Measurement of properties of the Higgs Boson in fermionic decay channels using the ATLAS detector

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on behalf of the ATLAS collaboration

SUSY2016 - Higgs Physics Session - 04/07/2016

ATLAS EXPERIMENT

LPNHE PARIS

Introduction and Outline

Main motivations: why fermionic channels?

- **production and decay modes' properties**

$H \rightarrow \tau\tau$

main results from Run1

CP-invariance test from VBF($H \rightarrow \tau\tau$)

Lepton Universality

$H \rightarrow \mu\mu$

Lepton Flavour Violating H

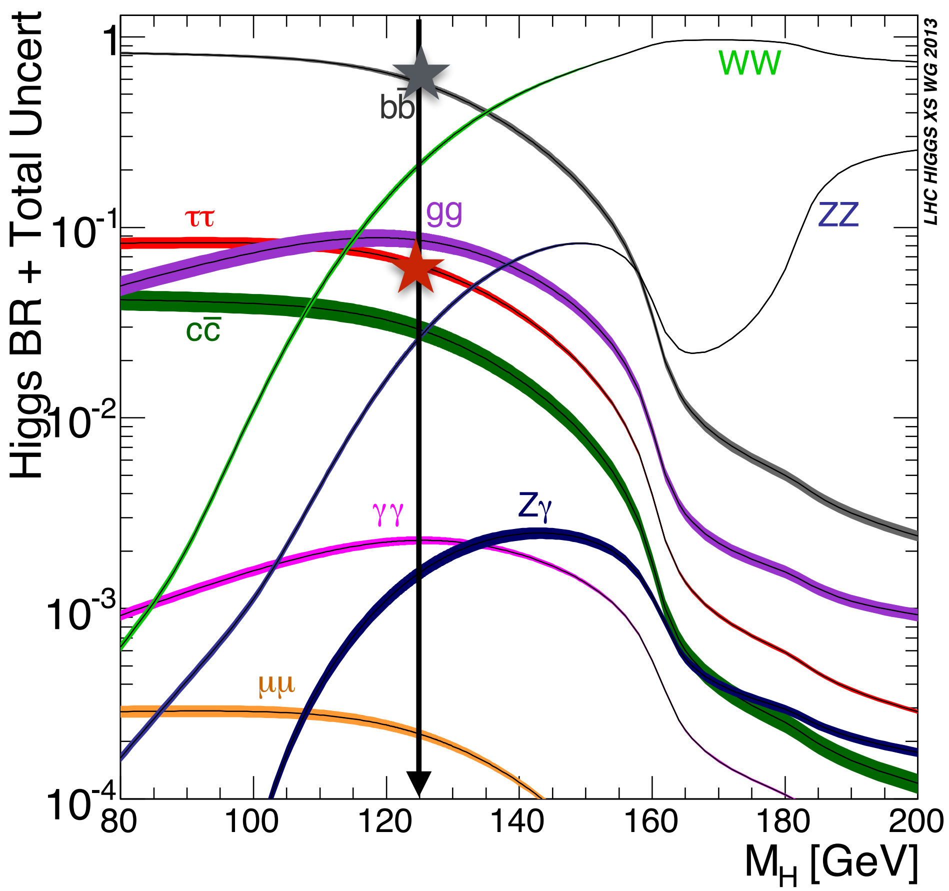
BR($H \rightarrow e\tau$) & BR($H \rightarrow \mu\tau$)

$H \rightarrow$ bottom quarks

VH, VBF and ttH channels

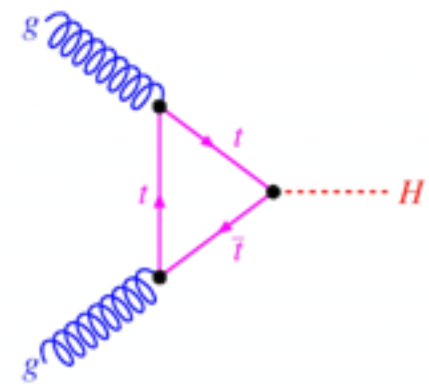
Fermionic channels in ATLAS Higgs combination

Higgs boson production & fermionic decays

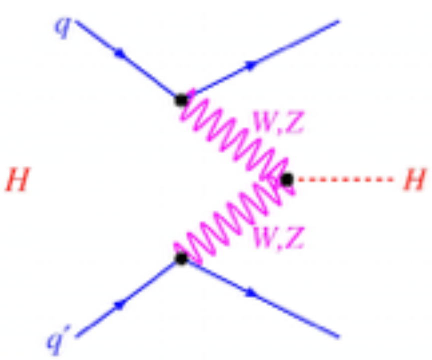


BR(H→fermions)@125GeV

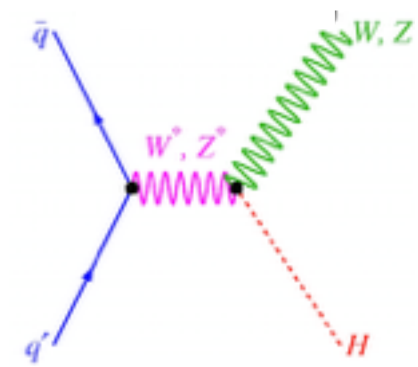
m_H=125GeV	H→bb	H→ττ	H→μμ
BR	57.7%	6.32%	0.0218%



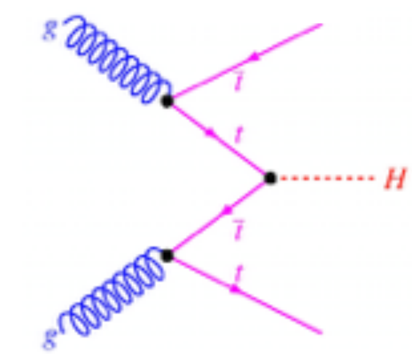
ggH



VBFH



VH



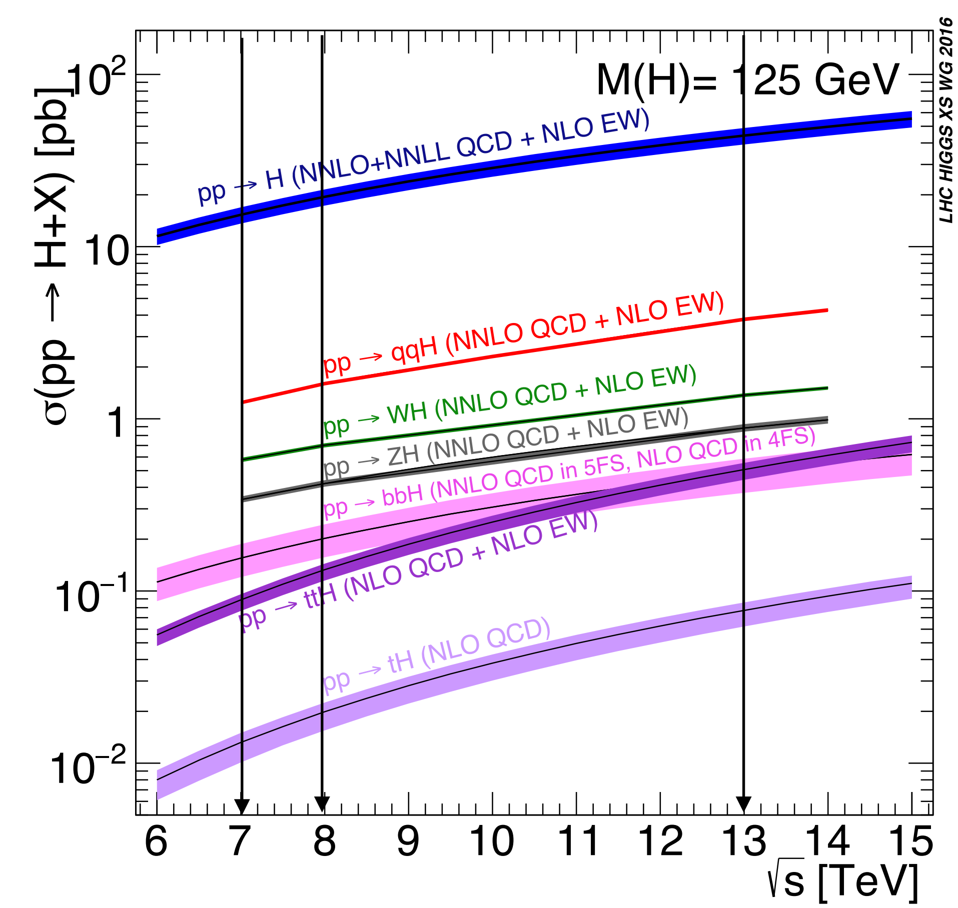
ttH

Fermionic decays provide some of the largest branching ratios for Higgs production at 125 GeV

Experimental signature may be less clean than bosonic decay channels: exploit production modes signature

What are the main results obtained by ATLAS from the LHC Run1 data in H(→fermions) channels?

What can we learn from them and what are the prospects?



Run1 **Run2**

H→ττ : Main Run1 Results

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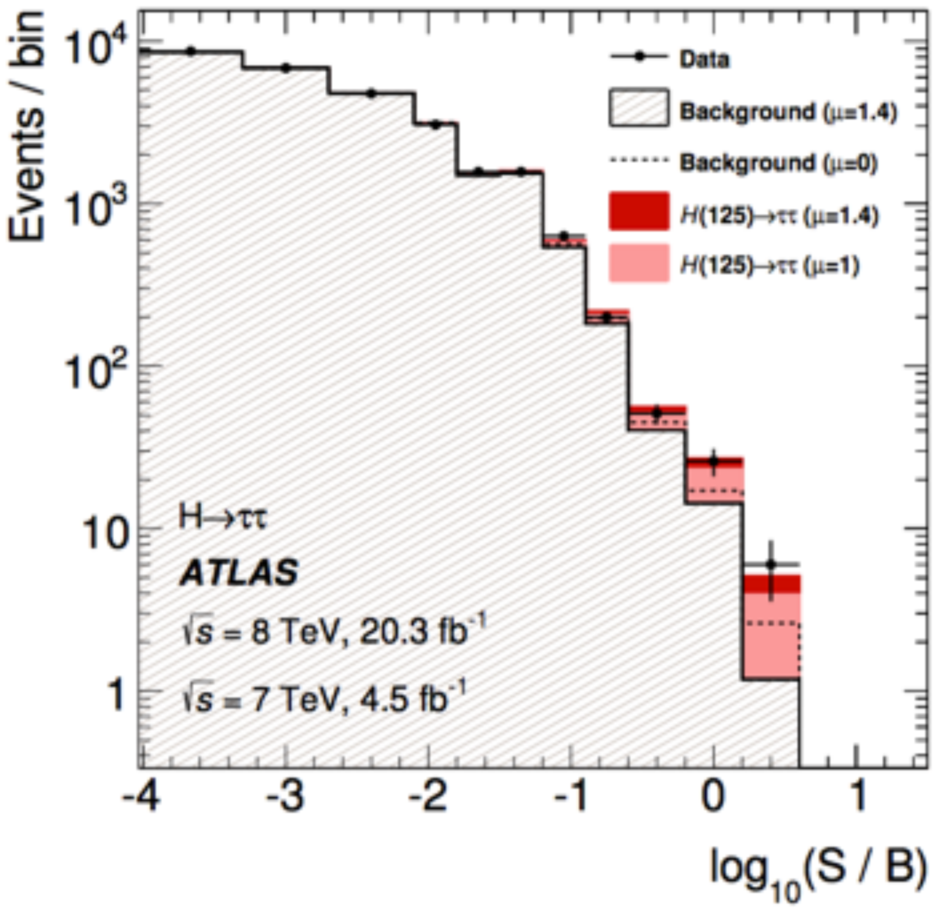
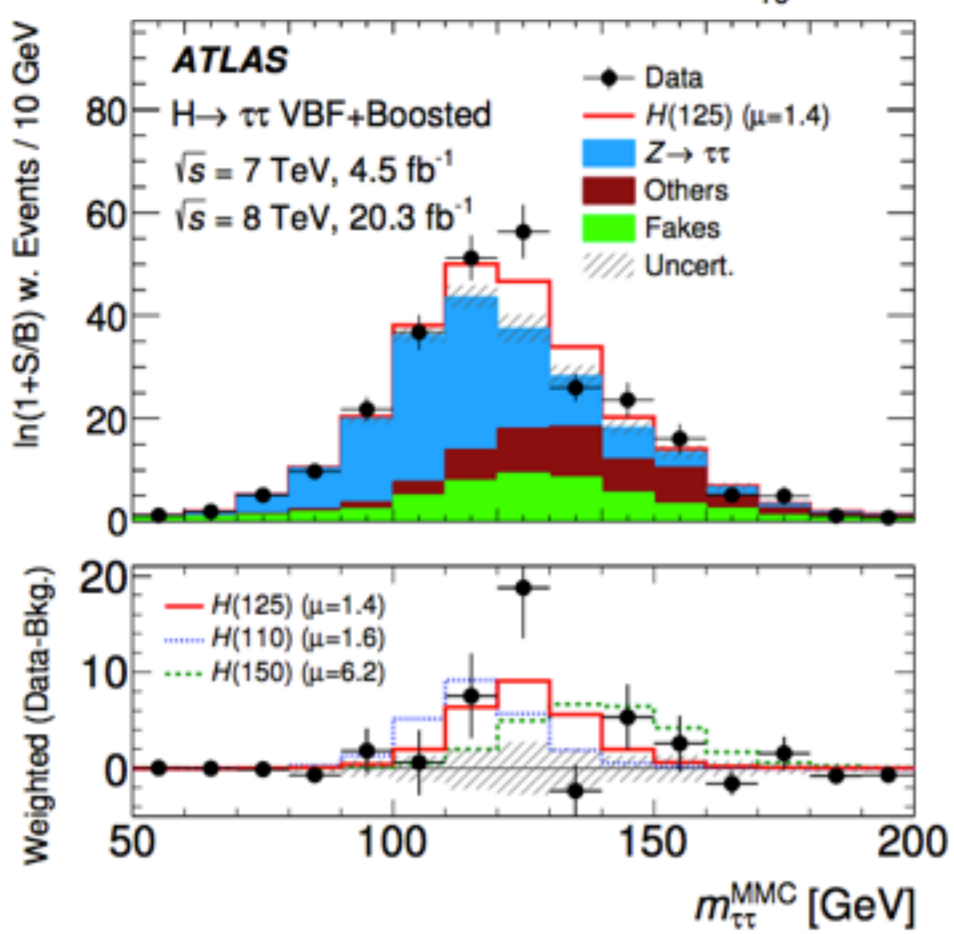
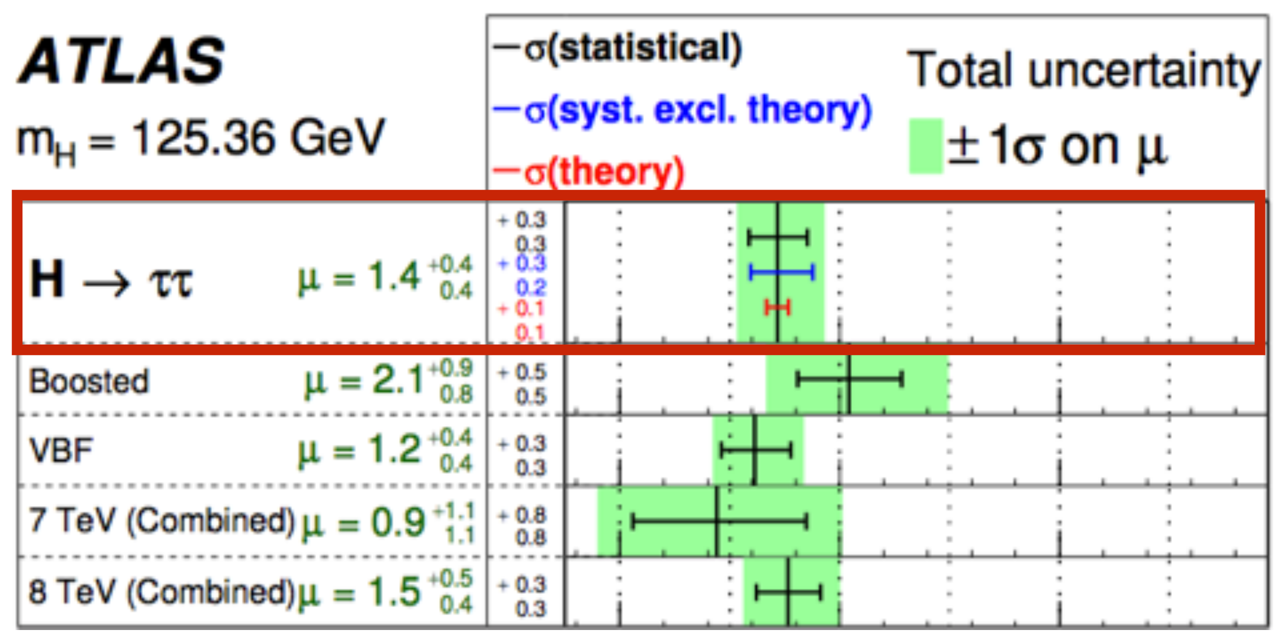


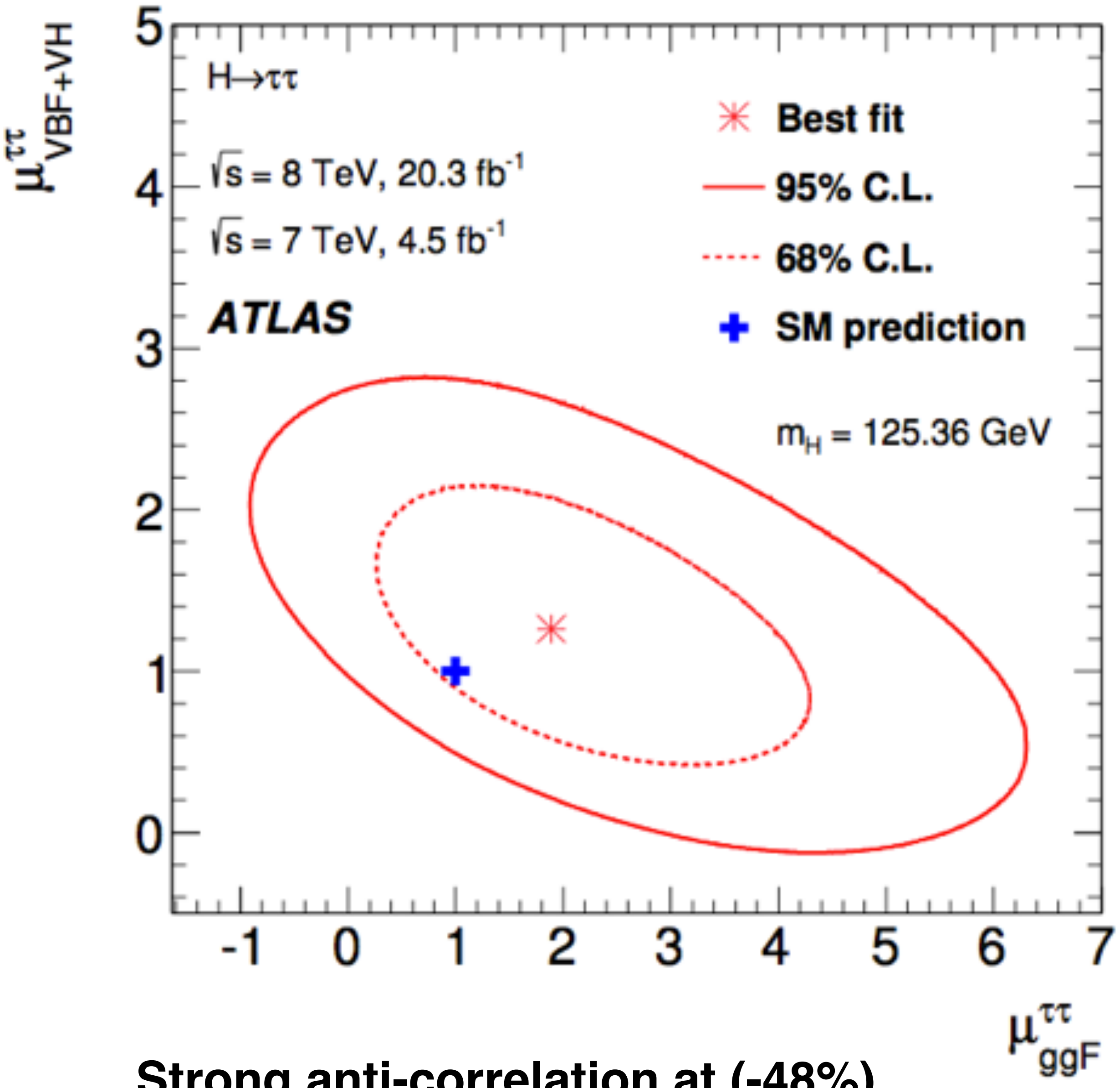


- **second largest BR(fermions):** lower than H(bb) but cleaner signature
- **3 analysis channels: $\tau_{lep}\tau_{lep}$ + $\tau_{lep}\tau_{had}$ + $\tau_{had}\tau_{had}$**
- events categorised in jet-multiplicity and $p_T(\tau\tau)$, **VBF-like and ggF-like categories**
- **Fit of multivariate discriminant (MVA) distribution**
- **main challenges of the ττ channel**
    - invariant mass reconstruction & resolution
    - background control: Z(→ττ) & fake-τ_{had} estimate
    - triggering in the $\tau_{had}\tau_{had}$ channel



Signal Strength μ	$\mu = 1.43\ ^{+0.27}_{-0.26}(\text{stat.})\ ^{+0.32}_{-0.25}(\text{syst.})\ \pm 0.09(\text{theory syst.})$
Significance σ	$\sigma_{observed} = 4.5$ $\sigma_{expected} = 3.4$

H→ττ : Production Modes



Strong anti-correlation at (-48%)

Main H→ττ search interpreted in [ggF] vs [VH+VBF] production modes couplings

VBF-enriched region:

- 2 high p_T jets with large pseudo-rapidity separation

ggF-enriched (boosted) region:

- $p_T(\tau\tau) \sim p_T(H) > 100$ GeV

Two dimensional fit of the Higgs signal strength separating the ggF from VH+VBF production modes

Prod. mode	Significance σ	
ggF	$\sigma_{observed} = 1.74$	$\sigma_{expected} = 0.95$
VH+VBF	$\sigma_{observed} = 2.25$	$\sigma_{expected} = 1.72$

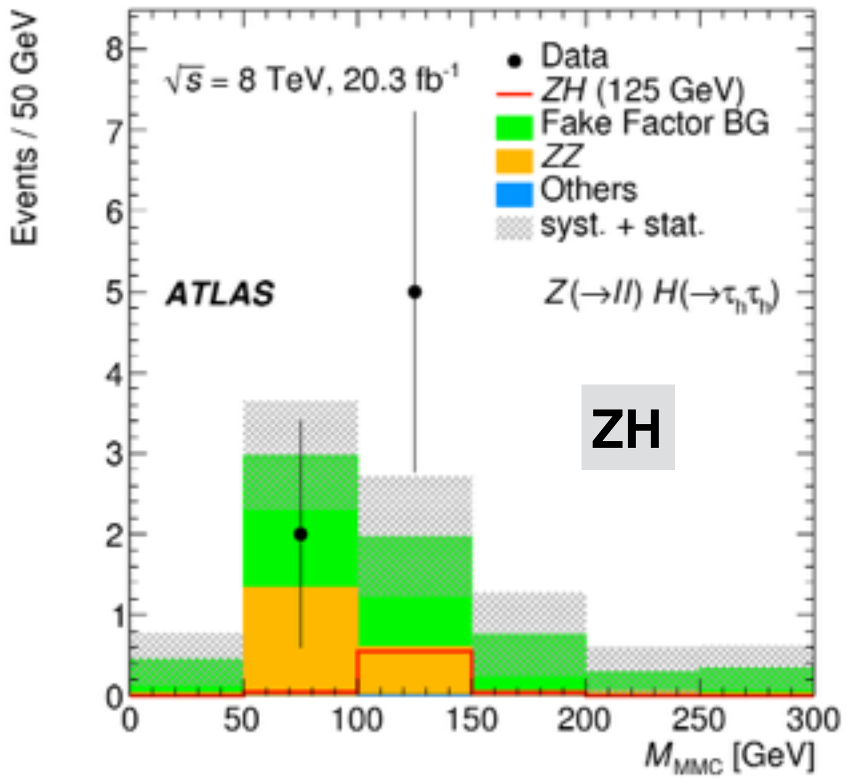
$$\mu^{\tau\tau}_{ggF} = 2.0 \;\pm 0.8(\text{stat.})\; ^{+1.2}_{-0.8}(\text{syst.}) \;\pm 0.3(\text{theory syst.})$$

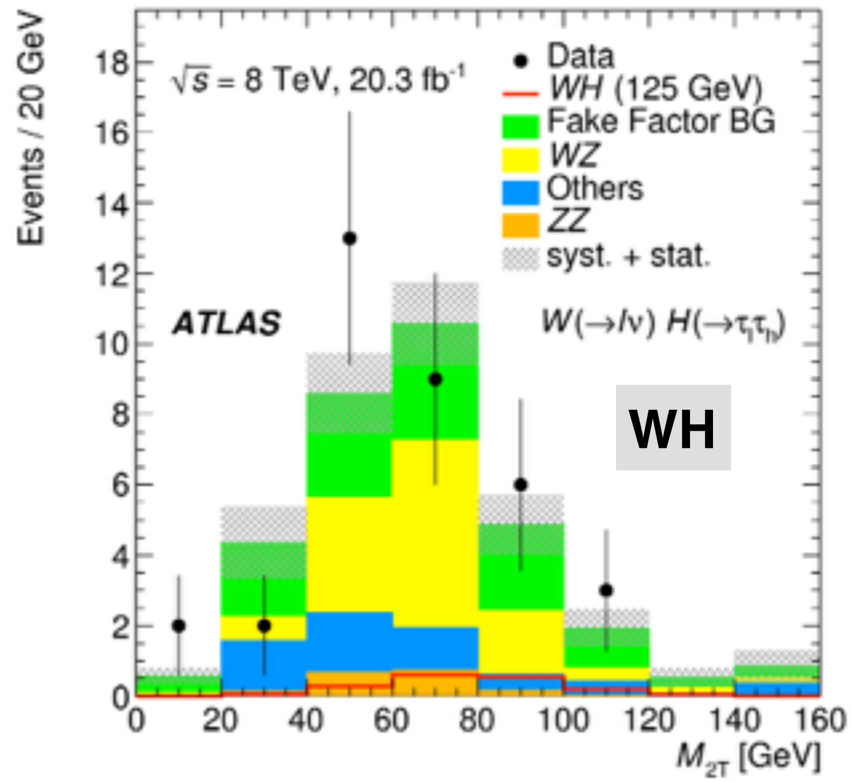
$$\mu^{\tau\tau}_{\text{VBF}+VH} = 1.24 \;^{+0.49}_{-0.45}(\text{stat.})\; ^{+0.31}_{-0.29}(\text{syst.}) \;\pm 0.08(\text{theory syst.})$$

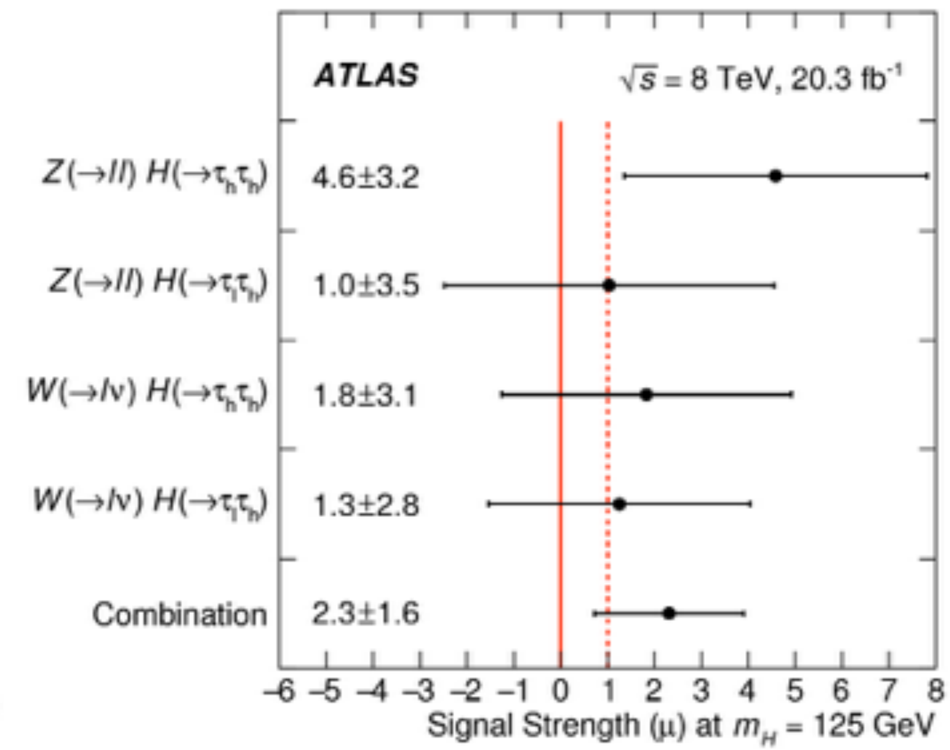
H→ττ : Production Modes

Dedicated VH(H→ττ) search in $\tau_{lep}\tau_{had}$ $\tau_{had}\tau_{had}$ channels

Phys. Rev. D 93, 092005







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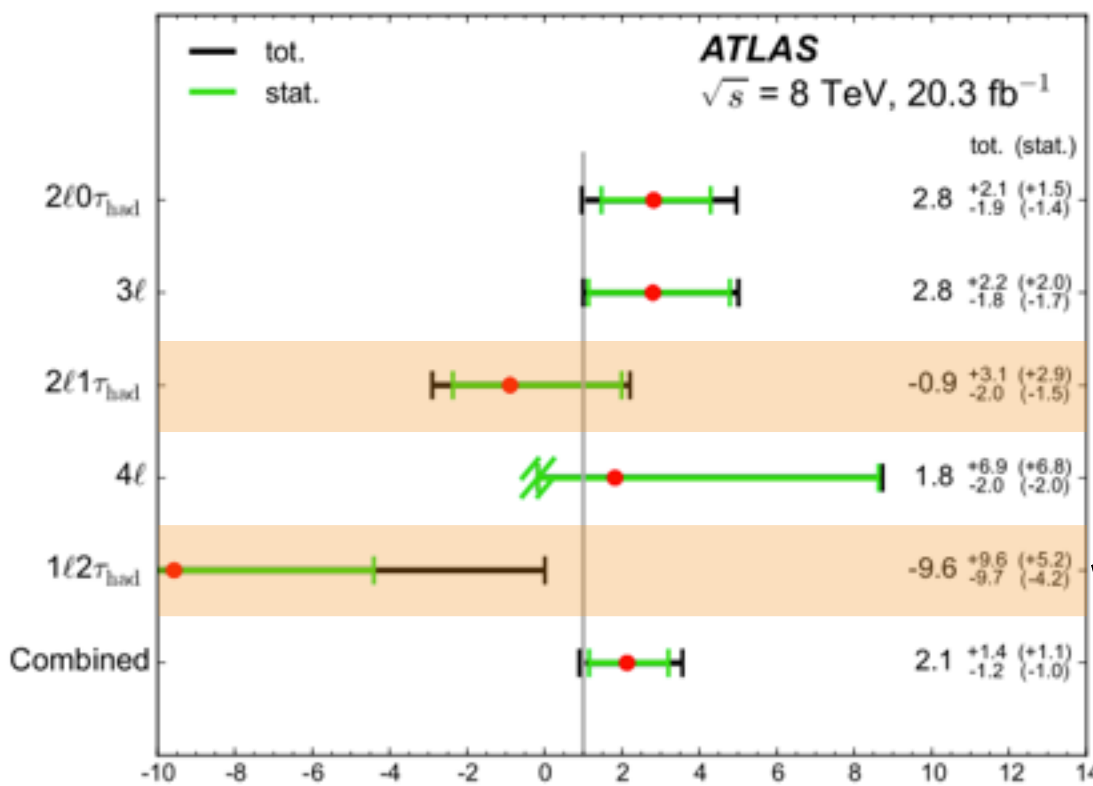
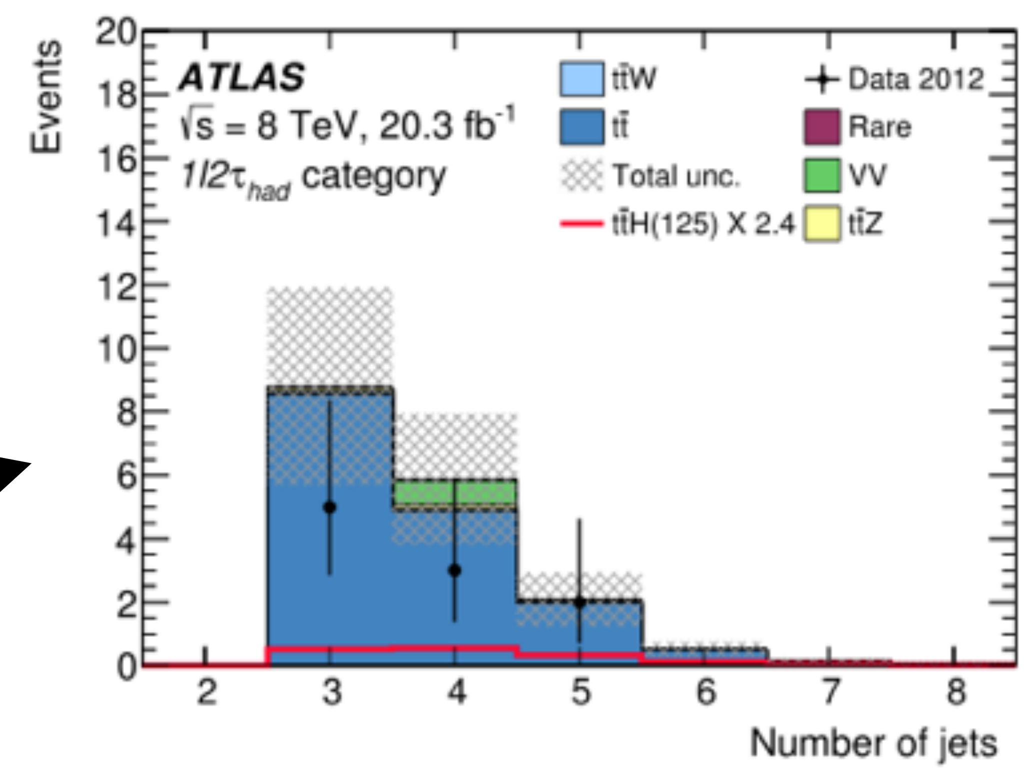


ttH production: from ttH(multilepton) analysis



VBF(H→ττ) : CP-invariance

HIGG-2015-06 Submitted to EPJC

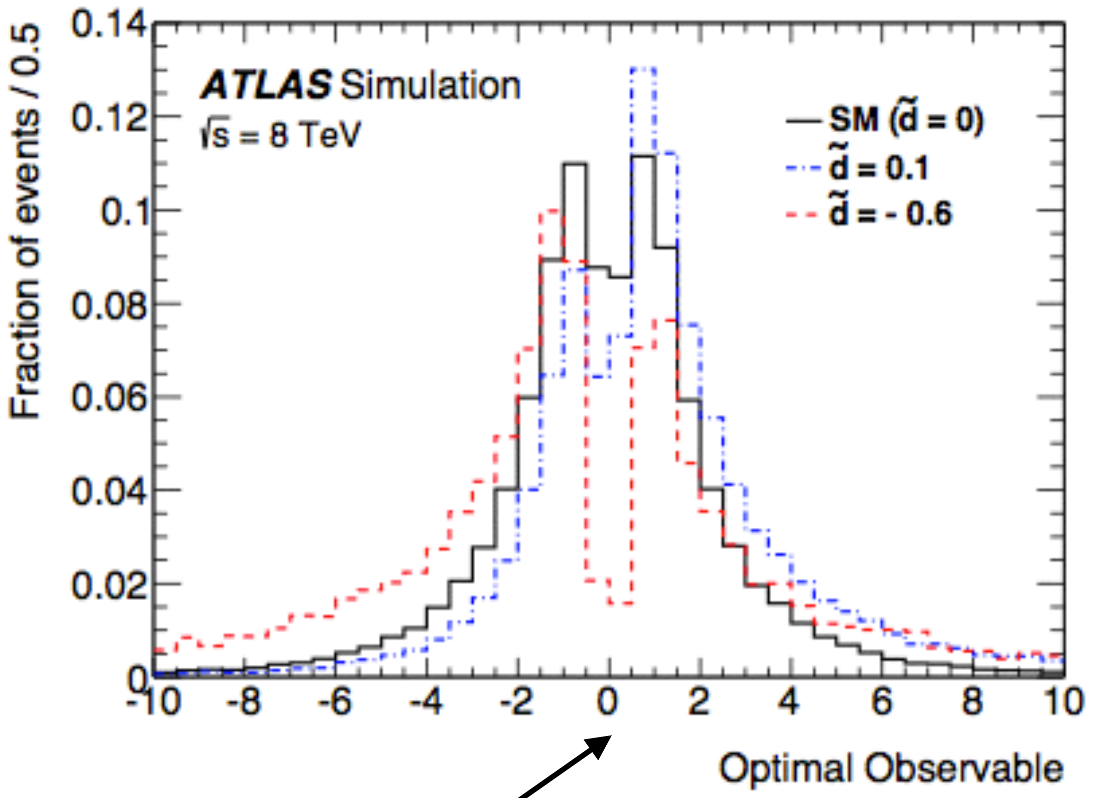
- **HVV couplings as a test of CP-violation / CP-invariance**

HWW, HZZ decays and Hγγ differential cross-section
no deviations from Run1 data

Direct test through VBF production (H→ττ)

- **CP-odd observable:**
sensitive to interference between SM and CP-odd contributions

- **Optimal observable:** combine multi-dimensional information in a single variable from the VBF production LO matrix-element [independent from H decay mode]



$$\boxed{OO = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}}$$

most sensitive for smallest values

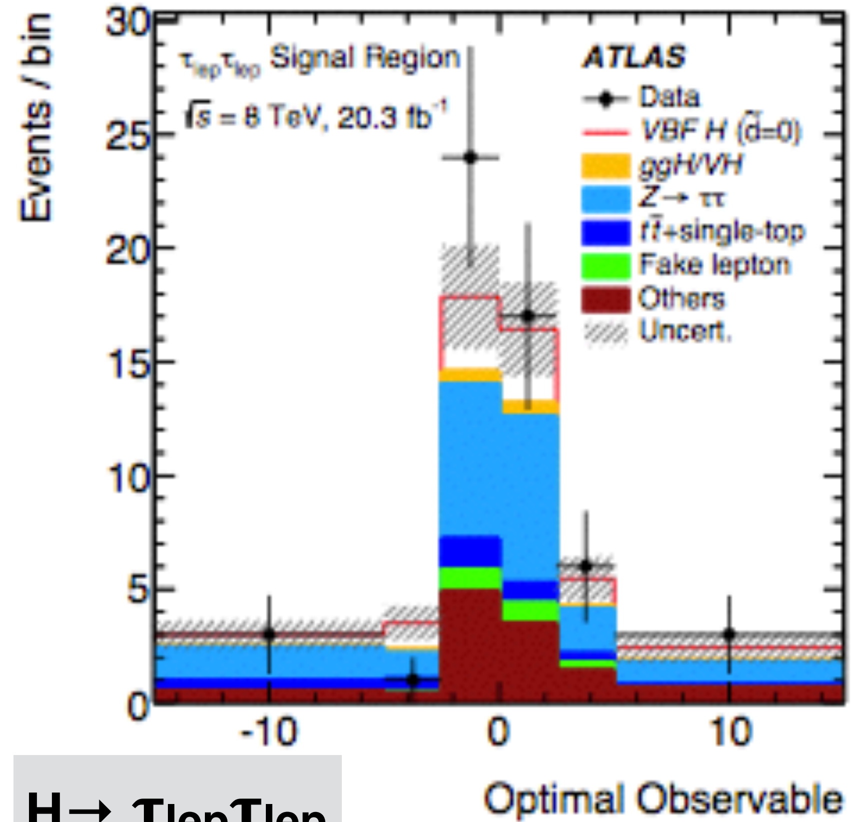
Results interpreted in the Effective Field Theory framework:
CP-violating effects from higher dimension operators on HVV: $\tilde{d}$ parameter

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

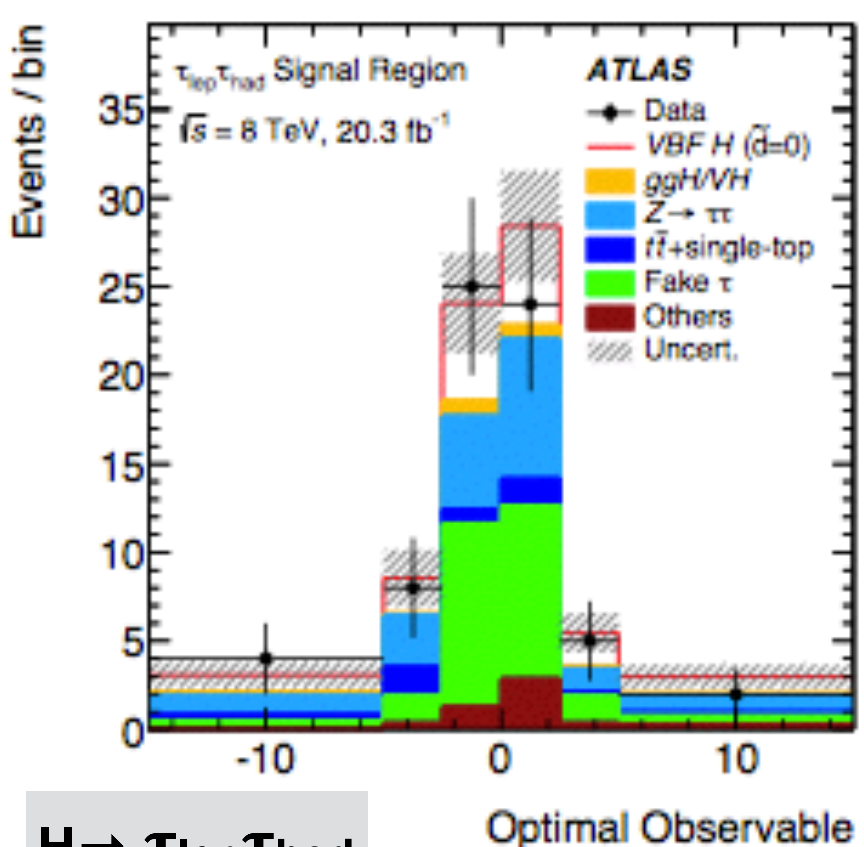
Couplings parametrisation: $\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}$

VBF($H \to \tau\tau$) : CP-invariance

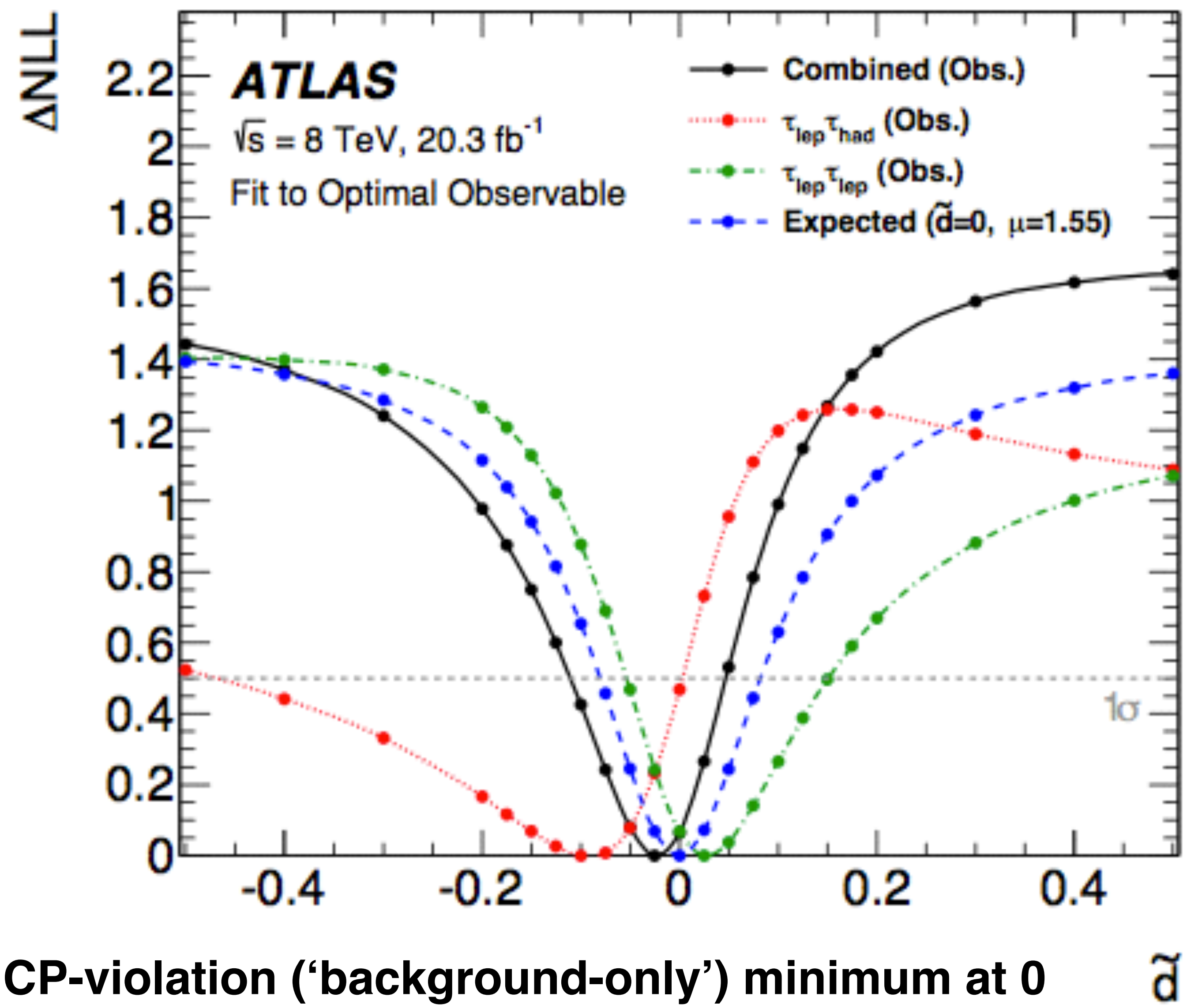
HIGG-2015-06 Submitted to EPJC



$H\to \tau_{lep}\tau_{lep}$



$H\to \tau_{lep}\tau_{had}$



No CP-violation ('background-only') minimum at 0

- [$-0.11 < \tilde{d} < 0.05$] compatible at 68% CL [competitive with limits from HWW, HZZ]
- same limit-setting with $\Delta\Phi^{sign}(jj)$ shows worse results [azimuthal angle between VBF-tagging jets]

Channel	Fitted value of $\tilde{d}$
$\tau_{lep}\tau_{lep}$	0.3 ± 0.5
$\tau_{lep}\tau_{had}$	-0.3 ± 0.4

H→μμ

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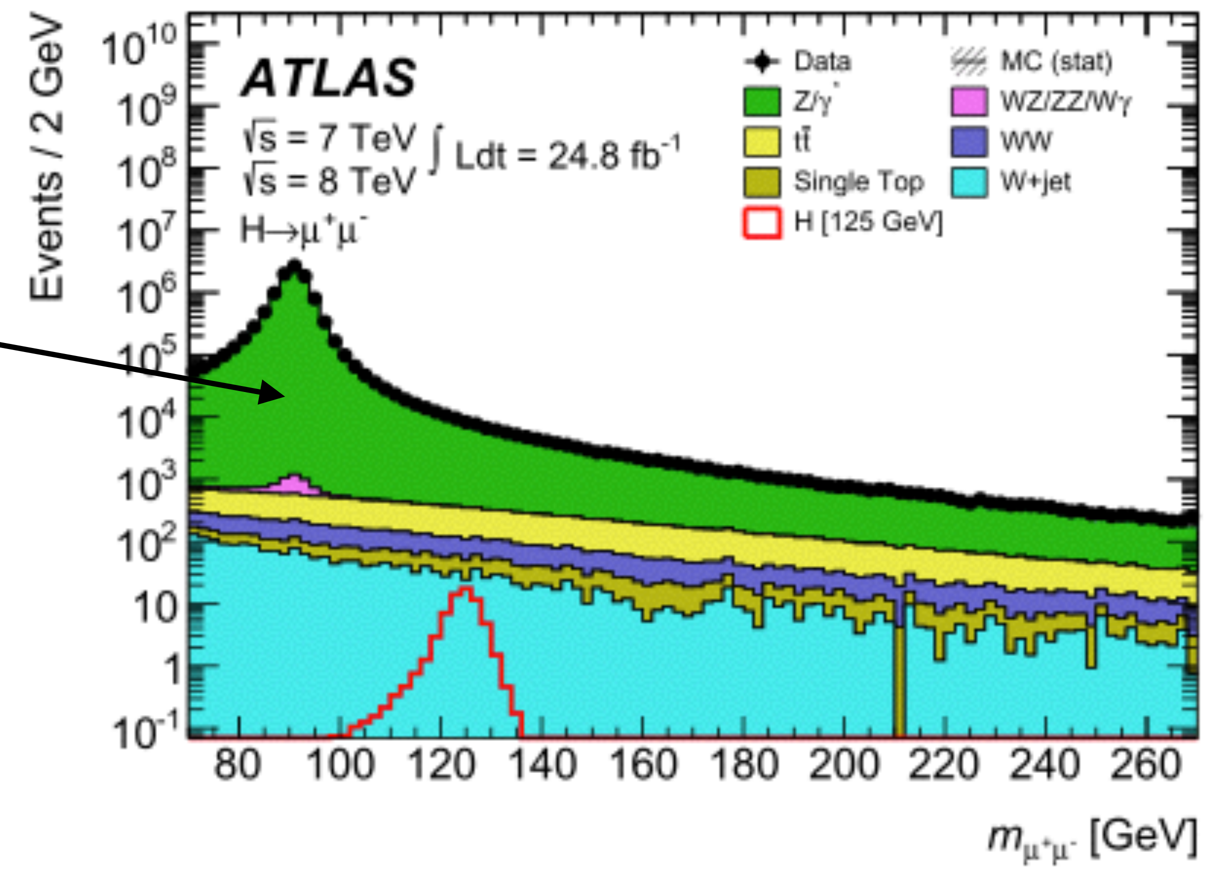
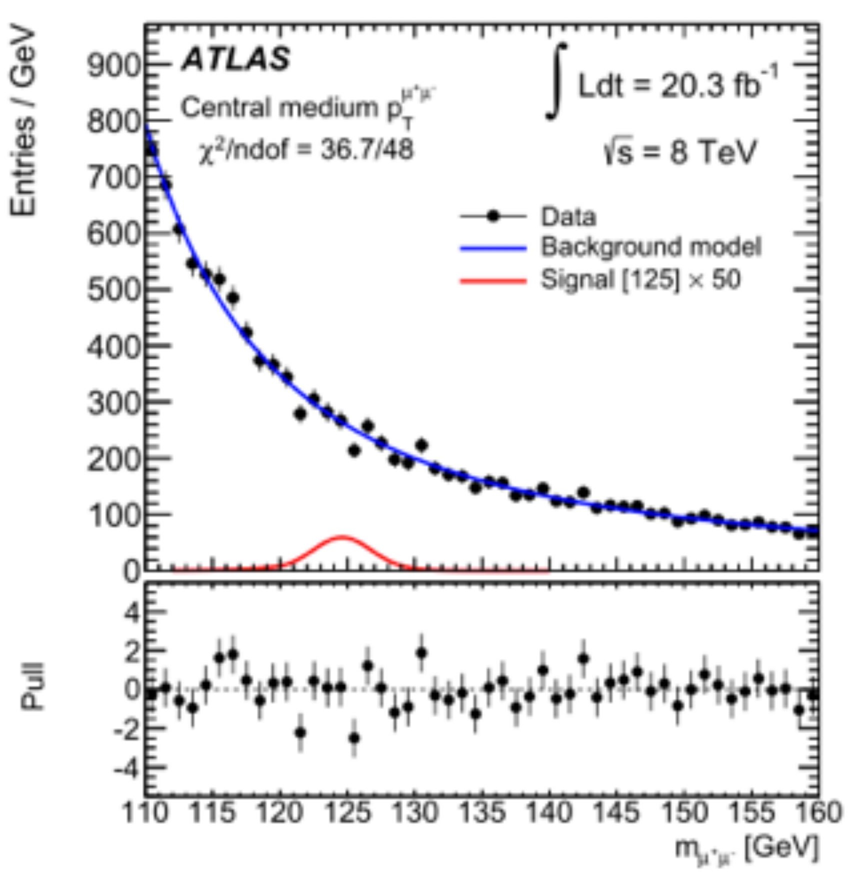
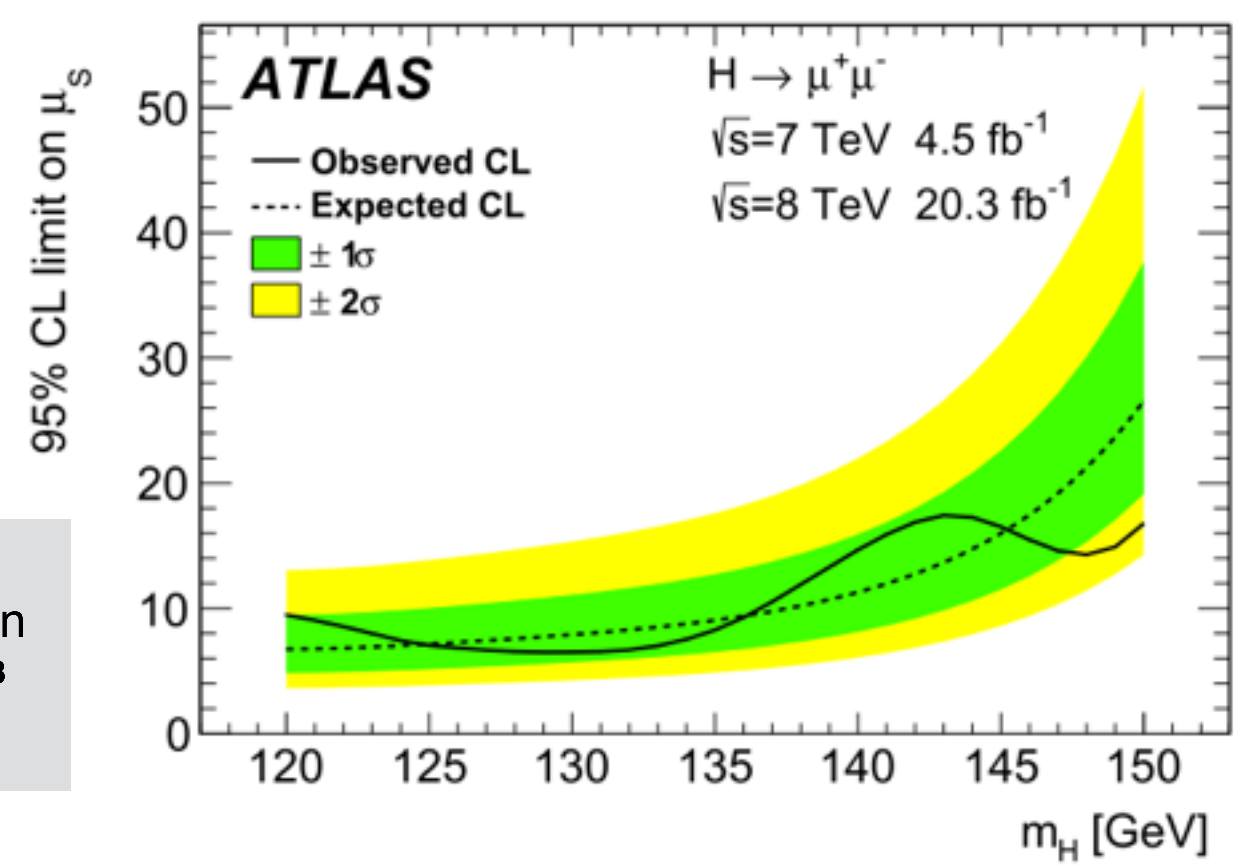
- **Test of the H coupling to leptons: flavour universal or mass dependent (SM) ?**
- **very clean signature from dimuon final state**
- **tiny BR(μμ) predicted for a SM Higgs**
- **Z/γ*→μμ overwhelming irreducible background**
- **events categorised according to**
  - **VBF** dijet signature
  - **p_T(μμ)** [high p_T: more sensitive]
  - **η(μ)** [central μ: better $m_{\mu\mu}$ resolution]





95% CL limit on μ
observed = 7.0
expected = 7.2

Upper limit on BR
for SM H(125) production
BR(H→μμ) < 1.5 x 10^{-3}
(SM BR = 2.176 x 10^{-4})



H LFV: Lepton Flavour Violating Decays

- **LFV decays forbidden in the SM theory, but allowed by several BSM models** (2HDMs, composite Higgs, …)
- **most stringent bounds on LFV:**

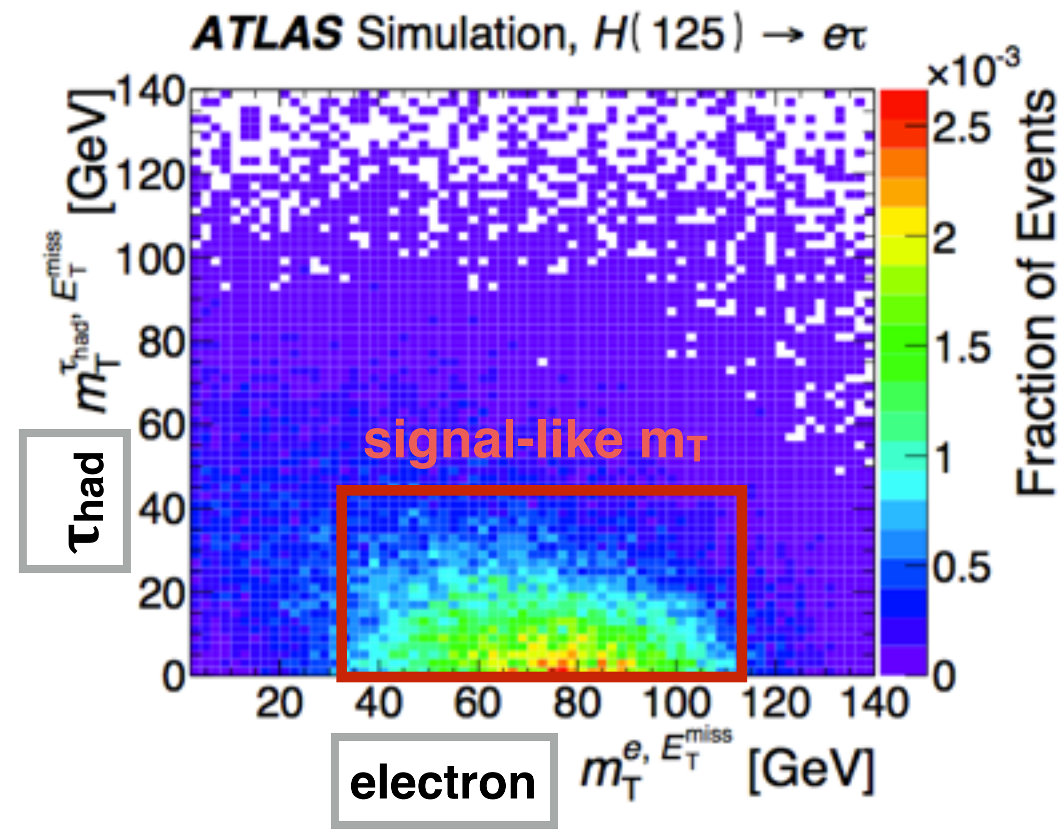
BR(H→eμ) < O(10^{-8}) [from indirect μ→eɣ]
BR(H→τe) < O(10%) [direct search]
BR(H→τμ) < O(1%) [direct search]

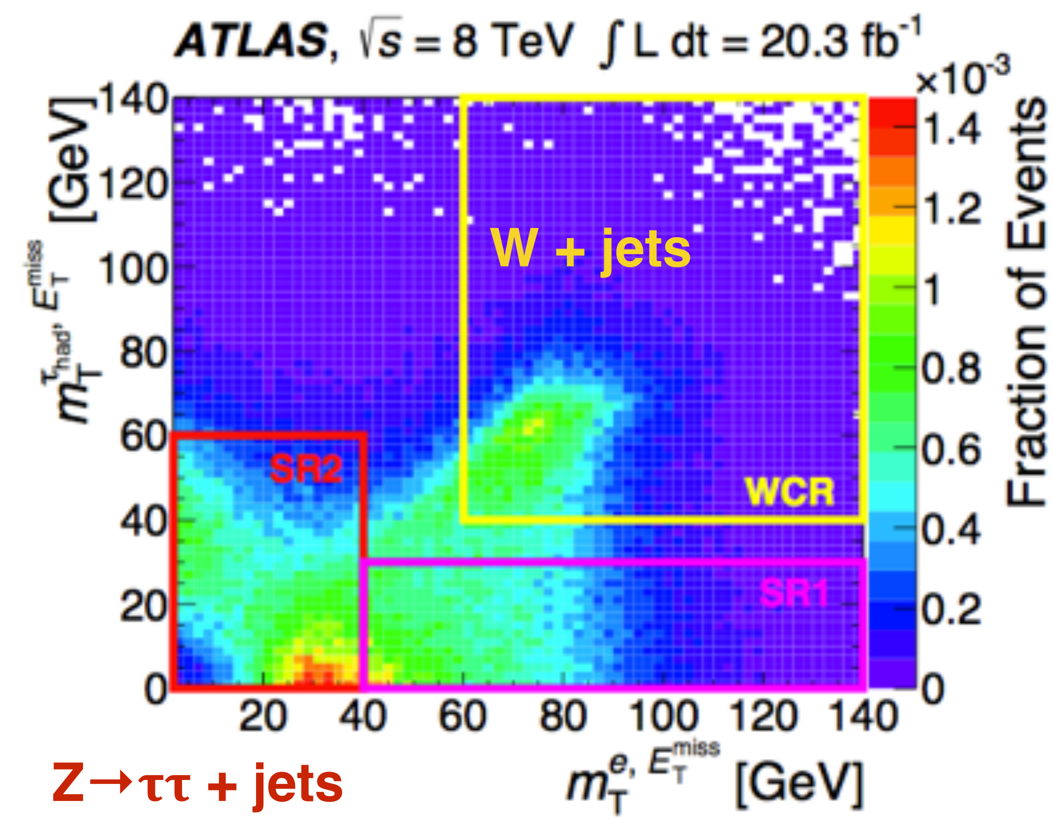
ATLAS direct searches focused on τe and τμ final states

- signature similar to SM H→**ττ**, with harder momenta for the leptons and neutrinos collinear to **τ** decay products
- events categorised according to the **m_T transverse mass**
  - **CR:** W+jets control region
  - **SR1**: Z+jets dominated
  - **SR2**: W+jets dominated
- fit of the reconstructed (**τ**+lepton) invariant mass
- both (l+τ_{lep}) and (l+τ_{had}) channels included

Note: CMS performed the first direct LFV **H→τμ** search reporting an excess of ~ 2.4 standard deviations over the background prediction [BR(H→τμ) < 1.51%]

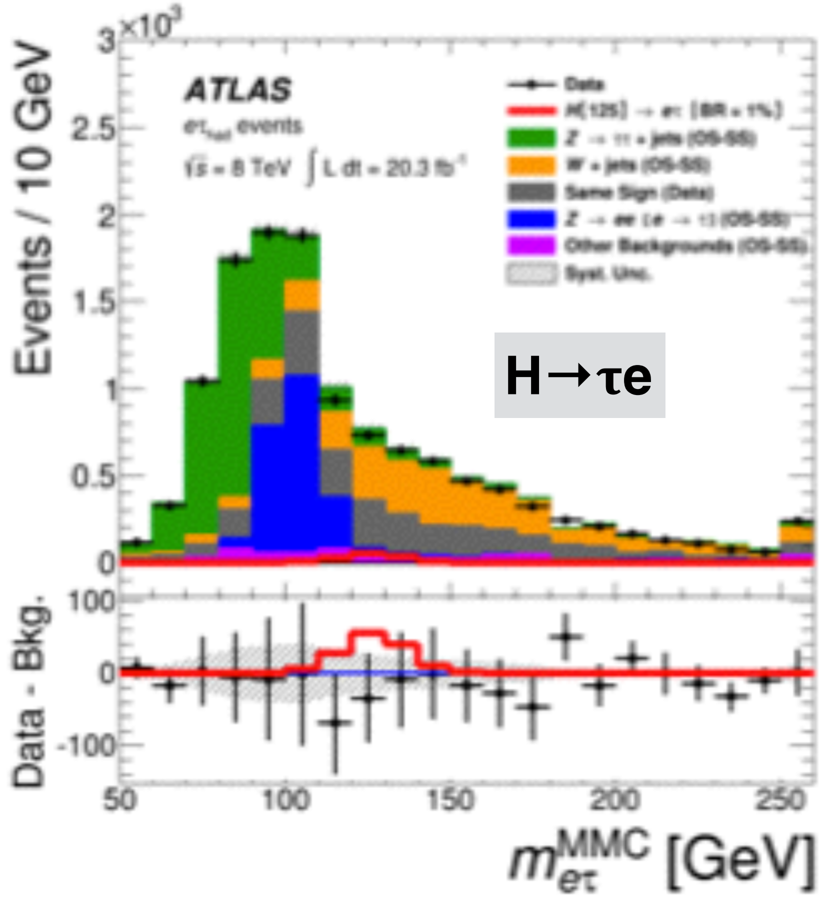
arxiv 1604.07730v1 submitted to EPJC

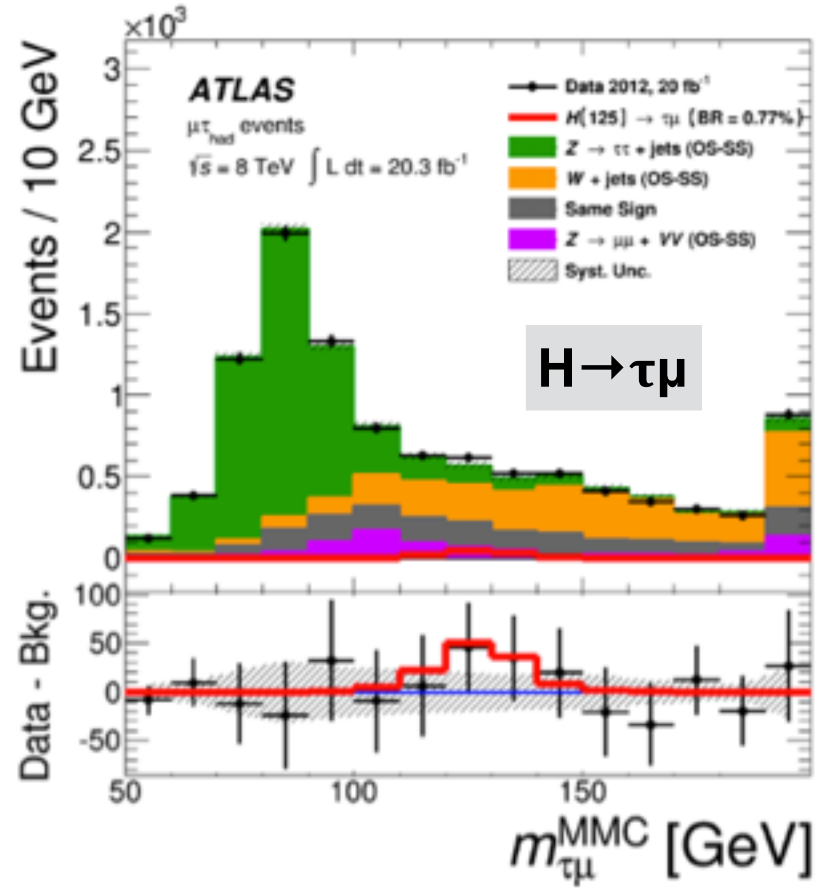




H LFV: Lepton Flavour Violating Decays

<u>arxiv 1604.07730v1 submitted to EPJC</u>

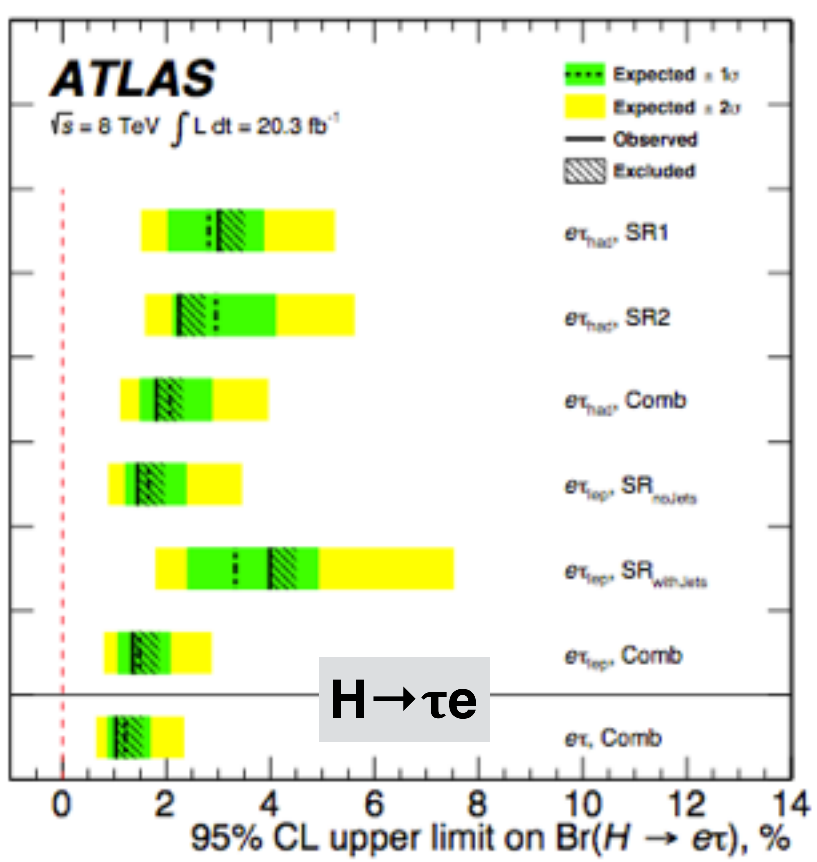


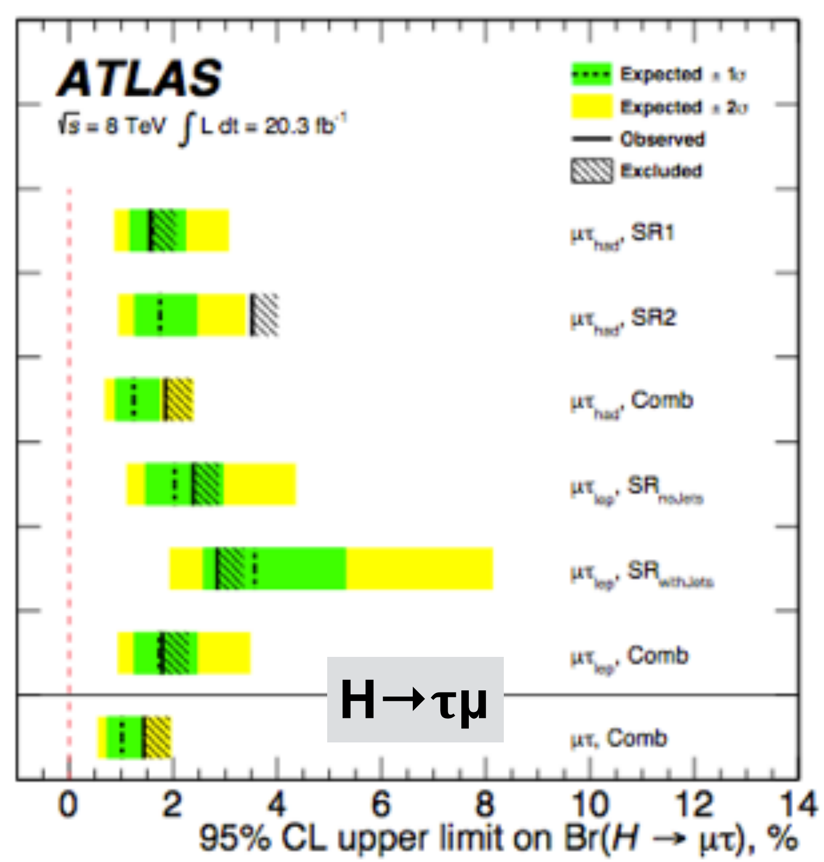


95% CL BRs upper limits

BR limit	H→τe
observed	1.04%
expected	$1.21^{+0.49}_{-0.34}$%

BR limit	H→τμ
observed	1.43%
expected	$1.01^{+0.40}_{-0.29}$%



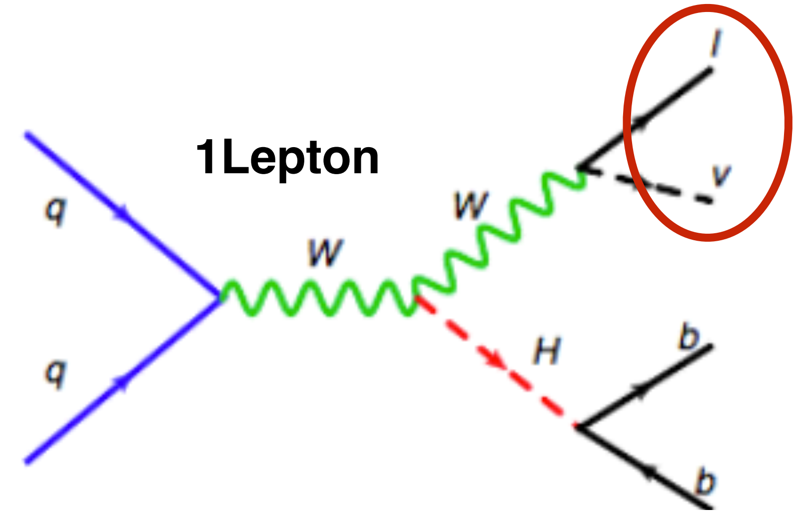


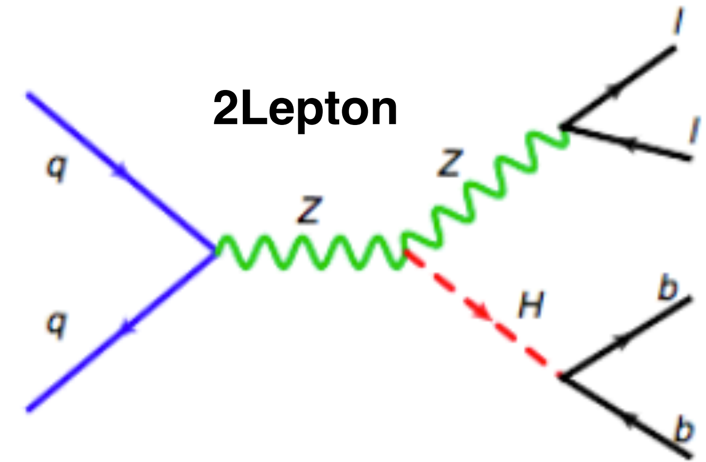
Small excess for **H→τμ** ~ 1σ over predicted backgrounds

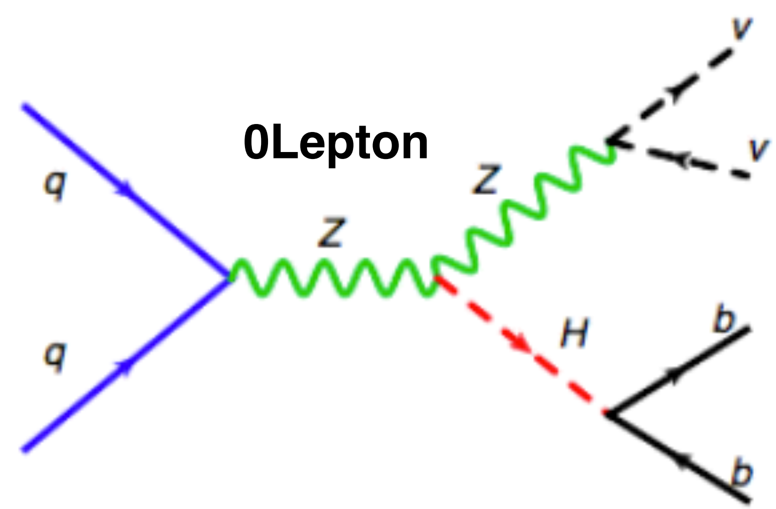
VH(H→bb) : Main Run1 Results

- **Largest branching ratio for a 125GeV SM Higgs, overwhelming background from QCD multi-jet production**

  Inclusive H→bb search extremely challenging
  Exploit associated production modes:
  cleaner signature from V boson leptonic decays







- **contribution from almost all SM backgrounds:**
  Z+jets, W+jets, ttbar, single-top, diboson, QCD multi-jet
- **multivariate techniques (MVA) necessary to achieve good S/B:**
  fit of the output distribution of the MVA classifier
- **complex phase space splitting** to control background modelling and obtain the highest signal significance

Variable

		1tag (CR)
$p_T^V < 120$ GeV	**2 jets**	**2tag Loose (SR)**
$p_T^V > 120$ GeV	**3 jets**	**2tag Medium (SR)**
		2tag Tight (SR)

b-tagger output

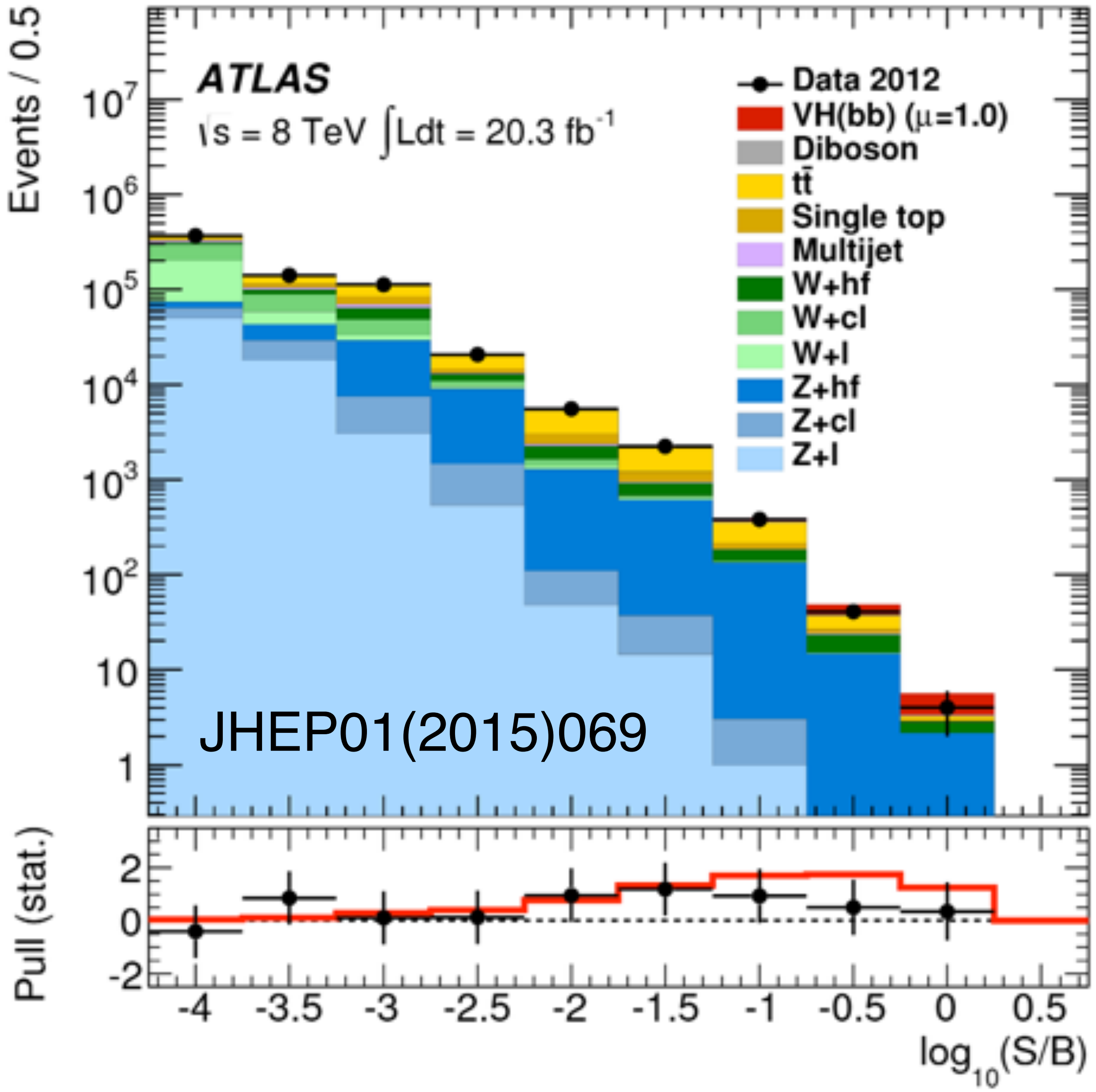
MVA

2 regions of transverse momentum of the vector boson **p_T^V**

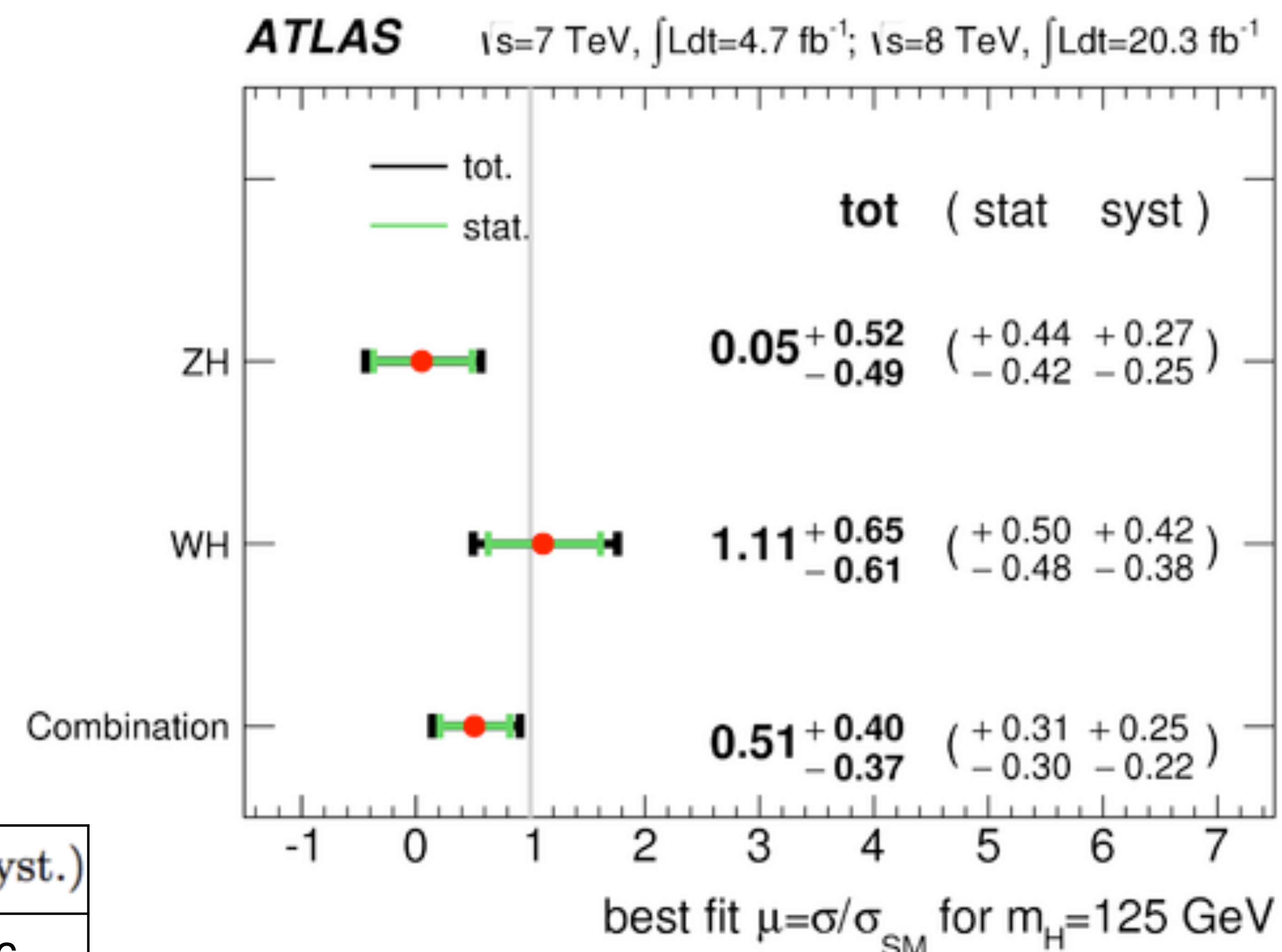
2 jet multiplicity regions

4 regions in number of b-tagged jets, and purity of the b-jet identification

VH(H→bb) : Main Run1 Results



Fitted value of the Higgs boson signal strength
for m_H=125GeV, separately for ZH and WH associated production modes



Signal Strength μ	$\mu = 0.51 \pm 0.31(\text{stat.}) \pm 0.24(\text{syst.})$
Significance σ	$\sigma_{observed}$ = 1.4 $\sigma_{expected}$ = 2.6

Highest expected significance for Hbb searches

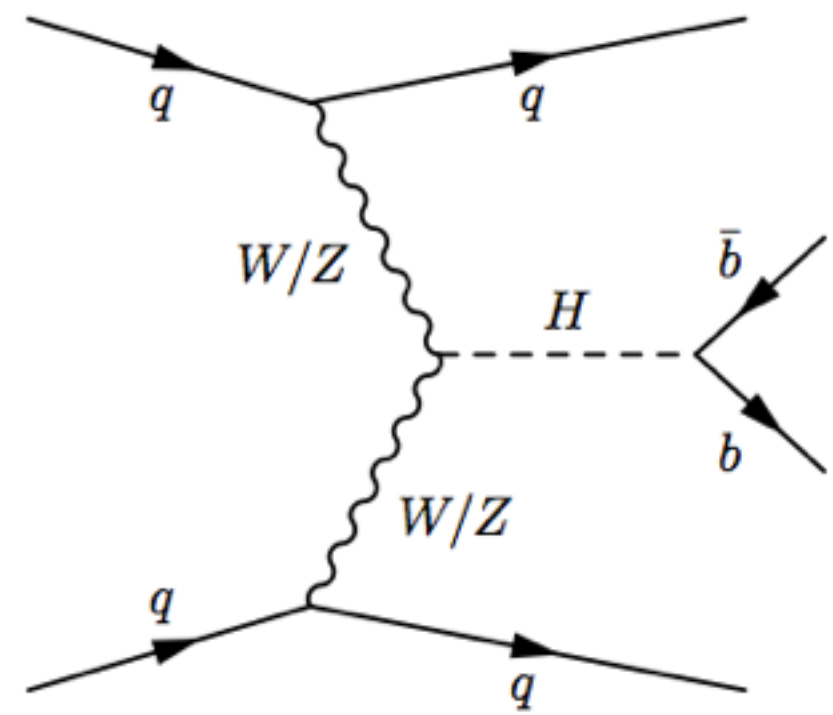
Multivariate analysis brings **O(30%)** improvement in the expected significance over a simple fit of the m_{BB} distribution

VBF($H\rightarrow bb$) : Main Run1 Results

arxiv 1606.0218 submitted to JHEP

- Similar to the VH($H\rightarrow bb$): **VBF production mode signature** to fight the QCD background and exploit the large BR($H\rightarrow bb$)

More difficult to exploit VBF than VH signature for $H\rightarrow bb$
Larger production cross-section



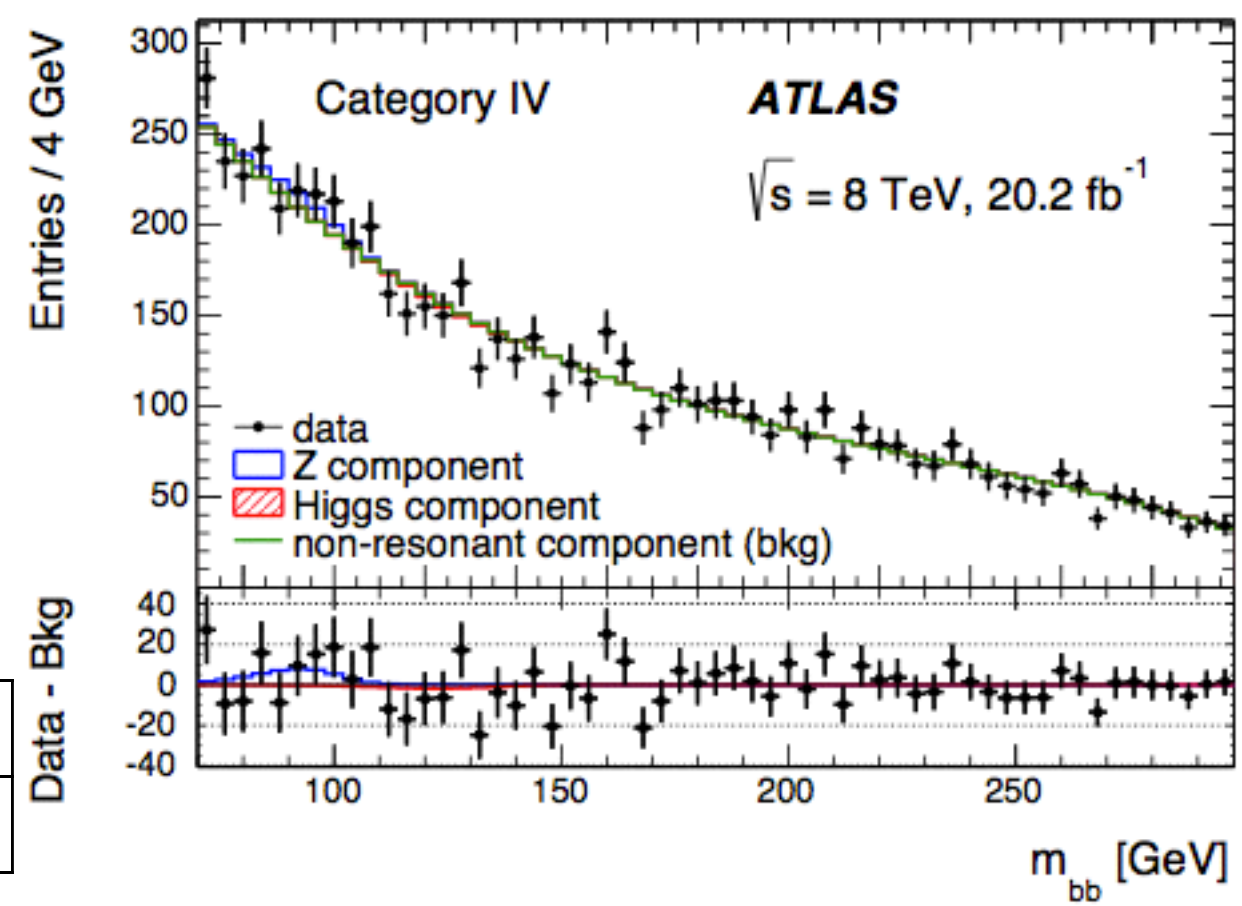
- **VBF-like topology:** 2 forward jets, central H production
- Large QCD multi-jet background and **irreducible VBF($Z\rightarrow bb$) production**
- **Triggers are a key element of this search:**
  - 4jets-2bjets trigger ($p_T > 35$GeV)
  - dedicated forward-jets trigger to enhance VBF

Analysis strategy:

A. **multivariate approach** (MVA) used to separate events in 4 categories of different S/B

B. in each MVA-category, signal and background predictions **fitted to data on the m_{bb}** invariant mass distribution

Signal Strength μ	$\mu = -0.8 \pm 1.3(\text{stat.})\ ^{+1.8}_{-1.9}(\text{syst.})$
95% CL limits on μ	observed = 4.4 expected=5.7



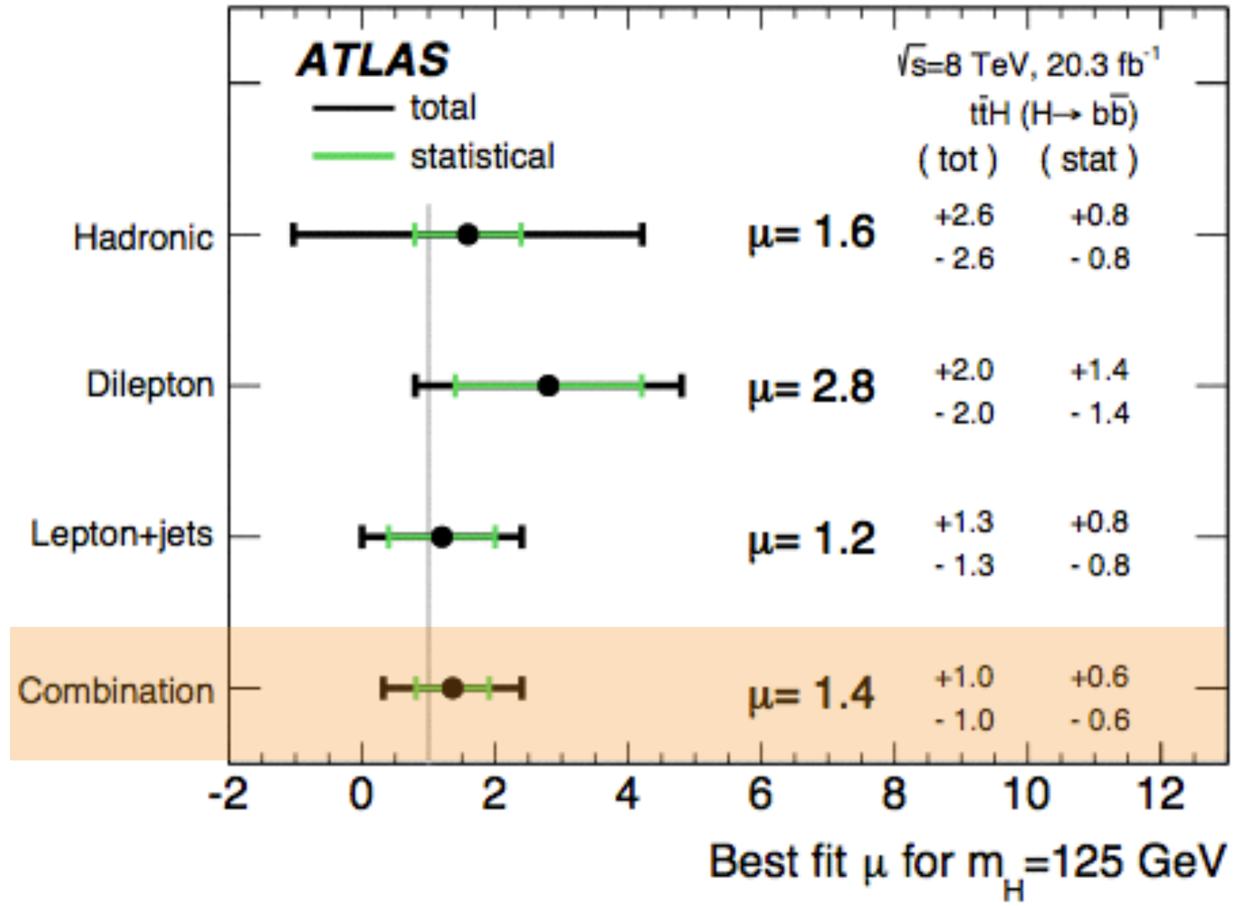
ttH(H→bb)

JHEP 05 (2016) 160 *Eur. Phys. J. C 75 (2015) 349*

Sensitive to direct coupling of H to top quarks, exploit the large BR(H→bb) in combination with all possible ttbar decay channels

- **events categorised in signal-enriched and depleted regions** based on #jets and #b-tagged jets
- **multivariate discriminant (MVA)** in signal-enriched regions

alljets	lepton(e,mu)+jets	dilepton(e,mu)
46%	30%	4%

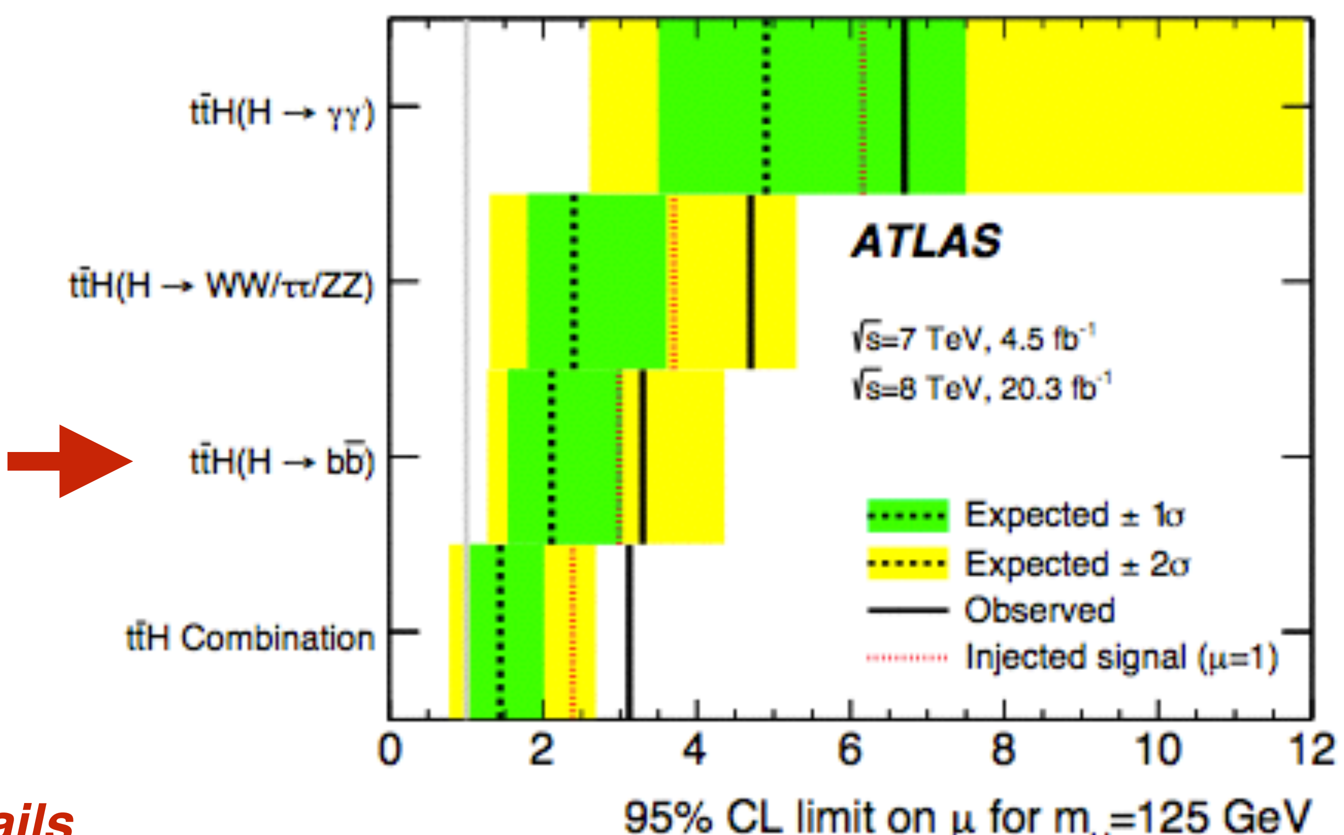


Leptonic channels:

- lower BR, but cleaner signature
- **tt+bb**: dominant and irreducible background, relying on MonteCarlo modelling

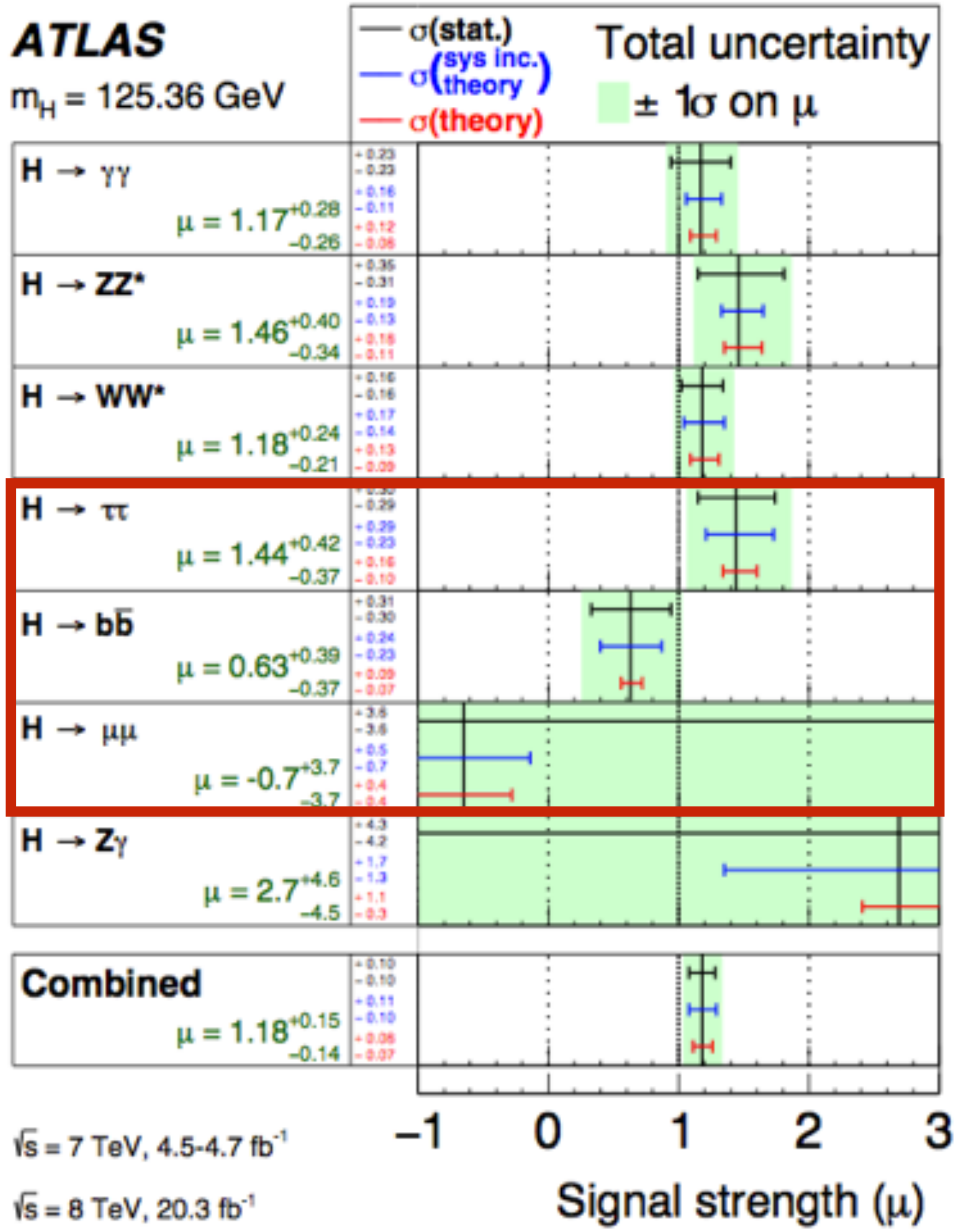
Fully hadronic channel:

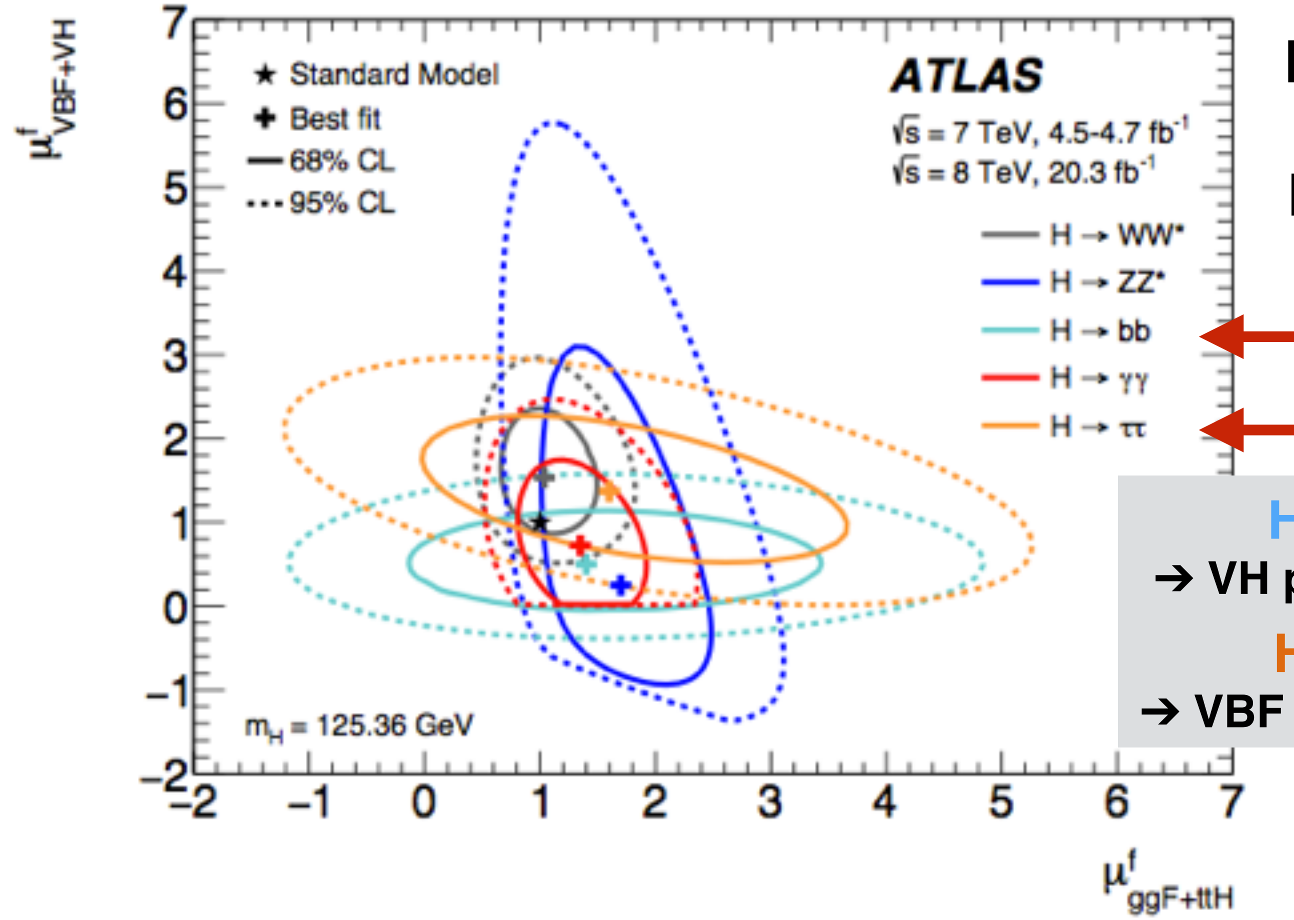
- largest BR, but 8+ jets final state dominated by QCD multi jets
- **data driven multi-jet estimate:** from data samples with same #jets multiplicity but lower #b-jets



following talk by Ricardo for more details

ATLAS Higgs Run1 combination: fermionic channels

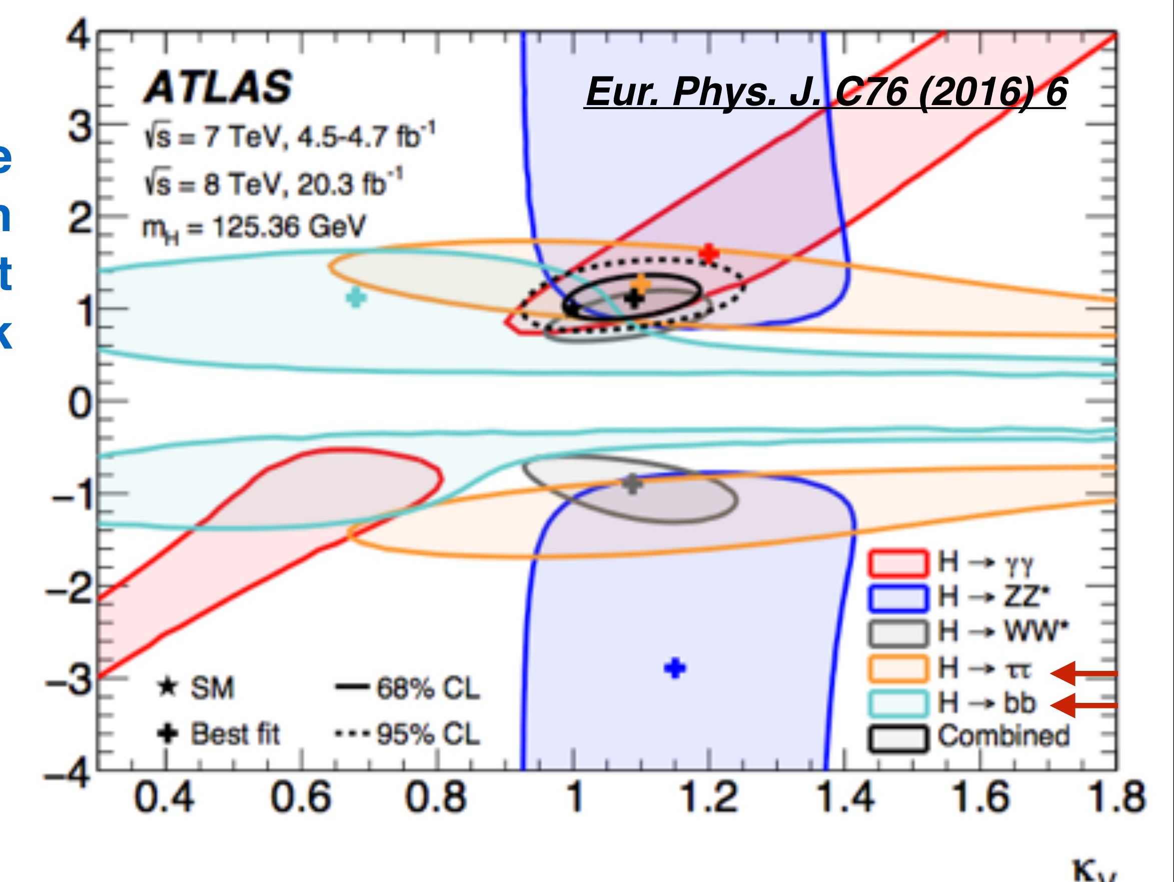




μ_{VH+VBF}
vs
$\mu_{ggF+ttH}$

H(bb)
→ VH production
H(ττ)
→ VBF production

Limits in the coupling-strength measurement framework



Fermionic decays (together with ttH) **offer a**
direct probe of k_F coupling
(accessible only from loop contributions in bosonic channels)

Direct exploration of the Higgs Yukawa mechanism

Conclusions & Outlook

Higgs(→fermions): crucial aspect of the Higgs measurement

- observation and evidence
- properties measurement
- hunt for BSM physics

H→ττ

Already observed with Run1 data

(combining different production modes)

Powerful channel for CP-invariance measurement

H→bb

Not observed in Run1, with the available Run2 data we should be very close

[Signature from production mode essential to reject background: VH, ttH]

In Run1 we only started to study the complex signatures of Higgs fermionic final states.

We are eagerly looking at these channels with the LHC Run2 data to exploit their full potential.

BACK-UP

ttH(H→bb) : Leptonic channels

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

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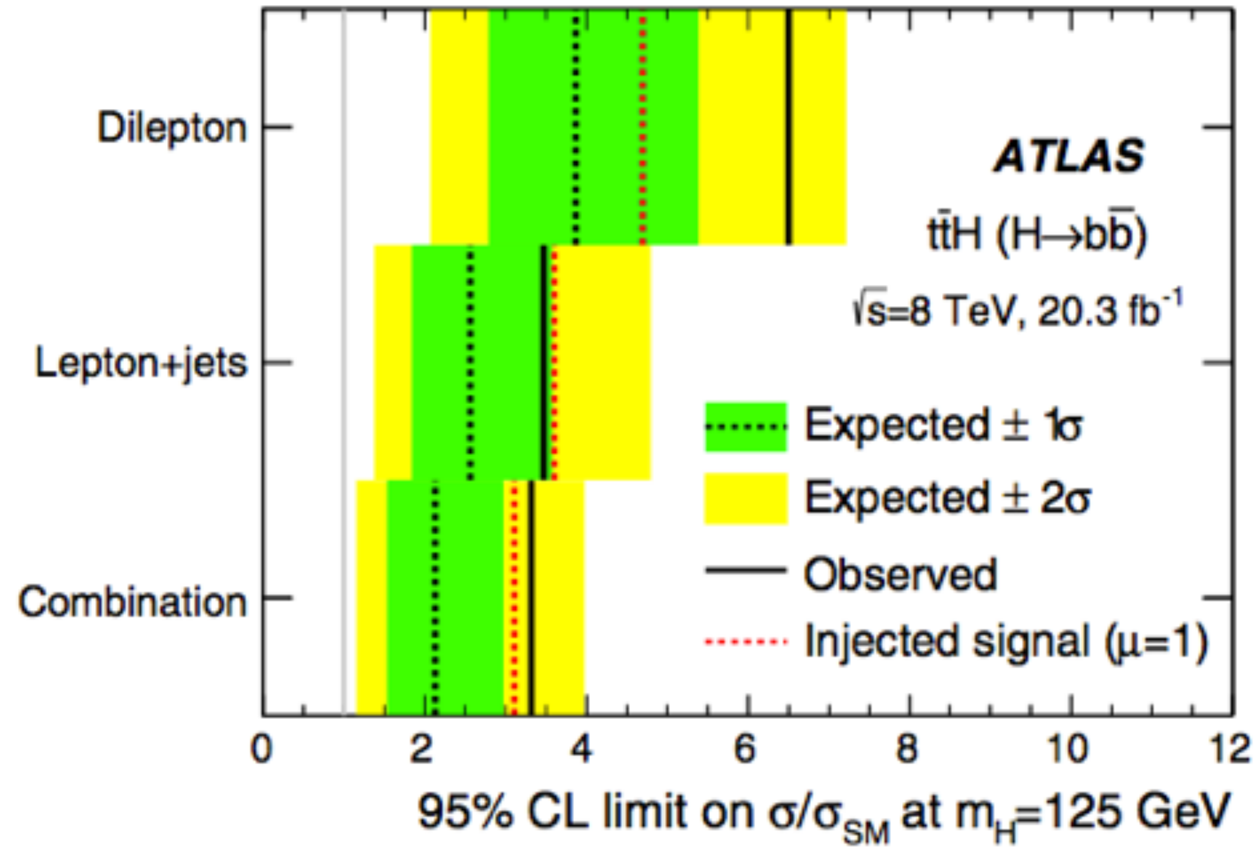

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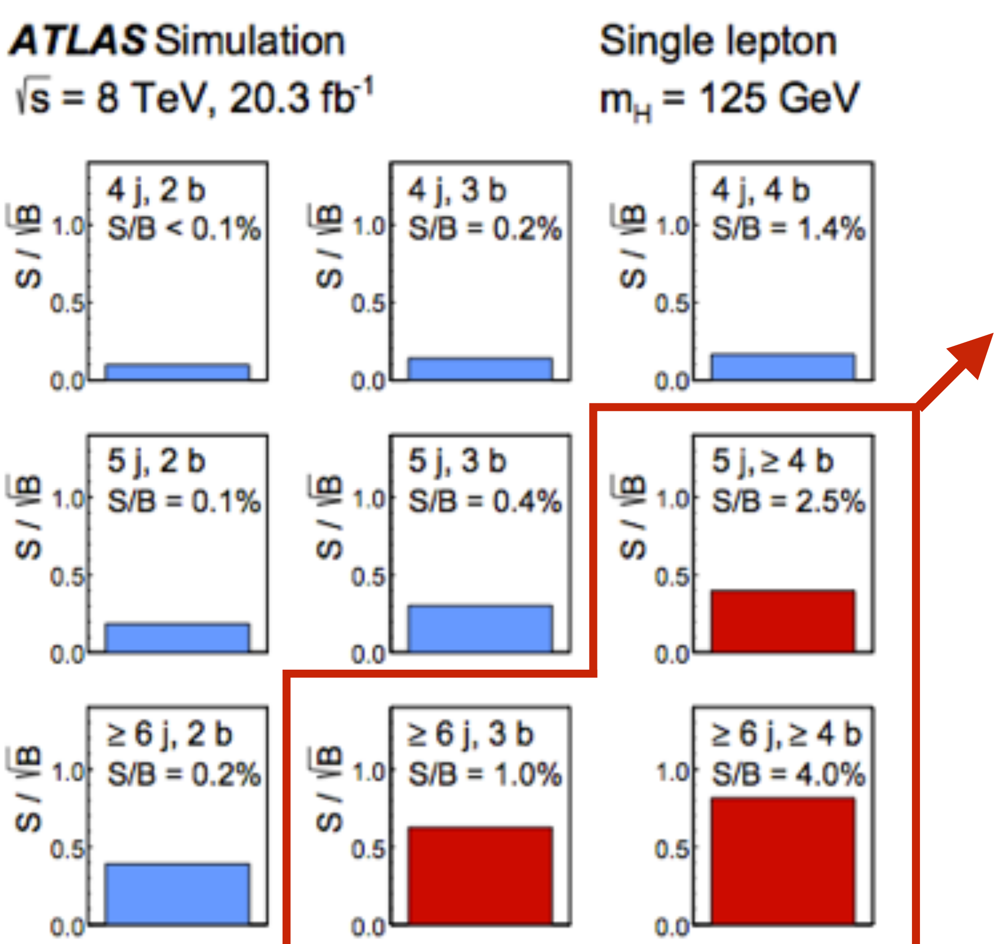
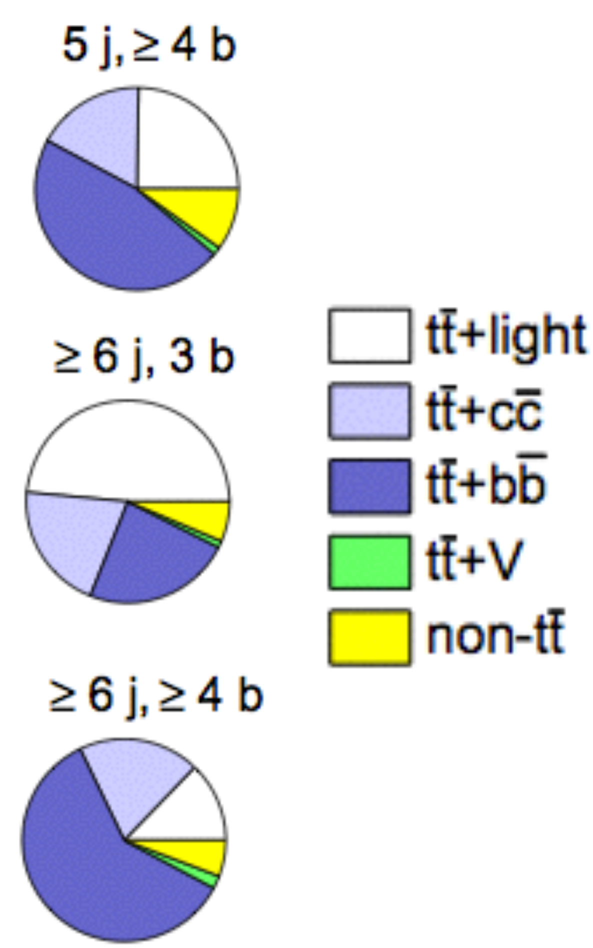
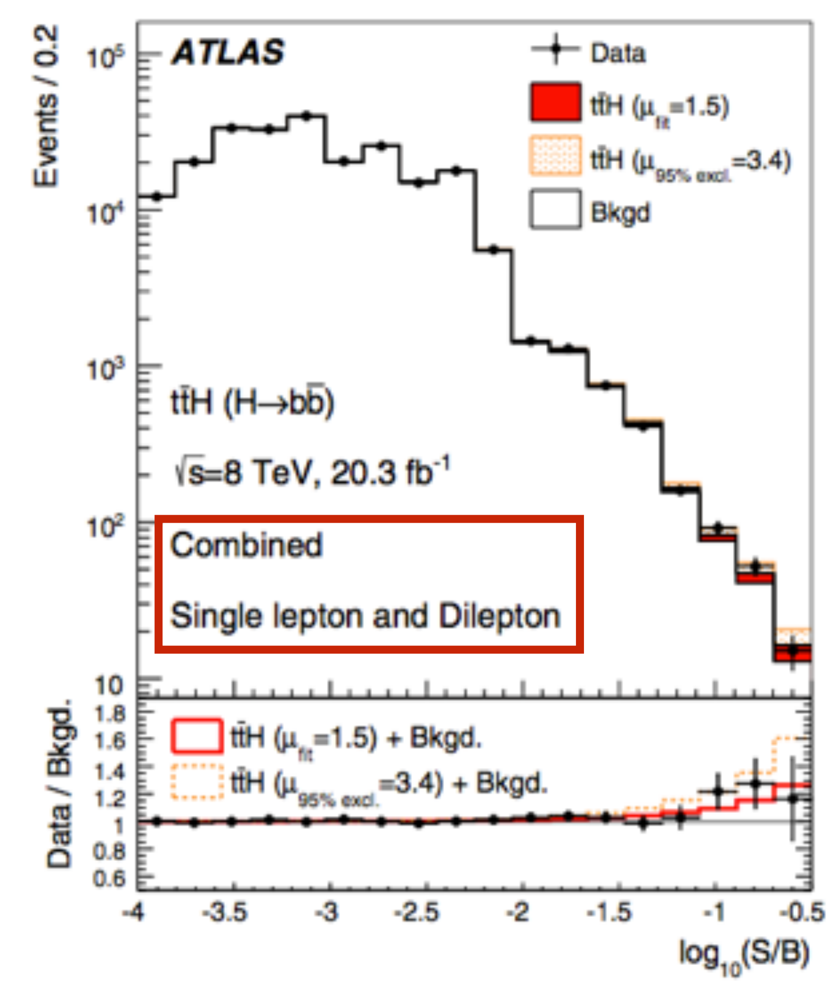
- **multivariate discriminant (MVA)** in signal-enriched regions
- **tt+bb**: dominant and irreducible background, relying on MonteCarlo modelling







ttH(H→bb) : Fully hadronic channel

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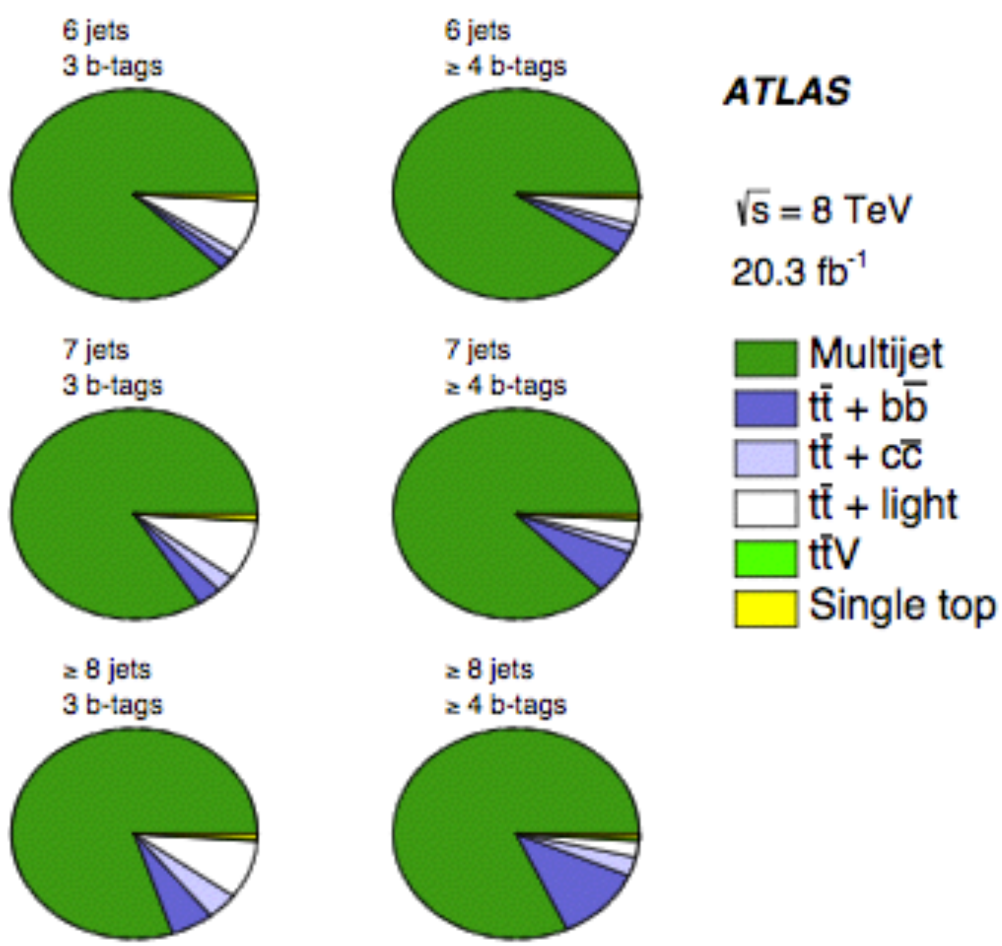
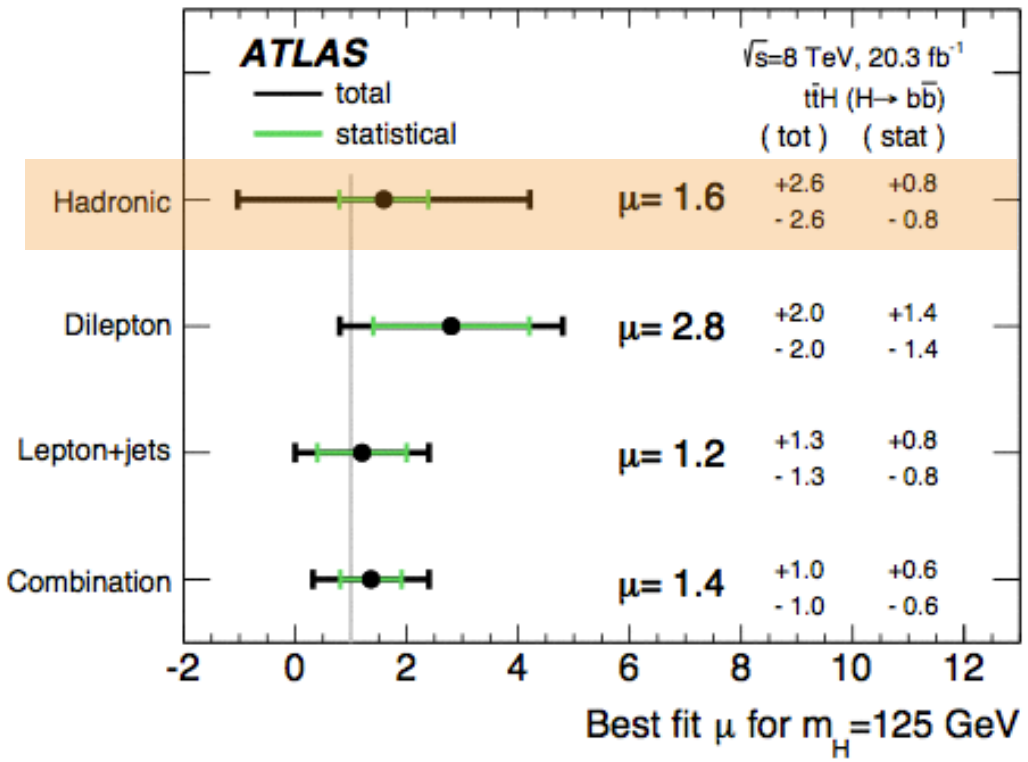
- **lower signal purity compared to ttbar leptonic channels, but largest branching ratio**

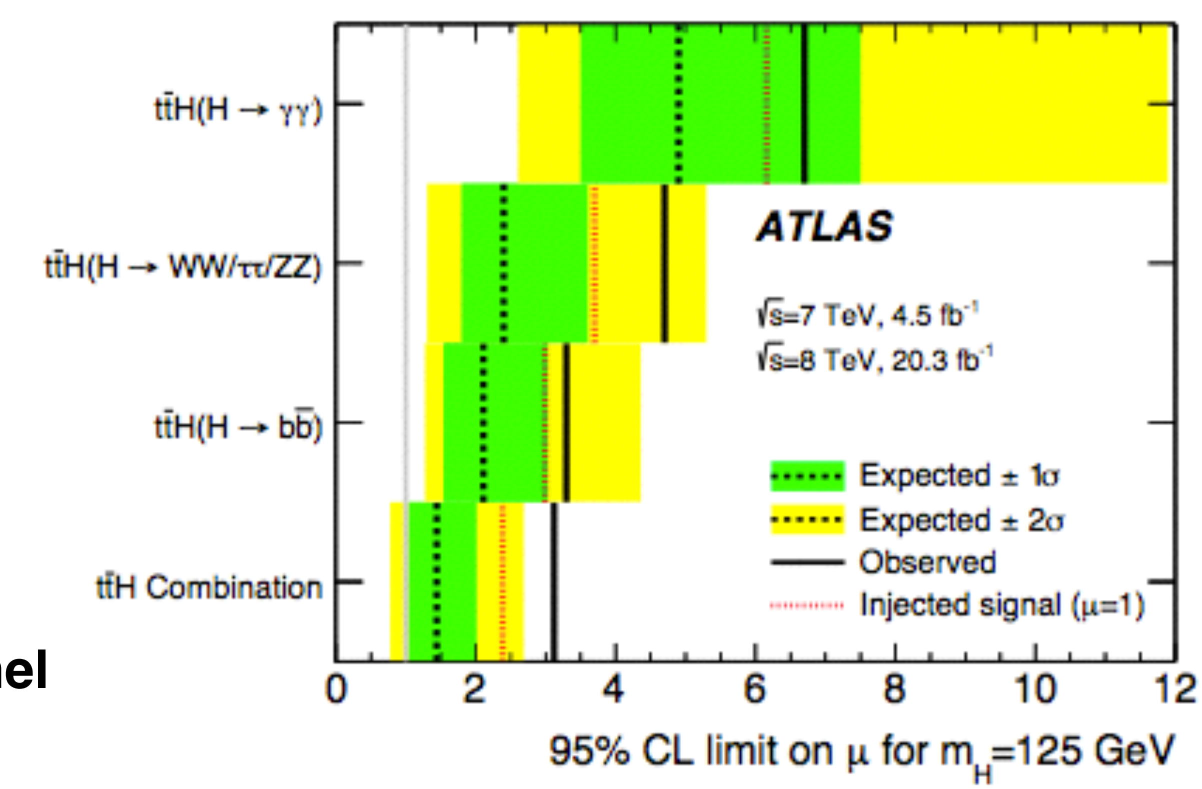
alljets	lepton(e,mu)+jets	dilepton(e,mu)
46%	30%	4%

Analysis strategy similar to the leptonic case:

- **8 jets final state: dominant multi-jets background**
- **data driven multi-jet estimate:** from data samples with same #jets multiplicity but lower #b-jets







ATLAS combination including all ttH(bb) channel
(single-lepton, dilepton, fully hadronic)

VH(H→bb) : The Analysis Strategy

3 lepton channels (νν, lν, ll) according to the V decay

$p_T^V < 120$ GeV	2 jets
$p_T^V > 120$ GeV	3 jets

2 regions of transverse momentum of the vector boson p_T^V

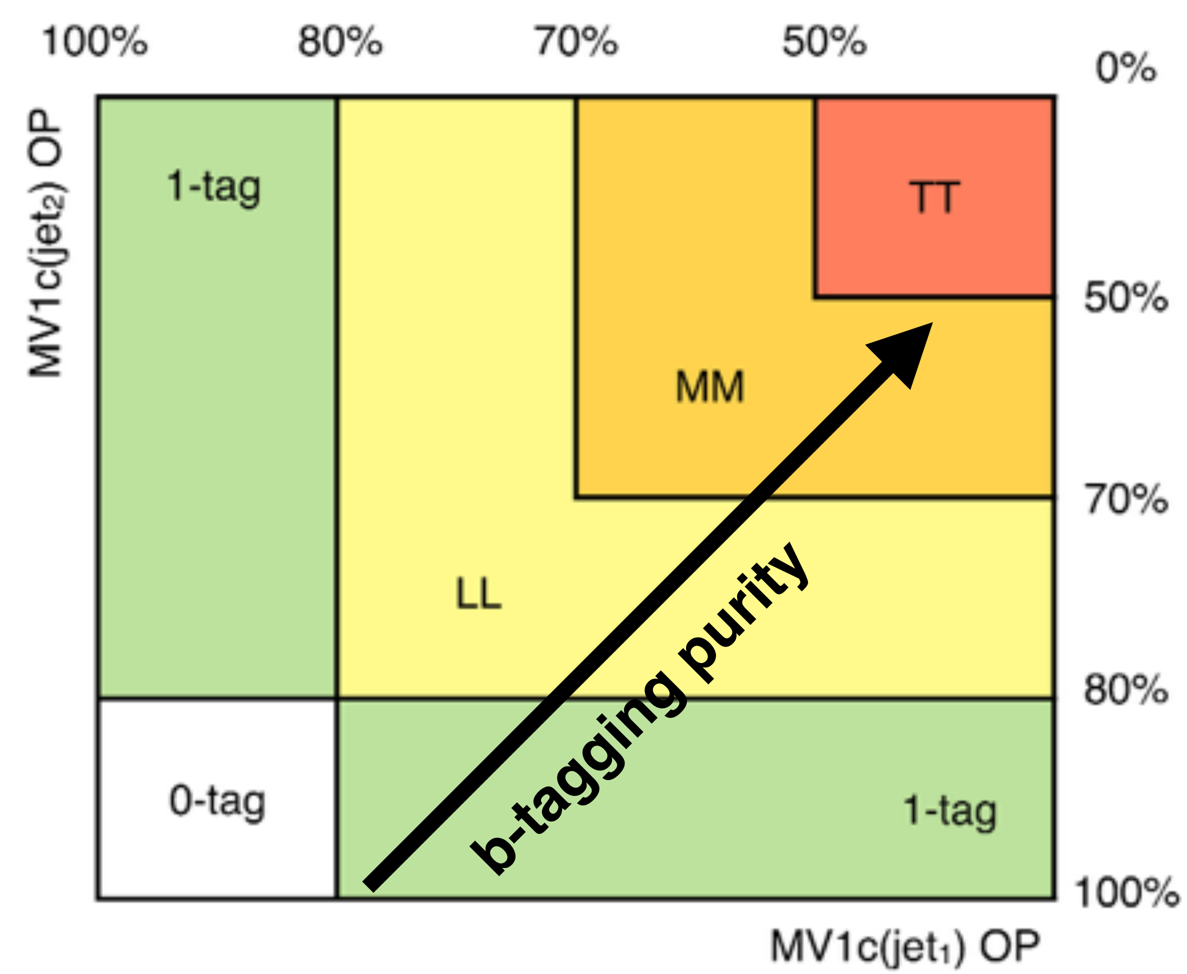
2 regions in jet multiplicity

	Variable
1tag (CR)	→ b-tagger output
2tag Loose (SR)	} → MVA BDT
2tag Medium (SR)	
2tag Tight (SR)	

4 regions in number of b-tagged jets, and purity of the b-jet identification

Total of 40-50 analysis regions

- additional selections specific to each lepton channel applied to reject backgrounds
- **BDT shape**, or **b-tagging discriminant**, used to fit the signal+background prediction to data
- **All regions** entering in a simultaneous **profile likelihood fit**

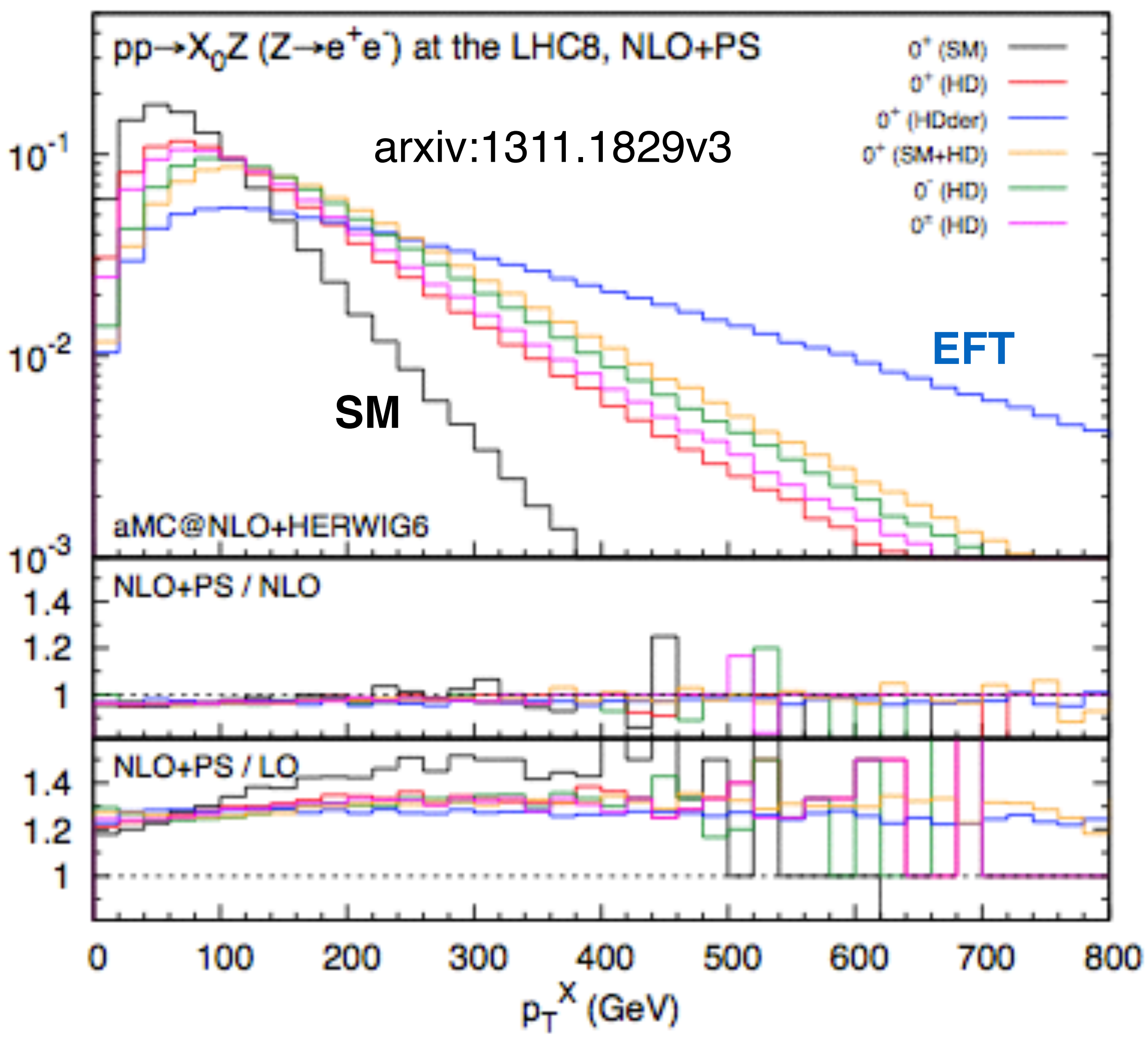


VH(H→bb) : Towards Run2 data [EFT]

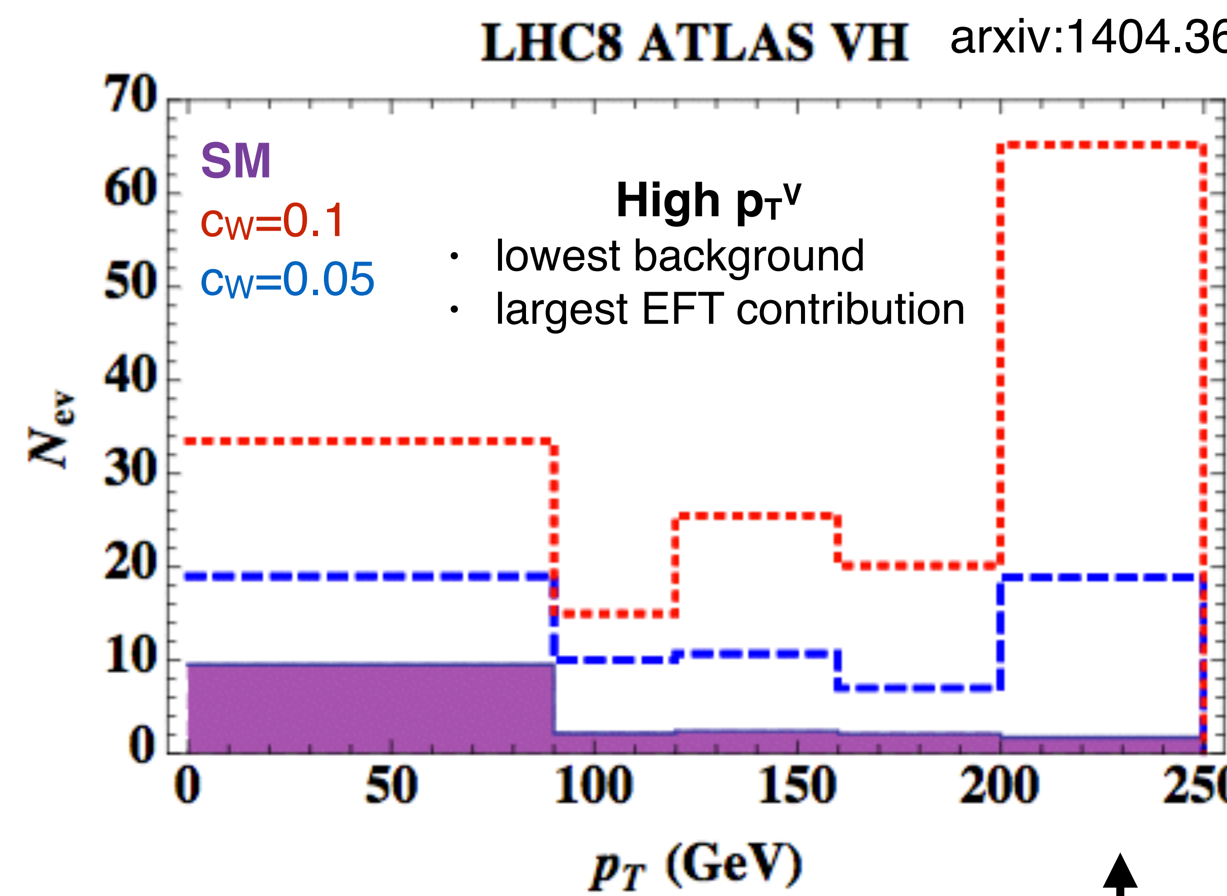
The VHbb channel is able to constrain some **combination of parameters** related to the dim-6 operators used to build the **EFT Lagrangian** (see arxiv:1404.3667 Ellis, Sanz, You)

EFT samples already under study in ATLAS:
mg5_aMC *Higgs Characterization Model*

MonteCarlo generation at NLO(QCD)+PS



arxiv:1404.3667



$$\mathcal{L} \supset \; - \; \frac{1}{4} g^{(1)}_{HZZ} Z_{\mu\nu} Z^{\mu\nu} h - g^{(2)}_{HZZ} Z_{\nu} \partial_{\mu} Z^{\mu\nu} h \\ - \; \frac{1}{2} g^{(1)}_{HWW} W^{\mu\nu} W^{\dagger}_{\mu\nu} h - \left[g^{(2)}_{HWW} W^{\nu} \partial^{\mu} W^{\dagger}_{\mu\nu} h + \text{h.c.} \right]$$

EFT Lagrangian with VH anomalous couplings (mass basis, unitary gauge)

VH(H→bb) : Towards Run2 data [EFT]

CP-even dim-6 Lagrangian

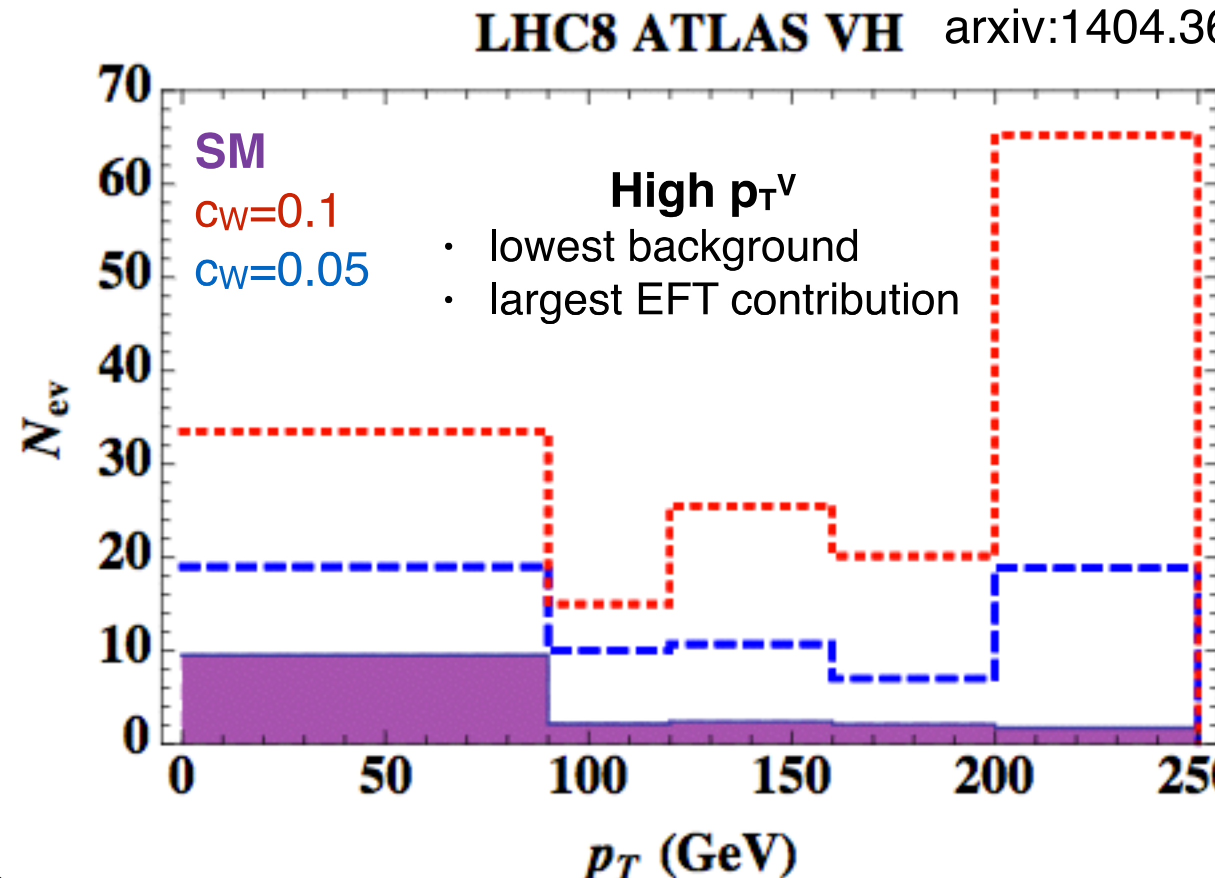
$$\begin{aligned}\mathcal{L} \supset\ & \frac{\bar{c}_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{g'^2\,\bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\,\bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G^{\mu\nu}_a \\ &+ \frac{2ig\,\bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger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

Independent set of parameters for Higgs physics

$$\bar{c}_i \equiv \left\{\bar{c}_H, \bar{c}_{t,b,\tau}, \bar{c}_W, \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g\right\}$$

Effettive Lagrangian in terms of anomalous Higgs couplings (in mass basis, unitary gauge)

$$\begin{aligned}\mathcal{L} \supset\ & -\ \frac{1}{4}g^{(1)}_{HZZ}Z_{\mu\nu}Z^{\mu\nu}h - g^{(2)}_{HZZ}Z_\nu\partial_\mu Z^{\mu\nu}h \\ & -\ \frac{1}{2}g^{(1)}_{HWW}W^{\mu\nu}W^\dagger_{\mu\nu}h - \left[g^{(2)}_{HWW}W^\nu\partial^\mu W^\dagger_{\mu\nu}h + \text{h.c.}\right]\end{aligned}$$



arxiv:1404.3667

$$\begin{aligned} g^{(1)}_{hzz} &= \frac{2g}{c_W^2 m_W}\left[\bar{c}_{HB}s_W^2 - 4\bar{c}_\gamma s_W^4 + c_W^2\bar{c}_{HW}\right] \\ g^{(2)}_{hzz} &= \frac{2g}{c_W^2 m_W}\left[(\bar{c}_{HW}+\bar{c}_W)c_W^2 + (\bar{c}_{HB}+\bar{c}_B)s_W^2\right] \\ g^{(1)}_{hww} &= \frac{2g}{m_W}\bar{c}_{HW} \\ g^{(2)}_{hww} &= \frac{g}{m_W}(\bar{c}_W + \bar{c}_{HW})\,. \end{aligned}$$

Constraint on **c_W** from ATLAS & CMS signal strength global fit, including (ggF,VBF) (Hττ,Hww,Hzz,Hγγ,Hγz):

$$\bar{c}_W \in [-0.05, 0.06]$$

Including VHbb differential fit (VpT from ATLAS, mVH from D0):

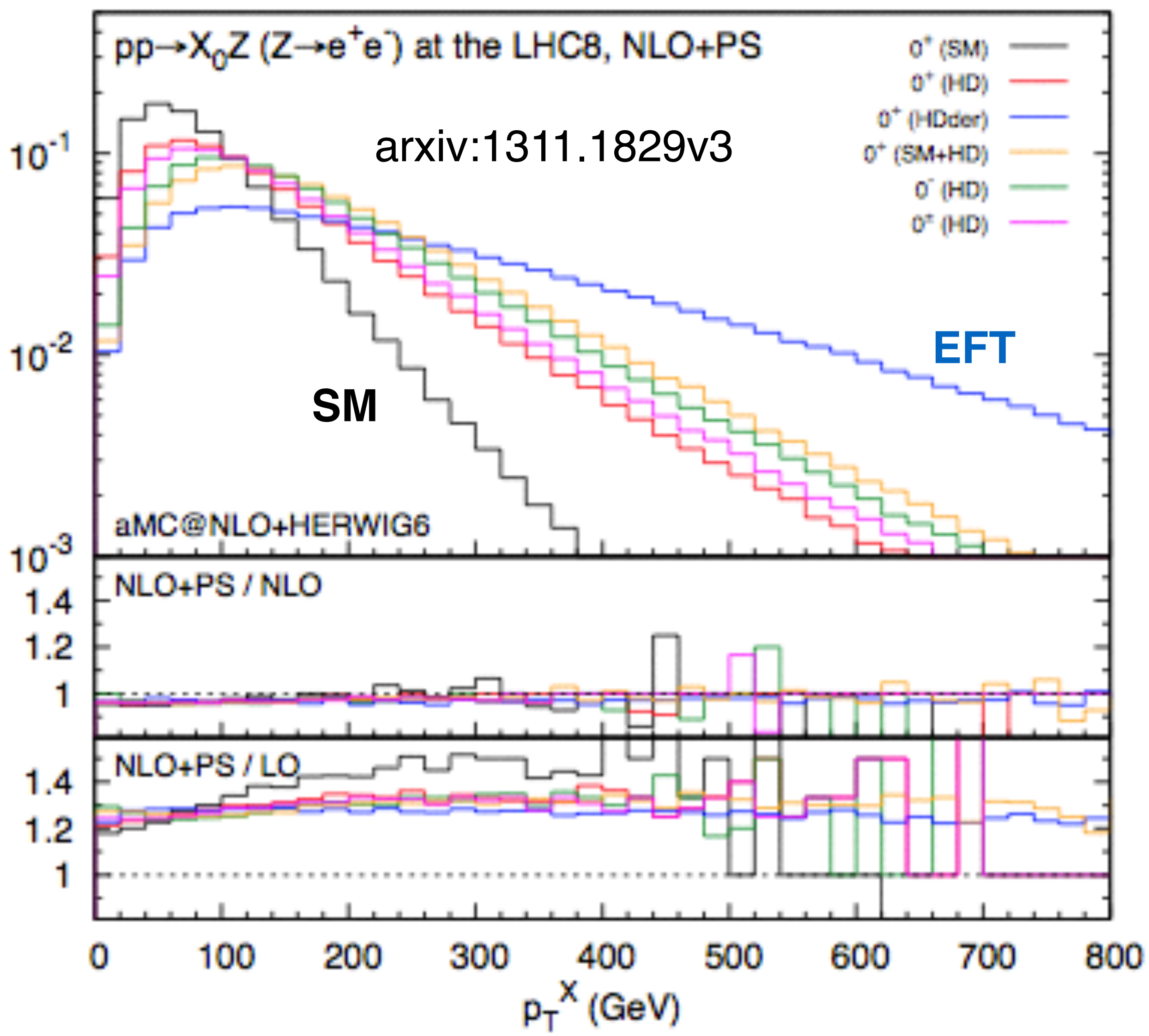
$$\bar{c}_W \in [-0.03, 0.01]$$

Considerable improvement for single operator fit
Even more important when fitting multiple operators

VH(H→bb) : Towards Run2 data [EFT]

EFT samples already under study in ATLAS:
mg5_aMC *Higgs Characterization Model*

MonteCarlo generation at NLO(QCD)+PS



Benchmark scenarios →

arxiv:1311.1829v3

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\big]$$ **SM**

CP-even **CP-odd**

$$-\frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu}\big]$$

$$-\frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}\big]$$

derivative operators

$$-\frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \big(\kappa_{H\partial W} W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\big)\big]$$

parameter	description
Λ [GeV]	cutoff scale
c_α ($\equiv \cos\alpha$)	mixing between 0^+ and 0^-
κ_i	dimensionless coupling parameter

scenario	HC parameter choice
0^+(SM)	$\kappa_{\rm SM} = 1$ $(c_\alpha = 1)$
0^+(HD)	$\kappa_{HZZ,HWW} = 1$ $(c_\alpha = 1)$
0^+(HDder)	$\kappa_{H\partial Z,H\partial W} = 1$ $(c_\alpha = 1)$
0^+(SM+HD)	$\kappa_{SM,HZZ,HWW} = 1$ $(c_\alpha = 1,\ \Lambda = v)$
0^-(HD)	$\kappa_{AZZ,AWW} = 1$ $(c_\alpha = 0)$
$0^\pm$(HD)	$\kappa_{HZZ,AZZ,HWW,AWW} = 1$ $(c_\alpha = 1/\sqrt{2})$

$H \to bb$ @ LHC

The global picture looking at ATLAS & CMS (Run1)

ATLAS Hbb combination (VH+ttH)
significance = 1.7 σ_{obs} (2.7 σ_{exp}),
signal strength $\mu = 0.63 \pm 0.4$

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CMS Hbb combination (VH+ttH+VBF)
significance = 2.6 σ_{obs} (2.7 σ_{exp}),
signal strength $\mu = 1.0 \pm 0.4$

CMS VHbb standalone
significance = 2.08 σ_{obs} (2.52 σ_{exp}),
signal strength $\mu = 0.89 \pm 0.43$

$H \to b\bar{b}$ Channel	Best fit (68% CL) Observed	Upper limits (95% CL) Observed	Upper limits (95% CL) Expected	Signal significance Observed	Signal significance 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

ttH(bb) from Run1

VBF(H→ττ) : CP-invariance

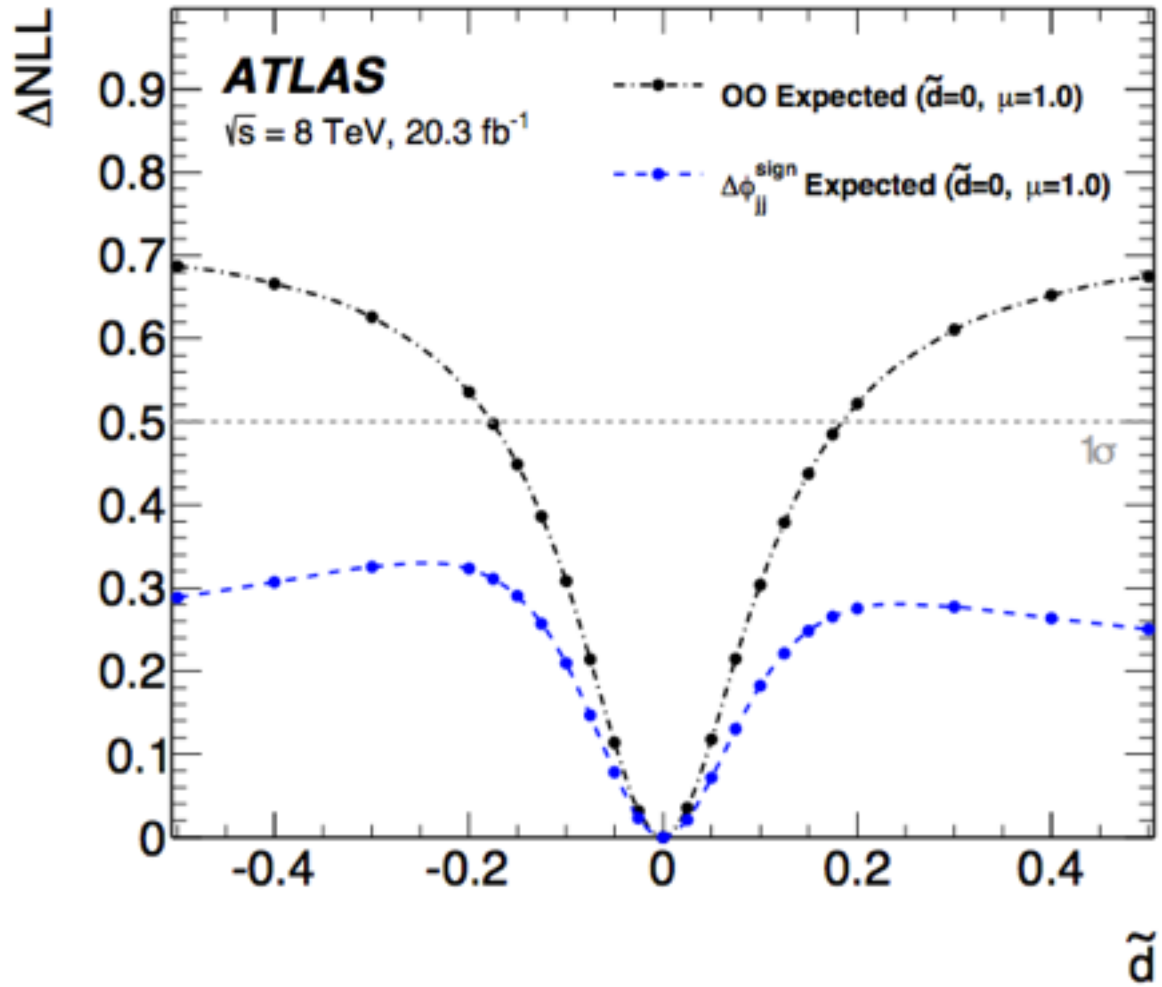
HIGG-2015-06 Submitted to EPJC

- **CP-odd observable:**
  sensitive to interference between
  SM and CP-odd contributions

$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \tilde{d} \cdot \mathcal{M}_{\mathrm{CP\text{-}odd}}.$$

$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \tilde{d} \cdot 2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\mathrm{CP\text{-}odd}}|^2 .$$

CP-odd interference term



- **Optimal observable:** combine multi-dimensional information in a single variable from the VBF production LO matrix-element [independent from H decay mode]

$$OO = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

- same limit-setting with $\Delta\Phi^{\mathrm{sign}}(jj)$ shows worse results
  [azimuthal angle between VBF-tagging jets]

$$\epsilon_{\mu\nu\rho\sigma} b_+^\mu p_+^\nu b_-^\rho p_-^\sigma = 2 p_{\mathrm{T}+} p_{\mathrm{T}-} \sin(\phi_+ - \phi_-) = 2 p_{\mathrm{T}+} p_{\mathrm{T}-} \sin \Delta\phi_{jj} .$$

H→ττ : Main Run1 Results

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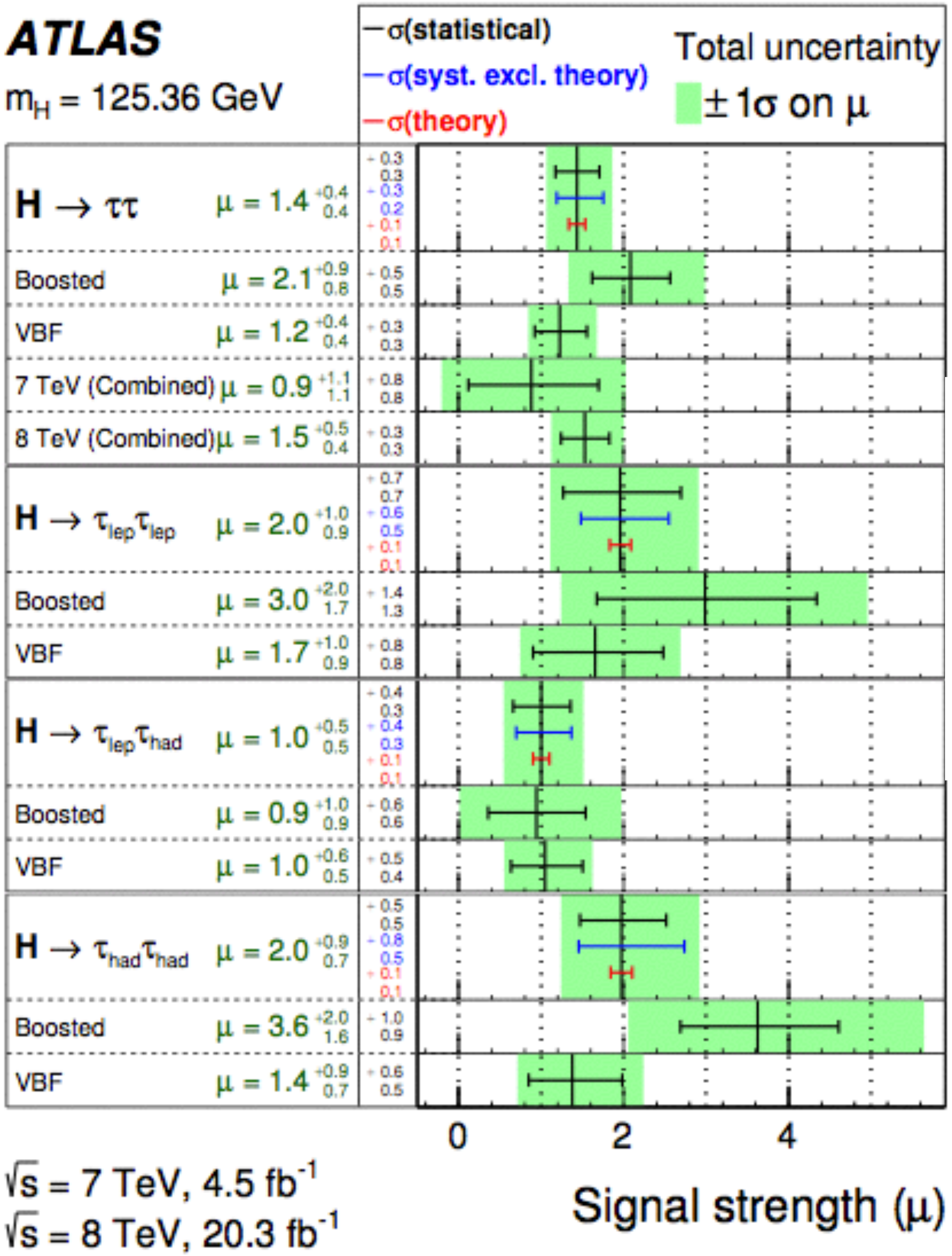

	Measured $\sigma \times$BR [pb]	Predicted $\sigma \times$BR [pb]
7 TeV	$1.0\ ^{+0.9}_{-0.8}$(stat.)$^{+0.9}_{-0.8}$(syst.)	1.09 ± 0.11
8 TeV	2.1 ± 0.4(stat.)$^{+0.5}_{-0.4}$(syst.)	1.39 ± 0.14
Gluon fusion, 8 TeV	1.7 ± 1.1(stat.)$^{+1.5}_{-1.1}$(syst.)	1.22 ± 0.14
VBF+VH, 8 TeV	0.26 ± 0.09(stat.)$^{+0.06}_{-0.05}$(syst.)	0.17 ± 0.01