

# *WH/ZH cross section studies in ATLAS*

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*(as a starting point for discussion)*

Giacinto Piacquadio  
(CERN)

*on behalf of the*  
ATLAS Higgs cross section Working Group

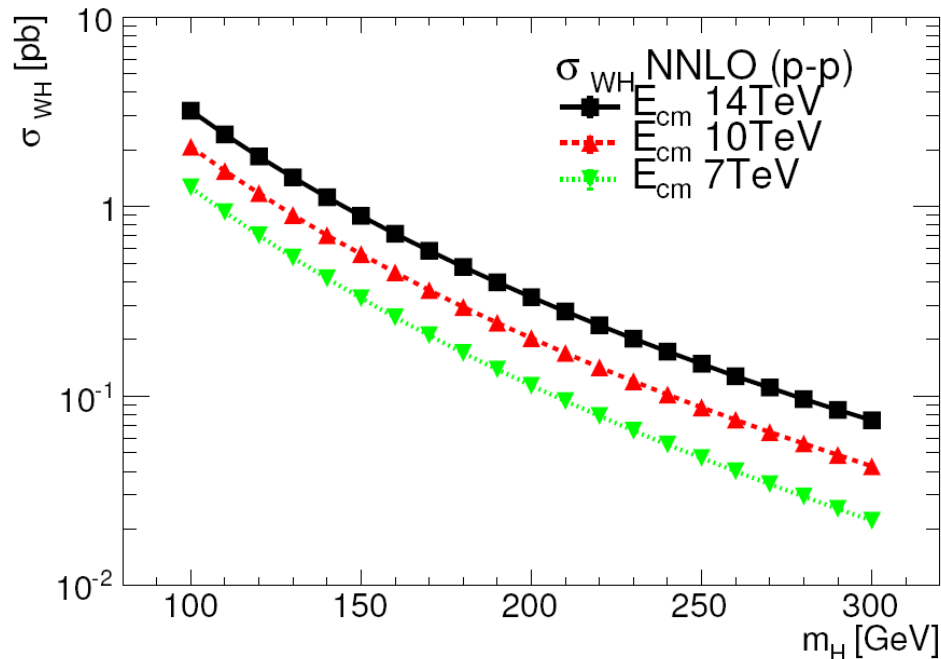
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# *What has been done in ATLAS*

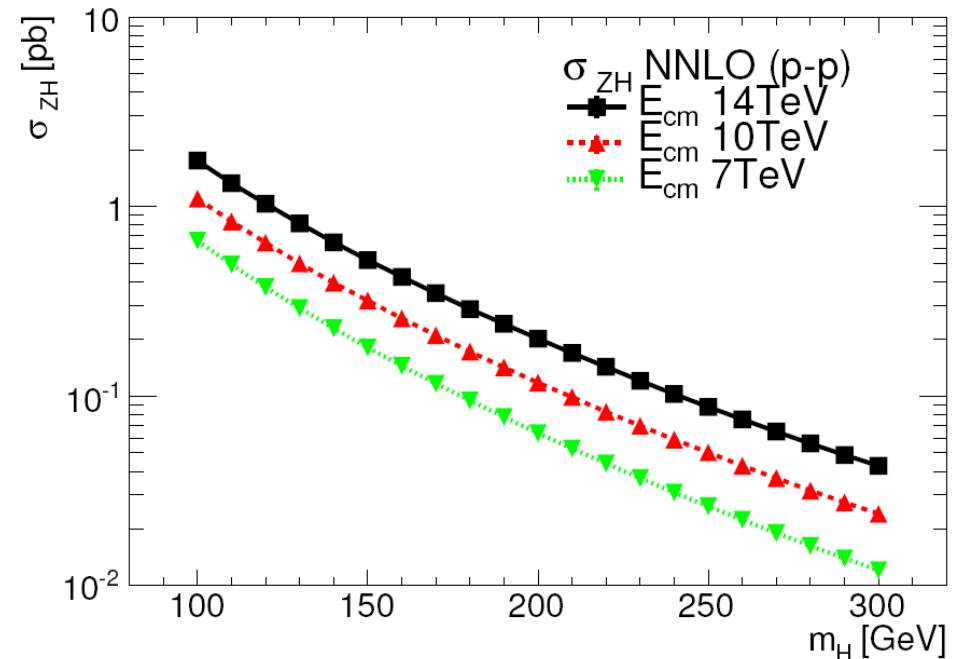
- ◆ Inclusive cross sections for WH and ZH production have been computed in collaboration with theorists, by factorizing the NLO EW and NNLO QCD corrections:
  - ◆ NNLO QCD [Brein, Djouadi, Harlander]
  - ◆ NLO EW [Ciccolini, Dittmaier, Kramer]
- ◆ using the formula:
  - ◆ 
$$\sigma = \sigma_0 \cdot (1 + \delta^{QCD}) \times (1 + \delta^{EW})$$
- ◆ Cross section obtained for:
  - ◆  $\sqrt{s} = 4, 6, 7, 8, 10, 14$  TeV
  - ◆  $m_H = 100 - 300$  GeV (10 GeV steps)
- ◆ and then extrapolation performed to join these points.

# Result for $\sqrt{s} = 14 \text{ TeV}$

- Work done by **Huaqiao Zhang** in ATLAS in collaboration with the theorists (use of private code).



(a) WH 14 TeV

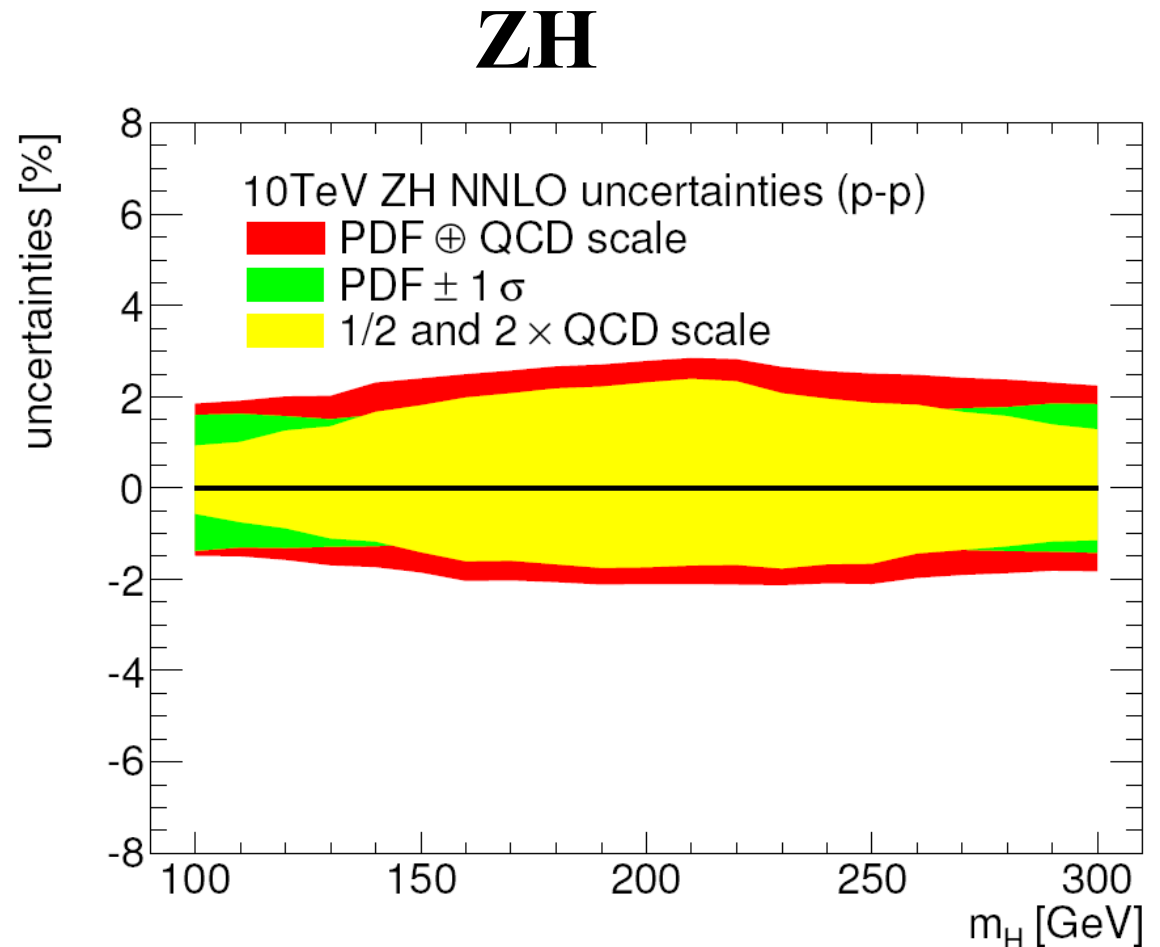


(b) ZH 14 TeV

+ the same for different center of mass energies.

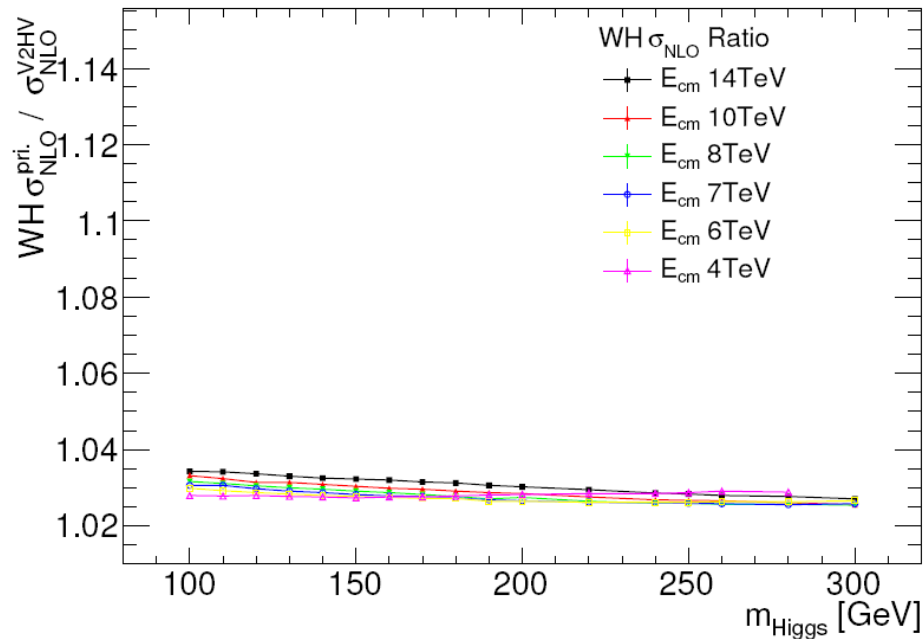
# Parameters used

- ◆ PDF sets:
  - ◆ MTSW2008 for NNLO QCD
  - ◆ MRST2004QCD for NLO EW
- ◆ Scale variation uncertainty:
  - ◆ Evaluated by varying by  $\frac{1}{2}$  and 2 the QCD renormaliz. and factoriz. scales
- ◆ Result:
  - ◆ PDF uncertainty dominates for WH, while for ZH the scale var. uncert. dominates (in both cases uncert.  $\sim 2\%$ )

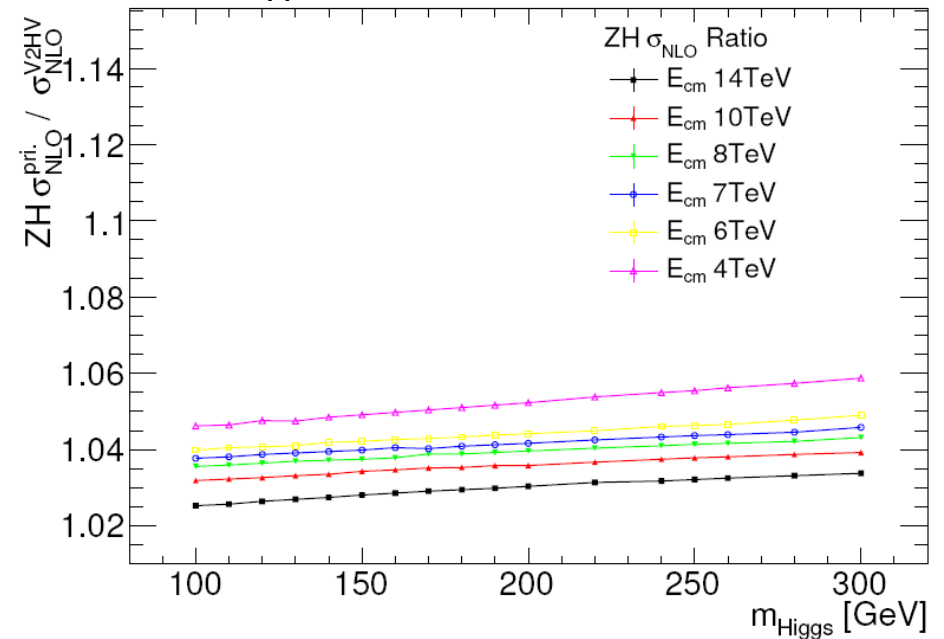


# Comparison with other codes

- Comparison with V2HV NLO code [Han, Willenbrock] gives sufficiently consistent results (+3 % ~flat in  $m_H$  and  $\sqrt{s}$ )



(a) WH



(b) ZH

- MC2FM NLO code also available

# *Use as starting point?*

- ◆ Can we use this as a good starting point for finding an agreement between ATLAS and CMS about the inclusive WH / ZH channels ?
- ◆ We are trying to get the whole material put together by ATLAS approved and should be then able to circulate it to all people involved.
- ◆ Are the parameters and PDF sets used in the computation still the one suggested by the cross section group or by the theorists?
- ◆ We could start from here and attach the other points we have on our to do list (comparison with PS, differential cross sections in  $p_T$ , specific studies for highly boosted topologies, ...)

# *Discussion points by Stefan*

- ◆ Assessment of state of the art in predicting WH/ZH cross sections: overview of available tools / programs
- ◆ Comparison between the NLO/NNLO codes and the available (N)LO parton shower Monte Carlos, in order to (de?)motivate possible re-weighting procedures
- ◆ Organization of concrete numerical evaluations of the state-of-the-art cross section for CM energies of 7TeV and 14TeV (more energies? Maybe also 10 TeV?)
- ◆ Identification of loose ends, i.e. we should work out where theorists still have some homework to do discussion of specific analysis-driven scenarios, e.g. Higgs at large  $p_T$ , etc.
- ◆ What can be expected from LHCb?
- ◆ Are there for instance specific requirements from theorists?

# *Useful links*

- ◆ Twiki page:
  - ◆ <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections>
  - ◆ Let's start to update it!
- ◆ Indico page:
  - ◆ <http://indico.cern.ch/categoryDisplay.py?categId=2792>
- ◆ Freiburg workshop (e-mail from Chiara Mariotti):
  - ◆ The agenda are being fixed now. One overview talk will be given by an experimentalist (CMS).
  - ◆ All the sessions are plenary. Each subgroup is given 55 minutes, and free to organize it.
  - ◆ example exp.(15min) + theory(15min) + debate(25min).
  - ◆ For closing, we shall have a discussion session.



# Additional material

## ◆ NNLO cross sections for WH

$\sqrt{s} = 7 \text{ TeV}$				$\sqrt{s} = 10 \text{ TeV}$				$\sqrt{s} = 14 \text{ TeV}$			
$m_H$ [GeV]	$\sigma_{NNLO}^{QCD}$ [pb]	PDF [%]	$M_{\mu,R}$ [%]	$m_H$ [GeV]	$\sigma_{NNLO}^{QCD}$ [pb]	PDF [%]	$M_{\mu,R}$ [%]	$m_H$ [GeV]	$\sigma_{NNLO}^{QCD}$ [pb]	PDF [%]	$M_{\mu,R}$ [%]
100	1.2632	+1.75	+0.12	100	2.0687	+1.63	+0.03	100	3.2031	+1.56	+0.16
		-1.44	-0.13			-1.39	-0.00			-1.41	-0.06
110	0.9348	+1.76	+0.14	110	1.5435	+1.64	+0.04	110	2.4050	+1.56	+0.14
		-1.44	-0.16			-1.38	-0.00			-1.40	-0.04
120	0.7040	+1.78	+0.16	120	1.1721	+1.65	+0.06	120	1.8376	+1.57	+0.11
		-1.44	-0.19			-1.38	-0.02			-1.39	-0.02
130	0.5386	+1.80	+0.19	130	0.9040	+1.65	+0.08	130	1.4260	+1.57	+0.09
		-1.44	-0.22			-1.38	-0.05			-1.38	-0.01
140	0.4177	+1.82	+0.21	140	0.7069	+1.67	+0.09	140	1.1219	+1.57	+0.07
		-1.45	-0.24			-1.38	-0.07			-1.37	-0.00
150	0.3280	+1.84	+0.22	150	0.5596	+1.68	+0.11	150	0.8935	+1.57	+0.04
		-1.45	-0.27			-1.38	-0.10			-1.37	-0.00
160	0.2605	+1.87	+0.24	160	0.4480	+1.69	+0.12	160	0.7196	+1.58	+0.03
		-1.46	-0.30			-1.38	-0.12			-1.36	-0.00
170	0.2089	+1.89	+0.26	170	0.3623	+1.70	+0.14	170	0.5853	+1.59	+0.05
		-1.47	-0.32			-1.38	-0.14			-1.36	-0.00
180	0.1691	+1.92	+0.27	180	0.2957	+1.72	+0.15	180	0.4805	+1.59	+0.06
		-1.47	-0.35			-1.38	-0.16			-1.35	-0.02
190	0.1381	+1.93	+0.29	190	0.2434	+1.73	+0.17	190	0.3978	+1.60	+0.07
		-1.49	-0.37			-1.38	-0.18			-1.35	-0.04
200	0.1136	+1.96	+0.30	200	0.2018	+1.75	+0.18	200	0.3319	+1.61	+0.08
		-1.49	-0.40			-1.39	-0.20			-1.35	-0.07
210	0.0941	+1.98	+0.32	210	0.1686	+1.76	+0.19	210	0.2788	+1.62	+0.09
		-1.50	-0.42			-1.39	-0.23			-1.35	-0.09
220	0.0785	+2.00	+0.33	220	0.1417	+1.78	+0.20	220	0.2358	+1.62	+0.10
		-1.51	-0.45			-1.40	-0.25			-1.34	-0.11
230	0.0658	+2.03	+0.34	230	0.1199	+1.79	+0.21	230	0.2006	+1.63	+0.11
		-1.52	-0.47			-1.40	-0.27			-1.34	-0.13
240	0.0555	+2.05	+0.36	240	0.1020	+1.81	+0.22	240	0.1716	+1.64	+0.12
		-1.53	-0.49			-1.41	-0.29			-1.34	-0.15
250	0.0471	+2.08	+0.37	250	0.0872	+1.83	+0.23	250	0.1476	+1.65	+0.13
		-1.54	-0.51			-1.42	-0.31			-1.35	-0.17
260	0.0401	+2.11	+0.38	260	0.0749	+1.85	+0.24	260	0.1276	+1.67	+0.14
		-1.55	-0.53			-1.42	-0.32			-1.35	-0.19
270	0.0343	+2.13	+0.39	270	0.0647	+1.86	+0.25	270	0.1108	+1.68	+0.15
		-1.56	-0.55			-1.43	-0.34			-1.35	-0.21
280	0.0295	+2.16	+0.41	280	0.0561	+1.88	+0.26	280	0.0966	+1.69	+0.15
		-1.57	-0.57			-1.44	-0.36			-1.35	-0.23
290	0.0255	+2.19	+0.42	290	0.0488	+1.90	+0.27	290	0.0846	+1.70	+0.16
		-1.58	-0.59			-1.44	-0.38			-1.35	-0.25
300	0.0221	+2.21	+0.43	300	0.0427	+1.92	+0.28	300	0.0743	+1.71	+0.17
		-1.59	-0.61			-1.45	-0.39			-1.36	-0.27

Table 23: NNLO QCD cross-section for  $pp \rightarrow WH$  at  $\sqrt{s} = 7, 10, 14 \text{ TeV}$ , using MSTW2008 NNLO PDF and QCD scale  $\mu_R = \mu_F = M_W^*$ . The PDF uncertainties estimated by using 68 % CL MSTW2008 error PDFs, scale uncertainties estimated by vary  $\mu_R$  and  $\mu_F$  a factor 2 and 1/2 synchronically from the central QCD scale. All calculation done using private code

# Additional material (II)

## ◆ NNLO cross sections for ZH

$\sqrt{s} = 7 \text{ TeV}$				$\sqrt{s} = 10 \text{ TeV}$				$\sqrt{s} = 14 \text{ TeV}$			
$m_H$ [GeV]	$\sigma_{NNLO}^{QCD}$ [pb]	PDF [%]	$M_{\mu,R}$ [%]	$m_H$ [GeV]	$\sigma_{NNLO}^{QCD}$ [pb]	PDF [%]	$M_{\mu,R}$ [%]	$m_H$ [GeV]	$\sigma_{NNLO}^{QCD}$ [pb]	PDF [%]	$M_{\mu,R}$ [%]
100	0.6594	+1.76	+0.77	100	1.1031	+1.60	+0.92	100	1.7432	+1.49	+0.98
		-1.42	-0.60			-1.37	-0.56			-1.33	-0.76
110	0.4938	+1.80	+0.92	110	0.8347	+1.63	+1.01	110	1.3290	+1.47	+1.12
		-1.39	-0.70			-1.29	-0.74			-1.30	-0.74
120	0.3761	+1.76	+1.12	120	0.6428	+1.57	+1.26	120	1.0330	+1.44	+1.33
		-1.40	-0.84			-1.31	-0.88			-1.28	-1.01
130	0.2907	+1.76	+1.25	130	0.5020	+1.51	+1.34	130	0.8134	+1.47	+1.68
		-1.39	-0.97			-1.29	-1.11			-1.23	-1.17
140	0.2277	+1.77	+1.47	140	0.3971	+1.60	+1.67	140	0.6489	+1.43	+2.00
		-1.36	-1.10			-1.28	-1.17			-1.20	-1.25
150	0.1805	+1.76	+1.52	150	0.3181	+1.58	+1.81	150	0.5235	+1.39	+2.17
		-1.37	-1.26			-1.22	-1.40			-1.20	-1.44
160	0.1443	+1.76	+1.70	160	0.2569	+1.51	+1.98	160	0.4255	+1.36	+2.28
		-1.36	-1.34			-1.25	-1.60			-1.19	-1.56
170	0.1163	+1.78	+1.78	170	0.2091	+1.51	+2.08	170	0.3495	+1.33	+2.27
		-1.35	-1.38			-1.25	-1.59			-1.15	-1.80
180	0.0947	+1.79	+1.85	180	0.1717	+1.54	+2.18	180	0.2886	+1.34	+2.60
		-1.36	-1.52			-1.21	-1.67			-1.12	-1.87
190	0.0775	+1.82	+1.97	190	0.1419	+1.54	+2.22	190	0.2401	+1.42	+2.50
		-1.36	-1.56			-1.19	-1.74			-1.10	-1.84
200	0.0639	+1.82	+1.98	200	0.1180	+1.56	+2.31	200	0.2013	+1.36	+2.58
		-1.37	-1.59			-1.20	-1.74			-1.10	-2.01
210	0.0529	+1.81	+2.05	210	0.0986	+1.55	+2.39	210	0.1691	+1.41	+2.60
		-1.41	-1.55			-1.23	-1.70			-1.14	-2.00
220	0.0441	+1.88	+1.93	220	0.0827	+1.58	+2.34	220	0.1426	+1.45	+2.46
		-1.40	-1.60			-1.27	-1.69			-1.06	-1.95
230	0.0369	+1.90	+1.86	230	0.0698	+1.64	+2.08	230	0.1208	+1.39	+2.22
		-1.39	-1.64			-1.21	-1.75			-1.15	-1.98
240	0.0310	+1.91	+1.78	240	0.0591	+1.65	+1.96	240	0.1027	+1.56	+2.22
		-1.46	-1.50			-1.26	-1.67			-1.06	-1.71
250	0.0262	+1.98	+1.63	250	0.0503	+1.69	+1.86	250	0.0878	+1.44	+2.20
		-1.47	-1.47			-1.31	-1.65			-1.19	-1.78
260	0.0222	+2.02	+1.60	260	0.0430	+1.69	+1.82	260	0.0753	+1.52	+1.87
		-1.49	-1.34			-1.36	-1.43			-1.20	-1.51
270	0.0190	+2.03	+1.44	270	0.0369	+1.75	+1.67	270	0.0650	+1.55	+1.81
		-1.51	-1.33			-1.35	-1.35			-1.17	-1.57
280	0.0162	+2.10	+1.38	280	0.0318	+1.78	+1.57	280	0.0563	+1.57	+1.63
		-1.52	-1.27			-1.37	-1.27			-1.21	-1.42
290	0.0139	+2.13	+1.30	290	0.0275	+1.85	+1.39	290	0.0489	+1.57	+1.61
		-1.54	-1.24			-1.38	-1.17			-1.32	-1.24
300	0.0120	+2.17	+1.22	300	0.0239	+1.84	+1.29	300	0.0428	+1.62	+1.17
		-1.56	-1.15			-1.42	-1.14			-1.29	-1.28

Table 24: NNLO QCD cross-section for  $pp \rightarrow ZH$  at  $\sqrt{s} = 7, 10, 14 \text{ TeV}$ , using MSTW2008 NNLO PDF and QCD scale  $\mu_R = \mu_F = M_{Z^*}$ . The PDF uncertainties estimated by using 68 % CL MSTW2008 error PDFs, scale uncertainties estimated by vary  $\mu_R$  and  $\mu_F$  a factor 2 and 1/2 synchronically from the central QCD scale. All calculation done using private code

# Additional material (III)

## ◆ NLO cross sections EW corrections for WH/ZH

7 TeV		
$m_H$ [GeV]	$\delta_{NLO}^{EW} - WH$ [%]	$\delta_{NLO}^{EW} - ZH$ [%]
100	-6.1	-4.9
110	-6.3	-5.0
120	-6.5	-5.1
130	-7.0	-5.2
140	-7.5	-5.4
150	-8.4	-5.8
160	-11.9	-8.5
170	-9.6	-5.6
180	-10.3	-6.6
190	-9.1	-5.7
200	-9.1	-5.3
210	-9.0	-5.0
220	-8.8	-4.6
230	-8.8	-4.3
240	-8.6	-4.0
250	-8.5	-3.7
260	-8.4	-3.5
270	-8.4	-3.4
280	-8.3	-3.3
290	-8.3	-3.2
300	-8.4	-3.2

10 TeV		
$m_H$ [GeV]	$\delta_{NLO}^{EW} - WH$ [%]	$\delta_{NLO}^{EW} - ZH$ [%]
100	-6.1	-5.0
110	-6.5	-5.1
120	-6.6	-5.1
130	-7.1	-5.3
140	-7.7	-5.4
150	-8.6	-5.9
160	-12.1	-8.6
170	-9.7	-5.8
180	-10.5	-6.8
190	-9.2	-5.9
200	-9.3	-5.5
210	-9.2	-5.2
220	-9.0	-4.8
230	-9.0	-4.5
240	-8.9	-4.3
250	-8.7	-4.0
260	-8.7	-3.9
270	-8.5	-3.7
280	-8.6	-3.7
290	-8.6	-3.6
300	-8.7	-3.7

14 TeV		
$m_H$ [GeV]	$\delta_{NLO}^{EW} - WH$ [%]	$\delta_{NLO}^{EW} - ZH$ [%]
100	-6.2	-5.0
110	-6.5	-5.1
120	-6.8	-5.2
130	-7.3	-5.3
140	-7.8	-5.5
150	-8.7	-6.0
160	-12.2	-8.7
170	-9.7	-5.9
180	-10.6	-6.9
190	-9.3	-6.0
200	-9.5	-5.7
210	-9.3	-5.3
220	-9.1	-5.0
230	-9.3	-4.8
240	-9.0	-4.5
250	-8.9	-4.3
260	-8.9	-4.2
270	-8.8	-4.0
280	-8.9	-4.0
290	-8.8	-4.0
300	-9.0	-4.0

Table 25: *WH/ZH NLO EW corrections, calculated using private code, MRST2004QCD and MRST2004 PDFs,  $\mu_R = \mu_F = M_{W^*/Z^*}$ . More details in the text.*