QCD+EW predictions for multiboson* production

*multibosons ≃ dibosons

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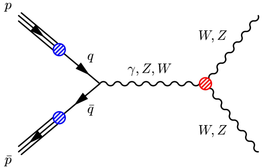
Outline

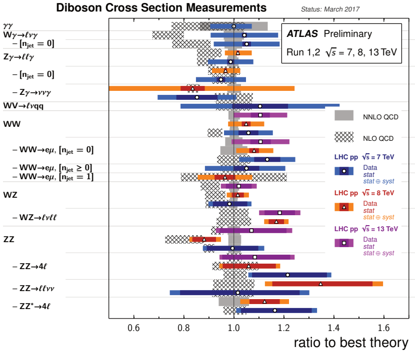
1. $W^{\pm}Z$ at NNLO QCD
2. $W^{+}W^{-}$ at NNLO QCD
3. $W^{+}W^{-}$ and ZZ at NLO EW

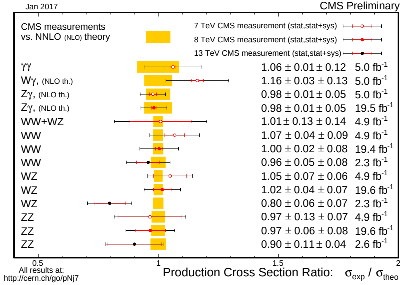
Diboson production at LHC



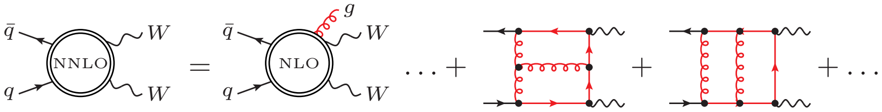
- test SU(2)×U(1) gauge structure
- backgrounds to $H \to VV^*$ and BSM (MET+multileptons, diboson resonances, . . .)

Experimental precision calls for NNLO QCD





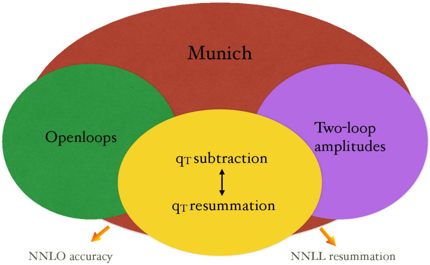
Diboson production at NNLO+NNLL with MATRIX



Flexible NNLO+NNLL framework based on q_T-subtraction [Catani, Grazzini '06]

Kallweit

Cascioli
Maierhöfer
Lindert
S.P.

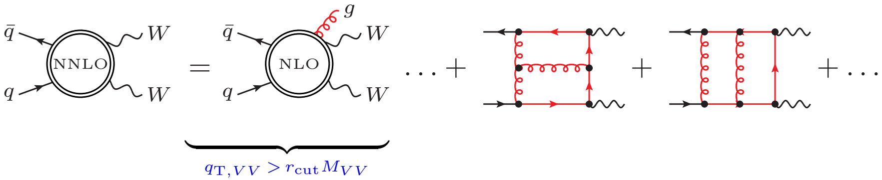


Gehrmann, Tancredi
von Manteuffel, Weihs;
Caola, Henn, Melnikov
Smirnov, Smirnov

Grazzini, Kallweit, Rathlev, Wiesemann

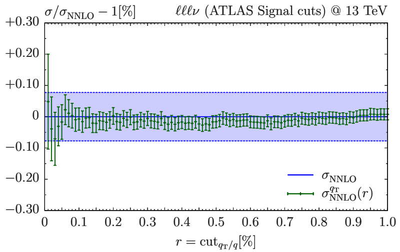
⇒ **predictions for $Z\gamma, W\gamma, ZZ, WW, WZ$ at NNLO(+NNLL)** [2013–17]

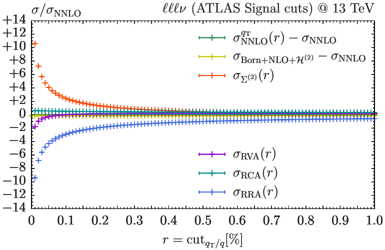
Cancellation of q_T dependence



Cancellation of unphysical q_T dependence requires $r_{\rm cut} \ll 1$

- separate parts up to $10 \times \sigma_{\rm NNLO}$ $\Rightarrow$ requires very high NLO stability in IR regions
- MUNICH+OPENLOOPS achieves $\mathcal{O}\left(10^{-4}\right)$ stability at NLO $\Rightarrow$ $\mathcal{O}\left(10^{-3}\right)$ at NNLO





Outline

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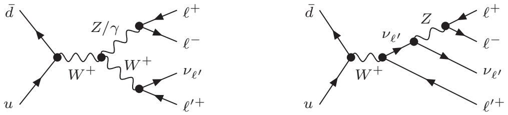
3. W^+W^- and ZZ at NLO EW

$pp \to W^{\pm}Z \to \ell'^{\pm}\nu_{\ell'}\ell^+\ell^-$ at NNLO [Grazzini, Kallweit, Rathlev, Wiesemann, 1703.09065]



Large QCD corrections (related to radiation zero at LO) $\mu = (M_Z + M_W)/2$

- $+80\%$ at NLO and $+10\%$ at NNLO
- $\sim 2\%$ scale uncertainty (realistic since $q\bar{q}$, qg, gg, qq channels all open)

	σ_{LO} [fb]	σ_{NLO} [fb]	σ_{NNLO} [fb]	σ_{EXP} [fb]
ATLAS 8 TeV	$18.35(0)^{+2.3\%}_{-3.2\%}$	$32.81(1)^{+5.4\%}_{-4.1\%}$	$35.59(2)^{+1.8\%}_{-1.9\%}$	$35.1 \pm 2.7\%(\text{stat}) \pm 2.4\%(\text{syst}) \pm 2.2\%(\text{lumi})$
ATLAS 13 TeV	$28.86(0)^{+5.4\%}_{-6.5\%}$	$57.76(1)^{+5.4\%}_{-4.3\%}$	$64.01(3)^{+2.3\%}_{-2.1\%}$	$63.2 \pm 5.2\%(\text{stat}) \pm 4.1\%(\text{syst}) \pm 2.4\%(\text{lumi})$
CMS 13 TeV	$148.4(0)^{+5.4\%}_{-6.4\%}$	$301.4(1)^{+5.5\%}_{-4.5\%}$	$334.3(2)^{+2.3\%}_{-2.1\%}$	$258 \pm 8.1\%(\text{stat})^{+7.4\%}_{-7.7\%}(\text{syst}) \pm 3.1(\text{lumi})$

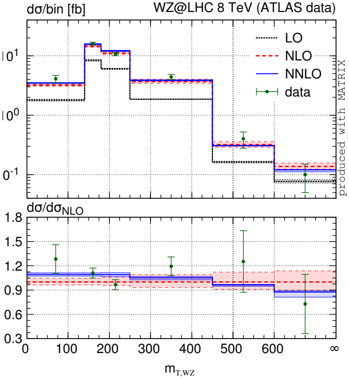
Fiducial cross sections (no jet veto)

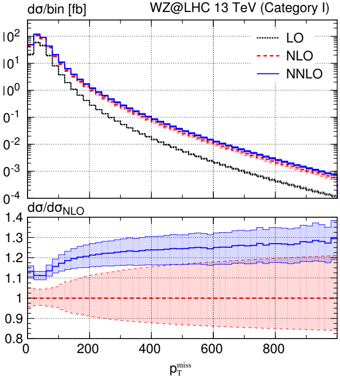
- agreement with ATLAS thanks to NNLO
- 2.5σ tension with CMS to be clarified with higher statistics

Differential distributions

QCD effects in the tails (relevant for aGCs and tri-lepton + MET searches)

- NNLO uncertainties typically well below 5%
- in the MET tail huge NLO corrections but moderate NNLO correction



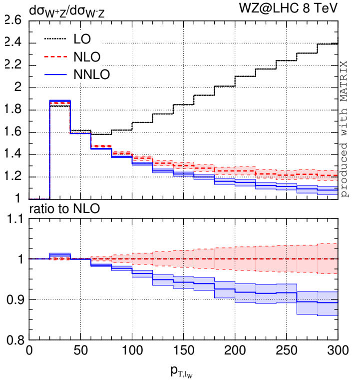


reasonable agreement with ATLAS data (precision tests require higher statistics)

$\sigma(W^+Z)/\sigma(W^-Z)$ ratio

Behaviour of QCD corrections and uncertainties

- typically very small (strong cancellations between numerator and denominator)
- large corrections in some tails (e.g. p_{T,ℓ_W}) $\Rightarrow$ naive correlation of uncertanties fails



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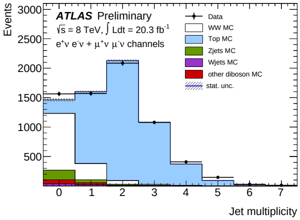
Definition of top-free W^+W^- production

Experimental definition (ATLAS/CMS)

(1) top-supressing jet veto

(2) subtraction of remnant top backgrounds

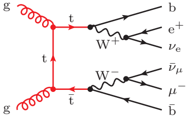
(3) MC extrapolation of W^+W^- to full phase space

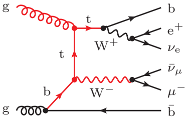


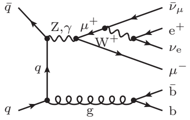
Top-free definition of *inclusive* WW cross section at NNLO

- **huge top contamination** from $pp \to W^{\pm}t \to W^+W^-b$ (40% at NLO) and $pp \to t\bar{t} \to W^+W^-b\bar{b}$ (400% at NNLO)
- **b-quarks emissions** needed to cancel collinear $g \to b\bar{b}$ singularities $(m_b = 0)$

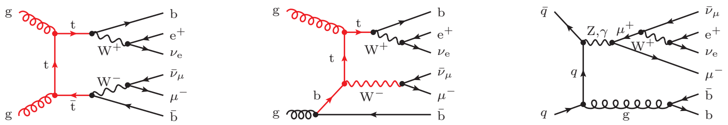
⇒ exclude b-quark emissions in the 4F scheme $(m_b > 0)$







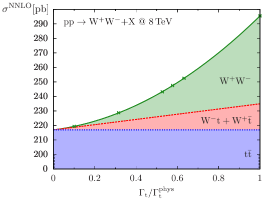
Ambiguity of top-free $\sigma(W^+W^-)$ [Gehrmann et al., 1408.5243]



Uncertainty of 4F-scheme definition $(m_b > 0)$

- **b-emission veto** $\Rightarrow \ln(m_b/M_W)$ **enhanced terms** wrt definition that includes b-emissions

$\Rightarrow$ might jeopardize NNLO accuracy of 3%!



Alternative 5F-scheme definition $(m_b = 0)$

$$\lim_{\xi_t \to 0} \sigma^{\rm 5F}_{\rm full}(\xi_t \Gamma_t) = \xi_t^{-2}\left[\sigma^{\rm 5F}_{t\bar{t}} + \xi_t\, \sigma^{\rm 5F}_{Wt} + \xi_t^2\, \sigma^{\rm 5F}_{W^+W^-}\right]$$

- **b-emissions included** and **"top-subtraction"** using Γ_t-scaling

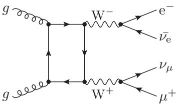
$\Rightarrow$ 1-2% agreement between NNLO 4F/5F predictions!

Basis for percent-level precision tests of W^+W^- physics!

NNLO predictions for $\sigma_{\text{tot}}(W^+W^-)$ [Gehrmann et al., 1408.5243]

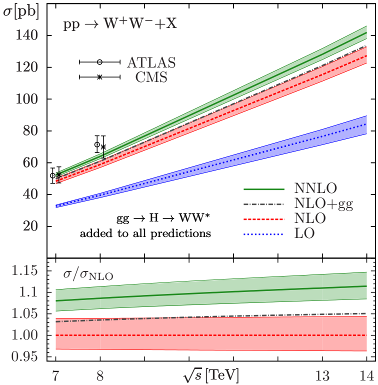
Unexpectedly large QCD corrections

- $+58\%$ NLO and $+12\%$ NNLO at 14 TeV
- well beyond expected size from scale uncertainties and $gg \to W^+W^-$ ($+4\%$)



Residual scale uncertainty

- 3% NNLO scale variation
- consistent with NLO correction to $gg \to W^+W^-$ [Melnikov et al. '15]



Comparison with ATLAS and CMS data at 8 TeV

- NNLO reduces significance of excess in preliminary measurements and is consistent with WW cross sections published by ATLAS and CMS

$pp \to W^+W^- \to \mu^+ e^- \nu_\mu \bar{\nu}_e$ at NNLO [Grazzini, Kallweit, S.P., Rathlev, Wiesemann, 1605.02716]

Inclusive cross section at $\mu_R = \mu_F = M_W$

	σ [fb]		$\sigma/\sigma_{\text{NLO}} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
NLO	$623.4^{+3.6\%}_{-2.9\%}$	$1205^{+3.9\%}_{-3.1\%}$	0	0
NLO'	$636.0^{+3.6\%}_{-2.8\%}$	$1236^{+3.9\%}_{-3.1\%}$	$+\ 2.0\%$	$+\ 2.5\%$
NLO'+gg	$655.8^{+4.3\%}_{-3.3\%}$	$1287^{+4.8\%}_{-3.7\%}$	$+\ 5.2\%$	$+\ 6.8\%$
NNLO	$690.4^{+2.2\%}_{-1.9\%}$	$1371^{+2.6\%}_{-2.3\%}$	$+10.7\%$	$+13.8\%$

$+11\,(14)\%$ NNLO corrections wrt NLO at 8 (13) TeV

- +2 (3)% from NNLO PDFs (NLO′)
- +3 (4)% from $gg \to WW$ **only $\sim 1/3$ of total NNLO correction**
- +6 (7)% remnant NNLO correction **large & positive!**

Off-shell effects

- negative 2% off-shell correction to absolute rates
- K-factors consistent with on-shell calculation

Cross section with WW cuts ($p_{T,\mathrm{jet}} < 25\,\mathrm{GeV}$)

	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
NLO	$153.1^{+1.9\%}_{-1.6\%}$	$236.2^{+2.8\%}_{-2.4\%}$	0	0
NLO'	$156.7^{+1.8\%}_{-1.4\%}$	$243.8^{+2.6\%}_{-2.2\%}$	$+2.4\%$	$+\ 3.2\%$
NLO'+gg	$166.4^{+1.3\%}_{-1.3\%}$	$267.3^{+1.5\%}_{-2.1\%}$	$+8.7\%$	$+13.2\%$
NNLO	$164.2^{+1.3\%}_{-0.8\%}$	$261.5^{+1.9\%}_{-1.2\%}$	$+7.2\%$	$+10.7\%$

$+7\,(11)\%$ NNLO corrections wrt NLO at 8 (13) TeV

- $+2\,(3)\%$ from NNLO PDFs
- $+6\,(10)\%$ from $gg \to WW$ $\sim 4/3$ **of total NNLO correction**
- $-1.5\,(2.5)\%$ remnant NNLO correction **small & negative!**

Jet veto

- suppresses all (N)NLO corrections driven by QCD radiation
- increases relative importance of gg
  (missing NLO correction to gg only $+20\%$ [Melnikov et al, '15])

Acceptance with WW cuts

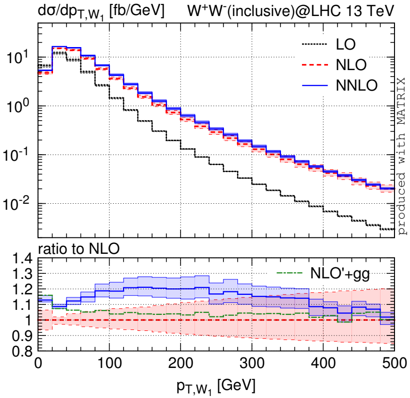
	$A = \sigma^{\mathrm{WW-cuts}}/\sigma^{\mathrm{incl}}$		$A/A_{\mathrm{NLO}} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
NLO	$0.2455^{+4.4\%}_{-4.7\%}$	$0.1960^{+4.4\%}_{-4.7\%}$	0	0
NLO'+gg	$0.2537^{+3.5\%}_{-3.7\%}$	$0.2077^{+3.2\%}_{-3.1\%}$	$+\ 3.3\%$	$+\ 6.0\%$
NNLO	$0.2378^{+1.3\%}_{-0.9\%}$	$0.1907^{+1.2\%}_{-0.9\%}$	$-\ 3.2\%$	$-\ 2.7\%$

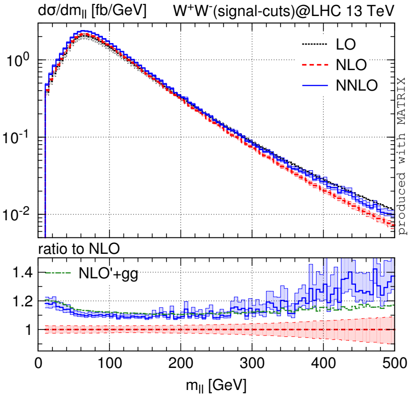
-3% NNLO corrections wrt NLO at 8 (13) TeV

- $+3\,(6)\%$ from $gg \to WW \Rightarrow$ **NLO$'$+gg unreliable!**
- $-6.5\,(9)\%$ remnant NNLO correction **c.f. -7-8% POWHEG correction to $\varepsilon_{\mathrm{veto}}$** (see [Monni, Zanderighi 1410.4745])

seems to leave little room for jet-veto resummation effects beyond NNLO

Differential distributions





Inclusive phase space

sizable non-gg corrections for observables sensitive to QCD radiation

WW cuts

negligible non-gg corrections for inclusive leptonic observables

Outline

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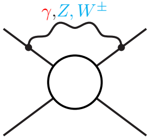
2. $W^{+}W^{-}$ at NNLO QCD
3. $W^{+}W^{-}$ and ZZ at NLO EW

Dominant EW vs QCD corrections



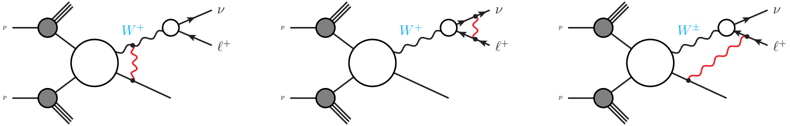
- real QCD radiation
- virtual EW corrections $\xrightarrow[Q \gg M_W]{} \quad -\frac{4\alpha}{\pi s_{\mathrm{w}}^2} \ln^2\left(\frac{1\,\mathrm{TeV}}{M_W}\right) \simeq -26\%$

Large negative corrections from universal Sudakov logs [Denner,S.P. '01]

$$\delta\mathcal{M}^{1-\mathrm{loop}}_{\mathrm{LL+NLL}} = \frac{\alpha}{4\pi}\sum_{k=1}^{n}\left\{\frac{1}{2}\sum_{l\neq k}\sum_{a=\gamma,Z,W^\pm} I^a(k)I^{\bar{a}}(l)\ln^2\frac{\hat{s}_{kl}}{M^2} + \gamma^{\mathrm{ew}}(k)\ln\frac{\hat{s}}{M^2}\right\}\mathcal{M}_0$$

- driven by external SU(2) charges $\Rightarrow$ biggest effects in (multi-)boson production

NLO EW production×resonance×decay + non-fact corrections



$\Rightarrow$ large effects from QED radiation off leptons

NLO EW automation

Tools	first results	
RECOLA*	$pp \to \ell^+\ell^- jj$	[1411.0916]
	$pp \to t\bar{t}H \to \ell^+\ell^- jj$	[1612.07138]
	$pp \to 4\ell$	[1611.05338]
	$pp \to t\bar{t}H \to e^+\mu^-\nu_e\bar{\nu}_\mu + 2$ jets	[1611.02951]
	$pp \to t\bar{t} \to b\bar{b}2\ell 2\nu$	[1607.05571]
	$pp \to e^+\mu^-\nu_e\bar{\nu}_\mu$	[1605.03419]
OPENLOOPS*+ MUNICH/SHERPA	$pp \to W + 1, 2, 3$ jets	[1412.5156]
	$pp \to \ell\ell/\ell\nu/\nu\nu + 0, 1, 2$ jets	[1511.08692]
	$pp \to \ell\ell\nu\nu$	[1705.00598]
	$pp \to \gamma j$	[1705.04664]
MADGRAPH5_AMC@NLO	$pp \to t\bar{t} + V$	[1504.03446]
	$pp \to t\bar{t}$	[1705.04105]
	$pp \to jj$	[1612.06548]
GOSAM+ MADDIPOLE	$pp \to W + 2$ jets	[1507.08579]

*with COLLIER [Denner et al. '14]

First automated tools and *multi-particle* applications (2015–17)

⇒ opens the door to **NLO QCD+EW for any** $2 \to 2, 3, 4, \ldots$ **SM process**

⇒ and matching to parton showers (and merging) at NLO QCD+EW (in progress)

Calculations for dibosons at NLO EW

On-shell $pp \to VV$ (without decays)

- W^+W^- [Bierweiler, Gieseke,Kasprzik, Kühn, Uccirati, 1208.3147; 1401.3964]
- $W^+W^-, W^\pm Z, ZZ$ [Baglio, Ninh, Weber, 1307.4331]

Pole approximation for decays (applicable close to resonances and above threshod)

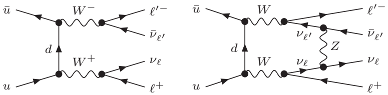
- $pp \to W^+W^- \to 2\ell 2\nu$ [Billoni, Dittmaier,Jäger, Speckner, 1310.1564]

Exact $pp \to 4\ell$ and $2\ell 2\nu$ (needed e.g. for $H \to VV^*$ backgrounds)

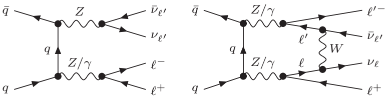
- $pp \to ZZ \to 4\ell$ [Biedermann, Denner, Dittmaier, Hofer, Jäger,1601.07787; 1611.05338]
- $pp \to W^+W^- \to e^+\mu^-\nu_e\bar{\nu}_\mu$ [Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder, 1605.03419]
- $pp \to W^+W^- + ZZ \to e^+\mu^-\nu_e\bar{\nu}_\mu + e^+e^-\nu\bar{\nu}$ [Kallweit, Lindert, S.P., Schönherr, 1705.00598]

$pp \to \ell\ell\nu\nu$ at NLO EW [Kallweit, Lindert, S.P., Schönherr,arXiv:1705.00598]

Different-flavour channel (WW)

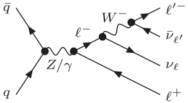


Same-flavour channel ($WW + ZZ$)



Other aspects/ingredients

- off-shell + non-resonant effects (e.g. $Z \to 2\ell 2\nu$)
- $\gamma\gamma \to 2\ell 2\nu$ an NLO EW
- (naive) matching to QED shower



Automated tools and possible combination of EW⊗QCD⊗PS (in the future)

- OpenLoops+Munich ⇒ NNLO+NNLL QCD in Matrix
- OpenLoops+Sherpa ⇒ MEPS@NLO QCD+EW [Kallweit, Lindert, Maierhöfer, S.P., Schönherr, 1511.08692] or UN^{2}LOPS [Höche, Li, Prestel]

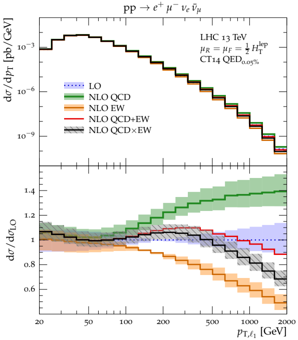
NLO QCD+EW corrections

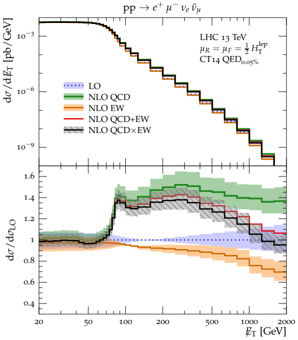
Sizable QCD corrections

- in spite of jet veto significant effects in the tails (see MET)
- QCD–EW combination crucial for description of QCD radiation and/or jet-veto

Sizable EW corrections in the tails

- EW Sudakov effects up to -50% at TeV scale (esp. relevant for $V \to$ jets)
- strongly depend on the observable

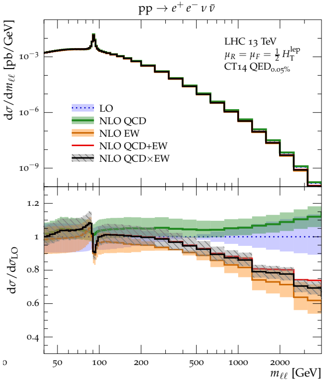


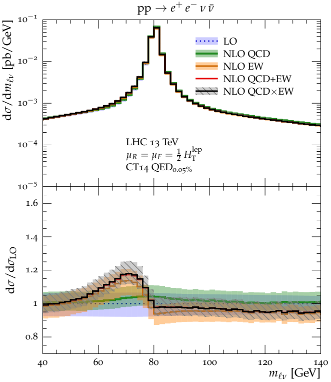


Large QED corrections to shape of resonances

ZZ and WW resonances in same-flavour $\ell\ell\nu\nu$ channel

- significant distortion of resonance shape due to QED radiation off final-state leptons
- relative effects in $Z \to \ell\ell$ attenuated by large W^+W^- continuum



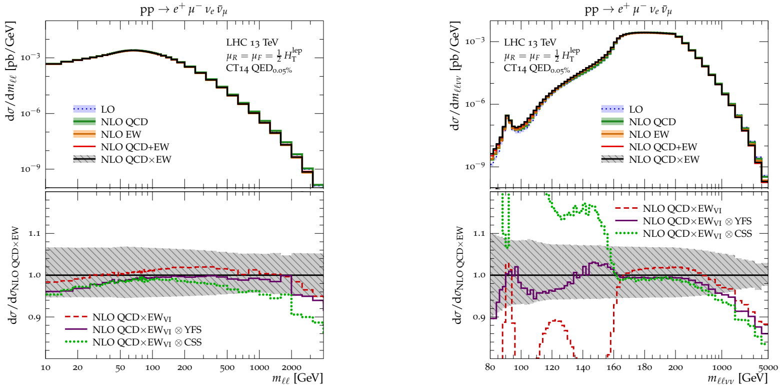


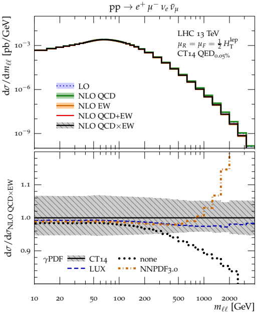
Naive NLO EW+PS matching in Sherpa+OpenLoops

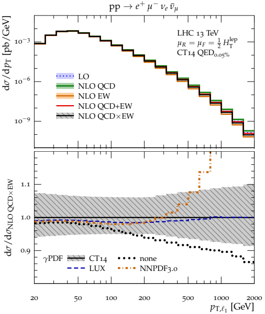
Virtual EW corrections + QED parton shower

- CSS dipole shower (not resonaonce aware) ⇒ significant mismodelling
- YFS resummation (resonaonce aware) ⇒ better approximation

⇒ applicable at particle level

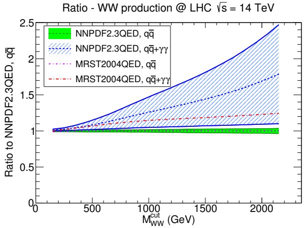




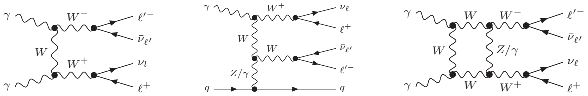


Motivation (NNPDF)

- up to $\mathcal{O}(100\%)$
- very large uncertainty



NLO EW calculation of $\gamma\gamma \to W^+W^- \to 2\ell 2\nu$

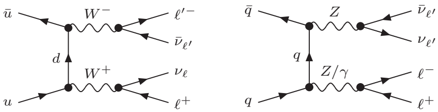


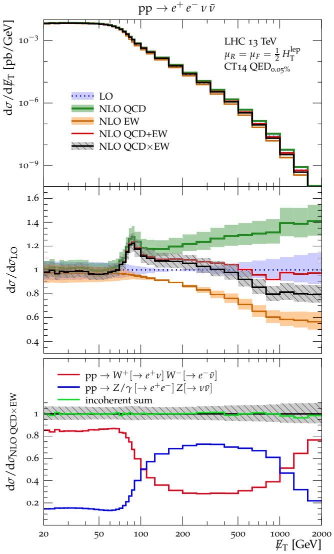
Comparison of PDFs

- up to 10–20% effects using CT14qed
- consistent with LUXqed PDFs (most precise γ-PDF!)
- nominal NNPDF3.0 qed prediction excluded

W^+W^-/ZZ interplay in same-flavour $2\ell 2\nu$

MET distribution for $pp \to W^+W^-/ZZ \to e^+e^-\nu\bar{\nu}$





Subtle QCD–EW interplay at MET $> 100\,\text{GeV}$

- non-trivial W^+W^-/ZZ interplay
- large QCD radiation
- large EW corrections (W^+W^-/ZZ dependent!)

Interference between W^+W^- and ZZ

- generally very strongly suppressed

Summary and Outlook

(Semi-) automated NNLO QCD+NLO EW tools

- key to fully exploit physics potential of LHC diboson data
- technical performance (and its continuous improvement!) crucial
- brain (of theorists) still very important ...

Various important things to address in the future

- ... understand TH uncertainties in nontrivial EXP observables and analyses (e.g. data-driven VV backgrounds in $H \to VV^*$ and BSM searches)
- proper combination of QCD and EW corrections
- etc. etc.

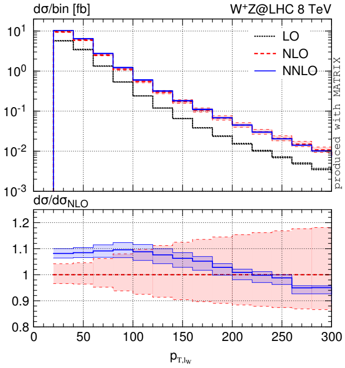
Backup slides

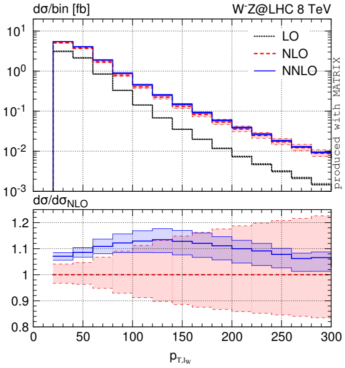
NNLO ingredients in Matrix

Technical ingredients of NNLO calculations with Matrix

- Two-loop master integrals [Gehrmann,Tancredi, von Manteuffel, Weihs '13–'14]; see also [Caola, Henn, Melnikov, Smirnov '14]
- Two-loop amplitudes [Gehrmann,Tancredi, von Manteuffel]
- IR stable one-loop amplitudes with OpenLoops [Cascioli, Maierhöfer, S.P. '12] Collier [Denner,Dittmaier,Hofer '05] CutTools [Ossola,Papadopoulos,Pittau '08] OneLoop [van Hameren '11]
- fast multi-channel MC [Kallweit, Rathlev] with dipole subtraction [Catani, Seymour '96] and NNLO q_T subtraction [Catani, Grazzini '07]

Distribution in p_{T} of letpton from W decay





Corrections to ZZ production beyond NNLO QCD

NLO QCD corrections to gg $\to$ ZZ (gg-channel, massless 2-loop amplitudes)
[Caola, Melnikov, Röntsch, Tancredi (2015)]
(based on amplitudes from [Caola, Henn, Melnikov, Smirnov, Smirnov (2015); von Manteuffel, Tancredi (2015)])

- The LO gg-fusion cross section is increased by $\mathcal{O}(60\% - 110\%)$ for $M_\mathrm{Z} < \mu_\mathrm{R} = \mu_\mathrm{F} < 4M_\mathrm{Z}$ at $\sqrt{s} = 8\,\mathrm{TeV}$ (slightly smaller at $\sqrt{s} = 13\,\mathrm{TeV}$).

$\hookrightarrow$ Corresponds to increase of full NLO QCD prediction by about **+6%** at $\sqrt{s} = 8\,\mathrm{TeV}$ and $13\,\mathrm{TeV}$ (correction exceeds the NNLO QCD scale band).

- **NLO QCD to gg $\to$ ZZ** including interference effects with off-shell Higgs.
  [Caola, Dowling, Melnikov, Röntsch, Tancredi (2016)]

NLO EW corrections to off-shell ZZ production
[Biedermann, Denner, Dittmaier, Hofer, Jäger (2016 & 2016)]

- Corrections of about **−4%** to the inclusive (LO) cross section at $\sqrt{s} = 8\,\mathrm{TeV}$.
  - $\hookrightarrow$ Larger (typically tens of per cent) corrections at high transverse momenta.

$\hookrightarrow$ **Both corrections are quantitatively relevant,** also at the level of inclusive cross sections, but happen to partially cancel.

Corrections to WW production beyond NNLO QCD

NLO QCD corrections to gg $\to \mathrm{W^+W^-}$ (gg-channel, massless 2-loop amplitudes)
[Caola, Melnikov, Röntsch, Tancredi (2015)]
(based on amplitudes from [Caola, Henn, Melnikov, Smirnov, Smirnov (2015); von Manteuffel, Tancredi (2015)])

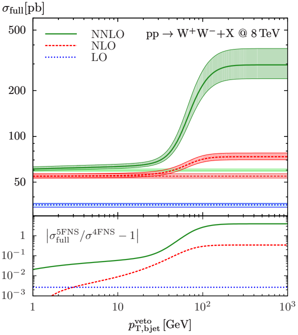
- The LO gg-fusion cross section is increased by $\mathcal{O}(24\% - 80\%)$ for $M_\mathrm{W}/2 < \mu_\mathrm{R} = \mu_\mathrm{F} < 2M_\mathrm{W}$ at $\sqrt{s} = 8\,\mathrm{TeV}$ (slightly smaller at $\sqrt{s} = 13\,\mathrm{TeV}$).
  - ↪ Corresponds to increase of full NLO QCD prediction by about **+2%** at $\sqrt{s} = 8$ and $13\,\mathrm{TeV}$ (covered by the NNLO QCD scale-uncertainty estimate).
- In the ATLAS fiducial region, NLO QCD corrections to gg shrink to about $+20\%$.
- **NLO QCD to gg $\to \mathrm{W^+W^-}$** including interference effects with off-shell Higgs.
  [Caola, Dowling, Melnikov, Röntsch, Tancredi (2016)]

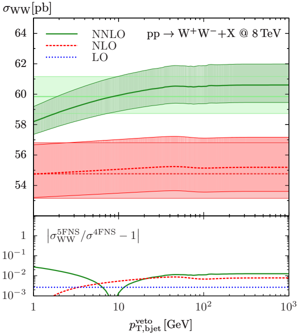
NLO EW corrections to off-shell $\mathrm{W^+W^-}$ production
[Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder (2016)]

- Corrections of about **−4%** (**−3%**) wrt. the inclusive (fiducial ATLAS) cross section at LO for both $\sqrt{s} = 8$ and $13\,\mathrm{TeV}$.
  - ↪ Larger (typically tens of per cent) corrections at high transverse momenta.
- Contribution from **$\gamma\gamma$-induced process** of about **+1%** wrt. both the inclusive and the fiducial ATLAS cross section at LO for both $\sqrt{s} = 8$ and $13\,\mathrm{TeV}$.

Top subtraction vs jet veto

Top resonances, $g \to b\bar{b}$ singularities and b-jet veto ($p_{\mathrm{T}} < p_{\mathrm{T},bjet}^{\mathrm{veto}}$)





Full 5F cross section vs 4F

- top contamination huge at large $p_{\mathrm{T},bjet}^{\mathrm{veto}}$ and 10% at 10 GeV, where sensitivity to singularity shows up
- no "robust" W^+W^- definition

Top-free 5F cross section vs 4F

- very stable top subtraction at $p_{\mathrm{T},bjet}^{\mathrm{veto}} > 10$ GeV
- 1% agreement with 4FNS

$\Rightarrow$ **NNLO prediction solid!**

Fiducial W^+W^- cross section with $H \to WW$ cuts [Grazzini, Kallweit, S.P., Rathlev, Wiesemann, 1605.02716]

	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$45.92\,^{+4.0\%}_{-5.0\%}$	$71.16\,^{+7.2\%}_{-8.2\%}$	$-\ 4.4\%$	$-\ 2.6\%$
NLO	$48.05\,^{+1.9\%}_{-1.7\%}$	$73.09\,^{+2.7\%}_{-2.4\%}$	0	0
NLO'	$49.32\,^{+1.7\%}_{-1.6\%}$	$75.58\,^{+2.5\%}_{-2.2\%}$	$+\ 2.7\%$	$+\ 3.4\%$
NLO'+gg	$53.50\,^{+2.0\%}_{-1.5\%}$	$85.23\,^{+2.5\%}_{-2.5\%}$	$+11.3\%$	$+16.6\%$
NNLO	$52.30\,^{+1.6\%}_{-1.0\%}$	$82.32\,^{+2.4\%}_{-2.6\%}$	$+\ 8.9\%$	$+12.6\%$

$+9\,(13)\%$ **NNLO corrections wrt NLO at 8 (13) TeV**

- $+3\%$ from NNLO PDFs
- $+9\,(13)\%$ from $gg \to WW$ $\sim 4/3$ **of total NNLO correction**
- $-2.5\,(4)\%$ remnant NNLO correction **small & negative!**

Similar behaviour as for WW cuts

Acceptance with $H \to WW$ cuts [Grazzini, Kallweit, S.P., Rathlev, Wiesemann, 1605.02716]

	$A = \sigma^{\mathrm{H-cuts}}/\sigma^{\mathrm{incl}}$		$A/A_{\mathrm{NLO}} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$0.1080\,^{+1.2\%}_{-1.4\%}$	$0.09135^{+1.5\%}_{-1.7\%}$	$+40.1\%$	$+50.6\%$
NLO	$0.07706^{+4.3\%}_{-4.6\%}$	$0.06065^{+4.3\%}_{-4.5\%}$	0	0
NLO'+gg	$0.08157^{+3.1\%}_{-3.1\%}$	$0.06623^{+2.7\%}_{-2.5\%}$	$+\ 5.9\%$	$+\ 9.2\%$
NNLO	$0.07575^{+1.2\%}_{-0.8\%}$	$0.06005^{+1.1\%}_{-0.9\%}$	$-\ 1.7\%$	$-\ 1.0\%$

$-2\,(1)\%$ NNLO corrections wrt NLO at 8 (13) TeV

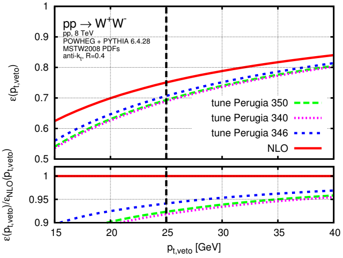
- $+6\,(9)\%$ from $gg \to WW$ $\Rightarrow$ **NLO$'$+gg unreliable!**
- $-8\,(10)\%$ remnant NNLO correction

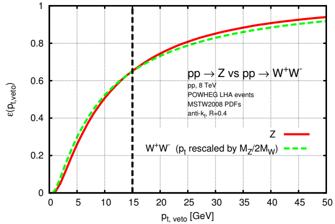
Non-gg NNLO correction: summary

- positive and large for σ_{incl} but negative and rather small for $\sigma_{\mathrm{fiducial}}$

$\Rightarrow$ **constant global K-factors not appropriate!**

$\Rightarrow$ **use NNLO everywhere!**





POWHEG jet-veto efficiency at 25 GeV

(1) 7–8% reduction wrt NLO

(2) Powheg veto efficiency for $pp \to Z$ at
$$p_{T,\mathrm{veto}}^{Z} = M_Z/(2M_W)\,p_{T,\mathrm{veto}}^{WW} \sim 15\,\mathrm{GeV}$$
is consistent with (1)

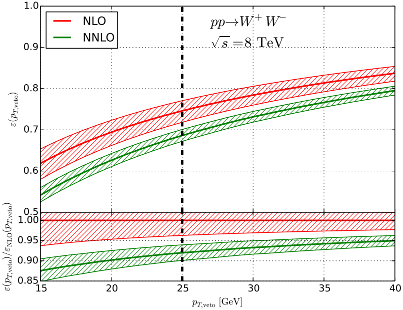
(3) NNLO+NNLO veto efficiency for $pp \to Z$ [Banfi, Monni, Salam, Zanderighi 1206.4998] at 15 GeV is consistent with (2)

Precision calculations mandatory

- NNLO should be enough for effects $\lesssim 10\%$
- NNLO+NNLL for $p_{T,WW}$ available [Grazzini, Kallweit, Rathlev, Wiesemann 1507.02565]

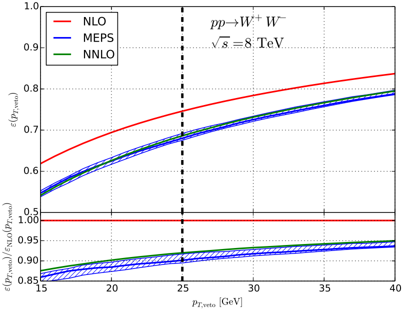
Jet-veto efficiency for $pp \to W^+W^-$ [Grazzini, Kallweit, Moretti, S.P, Rathlev (preliminary)]

NNLO vs NLO



- fiducial region of ATLAS (CMS) measurement involves jet veto at $p_T = 25(30)$ GeV
- NNLO correction of -8% wrt NLO
- NNLO seems consistent with Powheg

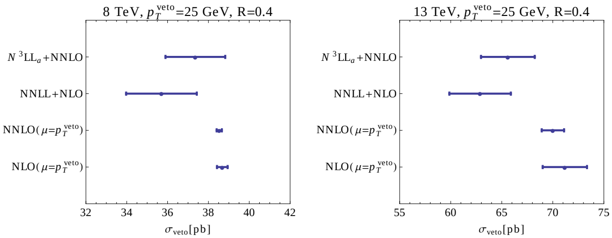
NNLO vs MEPS@NLO (Sherpa)



- MEPS@NLO $\Rightarrow$ 1st emission at NLO + LLs + particle level
- quite stable wrt scale variations
- consistent with NNLO

Calculational framework

- fully differential on-shell NNLO calculations for $pp \to WW$
- matched to partial N^3LL resummation of $\ln(p_{\mathrm{T},jet}^{\mathrm{veto}}/M_{WW})$ terms



- significant reduction of the vetoed XS: -3% (-6%) at 8 (13) TeV
- calls for comparisons against alternative resummations and data

W^+W^+ scattering at NLO EW [Biedermann, Denner, Pellen, 1611.02951]

Full $2 \to 6$ calculation for $pp \to e^+\nu_e\mu^+\nu_\mu jj$

- baed on Recola [Actis, Denner, Hofer, Lang, Scharf, Uccirati, 1605.01090] and Collier [Denner, Dittmaier, Hofer, 1604.06792]

NLO EW effects with VBS cuts ($m_{jj} > 500\,\mathrm{GeV}$, $\Delta y_{jj} > 2.5, \ldots$)

- surprisingly large EW corrections (-16%) to σ_{fiducial}
- EW logs of type $\ln(\hat{s}/M_W^2)\ln(\hat{s}/\hat{t}) \leftrightarrow$ bulk of XS at $\sqrt{s} \gtrsim 1\,\mathrm{TeV}$ (irresp. m_{jj} cut)
- large negative corrections in the tails (-40%)