Complete NLO corrections to $\text{pp} \to \mu^+\nu_\mu e^+\nu_e jj$

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Based on: **[arXiv:1611.02951] Phys.Rev.Lett. 118 (2017) no.26, 261801, [arXiv:1708.00268]**

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VBSCAN Cost Action kick-off meeting
Split, Croatia

9th of June 2017

Julius-Maximilians-
UNIVERSITÄT
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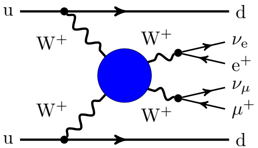
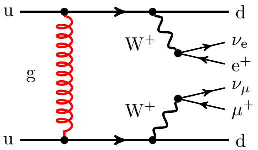
Vector-Boson Scattering (VBS)



- Crucial role of Higgs boson
- Key process to investigate electroweak symmetry breaking
- Evidence by ATLAS and CMS for Run-I [1405.6241, 1611.02428, 1410.6315]
  Measurement by CMS for run-II [CMS-PAS-SMP-17-004]
- Irreducible background process: QCD-induced process



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

- NLO QCD to VBS in the VBS approximation

  [Jäger, Oleari, Zeppenfeld; 0907.0580], [Denner, Hošeková, Kallweit; 1209.2389]

- NLO QCD to QCD-induced process

  [Melia et al.; 1007.5313, 1104.2327]

- Matching to parton shower

  [Jäger, Zanderighi; 1108.0864]

  → Available in VBFNLO [1311.6738, 1404.3940] or POWHEG-Box

→ **Full NLO EW and QCD corrections to:**

$$pp \to \mu^+\nu_\mu e^+\nu_e jj$$

Outline

Content

→ Calculation of both NLO QCD and EW corrections to

$$pp \to \mu^+\nu_\mu e^+\nu_e jj$$

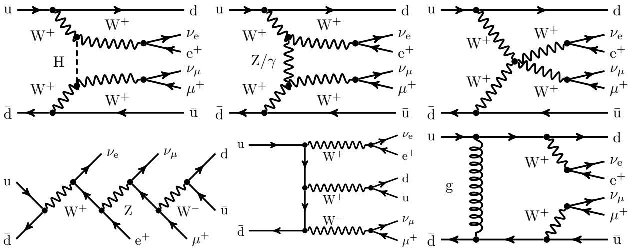
- Off-shell and non-resonant contributions
  → Realistic final state
- Full calculations vs. VBS approximation
- EW corrections can be large in certain phase space regions
  → Sudakov logarithms
- Theoretical and numerical challenge to consider $2 \to 6$ process
  → Virtual corrections involving up to 8-point functions

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

→ All partonic channels taken into account

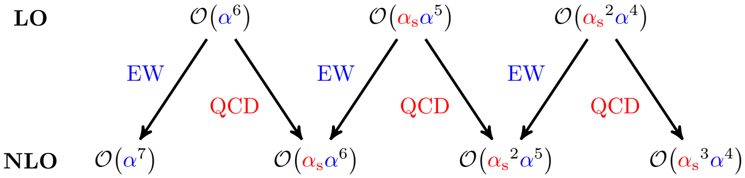
- $\mathrm{uu} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{dd}$
- $\mathrm{u\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{s\bar{c}}$
- $\mathrm{uc} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{sd}$
- $\mathrm{\bar{d}\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{\bar{u}\bar{u}}$
- $\mathrm{u\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{d\bar{u}}$
- $\mathrm{u\bar{s}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{d\bar{c}}$
- $\mathrm{\bar{s}\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{\bar{u}\bar{c}}$

→ Tree amplitudes of order $\mathcal{O}\left(g^6\right)$ and $\mathcal{O}\left({g_\mathrm{s}}^2 g^4\right)$



pp $\to \mu^+\nu_\mu e^+\nu_e jj$

LO cross sections at $\mathcal{O}(\alpha^6)$, $\mathcal{O}(\alpha_s\alpha^5)$, and $\mathcal{O}({\alpha_s}^2\alpha^4)$



NLO cross sections at $\mathcal{O}(\alpha^7)$, $\mathcal{O}(\alpha_s\alpha^6)$, $\mathcal{O}({\alpha_s}^2\alpha^5)$, and $\mathcal{O}({\alpha_s}^3\alpha^4)$

$\to$ Order $\mathcal{O}(\alpha_s\alpha^6)$ and $\mathcal{O}({\alpha_s}^2\alpha^5)$: QCD and EW corrections mix
  $\to$ Combined measurement

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

- NNPDF3.0QED [NNPDF collaboration]
- dynamical renormalisation and factorisation scale:

  $\mu_{\rm ren} = \mu_{\rm fac} = \sqrt{p_{\rm T,j_1}\, p_{\rm T,j_2}}$
- Cuts inspired by Refs. [1405.6241, 1611.02428, 1410.6315, CMS-PAS-SMP-17-004] :

  charged lepton: $p_{\rm T,\ell} > 20\,{\rm GeV}$, $|y_\ell| < 2.5$, $\Delta R_{\ell\ell} > 0.3$

  jets: $p_{\rm T,j} > 30\,{\rm GeV}$, $|y_j| < 4.5$, $\Delta R_{j\ell} > 0.3$

  missing energy: $p_{\rm T,miss} > 40\,{\rm GeV}$,

  → For the two leading jet in $p_{\rm T}$:

  jet-jet: $m_{jj} > 500\,{\rm GeV}$, $|\Delta y_{jj}| > 2.5$.

  → Final state: 2 jets, missing $p_{\rm T}$,, and 2 same sign leptons
- anti-$k_{\rm T}$ jet algorithm [Cacciari, Salam, Soyez; 0802.1189]

  $R = 0.4$ for jet recombination and $R = 0.1$ for photon recombination

→ LO fiducial cross sections:

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	Sum
$\sigma_{\rm LO}$ [fb]	1.4178(2)	0.04815(2)	0.17229(5)	1.6383(2)

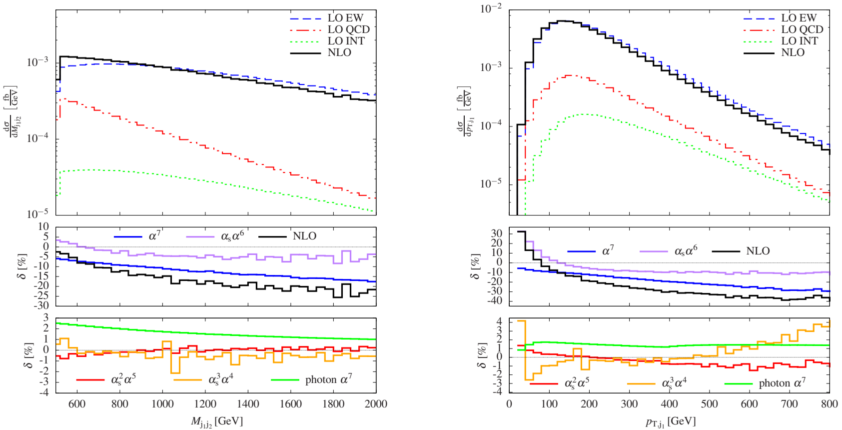
→ NLO fiducial cross sections: (normalised to $\sigma_{\rm LO}$)

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{\rm NLO}$ [fb]	−0.2169(3)	−0.0568(5)	−0.00032(13)	−0.0063(4)	−0.2804(7)
$\delta\sigma_{\rm NLO}/\sigma_{\rm LO}$ [%]	−13.2	−3.5	0.0	−0.4	−17.1

Updated with respect to Split presentation [Biedermann, Denner, MP; 1708.00268]

→ Large EW corrections at $\mathcal{O}(\alpha^7)$
→ Negative corrections at $\mathcal{O}(\alpha_s\alpha^6)$:
$\sim$ 0.6% difference with respect to VBS approximation
(negelecting *s*-channel and *t*-/*u*-channel interferences)
→ Tuned comparison against [Denner, et al.; 1209.2389] and [Jäger, et al.; 0907.0580]
→ VBS approximation in Recola
→ Photon PDF contribution at NLO (not included in NLO definitions):
+1.50% with LUXqed [Manohar et al.; 1607.04266]

Separated contributions

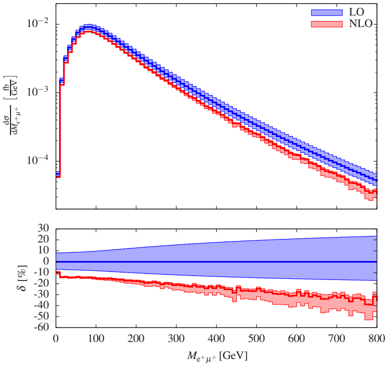


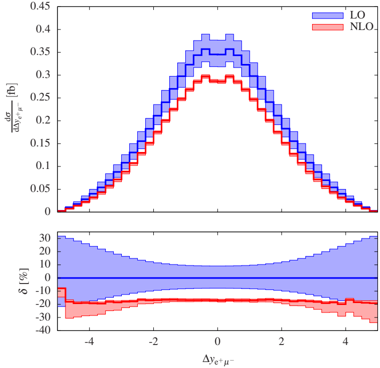
Updated with respect to Split presentation [Biedermann, Denner, MP; 1708.00268]

→ Clear hierarchy of LO contributions

→ Different behaviour of the NLO corrections (normalised to the full LO)

Combined predictions





Updated with respect to Split presentation [Biedermann, Denner, MP; 1708.00268]

→ Large negative corrections for the full process

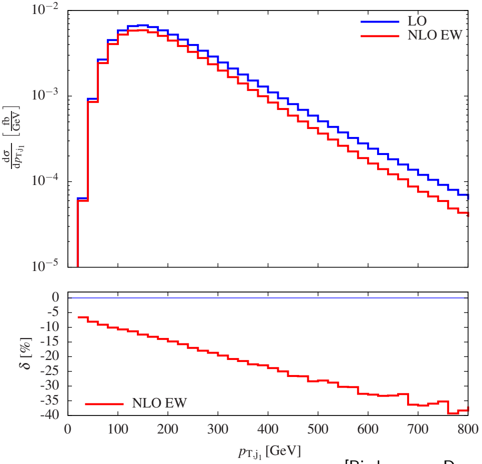
→ Corrections dominated by EW correction to EW process

  → Bands do not overlap

Content

LO: $\mathcal{O}(\alpha^6)$
NLO: $\mathcal{O}(\alpha^7)$

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

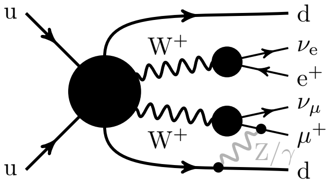


[Biedermann, Denner, MP; 1611.02951]

→ Huge NLO electroweak correction (!)

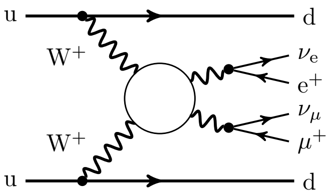
- Leading behaviour dominated by:
  Sudakov logarithms (bosonic part of the virtual), $\log^2\left(\frac{Q^2}{M_W^2}\right)$
  $\rightarrow$ Usually in the tail of the distribution (suppressed)
  $\rightarrow$ Usually small for total cross section
  $\rightarrow$ Usually smaller than the QCD corrections
- Large corrections not due to VBS cuts
  $\rightarrow$ remove $m_{jj} > 500\,\mathrm{GeV}$ and $|\Delta y_{jj}| > 2.5$
  $\rightarrow$ relax $p_{T,j}$ and $p_{T,miss}$

- Double-pole approximation: [Dittmaier, Schwan; 1511.01698]
  leading contribution of expansion about the resonance poles
  → Required two W bosons for the virtual contributions



- Agree within 1% with full calculation
- Dominated by factorisable corrections
  → Large corrections driven by the scattering process

- Effective Vector Boson approximation:



- Simplify the discussion to $W^+W^+ \to W^+W^+$
- Leading logarithm approximation [Denner, Pozzorini; hep-ph/0010201]

$$\sigma_{\mathrm{LL}} = \sigma_{\mathrm{LO}}\left[1 - \frac{\alpha}{4\pi} 4 C_{\mathrm{W}}^{\mathrm{ew}} \log^2\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right) + \frac{\alpha}{4\pi} 2 b_{\mathrm{W}}^{\mathrm{ew}} \log\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right)\right]$$

(double EW logs, collinear single EW logs, and single logs from parameter renormalisation included) (angular-dependant logarithms omitted)

$$\sigma_{\rm LL} = \sigma_{\rm LO}\left[1 - \frac{\alpha}{4\pi}4C_{\rm W}^{\rm ew}\log^2\left(\frac{Q^2}{M_{\rm W}^2}\right) + \frac{\alpha}{4\pi}2b_{\rm W}^{\rm ew}\log\left(\frac{Q^2}{M_{\rm W}^2}\right)\right]$$

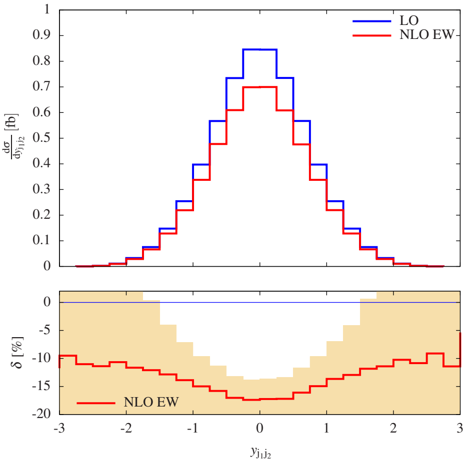
- For $Q = \langle m_{4\ell}\rangle \sim 390\,\text{GeV}$

$$\delta_{\rm EW}^{\rm LL} = -16\%\ (!)$$

→ Corrections 3-4 times larger than for $q\bar{q} \to \mathrm{W^+W^+}$

- $C^{\rm ew}$ larger for bosons than fermions
- $\langle m_{4\ell}\rangle$ larger for VBS (massive t-channel [Denner, Hahn; hep-ph/9711302])
  NB: $\langle m_{4\ell}\rangle \sim 250\,\text{GeV}$ for $q\bar{q} \to \mathrm{W^+W^+}$

Large NLO EW corrections:
intrinsic feature of VBS at the LHC



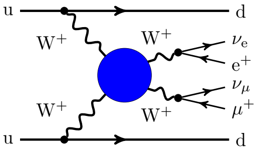
[Biedermann, Denner, MP; 1611.02951]

$\rightarrow$ Near $y_{j_1j_2} = 0$: two jets back-to-back
Bulk of the cross section, $\sim -16\%$ corrections
$\rightarrow$ Band: $\pm 1/\sqrt{N_{\text{obs}}}$ for 3000 fb^{-1} $\rightarrow$ probe of the EW sector

Content

Conclusion

- Full NLO corrections to pp $\to \mu^+\nu_\mu e^+\nu_e jj$:
  [Biedermann, Denner, MP; 1708.00268]
  - At NLO VBS and QCD-induced contributions mix:
    $\to$ Combined measurement
  - Full computations:
    $\to$ Small differences with respect to the VBS approximation
- NLO EW corrections to VBS:
  [Biedermann, Denner, MP; 1611.02951]
  - Unexpected large EW corrections
    $\to$ Probe of the EW sector



Back-up slides

BACK-UP

- Tools
  - → Virtual corrections: RECOLA [Actis, Denner, Hofer, Lang, Scharf, Uccirati] + COLLIER [Denner, Dittmaier, Hofer]
  - → Private Monte Carlos (MoCaNLO [Feger] + another one)
  - → Dipole subtraction scheme [Catani,Seymour], [Dittmaier]
  - → Complex-mass scheme [Denner et al.]
- Inputs
  - → G_μ scheme:

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

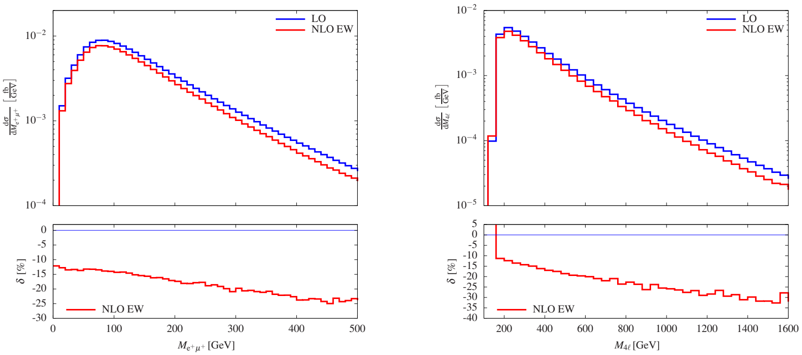
  - → Parameters:

$$\begin{aligned} m_t &= 173.21\,\text{GeV}, & \Gamma_t &= 0\,\text{GeV} \\ M_Z^{OS} &= 91.1876\,\text{GeV}, & \Gamma_Z^{OS} &= 2.4952\,\text{GeV} \\ M_W^{OS} &= 80.385\,\text{GeV}, & \Gamma_W^{OS} &= 2.085\,\text{GeV} \\ M_H &= 125\,\text{GeV} & \Gamma_H &= 4.07 \times 10^{-3}\,\text{GeV} \end{aligned}$$

Validations

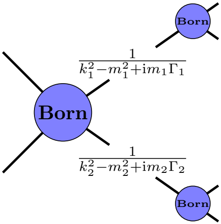
- Two independent Monte Carlo integrators
- Tree-level matrix elements: MadGraph5_aMC@NLO [Alwall et al.; 1405.0301]
- One-loop matrix elements:
  - vs. MadLoops [Hirschi et al.; 1103.0621]:
    - $\mathcal{O}(\alpha^7)$ and $\mathcal{O}(\alpha_\mathrm{s}^3\alpha^4)$
  - Two libraries in Collier [Denner, Dittmaier, Hofer; 1407.0087, 1604.06792]:
    - $\mathcal{O}(\alpha_\mathrm{s}\alpha^6)$, $\mathcal{O}(\alpha_\mathrm{s}^2\alpha^5)$, and $\mathcal{O}(\alpha_\mathrm{s}^3\alpha^4)$
- NLO computations:
  - DPA for $\mathcal{O}(\alpha^7)$ (automatised in [MP et al.; 1607.05571, 1612.07138] following [Dittmaier, Schwan; 1511.01698])
  - $\mathcal{O}(\alpha_\mathrm{s}\alpha^6)$ vs. [Denner, et al.; 1209.2389] in the VBS approximation
- IR-subtraction/finiteness:
  - Variation of α parameter [Nagy, Troscanyi; hep-ph/9806317]
  - Variation of technical cuts
  - Variation of IR-scale

Distributions extra

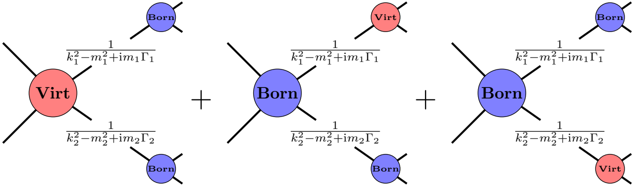


DPA (1) [Dittmaier, Schwan; 1511.01698]

- At LO



- At NLO



DPA (2) [Dittmaier, Schwan; 1511.01698]

- Factorisable corrections

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

- Non-factorisable corrections:

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

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