

State-of the art precision calculations for electroweak multi-boson processes



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- Electroweak multi-boson processes
- NLO predictions for VBS processes
- NLO predictions for VVV processes
- Conclusions

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Electroweak multi-boson processes

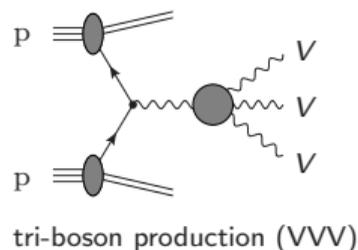
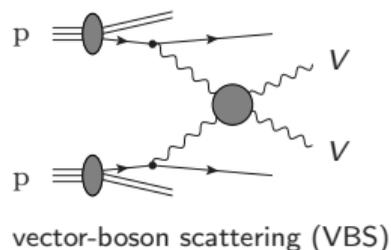
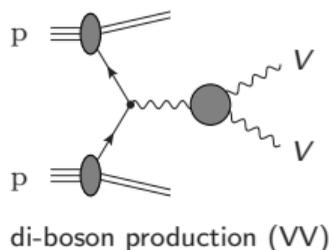
NLO predictions for VBS processes

NLO predictions for VVV processes

Conclusions



Electroweak multi-boson processes



Physics interest:

- ▶ strong sensitivity to **EW gauge-boson self-interaction**
- ▶ window to **EW symmetry breaking (EWSB)** via off-shell Higgs exchange at high energies, complementary to direct analyses of Higgs bosons

Analysis framework:

- ▶ **"SM Effective Theory (SMEFT)"** (or other EFTs) based on SM particle content

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i}{\Lambda^2} \mathcal{L}_i^{(\text{dim}-6)}, \quad \text{effective dim-6 operators}$$

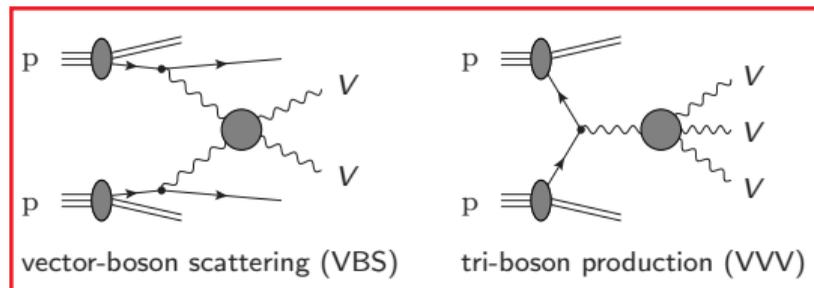
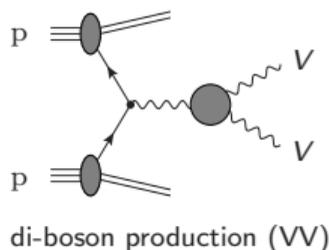
Buchmüller, Wyler '85;
Grzadkowski et al. '10

- ▶ **Specific SM extensions** (extended Higgs sectors, modified EWSB, etc.)

All channels measured by ATLAS & CMS → compatibility with SM

⇒ BSM effects (if accessible) subtle and small → **highest precision required !**

Electroweak multi-boson processes



This talk!

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Buchmüller, Wyler '85;
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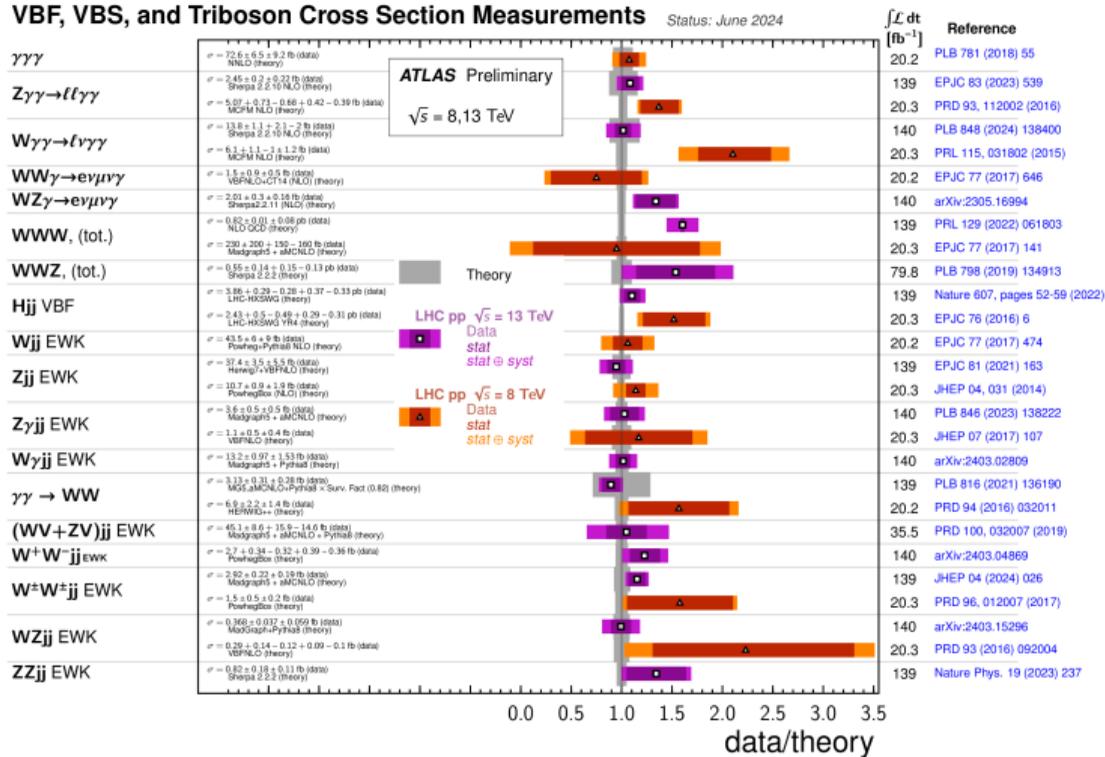
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VBF, VBS, and Triboson Cross Section Measurements

Status: June 2024



- ▶ good overall agreement between SM predictions and data
- ▶ significant increase in precision at HL-LHC

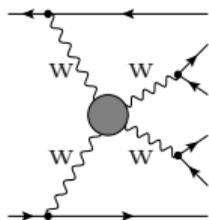
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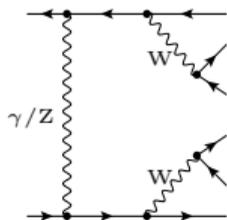


Classification of LO diagrams for $pp \rightarrow VV' + 2\text{jets}$

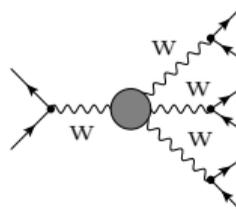
EW channels



VBS channels



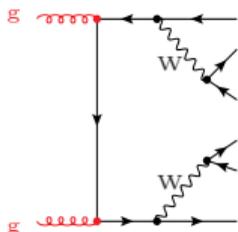
bkg diags



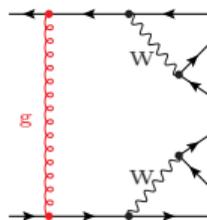
VVV channels

$$|\mathcal{M}_{EW}|^2 \propto \alpha^6$$

QCD channels



not for $W^\pm W^\pm$
production!



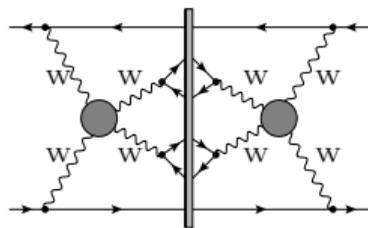
$$|\mathcal{M}_{QCD}|^2 \propto \alpha_s^2 \alpha^4$$

EW-QCD interference \rightarrow colour-suppressed = small $\propto \alpha_s \alpha^5$

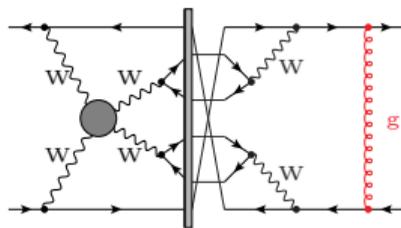
VBS analysis:

EW VBS contribution enhanced via dedicated VBS cuts ($m_{jj} \gtrsim 500 \text{ GeV}$, $|\Delta y_{jj}| \gtrsim 2.5$),
all channels/diagrams included in predictions (at least in LO)

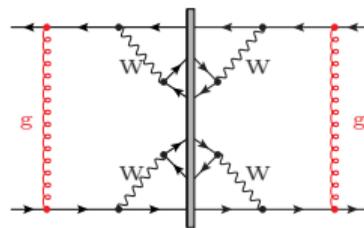
Schematic view of perturbative orders at LO and NLO



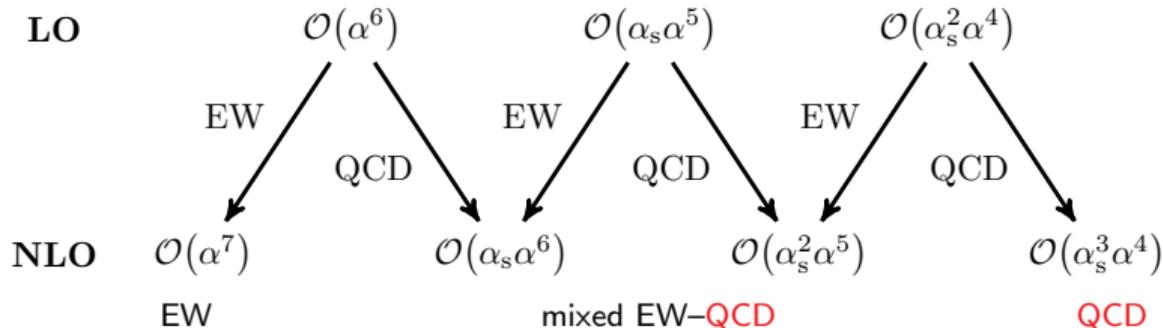
$$\mathcal{M}_{EW}^{LO} \mathcal{M}_{EW}^{LO*}$$



$$\mathcal{M}_{EW}^{LO} \mathcal{M}_{QCD}^{LO*} + \text{c.c.}$$

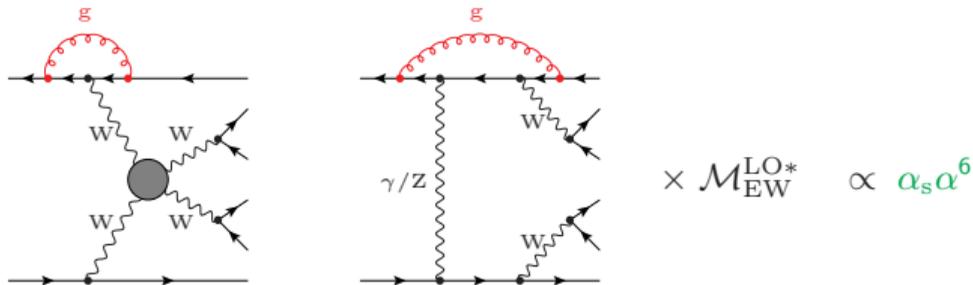


$$\mathcal{M}_{QCD}^{LO} \mathcal{M}_{QCD}^{LO*}$$



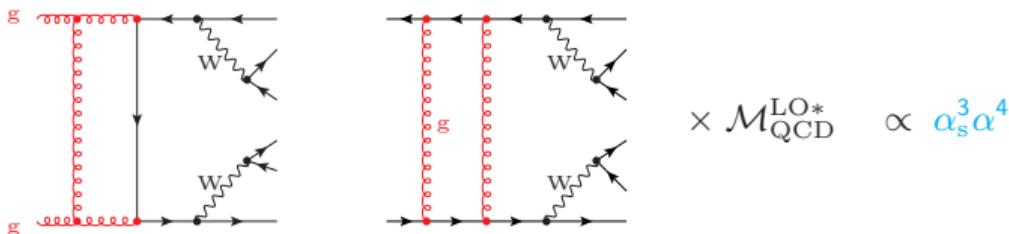
⇒ Tower of mixed EW-QCD corrections at NLO

QCD corrections to EW channels



→ QCD corrections only ~ 5% (little colour exchange between protons)

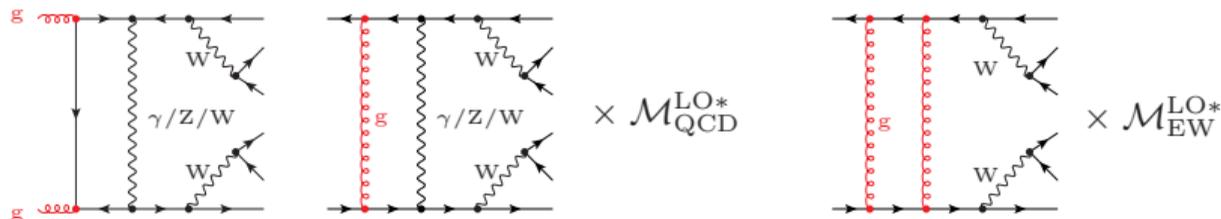
QCD corrections to QCD channels



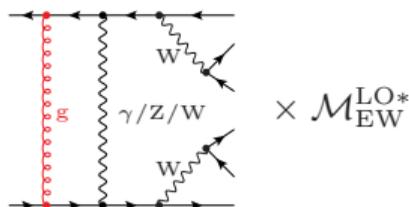
- ▶ no relation to EW VBS subprocess, just QCD $VV + 2jet$ production
- ▶ contribution damped by VBS cuts, but still quite large ($W^\pm W^\pm$ is exception with ~ 10%, since gg channel missing)

NLO corrections of EW and mixed QCD–EW types

Mixed QCD–EW contributions $\propto \alpha_s^2 \alpha^5$



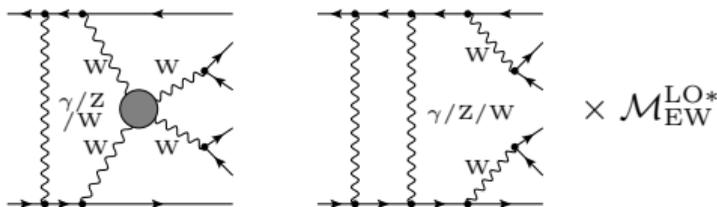
Mixed QCD–EW contributions $\propto \alpha_s \alpha^6$



mixed contributions not VBS enhanced,
colour/kinematically suppressed

\hookrightarrow very small

Purely EW contributions $\propto \alpha^7$



Sudakov-enhanced VBS corrections,
 $\sim -15\%$ (larger in distributions)

\hookrightarrow experimentally relevant!

NLO calculations for VBS processes:

- ▶ genuine QCD corrections available since more than 10 years (several groups)

- ▶ NLO predictions for full NLO tower very challenging, but available

$W^\pm W^\pm$: Biedermann et al. 1611.02951, 1708.00268; S.D. et al. 2308.16716;

WZ : Denner et al. 1904.00882; ZZ : Denner et al. 2009.00411, 2107.10688;

$W^\pm W^\mp$: Denner et al. 2202.10844

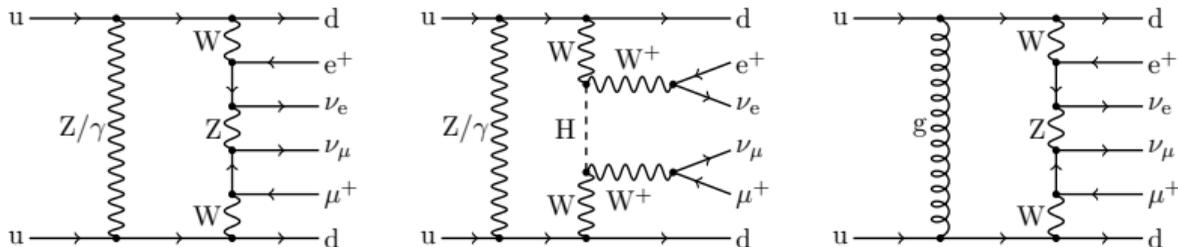
- ▶ Main challenges:

- ▶ **algebraic complexity** (many partonic channels, \sim some 10^5 diagrams)

\hookrightarrow amplitudes from OPENLOOPS2 Cascioli et al. 1111.5206; Buccioni et al. 1907.13071
 or RECOLA Actis et al. 1605.01090; Denner et al. 1711.07388

- ▶ **multi-leg tensor one-loop integrals** (8-point functions)

\hookrightarrow numerically stable evaluation with COLLIER library Denner, S.D., Hofer 1604.06792
 or improved OPENLOOPS2 reduction



NLO corrections and scale uncertainty of integrated cross sections:

W^+W^+ scattering with ATLAS cuts:

S.D. et al. 2308.16716

	order	σ [fb]	δ [%]	Scale uncertainty	
LO	$\mathcal{O}(\alpha^6 \alpha_s^0)$	1.24597(5)		-7.7%	9.9%
	$\mathcal{O}(\alpha^5 \alpha_s^1)$	0.051133(3)		-14.0%	17.7%
	$\mathcal{O}(\alpha^4 \alpha_s^2)$	0.18649(2)		-22.2%	31.6%
	sum	1.48359(5)		-9.8%	12.1%
NLO	$\mathcal{O}(\alpha^7 \alpha_s^0)$	-0.1747(5)	-11.8%		
	$\mathcal{O}(\alpha^6 \alpha_s^1)$	-0.0902(8)	-6.1%		
	$\mathcal{O}(\alpha^5 \alpha_s^2)$	-0.00017(19)	0.0%		
	$\mathcal{O}(\alpha^4 \alpha_s^3)$	-0.0033(7)	-0.2%		
	sum	-0.268(1)	-18.1%		
LO+NLO	sum	1.215(1)		-4.0%	1.5%

EW $\mathcal{O}(\alpha^7)$ contribution is largest NLO correction (soft/collinear W/Z exchange)

$\hookrightarrow \delta_{\alpha^7} = -12\%$ for integrated cross section within VBS cuts

Good description of dominant correction by leading EW high-energy logarithms:

$$\delta_{\alpha^7} \approx -\frac{2\alpha}{s_W^2 \pi} \ln^2 \left(\frac{Q^2}{M_W^2} \right) + \frac{19\alpha}{12s_W^2 \pi} \ln \left(\frac{Q^2}{M_W^2} \right), \quad Q \sim \langle M_{4\ell} \rangle \sim 400 \text{ GeV}$$

Biedermann et al. '16,'17

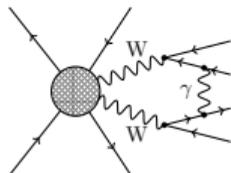
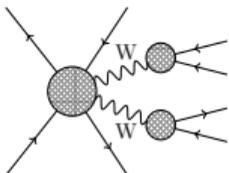
VBS approximation (VBSA)

VBSA = combination of two types of approximation:

▶ “double-pole approximation” (DPA)

↪ leading term of resonance expansion for produced W bosons in virtual corrections

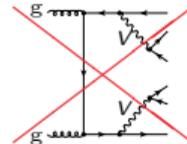
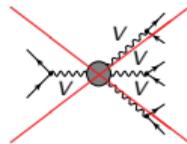
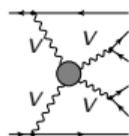
↪ *factorizable* and *non-factorizable corrections* (real corrections without DPA)



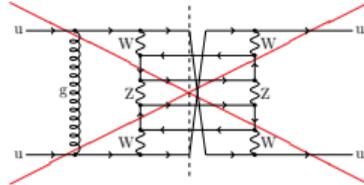
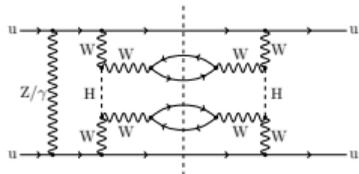
see, e.g.: Denner, S.D, 1912.06823

▶ selection of relevant partonic channels

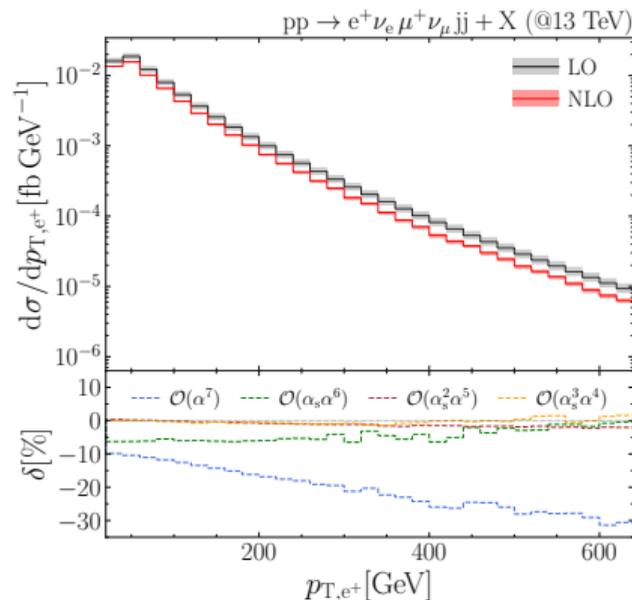
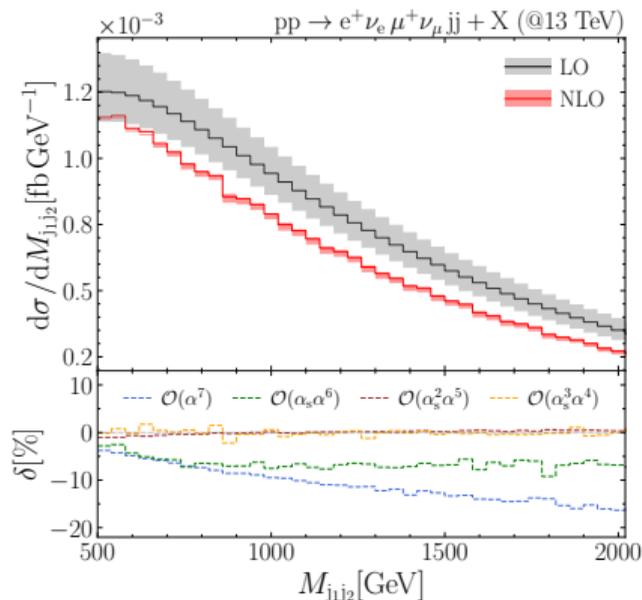
▶ only partonic channels featuring $VV \rightarrow VV$:



▶ no identical-particle interferences:



↪ only $uc \rightarrow W^+W^+ds$ loop amplitudes + crossed variants
+ corresponding γ/g emission graphs (+all $qg/q\gamma$ channels)



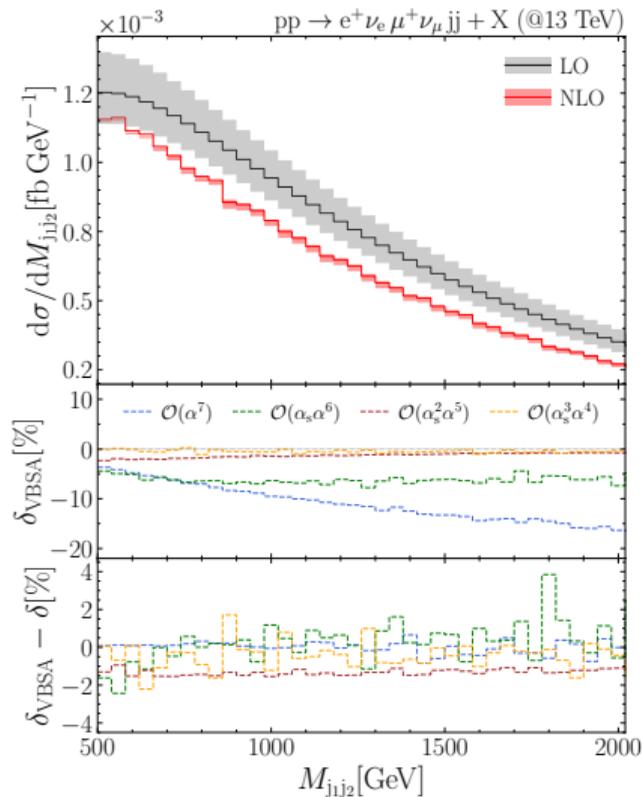
Most important corrections:

$$\mathcal{O}(\alpha^7) = \text{EW correction VBS} \sim 10\text{--}15\%$$

$$\mathcal{O}(\alpha_s \alpha^6) \approx \text{QCD correction VBS} \sim 5\%$$

Full and approximated NLO corrections to $W^+W^+ + 2j$ channel

Invariant-mass and transverse-momentum distributions: S.D. et al. 2308.16716



Quality of the VBSA: $\Delta_{\text{VBSA}} \lesssim 1.5\%$

(Note: quality of the DPA alone: $\Delta_{\text{DPA}} \lesssim 0.5\%$)

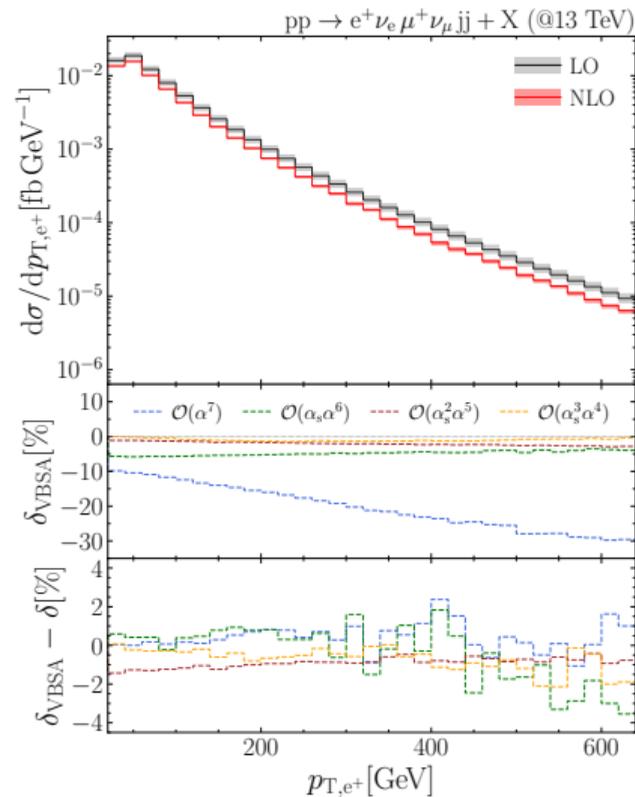


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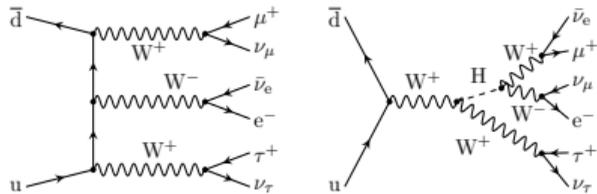
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- NLO predictions for VBS processes
- NLO predictions for VVV processes**
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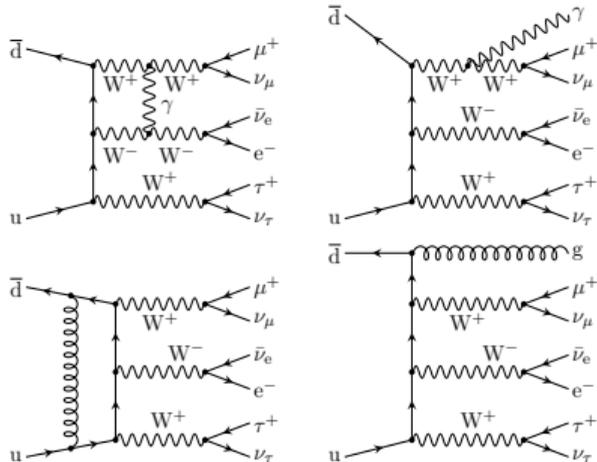
NLO predictions for VVV processes

Graphs for leptonic final states

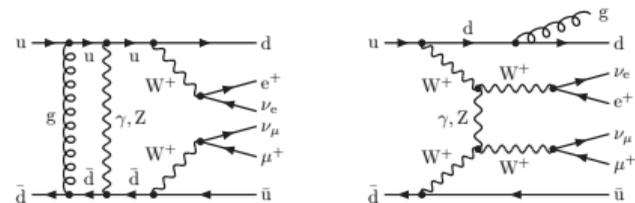
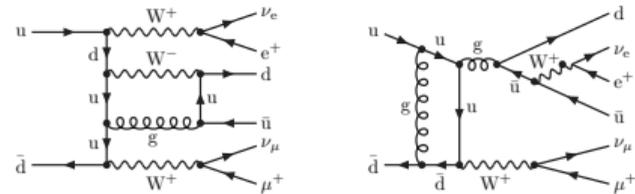
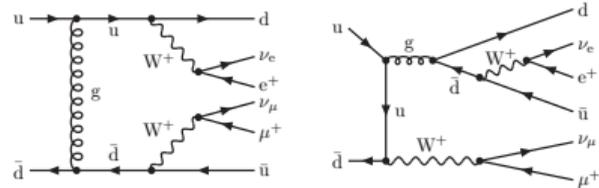
VVV production at LO



VVV production at NLO



+ graphs for semileptonic final states

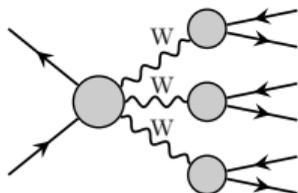


NLO predictions for off-shell VVV production:

leptonic final states

WWW: Campanario et al. 0809.0790 (only QCD);
Schönherr 1806.00307;
S.D. et al. 1912.04117

WWW in triple-pole approximation (TPA):
S.D. et al. 1912.04117



WZ γ : Cheng, Wackerath 2112.12052

semileptonic final states

WWW: Denner et al. 2406.11516

WWZ/WZZ: Denner et al. 2407.21558

NLO corrections to WWW production with leptonic W decays

S.D. et al. 1912.04117

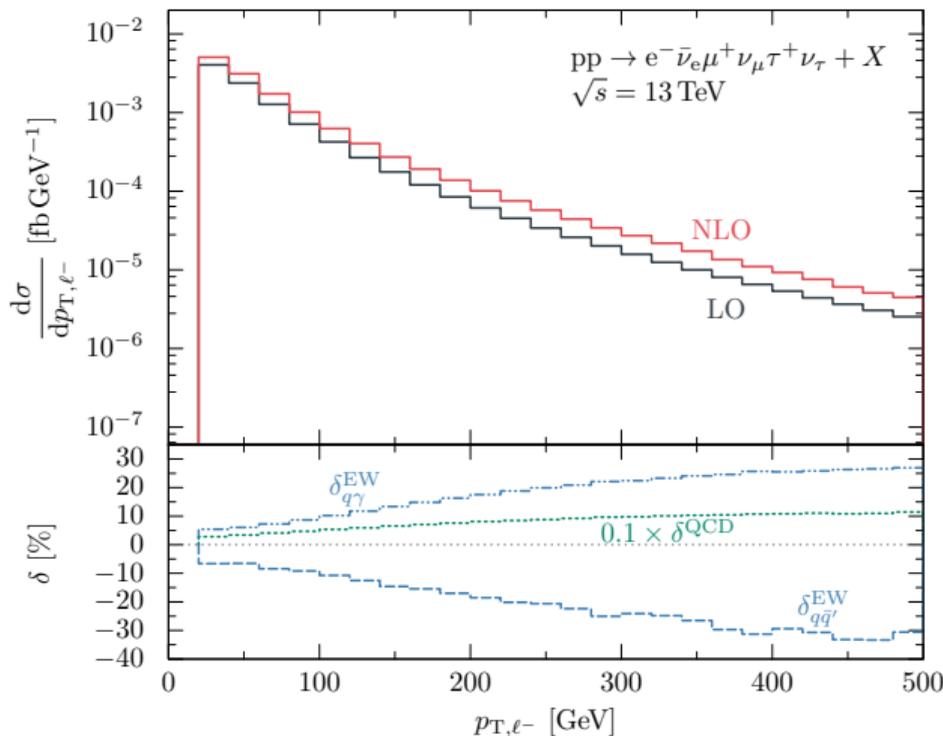
$$W^-W^+W^+: \quad pp \rightarrow e^- \bar{\nu}_e \mu^+ \nu_\mu \tau^+ \nu_\tau + X$$

\sqrt{s} [TeV]	σ_{LO} [fb]	σ_{NLO} [fb]	$\delta_{q\bar{q}}^{\text{EW}}$ [%]	$\delta_{q\gamma}^{\text{EW}}$ [%]	$\delta_{q\bar{q}}^{\text{QCD}}$
13	0.194990(19)	0.2626(10)	-7.7(4)	7.22	38.02(4)
14	0.20982(2)	0.2872(12)	-7.8(4)	7.78	40.04(4)

$$W^+W^-W^-: \quad pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu \tau^- \bar{\nu}_\tau + X$$

\sqrt{s} [TeV]	σ_{LO} [fb]	σ_{NLO} [fb]	$\delta_{q\bar{q}}^{\text{EW}}$ [%]	$\delta_{q\gamma}^{\text{EW}}$ [%]	$\delta_{q\bar{q}}^{\text{QCD}}$
13	0.118411(12)	0.1597(6)	-7.0(3)	7.26	37.17(4)
14	0.129986(13)	0.1779(7)	-7.2(4)	7.73	39.15(4)

$$\Delta_{\text{LO}}^{\text{scale}} \sim 1-2\%, \quad \Delta_{\text{NLO}}^{\text{scale}} \sim 2-3\%$$



- ← sizable γ -induced contribs.
- ← large QCD corrections
- ← large EW corrections (Sudakov logs)

- ▶ rather typical pattern of NLO corrections
- ▶ cancellations between EW corr. in $q\bar{q}$ channels against γ -induced contributions (accidental!)

Semileptonic final states in VVV production

VBS versus VVV in $e^+\nu_e\mu^+\nu_\mu jj$ production

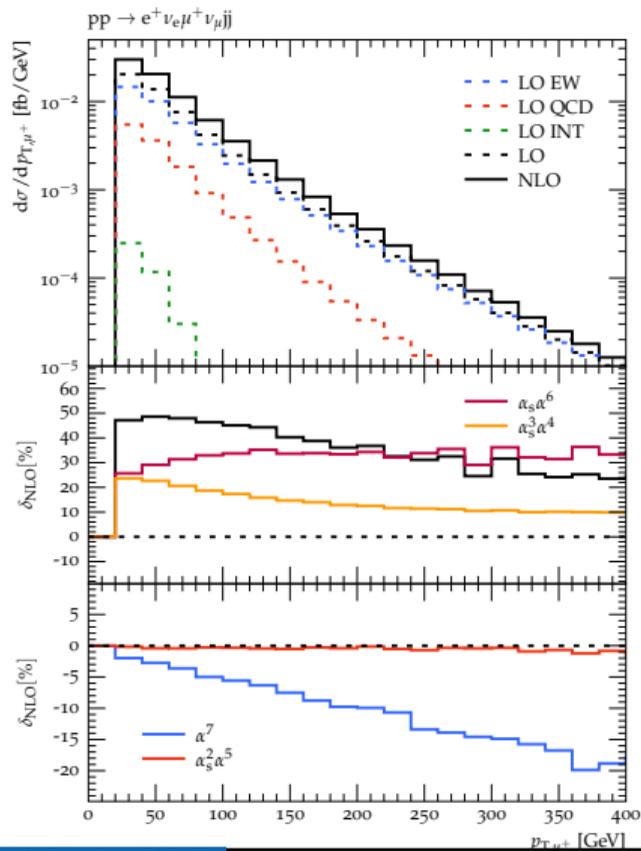
↔ One final state – two different event selections:

	VBS Biedermann et al. 1708.00268 S.D. et al. 2308.16716	VVV Denner et al. 2406.11516
cuts:	$M_{jj} > 500 \text{ GeV}, \quad \Delta y_{jj} > 2$ $M_{\ell\ell} > 20 \text{ GeV}, \dots$	$M_{jj} < 160 \text{ GeV}, \quad \Delta y_{jj} < 1.5$ $40 \text{ GeV} < M_{\ell\ell} < 400 \text{ GeV}, \dots$
LO contribs.:	$\Delta_{EW} \sim 85\%$	$\Delta_{EW} \sim 75\%$ $\Delta_{WWW} \sim 53\% \Delta_{EW}$ $\Delta_{WH} \sim 41\% \Delta_{EW}$
	$\Delta_{QCD} \sim 13\%$	$\Delta_{QCD} \sim 25\%$
EW $_{q\bar{q}\dots}$ corrs.	$\sim -16\% \Delta_{EW} + \dots$	$\sim -7\% \Delta_{EW} + \dots$
EW $_{\gamma}$ -induced	$\sim +3\% \Delta_{EW}$	$\sim +3\% \Delta_{EW}$
QCD corrs.	$\sim -7\% \Delta_{EW}$ $- 2\% \Delta_{QCD} + \dots$	$\sim +39\% \Delta_{EW}$ $+ 87\% \Delta_{QCD} + \dots$
Δ_{scale} :	LO $\sim 10\%$, NLO $\sim 4\%$	LO $\sim 5\%$, NLO $\sim 6\%$

VVV setup for $e^+ \nu_e \mu^+ \nu_\mu jj$ production

Different NLO contributions:

Denner et al. 2406.11516



← very sizable QCD corrections

← very large EW corrections (Sudakov logs)

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Conclusions

Higher-order predictions for VV, VBS, VVV processes:

▶ State-of-the-art:

VV: NNLO QCD \oplus NLO EW \oplus resummations

VBS,VVV: full tower of NLO QCD/EW corrections (this talk)

▶ Radiative corrections:

▶ known for off-shell and on-shell processes

▶ EW: $\sim 15\%$ for integrated EW VBS cross section
 $\sim 10\%–30\%$ in TeV range for VBS & VVV

▶ QCD: $\sim 40\%$ for integrated EW VVV cross section

Some recommendations from theorist's perspective:

▶ use state-of-the-art calculations (at NLO QCD+EW or better)

▶ perform sanity checks \rightarrow compare different calculations (multi-purpose + dedicated MCs!)

▶ do not presubtract/unfold final-state radiation (not properly defined, ruins data for later reanalysis)

▶ if approximations are used, check validity care fully
(pole expansions vs. off-shell calculations, VBS approximations, etc.)

▶ ... communicate with theorists (+ acknowledge relevant theory publications)

Backup slides



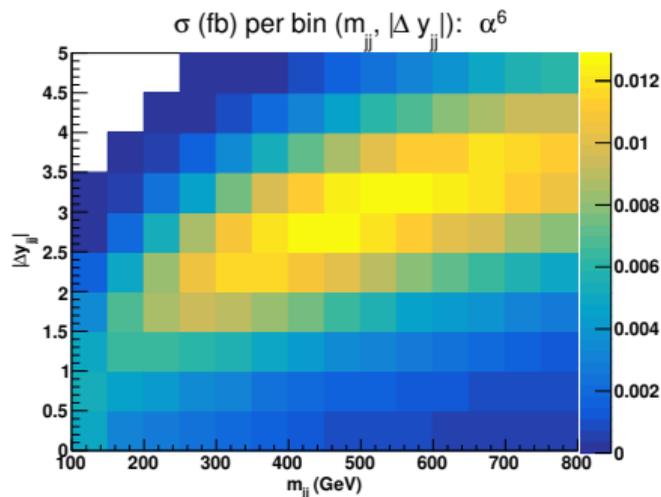
VBS kinematics and VBS cuts

Example: $pp(W^+W^+ \rightarrow W^+W^+) \rightarrow \mu^+\nu_\mu e^+\nu_e + 2\text{jets} + X$ at the LHC

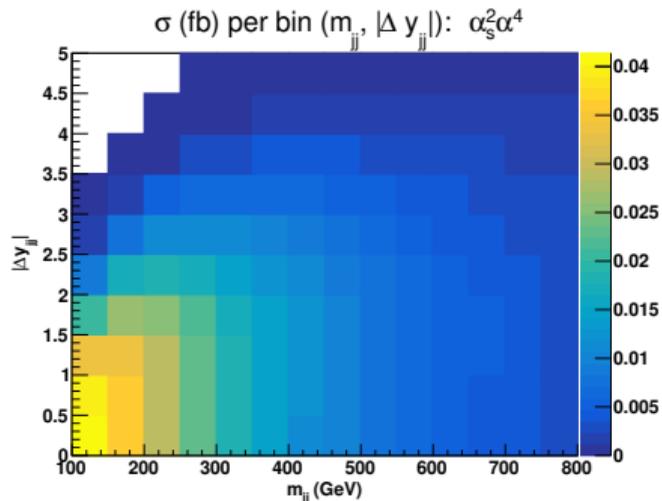
EW VBS versus QCD contributions:

VBSCAN (Ballestrero et al. 1803.07943)

EW VBS contribution:



QCD contribution:



Typical VBS cuts: $m_{jj} > 500$ GeV, $|\Delta y_{jj}| > 2.5 \rightarrow$ hard forward/backward jets

\hookrightarrow Strong suppression ($\lesssim 10\%$) of QCD (and WWW contributions) for $W^\pm W^\pm$ VBS!

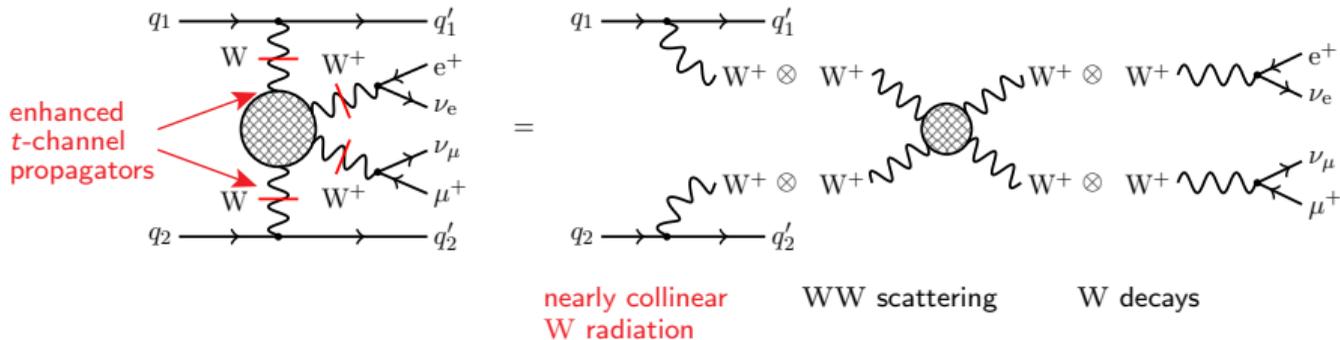
(Note: much weaker suppression for other VBS channels)

Effective vector-boson approximation (EVA) at LO

Basic idea: exploit collinear enhancement of W radiation off (anti)quarks

- ▶ factorization of VBS-like amplitudes

Kane, Repko '84; Chanowitz, Gaillard '84; Dawson '85; Lindfors '85; Kuss, Spiesberger '95; ...



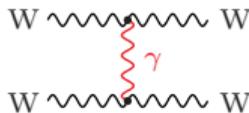
- ▶ neglect of all diagrams without double t -channel enhancement

↪ Reproduction of contributions enhanced by large $\ln(E/M_W)$

Issues:

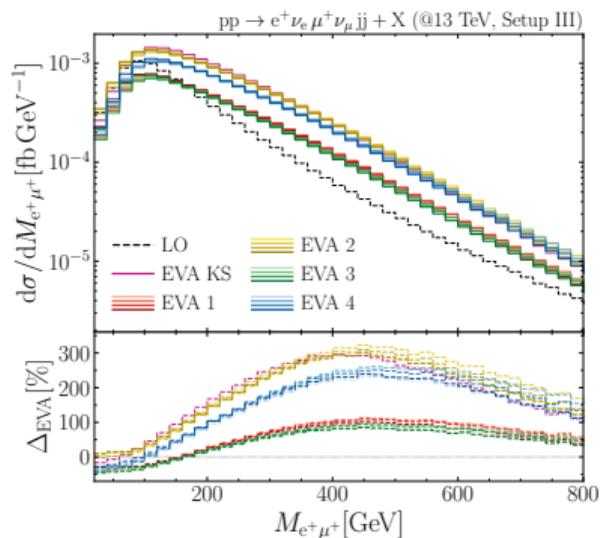
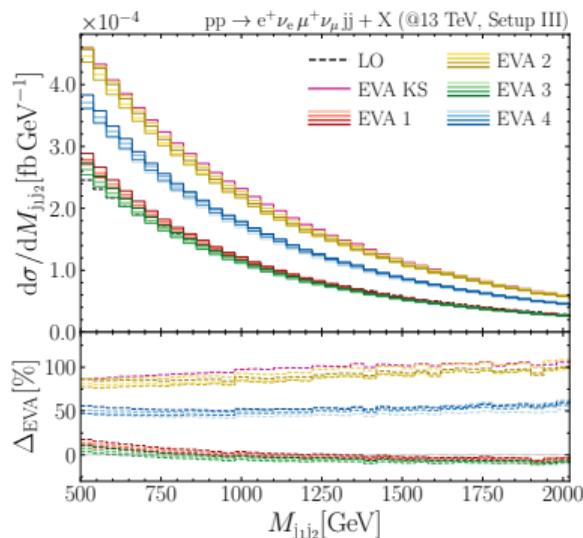
- ▶ on-shell (OS) projection of $qq \rightarrow 2q4\ell$ phase space to $WW \rightarrow WW$ phase space required
- ▶ gauge-invariance requirements for VBS subamplitude $\mathcal{M}_{WW \rightarrow WW}$

- ▶ Coulomb pole in $\mathcal{M}_{WW \rightarrow WW}$



Details of our EVA evaluation at LO: (see arXiv:2308.16716)

- ▶ Different variants for initial- and final-state W bosons
 - ↪ check influence/importance of different choices
 - ▶ OS projections → preserve location of Coulomb pole!
 - ▶ incoming W bosons in $\mathcal{M}_{WW \rightarrow WW}$ → transversality crucial
 - ▶ off-shell polarization vectors for incoming W bosons
 - ↪ always a compromise, never perfect
 - ▶ outgoing W bosons (transversality, OS projection)
 - ↪ minor influence
- ▶ Different phase-space regions:
 - ▶ LHC VBS cuts: $p_{T,\text{jet}1} > 65 \text{ GeV}, \dots$
 - ↪ **Problem:** no collinear jet emission, instead contamination by large $p_{T,\text{jet}}$!
 - ▶ “inverted $p_{T,\text{jet}}$ cuts”: $p_{T,\text{jet}} < 150(100) \text{ GeV}$
 - ↪ only region of collinear jet emission!
 - ↪ EVA has to be “good” in this region → consistency check ✓
- ▶ Numerical comparisons to full $2 \rightarrow 6$ LO predictions and to results from older EVA variant of Kuss/Spiesberger (KS) '95



$\Delta_{\text{EVA}} = d\sigma_{\text{EVA}}/\sigma_{\text{LO}} - 1$, EVA1/3 \rightarrow best choices of EVA variants

- ▶ Integrated cross section: $\Delta_{\text{EVA}}^{\text{LHC cuts}} \sim 100\%$, $\Delta_{\text{EVA}}^{\text{P}_{\text{T,jet}} < 100 \text{ GeV}} \sim 5\%$
- ▶ Differential distributions: **no reasonable approximation for LHC cuts!**

For inverted $p_{\text{T,jet}}$ cuts (where cross section is maximal):

- ▶ jet observables: $\Delta_{\text{EVA}} \sim 10\text{--}20\%$
- ▶ leptonic observables: $\Delta_{\text{EVA}} \sim 50\text{--}100\%$

Note: Earlier results with better approximative behaviour were typically for e^+e^- collisions and/or idealized cuts on W bosons.

NLO predictions for W^+W^+ scattering

NLO predictions for integrated cross sections:

Comparison between two independent NLO predictions for W^+W^+ scattering:

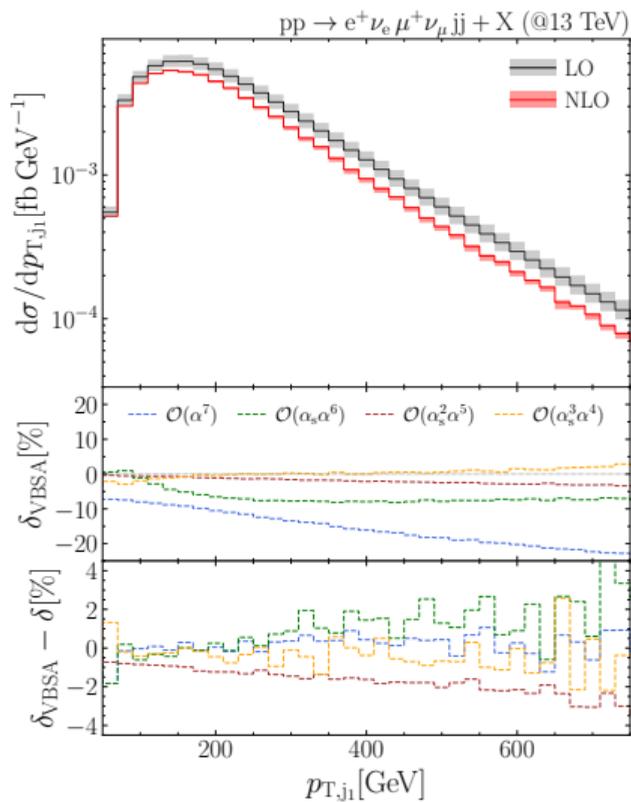
order		σ [fb]	σ [fb]
		Biedermann et al.	S.D. et al.
		1708.00268	2308.16716
LO	$\mathcal{O}(\alpha^6)$	1.4178(2)	1.41773(5)
	$\mathcal{O}(\alpha^5\alpha_s)$	0.04815(2)	0.048138(3)
	$\mathcal{O}(\alpha^4\alpha_s^2)$	0.17229(5)	0.17233(2)
NLO	$\mathcal{O}(\alpha^7)$	-0.1732(3)	-0.1728(6)
	$\mathcal{O}(\alpha^6\alpha_s)$	-0.0568(5)	-0.0560(8)
	$\mathcal{O}(\alpha^5\alpha_s^2)$	-0.00032(13)	0.0047(2)
	$\mathcal{O}(\alpha^4\alpha_s^3)$	-0.0063(4)	-0.0073(2)

issue resolved

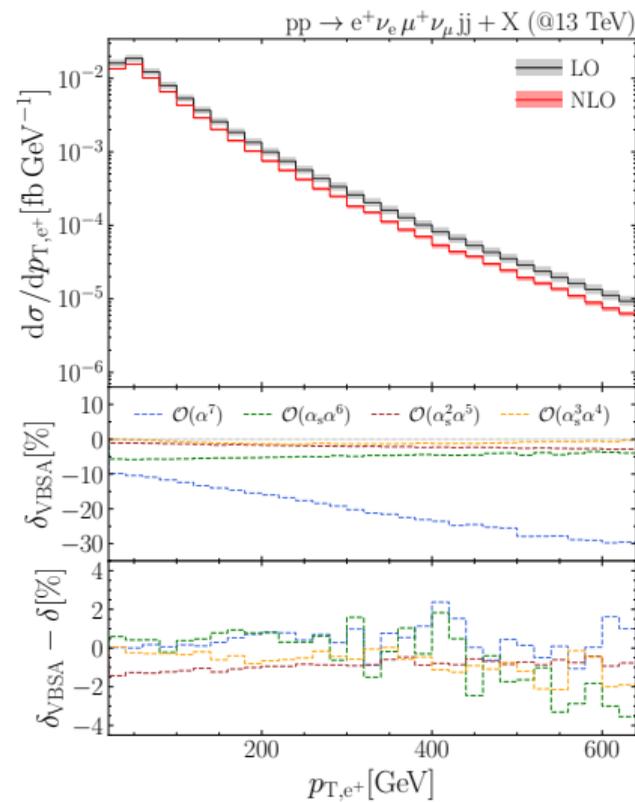
(RECOLA bug fixed by authors)

Agreement at the level of $1-2\sigma$

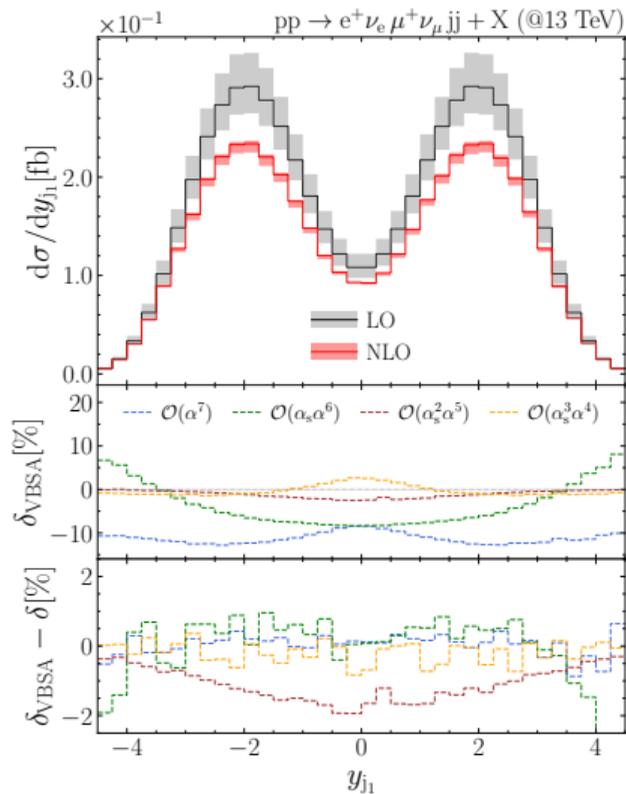
Transverse-momentum distributions:



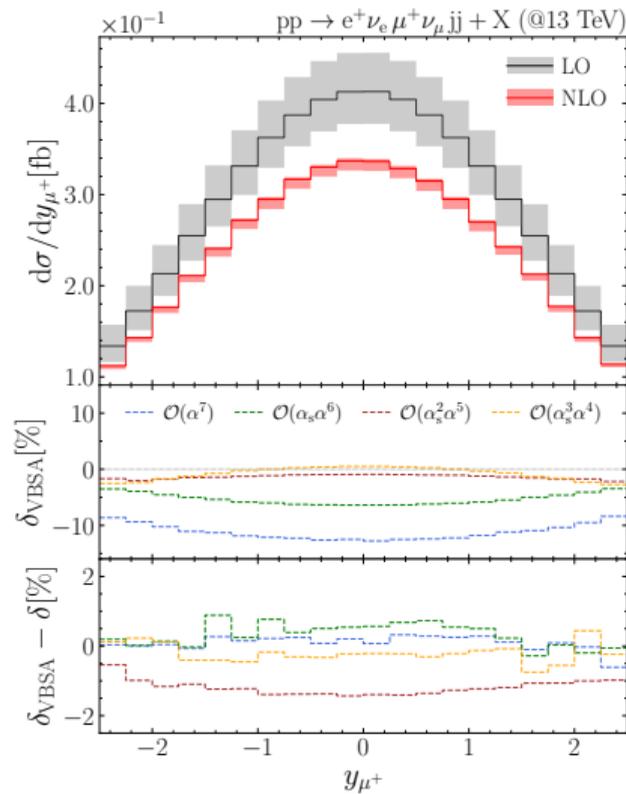
S.D. et al., 2308.16716



Rapidity distributions:

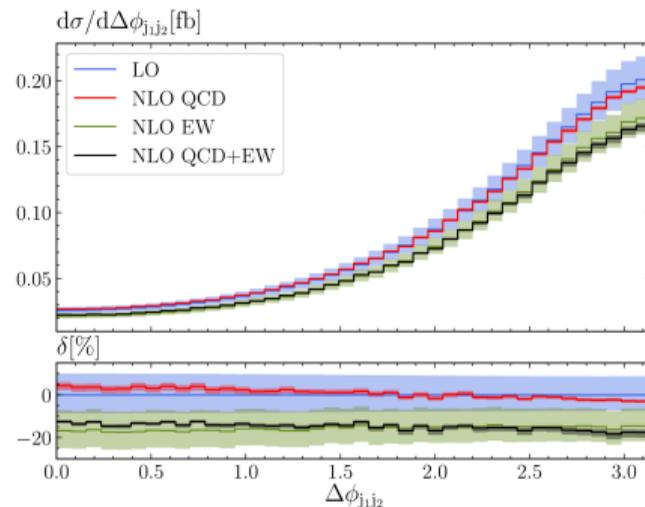
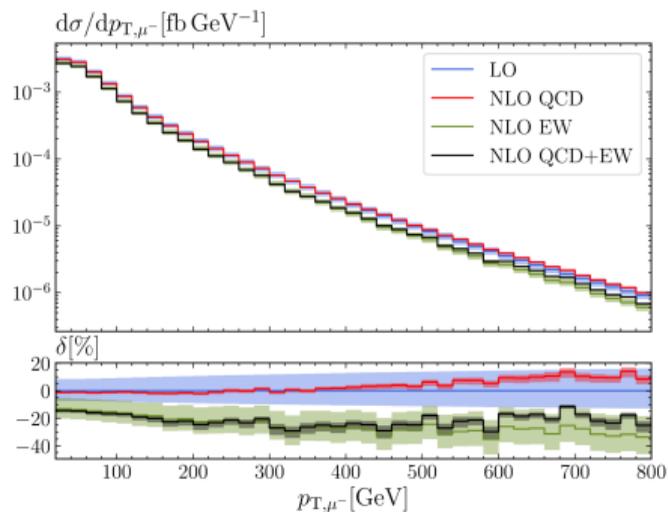


S.D. et al., 2308.16716



LO contributions and NLO corrections to WZ + 2j channel

Denner et al. 1904.00882



- ▶ LO contributions after VBS cuts:

$$\Delta_{\alpha^6} \sim 20\%, \quad \Delta_{\alpha_s \alpha^5} \sim 0.5\%, \quad \Delta_{\alpha_s^2 \alpha^4} \sim 80\%$$

- ▶ Corrections to the EW channel (relative to $\sigma_{\alpha^6}^{\text{LO}}$):

$$\delta_{\alpha^7} = -16\%, \quad \delta_{\alpha_s \alpha^6} = -2\%$$

$W^-W^+W^+$: $pp \rightarrow e^- \bar{\nu}_e \mu^+ \nu_\mu \tau^+ \nu_\tau + X$

\sqrt{s} [TeV]	σ_{LO} [fb]	σ_{NLO} [fb]	$\delta_{q\bar{q}}^{\text{EW}}$ [%]	$\delta_{q\gamma}^{\text{EW}}$ [%]	$\delta_{q\bar{q}}^{\text{QCD}}$
13	0.194990(19)	0.2626(10)	-7.7(4)	7.22	38.02(4)
14	0.20982(2)	0.2872(12)	-7.8(4)	7.78	40.04(4)

$W^+W^-W^-$: $pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu \tau^- \bar{\nu}_\tau + X$

\sqrt{s} [TeV]	σ_{LO} [fb]	σ_{NLO} [fb]	$\delta_{q\bar{q}}^{\text{EW}}$ [%]	$\delta_{q\gamma}^{\text{EW}}$ [%]	$\delta_{q\bar{q}}^{\text{QCD}}$
13	0.118411(12)	0.1597(6)	-7.0(3)	7.26	37.17(4)
14	0.129986(13)	0.1779(7)	-7.2(4)	7.73	39.15(4)

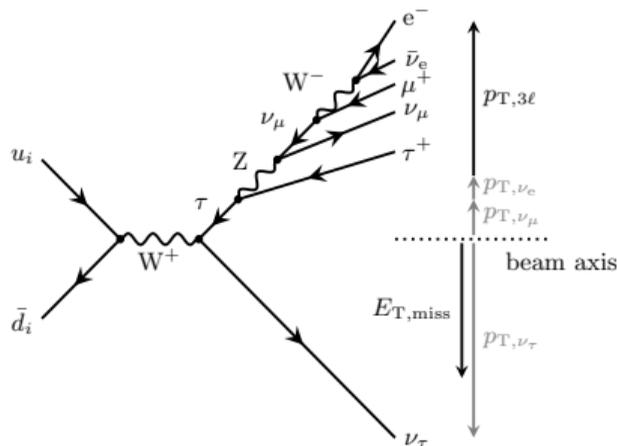
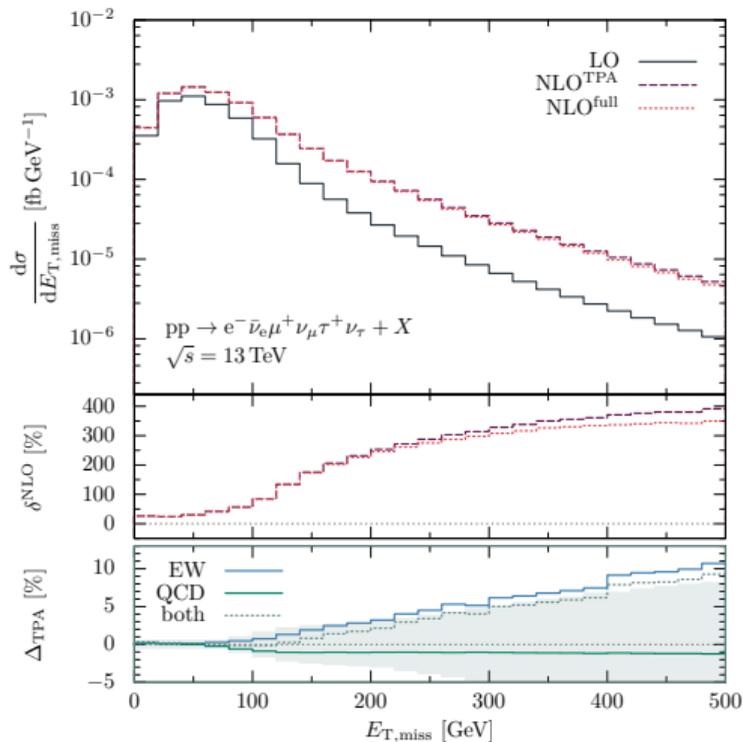
$$\Delta_{\text{LO}}^{\text{scale}} \sim 1-2\%, \quad \Delta_{\text{NLO}}^{\text{scale}} \sim 2-3\%$$

Comparison of different NLO calculations: ($W^-W^+W^+$ channels)

	σ_{LO} [fb]	$\sigma_{\text{NLO QCD}}$ [fb]
Campanario et al. 0809.0790	0.2256(2)	0.3589(4)
S.D. et al. 1912.04117	0.22548(5)	0.35944(14)

	σ_{LO} [fb]	$\delta_{q\bar{q}}^{\text{EW}}$ [%]	$\delta_{q\gamma/\bar{q}\gamma}^{\text{EW}}$ [%]
Schönherr 1806.00307	0.0955	-4.6	2.4
S.D. et al. 1912.04117	0.095480(11)	-8.5(4)	2.3906(11)

issue resolved (SHERPA bug fixed by author) → good agreement



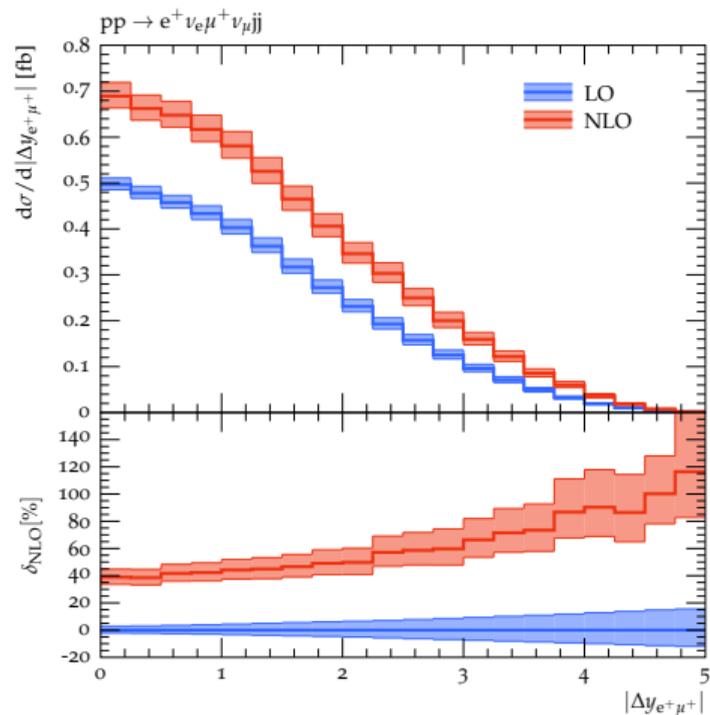
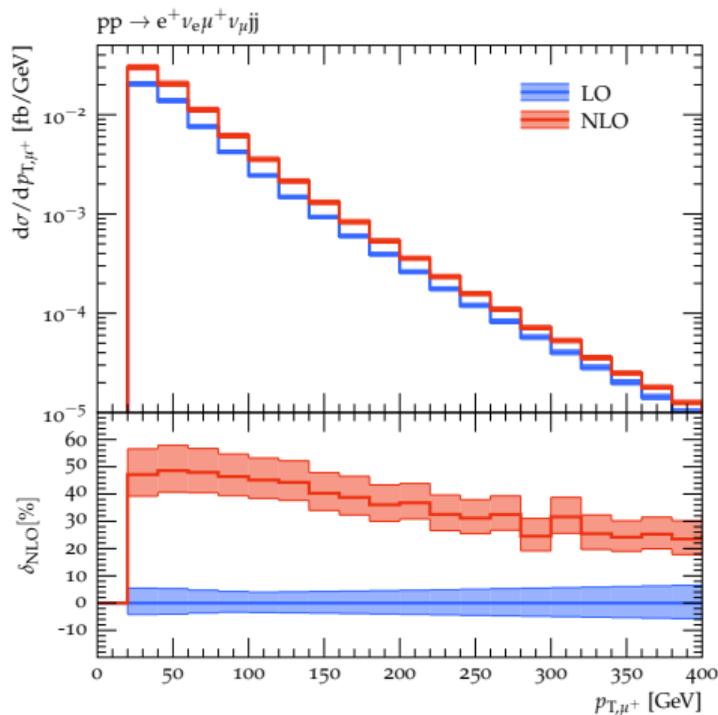
← gray area = estimate $\pm \Delta_{\text{TPA}}^{\text{estimate}}$ of TPA accuracy from LO accuracy $\Delta_{\text{TPA}}^{\text{LO}}$

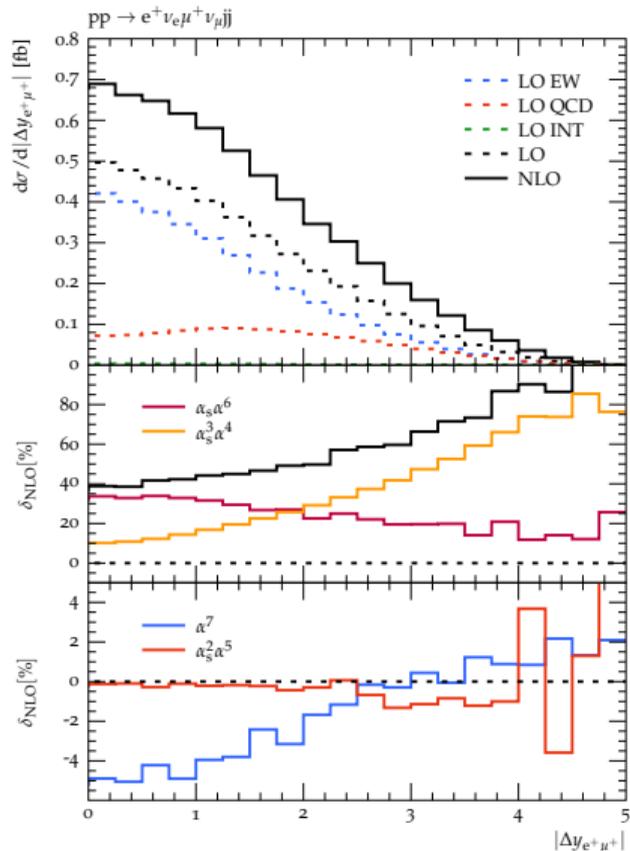
$$\Delta_{\text{TPA}}^{\text{estimate}} = \max \left\{ \underbrace{\frac{\alpha}{\pi} \frac{\Gamma_W}{M_W} c_{\text{EW}}, \frac{\alpha_s}{\pi} \frac{\Gamma_W}{M_W} c_{\text{QCD}}}_{\sim 0.5\%}, \underbrace{\left| \Delta_{\text{TPA}}^{\text{LO}} \Delta_{\text{virt}}^{\text{EW}} \right|, \left| \Delta_{\text{TPA}}^{\text{LO}} \Delta_{\text{virt}}^{\text{QCD}} \right|}_{\Delta_{\text{virt}}^{\text{EW/QCD}} = \text{size of approximated (finite part of) virtual corrections}} \right\}$$

VVV setup for $e^+ \nu_e \mu^+ \nu_\mu jj$ production

NLO corrections and scale uncertainties:

Denner et al. 2406.11516





very sizable QCD corrections

positive impact of γ -induced channels

Brief dictionary of approximations for multi-boson processes:

▶ Narrow-Width Approximations (NWA)

unstable particles = on-shell, $\sigma_{i \rightarrow X \rightarrow f} = \sigma_{i \rightarrow X} \times \text{BR}_{X \rightarrow f}$,

↔ no resonance description, improvements by spin correlations possible

▶ Leading-Pole Approximations (PA, DPA, TPA)

leading terms of expansion about resonances

↔ good description of resonance region, no description of far off-shell tails

▶ Vector-Boson Scattering Approximation (VBSA)

neglect of VVV channels and of t/u interferences in VBS processes

↔ good description of some VBS observables possible, but should be carefully validated

▶ Effective Vector-boson Approximation (EVA)

Weizsäcker–Williams-like (logarithmic) approximation, W/Z like partons in p/\bar{p}

↔ only qualitative predictions at the LHC

▶ Approximation by Goldstone-boson Equivalence Theorem (ET)

Longitudinal vector bosons replaced by Goldstone bosons in high-energy limit

↔ at best qualitative predictions at the LHC