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Electroweak multi-boson production and scattering

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Outline

Aim and Scope of talk

Focus of talk on recent results in

- Vector-boson scattering (VBS)
- triple vector boson (VVV) production
- polarised vector-boson production $\Rightarrow$ see also talk by Giovanni Pelliccioli

Experiments use general purpose codes, like SHERPA, MADGRAPH5_AMC@NLO or dedicated codes like VBF@NLO.
For complicated processes, these typically include

- NLO QCD corrections including parton-shower matching etc.
- no NLO EW corrections

Multi-boson and VBS processes

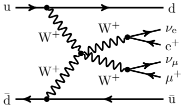
- receive large EW corrections
- require dedicated calculations

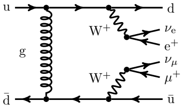
Expansion in multiple couplings

Example: $\mathrm{pp} \to 4\ell\mathrm{jj}$ (vector-boson scattering: $\mathrm{pp} \to \mathrm{VVjj}$)

LO: pure EW diagrams $\mathcal{O}(e^6)$ and

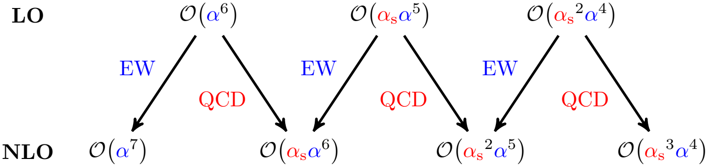
diagrams with gluons $\mathcal{O}(e^4 g_\mathrm{s}^2)$





NLO: EW and QCD corrections to both types of diagrams

at level of cross section:



consequences:

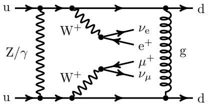
- QCD and EW corrections cannot be separated in general
- QCD corr. to EW LO overlap with EW corrections to LO interference
- consider complete (well-defined) orders $\mathcal{O}(\alpha_\mathrm{s}^n \alpha^m)$

Mixing of virtual EW and QCD corrections

Virtual diagrams mix QCD and EW corrections:

- EW correction to LO QCD amplitude
- QCD correction to LO EW amplitude
- QED and QCD IR singularities

example from VBS



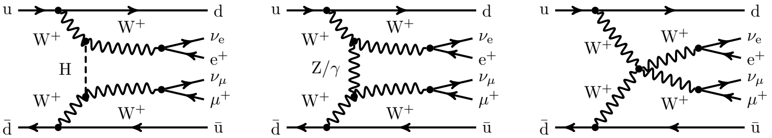
⇒ separation into QCD and EW is not well-defined at NLO

both real gluon and real photon bremsstrahlung needed!

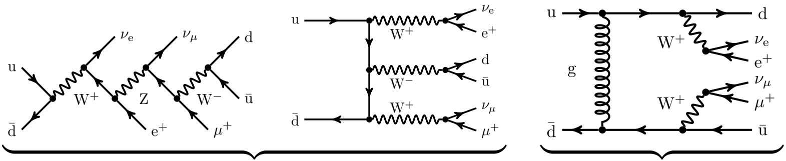
Contributions to $pp \to \mu^+\nu_\mu e^+\nu_e jj$ at LO

Example process: $pp \to W^+W^+ + 2j \to \mu^+\nu_\mu e^+\nu_e + 2j$

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



irreducible background to VBS:



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

QCD background $\mathcal{O}(g_s^2 g^4)$
t channel (also s channel)

t channel: incoming quarks/antiquarks connected to outgoing quarks/antiquarks

u channel: exchange identical quarks/antiquarks in final state

s channel: incoming quark and anti-quark connected, all boson propagators time like

VBS approximation

Figy, Oleari, Zeppenfeld '03, Jäger, Oleari, Zeppenfeld '09

- Neglect interferences between t- and u-channel contributions and all s-channel contributions
  $\Rightarrow$ keep only squares of t- and u-channel contributions
- calculation simplifies considerably (~ 1000 loop diagrams per channel at $\mathcal{O}(\alpha_s\alpha^6)$ instead of ~ 40000 at $\mathcal{O}(\alpha^7)$)
- only applicable to order α^6 and corresponding corrections for VBS cuts (tailored to VBS processes, not applicable to $\alpha_s^2\alpha^4$ irreducible background)
- EW and QCD corrections to VBS uniquely defined (interferences neglected by definition!)
- VBS approximation works within $\lesssim 1\%$ at LO for $M_{jj} > 500\,\mathrm{GeV}$
  Denner, Hošeková, Kallweit 1209.2389, Ballestrero et al. 1803.07943
- VBS approximation fails for NLO QCD corrections for small M_{jj}
  - $\sim 6\%$ for $\mathrm{pp} \to \mu^+\nu_\mu e^+\nu_e jj$ and $M_{jj} \sim 500\,\mathrm{GeV}$ 1803.07943
  - s channel contributes $\sim 20\%$ for $\mathrm{pp} \to \mu^+\mu^- e^+e^- jj$ and $M_{jj} \gtrsim 100\,\mathrm{GeV}$ 2009.00411

$\Rightarrow$ contribution to theoretical error

Calculations for massive VBS within the SM (for references see backup)

- all processes known at NLO QCD accuracy matched to QCD PS
  - for both QCD-/EW-induced process
  - all available in VBFNLO
  - all available in POWHEG-BOX ⇒ parton-shower (PS) matching
  - often in VBS approximation (no int., s channel sometimes included)
  - possible to generate in MG5_AMC@NLO or SHERPA
- NLO EW corrections known for $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$, WZ, ZZ, and $\mathrm{W}^{+}\mathrm{W}^{-}$ with leptonic decays
  NLO EW matched to QED PS and interfaced to QCD PS for $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$ in POWHEG-BOX-RES
- full NLO computation only for $\mathrm{W}^{+}\mathrm{W}^{+}$ and ZZ with leptonic decays
- NLO results for polarised $\mathrm{W}^{+}\mathrm{W}^{+}$ with leptonic decays
- no NLO results for hadronically decaying vector bosons
- no NNLO results known

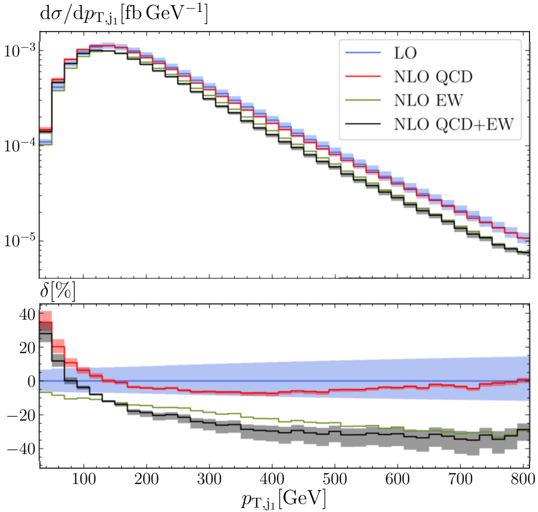
Large NLO EW corrections to VBS processes

process	$\sigma_{\mathrm{LO}}^{\mathcal{O}(\alpha^6)}$ [fb]	$\Delta\sigma_{\mathrm{NLO,EW}}^{\mathcal{O}(\alpha^7)}$ [fb]	δ_{EW} [%]
Biedermann et al. 1708.00268	(Dittmaier et al. 2308.16716)		
$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ $(\mathrm{W}^+\mathrm{W}^+)$	$1.4178(2)$	$-0.2169(3)$	-15.3
Denner et al. 1904.0088			
$\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ (ZW^+)	$0.25511(1)$	$-0.04091(2)$	-16.0
Denner et al. 2009.00411			
$\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\mathrm{e}^-\mathrm{jj}$ (ZZ)	$0.097681(2)$	$-0.015573(5)$	-15.9
Denner et al. 2202.10844			
$\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\mathrm{e}^-\mathrm{jj}$ $(\mathrm{W}^+\mathrm{W}^-)$	$2.6988(3)$	$-0.307(1)$	-11.4

- EW corrections similar for all processes and rather independent of cuts
  $\Rightarrow$ intrinsic feature of VBS process
- smaller corrections to $\mathrm{W}^+\mathrm{W}^-$ due to Higgs resonance in fiducial phase space (Higgs contribution about 25%, corresponding EW corrections -6.5%)
- NLO EW corrections to fiducial cross section well described by simple logarithmic approximation (Sudakov approximation $s, |t|, |u| \gg M_\mathrm{W}^2$)
- NLO EW corrections to distributions not well described by simple Sudakov approximation

Distribution in transverse momentum of the leading jet

Denner et al. 1904.00882



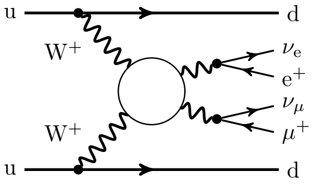
- $\mathcal{O}(\alpha^7) \sim -30\%$ at $p_{\mathrm{T,j_1}} = 800\,\mathrm{GeV}$
  (Sudakov logarithms)
  dominant correction
  larger than QCD scale uncertainty
- $\mathcal{O}(\alpha_\mathrm{s}\alpha^6) \lesssim 10\%$
  for $p_{\mathrm{T,j_1}} > 100\,\mathrm{GeV}$
  small QCD scale uncertainty owing to suitable 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

Source of large EW corrections

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

- DPA and EVBA reduce discussion to $V_1 V_2 \to V_3 V_4$
- DPA accurate for cross section within 1%
- EVBA crude approximation ($\sim 50\%$)
  Kuss, Spiesberger '96, Dittmaier et al. '23

sufficient to understand dominant effects



high-energy, logarithmic approximation for $V_1 V_2 \to V_3 V_4$ Denner, Pozzorini '00

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

$$C_{\mathrm{W}}^{\mathrm{EW}} = \frac{2}{s_{\mathrm{w}}^2}, \quad b_{\mathrm{W}}^{\mathrm{EW}} = \frac{19}{6 s_{\mathrm{w}}^2} \qquad \text{for transverse W bosons}, \qquad Q \to M_{4\ell}$$

(double EW logs, collinear single EW logs, and single logs from parameter renormalisation included) (angular-dependent logarithms omitted, $\log \frac{t}{u} \log \frac{Q}{M_{\mathrm{W}}}$)

large NLO EW corrections intrinsic feature of VBS

Simple formula for total cross section

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

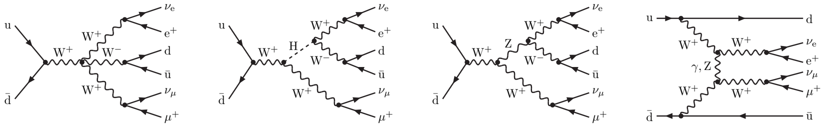
process	δ_{EW} [%]	$\delta_{\mathrm{EW}}^{\mathrm{log,int}}$ [%]	$\delta_{\mathrm{EW}}^{\mathrm{log,diff}}$ [%]	$\langle M_{4\ell}\rangle$ [GeV]
$\mathrm{pp} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$	-16.0	-16.1	-15.0	390
$\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$	-16.0	-17.5	-16.4	413
$\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-\mathrm{jj}$	-15.9	-15.8	-14.8	385

- surprisingly good agreement with complete calculation $(E = 13\,\mathrm{TeV})$
- large EW corrections are due to large gauge couplings of vector bosons (C^{EW}) and large scale $Q \sim \langle M_{4\ell}\rangle \sim 400\,\mathrm{GeV}$
- angular-dependent logarithms different for different processes ~ 1–2% owing to cancellations

large NLO EW corrections intrinsic feature of VBS

General features of VVV production

- Sensitive to quartic (and triple) gauge couplings
- involves Higgs production decaying to 4 fermions
  $\Rightarrow$ sensitive to EWSB
- purely leptonic final states:
  - only one coupling order at LO (no α_s)
  - QCD corrections simple (only initial state)
  - very small cross section $\sigma \sim 0.1\,\mathrm{fb}$
- semileptonic final states: share final states with VBS processes
  - same calculational complexity and same matrix elements
  - different phase-space regions / cuts
  - VBS becomes irreducible background
  - small cross section $\sigma \sim 1\,\mathrm{fb}$



Existing calculations for VVV production

Calculations for off-shell massive VVV production in the SM:

- NLO QCD corrections to VVV matched to QCD PS:
  - available in VBFNLO Baglio et al. 1404.3940 for leptonic and semileptonic decays (one hadronically decaying vector boson)
  - available within SHERPA Höche et al. 1403.7516
- NLO EW corrections for leptonic final states:
  Madgraph 1804.10017 (on-shell VVV)
  Schönherr 1806.00307, Dittmaier, Knippen, Schwan 1912.04117 (WWW)
- NLO EW corrections for semi-leptonic final states:
  Denner et al. 2406.11516 $[\mathrm{W^+W^+W^-} \to \mathrm{e}^+\nu_\mathrm{e}\mu^+\nu_\mu\mathrm{jj})]$
  Denner et al. 2407.21558 $[\mathrm{W^+Z}V \to \mathrm{e}^+\nu_\mathrm{e}\mu^+\mu^-\mathrm{jj})]$
- no NLO results for polarised bosons
- no NNLO results

Calculations for off-shell $VV\gamma$ production in the SM:

- NLO QCD and EW corrections for leptonic final states:
  Cheng, Wackeroth 2112.12052 $[\mathrm{W^+Z}\gamma \to \mathrm{e}^+\nu_\mathrm{e}\mu^+\mu^-\gamma]$

Denner, Pellen, Schönherr, Schumann 2406.11516

semi-leptonic final state: $\mathrm{e}^+\nu_\mathrm{e}\mu^+\nu_\mu\mathrm{jj}$
in triboson phase space

- full fixed-order off-shell NLO QCD+EW calculation
  using MoCaNLO and Recola
- comparison between off-shell result and sum of of relevant on-shell channels
  from Sherpa wit LO decays
- calculation matched to QCD parton shower
  using Sherpa and Recola including
  - NLO QCD corrections to $\mathcal{O}(\alpha^6)$ and $\mathcal{O}(\alpha_\mathrm{s}^2\alpha^4)$ matched to parton shower
    interference contribution of $\mathcal{O}(\alpha_\mathrm{s}\alpha^5)$ neglected
    interference between s and t/u channels at $\mathcal{O}(\alpha^6)$ neglected (small)
  - approximate NLO virtual EW corrections in $\mathrm{EW_{virt}}$ approximation to LO EW
    no EW corrections to LO QCD (small)
    no corrections from photon-induced processes
  - QED corrections for final-state fermions via YFS formalism

  (standard QCD MC@NLO matching)

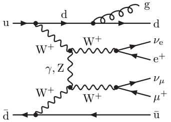
State-of-the-art calculation in $\mathrm{W^+W^+jj}$ channel

$\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^+\nu_\mu\mathrm{jj}$ Denner, Pellen, Schönherr, Schumann 2406.11516

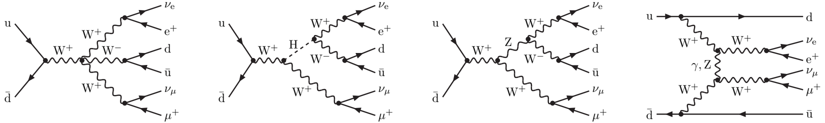
Contributing subprocesses at $\mathcal{O}(\alpha^6)$

subprocess	LO fraction	NLO fraction
$\mathrm{W^+W^+W^-}$	53%	48%
$\mathrm{W^+H}$	41%	40%
$\mathrm{W^+Z}$	$< 10^{-4}\%$	$< 10^{-5}\%$
$\mathrm{W^+W^+}$ VBS	3%	8%
off-shell contr.	3%	4%

- large NLO contribution of VBS
  owing to events where radiated gluon plays role of leading jet evading $M_\mathrm{jj} < 160\,\mathrm{GeV}$ cut
- no QCD corrections to decays included in on-shell calculations



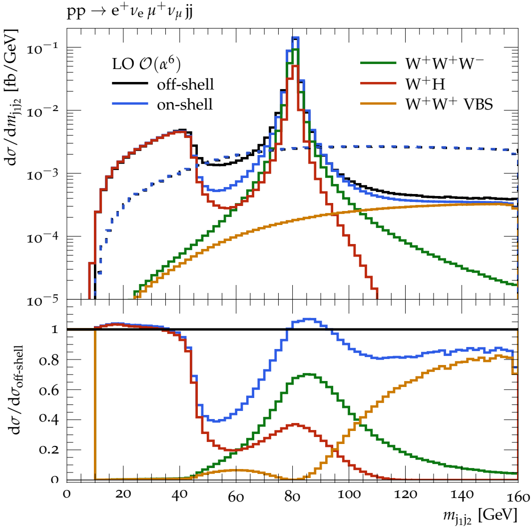
sample LO diagrams



Contribution of subprocesses at LO

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

Denner, Pellen, Schönherr, Schumann 2406.11516

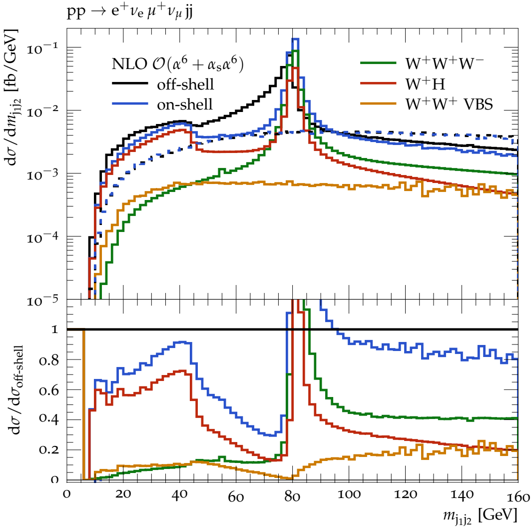


Distribution in
invariant mass of jet pair
on-shell approximation at LO

- misses up to 60%
  (for $m_{\mathrm{j}_1\mathrm{j}_2} \approx 50\,\mathrm{GeV}$)
  (in addition to $\mathrm{W} \to \mathrm{j}_1\mathrm{j}_2$ one further W or Higgs boson off shell!)
- overestimates result close to M_W and below $40\,\mathrm{GeV}$
- VBS becomes dominant for large $m_{\mathrm{j}_1\mathrm{j}_2}$

Contribution of subprocesses at NLO QCD

$\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^+\nu_\mu\mathrm{jj}$ Denner, Pellen, Schönherr, Schumann 2406.11516



Distribution in invariant mass of jet pair

on-shell approximation at NLO QCD

- enhanced close to and above M_W
- strongly suppressed for $M_\mathrm{H} - M_\mathrm{W} \lesssim m_{\mathrm{j}_1\mathrm{j}_2} \lesssim M_\mathrm{W}$
  - in addition to $\mathrm{W} \to \mathrm{j}_1\mathrm{j}_2$ one further W or Higgs boson off shell!
  - filled by final-state radiation in off-shell calculation
- VBS enhanced below M_W

Differences increase at NLO!

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

Denner et al. 1708.00268, 2406.11516, Dittmaier et al. 2308.16716

Result of full LO calculation

order	PS	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_\mathrm{s}\alpha^5)$	$\mathcal{O}(\alpha_\mathrm{s}^2\alpha^4)$	sum
σ_LO[fb]	VVV	0.78549(9)	0.00732(1)	0.25925(3)	1.05206(9)
$\sigma/\sigma_\mathrm{LO}^\mathrm{sum}$[%]	VVV	74.7	0.7	24.6	100
σ_LO[fb]	VBS	1.4178(2)(9)	0.04815(2)	0.17229(5)	1.6382(2)
$\sigma/\sigma_\mathrm{LO}^\mathrm{sum}$[%]	VBS	86.5	2.9	10.5	100

irreducible QCD background larger for VVV production

Result of full NLO calculation

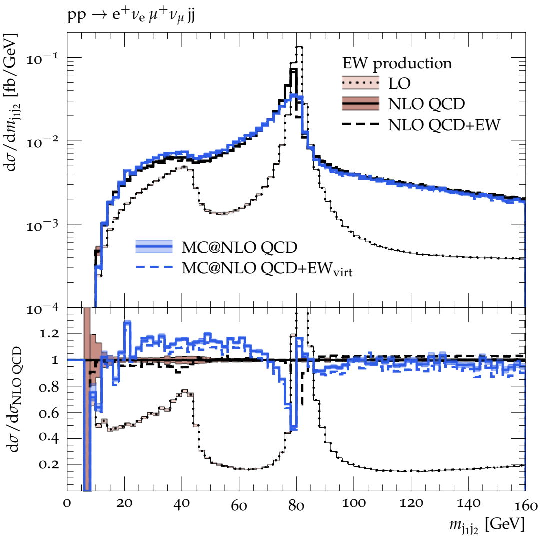
order	PS	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_\mathrm{s}\alpha^6)$	$\mathcal{O}(\alpha_\mathrm{s}^2\alpha^5)$	$\mathcal{O}(\alpha_\mathrm{s}^3\alpha^4)$	sum
$\delta\sigma$[fb]	VVV	$-0.035(1)$	0.305(1)	$-0.0032(3)$	0.2260(3)	0.493(2)
$\delta\sigma/\sigma_\mathrm{LO}^\mathrm{sum}$[%]	VVV	-3.4	29.0	-0.30	21.5	46.9
$\delta\sigma$[fb]	VBS	$-0.2169(3)$	$-0.0568(5)$	0.0047(2)	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma/\sigma_\mathrm{LO}^\mathrm{sum}$[%]	VBS	-13.2	-3.5	0.3	-0.4	-17.1

- NLO EW corrections much smaller for VVV production than for VBS
- NLO QCD corrections of $\mathcal{O}(\alpha_\mathrm{s}\alpha^6)$ and $\mathcal{O}(\alpha_\mathrm{s}^3\alpha^4)$ larger for VVV production

Predictions with parton-shower matching

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

Denner, Pellen, Schönherr, Schumann 2406.11516



Effects of PS matching on EW production mode:

fiducial cross section

- reduced by 7%
- EW corrections change from -3.2% to -4.3% ($+1.9\%$ of photon-induced contribution not included in $\mathrm{EW}_\mathrm{virt}$)

distribution in invariant mass of jet pair

- reduction by 5% above M_W
- increase by up to 15% below M_W

multiple emissions migrate events from higher to lower invariant masses

Semi-leptonic final state: $\mathrm{e}^+\nu_\mathrm{e}\mu^+\mu^-\mathrm{jj}$ Denner at al. 2407.21558

fixed-order off-shell NLO QCD+EW calculation

Result of full LO calculation

order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_\mathrm{s}\alpha^5)$	$\mathcal{O}(\alpha_\mathrm{s}^2\alpha^4)$	sum
σ_{LO}[ab]	50.230(2)	8.144(2)	847.7(5)	906.0(5)
$\sigma/\sigma_{\mathrm{LO}}^{\mathrm{sum}}$[%]	5.54	0.90	93.56	100.00

very large irreducible QCD background

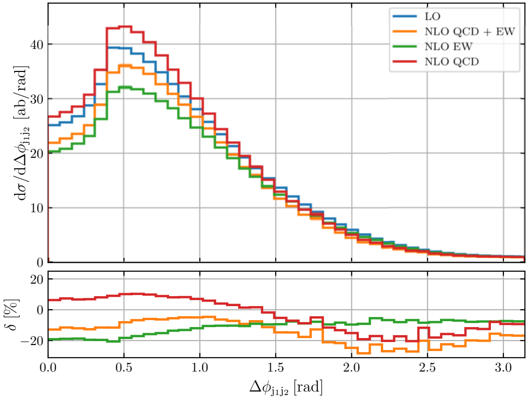
Result of NLO calculation

order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_\mathrm{s}\alpha^6)$
$\delta\sigma$[ab]	$-7.20(5)$	2.17(6)
$\delta\sigma/\sigma_{\mathrm{LO}}^{\alpha^6}$[%]	-14.3	4.3

- NLO EW correction for VVV production almost as large as for VBS (-16.0%) results from high average partonic COM energy, partially owing to cuts
- photon-induced processes contribute less than 2%
- small NLO QCD correction results from cancellations between $q\bar{q}$, $qq/\bar{q}\bar{q}$, and qg channels $(-14\%, +8\%, +11\%)$

Azimuthal-angle difference of jets for $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^+\mu^-\mathrm{jj}$

Denner, Lombardi, Lopez, Pelliccioli 2407.21558



- cancellations between EW and QCD corrections
- corrections vary by 15% and 30%
- small $\Delta\phi_{\mathrm{j_1j_2}}$ correlated to large energy of jet pair

Motivation

- polarised vector bosons are important probes of EW symmetry breaking

Method: definition of polarisation at amplitude level

⇒ talk by Giovanni Pelliccioli

- applicable to arbitrary processes and multiple resonances
  at LO, NLO QCD and EW and beyond
- extract contributions of resonant vector bosons via pole expansion
- separate polarisation modes via projectors in numerators of propagators
- definition of polarisation depends on reference frame
  preferred choice: centre-of-mass system of vector bosons
- use of spin-correlated narrow-width approximation (NWA) also possible

Method allows to separate

- polarised cross sections in arbitrary frames
- interference contributions between polarisations
- irreducible background.

All contributions that are not small need to be taken into account!

Existing calculations with polarised bosons

Massive diboson production with leptonic decays (for references see backup)

- NLO QCD corrections for all processes $\mathrm{W^+W^-}$, WZ, ZZ
- PS matching available via POWHEG-BOX-RES
- NLO EW corrections for all processes $\mathrm{W^+W^-}$, WZ, ZZ
- NNLO QCD results for $\mathrm{W^+W^-}$

Massive diboson production with semi-leptonic decays within the SM

- NLO QCD results for $\mathrm{ZW} \to \ell^+\ell^-\mathrm{jj}$

Massive VBS within the SM

- LO results exist within PHANTOM
- NLO QCD+EW results for $\mathrm{W^+W^+}$ scattering

Implementation in Monte Carlo generators

- MADGRAPH5_AMC@NLO: spin-correlated NWA at LO
- SHERPA: approximate NLO QCD in NWA

Example results for polarisation fractions in W^+W^+ scattering

$\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^+\nu_\mu + \mathrm{jj}$: Denner, Haitz, Pellicciolo 2409.03620

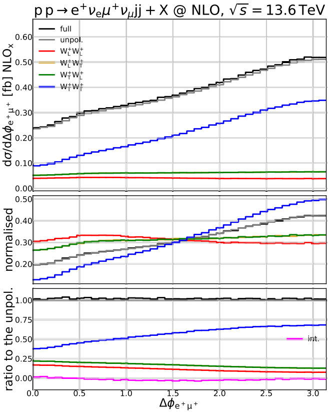
state	σ_{LO} [fb]	δ_{EW}	δ_{QCD}	δ_{NLO}	σ_{NLO} [fb]	f_{NLO} [%]
	$\mathcal{O}(\alpha^6)$	$\mathcal{O}\left(\frac{\alpha^7}{\alpha^6}\right)$	$\mathcal{O}\left(\frac{\alpha_\mathrm{s}\alpha^6}{\alpha^6}\right)$			
full	$1.4863(1)^{+9.2\%}_{-7.8\%}$	-0.140	-0.047	-0.188	$1.208(1)^{+1.6\%}_{-3.1\%}$	102.0
unp.	$1.46455(9)^{+9.2\%}_{-7.8\%}$	-0.142	-0.050	-0.192	$1.1836(5)^{+1.7\%}_{-3.3\%}$	100.0
LL	$0.14879(1)^{+8.3\%}_{-7.2\%}$	-0.101	-0.044	-0.145	$0.12715(8)^{+1.0\%}_{-2.1\%}$	10.7
LT	$0.23209(2)^{+9.1\%}_{-7.8\%}$	-0.131	-0.042	-0.173	$0.1919(1)^{+1.4\%}_{-2.8\%}$	16.2
TL	$0.23208(2)^{+9.1\%}_{-7.8\%}$	-0.131	-0.042	-0.173	$0.1918(1)^{+1.4\%}_{-2.8\%}$	16.2
TT	$0.87702(7)^{+9.4\%}_{-8.0\%}$	-0.154	-0.054	-0.208	$0.6944(4)^{+1.9\%}_{-3.7\%}$	58.7
int.	$-0.0254(1)^{-8.9\%}_{+10.6\%}$	-0.139	-0.007	-0.147	$-0.0217(7)^{-1.6\%}_{+0.7\%}$	-1.8

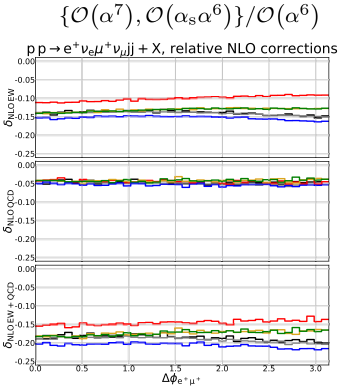
- irreducible background (2.0%) consistent with DPA accuracy
- small interferences (-1.8%)
- NLO EW corrections range from -15.4% for TT to -10.1% for LL
  different prefactors of Sudakov double and single logarithms!

Distributions for $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^+\nu_\mu + \mathrm{jj}$ $(\mathrm{W^+W^+jj})$

Azimuthal-angle difference of the charged leptons

Denner et al. 2409.03620



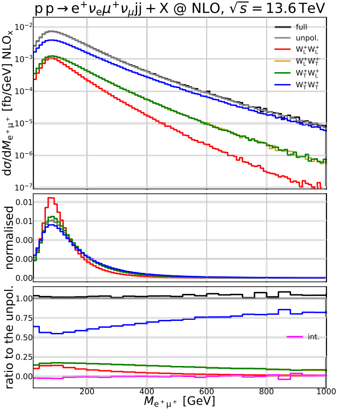


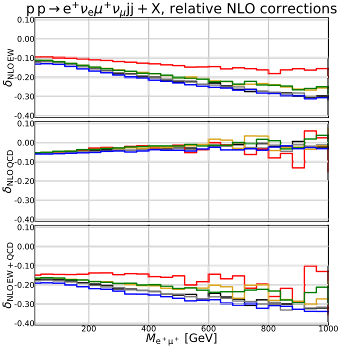
- Observable well suited to distinguish between polarised signals
- LL polarisation fraction increases to 20% for small $\Delta\phi_{\mathrm{e}^+\mu^+}$
- NLO corrections depend only weakly on $\Delta\phi_{\mathrm{e}^+\mu^+}$

Distributions for $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^+\nu_\mu + \mathrm{jj}$ $(\mathrm{W}^+\mathrm{W}^+\mathrm{jj})$

Invariant mass of the charged lepton pair

Denner et al. 2409.03620





- Distribution drops faster for longitudinal W bosons
- normalised shapes depend on polarisation
- LL polarisation fraction decreases to 1% for large $M_{\mathrm{e}^+\mu^+}$
- NLO corrections differ for different polarised modes

Outline

Theory status for multi-boson processes (including decays)

- NLO QCD matched to QCD PS available in Monte Carlo event generators
  include partially EW corrections
- NLO EW corrections calculable with dedicated tools
  - many results exist for leptonic final states
  - first results for semi-leptonic final states
- NLO EW corrections typically 5–16% for fiducial cross sections
- larger EW corrections
  - in radiative tails ($> 100\%$)
  - in high-energy tails of distributions [$\mathcal{O}(40\%)$]
- EW corrections in logarithmic approximation (plus improvements)
  implemented in automated tools $\Rightarrow$ approximative treatment of corrections
  should be checked with complete calculations if possible
- methods for EW corrections with polarised vector bosons established
  - many results for VV production available
  - first results for VBS obtained (like-sign WW scattering)

More results to come!

Thank You!

Outline

NLO EW matrix element providers

tool	collaboration	
GoSam	Chiesa et al.	1407.0823
MadGraph5_aMC@NLO	Frixione et al.	1804.10017
NLOX	Honeywell et al.	1812.11925, 2101.01305
OpenLoops	Pozzorini et al.	1907.13071
Recola	Actis et al.	1211.6316, 1605.01090

$2 \to 6$ and simpler processes routinely available.

More complicated processes require dedicated calculations!

Existing calculations for $VV + 2$ jet production

- Full LO predictions: Ballestrero, Franzosi, Maina '10 (PHANTOM)

NLO QCD separately for EW ($\mathcal{O}(\alpha^6)$) and QCD-induced production ($\mathcal{O}(\alpha_s^2\alpha^4)$)

- NLO QCD corrections to EW production in VBS approximation:
  Jäger, Oleari, Zeppenfeld (+ Bozzi) '06, '07, '09 (VBFNLO);
  Denner, Hošeková, Kallweit '12
  PS matching: Jäger, Zanderighi '11, '13 + Karlberg '14 ($\mathrm{W^+W^\pm}$, ZZ)
  Rauch, Plätzer '16 ($\mathrm{W^+W^-}$), Jäger, Karlberg, Scheller '18, '24 (WZ)
- NLO QCD corrections to QCD production:
  Melia, Melnikov, Röntsch, Zanderighi '10, '11 ($\mathrm{W^+W^+}$); Greiner et al. '12 ($\mathrm{W^+W^-}$);
  Campanario, Kerner, Ninh, Zeppenfeld '13, '14 (VBFNLO) ($\mathrm{W^+W^+}$, WZ, ZZ)
  PS matching: Melia, Nason, Röntsch, Zanderighi '11 ($\mathrm{W^+W^\pm}$, WZ, ZZ)
- EW corrections for complete processes $\mathrm{pp} \to 4f + 2\mathrm{j}$
  - NLO EW and QCD corrections for VBS into $\mathrm{W^+W^\pm}$, $\mathrm{W^+Z}$, ZZ
    Biedermann et al.'16; Denner et al.'19, '20, '22; Dittmaier et al. '23
  - full NLO corrections to VBS into $\mathrm{W^+W^+}$ and ZZ
    Biedermann, Denner, Pellen '17; Denner, Franken, Pellen, Schmidt '21
  - NLO EW matched to QED PS and interfaced to QCD PS for $\mathrm{W^\pm W^\pm}$ within POWHEG-BOX-RES Chiesa, Denner, Lang, Pellen '19

Existing calculations with polarised bosons

Fixed-order results at (N)NLO

- results at LO for VBS for ss-WW, WZ, ZZ, os-WW
  Ballestrero, Maina, Pellicciioli '17, '19, '20 [PHANTOM]
- results at NLO QCD for
  - $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}$ $(\mathrm{W}^+\mathrm{W}^-)$ Denner, Pellicciioli 2006.14867
  - $\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\nu_\mathrm{e}$ $(\mathrm{W}^+\mathrm{Z})$ Denner, Pellicciioli 2010.07149
  - $\mathrm{pp} \to \mathrm{jj}\ell^+\ell^-$ $(\mathrm{W}^+\mathrm{Z})$ Denner, Haitz, Pellicciioli 2211.09040
- results at NLO EW for
  - $\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\mathrm{e}^-$ (ZZ) Denner, Pellicciioli 2107.06579
  - $\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\nu_\mathrm{e}$ $(\mathrm{W}^+\mathrm{Z})$ Baglio, Dao, Le 2203.01470, 2208.09232
  - $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu$ (WW) Denner, Pellicciioli 2311.16031, Dao, Le 2311.17027
  - $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^+\nu_\mu\mathrm{jj}$ $(\mathrm{W}^+\mathrm{W}^+\mathrm{jj})$ Denner, Haitz, Pellicciioli 2409.03620
- results at NNLO QCD for
  - $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}$ $(\mathrm{W}^+\mathrm{W}^-)$ (DPA and NWA) Poncelet, Popescu 2102.13583

Implementation in Monte Carlo generators

- MADGRAPH5_AMC@NLO: spin-correlated narrow-width approximation (NWA), LO Franzosi, Mattelaer, Ruiz, Shil 1912.01725
- SHERPA: approximate NLO QCD (NWA) Hoppe, Schönherr, Siegert 2310.14803
- POWHEG-BOX-RES: diboson processes at NLO QCD
  Pellicciioli, Zanderighi 2311.05220

Setup for W^+W^+ scattering

Energy: $13\,\mathrm{TeV}$ Biedermann, Denner, Pellen 1708.00268

PDFs

NNPDF3.0QED Ball et al. 1308.0598, 1410.8849

factorisation and renormalisation 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 for jets with $R = 0.4$ Cacciari, Salam, Soyez 0802.1189

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: $13\,\mathrm{TeV}$ $(14\,\mathrm{TeV})$ Denner et al. 1904.00882

PDFs

NNPDF3.1QED Ball et al. 1410.8849, Bertone et al. 1712.07053

factorisation and renormalisation 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 for jets with $R = 0.4$ Cacciari, Salam, Soyez 0802.1189

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

Setup for VBS into ZZ

Energy: $13\,\mathrm{TeV}$ Denner, Franken, Pellen, Schmidt 2009.00411

PDFs

NNPDF3.1QED Ball et al. 1410.8849, Bertone et al. 1712.07053

factorisation and renormalisation 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 for jets with $R = 0.4$ Cacciari, Salam, Soyez 0802.1189

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

Cuts: inspired by CMS 1708.02812

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

$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}$, $|y_\ell| < 2.5$, $\Delta R_{\ell\ell'} > 0.05$, $M_{\ell^+\ell'^-} > 4\,\mathrm{GeV}$

$60\,\mathrm{GeV} < M_{\ell^+\ell^-} < 120\,\mathrm{GeV}$

inclusive setup: $M_{\mathrm{jj}} > 100\,\mathrm{GeV}$, VBS setup $M_{\mathrm{jj}} > 500\,\mathrm{GeV}$

require ≥ 2 jets, 4 leptons

Setup for VBS into W^+W^- (VBS setup)

Energy: $13\,\mathrm{TeV}$ Denner, Franken, Schmidt, Schwan 2202.10844

PDFs

NNPDF3.1QED Ball et al. 1410.8849, Bertone et al. 1712.07053

factorisation and renormalisation 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 for jets with $R = 0.4$ Cacciari, Salam, Soyez 0802.1189

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

Cuts: similar to CMS 2205.05711

$p_{\mathrm{T,j}} > 30\,\mathrm{GeV}$, $|y_\mathrm{j}| < 4.5$, $\Delta R_{\mathrm{j}\ell} > 0.4$ $\Delta R_{ij} = \sqrt{(\Delta y_{ij})^2 + (\Delta\phi_{ij})^2}$

$p_{\mathrm{T},\ell} > 25\,\mathrm{GeV}$, $|y_\ell| < 2.4$, $p_{\mathrm{T},\ell^+\ell^-} > 30\,\mathrm{GeV}$, $M_{\ell^+\ell^-} > 20\,\mathrm{GeV}$

$p_{\mathrm{T,miss}} > 20\,\mathrm{GeV}$

$M_\mathrm{jj} > 500\,\mathrm{GeV}$, $\Delta y_\mathrm{jj} > 2.5$

require ≥ 2 jets, 2 leptons

Setup for VBS into W^+W^- (Higgs setup)

Energy: $13\,\mathrm{TeV}$ Denner, Franken, Schmidt, Schwan 2202.10844

PDFs

NNPDF3.1QED Ball et al. 1410.8849, Bertone et al. 1712.07053

factorisation and renormalisation 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 for jets with $R = 0.4$ Cacciari, Salam, Soyez 0802.1189

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

Cuts: following CMS 1806.05246 (Higgs search)

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

$p_{\mathrm{T},\ell}^{\mathrm{lead}} > 25\,\mathrm{GeV}$, $p_{\mathrm{T},\ell}^{\mathrm{trail}} > 10\,\mathrm{GeV}$, $|y_\ell| < 2.4$,

$p_{\mathrm{T},\ell^+\ell^-} > 30\,\mathrm{GeV}$, $M_{\ell^+\ell^-} > 12\,\mathrm{GeV}$, $\Delta R_{\ell^+\ell^-} > 0.4$

$p_{\mathrm{T,miss}} > 20\,\mathrm{GeV}$, $60\,\mathrm{GeV} < M_{\mathrm{T},\ell^+\ell^-,\mathrm{miss}} < 125\,\mathrm{GeV}$

$M_{\mathrm{j_1 j_2}} > 400\,\mathrm{GeV}$, $\Delta y_{\mathrm{j_1 j_2}} > 3.5$, $p_{\mathrm{T,j_3}} < 30\,\mathrm{GeV}$ (jet veto on 3rd jet)

$|z_{\ell\mathrm{j_1j_2}}| < 0.5$, $z_{\ell\mathrm{j_1j_2}} = \frac{2y_\ell - y_{\mathrm{j_1}} - y_{\mathrm{j_2}}}{2|y_{\mathrm{j_1}} - y_{\mathrm{j_2}}|}$, require 2 jets, 2 leptons

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

Energy: $13.6\,\mathrm{TeV}$ Denner, Haitz, Pellicciolì 2409.03620

PDFs

`NNPDF40_nnlo_as_01180_qed` Ball et al. 2401.08749

factorisation and renormalisation 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 for jets with $R = 0.4$ Cacciari, Salam, Soyez 0802.1189

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

Cuts: based on CMS 2009.09429

$p_{\mathrm{T,j}} > 50\,\mathrm{GeV}, \quad |y_\mathrm{j}| < 4.7, \quad \Delta R_{\mathrm{j}\ell} > 0.4$

$p_{\mathrm{T},\ell_1} > 25\,\mathrm{GeV}, \quad p_{\mathrm{T},\ell_2} > 20\,\mathrm{GeV}, \quad |y_\ell| < 2.5, \quad M_{\mathrm{e}^+\mu^+} > 20\,\mathrm{GeV}$

$\Delta R_{ij} = \sqrt{(\Delta y_{ij})^2 + (\Delta\phi_{ij})^2}$

$p_{\mathrm{T,miss}} > 30\,\mathrm{GeV}, \quad \max_\ell \left| y_\ell - \frac{y_{\mathrm{j}_1}+y_{\mathrm{j}_2}}{2} \right| < 0.75\,|\Delta y_{\mathrm{j_1j_2}}|, \quad \ell = \mathrm{e}^+, \mu^+$

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

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

Setup for semileptonic $W^+W^+W^-$ production

Energy: $13.6\,\mathrm{TeV}$ Denner, Pellen, Schönherr, Schumann 2406.11516

PDFs

NNPDF31_nnlo_as_0118_luxqed Bertone et al. 1712.07053

factorisation and renormalisation scales: $\mu_\mathrm{F} = \mu_\mathrm{R} = m_{\mathrm{T,jj}} + m_{\mathrm{T},\nu_\mathrm{e}\mathrm{e}^+} + m_{\mathrm{T},\nu_\mu\mu^+}$

$$m_{\mathrm{T},ij} = \sqrt{m_{ij}^2 + p_{\mathrm{T},ij}^2}$$

Recombination / jet clustering

Anti-k_T algorithm for jets/photons with $R = 0.4$ Cacciari, Salam, Soyez 0802.1189

recombination of remaining photons with charged leptons with $R = 0.1$

Cuts: based on ATLAS 2201.13045

$p_{\mathrm{T},\ell^+} > 20\,\mathrm{GeV}$, $|y_\ell^+| < 2.5$, $40\,\mathrm{GeV} < M_{\ell^+\ell^+} < 400\,\mathrm{GeV}$

$p_{\mathrm{T,j}} > 20\,\mathrm{GeV}$, $|y_\mathrm{j}| < 4.5$

$M_\mathrm{jj} < 160\,\mathrm{GeV}$, $|\Delta y_\mathrm{jj}| < 1.5$ for two hardest jets

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

Setup for semileptonic W^+ZV production

Energy: $13.6\,\mathrm{TeV}$ Denner, Lombardi, Lopez, Pellicciolli 2407.21558

PDFs

NNPDF40_nnlo_as_0118_qed Ball et al. 2401.08749

factorisation and renormalisation scales: $\mu_\mathrm{F} = \mu_\mathrm{R} = M_\mathrm{Z}$

Recombination / jet clustering

Anti-k_T algorithm for jets with $R = 0.4$ Cacciari, Salam, Soyez 0802.1189

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

perfect bottom-jet veto

Cuts: inspired by ATL-PHYS-PUB-2018-030

$p_{\mathrm{T,j}} > 40\,\mathrm{GeV}$, $|y_\mathrm{j}| < 3$ for exactly 2 jets

$p_{\mathrm{T},\ell_1} > 50\,\mathrm{GeV}$, $p_{\mathrm{T},\ell_2} > 40\,\mathrm{GeV}$, $p_{\mathrm{T},\ell_3} > 20\,\mathrm{GeV}$, $|y_\ell| < 4$

$76\,\mathrm{GeV} < M_{\mu^+\mu^-} < 106\,\mathrm{GeV}$,

$M_{\mathrm{T,W^+}} = \sqrt{2\,p_{\mathrm{T,e^+}}p_{\mathrm{T}\nu_\mathrm{e}}\left(1-\cos(\phi_{\mathrm{e}^+}-\phi_{\nu_\mathrm{e}})\right)} > 20\,\mathrm{GeV}$

$50\,\mathrm{GeV} < M_\mathrm{jj} < 100\,\mathrm{GeV}$

require exactly 2 jets, 3 charged leptons $(\mu^+\mu^-\mathrm{e}^+)$