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Higher-order corrections for VBS and polarised multi-boson processes

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Outline

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Aim and Scope of talk

Motivation

- Vector-boson scattering (VBS)
  important process to test the Standard Model (SM)
  - sensitive to quartic gauge couplings
  - sensitive to Higgs sector and electroweak symmetry breaking (EWSB)
- polarised vector bosons
  offer new observables to test SM and mechanism of EWSB
  - production of polarised vector boson pairs
  - longitudinal VBS scattering

Experiments use general purpose codes like SHERPA, MADGRAPH5_AMC@NLO or POWHEG/PYTHIA including

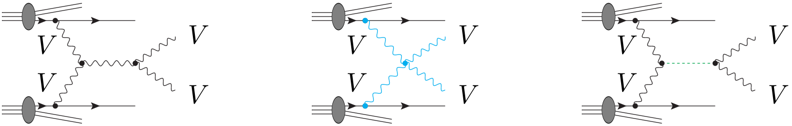
- NLO QCD corrections including parton-shower matching etc.
- but no NLO EW corrections

Focus of the talk

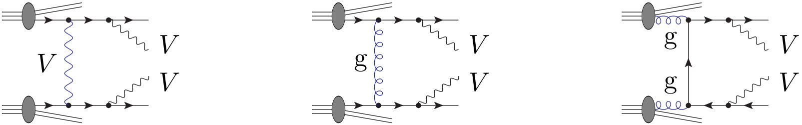
- EW corrections
- available results for (mostly) leptonic final states
- remarks on incorporation in experimental analyses ⇒ discussion

Processes: $\mathrm{pp} \to VV + 2\mathrm{j} \to 4\ell + 2\mathrm{j}$

Vector-boson scattering (VBS) signal (decays not shown)



Irreducible background to VBS



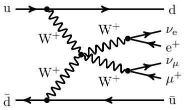
- EW process: $\mathcal{O}(\alpha^4)$ for stable Vs, $\mathcal{O}(\alpha^6)$ with decays
- QCD-induced process: $\mathcal{O}(\alpha_s^2\alpha^2)$ for stable Vs, $\mathcal{O}(\alpha_s^2\alpha^4)$ with decays
- interferences between EW and QCD contributions:
  $\mathcal{O}(\alpha_s\alpha^3)$ for stable Vs, $\mathcal{O}(\alpha_s\alpha^5)$ with decays
- gluonic channels for neutral final states

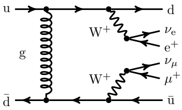
Expansion in multiple couplings

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:

LO $\mathcal{O}(\alpha^6)$ $\mathcal{O}(\alpha_\mathrm{s}\alpha^5)$ $\mathcal{O}(\alpha_\mathrm{s}{}^2\alpha^4)$

EW QCD EW QCD EW QCD

NLO $\mathcal{O}(\alpha^7)$ $\mathcal{O}(\alpha_\mathrm{s}\alpha^6)$ $\mathcal{O}(\alpha_\mathrm{s}{}^2\alpha^5)$ $\mathcal{O}(\alpha_\mathrm{s}{}^3\alpha^4)$

consequences:

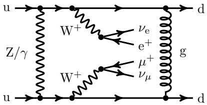
- QCD and EW corrections cannot be separated in general
- consider complete (well-defined) orders $\mathcal{O}(\alpha_\mathrm{s}^n\alpha^m)$
- QCD corrections to leading LO terms, i.e. $\mathcal{O}(\alpha_\mathrm{s}^3\alpha^4)$, well defined
- QCD corr. to EW LO overlaps with EW corrections to LO interference

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



$\Rightarrow$ separation into QCD and EW is not well-defined at NLO

real subtraction terms with both gluons and photons needed

Treatment of VBS in experiment

Strategy

- isolate EW process
- subtract QCD-induced process based on theoretical predictions

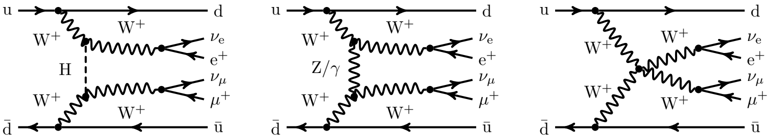
⇒ measurement of EW $VV\mathrm{jj}$ production

Issues

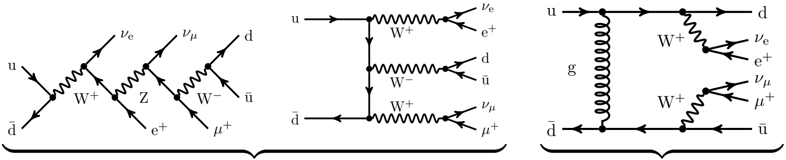
- QCD and EW corrections must be included in EW signal
- QCD and EW corrections should be included in irreducible QCD background (potentially large!)
- QCD–EW interference should be taken into account (if relevant)

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

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 $\mathcal{O}\left(g_\mathrm{s}^2 g^4\right)$ 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 $\mathcal{O}(\alpha_{\mathrm{s}}\alpha^6)$)
- only applicable to order α^6 and corresponding corrections for VBS cuts
  (tailored to VBS processes, not applicable to $\alpha_{\mathrm{s}}^2\alpha^4$)
- EW and QCD corrections to VBS uniquely defined
  (interferences neglected by definition!)
- VBS approximation works within $\lesssim 1\%$ at LO for $M_{\mathrm{jj}} > 500\,\mathrm{GeV}$
  Denner, Hošeková, Kallweit 1209.2389, Ballestrero et al. 1803.07943
- VBS approximation fails for NLO QCD corrections for small M_{jj}
  - $\sim 6\%$ for $\mathrm{pp} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ and $M_{\mathrm{jj}} \sim 500\,\mathrm{GeV}$ 1803.07943
  - $\sim 24\%$ for $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-\mathrm{jj}$ and $M_{\mathrm{jj}} \gtrsim 100\,\mathrm{GeV}$ 2009.00411

  $\Rightarrow$ contribution to theoretical error

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

Calculations for massive VBS within the SM

- 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 EW 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
- no NLO results for hadronically decaying vector bosons
- no NLO results for polarised vector bosons
- no NNLO results known

Large NLO EW corrections to VBS processes

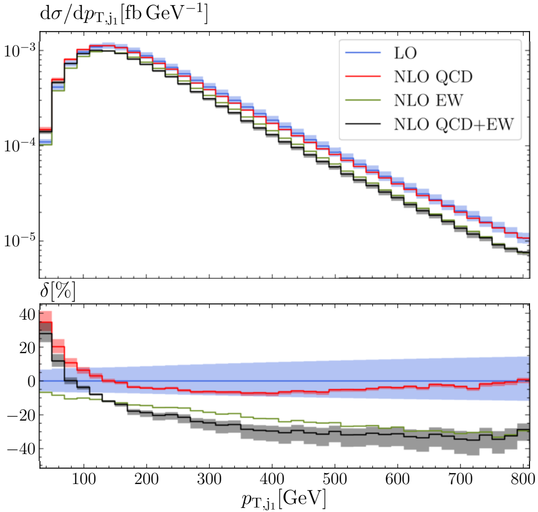
process	$\sigma^{\mathcal{O}(\alpha^6)}_{\mathrm{LO}}$ [fb]	$\Delta\sigma^{\mathcal{O}(\alpha^7)}_{\mathrm{NLO,EW}}$ [fb]	δ_{EW} [%]
Biedermann et al. 1708.00268	(Dittmaier et al. 2308.16716)		
$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ ($\mathrm{W}^+\mathrm{W}^+$)	1.4178(2)	−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
  ⇒ 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 Sudakov approximation

Distributions for $pp \to \mu^+\mu^- e^+\nu_e jj$ (ZW^+jj)

Distribution in transverse momentum of the leading jet

Denner et al. 1904.00882



- $\mathcal{O}(\alpha^7) \sim -30\%$
  at $p_{T,j_1} = 800\,\text{GeV}$
  (Sudakov logarithms)
  dominant correction
  larger than QCD scale uncertainty
- $\mathcal{O}(\alpha_s\alpha^6) \lesssim 10\%$
  for $p_{T,j_1} > 100\,\text{GeV}$
  small QCD scale uncertainty
  owing to suitable dynamical scale $\mu = \sqrt{p_{T,j_1} p_{T,j_2}}$
- large correction for small p_{T,j_1} due to phase-space suppression at LO
  (all jets have small p_T)
  redistribution of events at NLO

Corrections of order $\mathcal{O}(\alpha_s^2\alpha^5)$ normalised to $\mathcal{O}(\alpha_s^2\alpha^4)$
("EW corrections to LO QCD contribution")

- $pp \to \mu^+\nu_\mu e^+\nu_e jj$ (W^+W^+):
  - negligible: 0.2% for $M_{j_1j_2} > 500\,\mathrm{GeV}$, result of cancellations
  - EW corrections to LO QCD $\mathcal{O}(\alpha_s^2\alpha^4)$: -12.3%
  - QCD corrections to LO interference $\mathcal{O}(\alpha_s\alpha^5)$: 12.5%
  - LO interference reaches 30% of LO QCD contribution
  - LO QCD amounts to 12% of LO cross section
- $pp \to \mu^+\mu^- e^+e^- jj$ (ZZ):
  - sizeable: -10% (-8%) for $M_{j_1j_2} > 500\,\mathrm{GeV}$ $(100\,\mathrm{GeV})$
  - EW corrections to LO QCD $\mathcal{O}(\alpha_s^2\alpha^4)$: -11.6% (-8.2%)
  - QCD corrections to LO interference $\mathcal{O}(\alpha_s\alpha^5)$: 1.3% (0.3%)
  - LO interference only 0.8% (4%) of LO QCD contribution
  - LO QCD amounts to 60% (82%) of LO cross section

$\Rightarrow$ EW $\mathcal{O}(\alpha_s^2\alpha^5)$ corrections generically large
(also seen in individual partonic processes)

Outline

Physical interest in polarisation and problems

Observables with polarised massive vector bosons

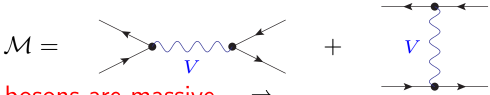
- are important probes of Standard Model gauge and Higgs sectors,
- may provide discrimination power between SM and beyond-SM physics.

Longitudinal polarisation mode of vector bosons is

- a consequence of the EW Symmetry Breaking
- very sensitive to deviations from SM:
  unitarity of cross sections with longitudinally polarised vector bosons realised in SM via cancellation of different contributions.

Challenges and problems

- Unstable massive vector bosons appear only as virtual particles $\Rightarrow$
  - no unique definition of vector-boson polarisations for off-shell bosons
  - diagrams without resonant vector bosons contribute to physical final state



- vector bosons are massive $\Rightarrow$
  definition of polarisation depends on reference frame

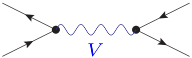
Definition of polarisation based on pole expansion I

Idea: use pole expansion to extract resonant (vector-boson) contributions in gauge-invariant way Ballestrero, Maina, Pellicciolii 1710.09339, 1907.04722

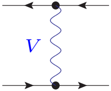
formulation for NLO developed by Denner, Pellicciolii 2006.14867

- not all diagrams involve required resonances
  resonant diagrams non-resonant diagrams

$$\frac{R(k^2)}{k^2 - M^2 + \mathrm{i}M\Gamma} =$$



$$N(k^2) =$$



- split full matrix element into resonant part and non-resonant part using pole expansion (gauge-invariant)

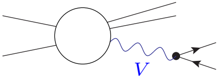
$$\begin{aligned}\mathcal{A} &= \frac{R(k^2)}{k^2 - M^2 + \mathrm{i}M\Gamma} + N(k^2)\\ &= \frac{R(M^2)}{k^2 - M^2 + \mathrm{i}M\Gamma} + \frac{R(k^2) - R(M^2)}{k^2 - M^2} + N(k^2) = \mathcal{A}_{\mathrm{res}} + \mathcal{A}_{\mathrm{nonres}}\end{aligned}$$

- consider non-resonant part as irreducible background: no resonance
- define polarisation for on-shell residue $R(M^2)$ (gauge invariant)

Definition of polarisation based on pole approximation II

Separate polarisation modes of resonant amplitude

split propagator numerator of resonant particle



$$\mathcal{A}_{\mathrm{res}} = \mathcal{P}_\mu \frac{-g^{\mu\nu}}{k^2 - M_{\mathrm{W}}^2 + \mathrm{i}\Gamma_{\mathrm{W}} M_{\mathrm{W}}} \mathcal{D}_\nu = \mathcal{P}_\mu \frac{\sum_\lambda \varepsilon_\lambda^{\mu\,*}(k) \varepsilon_\lambda^\nu(k)}{k^2 - M_{\mathrm{W}}^2 + \mathrm{i}\Gamma_{\mathrm{W}} M_{\mathrm{W}}} \mathcal{D}_\nu$$

$$= \sum_{\lambda=\mathrm{L},\pm} \frac{\mathcal{M}_\lambda^{\mathrm{prod}} \mathcal{M}_\lambda^{\mathrm{dec}}}{k^2 - M_{\mathrm{W}}^2 + \mathrm{i}\Gamma_{\mathrm{W}} M_{\mathrm{W}}} =: \sum_{\lambda=\mathrm{L},\pm} \mathcal{A}_\lambda \,,$$

$$\left|\mathcal{A}_{\mathrm{res}}\right|^2 = \sum_\lambda \left|\mathcal{A}_\lambda\right|^2 + \sum_{\lambda\neq\lambda'} \mathcal{A}_\lambda^* \mathcal{A}_{\lambda'}$$

- incoherent sum $\sum_\lambda \left|\mathcal{A}_\lambda\right|^2$: $\left|\mathcal{A}_\lambda\right|^2 \propto$ "polarised cross sections",

  "polarisation fractions": $\quad f_\lambda = \dfrac{\left|\mathcal{A}_\lambda\right|^2}{\sum_\lambda \left|\mathcal{A}_\lambda\right|^2}$
- interferences $\sum_{\lambda\neq\lambda'} \mathcal{A}_\lambda^* \mathcal{A}_{\lambda'}$
  vanish for observables fully inclusive in decay products
  in general to be considered as extra background

Method

- applicable to arbitrary processes and multiple resonances at LO, NLO QCD and EW and beyond
- needs pole approximation/ pole expansion for all NLO contributions including subtraction terms ⇒ technical complication
- implementation for processes with two polarised vector bosons complete in double-pole approximation (DPA) for NLO QCD and EW
- use of spin-correlated narrow-width approximation (NWA) also possible (simpler but potentially less precise)

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!

Fixed-order results at (N)NLO

- results at LO for VBS for ss-WW, WZ, ZZ, os-WW
  Ballestrero, Maina, Pelliccioli '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, Pelliccioli 2006.14867
  - $\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\nu_\mathrm{e}$ $(\mathrm{W}^+\mathrm{Z})$ Denner, Pelliccioli 2010.07149
  - $\mathrm{pp} \to \mathrm{jj}\ell^+\ell^-$ $(\mathrm{W}^+\mathrm{Z})$ Denner, Haitz, Pelliccioli '22
- results at NLO EW for (diboson production)
  - $\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\mathrm{e}^-$ (ZZ) Denner, Pelliccioli 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, Pelliccioli 2311.16031, Dao, Le 2311.17027
- 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: for diboson processes at NLO QCD
  Pellicciolі, Zanderighi 2311.05220

Existing calculations with polarised bosons

Massive diboson production with leptonic decays within the SM

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

Massive diboson production with semi-leptonic decays within the SM

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

Massive VBS within the SM

- LO results exist within PHANTOM
- first NLO QCD+EW results being calculated

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 WW production

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$ (WW): Denner, Haitz, Pellicciolì 2311.16031

state	σ_{LO} [fb]	$\sigma_{\mathrm{NLO\,EW}}$ [fb]	$\delta_{\mathrm{EW}}[\%]$	$f_{\mathrm{NLO\,EW}}[\%]$
		$\mathrm{b\bar{b}}$ included, $\gamma\mathrm{b}$, $\gamma\mathrm{\bar{b}}$ excluded		
full	259.02(2)	253.95(9)	−1.96	103.4
unp.	249.97(2)	245.49(2)	−1.79	100.0
LL	21.007(2)	20.663(2)	−1.64	8.4
LT	33.190(3)	33.115(3)	−0.23	13.5
TL	34.352(5)	34.230(5)	−0.35	13.9
TT	182.56(2)	178.21(3)	−2.38	72.6
int.	−21.14(5)	−20.6(2)	−2.45	−8.4

- irreducible background (3.4%) consistent with DPA accuracy
- sizeable interferences (-8.4%) from p_{T} cuts on charged leptons
- NLO EW corrections differ for various polarised and unpolarised cross sections
- expect larger differences for VBS

Outline

Existing results for EW corrections

- no public codes
  except for $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$ within POWHEG-BOS-RES
  NLO EW matched to EW PS and interfaced to QCD PS
  Chiesa, Denner, Lang, Pellen 1906.01863
- fiducial cross sections and various distributions for specific setups
  (one-dimensional histograms)
- for other setups obtainable with some numerical efforts
- can be used to reweight Monte Carlo events
  (as has been done in the past)

Long-term goal (not available soon)

- Les Houches events including EW corrections
- suitable for matching to (e.g. PYTHIA) parton shower
- public codes

QCD corrections

- Standard procedure: 7-point scale variations to estimate uncertainty owing to missing higher-order corrections
- conventional, simple, easy to use, but not reliable

EW corrections

- no standard method to estimate missing higher-order corrections
- available approaches
  - differences between renormalisation schemes, e.g. $\alpha(M_\mathrm{Z})$ versus α_{G_μ}
  - square of relative NLO correction as uncertainty
  - resummation in Sudakov approximation as uncertainty estimate
  - counting of powers of couplings and logarithms
  - use process-specific combination of estimates
- sensible estimate needs agreement of experts
  $\Rightarrow$ task for LHC EW WG?

Theoretical uncertainties (cont,)

Other sources of errors

- use of approximations
  - VBS approximation
  - pole approximation
  - NWA
- QED final-state radiation
- photon-induced contributions

Estimates from comparison of results of different codes

- done for unpolarised $\mathrm{W^+W^+}$ scattering at NLO QCD within VBSCAN COST network Ballestrero et al. 1803.07943
- ongoing for polarised ZZ production within COMETA WG1 https://foswiki.web.cern.ch/COMETA/WkG1

Open issues

- check of our results by other codes
  done for $\mathrm{W^+W^+}$ scattering by Freiburg group Dittmaier et al. 2308.16716
  bug with minor impact found [$0.005\,\mathrm{fb}$ in $\mathcal{O}\big(\alpha_\mathrm{s}^2\alpha^5\big)$]
- NLO corrections to polarised VBS ⇒ in the making for $\mathrm{W^+W^+}$
  needed for other channels?
- estimate of theoretical uncertainty ⇒ see above
- resummation of EW logarithms ⇒ needed for LHC?
  more relevant for higher energies
- matching of EW corrections to parton showers (including EW effects)
  ⇒ work ongoing by different groups
- . . .

Conclusion

Higher-order (EW) corrections in VBS

- NLO QCD matched to QCD PS available in Monte Carlo generators
- results for EW corrections exist in form of one-dimensional histograms
- EW corrections typically at the level of 10–20%
  similarly large for irreducible background
- estimate of theoretical uncertainties to be developed

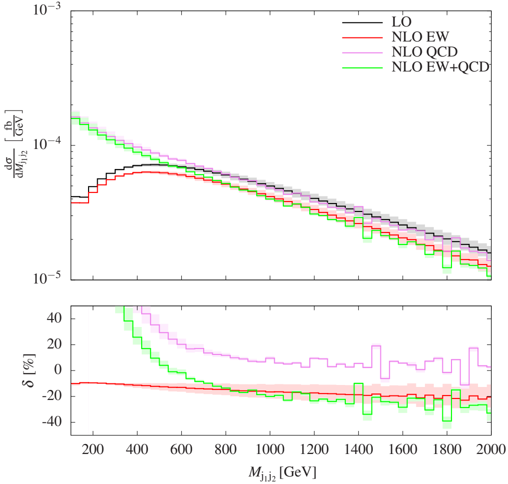
Polarised multi-boson processes

- MADGRAPH5_AMC@NLO: spin-correlated NWA at LO
- SHERPA: approximate NLO QCD in NWA
- diboson production with leptonic decays
  - NLO QCD and matching to PS via POWHEG-BOX-RES
  - EW corrections in form of one-dimensional histograms
  - NLO (EW) corrections depend on boson polarisations
- VBS
  - LO results exist within PHANTOM
  - NLO QCD+EW results being calculated.

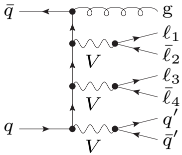
Outline

NLO QCD and EW corrections to ZZ production in VBS

$\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-\mathrm{jj}$ Denner et al. 2009.00411



- Loose VBS cut:
  $M_{\mathrm{j_1j_2}} > 100\,\mathrm{GeV}$
  based on 1708.02812 (CMS)
- 24% NLO QCD corrections to fiducial cross section
- s-channel NLO contribution involving tri-boson production



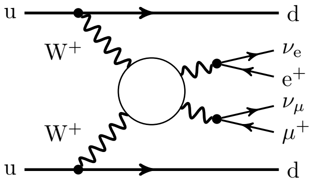
Less suppression at NLO owing to extra gluon jet

⇒ include tri-boson contribution (s-channel) and interferences for loose VBS cuts

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 $V_1V_2 \to V_3V_4$
- 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 $V_1V_2 \to V_3V_4$ Denner, Pozzorini '00

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

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

(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
- 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

Process $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$ Denner, Franken, Schmidt, Schwan 2202.10844

- EW corrections smaller than for other VBS processes
- fiducial phase space contains Higgs resonance

setup	$\sigma_{LO}^{\mathcal{O}(\alpha^6)}$ [fb]	$\Delta\sigma_{NLO,EW}^{\mathcal{O}(\alpha^7)}$ [fb]	δ_{EW} [%]
VBS setup	$2.6988(3)$	$-0.307(1)$	-11.4
VBS setup, Higgs cut out VBS channels only	$1.6117(2)$	$-0.239(2)$	-14.8
VBS setup, Higgs cut out	$1.9750(2)$	$-0.260(2)$	-13.2
VBS setup, Higgs contribution	$0.7238(2)$	$-0.047(2)$	-6.5
Higgs setup	$1.5322(2)$	$-0.103(1)$	-6.7

- EW corrections to generic VBS contributions $\sim -15\%$
- EW corrections to Higgs resonance contribution $\sim -6.5\%$
- Higgs cut: $|M_{4\ell} - M_H| > 20\Gamma_H \approx 80\,\text{MeV}$, removes 98.4% of resonance
- Higgs contribution: $|M_{4\ell} - M_H| < 20\Gamma_H$
- Higgs setup: cuts inspired by CMS Higgs search CMS 1806.05246

Setup for W^+W^+ scattering

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

PDFs

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

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

PDFs

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

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 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

Setup for VBS into ZZ

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

PDFs

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

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 with $R = 0.4$ Cacciari, Salam, Soyez '08

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

PDFs

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

factorisation and renormalisation scales: $\mu_\text{F} = \mu_\text{R} = \sqrt{p_{\text{T,j}_1} p_{\text{T,j}_2}}$

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: similar to CMS 2205.05711

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

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

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

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

require ≥ 2 jets, 2 leptons

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

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

PDFs

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

factorisation and renormalisation scales: $\mu_F = \mu_R = \sqrt{p_{T,j_1} p_{T,j_2}}$

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: following CMS 1806.05246 (Higgs search)

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

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

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

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

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

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

Example results for polarisation fractions

$\mathrm{pp} \to \mathrm{e^+e^-}\mu^+\mu^-$ (ZZ):

Denner, Pellicciolí 2107.06579

mode	σ_{LO} [fb]	δ_{QCD}	δ_{EW}	δ_{gg}	σ_{NLO_+} [fb]
full	$11.1143(5)^{+5.6\%}_{-6.8\%}$	$+34.9\%$	-11.0%	$+15.6\%$	$15.505(6)^{+5.7\%}_{-4.4\%}$
unpol.	$11.0214(5)^{+5.6\%}_{-6.8\%}$	$+35.0\%$	-10.9%	$+15.7\%$	$15.416(5)^{+5.7\%}_{-4.4\%}$
$\mathrm{Z_LZ_L}$	$0.64302(5)^{+6.8\%}_{-8.1\%}$	$+35.7\%$	-10.2%	$+14.5\%$	$0.9002(6)^{+5.5\%}_{-4.3\%}$
$\mathrm{Z_LZ_T}$	$1.30468(9)^{+6.5\%}_{-7.7\%}$	$+45.3\%$	-9.9%	$+2.8\%$	$1.8016(9)^{+4.3\%}_{-3.5\%}$
$\mathrm{Z_TZ_L}$	$1.30854(9)^{+6.5\%}_{-7.7\%}$	$+44.3\%$	-9.9%	$+2.8\%$	$1.7933(9)^{+4.3\%}_{-3.4\%}$
$\mathrm{Z_TZ_T}$	$7.6425(3)^{+5.2\%}_{-6.4\%}$	$+31.2\%$	-11.2%	$+20.5\%$	$10.739(4)^{+6.2\%}_{-4.7\%}$

- small irreducible background (0.5%) and interferences (1.2%)
- sizeable QCD and EW corrections
- substantial contribution from loop-induced gg fusion for LL and TT
- polarisation fractions roughly conserved by NLO corrections owing to cancellations