Higgs with top quarks: searches and measurements from the LHC

Lorenzo Bianchini[1] and Michele Pinamonti[2]

[1]ETH Zürich, [2]INFN Trieste & SISSA

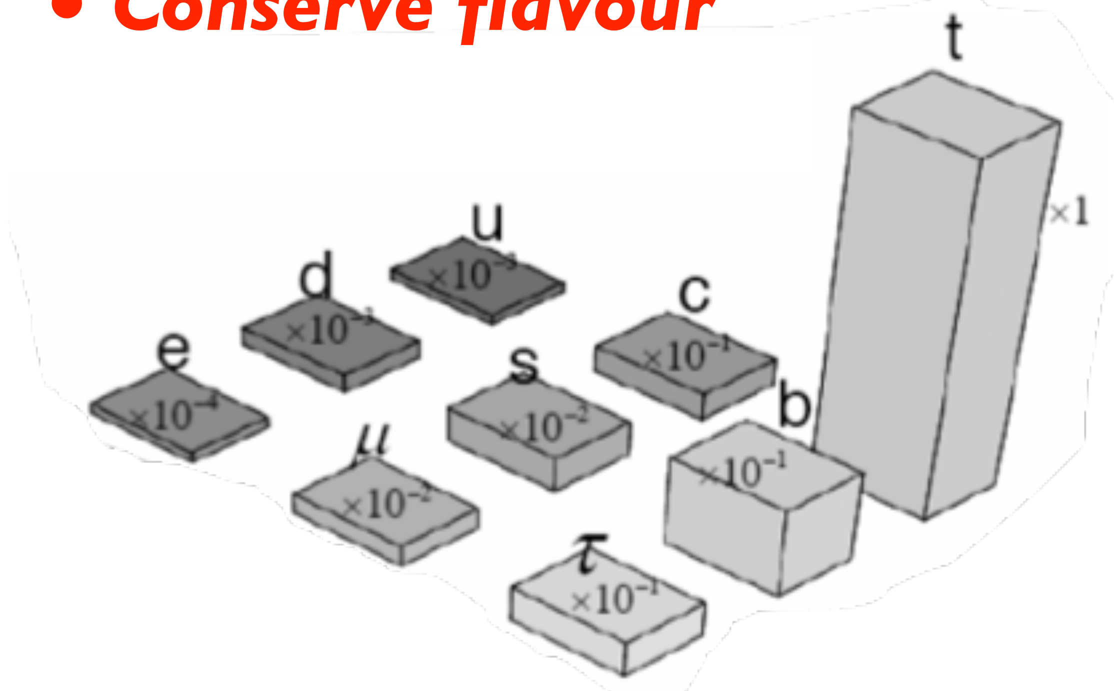
PP @ LHC 2016

Pisa, 16-18 maggio 2016

Overview

$$\lambda_{ij}\bar{\Psi}_i\Psi_j\Phi_H \xrightarrow{\text{EWSB}} \lambda_\psi\bar{\psi}_{\rm L}\psi_{\rm R}H + h.c.$$

- ***Coupling strength***
- ***Scalar interactions***
- ***Conserve flavour***



- Largeness of λ_t suggests a special role of the top quark in EWSB
  - LHC will offer unique chance of measuring it for the next decades
    - ultimate accuracy of 5% may be achievable at HL-LHC

- How to measure it at the LHC?
  - no direct decay into top quarks
  - *INDIRECT* constraints from GGF and BR($H\to\gamma\gamma$)
  - top+H cross section sensitive to λ_t at tree-level

generated by top loop

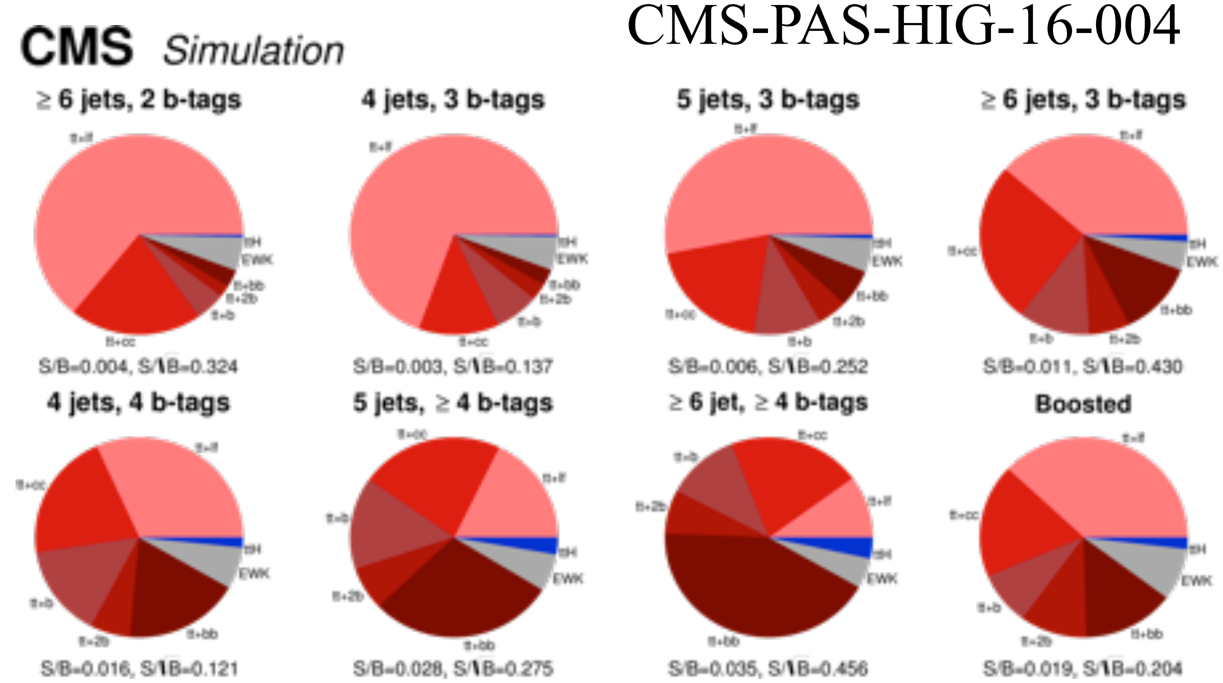
$$O_g(m_H) \approx \frac{g_s^2}{48\pi^2}(c_g + c_t)\frac{h}{v}G_{\mu\nu}G^{\mu\nu}$$

generated by ∞-mass particles

Overview of ttH searches

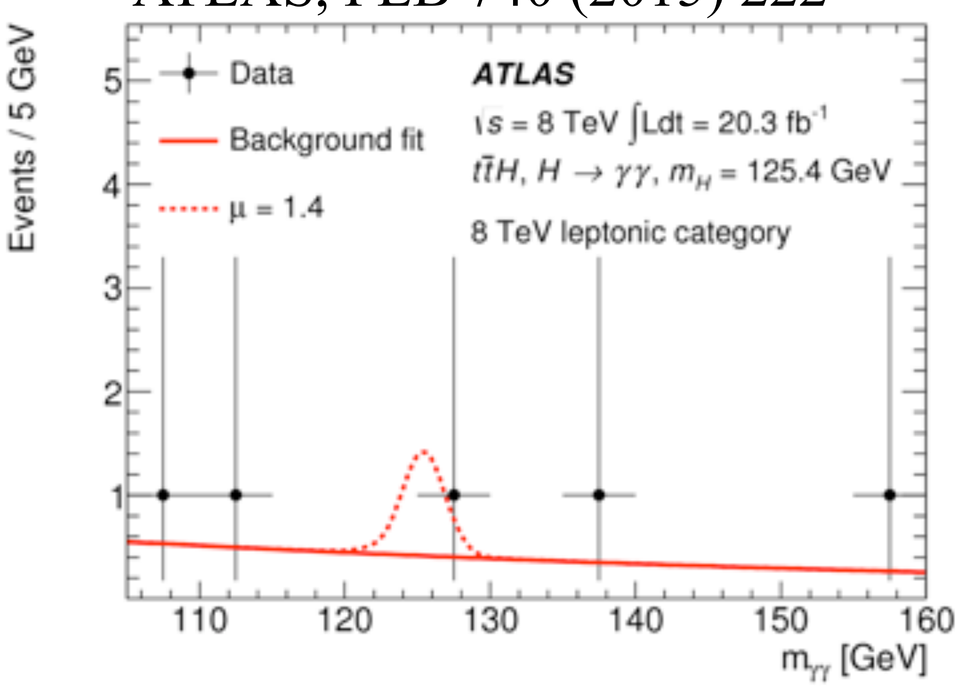
- H → bb
  - large backgrounds from tt+jets
    - tt+bb irreducible
  - no single discriminating variable
  - mastering top bkg. is the key

CMS-PAS-HIG-16-004

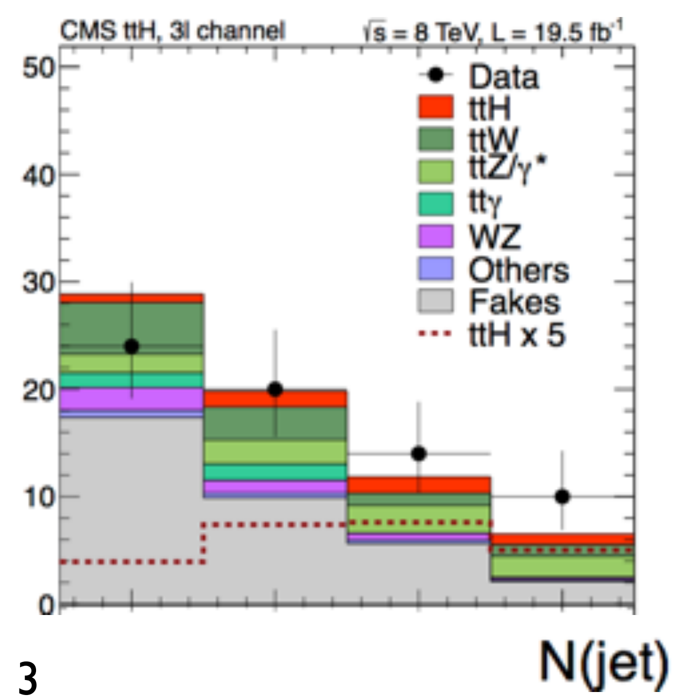


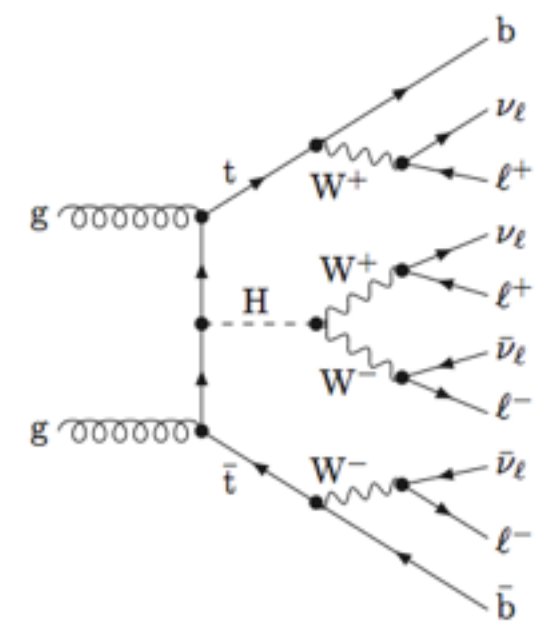
- H → γγ
  - small BR, but small systematics

ATLAS, PLB 740 (2015) 222



- H → WW/ZZ/ττ
  - clean signature, but suffering from irreducible SM backgrounds (ttV)





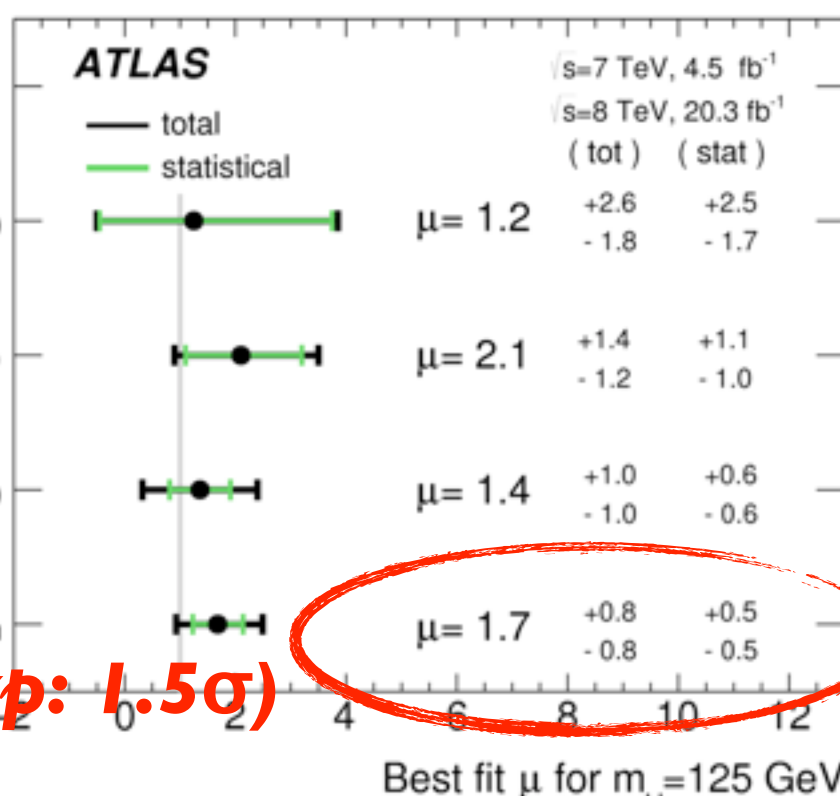
CMS, JHEP 09 (2014) 087

RunI summary: ttH

Channel	Experiment	95% U.L.	$\mu^{fit} \pm 1\sigma$	References
H → bb	ATLAS	< 3.4 (2.2)	$1.4^{+1.2}_{-1.2}$	EPJC 75 (2015) 349 arXiv:1604.0381
	CMS	< 4.1 (3.5)	$0.7^{+1.9}_{-1.9}$	JHEP 09 (2014) 087 CMS, EPJC 75 (2015) 212
H → γγ	ATLAS	< 6.7 (4.9)	$1.4^{+2.1}_{-1.4}$	PLB 740 (2015) 222
	CMS	< 7.4 (4.7)	$2.7^{+2.6}_{-1.8}$	JHEP 09 (2014) 087
H → WW	ATLAS	< 4.7 (2.4)	$2.1^{+1.4}_{-1.2}$	PLB 749 (2015) 519
	CMS	< 6.6 (2.4)	$3.7^{+1.6}_{-1.4}$	JHEP 09 (2014) 087

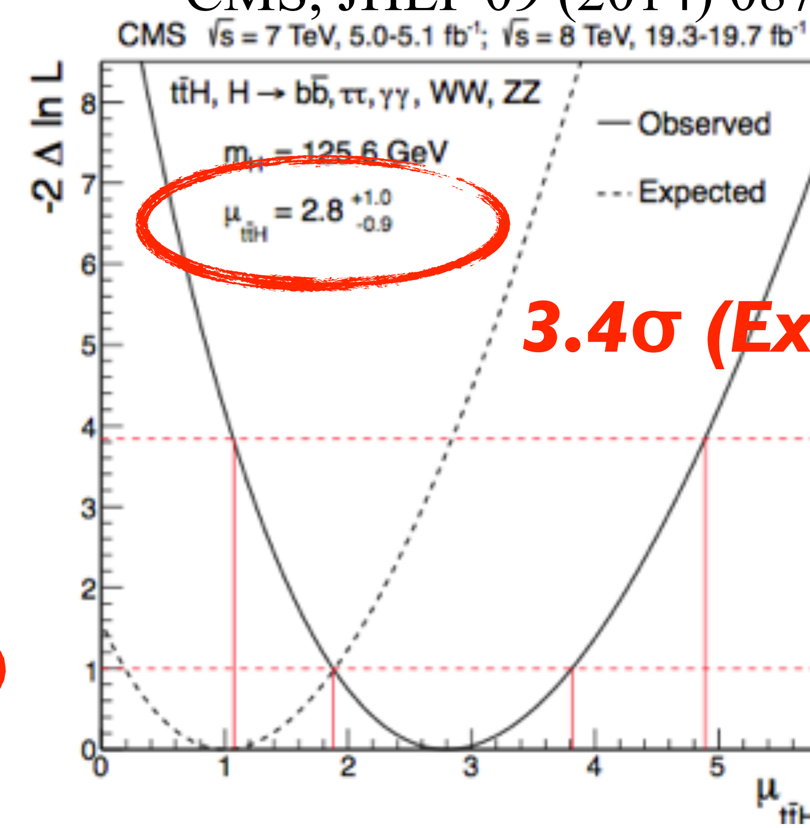
ATLAS, arXiv:1604.0381

Includes new AH channel



2.3σ (Exp: 1.5σ)

CMS, JHEP 09 (2014) 087



3.4σ (Exp: 1.2σ)

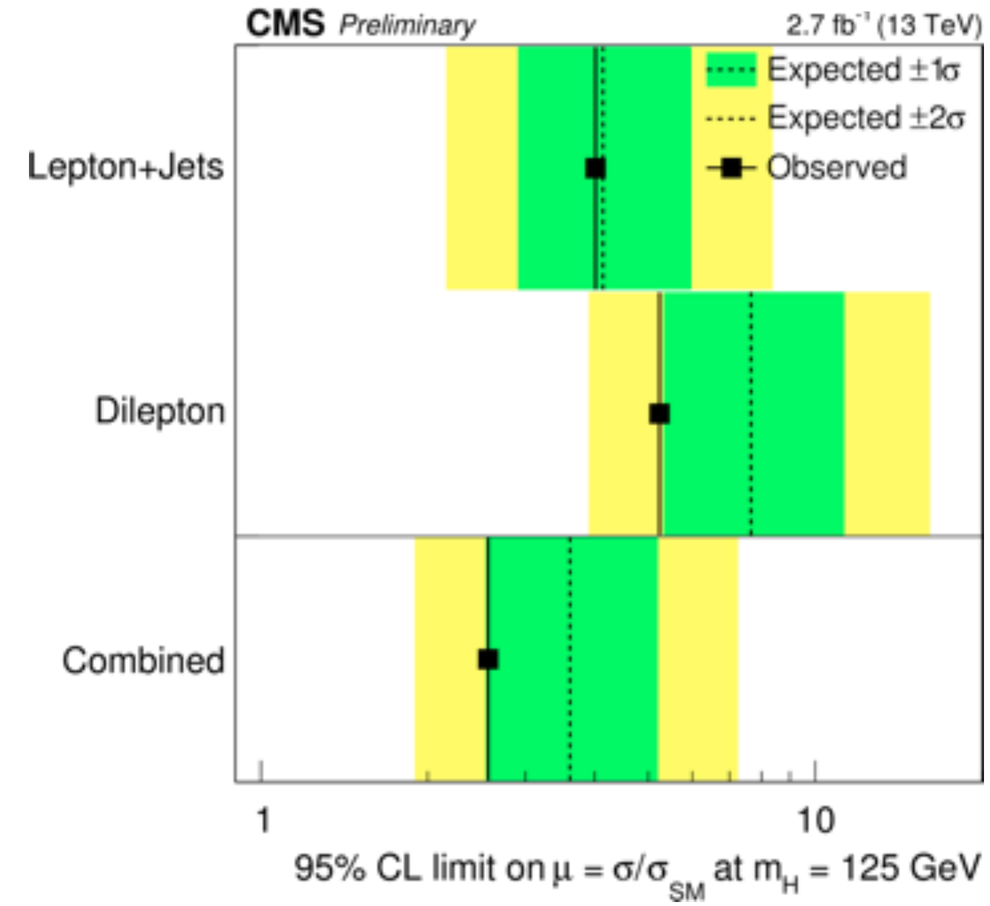
Run2 preliminary: ttH

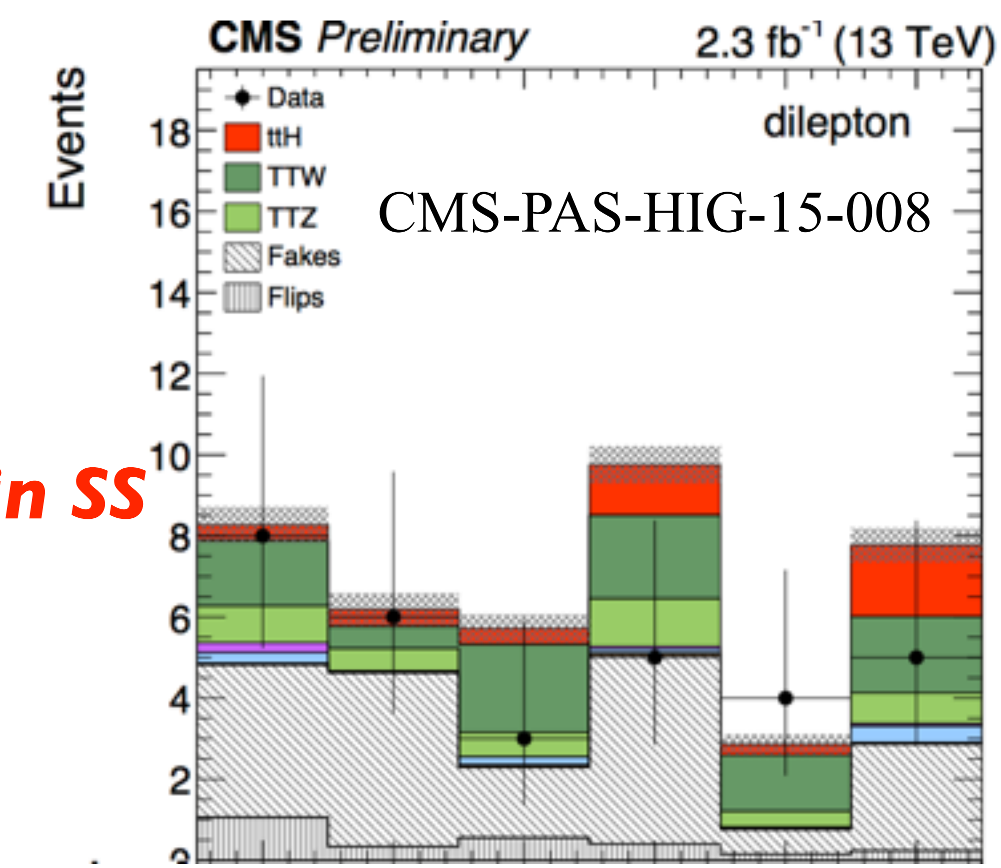
- H→bb
  - improved analysis strategy
    - simultaneous deployment of MEM and BDT discriminants
    - boosted top-Higgs category
  - sensitivity close to Run1!

- H→WW/ZZ/ττ
  - improved fake lepton rejection
  - better separation against tt+V
  - sensitivity close to Run1!

- Search for H→γγ
  - statistically limited

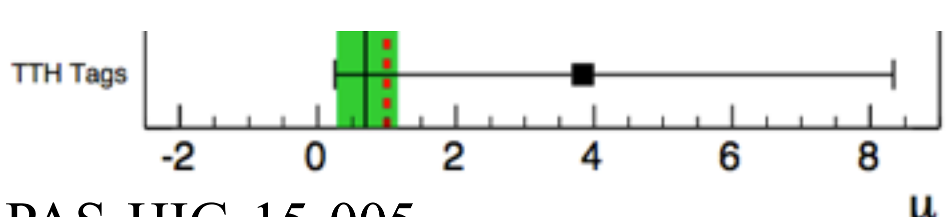
CMS-PAS-HIG-16-004





CMS-PAS-HIG-15-008

No excess observed in SS channel...



CMS-PAS-HIG-15-005

ATLAS vs CMS: ttH→bb

changed since Run1

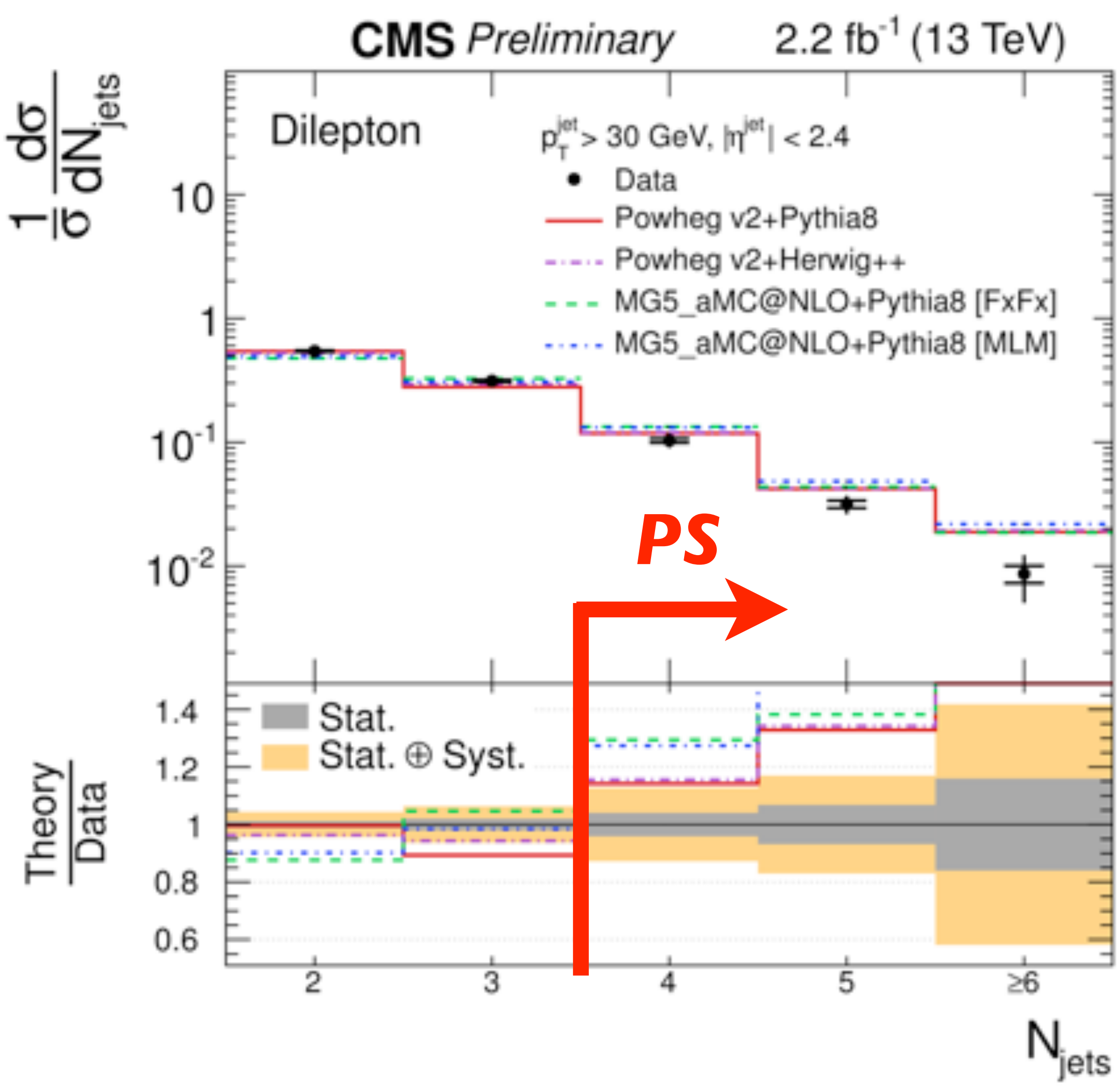
	ATLAS	CMS	CMS Run2
Jet p_T	>25	>30	>30
Jet radius	0.4	0.5	0.4
SL lepton p_T	>25	>30	>25
DIL lepton p_T	>25,15	>20,15	>20,15
Additional SL cat.	(4j,2t), (5j,2t)	-	-
Additional DIL cat.	(2j,2b) (>=4j,3t), (3j,2t)	- (>=3j,3t)	- (>=4j,3t), (3j,2t)
B tagging: $\varepsilon_b : \varepsilon_{light}$	70% : 1%	70% : 2%	70% : 1%
Jet flavour definition	parton-matching	parton-matching	(Ghost) hadron-matching
tt+jets splitting	bb,cc, LF	bb, b, cc, LF	bb, b, 2b, cc, LF
tt+bb prediction	POWHEG reweighted to SherpaOL	MG5+PY6	POWHEG+PY8

Run2 issues: tt+jets modeling

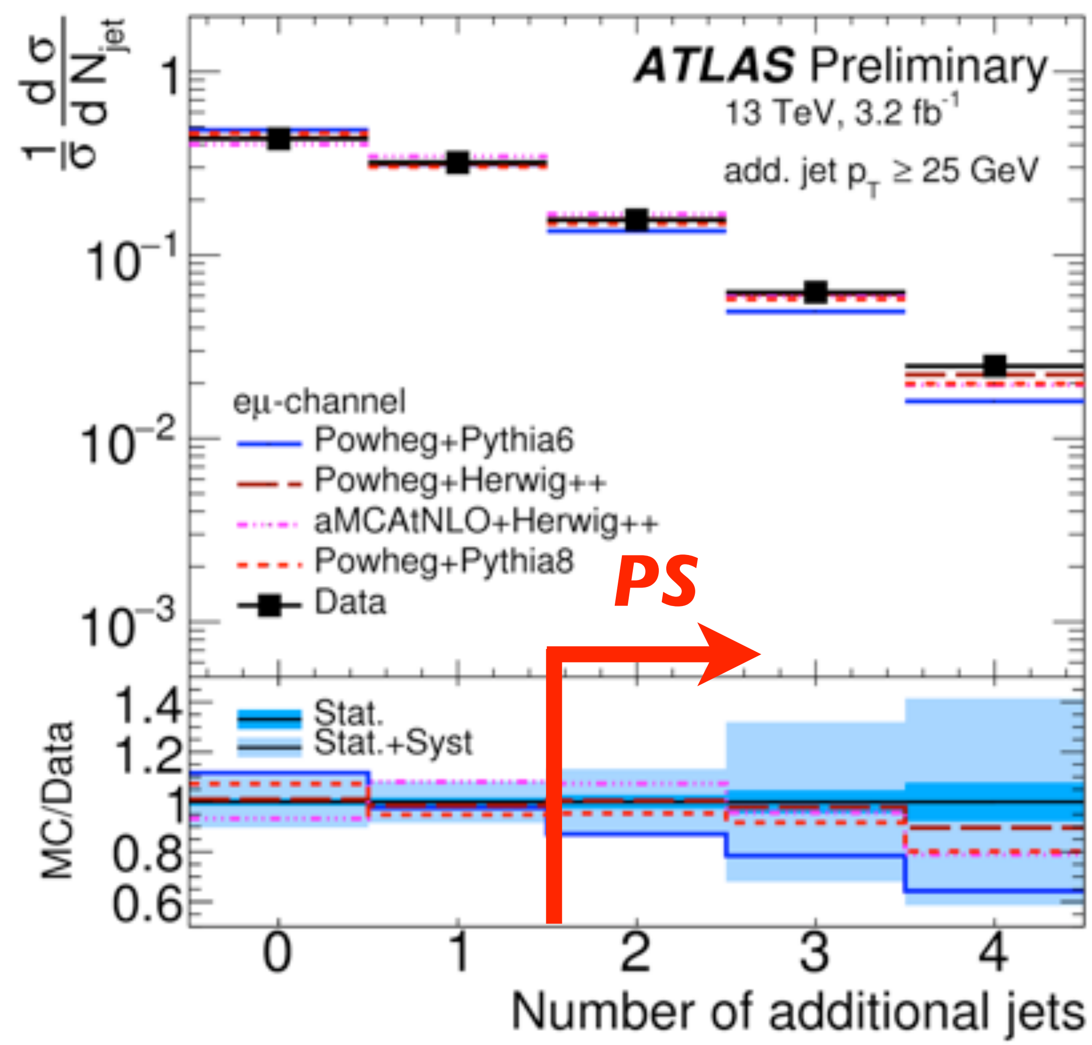
ATLAS and CMS see different things when comparing 13 TeV data with “same” MC (Powheg+Pythia)

- jet multiplicity

CMS-PAS-TOP-16-011



ATLAS-CONF-2016-020



Large disagreement in extra jet multiplicity

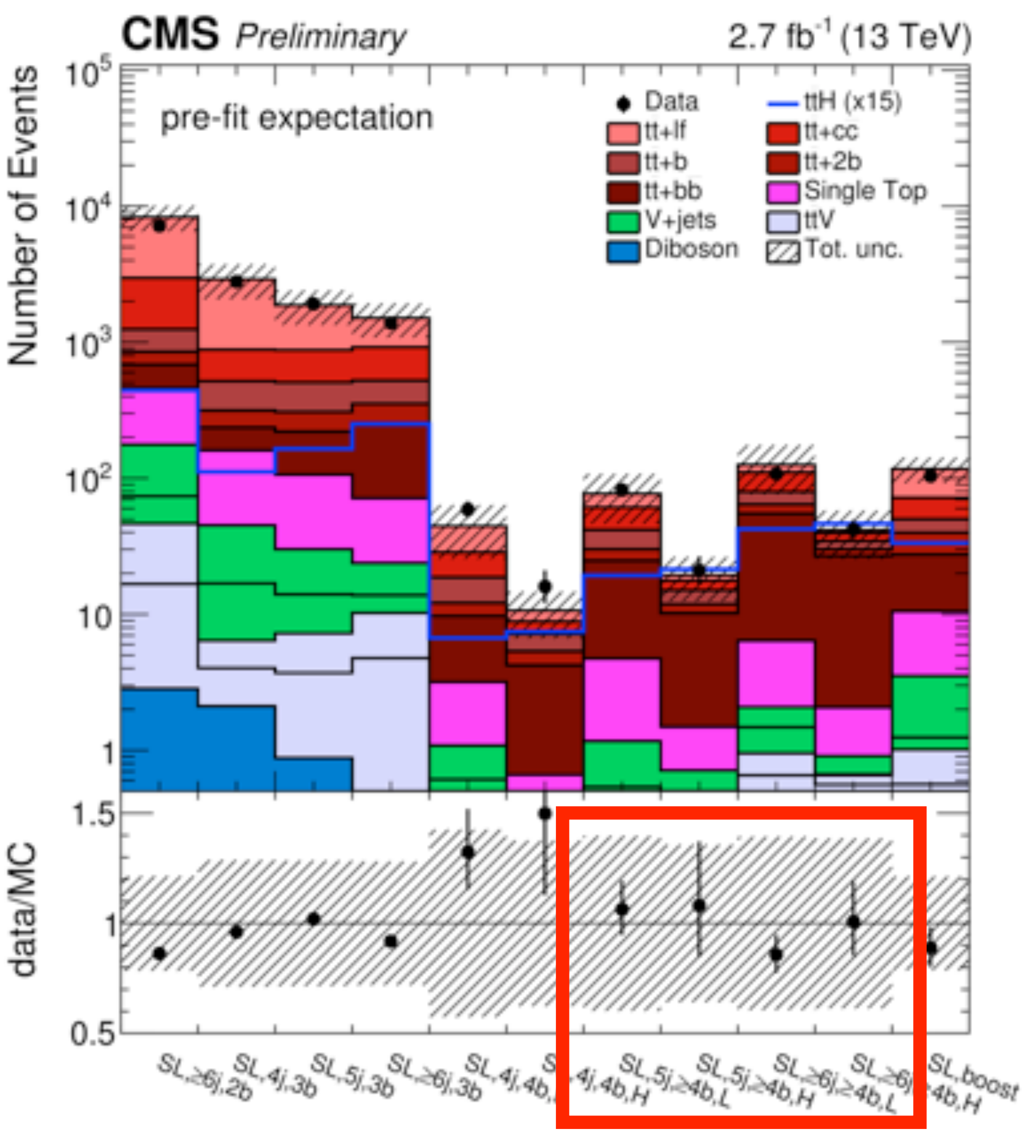
Data/MC in opposite direction (but within syst. band)

Run2 issues: tt+jets modeling

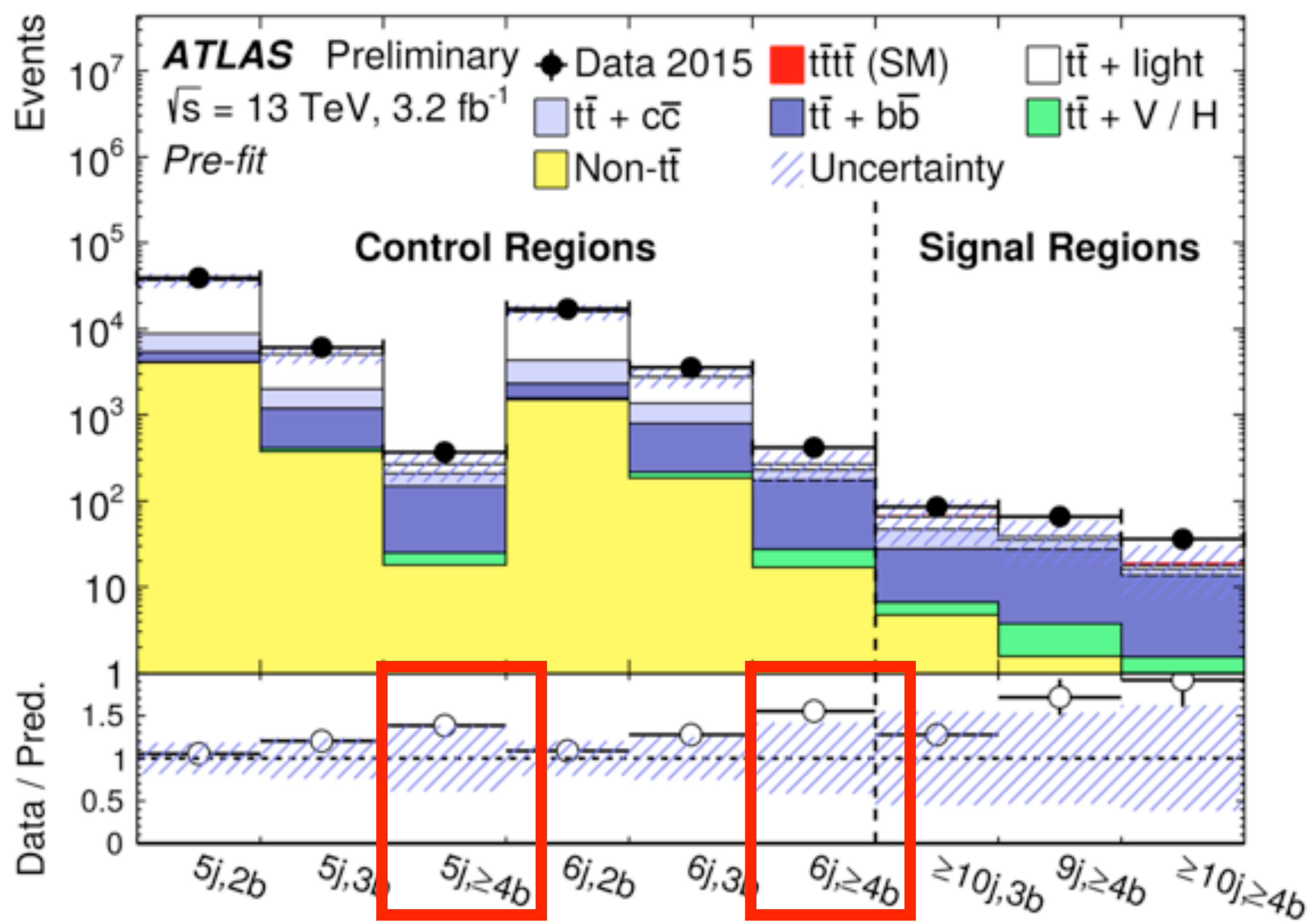
ATLAS and CMS see different things when comparing 13 TeV data with "same" MC (Powheg+Pythia)

- b-tag multiplicity ⇒ tt+HF modeling

CMS-PAS-HIG-16-004



ATLAS-CONF-2016-020



Good pre-fit agreement in tt+HF categories

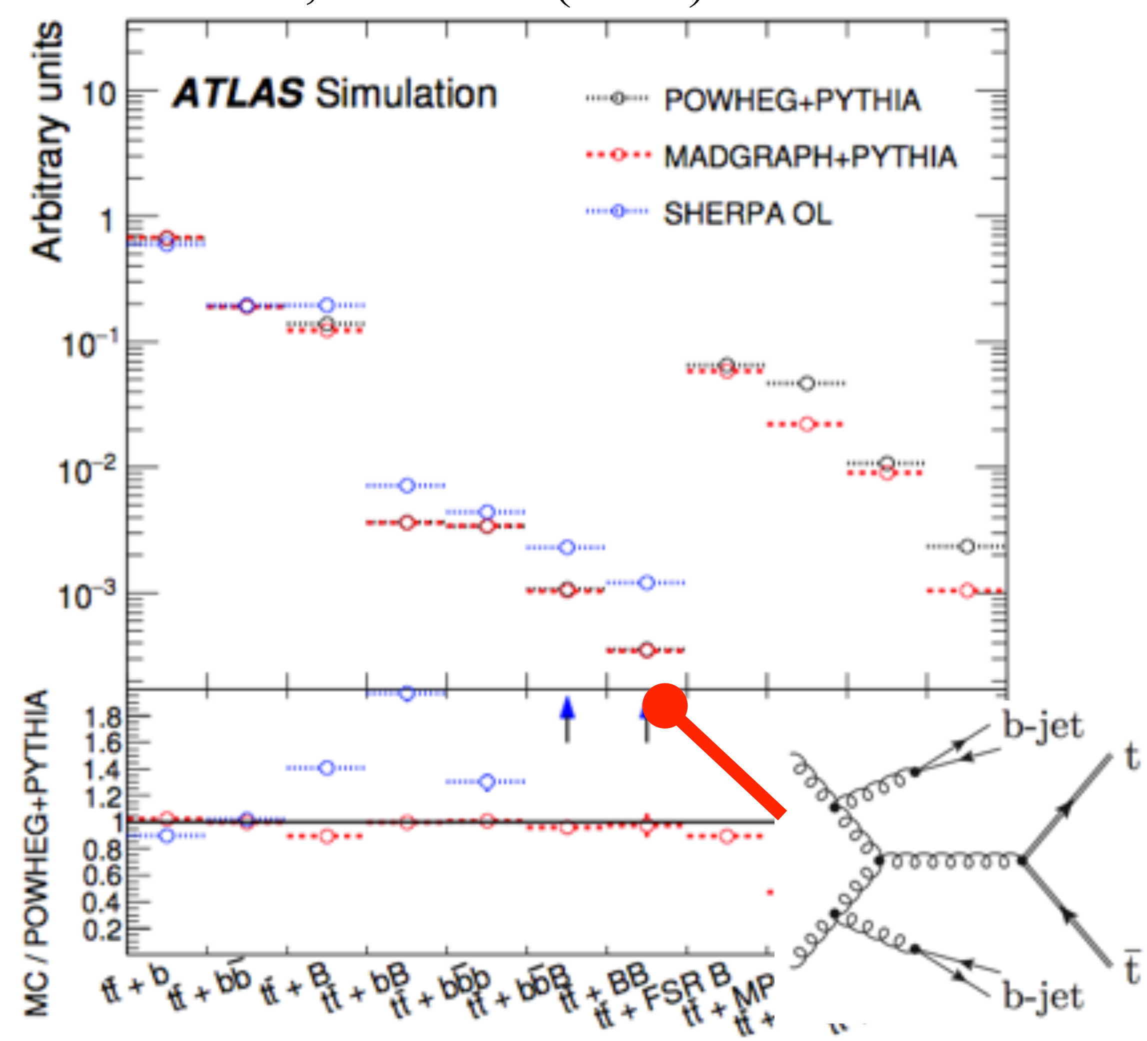
Simulation underpredicts in same tt+HF categories

Run2 issues: tt+jets modeling

- Which MC's are used to model tt+jets?
  - ATLAS → Powheg+Pythia6
  - CMS → Powheg+Pythia8
    - ATLAS sees no difference when using Pythia8
    - ATLAS reweights its tt+HF prediction to SherpaOL (NLO accurate)
    - Same Powheg settings, different ME-PS matching options & different PS tunes

- What about tt+HF?
  - in YR4 (to be public soon), MG5_aMC@NLO is compared to SherpaOL and HELAC
    - much larger predictions from MG5_aMC@NLO, and in the direction of ATLAS tt+HF excess

ATLAS, EPJC 75 (2015) 349



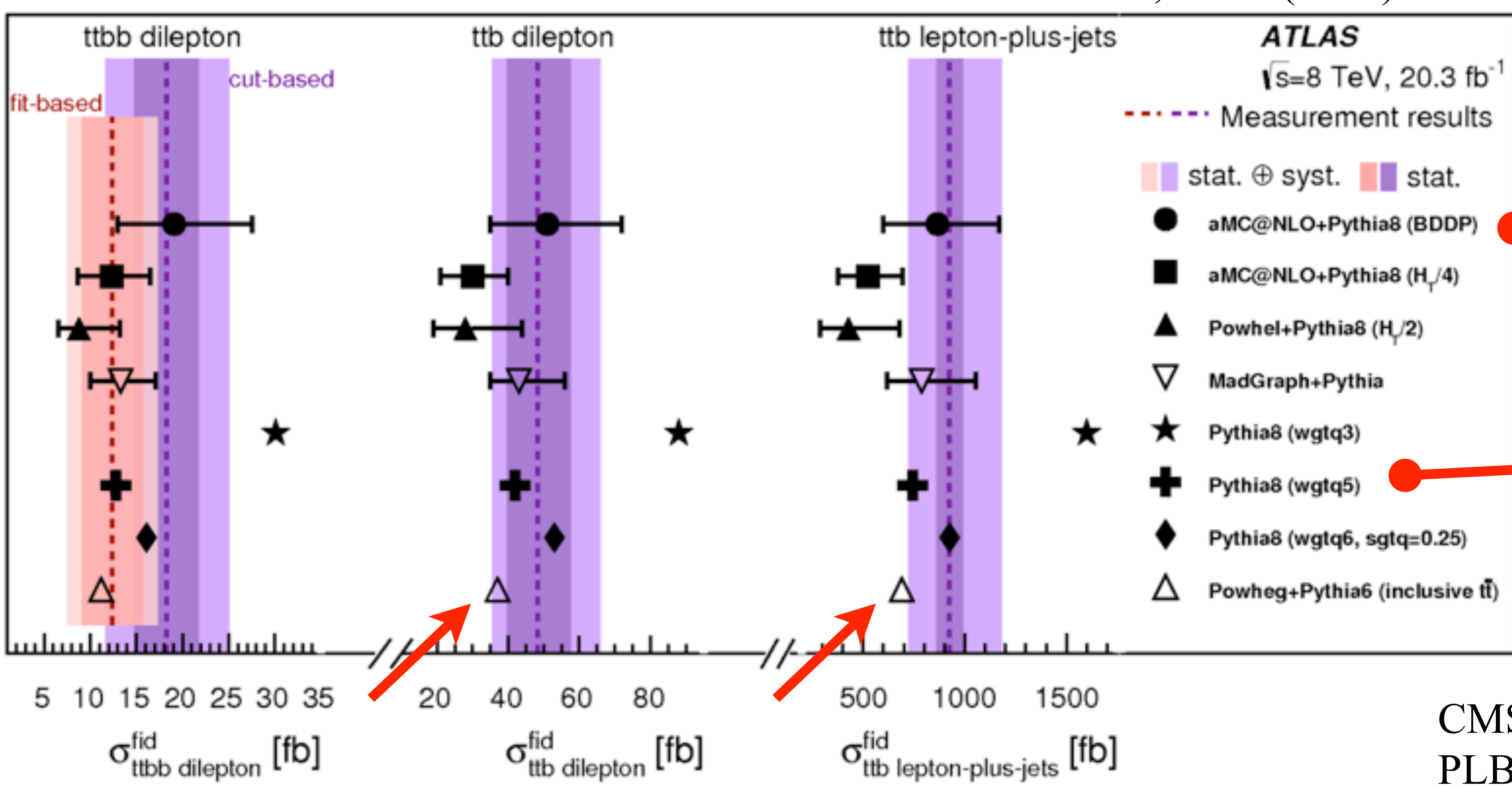
Workshop on Heavy Flavour Production:
- ALTAS: link
- CMS: link

tt+bb: experiment

Both experiments have measured 8TeV fiducial cross sections

- possibly some underestimation of tt+b, but within uncertainties

ATLAS, EPJC (2016) 76:11



Functional form of μ_R

g→bb tunes

CMS-PAS-TOP-13-016
PLB 746 (2015) 132

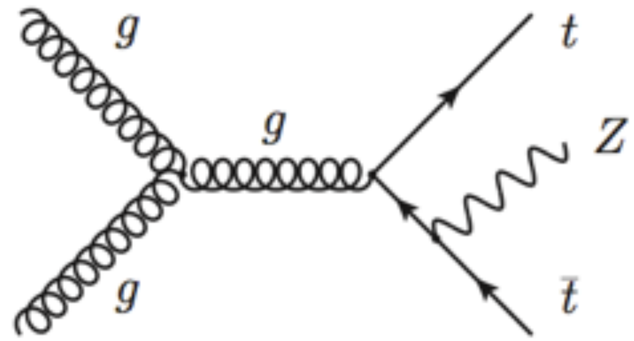
	dilepton	lep+jets
CMS	**0.36±0.13 pb**	**0.35±0.13 pb**
NLO	0.23±0.05 pb	0.23±0.05 pb

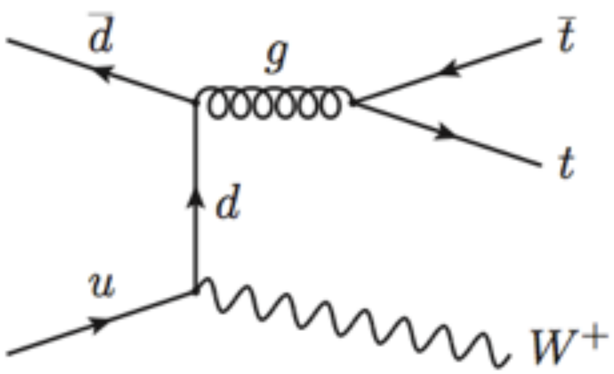
CMS observes larger tt+bb: (compatible within uncert.)

See also: CMS, arXiv:1510.03072

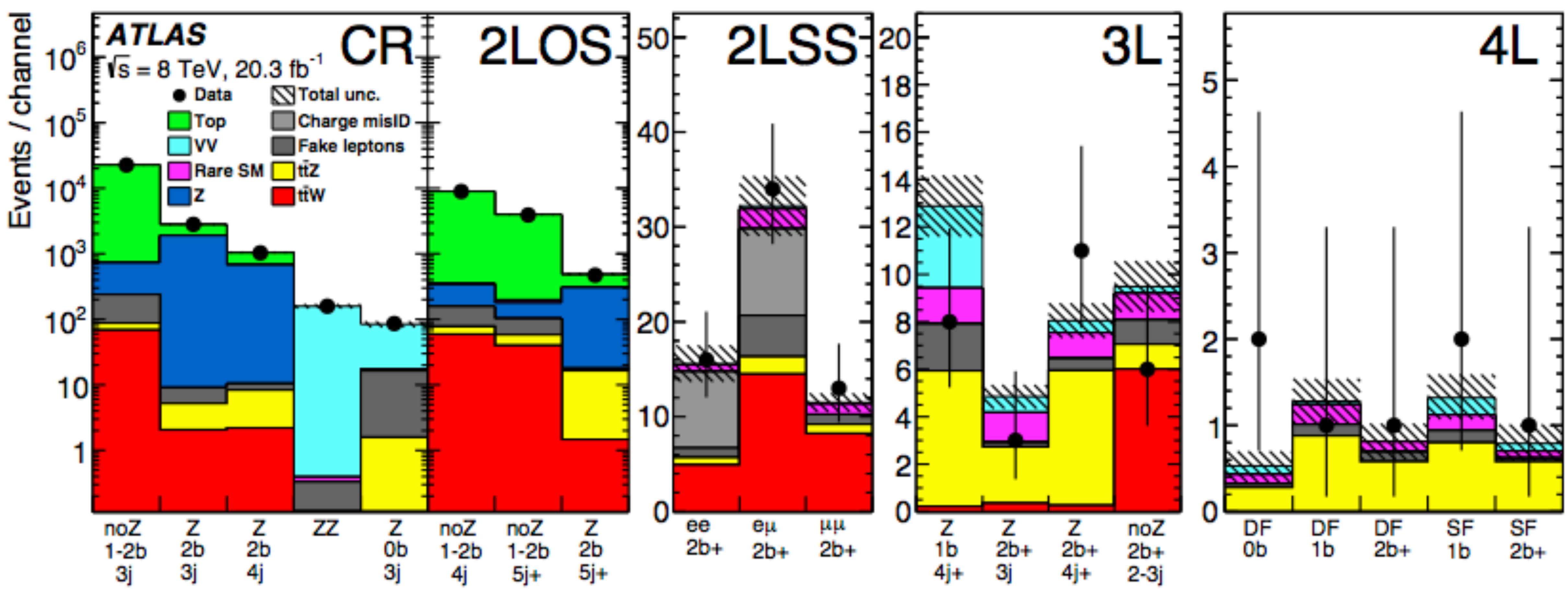
Top+Z/W: a SM measurement

- Irreducible backgrounds for ttH→leptons
  - prompt leptons and b jets
- Measurement of multi-leptonic final states with jets
  - reduces prompt VV background



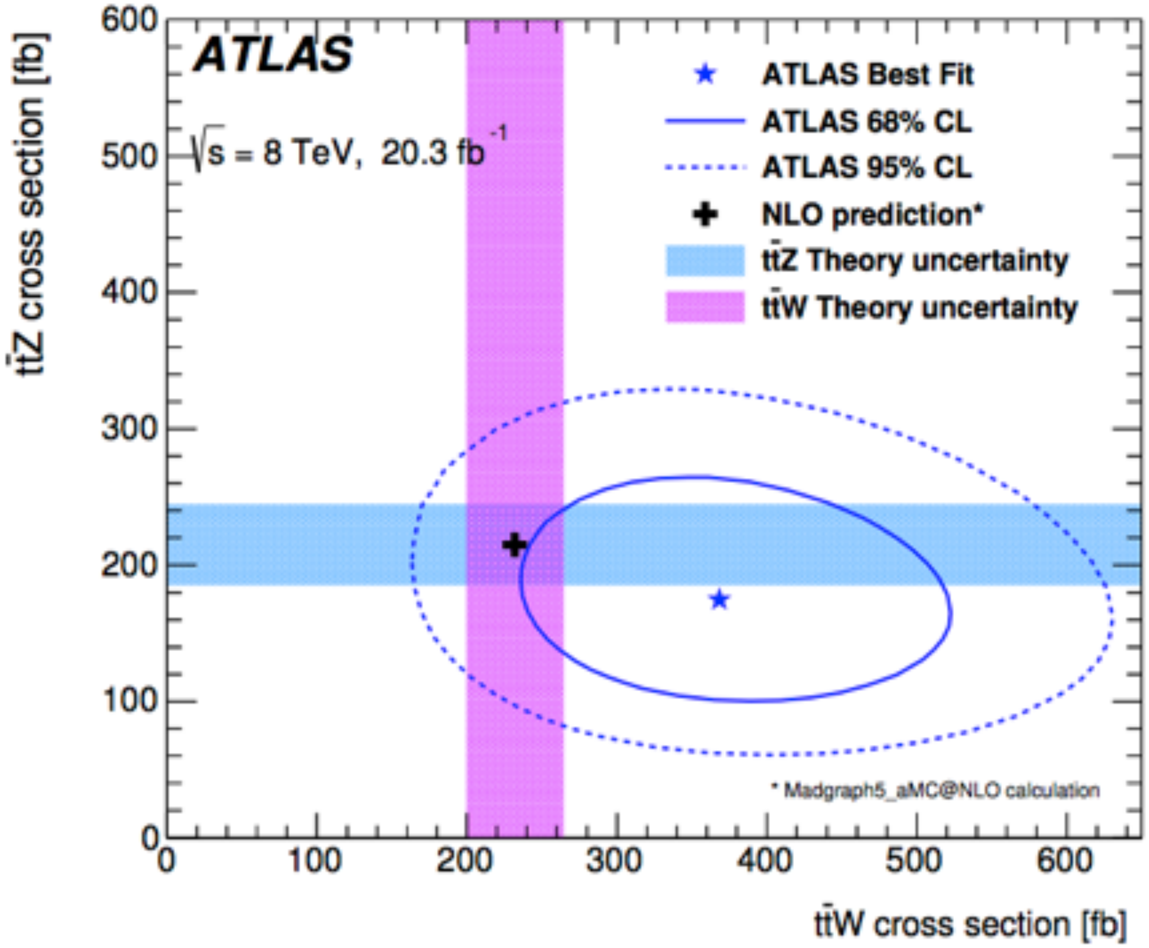


ATLAS, JHEP 11 (2015) 172

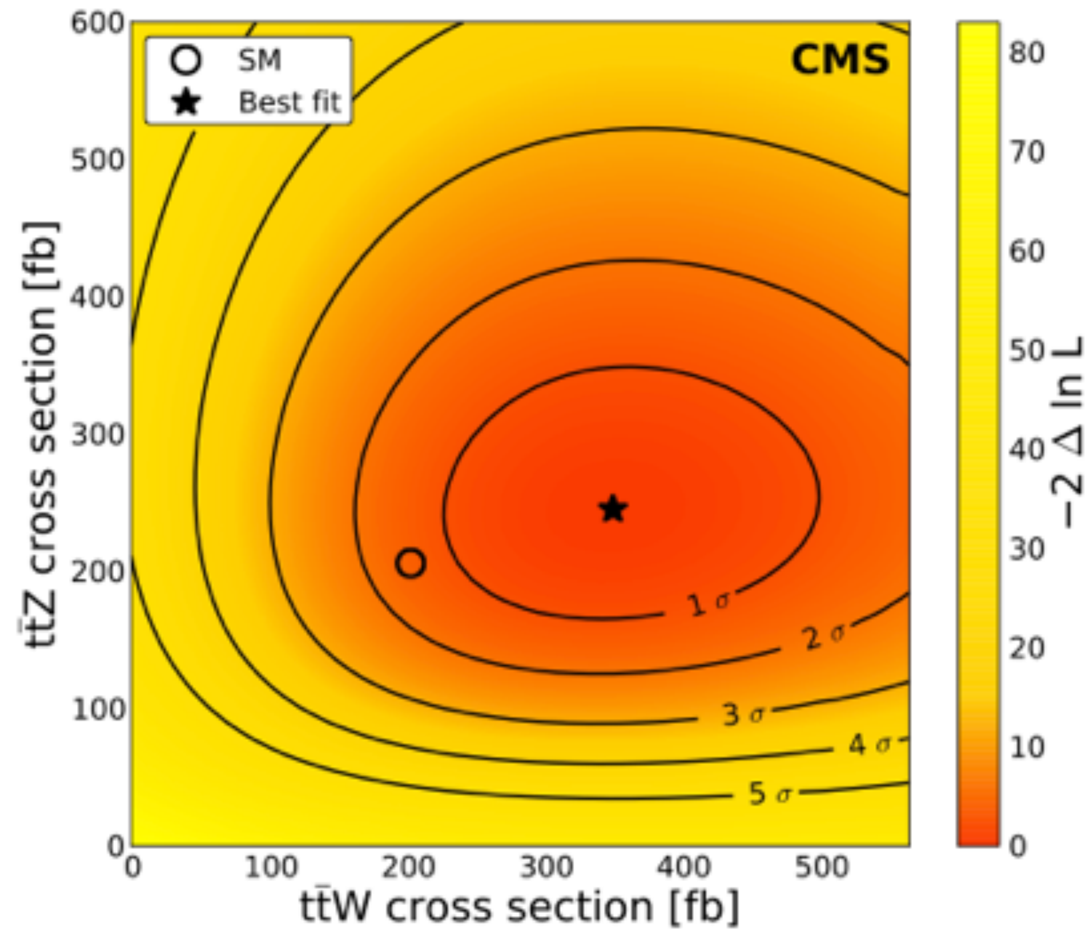


tt+V: Run I legacy

ATLAS, JHEP 11 (2015) 172



CMS, JHEP 01 (2016) 096



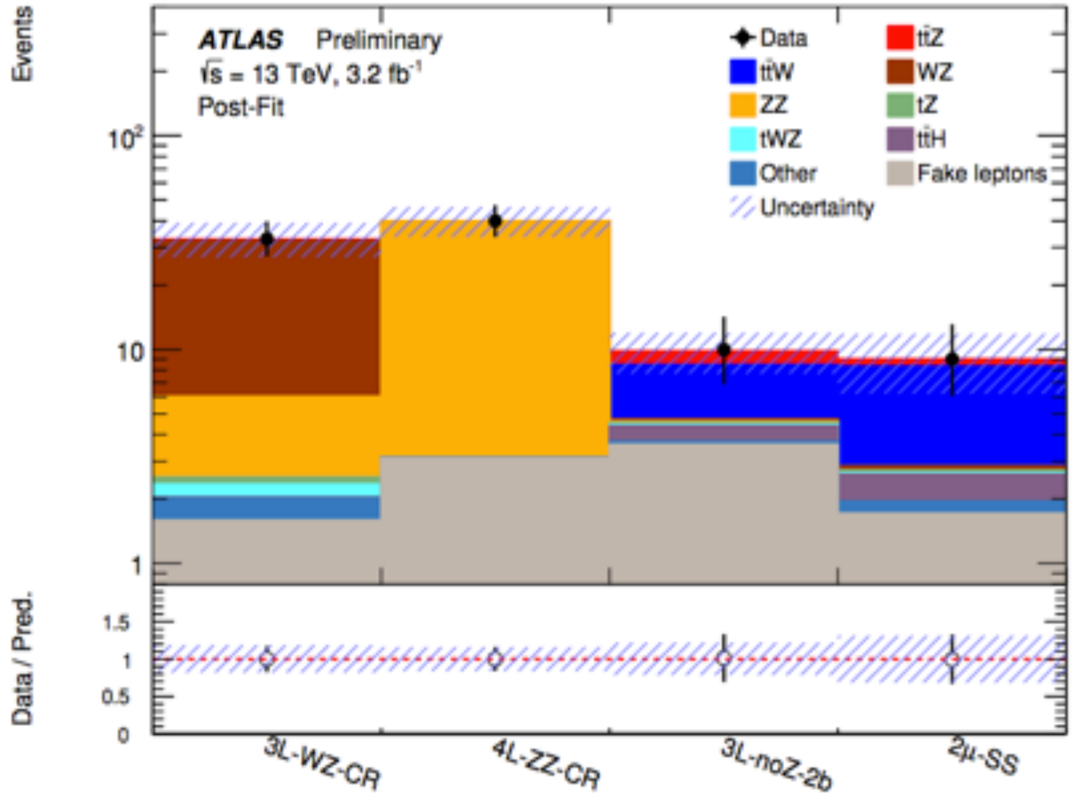
	ttW obs (exp)	ttZ obs (exp)
ATLAS	5.0σ (3.2σ)	4.5σ (4.2σ)
CMS	4.8σ (3.5σ)	6.4σ (5.7σ)

σ_{ttV} measured with 30-40% uncertainty

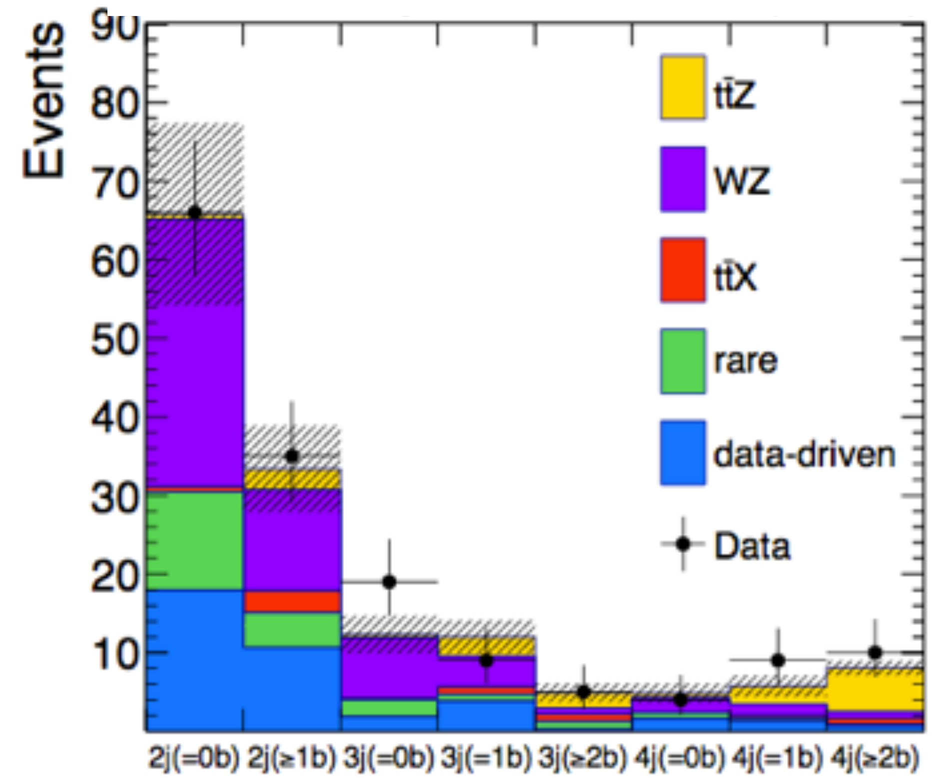
- statistically dominated
- in agreement with NLO computation

Run2 preliminary: tt+V

ATLAS-CONF-2016-003



CMS-PAS-TOP-16-009



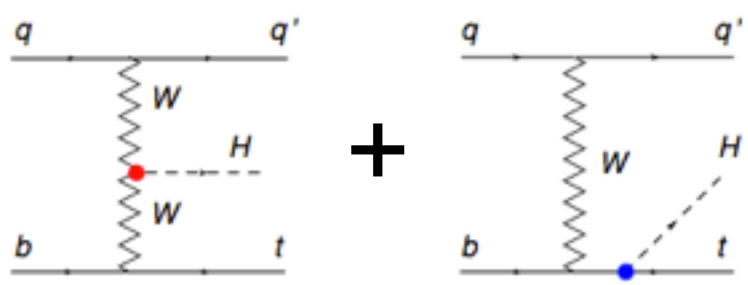
- Preliminary ttZ/ttW measurements from ATLAS
  - same precision as in Run-1
    - σ_{ttZ} = 0.9±0.3 pb (NLO: 0.76)
  - ttW with 50% uncertainty
    - σ_{ttW} = 1.4±0.8 pb (NLO: 0.57)

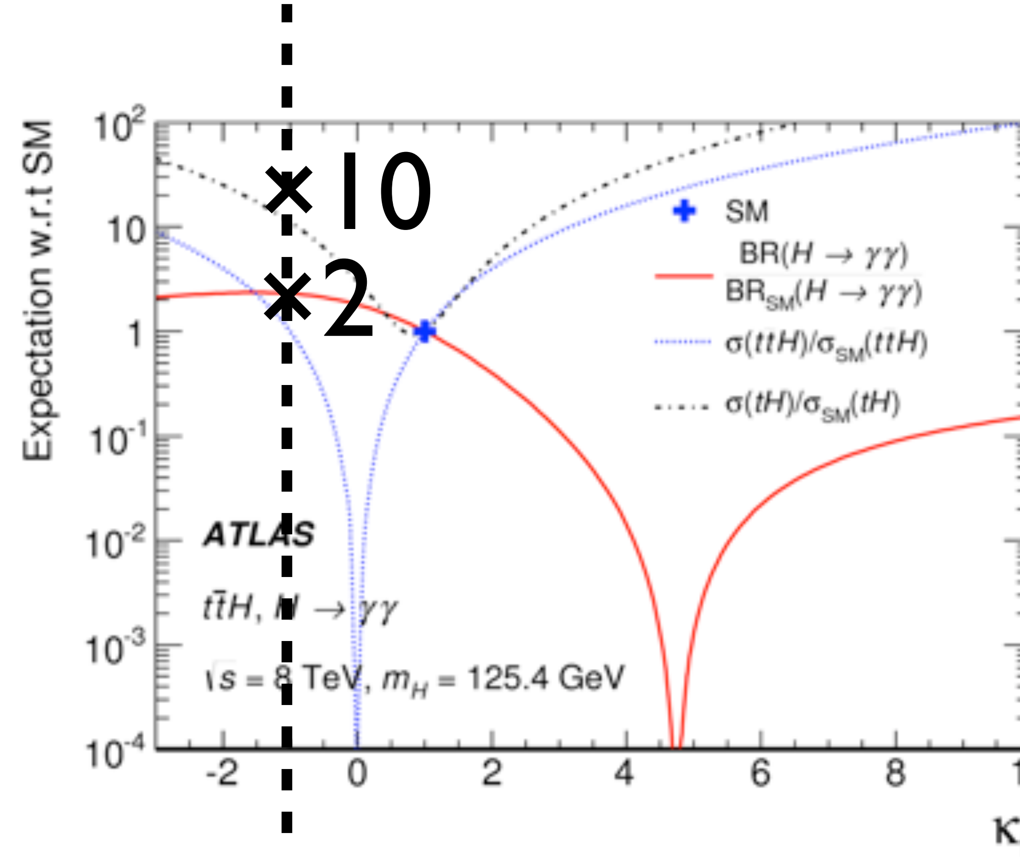
- ... and ttZ from CMS:
  - simpler version of Run1 analysis
    - σ_{ttZ} = 1.1±0.4 pb (NLO: 0.76)
    - 3.6σ evidence

Top+Higgs: the single-top channel

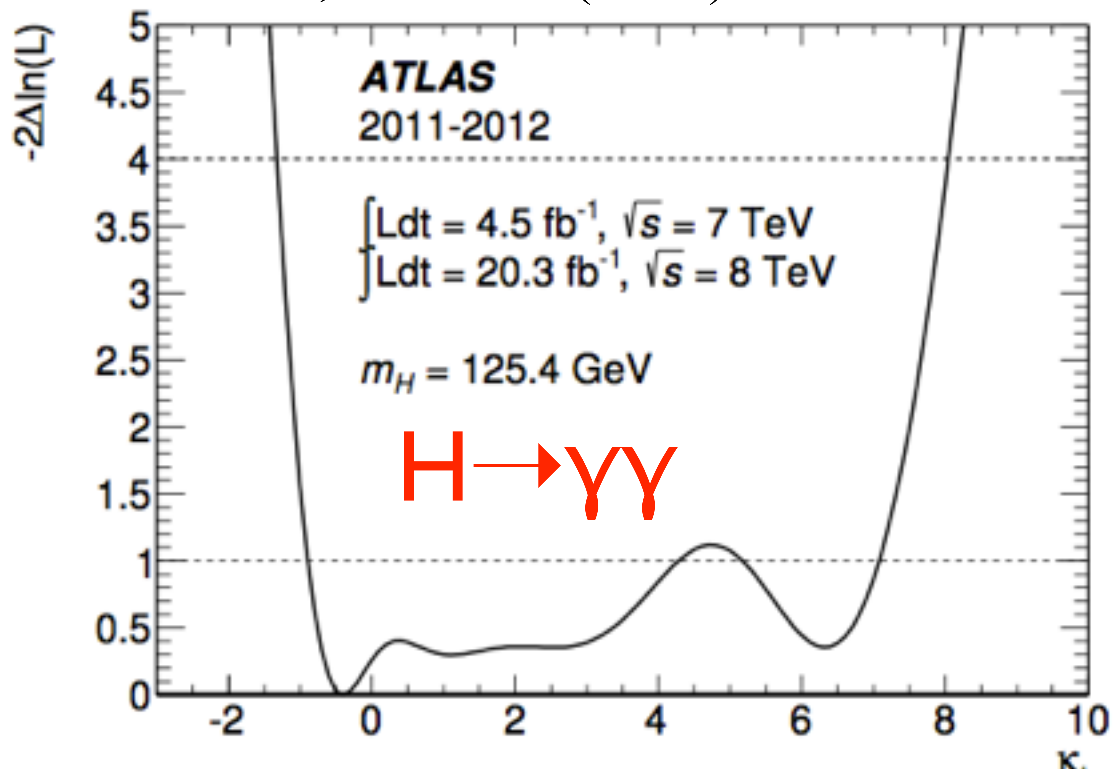
Search for single top + Higgs

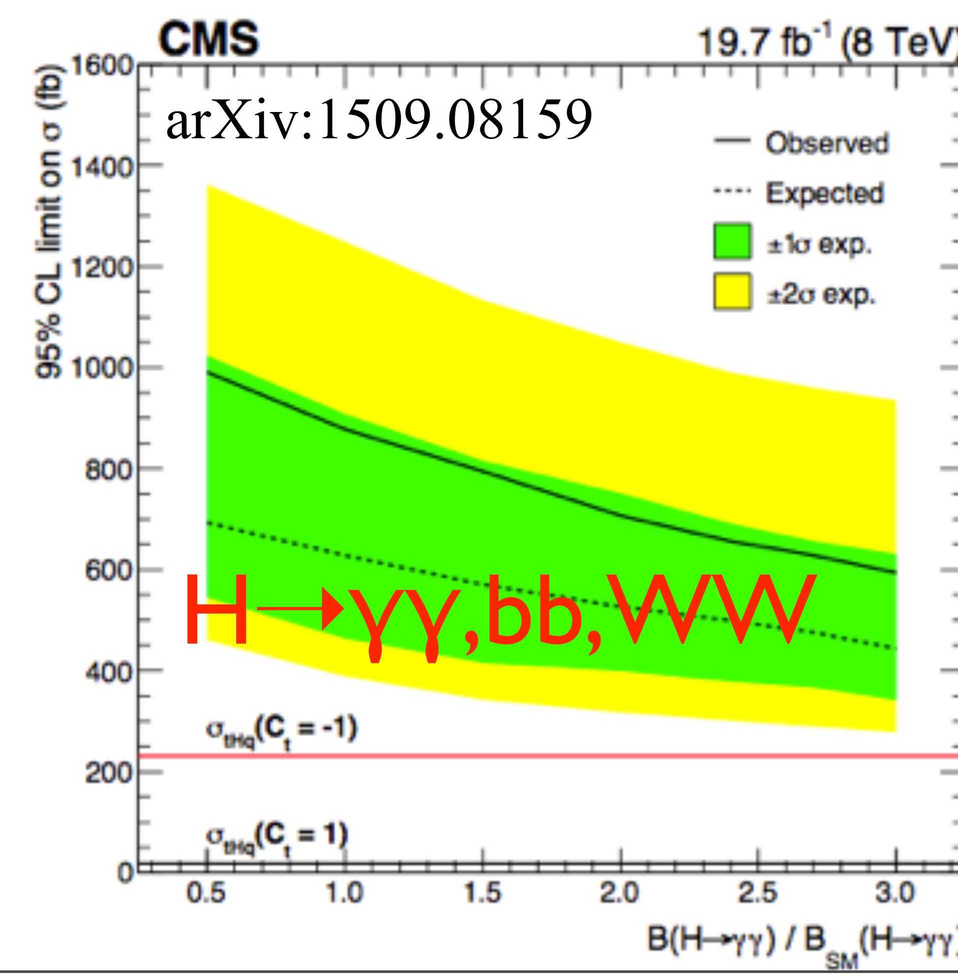
- suppressed in SM (σ_{NLO} ~18 fb)
- enhanced for non-SM couplings
- lifts sign degeneracy in coupling fits
- most analyses optimised fot t-channel (tHq)





ATLAS, PLB 740 (2015) 222





Run1 legacy: κ_t

ttH→ff:

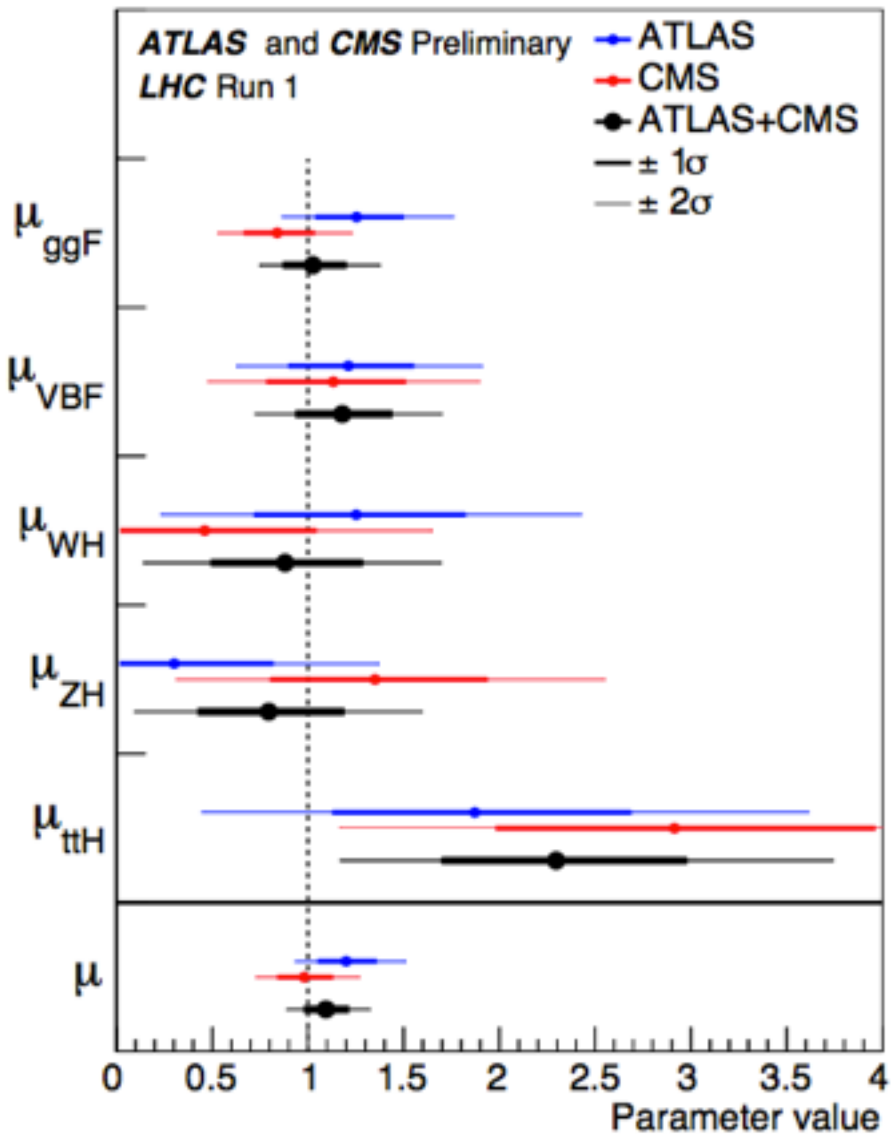
$$\frac{\kappa_t^2 \kappa_b^2}{\kappa_H^2(\kappa_V^2, \kappa_b^2)} \quad \frac{\kappa_t^2 \kappa_\tau^2}{\kappa_H^2(\kappa_V^2, \kappa_b^2)}$$

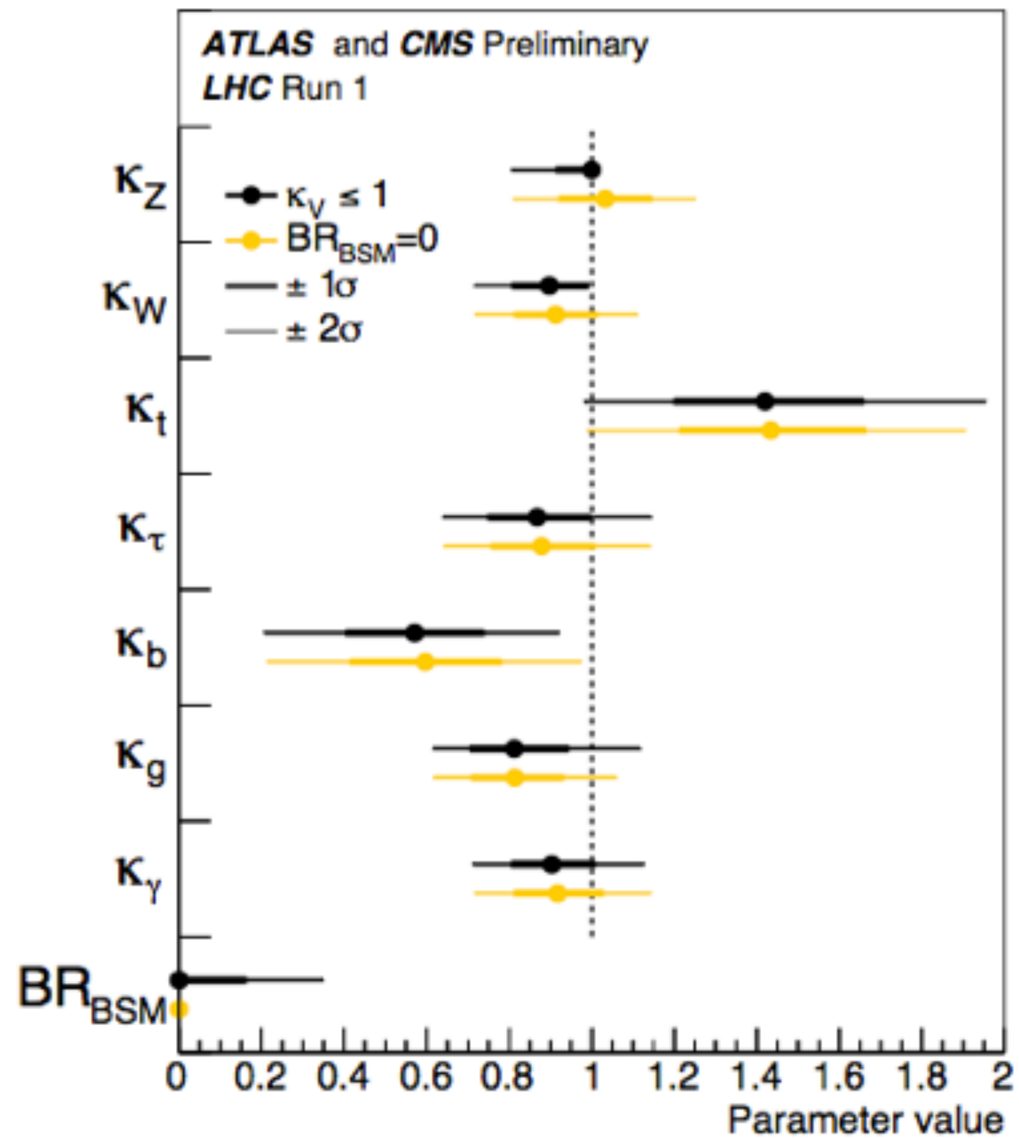
ttH→VV,γγ:

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

tH→γγ:

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



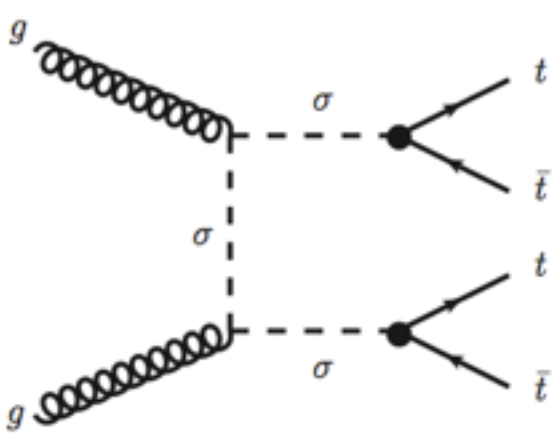


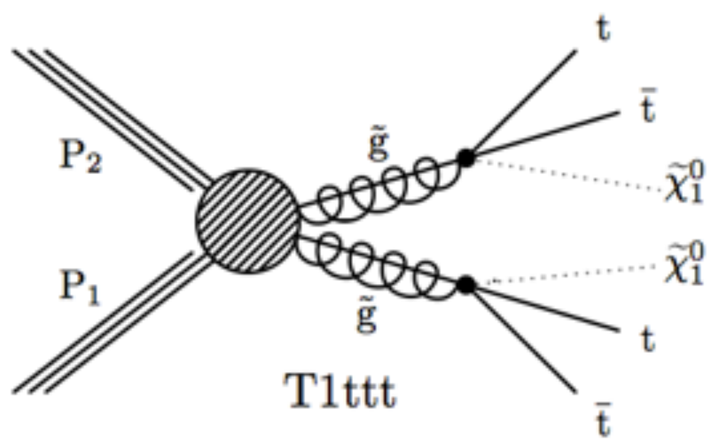
ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

Exotic searches in t(t)H-like final states

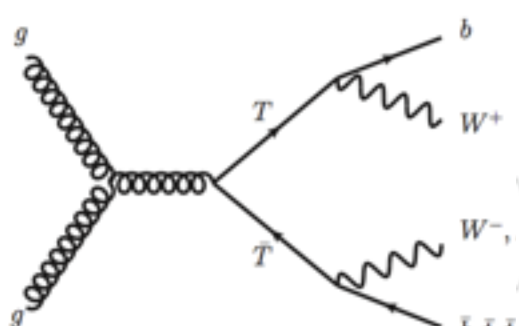
t(t)H-like final states provide typical signatures of BSM physics

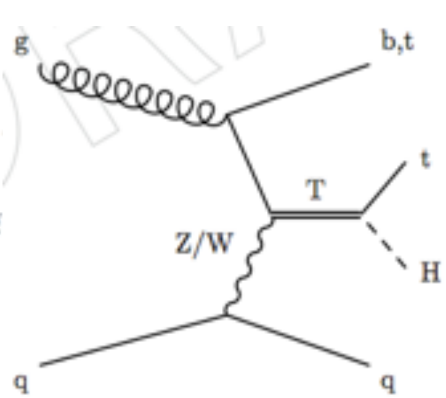
- high number of b-jets, leptons, and MET

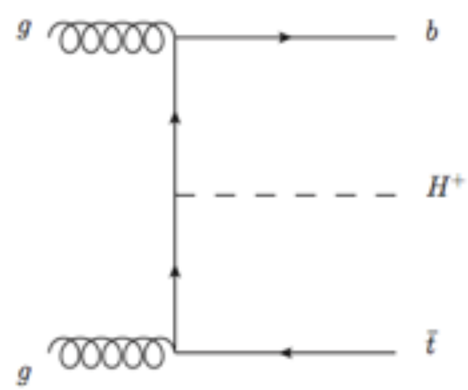




tttt production
(E.g. gluino pair production)







"ttbb" and "tHq" final states
(E.g. TT→bWtH, H⁺→tb, single T→tH)

ATLAS, JHEP 08 (2015) 105
CMS PRD 93 (2016) 012003
CMS, JHEP 11 (2014) 154
ATLAS-CONF-2016-020
ATLAS-CONF-2016-013
JHEP 03 (2016) 127

⇒ we may see ttH-like deviations even for SM top-Higgs coupling

- with more data, differential measurements will tell apart coupling shifts from other new physics

FCNC from the Yukawa sector

- FCNC are GIM-suppressed in SM
  - BR ($t \to cH$) < 10^{-15}
- GIM can be broken in SM extensions
  - tree-level currents
    - e.g. 2HDM, Q-singlets, ...
  - ...or large loop enhancement
    - for example: BR ~ 10^{-5} in MSSM
  - in general, effect of higher-order operators (EFT)

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

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

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

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

$$\underbrace{(vY^{ij} + v^3\varepsilon^{ij})}_{vY_{\text{eff}}}\,\psi_L{}^i\psi_R{}^j + (Y^{ij} + 3v^2\varepsilon^{ij})\,\psi_L{}^i\psi_R{}^j\,h + \ldots$$

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

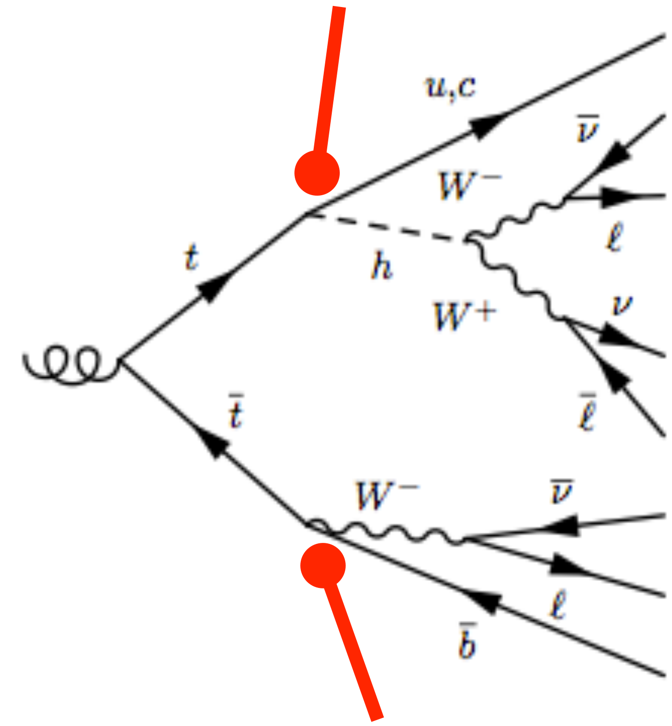
G. Isidori, HL-LHC workshop

Signatures of FCNC

- Flavour-changing decays of top quarks
  - profit from large σ(pp→tt)
    - experimentally challenging to separate t→Hc from t→Hu
    - turn BR limits into constraints on FCNC coupling:

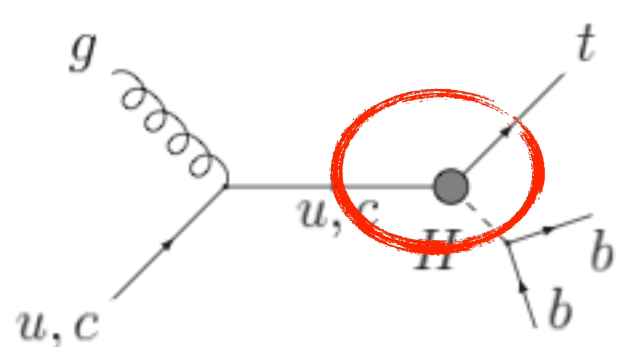
$$\mathcal{B} = (\lambda_{tcH}^2 + \lambda_{tuH}^2)/(g^2 \cdot |V_{tb}|^2 \cdot \chi^2)$$

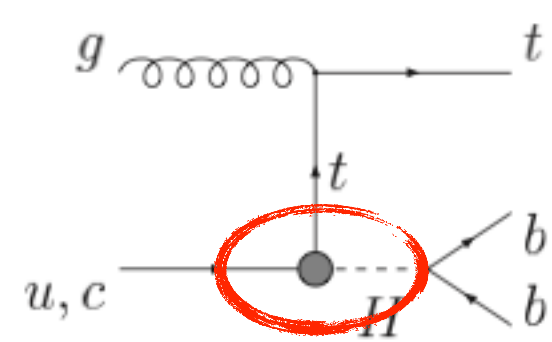
$$\boxed{\lambda_{t(u,c)H}\ \bar{t}(u,c)\ H}$$



$$\boxed{-\frac{g}{\sqrt{2}} V_{tb}\ \bar{t}_{\mathrm{L}} \gamma^{\mu} b_{\mathrm{L}}\ W_{\mu}^{+}}$$

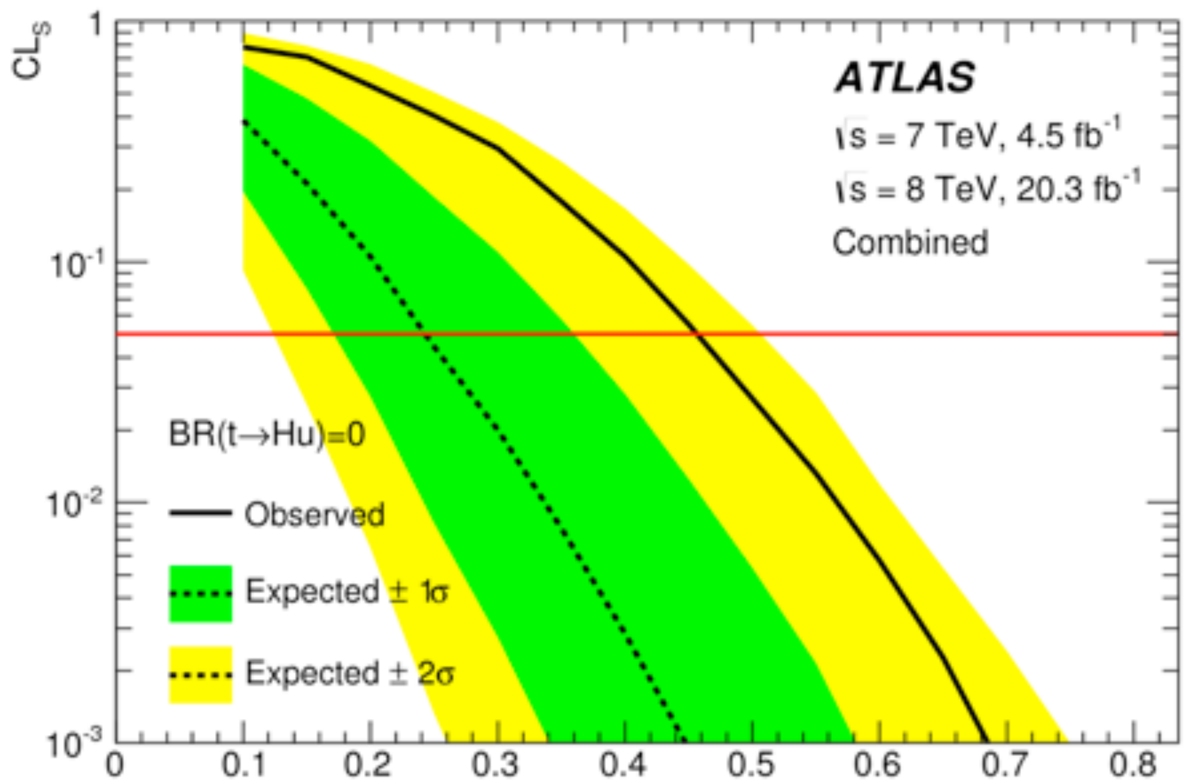
- Enhanced single-top plus Higgs production
  - Run1 analysis mostly focusing on tHq





FCNC in top quark decays

- ATLAS combination:

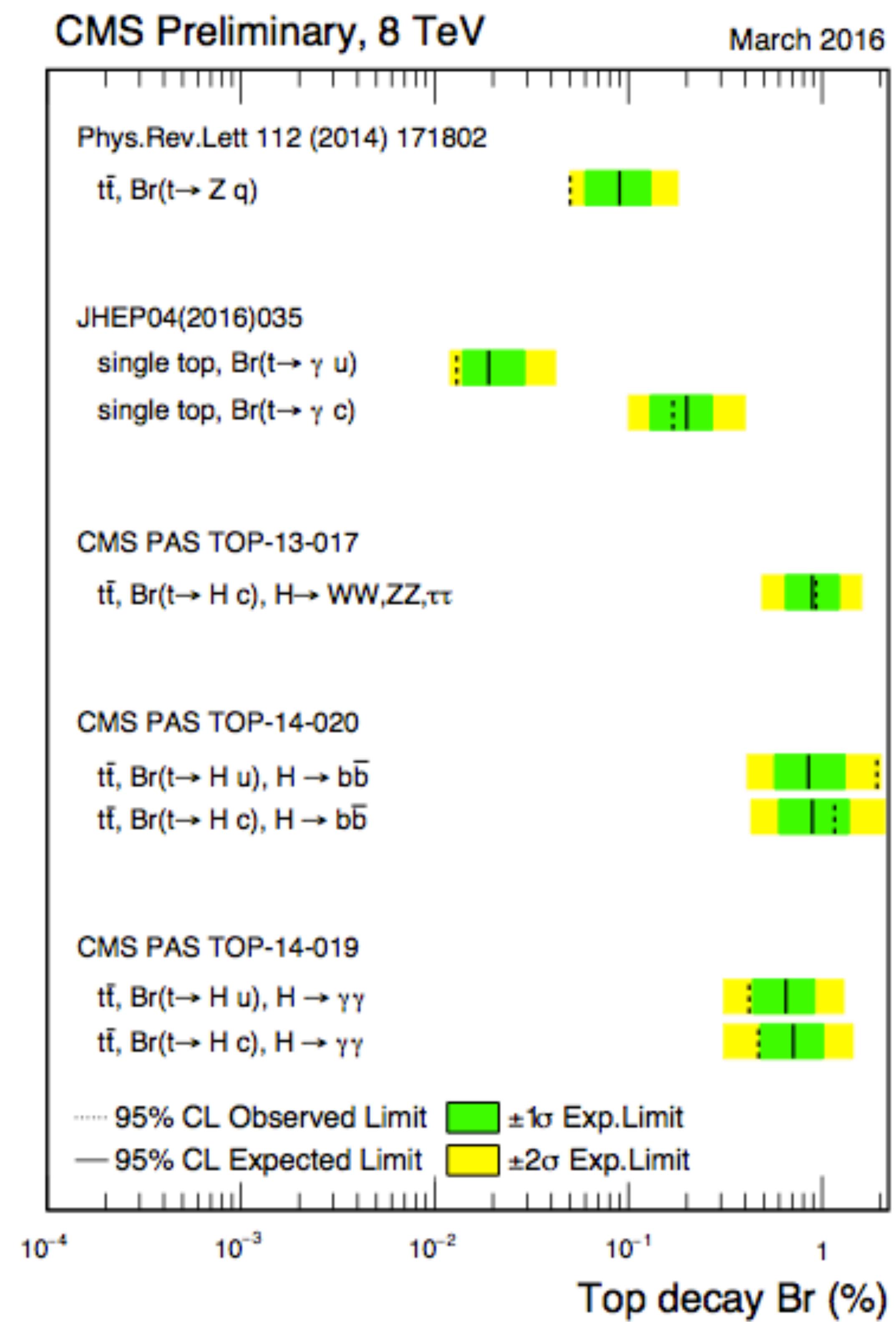


ATLAS JHEP 12 (2015) 061

B(t→cH) 95% CL	Exp.	Obs.
ATLAS	0.25%	**0.46%**

N.B. $g_{qt} \simeq \frac{\sqrt{m_q m_t}}{M_W}$ $\Rightarrow$ ***BR ~ 0.15%***

- CMS summary:



Summary

- We have presented the Run1 results on top+Higgs searches and measurements from ATLAS and CMS
  - ttH is the flagship to measure the Yukawa coupling
    - a firm evidence of this process is still missing, maybe possible already at the end of this year?
  - tH sensitivity in the ballpark for a flipped Yukawa coupling (*)
    - SM tH production remains beyond the scope of the LHC
  - searches for exotic ttH-like final states revealed no significant excess
  - measurement of the SM backgrounds to ttH final states remains an important task. Some measurements start to be systematically limited!

- New results at 13 TeV recently made public
  - ttH analyses close to Run1 sensitivity already
    - no excess of SS events in ttH search
  - issues on tt+jets modeling should be settled as soon as possible

* A. Giammanco, Rev. Phys. 1 (2016) 1-12

Grazie
per l'attenzione!

Back up

ttH→bb: theory

ttH	NLO	PRL 87 (2001) 201805 NPB 653 (2003) PRD 68 (2003) 034022
	Interference	arXiv:1412.5290
	EWK corrections	arXiv:1504.03446
tt+bb	tt+bb @NLO	PRL 103 (2009) 012002
	tt+bb NLO+PS	PLB 734 (2014) 210 JHEP 07 (2014) 135 JHEP 1503 (2015) 083
	tt+jj NLO	PRD 84 (2011) 114017
	tt+jj NLO+PS	PLB 748 (2015) 74

Principle

Assign each reconstructed event with its probability density

$$\mathrm{P}\{\vec{y} \in [\vec{y}_0, \vec{y}_0 + d\vec{y}] \mid S, \boldsymbol{\theta}\} = p_S(\vec{y}_0|\boldsymbol{\theta})d\vec{y} \qquad \int_{\mathcal{A}} p_S(\vec{y}\,|\boldsymbol{\theta})d\vec{y} = 1$$

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

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

normalisation

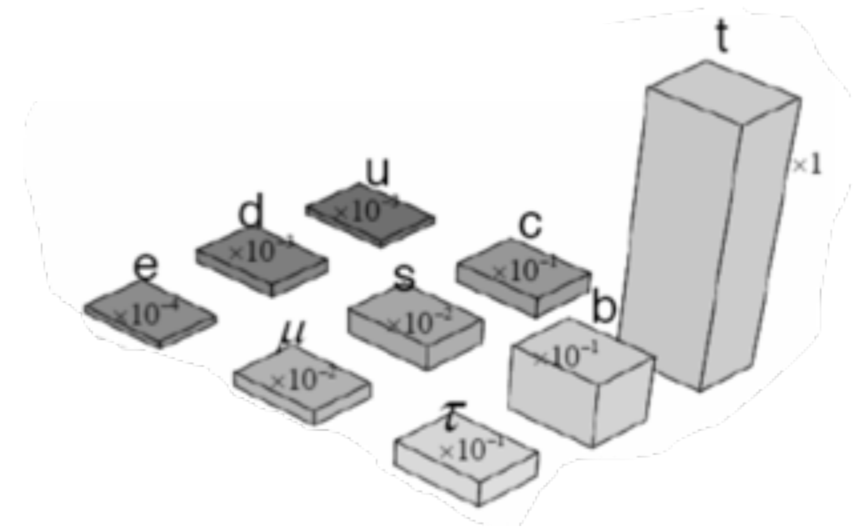
- if the underlying scattering process is theoretically known:

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

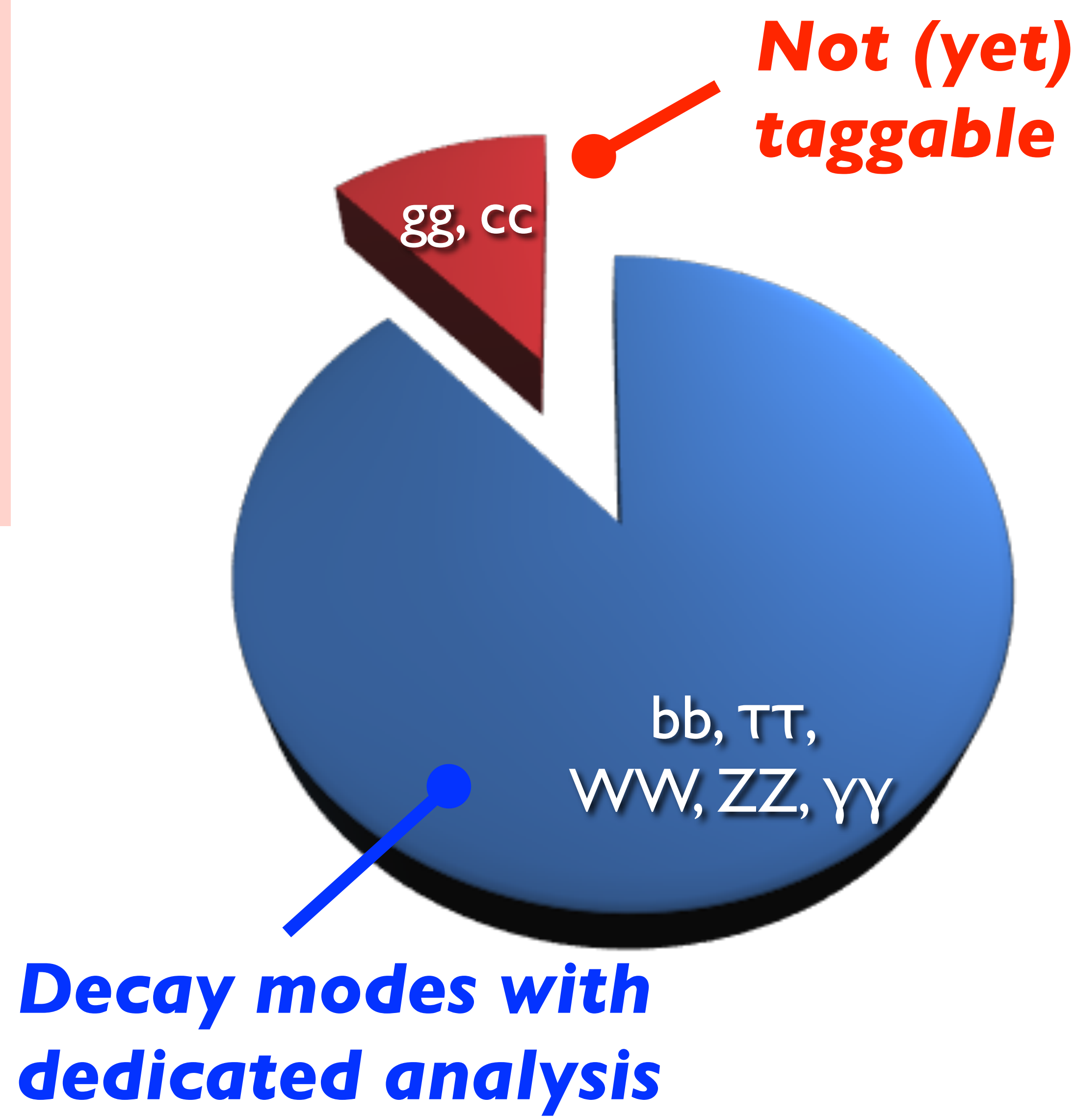
$$d\sigma_S(\vec{y}\,|\boldsymbol{\theta}) = \left[\int d\Phi(\vec{x})dx_{\mathrm{a}}dx_{\mathrm{b}} \sum_{i,j} \frac{f_i(x_{\mathrm{a}})f_j(x_{\mathrm{b}})}{(1+\delta_{ij})x_{\mathrm{a}}x_{\mathrm{b}}s} |\mathcal{M}_S(\vec{x},\boldsymbol{\theta})|^2 W(\vec{y},\vec{x};\boldsymbol{\theta})\right] d\vec{y}$$

- convolution of $\left\{\begin{array}{l}\textbf{\textit{theoretical prediction}}\\ \textbf{\textit{detector resolution}}\end{array}\right.$

The top quark Yukawa



	$H \to VV, ff$	$H \to \gamma\gamma$
σ_{GGF}	κ_t^2 [loop]	$\lvert\kappa_t \mathcal{M}_a + \kappa_V \mathcal{M}_b\rvert^2$ [loop]
σ_{ttH}	κ_t^2 [tree]	
σ_{tH}	$\lvert\kappa_t \mathcal{M}_a + \kappa_V \mathcal{M}_b\rvert^2$ [tree]	

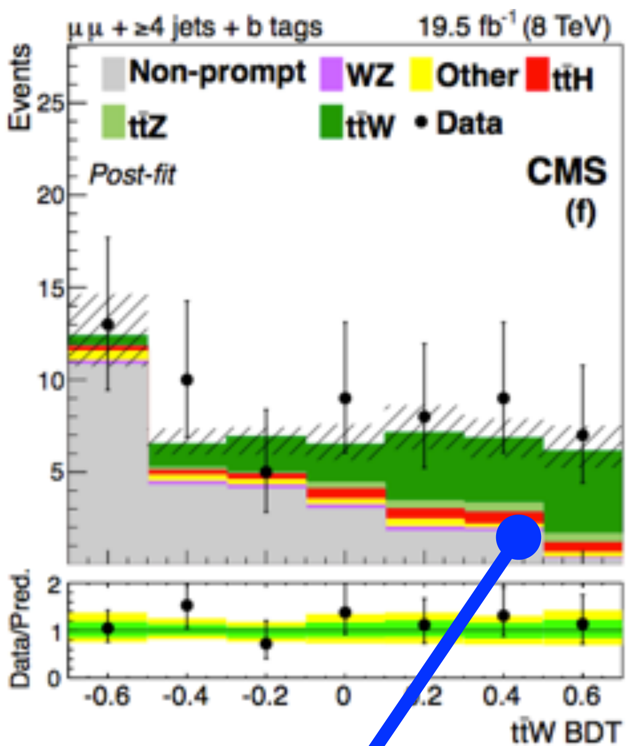


tt+V: signal extraction

Signal extraction from simultaneous fit to lepton categories

- improve sensitivity by dedicated 1D discriminant
  - CMS uses of an event reconstruction algorithm to boost sensitivity

2SS

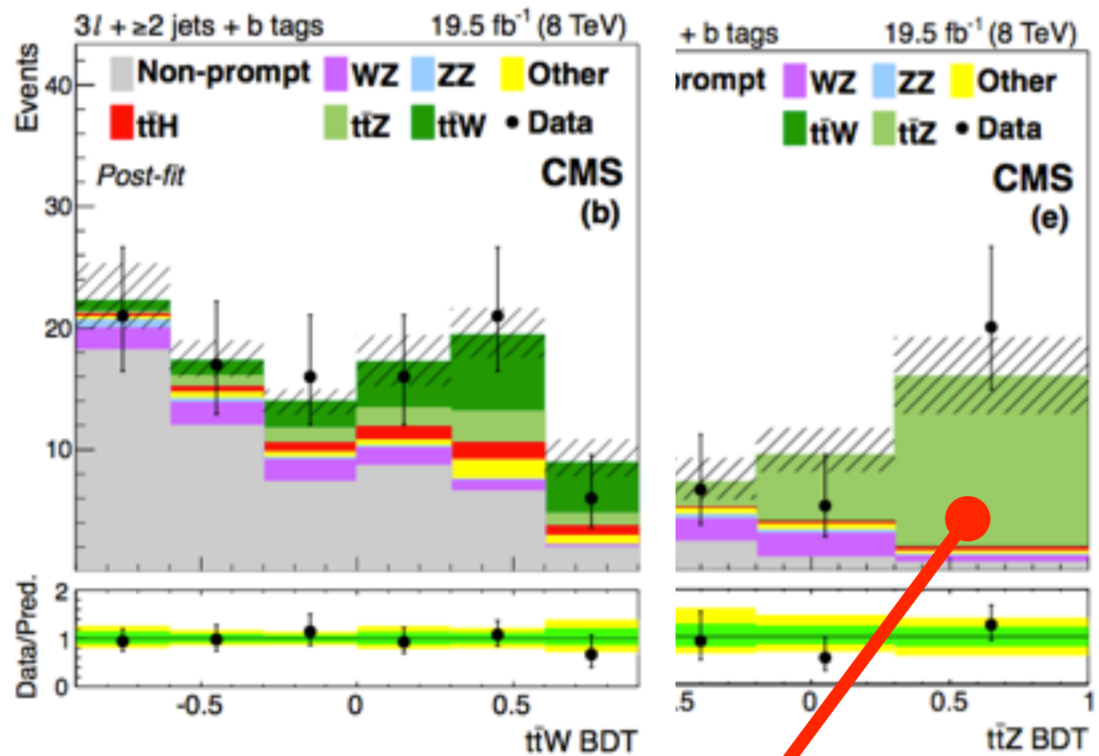


Main backgrounds: fakes, ttH, ttZ

3 lep

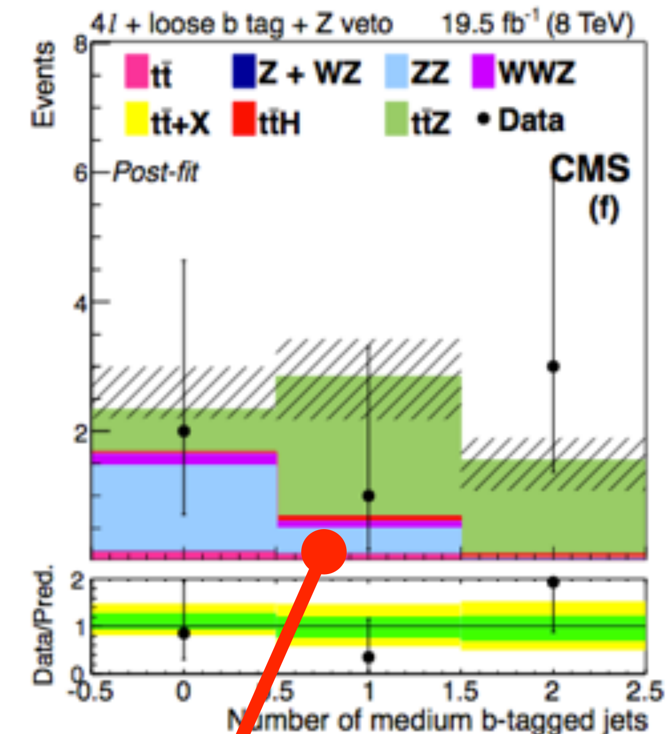
noZ

Z



ttZ almost background free

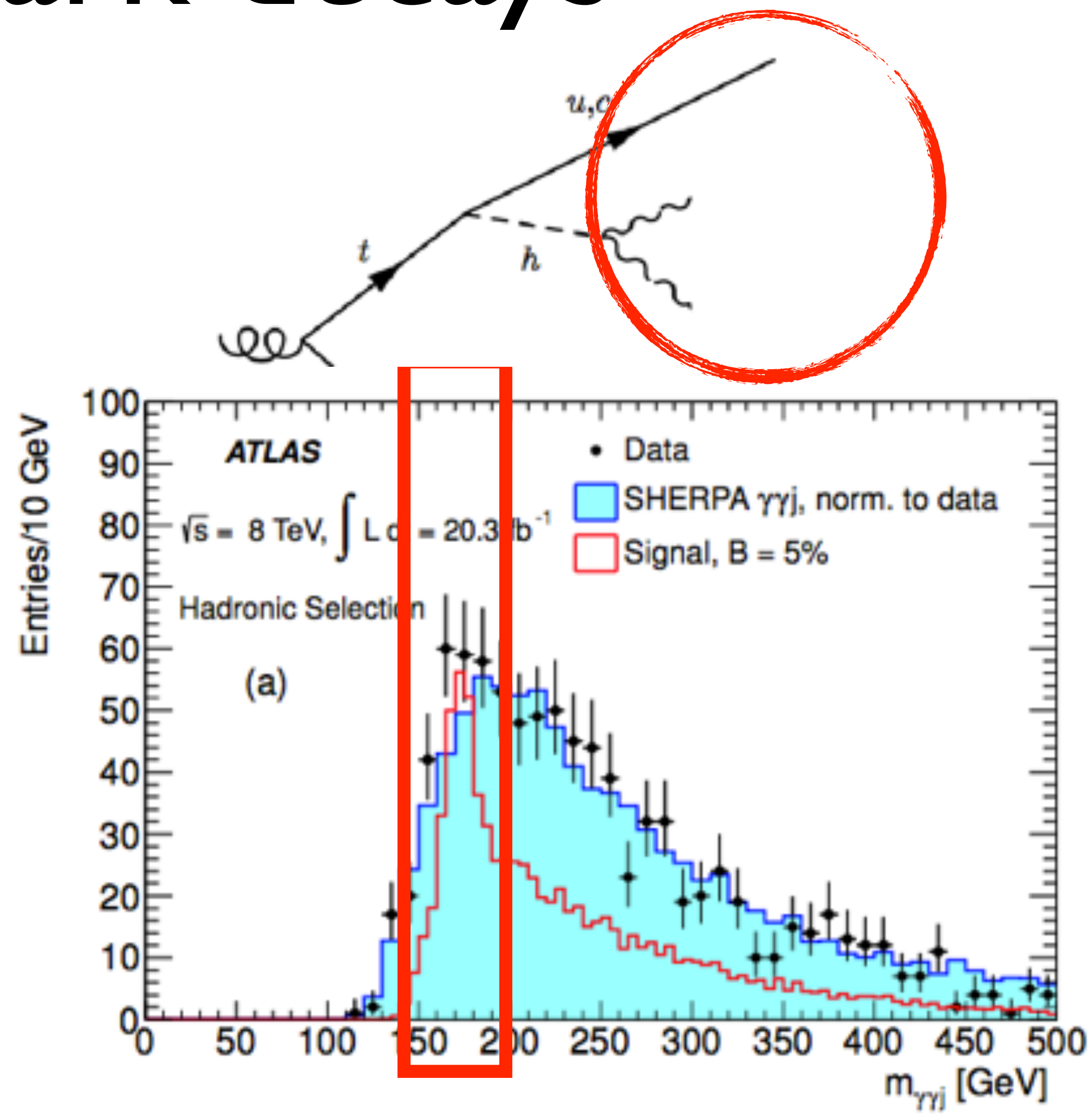
4 lep



Main irreducible backgrounds: WZ, ZZ

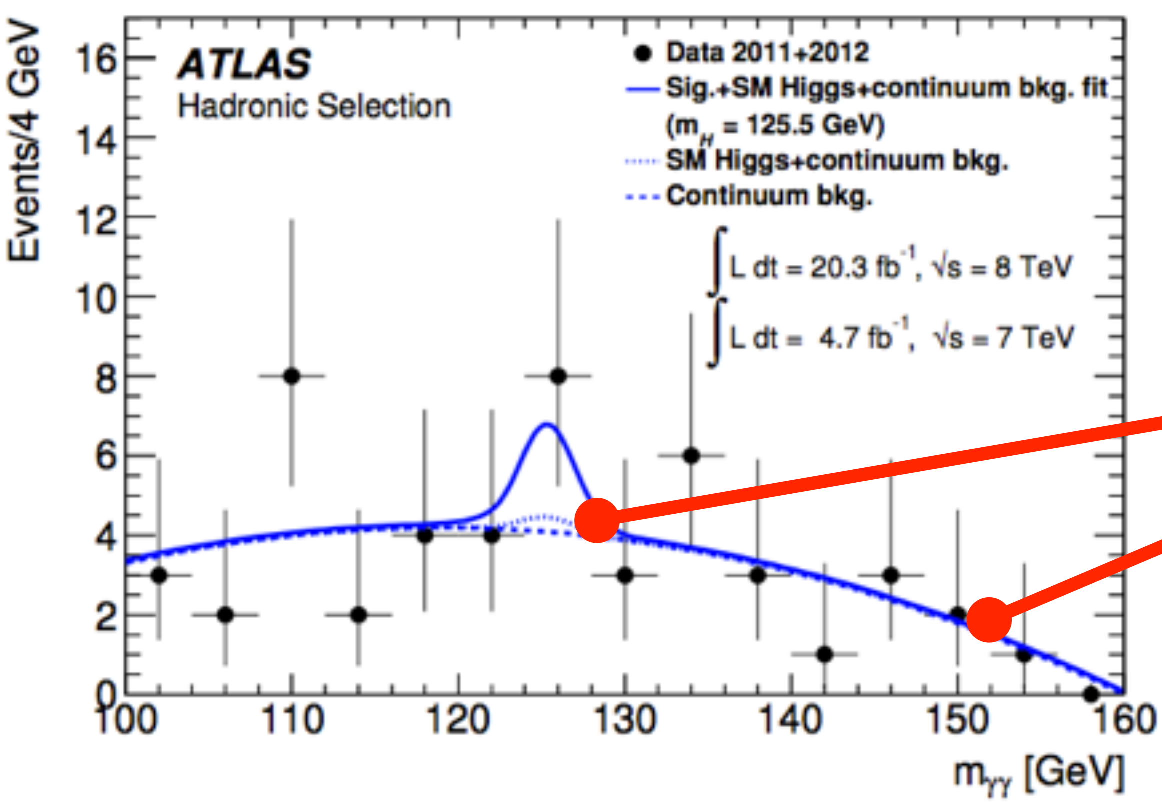
CMS, JHEP 01 (2016) 096

FCNC in top quark decays



H→γγ

- diphoton events with E_T^{miss}, leptons, jets
  - top reconstruction to suppress γγ +jets continuum
- fit to $m_{\gamma\gamma}$ spectrum:



Resonant H→γγ from MC

Non-resonant from fit

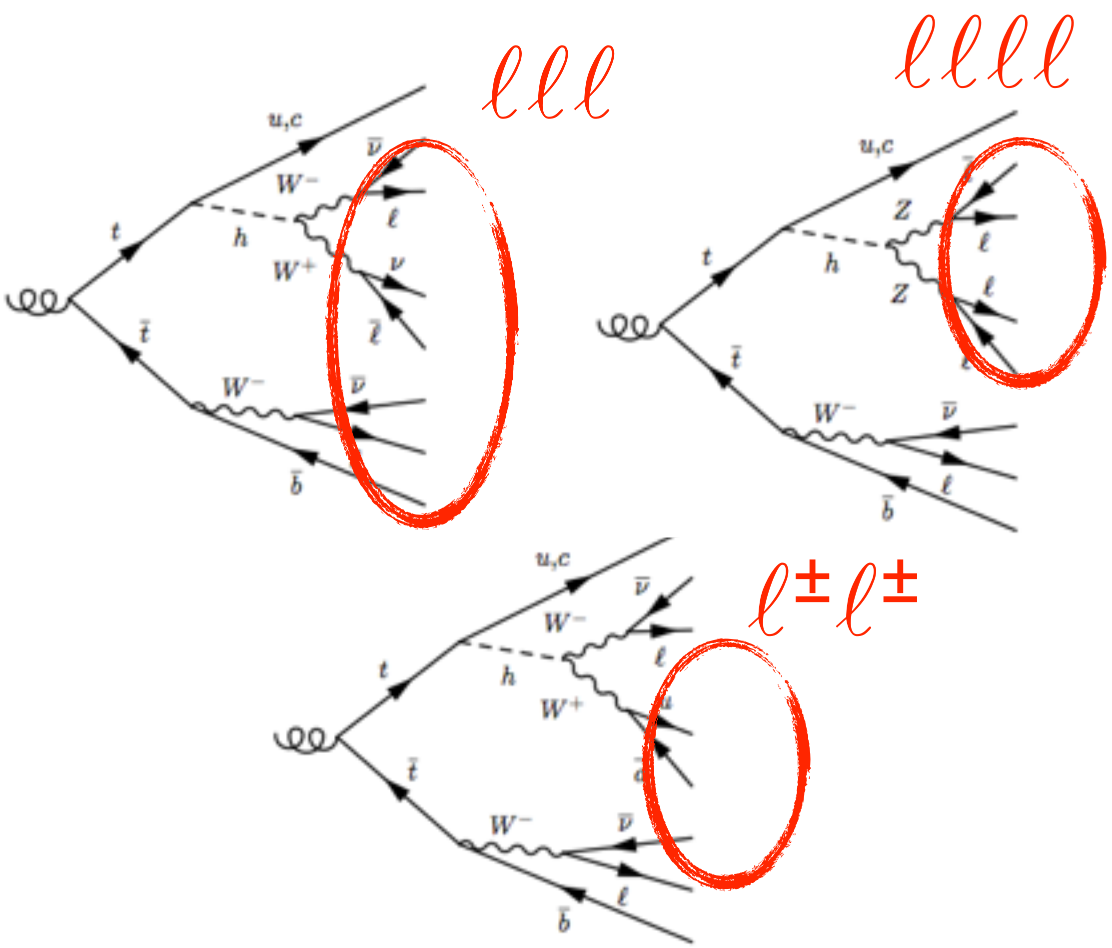
B(t→cH) 95% CL	Exp.	Obs.
ATLAS	0.51%	**0.79%**
CMS	0.71%	**0.47%**

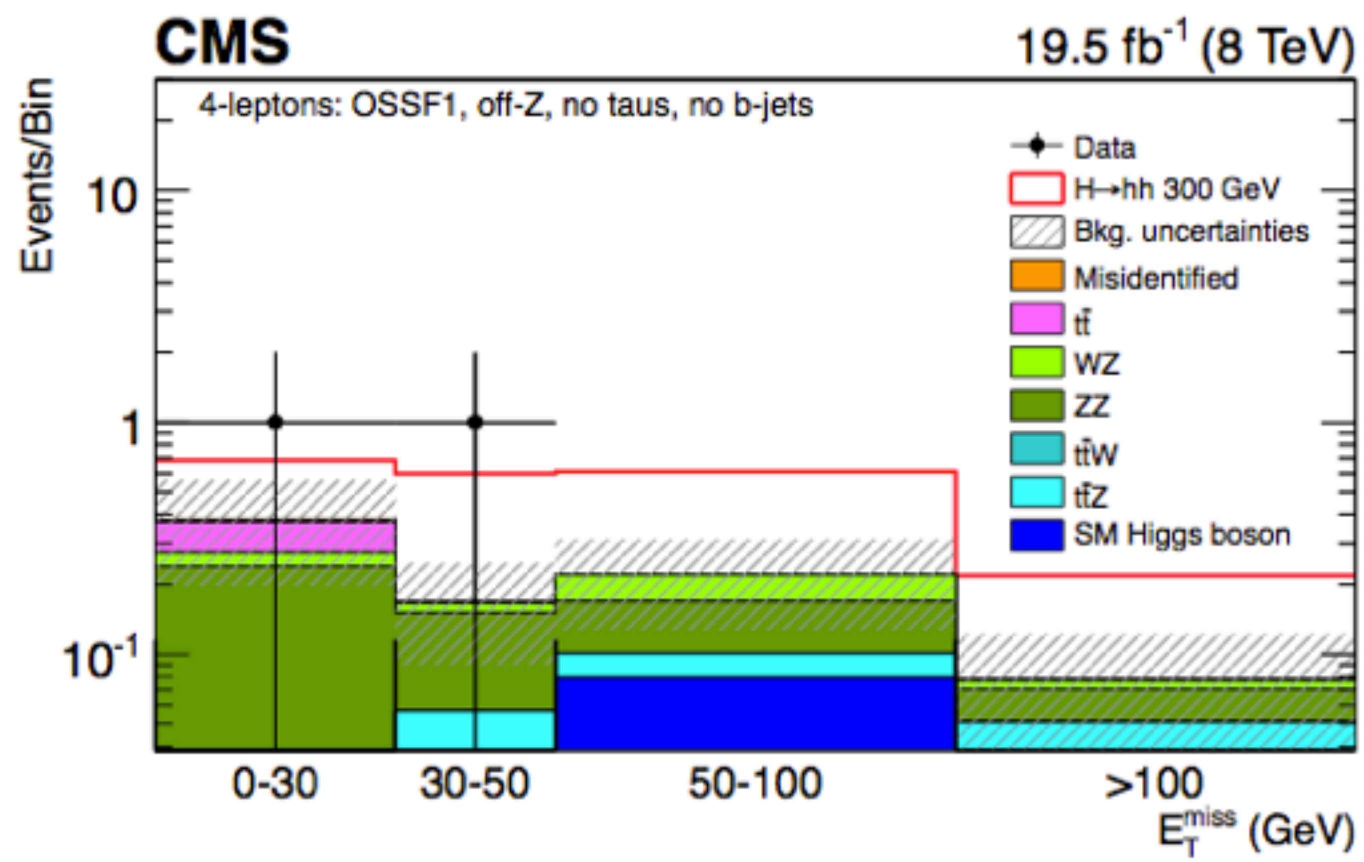
ATLAS, JHEP 06 (2014) 008
CMS, PRD 90 112013 (2013)
CMS, PAS-TOP-14-019

FCNC in top quark decays

H→WW, ZZ

- 2,3,4 lepton final states
  - with b-tags and E_T^{miss}





$\boldsymbol{B}$(t→cH) 95% CL	Exp.	Obs.
ℓℓℓ, ℓℓℓℓ	1.17%	**1.28%**
ℓℓℓ, ℓℓℓℓ + γγℓ	0.65%	**0.56%**
ℓ±ℓ±, ℓℓℓ	0.89%	**0.93%**

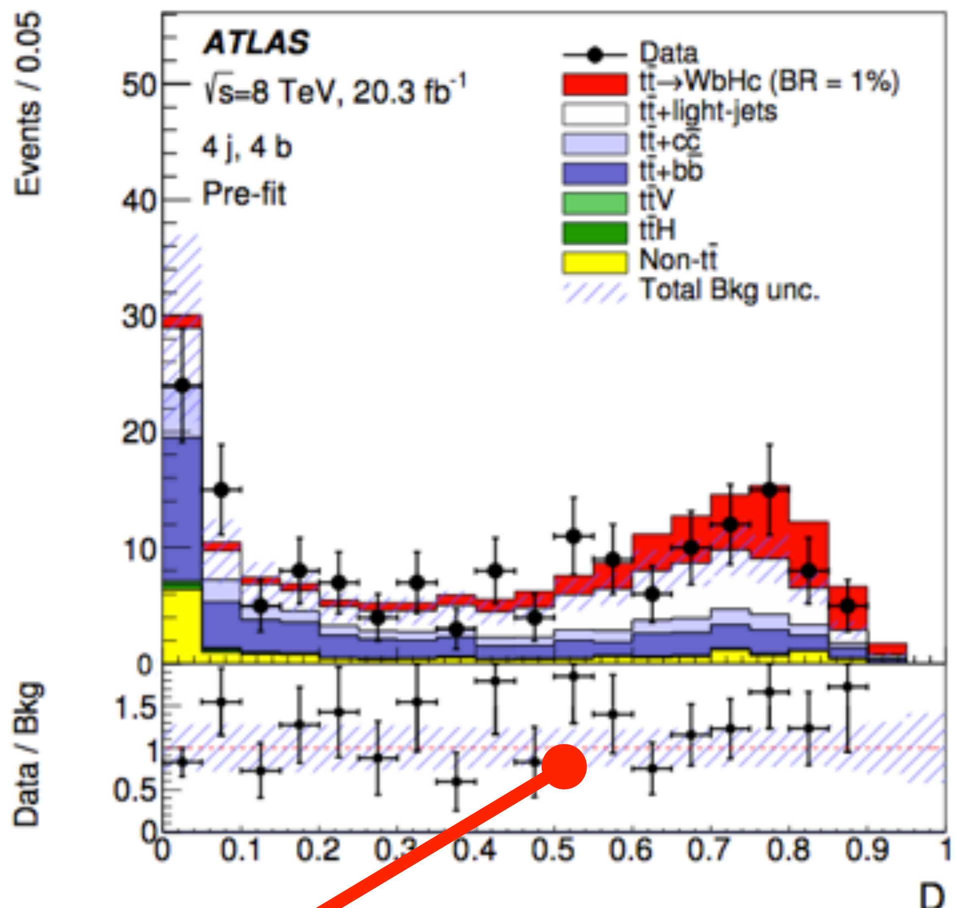
CMS, PRD 90 112013 (2013)
CMS, PAS-TOP-13-017

FCNC in top quark decays

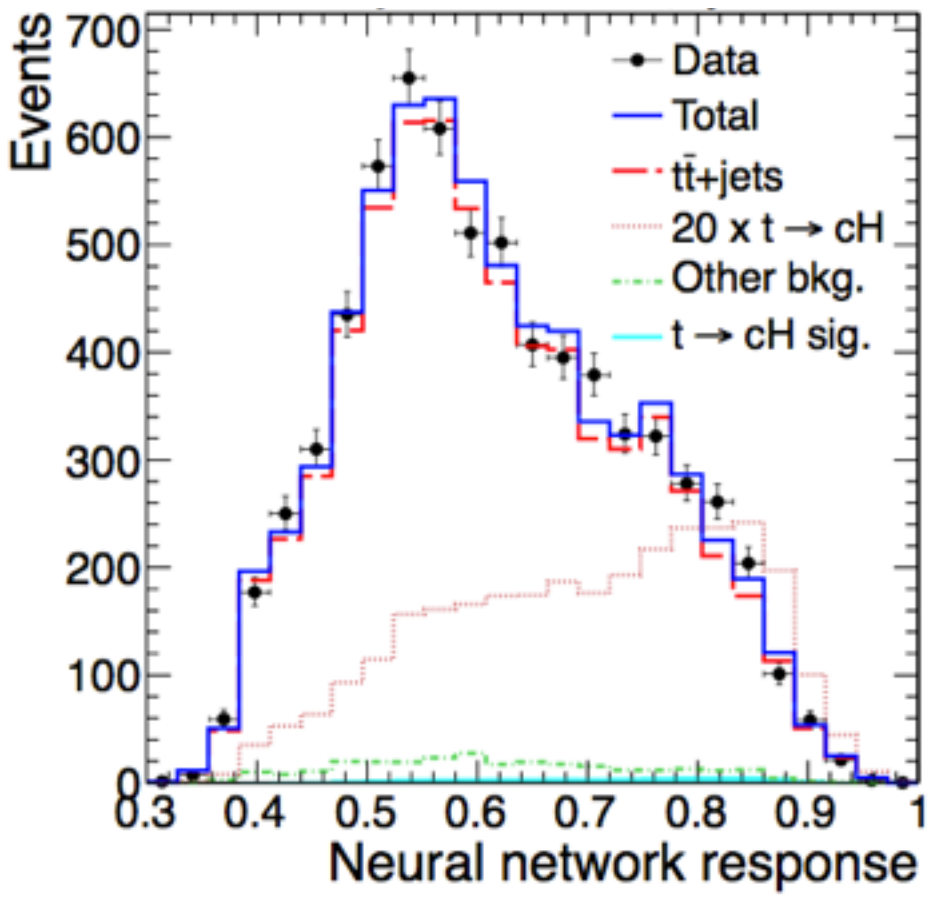
H→bb

- search region is 4j+3/4 tags (it overlaps with ttH/tHq)

ATLAS JHEP 12 (2015) 061



CMS, PAS-TOP-14-020



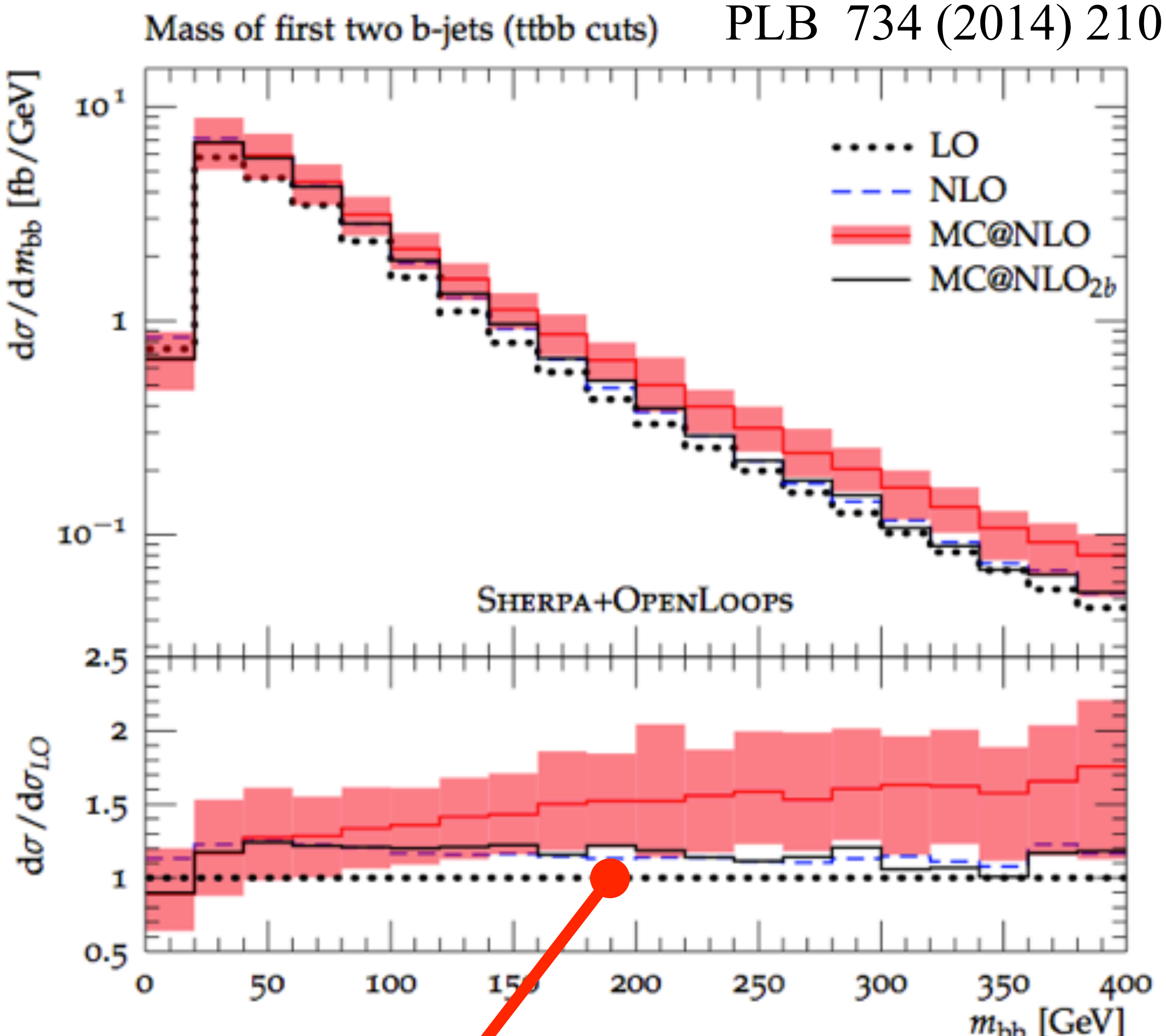
Analytical event likelihood

B(t→cH) 95% CL	Exp.	Obs.
ATLAS	0.51%	**0.79%**
CMS	0.89%	**1.16%**

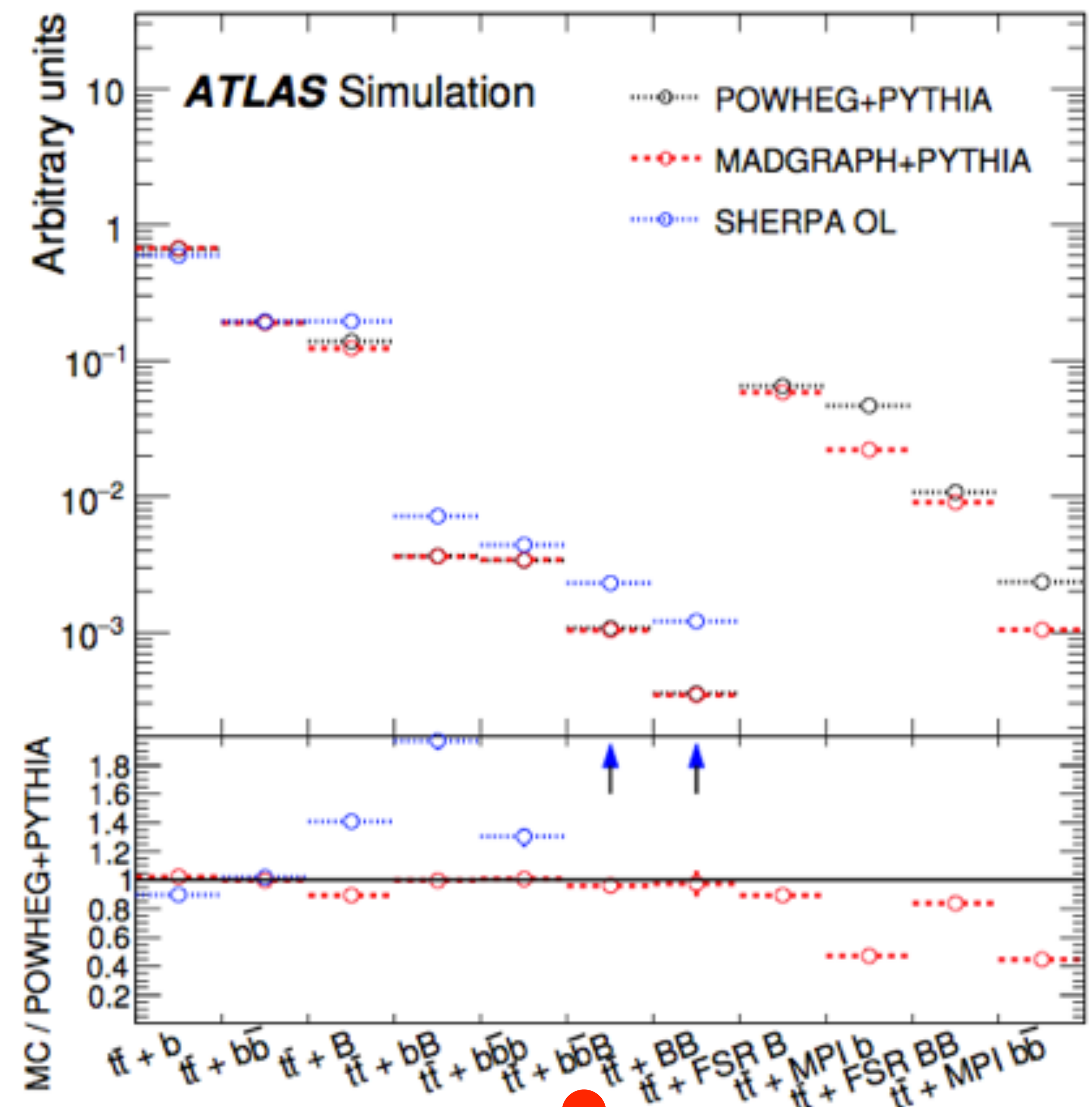
tt+bb: theory

State-of-the-art tt+bb prediction: 4F NLO+PS (e.g. SherpaOL)

PLB 734 (2014) 210

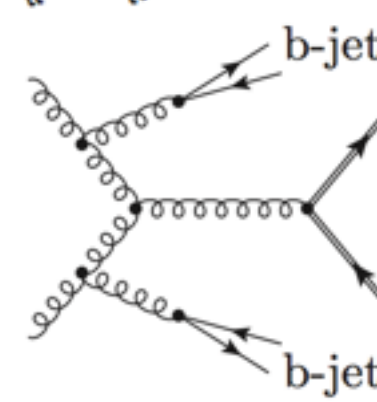


ATLAS, EPJC 75 (2015) 349



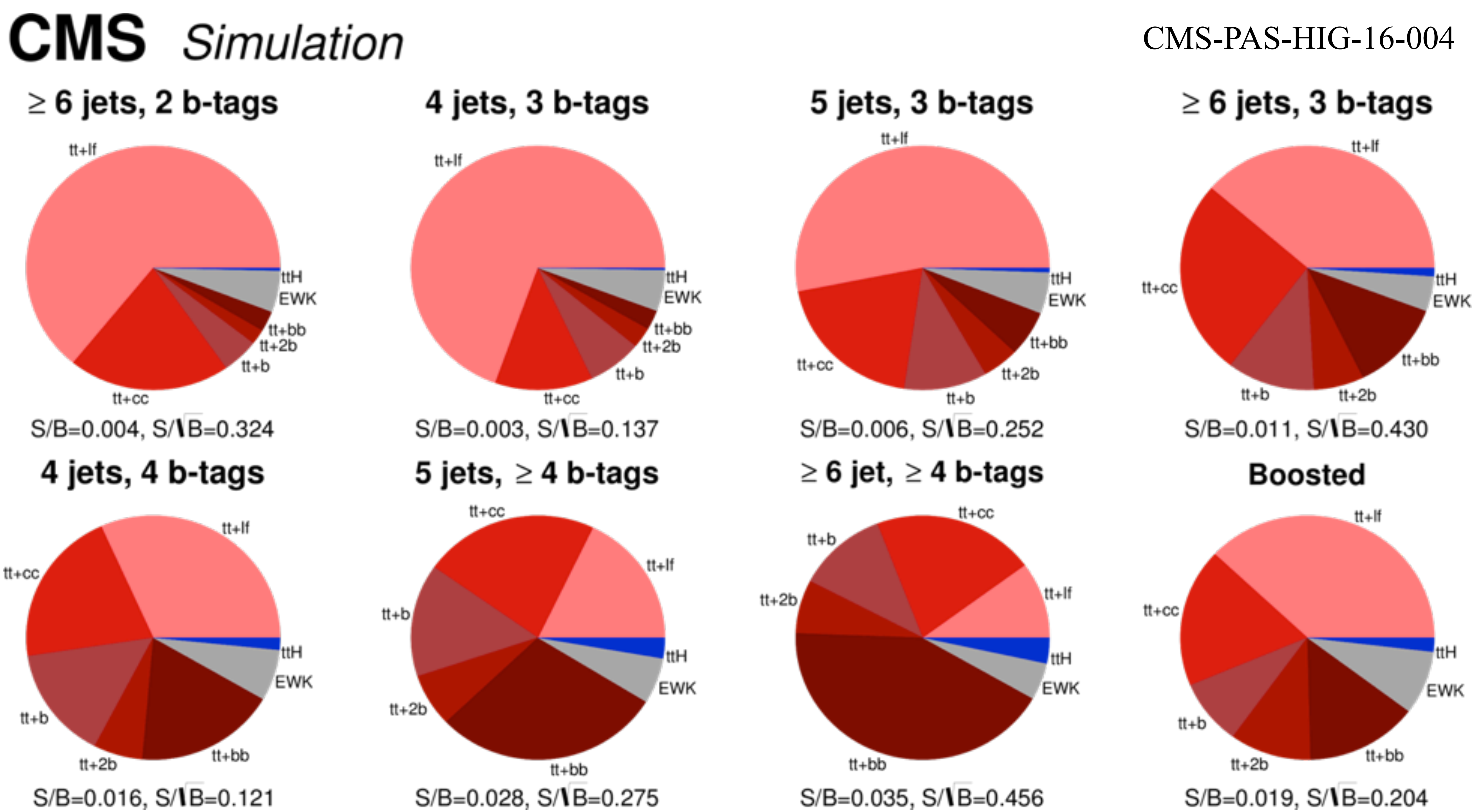
Non trivial K-factor.
Choice of μ_R scale impacts key observables (e.g. m_{bb} mass)

Enhanced double gluon splitting



Tuesday, May 17, 16

tt+bb: theory


CMS Simulation
CMS-PAS-HIG-16-004
≥ 6 jets, 2 b-tags
tt+lf
ttH
EWK
tt+bb
tt+2b
tt+b
tt+cc
S/B=0.004, S/√B=0.324
4 jets, 3 b-tags
tt+lf
ttH
EWK
tt+bb
tt+2b
tt+b
tt+cc
S/B=0.003, S/√B=0.137
5 jets, 3 b-tags
tt+lf
ttH
EWK
tt+bb
tt+2b
tt+b
tt+cc
S/B=0.006, S/√B=0.252
≥ 6 jets, 3 b-tags
tt+lf
tt+cc
ttH
EWK
tt+bb
tt+2b
tt+b
S/B=0.011, S/√B=0.430
4 jets, 4 b-tags
tt+lf
tt+cc
ttH
EWK
tt+b
tt+2b
tt+bb
S/B=0.016, S/√B=0.121
5 jets, ≥ 4 b-tags
tt+cc
tt+lf
tt+b
ttH
EWK
tt+2b
tt+bb
S/B=0.028, S/√B=0.275
≥ 6 jet, ≥ 4 b-tags
tt+cc
tt+b
tt+lf
tt+2b
ttH
EWK
tt+bb
S/B=0.035, S/√B=0.456
Boosted
tt+lf
tt+cc
ttH
EWK
tt+b
tt+2b
tt+bb
S/B=0.019, S/√B=0.204

ATLAS vs CMS: ttH→bb

changed since Run I (orange cells)

	ATLAS	CMS	CMS Run2
Top p_T reweighing	- tt+LF - tt+cc	same for all tt+jets subprocesses	-
PS modeling	PYTHIA vs HERWIG (uncorrelated among tt+X)	-	PS scale variations (nominal, up, down)
tt+cc modeling	- $\mu_R/\mu_F/\mu_Q$ variations - c quark mass - MG5 vs POWHEG	μ_R/μ_F scale	μ_R/μ_F scale, PS scale
tt+bb modeling	μ_R/μ_F scale, PS, PDF	μ_R/μ_F scale	μ_R/μ_F scale, PS scale
Single-top modeling	μ_R/μ_F scale, PS, PDF	-	-
tt+V modeling	μ_R/μ_F scale, PS, PDF	-	μ_R/μ_F scale, PDF
ttH modeling	μ_R/μ_F scale, PS, PDF	-	μ_R/μ_F scale, PS scale, PDF