Julius-Maximilians-
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Precise theoretical predictions for VBS

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in collaboration with

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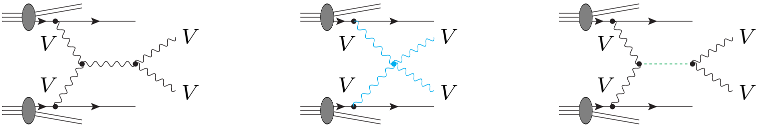
Outline

Outline

- Run 1:
  - Discovery of the Higgs boson
  - exclusion limits for new physics models
- Run 2:
  - Study of properties of the Higgs boson
  - precise measurements of standard-candle processes (Drell-Yan, $\mathrm{t\bar{t}}$, VV, . . .)
  - measurement of new SM processes ($\mathrm{t\bar{t}H}$, VBS, VVV, . . .)
  - further exclusion limits for new physics models
- Run 3 and beyond:
  - Improved precision tests of SM processes and parameters
  - measurement of further new SM processes
  - discovery of New Physics?

Precise theoretical predictions needed to match improved experimental accuracy!



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

Improvement of experimental precision

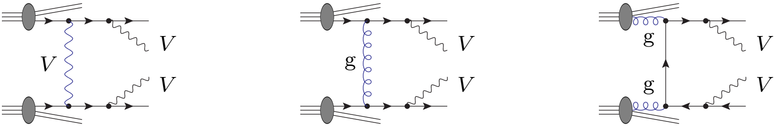
Integrated Luminosity	36 fb	150 fb	300 fb	3000 fb-
Year	2016	2019	2022	2038
EW(VBS) W±W±	20%	10%	7%	2%
EW (VBS) ZZ	35%	18%	13%	6%
EW (VBS) WZ	35% personally anticipated	18%	13%	6%

Jakob Salfeld-Nebgen in https://indico.cern.ce/event/711256

must be matched by theoretical calculations

Irreducible background to VBS

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



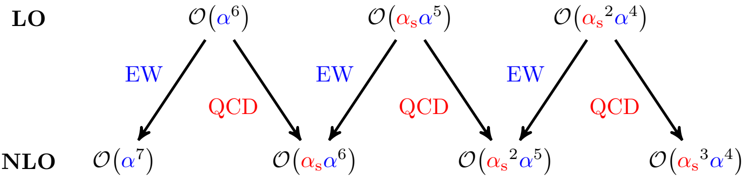
- Full electroweak (EW) process [$\mathcal{O}(\alpha^4)$ for stable Vs]
  not separable from VBS
- QCD process [$\mathcal{O}(\alpha_{\mathrm{s}}^2\alpha^2)$ for stable Vs]
  gauge-invariant contribution
- interferences between EW and QCD contributions
  [$\mathcal{O}(\alpha_{\mathrm{s}}\alpha^3)$ for 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 $|\Delta y_{\mathrm{jj}}|$
  $\sigma_{\mathrm{EW}}^{\mathrm{W^+W^+}} \sim 10\,\sigma_{\mathrm{QCD}}^{\mathrm{W^+W^+}}, \qquad \sigma_{\mathrm{EW}}^{\mathrm{W^+Z}} \sim 0.25\,\sigma_{\mathrm{QCD}}^{\mathrm{W^+Z}}, \qquad \sigma_{\mathrm{EW}}^{\mathrm{ZZ}} \sim 0.1\,\sigma_{\mathrm{QCD}}^{\mathrm{ZZ}}$

Expansion in multiple couplings

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

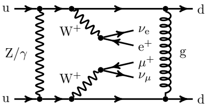
NLO: EW and QCD corrections to both types of diagrams

at level of cross section:



Virtual diagrams mix QCD and EW corrections:

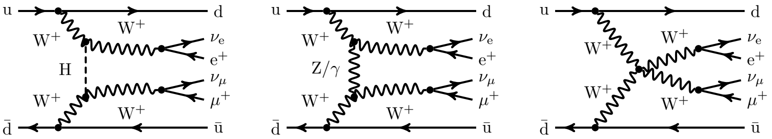
- EW correction to LO QCD amplitude
- QCD correction to LO EW amplitude



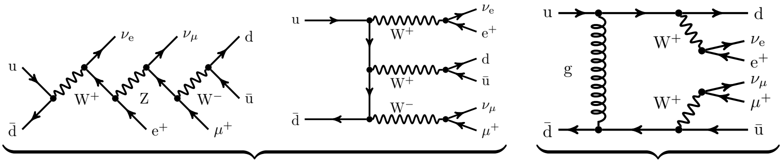
$\Rightarrow$ QCD and EW corrections mix at $\mathcal{O}(\alpha_s \alpha^6)$ and $\mathcal{O}(\alpha_s^2 \alpha^5)$
QCD and EW corrections cannot be separated in general
possible in VBS approximation (neglects interferences)

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 $\mathcal{O}\left(g_s^2\, g^4\right)$
only t 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: only t and u channel, no interferences

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 $(\mathrm{W^+W^+}, \mathrm{W^+W^-}, \mathrm{ZZ})$
  Rauch, Plätzer '16 $(\mathrm{W^+W^-})$, Jäger, Karlberg, Scheller '18 (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) $(\mathrm{W^+W^+}, \mathrm{WZ}, \mathrm{ZZ})$
  PS matching: Melia, Nason, Röntsch, Zanderighi '11 $(\mathrm{W^+W^+})$
- EW corrections for complete processes $\mathrm{pp} \to 4f + 2\mathrm{j}$
  - NLO EW and QCD corrections for $\mathrm{W^\pm W^\pm}$, WZ and ZZ final states
    Biedermann, Denner, Pellen '16; Denner, Dittmaier, Pellen, Schwan '19,
    Denner, Franken, Pellen, Schmidt '20
  - full NLO corrections to $\mathrm{W^\pm W^\pm}$ Biedermann, Denner, Pellen '17
  - NLO EW matched to EW PS and interfaced to QCD PS for $\mathrm{W^\pm W^\pm}$
    Chiesa, Denner, Lang, Pellen '19

Calculations for VBS within the SM

- 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 known for $\mathrm{W^+W^+}$, WZ, and ZZ ($\mathrm{W^+W^-}$ in progress)
- full NLO computation only available for $\mathrm{W^+W^+}$ (ZZ in progress)
- no NNLO results known

Fiducial cross section for $\mu^+\nu_\mu e^+\nu_e jj$ (W^+W^+jj)

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

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

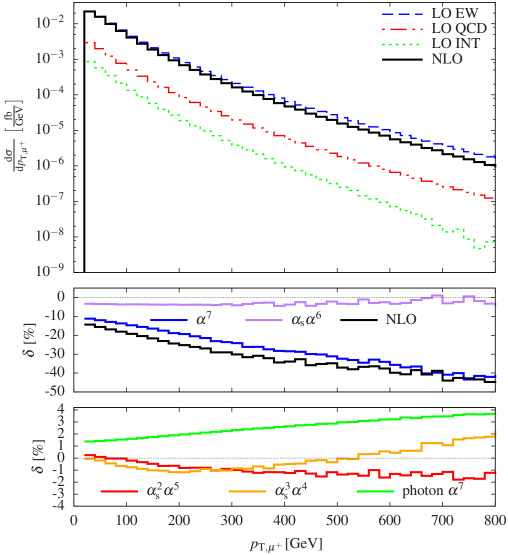
results for separate orders:

order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	sum
σ_{LO} [fb]	$1.4178(2)$	$0.04815(2)$	$0.17229(5)$	$1.6383(2)$
$\delta\sigma_{LO}/\sigma_{LO}$ [%]	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
$\delta\sigma_{NLO}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{NLO}/\sigma_{LO}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

- LO EW contribution dominates for 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)

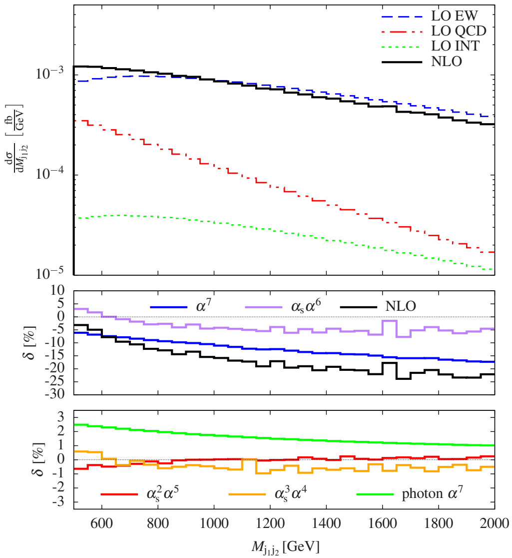
Distribution in transverse momentum of the anti-muon



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

- EW contribution dominates everywhere
- $\mathcal{O}(\alpha^7)$ -40% at $800\,\mathrm{GeV}$ (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 $p_{T\mu^+} = 800\,\mathrm{GeV}$ (photon PDF grows with energy)

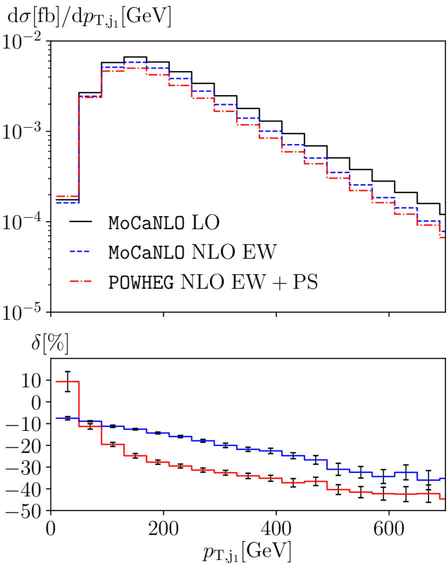
Di-jet invariant-mass distribution



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

- 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}

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



Chiesa et al. ’19

- Event generator based on POWHEG and RECOLA for $pp \to \mu^{\pm}\nu_{\mu}e^{\pm}\nu_{e}jj$ and $pp \to e^{\pm}\nu_{e}e^{\pm}\nu_{e}jj$ 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

Corrections to fiducial cross sections

Large universal NLO EW corrections to VBS processes

process	$\sigma_{\mathrm{LO}}^{\mathcal{O}(\alpha^6)}$ [fb]	$\sigma_{\mathrm{NLO,EW}}^{\mathcal{O}(\alpha^7)}$ [fb]	δ_{EW} [%]
Biedermann et al. '16			
$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ ($\mathrm{W^+W^+}$)	$1.5348(2)$	$1.2895(6)$	-16.0
Denner et al. '19			
$\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ ($\mathrm{ZW^+}$)	$0.25511(1)$	$2.142(2)$	-16.0
Denner et al. '20			
$\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\mathrm{e}^-\mathrm{jj}$ (ZZ)	$0.097681(2)$	$0.08214(5)$	-15.9

largely independent of cuts ⇒ intrinsic feature of VBS processes

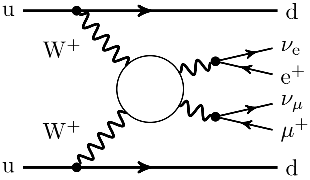
Relative NLO EW corrections in logarithmic approximation

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

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 but sufficient to understand dominant effects



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

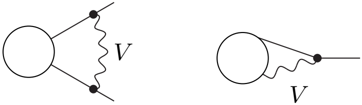
$$\mathrm{d}\sigma_{\mathrm{LL}} = \mathrm{d}\sigma_{\mathrm{LO}}\left[1 - \frac{\alpha}{4\pi} 4 C_{\mathrm{W}}^{\mathrm{ew}} \log^2\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right) + \frac{\alpha}{4\pi} 2 b_{\mathrm{W}}^{\mathrm{ew}} \log\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right)\right]$$

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

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

large NLO EW corrections intrinsic feature of VBS

Feynman diagrams leading to double- and single-logarithmic corrections

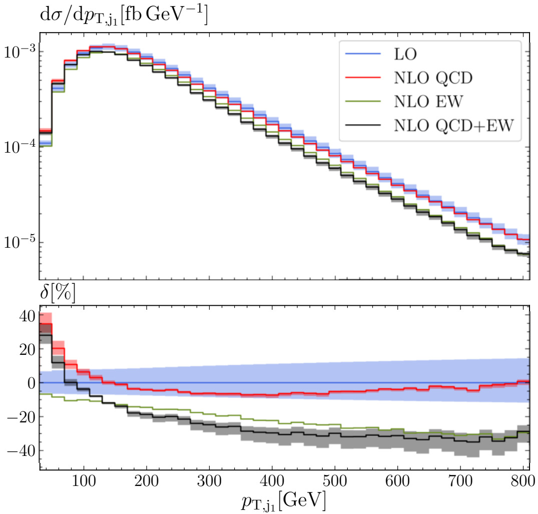


- Leading-logarithmic EW corrections depend only on gauge structure of model, external lines and polarisations of process.
- For all VBS processes, leading double logarithms and single logarithms universal for fixed polarisations ($\mathrm{U}_Y(1)$ does not contribute to VBS).
- Angular-dependent single logarithms (not included in approximation) turned out to be small so far (~ 1–2% owing to cancellations)
- Expect similarly large EW corrections for SMEFT or extended models that do not modify the $\mathrm{SU}(2) \times \mathrm{U}(1)$ gauge structure of the SM.
- Expect smaller corrections for scattering of longitudinal vector bosons different coefficients in logarithmic corrections
  $\Rightarrow$ very naively $\sim 40\%$ of those for transverse bosons $\Rightarrow \sim 6\%$

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

Distribution in transverse momentum of the leading jet

Denner et al. '19



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

Experimentally

- Semileptonic final state offer more statistics
- much stronger QCD background
- hadronically decaying vector boson can be reconstructed using jet-substructure techniques $\Rightarrow 6.5\%$ at $3\mathrm{ab}^{-1}$ and $27\,\mathrm{TeV}$ Cavaliere et al. '18
- first results from ATLAS 1905.07714 (2σ significance) and CMS 1905.07445

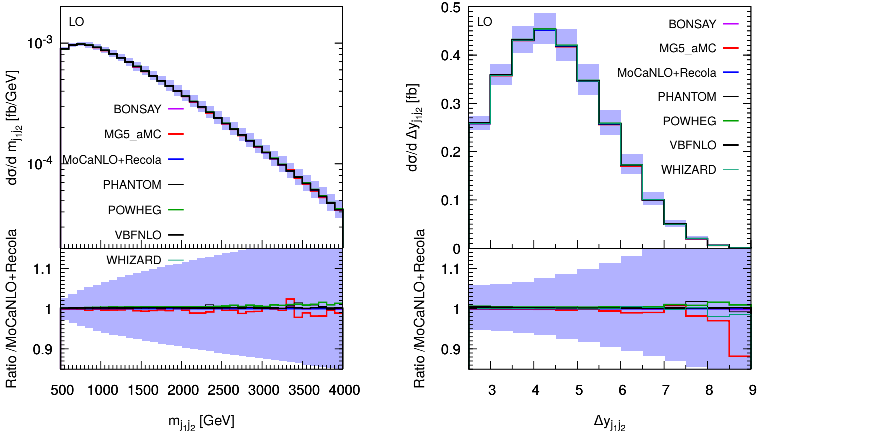
theoretically

- Proliferation of partonic channels in full calculation
  60 quark-induced partonic channels for $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-\mathrm{jj}$,
  + 40 gluon-induced channels (+ b-induced channels)
  even more channels for semi-leptonic final states (4-quark final states)
- LO diagrams of orders $\mathcal{O}(g^6)$, $\mathcal{O}(g^4 g_\mathrm{s}^2)$, $+\,\mathcal{O}(g^2 g_\mathrm{s}^4)$
  $\Rightarrow$ need strategy to simplify calculation
- consider only contributions involving a virtual VV' pair in theoretical calculation to reduce number of contributions
  use double-pole approximation to calculate NLO corrections
  (gauge invariant, accuracy of DPA 1% for $\mathrm{pp} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$)
  $\Rightarrow$ calculation of NLO corrections should be feasible

Vector-boson scattering approximation at LO

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)



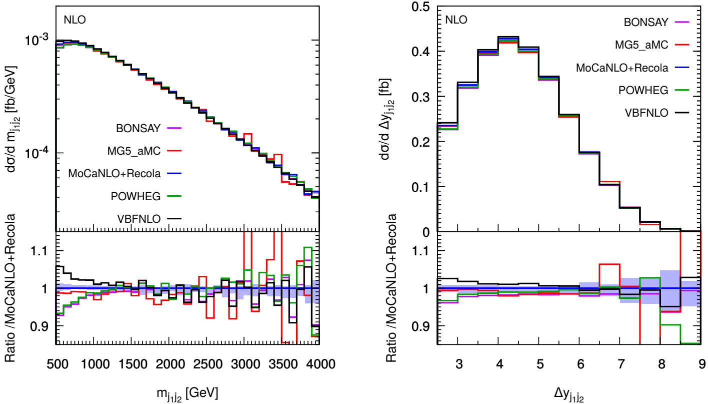
Differences between codes below $\sim 1\%$ in fiducial region

$\Rightarrow$ 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% outside the QCD scale uncertainty band

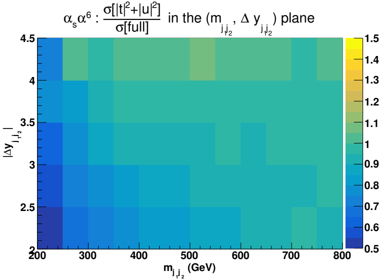
POWHEG, Bonsay: no s channel ⇒ reduction at small M_{jj}

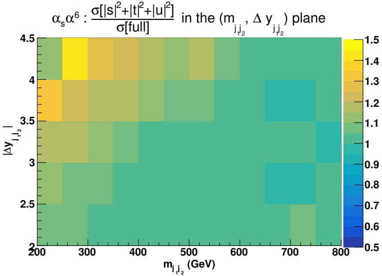
VBFNLO: no interference ⇒ enhancement at small M_{jj}

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)



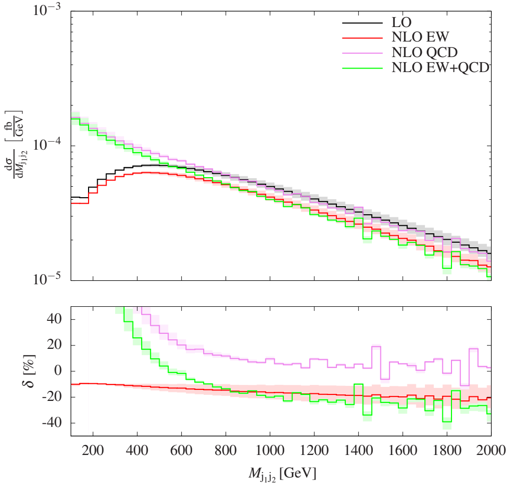


- approximations worse at NLO than at LO:
  difference of up to 20% in fiducial region $M_{\mathrm{jj}} > 500\,\mathrm{GeV}$, $\Delta y_{\mathrm{jj}} > 2.5$
  (gluon bremsstrahlung fakes tagging jet in s channel)
- difference for fiducial cross section: $(M_{\mathrm{jj}} > 500\,\mathrm{GeV},\ \Delta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

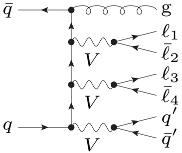
NLO QCD and EW corrections to ZZ production in VBS

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

Denner et al. '20



- Loose VBS cut: $M_{\mathrm{jj}} > 100\,\mathrm{GeV}$ based on 1708.02812 (CMS)
- s-channel NLO contribution involving tri-boson prod.



  Less suppression at NLO owing to extra gluon jet
- 24% NLO QCD corrections to fiducial cross section

$\Rightarrow$ include tri-boson contrib. for loose VBS cuts

Outline

Preliminaries

- All information about polarised cross-sections is within angular distributions of final-state particles.
- Extracting polarised observables simplifies interpretation and theoretical analysis.

Polarized observables

- 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 Electroweak Symmetry Breaking,
- very sensitive to deviations from SM:
  unitarity of cross sections with longitudinally polarised vector bosons realized in SM via cancellation of different contributions

$\Rightarrow$ Extract experimental results for cross-sections with longitudinally polarised vector bosons.

- Massive vector bosons appear only as virtual particles $\Rightarrow$
  - no unique definition of vector-boson polarisations
  - diagrams without resonant vector bosons contribute to physical final state
- vector bosons are massive $\Rightarrow$
  definition of polarisation depends on frame and on mass

Different definitions of polarised cross sections in the literature:

- Definition via projections on LO decay-angle distributions
  Baglio, Le Duc '18, '19
  - tailored to inclusive LO predictions
  - assumes small non-resonant background
  - only applicable for one polarised vector boson
  - results depend on cuts, background and NLO corrections
- Definition based on on-shell production and decay with spin correlations Franzosi et al. [Madgraph] '19
  - neglects non-resonant contributions
  - only available for LO

Definition of polarisation based on pole approximation I

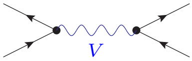
Idea: use pole approximation to extract resonant contributions in gauge-invariant way Ballestrero, Maina, Pellicciolі '17, '19

Formulation developed by Denner, Pellicciolі '20

- Not all diagrams involve required resonances

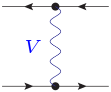
resonant diagrams

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



non-resonant diagrams

$$N(k^2) =$$



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

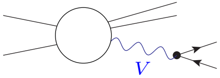
$$\begin{aligned}\mathcal{A} &= \frac{R(k^2)}{k^2 - M^2 + \mathrm{i}M\Gamma} + N(k^2) \\ &= \frac{R(M^2)}{k^2 - M^2 + \mathrm{i}M\Gamma} + \frac{R(k^2) - R(M^2)}{k^2 - M^2} + N(k^2) = \mathcal{A}_{\mathrm{res}} + \mathcal{A}_{\mathrm{nonres}}\end{aligned}$$

- consider non-resonant part as irreducible background: no resonance

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”
- interferences $\sum_{\lambda\neq\lambda'} \mathcal{A}_\lambda^* \, \mathcal{A}_{\lambda'}$
  vanish for quantities fully inclusive in decay products but not in general

Polarisation vectors are defined in specific frames. Natural choices are the (di-boson-)centre-of-mass frame and the laboratory frame.

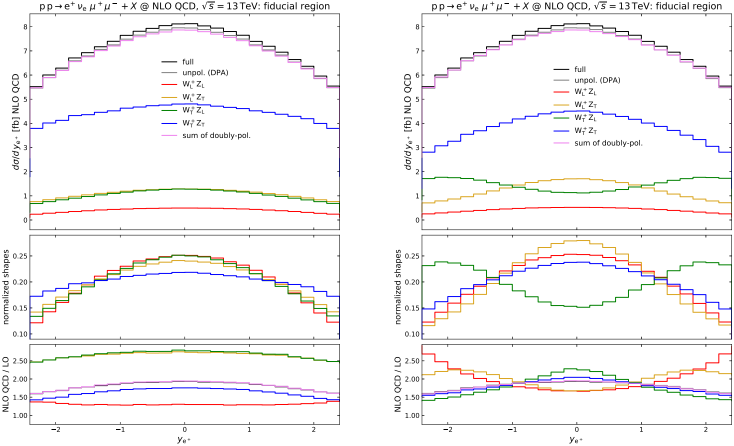
- Method is applicable to arbitrary processes and multiple resonances at LO, NLO and beyond.
- needs pole approximation (or double-pole approximation) for all NLO contributions including subtraction terms!
- results at NLO QCD exist for
  - $\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}$ ($\mathrm{W}^+\mathrm{W}^-$ production) Denner, Pellicciolli '20 and
  - $\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\nu_\mathrm{e}$ ($\mathrm{W}^+\mathrm{Z}$ production) Denner, Pellicciolli '20
- results at LO exist for VBS for ss-WW, WZ, ZZ, os-WW
  Ballestrero, Maina, Pellicciolli '17, '19, '20 [PHANTOM]
- generalisation in progress towards VBS at NLO QCD and NLO EW

Method allows to separate

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

Example results

$\mathrm{pp} \to \mathrm{e}^+ \nu_\mathrm{e} \mu^+ \mu^-$: Distributions in the positron rapidity in the fiducial region for polarisations defined in the CM (left) and in the LAB (right) frame.



Distributions for pol. cross sections defined in different frames differ considerably!

Conclusion

Status of NLO calculations for VBS

- NLO QCD corrections matched to PS available for all VBS processes
  NLO QCD corrections at level of few percent if $p_{\mathrm{T,j}}$ or M_{jj} not small
- VBS approximation might not be sufficient at NLO Ballestrero et al. '18
  NLO-QCD tri-boson contributions of $\mathcal{O}(20\%)$ for loose VBS cuts
- 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
    $\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\mathrm{e}^-\mathrm{jj}$ (ZZ) Denner et al. '20
  - -16% EW corrections for fiducial cross section
    intrinsic feature of VBS, 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
  only measurement of full process is well-defined!

Significant theoretical progress in VBS in recent years!

Expected progress in theoretical predictions to VBS

- NLO EW corrections for $\mathrm{pp} \to \mu^+\nu_\mu\bar{\nu}_\mathrm{e}\mathrm{e}^-\mathrm{jj}$ ($\mathrm{W}^+\mathrm{W}^-$) (in progress)
- predictions for VBS with semileptonic final states (needed?)
- NLO corrections for polarised VBS within reach
- matching to EW parton showers (long term project)
- predictions for VBS within extended models feasible once LO and NLO matrix elements available
- predictions for VBS within SMEFT including (approximative) NLO corrections $\Rightarrow$ need to extend/combine tools

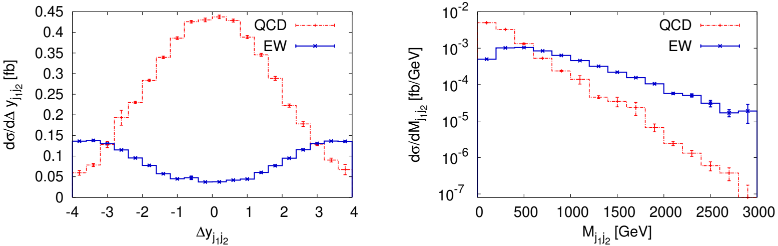
Input on priorities would be useful!

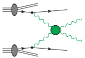
Outline

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

Jäger, Zanderighi '11

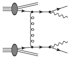
$\sqrt{s} = 7\,\mathrm{TeV}$, NLO QCD, basic cuts: $p_{\mathrm{T},j} > 20\,\mathrm{GeV}$





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:

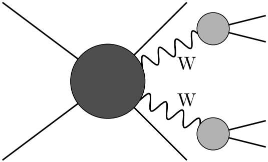
- small rapidity separation Δy_{jj}
- prefers small M_{jj}
- $\sigma_{\mathrm{QCD}}^{\mathrm{inclusive}} = 2.12\,\mathrm{fb}$ 192%
- $\sigma_{\mathrm{QCD}}^{\mathrm{VBFcuts}} = 0.0074\,\mathrm{fb}$ 3.7%

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:

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

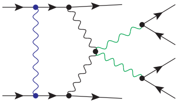
- only contributions with two resonant W bosons $\Rightarrow$ dominant contribution
- momenta in numerator projected on shell $\Rightarrow$ gauge invariance



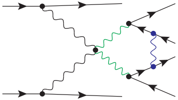
Double-pole approximation for $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}$

NLO:

- factorizable corrections:
  corrections to production
  or decay matrix elements



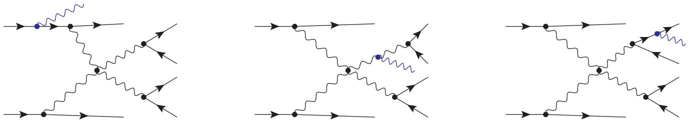
- non-factorizable corrections:
  IR-singular corrections connecting
  production and decay
  $\Rightarrow$ universal correction factors
  Denner et al. ’00; Accomando et al. ’04;
  Dittmaier, Schwan ’15



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

Real EW NLO corrections



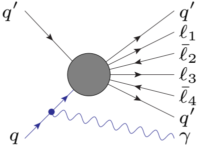
soft and collinear singularities

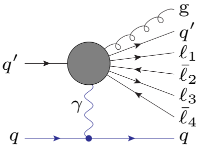
- Catani–Seymour dipole subtraction   Catani, Seymour ’96; Dittmaier ’99
- recombination of collinear parton–photon, lepton–photon, and parton–parton pairs (jet clustering)
  $\Rightarrow$ cancellation of soft and final-state collinear singularities
- initial-state collinear singularities cancelled by $\overline{\mathrm{MS}}$ 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

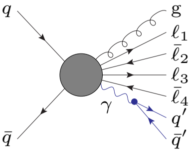
Soft and collinear singularities

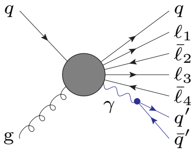
- initial-state collinear singularities ⇒ parton distribution functions



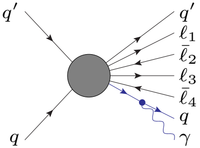


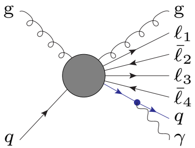
- final-state $\gamma \to q\bar{q}$ splitting ⇒ photon-to-quark conversion function





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





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

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

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

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

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

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

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

Setup for VBS into ZZ

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

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: 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

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

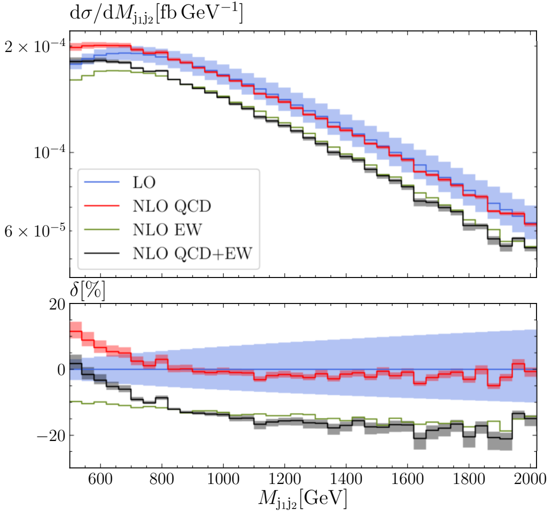
Order	$\mathcal{O}(\alpha^6)$ LO	$\mathcal{O}(\alpha^7)$ NLO EW	$\mathcal{O}(\alpha_\mathrm{s}\alpha^6)$ NLO QCD	$\mathcal{O}(\alpha^7) + \mathcal{O}(\alpha_\mathrm{s}\alpha^6)$ NLO EW+QCD
σ[fb]	$0.2551^{+9.0\%}_{-7.8\%}$	$0.2142^{+8.5\%}_{-7.4\%}$	$0.2506^{+1.0\%}_{-1.0\%}$	$0.2097^{+1.3\%}_{-2.2\%}$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

- large EW corrections similar to $\mathrm{W^+W^+}$ 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 jet–jet invariant mass

Process: $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ $\sqrt{s} = 13\,\mathrm{TeV}$

Denner et al. '19



- $\mathcal{O}(\alpha^7) \sim -18\%$ at $2\,\mathrm{TeV}$ (Sudakov logarithms) dominant correction
- $\mathcal{O}(\alpha_\mathrm{s}\alpha^6) \lesssim 10\%$ 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 $M_{j_1j_2}$

Fiducial LO cross section for ZZjj

Process: $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-\mathrm{jj}$ $\sqrt{s} = 13\,\mathrm{TeV}$ Denner et al. '20

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	$\mathcal{O}(\alpha_s^4\alpha^4)$	Sum
$M_{j_1j_2} > 100\,\mathrm{GeV}$					
$\sigma_{\mathrm{LO}}[\mathrm{fb}]$	$0.097683^{+6.8\%}_{-6.0\%}$	0.008628	1.062478	0.12101	1.28980
fraction[%]	7.57	0.67	82.38	9.38	100
$M_{j_1j_2} > 500\,\mathrm{GeV}$					
$\sigma_{\mathrm{LO}}[\mathrm{fb}]$	$0.073676^{+8.6\%}_{-7.5\%}$	0.005567	0.136143	0.01345	0.22883
fraction[%]	32.20	2.43	59.49	5.88	100

- very large QCD contribution reduced by $M_{j_1j_2}$ cut
- EW contributions even smaller than for $\mathrm{W}^+\mathrm{Z}$ (Z boson)
- small interference (colour and kinematic suppression)
- loop-induced gg contribution reduced by $M_{j_1j_2}$ cut
- photon-induced and bottom contributions ($< 3\%$) omitted

Fiducial NLO cross section for ZZjj

Process: $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-\mathrm{jj}$ $\sqrt{s} = 13\,\mathrm{TeV}$ Denner et al. '20

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha^6+\alpha^7)$	$\mathcal{O}(\alpha^6+\alpha_s\alpha^6)$	$\mathcal{O}(\alpha^6+\alpha^7+\alpha_s\alpha^6)$
$M_{\mathrm{j_1j_2}} > 100\,\mathrm{GeV}$				
$\sigma\,[\mathrm{fb}]$	$0.09768^{+6.8\%}_{-6.0\%}$	$0.08211^{+6.3\%}_{-5.6\%}$	$0.12078^{+3.8\%}_{-3.5\%}$	$0.10521^{+3.0\%}_{-2.8\%}$
$\delta\,[\%]$	100	-15.9	$+23.6$	$+7.7$
$M_{\mathrm{j_1j_2}} > 500\,\mathrm{GeV}$				
$\sigma\,[\mathrm{fb}]$	$0.07368^{+8.6\%}_{-7.5\%}$	$0.06069^{+8.2\%}_{-7.1\%}$	$0.07375^{+1.2\%}_{-1.3\%}$	$0.06077^{+1.2\%}_{-1.6\%}$
$\delta\,[\%]$	100	-17.6	0.1	-17.5

- large EW corrections similar to $\mathrm{W}^+\mathrm{W}^+$ scattering
- QCD corrections large for $M_{\mathrm{j_1j_2}} > 100\,\mathrm{GeV}$, small for $M_{\mathrm{j_1j_2}} > 500\,\mathrm{GeV}$
- corrections are larger in distributions
- bottom-quark contributions omitted (b-tagging)
- photon-induced contributions at NLO omitted (small)