Precise Standard-Model predictions for tri-boson

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Joint WG1+WG3 meeting on triple vector-boson production, COMETA COST action

5th of April 2024

Triboson

Motivation

- Quartic gauge coupling (like in VBS)
  → Another test of the EWSB mechanism and SM

History

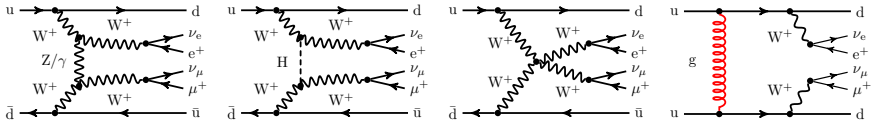
- NLO QCD ∼**2007** [Lazopoulos, Melnikov, Petriello; hep-ph/0703273]
  + EW ∼**2013** [Dao Thi, Le Duc, Weber; 1307.7403]
  → NLO QCD + NLO EW for ON-shell for all processes (see [Huss, Huston, Jones, MP; 2207.02122])

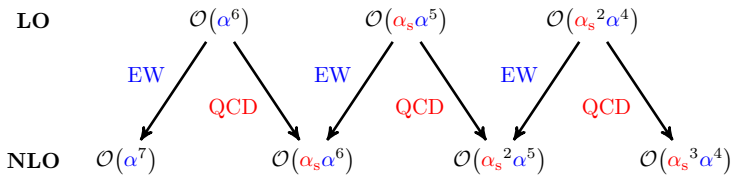
State of the art

- NLO QCD + NLO EW for OFF-shell for WWW
  [Schönherr; 1806.00307], [Dittmaier, Knippen, Schwan; 1912.04117]
- NLO QCD + NLO EW for OFF-shell for $V\gamma\gamma$ [Greiner, Schönherr; 1710.11514]
- NLO QCD + NLO EW for OFF-shell for WZγ [Cheng, Wackeroth; 2112.12052]
  ⚠ only leptonic decays considered

Triboson - [Denner, MP, Schönherr, Schumann; to appear]

Signature: W^+W^+jj ... golden channel for vector-boson scattering





→ Full NLO EW+QCD [Biedermann, Denner, MP; 1708.00268]

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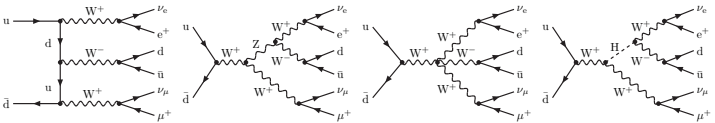
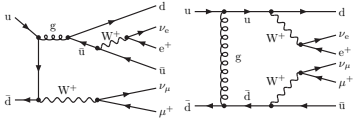
- **EW process**



- **QCD process**



→ Measurement by ATLAS [ATLAS; 2201.13045]

→ Investigation of EW corrections [Biedermann, Denner, MP; 1611.02951]

→ Full NLO QCD+EW + **PS corrections using** SHERPA

→ Typical phase space (inspired by [ATLAS; 2201.13045]):

$$
\begin{aligned}
p_{\mathrm{T},\ell^+} &> 20\,\mathrm{GeV} \quad \text{and} \quad |y_{\ell^+}| < 2.5 \\
p_{\mathrm{T,j}} &> 20\,\mathrm{GeV} \quad \text{and} \quad |y_{\mathrm{j}}| < 4.5 \\
m_{\mathrm{jj}} &< 160\,\mathrm{GeV} \quad \text{and} \quad |\Delta y_{\mathrm{jj}}| < 1.5
\end{aligned}
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40\,\mathrm{GeV} < m_{\ell^+\ell^+} < 400\,\mathrm{GeV}
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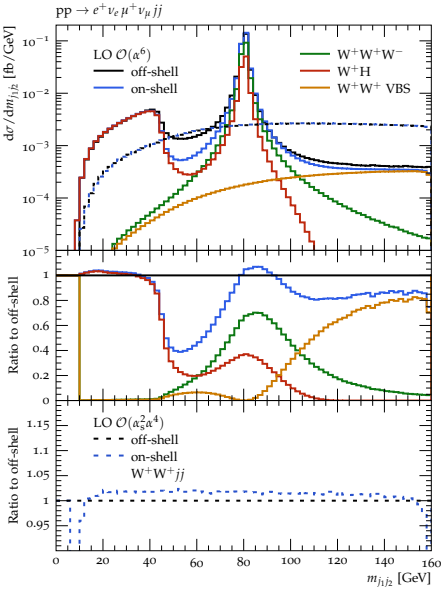
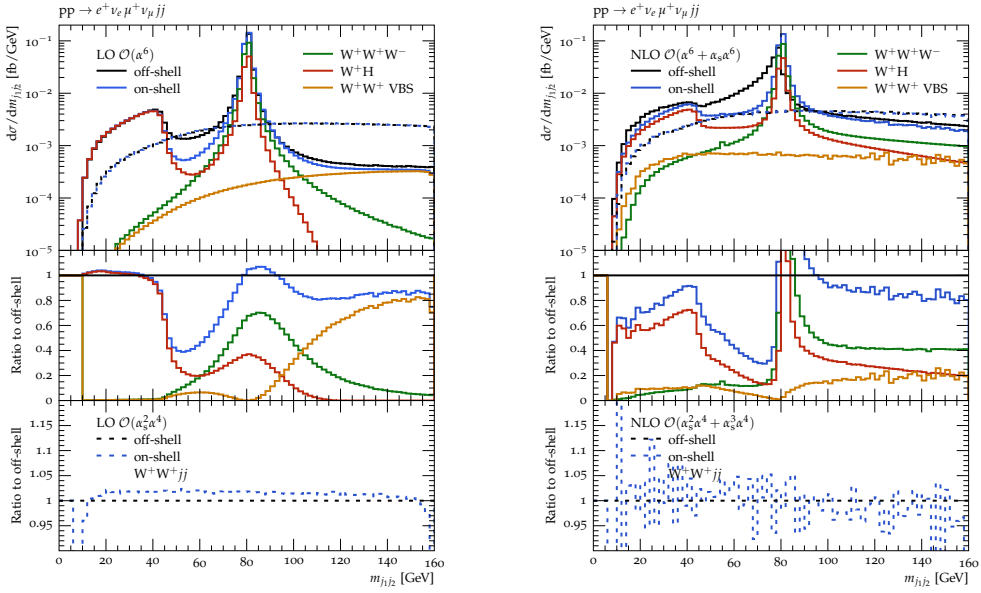
$\mathcal{O}(\alpha^6)$	off-shell	on-shell	on-shell subprocess			
Process	$\mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$	sum	$\mathrm{W}^+\mathrm{W}^+\mathrm{W}^-$	$\mathrm{W}^+\mathrm{H}$	$\mathrm{W}^+\mathrm{Z}$	$\mathrm{W}^+\mathrm{W}^+$ VBS
σ_{LO}[fb]	0.7917	0.7738	0.4207	0.3265	$5 \cdot 10^{-7}$	0.0266
$\sigma/\sigma_{\mathrm{LO}}^{\text{off-shell}}$[%]	100	97.7	53.1	41.2	$7 \cdot 10^{-5}$	3.3

⚠ Large contribution from WH! ⚠ **preliminary**

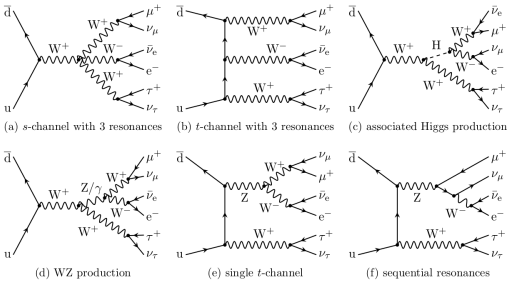


[Denner, MP, Schönherr, Schumann] ⚠ **preliminary**

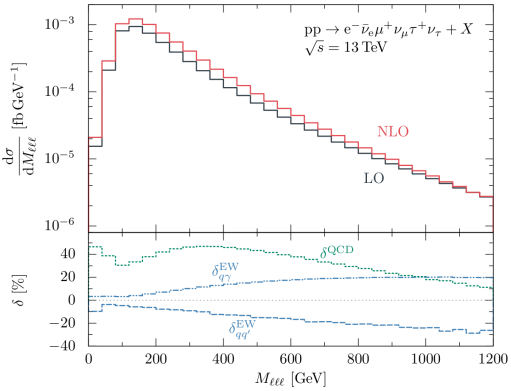


[Denner, MP, Schönherr, Schumann] ⚠ **preliminary** → More complex picture with higher-orders

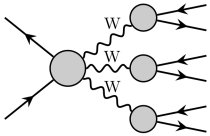
NLO QCD + EW to pp $\to e^- \bar{\nu}_e \mu^+ \nu_\mu \tau^+ \nu_\tau$ [Dittmaier, Knippen, Schwan; 1912.04117]



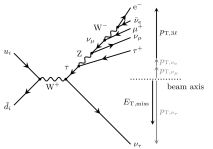
- Large cancellations between different corrections

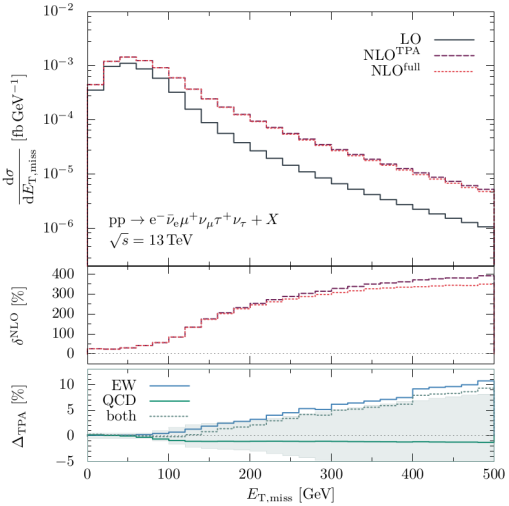


- Triple pole approximation



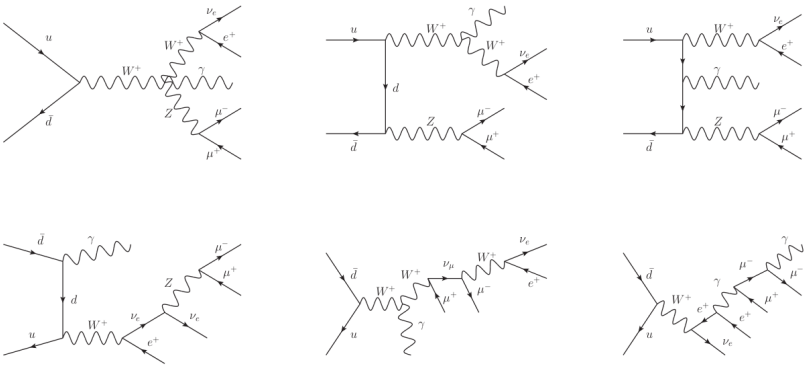
→ Responsible diagram





→ Excellent approximation of full process where VH not relevant!

NLO QCD + EW to pp $\to e^+\nu_e\mu^+\mu^-\gamma$ [Cheng, Wackeroth; 2112.12052]



- Off-shell effects, spin correlations, and non-resonance contributions **accounted**

σ_{LO} [fb]	σ_{QCD} [fb]	K-factor	σ_{EW} [fb]	δ_{EW} [%]	$\delta_{\text{EW}}^{q\bar{q}}$ [%]	$\delta_{\text{EW}}^{\gamma q(\bar{q})}$ [%]
$0.20869(5)$	$0.3588^{+3.90\%}_{-3.23\%}(2)$	$1.719(1)$	$0.2101(1)$	$0.97(1)$	-3.99(4)	$+4.96(1)$

→ At NLO EW:
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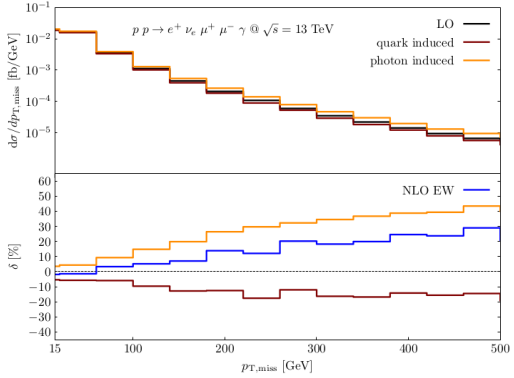
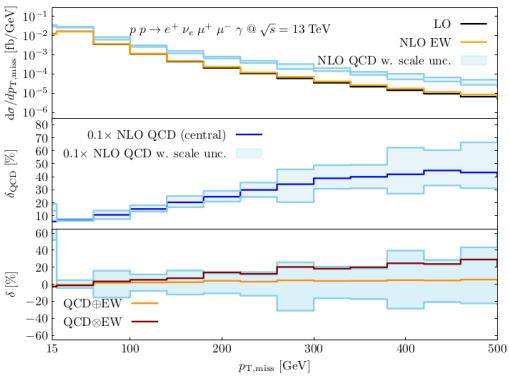


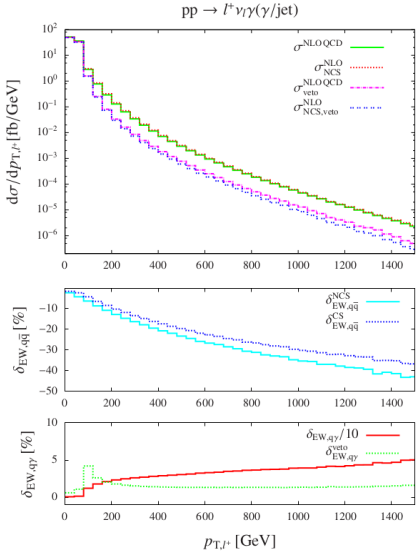


Sudakov logarithms vs. photon-induced

→ Large effect of photon-induced contributions also in pp → Wγ

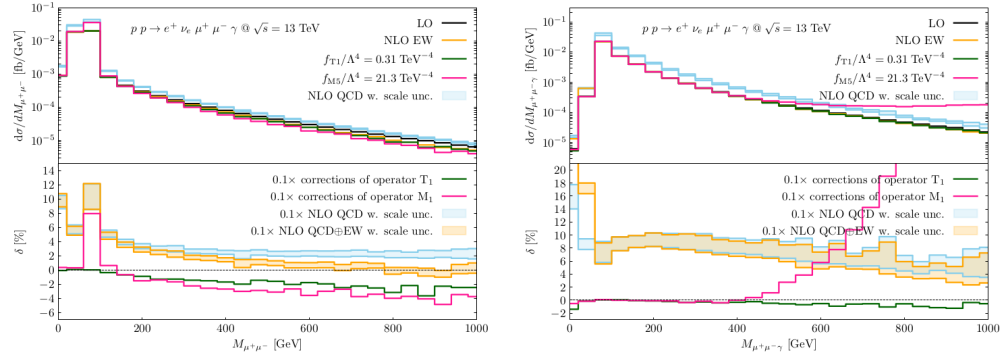
[Denner, Dittmaier, Hecht, Pasold; 1412.7421]

→ Effect due to hard-jet configurations
→ significantly reduced with jet veto
⚠ Important to be considered in experimental analysis



- Dim-8 operator in SMEFT:

$$\mathcal{O}_{\mathrm{M},5} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\nu \Phi\right] \times B^{\beta\mu}, \quad \mathcal{O}_{\mathrm{T},1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$



→ Missing EW corrections can mimic dim-8 operator ...

... if looking at single distributions

Summary

Recent computations:

- $pp \to WWW$ with hadronic decays [Denner, MP, Schönherr, Schumann; to appear]
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  $\to$ Precision programme at the LHC
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