Measurement of Higgs couplings to fermions in the ATLAS experiment

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for the ATLAS Collaboration

Contents:

- $H \to \tau^+\tau^-$ (1501.04943, subm. to JHEP)
- $H \to \mu^+\mu^-$ (1406.7663, PL B738 (2014) 68)
- $H \to b\bar{b}$ (1409.6212, JHEP01 (2015) 69)
- $t\bar{t}(H \to \gamma\gamma)$ (1409.3122, PL B740 (2014) 222)

Not discussing $t\bar{t}H \to b\bar{b}$: discussed in detail by J. Montejo
Interpretation in terms of coupling constants: A. Armbruster

ATLAS EXPERIMENT http://atlas.ch

Nikhef

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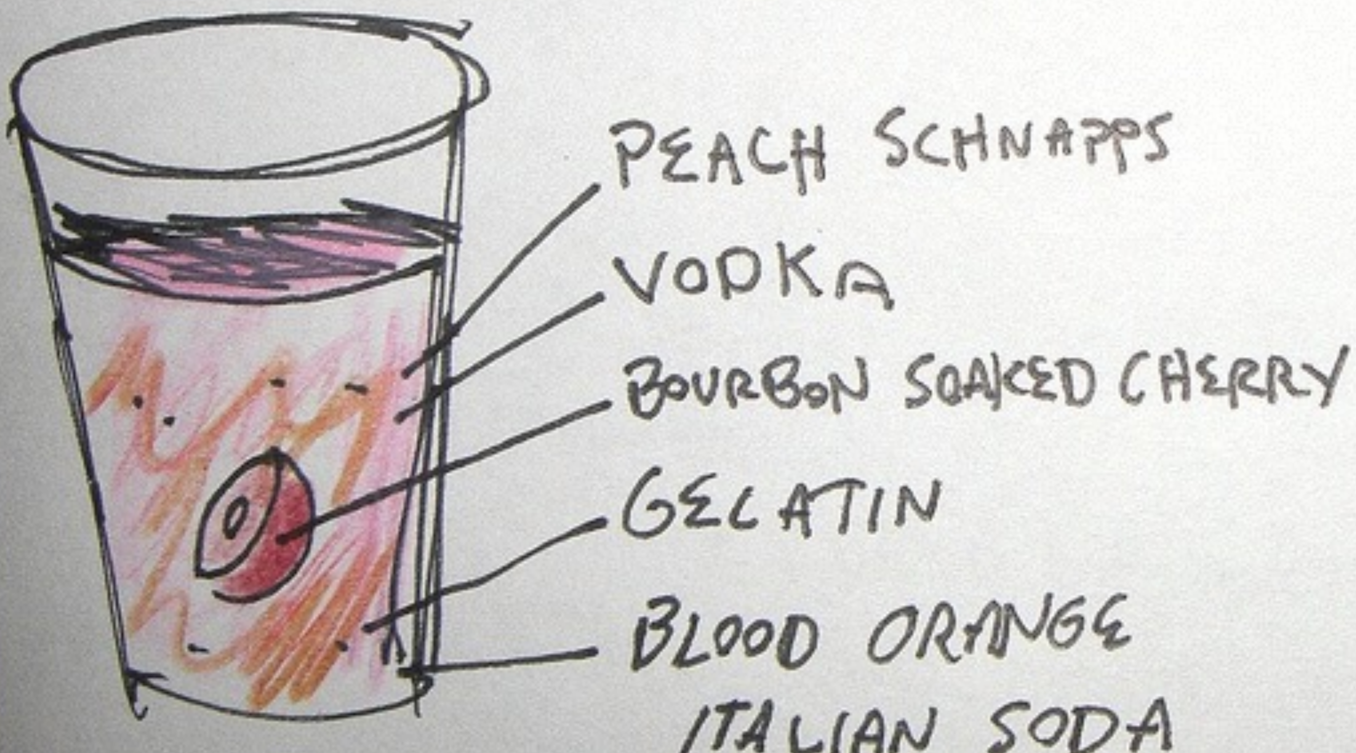
Radboud Universiteit Nijmegen

HIGGS BOSON "PARTY"-SICLE



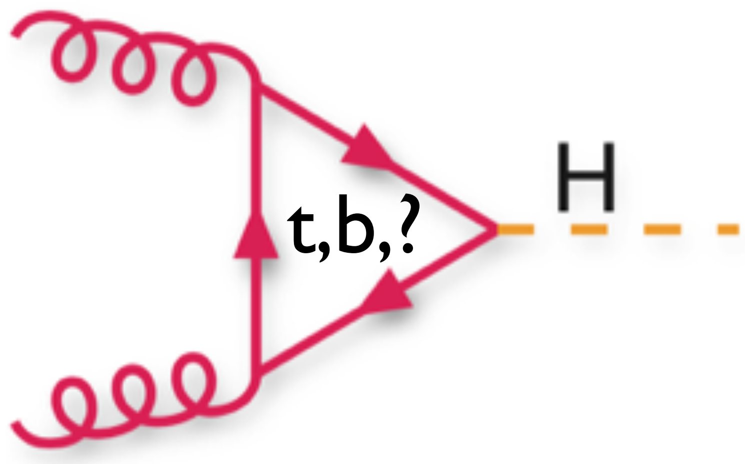
HIGGS BOSON aka "The GOD PARTICLE" is a hypothetical massive scalar elementary particle predicted to exist by Standard Model of particle physics,

~~Only particle that has yet to be observed...~~

Motivation

BEH discovery essentially involved bosons only (even if in part through couplings to fermions) ➠ opportune to focus on fermions now!

- extra particles in loop?
- non-SM couplings?



Type-2 2HDM:

SM particle type	h coupling	H coupling	A coupling
up-type quarks	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$
down-type quarks, $\ell^{\pm}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\tan\beta$
W, Z bosons	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0

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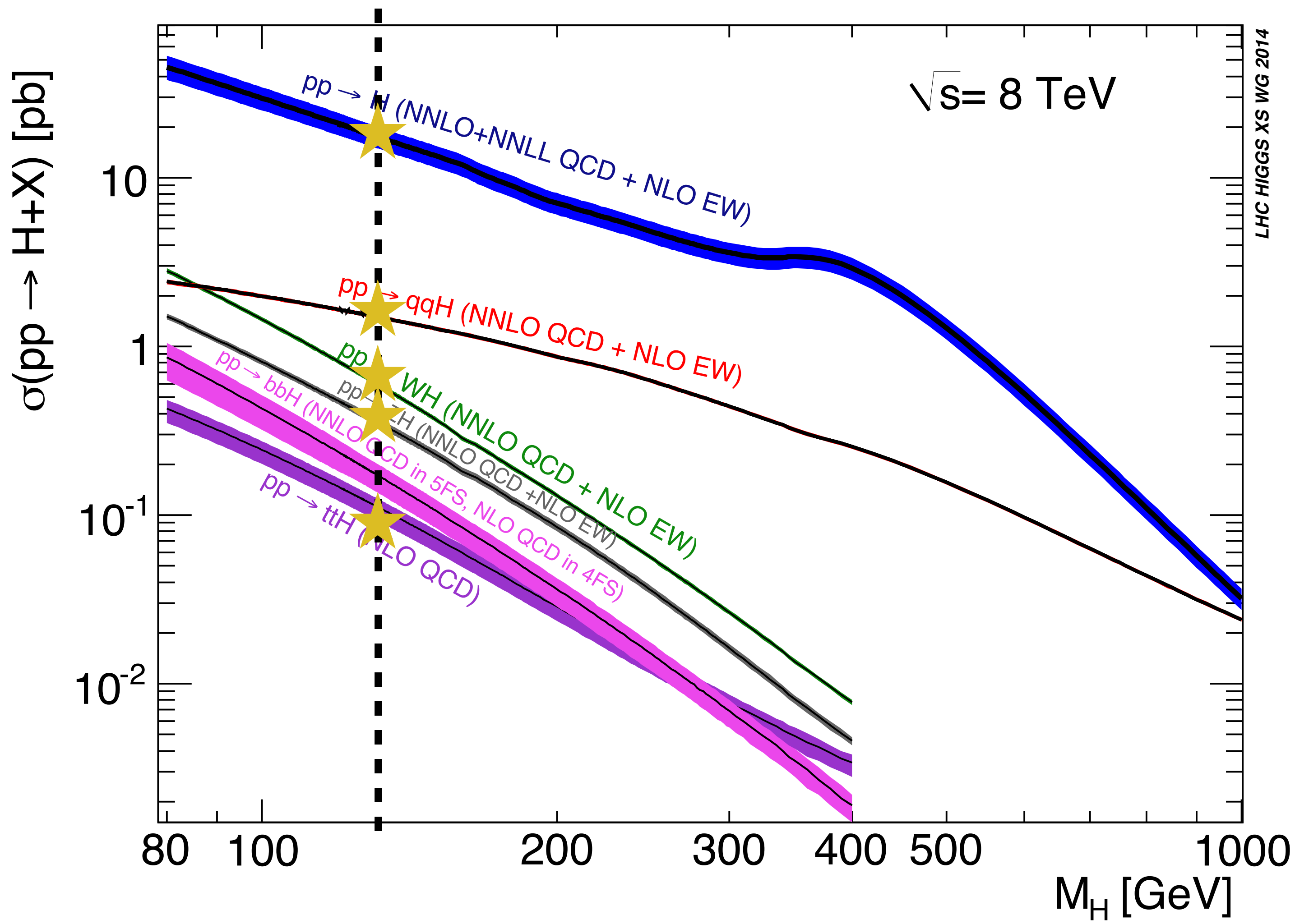
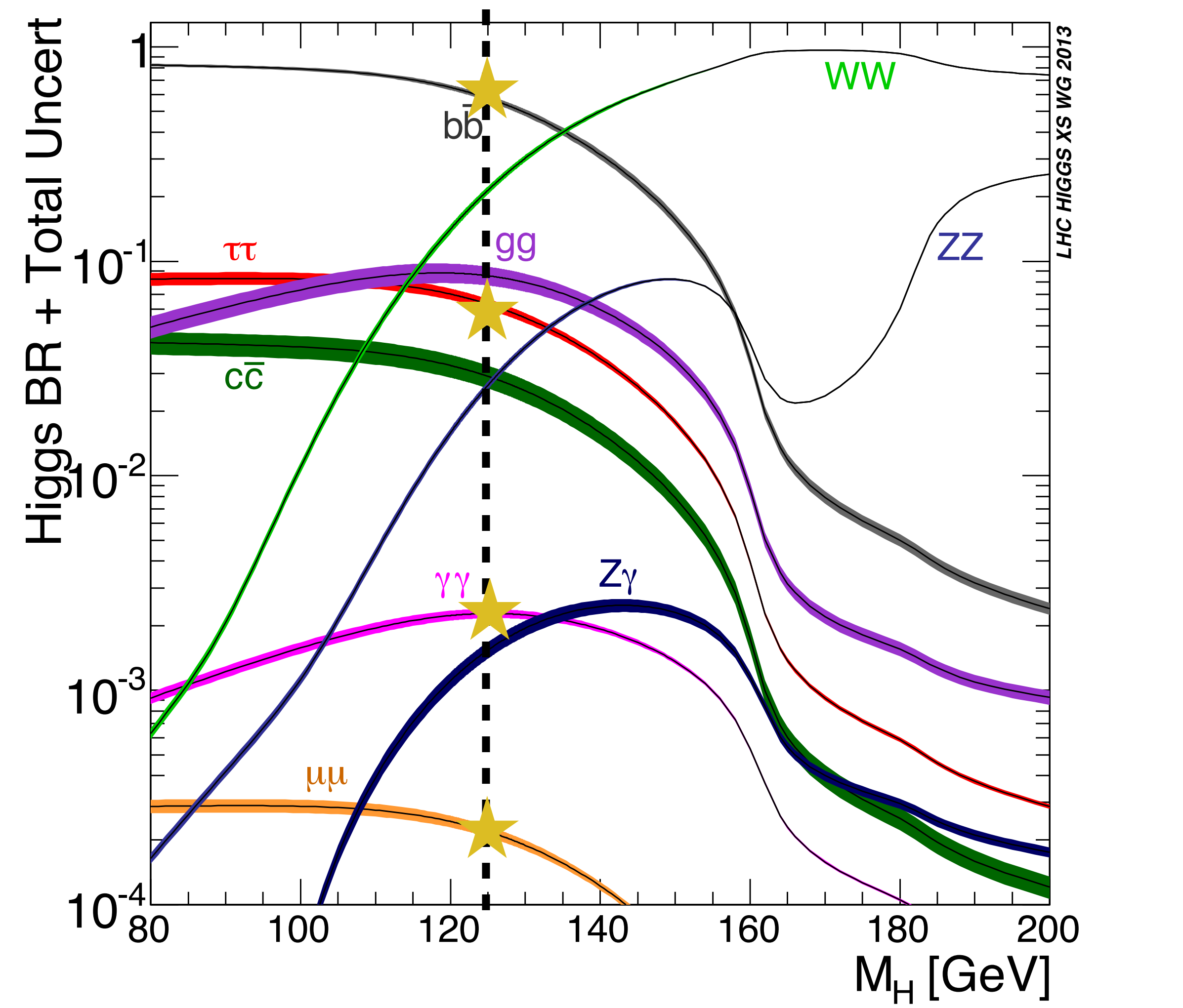
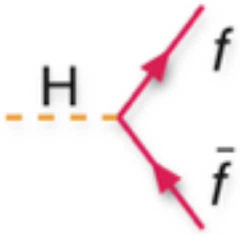




Challenging analyses

- most sensitive ($H \rightarrow \tau^+\tau^-$, $b\bar{b}$) use all the available sophistication (MVA)
- analyses use full Run-1 dataset; will show essentially no 2011 results

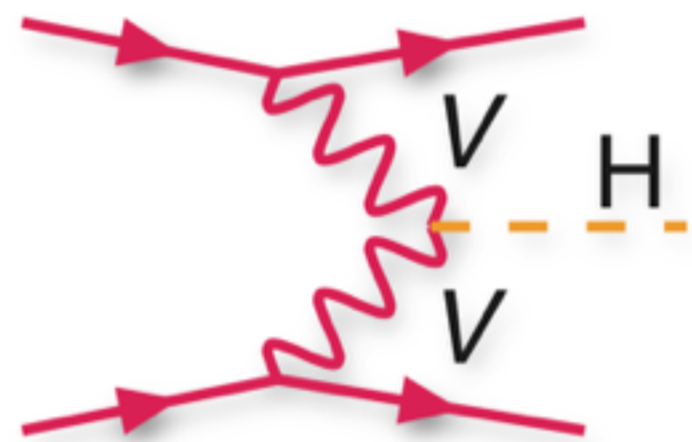


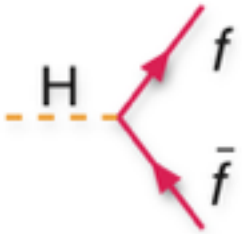
$H \rightarrow \tau^+\tau^-$

High production cross section & decent branching fraction… but many τ decay modes involving ν present significant complications

Strategy: after preselection, optimise separately in

- $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$ decay modes
- VBF, boosted ggF ($p_T(H)$ > 100 GeV) production modes





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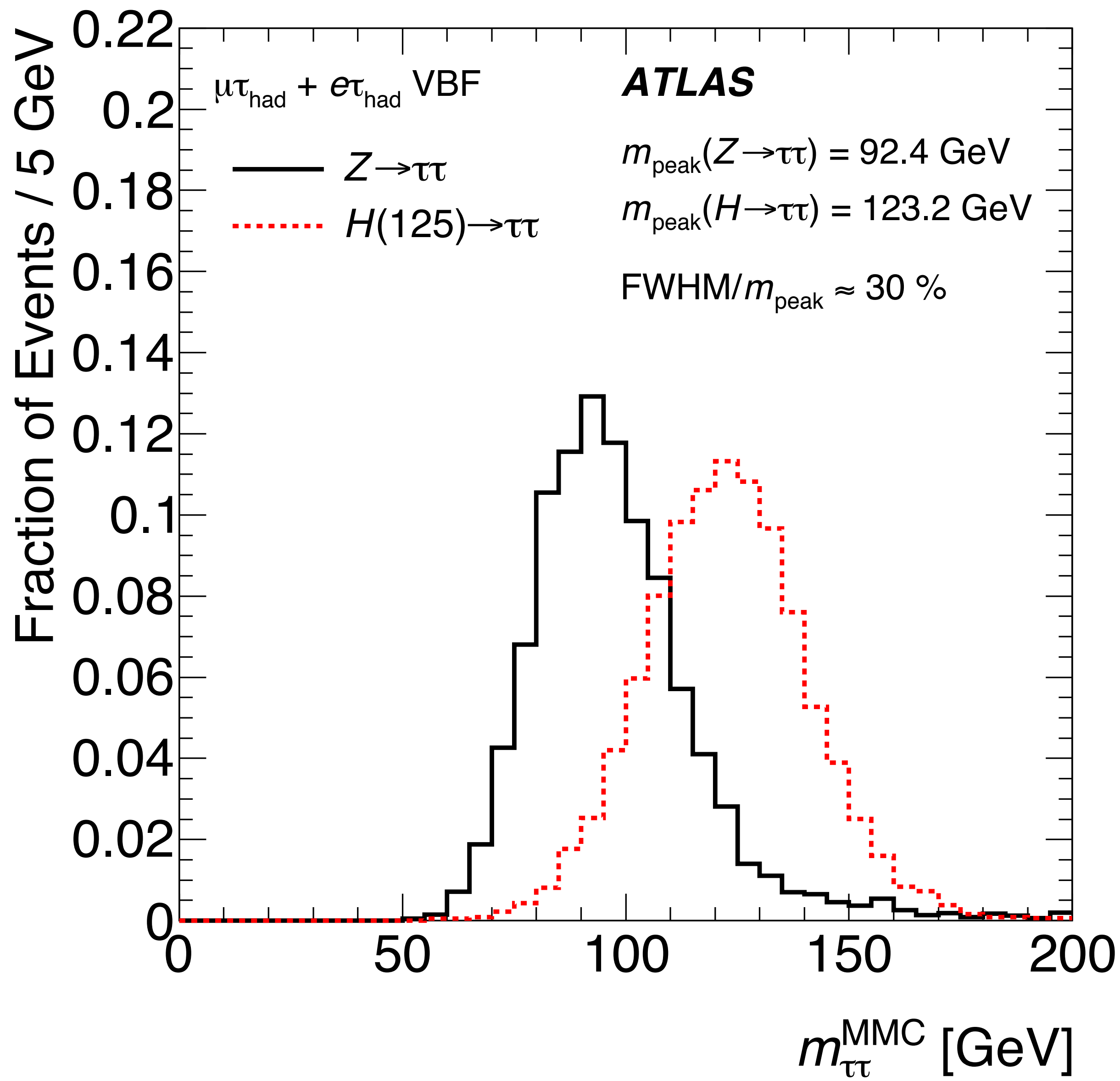
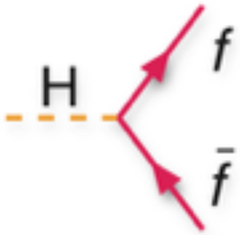
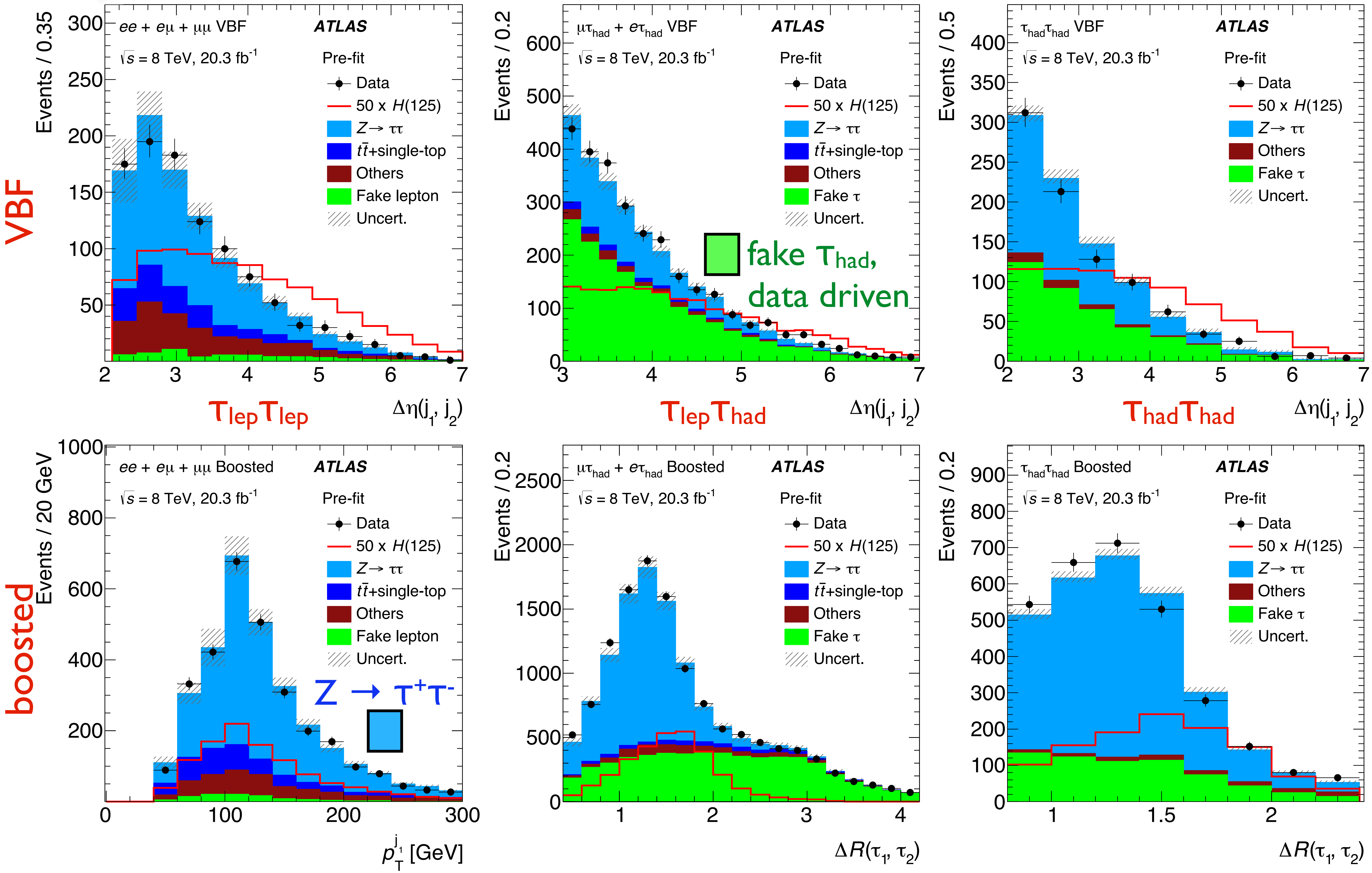
Tools:

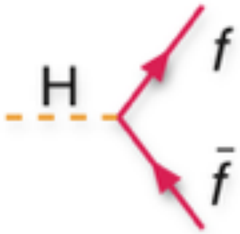
- Missing Mass Calculator: under-constrained system improving $m_{\tau\tau}$ measurement
- "embedding": in data $Z/\gamma^* \rightarrow \mu^+\mu^-$ events ($m_{\mu\mu}$ >40 GeV), replace μ with simulated τ
- BDT analyses in all 6 categories
  - exploiting VBF/boosted event kinematics





$H \rightarrow \tau^+\tau^-$ (2)





$H \rightarrow \tau^+\tau^-$ (3)

Results extracted using profile likelihood ratio fits

$$\lambda(\mu) = L\left(\mu, \hat{\hat{\vec{\theta}}}(\mu)\right) / L\left(\hat{\mu}, \hat{\vec{\theta}}\right)$$

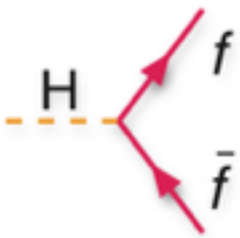
global maximum of L

assumed signal strength

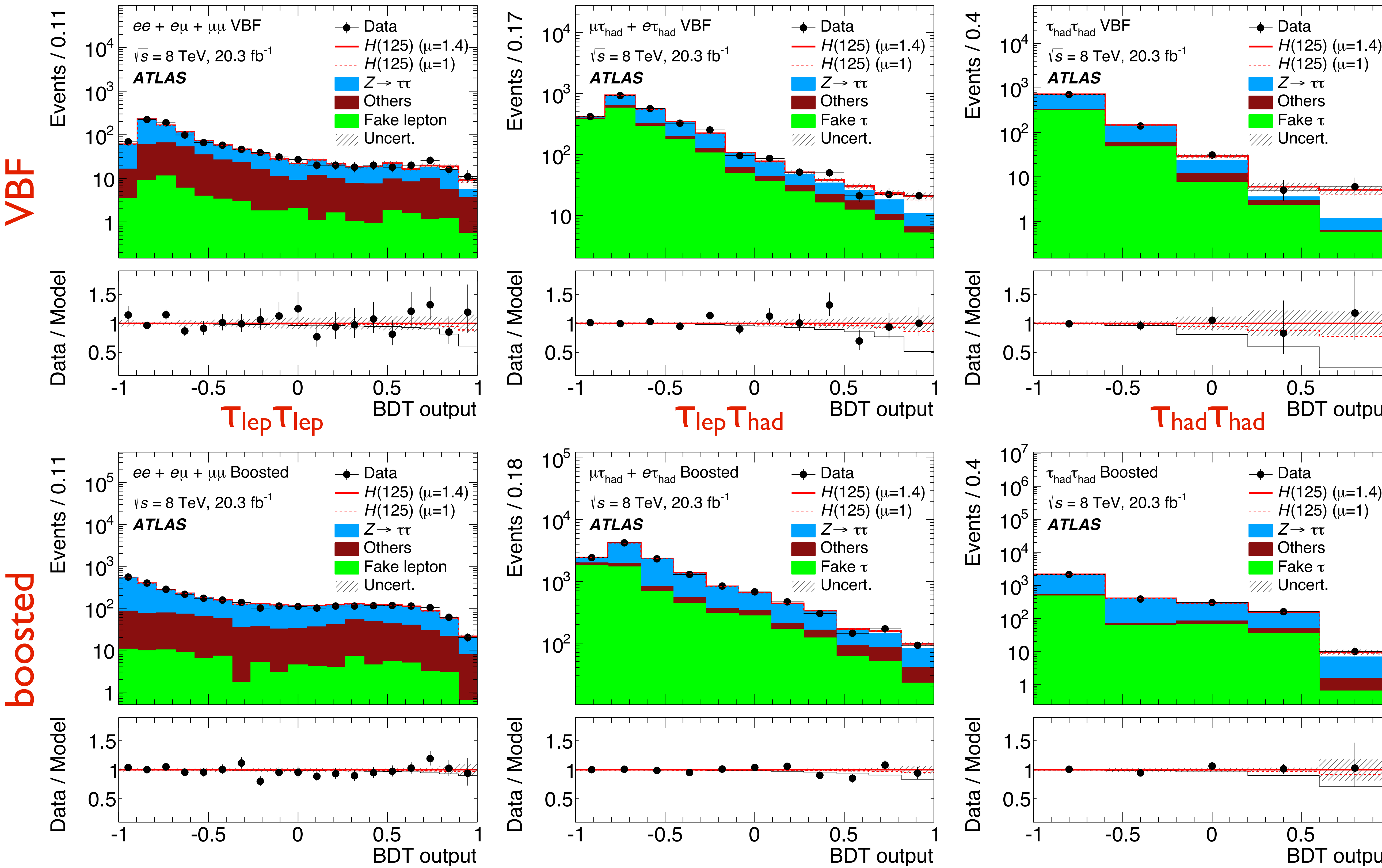
best-fit nuisance parameters for given μ

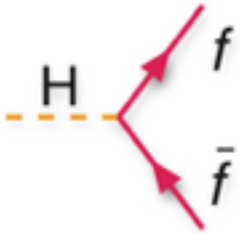
Dominant uncertainties:

- jet energy scale & resolution ($\lesssim$ 10%, mostly signal)
- τ_{had} identification ($\lesssim$ 7%, signal + bg)
- higher-order QCD corrections (~ 10% VBF signal, ~20% boosted ggF signal)



$H \rightarrow \tau^+\tau^-$ (4)





$H \to \tau^+\tau^-$ (5)

Results:

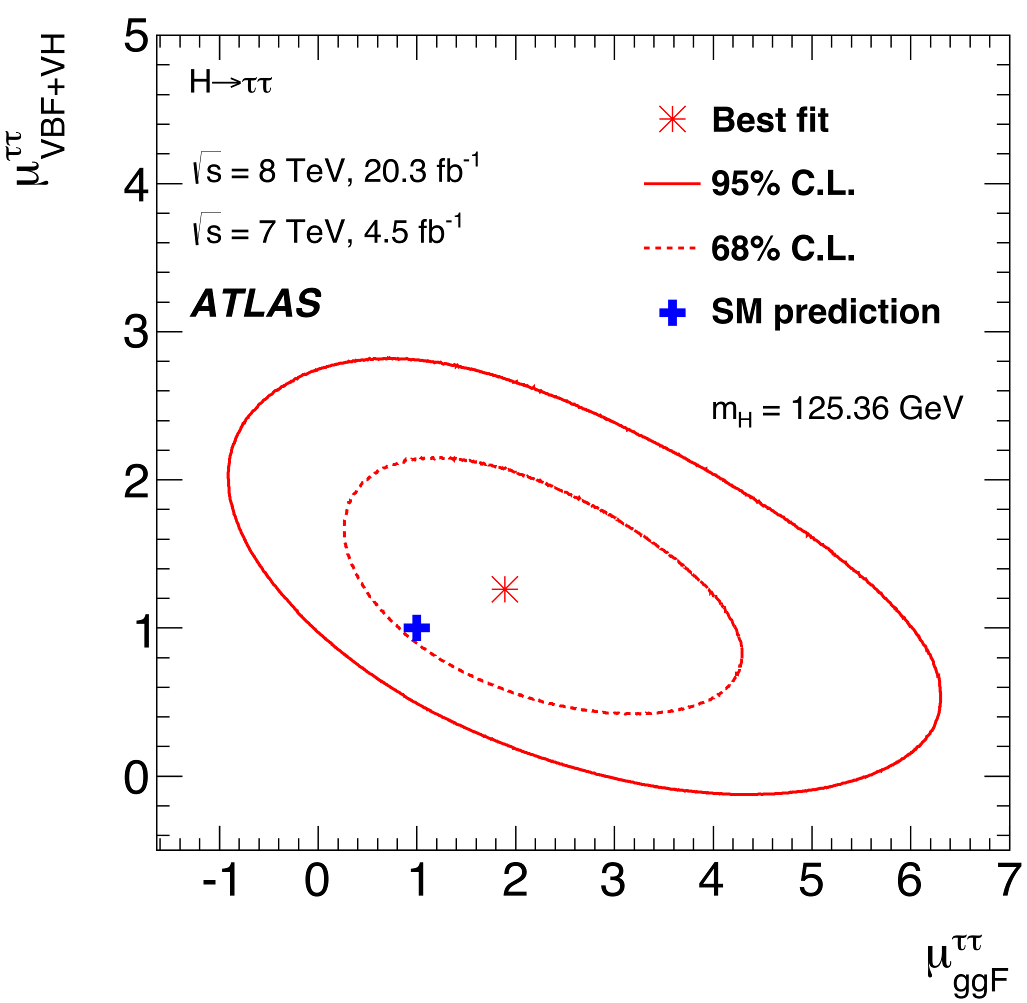
- grand combination:

$$\mu = 1.43^{+0.27}_{-0.26}(\text{stat.})^{+0.32}_{-0.25}(\text{syst.}) \pm 0.09(\text{theory})$$

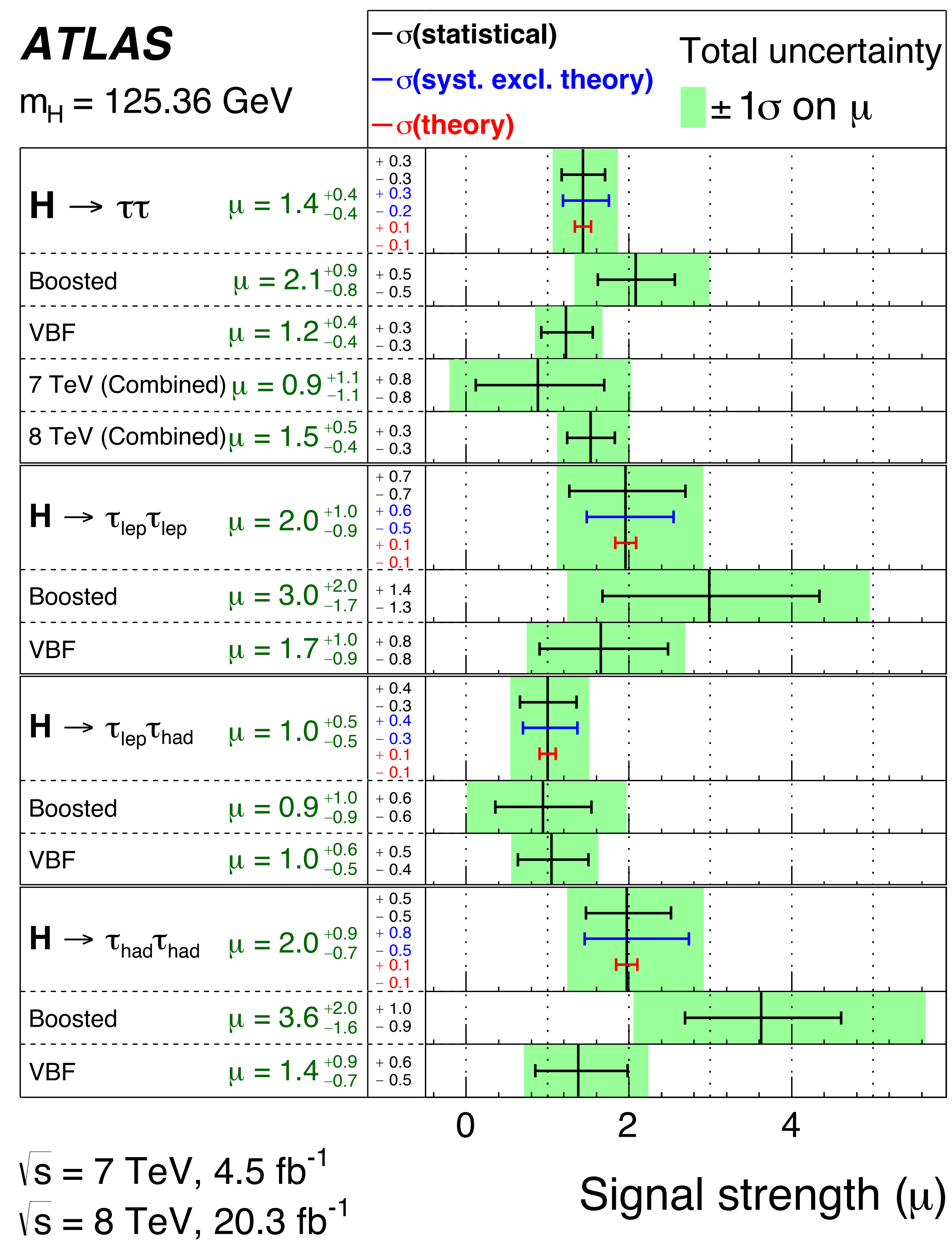
- separate VBF / ggF signal strengths:

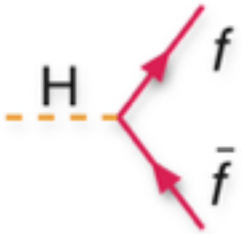
$$\mu_{ggF} = 2.0 \pm 0.8(\text{stat.})^{+1.2}_{-0.8}(\text{syst.}) \pm 0.3(\text{theory})$$

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



- observed discovery significance: 4.5σ (expected: 3.4σ)

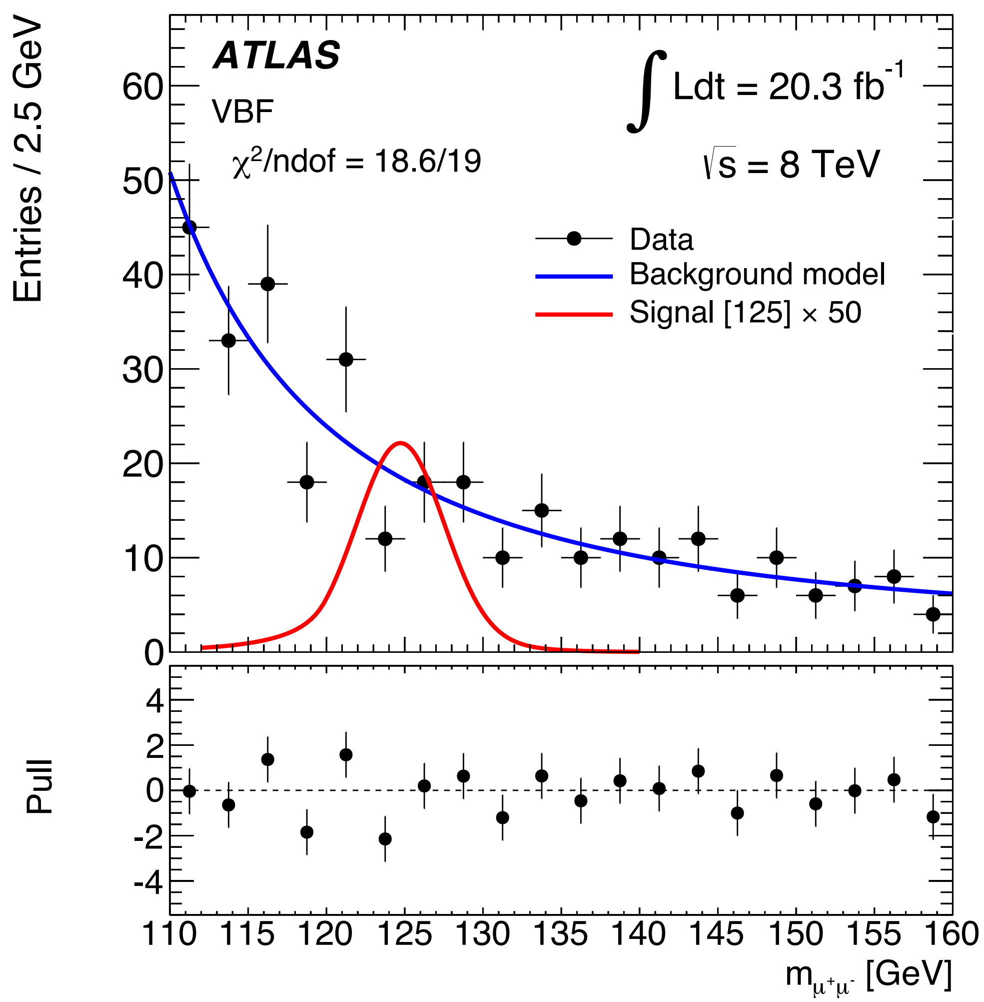


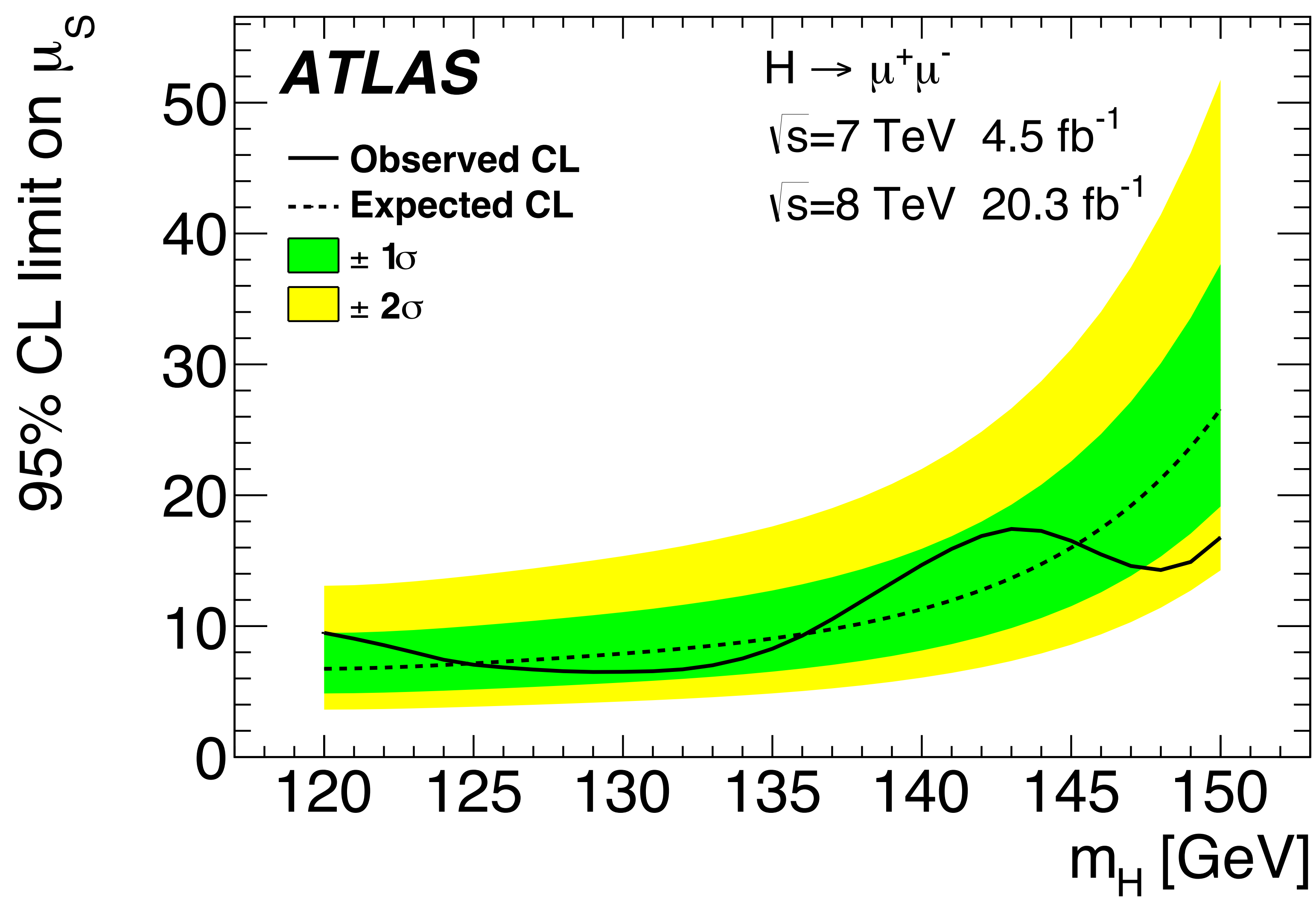


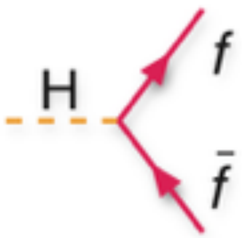
$H \rightarrow \mu^+\mu^-$

"Simple" analysis but made difficult by low branching fraction and overwhelming $Z/\gamma^* \rightarrow \mu^+\mu^-$ background

- categories similar to $H \rightarrow \tau^+\tau^-$: VBF / 3 separate $p_T(H)$ bins
- result: observed $\mu < 7.0$ (95% CL) (expected: $\mu < 7.2$)



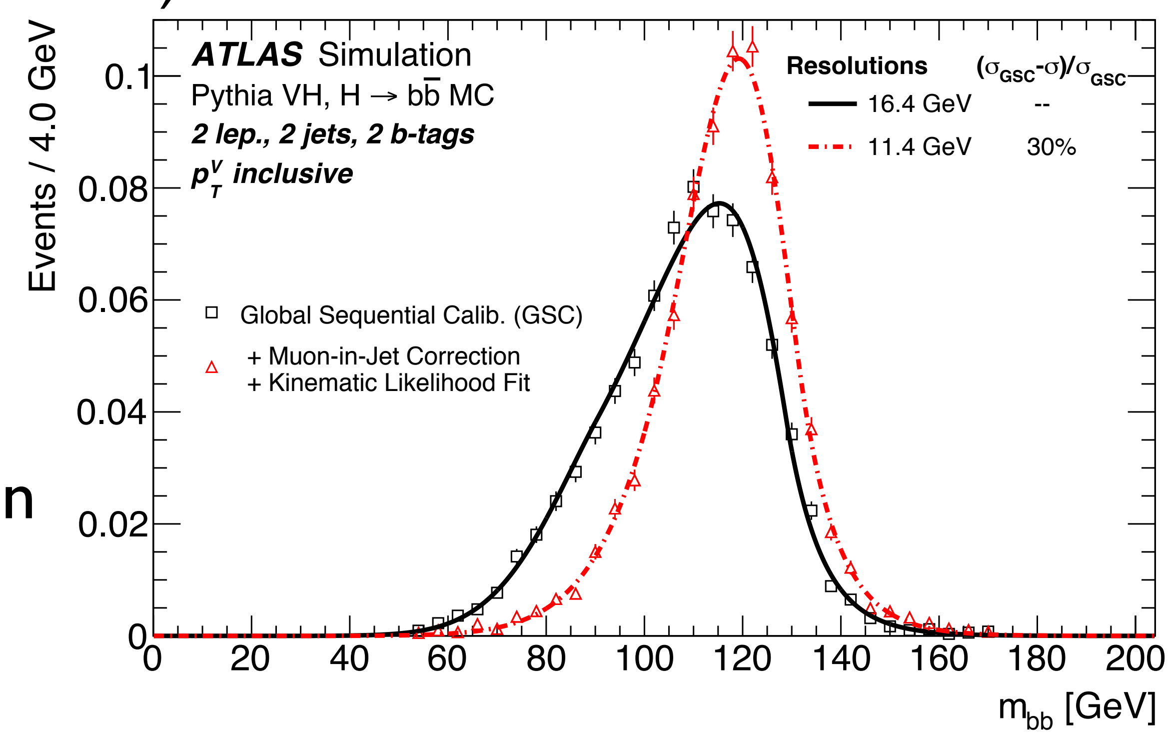




$H \to b\bar{b}$

Due to QCD $b\bar{b}$ background, little hope to observe in ggF production; use W/Z associated production.
"Simple" topology but separate analyses in many categories!

- leptonic W/Z decays: $Z \to \nu\nu$, $W \to l\nu$, $Z \to ll$ (l = e, μ)
- events with 2 or 3 jets (with $|\eta| < 2.5$, $p_T > 20$ GeV)
- 2 $p_T(V)$ regions (120 GeV boundary)
  - 0-lepton: $p_T(Z) > 100$ GeV (trigger)



2-lepton channel: kinematic fit to improve mass resolution

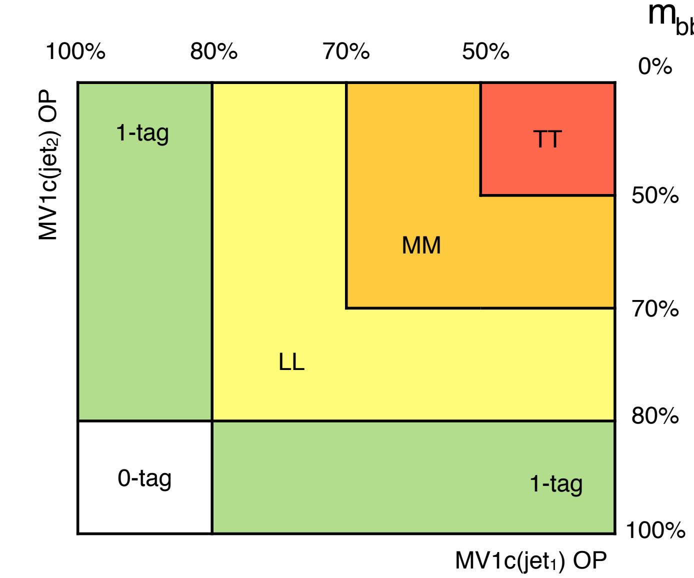
- 0, 1-lepton channels: dedicated b-jet correction

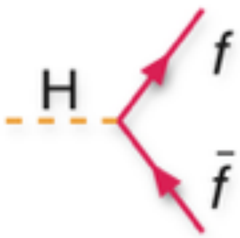
0-lepton channel: improve multijet rejection using both calorimeter & track based E_T(miss)

- consistency check: $\Delta\varphi(\mathbf{p}_T(\text{miss}), \mathbf{E}_T(\text{miss})) < \pi/2$

Analysis binned in discriminant output of b-jet tagger with improved c-jet rejection (after loose b-jet requirement):

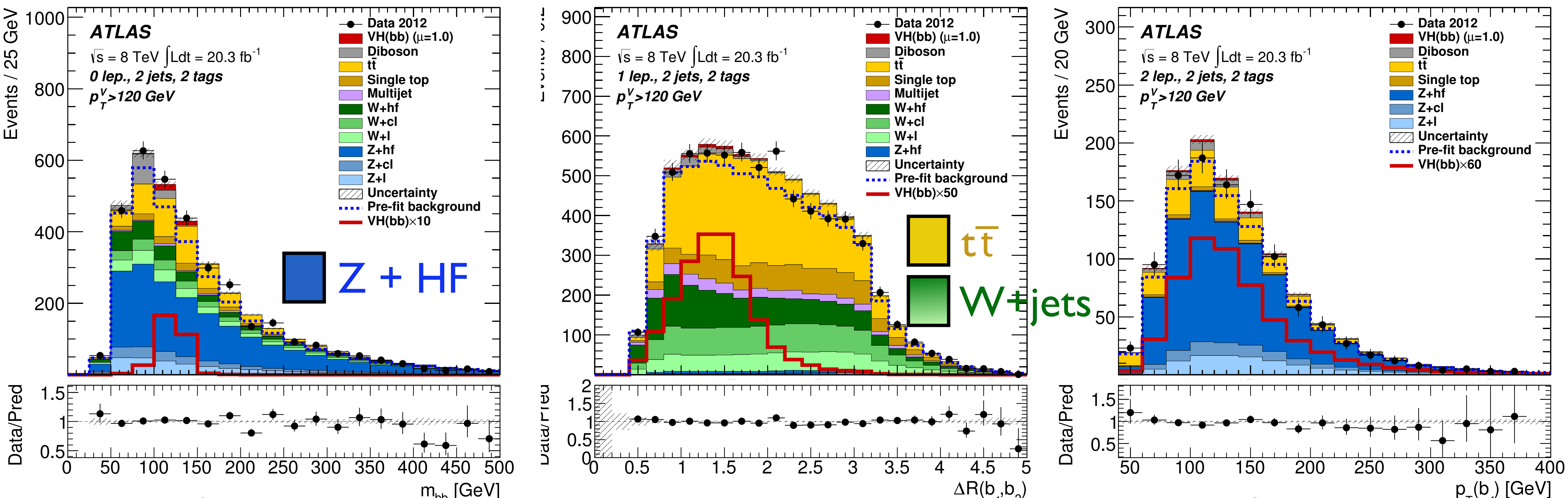
- Loose (80%), Medium (70%), Tight (50%)



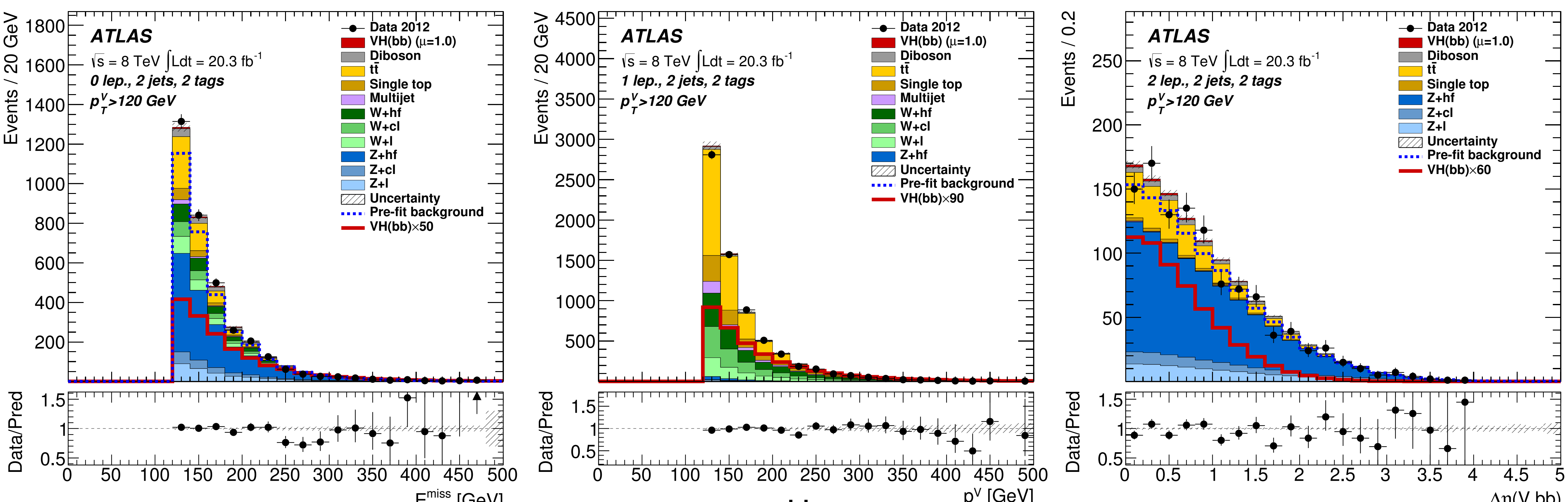


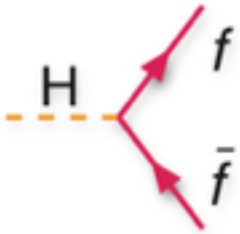
$H \rightarrow b\bar{b}$ (2)

BDT input variables



0-lepton 1-lepton 2-lepton

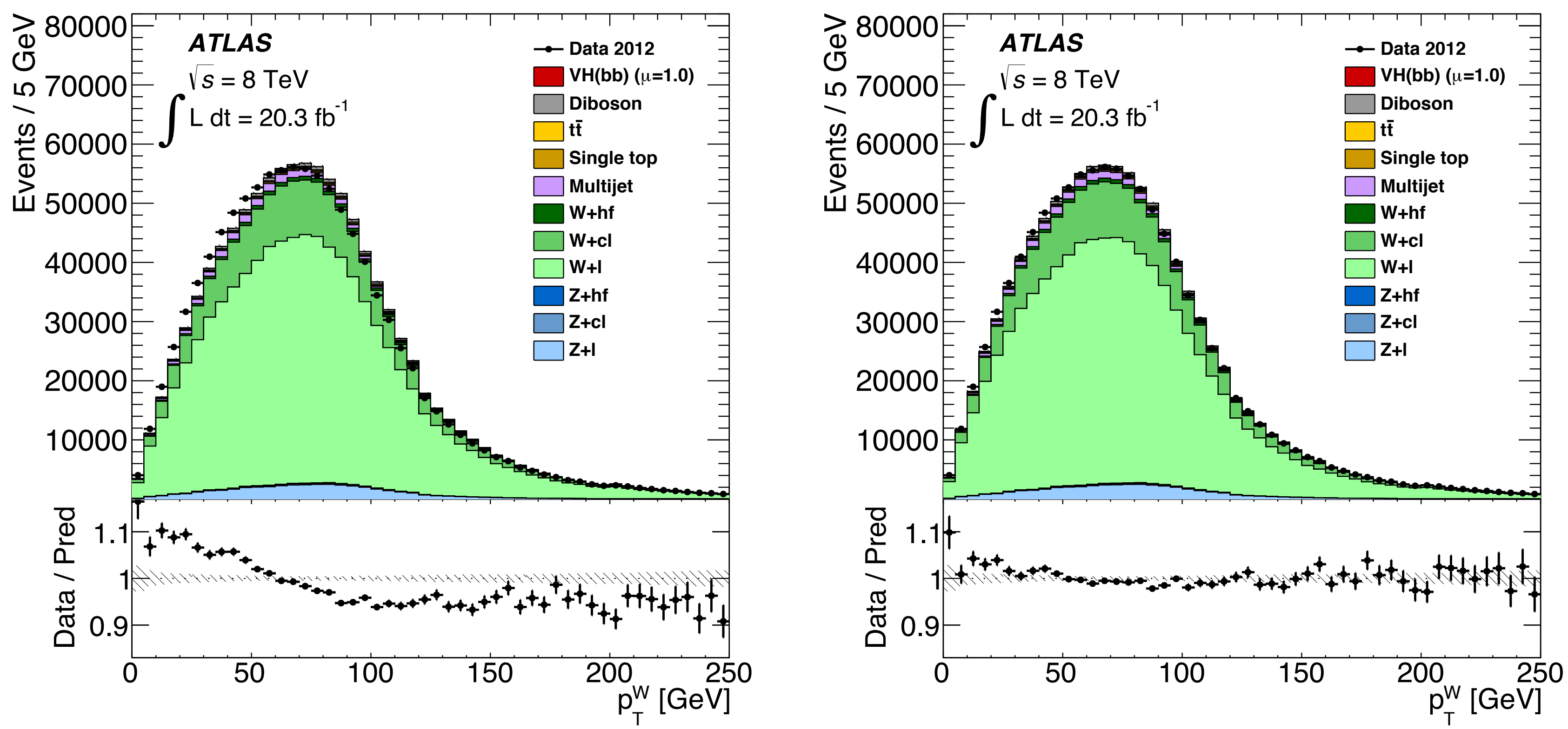




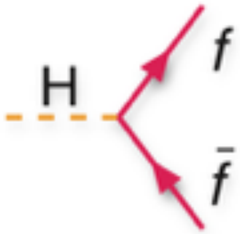
$H \rightarrow b\bar{b}$ (3)

Extensive background modelling required (only small multijet background estimated using data driven methods)

- SHERPA modelling of $p_T(W)$ distribution improved by reweighting $\Delta\varphi(j_1, j_2)$
  - applied to W+l, W+cl

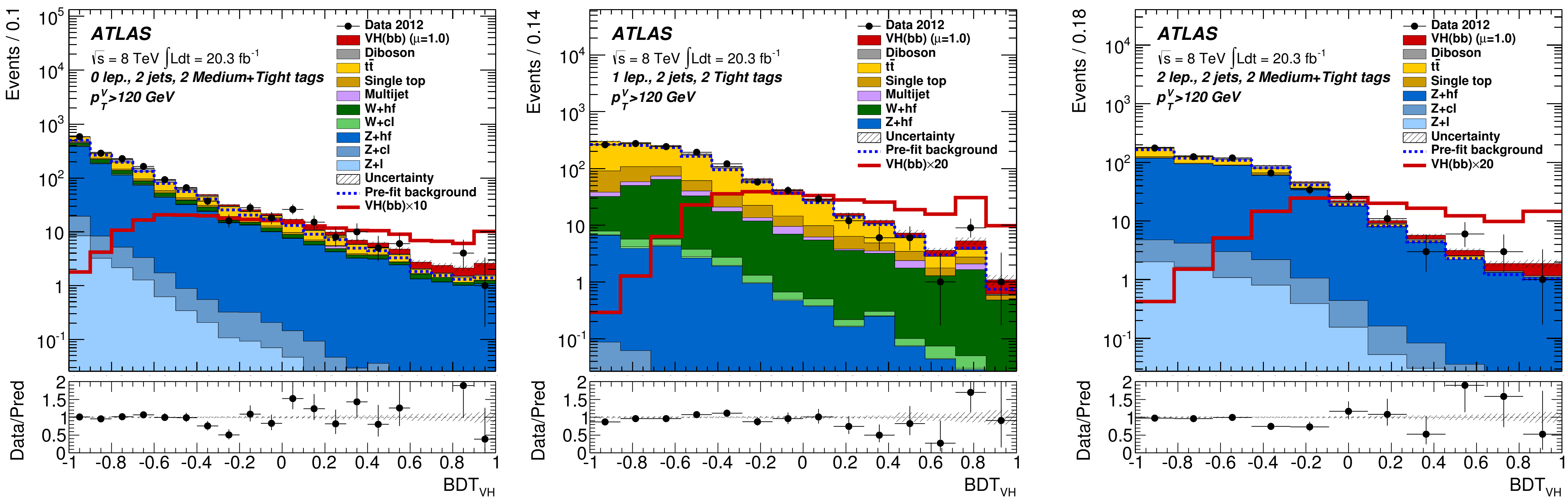


- similar reweighting carried out for (SHERPA) Z+jets background
  - $\Delta\varphi(j_1, j_2)$ reweighted for Z+l; directly $p_T(Z)$ for Z+b, Z+c
- $p_T(t)$ spectrum in $t\bar{t}$ reweighted to bring it in agreement with measurement



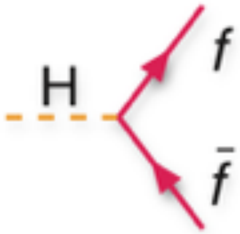
$H \to b\bar{b}$ (4)

BDT output distributions in most discriminating 0-, 1-, 2-lepton regions



Systematic uncertainties obtained mostly from generator comparisons (bg), theory (signal). Dominant contributions and impact on signal strength estimate:

- W+HF m_{jj} shape (0.06), W+bl/$b\bar{b}$ ratio, W+$b\bar{b}$ normalisation, W+HF $p_T(V)$ shape (0.05), Z+bl/$b\bar{b}$ ratio, b-jet energy resolution (0.04)
- signal: effect μ_F, μ_R scale variations on acceptance (0.04)

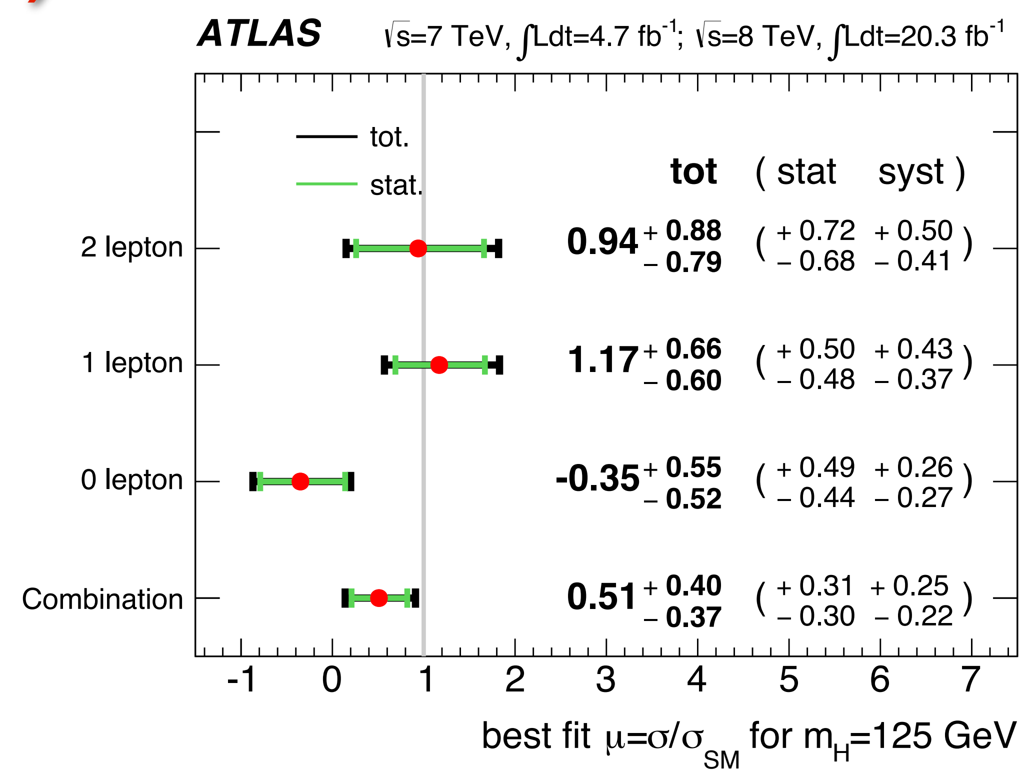


$H \to b\bar{b}$ (5)

Profile likelihood fit (as in $H \to \tau^+\tau^-$ analysis):

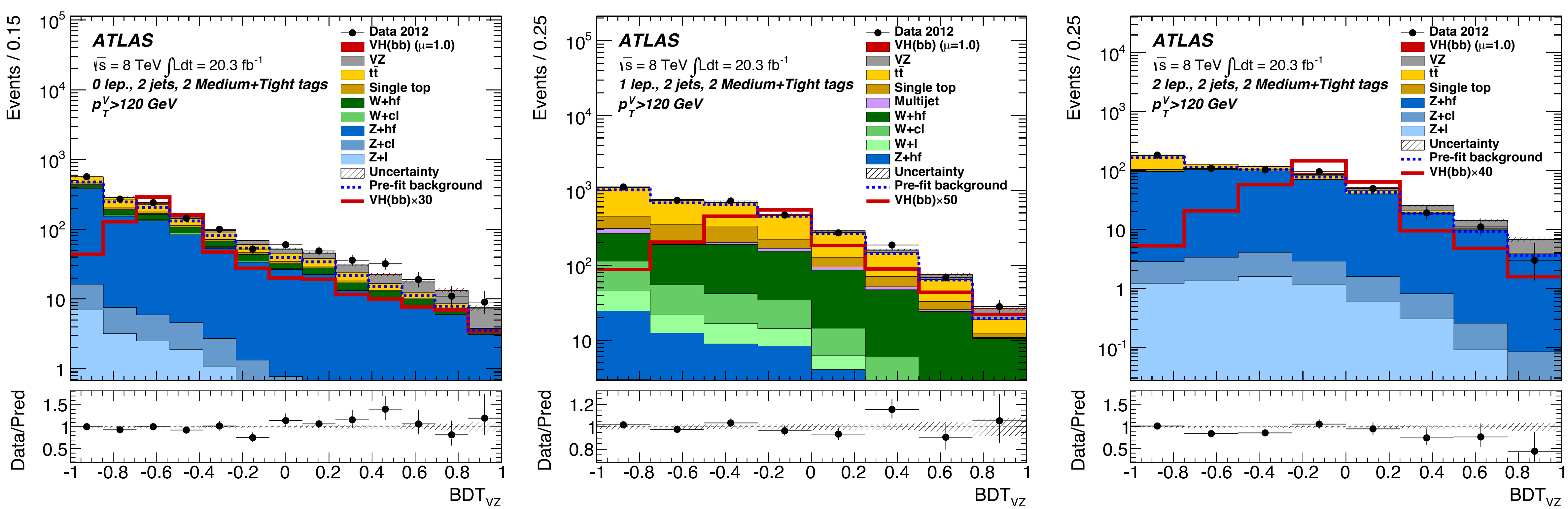
$$\mu = 0.51^{+0.31}_{-0.30}(\text{stat.})^{+0.25}_{-0.22}(\text{syst.})$$

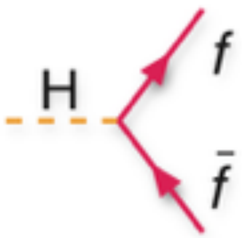
- significance: 1.4σ (expected: 2.6σ)
- μ < 1.2 at 95% CL (expected: 0.8)



Cross-check analysis done searching for W/Z+Z→bb events

- 5 times larger cross section; softer $p_T(Z)$ spectrum





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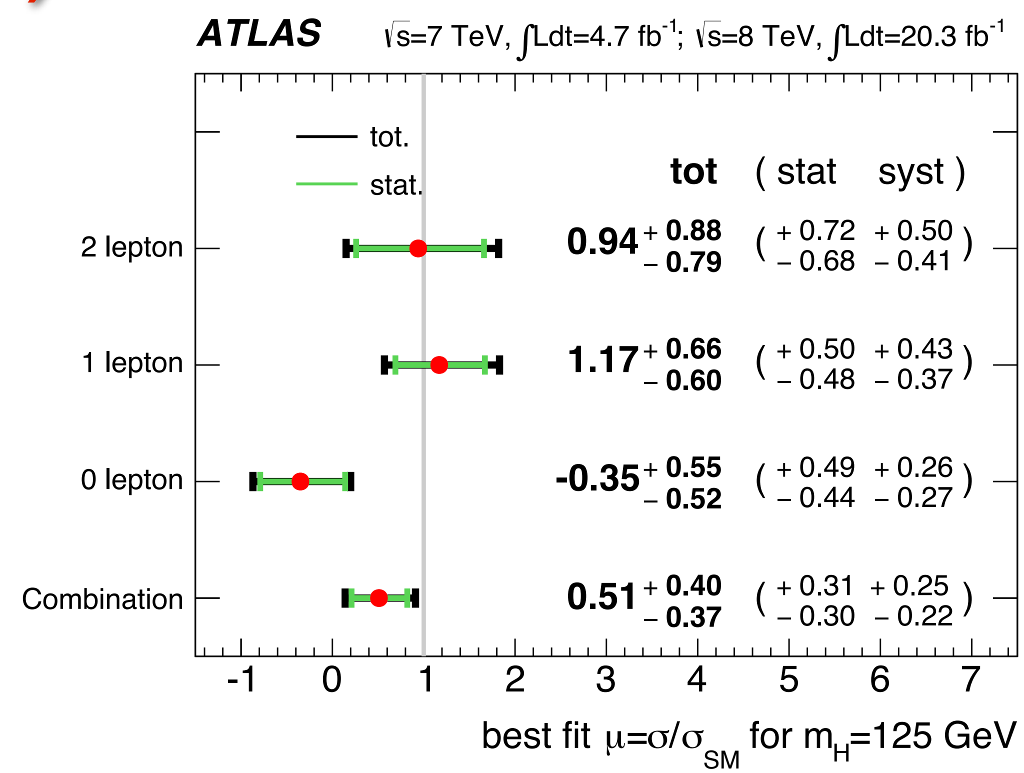

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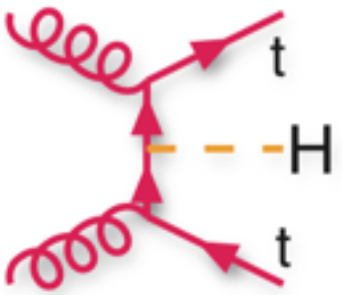
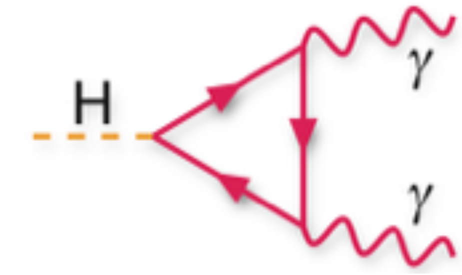
- $\mu < 1.2$ at 95% CL (expected: 0.8)

Cross-check analysis done searching for W/Z+Z→bb events

- 5 times larger cross section; softer $p_T(Z)$ spectrum
- separately trained BDTs (SM W/Z+H “background”)
- results:
  - $\mu_{VZ} = 0.74 \pm 0.09$ (stat.) ± 0.14 (syst.)
  - simultaneous fit of μ, μ_{VZ} does not affect the measured μ (correlation between systematics only 35%)

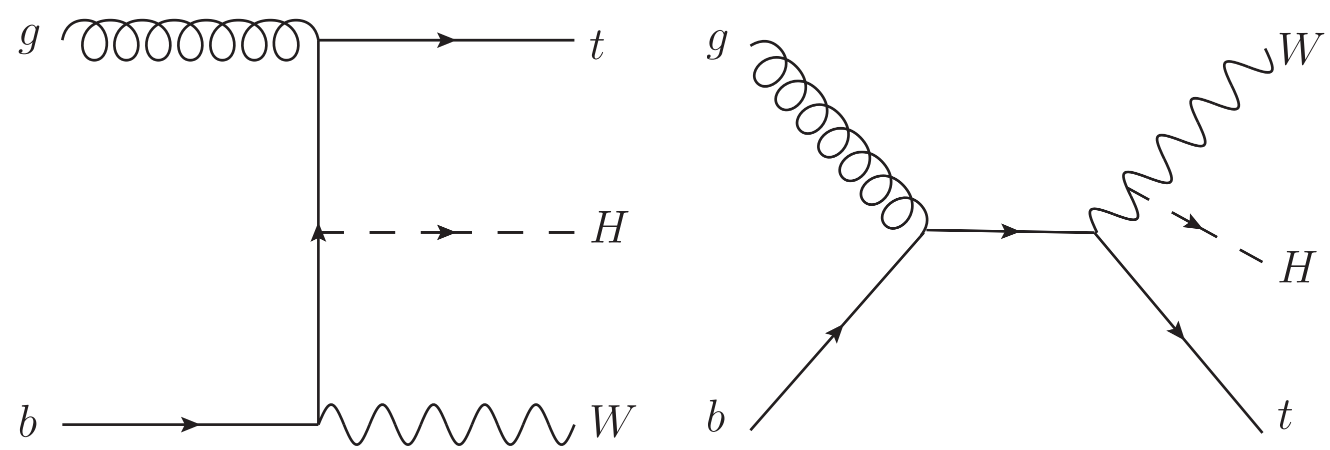


$t\bar{t}$ H

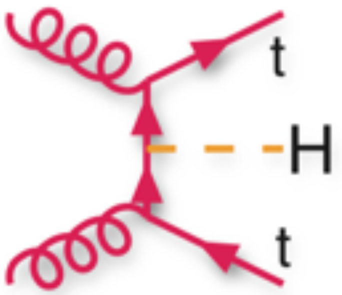


Process provides tree level access to Htt coupling

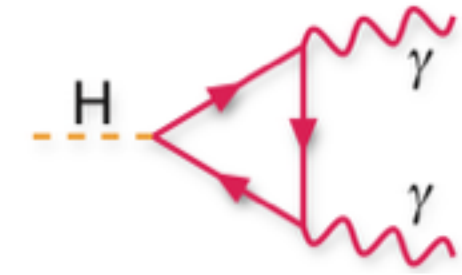
- H → γγ decay mode: tiny branching fraction ($2.3 \cdot 10^{-3}$), but very low background which can be estimated from $m_{\gamma\gamma}$ sidebands (except contributions from other H → γγ decays)
- selection kept inclusive to allow tHqb and tHW contributions
  ➠ sensitivity to relative sign of Htt and HWW couplings, due to destructive interference in tHW final state



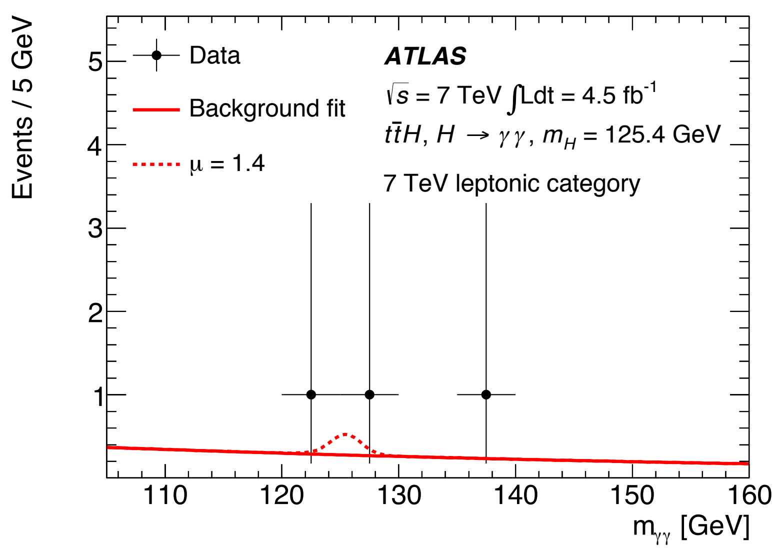
  - similar interference for tHqb production
  - parametrise Htt coupling using additional factor κ_t
- loose $t\bar{t}$ selection for both l+jets ("leptonic") and hadronic final states
  - but tight photon selection

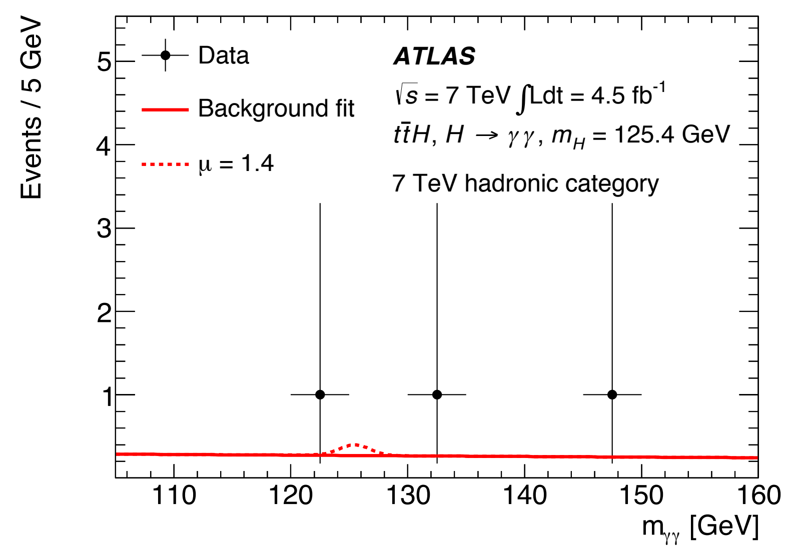


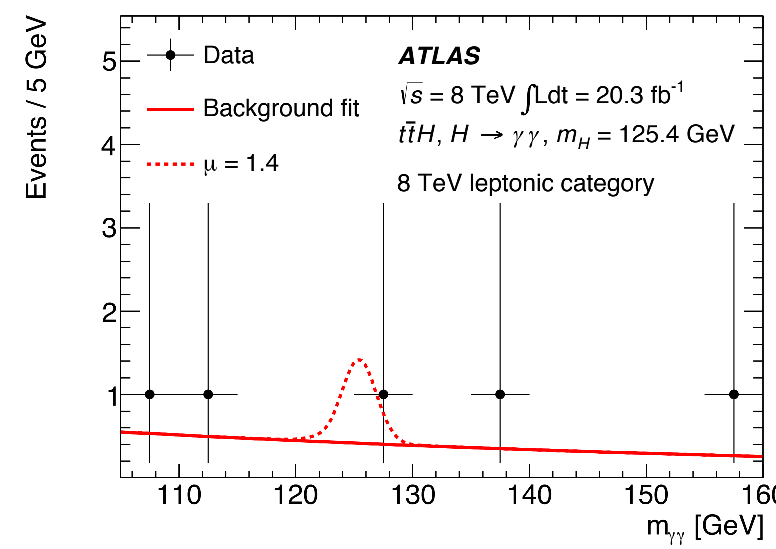
$t\bar{t}$ H (2)



Results obtained from unbinned fit to $m_{\gamma\gamma}$ spectrum assuming signal + exponential background

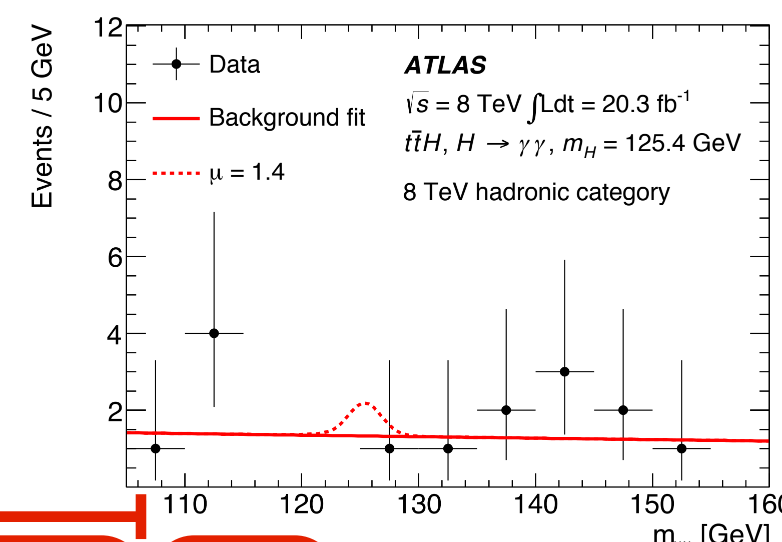




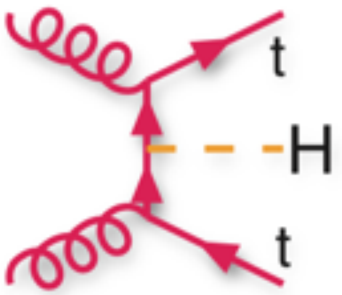


Expected composition in 120—130 GeV range:

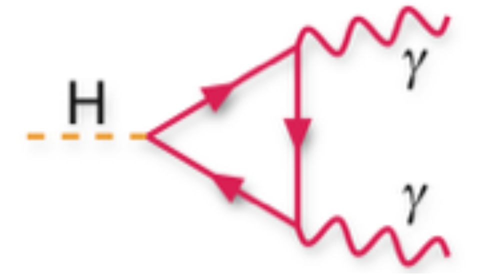
- background from fit
- signal composition dominated by processes involving Htt coupling



Category	N_H	ggF	VBF	WH	ZH	$t\bar{t}H$	$tHqb$	WtH	N_B
7 TeV leptonic selection	0.10	0.6	0.1	14.9	4.0	72.6	5.3	2.5	$0.5^{+0.5}_{-0.3}$
7 TeV hadronic selection	0.07	10.5	1.3	1.3	1.4	80.9	2.6	1.9	$0.5^{+0.5}_{-0.3}$
8 TeV leptonic selection	0.58	1.0	0.2	8.1	2.3	80.3	5.6	2.6	$0.9^{+0.6}_{-0.4}$
8 TeV hadronic selection	0.49	7.3	1.0	0.7	1.3	84.2	3.4	2.1	$2.7^{+0.9}_{-0.7}$



$t\bar{t}$ H (3)



Results:

- best-fit signal strength:

  $\mu = 1.4^{+2.3}_{-1.4}(\text{stat.})^{+0.6}_{-0.3}(\text{syst.})$

  - not far less precise than result obtained using $t\bar{t}H \to b\bar{b}$ (1.5 ± 1.1)

- fixing other H → γγ contributions to SM:

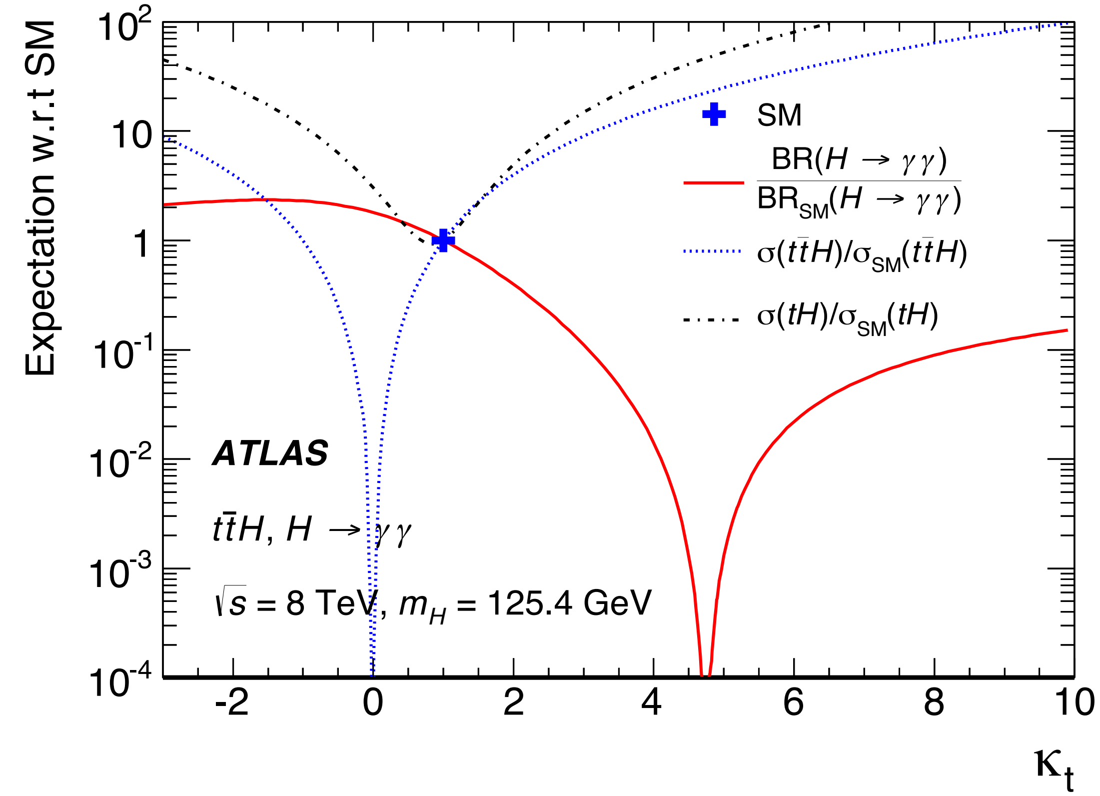
  $\mu_{t\bar{t}H} = 1.3^{+2.5}_{-1.7}(\text{stat.})^{+0.8}_{-0.4}(\text{syst.})$

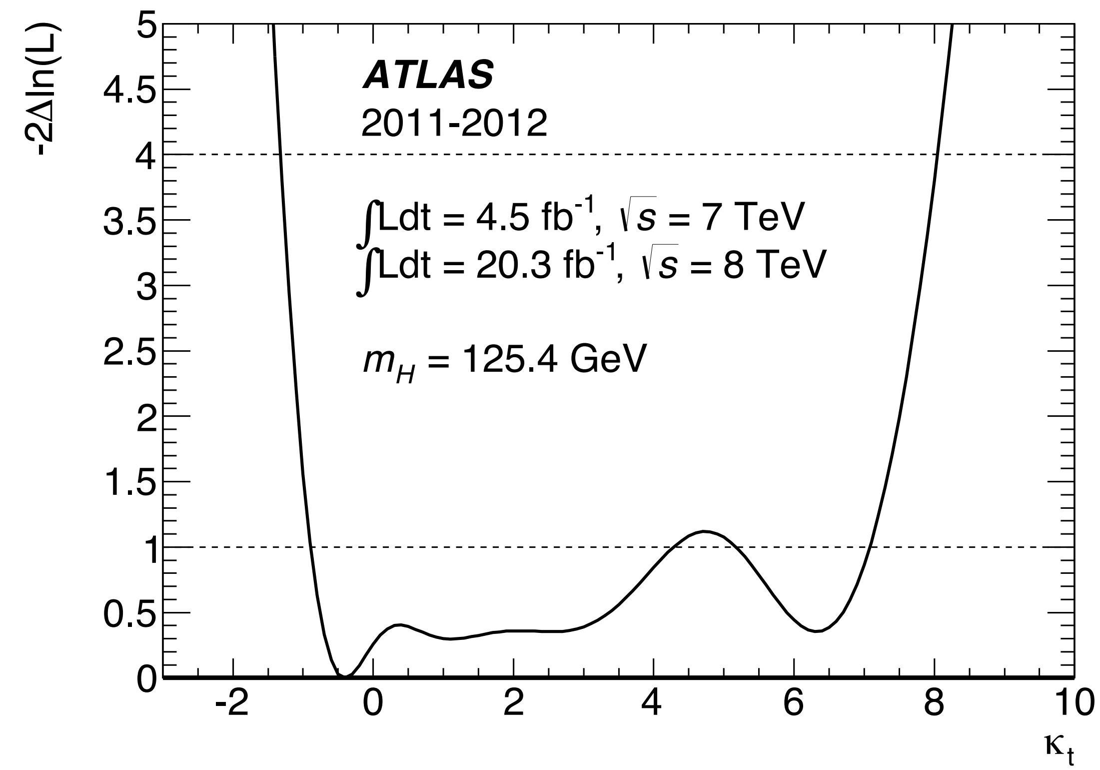
  - μ_{ttH} < 6.7 at 95% CL

Interpretation of μ_{ttH} in terms of κ_t:

- also interference with W boson loop in H → γγ
- significant constraints imposed especially on negative values:

  -1.3 < κ_t < 8.0 at 95% CL



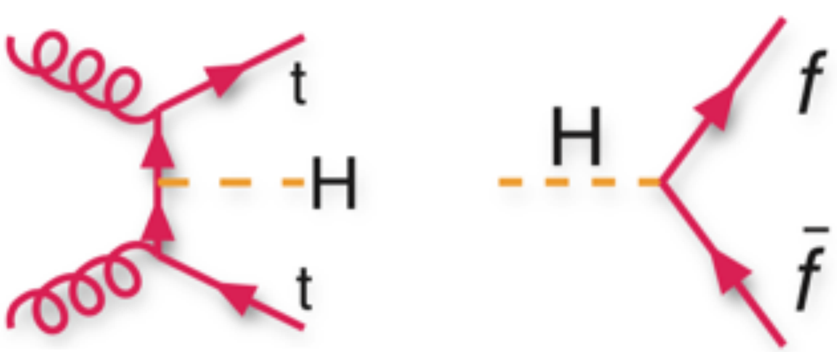


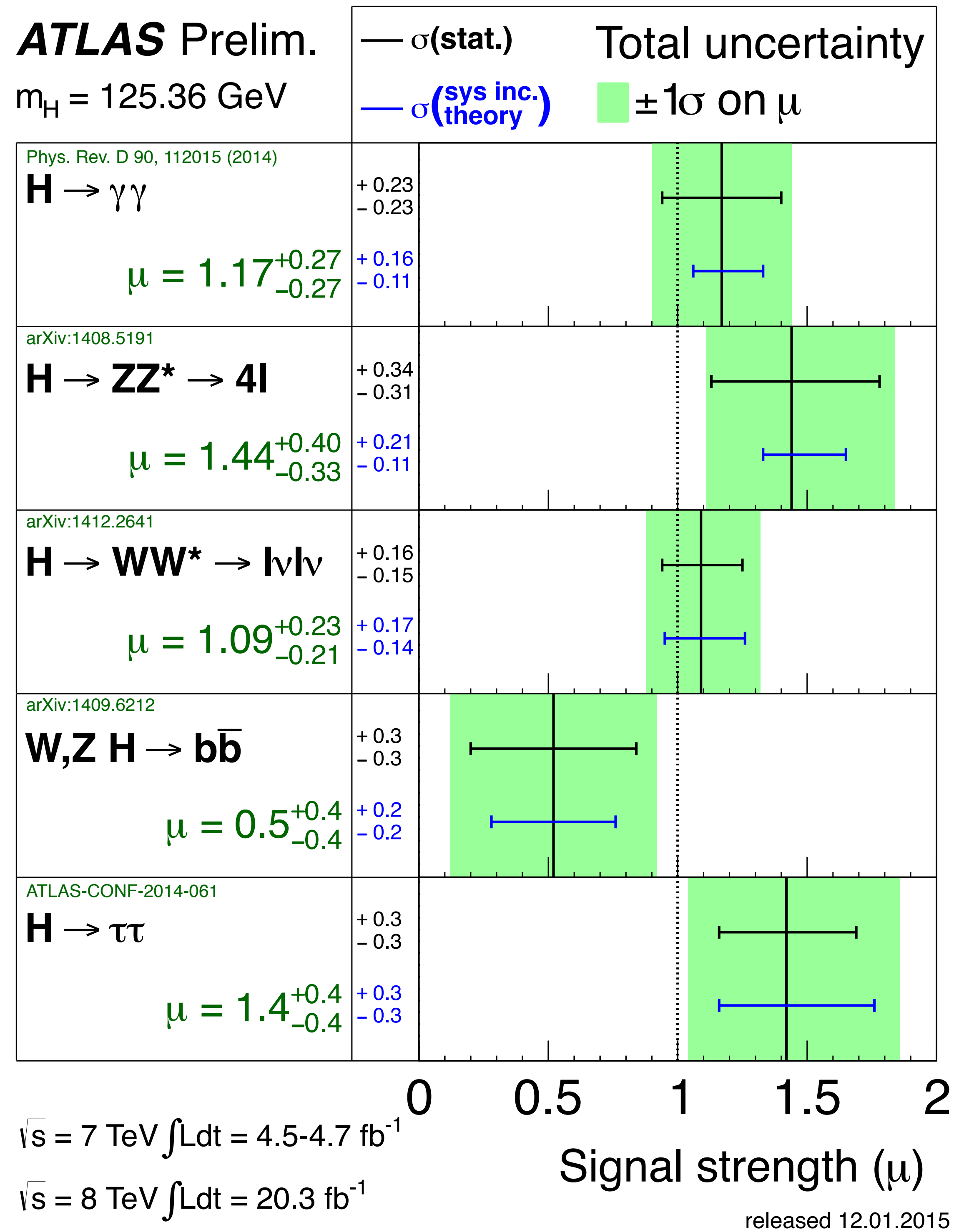
Conclusion & outlook

After the BEH boson's discovery, tremendous progress has been made in constraining its couplings to fermions

No significant deviations from SM predictions observed yet… but the search continues!

- systematic uncertainties becoming important in many analyses
- but higher statistics promised for Run 2 will definitely help to improve precision





(incomplete) list of channels

Backup

$H \to \tau^+\tau^-$: generators

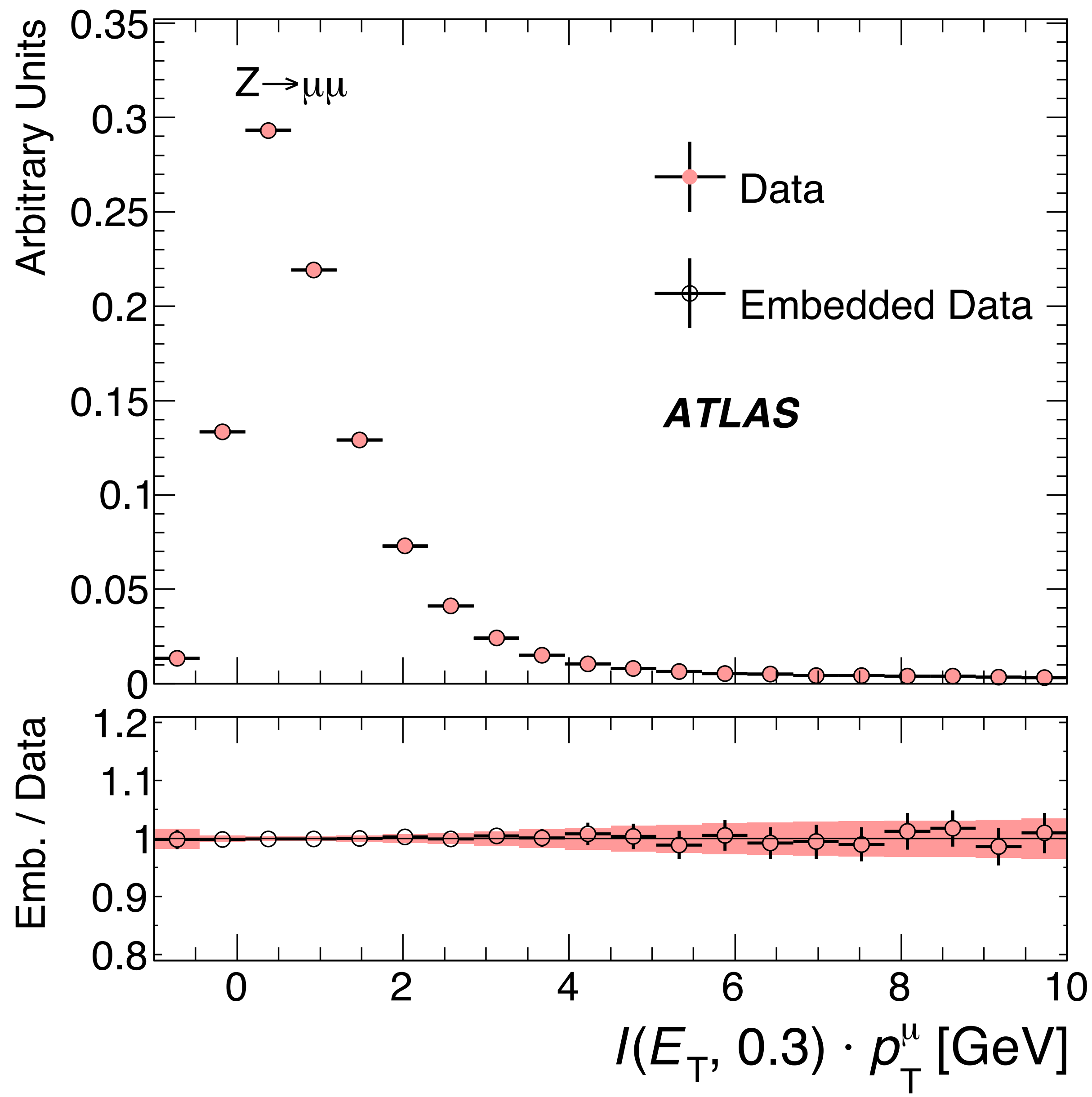
Signal ($m_H = 125$ GeV)	MC generator	$\sigma\times$BR [pb] $\sqrt{s} = 8$ TeV		
ggF, $H \to \tau\tau$	Powheg [36–39] + Pythia8 [40]	1.22	NNLO+NNLL	[42–47, 78]
VBF, $H \to \tau\tau$	Powheg + Pythia8	0.100	(N)NLO	[51–53, 78]
WH, $H \to \tau\tau$	Pythia8	0.0445	NNLO	[56, 78]
ZH, $H \to \tau\tau$	Pythia8	0.0262	NNLO	[56, 78]
Background	**MC generator**	**$\sigma\times$BR [pb] $\sqrt{s} = 8$ TeV**		
$W(\to \ell\nu)$, $(\ell = e, \mu, \tau)$	Alpgen [71]+Pythia8	36800	NNLO	[79, 80]
$Z/\gamma^*(\to \ell\ell)$, 60 GeV$< m_{\ell\ell} <$ 2 TeV	Alpgen+Pythia8	3910	NNLO	[79, 80]
$Z/\gamma^*(\to \ell\ell)$, 10 GeV$< m_{\ell\ell} <$ 60 GeV	Alpgen+Herwig [81]	13000	NNLO	[79, 80]
VBF $Z/\gamma^*(\to \ell\ell)$	Sherpa [82]	1.1	LO	[82]
$t\bar{t}$	Powheg + Pythia8	$253^\dagger$	NNLO+NNLL	[83–88]
Single top : Wt	Powheg + Pythia8	$22^\dagger$	NNLO	[89]
Single top : s-channel	Powheg + Pythia8	$5.6^\dagger$	NNLO	[90]
Single top : t-channel	AcerMC [74]+Pythia6 [67]	$87.8^\dagger$	NNLO	[91]
$q\bar{q} \to WW$	Alpgen+Herwig	$54^\dagger$	NLO	[92]
$gg \to WW$	gg2WW [73]+Herwig	$1.4^\dagger$	NLO	[73]
WZ, ZZ	Herwig	$30^\dagger$	NLO	[92]
$H \to WW$	same as for $H \to \tau\tau$ signal	$4.7^\dagger$		

$H \to \tau^+\tau^-$: embedding

In data $Z/\gamma^* \to \mu^+\mu^-$ events ($m_{\mu\mu}$ > 40 GeV), replace μ with simulated τ

- also requires removing energies deposited in the calorimeter by the muon

Technical test replacing the real muon with a simulated one



$H \to \tau^+\tau^-$: BDT variables

Variable	VBF $\tau_{\text{lep}}\tau_{\text{lep}}$	VBF $\tau_{\text{lep}}\tau_{\text{had}}$	VBF $\tau_{\text{had}}\tau_{\text{had}}$	Boosted $\tau_{\text{lep}}\tau_{\text{lep}}$	Boosted $\tau_{\text{lep}}\tau_{\text{had}}$	Boosted $\tau_{\text{had}}\tau_{\text{had}}$
$m_{\tau\tau}^{\text{MMC}}$	•	•	•	•	•	•
$\Delta R(\tau_1, \tau_2)$	•	•	•		•	•
$\Delta\eta(j_1, j_2)$	•	•	•			
m_{j_1,j_2}	•	•	•			
$\eta_{j_1} \times \eta_{j_2}$		•	•			
$p_{\text{T}}^{\text{Total}}$		•	•			
Sum p_{T}					•	•
$p_{\text{T}}^{\tau_1}/p_{\text{T}}^{\tau_2}$					•	•
$E_{\text{T}}^{\text{miss}}\phi$ centrality		•	•	•	•	•
m_{ℓ,ℓ,j_1}				•		
m_{ℓ_1,ℓ_2}				•		
$\Delta\phi(\ell_1, \ell_2)$				•		
Sphericity				•		
$p_{\text{T}}^{\ell_1}$				•		
$p_{\text{T}}^{j_1}$				•		
$E_{\text{T}}^{\text{miss}}/p_{\text{T}}^{\ell_2}$				•		
m_{T}		•			•	
$\min(\Delta\eta_{\ell_1\ell_2,\text{jets}})$	•					
$C_{\eta_1,\eta_2}(\eta_{\ell_1}) \cdot C_{\eta_1,\eta_2}(\eta_{\ell_2})$	•					
$C_{\eta_1,\eta_2}(\eta_\ell)$		•				
$C_{\eta_1,\eta_2}(\eta_{j_3})$	•					
$C_{\eta_1,\eta_2}(\eta_{\tau_1})$			•			
$C_{\eta_1,\eta_2}(\eta_{\tau_2})$			•			

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_j |\vec{p}_j|^2}$$

$$C_{\eta_1,\eta_2}(\eta) \equiv \exp\left(\frac{-4}{(\eta_1 - \eta_2)^2}\left(\eta - \frac{1}{2}(\eta_1 + \eta_2)\right)^2\right)$$

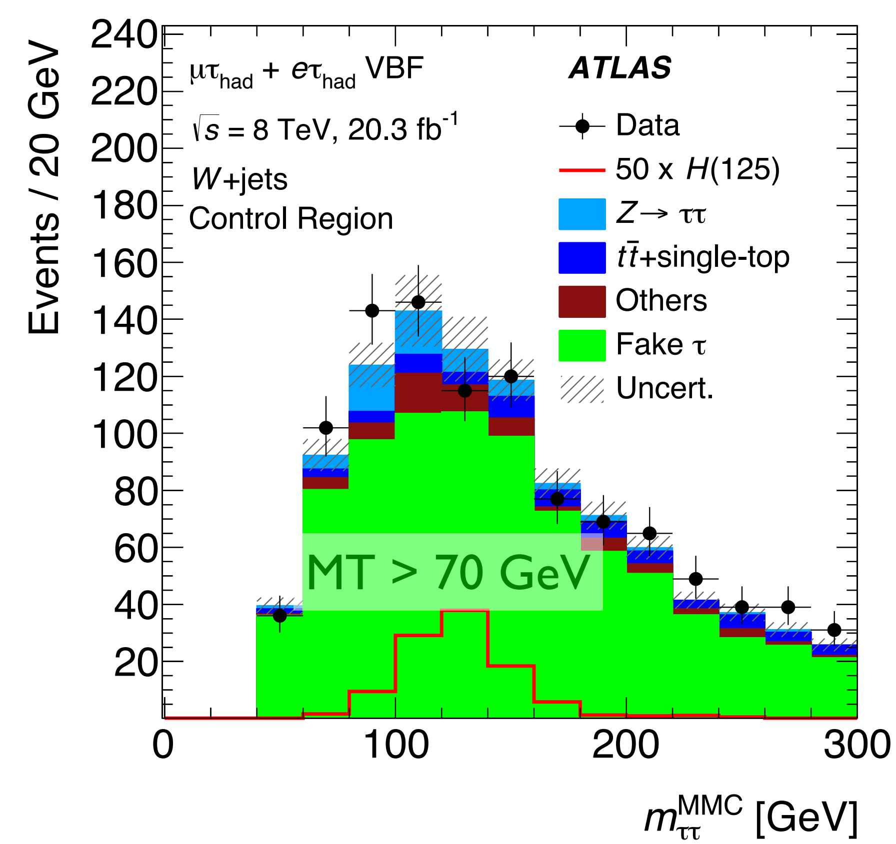
$H \rightarrow \tau^+\tau^-$: fake τ contribution

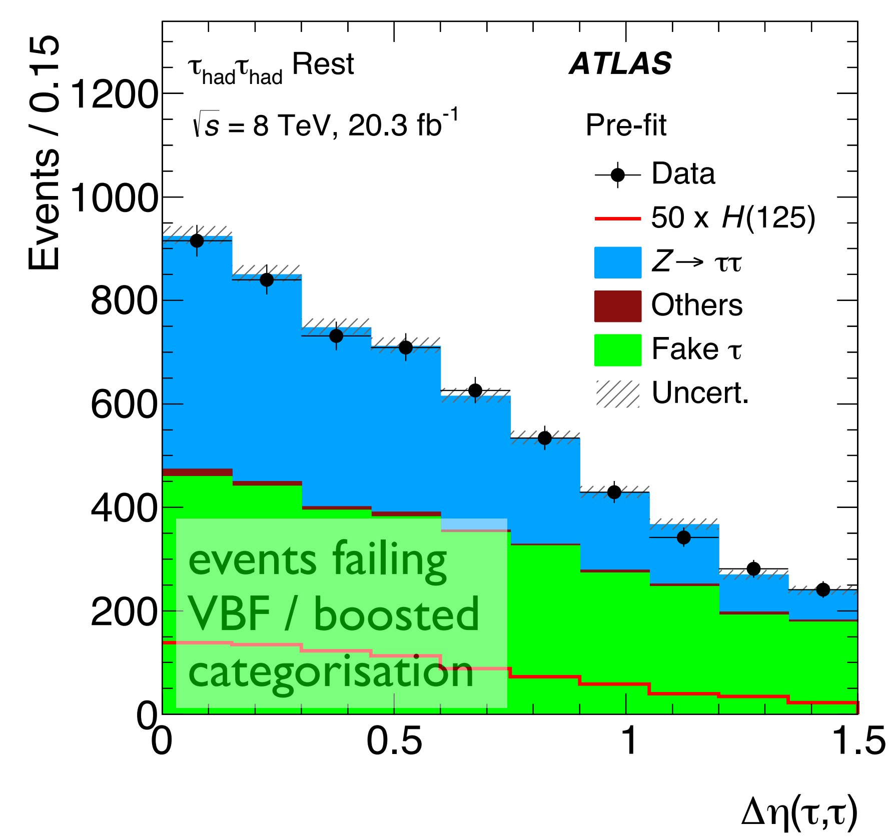
Substantial contribution from fake τ_{had} candidates ➠ data driven estimates

- $\tau_{lep}\tau_{had}$ decay mode: fake contribution from W/Z+jets, ttbar, multijet (MJ) events
- "fake factors" applied to samples with τ_{had} satisfying only looser criteria, as a function of $p_T(\tau)$ & separately for 1-/3-prong τ_{had}
  - different for quarks and gluons ➠ evaluated for separate contributions, combined weighted by expected fractions
- similar procedure for $\tau_{had}\tau_{had}$ mode, modelled using τ_{had} failing isolation / opposite-charge requirements

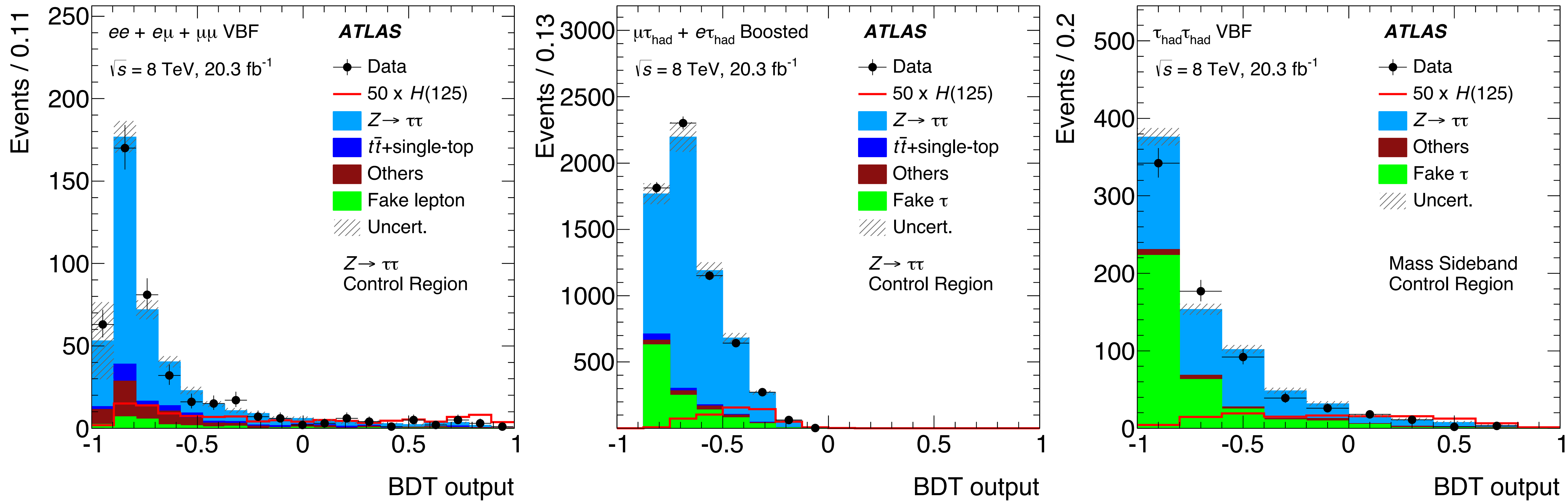
Small fake lepton candidate contribution

- estimated from sample with inverted isolation requirement





$H \rightarrow \tau^+\tau^-$: validation of BDT response



BDT outputs validated in regions with significant $Z \rightarrow \tau^+\tau^-$ / fake τ_{had} contributions

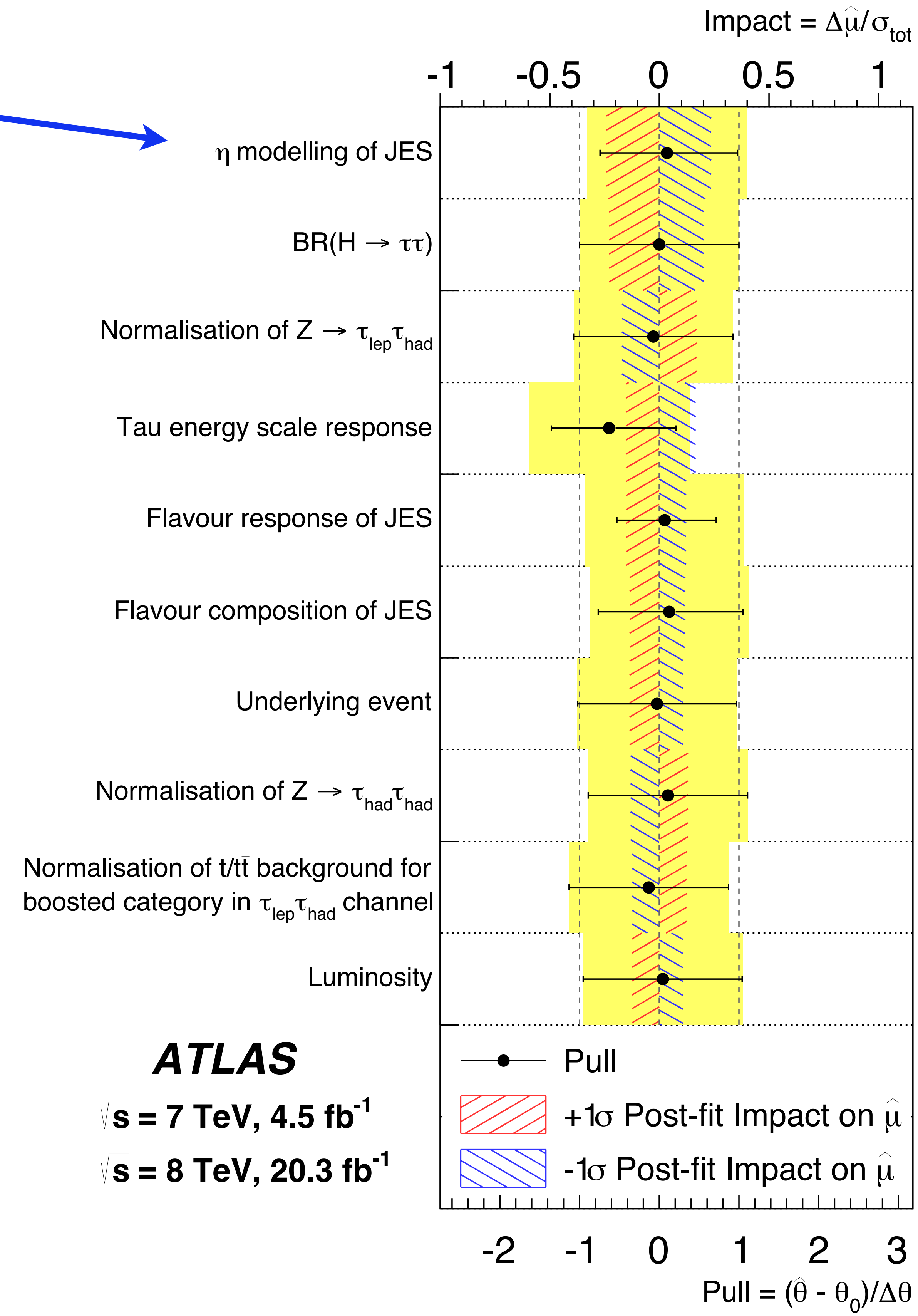
- m_{ll}, $m_{l\tau}$ ~ M_Z region ($\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$)
- $m_{\tau\tau}$(MMC) sidebands ($\tau_{had}\tau_{had}$)

$H \rightarrow \tau^+\tau^-$: results

Dominant uncertainties

Background normalisations

Channel	Background	Scale factors (CR)	
		VBF	Boosted
$\tau_{lep}\tau_{lep}$	Top	0.99 ± 0.07	1.01 ± 0.05
	$Z \rightarrow ee$	0.91 ± 0.16	0.98 ± 0.10
	$Z \rightarrow \mu\mu$	0.97 ± 0.13	0.96 ± 0.08
$\tau_{lep}\tau_{had}$	Top	0.84 ± 0.08	0.96 ± 0.04



$H \to b\bar{b}$: generators

Process	Generator
Signal$^{(\star)}$	
$q\bar{q} \to ZH \to \nu\nu bb/\ell\ell bb$	PYTHIA8
$gg \to ZH \to \nu\nu bb/\ell\ell bb$	POWHEG+PYTHIA8
$q\bar{q} \to WH \to \ell\nu bb$	PYTHIA8
Vector boson + jets	
$W \to \ell\nu$	SHERPA 1.4.1
$Z/\gamma* \to \ell\ell$	SHERPA 1.4.1
$Z \to \nu\nu$	SHERPA 1.4.1
Top-quark	
$t\bar{t}$	POWHEG+PYTHIA
t-channel	ACERMC+PYTHIA
s-channel	POWHEG+PYTHIA
Wt	POWHEG+PYTHIA
Diboson$^{(\star)}$	POWHEG+PYTHIA8
WW	POWHEG+PYTHIA8
WZ	POWHEG+PYTHIA8
ZZ	POWHEG+PYTHIA8

$H \to b\bar{b}$: cuts & BDT variables

Variable	Dijet-mass analysis					Multivariate analysis	
Common selection							
p_{T}^{V} [GeV]	0–90	$90^{(*)}$–120	120–160	160–200	> 200	0–120	> 120
$\Delta R(\mathrm{jet}_1, \mathrm{jet}_2)$	0.7–3.4	0.7–3.0	0.7–2.3	0.7–1.8	< 1.4	> 0.7 (p_{T}^{V}<200 GeV)	
0-lepton selection							
$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	NU	> 30	> 30			NU	> 30
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}} vec)$		$< \pi/2$	$< \pi/2$				$< \pi/2$
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})]$		–	> 1.5				> 1.5
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{dijet})$		> 2.2	> 2.8				> 2.8
$\sum_{i=1}^{N_{\mathrm{jet}}=2(3)} p_{\mathrm{T}}^{\mathrm{jet}_i}$ [GeV]		> 120 (NU)	> 120 (150)				> 120 (150)
		See text	–				–
1-lepton selection							
m_{T}^{W} [GeV]	< 120					–	
H_{T} [GeV]	> 180		–			> 180	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	–		> 20		> 50	–	> 20
2-lepton selection							
$m_{\ell\ell}$ [GeV]	83-99					71-121	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	< 60					–	

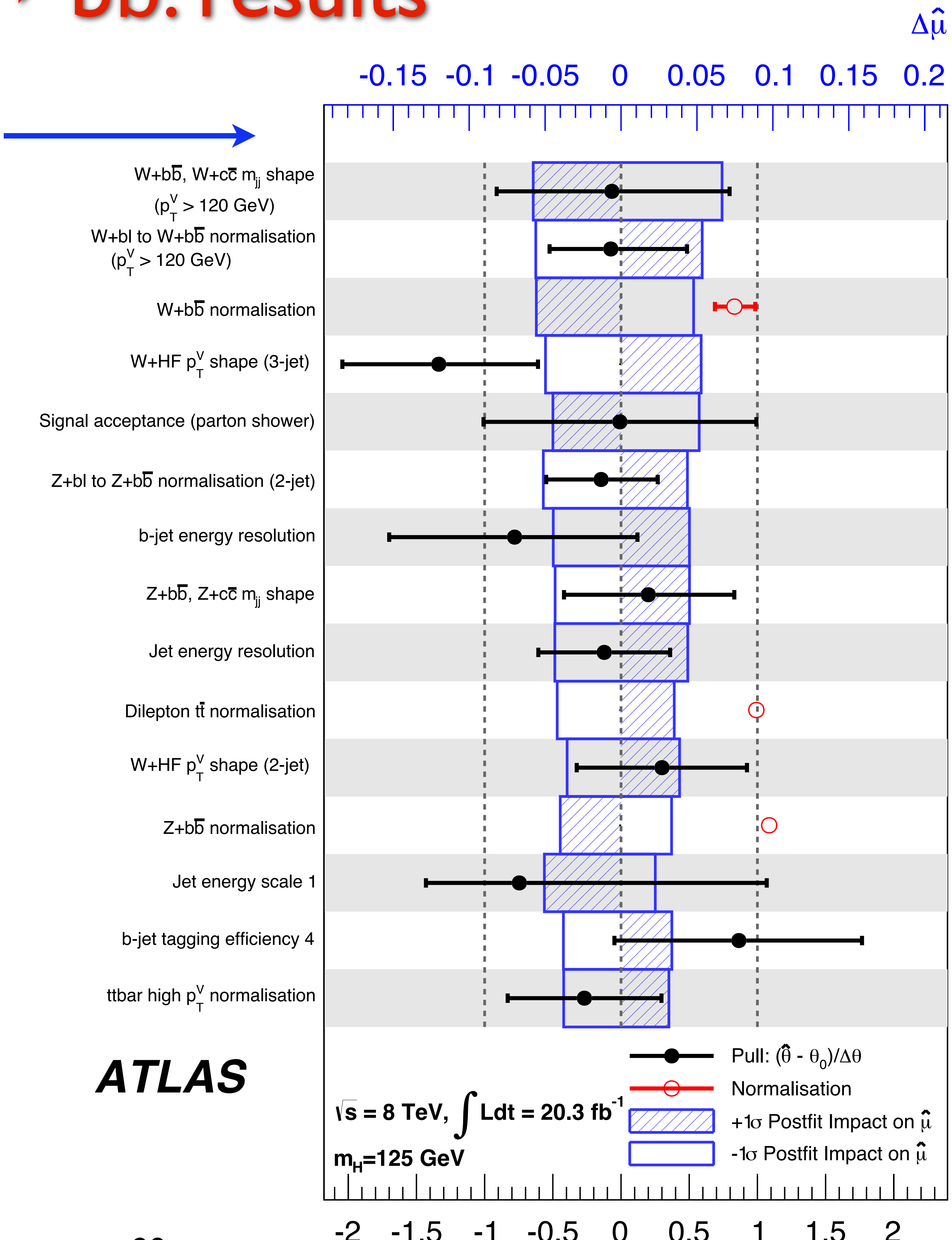
Variable	0-Lepton	1-Lepton	2-Lepton
p_{T}^{V}		×	×
$E_{\mathrm{T}}^{\mathrm{miss}}$	×	×	×
$p_{\mathrm{T}}^{b_1}$	×	×	×
$p_{\mathrm{T}}^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\lvert \Delta E_{\mathrm{T}} a(b_1, b_2) \rvert$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\lvert \Delta E_{\mathrm{T}} a(V, bb) \rvert$			×
H_{T}	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_{T}^{W}		×	
$m_{\ell\ell}$			×
$MV1c(b_1)$	×	×	×
$MV1c(b_2)$	×	×	×
	Only in 3-jet events		
$p_{\mathrm{T}}^{\mathrm{jet}_3}$	×	×	×
m_{bbj}	×	×	×

$H \to b\bar{b}$: results

Impact of nuisance parameters

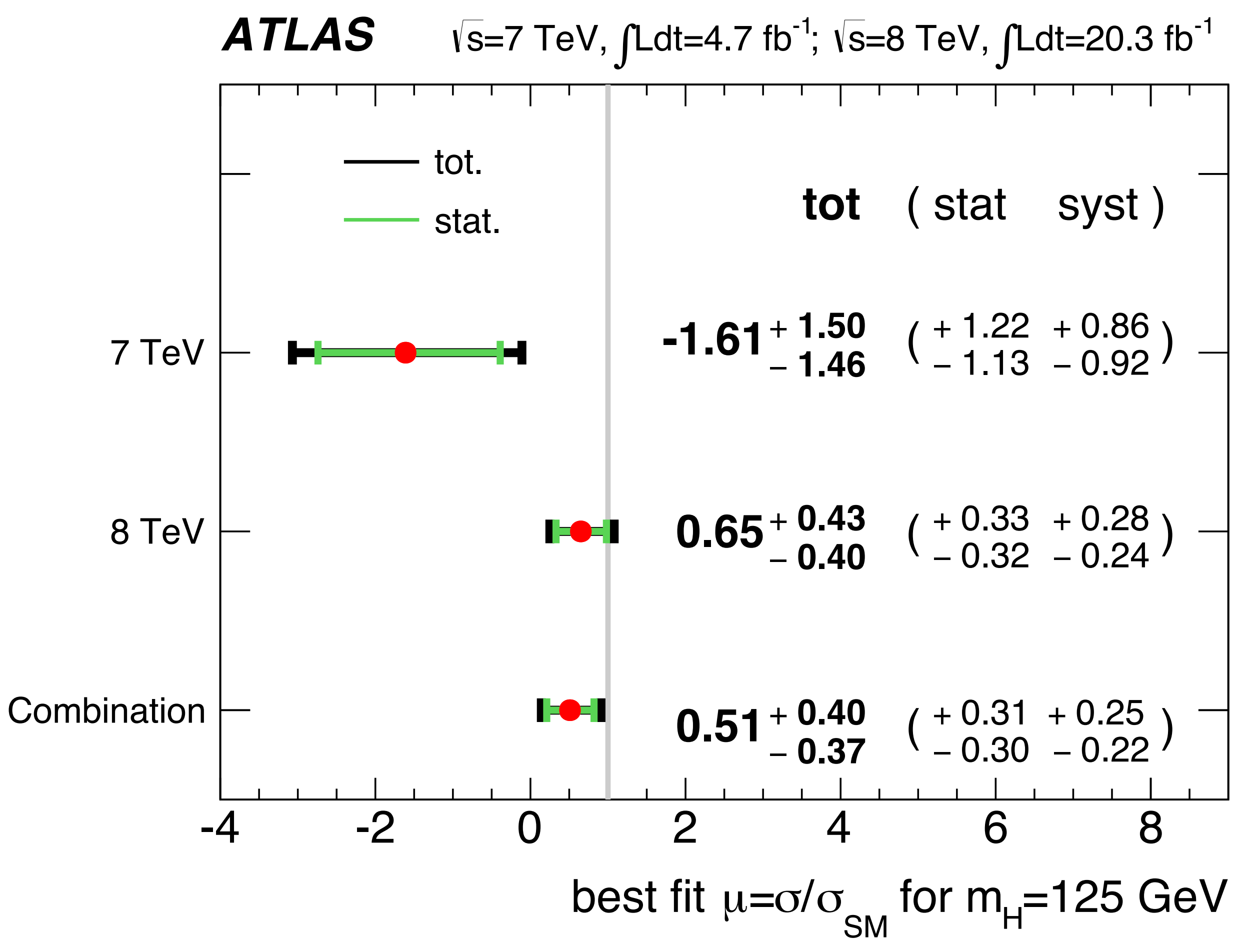
Yields scale factors

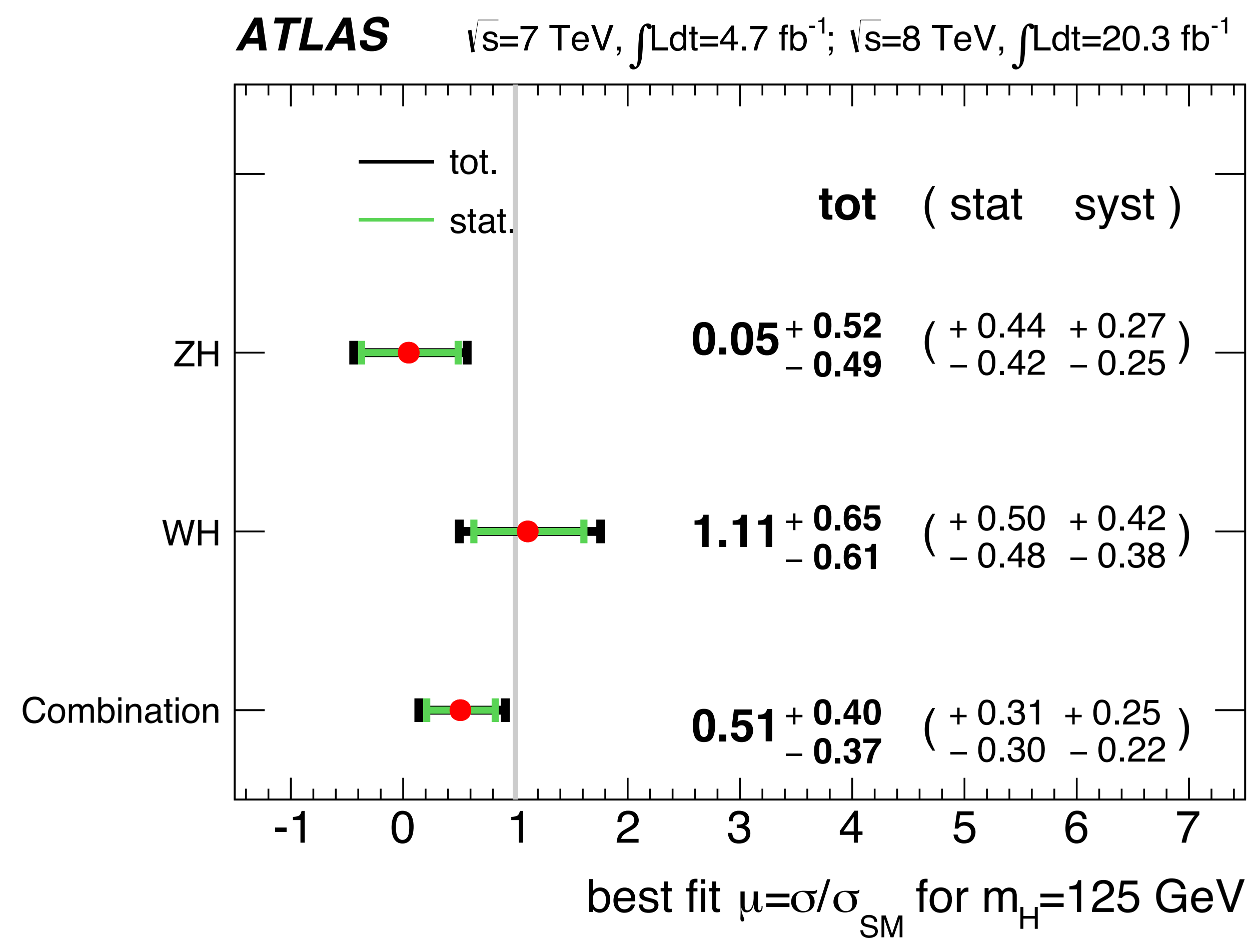
Process	Scale factor
$t\bar{t}$ 0-lepton	1.36 ± 0.14
$t\bar{t}$ 1-lepton	1.12 ± 0.09
$t\bar{t}$ 2-lepton	0.99 ± 0.04
Wbb	0.83 ± 0.15
Wcl	1.14 ± 0.10
Zbb	1.09 ± 0.05
Zcl	0.88 ± 0.12



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

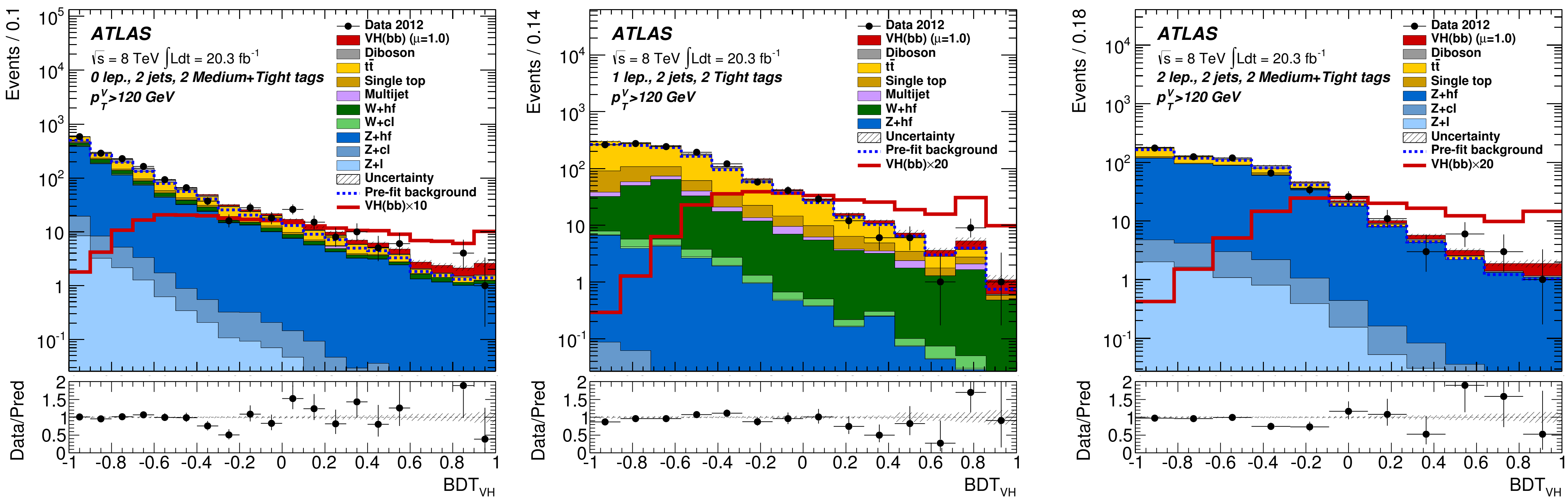
Separate 7, 8 TeV measurements; combination of 0-lepton, 2-lepton channels





$H \to b\bar{b}$ (4)

BDT output distributions in most discriminating 0-, 1-, 2-lepton regions



Systematic uncertainties mostly determined from generator comparisons:

- $t\bar{t}$, single top: normalisations (floating for 2-jet, 3/2 ratio constrained to 20%), separately for 0+1 and 2-lepton channels; m_{bb} and $p_T(V)$ shapes
- Z+jets: 2-jet Z+bb, Z+cl floated in fit; 3/2 ratios constrained to 20% (26%); non-bb fractions in Z+HF constrained to 12%; half of $\Delta\varphi(j_1, j_2)$ / full $p_T(Z)$ reweighting
- W+jets: half of (full) $\Delta\varphi(j_1, j_2)$ reweighting for W+l, W+cl (W+HF); m_{bb} and $p_T(W)$ shapes; non-bb fractions in W+HF constrained to 35% (W+bl), 12% (W+bc, cc)
- signal: scale, PDF, parton shower