

Diboson production in higher order QCD and EW

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Workshop on the physics of HL-LHC, and perspectives at HE-LHC



NNLO QCD and NLO EW HL/HE-LHC

NNLO QCD

- diboson production Grazzini, Kallweit, Wiesemann
- ZZ incl. massive two-loop corrections Heinrich, Jahn, Jones, Kerner, Pires

NLO EW

- diboson production Kallweit, Linder, Pozzorini, MS
- $\gamma\gamma + V$ production Greiner, MS
- triboson production MS

for both HL-LHC and HE-LHC

NNLO QCD results

process (\${process_id})	σ_{LO}	σ_{NLO}	σ_{loop}^{loop} ($\sigma_{loop}/\Delta\sigma_{NNLO}^{loop}$)	σ_{NNLO}^{stat}	$\sigma_{NNLO}^{extrapolated}$	K_{NLO}	K_{NNLO}
$pp \rightarrow \gamma\gamma$ (ppaa02)	5.592(1) $^{+10\%}_{-11\%}$ pb	25.75(1) $^{+8.8\%}_{-7.3\%}$ pb	2534(1) $^{+24\%}_{-17\%}$ fb (+7.4%)	40.86(2) $^{+8.7\%}_{-7.2\%}$ pb	40.28(30) $^{+8.7\%}_{-7.0\%}$ pb	+361%	+56.4%
$pp \rightarrow \gamma\gamma$ (ppaa02)	10.34(0) $^{+15\%}_{-15\%}$ pb	54.63(5) $^{+9.9\%}_{-11\%}$ pb	6701(17) $^{+24\%}_{-17\%}$ fb (+7.4%)	88.76(30) $^{+9.1\%}_{-7.4\%}$ pb	88.45(51) $^{+9.9\%}_{-7.4\%}$ pb	+428%	+61.9%
$pp \rightarrow ZZ$ (ppzz02)	9.845(1) $^{+5.2\%}_{-6.3\%}$ pb	14.10(0) $^{+2.9\%}_{-2.6\%}$ pb	1361(1) $^{+25\%}_{-19\%}$ fb (+2.9%)	16.68(1) $^{+3.2\%}_{-2.6\%}$ pb	16.67(1) $^{+3.2\%}_{-2.6\%}$ pb	+43.3%	+18.2%
$pp \rightarrow ZZ$ (ppzz02)	23.59(1) $^{+10\%}_{-11\%}$ pb	35.56(2) $^{+3.2\%}_{-4.1\%}$ pb	4821(11) $^{+25\%}_{-18\%}$ fb (+2.9%)	44.36(17) $^{+4.2\%}_{-3.4\%}$ pb	44.46(33) $^{+4.3\%}_{-3.5\%}$ pb	+50.7%	+25.0%
$pp \rightarrow W^+W^-$ (ppww02)	66.64(1) $^{+5.7\%}_{-6.7\%}$ pb	103.2(0) $^{+3.9\%}_{-3.1\%}$ pb	4091(3) $^{+27\%}_{-19\%}$ fb (+3.5%)	117.1(1) $^{+2.5\%}_{-2.2\%}$ pb	117.1(1) $^{+2.5\%}_{-2.2\%}$ pb	+54.9%	+13.4%
$pp \rightarrow W^+W^-$ (ppww02)	152.5(0) $^{+10\%}_{-11\%}$ pb	254.7(2) $^{+4.4\%}_{-4.6\%}$ pb	13.87(3) $^{+27\%}_{-19\%}$ pb (+3.5%)	300.4(1.1) $^{+3.3\%}_{-3.0\%}$ pb	299.8(1.3) $^{+3.3\%}_{-2.9\%}$ pb	+67.0%	+17.7%
$pp \rightarrow e^- \mu^+ e^+ \mu^+$ (ppenex04)	11.34(0) $^{+6.3\%}_{-7.3\%}$ fb	16.87(0) $^{+3.0\%}_{-2.5\%}$ fb	1.971(1) $^{+25\%}_{-19\%}$ fb (+3.5%)	20.30(1) $^{+3.5\%}_{-2.9\%}$ fb	20.30(1) $^{+3.5\%}_{-2.9\%}$ fb	+48.8%	+20.3%
$pp \rightarrow e^- \mu^+ e^+ \mu^+$ (ppenex04)	22.49(1) $^{+11\%}_{-12\%}$ fb	35.78(3) $^{+3.4\%}_{-4.5\%}$ fb	6.140(20) $^{+25\%}_{-18\%}$ fb (+3.5%)	45.78(21) $^{+4.6\%}_{-3.8\%}$ fb	45.28(83) $^{+4.4\%}_{-3.6\%}$ fb	+59.1%	+26.6%
$pp \rightarrow e^- \mu^+ \nu_\mu \bar{\nu}_\mu$ (ppenxnx04)	232.9(0) $^{+6.6\%}_{-7.6\%}$ fb	236.1(1) $^{+2.8\%}_{-2.4\%}$ fb	26.93(1) $^{+27\%}_{-19\%}$ fb (+3.5%)	264.7(1) $^{+2.2\%}_{-1.4\%}$ fb	264.6(2) $^{+2.2\%}_{-1.4\%}$ fb	+1.34%	+12.1%
$pp \rightarrow e^- \mu^+ \nu_\mu \bar{\nu}_\mu$ (ppenxnx04)	439.0(1) $^{+11\%}_{-12\%}$ fb	429.0(4) $^{+3.5\%}_{-3.2\%}$ fb	79.19(9) $^{+27\%}_{-19\%}$ fb (+3.5%)	507.0(1.4) $^{+3.2\%}_{-2.1\%}$ fb	507.5(1.9) $^{+3.3\%}_{-2.1\%}$ fb	-2.27%	+18.3%
$pp \rightarrow e^- \mu^+ e^+ \bar{\nu}_\mu$ (ppenxnx04)	11.50(0) $^{+5.7\%}_{-6.8\%}$ fb	23.55(1) $^{+5.5\%}_{-4.5\%}$ fb	—	26.15(1) $^{+2.2\%}_{-2.1\%}$ fb	26.15(2) $^{+2.3\%}_{-2.1\%}$ fb	+105%	+11.1%
$pp \rightarrow e^- \mu^+ e^+ \bar{\nu}_\mu$ (ppenxnx04)	23.18(4) $^{10.9\%}_{11.5\%}$ fb	53.21(9) $^{+6.1\%}_{-5.3\%}$ fb	—	62.18(65) $^{+2.2\%}_{-3.2\%}$ fb	62.07(84) $^{+2.3\%}_{-3.1\%}$ fb	+129.5%	+16.6%

×2.2

×2.7

×2.6

×2.3

×1.9

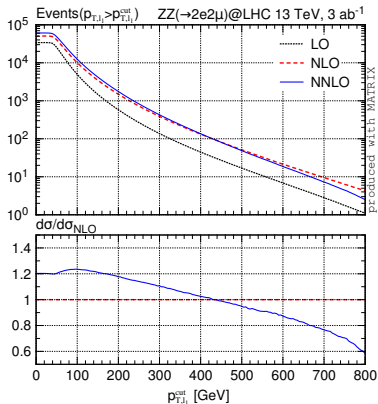
×2.4

on-shell

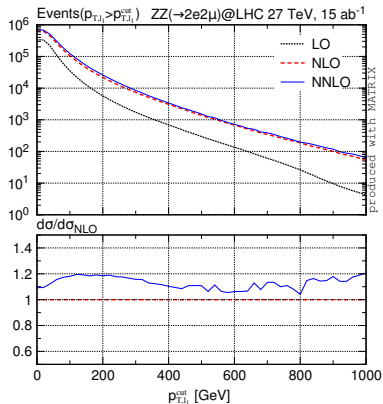
off-shell

NNLO QCD results – ZZ

13 TeV



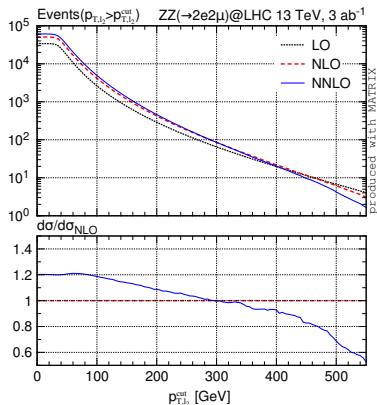
27 TeV



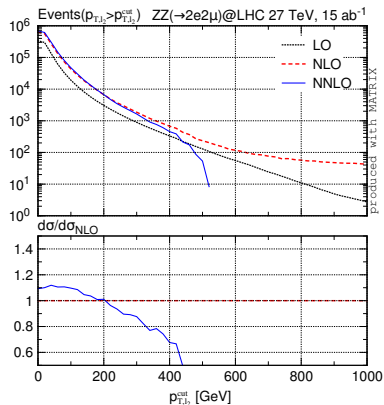
⇒ still limited stats for 27 TeV

NNLO QCD results – ZZ

13 TeV



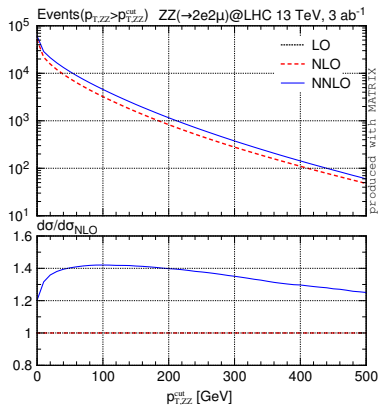
27 TeV



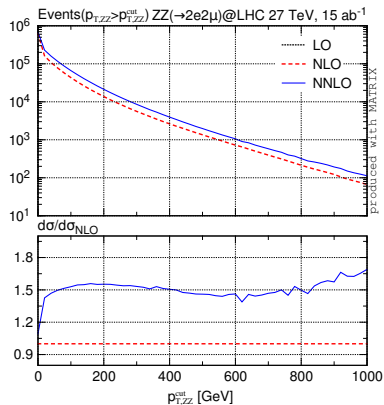
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NNLO QCD results – ZZ

13 TeV

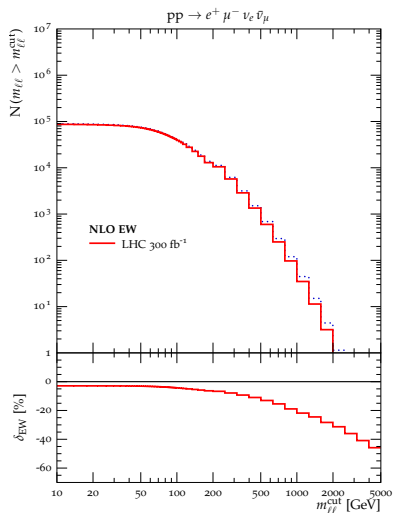


27 TeV



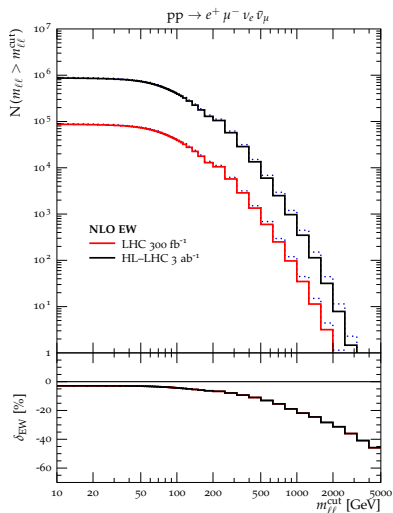
⇒ still limited stats for 27 TeV

NLO EW results – WW



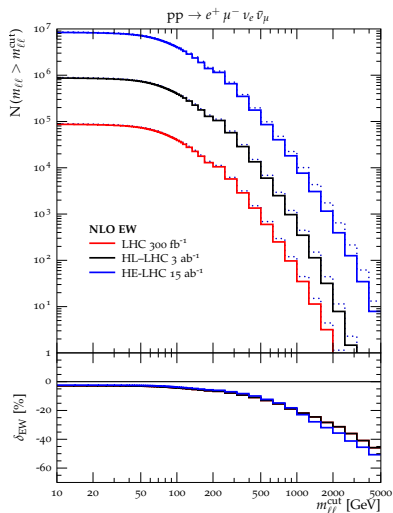
- increased reach with increased luminosity
13 TeV \Rightarrow 14 TeV
300 fb⁻¹ \Rightarrow 3 ab⁻¹
- increased reach with increased collider energy
14 TeV \Rightarrow 27 TeV
3 ab⁻¹ \Rightarrow 15 ab⁻¹
- EW corrections important, mild dependence on collider energy

NLO EW results – WW



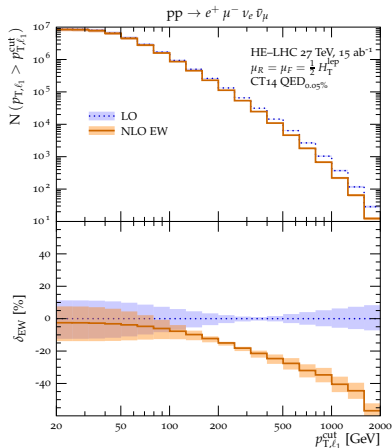
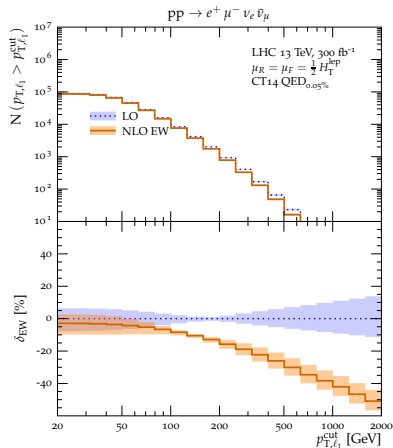
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NLO EW results – WW



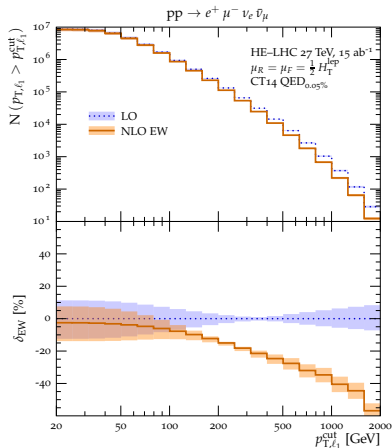
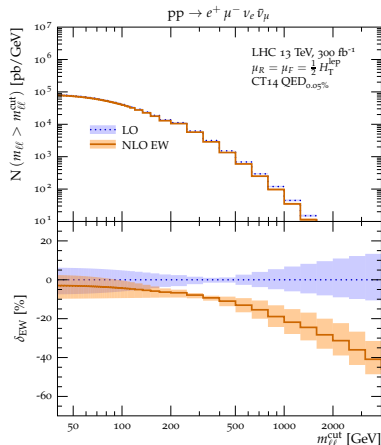
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NLO EW results – WW



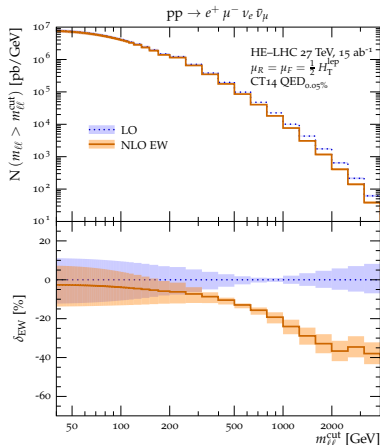
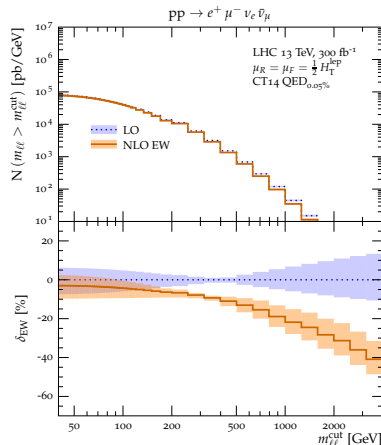
- most important gain from additional luminosity
- xs increase in identical fiducial region:
inclusive ~ 2 , with $p_T > 500 \text{ GeV} \sim 5.5$

NLO EW results – WW



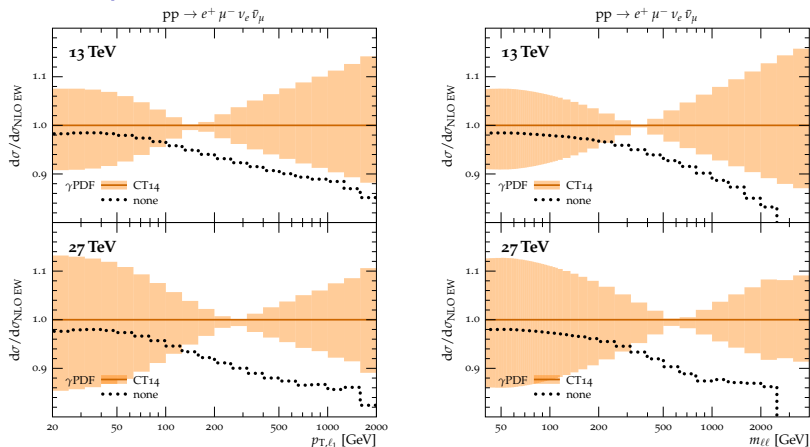
- most important gain from additional luminosity
- xs increase in identical fiducial region:
 inclusive ~ 2 , with $p_T > 500$ GeV ~ 5.5 , or with $m_{\ell\ell} > 1$ TeV ~ 4.5

NLO EW results – WW



- most important gain from additional luminosity
- xs increase in identical fiducial region:
 inclusive ~ 2 , with $p_T > 500$ GeV ~ 5.5 , or with $m_{\ell\ell} > 1$ TeV ~ 4.5

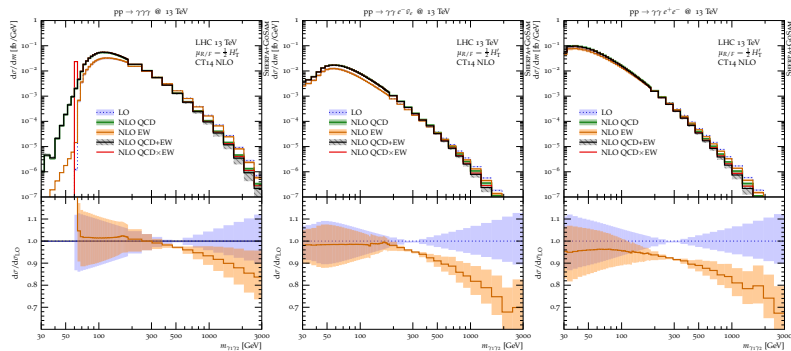
γ -PDF importance at 13 and 27 TeV



- importance of γ -PDF in same order of magnitude, but somewhat larger at 27 TeV

NLO EW results – $\gamma\gamma + V$ production

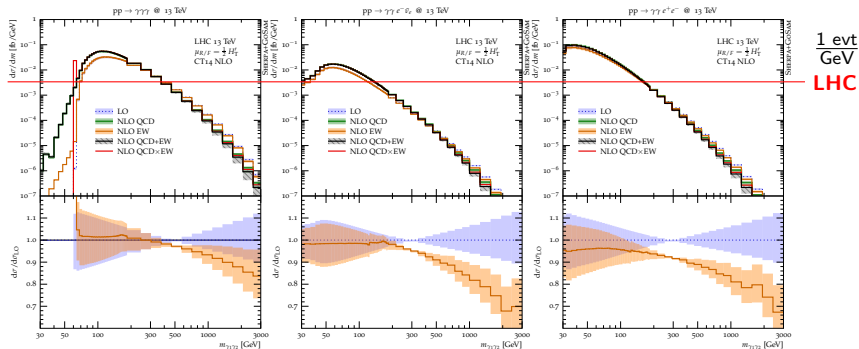
Greiner, MS arXiv:1710.11514



- higher luminosity \Rightarrow more events in tails
- EW correction more important

NLO EW results – $\gamma\gamma + V$ production

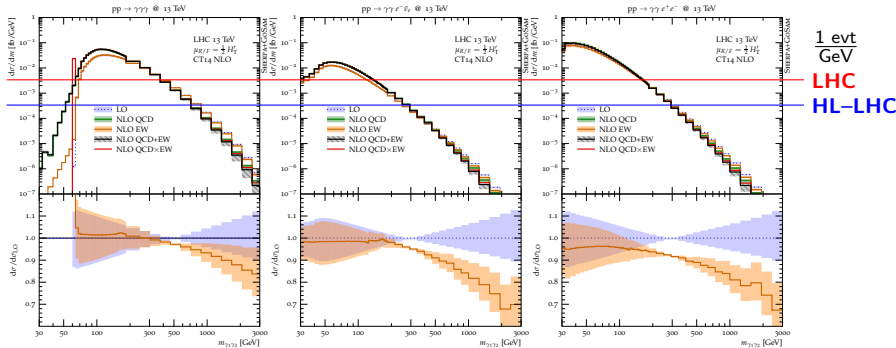
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NLO EW results – $\gamma\gamma + V$ production

Greiner, MS arXiv:1710.11514

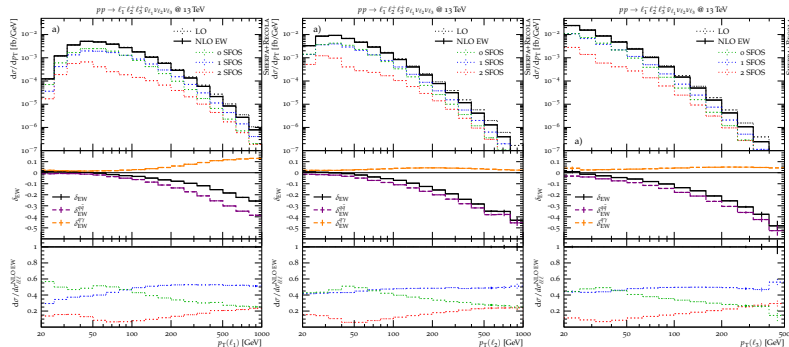


$\frac{1 \text{ evt}}{\text{GeV}}$
LHC
HL-LHC

- higher luminosity \Rightarrow more events in tails
- EW correction more important

NLO EW results – off-shell $W^+W^+W^-$ production

MS arXiv:1806.00307



- includes 0, 1, 2 SFOS processes (WWW and WZZ structures)
- higher luminosity \Rightarrow more events
- EW correction (incl. γ -induced) important

Fiducial phase space for HL- & HE-LHC

Diboson:

cut	value
$p_T(\ell_{1,2})$	$[20 \text{ GeV}, \infty)$
$p_T(\ell)_{3,4}$	$[10 \text{ GeV}, \infty)$
$\eta(\ell)$	$[-4.0, 4.0]$
$\Delta R(\ell, \ell)$	$[0.2, \infty)$
MET	$[40 \text{ GeV}, \infty)$
$m_{\ell\ell}^{\text{SFOS}}$	$[20 \text{ GeV}, \infty)$

Triboson:

cut	value
$p_T(\ell)$	$[30 \text{ GeV}, \infty)$
$\eta(\ell)$	$[-4.0, 4.0]$
$m_{\ell\ell}^{\text{SFOS}}$	$[0, m_Z - 15 \text{ GeV}]$ \wedge $[m_Z + 15 \text{ GeV}, \infty)$
$p_T(\gamma)$	$[30 \text{ GeV}, \infty] \text{ (??)}$
$\eta(\gamma)$	$[-4.0, 4.0] \text{ (??)}$
γ -iso	as LHC ?
n_{jet}	$[0, 1]$
$n_{b\text{-jet}}$	0

Planned contributions

- studies for 14 & 27 TeV:

- NNLO QCD and NLO EW for diboson processes

Grazzini, Kallweit, Wiesemann
Heinrich, Jahn, Jones, Kerner, Pires
Kallweit, Lindert, Pozzorini, MS

- NLO QCD and NLO EW for $\gamma\gamma\gamma$, $\gamma\gamma\ell\ell$, $\gamma\gamma\ell\nu$

Greiner, MS

- NLO EW for $\ell_1^+ \ell_2^+ \ell_3^- \nu_{\ell_1} \nu_{\ell_2} \bar{\nu}_{\ell_3}$ ($\ell_i = e, \mu$)

MS

- progressing well, many numbers already there
- are the fiducial regions final?
- anything of particular interest?

Thank you for your attention!