EW corrections and combination with QCD for diboson production

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based on

M. Grazzini, S. Kallweit, J. Lindert, S. P., M. Wiesemann

JHEP 02 (2020) 087 [arXiv:1912.00068]

LHPC 2020 Online, May 27, 2020

Fonds national suisse
Schweizerischer Nationalfonds
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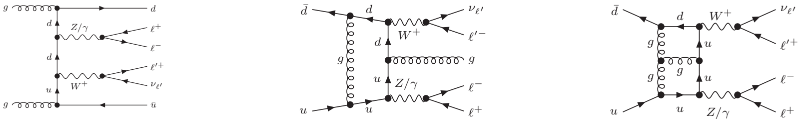
Swiss National Science Foundation

Universität Zürich[UZH]

NNLO QCD corrections to $pp \to VV$ [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteufel, S.P., Rathlev, Tancredi, Weihs, Wiesemann, Yook '14–'20]



Sample $pp \to WZ$ diagrams at order α_s^2

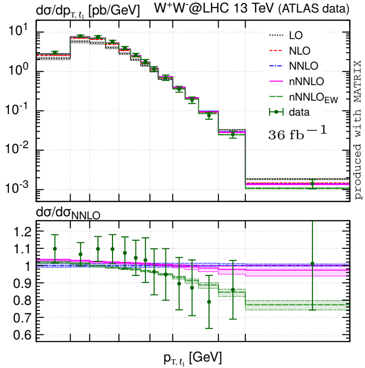
Main ingredients

- $pp \to VVj$ at NLO with MUNICH [Kallweit] + OPENLOOPS [Buccioni et al]
- 2-loop amplitudes [Gehrmann, von Manteuffel, Tancredi '15]
- q_T-subtraction method [Catani, Grazzini '07]

Matrix [Grazzini, Kallweit, Wiesemann '17–'20]

- all $pp \to 4$ leptons/neutrinos diboson processes (and more)
- parton-level predictions at NNLO QCD plus $gg \to VV$ at NLO

Relevance of NNLO precision



[Grazzini, Kallweit, Wiesemann, Yook '20]

Few-percent QCD uncertainties

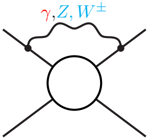
$\Rightarrow$ improved SM tests, EFT fits and searches with VV backgrounds

$\Rightarrow$ EW corrections increasingly relevant at high p_T

$pp \to VV$ and decays to leptons & ν at NLO EW [Biedermann, Denner, Dittmanier, Jäger, Kallweit, Lindert, Maieröfer, Pellen, S.P., Schönherr '16–20]

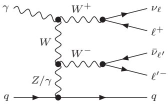
Typically of $\mathcal{O}(1\%)$ but possible large enhancements, especially in high-energy tails

Sudakov logarithms from *virtual* EW bosons



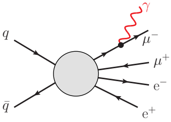
- negative corrections $\propto \alpha_{\rm w} \ln^2(Q^2/M_W^2) \sim 25\%$ at $Q \sim 1$ TeV
- prop. to external SU(2) charges $\Rightarrow$ large in VV production

Photon-induced processes: $\gamma\gamma \to VV$ and $\gamma q \to VVq$



- $\mathcal{O}(10\%)$ in TeV tails through t-channel W-exchange
- precise γ-density in NNPDF3.1 with LUX methodology [Manohar, Nason, Salam, Zanderighi '16]

$\alpha \ln(Q/m_\ell)$ effects from lepton fragmentation



- largest in $m_{\ell\ell}$ and $m_{4\ell}$ (attenuated by lepton dressing)

Tools for $pp \to VV$ at NNLO QCD+NLO EW

OpenLoops 2 [Buccioni, Lang, Lindert, Maierhöfer, S. P., Zhang, Zoller '19]

- automated NLO QCD+EW matrix elements for any SM process
- new methods for stable real-virtual NNLO matrix elements

Munich [S.Kallweit] **+ OpenLoops**

- full NLO QCD+EW automation [Kallweit, Lindert, Maierhöfer, S.P., Schönherr '16]

Matrix+OpenLoops [Grazzini, Kallweit, Lindert, S.P., Wiesemann '20]

- NNLO QCD+NLO EW for all processes $pp \to$ 4 leptons/neutrinos
- public code coming soon

channels	# lept	final state
ZZ	4	$\ell^+\ell^-\ \ell^+\ell^-$
ZZ	4	$\ell^+\ell^-\ \ell'^+\ell'^-$
WZ	3	$\ell^+\ell^-\ \ell\nu_\ell$
WZ	3	$\ell^+\ell^-\ \ell'\nu_{\ell'}$
ZZ	2	$\ell^+\ell^-\ \nu_{\ell'}\bar{\nu}_{\ell'}$
ZZ, WW	2	$\ell^+\ell^-\ \nu_\ell\bar{\nu}_\ell$
WW	2	$\ell^+\ell'^-\ \nu_\ell\bar{\nu}_{\ell'}$

NNLO QCD+NLO EW predictions for diboson production and decay [M. Grazzini, S. Kallweit, J. Lindert, S. P., M. Wiesemann '20]

Building blocks (note $q\bar{q}$, $\gamma\gamma$ and gg channels)

$$\begin{aligned}
d\sigma^{\mathrm{LO}} &= d\sigma^{\mathrm{LO}}_{q\bar{q}} + d\sigma^{\mathrm{LO}}_{\gamma\gamma} \\
d\sigma^{\mathrm{NNLO\,QCD}} &= d\sigma^{\mathrm{LO}}\left(1+\delta_{\mathrm{QCD}}\right) + d\sigma^{\mathrm{LO}}_{gg} \\
d\sigma^{\mathrm{NLO\,EW}} &= d\sigma^{\mathrm{LO}}\left(1+\delta_{\mathrm{EW}}\right)
\end{aligned}$$

Idea of the paper

- comparative study of ZZ, WW, WZ production with (off-shell) leptonic decays
- study behaviour of (reconstructed) vector bosons
- focus on high p_T, where QCD and EW corrections can be very large and their interplay nontrivial

Combination of QCD and EW corrections

$$d\sigma^{\mathrm{QCD+EW}} = d\sigma^{\mathrm{LO}}\left(1 + \delta_{\mathrm{QCD}} + \delta_{\mathrm{EW}}\right) + d\sigma^{\mathrm{LO}}_{gg} \tag{1}$$

$$d\sigma^{\mathrm{QCD\times EW}} = d\sigma^{\mathrm{NNLO\,QCD+EW}} + d\sigma^{\mathrm{LO}}\,\delta_{\mathrm{QCD}}\,\delta_{\mathrm{EW}} \tag{2}$$

Difference between additive (1) and multiplicative (2,3) prescriptions

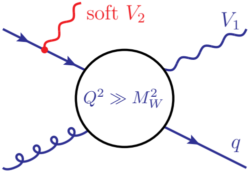
- factorisation generates extra $\delta_{\mathrm{QCD}}\,\delta_{\mathrm{EW}}$ correction of $\mathcal{O}(\alpha\alpha_S)$
- can be quite large at high p_T
- should be interpreted as $\mathcal{O}(\alpha\alpha_S)$ uncertainty *unless there are theoretical arguments that support* $\mathrm{QCD}\times\mathrm{EW}$ *factorisation*

More consistent factorisation (excluding NLO EW $\gamma\gamma$ and γq channels)

$$d\sigma^{\mathrm{QCD\times EW}_{q\bar{q}}} = d\sigma^{\mathrm{NNLO\,QCD+EW}} + d\sigma^{\mathrm{LO}}\,\delta_{\mathrm{QCD}}\,\delta^{q\bar{q}}_{\mathrm{EW}} \tag{3}$$

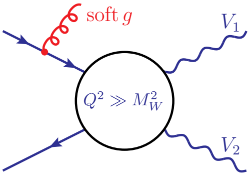
QCD radiation patterns at high p_T

two very different configurations depending on recoiling object



Hard-VJ configurations (see later)

- $p_{T,V_1} \sim p_{T,\mathrm{jet}} \gg M_W$
- $p_{T,V_2} \lesssim M_W$



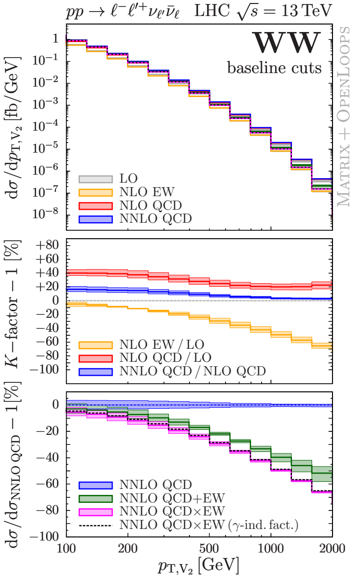
Hard-VV configurations

- $p_{T,V_1} \sim p_{T,V_2} \gg M_W$
- $p_{T,\mathrm{jet}} \lesssim M_W$

$\Rightarrow$ Sudakov logs dominate EW corrections and factorise wrt QCD corrections [Manohar et al]

$\Rightarrow$ $\mathrm{QCD} \times \mathrm{EW}_{q\bar{q}}$ combination correctly accouns for dominant $\mathcal{O}(\alpha\alpha_S)$ effects

Hard-VV dominated observable: p_{T,V_2}



QCD corrections (middle panel)

- moderate shape and normalisation corrections
- few-percent NNLO scale uncertainties

EW corrections (middle panel)

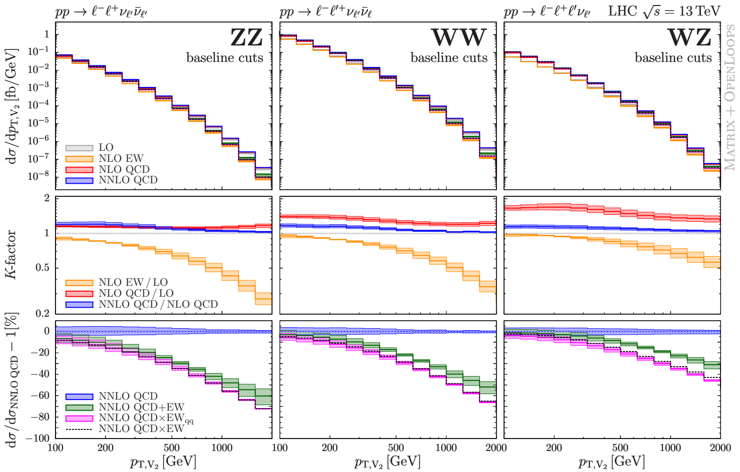
- dominated by large negative Sudakov logs
- far beyond NNLO uncertainties at $p_T \gg M_W$

Best combination $=$ $\mathrm{QCD} \times \mathrm{EW}_{q\bar{q}}$ (lower panel, pink)

- captures dominant $\mathcal{O}(\alpha\alpha_S)$ effects
- percent-level scale uncertainty
- uncertainty dominated by missing $\mathcal{O}(\alpha^2)$ Sudakov logs $\sim \frac{1}{2}\delta^2_{\mathrm{EW}}$

[Denner, Manohar, Kühn, S.P., . . .]

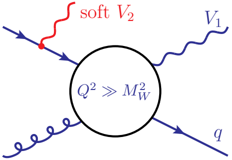
p_{T,V_2} distribution in $pp \to WW, WZ, ZZ$



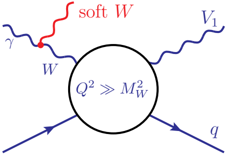
- similar behaviour in all channels
- largest QCD corrections in WZ and largest EW corrections in ZZ (see more details in the paper)

Hard-Vj configurations at high p_T (recoil absorbed by jet)

NLO QCD



NLO EW



Giant NLO QCD correction from $pp \to Vj$ with soft V_2 radiation

[Baglio, Ninh, Weber '13]

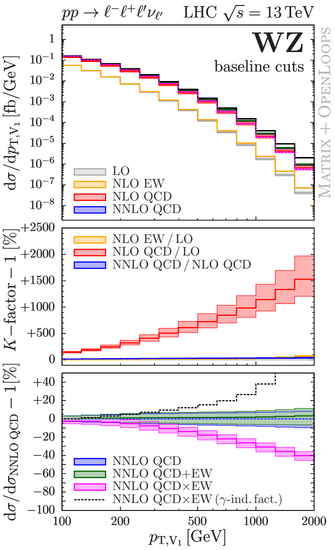
$$\mathrm{d}\sigma^{V(V)j} \propto \mathrm{d}\sigma^{Vj}_{\mathrm{LO}} \times \frac{\alpha_{\mathrm{w}}}{2\pi} \log^2\left(\frac{Q^2}{M_W^2}\right) \propto \mathrm{d}\sigma^{\mathrm{LO}}_{VV} \times \underbrace{\alpha_S \log^2\left(\frac{Q^2}{M_W^2}\right)}_{\sim 3 \text{ at } 1\,\mathrm{TeV}}$$

- no such log enhancement beyond NLO (since due to soft V radiation)

Giant NLO EW correction from soft W radiation in γq channel

$\Rightarrow$ no QCD$\times$ EW factorisation (dominant QCD and EW corrections from different hard subprocesses)

Hard-Vj dominated observable: p_{T,V_1}



QCD corrections (middle panel)

- huge NLO corrections and uncertainty
- moderate NNLO correction and uncertainty

EW corrections (middle panel)

- large negative Sudakov logs overcompensated by huge $\gamma q \to VWq$ correction

QCD–EW combination at $p_T \gg M_W$ (lower panel)

- large differences between various prescriptions

$\Rightarrow$ large $\mathcal{O}(\alpha\alpha_S)$ uncertainty spoils TH precision

Possible solutions

(A) Include $\mathcal{O}(\alpha\alpha_S)$ EW corrections to hard-Vj configurations

- possible with MEPS merging at $\mathrm{NLO\,QCD} + \mathrm{EW}_{virt}$ [Kallweit, Lindert, Maierhöfer, S.P., Schönherr '16] available in Sherpa
- very recently applied to WW production [Bräuer et al, 2005.12128]

(only NLO QCD+EW accuracy)

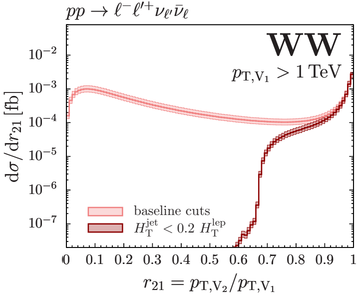
(B) Veto against hard-Vj configurations [Grazzini et al. '20]

- NNLO QCD+EW with mild jet veto

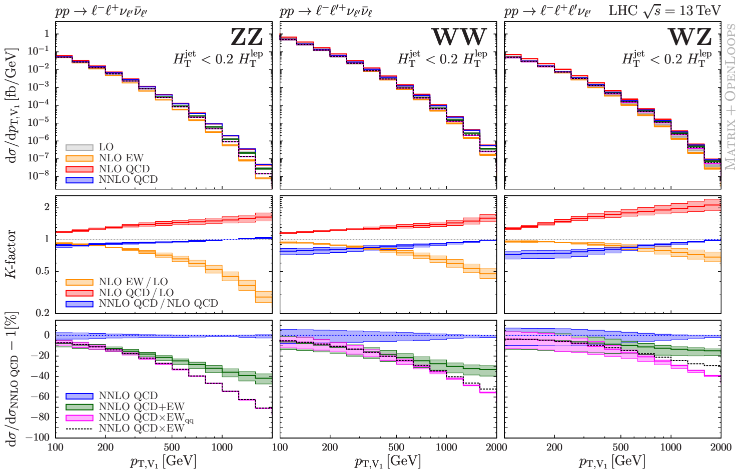
$$H_T^{\rm jets} < 0.2\, H_T^{\rm lep}$$

⇒ suppression of hard-Vj with soft V_2 radiation ($r_{21} \ll 1$)

⇒ inclusion of hard-VV with soft QCD radiation ($r_{12} \to 1$)



p_{T,V_1} distributions with H_T^{jets} veto



- similarly good behaviour and NNLO QCD+EW accuracy as for hard-VV dominated distributions
- NLO QCD enhancement in the tail can be further reduced with optimised veto

Conclusions

NNLO QCD+NLO EW for all processes $pp \to 4$ leptons/neutrinos

- implemented in MATRIX+OPENLOOPS (code coming soon)
- at $p_T \gg M_W$ very large QCD and EW corrections and nontrivial interplay

Hard-VV dominated observables

- typical NNLO QCD uncertainties of few percent
- large Sudakov EW logs factorise wrt QCD $\Rightarrow$ high precision up to few 100 GeV

(2-loop EW logs needed at TeV scale)

Hard-Vj dominated observables

- very large NLO QCD and EW corrections, but NNLO QCD quite stable
- large $\mathcal{O}(\alpha\alpha_S)$ uncertainties can be avoided with mild veto (or multi-jet merging)

Important implications for sensitivity of BSM and EFT studies at high p_T

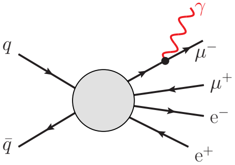
Q&A on Zoom after the end of this session

Meeting ID : 266 192 3471

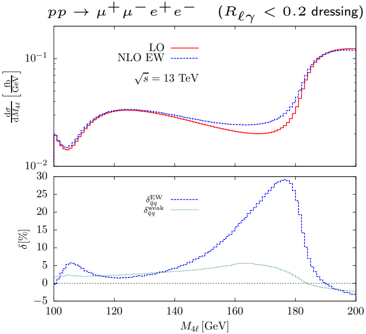
Password : same as this session

Backup slides

QED logarithmic corrections from lepton fragmentation

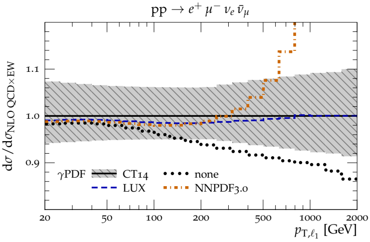


- $\alpha \ln(Q/m_\ell)$ corrections with bare leptons
- attenuated by lepton dressing
- largest effects in $m_{\ell\ell}$ and $m_{4\ell}$



[Biedermann et.al. '16]

Photon-induced processes



[Kallweit, Lindert, S.P., Schönherr '17]

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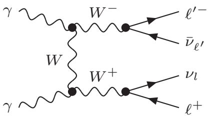
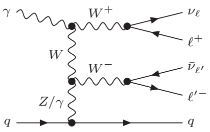


$\mathcal{O}\,(10\%)$ at $m_{VV} \sim 1$ TeV

NLO EW



$\mathcal{O}\,(10\%)$ at $p_{T,\ell} \sim 1$ TeV

- $\mathcal{O}\left(\alpha^2\right)$ like $q\bar{q} \to VV$ but usually not included in QCD predictions
- $\mathcal{O}\,(10\%)$ effects in TeV tails through t-channel W-exchange
- large γ-PDF uncertainties in NNPDF3.0 now strongly reduced with LUXQED PDFs [Manohar, Nason, Salam, Zanderighi '16]

Inclusive p_{T,V_1} distribution in $pp \to WW, WZ, ZZ$