Chicago 2012 Workshop on LHC Physics

VV and *VV*+jet backgrounds

in Higgs searches

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in collaboration with

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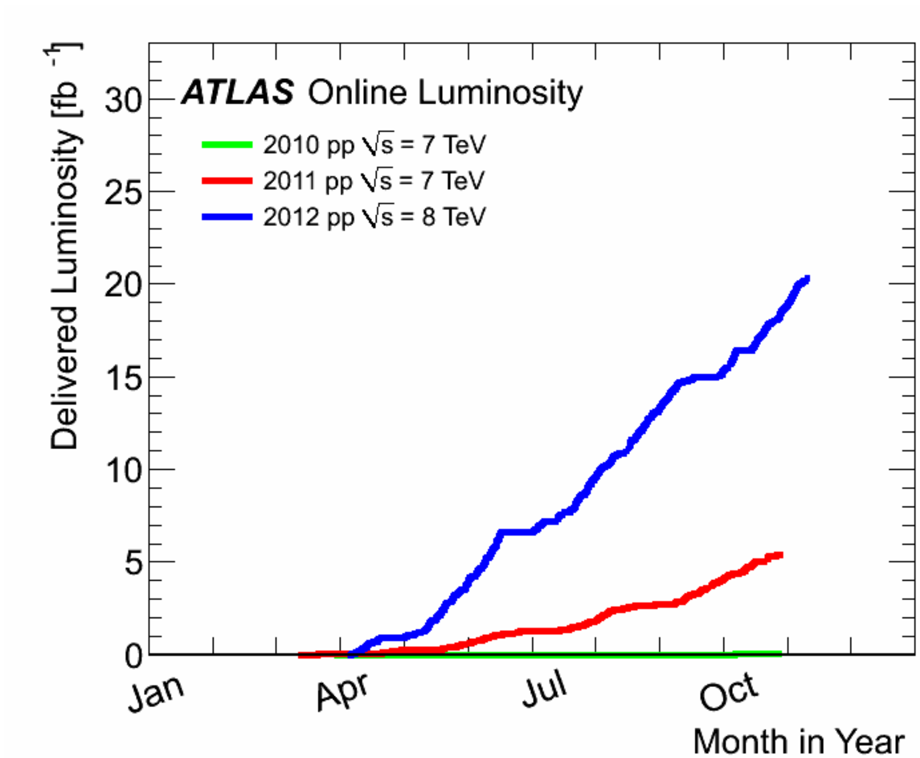
Expectation for the near future

"near future" ≈ tonight 10pm (i.e. 11am in Kyoto)

CMS and ATLAS will present updated Higgs search results from ~ 15 fb^{-1}



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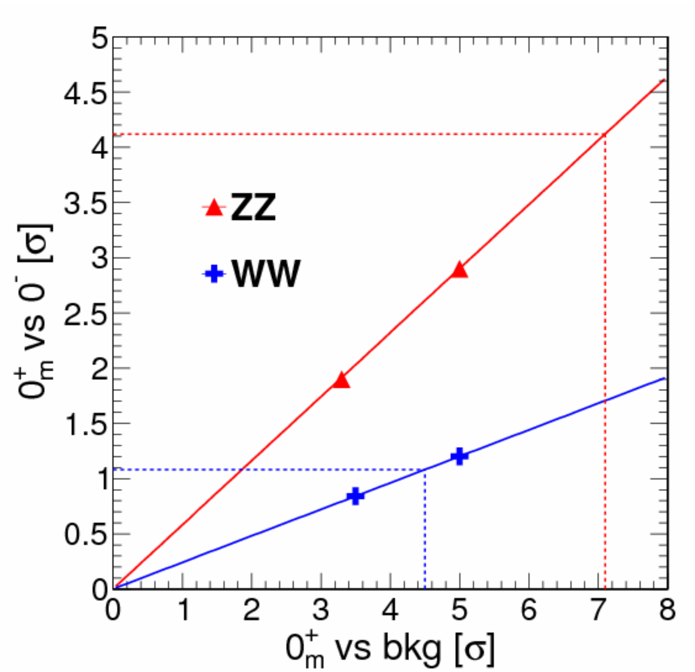
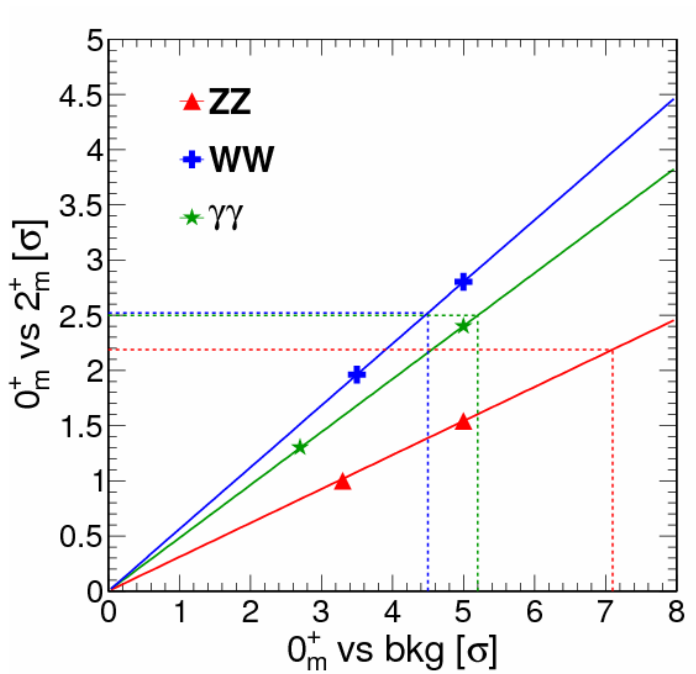
Expectations





[Bolognesi,Gao,Gritsan,Melnikov,M.S.,Tran,Whitbeck]

dashed lines: what might be expected with 35 fb^{-1} from one experiment

Outline

Review our understanding of the main backgrounds

- Since backgrounds in the $\gamma\gamma$ channel are modeled from data, I will concentrate on ZZ and WW final states

[ATLAS-CONF-2012-098]:

"The uncertainty on the shape of the total background is dominated by the uncertainty on the normalization of the individual backgrounds."

- What are the uncertainty estimates?
  - Enhancement and uncertainty of gg induced contributions
  - Interference effects, finite width effects
  - Electroweak corrections, $\gamma\gamma \rightarrow$ VV induced contributions

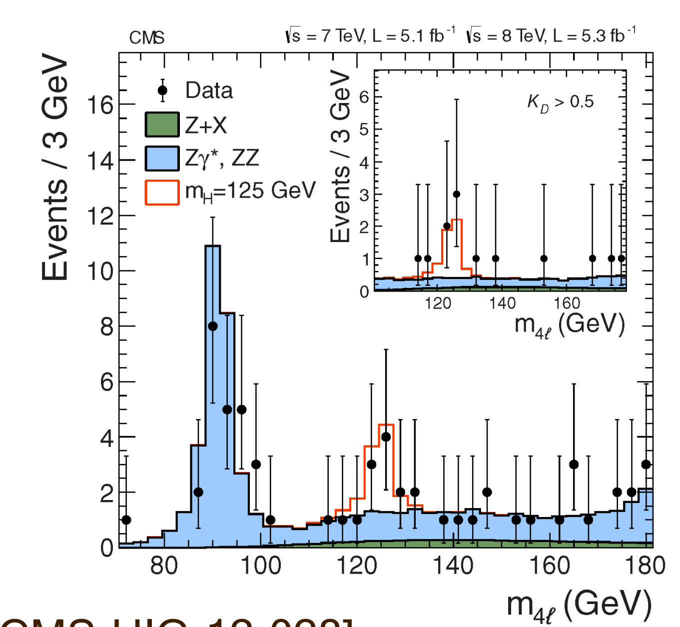
ZZ final states

ZZ final states

Experimental analysis

- very clean channel: select four isolated leptons
- selection cuts: $$Z: \; 50 \le m_{\ell\ell} \le 120 \text{ GeV} \qquad Z^*: \; m_{\ell\ell} \ge 12 \text{ GeV}$$ $+\ldots$
- background: mainly continuum ZZ and Z+jets

Discovery signal: Significance = 3.2 σ (CMS), 3.4 σ (ATLAS)   L(7TeV)≈ 5 fb^{-1} + L(8TeV)≈ 5 fb^{-1}



[CMS-HIG-12-028]

Table 3: The number of selected events, compared to the expected background yields and expected number of signal events ($m_H = 125$ GeV) for each final state in the H → ZZ analysis. The estimates of the $Z+X$ background are based on data. These results are given for the mass range from 110 to 160 GeV. The total background and the observed numbers of events are also shown for the three bins ("signal region") of Fig. 4 where an excess is seen ($121.5 < m_{4\ell} < 130.5$ GeV).

Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.7 ± 0.3	5.7 ± 0.6	7.2 ± 0.8	15.6 ± 1.4
$Z+X$	$1.2^{+1.1}_{-0.8}$	$0.9^{+0.7}_{-0.6}$	$2.3^{+1.8}_{-1.4}$	$4.4^{+2.2}_{-1.7}$
All backgrounds ($110 < m_{4\ell} < 160$ GeV)	4.0 ± 1.0	6.6 ± 0.9	9.7 ± 1.8	20 ± 3
Observed ($110 < m_{4\ell} < 160$ GeV)	6	6	9	21
Signal ($m_H = 125$ GeV)	1.36 ± 0.22	2.74 ± 0.32	3.44 ± 0.44	7.54 ± 0.78
All backgrounds (signal region)	0.7 ± 0.2	1.3 ± 0.1	1.9 ± 0.3	3.8 ± 0.5
Observed (signal region)	1	3	5	9

ZZ final states

Continuum ZZ production

Main backgrounds are estimated from MC studies

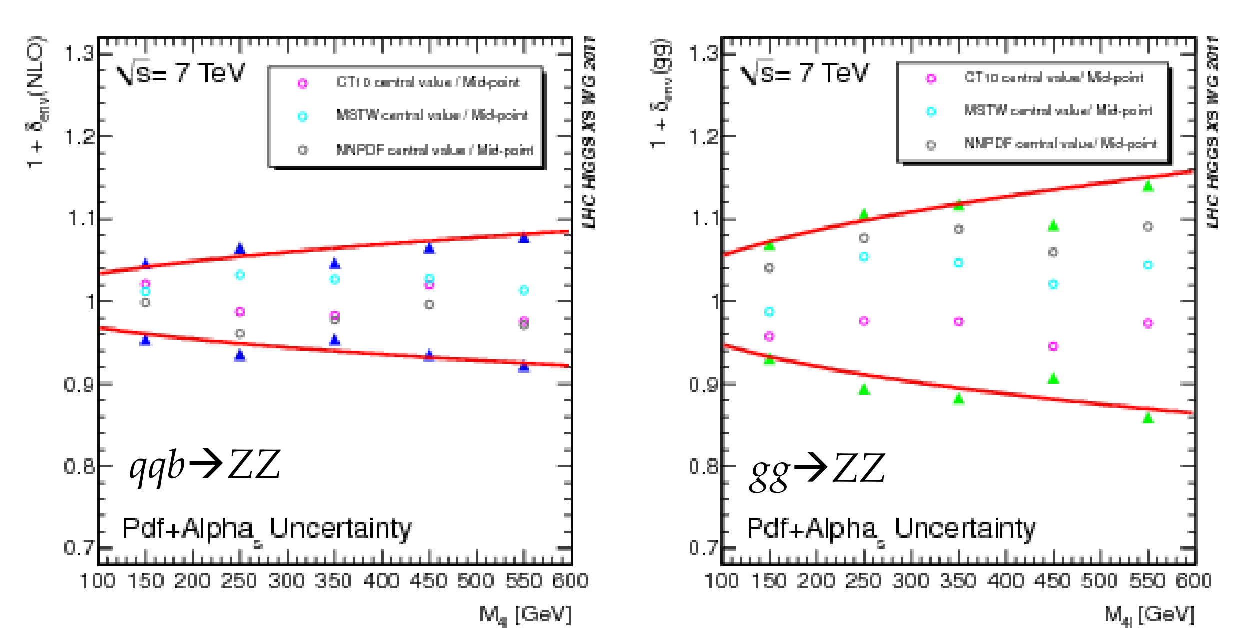
qqb → *ZZ* from `Powheg+Pythia`

gg → *ZZ* from `gg2ZZ/MCFM`

Z+jets background is estimated from data (much larger rel. error)

[Handbook of LHC Higgs cross sections]:

pdf and α_s uncertainty:



ZZ final states

Continuum ZZ production

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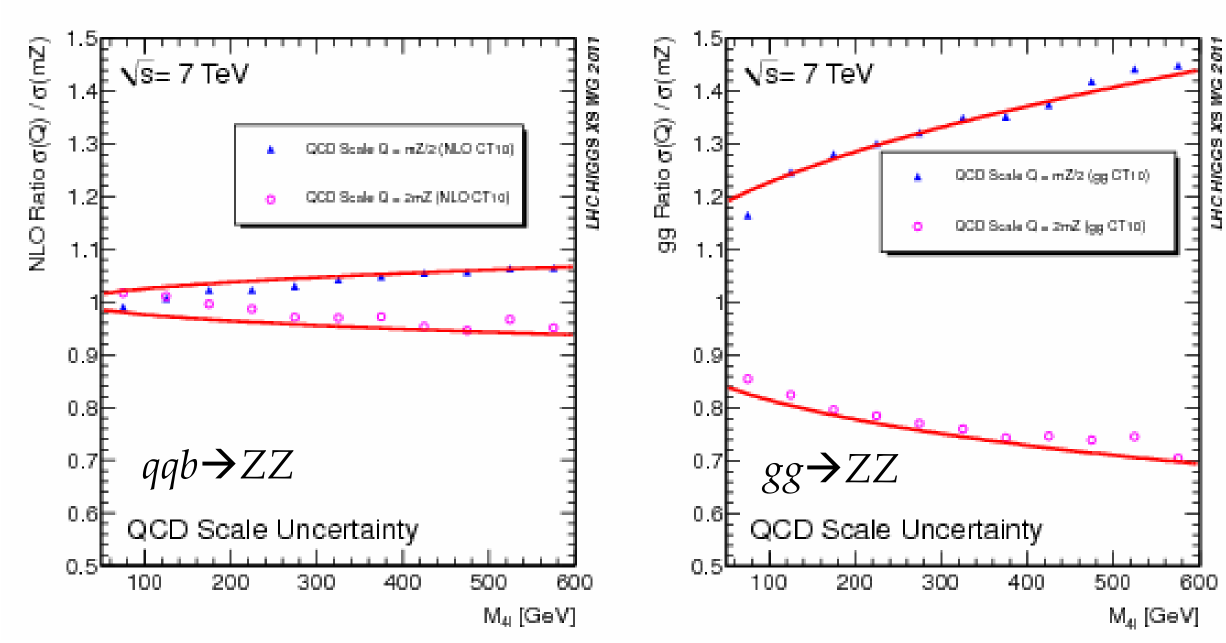
[Handbook of LHC Higgs cross sections]:

QCD scale uncertainty:

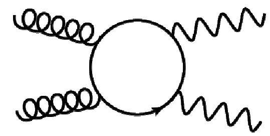


ZZ final states

Gluon induced contributions

[Dicus,Kao,Repko], [Glover,vdBij]
[Campbell,Ellis,Williams], [Kauer,Passarino]

$gg \rightarrow ZZ$

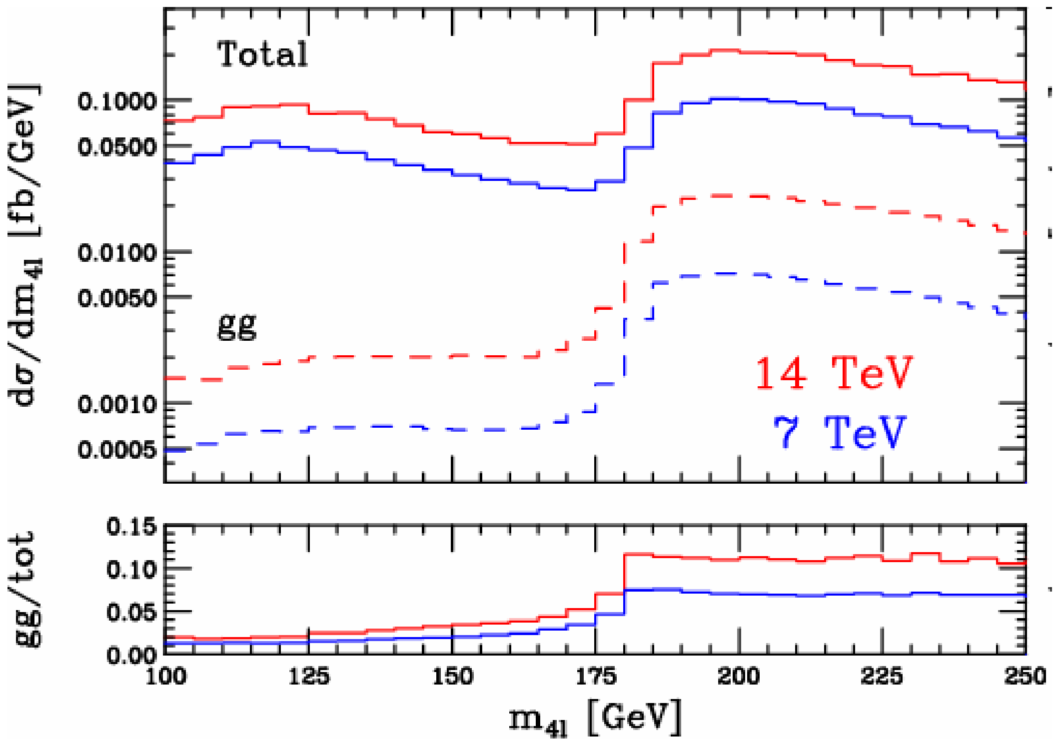


- Loop induced at LO
- $gg \rightarrow ZZ$ contributes to the NNLO for $pp \rightarrow ZZ$ because there is no gg tree. Hence, it is a finite and gauge-invariant sub-process
- Low ZZ threshold and large gluon flux may compensate α_s suppression

ZZ final states

Gluon induced contributions

[Dicus,Kao,Repko], [Glover,vdBij]
[Campbell,Ellis,Williams], [Kauer,Passarino]



gg induced contribution is about 10% of the total cross section but only 1-2% in the region of around m_{4l}=125 GeV

→ relevant for high-mass searches

ZZ final states

Finite width and background interference

[Kauer,Passarino]

- Finite width effects are param. suppressed by Γ/M

$$P_H(q^2) = \frac{1}{(q^2 - M_H^2)^2 + \Gamma_H^2 M_H^2} = \frac{\pi}{M_H \Gamma_H}\delta(q^2 - M_H^2) + \mathcal{O}(\Gamma_H/M_H)$$

this can be violated in gg→H→ZZ for M_{ZZ}>$2M_Z$

and might affect normalizations in control regions

- Interference between signal and background

$$|\mathcal{A}_{ZZ}|^2 = |\mathcal{A}_H|^2 + |\mathcal{A}_{\rm cont}|^2 + 2{\rm Re}(\mathcal{A}_H \mathcal{A}^*_{\rm cont})$$

	$gg\ (\to H) \to ZZ \to 4\ell$ and $2\ell\, 2\ell'$						
	σ [fb], pp, $\sqrt{s} = 8$ TeV, $M_H = 125$ GeV				ZWA	interfer	
mode	$H_{\rm ZWA}$	$H_{\rm offshell}$	cont	$\|H_{\rm ofs}\text{+cont}\|^2$	R_0	R_1	
$\ell\bar{\ell}\ell\bar{\ell}$	0.0748(2)	0.0747(2)	0.000437(3)	0.0747(6)	1.002(3)	0.994(8)	
$\ell\bar{\ell}\ell'\bar{\ell}'$	0.1395(2)	0.1393(2)	0.000583(2)	0.1400(3)	1.002(2)	1.001(2)	1.001(2)

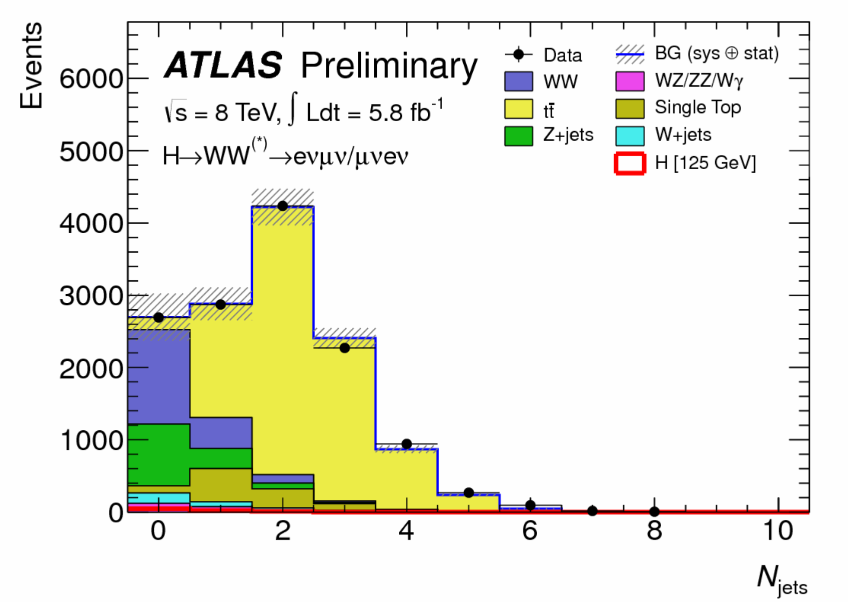
Table 3. Cross sections for $gg\ (\to H) \to ZZ \to \ell\bar{\ell}\ell\bar{\ell}$ and $\ell\bar{\ell}\ell'\bar{\ell}'$ in pp collisions at $\sqrt{s} = 8$ TeV for $M_H = 125$ GeV and $\Gamma_H = 0.004434$ GeV calculated at LO with gg2VV. The zero-width approximation (ZWA) and off-shell Higgs cross sections, the continuum cross section and the sum

WW final states

WW final states

Signature

- Signal is two OC leptons and large momentum imbalance due to two neutrinos.
- Most sensitive channel in the mass range around 160 GeV
  → it is possible to extend the sensitivity down to 120 GeV
- The background rate and relative composition depends on the number of accompanying jets. → enhance sensitivity by pre-selection into jet multiplicities



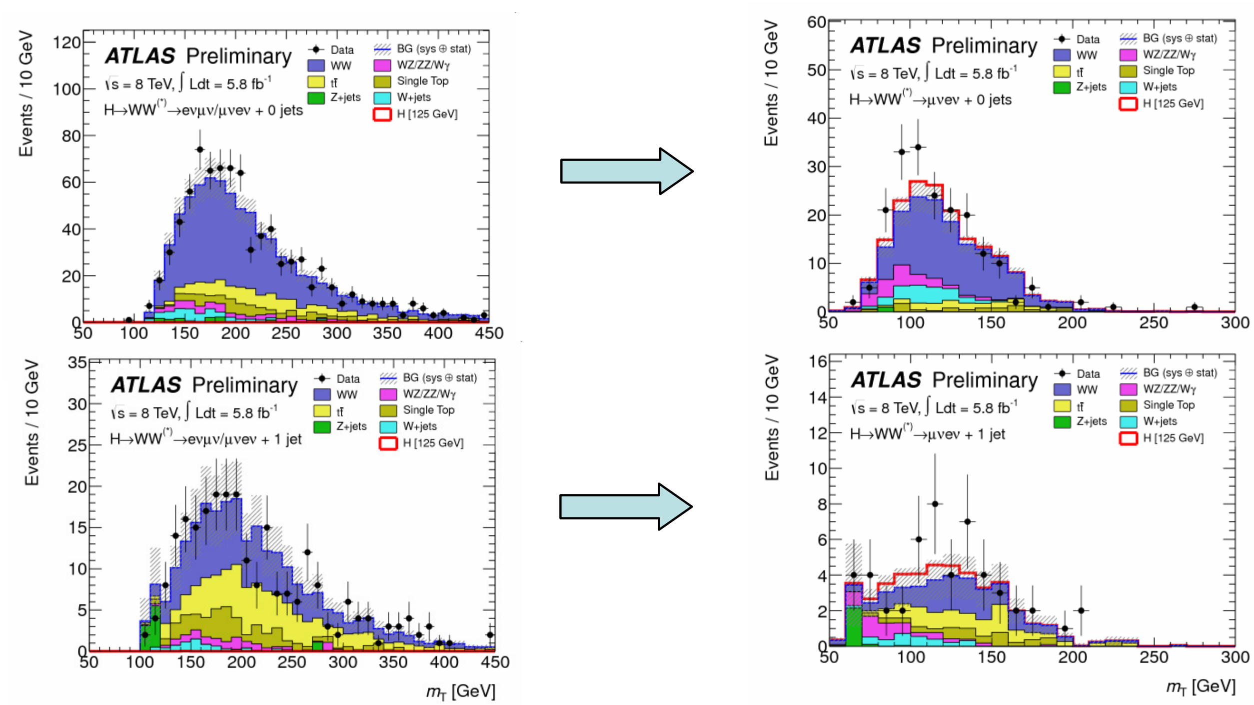
WW final states

Further selection:

- b-tagging to remove ttb background
- spin-0 nature and V-A structure of W coupling forces leptons to fly preferably into the same direction

$\Delta\phi_{\ell\ell} \leq 1.8$ and $m_{\ell\ell} \leq 50$ GeV in the signal region for 0- and 1-jet bin

$0.75\, m_H \leq m_{\mathrm{T}} \leq m_H$



WW final states

Background modeling

"semi-data driven" method:

- normalize MC predictions to data in the control region and extrapolate into the signal region.

→ extrapolation is obtained from computation of $\alpha = N_{\rm SR}/N_{\rm CR}$ and used to obtain $N_{\rm SR} = \alpha\ N_{CR}$

qqb → *WW* from MC@NLO+Herwig, MCFM
gg → *WW* from MCFM, gg2WW

[Handbook of LHC Higgs cross sections]

$$\frac{\alpha(\mathrm{MCNLO})}{\alpha(\mathrm{MCFM})} = 0.980 \pm 0.015 \qquad \delta\alpha(\mathrm{PDFs}) \approx 2.5\%$$

→ Experiments adpot an uncertainty of 3.5% on α

WW final states

[ATLAS-CONF-2012-098]

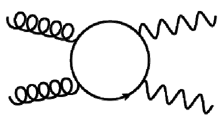
Table 4: Main systematic uncertainties on the predicted numbers of signal (m_H = 125 GeV) and background events for the $H+$0-jet and $H+$1-jet analyses, relative to the total signal and background expectations. The same m_T criteria as in Table 3 are imposed. All numbers are summed over lepton flavours. The effect of the quoted inclusive signal cross section renormalisation and factorisation scale uncertainties on exclusive jet multiplicities is explained in Section 5. Sources of uncertainty that are negligible or not applicable in a particular column are marked with a '-'.

Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal ren./fact. scale	13	-
1-jet incl. ggF signal ren./fact. scale	10	-
Parton distribution functions	8	2
Jet energy scale	7	4
WW normalisation	-	7
WW modelling and shape	-	5
W+jets fake factor	-	5
QCD scale acceptance	4	2

	0-jet
Signal	20 ± 4
Total Background	142 ± 16
Observed	185

WW final states

Gluon-induced WW background to Higgs boson searches at the LHC



[Glover,Bij],[Kao,Dicus]
(1989,1991)
[Binoth,Ciccolini,Kauer,Krämer]
(2005)

Early calculations for the SSC found: gg is the dominant production process

this was later revised after using modern parton distribution functions & updated α_s

From the abstract of [Binoth,Ciccolini,Kauer,Krämer]

„We find that gg → WW provides only a moderate correction (ca. 5%) to the inclusive W-pair production cross section at the LHC. However, after taking into account realistic experimental cuts, the gluon-fusion process becomes significant and increases the theoretical WW background estimate [...] by approximately 30%.“

	$\sigma(pp \to W^*W^* \to \ell\bar{\nu}\bar{\ell}'\nu')$ [fb]				
	gg	$q\bar{q}$ LO	$q\bar{q}$ NLO	$\frac{\sigma_{NLO}}{\sigma_{LO}}$	$\frac{\sigma_{NLO+gg}}{\sigma_{NLO}}$
σ_{tot}	$53.61(2)^{+14.0}_{-10.8}$	$875.8(1)^{+54.9}_{-67.5}$	$1373(1)^{+71}_{-79}$	1.57	1.04
σ_{std}	$25.89(1)^{+6.85}_{-5.29}$	$270.5(1)^{+20.0}_{-23.8}$	$491.8(1)^{+27.5}_{-32.7}$	1.82	1.05
σ_{bkg}	$1.385(1)^{+0.40}_{-0.31}$	$4.583(2)^{+0.42}_{-0.48}$	$4.79(3)^{+0.01}_{-0.13}$	1.05	1.29

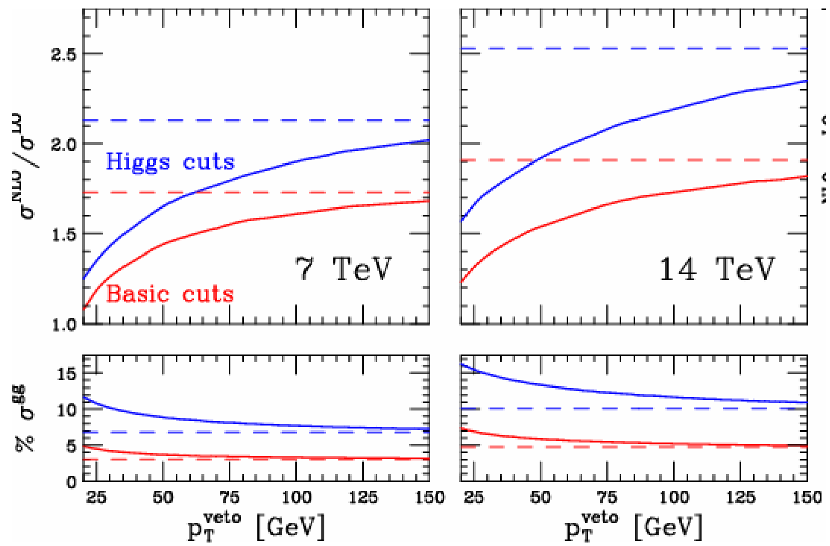
cuts: $\Delta\phi \leq 0.8$

$m_{\ell\ell} \leq 35$ GeV

+ ...

WW final states

Re-evaluation using search cuts of ATLAS & CMS:



[Campbell,Ellis,Williams]: 0-jet bin

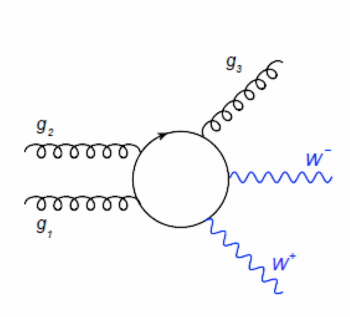
$\sqrt{s}$ [TeV] and cuts	$\sigma^{LO}(e^+\mu^-\nu_e\overline{\nu}_\mu)$ [fb]	$\sigma^{NLO}(e^+\mu^-\nu_e\overline{\nu}_\mu)$ [fb]	K-factor	% gg
7 (Basic)	144	249	1.73	3.05
7 (Higgs)	7.14	15.19	2.13	6.85
14 (Basic)	296	566	1.91	4.73
14 (Higgs)	13.7	34.7	2.53	10.09

[Melia,Melnikov,Röntsch,Zanderighi,M.S.]: 0-jet (and 1-jet bin)

Higgs search cuts

		σ_{LO}	σ_{NLO}^{incl}	σ_{NLO}^{excl}	$\delta\sigma_{NNLO}$	$\delta\sigma_{NNLO}/\sigma_{NLO}^{excl}$
8 TeV	WW	$35.6(1)^{+0.9}_{-1.3}$	$51.1(1)^{-0.4}_{+0.9}$	$38.8(1)^{+1.0}_{-0.8}$	$2.7(1)^{-0.5}_{+0.7}$	7.0%
14 TeV	WW	$63.4(1)^{+3.9}_{-4.7}$	$91.9(2)^{-0.1}_{+0.4}$	$63.4(2)^{+2.1}_{-2.0}$	$7.5(1)^{-1.2}_{+1.5}$	11.8%

WW final states

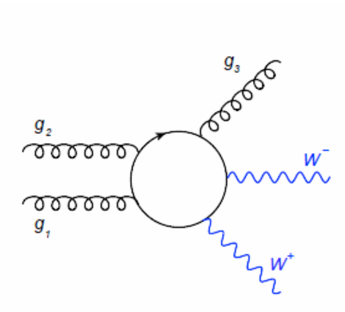


Gluon fusion contribution to WW+1jet

[Melia,Melnikov,Röntsch,Zanderighi,M.S.]

- Loop induced tree level with five external particles
- We use modern unitarity techniques to calculate this process
- We include all spin correlations, singly-resonant diagrams, off-shell effects
- We combine our results with the NLO calculation for quark induced channels [Campbell,Ellis,Zanderighi]
- Add-on to MCFM is publicly available

WW final states



Gluon fusion contribution to WW+1jet

[Melia,Melnikov,Röntsch,Zanderighi,M.S.]

+combined with quark induced channels at NLO QCD
[Campbell,Ellis,Zanderighi]

Higgs search cuts

		σ_{LO}	σ_{NLO}^{incl}	σ_{NLO}^{excl}	$\delta\sigma_{NNLO}$	$\delta\sigma_{NNLO}/\sigma_{NLO}^{excl}$
8 TeV	WW	$35.6(1)^{+0.9}_{-1.3}$	$51.1(1)^{-0.4}_{+0.9}$	$38.8(1)^{+1.0}_{-0.8}$	$2.7(1)^{-0.5}_{+0.7}$	7.0%
	WWj	$12.6(1)^{-1.5}_{+1.8}$	$10.8(1)^{+0.3}_{-0.7}$	$10.6(1)^{+0.3}_{-0.9}$	$0.6(1)^{-0.2}_{+0.2}$	5.7%
14 TeV	WW	$63.4(1)^{+3.9}_{-4.7}$	$91.9(2)^{-0.1}_{+0.4}$	$63.4(2)^{+2.1}_{-2.0}$	$7.5(1)^{-1.2}_{+1.5}$	11.8%
	WWj	$28.7(1)^{-2.6}_{+2.9}$	$21.6(1)^{+1.2}_{-2.1}$	$20.5(1)^{+1.7}_{-2.2}$	$1.8(2)^{-0.5}_{+0.7}$	8.8%

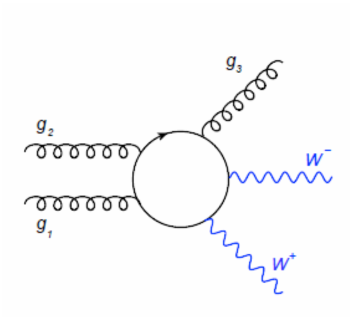
experiments do not yet include simulation data but associate a large system. uncertainty

Source (1-jet)	Signal (%)	Bkg. (%)
1-jet incl. ggF signal ren./fact. scale	28	-
WW normalisation	0	25
2-jet incl. ggF signal ren./fact. scale	16	-
b-tagging efficiency	-	10
Parton distribution functions	7	1
W+jets fake factor	0	5

similar in CMS analysis
~ 30% norm.uncert.

[ATLAS-CONF-2012-098]

WW final states



Gluon fusion contribution to WW+1jet

[Melia,Melnikov,Röntsch,Zanderighi,M.S.]

+combined with quark induced channels at NLO QCD
[Campbell,Ellis,Zanderighi]

Higgs search cuts

		$\sigma_{\rm LO}$	$\sigma_{\rm NLO}^{\rm incl}$	$\sigma_{\rm NLO}^{\rm excl}$	$\delta\sigma_{\rm NNLO}$	$\delta\sigma_{\rm NNLO}/\sigma_{\rm NLO}^{\rm excl}$
8 TeV	WW	$35.6(1)^{+0.9}_{-1.3}$	$51.1(1)^{-0.4}_{+0.9}$	$38.8(1)^{+1.0}_{-0.8}$	$2.7(1)^{-0.5}_{+0.7}$	7.0%
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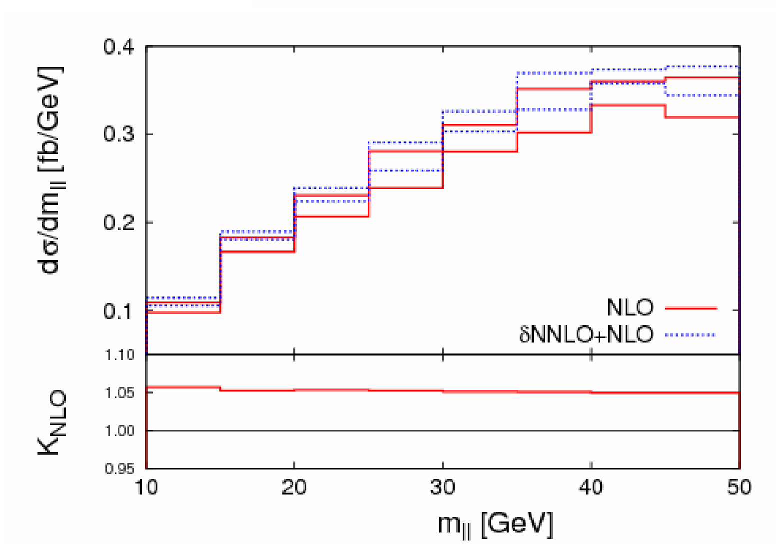
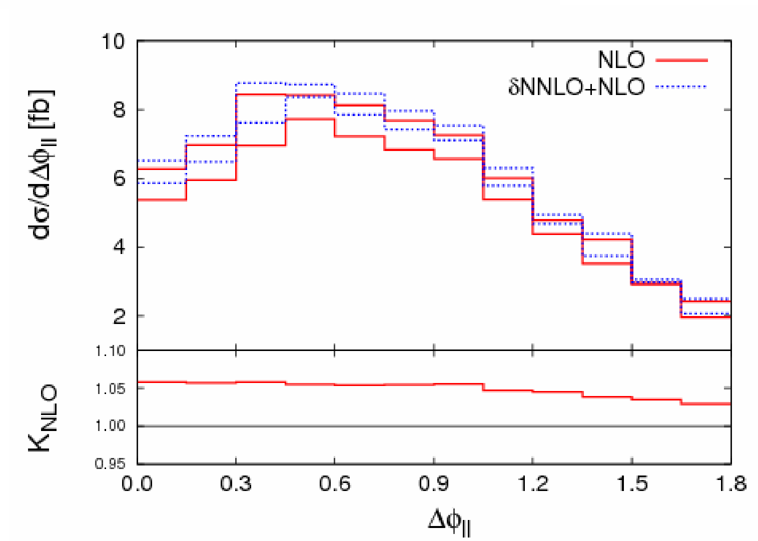
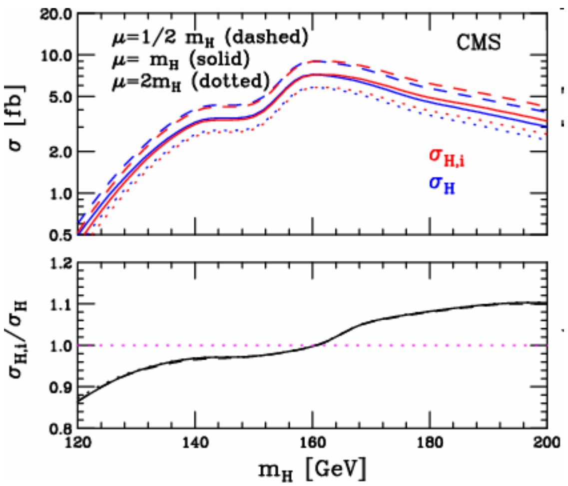


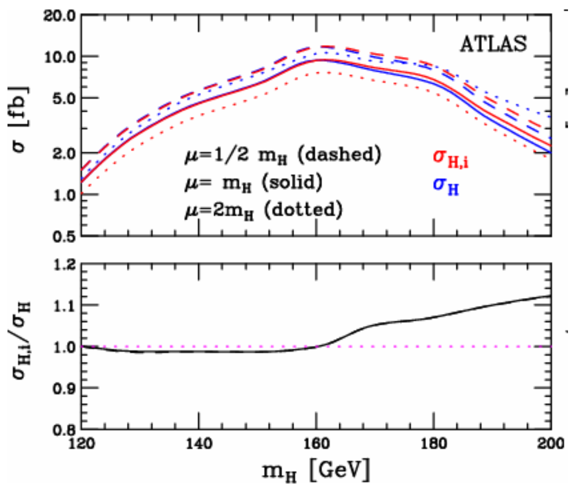


WW final states

Background interference effects

[Campbell,Ellis,Williams]





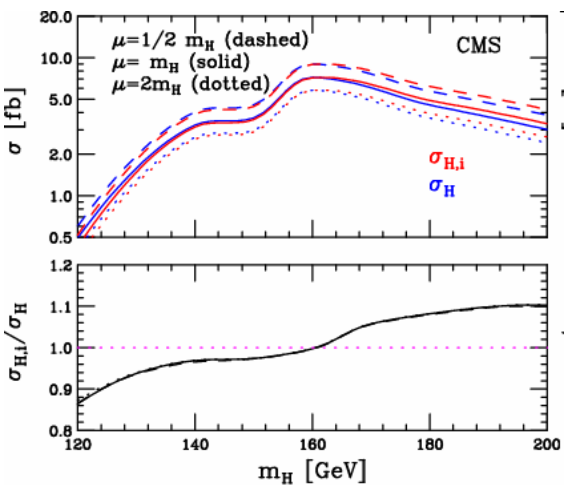
- main difference is that "CMS" is missing a cut on $m_T < 125$ GeV
  (CMS does cut on m_T in their actual analysis)

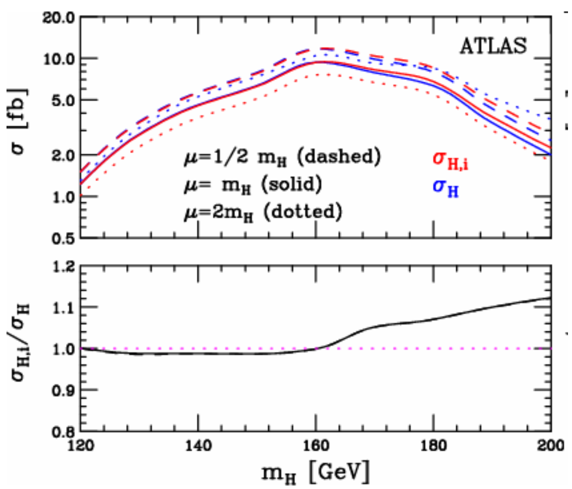
→ cut on mT is important to suppress interference

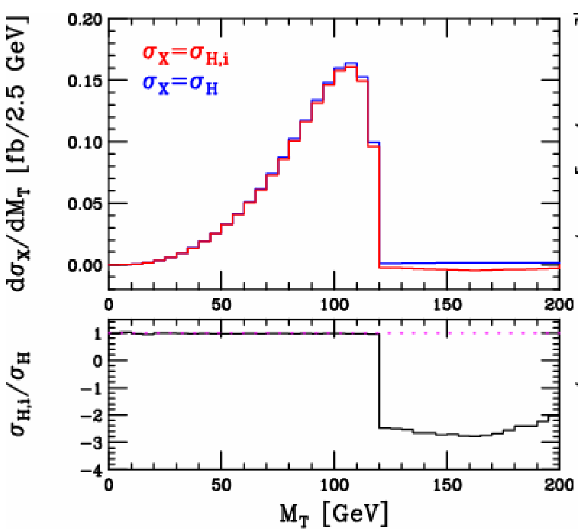
WW final states

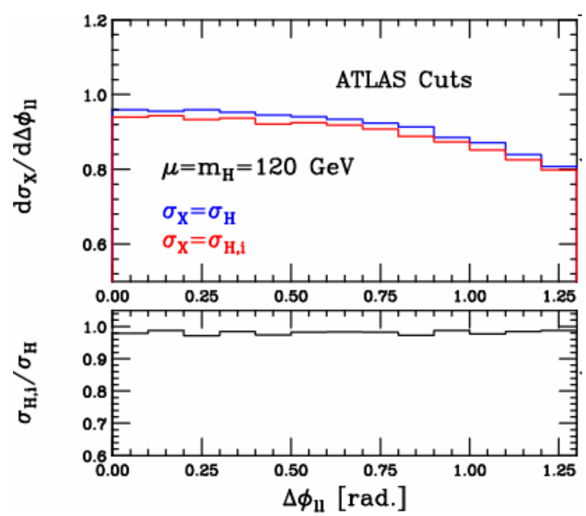
Background interference effects

[Campbell,Ellis,Williams]







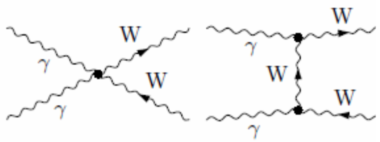


- main difference is that "CMS" is missing a cut on $m_T < 125$ GeV
  (CMS does cut on m_T in their actual analysis)

→ cut on mT is important to suppress interference

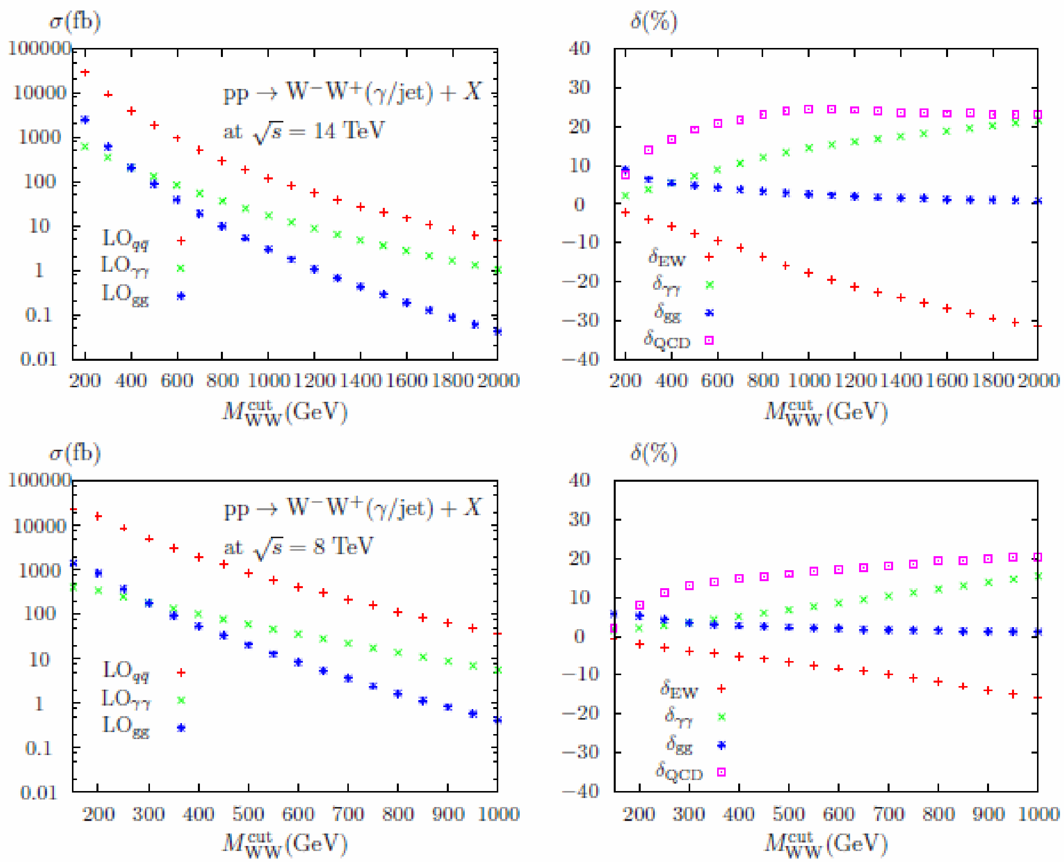
- after cutting on m_T interference effects are O(2%) and almost const.

WW final states



Electroweak corrections and photon initial states

[Bierweiler,Kasprzik,Kühn,Uccirati]



M_{WW}^{cut} (GeV)	σ_{LO}^{qq} (pb)	δ_{EW} (%)	$\delta_{\gamma\gamma}$ (%)	δ_{gg} (%)	δ_{QCD}^{veto} (%)	δ_{WWV} (%)
200	28.84	−2.2	2.2	8.9	7.4	0.5
300	9.492	−4.1	3.8	6.4	14.0	0.8
500	1.841	−7.5	7.2	4.8	19.2	1.4
1000	$12.08 \cdot 10^{-2}$	−17.7	14.4	2.6	24.5	3.2
1500	$20.37 \cdot 10^{-3}$	−25.4	18.1	1.4	23.5	4.2
2000	$48.79 \cdot 10^{-4}$	−31.4	21.6	0.9	23.0	4.9
2500	$13.81 \cdot 10^{-4}$	−36.3	25.6	0.6	22.6	5.2
3000	$42.99 \cdot 10^{-5}$	−40.6	30.5	0.4	22.4	5.4

- stable W`s; i.e. no Higgs search cuts

  but relevant for high-mass searches
- sizable cancellations between different contributions → dependence on cuts

SUMMARY

- ZZ background is under good control:
  - exp. analyses include NLO QCD simulations,
  - gg induced channels, background interference & finite width effects are small in the 125 GeV range

- WW in the 0-jet bin is under good control:
  - analyses use semi-data driven methods
  - gg induced channels are included in simulations
  - background interference is effectively removed by cut on m_T

- WW in the 1-jet bin:
  - higher order corrections exist
  - exp. analyses use LO tools and assign large uncertainty
  - gg induced contribution (NNLO) is larger than NLO scale variation and very dependent on kinematic cuts

- high-mass searches might have to account for background interference, gg/$\gamma\gamma$ induced channels, el.weak corrections