, effect of higher-order operators (EFT)

	SM
$t \rightarrow uZ$	8×10^{-17}
$t \rightarrow u\gamma$	3.7×10^{-16}
$t \rightarrow ug$	3.7×10^{-14}
$t \rightarrow uH$	2×10^{-17}
$t \rightarrow cZ$	1×10^{-14}
$t \rightarrow c\gamma$	4.6×10^{-14}
$t \rightarrow cg$	4.6×10^{-12}
$t \rightarrow cH$	3×10^{-15}

$$Y^{ij} \psi_L^i \psi_R^j \phi + \varepsilon^{ij} \psi_L^i \psi_R^j \phi^3 + \dots$$

$$\downarrow \varepsilon^{ij} = \frac{c^{ij}}{\Lambda^2}$$

$$(v Y^{ij} + v^3 \varepsilon^{ij}) \psi_L^i \psi_R^j + \textcircled{(} (Y^{ij} + 3v^2 \varepsilon^{ij}) \psi_L^i \psi_R^j h \textcircled{)} + \dots$$

Aguilar-Saavedra, Acta Phys.Polon.
B35:2695-2710 (2004)

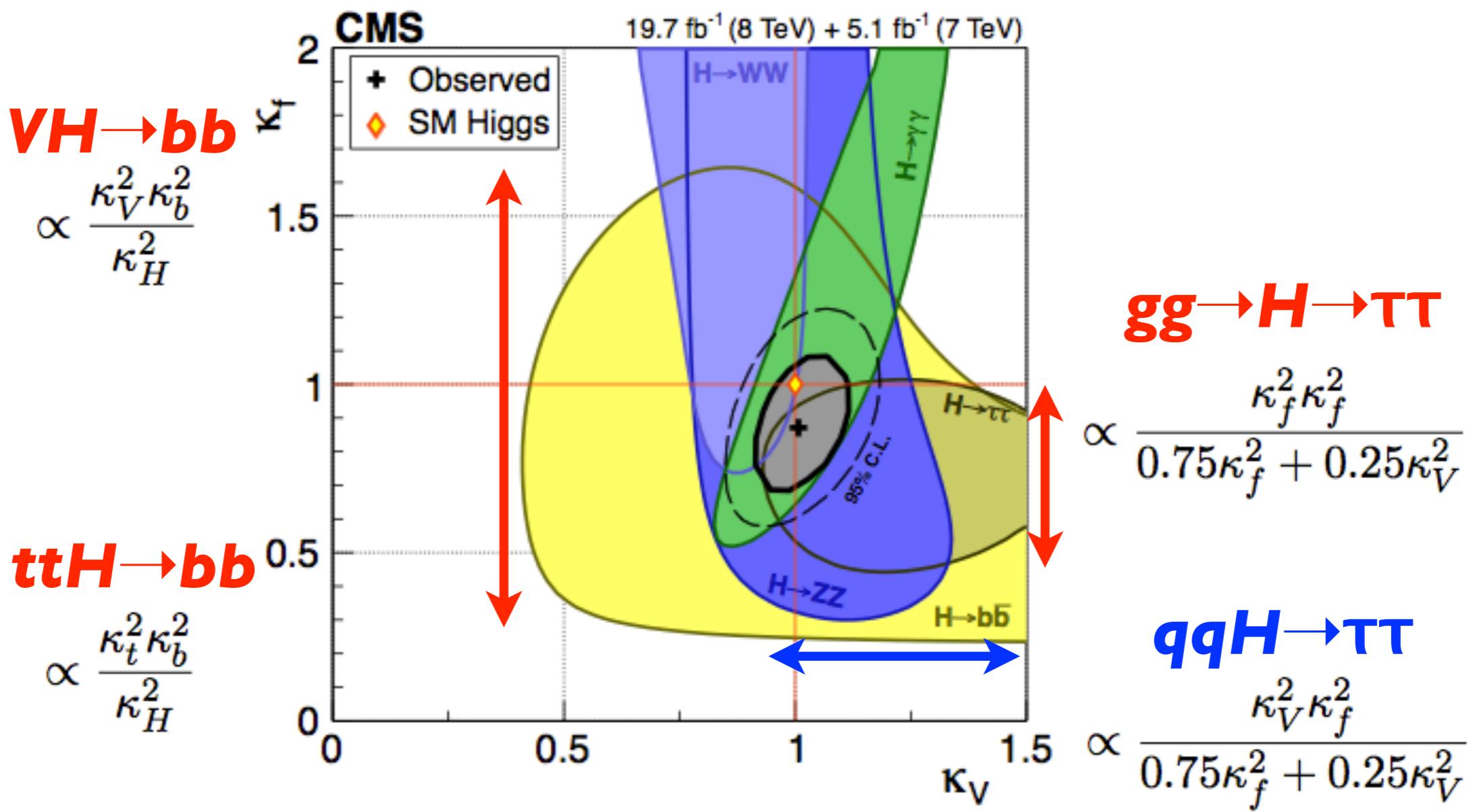
$$v Y_{\text{eff}}$$

h FCNC couplings if $Y^{ij} \neq c \varepsilon^{ij}$

G. Isidori,
HL-LHC workshop

Combination

CMS, arXiv:1412.8662



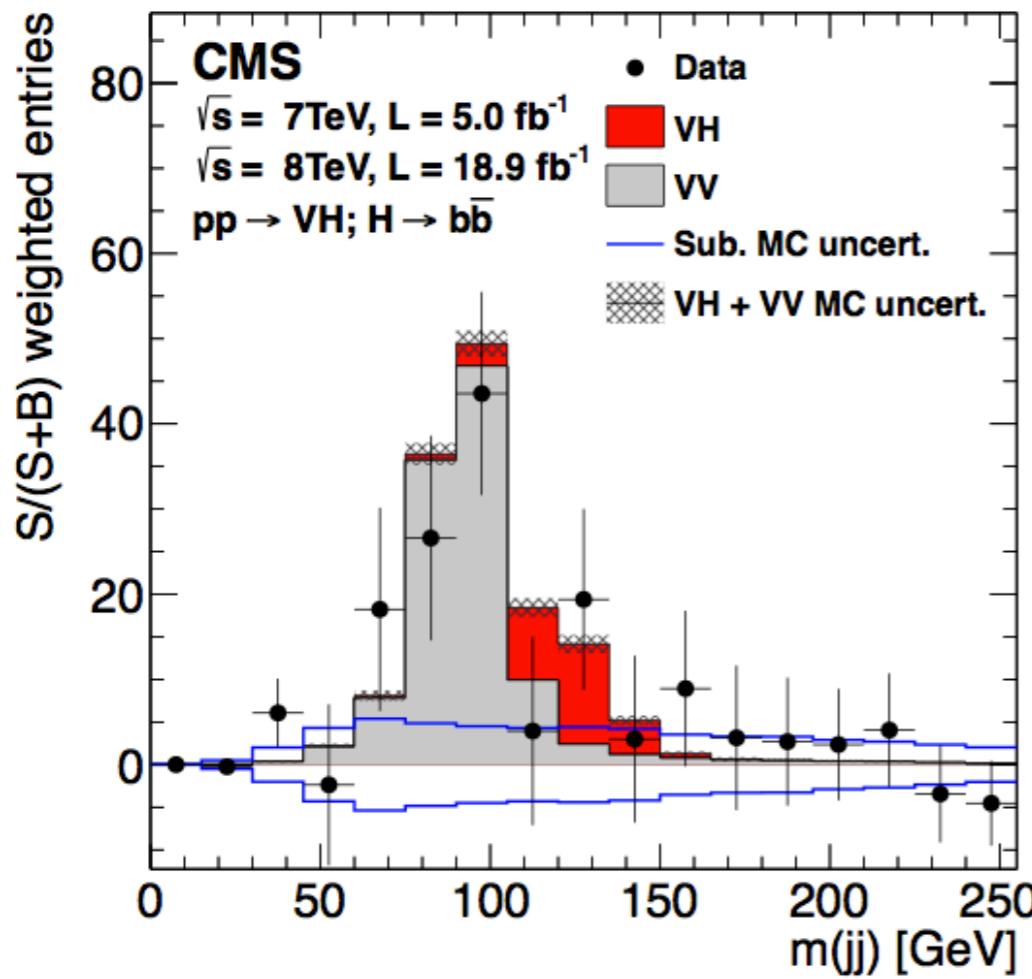
VH production, $H \rightarrow b\bar{b}$

Highest sensitivity channel

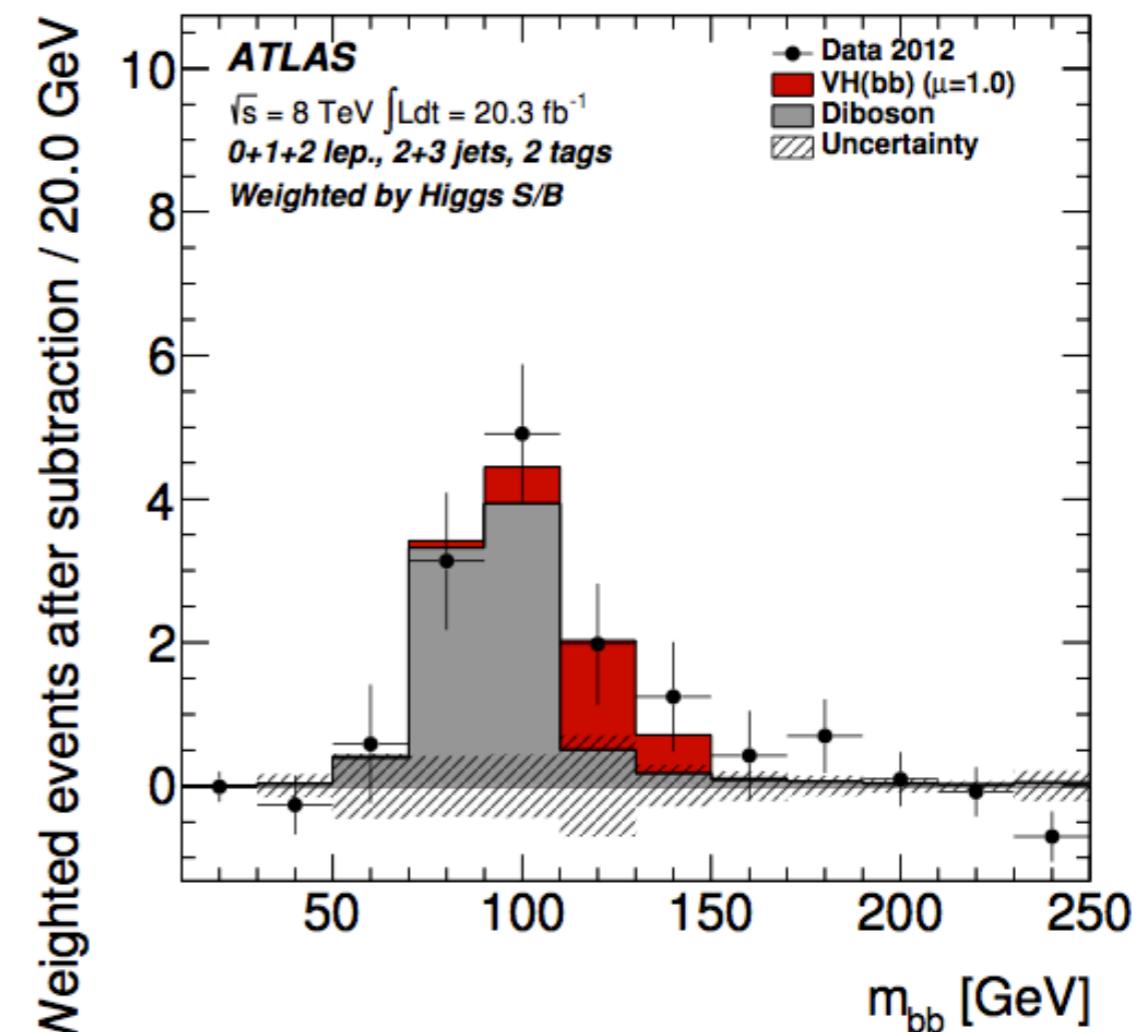
- ▶ tagging leptonic and invisible V decays
- ▶ visible as a bump on the di-jet mass spectrum
- in-situ calibration using $VZ, Z \rightarrow b\bar{b}$ ($>7\sigma$ observation)

	Exp.	Obs.
CMS	2.1σ	2.1σ
ATLAS	2.6σ	1.4σ

CMS, PRD 89 012003 (2014)



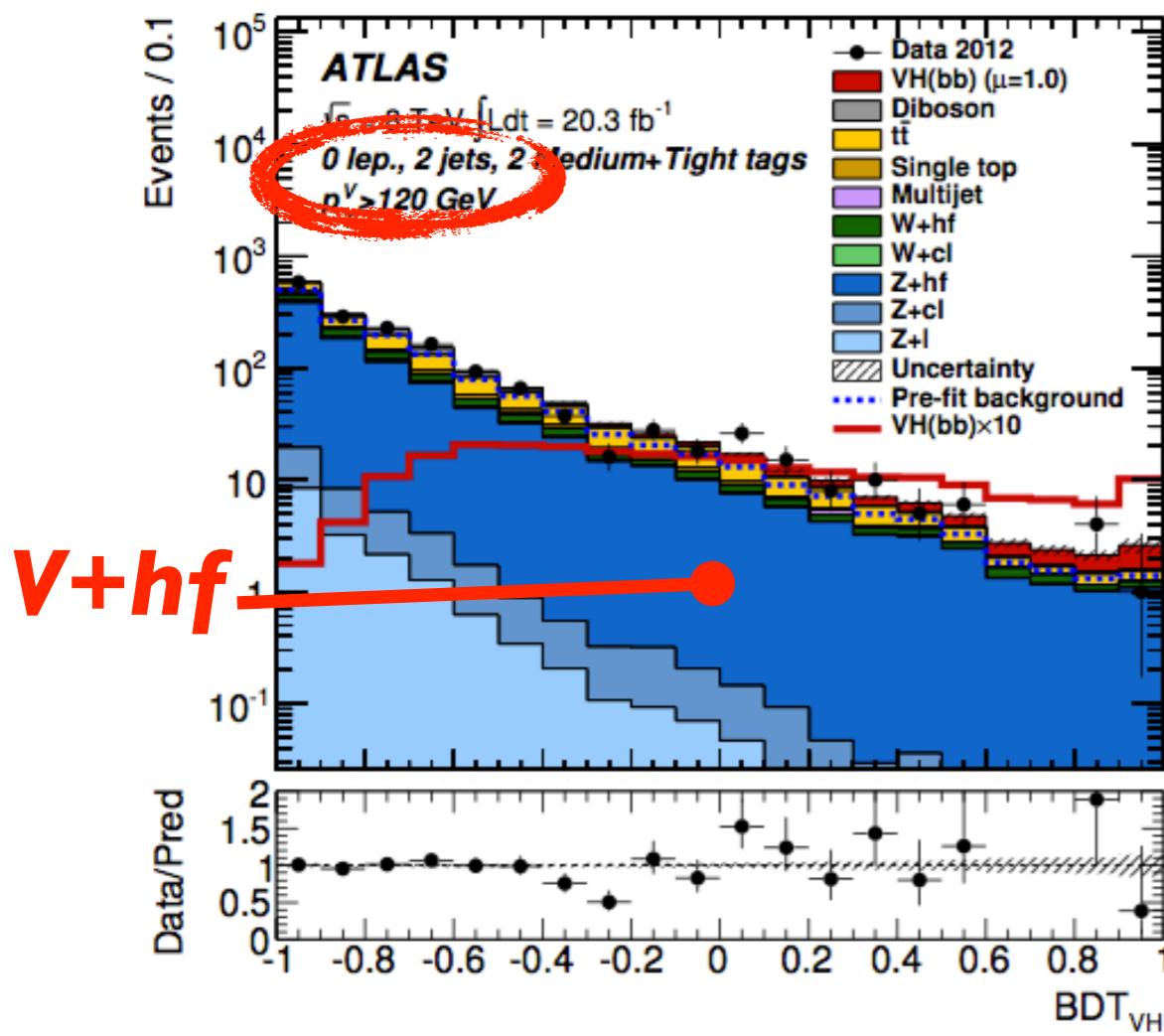
ATLAS, JHEP 01 (2015) 069



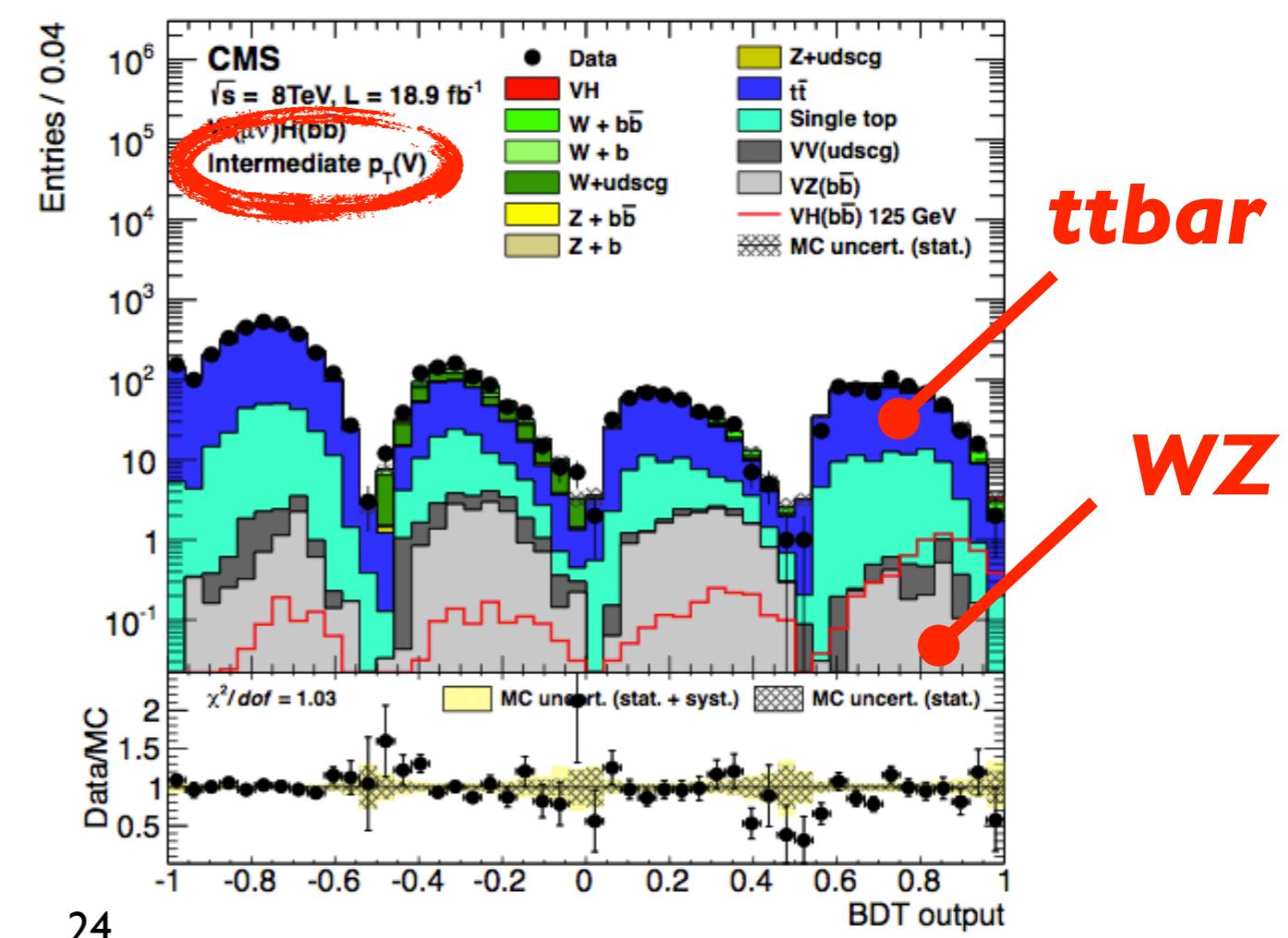
Analysis overview

- Phase-space slicing by p_T^V and/or N_{jet}
 - ▶ enhance sensitivity to higher-order corrections (Higgs p_T and jet radiation)
- Main backgrounds: **V+h.f., ttbar, diboson**
- MVA approach for maximal S/B
 - ▶ modeling of differential distributions & correlations

ATLAS, JHEP 01 (2015) 069

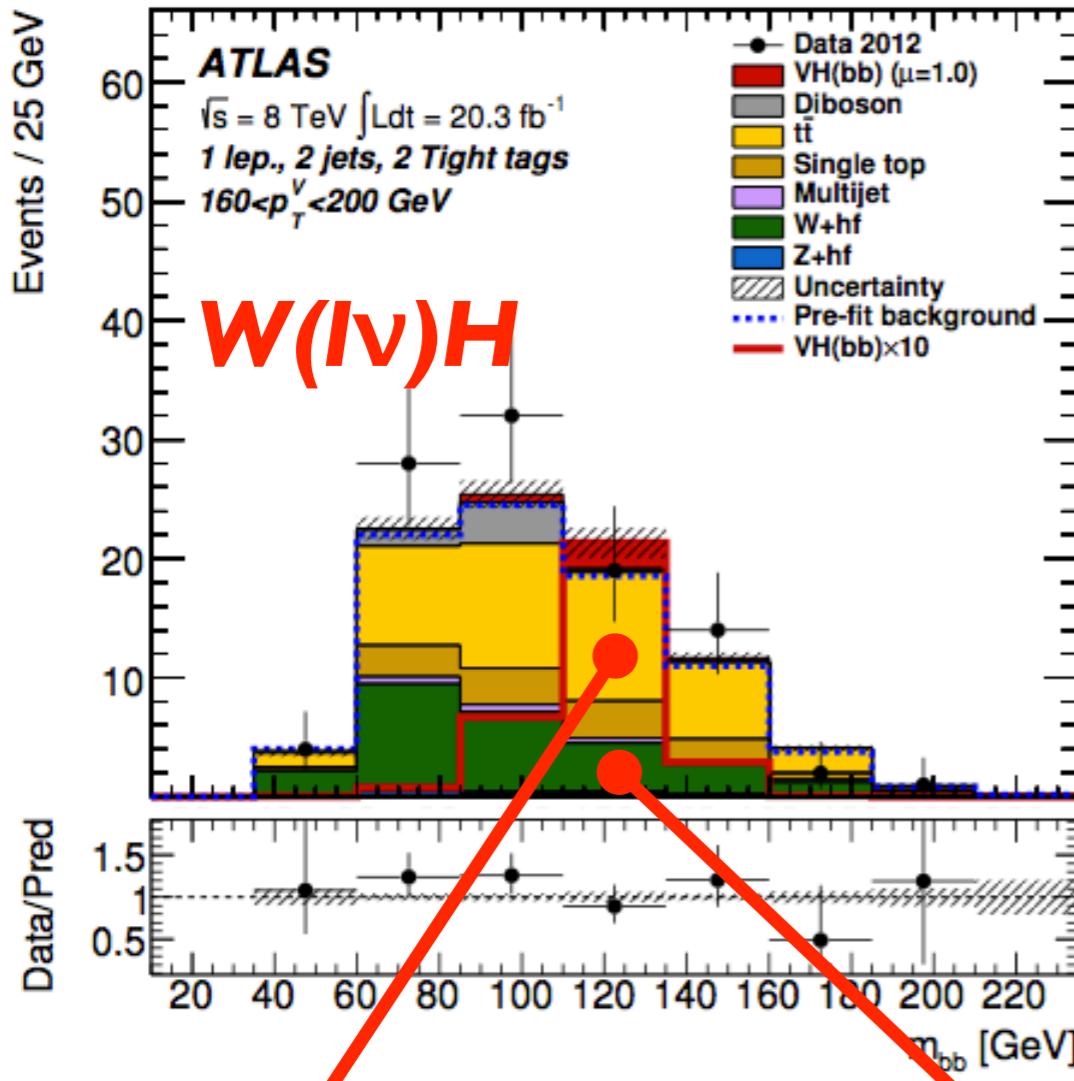


CMS, PRD 89 01 (2014) 012003



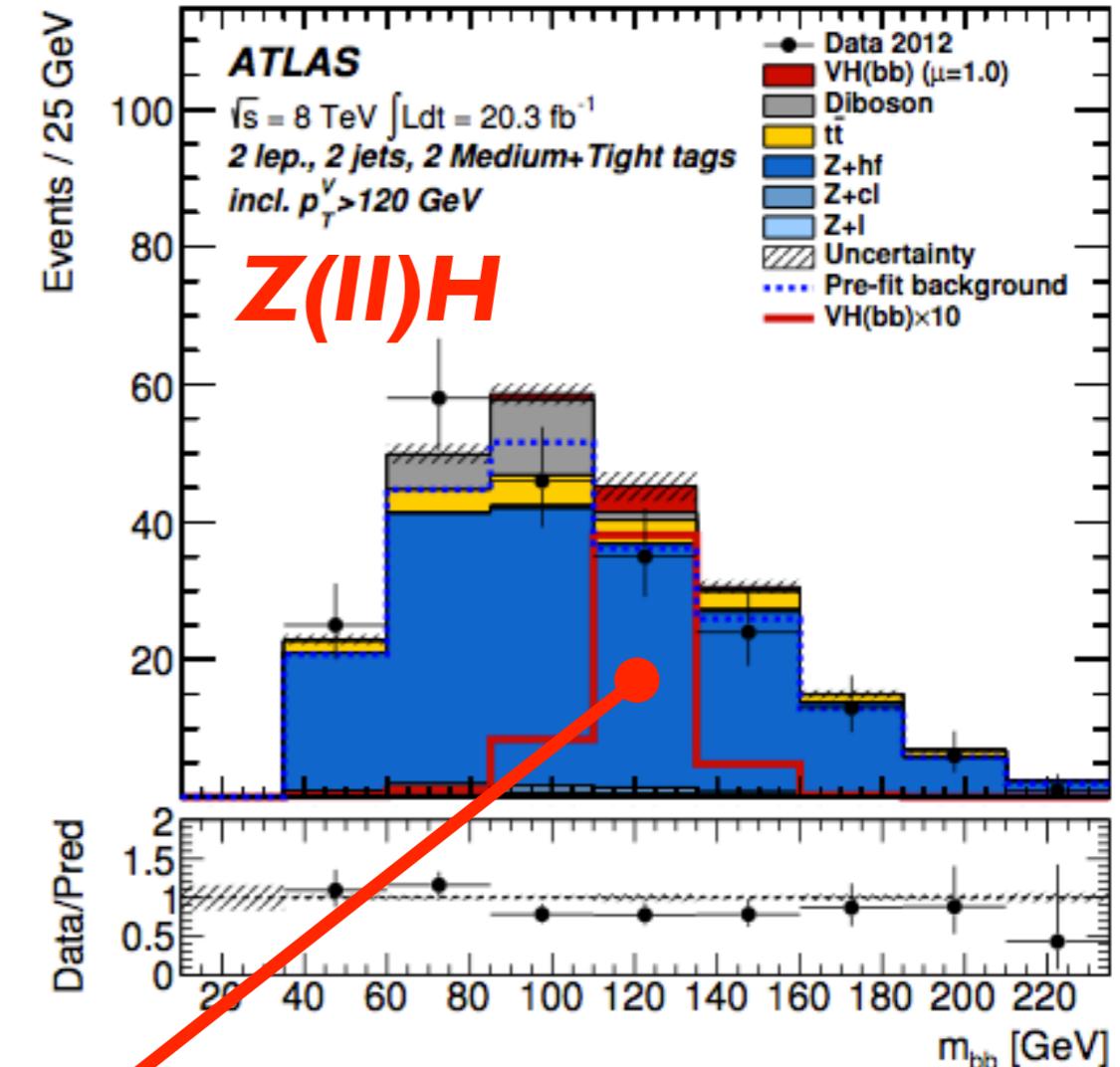
VH(bb): main SM backgrounds

ATLAS, JHEP 01 (2015) 069



Top-pairs

- ▶ four-fold increase in top pairs at 14 TeV



V+jets

- ▶ mixed flavour composition

Rates estimated from sidebands

The Run I analysis

- Categorise events by p_T^V and N_{jet}
 - ▶ enhance signal acceptance sensitivity to higher-order corrections
- Main backgrounds: V+h.f., ttbar, diboson
 - ▶ increase separation by BDT

ATLAS, JHEP 01 (2015) 069

Variable	0-Lepton	1-Lepton	2-Lepton
p_T^V		✗	✗
E_T^{miss}	✗	✗	✗
$p_T^{b_1}$	✗	✗	✗
$p_T^{b_2}$	✗	✗	✗
m_{bb}	✗	✗	✗
$\Delta R(b_1, b_2)$	✗	✗	✗
$ \Delta \eta(b_1, b_2) $	✗		✗
$\Delta \phi(V, bb)$	✗	✗	✗
$ \Delta \eta(V, bb) $			✗
H_T	✗		
$\min[\Delta \phi(\ell, b)]$		✗	
m_T^W		✗	
$m_{\ell\ell}$			✗
$MV1c(b_1)$	✗	✗	✗
$MV1c(b_2)$	✗	✗	✗
Only in 3-jet events			
$p_T^{\text{jet}_3}$	✗	✗	✗
m_{bbj}	✗	✗	✗

* CMS also uses N_{jet}

Theory uncertainties: VH

LHCXSWG,
arXiv:1307.1347

NLO MCs reweighted to best accuracy:

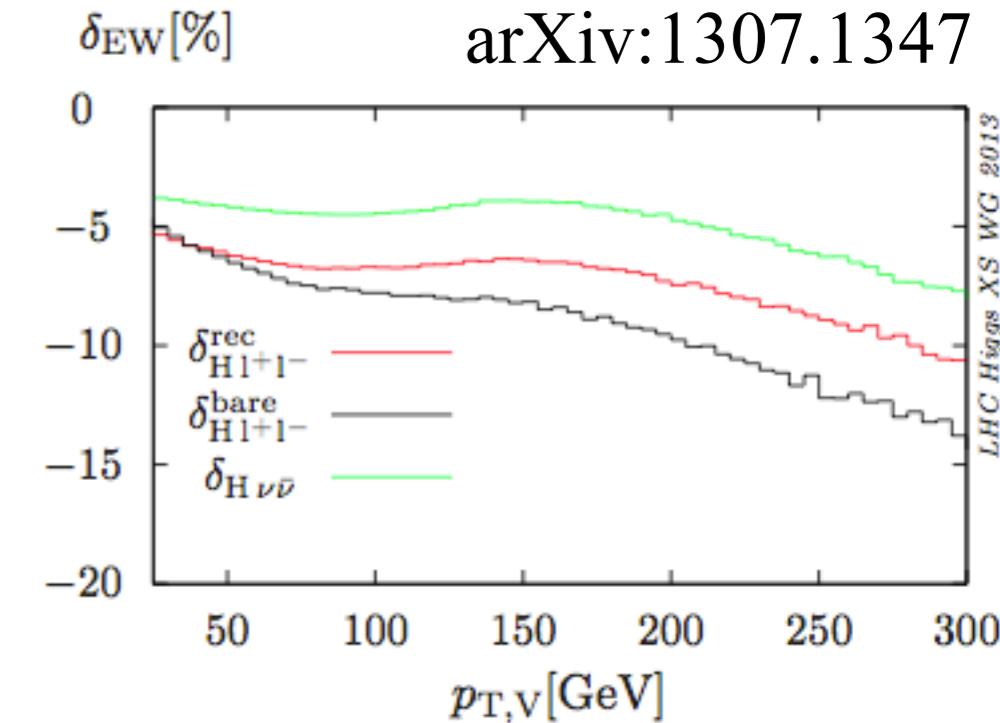
	qqVH	NNLO	fully differential
QCD	ggZH	NLO	infinite-top mass
EWK	NLO		factorised

ATLAS, JHEP 01 (2015) 069

Signal	
Cross section (scale)	1% ($q\bar{q}$) 50% (gg)
Cross section (PDF)	2.4% ($q\bar{q}$) 17% (gg)
Branching ratio	3.3 %
Acceptance (scale)	1.5%–3.3%
3-jet acceptance (scale)	3.3%–4.2%
p_T^V shape (scale)	S 2%–5%
Acceptance (PDF)	S
p_T^V shape (NLO EW correction)	8%–13%
Acceptance (parton shower)	

PDFs

Can be related to other
Drell-Yan measurements?



ggZH $\sim 10\% \sigma_{VH}$ @ 14 TeV

e.g. PYTHIA vs HERWIG

Can it be constrained by WZ/ZZ?

$\sigma_{\text{stat}}^{\text{WZ/ZZ}} \sim 2\%$ at 3000 fb^{-1}

Background shape uncertainties

CMS:

- ▶ take envelope between BDT outputs from independent MCs
- “ The uncertainty in the background event yields estimated from data is approximately 10%. For $V+jets$, the difference between the shape of the BDT output distribution for events generated with the MADGRAPH and the HERWIG ++ Monte Carlo generators is considered as a shape systematic uncertainty. For $t\bar{t}$ the differences in the shape of the BDT output distribution between the one obtained from the nominal MADGRAPH samples and those obtained from the POWHEG and MC@NLO [60] generators are considered as shape systematic uncertainties.

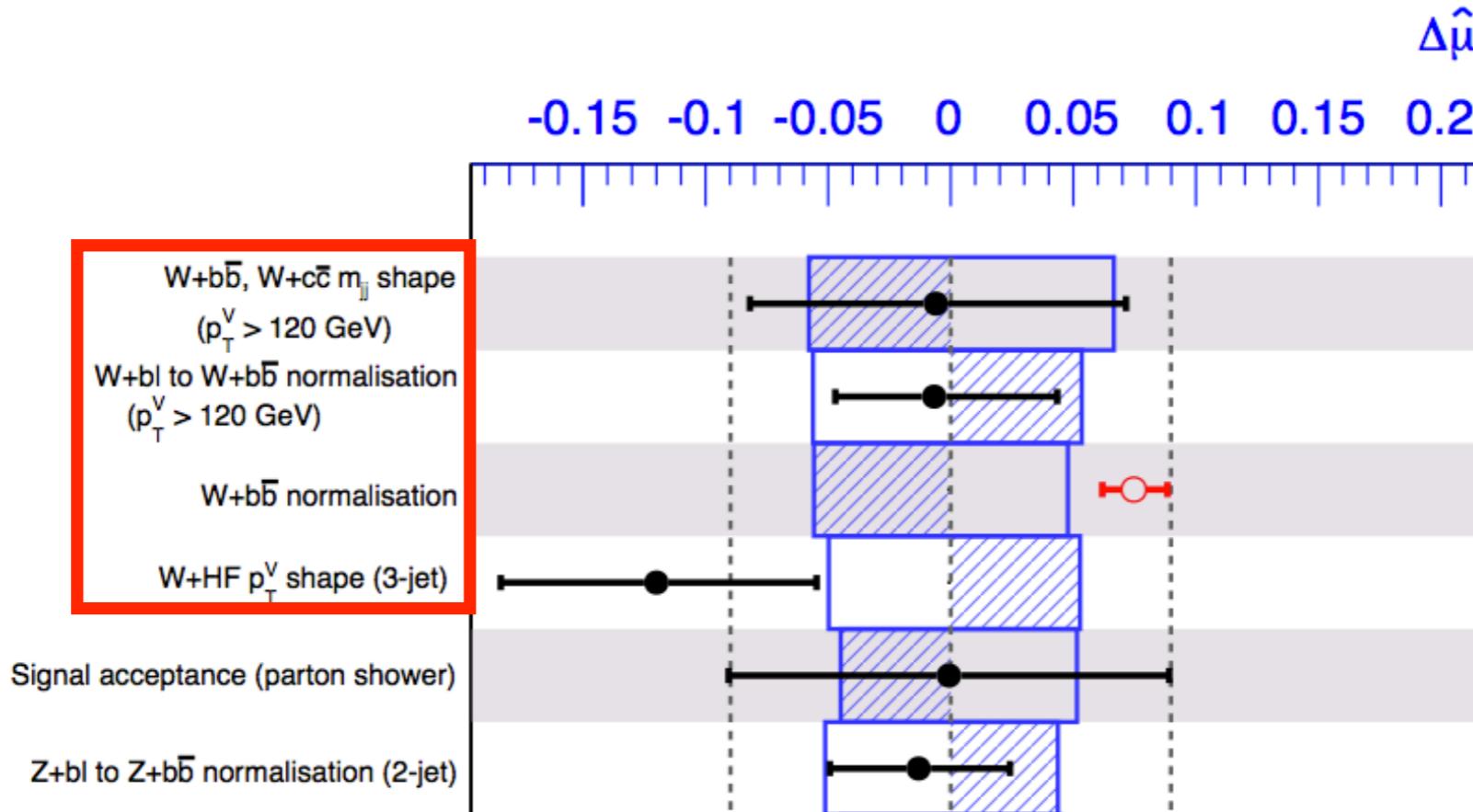
”

ATLAS:

- ▶ assess uncertainty on modeling of BDT input variables
 - m_{bb} , p_T^V , N_{jet}
- “ Details of the assessment of systematic uncertainties are provided below in the context of the MVA. When systematic uncertainties are derived from a comparison between generators, all relevant variables are considered independently. The variable showing the largest discrepancy in some generator with respect to the nominal generator is assigned an uncertainty covering this discrepancy, which is symmetrised. If, once propagated to the BDT_{VH} discriminant, this uncertainty is sufficient to cover all variations observed with the different generators, it is considered to be sufficient. If not, an uncertainty is considered in addition on the next most discrepant variable and the procedure is iterated until all variations of the BDT_{VH} discriminant are covered by the assigned uncertainties.

”

Run I systematics



ATLAS, JHEP 01 (2015) 069

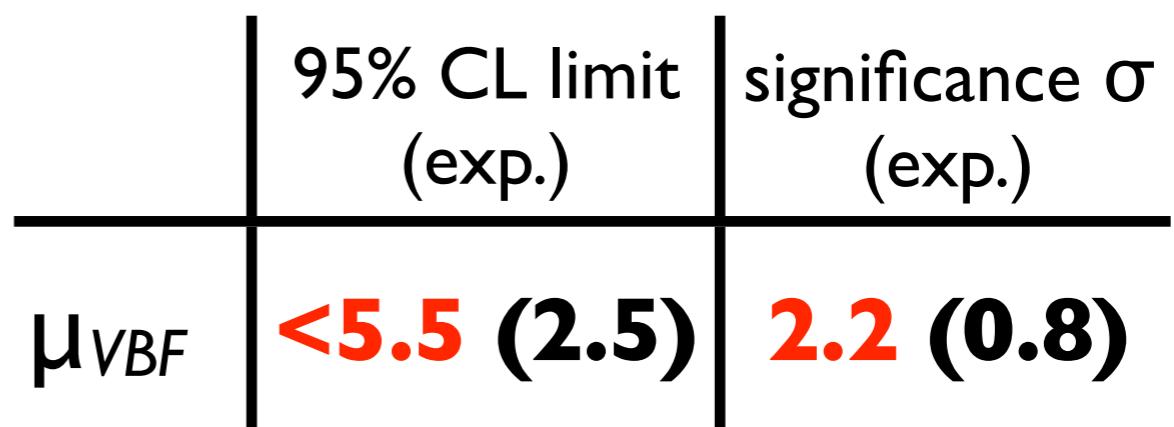
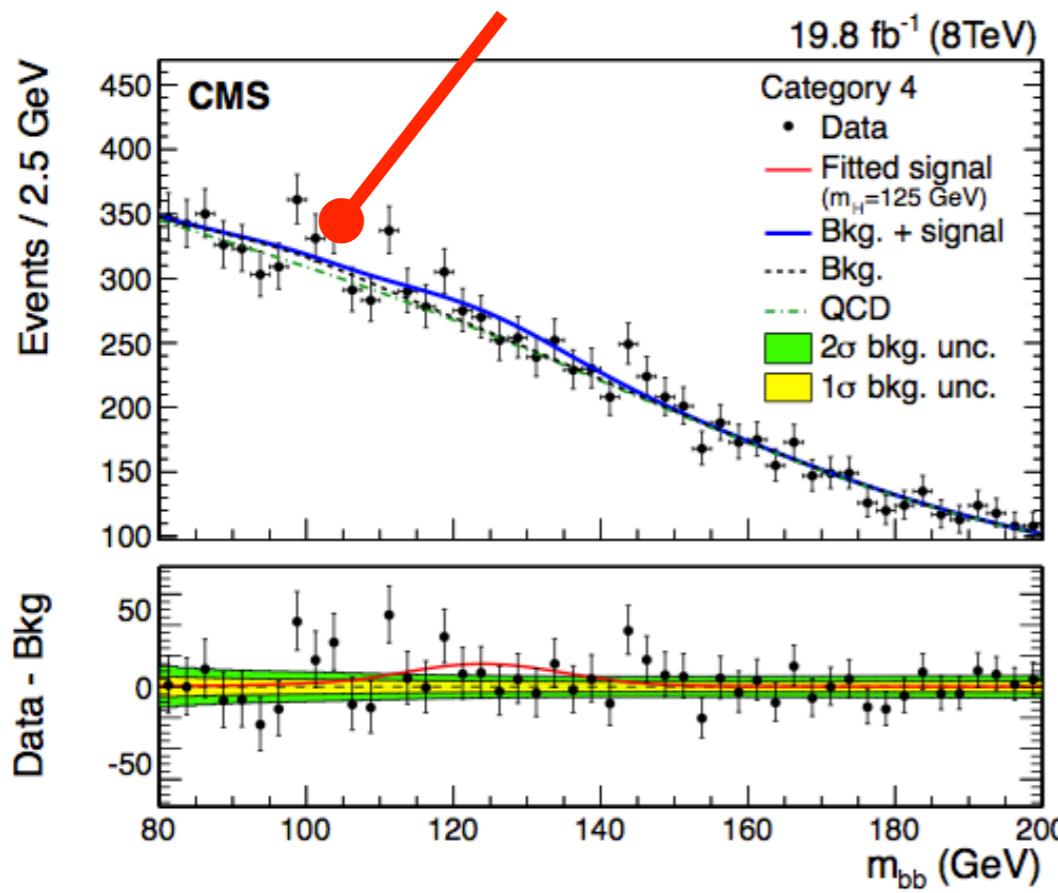
Source	Type	Event yield uncertainty range (%)	Individual contribution to μ uncertainty (%)	Effect of removal on μ uncertainty (%)
b-tagging	shape	3–15	10.2	2.1
Signal cross section (scale and PDF)	norm.	4	3.9	0.3
Signal cross section (p_T boost, EW/QCD)	norm.	2/5	3.9	0.3
Monte Carlo statistics	shape	1–5	13.3	3.6
Backgrounds (data estimate)	norm.	10	15.9	5.2
Single-top-quark (simulation estimate)	norm.	15	5.0	0.5
Dibosons (simulation estimate)	norm.	15	5.0	0.5
MC modeling (V+jets and t \bar{t})	shape	10	7.4	1.1

VBF, $H \rightarrow bb$

First SM Higgs search at LHC in fully-hadronic final states

- ▶ dedicated data parking strategy to maximise trigger efficiency
- ▶ huge hadronic background
 - continuum multi-jet + irreducible EWK backgrounds
 - in-situ calibration using $Z \rightarrow bb$ (3.6σ evidence)

**VBF cuts +
fit to m_{bb} spectrum**

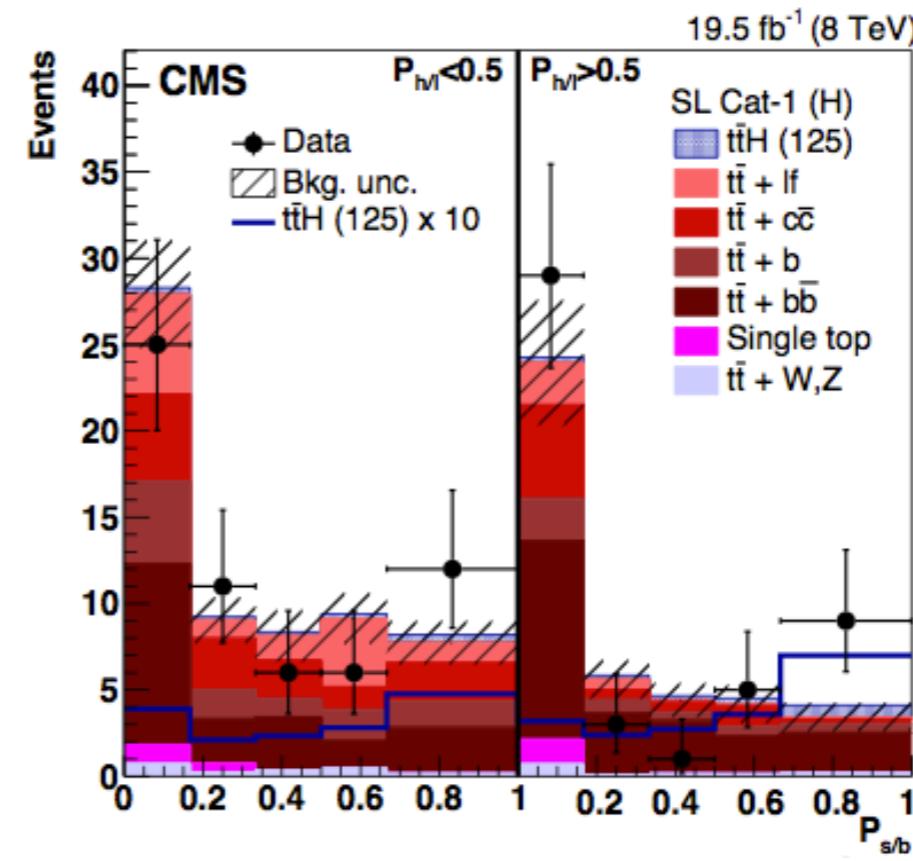
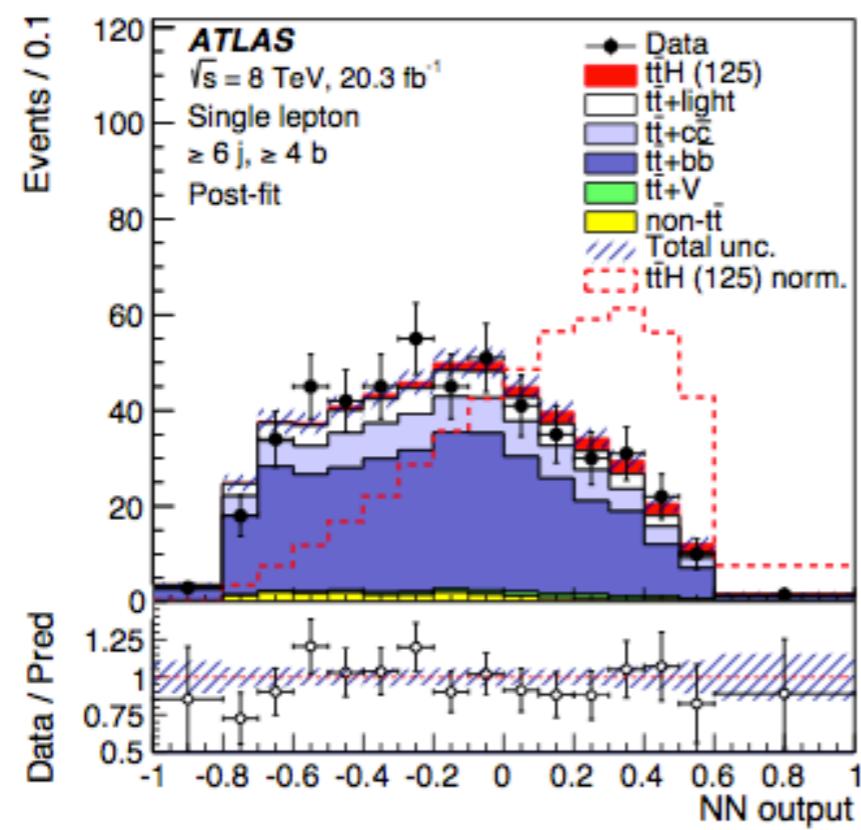


CMS, arXiv:1506.01010,
submitted to PRD

ttH(bb): analysis overview

- Event categorisation (N_{jet} , N_{tag})
- Signal extraction from fit to NN output
 - ▶ jet-jet correlations
 - ▶ event shapes
 - ▶ jet b tagging
- Matrix element method for ttH/ttbb separation
 - ▶ performing in signal-enriched regions

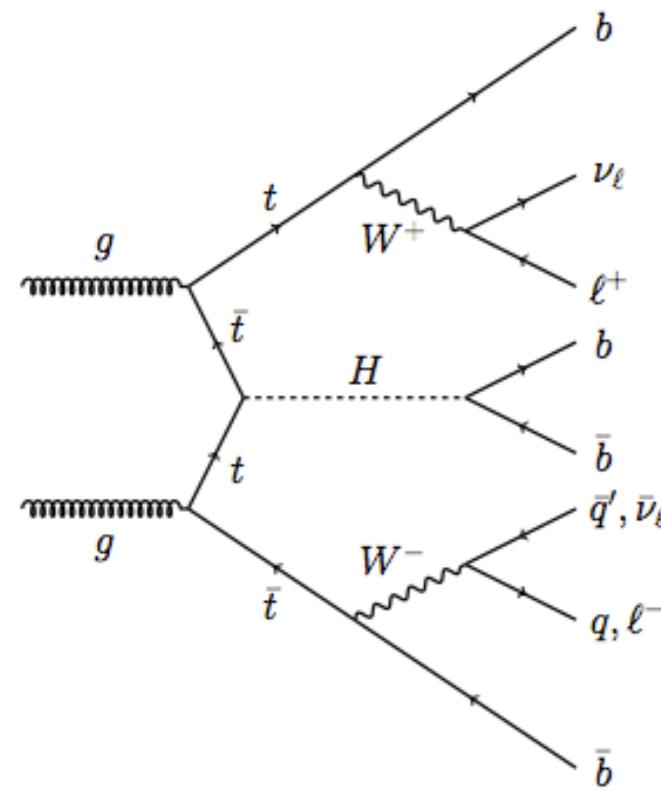
CMS, JHEP 09 (2014) 087
CMS, EPJC 75 (2015) 212
ATLAS, EPJC 75 (2015) 349



ttH: theoretical developments

	Accuracy	Some references
Signal modeling	NLO	PRL 87 (2001) 201805 NPB 653 (2003) PRD 68 (2003) 034022
	bkg interference	arXiv:1412.5290
	EWK corrections	arXiv:1504.03446
	NLO + PS	aMC@NLO+PYTHIA Sherpa+OpenLoops POWHEG+HELAC
Background modeling	tt+bb @NLO	PRL 103 (2009) 012002
	tt+bb @NLO + PS (4FS, 5FS)	PLB 734 (2014) 210 JHEP 07 (2014) 135 JHEP 1503 (2015) 083
	tt+jj @NLO	PRD 84 (2011) 114017
	tt+jj @NLO + PS	arXiv:1402.6293

Tackling $H \rightarrow bb$ final states

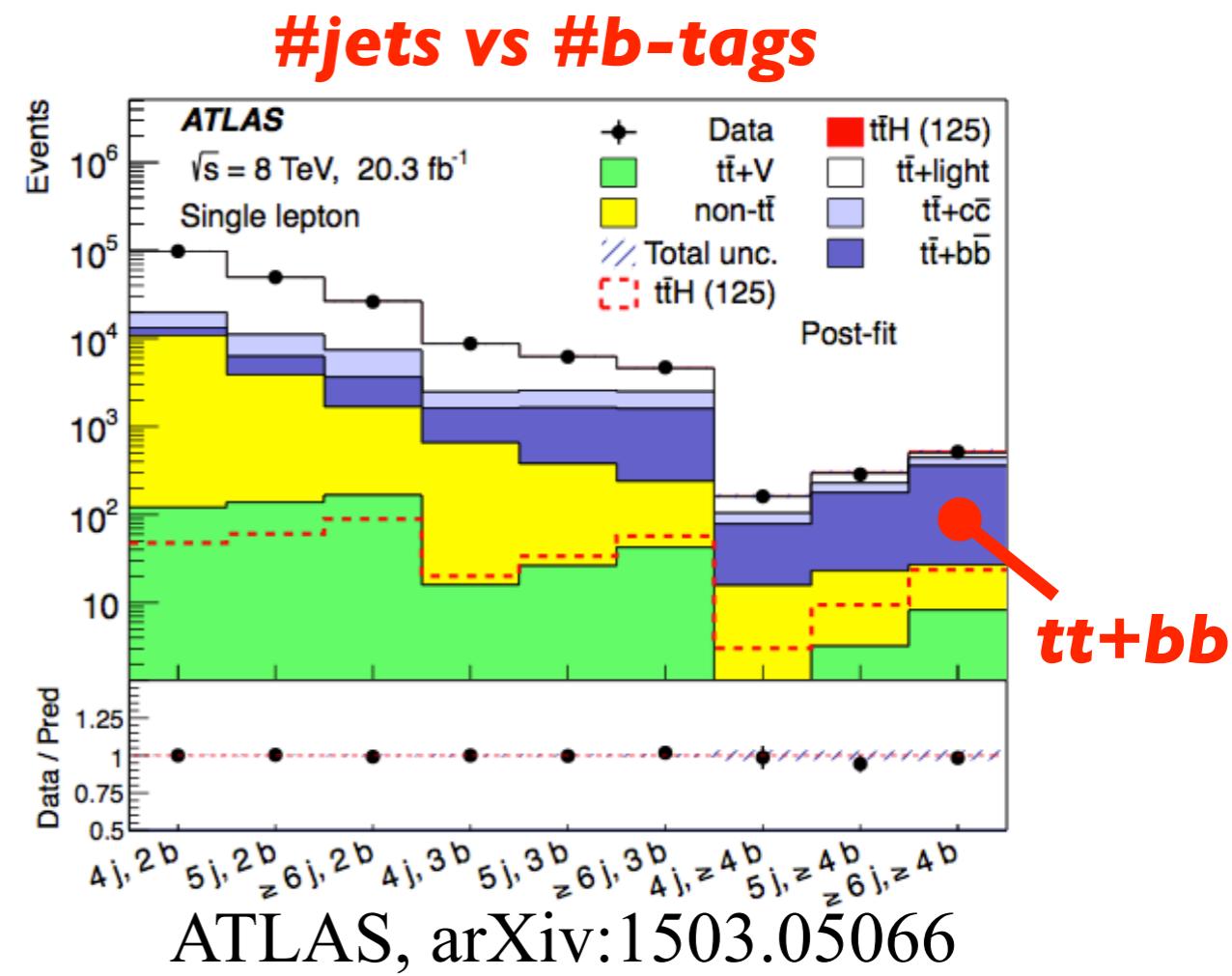


$$J = t \rightarrow b q \bar{q}'$$

$$L = t \rightarrow b \ell^+ \nu$$

	LL	LJ	JJ
quarks	4	6	8
b-quarks	4	4	4
leptons	2	1	0

- High jet multiplicities
 - ▶ up to four b-jets
- Require ≥ 1 lepton
 - ▶ trigger efficiency and negligible multi-jet background
- All-hadronic channel not yet explored
 - ▶ ideal case for boosted techniques



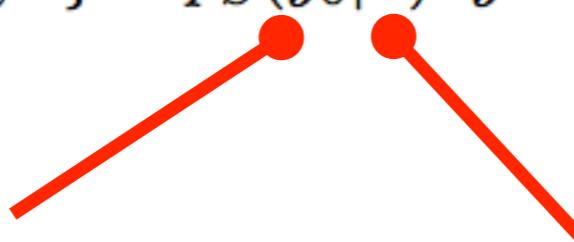
Principle

Assign each reconstructed event with its probability density

$$P\{\vec{y} \in [\vec{y}_0, \vec{y}_0 + d\vec{y}] \mid S, \theta\} = p_S(\vec{y}_0 | \theta) d\vec{y}$$

$$\int_A p_S(\vec{y} | \theta) d\vec{y} = 1$$

observed quantities
(e.g. jet, lepton momenta)



model parameters
(e.g. JES, particle masses)

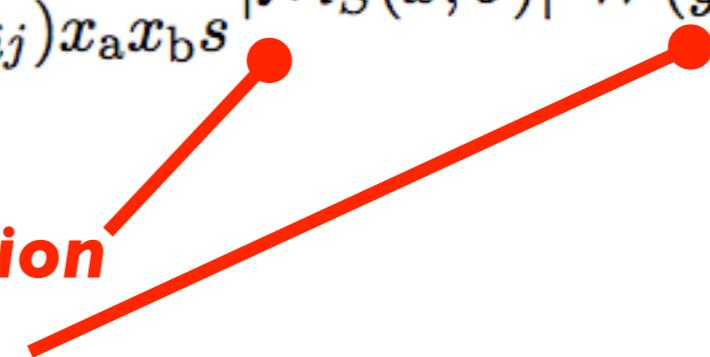
normalisation

- if the underlying scattering process is theoretically known:

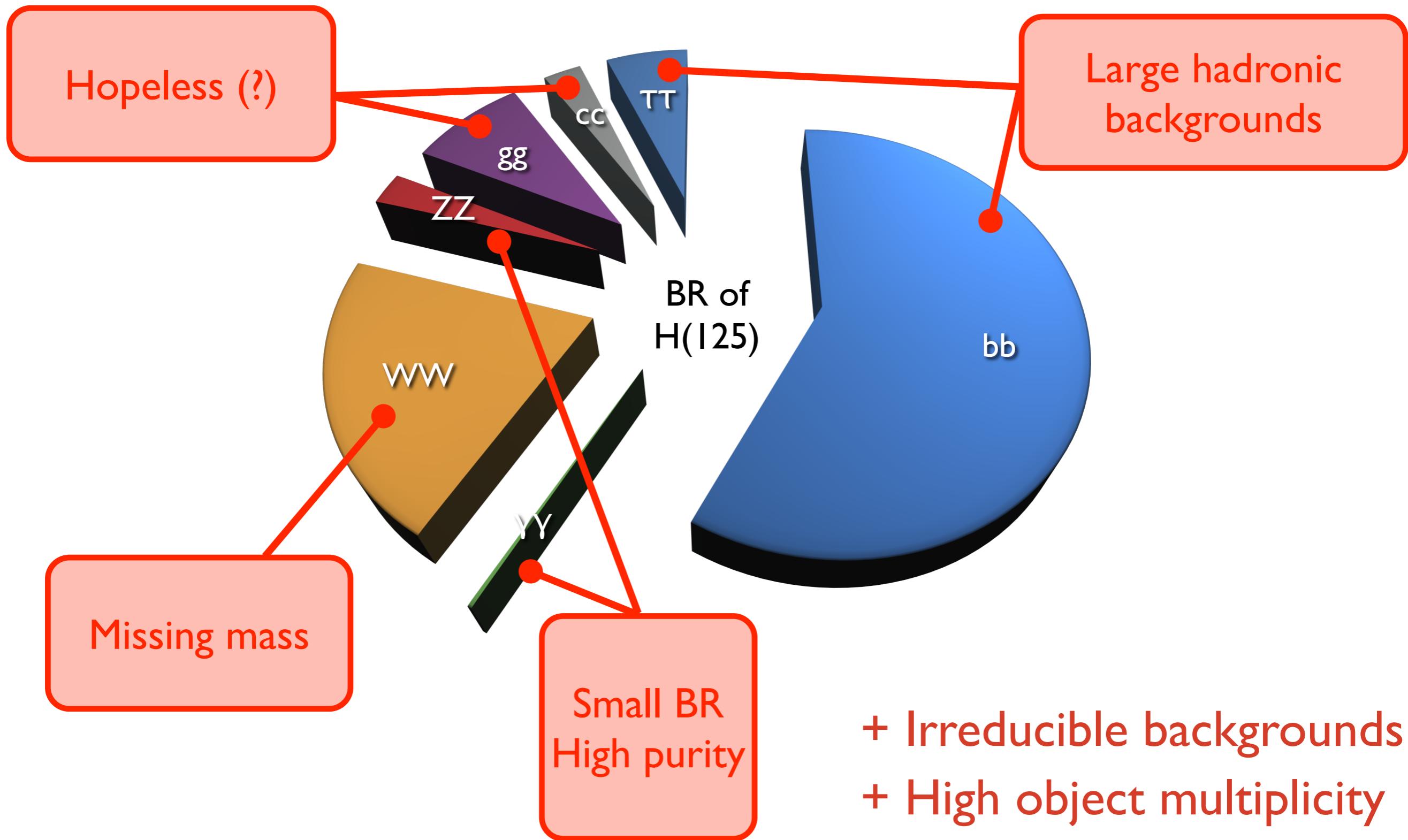
$$p_S(\vec{y} | \theta) = \frac{1}{\sigma_S(\theta)} \frac{d\sigma_S}{d\vec{y}}(\vec{y}, \theta)$$

$$d\sigma_S(\vec{y} | \theta) = \left[\int d\Phi(\vec{x}) dx_a dx_b \sum_{i,j} \frac{f_i(x_a) f_j(x_b)}{(1 + \delta_{ij}) x_a x_b s} |\mathcal{M}_S(\vec{x}, \theta)|^2 W(\vec{y}, \vec{x}; \theta) \right] d\vec{y}$$

- convolution of $\begin{cases} \text{theoretical prediction} \\ \text{detector resolution} \end{cases}$



ttH: experimental break-down

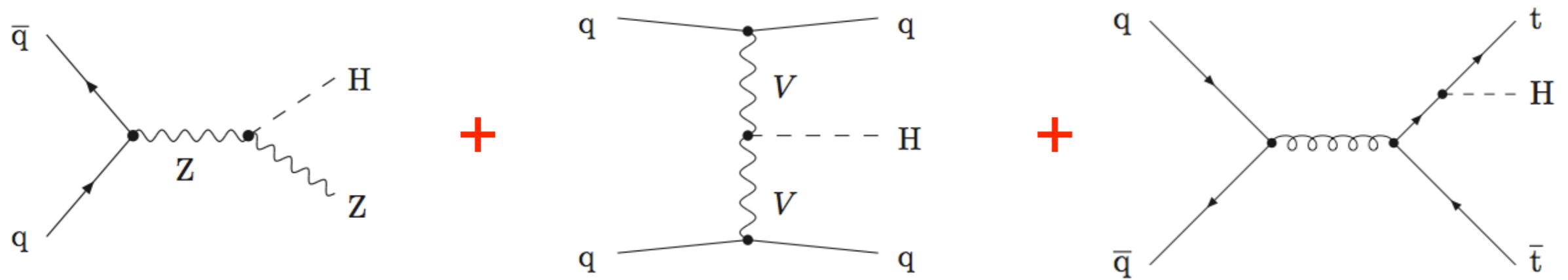


+ Irreducible backgrounds
+ High object multiplicity
(overlap, acceptance,
combinatorics)

Results from Run I: $\mu\sigma \times Br$

Combination of CMS $xx \rightarrow H \rightarrow bb$ channels

- ▶ 10% larger expected sensitivity from VBF and ttH channels



CMS, arXiv:1506.01010, submitted to PRD

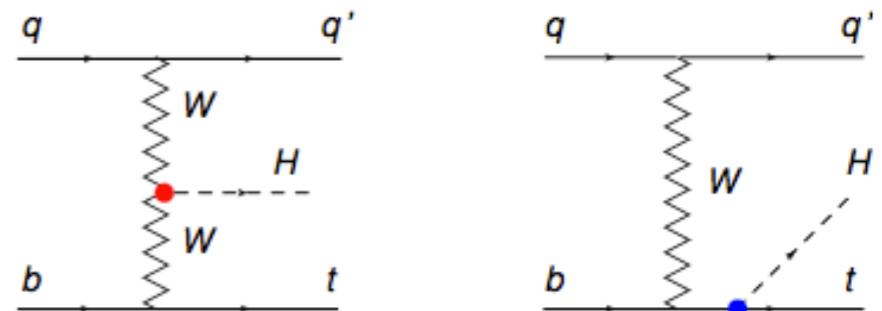
$H \rightarrow b\bar{b}$ Channel	Best fit (68% CL) Observed	Upper limits (95% CL) Observed	Upper limits (95% CL) Expected	Signal significance	
				Observed	Expected
VH	0.89 ± 0.43	1.68	0.85	2.08	2.52
$t\bar{t}H$	0.7 ± 1.8	4.1	3.5	0.37	0.58
VBF	$2.8^{+1.6}_{-1.4}$	5.5	2.5	2.20	0.83
Combined	$1.03^{+0.44}_{-0.42}$	1.77	0.78	2.56	2.70

2.6 σ significance

Top+Higgs: tH

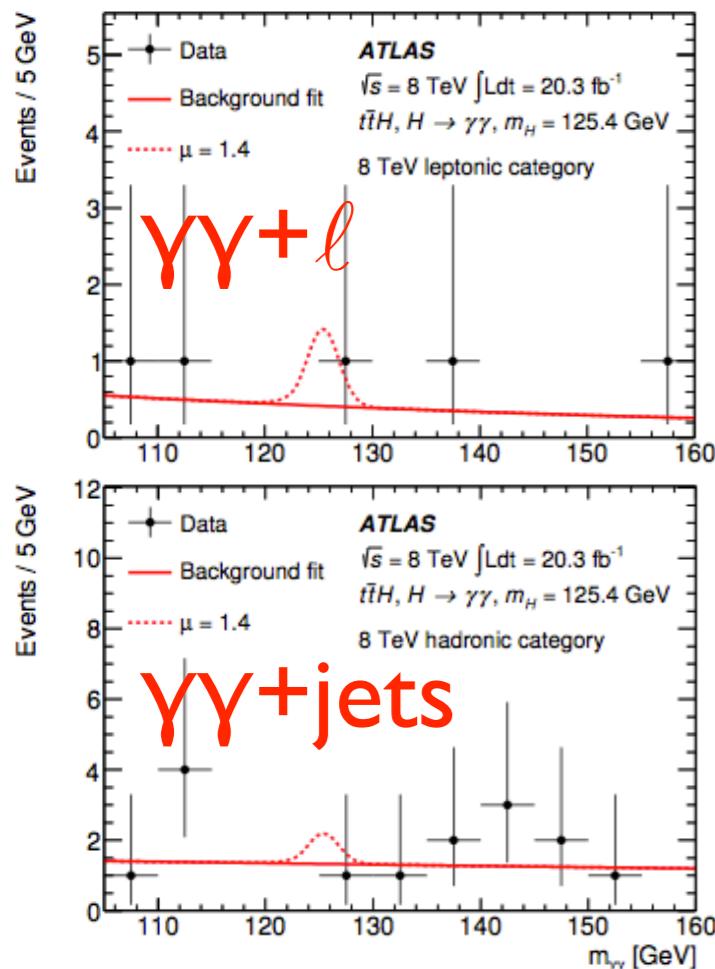
Searching for tHq/WtH production

- ▶ suppressed in SM ($\sigma_{\text{NLO}} \sim 18 \text{ fb}$)
- ▶ opportunity to access
 - coupling phase (CP violation)
 - FCNC
 - tH resonances

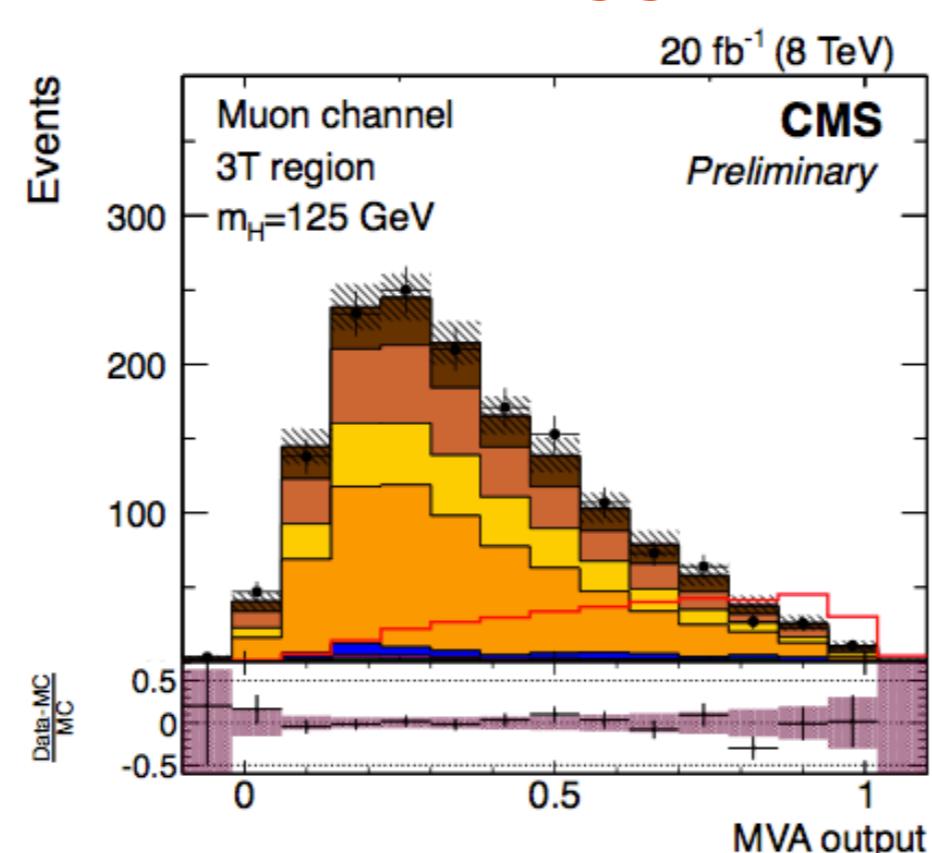


ATLAS, PLB 740 (2015) 222
 CMS, PAS-HIG-14-001
 CMS, PAS-HIG-14-015
 CMS, PAS-HIG-14-026

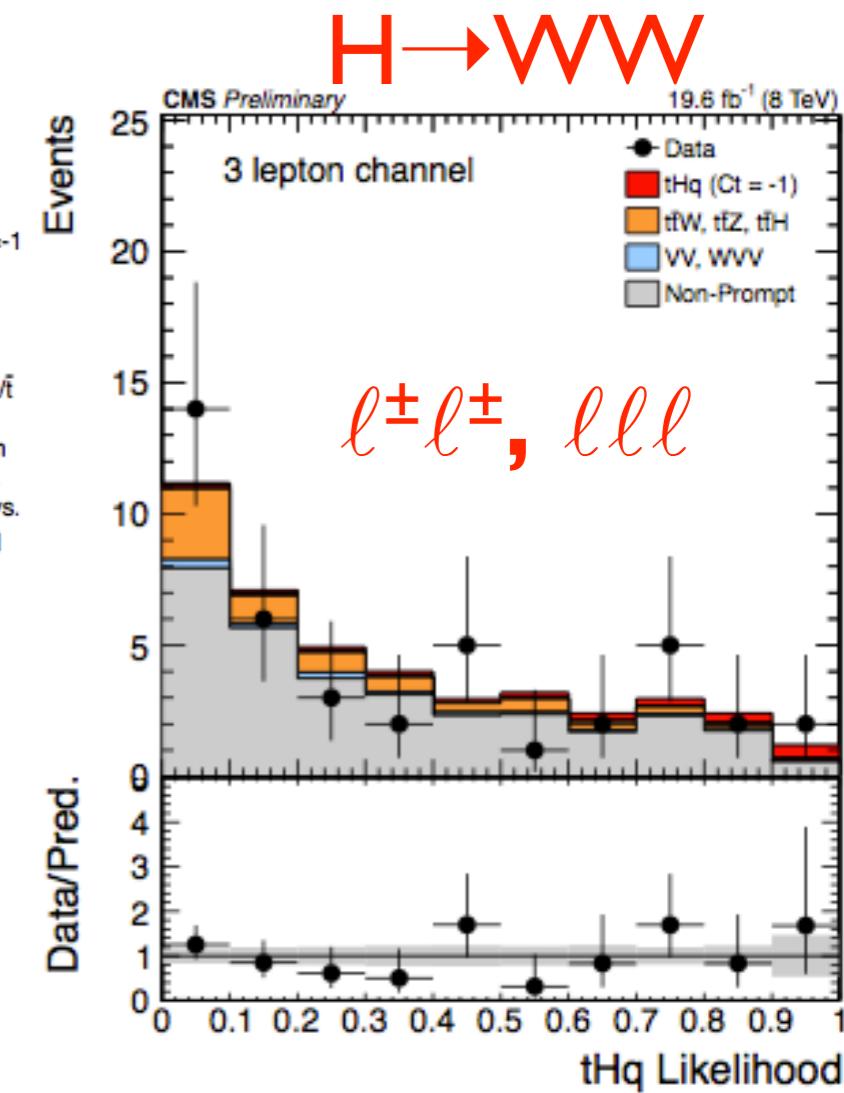
$H \rightarrow \gamma\gamma$



$H \rightarrow bb$



$H \rightarrow WW$

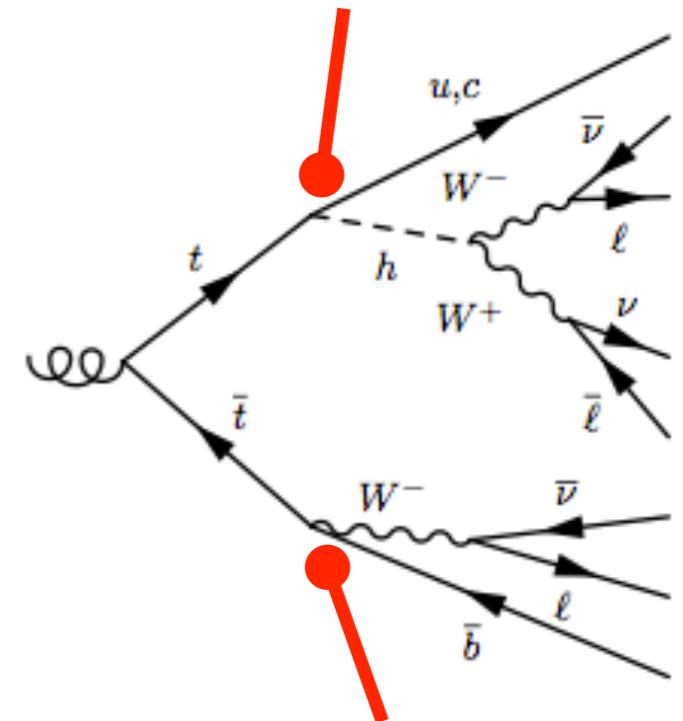


FCNC from the Yukawa sector

- FC currents from tqH interaction highly suppressed in SM
 - ▶ $BR(t \rightarrow cH) < 10^{-15}$
 - ▶ appear naturally in BSM
- Search for FC decays of top quarks
 - ▶ profit from large $\sigma(pp \rightarrow tt)$
 - constraints on FC coupling:

$$\mathcal{B} = (\lambda_{tcH}^2 + \lambda_{tuH}^2) / (g^2 \cdot |V_{tb}|^2 \cdot \chi^2)$$

$$\lambda_{t(u,c)H} \bar{t}(u, c) H$$



$$-\frac{g}{\sqrt{2}} V_{tb} \bar{t}_L \gamma^\mu b_L W_\mu^+$$

CMS, PRD 90 112013 (2013)

CMS, PAS-TOP-13-017

CMS, PAS-TOP-14-019

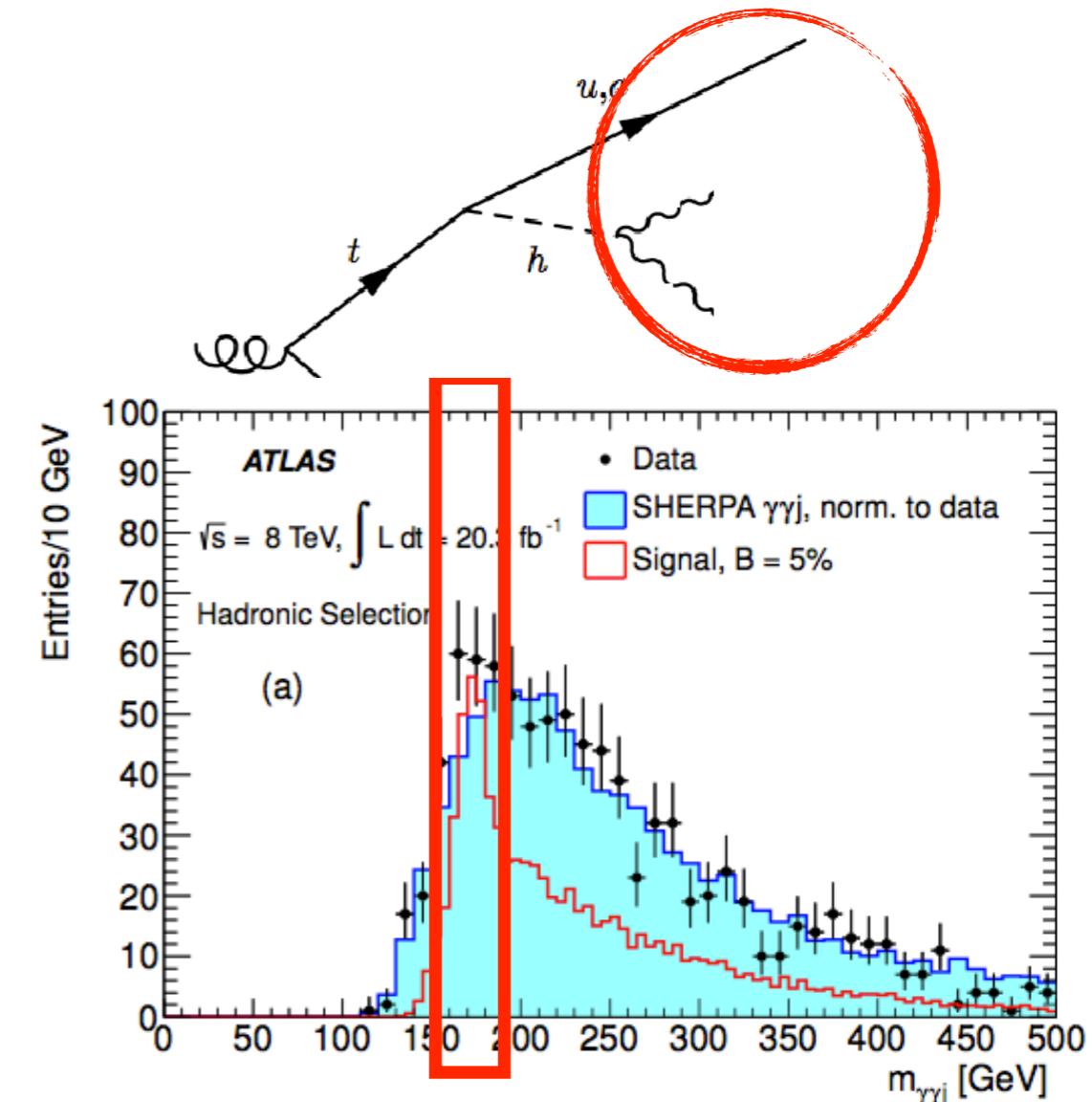
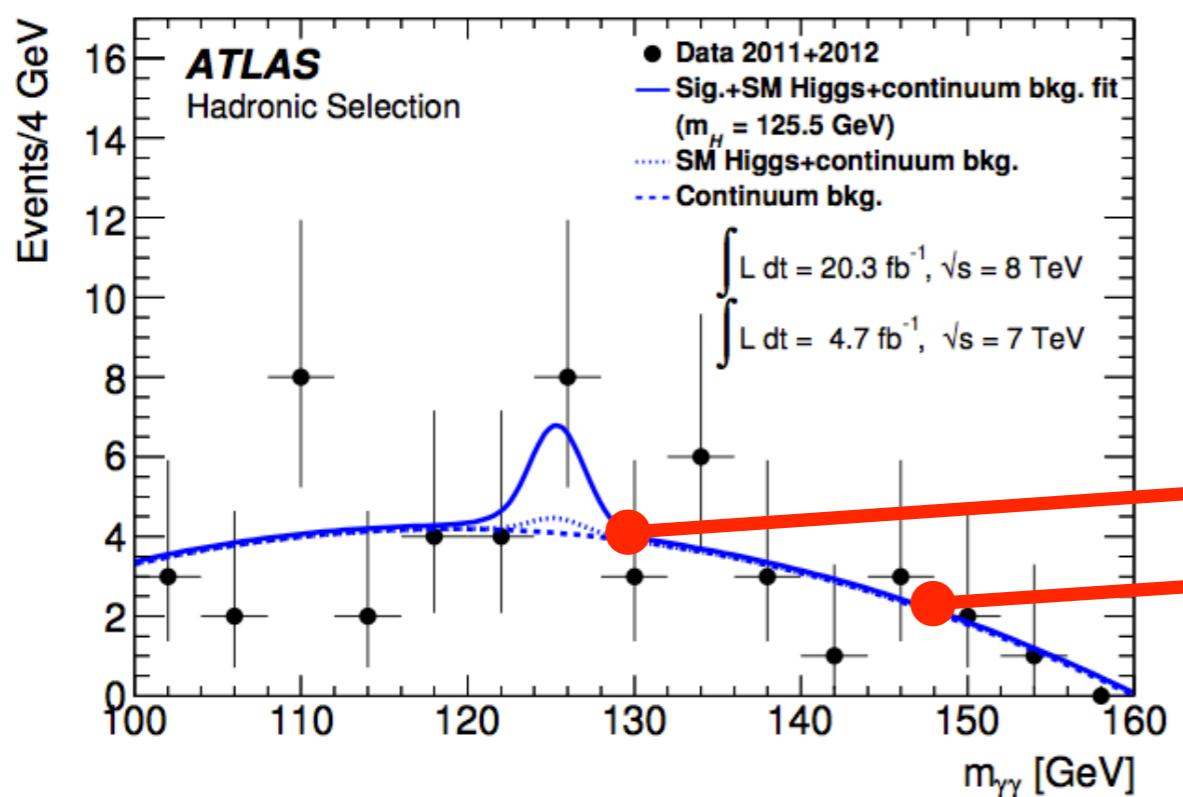
ATLAS, JHEP 06 (2014) 008

FCNC in top quark decays

$H \rightarrow \gamma\gamma$ channel

- ▶ cut-based selection
 - $\gamma\gamma + \text{jets} + \text{btag} + 0/1 \text{ leptons}$
 - top reconstruction to suppress $\gamma\gamma + \text{jets}$ continuum

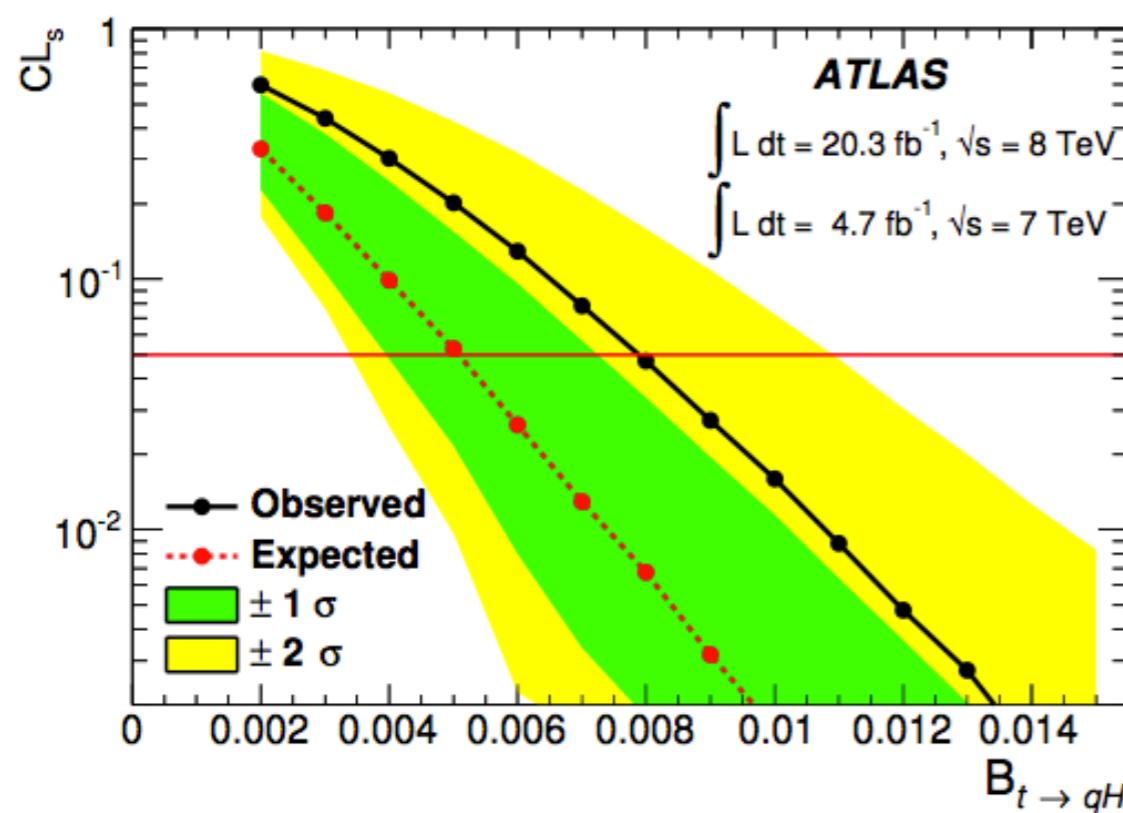
- ▶ fit to $m_{\gamma\gamma}$ spectrum:



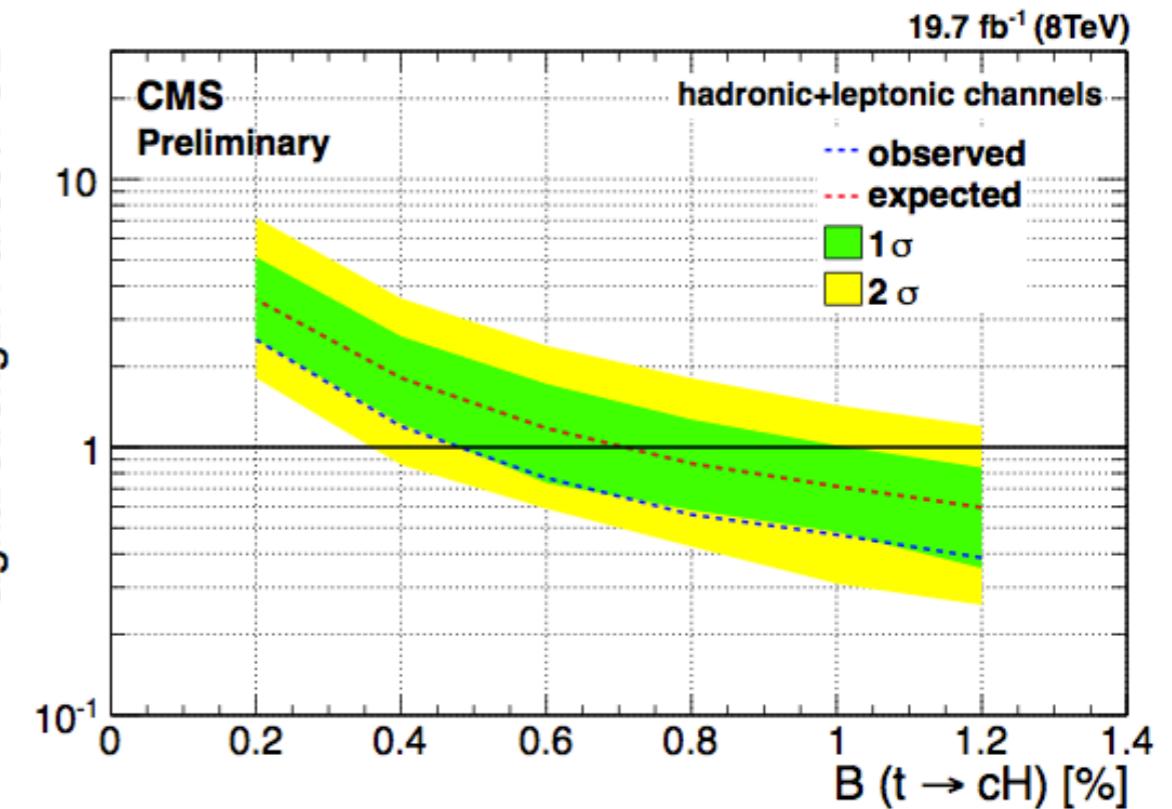
- **Resonant $H \rightarrow \gamma\gamma$ from MC**
- **Continuum background from fit**

FCNC in top quark decays

ATLAS, JHEP 06 (2014) 008



CMS, PAS-TOP-14-019



$B(t \rightarrow cH)$ 95% CL	Exp.	Obs.
CMS	0.71%	0.47%
ATLAS	0.51%	0.79%



$$\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.17$$

FCNC in top quark decays

H \rightarrow multilepton channel

- ▶ cut-and-count
 - 3/4 leptons + btag + E_T^{miss}
 - prompt & fake lepton backgrounds
- ▶ recently added same-sign dilepton channel

$B(t \rightarrow cH)$ 95% CL	Exp.	Obs.
lll, llll	1.17%	1.28%
lll, llll + $\gamma\gamma\ell$	0.51%	0.79%
$\ell^\pm\ell^\pm$, lll	0.89%	0.93%

CMS, PRD 90 112013 (2013)

CMS, PAS-TOP-13-017

