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VBS precision predictions

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1. Introduction
2. Calculational set-up
3. NLO corrections to vector-boson pair plus jet-pair production
4. Electroweak corrections to vector-boson scattering (VBS)
5. Quality of vector-boson scattering approximation
6. Conclusion

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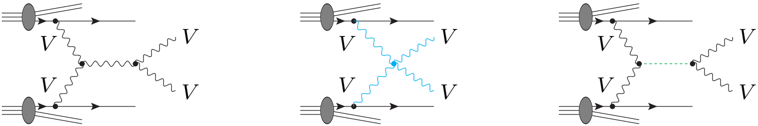
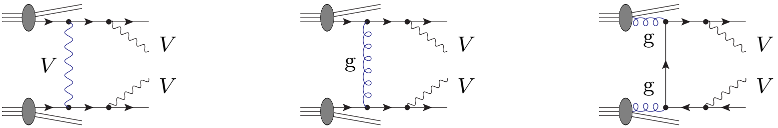


Physics issues of vector-boson scattering (VBS): $(V = \mathrm{W}, \mathrm{Z})$

- key process to test electroweak symmetry breaking
  Higgs boson crucial for unitarity of process
- search for anomalous quartic-gauge-boson couplings
  sensitivity grows with energy of gauge bosons
  $\hookrightarrow$ EW corrections significant $\propto \alpha \log^2(E/M_\mathrm{W})$
- VBS purely EW process [$\mathcal{O}(\alpha^4)$ for stable Vs]
- experimental signature
  - two forward/backward jets at large rapidities
  - large rapidity separation (Δy_jj) between jets
  - large di-jet invariant mass (M_jj)
  - final-state vector bosons in central region

Irreducible background to VBS

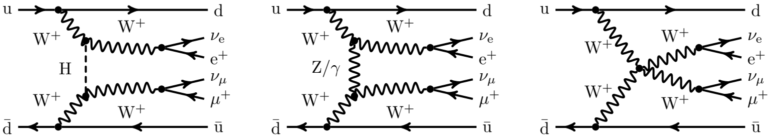
Final state: $VV + 2\mathrm{j} \quad (4l + 2\mathrm{j})$



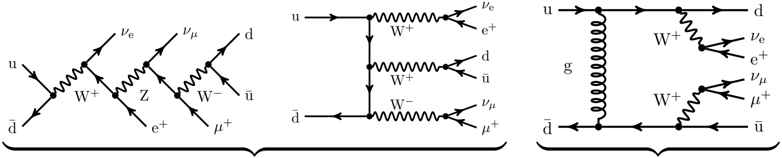
- Full EW process [$\mathcal{O}(\alpha^4)$ for stable Vs as above)]
  not separable from VBS
- QCD process [$\mathcal{O}(\alpha_\mathrm{s}^2\alpha^2)$ for stable Vs]
  gauge-invariant contribution
- interferences between EW and QCD contributions
  [$\mathcal{O}(\alpha_\mathrm{s}\alpha^3)$ for stable Vs]
  appear only for channels with identical or weak-isospin partner quarks
- gluonic channels for neutral final states
- irreducible background can be suppressed by cuts on M_jj and $|\Delta y_\mathrm{jj}|$
  $\sigma_\mathrm{EW}^{\mathrm{W^+W^+}} \sim 10\,\sigma_\mathrm{QCD}^{\mathrm{W^+W^+}}, \qquad \sigma_\mathrm{EW}^{\mathrm{W^+Z}} \sim 0.25\,\sigma_\mathrm{QCD}^{\mathrm{W^+Z}}, \qquad \sigma_\mathrm{EW}^{\mathrm{ZZ}} \sim 0.1\,\sigma_\mathrm{QCD}^{\mathrm{ZZ}}$

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

Vector-boson scattering (VBS) topologies: $\mathcal{O}\left(g^6\right)$ all t channel



irreducible background to VBS:



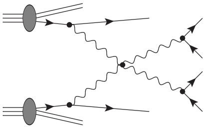
EW background $\mathcal{O}(g^6)$, s channel

QCD background $\mathcal{O}\left(g_\mathrm{s}^2\, g^4\right)$
only t channel

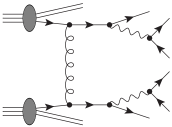
t channel: incoming quarks/antiquarks connected to outgoing quarks/antiquarks
u channel: exchange identical quarks/antiquarks
s channel: incoming quark and anti-quark connected, all boson propagators time like
VBS approximation: only t and u channel, no interferences

Existing calculations for $VV + 2$ jet production

EW production: $\mathcal{O}(\alpha^6)$



QCD-induced production: $\mathcal{O}(\alpha_s^2\alpha^4)$



- full LO predictions: Ballestrero, Franzosi, Maina '10 (PHANTOM)
- NLO QCD corrections to EW diagrams:
  Jäger, Oleari, Zeppenfeld (+ Bozzi) '06, '07, '09 (VBFNLO);
  Denner, Hosekova, Kallweit '12
  PS matching: Zanderighi, Jäger '11, '13 + Karlberg '14 $(\mathrm{W^+W^+}, \mathrm{W^+W^-}, \mathrm{ZZ})$
  Rauch, Plätzer '16 $(\mathrm{W^+W^-})$, Jäger, Karlberg, Scheller '18 (WZ)
- NLO QCD corrections to QCD diagrams:
  Melia, Melnikov, Röntsch, Zanderighi '10, '11 $(\mathrm{W^+W^+})$; Greiner et al. '12 $(\mathrm{W^+W^-})$;
  Campanario, Kerner, Ninh, Zeppenfeld '13, '14 (VBFNLO) $(\mathrm{W^+W^+}, \mathrm{WZ}, \mathrm{ZZ})$
  PS matching: Melia, Nason, Röntsch, Zanderighi '11 $(\mathrm{W^+W^+})$
- New: calculation for complete processes $\mathrm{pp} \to 4f + 2\mathrm{j}$
  - NLO EW and QCD corrections for $\mathrm{W^+W^-}$ and WZ scattering
    Biedermann, Denner, Pellen '16; Denner, Dittmaier, Pellen, Schwan '19
  - full NLO corrections to $\mathrm{W^+W^-}$ Biedermann, Denner, Pellen '17

Existing NLO calculations – state of the art

- all processes known at NLO QCD accuracy matched to PS
  - in VBS approximation (no s channel, no interferences)
  - for both QCD-/EW-induced process
  - all available in VBFNLO (apart from QCD-induced $\mathrm{W^+W^-}$)
  - all available in POWHEG-BOX (⇒ PS matching)
  - possible to generate in MG5_AMC@NLO or SHERPA
- NLO EW corrections only known for $\mathrm{W^+W^+}$ and WZ (ZZ in progress)
- full NLO computation only known for $\mathrm{W^+W^+}$
- no NNLO results known

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Contributions to vector-boson scattering

Consider $\mathrm{pp} \to 4\ell + 2\mathrm{j}$

- all off-shell and non-resonant contributions $\Rightarrow$ realistic final state
- all relevant partonic channels:
  e.g. for $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ $(\mathrm{W}^+\mathrm{W}^+)$: 12 qq channels
  - $\mathrm{uu} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{dd}$ (67%)
  - $\mathrm{uc} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{ds}$ (6%)
  - $\mathrm{cc} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{ss}$
  - $\mathrm{u\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{d\bar{u}}$ (17%)
  - $\mathrm{u\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{s\bar{c}}$
  - $\mathrm{u\bar{s}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{d\bar{c}}$ (8%)
  - $\mathrm{c\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{s\bar{u}}$
  - $\mathrm{c\bar{s}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{d\bar{u}}$
  - $\mathrm{c\bar{s}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{s\bar{c}}$
  - $\mathrm{\bar{d}\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{\bar{u}\bar{u}}$
  - $\mathrm{\bar{d}\bar{s}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{\bar{u}\bar{c}}$
  - $\mathrm{\bar{s}\bar{s}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{\bar{c}\bar{c}}$

  more partonic channels for WZ $(40\ qq)$, ZZ scattering $(56\ qq)$
  plus channels with initial gluons (large contribution)
- $2 \to 6$ process is theoretical and numerical challenge
  virtual corrections involve up to 8-point functions

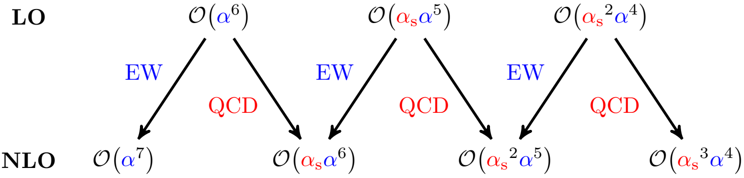
Expansion in multiple couplings

Example: $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ (vector-boson scattering: $\mathrm{pp} \to \mathrm{W}^+\mathrm{W}^+\mathrm{jj}$)

LO: pure EW diagrams $\mathcal{O}(e^6)$ and diagrams with gluons $\mathcal{O}(e^4 g_\mathrm{s}^2)$

NLO: EW and QCD corrections to both types of diagrams

at level of cross section:

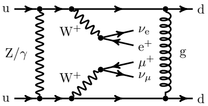


consequences:

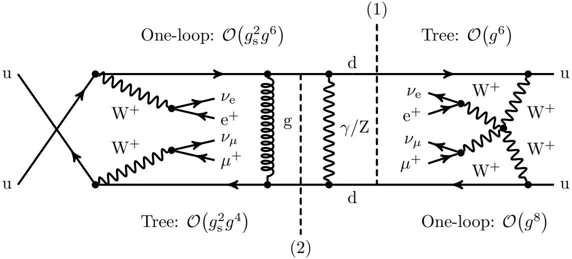
- QCD and EW corrections cannot be separated in general
  $\hookrightarrow$ distinction of EW signal and QCD background convention at NLO
  $\hookrightarrow$ consider well-defined orders $\mathcal{O}(\alpha_\mathrm{s}^n\alpha^m)$
- QCD corrections to leading LO terms well defined $\mathcal{O}(\alpha_\mathrm{s}^3\alpha^2)$
  EW corrections to EW LO process well defined $\mathcal{O}(\alpha^7)$

Virtual diagrams mix QCD and EW corrections:

- EW correction to LO QCD amplitude
- QCD correction to LO EW amplitude



⇒ QCD and EW corrections mix at $\mathcal{O}\left(\alpha_s\alpha^6\right)$ and $\mathcal{O}\left(\alpha_s^2\alpha^5\right)$



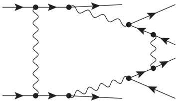
- (1) QCD correction to EW LO cross section
- (1) EW correction to LO QCD amplitude interfered with EW amplitude
- (2) EW correction to LO EW amplitude interfered with QCD amplitude

⇒ separation into QCD and EW is not well-defined at NLO
(well-defined in VBS approximation since interferences neglected)

Details on virtual EW corrections

Considered processes: $\mathrm{pp} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ $(\mathrm{W^+W^+})$, $\mu^+\mu^-\mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ (WZ)

- All diagrams of considered order(s) for full process included
- on-shell renormalization scheme
- G_μ scheme for electromagnetic coupling:



$$\alpha_{G_\mu} = \frac{\sqrt{2}G_\mu M_\mathrm{W}^2}{\pi}\left(1 - \frac{M_\mathrm{W}^2}{M_\mathrm{Z}^2}\right)$$

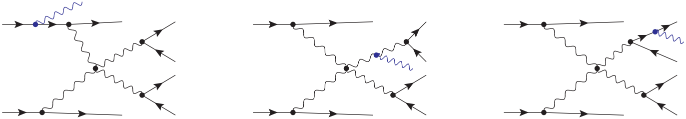
  absorbs running of α to EW scale and some universal corrections $\propto m_\mathrm{t}^2$
- complex-mass scheme for gauge-boson resonances

  Denner, Dittmaier, Roth, Wackeroth, Wieders '99, '05

  complex poles: $\mu_\mathrm{W}^2 = M_\mathrm{W}^2 - \mathrm{i}M_\mathrm{W}\Gamma_\mathrm{W}$, $\mu_\mathrm{Z}^2 = M_\mathrm{Z}^2 - \mathrm{i}M_\mathrm{Z}\Gamma_\mathrm{Z}$
  $\Rightarrow$ gauge-invariant amplitudes, universal treatment of resonances
- all matrix elements calculated with RECOLA Actis et al. '12, '16
  and COLLIER Denner et al. '16
  for WZ independent calculation with OPENLOOPS

  Cascioli, Maierhöfer, Pozzorini '11, Kallweit et al. '14

Real EW NLO corrections



soft and collinear singularities

- Catani–Seymour dipole subtraction Catani, Seymour '96; Dittmaier '99
- recombination of collinear parton–photon, lepton–photon, and parton–parton pairs (jet clustering)
  $\Rightarrow$ cancellation of soft and final-state collinear singularities
- initial-state collinear singularities cancelled by $\overline{\mathrm{MS}}$ redefinition of PDFs
- final-state photon splitting into quark pairs at $\mathcal{O}(\alpha_{\mathrm{s}}\alpha^6)$ requires photon-to-quark conversion function Denner, Dittmaier, Pellen, Schwan '19
- photon–jet separation at $\mathcal{O}(\alpha_{\mathrm{s}}^2\alpha^5)$ requires quark-to-photon fragmentation function Glover, Morgan '93

Phase-space integration with multi-channel Monte Carlo codes

Outline

Fiducial cross section for $\mathrm{W^+W^+jj}$

Scale uncertainty reduced by factor 5: Biedermann et al. '17

$$\sigma_{\mathrm{LO}} = 1.6383(2)^{+11.66(2)\%}_{-9.44(2)\%}\,\mathrm{fb}, \qquad \sigma_{\mathrm{NLO}} = 1.3577(7)^{+1.2(1)\%}_{-2.7(1)\%}\,\mathrm{fb}$$

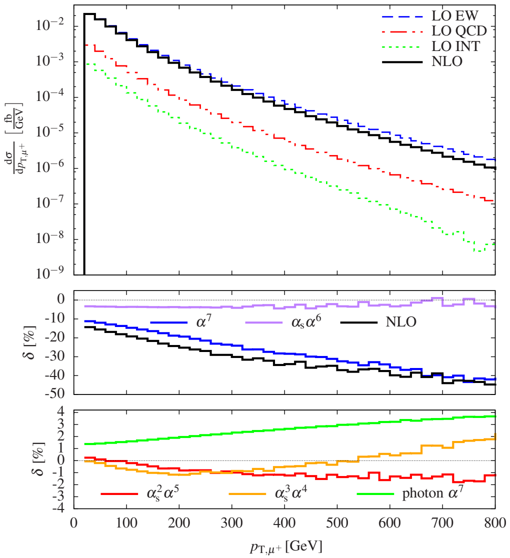
results for separate orders:

order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	sum
σ_{LO} [fb]	$1.4178(2)$	$0.04815(2)$	$0.17229(5)$	$1.6383(2)$
$\delta\sigma_{\mathrm{LO}}/\sigma_{\mathrm{LO}}$ [%]	86.5	2.9	10.5	100

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
$\delta\sigma_{\mathrm{NLO}}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

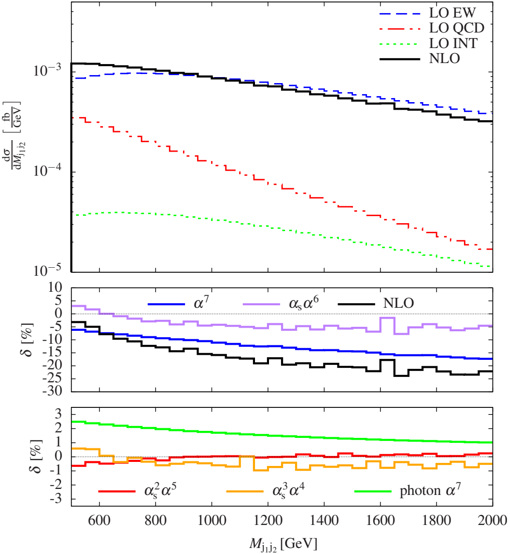
- LO EW contribution dominates for $\mathrm{W^+W^+jj}$
- LO interference small but non-negligible
- surprisingly large EW corrections at $\mathcal{O}(\alpha^7)$
- photon-induced contribution at NLO $+1.5\%$ (LUXqed Manohar et al. '16, '17)

Distribution in transverse momentum of the anti-muon



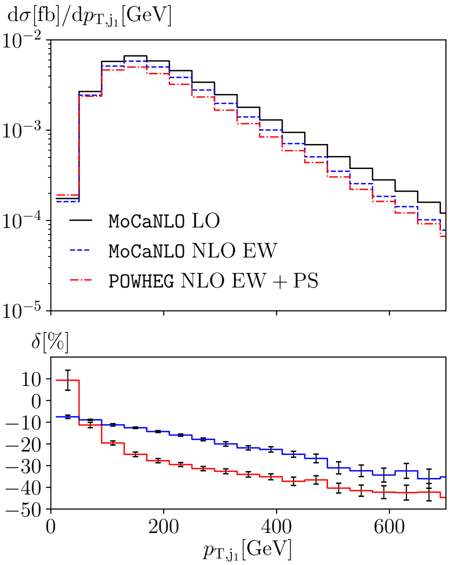
- EW contribution dominates everywhere
- $\mathcal{O}(\alpha^7)$ -40% at $800\,\text{GeV}$ (Sudakov logarithms) dominant correction
- $\mathcal{O}(\alpha_s\alpha^6)$ $-4\% - 0\%$
- $\mathcal{O}(\alpha_s^2\alpha^5)$, $\mathcal{O}(\alpha_s^3\alpha^4)$ between -2% and $+2\%$ cancelling for large $p_{T\mu^+}$
- photon-induced corrections increase to 4% at $p_{T\mu^+} = 800\,\text{GeV}$ (photon PDF grows with energy)

Di-jet invariant-mass distribution



- Large cross section also for high M_{jj}
- QCD-induced contrib. drops much faster
- $\mathcal{O}(\alpha^7)$ $-6\% - -17\%$
- $\mathcal{O}(\alpha_s\alpha^6)$ $+5\% - -5\%$
- $\mathcal{O}(\alpha_s^2\alpha^5)$, $\mathcal{O}(\alpha_s^3\alpha^4)$ tiny
- photon-induced corrections decrease with M_{jj} (non-VBS contributions suppressed)

Event generator for $W^{\pm}W^{\pm}$ with QED PS matching



Chiesa et al '19

- event generator based on POWHEG and RECOLA for
  $pp \to \mu^{\pm}\nu_{\mu}e^{\pm}\nu_{e}jj$
  $pp \to e^{\pm}\nu_{e}e^{\pm}\nu_{e}jj$
  including EW corrections matched to QED parton shower and interfaced to QCD parton shower
- PS shifts events to smaller p_{T,j_1}, partially out of acceptance

Fiducial LO cross section for WZjj

Process: $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ $\sqrt{s} = 13\,\mathrm{TeV}$ Denner et al. '19

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_\mathrm{s}\alpha^5)$	$\mathcal{O}(\alpha_\mathrm{s}^2\alpha^4)$	Sum
$\sigma_\mathrm{LO}[\,\mathrm{fb}]$	$0.2551^{+9.0\%}_{-7.8\%}$	$0.0068^{+18\%}_{-14\%}$	$1.097^{+37\%}_{-25\%}$	1.359
$\Delta[\%]$	18.8	0.5	80.7	100

Contribution	γ-induced	bottom
$\Delta\sigma_\mathrm{LO}[\,\mathrm{fb}]$	$0.00099^{+11.0\%}_{-9\%}$	$0.195^{+3.6\%}_{-7.2\%}$
$\Delta\sigma_\mathrm{LO}/\sigma_\mathrm{LO}^{\mathcal{O}(\alpha^6)}[\%]$	0.4	76.2

- very large QCD contribution mainly due to gluon PDF
- EW contributions smaller than for $\mathrm{W}^+\mathrm{W}^+$ (Z boson)
- small interference (colour and kinematic suppression)
- photon-induced ($\gamma\gamma$) contribution completely irrelevant
- bottom contribution important, dominated by $\mathrm{tZ}+\mathrm{j}$ production
  $\Rightarrow$ different process, eliminate via b tagging

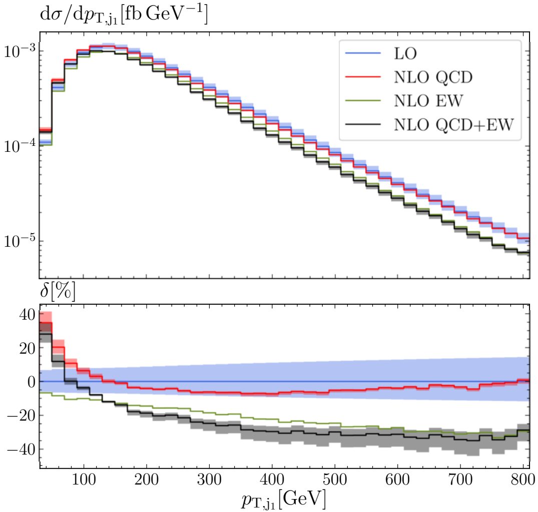
Fiducial NLO cross section for WZjj

Process: $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$, $\sqrt{s} = 13\,\mathrm{TeV}$ — Denner et al. '19

$\mathcal{O}(\alpha^6)$ LO	$\mathcal{O}(\alpha^7)$ NLO EW	$\mathcal{O}(\alpha_\mathrm{s}\alpha^6)$ NLO QCD	$\mathcal{O}(\alpha^7) + \mathcal{O}(\alpha_\mathrm{s}\alpha^6)$ NLO EW+QCD
$0.2551^{+9.0\%}_{-7.8\%}$	$0.2142^{+8.5\%}_{-7.4\%}$	$0.2506^{+1.0\%}_{-1.0\%}$	$0.2097^{+1.3\%}_{-2.2\%}$
100%	-16.0%	-1.8%	-17.8%

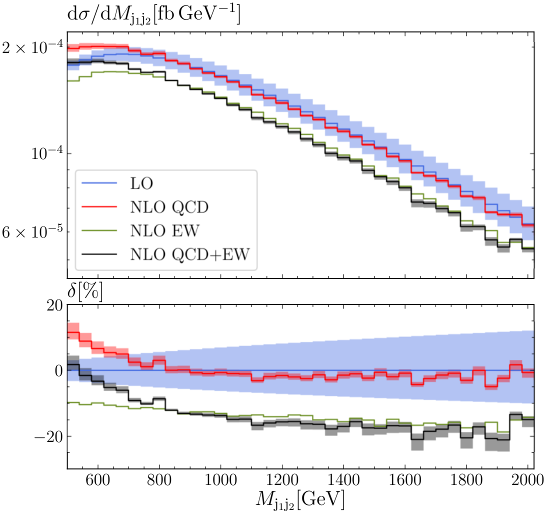
- large EW corrections similar to $\mathrm{W}^+\mathrm{W}^+$ scattering
- rather small QCD corrections
- corrections are larger in distributions
- bottom-quark contributions omitted (b-tagging)
- photon-induced contributions at NLO omitted (small)

Distribution in transverse momentum of the leading jet



- $\mathcal{O}(\alpha^7) \sim -25\%$ at $p_{\mathrm{T,j_1}} = 800\,\mathrm{GeV}$ (Sudakov logarithms) dominant correction
- $\mathcal{O}(\alpha_s\alpha^6) \lesssim 10\%$ for $p_{\mathrm{T,j_1}} > 100\,\mathrm{GeV}$ small QCD scale uncertainty owing to dynamical scale $\mu = \sqrt{p_{\mathrm{T,j_1}} p_{\mathrm{T,j_2}}}$
- large correction for small $p_{\mathrm{T,j_1}}$ due to phase-space suppression at LO (all jets have small p_{T}) redistribution of events at NLO

Distribution in jet–jet invariant mass



- $\mathcal{O}(\alpha^7) \sim -18\%$ at $2\,\mathrm{TeV}$ (Sudakov logarithms) dominant correction
- $\mathcal{O}\left(\alpha_{\mathrm{s}}\alpha^6\right) \lesssim 10\%$ for $M_{\mathrm{j_1j_2}} > 600\,\mathrm{GeV}$
  small QCD scale uncertainty owing to dynamical scale
  $\mu = \sqrt{p_{\mathrm{T,j_1}} p_{\mathrm{T,j_2}}}$
- small $M_{j_1j_2} \Rightarrow$ small $p_{\mathrm{T,j_1}}$
  $\Rightarrow$ large positive QCD corrections
  accidental cancellation of QCD and EW corrections for small $M_{j_1j_2}$

Outline

Integrated cross section $\mathrm{W^+W^+}$

Process: $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ (fixed scale)

Biedermann et al. '16

$\sigma_{\mathrm{LO}}^{\mathcal{O}(\alpha^6)}$ [fb]	$\sigma_{\mathrm{NLO,EW}}^{\mathcal{O}(\alpha^7)}$ [fb]	δ_{EW} [%]
$1.5348(2)$	$1.2895(6)$	-16.0

- surprisingly large EW corrections for fiducial cross section
- large EW corrections arise from bosonic virtual corrections
- EW corrections similarly large for more inclusive setups
  $\Rightarrow$ intrinsic feature of VBS process
- σ^{LO} receives sizeable contributions involving large invariants s_{ij}
  average partonic centre-of-mass energy $\langle\sqrt{\hat{s}}\rangle \sim 2.2\,\mathrm{TeV}$
  average four-lepton invariant mass $\langle M_{4\ell}\rangle \sim 390\,\mathrm{GeV}$

Integrated cross section WZ and ZZ

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

Denner et al. '19

$\sigma_{\mathrm{LO}}^{\mathcal{O}(\alpha^6)}$ [fb]	$\sigma_{\mathrm{NLO,EW}}^{\mathcal{O}(\alpha^7)}$ [fb]	δ_{EW} [%]
0.25511(1)	2.142(2)	−16.0

average four-lepton invariant mass $\langle m_{4\ell}\rangle \sim 413\,\mathrm{GeV}$

Process: $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-\mathrm{jj}$

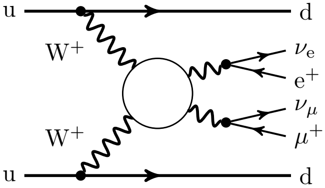
Denner et al. in preparation
preliminary

$\sigma_{\mathrm{LO}}^{\mathcal{O}(\alpha^6)}$ [fb]	$\sigma_{\mathrm{NLO,EW}}^{\mathcal{O}(\alpha^7)}$ [fb]	δ_{EW} [%]
0.097681(2)	0.08214(5)	−15.9

average four-lepton invariant mass $\langle m_{4\ell}\rangle \sim 385\,\mathrm{GeV}$

Double-pole approximation (DPA) for outgoing W bosons
Effective vector-boson approximation (EVBA) for incoming W bosons

- DPA and EVBA reduce discussion to $\mathrm{W^+W^+} \to \mathrm{W^+W^+}$
- DPA accurate for cross section within 1%
- EVBA crude approximation but sufficient to understand dominant effects



leading-logarithmic approximation for $\mathrm{WW} \to \mathrm{WW}$ Denner, Pozzorini '00

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

$$C^{\mathrm{ew}}_{\mathrm{W}} = \frac{2}{s_{\mathrm{w}}^2}, \qquad b^{\mathrm{ew}}_{\mathrm{W}} = \frac{19}{6s_{\mathrm{w}}^2}$$

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

Source of large EW corrections

Simple formula for total cross section

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

- for $Q = \langle m_{4\ell} \rangle \sim 390\,\mathrm{GeV}$ (from LO MC run)

$\delta_{\mathrm{EW}}^{\mathrm{LL}} = -16.1\%$ (!), $\delta_{\mathrm{EW}}^{\mathrm{LL}} = -15\%$ if applied differentially

surprisingly good agreement with complete calculation ($\delta_{\mathrm{EW}} = -16.0\%$)

$\Rightarrow$ corrections 3–4 times larger than for $q\bar{q} \to \mathrm{W}^+\mathrm{W}^-$

- C^{ew} larger for bosons than fermions
- $\langle m_{4\ell} \rangle$ larger for VBS (massive t-channel exchange Denner, Hahn '97)
  $\langle m_{4\ell} \rangle \sim 250\,\mathrm{GeV}$ for $q\bar{q} \to \mathrm{W}^+\mathrm{W}^+$
- less cancellation between double and single logs

large NLO EW corrections intrinsic feature of VBS

Source of large EW corrections

Simple formula for total cross section holds for all VBS processes

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

- $\mathrm{pp}\to\mu^+\mu^-\mathrm{e}^+\nu_{\mathrm{e}}\mathrm{jj}$
  for $Q = \langle m_{4\ell}\rangle \sim 413\,\mathrm{GeV}$ (from LO MC run)

$\delta_{\mathrm{EW}}^{\mathrm{LL}} = -17.5\%$, $\delta_{\mathrm{EW}}^{\mathrm{LL}} = -16.4\%$ if applied differentially

good agreement with complete calculation ($\delta_{\mathrm{EW}} = -16.0\%$)

- $\mathrm{pp}\to\mu^+\mu^-\mathrm{e}^+\mathrm{e}^-\mathrm{jj}$
  for $Q = \langle m_{4\ell}\rangle \sim 385\,\mathrm{GeV}$ (from LO MC run)

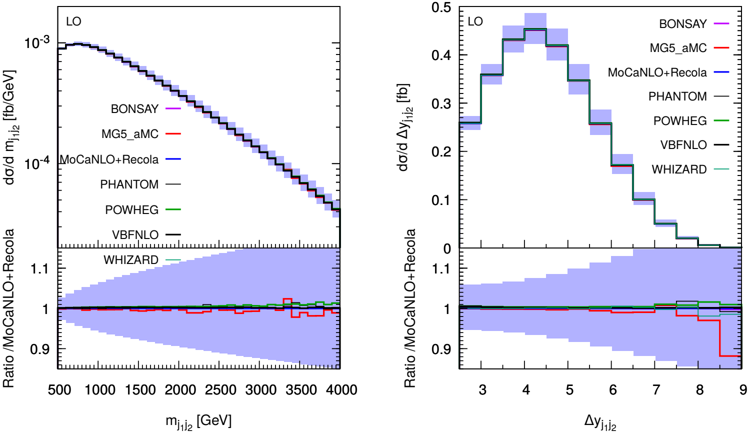
$\delta_{\mathrm{EW}}^{\mathrm{LL}} = -15.8\%$, $\delta_{\mathrm{EW}}^{\mathrm{LL}} = -14.8\%$ if applied differentially

good agreement with complete calculation ($\delta_{\mathrm{EW}} = -15.9\%$)

angular-dependent logarithms different for different processes
$\sim 1-2\%$ owing to cancellations

Comparison of codes with VBS approximation (BONSAY, POWHEG, VBFNLO) and without (MOCANLO+RECOLA, MG5_AMC, PHANTOM, WHIZARD)

$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ Ballestrero et al. '18 (VBSCAN)

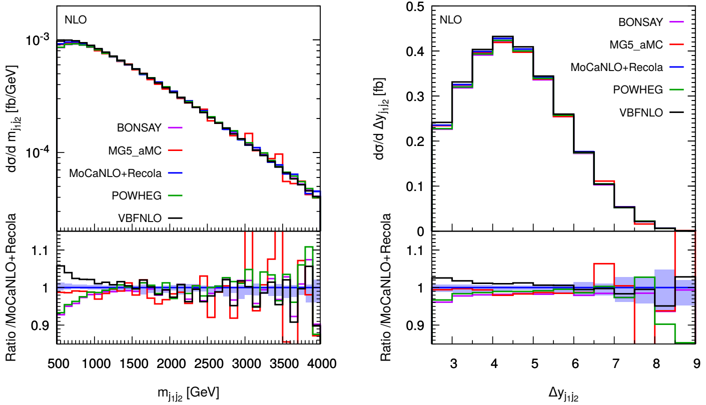


Differences between codes below $\sim 1\%$ in fiducial region

$\Rightarrow$ accuracy of VBS approximation below $\sim 1\%$ at LO

Comparison of codes with VBS approximation (BONSAY, POWHEG VBFNLO) and without VBS approximation (MOCANLO+RECOLA, MG5_AMC)

$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ Ballestrero et al. '18 (VBSCAN)



differences up to 10% lie outside the QCD scale uncertainty band

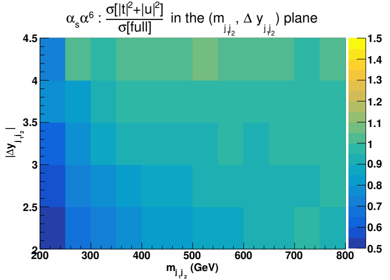
POWHEG, Bonsay: no s channel $\Rightarrow$ reduction at small M_{jj}

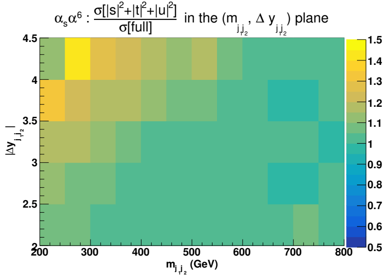
VBFNLO: no interference $\Rightarrow$ enhancement at small M_{jj}

Comparison of codes with VBS approximation (VBFNLO)
and without VBS approximation (MoCaNLO+Recola)

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

Ballestrero et al. '18 (VBSCAN)





- approximations worse at NLO than at LO:
  difference of up to 20% in fiducial region $m_{\mathrm{jj}} > 500\,\mathrm{GeV}$, $\Delta y_{\mathrm{jj}} > 2.5$
  (gluon bremsstrahlung fakes tagging jet in s channel)
- difference for fiducial cross section: $(m_{\mathrm{jj}} > 500\,\mathrm{GeV},\ \Delta y_{\mathrm{jj}} > 2.5)$
  $|t| + |u|$ approximation: $\lesssim 2\%$ $|s| + |t| + |u|$ approximation: $\lesssim 1\%$
- difference for inclusive cross section: $(m_{\mathrm{jj}} > 200\,\mathrm{GeV},\ \Delta y_{\mathrm{jj}} > 2)$
  $|t| + |u|$ approximation: -6% $|s| + |t| + |u|$ approximation: $+2.6\%$

Conclusion

Significant interest in VBS in theory and experimental community

- NLO QCD corrections matched to PS available for all VBS processes
  NLO QCD corrections at level of few percent if $p_{\mathrm{T,j}}$ not small
- VBS approximation might not be sufficient at NLO   Ballestrero et al. '18
- Electroweak corrections for VBS
  - full NLO EW corrections known for
    $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ $(\mathrm{W^+W^+})$ Biedermann et al. '16, '17
    $\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ (WZ) Denner et al. '19
  - DPA for $\mathrm{W^+W^+}$provides good approximation within 1%
  - -16% EW corrections for fiducial cross section
    $\Rightarrow$ intrinsic feature of VBS process, reproducible by simple approximations
  - EW corrections in distributions even larger
    -40% for $p_{\mathrm{T,j_1}} = 800\,\mathrm{GeV}$
- NLO EW corr. for $\mathrm{W^+W^+}$scattering matched to QED PS   Denner et al. '19
- Full NLO corrections for $\mathrm{W^+W^+}$scattering   Denner et al. '17
  $\Rightarrow$ only measurement of full process is well-defined

Significant theoretical progress in VBS, more to come!

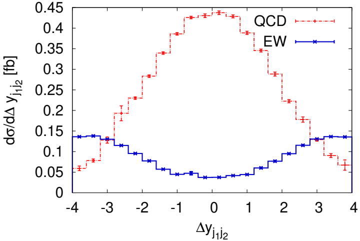
Outline

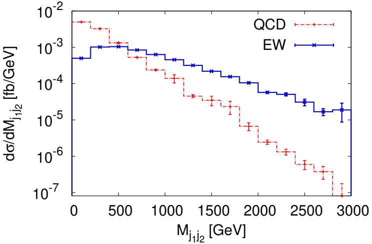
7 Backup

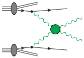
W^+W^+jj: QCD versus EW production

Jäger, Zanderighi '11

$\sqrt{s} = 7\,\mathrm{TeV}$, NLO QCD, basic cuts: $p_{\mathrm{T},j} > 20\,\mathrm{GeV}$

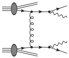






EW production:

- large rapidity separation Δy_{jj}
- dominant for large M_{jj}
- $\sigma_{\mathrm{EW}}^{\mathrm{inclusive}} = 1.10\,\mathrm{fb}$
- $\sigma_{\mathrm{EW}}^{\mathrm{VBFcuts}} = 0.201\,\mathrm{fb}$



QCD production:

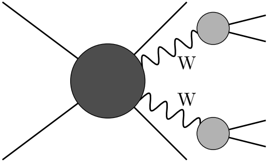
- small rapidity separation Δy_{jj}
- prefers small M_{jj}
- $\sigma_{\mathrm{QCD}}^{\mathrm{inclusive}} = 2.12\,\mathrm{fb}$ 192%
- $\sigma_{\mathrm{QCD}}^{\mathrm{VBFcuts}} = 0.0074\,\mathrm{fb}$ 3.7%

VBF cuts: $M_{\mathrm{jj}} > 600\,\mathrm{GeV}, \quad |\Delta y_{\mathrm{jj}}| > 4, \quad y_{\mathrm{j}_1} \times y_{\mathrm{j}_2} < 0$

Leading order:

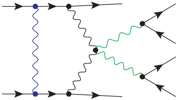
$$\mathcal{M}_{\mathrm{LO,DPA}}^{qq\to \mathrm{WW}qq\to 4fqq} = \sum_{\lambda_{\mathrm{W}_1},\lambda_{\mathrm{W}_2}} \frac{\left[\mathcal{M}_{\mathrm{LO}}^{qq\to \mathrm{WW}qq}(\lambda_{\mathrm{W}_1},\lambda_{\mathrm{W}_2})\mathcal{M}_{\mathrm{LO}}^{\mathrm{W}\to 2f}(\lambda_{\mathrm{W}_1})\mathcal{M}_{\mathrm{LO}}^{\mathrm{W}\to 2f}(\lambda_{\mathrm{W}_2})\right]_{\text{on-shell}}}{(p_{\mathrm{W}_1}^2 - M_{\mathrm{W}}^2 + \mathrm{i}M_{\mathrm{W}}\Gamma_{\mathrm{W}})(p_{\mathrm{W}_2}^2 - M_{\mathrm{W}}^2 + \mathrm{i}M_{\mathrm{W}}\Gamma_{\mathrm{W}})}$$

- only contributions with two resonant W bosons ⇒ dominant contribution
- momenta in numerator projected on shell ⇒ gauge invariance

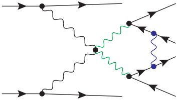


NLO:

- factorizable corrections:
  corrections to production
  or decay matrix elements



- non-factorizable corrections:
  IR-singular corrections connecting
  production and decay
  $\Rightarrow$ universal correction factors
  Denner et al. '00; Accomando et al. '04;
  Dittmaier, Schwan '15

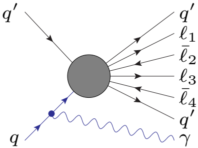


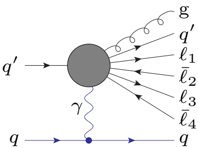
Implementation

- DPA applied only to squared matrix element for (subtracted) virtual corrections
- leading order and real corrections treated exactly
- phase-space integration treated exactly
- naive error estimate: $\mathcal{O}(\Gamma_\mathrm{W}/M_\mathrm{W}) \times \delta_\mathrm{EW} \sim \mathcal{O}(0.2\%)$
- DPA worse, where non-doubly-resonant contributions sizeable

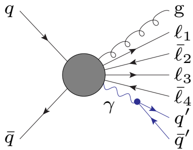
Soft and collinear singularities

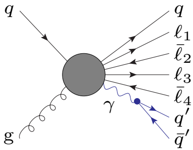
- initial-state collinear singularities ⇒ parton distribution functions



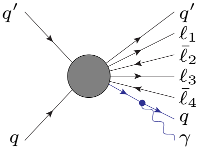


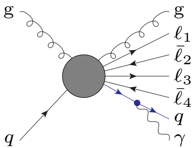
- final-state $\gamma \to q\bar{q}$ splitting ⇒ photon-to-quark conversion function





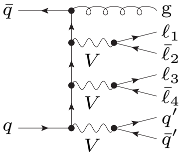
- final-state collinear singularities, photon–jet separation
  ⇒ photon-to-quark fragmentation function





Real NLO s-channel diagram

Typical s-channel NLO contribution:



Less suppression at NLO owing to extra jet from real radiation

Validation

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

- tree-level matrix elements and LO hadronic cross section successfully compared with MG5@NLO Alwall et al. '14
- IR-singularities, Monte Carlo integration
  - variation of α_{dipole} parameter in subtraction terms Nagy, Trócsányi '98
  - variation of IR scale and technical cuts
  - two independent implementations of Monte Carlo integration
- one-loop cross section / matrix elements checked against
  - double-pole approximation for $\mathcal{O}(\alpha^7)$, agreement within 1%
  - Denner, Hosekova, Kallweit '12 for $\mathcal{O}(\alpha_\mathrm{s}\alpha^6)$
  - MadLoop Hirschi et al '11 matrix elements for $\mathcal{O}(\alpha^7)$ and $\mathcal{O}(\alpha_\mathrm{s}^3\alpha^4)$

$\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$: in addition

- additional independent Monte Carlo integration
- two independent calculations of loop diagrams based on Recola and OpenLoops Cascioli et al. '11
- point-wise comparison of virtual and real QCD corrections

Setup for $\mathrm{W}^+\mathrm{W}^+$ scattering

Energy: $13\,\mathrm{TeV}$

PDFs

NNPDF3.0QED Ball et al. '13, '14

factorization and renormalization scales: $\mu_\mathrm{F} = \mu_\mathrm{R} = \sqrt{p_{\mathrm{T,j_1}} p_{\mathrm{T,j_2}}}$

Recombination / jet clustering

Anti-k_T algorithm with $R = 0.4$ Cacciari, Salam, Soyez '08

recombination of photons with charged partons with $R = 0.1$

Cuts: based on ATLAS 1405.6241, 1611.02428 and CMS 1410.6315

$p_{\mathrm{T,j}} > 30\,\mathrm{GeV}$, $|y_\mathrm{j}| < 4.5$, $\Delta R_{\mathrm{j}\ell} > 0.3$

$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}$, $|y_\ell| < 2.5$, $\Delta R_{\ell\ell} > 0.3$, $\Delta R_{ij} = \sqrt{(\Delta y_{ij})^2 + (\Delta\phi_{ij})^2}$

$E_{\mathrm{T,miss}} > 40\,\mathrm{GeV}$

$M_{\mathrm{jj}} > 500\,\mathrm{GeV}$, $|\Delta y_{\mathrm{jj}}| > 2.5$ (VBF cuts)

require ≥ 2 jets, 2 same-sign leptons and missing energy

Setup for WZ scattering

Energy: $13\,\mathrm{TeV}$ $(14\,\mathrm{TeV})$

PDFs

NNPDF3.1QED   Ball et al. ’14, Bertone et al. ’17

factorization and renormalization scales: $\mu_\mathrm{F} = \mu_\mathrm{R} = \sqrt{p_{\mathrm{T,j_1}} p_{\mathrm{T,j_2}}}$

Recombination / jet clustering

Anti-k_T algorithm with $R = 0.4$ Cacciari, Salam, Soyez ’08

recombination of photons with charged partons with $R = 0.4$

Cuts: loose fiducial region of CMS 1901.04060

$p_{\mathrm{T,j}} > 30\,\mathrm{GeV}$, $|y_\mathrm{j}| < 4.7$, $\Delta R_{\mathrm{j}\ell} > 0.4$ $\Delta R_{ij} = \sqrt{(\Delta y_{ij})^2 + (\Delta\phi_{ij})^2}$

$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}$, $|y_\ell| < 2.5$, $M_{3\ell} > 100\,\mathrm{GeV}$, $M_{\ell\ell} > 4\,\mathrm{GeV}$

$|M_{\mu^+\mu^-} - M_\mathrm{Z}| < 15\,\mathrm{GeV}$

$M_\mathrm{jj} > 500\,\mathrm{GeV}$, $|\Delta y_\mathrm{jj}| > 2.5$ (VBF cuts)

require ≥ 2 jets, 3 leptons