Ricerca del bosone di Higgs in associazione con un bosone vettore con il rivelatore ATLAS a LHC

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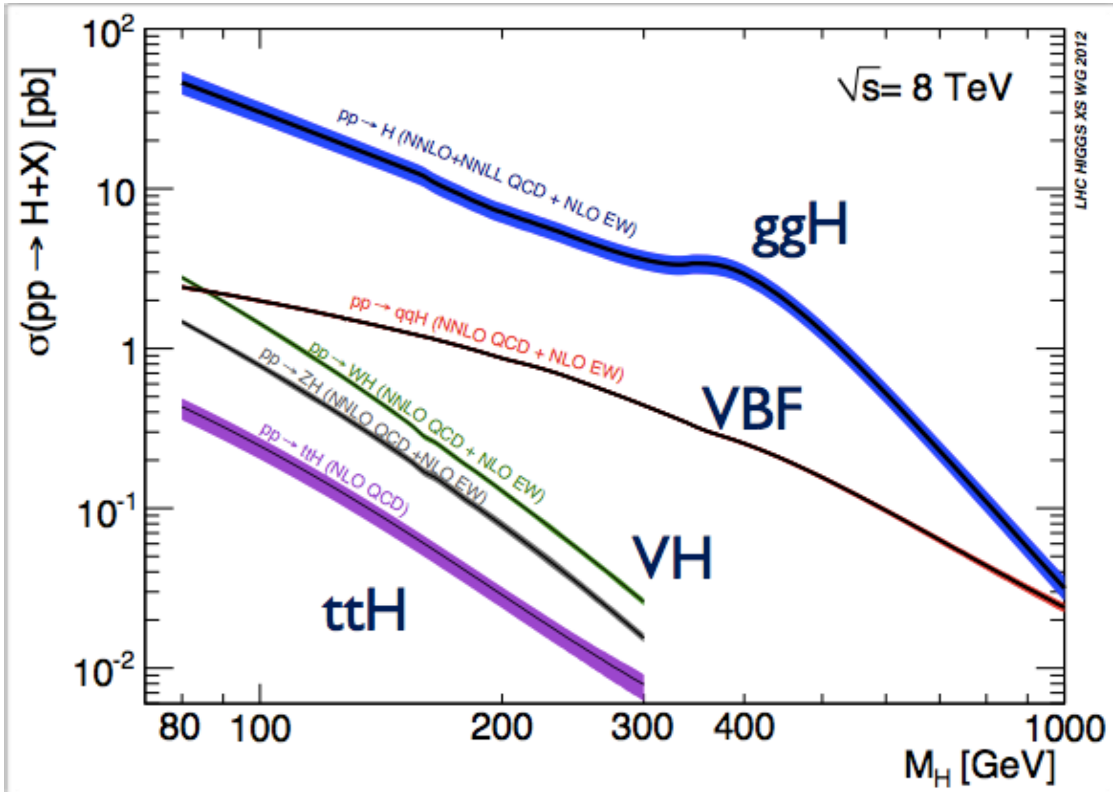
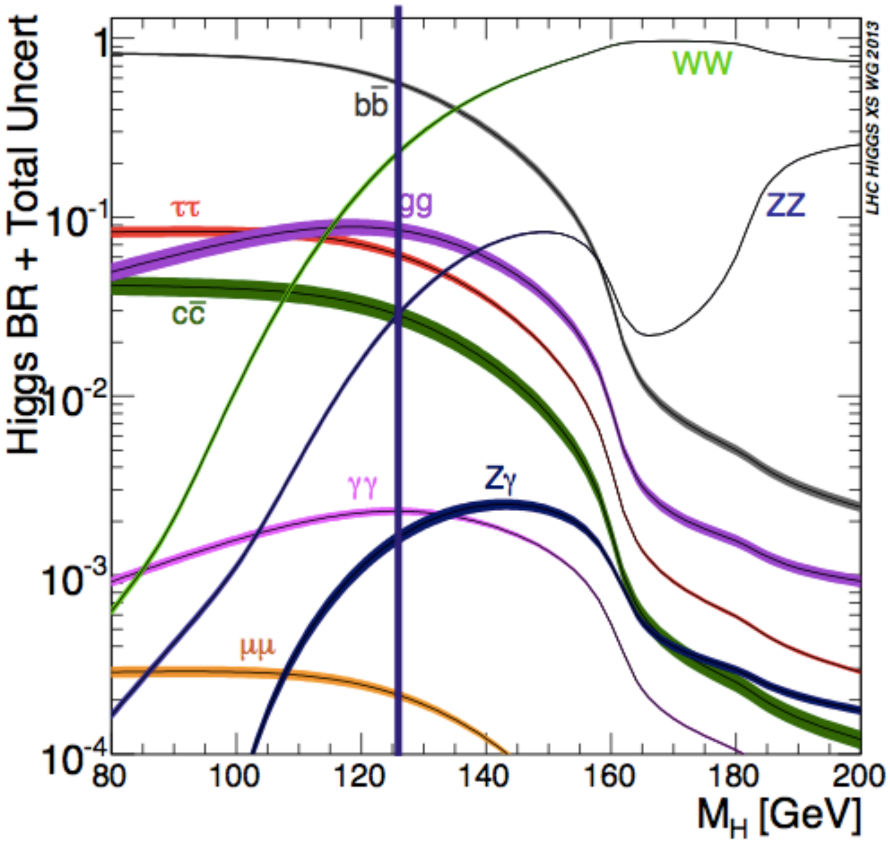
Bosone di Higgs: canali di produzione



σ(pb) @125 GeV	7 TeV	8 TeV
ggF	15	19
VBF	1.2	1.6
WH	0.57	0.70
ZH	0.33	0.41
ttH	0.09	0.13

- VH: accesso diretto agli accoppiamenti del bosone di Higgs con i bosoni di gauge
- Nessuna evidenza di segnale VH osservata finora a LHC
- CFD e D0 @ Tevatron: eccesso di eventi in produzione associata (W/Z H) nel canale H->bb con significanza 2.8 σ per mH= 125 GeV (Phys.Rev.Lett.109(2012)071804)

Bosone di Higgs: canali di decadimento



(m_H=125.5GeV)	BR(%)
$H \to \gamma\gamma$	0.23
$H \to ZZ$	2.8
$H \to WW$	22
$H \to \tau\tau$	6.2
$H \to bb$	57

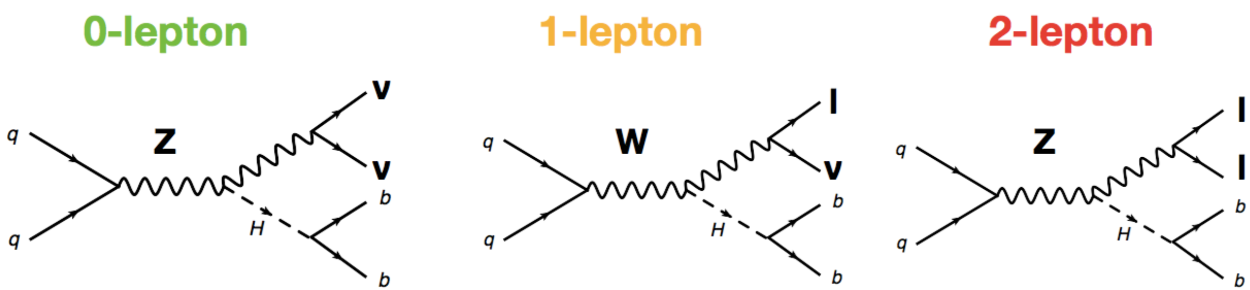
In questo talk:
- VH, H->bb
- VH, H->WW

- H→WW: il bosone di Higgs si accoppia solo a bosoni vettori sia nel vertice di produzione che nel vertice di decadimento
- H→bb: produzione associata permette di discriminare il segnale dal fondo di eventi multijet. Misura dell'accoppiamento ai fermioni

VH, H->bb – Strategia di analisi

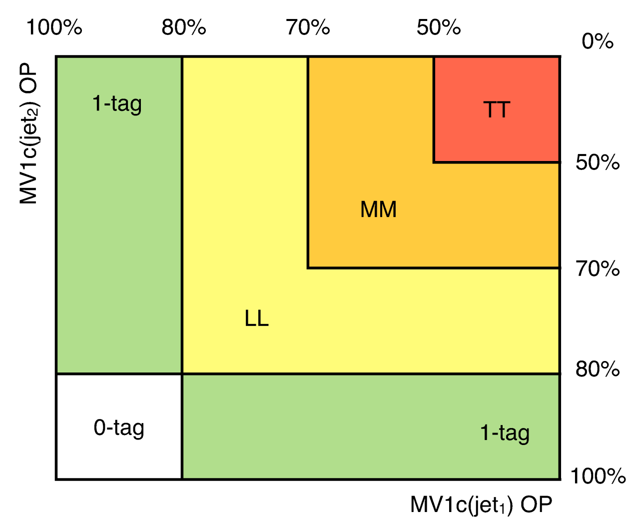
Full 2011+2012 datasets:
7 TeV: L = 4.7 fb^{-1}
8 TeV: L = 20.3 fb^{-1}

- Analisi separata in diverse categorie/classi di eventi per aumentare la sensibilità
- Tre canali:



MV1c: algoritmo di b-tagging (NN) per identificaz di quark b e c all'interno di un jet
4 punti di lavoro (OP): ε= 50%,60%,70%,80%

- Due regioni in pTV
  <120 GeV, > 120 GeV (s/b migliore per alti pTV)
- Due regioni in n.jets (|η|<2.5, pT > 20 GeV)
  2,3 jets
- Quattro regioni in n. b-jets (i.e. jets originati da quark b)
  1 b-tag, 2 b-tag (LL, MM, TT)
  1 b-tag: regioni di controllo
- Variabili discriminanti:
  1 b-tag: MV1c
  2 b-tag: BDT, mjj



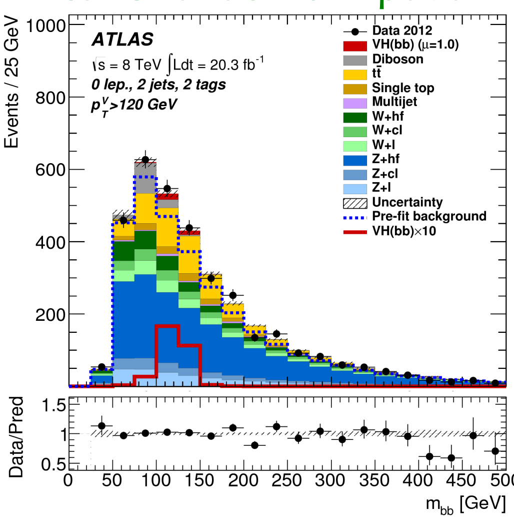
Selezione con 3 OP: Loose L (ε=80%), Medium M (ε=70%), Tight T (ε=50%)

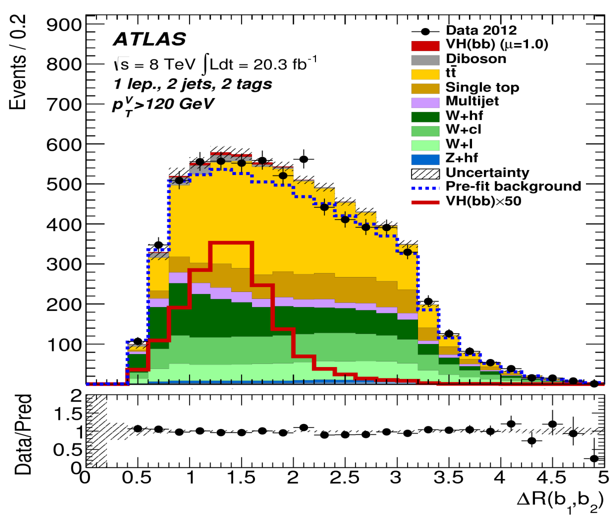
VH, H->bb – Strategia di analisi (II)

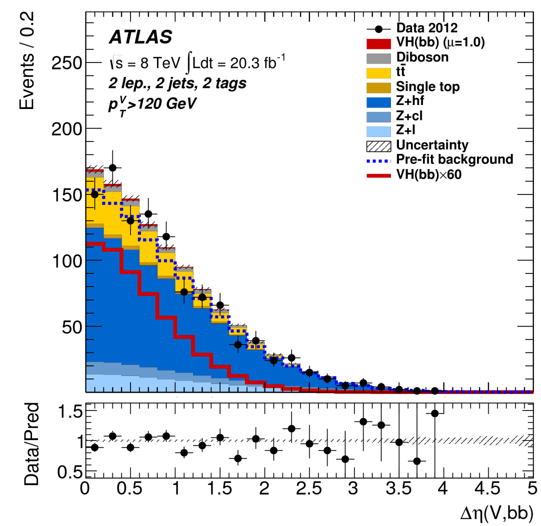
- Selezione comune: DR(jj) > 0.7 per ridurre fondo V+jets
- 0,1-lep: tagli su ptmiss/Emiss per ridurre fondo multijet
- 2-lep: mll compatibile con mZ
- Risoluz mbb: muon-in-jet correction, fit cinematico (2-lep)
- Categorie 2b-tag: analisi multivariata, Boosted Decision Tree (BDT) con 17 variabili di input. Variabile più discriminante: mbb. Separaz angolare tra i due jets piccola nel segnale (soprattutto a pT alti) -> discriminaz fondo top
- Info del b-tagging usate come bin di input al BDT
- Miglioramento rispetto ad un solo OP ~15%, BDT~ +30%

Variable	0-Lepton	1-Lepton	2-Lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\lvert\Delta\eta(b_1, b_2)\rvert$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\lvert\Delta\eta(V, bb)\rvert$			×
H_T	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
$MV1c(b_1)$	×	×	×
$MV1c(b_2)$	×	×	×
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

Alcune variabili di input al BDT:







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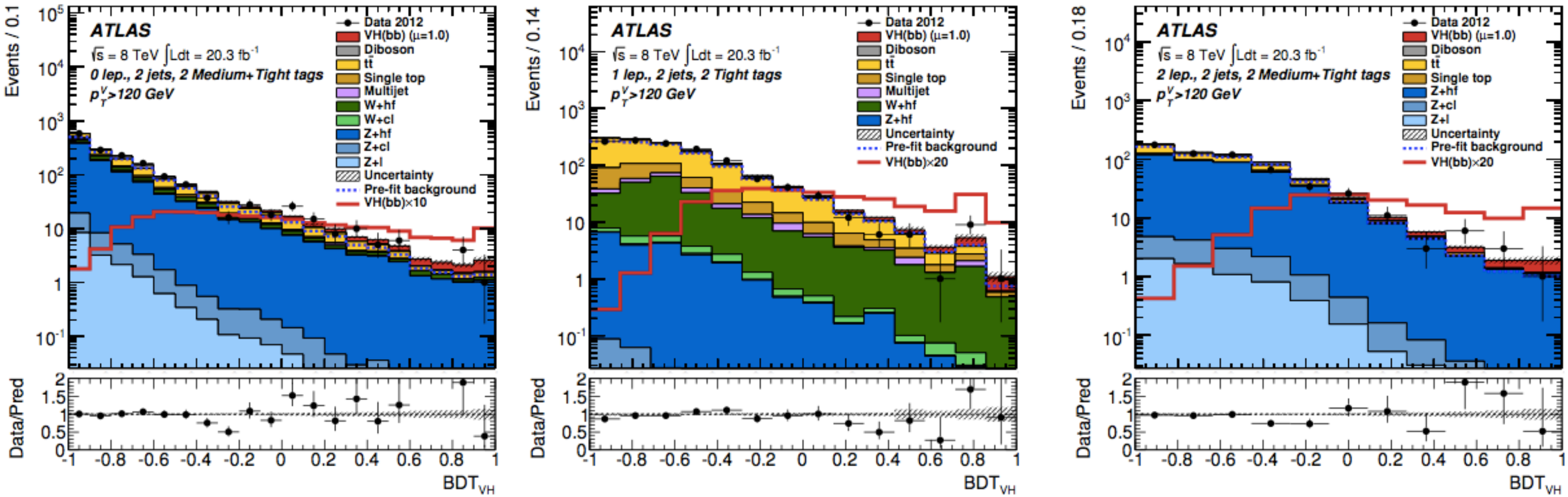
VH, H->bb – Strategia di analisi (III)

- Distribuzioni di output del BDT per le regioni 0-,1-,2-lep più discriminanti:



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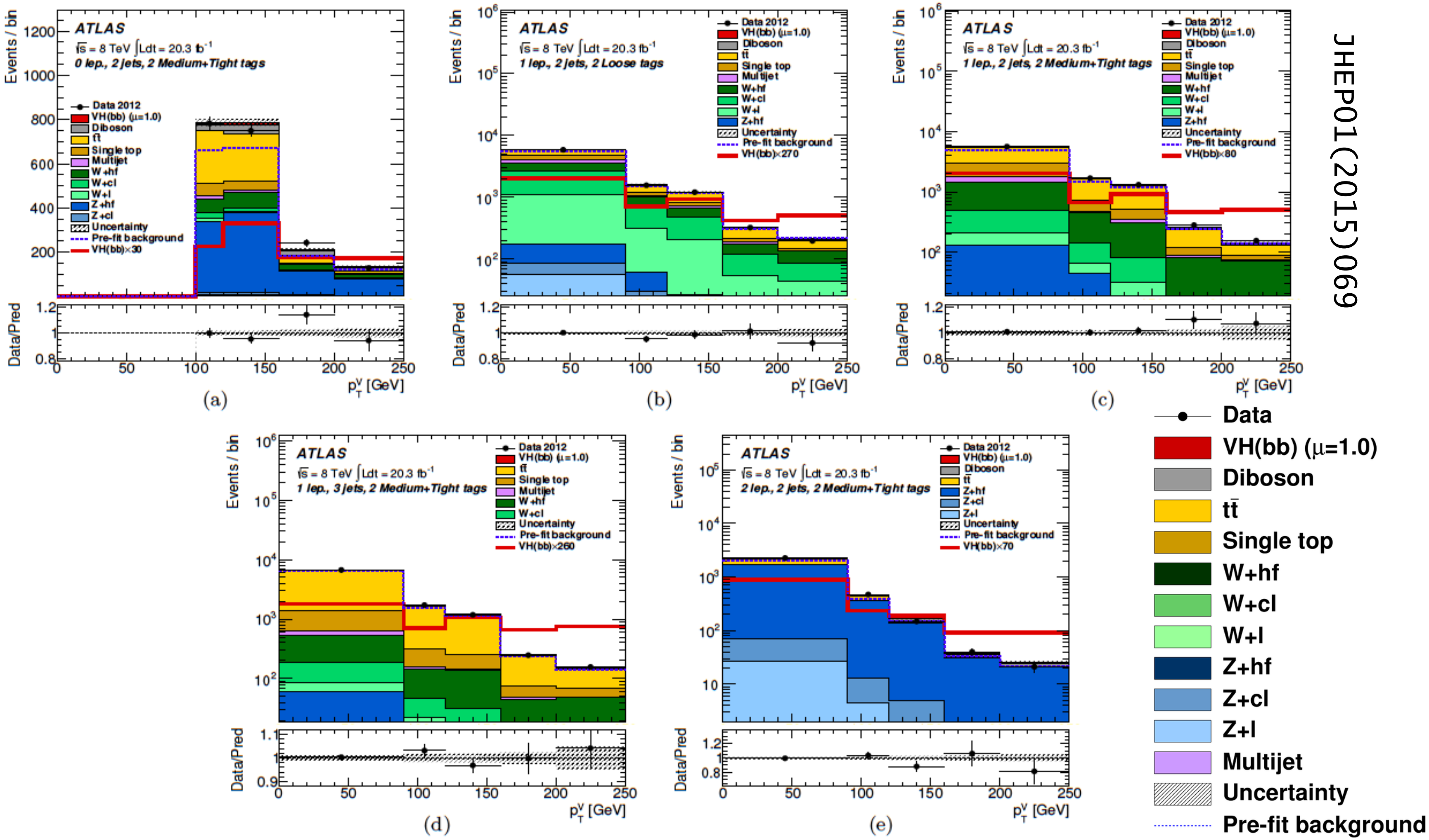
- BDT output ri-binnato: bin più fini nelle regioni con più alto contributo di segnale
- Accettanza per il segnale dopo i tagli di analisi:

$m_H = 125$ GeV at $\sqrt{s} = 8$TeV				
Process	Cross-section × BR [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$q\bar{q} \to (Z \to \ell\ell)(H \to b\bar{b})$	14.9	–	1.3	8.9
$gg \to (Z \to \ell\ell)(H \to b\bar{b})$	1.3	–	0.9	7.2
$q\bar{q} \to (W \to \ell\nu)(H \to b\bar{b})$	131.7	0.3	3.9	
$q\bar{q} \to (Z \to \nu\nu)(H \to b\bar{b})$	44.2	3.8	–	–
$gg \to (Z \to \nu\nu)(H \to b\bar{b})$	3.8	5.8	–	–

VH, H->bb – Stima dei fondi

- La composizione del fondo varia molto a seconda della categoria
- Fondi principali: Zbb, tt, Wbb (quest'ultimo soprattutto nella cat 1-lep)



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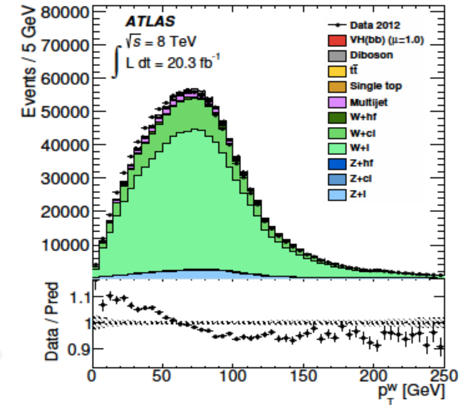
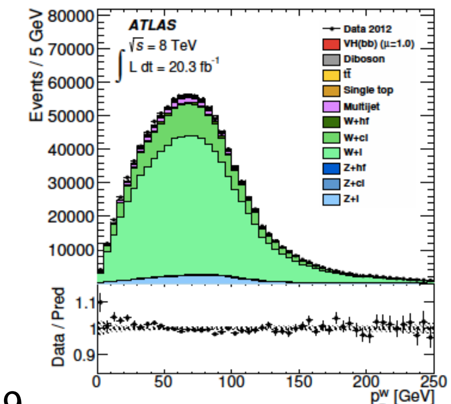
VH, H->bb – Stima dei fondi (II)

- Eventi 0-tag usati per studiare modelling dei fondi Vjets (simulati con SHERPA)
  - modelling di pT(W) migliora dopo reweighting di Δφ(j1, j2) applicato a Wl,Wcl nel canale 1-lep
  - Procedura simile per Zl, Zb, Zc nel canale 2-lep
- Reweighting applicato allo spettro in pT per il fondo tt (POWHEG)

prima



dopo



- Fondo multijet -> data driven
- Wjets, Zjets, ttbar -> normalizzati in regioni di controllo -> e.g. shape MV1c in regioni 1 b-tag:

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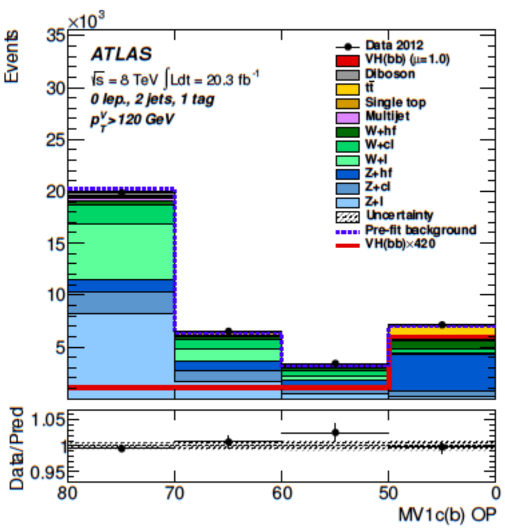

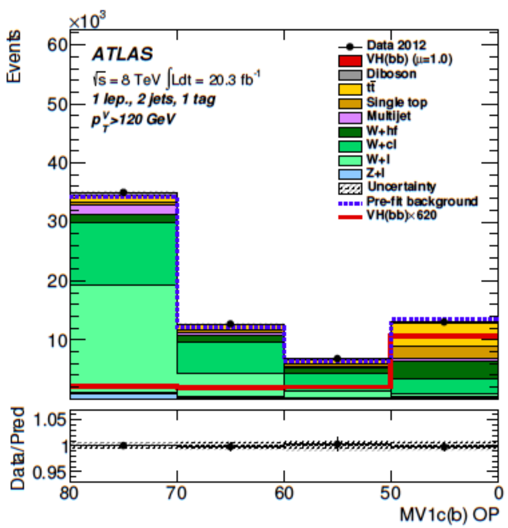

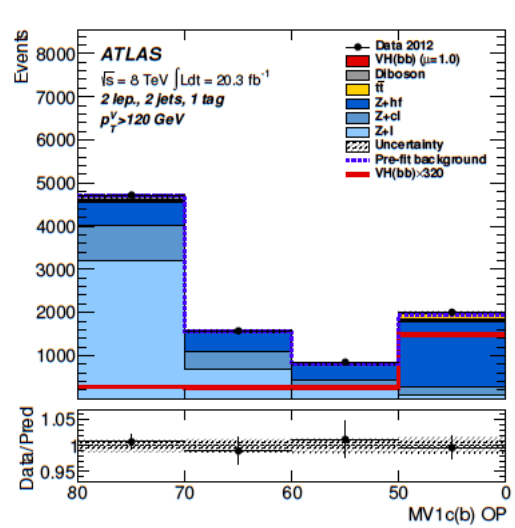

VH, H->bb – Procedura di fit

✧ Metodo utilizzato: profile likelihood ratio

$$L(\mu, \boldsymbol{\theta}) = \prod_i^{N_{SR}} P_s(N_i \mid \mu S_i(\boldsymbol{\theta}) + B_i(\boldsymbol{\theta})) \times A(\boldsymbol{\theta})$$

μ= signal strength = $\sigma/\sigma SM$
θ= nuisance parameters (per incertezze sistematiche)
$A(\theta)$ dipende dal tipo di sistematica (tipicamente constraint gaussiani)

✧ Fit simultaneo di tutte le regioni alle distribuzioni di BDT, mjj, MV1c:

✧ 24 regioni di segnale (SR) 2 b-tag -> variabile usata nel fit: BDT output
   - ✧ Unica cat MM+TT per 0-lep pT>120 GeV e per 2-lep

✧ 3 regioni di segnale (SR) cut based 2 b-tag -> variabile usata nel fit: mjj
   - ✧ 0-lep 100-120 GeV (MM, LL, TT): mjj usata invece del BDT

✧ 11 regioni di controllo (CR) 1-tag -> variabile usata nel fit: MV1c
   - ✧ 1-lep 2-tag 3-jets: agisce in pratica come control region (fondo tt dominante)

✧ ~170 nuisance parameters (NP) per descrivere l'effetto delle incertezze sistematiche

✧ 7 fattori di normalizzazione (NF) per i fondi (lasciati liberi nel fit): tt(0-lep), tt(1-lep), tt(2-lep), Wbb, Wcl, Zbb, Zcl

Process	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9
Data	368550	141166	111865	20740	5538	2245	382	41	4
Signal	29	43	96	57	58	62	32	10.7	2.3
Background	368802	140846	111831	20722	5467	2189	364	37.9	3.4
S/B	8×10^{-5}	0.0003	0.0009	0.003	0.01	0.03	0.09	0.3	0.7

Bin delle SR ri-mappati in bin di log(S/B)

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VH, H->bb – Risultati

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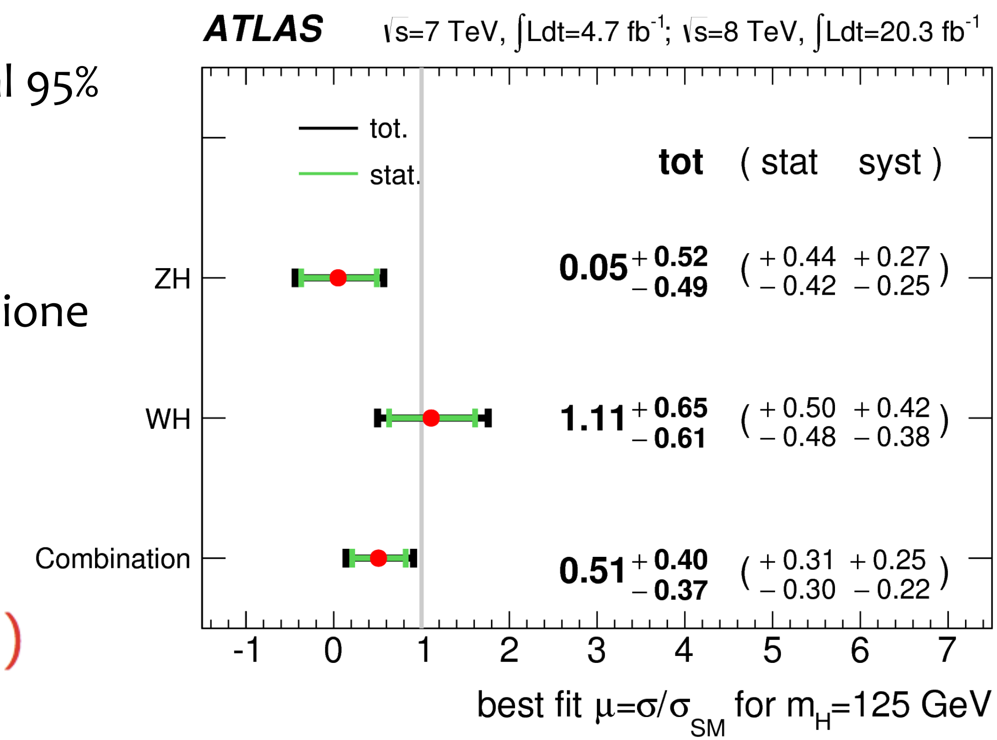
- Limiti superiori sulla sezione d'urto al 95% CL per mH= 125 GeV:
  obs 1.2 x SM, exp 0.8 x SM
- Significanza per mH=125 GeV (deviazione rispetto all'ipotesi di solo fondo):
  obs 1.4 σ, exp 2.6 σ
- Signal strength per mH=125 GeV:

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



Incertezze sistematiche con maggiore impatto sulla signal strength:

- Incertezze sul modeling dei fondi: distribuzione mjj di W+hf per pT>120 GeV, rapporto W+bl/bb per pT>120 GeV, normalizzazione Wbb, distribuzione pTV di W+hf nella cat 3-jet, rapporto Z+bl/bb nella cat 2-jet
- Incertezze teoriche sul segnale: variazioni di accettanza (parton shower modeling)
- Incertezze sperimentali: risoluzione in energia dei b-jet

VH, H->bb – Risultati (II)

- BDT training specifico per ogni massa
- Analisi 7 TeV solo cut based (mjj, no BDT)

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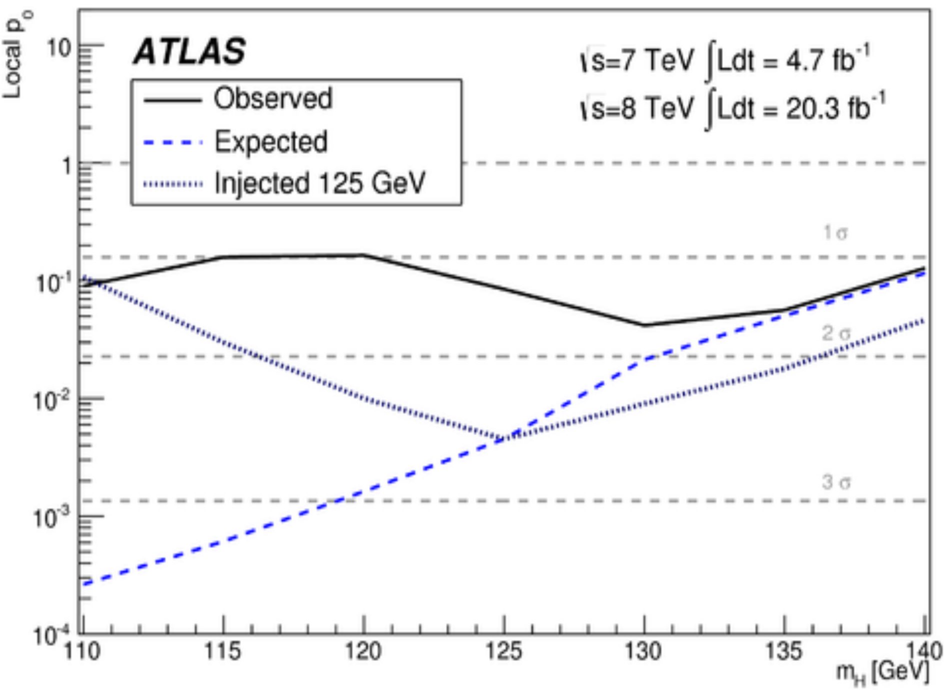
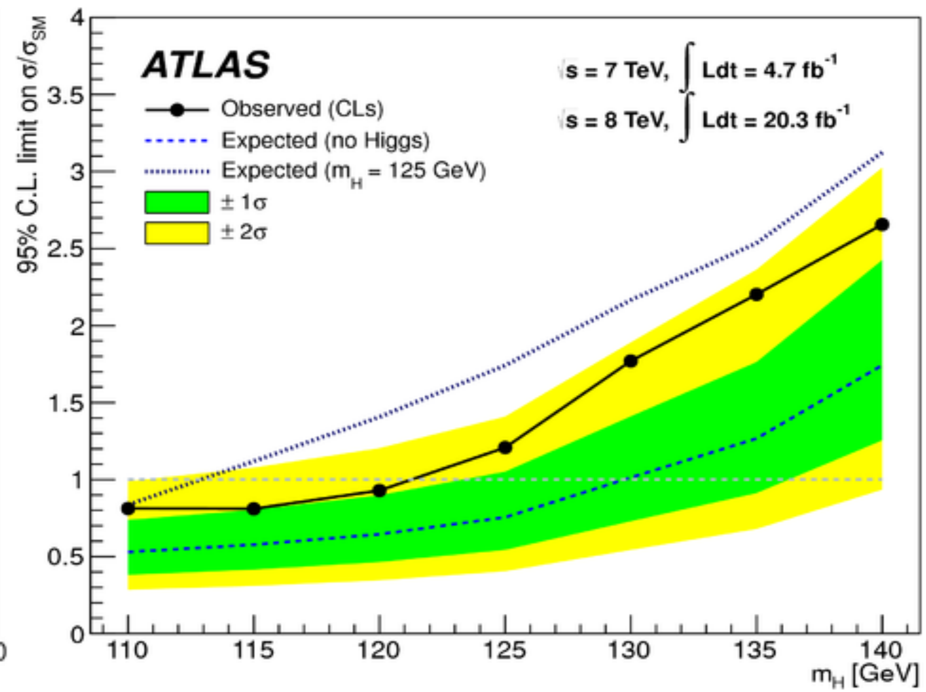




Cross checks:

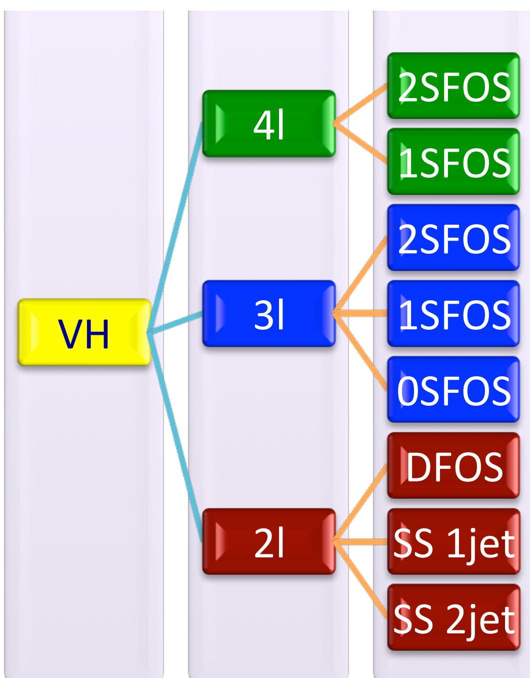
- VZ, Zbb
- Analisi cut based per 8 TeV (mjj)

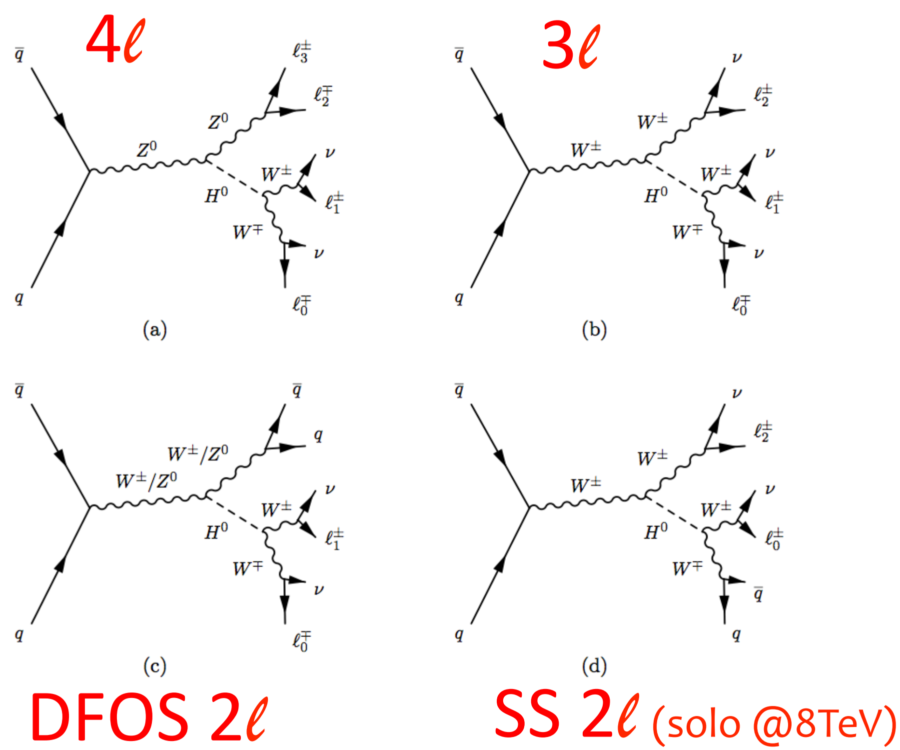
VH, H->WW – Strategia di analisi

Full 2011+2012 datasets:
7 TeV: L = 4.7 fb^{-1}
8 TeV: L = 20.3 fb^{-1}

- Differenti categorie con diversa composizione di segnale e fondo
  - SFOS: Same flavor opposite sign
  - DFOS: Different flavor opposite sign
  - SS: Same sign

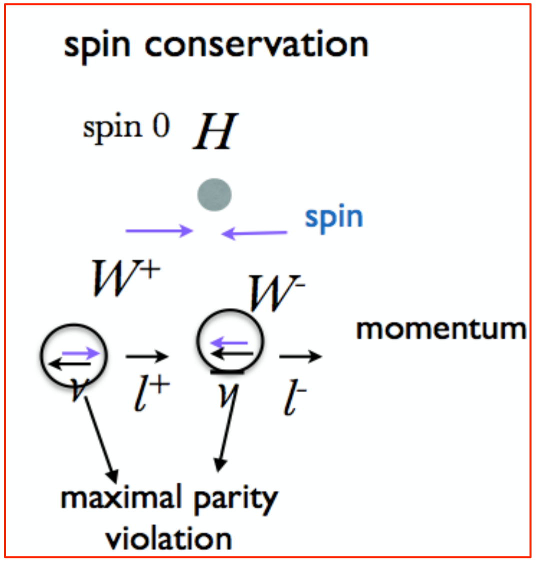
Process	$\sigma \times$ Br [pb] 8 TeV, 7 TeV
Higgs	
VH ($H \to WW^*$)	0.25, 0.20
ggF ($H \to WW^*$)	0.44, 0.34
VBF ($H \to WW^*$)	0.035, 0.027
$t\bar{t}$H ($H \to WW^*$)	0.028, 0.023





VH, H->WW – Strategia di analisi (II)

- b-tag veto per ridurre fondo tt
- Tagli sulla MET per ridurre fondo Z+jets
- Veto su MZ per ridurre fondi WZ, ZZ, Z+jets
- Spin-0 dell'Higgs + natura V-A dell'interazione debole -> leptoni da H->WW emessi con angolo di apertura piccolo -> tagli topologici su m_{ll}, $m_{lJ(J)}$, $\Delta\phi$



- Accettanza del segnale dopo I tagli di analisi:
  W(H→lvlv) 3.7%, W(H→lvqq) 0.3%, Z(H→lvlv) 1.9%
- Contaminazione di H→tautau non trascurabile (trattato come fondo SM)
- Contributo ggF nel canale DFOS 2l ~50% del segnale (trattato come fondo e fittato)

(a) 8 TeV data analysis — Eventi di segnale attesi dopo I tagli di analisi

Channel	4ℓ		3ℓ			2ℓ		
Category	2SFOS	1SFOS	2SFOS	1SFOS	0SFOS	DFOS	SS2jet	SS1jet
$WH\ (H \to WW^*)$	—	—	0.563	1.43	1.284	1.48	1.02	1.84
$ZH\ (H \to WW^*)$	0.208	0.235	0.168	0.179	0.145	0.668	0.017	0.195
$VH\ (H \to WW^*)$	0.208	0.235	0.731	1.62	1.428	2.15	1.04	2.04
(all categories)	9.44							

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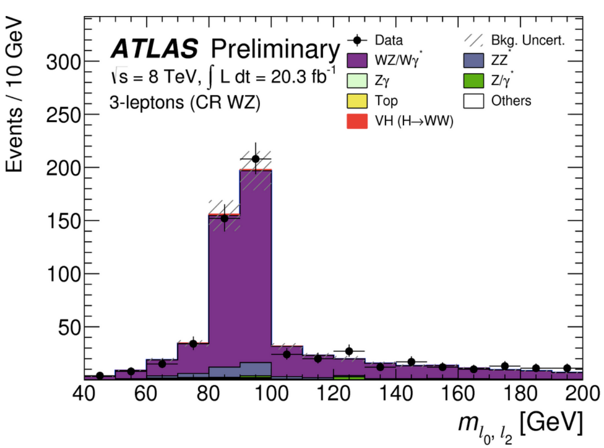
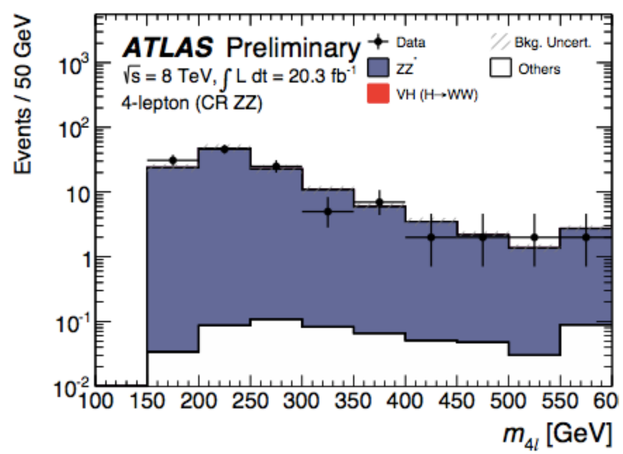
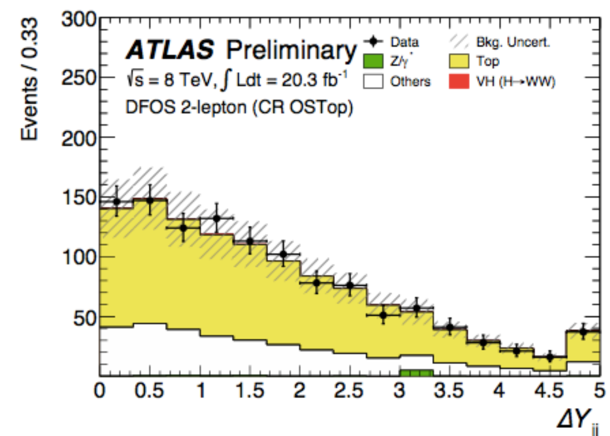
VH, H->WW – Stima dei fondi

- Fondi principali:
  - 4l : ZZ (85%), VVV(15%)
  - 3l : WZ, top, VVV (WZ dominante in 1-,2-SFOS)
  - 2l DFOS : top (50%), Z→tt (20%), WW(10%)
  - 2l SS : WZ (30%), W+jets (30%), Wg (15%)
- Stima dei fondi:
  - Da predizioni MC (e.g. VVV)
  - Normalizzazione con regioni di controllo ortogonali alle regioni di segnale (e.g. top nel canale 2-lep DFOS, ZZ* nel canale 4-lep, WZ/Wg* nei canali 3-lep e 2-lep SS)
    - Fattori di normalizzazione estratti con un fit simultaneo a tutte le regioni
  - Data driven: multijets and W+jet







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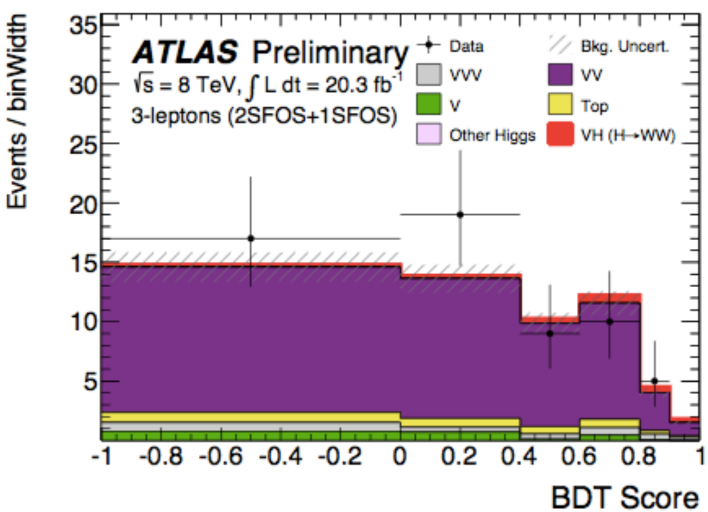
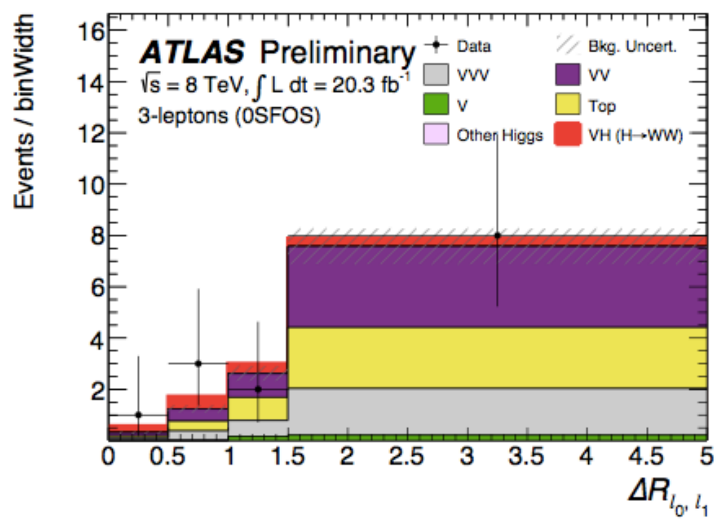
VH, H->WW – SR 3-lep

- 3l-0SFOS: categoria più sensibile dell’analisi
- 3l-2SFOS e 3l-1SFOS: analisi multivariata basata sul BDT per distinguere il segnale dal fondi WZ/ZZ
- Per le categorie 3-lep viene fatta un’analisi di shape: nel fit vengono utilizzate le distribuzioni di
  - BDT output nei canali 3l-2SFOS e 3l-1SFOS
  - DR_{l0l1} nel canale 3l-0SFOS
  - Ogni bin è trattato come una singola regione di segnale nella likelihood. La larghezza dei bin è determinata in modo da massimizzare la sensibilità
- Per le altre categorie (2-lep DFOS, 2-lep SS, 4-lep) l’analisi è di tipo cut&count





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VH, H->WW – Procedura di fit

- Metodo utilizzato: profile likelihood ratio
  - Categorie 3l-2SFOS e 1SFOS divise in bin di BDT (per un totale di 12 bin)
  - Categoria 3l-0SFOS divisa in bin di DR_{l0l1} (per un totale di 4 bin)
  - Cut&count per le altre categorie
  - Ognuna delle categorie 2l-SS2jet and 2l-SS1jet è divisa in 4 sotto-categorie a seconda del flavor dei leptoni leading e sub-leading (mm, em, me, ee)
  - In totale vengono fittate 27 regioni di segnale e 14 regioni di controllo (8 TeV), + 19 regioni di segnale e 8 regioni di controllo (7 TeV)
- Risultati ottenuti fittando simultaneamente anche I canali ggF/VBF dell'analisi H->WW
- Tutti I risultati sono ottenuti assumendo m_H=125.36 GeV

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(a) 8 TeV data analysis

Process	4ℓ		3ℓ			2ℓ		
Category	2SFOS	1SFOS	2SFOS	1SFOS	0SFOS	DFOS	SS2jet	SS1jet
Higgs								
$VH\ (H \to WW^*)$	0.208 ± 0.025	0.235 ± 0.029	0.73 ± 0.10	1.61 ± 0.18	1.43 ± 0.16	2.15 ± 0.24	1.04 ± 0.17	2.04 ± 0.28
$VH\ (H \to \tau\tau)$	0.0126 ± 0.0036	0.0087 ± 0.0030	0.057 ± 0.010	0.152 ± 0.022	0.248 ± 0.034	—	0.0365 ± 0.0080	0.270 ± 0.035
ggF	—	—	0.076 ± 0.015	0.085 ± 0.018	—	2.43 ± 0.49	—	—
VBF	—	—	—	—	—	0.180 ± 0.025	—	—
ttH	—	—	—	—	—	—	—	—
Background								
V	—	—	0.22 ± 0.16	1.87 ± 0.62	0.37 ± 0.15	13.7 ± 3.6	7.9 ± 3.7	14.9 ± 4.8
VV	1.17 ± 0.20	0.306 ± 0.059	19.2 ± 3.0	27.5 ± 4.1	4.70 ± 0.57	10.1 ± 1.6	11.2 ± 2.1	26.3 ± 3.7
VVV	0.117 ± 0.044	0.102 ± 0.036	0.80 ± 0.28	2.15 ± 0.74	2.93 ± 0.29	—	—	0.467 ± 0.049
Top	0.014 ± 0.011	—	0.91 ± 0.26	2.43 ± 0.63	3.72 ± 0.91	23.9 ± 3.9	0.75 ± 0.19	1.34 ± 0.51
Others	—	—	—	—	—	2.31 ± 0.95	0.71 ± 0.30	0.60 ± 0.24
Total	1.30 ± 0.25	0.41 ± 0.10	21.1 ± 3.6	34.0 ± 6.0	11.7 ± 1.8	49.9 ± 5.4	20.6 ± 4.6	43.6 ± 6.1
Observed events	0	3	22	38	14	63	25	62

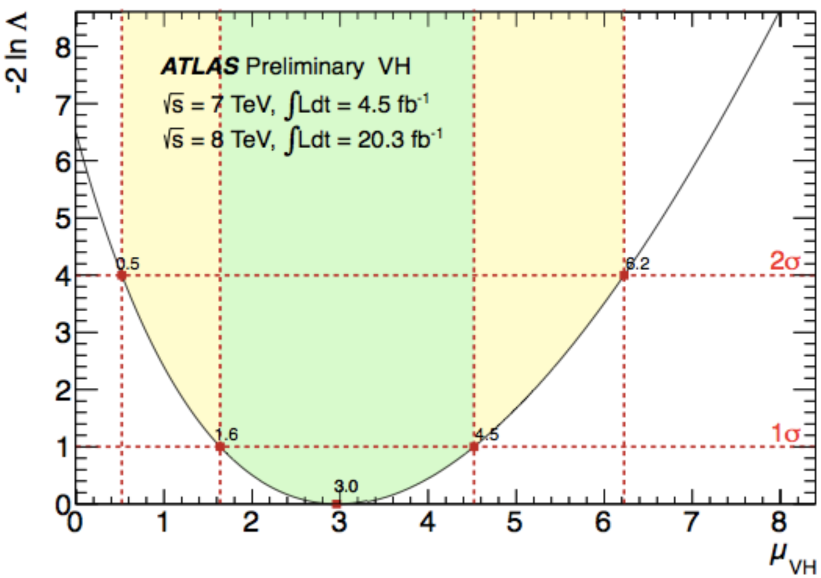
VH, H->WW – Risultati

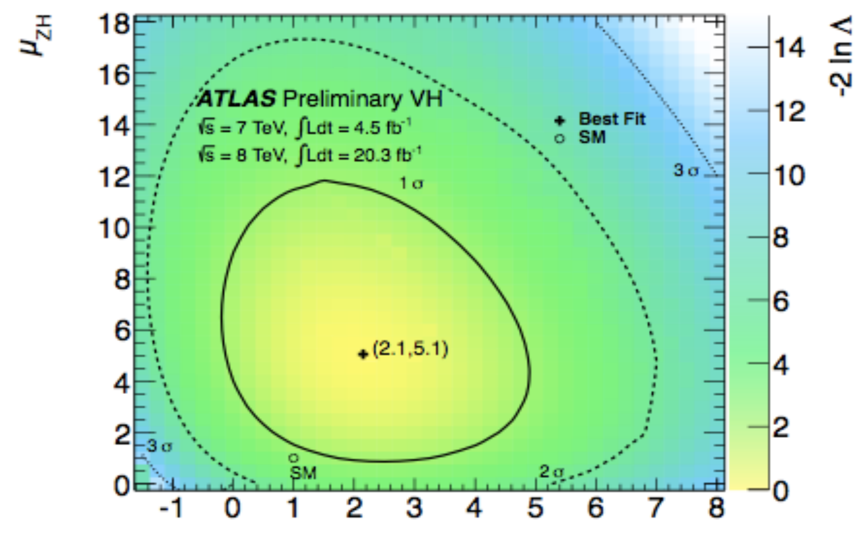
$$\mu_{WH} = 2.1^{+1.5}_{-1.3}\,(\text{stat.})^{+1.2}_{-0.8}\,(\text{sys.}),\ \ \mu_{ZH} = 5.1^{+3.8}_{-3.0}\,(\text{stat.})^{+1.9}_{-0.9}\,(\text{sys.})$$

$$\mu_{VH} = 3.0^{+1.3}_{-1.1}\,(\text{stat.})^{+1.0}_{-0.7}\,(\text{sys.})$$

Significanza [obs (exp)]:

- VH 2.5 σ (0.93 σ)
- WH 1.4 σ (0.77 σ)
- ZH 2.0 σ (0.30 σ)





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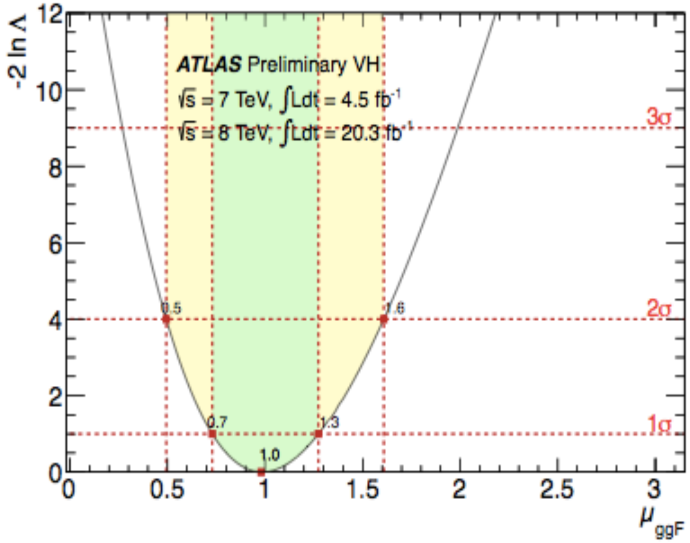
Principali incertezze teoriche:

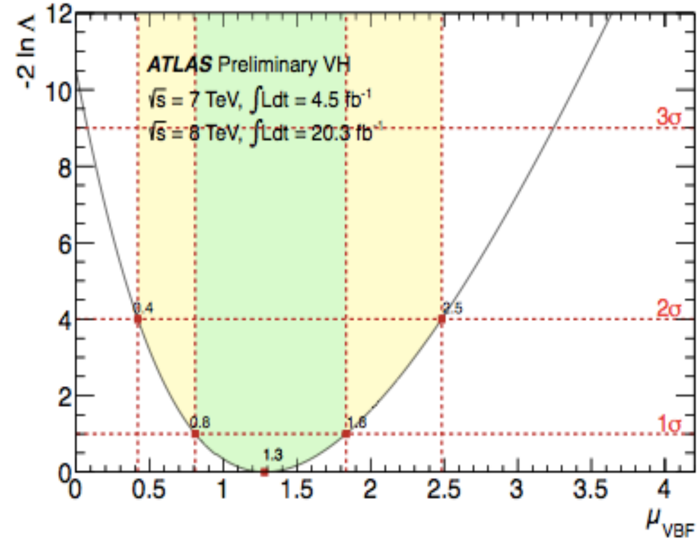
- VH: NLO2LO ~10%, BR(H->WW) ~4%
- Fondi: MC modeling

Principali incertezze sperimentali:

- VH: JES+JER, ricostruzione leptoni
- Fondi: JES+JER, fake rate in canali 2l (prob di identificare jet come leptoni)

H->WW – Combinazione ggF/VBF/VH





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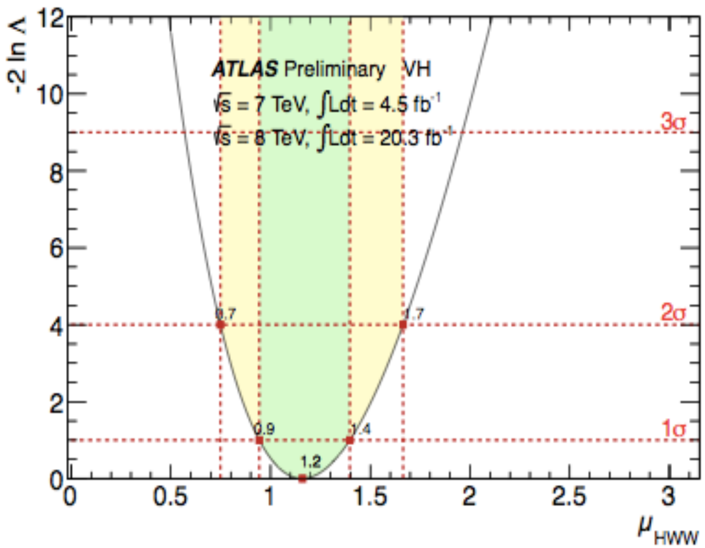


Signal strength:

μ ggF $= 0.98^{+0.29}_{-0.26}(stat)^{+0.22}_{-0.18}(syst)$

μ VBF $= 1.28^{+0.55}_{-0.47}(stat)^{+0.32}_{-0.25}(syst)$

μ ggF+VBF+VH $= 1.16^{+0.24}_{-0.21}(stat)^{+0.18}_{-0.15}(syst)$

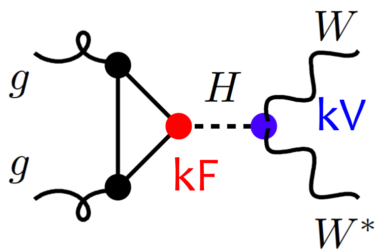
Significanza [obs (exp)]:

- ggF 4.2 σ (4.4 σ)
- VBF 3.2 σ (2.6 σ)
- ggF+VBF+VH 6.5 σ (5.9 σ)

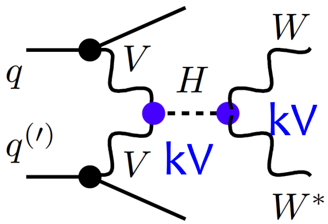
-> vs ggF+VBF 6.1 σ (5.8 σ) ATLAS-HIGGS-2013-13

VH+ggF/VBF, H->WW – Couplings

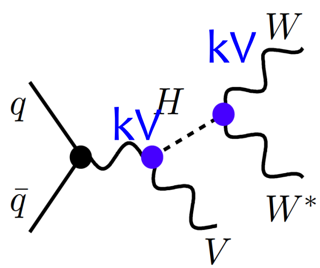
k- framework: deviazione dallo SM parametrizzata con fattori di scala k



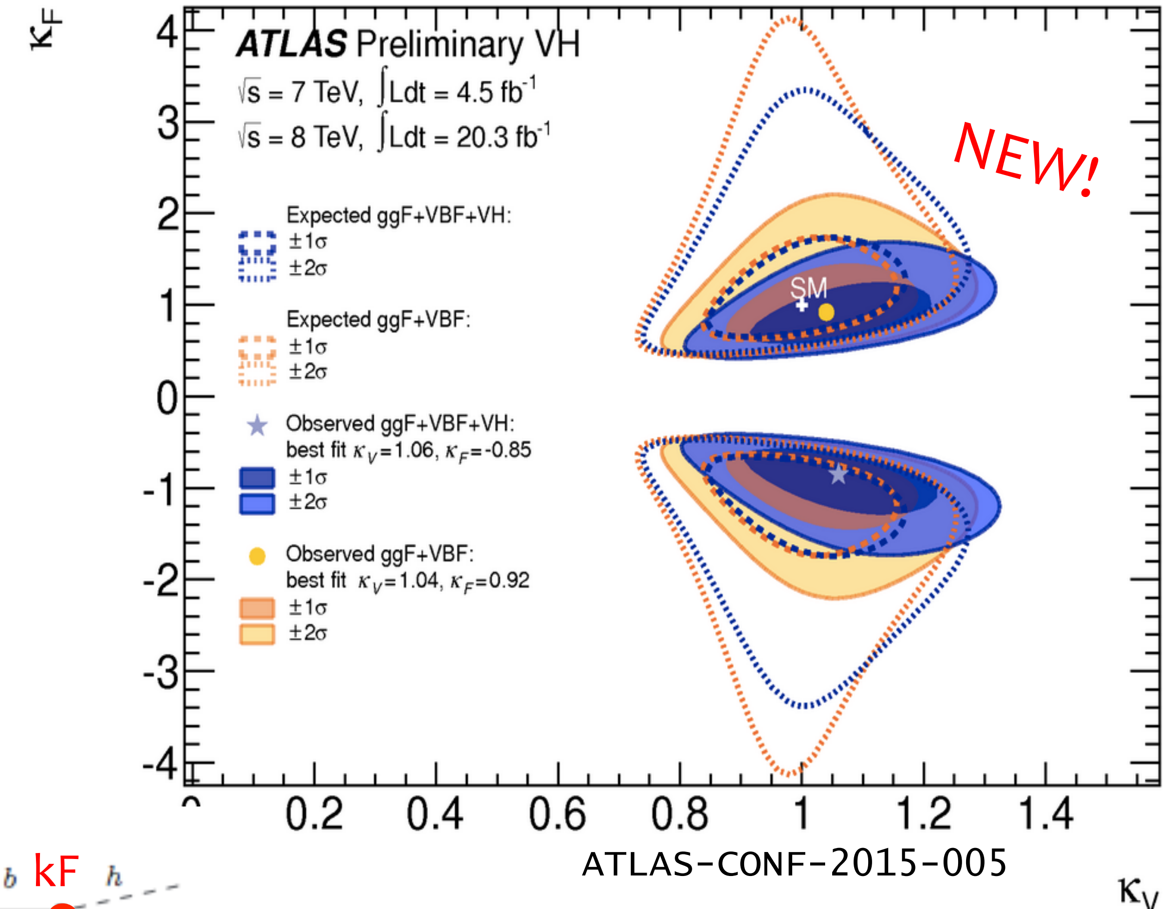
ggF production



VBF production

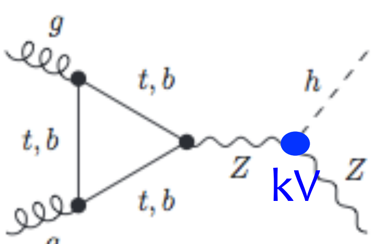


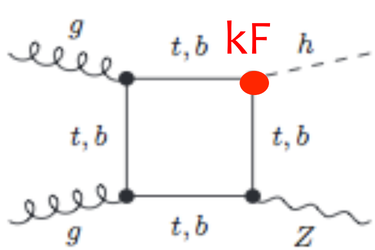
VH production



ATLAS-CONF-2015-005

σ ggZH: funzione complessa di kV e kF – sensibile a segno di kF attraverso interferenze





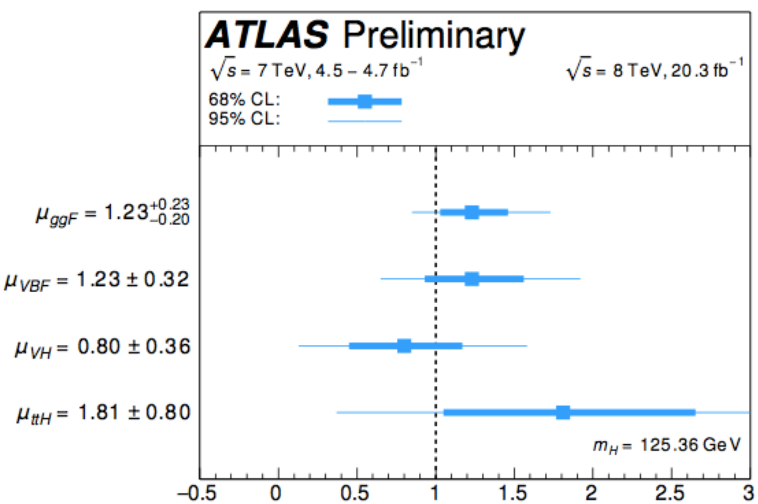
$$|k_F| = 0.85^{+0.26}_{-0.20} \quad |k_V| = 1.06^{+0.10}_{-0.10}$$

ATLAS risultati combinati – Signal strength

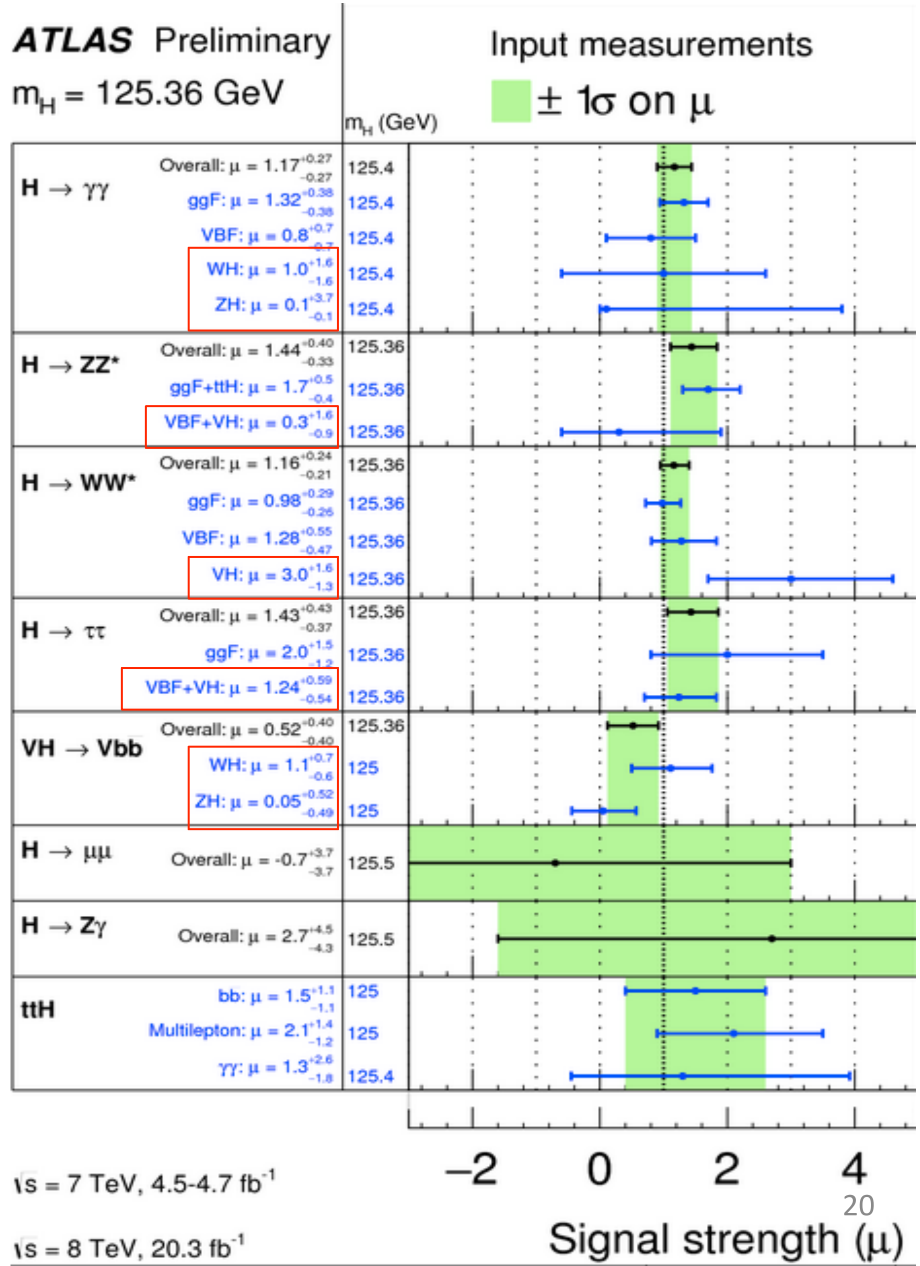
- Categorie VH presenti in H->γγ, H->ZZ
- H->tautau: piccolo contributo di segnale VH nella categoria VBF

- Combinando I risultati ATLAS per tutti I canali di decadimento:

	Significance	
Mechanism	Obs	Exp
VH	2.6	3.1

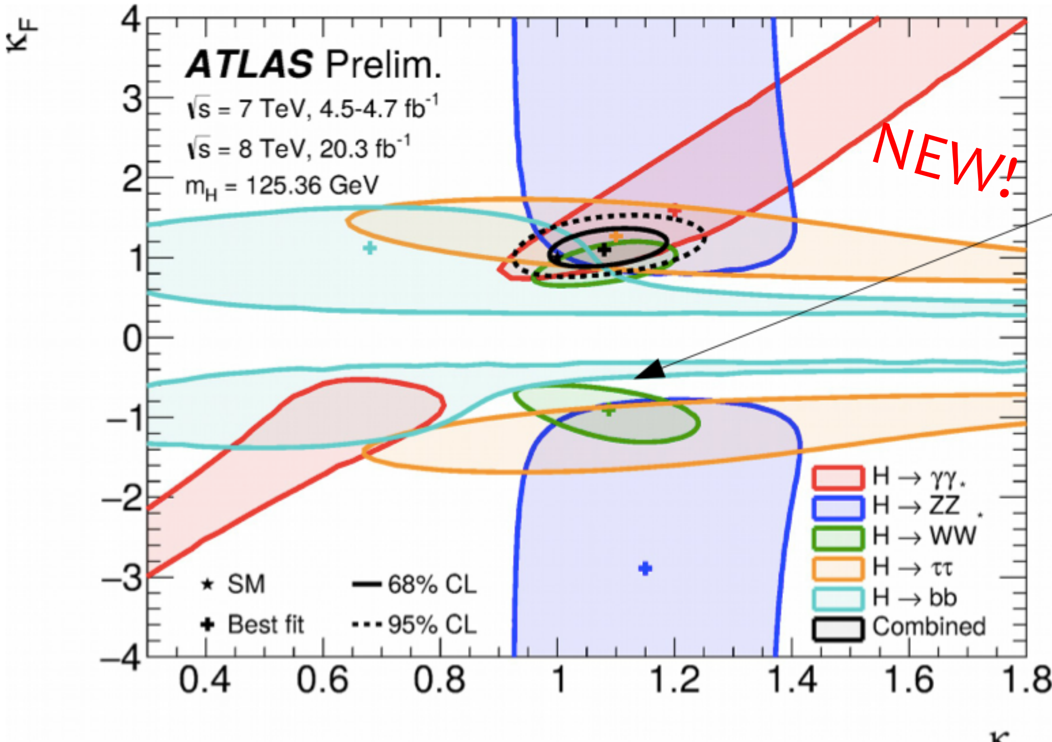


ATLAS-CONF-2015-007



ATLAS risultati combinati – Couplings

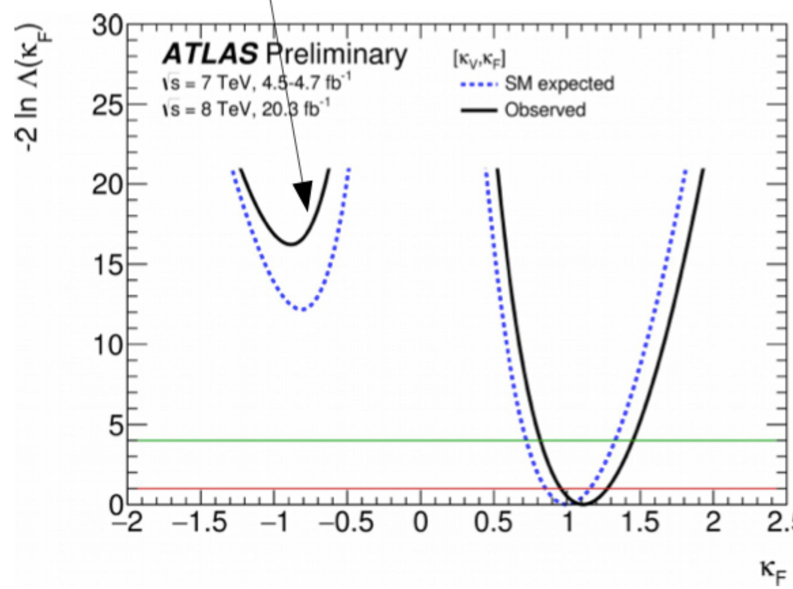
H->bb sensibile a kF



ATLAS-CONF-2015-007

Segno relativo di kF risolto da interferenze in H->gg, tH, gg->ZH

Soluzione non –SM sfavorita a 4σ



Conclusioni

- Sono stati presentati i risultati delle analisi VH,H-> bb e VH,H-> WW in ATLAS utilizzando tutti i dati raccolti nel Run1
- Molti miglioramenti rispetto alle versioni precedenti: tecniche multivariate (BDT), catgorizzazione, analisi che sfruttano le forme delle distribuzioni, calibrazione dell'algoritmo di b-tagging
- Le analisi sono ancora limitate statisticamente
- Run2: la difficoltà maggiore per entrambi I canali sarà il controllo del fondo da top

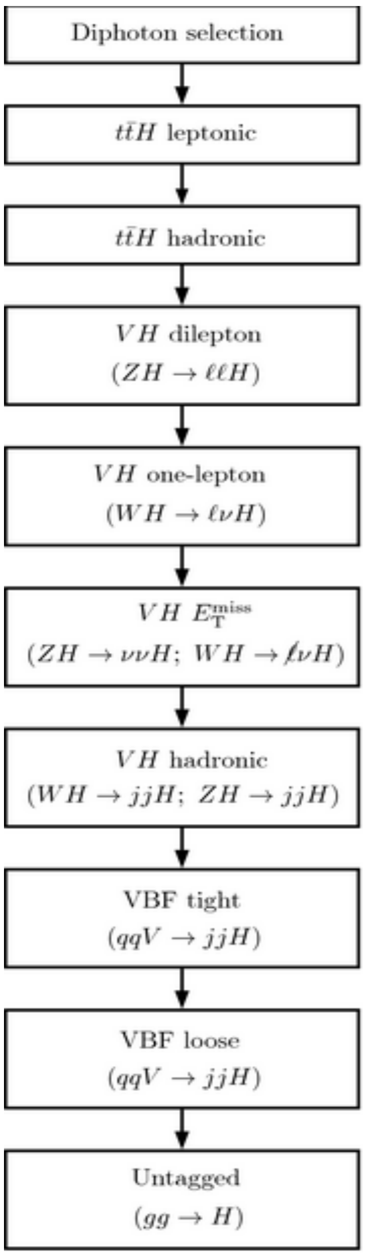
BACKUP SLIDES

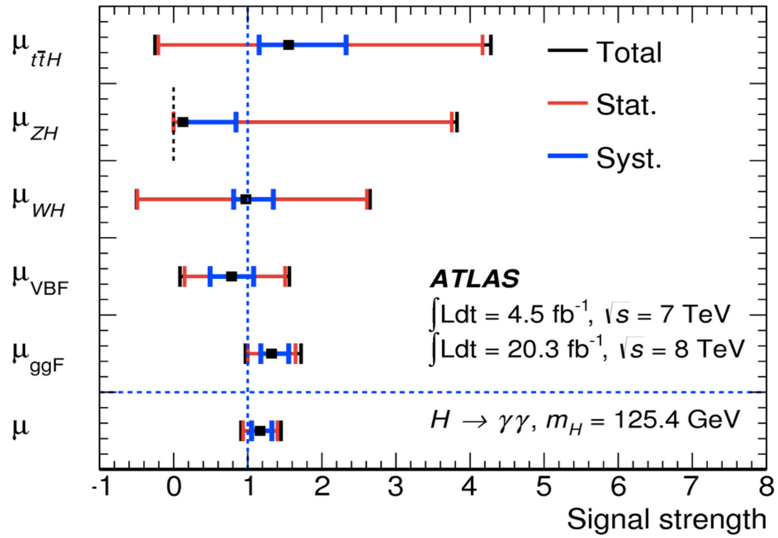
References:

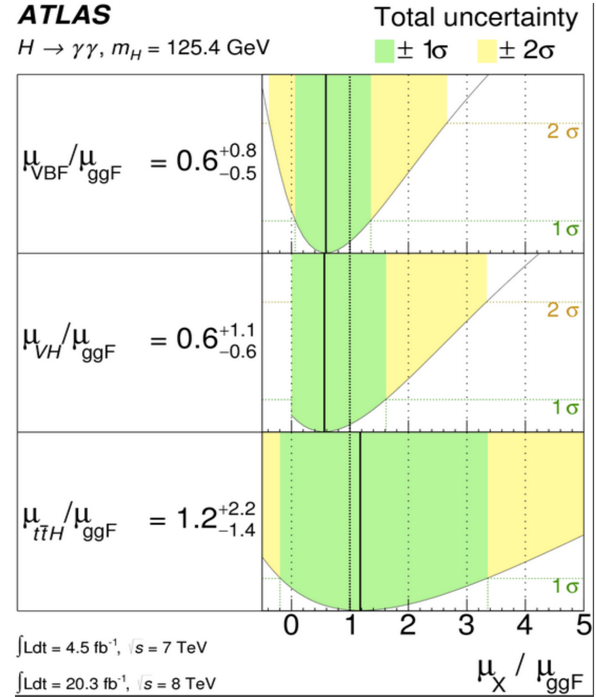
- ✓ VH, Hbb: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-23/
- ✓ VH, HWW https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-005/
- ✓ Hgg: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-08/
- ✓ Htautau: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-32/
- ✓ HZZ: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-21/
- ✓ HWW: http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-13/

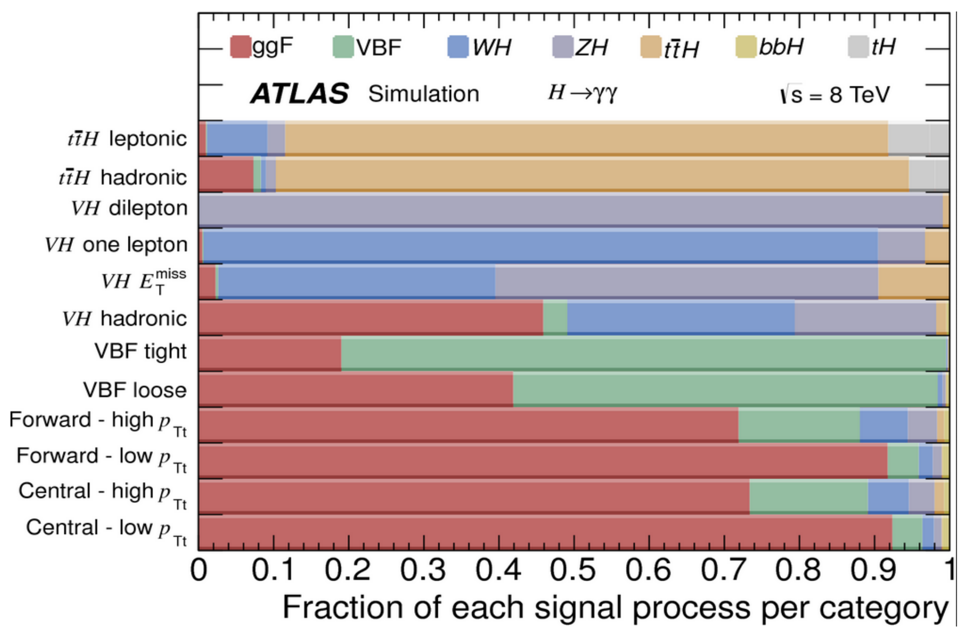
VH in Hγγ

Phys.Rev.D90(2014)112015

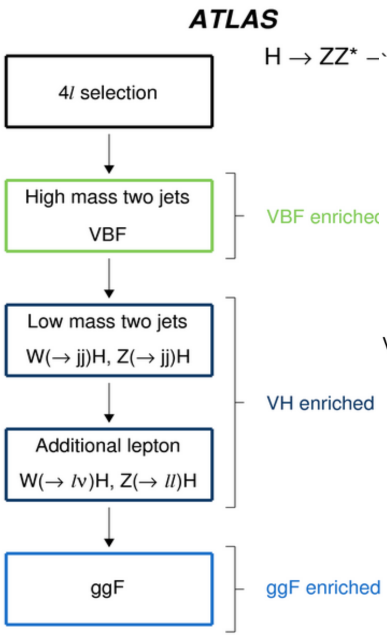


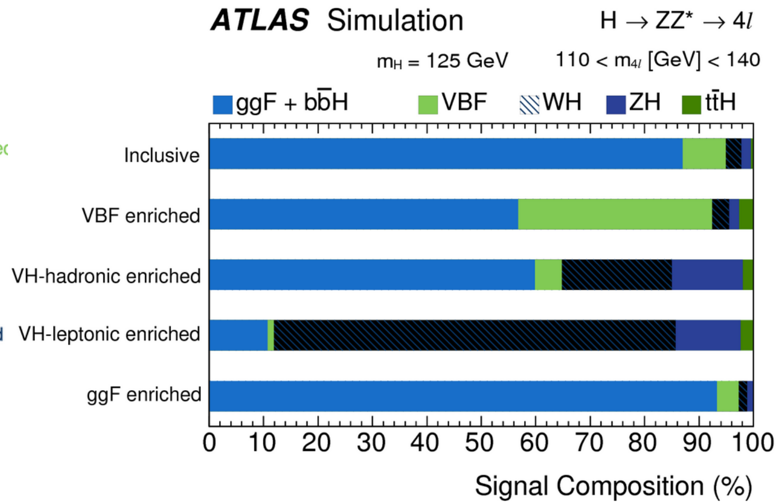


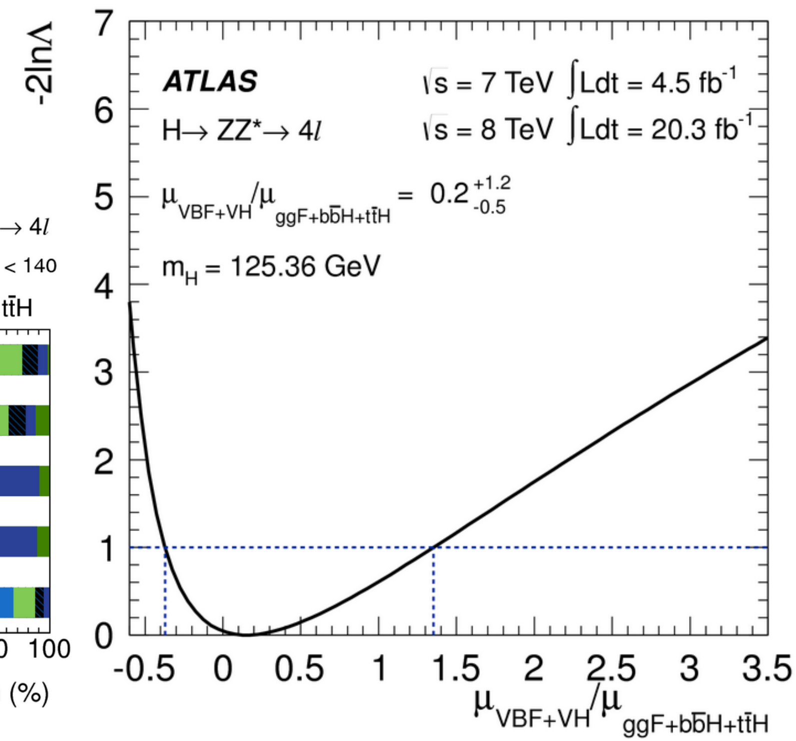




VH in HZZ Phys.Rev.D91(2015)012006







Enriched category	Signal $ggF+b\bar{b}H+t\bar{t}H$	Signal VBF	Signal VH-hadronic	Signal VH-leptonic	Background ZZ^*	Background $Z+$jets, $t\bar{t}$	Total expected	Observed
$120 < m_{4\ell} < 130$ GeV								
VBF	1.18 ± 0.37	0.75 ± 0.04	0.083 ± 0.006	0.013 ± 0.001	0.17 ± 0.03	0.25 ± 0.14	2.4 ± 0.4	3
($\mathrm{BDT}_{VBF} > 0$)	0.48 ± 0.15	0.62 ± 0.04	0.023 ± 0.002	0.004 ± 0.001	0.06 ± 0.01	0.10 ± 0.05	1.26 ± 0.15	1
VH-hadronic	0.40 ± 0.12	0.034 ± 0.004	0.20 ± 0.01	0.009 ± 0.001	0.09 ± 0.01	0.09 ± 0.04	0.80 ± 0.12	0
VH-leptonic	0.013 ± 0.002	< 0.001	< 0.001	0.069 ± 0.004	0.015 ± 0.002	0.016 ± 0.019	0.11 ± 0.02	0
ggF	12.8 ± 1.3	0.57 ± 0.02	0.24 ± 0.01	0.11 ± 0.01	7.1 ± 0.2	2.7 ± 0.4	23.5 ± 1.4	34
$m_{4\ell} > 110$ GeV								
VBF	1.4 ± 0.4	0.82 ± 0.05	0.092 ± 0.007	0.022 ± 0.002	20 ± 4	1.6 ± 0.9	$24. \pm 4.$	32
($\mathrm{BDT}_{VBF} > 0$)	0.54 ± 0.17	0.68 ± 0.04	0.025 ± 0.002	0.007 ± 0.001	8.2 ± 1.6	0.6 ± 0.3	10.0 ± 1.6	12
VH-hadronic	0.46 ± 0.14	0.038 ± 0.004	0.23 ± 0.01	0.015 ± 0.001	9.0 ± 1.2	0.6 ± 0.2	10.3 ± 1.2	13
VH-leptonic	0.026 ± 0.004	< 0.002	< 0.002	0.15 ± 0.01	0.63 ± 0.04	0.11 ± 0.14	0.92 ± 0.16	1
ggF	14.1 ± 1.5	0.63 ± 0.02	0.27 ± 0.01	0.17 ± 0.01	$351. \pm 20$	16.6 ± 2.2	$383. \pm 20$	420

VH in Hττ ATLAS-HIGG-2013-32

τ lep-lep

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
ggF: $H \to \tau\tau$ $(m_H = 125GeV)$	9.8 ± 3.4	0.73 ± 0.26	0.35 ± 0.14	21 ± 8	2.4 ± 0.9	1.3 ± 0.5
VBF: $H \to \tau\tau$	13.3 ± 4.0	2.7 ± 0.7	3.3 ± 0.9	5.5 ± 1.5	0.95 ± 0.26	0.49 ± 0.13
$WH:\ H \to \tau\tau$	0.25 ± 0.07	< 0.1	< 0.1	3.8 ± 1.0	0.44 ± 0.12	0.22 ± 0.06
$ZH:\ H \to \tau\tau$	0.14 ± 0.04	< 0.1	< 0.1	2.0 ± 0.5	0.21 ± 0.06	0.113 ± 0.031
Total background	980 ± 22	15.4 ± 1.8	5.6 ± 1.4	3080 ± 50	55 ± 4	19.2 ± 2.1
Total signal	24 ± 6	3.5 ± 0.9	3.6 ± 1.0	33 ± 10	4.0 ± 1.2	2.1 ± 0.6
Data	1014	16	11	3095	61	20

τ lep-had

ggF: $H \to \tau\tau$ $(m_H = 125GeV)$	16 ± 6	1.0 ± 0.4	1.2 ± 0.6	60 ± 20	9.2 ± 3.2	10.1 ± 3.4
VBF: $H \to \tau\tau$	31 ± 8	4.5 ± 1.1	9.1 ± 2.2	16 ± 4	2.5 ± 0.6	2.9 ± 0.7
$WH:\ H \to \tau\tau$	0.6 ± 0.4	< 0.1	< 0.1	9.1 ± 2.3	1.3 ± 0.4	1.9 ± 0.5
$ZH:\ H \to \tau\tau$	0.16 ± 0.07	< 0.1	< 0.1	4.6 ± 1.2	0.77 ± 0.20	0.93 ± 0.24
Total background	2760 ± 40	18.1 ± 2.3	10.7 ± 2.7	12860 ± 110	143 ± 6	82 ± 6
Total signal	48 ± 12	5.5 ± 1.3	10.3 ± 2.5	89 ± 26	14 ± 4	16 ± 4
Data	2830	22	21	12952	170	92

τ had-had

ggF: $H \to \tau\tau$ $(m_H = 125GeV)$	8.0 ± 2.7	0.67 ± 0.23	0.53 ± 0.20	21 ± 8	9.1 ± 3.3	1.6 ± 0.6
VBF: $H \to \tau\tau$	12.0 ± 3.1	1.8 ± 0.5	3.4 ± 0.9	6.3 ± 1.6	2.8 ± 0.7	0.52 ± 0.13
$WH: H \to \tau\tau$	0.25 ± 0.07	< 0.1	< 0.1	4.0 ± 1.1	1.9 ± 0.5	0.41 ± 0.11
$ZH:\ H \to \tau\tau$	0.16 ± 0.04	< 0.1	< 0.1	2.4 ± 0.6	1.13 ± 0.30	0.23 ± 0.06
Total background	883 ± 18	3.6 ± 1.3	1.2 ± 1.0	2960 ± 50	143 ± 6	7.0 ± 1.8
Total signal	20 ± 5	2.5 ± 0.6	3.9 ± 1.0	34 ± 10	15 ± 4	2.7 ± 0.8
Data	892	5	6	3020	161	10

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

VH, H->bb – Selections

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Variable	Dijet-mass analysis					Multivariate analysis	
Common selection							
p_T^V [GeV]	0–90	90$^{(*)}$–120	120–160	160–200	> 200	0–120	> 120
$\Delta R(\text{jet}_1, \text{jet}_2)$	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_T^{miss} [GeV]	NU	> 30	> 30			NU	> 30
$\Delta\phi(\boldsymbol{E}_T^{\text{miss}}, \boldsymbol{p}_T^{\text{miss}})$		$< \pi/2$	$< \pi/2$				$< \pi/2$
$\min[\Delta\phi(\boldsymbol{E}_T^{\text{miss}}, \text{jet})]$		–	> 1.5				> 1.5
$\Delta\phi(\boldsymbol{E}_T^{\text{miss}}, \text{dijet})$		> 2.2	> 2.8				–
$\sum_{i=1}^{N_{\text{jet}}=2(3)} p_T^{\text{jet}_i}$ [GeV]		> 120 (NU)	> 120 (150)				> 120 (150)
1-lepton selection							
m_T^W [GeV]	< 120					–	
H_T [GeV]	> 180		–			> 180	–
E_T^{miss} [GeV]	–		> 20		> 50	–	> 20
2-lepton selection							
$m_{\ell\ell}$ [GeV]	83-99					71-121	
E_T^{miss} [GeV]	< 60					–	

Table 2. Event topological and kinematic selections. NU stands for 'Not Used'. (*) In the 0-lepton channel, the lower edge of the second p_T^V interval is set at 100 GeV instead of 90 GeV. For the 1-lepton channel, only the 1-muon sub-channel is used in the $p_T^V < 120$ GeV intervals.

VH, H->bb – BDT input var

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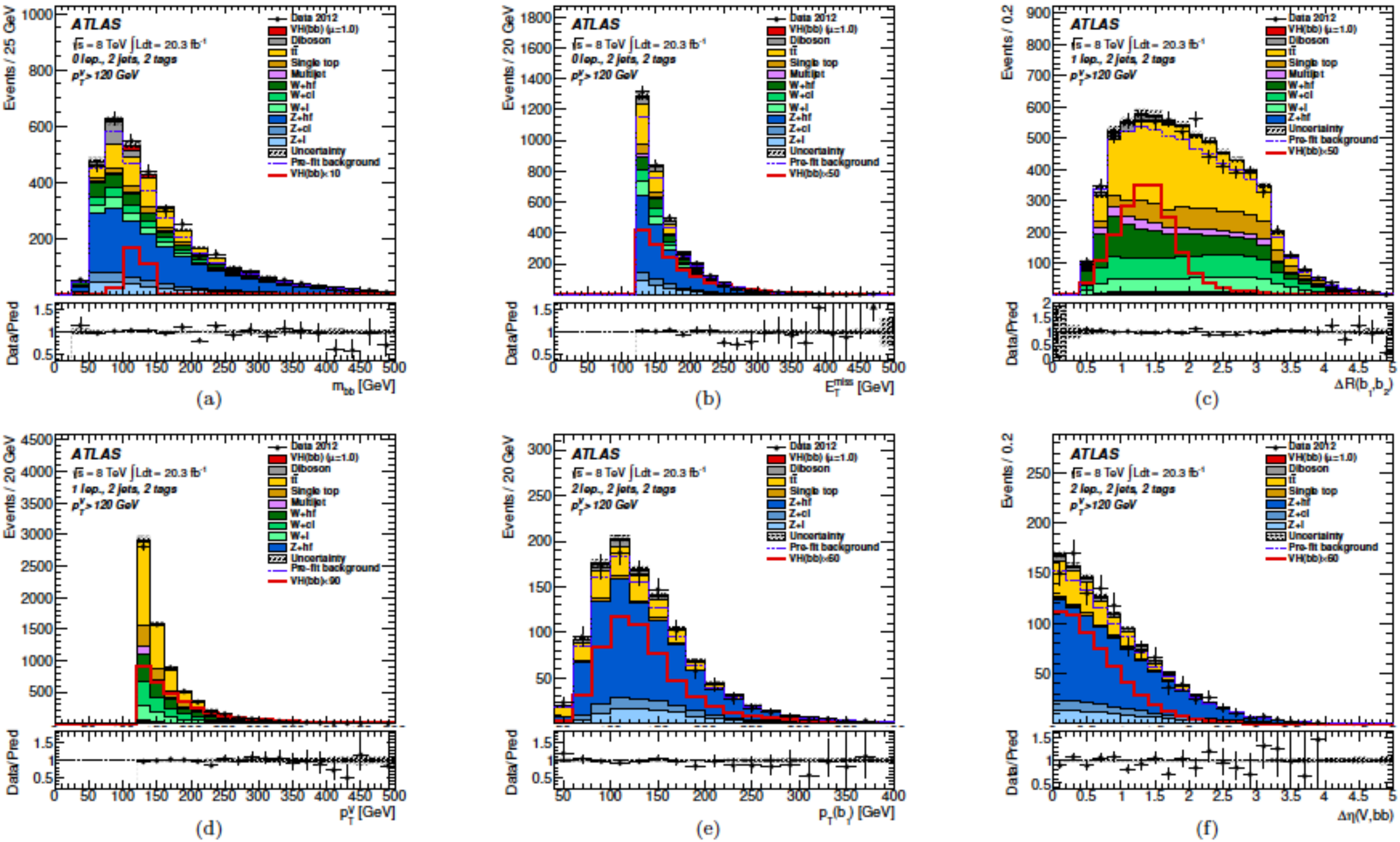
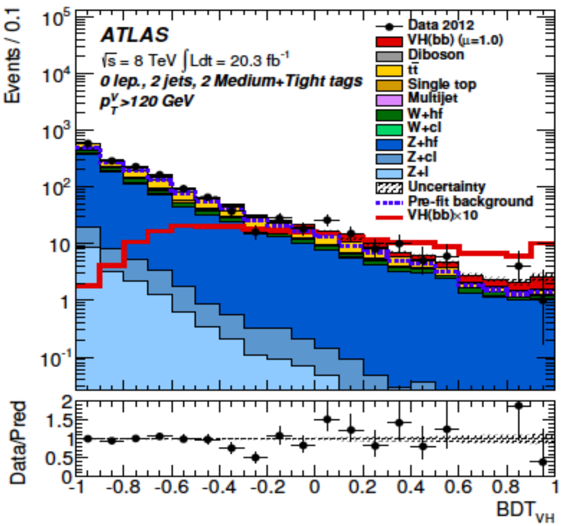
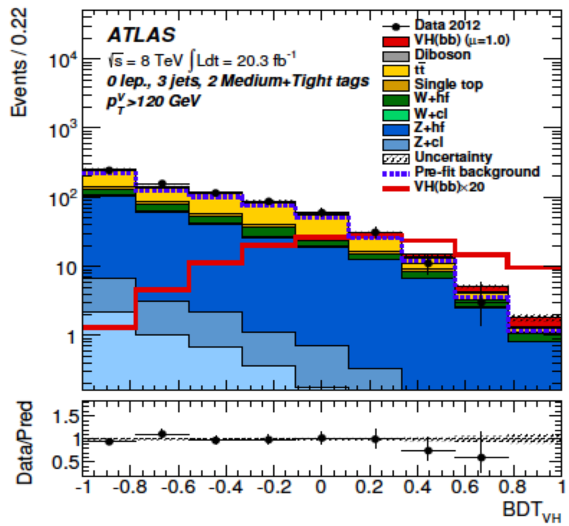


VH, H->bb – BDT output in 0-,2-lep cat





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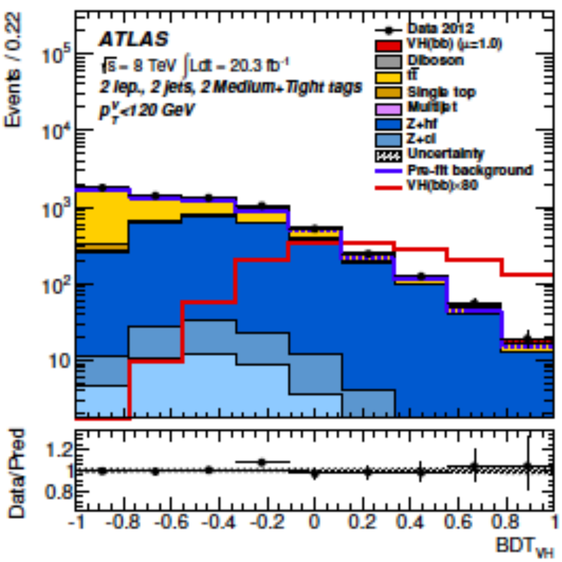

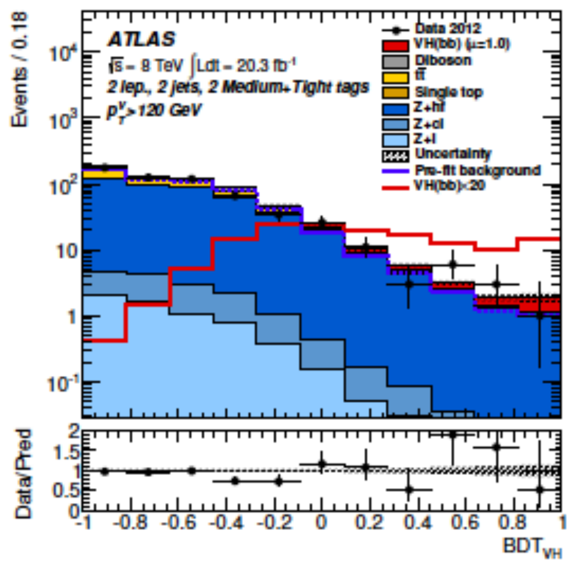

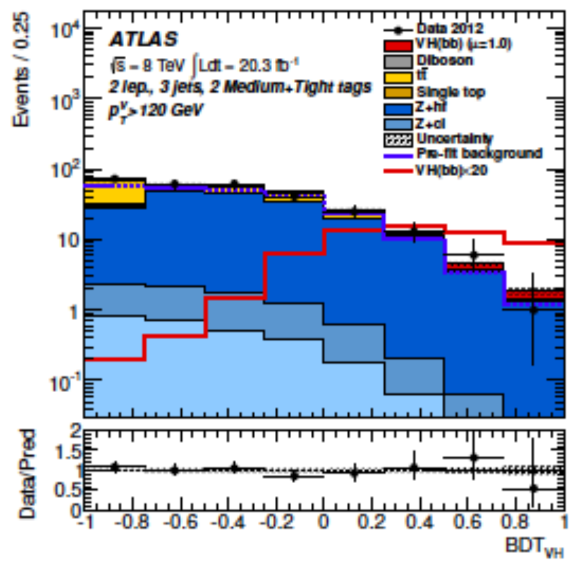

VH, H->bb – BDT output in 1-lep cat

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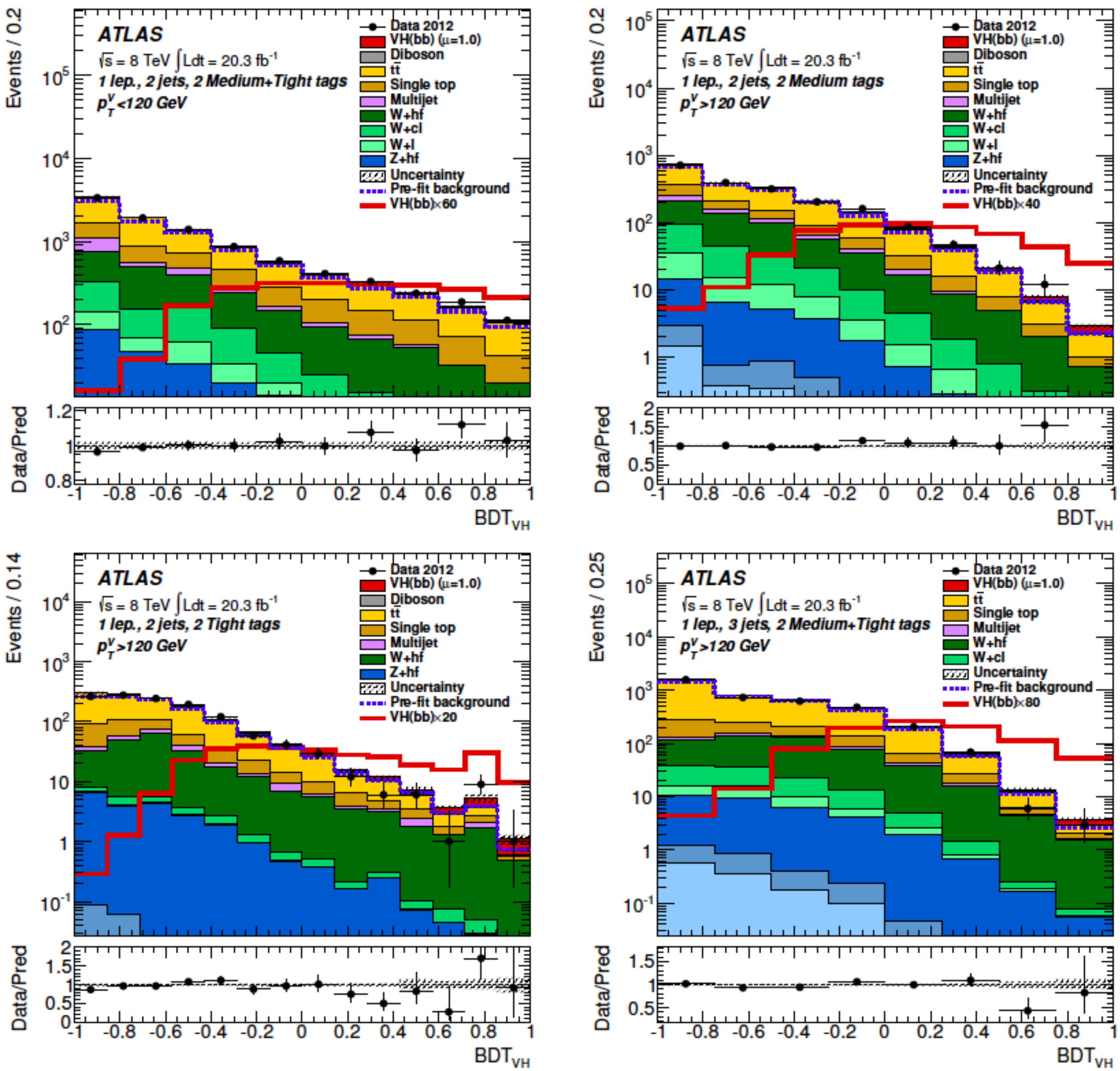

VH, H->bb – Event yields

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Process	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6	Bin 7	Bin 8	Bin 9
Data	368550	141166	111865	20740	5538	2245	382	41	4
Signal	29	43	96	57	58	62	32	10.7	2.3
Background	368802	140846	111831	20722	5467	2189	364	37.9	3.4
S/B	8×10^{-5}	0.0003	0.0009	0.003	0.01	0.03	0.09	0.3	0.7
W+hf	14584	10626	15297	1948	618	250	45	8.2	0.7
Wcl	96282	30184	15227	1286	239	47	4.2	0.2	0.005
Wl	125676	14961	3722	588	107	16	1.3	0.03	0.001
Z+hf	10758	14167	21684	7458	1178	577	130	14.8	2.2
Zcl	13876	11048	4419	941	61	22	2.1	0.1	0.008
Zl	49750	18061	3044	537	48	15	1	0.05	0.004
$t\bar{t}$	30539	24824	26729	5595	2238	922	137	10	0.3
Single top	10356	9492	14279	1494	688	252	31	2.7	0.1
Diboson	4378	1831	1247	474	186	62	9.7	1	0.2
Multijet	12603	5650	6184	400	103	26	3	0.9	0

Final-discriminant bins in all signal regions are combined into bins of log(S/B) @8 TeV

VH, H->bb – Syst

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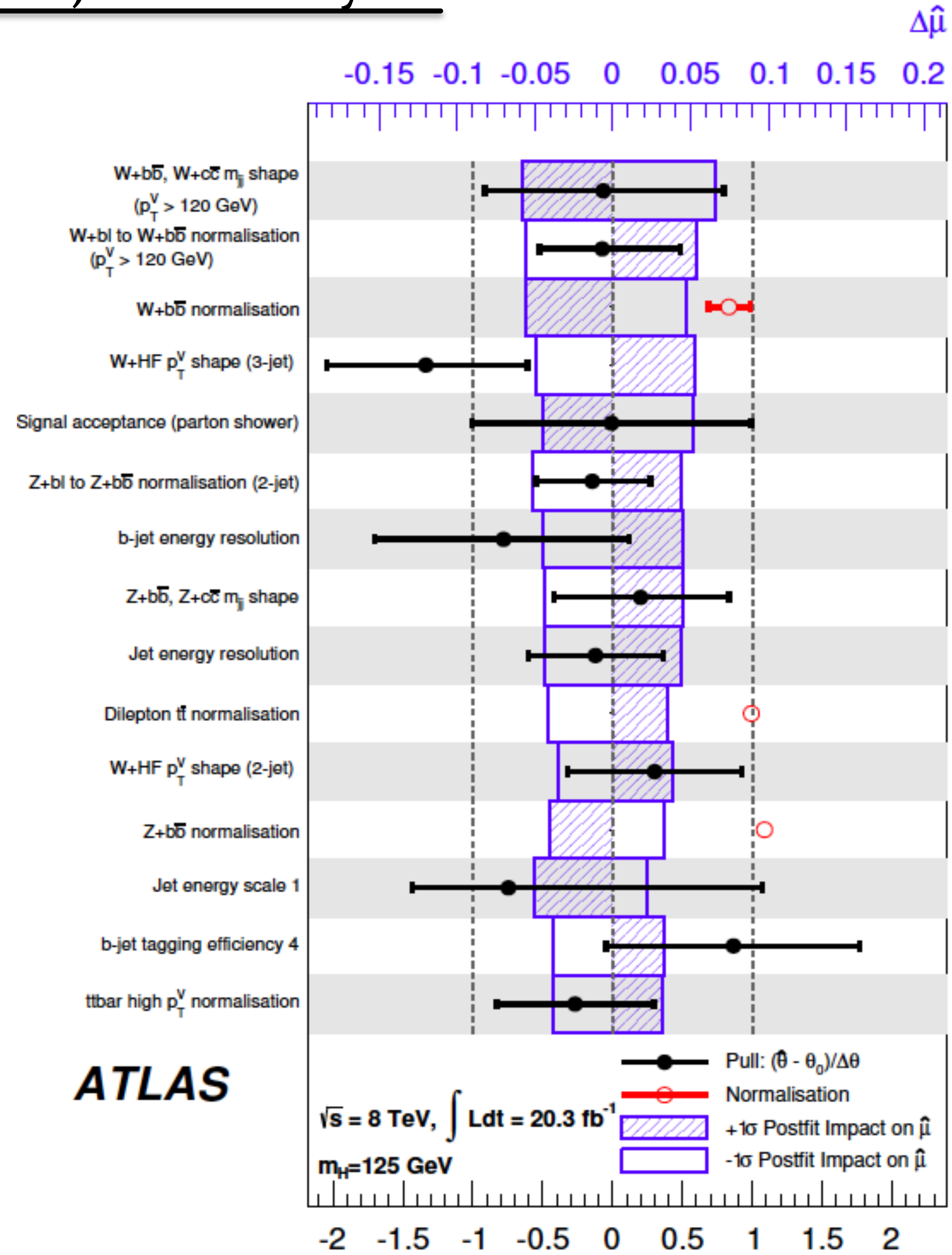
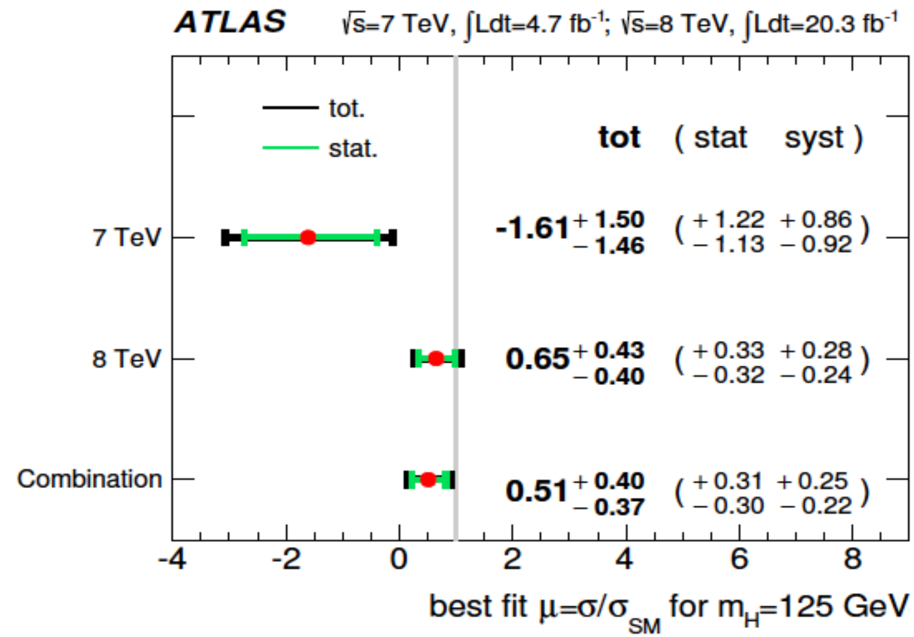


Signal	
Cross section (scale)	1% ($q\bar{q}$), 50% (gg)
Cross section (PDF)	2.4% ($q\bar{q}$), 17% (gg)
Branching ratio	3.3 %
Acceptance (scale)	1.5%–3.3%
3-jet acceptance (scale)	3.3%–4.2%
p_T^V shape (scale)	S
Acceptance (PDF)	2%–5%
p_T^V shape (NLO EW correction)	S
Acceptance (parton shower)	8%–13%
Z+jets	
Zl normalisation, 3/2-jet ratio	5%
Zcl 3/2-jet ratio	26%
Z+hf 3/2-jet ratio	20%
Z+hf/Zbb ratio	12%
$\Delta\phi(\text{jet}_1, \text{jet}_2)$, p_T^V, m_{bb}	S
W+jets	
Wl normalisation, 3/2-jet ratio	10%
Wcl, W+hf 3/2-jet ratio	10%
Wbl/Wbb ratio	35%
Wbc/Wbb, Wcc/Wbb ratio	12%
$\Delta\phi(\text{jet}_1, \text{jet}_2)$, p_T^V, m_{bb}	S
$t\bar{t}$	
3/2-jet ratio	20%
High/low-p_T^V ratio	7.5%
Top-quark p_T, m_{bb}, E_T^{miss}	S
Single top	
Cross section	4% (s-,t-channel), 7% (Wt)
Acceptance (generator)	3%–52%
m_{bb}, $p_T^{b_1}$	S
Diboson	
Cross section and acceptance (scale)	3%–29%
Cross section and acceptance (PDF)	2%–4%
m_{bb}	S
Multijet	
0-, 2-lepton channels normalisation	100%
1-lepton channel normalisation	2%–60%
Template variations, reweighting	S

VH, H->bb – Results



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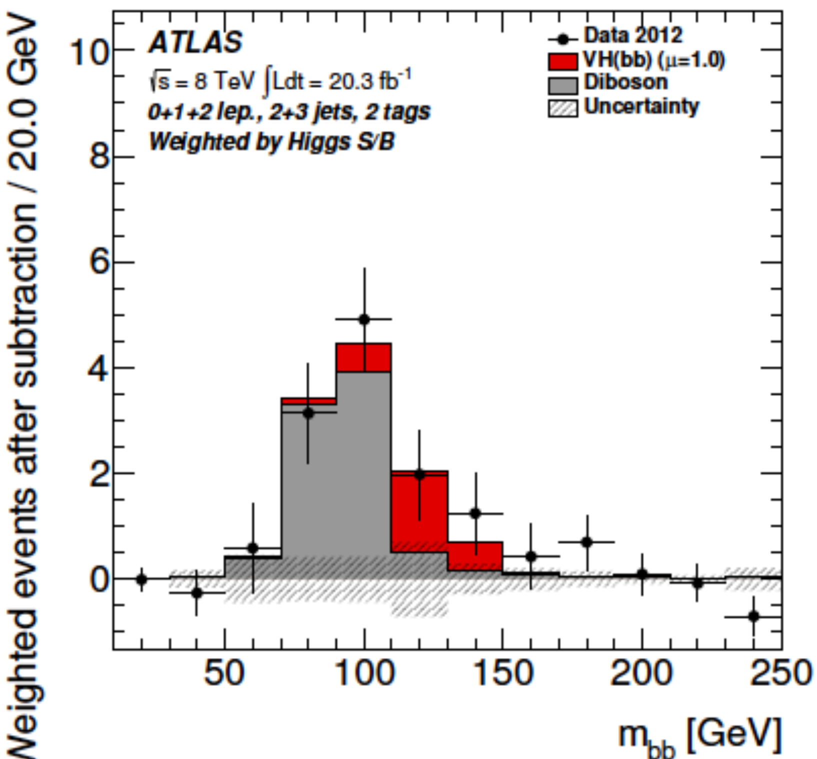

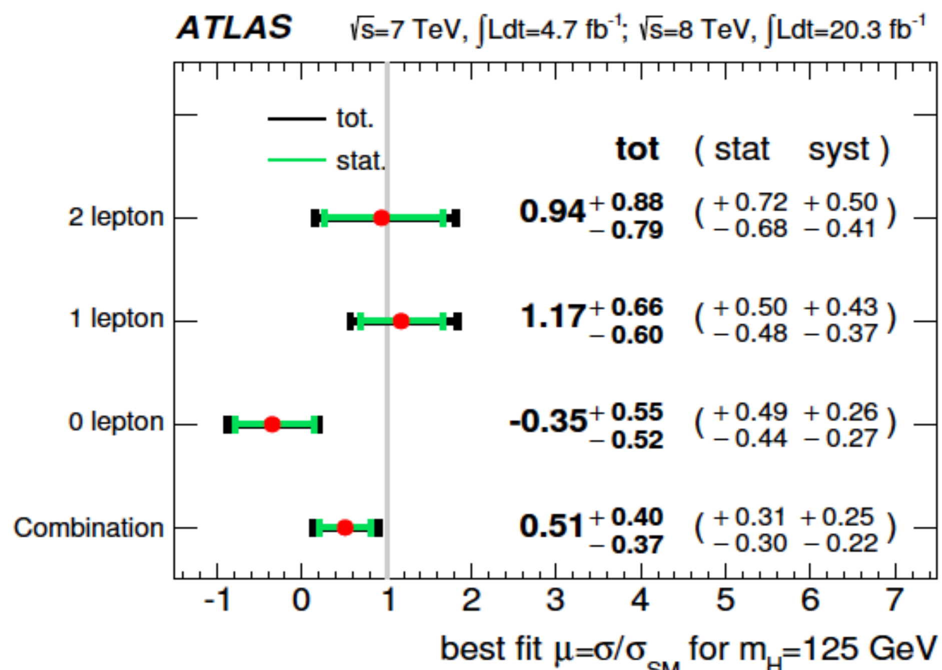

VH, H->WW – Selection

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Channel	4ℓ		3ℓ			2ℓ		
Category	2SFOS	1SFOS	2SFOS	1SFOS	0SFOS	DFOS	SS2jet	SS1jet
Trigger	single lepton triggers		single lepton triggers			single & dilepton triggers		
Num. of leptons	4	4	3	3	3	2	2	2
Total lepton charge	0	0	±1	±1	±1	0	±2	±2
Num. of SFOS	2	1	2	1	0	0	0	0
Num. of jets	≤ 1	≤ 1	≤ 1	≤ 1	≤ 1	≥ 2	2	1
Num. of b-tagged jets	0	0	0	0	0	0	0	0
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 20	> 20	> 30	> 30	—	> 20	> 50	> 45
$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 15	> 15	> 20	> 20	—	—	—	—
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	$< 10\ (m_{\ell_2\ell_3})$	$< 10\ (m_{\ell_2\ell_3})$	> 25	> 25	—	—	> 15	> 15
Min. $m_{\ell\ell}$ [GeV]	$> 10\ (m_{\ell_0\ell_1})$	$> 10\ (m_{\ell_0\ell_1})$	> 12	> 12	> 6	> 10	$> 12\ (ee,\mu\mu)$ $> 10\ (e\mu)$	$> 12\ (ee,\mu\mu)$ $> 10\ (e\mu)$
Max. $m_{\ell\ell}$ [GeV]	$< 65\ (m_{\ell_0\ell_1})$	$< 65\ (m_{\ell_0\ell_1})$	< 200	< 200	< 200	< 50	—	—
$m_{4\ell}$ [GeV]	> 140	—	—	—	—	—	—	—
$p_{\mathrm{T},4\ell}$ [GeV]	> 30	—	—	—	—	—	—	—
$M_{\tau\tau}$ [GeV]	—	—	—	—	—	< 66.2	—	—
$\Delta R_{\ell_0\ell_1}$	—	—	< 2.0	< 2.0	—	—	—	—
$\Delta\phi_{\ell_0\ell_1}$ [rad]	$< 2.5\ (\Delta\phi_{\ell_0\ell_1}^{\mathrm{boost}})$	$< 2.5\ (\Delta\phi_{\ell_0\ell_1}^{\mathrm{boost}})$	—	—	—	< 1.8	—	—
m_{T} [GeV]	—	—	—	—	—	< 125	—	$> 105\ (m_{\mathrm{T}}^{\mathrm{Lead}})$
Min. $m_{\ell_1 j(j)}$ [GeV]	—	—	—	—	—	—	< 115	< 70
Min. $\phi_{\ell_1 j}$ [rad]	—	—	—	—	—	—	< 1.5	< 1.5
ΔY_{jj}	—	—	—	—	—	< 1.2	—	—
$\lvert m_{jj} - 85 \rvert$ [GeV]	—	—	—	—	—	< 15	—	—

VH, H->WW – Event yields in SR

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(a) 8 TeV data analysis

Process	4ℓ		3ℓ			2ℓ		
Category	2SFOS	1SFOS	2SFOS	1SFOS	0SFOS	DFOS	SS2jet	SS1jet
Higgs								
$VH\ (H \to WW^*)$	0.208 ± 0.025	0.235 ± 0.029	0.73 ± 0.10	1.61 ± 0.18	1.43 ± 0.16	2.15 ± 0.24	1.04 ± 0.17	2.04 ± 0.28
$VH\ (H \to \tau\tau)$	0.0126 ± 0.0036	0.0087 ± 0.0030	0.057 ± 0.010	0.152 ± 0.022	0.248 ± 0.034	—	0.0365 ± 0.0080	0.270 ± 0.035
ggF	—	—	0.076 ± 0.015	0.085 ± 0.018	—	2.43 ± 0.49	—	—
VBF	—	—	—	—	—	0.180 ± 0.025	—	—
ttH	—	—	—	—	—	—	—	—
Background								
V	—	—	0.22 ± 0.16	1.87 ± 0.62	0.37 ± 0.15	13.7 ± 3.6	7.9 ± 3.7	14.9 ± 4.8
VV	1.17 ± 0.20	0.306 ± 0.059	19.2 ± 3.0	27.5 ± 4.1	4.70 ± 0.57	10.1 ± 1.6	11.2 ± 2.1	26.3 ± 3.7
VVV	0.117 ± 0.044	0.102 ± 0.036	0.80 ± 0.28	2.15 ± 0.74	2.93 ± 0.29	—	—	0.467 ± 0.049
Top	0.014 ± 0.011	—	0.91 ± 0.26	2.43 ± 0.63	3.72 ± 0.91	23.9 ± 3.9	0.75 ± 0.19	1.34 ± 0.51
Others	—	—	—	—	—	2.31 ± 0.95	0.71 ± 0.30	0.60 ± 0.24
Total	1.30 ± 0.25	0.41 ± 0.10	21.1 ± 3.6	34.0 ± 6.0	11.7 ± 1.8	49.9 ± 5.4	20.6 ± 4.6	43.6 ± 6.1
Observed events	0	3	22	38	14	63	25	62

(b) 7 TeV data analysis

Higgs						
$V(H \to WW^*)$	0.0226 ± 0.0028	0.0208 ± 0.0025	0.129 ± 0.014	0.325 ± 0.034	0.291 ± 0.030	0.285 ± 0.041
$V(H \to \tau\tau)$	0.0031 ± 0.0011	0.00145 ± 0.00074	0.0163 ± 0.0035	0.0411 ± 0.0063	0.0670 ± 0.0095	0.0075 ± 0.0031
ggF	—	—	0.0452 ± 0.0015	0.0106 ± 0.0050	0.0048 ± 0.0027	0.322 ± 0.090
VBF	—	—	—	—	—	0.0212 ± 0.0038
ttH	—	—	—	0.0061 ± 0.0040	0.0041 ± 0.0032	—
Background						
V	—	—	0.36 ± 0.30	0.59 ± 0.34	0.36 ± 0.22	3.4 ± 1.3
VV	0.37 ± 0.13	0.031 ± 0.012	4.08 ± 0.64	5.7 ± 1.0	1.32 ± 0.20	0.89 ± 0.54
VVV	0.0140 ± 0.0011	0.00952 ± 0.00095	0.082 ± 0.028	0.207 ± 0.071	0.338 ± 0.031	—
Top	0.0055 ± 0.0040	—	0.12 ± 0.14	0.44 ± 0.27	0.44 ± 0.29	3.18 ± 0.76
Others	—	—	—	—	—	—
Total	0.39 ± 0.14	0.041 ± 0.013	4.6 ± 1.1	7.0 ± 1.9	2.46 ± 0.66	7.5 ± 1.7
Observed events	1	0	5	6	2	7

VH, H->WW – Event yields in CR

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(a) 8 TeV data analysis

Channel	4ℓ	3ℓ					2ℓ	
CR	CR-ZZ	CR-WZ	CR-ZZ	CR-Zjets	CR-Top	CR-Zgamma	CR-Ztautau	CR-OSTop
Observed events	122	578	60	251	55	156	328	1169
MC prediction	121 ± 17	576 ± 63	60 ± 10	249 ± 46	55 ± 12	155 ± 31	326 ± 55	1160 ± 150
MC (no NFs)	117 ± 10	543 ± 50	47.9 ± 3.7	351 ± 40	48.4 ± 6.3	188 ± 17	354 ± 56	1120 ± 140
Composition (%)								
$WZ/W\gamma^*$	—	89.3 ± 1.3	5.5 ± 3.0	25.9 ± 2.8	20.3 ± 5.4	1.7 ± 1.0	—	—
ZZ^*	99.5 ± 0.6	6.7 ± 1.0	90.1 ± 3.8	36.3 ± 2.5	3.6 ± 2.5	46.9 ± 4.0	—	—
$Z\gamma$	—	0.54 ± 0.31	0.6 ± 1.0	5.5 ± 1.4	2.3 ± 2.0	42.7 ± 4.0	—	—
Z+jets	—	1.08 ± 0.43	2.1 ± 1.9	29.1 ± 2.9	5.5 ± 3.1	8.3 ± 2.2	78.2 ± 2.3	0.75 ± 0.25
Top	0.02 ± 0.01	0.66 ± 0.34	0.27 ± 0.67	0.08 ± 0.18	64.0 ± 6.5	0.10 ± 0.30	10.5 ± 1.7	71.3 ± 1.3
Others	0.48 ± 0.63	0.81 ± 0.37	1.1 ± 1.4	0.87 ± 0.59	3.7 ± 2.6	0.34 ± 0.46	11.2 ± 1.7	28.0 ± 1.3
$VH\ (H \to WW^*)$	0.02 ± 0.14	0.93 ± 0.40	0.26 ± 0.66	0.37 ± 0.39	0.52 ± 0.97	0.05 ± 0.18	0.10 ± 0.18	0.21 ± 0.24

Channel	SS 2ℓ				
CR	CR-Wgamma	CR-WZ	CR-WW	CR-SSTop	CR-Zjets
Observed events	228	331	769	5142	39731
MC prediction	229 ± 41	311 ± 66	742 ± 63	5080 ± 350	41000 ± 14000
MC (no NFs)	218 ± 35	335 ± 68	787 ± 58	4930 ± 330	47000 ± 16000
Composition (%)					
$W\gamma$	85.0 ± 2.4	—	0.46 ± 0.25	0.049 ± 0.031	0.0221 ± 0.0074
$WZ/W\gamma^*$	1.02 ± 0.66	86.8 ± 1.9	2.34 ± 0.56	0.200 ± 0.063	0.381 ± 0.031
WW	0.37 ± 0.40	0.029 ± 0.097	23.9 ± 1.6	1.43 ± 0.17	0.572 ± 0.037
Z+jets	4.2 ± 1.3	7.0 ± 1.4	7.01 ± 0.94	2.15 ± 0.20	97.701 ± 0.074
Top	0.68 ± 0.54	1.50 ± 0.69	62.7 ± 1.8	95.50 ± 0.29	0.856 ± 0.046
Others	8.7 ± 1.9	5.2 ± 1.3	3.24 ± 0.65	0.63 ± 0.11	0.441 ± 0.033
$VH\ (H \to WW^*)$	—	0.77 ± 0.50	0.32 ± 0.21	0.036 ± 0.027	0.0077 ± 0.0043

VH, H->WW CR plots

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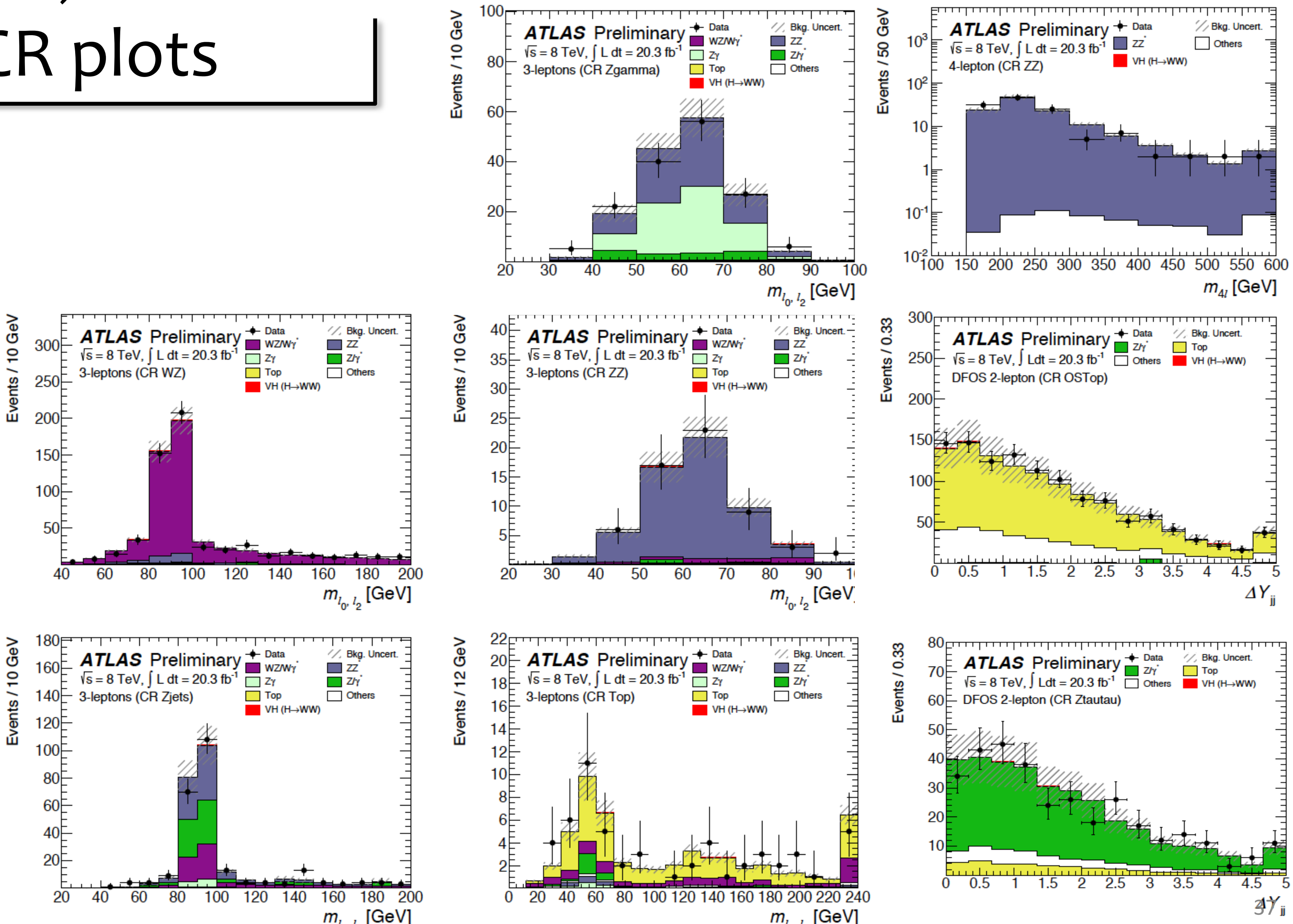

VH, H->WW – Systematics

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(a) Uncertainties on the signal (%)

Channel	4ℓ		3ℓ			2ℓ		
Category	2SFOS	1SFOS	2SFOS	1SFOS	0SFOS	DFOS	SS2jet	SS1jet
Normalisation uncertainties								
NLO Acceptance	10	10	10	10	10	10	10	10
Higgs boson branch. fraction	4.1	4.0	4.0	3.9	3.7	4.2	4.2	3.9
QCD scale	3.1	3.1	1.5	1.2	1.2	1.7	1.0	1.0
PDFs and α_s	2.5	2.5	2.3	2.3	2.3	2.4	2.3	2.3
VH NLO EW corrections	2.1	2.1	2.0	2.0	2.0	2.1	2.1	2.1
Experimental uncertainties								
Jet	2.3	3.7	2.7	2.4	3.3	5.1	7.4	4.0
$E_{\mathrm{T}}^{\mathrm{miss}}$ Soft term	0.3	0.5	0.2	–	–	0.4	1.0	–
Electron	2.5	2.8	1.6	2.3	2.3	1.6	1.6	1.4
Muon	2.6	2.4	3.7	3.1	2.9	0.9	2.2	3.7
Trigger efficiency	0.2	0.1	0.4	0.3	0.3	0.5	0.6	0.5
b-tagging efficiency	0.9	0.8	0.9	0.8	0.8	2.9	3.5	2.6
Pile-up	2.0	0.5	1.7	2.1	1.5	2.4	0.9	3.2
Luminosity	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8

(b) Uncertainties on the background (%)

Normalisation uncertainties								
QCD scale	0.3	0.2	1.0	0.9	–	3.7	13	1.5
PDFs and α_s	0.2	2.3	0.1	0.1	1.2	1.4	0.5	0.6
VVV K factor	2.8	8.1	1.1	1.9	0.5	–	–	–
MC modelling	5.2	4.3	7.1	6.6	–	4.1	0.2	0.3
CR statistics	8.1	6.6	4.2	3.9	8.8	2.5	2.8	3.5
Experimental uncertainties								
Jet	3.7	2.5	4.3	1.9	3.9	9.7	4.7	2.3
$E_{\mathrm{T}}^{\mathrm{miss}}$ Soft term	2.5	0.8	0.8	1.0	0.5	1.1	0.3	0.1
Electron	1.4	1.4	0.5	0.4	1.1	1.9	1.6	0.7
Muon	1.2	1.2	1.8	0.6	0.7	2.3	0.5	1.5
Trigger efficiency	–	0.2	0.2	–	–	0.1	–	–
b-tagging efficiency	0.6	0.7	0.6	0.8	2.5	0.7	1.4	0.4
Fake factor	–	–	–	–	–	3.2	11	12
Charge mis-assignment	–	–	–	–	1.4	–	0.6	0.6
Photon conversion rate	–	–	–	–	–	–	1.1	0.9
Pile-up	1.6	0.7	1.1	0.7	0.9	0.9	0.3	1.3
Luminosity	0.4	0.8	0.1	0.2	0.7	–	0.7	0.3

VH, H->WW – Results

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Category	Signal significance Z_0: Exp. Z_0	Signal significance Z_0: Obs Z_0	Signal significance Z_0: Obs. Z_0	Observed signal strength μ_{obs}: μ	Tot. err. +	Tot. err. −	Syst. err. +	Syst. err. −	μ
4ℓ	0.44	1.9		4.9	4.6	3.1	1.2	0.35	
2SFOS	0.31	0		−5.9	6.8	4.1	0.33	0.72	
1SFOS	0.40	2.5		9.6	8.1	5.4	2.1	0.64	
3ℓ	0.84	0.66		0.72	1.3	1.1	0.42	0.27	
1SFOS and 2SFOS	0.57	0		−2.9	3.2	3.2	2.1	2.5	
0SFOS	0.69	1.2		1.6	1.9	1.4	0.51	0.29	
2ℓ	0.61	2.0		3.7	1.9	1.8	1.2	1.4	
DFOS	0.57	1.1		2.2	2.0	1.9	1.1	1.0	
SS2jet	0.24	1.4		7.7	6.0	5.5	3.2	3.3	
SS1jet	0.63	2.3		8.4	4.3	3.8	2.3	2.0	

Category	Signal significance Z_0: Exp. Z_0	Signal significance Z_0: Obs. Z_0	Signal significance Z_0: Obs. Z_0	Observed signal strength μ_{obs}: μ	Tot. err. +	Tot. err. −	Syst. err. +	Syst. err. −	μ
ggF	4.4	4.2		0.98	0.29	0.26	0.22	0.18	
VBF	2.6	3.2		1.28	0.55	0.47	0.32	0.25	
VH	0.93	2.5		3.0	1.6	1.3	0.95	0.65	
WH only	0.77	1.4		2.1	1.9	1.6	1.2	0.79	
ZH only	0.30	2.0		5.1	4.3	3.1	1.9	0.89	
ggF+VBF+VH	5.9	6.5		1.16	0.24	0.21	0.18	0.15	