Large electroweak corrections to Vector-Boson Scattering at the LHC

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Based on: [arXiv:1611.02951]

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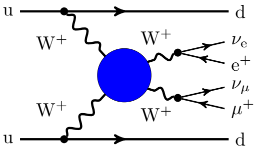
Vector-Boson Scattering (VBS)



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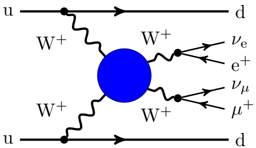
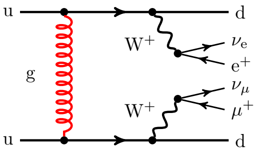


- Crucial role of Higgs boson
- Key process to investigate electroweak symmetry breaking
- Experimental evidence reported by ATLAS and CMS from Run-I [1405.6241, 1611.02428, 1410.6315]
- Background process: QCD-induced process



→ Need for precise and appropriate theoretical predictions for ...
.. both VBS and the QCD-induced process:

- NLO QCD to VBS [Jäger, Oleari, Zeppenfeld; 0907.0580], [Denner, Hǒseková, Kallweit; 1209.2389]
- NLO QCD to QCD-induced process [Melia et al.; 1007.5313, 1104.2327]
- Matching to parton shower [Jäger and Zanderighi; 1108.0864]
  → Available in VBFNLO [1311.6738, 1404.3940] or POWHEG-Box

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NLO EW calculations still missing

→ Calculation of NLO EW corrections to off-shell VBS:

$$\mathrm{pp} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$$

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$$\mathrm{pp} \to \mu^+ \nu_\mu \mathrm{e}^+ \nu_\mathrm{e} \mathrm{jj}$$

- Off-shell and non-resonant contributions
  → Realistic final state
- EW corrections can be large in certain phase space regions
  → Sudakov logarithms
- Theoretical and numerical challenge to consider $2 \to 6$ process
  → Up to 6 external charged particles and 4 intermediate resonances
  → Virtual corrections involving up to 8-point functions

$$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$$

$\rightarrow$ All partonic channels taken into account

- $\mathrm{uu} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{dd}$
- $\mathrm{u\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{s\bar{c}}$
- $\mathrm{uc} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{sd}$
- $\mathrm{\bar{d}\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{\bar{u}\bar{u}}$
- $\mathrm{u\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{d\bar{u}}$
- $\mathrm{u\bar{s}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{d\bar{c}}$
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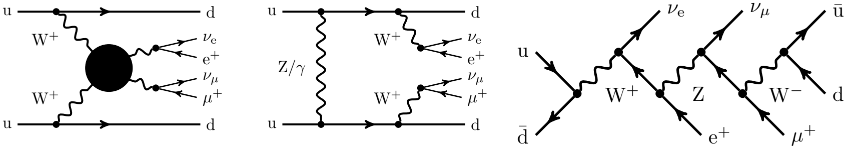
→ The LO is defined at order $\mathcal{O}\left(\alpha^6\right)$



NB: The LO QCD-induced process is of order $\mathcal{O}\left(\alpha^4\alpha_s^2\right)$ (not discussed)

→ NLO EW corrections are of order $\mathcal{O}\left(\alpha^7\right)$

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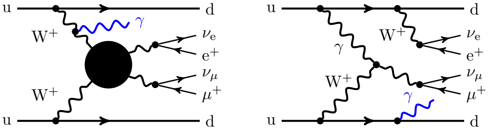
→ Include all possible real photonic corrections

$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}\gamma$



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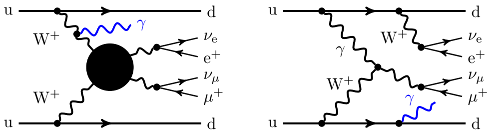
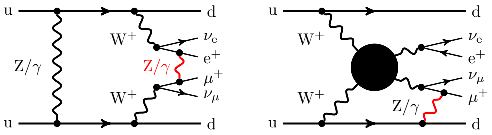


→ Include all virtual corrections

(with up to 8-point functions)



- Tools
  - → Virtual corrections: RECOLA [Actis, Denner, Hofer, Lang, Scharf, Uccirati]
  - + COLLIER [Denner, Dittmaier, Hofer]
  - → In-house Monte Carlo - MOCANLO [Feger]
  - → Dipole subtraction scheme [Catani,Seymour], [Dittmaier]
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- Inputs
  - → Fixed renormalisation and factorisation scale $\mu_R = \mu_F = M_{\rm W}$
  - → G_μ scheme:

$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_{\rm W}^2 \left(1 - \frac{M_{\rm W}^2}{M_{\rm Z}^2}\right) \quad \text{with} \quad G_\mu = 1.16637 \times 10^{-5}\,\text{GeV}$$

  - → Parameters:

$$\begin{aligned} m_{\rm t} &= 173.21\,\text{GeV}, & \Gamma_{\rm t} &= 0\,\text{GeV} \\ M_{\rm Z}^{\rm OS} &= 91.1876\,\text{GeV}, & \Gamma_{\rm Z}^{\rm OS} &= 2.4952\,\text{GeV} \\ M_{\rm W}^{\rm OS} &= 80.385\,\text{GeV}, & \Gamma_{\rm W}^{\rm OS} &= 2.085\,\text{GeV} \\ M_{\rm H} &= 125\,\text{GeV} & \Gamma_{\rm H} &= 4.07 \times 10^{-3}\,\text{GeV} \end{aligned}$$

Validations

- Two independent Monte Carlo integrators
- Tree-level matrix elements: MadGraph5_aMC@NLO [Alwall et al.; 1405.0301]
- One-loop matrix elements:
  - DPA
- IR-subtraction/finiteness:
  - Variation of α parameter [Nagy, Troscanyi; hep-ph/9806317]
  - Variation of technical cuts
  - Variation of IR-scale
- Born hadronic cross sections: MadGraph5_aMC@NLO

Predictions for $\sqrt{s} = 13\text{TeV}$ at the LHC

$$\mathrm{pp} \to \mu^+ \nu_\mu \mathrm{e}^+ \nu_\mathrm{e} \mathrm{jj}$$

Predictions for $\sqrt{s} = 13$TeV at the LHC
$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$

- NNPDF3.0QED [NNPDF collaboration]
- Cuts inspired by Refs. [1405.6241, 1611.02428, 1410.6315] :

$$
\begin{aligned}
\text{jets:} \quad & p_{\mathrm{T,j}} > 30\,\mathrm{GeV}, & |y_\mathrm{j}| < 4.5, \\
\text{charged lepton:} \quad & p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}, & |y_\ell| < 2.5, \\
\text{missing transverse momentum:} \quad & p_{\mathrm{T,miss}} > 40\,\mathrm{GeV}, & \\
\text{jet-jet:} \quad & m_\mathrm{jj} > 500\,\mathrm{GeV}, & |\Delta y_\mathrm{jj}| > 2.5, \\
\ell\ell \text{ and } \mathrm{j}\ell \text{ distance:} \quad & \Delta R_{\ell\ell} > 0.3, & \Delta R_{\mathrm{j}\ell} > 0.3.
\end{aligned}
$$

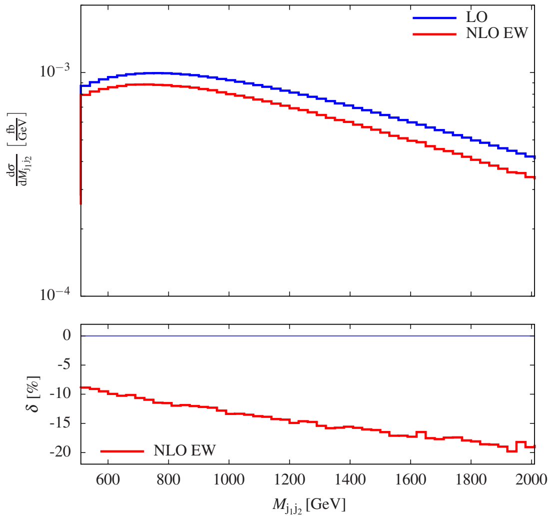
$\rightarrow$ Final state: 2 jets, missing $p_{\mathrm{T},}$, and 2 same sign leptons

- anti-k_T jet algorithm [Cacciari, Salam, Soyez]
  $R = 0.4$ for jet recombination and $R = 0.1$ for photon recombination

Fiducial cross section

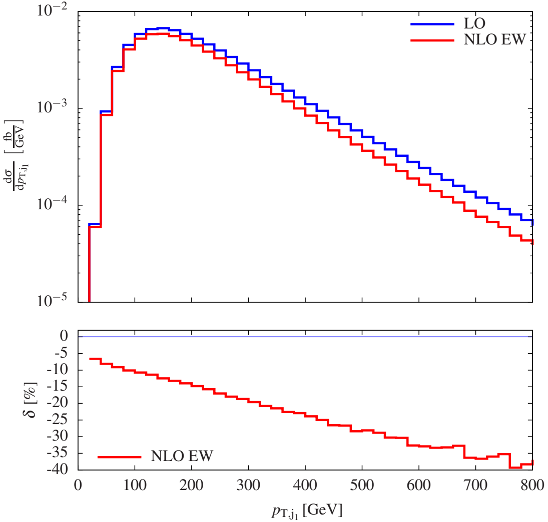
σ^{LO} [fb]	$\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$ [fb]	δ_{EW} [%]
1.5348(2)	1.2895(6)	−16.0

- $\mathrm{uu} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{dd}$ accounts for 2/3 of the cross section
- Large negative EW corrections
- Process featuring various large scales
  $\to \langle\sqrt{\hat{s}}\rangle \sim 2.4\,\mathrm{TeV}$, $\langle m_{\mathrm{jj}}\rangle \sim 1.8\,\mathrm{TeV}$, $\langle m_{4\ell}\rangle \sim 450\,\mathrm{GeV}$
- Large EW logarithms $\to \log\frac{\hat{s}_{ij}}{M_\mathrm{W}^2}$, $\log\frac{\hat{s}_{ij}}{\hat{s}_{kl}}$



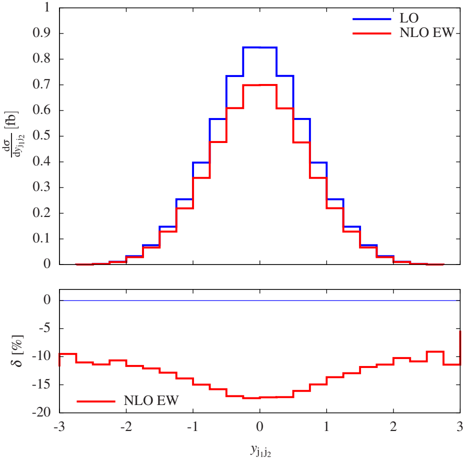
→ Example of large scale: $\langle m_{jj} \rangle \sim 1.8\,\mathrm{TeV}$

→ Sudakov logarithms → -20%



→ -7% to -40% corrections over the whole range: huge effect

→ EW corrections should be taken into account



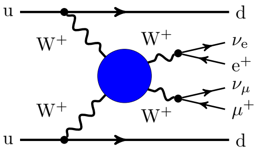
$\rightarrow$ Near $y_{j_1j_2} = 0$: two jets back-to-back
Bulk of the cross section, $\sim -16\%$ corrections
$\rightarrow$ For large $|y_{j_1j_2}|$: two jets in same hemisphere
Invariant mass M_{jj} smaller $\Rightarrow \log(M_{j_1j_2}/M_W)$ smaller

Summary

- First NLO EW calculation of the full VBS process
  $\rightarrow$ $\mathrm{pp} \rightarrow \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$
- EW corrections are large
  $\rightarrow$ They should be taken into account

$\rightarrow$ For more details please look at:

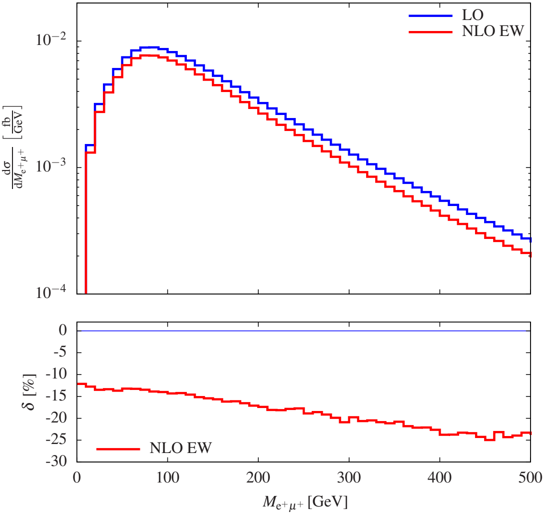
[arXiv:1611.02951]



Back-up slides

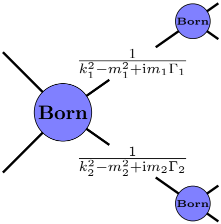
BACK-UP

Distributions extra

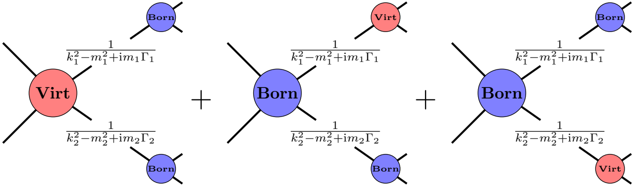


DPA (1) [Dittmaier, Schwan; 1511.01698]

- At LO



- At NLO



DPA (2) [Dittmaier, Schwan; 1511.01698]

- Factorisable corrections

$$\mathcal{M}_{\rm virt,fact,PA} = \sum_{\lambda_1,\ldots,\lambda_r} \left(\prod_{i=1}^{r} \frac{1}{K_i}\right) \Bigg[\mathcal{M}_{\rm virt}^{I\to N,\overline{R}} \prod_{j=1}^{r} \mathcal{M}_{\rm LO}^{j\to R_j} + \mathcal{M}_{\rm LO}^{I\to N,\overline{R}} \sum_{k=1}^{r} \mathcal{M}_{\rm virt}^{k\to R_k} \prod_{j\neq k}^{r} \mathcal{M}_{\rm LO}^{j\to R_j}\Bigg]_{\left\{\bar{k}_l^2 \to \hat{\bar{k}}_l^2 = M_l^2\right\}_{l\in\overline{R}}}$$

- Non-factorisable corrections:

$$2{\rm Re}\left\{\mathcal{M}^{*}_{\rm LO,PA}\mathcal{M}_{\rm virt,nfact,PA}\right\} = \left|\mathcal{M}_{\rm LO,PA}\right|^2 \delta_{\rm nfact}$$

- On-shell projection
- DPA applied to virtual corrections and I-operator
- Full Born and Real contributions: